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## **Keywords**

Precision Machinery Engineering

## **Comments**

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# Investigation of magneto-mechanical properties of Galfenol for coil-less magnetic force control using inverse magnetostrictive effect

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## ABSTRACT

We have been proposing a magnetic force control method using the inverse magnetostrictive effect of magnetostrictive materials. With a parallel magnetic circuit consisting of iron yokes and permanent magnet, the magnetic force exerting on the yoke can be varied by the mechanical stress applied to the magnetostrictive material. The magneto-mechanical property of the material is key of the method which determines the behavior of the magnetic force, such as stress-sensitivity and range of the variation. So far we have used Terfenol-D (Tb-Dy-Fe alloy) for the magnetostrictive material because of the high piezoelectric constant and compliance, and low permeability. Recently, Galfenol, Iron-Gallium alloy with larger magneto-mechanical coupling, low hysteresis and high saturation, is widely noticed for alternative for the Terfenol. In this paper, we discuss the advantages of the Galfenol over the Terfenol in the inverse magnetostrictive properties and demonstrate how they are reflected on the behavior of the magnetic force. The measurements with parameter of gap length in the magnetic circuit clarifies the relationship between the gap and bias of the magnetic force and magnetic field, and the appropriate usage of the Galfenol for practical applications.

**Keywords:** Galfenol, Terfenol-D, inverse magnetostrictive effect, magnetic force

## 1. INTRODUCTION

Electromagnets are essential devices for converting electric energy to mechanical energy and for controlling magnetic forces in various devices. The magnetic force is based on the magnetomotive force on the coils, which is proportional to the number of the turns of the windings and the currents. 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 heating in the coils as a result of their resistance. In controlling magnetic forces during long periods of operation, Joule heating can represent a significant loss of energy. To overcome this problem, we have proposed a method of controlling magnetic forces that does not use coils.<sup>1</sup> This method is based on the inverse magnetostrictive effect of magnetostrictive materials, in which variation of the magnetization of magnetostrictive materials with compressive stress is converted to variations of magnetic force by magnetic circuits. In this method, no energy is required to maintain control of a constant force. We have previously demonstrated the variation of magnetic force using a Terfenol-D<sup>2,3</sup> with a large piezomagnetic constant and small permeability, which produces an adequate magnetic force when unstressed, and allows large variation of the force. For example, the magnetization of the Terfenol reduces from the saturation of 0.7T to nearly 0 by the inverse magnetostrictive effect with compression of around -2000ppm and then the magnetic force increases more than 100% from a bias. The behavior of the magnetic force is dependant on the magnetic, mechanical and magneto-mechanical coupling properties of the magnetostrictive materials. The bias and the range of the variation of the force are determined by the permeability and bias flux density, and the sensitivity of the force against the stress is dependent on the piezomagnetic constant. Therefore, the magnetostrictive material with low permeability, high saturation and high piezomagnetic constant is preferable.

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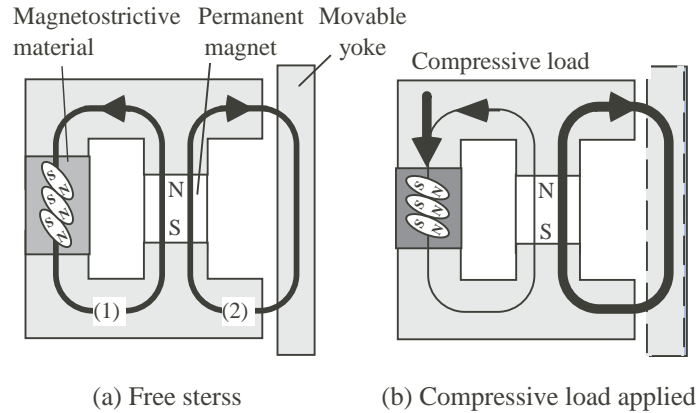
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Recently the Galfenol, Iron-Gallium alloy<sup>4567</sup> is widely noticed for alternative of the Terfenol because of its large magneto-mechanical coupling, low hysteresis loss and high saturation. Even with lower magnetostriction, it is reported that the Galfenol with higher inverse magnetostrictive properties is suitable for sensor usage.<sup>8</sup> In this first part of this paper, we review the formulation of the magnetic force and how the magnetostrictive properties are reflected on the behavior of the magnetic force. In the second part, we show the measurements results of fundamental magnetostrictive properties of the Galfenol and Terfenol and show advantages of the Galfenol in using its inverse magnetostrictive effect. The magnetic forces arising from the compression of the magnetostrictive materials integrated into magnetic circuit are investigated in the third part. The advantages and appropriate condition, such as bias gap and stress ranges, of the Galfenol for practical application are discussed for the design of the magnetic circuit.

