A magnetostrictive–shape memory piezoelectric material composite is proposed to realize a magnetic field memory effect. An imprint electrical field enables a shape memory piezoelectric actuator, and the shape memory effect maintains a certain permeability of the magnetostrictive materials. A new magnetic flux memory effect is generated using a composite of the magnetostrictive–shape memory piezoelectric actuator and a permanent magnet. This magnetic flux memory effect can be operated with a pulsed voltage to the shape memory piezoelectric actuator, so that no energy is consumed to maintain a certain magnetic effect.

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1. Introduction

Ferroelectric materials have multifunctional properties, such as piezoelectricity, large permittivity, nonvolatile charge and electro-optical functions. We have proposed to control the imprint electrical field in order to realize a memory effect of these properties [1–6]. Conventional piezoelectric actuators are driven with a DC voltage to maintain certain positions. However, with the use of imprint electrical field control, a piezoelectric actuator can be operated with a pulse-shaped voltage, so that conventional piezoelectric actuators can have a memory effect.

Magnetic actuators, such as stepping motors, voice coil motors and solenoids are widely utilized in practical applications. Compared to piezoelectric actuators, magnetic actuators realize a long stroke with a relative large output force. However, there are difficulties in miniaturizing magnetic actuators, due to their complicated coil structure. Furthermore, the magnetic coils are operated with current flow, which results in Joule heating problems, and high response is restricted due to impedance from inductance. In recent years, magnetostrictive materials that have giant magnetostriction (over 1000 ppm) have been produced, such as Terfenol-D (Tb1−xDy1−xFe2), and various application have been investigated [7–9]. A voltage controllable mechanism was proposed by using this material with a piezoelectric material and a permanent magnet material [10,11]. In these studies, the shape change induced by the piezoelectric actuator is utilized for change in the permeability of a magnetostrictive material. The permeability change results in a magnetic flux density. This principle has been applied to realize voltage control for a magnetic flux density without coil; however, to maintain a certain magnetic flux density, continuous voltage supply is required.

In this study, a magnetostrictive material was adhered to a piezoelectric actuator similar to the previous research [10,11]. The magnetic permeability of the magnetostrictive material is controllable depending on its strain condition. With a permanent magnet attached to a magnetostrictive–piezoelectric actuator composite, the magnetic flux density can be controlled by the voltage to the piezoelectric actuator. The advantage of this system is a coil-less structure, and voltage operation instead of current operation. The innovative aspect of this study is to apply a shape memory piezoelectric actuator to the system. The shape memory piezoelectric actuator is fabricated with control of the imprint electrical field, which enables the use of a pulse-shaped voltage. By attaching the shape memory piezoelectric to a magnetostrictive material, the magnetic permeability can be operated with a pulsed voltage and the memory effect can be obtained without voltage input. The combination of this composite with a permanent magnet is expected to result in an innovative magnetic actuator with a magnetic memory effect.
2. Principle

2.1. Shape memory piezoelectric actuator

We have already demonstrated a shape memory piezoelectric actuator that utilizes polarization reversal [1–5]. This approach was quite different from that of conventional piezoelectric actuators. The piezoelectric actuator has a completely symmetric butterfly curve, due to the perfect reversal of its polarization, and therefore, it does not have a memory effect. However, with an imprint electrical field, asymmetric butterfly piezoelectric curves are observed [4,5]. The imprint electrical field is an internal electrical field of ferroelectric materials, and is a well-known phenomenon in the field of ferroelectric thin films [12,13]. The imprint electrical field seems to be caused by several factors, such as trapped electrons or holes, lattice defects, lattice
mismatching, etc., and the precise origin has yet to be clarified.

As shown in Fig. 1, the $D-E$ hysteresis characteristics of ferroelectric materials shift to the direction of the electric field axis and become asymmetric with the imprint electric field. This asymmetric feature causes memory effects, not only for the polarization, but also for the piezoelectric strain, permittivity, optical properties, and so on. With an asymmetric butterfly curve, the shape memory piezoelectric actuator has two different stable points of strain at the point of 0 V, depending on its direction of polarization.

There are some important advantages of a shape memory piezoelectric actuator. For example, when a conventional piezoelectric actuator is utilized for a mechanical relay switch, a continuous driving voltage is required to maintain the "on" or "off" conditions. In this case, the energy consumption is not zero, because of the leak current. Moreover, a conventional actuator requires a large DC voltage to maintain a certain position, so that large electric amplifiers are usually required, which consume electrical power.

In contrast, the shape memory piezoelectric actuator does not require any voltages to maintain the "on" and "off" state, because it has two stable positions without electrical input, depending on its direction of polarization. When the switch mode is required to change its state, it is realized by a pulsed voltage that reverses the polarization of the shape memory piezoelectric actuator. After this operation is performed, no electrical field is needed; therefore, the energy consumption to maintain the piezoelectric displacement is zero.

