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The influence of magnetic bias and prestress on magnetostriction characteristics of a giant magnetostrictive actuator

***Abstract**. In the paper, a construction and principle of working of a giant magnetostrictive actuator have been presented. The effects of varied operating conditions such as magnetic bias and mechanical prestress on the magnetostriction characteristics is discussed. The magnetic circuit of the actuator is analyzed using finite element method. The selected results of calculations are presented.*

Streszczenie.** W pracy omówiono budowę i zasadę działania magnetostrykcyjnego aktuatora z rdzeniem wykonanym z Terfenolu-D. Analizowano wpływ namagnesowania i naprężenia wstępnego rdzenia z Terfenolu-D na pracę magnetostrykcyjnego aktuatora. Do wyznaczania rozkładu pola wykorzystano metodę elementów skończonych. Przedstawiono wybrane wyniki obliczeń symulacyjnych. (**Wpływ namagnesowania i naprężenia wstępnego na magnetostrykcyjne charakterystyki aktuatora z rdzeniem wykonanym z materiału o gigantycznej magnetostrykcji)

Słowa kluczowe: materiały o gigantycznej magnetostrykcji, magnetostrykcyjny aktuator, namagnesowanie wstępne, naprężenie wstępne.
Keywords: magnetostriction, Terfenol-D rod, giant magnetostrictive actuator, magnetic bias, mechanical prestress.

Introduction

The giant magnetostrictive material (GMM) is a new type of efficient functional material. The phenomenon of magnetostriction, which is observable in all magnetic materials, is becoming more and more interesting for developing smart actuators and sensors [1]. Magnetostrictive devices, which are based on the use of multifunctional giant magnetostrictive materials, exhibit interesting electro-magneto-mechanical properties; in particular, when compared with piezoelectric devices, they show higher forces and dynamic response, avoiding the need of heavy electrical insulations, required by high voltages, which reduce the cooling efficiency [1,2,3].

Magnetostriction is the changing of a material's physical dimensions in response to changing its magnetization. Strain is generated in response to an applied magnetic field, whereas stresses in the materials produce measurable changes in magnetization [4,5,6]. Linear magnetostriction λ is defined as the $\Delta l/l_0$, where l_0 is the length of the material in its un-magnetized state, along a given direction, and Δl is the resulting strain. One of the best of the new magnetostrictive material known as Terfenol-D, typically $Tb_{0.7}Dy_{0,.3}Fe_{1,9\text{-}2}$, generates strains in the region 1000-2000 ppm (parts per million) at 50-200 kA/m [6,7].

The giant magnetostrictive actuators (GMA) using magnetostrictive material (e.g. Terfenol-D) which has properties of large strain, high force and high energy density are suitable for applications in which high force is needed such as transducer for heavy loads, valve drive and vibration control, etc. [1,2,7,8].

Figure 1 shows a standard structure of the giant magnetostrictive actuator. This structure is typical and applied nowadays in many applications [5,6,7]. The main components of the actuator consist of a cylindrical magnetostrictive rod, a wound excitation coil, an enclosing permanent magnet, and a prestress spring washer. The time-dependent current in solenoid generates a varying magnetic field within the magnetostrictive rod. Then the strain is generated in accordance with the magnetic field.

Strains in an unbiased magnetostrictive rod are always positive since the rotation of magnetic moments in response to an applied field always produces an increase in length. To attain bidirectional strains, a magnetic bias is provided by the enclosing cylindrical magnet (alternatively, a biasing DC current could be applied to the solenoid) [9].

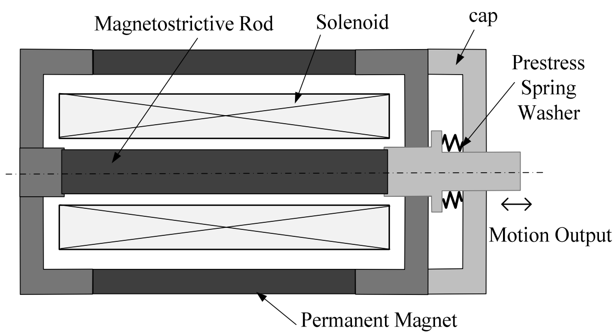

Fig. 1. Structure of the actuator GMA

A prestress spring provides a prestress σ_0 on the magnetostrictive rod. A high total efficiency and higher strain can be obtained by choosing appropriate prestress.