## 2. MAGNETIC FORCE CONTROL BY THE INVERSE MAGNETOSTRICTIVE EFFECT

### 2.1. Principle and formulation of magnetic force

A basic magnetic circuit for converting a mechanical load to variation of a magnetic force is shown in Fig.1(a). The magnetic circuit consists of fixed and movable yokes, a permanent magnet, and a magnetostrictive material which exhibits a positive magnetostriction in a magnetic field. Neglecting leakage, two sets of flux loops arise: one consists of the magnet and magnetostrictive material (labeled 1), and the other includes the magnet and the gap (labeled 2). The magnetomotive force of the magnet is used to magnetize the magnetostrictive material accompanied by a magnetostriction and generate a magnetic force between the fixed and movable yokes. For a

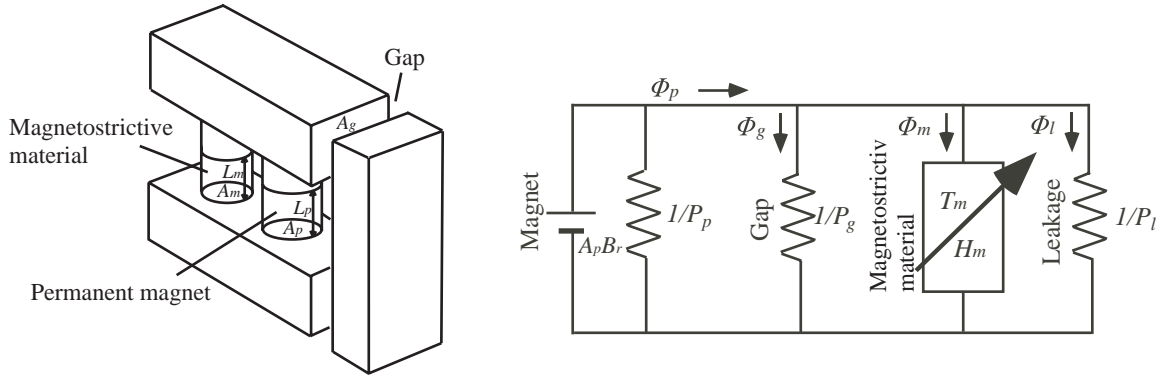


**Figure 1.** Magnetic circuit with free stress (a) and compressive stress (b) on magnetostrictive material.

fixed gap, the sum of the fluxes in two paths is approximately conserved, so that the magnetic force is varied by the magnetization of the magnetostrictive material, which can be controlled by mechanical stress. Application of a compressive stress to a suitably biased magnetostrictive material changes the flux distribution as shown in Fig.1(b); the magnetization of the magnetostrictive material decreases by the inverse magnetostrictive effect, and conversely the flux in path 2, the resulting magnetic force, increases.

Variation in the magnetic force is calculated by solving the equivalent magnetic circuit shown in Fig.2.<sup>9</sup> A parallel leakage path can be taken into account for more accurate calculations. Length and cross-sectional area of the magnetostrictive material, magnet and gap are respectively denoted  $L$  and  $A$ , with subscripts  $m$  (magnetostrictive material),  $p$  (permanent magnet) and  $g$  (gap). The magnetic field, flux density and flux are respectively denoted  $H, B$  and  $\Phi$  with subscripts  $m, p, g$  and  $l$  (leakage). The temperature is taken to be constant. The flux density  $B_m$  of the magnetostrictive material varies with  $H_m$  and the compressive stress  $T_m$  according to the inverse magnetostrictive effect:

$$B_m = B_m(H_m, T_m) \quad (1)$$



**Figure 2.** Parameters and equivalent magnetic circuit.

The demagnetizing curve in the second quadrant for the magnet gives the relation between  $B_p$  and  $H_p$  as

