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Finite Element Magnetostatic Analysis of Magnetostrictive ($Tb_{0.3}Dy_{0.7}Fe_{1.95}$) Actuator with Different Housing Materials

Raghavendra Joshi*, Subba Rao M. and Ravikiran Kadoli

National Institute of Technology, Surathkal-575 025, India
**E-mail: achyut61@gmail.com*

ABSTRACT

Permeability of a housing material is one of the significant factors affecting the performance of $Tb_{0.3}Dy_{0.7}Fe_{1.95}$ based magnetostrictive actuator. According to Lenz's law the rate of flux transfer depends on permeability of housing material surrounding the terfenol-D. In this paper the co-axial coils in a free air are analysed under direct current excitation and the results are found to agree well with both analytical and Maxwell simulation. Also, the comparison of flux density distribution in co-axial coils placed inside different housing materials of magnetostrictive actuator is found by solving magnetostatic equations using Ansoft Maxwell 2D solver. The axial distribution of magnetic flux density, radial distribution of magnetic flux density and flux distribution in the actuator assembly with different housing materials namely mild steel, cast iron and aluminium with and without Terfenol-D are discussed.

Keywords: Permeability of housing material, magnetostrictive actuator, Terfenol-D, Ansoft maxwell 2D solver

1. INTRODUCTION

The intensity and uniformity of a magnetic field are the key factors that influence the performance of a giant magnetostrictive actuator. These factors govern the sensitivity and linearity of the output motion. Moreover, the domain of drive current to meet design requirement and linear working domain of a magnetostrictive actuator can be effectively computed by analysing the magnetic field. In magnetic field analysis the common methods existing in practice to find associated magnetic field parameters like B, H and ϕ are reluctance method, finite difference method and finite element method. The effective rate of flux transfer to the Terfenol-D rod depends on the permeability of housing material. An insight in to flux density distribution could be perceived by magnetostatic analysis using finite element method. Studies have been carried out with different types of magnetic circuits to understand the magnetic field distribution along the magnetostrictive rod using FEA[1] and COSMOSM[2]. Theoretically magnetic field parameters for the given strain and force requirement[3] and the effect of magnetic circuit components like gap's magnetic permeability, evenness of driving magnetic field[4] has been analysed. Magnetic circuit of magnetostrictive actuator developed for different applications like undersea propagation[5], precise controlled flow[6], low machining precision problem affected due to vibration disturbance[7] and precise machining of non-cylinder pin-hole of a piston[8] has been analysed. Comparison of experimental and numerical results of magnetic flux density obtained with FEMM[9,10] has shown good agreement. FEA analysis using Ansoft has been proved effective and dose support theoretically the design of GMM actuator and GMM motor[11]. Radial distribution rules of internal magnetic field intensity and internal stress and strain in a high frequency driven Terfenol-D rod provided theoretical guidance for the development of magnetostrictive application devices using ANSYS software[12,13]. In all these studies the emphasis is made for the optimisation of magnetic circuit of an actuator to enhance the intensity and uniformity of magnetic field intensity. The output displacement and force of the Terfenol-D linear actuator is mainly decided by the distribution of the magnetic field in Terfenol-D rod. In order to gain a magnetic field which meets the drive requirements, the relationship between the current supplied to actuator's coils and magnetic field intensity in Terfenol-D rod should be analysed in the process of electromagnetic design. The objective of the present paper is to provide a detailed overview involved in magnetic field analysis, under direct current input for a giant magnetostrictive actuator with different housing materials having different permeabilities namely mild steel, cast iron and aluminium, using finite element method.

2. LAYOUT AND MAGNETIC CIRCUIT OF TERFENOL-D ACTUATOR

The design of actuator has been carried out based on magnetic field requirements. Terfenol-D rod surrounded by coils (TC layout) is chosen for analysing the actuator. This layout consists of two co-axially placed coils namely coil 1 and coil 2. By providing DC input to coil 1, a bias magnetic field will be generated and helps to achieve linear response and over