The aim of the paper is to find the effects of varied operating conditions such as magnetic bias and mechanical prestress on the magnetostriction characteristics of GMA.

Mathematical model

The linearized constitutive equations for magnetostrictive material which define the mechanical strain and magnetic flux behaviour are known to be [6],

$$\varepsilon = s^H \sigma + dH \quad (1)$$

$$B = d\sigma + \mu^\sigma H \quad (2)$$

where ε is the strain, σ is the stress, H is the applied magnetic field intensity, and B is the magnetic flux density, $s^H = \left.\frac{\partial \varepsilon}{\partial \sigma}\right|_{H=\text{const}} = \frac{1}{E^H}$, E^H is the Young's modulus at constant magnetic field intensity, d is the material constant relating applied magnetic field to induced strain, and μ^σ is the permeability at constant stress.

Due to the magnetostrictive property of the rod and a mechanical configuration, output displacement and input current characteristics of actuators are nonlinear and exhibit hysteresis. In order to describe the magnetization process in giant magnetostrictive materials the Jiles-Atherton model has been applied [9, 10]. In this approach, the effective field H_e, anhysteretic magnetization M_{an}, irreversible and reversible component of magnetization M_{irr}, M_{rev}

respectively and total magnetization M are quantified through the expressions,

(3) $$H_e = H + \alpha M + H_\sigma$$

Where $H(t) = Ni(t) + H_b$ denotes the magnetic field generated by a solenoid having N turns per unit length with an input current *i(t)* and the bias magnetic field H_b produced by permanent magnets or a DC current. αM quantifies contributions due to the magnetic interaction between domains and $H_\sigma = \frac{3}{2}\frac{\sigma}{\mu_0}\frac{\partial\lambda}{\partial M}$ is the field resulting from magnetoelastic domain interaction.

The total magnetization M of a material is caused by the factors representing reversible processes M_{rev} and irreversible processes M_{irr} occurring during the magnetization of the core

(4) $$M = M_{rev} + M_{irr}$$

in the above equation, the irreversible processes occurring in the course of magnetization are described by a differential equation

(5) $$\frac{\mathrm{d}M_{irr}}{\mathrm{d}H} = \frac{M_{an} - M_{irr}}{k\delta - \tilde{\alpha}(M_{an} - M_{irr})}$$

where $\delta = sign(dH/dt)$, M_{an} is a non-hysteresis magnetization curve

(6) $$M_{an} = M_s\left[\coth\left(\frac{H_e}{a}\right) - \left(\frac{a}{H_e}\right)\right]$$

In the above relations, k and α are the factors depending on material parameters, a is the shape factor and the saturation magnetization is denoted by M_S.

The parameter $\tilde{\alpha}$ quantifies the magnetic interactions and stress coefficient, and can be calculated as follows [11],

(7) $$\tilde{\alpha} = \alpha + \left[4\sigma_0 - \sigma_s \ln\left(\cosh\left(2\sigma_0/\sigma_s\right)\right)\right]\lambda_s/(2\mu_0 M_s^2)$$

where σ_S is the saturation stress, λ_S is the saturation magnetostriction.

In the model, it is assumed that the reversible processes inside a material are described by the equation

(8) $$M_{rev} = c\left[M_{an} - M_{irr}\right]$$

where c is the factor depending on the type of material.

By substituting (8) into (4) and then differentiating the achieved expression it is obtained as follows

(9) $$\frac{\mathrm{d}M}{\mathrm{d}H} = \frac{(1-c)(M_{an} - M_{irr})}{k\delta - \tilde{\alpha}(M_{an} - M_{irr})} + c\frac{\mathrm{d}M_{an}}{\mathrm{d}H}$$

In order to solve equations (9) i.e., to determine the magnetization M, numerical methods of solving differential equations, for example the difference methods or the Runge-Kutta method can be used.

As detailed in [11], magnetostriction λ, which is a function of magnetization M can be expressed as,

(10) $$\lambda = \lambda_S\left(1 - \frac{1}{2}tgh\frac{2\sigma_0}{\sigma_S}\right)\left(\frac{M}{M_S}\right)^2$$

Selected results

The giant magnetostrictive actuator as shown in Fig. 1 is analysed. The magnetostrictive rod is made from the material Terfenol-D. The length of the Terfenol-D rod is 100 mm and the diameter is 10 mm (Fig. 2). Figure 3 shows the magnetostriction characteristics with a constant prestress measured by the manufacturer of the Terfenol-D rod [12].