Another advantage of a shape memory piezoelectric actuator is low voltage operation with a combination of a small voltage source, capacitors and transformers. Usually, the voltage required to reverse the polarization is larger than that required to drive a conventional piezoelectric actuator. However, after accumulation of the charge to the capacitor, the charge can then be used for operation of the shape memory piezoelectric actuator through a transformer as a pulse-shaped voltage. Therefore, it is possible to operate a shape memory piezoelectric actuator at low voltage.

2.2. Magnetic flux density memory effect

Magnetostrictive materials are functional materials with magnetic permeability controlled by its strain condition. In the proposed device, the magnetostrictive material is adhered to the shape memory piezoelectric actuator, and the mechanical strain is controlled using the piezoelectric shape memory (Fig. 2). With the addition of a permanent magnet, the magnetic flux density can be controlled as a function of the permeability of the magnetostrictive material.

The proposed system is operated with a pulsed voltage, which is different to that of conventional magnetic devices, so that it is free from Joule heating problems. In addition, the simple coil-less structure is advantageous for miniaturization purposes.

3. Experiment

3.1. Fabrication process of the magnetostrictive–piezoelectric composite

A multilayered lead zirconate titanate (PZT) bimorph type actuator (Nihon Ceratec Co., Ltd., PAB4010), which had three layers on one side, was used for the experiments. The dimensions of the piezoelectric actuator were $0.55 \text{ mm} \times 40 \text{ mm} \times 10 \text{ mm}$, and the thickness of each PZT layer was 0.08 mm.

To apply the memory effect, an imprint electrical field was induced to the actuator with a 280 V DC voltage to the driving electrode at 150 °C for 5 h in an electric oven (Yamato Co., Ltd., DKN302). This method was determined by reference to Kim’s paper [14]. Control of the imprint electrical field was induced, so that the polarization direction of PZT was opposite on each side. The shape memory piezoelectric material and the Terfenol-D magnetostrictive material (Etrema Products Inc., Tb0.3Dy0.7Fe1.92, $1 \text{ mm} \times 30 \text{ mm} \times 5 \text{ mm}$) were attached using an epoxide-based adhesive to form a composite structure.

The magnetic circuit was composed of a permanent magnet (Nd–B–Fe, 0.25 T), silicon steel, a Hall-effect sensor (Toshiba, THS119) and the composite. The magnetic flux density was detected using the Hall-effect sensor (Fig. 3), to examine the possibility of maintaining a magnetic flux density memory. The operating voltage was applied from a function generator (NF Co., Ltd., WF1946) through a voltage amplifier (NF Co., Ltd., 4010). To realize only longitudinal direction and prevent bending, different amplitude driving voltages were applied to each side of the shape memory actuator. One end of the composite actuator was clamped and its piezoelectric displacement in the longitudinal direction was measured using a laser displacement sensor (Canon Co., Ltd., DS-80).

![Fig. 3. Experimental setup.](image)

![Fig. 4. Relationship between piezoelectric displacement and the variation in magnetic flux density with voltage applied to the adhered side.](image)
4. Results and discussion

4.1. Relationship between piezoelectric displacement and magnetic flux density

A triangular voltage of 130 Vpp at 1 Hz was applied to one electrode (adhered side) of the shape memory piezoelectric material. A 30 Vpp voltage of the same phase was applied to the opposite side (reverse side).

The piezoelectric butterfly curve and change in magnetic flux density are shown in Fig. 4. The voltage applied to the reverse side is not shown in the figure. The piezoelectric strain displayed an asymmetric curve, and the change in magnetic flux density had two distinct values at 0 V. The memory value of strain was confirmed as 1.5 μm, and that for the magnetic flux density was 0.5 mT.

4.2. Magnetic flux density memory effect by pulse voltage operation

The magnetic flux density memory was controlled using the pulse voltage driven composite. Positive and negative pulse voltages of 65 Vop (pulse width: 100 ms) at 0.25 Hz were alternately applied to the adhered side of the shape memory piezoelectric actuator, and synchronous voltage of 15 Vop (pulse width: 100 ms) was applied to the reverse side. The magnetic flux density results are shown in Fig. 5. The shape memory composite displayed two distinct stable values depending on the polarization direction. When the pulse voltage was applied, the direction of length was transformed by an asymmetric curve, and the change in magnetic flux density had two distinct values at 0 V. The memory value of strain was confirmed as 1.5 μm, and that for the magnetic flux density was 0.5 mT.

5. Conclusions

A composite comprised of a shape memory piezoelectric actuator attached to a magnetostrictive material was proposed to obtain a magnetic permeability memory effect. The memory effect realizes a magnetic flux density using a permanent magnet. The system was successfully operated under a pulsed voltage. In contrast to conventional magnetic devices, the principle of the proposed device enables operation with a pulsed voltage, eliminating Joule heating problems. The simple coil-less structure is one of the advantages for miniaturization. Optimization of the magnetic circuit is ongoing, with an aim to maintain a larger magnetic flux density memory for practical applications.

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