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which is superimposed the magnetic field strength produced by coil 2 due to direct current or alternating current input. The Terfenol-D rod and co-axially placed coils are enclosed in a housing made up of different housing materials namely mild steel, cast iron and aluminium respectively. The magnetic circuit of an actuator is composed of other components like plunger and aluminium bobbins as shown in Fig. 1(a). Since the axial length and diameter of co-axial coils is finite, end effect and magnetic leakage are unavoidable. Hence the driving magnetic field is inhomogeneous. Therefore, the lengths of co-axially placed coils are chosen slightly longer than that of the Terfenol-D rod, which results in the rod being surrounded by homogeneous magnetic field. A close magnetic circuit structure is adopted to reduce the leakage of flux. A work out on the number of turns for coil 1 and coil 2 has been arrived at using the ampere's law and reluctance approach. The number of turns for coil 1 is 560 and coil 2 is 440. Length of coil is 80 mm. Maximum amperage of the copper wires used for the coils is 4 A. The solenoid coils are capable of providing 50 kA/m of magnetic field. Terfenol-D rod of diameter 28 mm and length 80 mm are chosen in the present work. The Terfenol-D actuator proposed here is used for operating the friction pads of a disc brake system.

3. EXPERIMENTAL SETUP FOR MEASURING MAGNETIC FLUX DENSITY

Magnetic flux density has been measured using Lakeshore guassmeter-410 with hall probes HT5891 (Transverse Probe) and HA3863 (Axial Probe) as shown in Fig. 1(b). Transverse probe has a hall sensor mounted parallel to the probe axis and measures magnetic fields perpendicular to the probe axis. Axial probe has a hall sensor mounted perpendicular to the probe axis and measures magnetic fields parallel to the probe axis. APLAB-LD6405 power supply is used for varying DC input to coils from 0A to 4A in a step of 0.25 A. The distance between the coils and the probe is maintained constant 5 mm during measurement.

4. FUNDAMENTAL EQUATION OF FE ANALYSIS FOR LINEAR MAGNETOSTATIC FIELD

Under static magnetic fields the energy input due to magnetic field should be equal to the magnetic energy stored in the material provided there is no power loss[14] hence

$$W_{in} = W_{stored} \tag{1}$$

Input energy in magnetic fields is a function of current density $\boldsymbol{J}$ and the corresponding energy. $\frac{1}{2}\int \mathbf{J}.\mathbf{A}dv$ and the energy stored is a function of magnetic induction $\boldsymbol{B}$ and the corresponding energy is $\int \frac{B^2}{2\mu} dv$. Therefore Eqn. (1) can be written as

$$\frac{1}{2}\int \mathbf{J}.\mathbf{A}dv = \int \frac{B^2}{2\mu} dv \tag{2}$$

The magnetic vector potential $\boldsymbol{A}$ is related to the magnetic flux density as follows

$$\mathbf{B} = \nabla \times \mathbf{A} \tag{3}$$

The energy functional is the difference between stored energy and input energyfor linear magnetic fields**.**

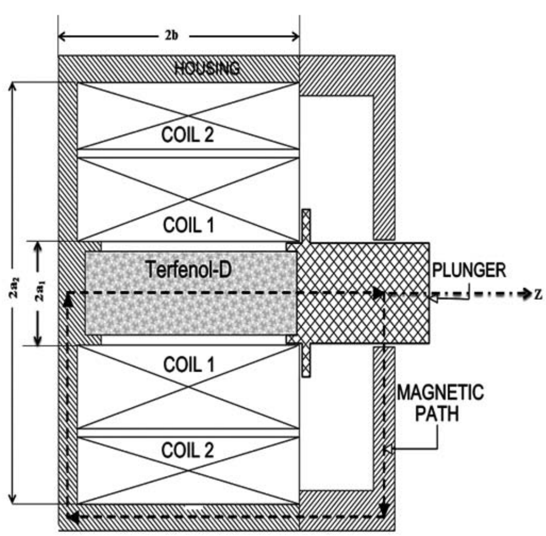
$$F = W_{\text{stored}} - W_{\text{input}} \tag{4}$$

$$F = \left[\int \frac{B^2}{2\mu} dv - \frac{1}{2}\int \mathbf{J}.\mathbf{A}dv \right] \tag{5}$$

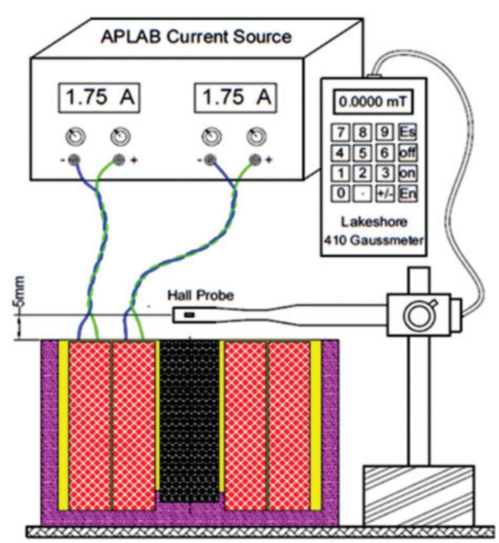
The law of energy conversation requires the functional $\boldsymbol{F}$ to be zero. In finite element method the functional $\boldsymbol{F}$ is minimized to obtain the magnetic vector potential $\boldsymbol{A}$ and magnetic flux density $\boldsymbol{B}$, i.e.