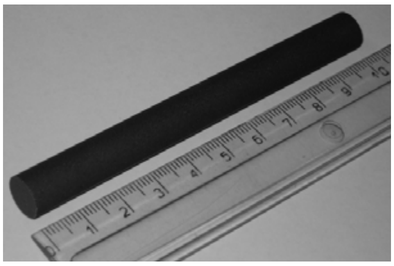

Fig. 2. Terfenol-D rod

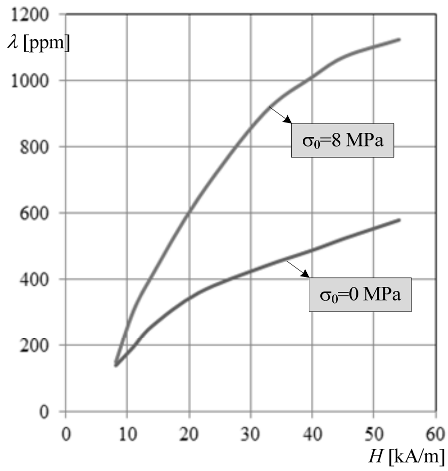

Fig. 3. Magnetostriction vs magnetic field curves for prestresses of 0 and 8 MPA

The 2D finite element method to achieve optimal designs for the magnetic circuit of GMA has been used. The actuator is equipped with rare-earth $SmCo_{18}$ type permanent magnets. The demagnetisation curve of permanent magnet is approximated by a linear function. The calculations have been performed for different sizes of the permanent magnet.

The calculated distribution of the magnetic field intensity H_b in the Terfenol-D rod is shown in Fig. 4. Figure 4 shows the results when the magnetic bias field H_b is applied only by the permanent magnets i.e. current is equal to zero. Calculations were performed for permanent magnet with dimensions $\phi 61\times\ \phi 51\times\ 90$ mm (actuator GMA1). The value of the intensity H_b for both ends of the Terfenol-D rod is greater by about 25% of the value of H_b in the middle section of the core.

Figure 5 shows the calculated distribution of the magnetic field intensity H_b in the Terfenol-D rod after change of dimensions of permanent magnet. The calculations were done for permanent magnet with dimensions $\phi 61\times\ \phi 51\times\ 70$ mm (actuator GMA2) and when current is equal to zero. The value of the magnetic field intensity H_b for both ends of the Terfenol-D rod is less by about 35% of the value of H_b in the middle section of the core.

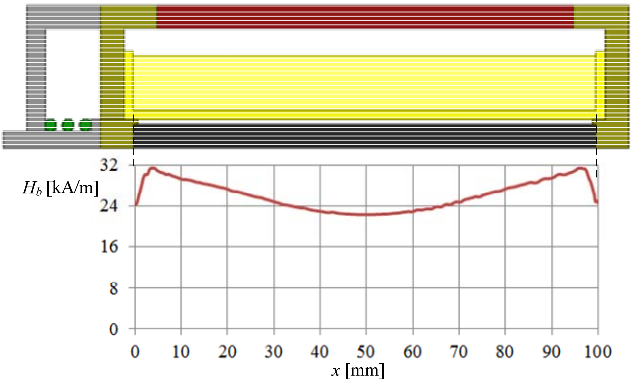

Fig. 4. The distribution of the magnetic field intensity H_b in the Terfenol-D rod (actuator GMA1, I_m=0 A)

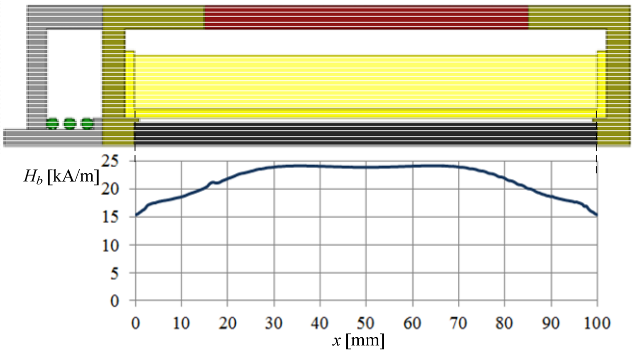

Fig. 5. The distribution of the magnetic field intensity H_b in the Terfenol-D rod (actuator GMA2, I_m=0 A)

Two additional rings of permanent magnets (actuator GMA3) have been added to improve the uniformity of the magnetic field in the Terfenol-D rod – see Fig. 6.

