Magnetic levitation by composite element of functional materials

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ABSTRACT

A magneto-electric composite element of functional materials, giant magnetostrictive (GMM) and piezoelectric materials, is developed for magnetic force control. This force control is based on the inverse magnetostrictive effect of GMM and realized by composing a closed parallel magnetic circuit with a permanent magnet in magnetic yoke. The magnetic force between two yokes can be adjusted by controlling the strain in the magnetostrictive rod. For the purpose of efficiently controlling the strain of the GMM rod, a magneto-electric composite element is constructed, in which two active materials, a magnetostrictive rod and a piezoelectric ring actuator, are mechanically coupled via strain. The magnetization in the magnetostrictive rod can be controlled by adjusting the voltage of the piezoelectric actuator. It is confirmed that this element works to adjust magnetic force and has wide frequency bandwidth. As an application of this element magnetic levitation system is proposed and movable yoke was levitated by simple PD control.

INTORODUCTION

Ferromagnetic material deforms in magnetic field, while the magnetization in the material varies with applied stress. The former phenomenon is called magnetostrictive effect and the latter is inverse magnetostrictive effect. Magnetostriction in iron and nickel is in the order of 10 ppm at the largest, but $Tb_xDy_{1-x}Fe_{1.9-2}$ alloy known as giant magnetostrictive material has more than 2000 ppm magnetostriction in room temperature [1][2][3]. Since its discovery, a lot of applications utilizing this large magnetostriction have been proposed in actuators and sensors. However the advantage of magnetostrictive material is that the variation of the magnetization can be converted into different kind of variation as magnetic force via magnetic circuit[4]. We use this effect to develop a composite element of two functional materials: a piezoelectric actuator and a giant magnetostrictive material, which can control magnetic force by only applying voltage to the actuator. This coil-less magnetic force control system is expected to have high energy efficiency and high response inherited from the characteristic of both materials. Furthermore the actuator needs little current in static operation, therefore the element saves much energy and avoids heat generation. In this paper we describe how the magnetic force is adjusted by voltage in the element and show some obtained characteristics of magnetic force. As an application of the element, we also propose a magnetic levitation system using this element to demonstrate its controllability.

Magneto-electric composite element

Primary components of a magneto-electric element include a giant magnetostrictive rod, a ring permanent magnet and a ring stack piezoelectric actuator as shown in Fig. 1. Since both strains of the rod and the actuator are mechanically coupled via prestress mechanism with a washer spring, the stress of the rod can be controlled by adjusting input voltage to the actuator.

In the element, two branches of a parallel magnetic circuit, one consisting of the magnet and the rod, the other the magnet and the gap, are composed. The permanent magnet is used to provide steady-state attractive force between yokes and induce a bias magnetization in the rod. The variation of magnetization in the rod is converted to that of magnetic force in this parallel magnetic circuit. Assuming that leakage flux is negligible, the flux in the gap Φ_g is calculated by simply solving a equivalent magnetic circuit as shown in Fig.2 according to analogy of electric circuit.

$$\Phi_g = \frac{R_m}{R_p\left(R_g + R_m\right)}U_p - \frac{1}{R_g + R_m}U_m \qquad (1)$$

where R_m, R_p, R_g is magnetic reluctance of the rod, the magnet, and the gap which are determined by their shape and permeability, U_p is a constant magnetomotive force of the magnet and U_m is a magnetomotive force varied by stress. The first term on left hand of Eq.(1) is bias flux generated by the magnet and the second term is the flux varying with applied stress. It is clear that the flux in the gap is affected significantly by small change of the magnetization in rod, when R_g and R_m are small. As mentioned above, the stress can be adjusted by the input voltage e, so that Φ_g and attractive force can be controlled by the input voltage. The photograph of the element and the dimensions of the main components are showed in Fig.3.

