Design Procedure for Optimum Efficacy of Magnetostrictive Material ($Tb_{0.3}Dy_{0.7}Fe_{1.95}$) in Actuator Applications

Raghavendra Joshi, Subba Rao M, Ravikiran Kadoli

Abstract*— *Magnetostrictive materials are attracting increasing research attention due to inherent advantages such as outstanding magnetostriction, high energy density, high Curie temperature and quick response compared to PZT materials. Actuators using magnetostrictive materials show great potential due to their high forces and short reaction times for applications on heavy and stiff structures such as in aeronautics, civil structures and machine tools. This paper discusses the layout and design of magnetostrictive actuator to decide the suitable number of coil turns based on required magnetic field. In addition the systematic design procedure mainly focusing on electric, magnetic, thermal and mechanical aspects is being discussed. Analytical expressions such as equivalent magnetic circuit equation, flux, magnetic field intensity, shape factor of coils, peak to peak expression for magnetic field intensity and as well as for driving current, different losses in a actuator for the optimal usage of magnetostrictive material in the applications of actuator are being outlined. Significance of leakage inductance of the actuator and choice of feeding amplifiers affecting actuator drive coils dimensioning are illustrated.

Keywords-* *magnetostriction, Curie temperature, magnetostrictive actuator, shape factor, leakage inductance.

I. INTRODUCTION

Rare earth giant magnetostrictive material has a lot of superior properties such as high stress value, large energy density and fast response compared to piezoelectric material. These properties initiated the researchers to use magnetostrictive materials in various fields of applications mainly the actuator unit using these materials. Therefore one has to identify the requirements regarding functional features of actuators in terms of required strain and forces for certain frequency ranges, amplifier requirements, space and weight requirements and loss constraints in the applications of actuators using magnetostrictive materials. The task of achieving optimal use of magnetostrictive materials is complex as the optimization must be made with respect to various aspects like simultaneous electric, magnetic, thermal and mechanical simultaneously. This will make us to adopt a systematic approach for the optimal usage of magnetostrictive material in actuator applications. Terfenol-D rod is the core component of giant magnetostrictive actuator. In recent years, investigations of giant magnetostrictive (GMA) linear actuators employing $Tb_{0.3}Dy_{0.7}Fe_{1.95}$ for micro positioning, active vibration control and adaptive structure applications have been attracting more attention.

The potential use of giant magnetostrictive material namely Terfenol-D has been growing drastically as is evident from the various research publications. The various magnetostriction effects, devices and the methods of measuring magnetostriction of magnetostrictive materials has been discussed [1]. The performance of a high power non-resonant using Terfenol-D has been evaluated and achieved a large displacement of 550 μm at 3 kN with DC input and 9 kN with AC input supply [2]. Tonpilz-type single ended transducer having two Terfenol-D rods has been fabricated to study the underwater acoustic characteristics like TCR, TVR, RS and SL have been measured using impulse method [3]. An inchworm linear motion mini actuator has been developed to position an object over a range of some millimeters with nanometer resolution of up to 4 nm [4]. An extensive computer modeling using finite element method has been performed on a basic actuator with different magnetic circuit configurations to ensure homogeneous magnetic field along the magnetostrictive rod [5]. The results of magnetic field simulation using FEMM software package and experimental measurements of the magnetic flux density on a magnetostrictive actuator yielded good agreement [6].

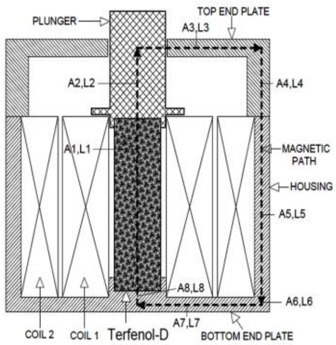

Fig.1. Structure of a magnetostrictive actuator.

The magnetic field of the magnetostrictive actuator has been analyzed using FEM by building an axial symmetric model [7]. An analytical approach to estimate the magnetic field distribution in the cross section of Terfenol-D rod has been discussed [8].