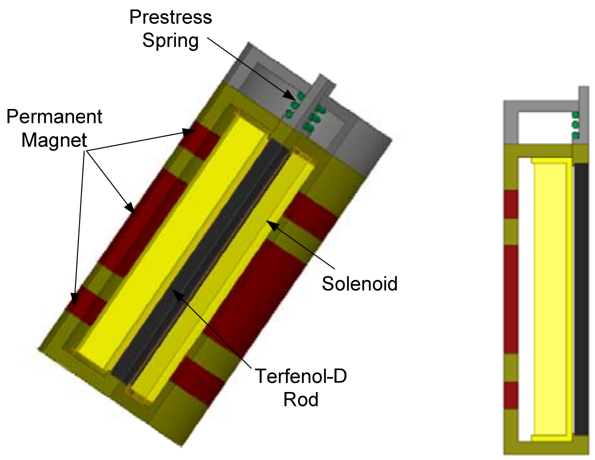

Fig. 6. The structure of GMA3

Figure 7 shows the distribution of the magnetic field intensity H in the Terfenol-D rod of actuator GMA3.

Finally the distributions of the magnetic field intensity H_b (I_m=0 A) in the Terfenol-D rod for three structures of actuator: GMA1, GMA2 and GMA3 are presented in Fig. 8.

In the farther part of the paper the influence of mechanical prestress on the magnetostriction characteristics of GMA has been considered. The presented above mathematical method it means equations from (3) to (10) has been used in the analysis of the GMA. It was assumed that the driving current is sinusoidal, i.e. $i(t) = I_m \sin(\omega t)$. The specific design parameters are given as follows: source frequency f = 50 Hz; number of turns n = 1000; saturation strain λ_S = 1000 ppm; maximum stress σ_S = 60 MPa. The values of five magnetization parameters taken from [6, 9] are: M_s = 765 kA/m, a = 7012 A/m, c = 0.18, $\tilde{\alpha}$ = -0.01, k = 3600 A/m, respectively.

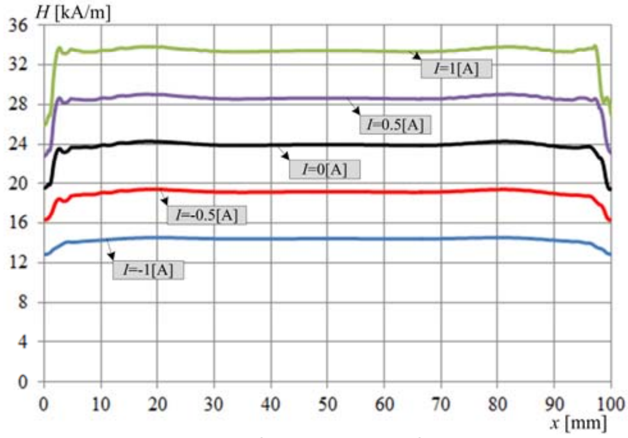

Fig. 7. The distribution of the magnetic field intensity H in the Terfenol-D rod (actuator GMA3)

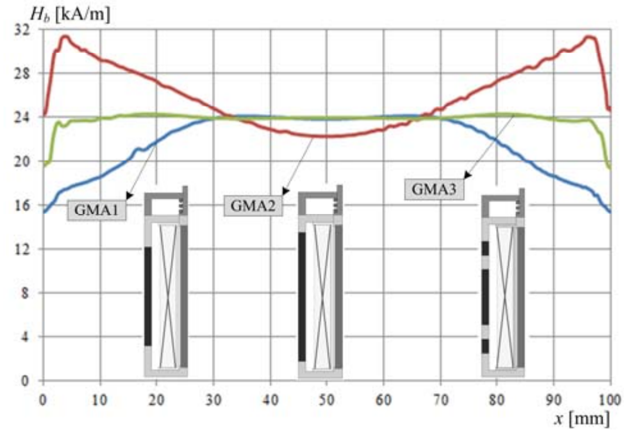

Fig. 8. Magnetic field intensity distribution in TerfenoD rod (I_m=0 A)

Figure 9 shows the magnetostriction versus applied field characteristics for different compressive prestresses. The calculations have been given for I_m=8 A and H_b = 0 A/m. In this case the maximum value of magnetostriction λ is obtained for prestress σ_0 = 8 MPa.