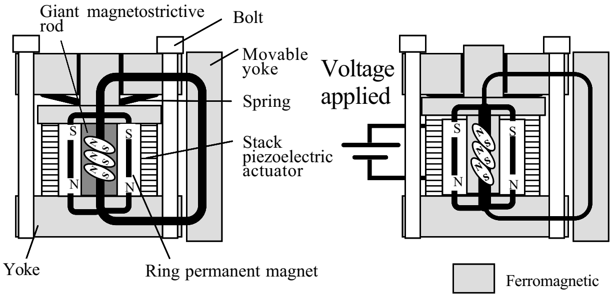

FIGURE 1: Configuration of magneto-electric composite element

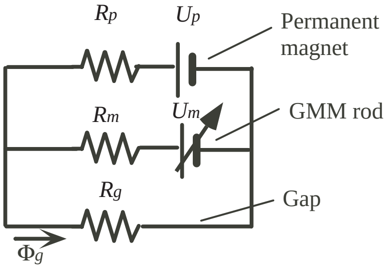

FIGURE 2: Equivalent magnetic circuit

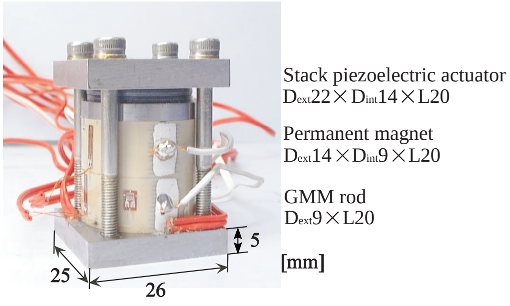

FIGURE 3: Photograph of composite element

Measurement of magnetic force

Figure 4 shows an experimental apparatus used to measure attractive force exerted on the movable yoke. The position of movable yoke is adjusted with a micrometer and measured with a laser sensor. The strain of the rod is measured with 4 strain gages wired in series so as to give average signal. Constant and alternatives voltage up to 1kHz generated by a signal generator is amplified through voltage amplifier and applied to the piezoelectric actuator. Static attractive force is measured with a load cell. In high frequency range, it is impossible to measure the small variation of the force because of the restrictions of resolution and bandwidth of the load cell. Thus the magnetic flux density in the gap is measured instead. A pickup coil is wound around the magnetic yoke and its induced voltage is amplified and integrated for the evaluation of it.

Figure 5 and 6 show measured relationship between the gap and force taken at constant voltage of –100, 0, 100, 200, 300V and the relationship between voltage and force taken at constant gap respectively. The mechanism of the element described above is supported by the result that the force increases with the applied voltage. For the present configuration of the element, maximum force variation of 5N is obtained at 0.2 mm fixed gap. A hysteretic relationship between the voltage and force, which is inherited from the actuator and the magnetostrictive rod, is observed for each gap.

Figure 7 shows the frequency characteristics of amplitude and phase of the strain and the magnetic flux density, which have been normalized by those of 10Hz. The bandwidth of magnetic flux is about 1kHz. Generally magnetization can respond to strain with little delay even in high frequency range. Hence the difference of phase between the strain and the flux density is due to eddy current occurred in the yoke.

Here we summarize the advantage of this element compared with electromagnets.

1) Energy consumption is very low at low driving frequency and almost zero in static operation. Electromagnets need current supply to generate constant force even in steady state.
2) Heat generation is small in low frequency and almost zero in static operation. Electromagnets generate Joule heat in coil.
3) In electromagnet, inductance of coil dominates the response of current, however this element has no coil and response depends on the performance of the actuator used to change the strain of GMM rod.

The performance of the element is mainly dependent on piezoelectric actuator.