$$B_p = B_r + \mu_r H_p \quad (2)$$

where  $\mu_r$  is the recoil permeability and  $B_r$  is the remanent induction. By applying Kirchoff's law to the leakage and air gap flux paths, the relation between magnetomotive forces is written as

$$U_p + U_g = U_p + U_l = 0 \quad (3)$$

The sum of the fluxes  $\Phi_m, \Phi_g$  and  $\Phi_l$  is equal to  $\Phi_p$ ;

$$\Phi_p = \Phi_g + \Phi_m + \Phi_l \quad (4)$$

Substitution of (2) and (3) into (4) and  $\Phi = PU$  yield the relation between  $\Phi_g$  and  $\Phi_m$  as

$$\Phi_g = \lambda (A_p B_r - \Phi_m) \quad (5)$$

where

$$\lambda = \frac{P_g}{P_g + P_l + P_p} \quad (6)$$

Eq.(5) shows that  $\Phi_g$  is a linear function of  $\Phi_m$  with slope  $-\lambda$  determined by the components of the magnetic circuit excluding the magnetostrictive material. The magnetic force  $F_g$  is therefore

$$F_g = \frac{1}{\mu_0 A_g} \Phi_g^2 = \frac{1}{\mu_0 A_g} (\Phi_{g0}^2 + 2\Phi_{g0} d\Phi_g + d\Phi_g^2) \quad (7)$$

where  $\Phi_{g0}$  is the bias gap flux provided by the magnetomotive force of the permanent magnet with free stress. The first term of (7) is a bias force  $F_{g0}$  and the third term is negligible when  $\Phi_{g0} \gg d\Phi_g$ . The variation  $dF_g$  follows by substituting (5) into the second term of (7),

$$dF_g = \frac{2\Phi_{g0}}{\mu_0 A_g} \lambda d\Phi_m \quad (8)$$

Unless the gap is changed,  $H_m$  is constant. Hence,  $dF_g$  varies only with the stress  $T_m$  for a fixed gap, and can be written as

$$dF_g = \frac{2\Phi_{g0}}{\mu_0 A_g} \lambda \times A_m dB_m|_{H_m} \quad (9)$$

$dF_g$  of (9) is the product of two terms. The first term depends on the geometries and permeability of the components of the magnetic circuits. The second term  $A_m dB_m$  is the change of flux of the magnetostrictive

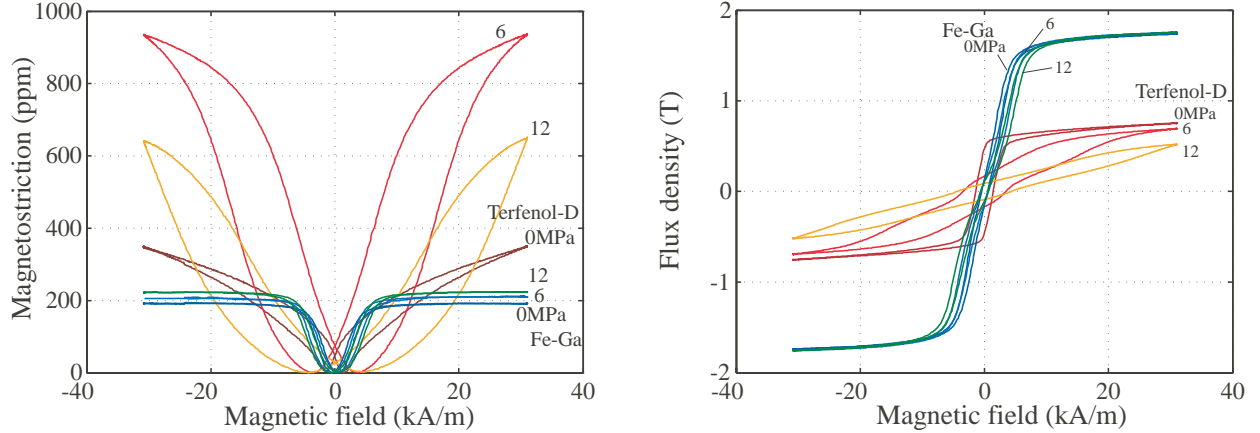
material with stress at constant field. According to (9), small permeability is required for the magnetostrictive material to produce adequate (not zero)  $\Phi_{g0}$  for a bias force. (if the permeability is large, no flux passes in the gap.) In addition, because the variation range of the magnetic force  $dF_g$  is determined by that of the flux density  $dB_m$ , large saturation is preferable for the magnetostrictive material. (The maximum variation of  $dB_m$  by the inverse magnetostrictive effect is regarded as the saturation.) The change of the flux density  $dB_m$  is decomposed as