In all these studies the emphasis is laid for the proper static and dynamic design requirement on the magnetic circuit as well as mechanical strength point of view. The objective of the present paper is to provide a systematic procedure to use magnetostrictive material ($Tb_{0.3}Dy_{0.7}Fe_{1.95}$) in the applications of magnetostrictive actuator as the performance of the actuator depends on driving magnetic field and the magnetic properties of the material of various components used.

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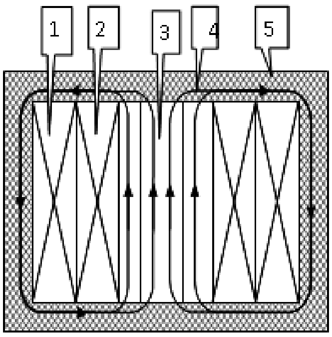
II. STRUCTURE AND MANGETIC CIRCUIT OF THE GIANT MAGNETOSTRICTIVE ACTUATOR

The magnetostrictive actuator has been designed based on known dimensions of Terfenol-D rod (diameter 28 mm and length 80 mm) and magnetic field requirements. The TC layout is chosen for actuator. This layout consists of two co-axially placed coils namely coil 1 and coil 2 as shown in Fig. 1. By providing direct current input to Coil 1, a bias magnetic field will be generated and helps to achieve linear response and over which is superimposed the magnetic field strength produced by coil 2 under direct current or alternating current inputs. In the present work the number of coils for coil 1 and coil 2 are 560 and 440 respectively. The Terfenol-D rod and co-axially placed coils are enclosed in housing. The schematic diagram of magnetostrictive actuator with flux lines is shown in Fig. 2.



1. Coil 1
2. Coil 2
3. Terfenol-D
4. Flux path
5. Housing

Fig.2. Schematic diagram of a magnetostrictive actuator with flux lines

III. DESIGN AND OPTIMIZATION OF MAGNETIC CIRCUIT DESIGN OF A MAGNETOSTRICTIVE ACTUATOR

In a magnetostrictive actuator the input electric power generates a varying magnetic field energy variation. The fraction of the magnetic energy that is located inside the magnetostrictive material determines the efficiency of the magnetizing arrangement of the actuator. The performance of this can be described in terms of its flux leakage and flux return path reluctance.

A. Equivalent magnetic circuit equation

Fig. 3 shows the equivalent electric and magnetic circuits of a magnetostrictive actuator with its magnetizing coil and flux return path. The magnetic source and the energy conversion of giant magnetostrictive material can be effectively improved by analysis and optimization of the magnetic circuit.

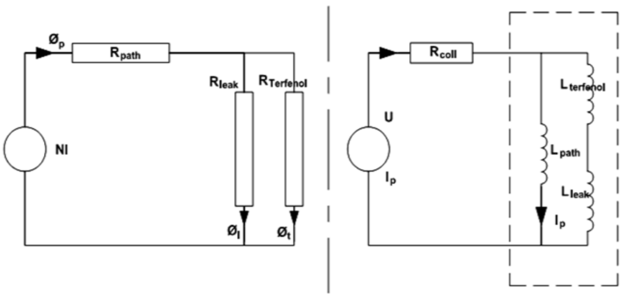


Fig.3. Equivalent magnetic and electric circuit of a magnetostrictive actuator

According to the principle of continuity of magnetic flux and neglect the leak of the actuator, the equation can be expressed as

$$\phi = \phi_{coils} = \phi_{air} + \phi_{rod} \tag{1}$$

Where ϕ is total magnetic flux whose value is equal to magnetic flux of the shell and is equivalent to the sum of ϕ_{air} and ϕ_{rod} .The ϕ_{air} is the internal air magnetic flux of the actuator and the ϕ_{rod} is the magnetic flux of the Terfenol-D rod. By Ampere's loop theorem and the Ohm's law for the magnetic circuit including the existence of leakage flux:

$$\phi = BA = \frac{\dfrac{NI}{K_{coils}}}{Rc + \dfrac{R_{rod}R_{air}}{R_{air} + R_{rod}}} \tag{2}$$

$$\phi = \frac{\dfrac{NI}{K_{coils}}}{\dfrac{l_c}{\mu_c\mu_o A_c} + \dfrac{l_m l}{\mu_0\pi\left[l_m\mu_{air}\left(r_1 - \dfrac{d_m}{2}\right)^2 + l\mu_r\left(\dfrac{d_m}{2}\right)^2\right]}} \tag{3}$$

l_c , μ_c , A_c are the length of the magnetic circuit of the shell, the relative magnetic conductivity of the shell material and surface area of the magnetic circuit of the shell. μ_0 , μ_{air} , μ_r are the magnetic conductivity in vacuum, the relative magnetic conductivity in the air and the relative magnetic conductivity of the Terfenol-D rod.

The leakage inductance L_{leak} of an actuator decides how much magnetic reactance is associated with magnetic flux in the magnetizing coils. A single magnetizing coil can be described by the parameters $\alpha = \frac{a_2}{a_1}$, $\beta = \frac{l_c}{2a_1}$ and $\gamma = \frac{a_1}{r_r}$.Where r_r is the radius of the Terfenol-D rod, a_1 and a_2 the inner and outer radius of the each magnetizing coils and l_c the length of the each driver coil. Applying Biot and Savart's law over the cross section of the coils by assuming field penetrates a linear homogeneous soft magnetic material; the magnetic field intensity (*H*) inside the coils and the corresponding leakage inductance can be derived and is given in [12]:

$$H_{coil} = G_{coil}\ \alpha,\beta\ NI_{coil}\sqrt{\frac{\pi\ \ \alpha+1}{l_c a_1\ \ \alpha-1}} \tag{4}$$

$$L_{leak} = \mu_0\pi^2 G_{coil} N^2\left[r_r\frac{\gamma^2\text{-}1\ \ \alpha+1}{\gamma\ \ \alpha\text{-}1} + \frac{1}{6}a_1\ \ \alpha+1\ \ \alpha+3\right] \tag{5}$$

In actual practice the magnetic field obviously does not penetrate a homogeneous soft magnetic material in an actuator as shown in Figure 2. The above formulas yield fairly well for magnetic field intensity and leakage inductance of an actuator with a relatively low flux return path reluctance R_{path} . The fraction of the leakage inductance relatively the inductance corresponding to the magnetostrictive material

$L_{rel.leak}$ as given in Eq. (4) should be kept low at higher frequencies. It represents an inductive reactance that does not contribute to the magnetostriction and delimits the magnetization current for a given input voltage.

$$L_{rel.leak}=\frac{1}{\mu_r}\left[\ \gamma^2-1\ +\frac{1}{6}.\gamma^2\ \ \alpha-1\ \ \alpha+3\ \right] \tag{6}$$

$$G\ \ \alpha,\beta\ \ =\frac{1}{5}\left(\frac{2\pi\beta}{\alpha^2-1}\right)^{\frac{1}{2}}\ln\left[\frac{\alpha+\ \ \alpha^2+\beta^2\ \ ^{\frac{1}{2}}}{1+\ \ 1+\beta^2\ \ ^{\frac{1}{2}}}\right] \tag{7}$$

The quantity G_{coil} is called as G-factor of the magnetizing coil and it is a function of α and β given in Eq. (7).To attain optimal operation i.e. to achieve maximal efficiency under the main load conditions, the magnetic and mechanical bias levels should be chosen according to the thumb rule reported in [12]:

$$T_{bias}=480.H_{bias}+10^6\Leftrightarrow H_{bias}=\frac{T_{bias}-10^6}{480} \tag{8}$$

