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.


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 $\Delta l/l_0$ 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 $\Delta l$ 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$_{1.9}$-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].

Mathematical model

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

\[
\varepsilon = s^H \sigma + dH \quad \text{(1)}
\]

\[
B = d\sigma + \mu^R H \quad \text{(2)}
\]

where $\varepsilon$ is the strain, $\sigma$ is the stress, $H$ is the applied magnetic field intensity, and $B$ is the magnetic flux density, $s^H$ is the reversible component of magnetization $M_{rev}$, $d$ is the material constant relating applied magnetic field to induced strain, and $\mu^R$ 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 $M_{irr}$, $M_{rev}$.

**Fig. 1. Structure of the actuator GMA**
respectively and total magnetization $M$ are quantified through the expressions,

$$H_e = H + \alpha M + H_\sigma$$

(3)

Where $H(i) = N i(t) + H_b$ 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. $\alpha M$ quantifies contributions due to the magnetic interaction between domains and $H_\sigma = \frac{3}{2} \sigma \frac{\partial \lambda}{\partial M}$ 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.

$$M = M_{rev} + M_{irr}$$

(4)

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

$$\frac{dM_{irr}}{dH} = \frac{M_{an} - M_{irr}}{k \delta - \alpha (M_{an} - M_{irr})}$$

(5)

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

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

(6)

In the above relations, $k$ and $\alpha$ are the factors depending on material parameters, $\alpha$ is the shape factor and the saturation magnetization is denoted by $M_0$.

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

$$\alpha = \alpha + \left[ 4 \sigma_0 - \sigma_s, \ln(\cosh(2\sigma_0 / \sigma_s)) \right] \hat{H}_0 / (2 \mu_0 M_s^2)$$

(7)

where $\sigma_s$ is the saturation stress, $\lambda_s$ is the saturation magnetostriction.

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

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

(8)

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

$$\frac{dM}{dH} = \frac{(1-c)(M_{an} - M_{irr})}{k \delta - \alpha (M_{an} - M_{irr})} + c \frac{dM_{an}}{dH}$$

(9)

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 $\lambda$, which is a function of magnetization $M$, can be expressed as,

$$\lambda = \lambda_s \left( 1 - \frac{1}{2} \tanh \frac{2 \sigma_0}{\sigma_S} \left( \frac{M}{M_S} \right)^2 \right)$$

(10)

**Selected results**

The giant magnetostrictive actuator as shown in Fig. 1 is analyzed. 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].
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.

Figure 7 shows the distribution of the magnetic field intensity $H_b$ in the Terfenol-D rod (actuator GMA3). 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 further 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 $\lambda_S = 1000$ ppm; maximum stress $\sigma_S = 60$ MPa. The values of five magnetization parameters taken from [6, 9] are: $M_s = 765$ kA/m, $a = 7012$ A/m, $c = 0.18$, $\alpha = -0.01$, $k = 3600$ A/m, respectively.

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 $\lambda$ is obtained for prestress $\sigma_0 = 8$ MPa.

Figure 9. Magnetostriction curves for compressive prestresses of 4, 8, 12, and 16 MPa
Based on magnetostriction characteristic for prestress $\sigma_0 = 8$ 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 $\sigma_0 = 8$ 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 ($\sigma_0 = 8$ 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.

REFERENCES


Author: dr inż. Dorota Stachowiak, MSc PhD Eng, Poznań University of Technology, Institute of Electrical Engineering and Electronics, ul. Piotrowo 3a, 60-965 Poznań, E-mail: dorota.stachowiak@put.poznan.pl