$$dB_m = \left. \frac{\partial B_m}{\partial T_m} \right|_{H_m} dT_m = \left. \frac{\partial B_m}{\partial S_m} \right|_{H_m} \left. \frac{\partial S_m}{\partial T_m} \right|_{H_m} dT_m \quad (10)$$

where  $\partial B_m/\partial T_m|_{H_m}$ ,  $S_m$  and  $\partial S_m/\partial T_m|_{H_m}$  respectively denote the piezomagnetic constant  $d^H$ , strain and compliance  $s^H$  of the magnetostrictive material. This means that the sensitivity of the variation of the magnetic force with applied mechanical stress is determined by the magneto-mechanical coupling properties of the magnetostrictive material.

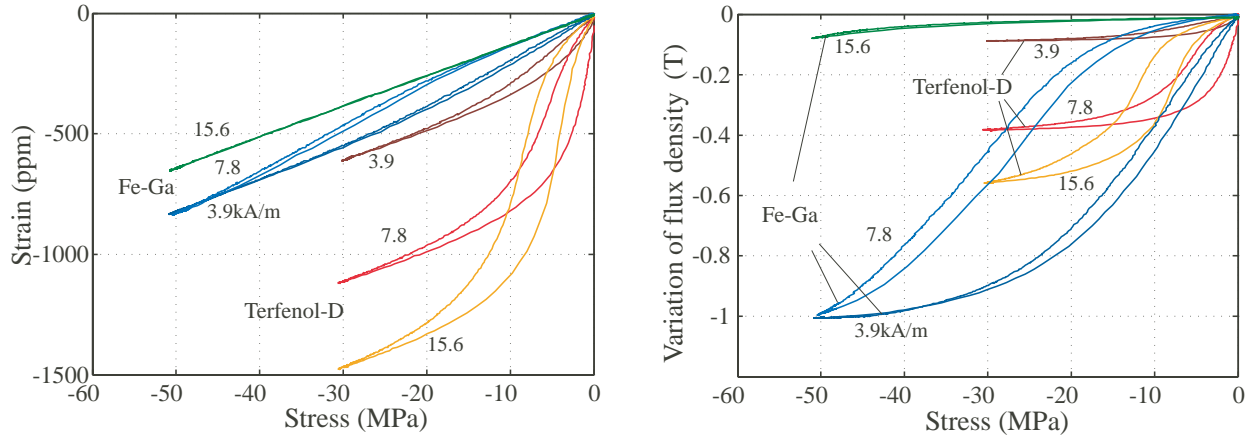
## 2.2. Comparison of magnetostrictive materials

We make comparison of the magnetic, mechanical and magneto-mechanical coupling properties of two magnetostrictive materials, Terfenol-D ( $Tb_{0.3}Dy_{0.7}Fe_2$ ) and Galfenol ( $Fe_{81.6}Ga_{18.4}$ ). The strain and flux density of the rod of the sample, diameter of 8mm and length of 50mm, grain oriented in the longitudinal direction were measured by an experimental setup using solenoid coil and a hydraulic jack. In the experiments, the maximum compressive stress was limited 50 MPa because of the elastic limit of prestressing springs. Figure 3 shows magnetostriction and flux density with a magnetic field under prestress of 0,6 and 12MPa. The magnetostriction of the Galfenol of around 200ppm is much smaller than that of the Terfenol while the saturation of the Galfenol of 1.7T is much larger than that of the Terfenol. The permeability at zero stress of both materials is almost same, however their decrease in this range of the prestress is larger in the Terfenol.