$$\frac{\partial F}{\partial A} = 0 \quad \text{i.e.} \quad \frac{\partial}{\partial A}\left(\int \frac{B^2}{2\mu} dv - \frac{1}{2}\int \mathbf{J}dv \right) = 0 \tag{6}$$

Eqn. (6) is the basis for finite element analysis of linear magnetostatic problems.



(a)



(b)

Figure 1. (a) Layout and structure of a terfenol-D actuator, (b) Experimental setup.

5. RESULTS AND DISCUSSIONS

5.1 Magnetic Flux Density Distribution from the Coil in Free Air

The axial magnetic flux density distribution at the center of coaxial coils can be calculated using the analytical expression[15].

$$B_z = \frac{\mu_0 J}{2}\left[(b-z)\ln\frac{a_2+\sqrt{a_2^2+(b-z)^2}}{a_1+\sqrt{a_1^2+(b-z)^2}}+(b+z)\ln\frac{a_2+\sqrt{a_2^2+(b+z)^2}}{a_1+\sqrt{a_1^2+(b+z)^2}}\right] \quad (7)$$

where μ_0 = permeability of material in free space, $4\pi\times10^{-7}$ T-m/A, $J = \frac{NI}{A}$, Current density in A/m^2, $2b$= height of the coil, $2a_1$= Inner diameter of coil, $2a_2$ =outer diameter of coil, Z = axial distance along the axis. The cross-section and other parameters of a coil in the present work are a_1 = 16.5 mm, a_2 = 57.5 mm, b = 41.5 mm and current density is $J = 3.75\times10^4$ A/m^2. The axial magnetic flux density distribution has been calculated using the Eqn. (7) along the length of the Terfenol-D rod in steps of 10 mm on either side of mid-plane. Co-axial coils in free air are energised with direct current to analyse the magnetic flux density using the finite element analysis in Maxwell 2D solver. Figure 2 summarizes the results on magnetic flux density obtained for co-axial coils alone in free air. The comparison of analytical, numerical and experimental results obtained for co-axial coils in free air shows good agreement with each other. It may be concluded that this study gave scope for analysing magnetic field for a whole actuator assembly with and without Terfenol-D. Figure 3 shows the comparison of experimental and Ansoft simulated axial magnetic flux density distribution along the length of Terfenol-D rod for different housings with a co-axially placed coils. It is observed that the axial flux density values are in close agreement with each other and small deviations are observed due to varying experimental conditions. The magnitude of axial magnetic flux density has been observed 32.3 mT in mild steel housing with coils compared to cast iron and aluminium housing with 31.1 mT and 26.9 mT respectively.

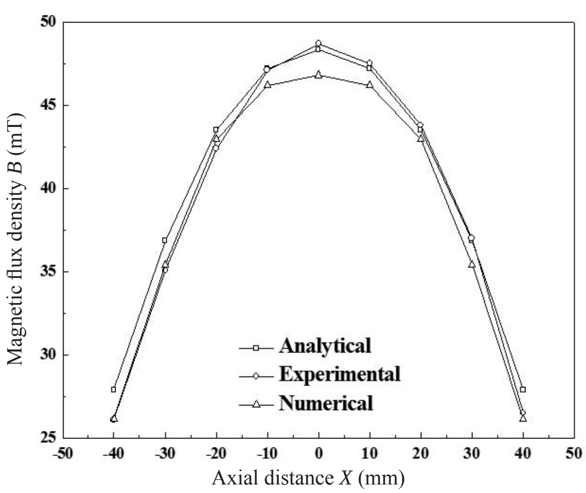


Figure 2. Axial magnetic flux density of coaxial coils in free air.