The peak to peak dynamic magnetic field intensity maximally can be $2H_{bias}$ to avoid frequency doubling for a chosen H_{bias}. The corresponding maximal peak to peak drive current can be estimated by using Eq. (4) and (8).

$$H_{p-p}=G_{coil}\sqrt{2\pi\beta\frac{\alpha+1}{\alpha-1}}\frac{NI_{p-p}}{l_r} \tag{9}$$

$$I_{p-p}=\frac{H_{p-p}l_r}{NG_{coil}}\sqrt{\frac{1\ \ \alpha-1}{2\pi\beta\ \ \alpha+1}} \tag{10}$$

On simplifying the Eq. (9) and Eq. (10) yields:

$$I\ \ t\ \ =\frac{l_rH_{p-p}}{2NG_{coil}}\sqrt{\frac{1\ \ \alpha-1}{2\pi\beta\ \ \alpha+1}}\left[1+\sin\ \ \omega t\ \ \right] \tag{11}$$

$$I_{rms}=\frac{l_rH_{p-p}}{2NG_{coil}}\sqrt{\frac{1}{\pi\beta}\frac{\alpha-1}{\alpha+1}}\approx\frac{l_rH_{p-p}}{N}$$

$$I_{rms}\approx\frac{T_{bias}-10^6}{480}.\frac{l_r}{N}\approx\frac{T_{bias}l_c}{460N} \tag{12}$$

B. Number of turns and amplifier requirements

The required magnetizing current according to Eq. (11) and (12) is inversely proportional to the number of turns and proportional to the length of the active material. The required voltage is proportional to the total inductance of the actuator and the operating frequency. At a given operating frequency f and corresponding maximal available input voltage $U_{\max}$, it is then possible to estimate the number of coil turns and corresponding actuator inductance L_{act} for optimal H_{bias} and T_{bias}.

Assuming sinusoidal variation the input voltage is given by

$$2\pi f.L_{act}.I_{\max}=U_{\max}\Leftrightarrow 2\pi f.L_{act}.\frac{\sqrt{2}I_{\max}}{2}=U_{\max} \tag{13}$$

The total magnetic energy of the actuator is given by

$$W_{\max}=\frac{1}{2}.L_{act}.\left[\frac{\sqrt{2}I_{\max}}{2}\right]^2 \tag{14}$$

On simplifying gives

$$N=\frac{U_{\max}.T_{bias}.l_r}{\sqrt{2}.2\pi f.920.W_{\max}}\ \text{and}\ L_{act}=\frac{4.W_{\max}.460^2.N^2}{T_{bias}^2l_r^2} \tag{15}$$

C. Losses in an actuator

The different losses are to be taken in to account in the design of magnetostrictive actuator are eddy current losses in the active material, hysteresis losses and resistive losses in the drive coil. These losses are to be avoided for optimal use of giant magnetostrictive actuator in various applications. To avoid eddy current losses in the active material up to breaking frequency *f* by using laminated material of thickness d and is given by

$$f_c=\frac{\rho}{2\pi\mu_r\mu_0d^2} \tag{16}$$

Where ρ = resistivity and μ_r =average permeability of active material under mechanical clamped conditions.

The hysteresis losses can be avoided by using appropriate hysteresis models in dynamic simulations of the actuator. The resistive losses in the drive coil can be avoided by computing coil resistance and the analytical expression:

$$R_{coil}=\frac{N^2\rho\pi\ \ \alpha+1}{\lambda l_c\ \ \alpha-1} \tag{17}$$

Where R_{coil} = coil resistance, N =number of coil turns, ρ =resistivity of coil, λ = fill factor of the coil and l_c =length of the coil.

IV. CONCLUSION

In this paper the systematic design technique for optimum use of giant magnetostrictive material in the applications of actuator has been outlined based on given strain and force requirements. However a more detailed approach including dynamic simulations must be carried out to attain performance features of an actuator to be designed and fabricated.

V. ACKNOWLEDGEMENT

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