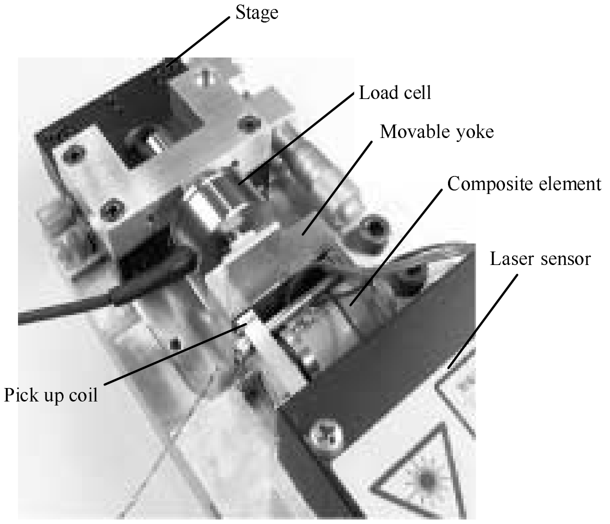

FIGURE 4: Experimental setup to measure attractive force

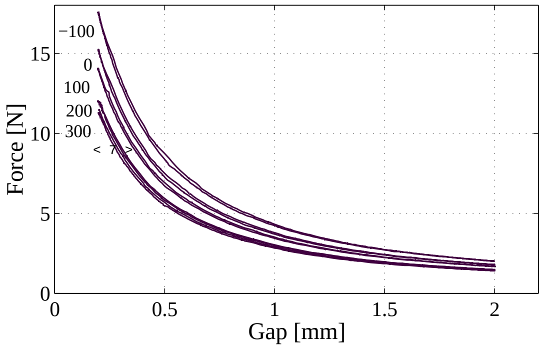

FIGURE 5: Gap vs. Force ¢Voltage fixed £

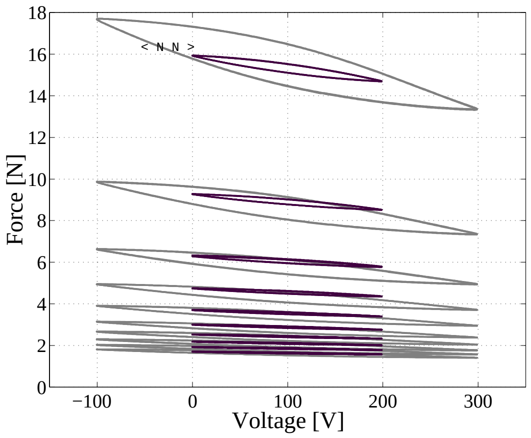

FIGURE 6: Voltage vs. Force ¢Gap fixed £

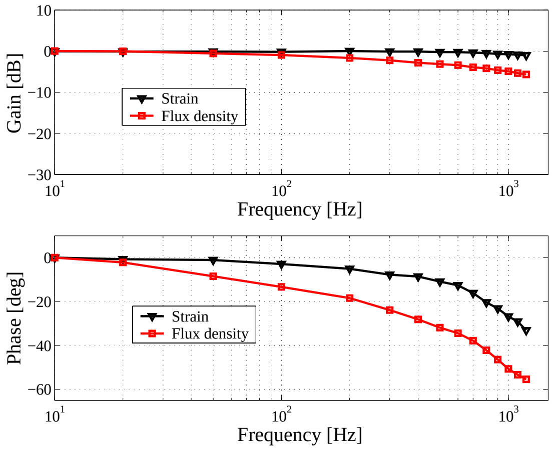

FIGURE 7: Frequency response of strain and magnetic flux density

Magnetic levitation by magneto-electric element

The element has been demonstrated to work efficiently and has wide bandwidth. Since the configuration of the element is similar to electromagnets, it is applicable to a magnetic levitation system. For example, in conventional system using electromagnets, current must be continuously supplied to maintain levitation and this sometimes causes heat generation and energy loss. To save energy, permanent magnets are used in conjunction with electromagnets, so that a bias attractive force is generated by the magnets. The levitation system has same advantages of saving energy and avoiding heat generation. Here we try to control the input voltage so as to balance the attractive force and the gravity acting on levitated object (mass: m). Configuration of the system (Fig.8) is almost same as the experimental setup of Fig.4 except that the element is placed vertically. The input voltage fed to the actuator is calculated by a DSP controller using sensed signal of the gap.

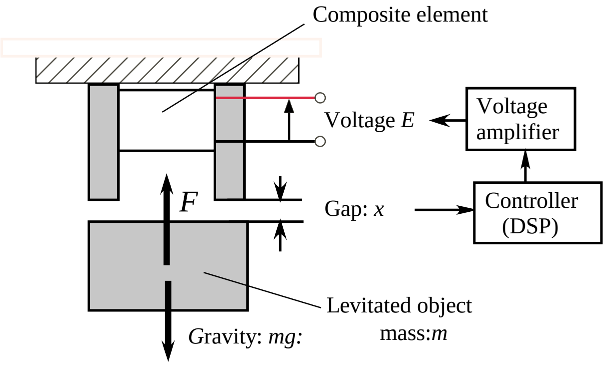

FIGURE 8: Configuration of levitation system

The attractive force F is a function of gap X and voltage E. Assuming that the bias attractive force F_0 is equal to the gravity in operation point P, F can be linearized and kinetic equation around P is written in the form of Eq.(2) considering small variation(*de*,*dx*) from P.