5.2 Distribution of Axial and Radial Magnetic Flux Density Distribution in Actuator

Figures 4 (a), 4 (b) and 5 (a), 5 (b) shows the comparison of axial and radial magnetic flux density distribution with and without Terfenol-D in an actuator with mild steel and cast iron housing. The

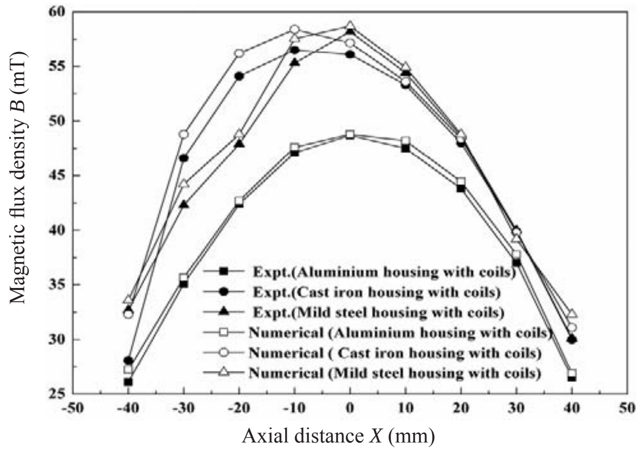


Figure 3. Axial magnetic flux density of coaxial coils in different housing materials.

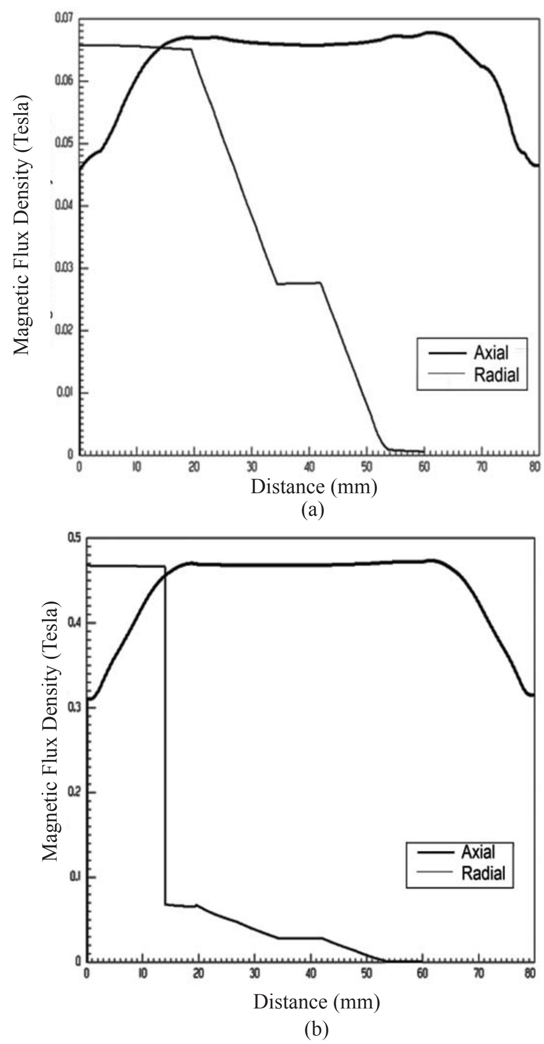


Figure 4. Axial and radial magnetic flux density distribution in a mild steel housing (a) without Terfenol-D (b) with Terfenol-D.