**Figure 3.** Magnetostriction (left) and flux density (right) vs. magnetic field under constant stress.

Figure 4 shows the compressive strain and decrease of the flux density with compressive stress under constant magnetic field. The behavior of  $d^H$  and  $s^H$  is strongly affected by bias magnetic field and  $s^H$  generally tends to take large value where  $d^H$  is large. Comparison at low magnetic fields shows us advantages of the Galfenol over the Terfenol in the inverse magnetostrictive effect. Compression of the Galfenol up to 30MPa at  $H_m = 3.9$  and 7.8kA/m yields the decrease of the magnetization of 0.9 and 0.5T respectively, while that of the Terfenol does decrease of 0.08 and 0.4T. In addition, the Galfenol then requires less mechanical work than the Terfenol due to the small compliance. Therefore the energy conversion efficiency defined by the output magnetic energy/ input mechanical energy of the Galfenol is much larger than that of the Terfenol. In addition, the expected maximum decrease of the magnetization of the Galfenol (almost equal to the value of the saturation) is much larger than that of the Terfenol. As indicated in  $H_m = 15.8$ kA/m, the magnetization of the Galfenol at low compressive



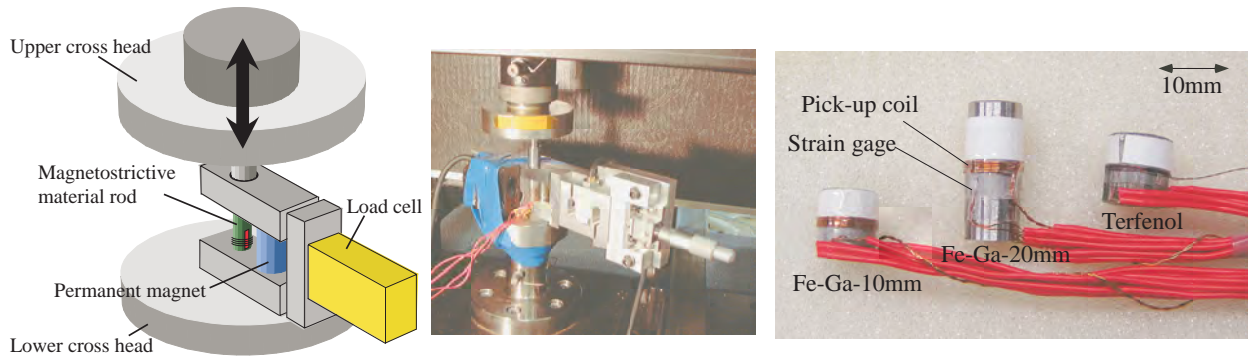
**Figure 4.** Strain (left) and variation of flux density (right) vs. stress under constant magnetic field.

stress remains constant and begin to decrease from "critical stress". Atulasimaha *et al* examined the behavior of the magnetization with higher stress and magnetic field.<sup>8</sup> They explain the stress range which yields the decrease of the magnetization is shifted higher with magnetic field because the mechanical work necessary to begins domains orientation increases. Thus operating stress range must be appropriately chosen according to the applied magnetic field to make full use of the inverse magnetostrictive properties of the Galfenol.