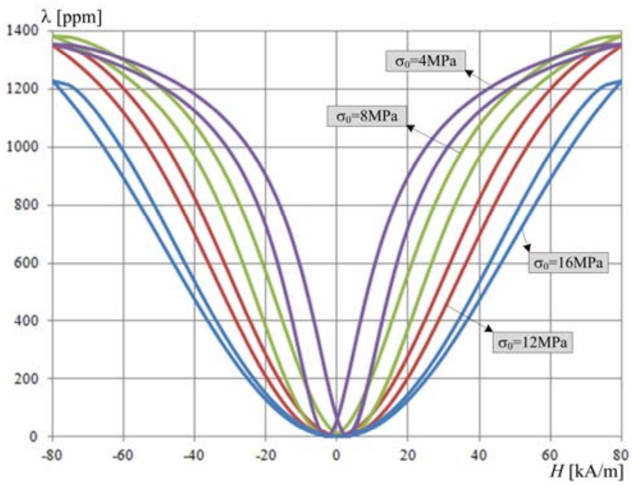

Fig. 9. Magnetostriction curves for compressive prestresses of 4, 8, 12, and 16 MPa

Based on magnetostriction characteristic for prestress σ_0 =8 MPa the magnetic bias H_b = 24 kA/m has been estimated. Figure 10 shows magnetostriction versus current characteristic of GMA for I_m= 8 A, prestress σ_0 =8 MPa and magnetic bias H_b = 24 kA/m. From the obtained results it can be noticed that there is minimum in the magnetostriction at I = -2.28 A. It means that the driving current should be set in the range from I = -2 A to I = 2 A.

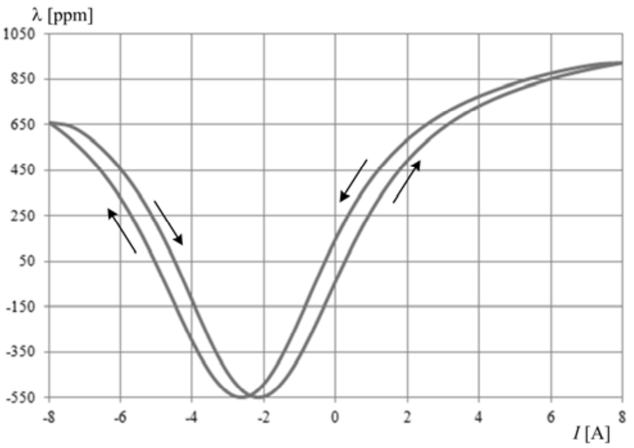

Fig. 10. Magnetostriction versus current characteristic of GMA (σ_0=8 MPa; H_b = 24 kA/m, I_m= 8 A)

The relationship between output displacement and input current for the GMA has been presented in Figure 11.

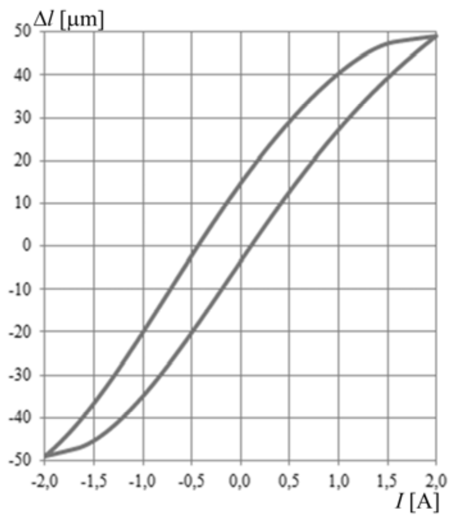

Fig. 11. The output displacement of GMA versus input current

The total output displacement of designed GMA under prestress 8 MPa and magnetic field bias 24 kA/m can be obtained up to 100 μm.

Summary

The influence of magnetic bias and mechanical prestress on the magnetostriction characteristics of the giant magnetostrictive actuator have been calculated. The improved magnetic circuit of the giant magnetostrictive actuator was designed. The calculations results show that applied magnetic bias using permanent magnet is effective.

The used model of the giant magnetostrictive actuator is suitable to describe relation between the input magnetic field, the magnetization in the magnetostrictive rod, the output displacement and magnetostriction.

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