$$m d\ddot{x} = mg - F_0 - dF = -\left.\frac{\partial F}{\partial x}\right|_{E_0,X_0} dx - \left.\frac{\partial F}{\partial e}\right|_{E_0,X_0} de \qquad (2)$$

$$m d\ddot{x} + K_x dx + K_e de = 0 \qquad (3)$$

Here

$$F_0 = mg \qquad (4)$$

$$K_x = \left.\frac{\partial F}{\partial x}\right|_{E_0,X_0}, K_e = \left.\frac{\partial F}{\partial e}\right|_{E_0,X_0} \qquad (5)$$

This system is unstable because K_x is negative in Eq.(2). By applying PD control so that input *de* is a linear combination of *dx* and $d\dot{x}$:

$$de = -k_p dx - k_d d\dot{x} \quad (k_p, k_d > 0) \qquad (6)$$

where K_p and K_d are gains of PD controller. Substitution of Eq.(6) into Eq.(2) gives

$$m d\ddot{x} - k_d K_e d\dot{x} + (K_x - k_p K_e) dx = 0 \qquad (7)$$

This system is stable if

$$K_x - k_p K_e > 0 \qquad (8)$$

In order to design the gain k_p and k_d, we simply obtained K_x and K_e from the slope of *x* versus *F* curve in Fig. 5 and *E* versus *F* curve in Fig.6 at the operation point (1.05mm, 0V). In Fig.9, the attractive force is controlled around P in which k_p is set to 2000, 4000 and 6000 [V/mm]. When k_p is more than 4000, the object is stable, since the inclination of the curve changes from negative to positive. It is desirable to set larger k_p to stabilize the system, but larger k_p makes the range of stabilized gap narrower because of the limitation of input voltage. Figure 10 shows time history of the gap and the input voltage. After released quietly from start point 1.0mm, the object vibrated for a short time and finally became stable about 0.02mm below. Even this system includes some unknown factors such as nonlinearity and hysteresis as shown in Fig.6, the system is modeled as same as that with electromagnets. Hence the element can be easily installed in a conventional magnetic levitation system.

CONCLUSION

In this paper, we developed a magneto-electric composite element of two functional materials: giant magnetostrictive material and piezoelectric material. After the investigation of the static and dynamic behavior of attractive force and magnetic flux, it was confirmed that the element can control the magnetic force by voltage and has wide bandwidth compared with electromagnet. As an application of the element magnetic levitation system using the element is proposed and levitation is achieved by the same method as electromagnets.

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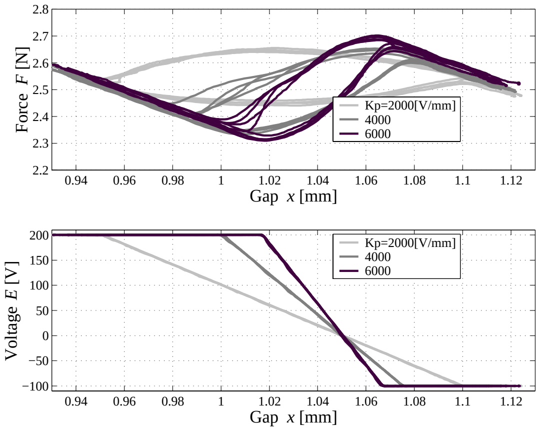

FIGURE 9: controlled attractive force (up) and input voltage(down)

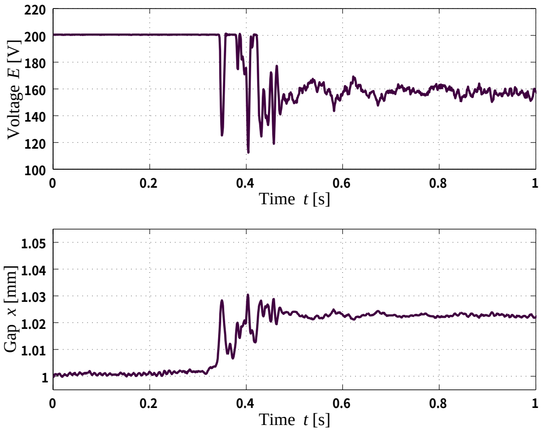

FIGURE 10: Time history of input voltage (up) and the gap(down)