### 2.3. Measurement of magnetic force variation

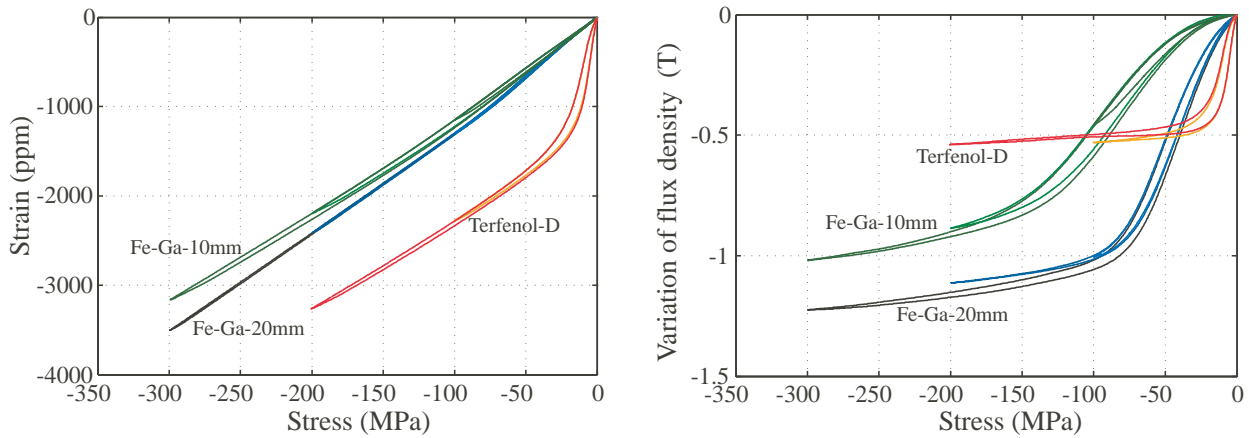
The magnetic force variation arising from the compression of the magnetostrictive materials was measured by an experiment setup shown in Fig.5. The magnetic circuit consists of fixed iron plates (gap area:  $15 \times 20 \text{mm}^2$ ) and a movable yoke, a Nd-B-Fe permanent magnet (diameter 16mm, length 30mm, BHmax: 37MGoe), and the magnetostrictive material. Three rods of the magnetostrictive materials grain oriented in the longitudinal direction shown in Fig.5 (right) were tested for comparison. Two rods of the Galfenol ( $\text{Fe}_{81.6}\text{Ga}_{18.4}$ ) were diameter of 8mm and length of 10 or 20mm, and that of the Terfenol was diameter of 9mm and length of 10mm. Four strain gages were affixed  $90^\circ$  apart on its cylindrical surface and 5 turn pick-up coil was wound to measure the average longitudinal compressive strain and the changes of the flux respectively. These components were mounted on the lower cross head made of a non-magnetic stainless steel of an universal test machine (Model 5582, INSTRON Inc., USA), and cycle of compressive stress up to 300MPa for the Galfenol and 200MPa for the Terfenol were applied to the rods by an iron rod which slides through the fixed yoke. The gap length was fixed 0.2 or 0.5mm, and the magnetic force exerting on the movable yoke during the compression was measured by a load cell (Model LC1205, ADF Inc., Japan).

The strain (left) and variation of flux density (right) vs. stress, and the magnetic force vs. stress (left) and flux in gap vs. flux variation in the rod (right) under fixed gap of 0.2mm are shown in Figs.6 and 7 respectively. The magnetic force is increased from bias (zero-stress) as the magnetization of the magnetostrictive material is decreased by the compression. The magnetostrictive properties of the Galfenol are reflected as advantage and disadvantage for the magnetic force control. Since the ratio of the flux conversion in the gap and rod is constant (indicated in Eq.(6) and confirmed in Fig.7), the variation of the magnetic force  $dF_g$  is basically proportional to the range of the flux decrease  $d\Phi_m$ . Actually, the decrease of the flux density is approaching to the value of the saturation, thus the Galfenol would possibly provide more than twice of the variation of the magnetic force. However it must be noticed that the large saturation reduces the bias of the magnetic force  $F_{g0}$ . As indicated in Eq.(8), the bias flux  $\Phi_{g0}$  is contributed as factor for the variation  $dF_g$ . As a result, the variation  $dF_g$  of 24.0N of the Galfenol-10mm is smaller than that of the Terfenol due to the low  $\Phi_{g0}$  even  $d\Phi_m$  is 1.2 times larger. The bias magnetic force is determined by the dimensions and permeability of the components of the magnetic circuit. The permeability of both magnetostrictive materials does not differ much at zero stress (see Fig.3), thus the reducing the cross-sectional area of the Galfenol can increase the bias force. We expect this



**Figure 5.** Measurement setup (left) and samples tested (right).

will be advantage of the Galfenol that much less volume is necessary to produce same magnetic force compared with the Terfenol. From  $\Phi_{g0}$  and Ampere's law, the magnetic field at bias in the rod are calculated 11.2 6.3 15.1kA/m for the Galfenol-10, 20mm and Terfenol respectively. The Galfenol-20mm was applied appropriate bias field and larger  $s^H$  and  $d^H$  are observed on low stress range.