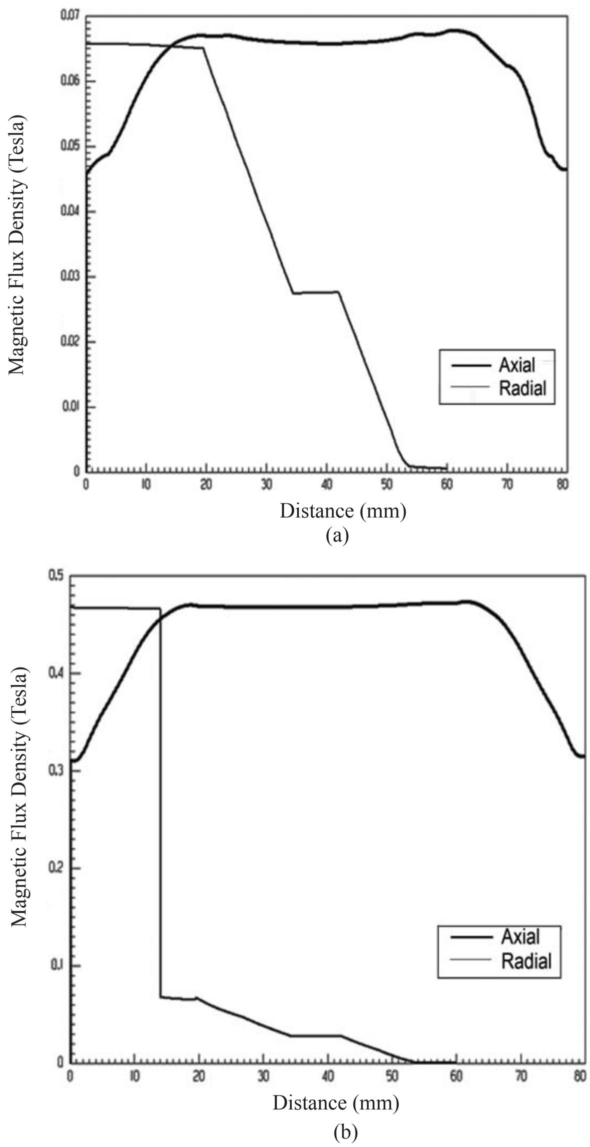


Figure 5. Axial and radial magnetic flux density distribution in cast iron housing (a) without Terfenol-D (b) with Terfenol-D.

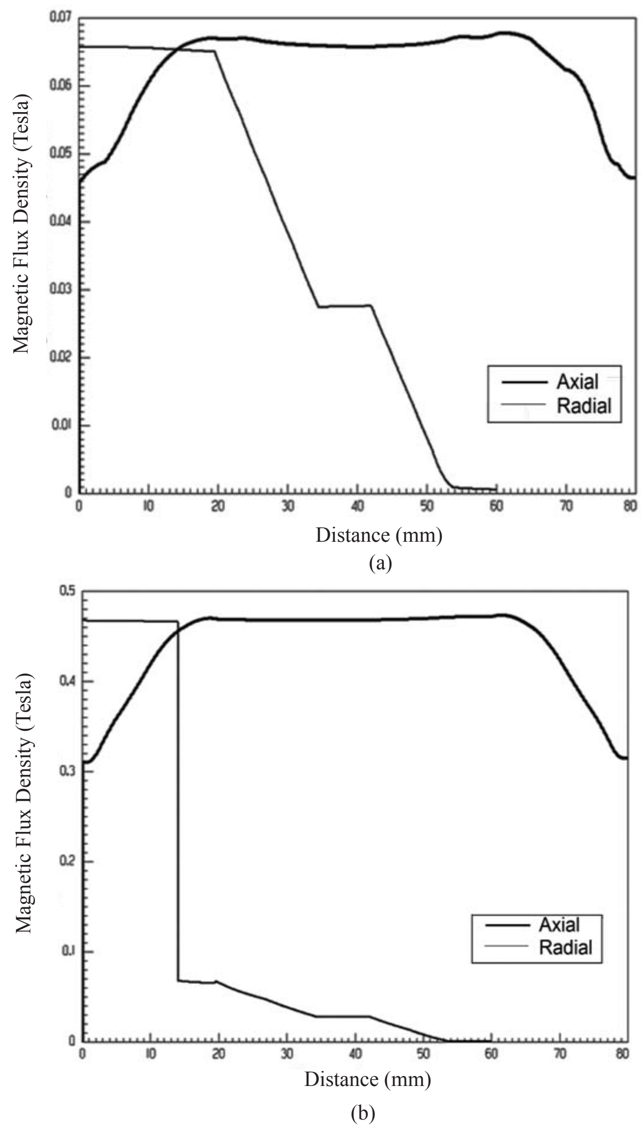


Figure 6. Axial and radial magnetic flux density distribution in aluminium housing (a) without Terfenol-D (b) with Terfenol-D.

current density input to the coil 1 and coil 2 are 2.7×10^6 amp-turns/m^2 and 1.18×10^6 amp-turns/m^2 for 4 A , respectively. It is observed that the magnetic flux density increases from either ends and remains uniform within the coil with Terfenol-D rod and without Terfenol-D. The radial magnetic flux distribution has discontinuities due to the presence of various materials. The radial magnetic flux density is uniform in air and in presence of Terfenol-D, decreases linearly due to presence of coils, bobbin material and wall of the housing as shown in Figs. 4 and 5. The profile of axial and radial magnetic flux density distribution is almost same compared to aluminium housing. This may be because of relative permeability of aluminium material which is almost equal to relative permeability of free space. Figures 6 (a) and 6(b) shows the comparison of axial and radial magnetic flux density distribution with and without Terfenol-D in an actuator with aluminium housing. It is observed that the magnitude of axial magnetic flux density is more at the center of coils with and without Terfenol-D. The radial distribution of magnetic flux density is almost same compared to both mild steel and cast iron housing.