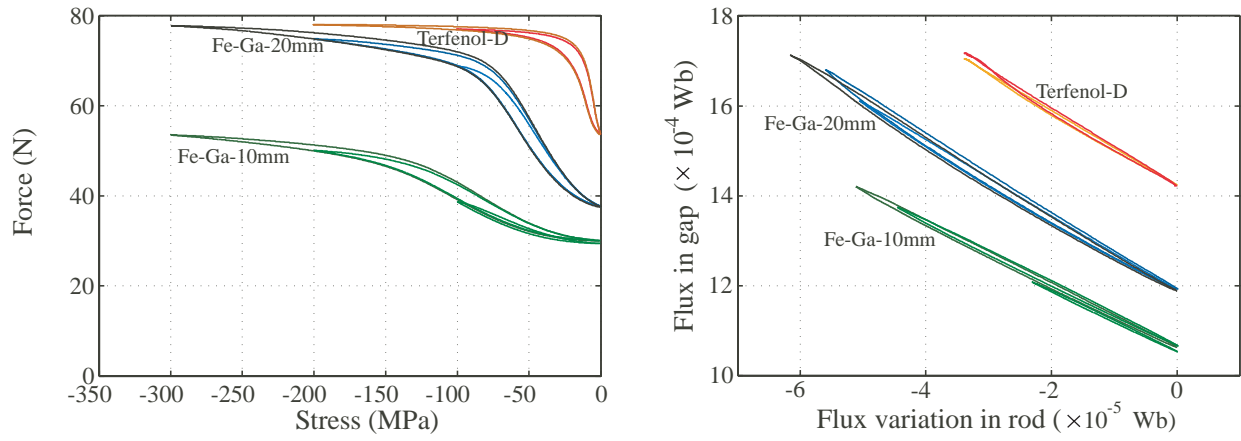


**Figure 6.** Strain vs. stress (left) and variation of flux density in rod vs. stress (right) under fixed gap of 0.2mm.

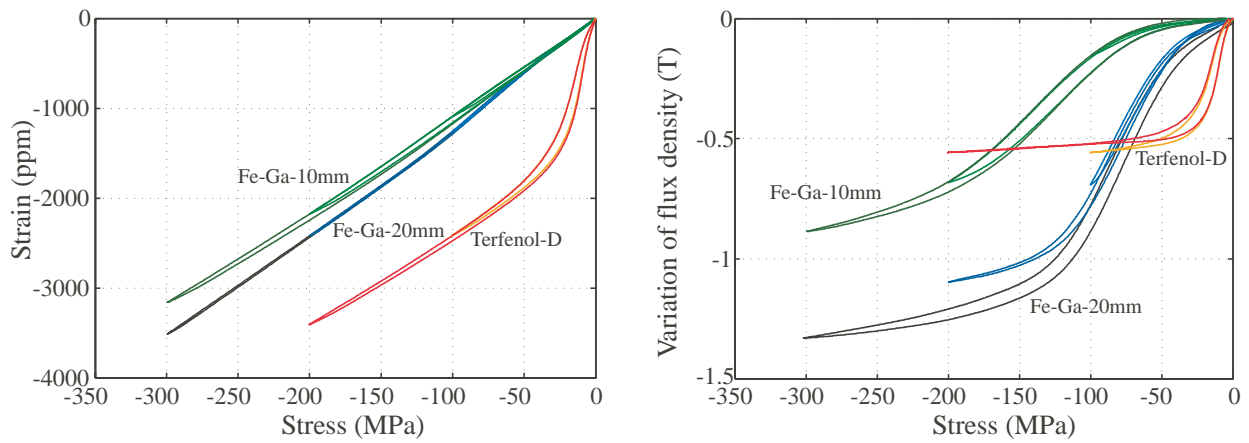
The results under fixed gap of 0.5mm are shown in Figs.8 and 9. With the increase of the gap length, the bias forces are decreased, while the bias magnetic fields in the rod are increased (21.1 11.1 and 26.3kA/m in Galfenol of 10, 20mm and Terfenol respectively). Due to the higher field,  $d^H$  at low stress range are lower than the case of 0.2mm. Generally, the operating stress is in a low range from zero in a practical usage and larger magnetic force is preferable. Therefore, smaller gap is better for bias magnetic field and bias force.

By the way, it seems that the Terfenol with larger decrease of the magnetization in a low stress range (<50MPa) is more useful than the Galfenol. We think that the Galfenol with high  $d^H$  but low  $s^H$  is suitable for the composite in Fig.10<sup>10</sup>,<sup>11</sup> where the mechanical stress in the magnetostrictive plate is controlled by bonded piezoelectric plates. If the piezoelectric plates have high stiffness and sufficient volume, the amount of the deformation is mainly dominated by "strain". In addition, the operating strain range of the piezoelectric material (PZT ~1200ppm) would exploit more the magneto-mechanical properties of Galfenol. We hopefully clarify these merits on the composite and develop magnetic force control devices endurable for industrial applications.

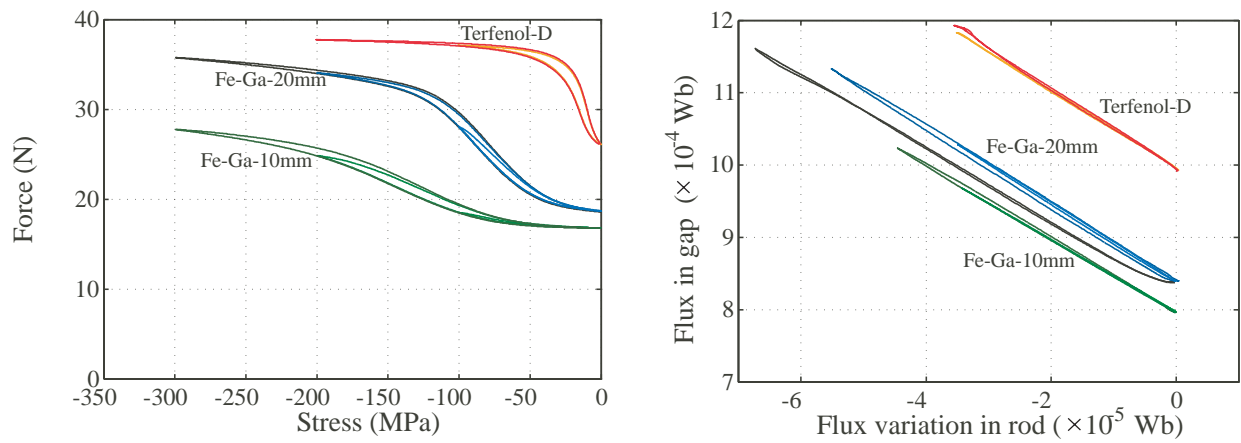




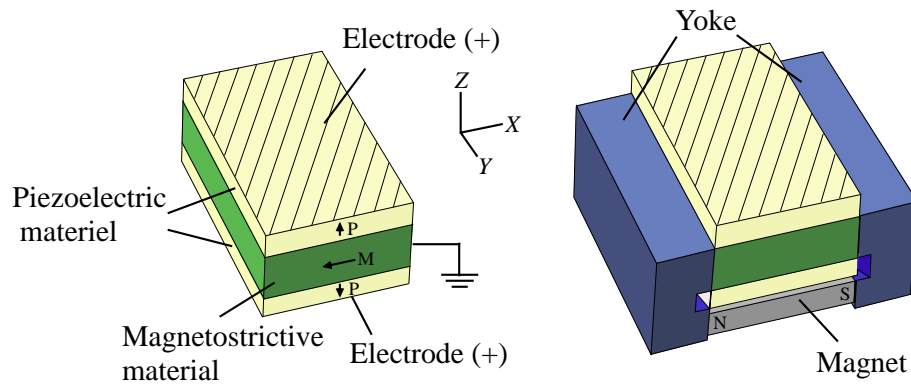
**Figure 7.** Magnetic force vs. stress (left) and flux in gap vs. flux variation in rod (right) under fixed gap of 0.2mm.



**Figure 8.** Strain vs. stress (left) and variation of flux density in rod vs. stress (right) under fixed gap of 0.5mm.



**Figure 9.** Magnetic force vs. stress (left) and flux in gap vs. flux variation in rod (right) under fixed gap of 0.5mm.



**Figure 10.** Laminate composite of magnetostrictive and piezoelectric plates (left) and its integrated into magnetic circuit to control magnetic force (right).

### 3. CONCLUSION

The magnetostrictive properties of Galfenol and its behavior in the magnetic circuit were investigated. The comparison of the measurements with Terfenol-D clarified that the large saturation of the Galfenol is advantageous for the magnetic force control method, which enlarges the range of the variation of the magnetic force. In this paper, we could not confirm the superior effect arising from high piezomagnetic constant of the Galfenol. But the appropriately magnetic field-biased Galfenol has possibility to yield larger variation of the magnetic force with lower compressive stress. We hope that the advantages of the Galfenol are practically used in the laminate composite with piezoelectric materials.

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