5.3 Comparison of Flux Distribution in an Actuator

The comparison of distribution of flux in an assembly of actuator having mild steel, cast iron and aluminium housing with and without Terfenol-D rod has been discussed. According to Lenz's law the rate of flux transfer from the housing material will be effective and faster whenever the magnetic permeability of housing material is more compared to Terfenol-D rod. With and without Terfenol-D, the intensity and magnitude of a flux lines in an actuator assembly contained with mild steel housing are dense and high compared to cast iron and aluminium housing have been observed. This is due to high relative permeability of mild steel $(\mu_r = 4000)$ compared to cast iron $(\mu_r = 600)$ and aluminium $(\mu_r = 1)$. The flux in an actuator assembly enclosed with aluminium housing was more in the absence of Terfenol-D compared to the presence of Terfenol-D. This may be due to high magnetic permeability of Terfenol-D $(\mu_r \approx 4-12)$ compared to aluminium housing material $(\mu_r = 1)$. Maximum flux of 4.5778×10^{-5} Wb/m^2, 4.5059×10^{-5} Wb/m^2, 2.7312×10^{-5}

Table 1. Percentage of flux in an actuator assembly with different housing materials

Housing material	Flux without Terfenol-D (*T*)	Flux with Terfenol-D (*T*)	Flux variation (%)	
			Increase	Decrease
Mild steel	4.5778×10^{-5}	1.1123×10^{-4}	58.8	-----
Cast iron	4.5059×10^{-5}	1.09×10^{-4}	58.6	-----
Aluminium	2.7312×10^{-5}	4.62×10^{-5}	-----	40.8

Wb/m^2 and 1.1123×10^{-4} Wb/m^2, 1.09×10^{-4} Wb/m^2, 4.62×10^{-5} Wb/m^2 is observed in a mild steel, cast iron and aluminium housing without and with Terfenol-D rod respectively with an input supply of 4 A.

Table 1 shows the percentage of variation in flux for an actuator assembly with different housing materials. The increase in flux was 58.8 per cent and 58.6 per cent with mild steel and cast iron housing in the presence of Terfenol-D. The decrease in flux was around 41 per cent in the presence of Terfenol-D with an actuator containing aluminium housing. The percentage of increase in the flux was around 58.46 per cent and 57.6 per cent in an actuator assembly with mild steel and cast iron housing compared to aluminium housing in the presence of Terfenol-D rod.

6. CONCLUSION

An insight into flux density distribution provides good support for the design distribution provided theoretically good support for the design of Terfenol-D actuator. Also, it is clear that the performance of actuator depends on driving magnetic field and the magnetic properties of materials used more importantly housing materials. A uniform axial magnetic flux density distribution in the actuator assembly with mild steel housing has been observed with and without Terfenol-D compared to actuator with cast iron and aluminium housing. It is observed that the magnetic flux distribution is stronger by 58.8 per cent with mild steel, 58.6 per cent with cast iron and weaker by 40.8 per cent with aluminium when the actuator is contained with Terfenol-D. It is summarized that the magnetic field distribution on Terfenol-D is influenced due to magnetic permeability of housing material, hence a suitable housing material like mild steel is preferable for the effective magnetic field distribution and to improve the performance of actuator.

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Contributors

Mr Raghavendra Joshi obtained his MTech (Machine Design) from Jawaharlal Nehru Technological University, Hyderabad. Presently, he is a research scholar in the Department of Mechanical Engineering, NIT, Surathkal. His areas of research are: Hysteresis modeling and applications of magnetostrictive materials, vibration and conditioning monitoring.

Mr Subba Rao M obtained his MTech (Manufacturing Engineering) from National Institute of Technology, Surathkal and is involved in the development of actuator using magneostrictive material. Presently, he is working as Assistant Professor in the Department of Mechanical Engineering, Madanapalle Institute of Technology & Science, Madanapalle. His area of research is applications of magnetostrictive materials.

Dr Ravikiran Kadoli obtained his PhD from Indian Institute of Technology, Madras. Presently he is a Professor in the Department of Mechancial Engineering, NIT, Surathkal. He is actively involved in the research activities and guided one PhD and many UG and PG Projects. His areas of research are: Structural mechancis, magnetostrictive technology, computational fluid dynamics, heat transfer, thermally induced vibrations.