Mechanical and Magnetic Analysis of Magnetostrictive Disc Brake System

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***Abstract*— The present work is related to an electrically driven magnetostrictive brake for use in brake system of the vehicles, more particularly design of magnetostrictive actuator for moving friction pads in disc brake back and forth thus, capable of readily accomplishing intelligent braking functions similar to that achieved using antilock braking system. The detail of the mechanical and magnetic circuit design of magnetostrictive disc brake is elaborated here.**

Keywords-Magnetostriction, Terfenol D, Disc brake sytem.

I. INTRODUCTION

Brake is a device for decelerating or to completely stop the motion of an object as in various prime movers. This is accomplished by pressing the friction material against the wheel or rotor of the system thus causing the wheel either to stop completely or to reduce its speed. In general there are two types of brake, drum brake and disc brake [1]. In drum brake, brake shoes are operated by mechanical links and hydraulic actuation. In disc brakes the friction pads can be brought into operation by any one, such as mechanical means, hydraulic actuation, actuation by vacuum and electrically [2]. With the discovery of giant magnetostrictive material namely Terfenol D by A.E.Clark [3], which is capable of producing strains of the order 1600 ppm, many researchers have established its potential application as magnetostrictive actuator for vibration control [4], air borne and ground based lidar transmitters and receivers, rapid tunable lasers, high speed scanners, target acquisition [5] and for many other applications as described in [6]. Magnetostriction is the change in dimensions of the magnetic material in response to the change in its magnetization. This is the result of domain orientation that takes place during magnetization of the material. Terfenol-D shows better performance features like high strain capability, large force output, wide band width, high reliability, wide temperature range, microsecond response time and withstand large dynamic load under low frequency operation. Terfenol D magnetostrictive material has a typical composition of Terbium-0.3%,Dysprosium-0.7% and Iron-2%. Some advantages gained with magnetostrictive brake are that: it is capable of accomplishing antilock braking, possibility of size reduction, capable of producing large displacement for transferring the motion to the friction materials and of increasing the allowable wear capacity of the friction materials, reducing power consumption and also provides good response.

II. DESCRIPTION OF THE MAGNETOSTRICTIVE BRAKE

The proposed magnetostrictive brake [7] with its components is shown in "Fig.1". Magnetostrictive brake consists of housing made up of silicon steel which has permeability μ_r =4000. It is chosen with a purpose so as to ensure maximum flux to pass through the Terfenol D. There are two coils, DC coil for magnetic bias and AC for excitation to get the required actuation. Terfenol D rod is kept at the center.

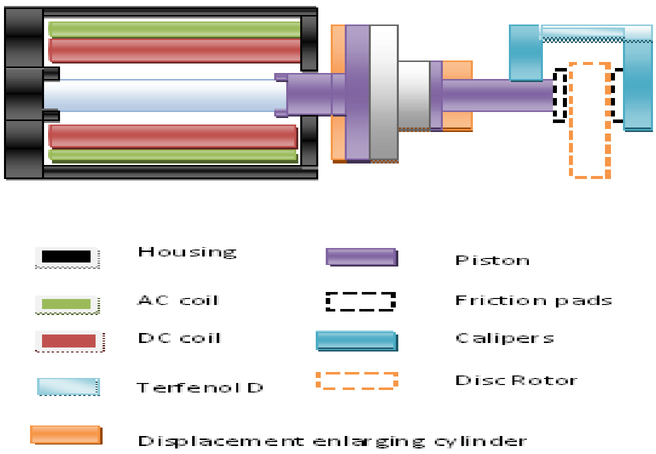

Figure 1.Schematic of magnetostrictive disc brake

Its one end is fixed at the bottom such that its elongation is restricted and to the other end, a plunger is fitted. When Terfenol D rod is excited it generates an actuation force corresponding to the magnetization. As the dimensional change in Terfenol D rod is very small it need to be amplified to the required displacement. There is a fluid displacement enlarging mechanism. It has a cylinder with two pistons, one with larger diameter and the other with smaller diameter on either side. The displacement is amplified using this fluid enlarging displacement enlarging mechanism in the ratio of cross sectional area of the larger diameter piston to smaller diameter piston. The plunger is coupled to the larger diameter end. To the smaller diameter piston end one end of the calipers and friction pads are connected. The force generated by Terfenol D rod is transmitted to the plunger which in turns transmits it to the larger diameter piston. The fluid displacement enlarging mechanism amplifies the displacement

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and transmits the force to the friction pads, and then friction pads will come in contact with disc rotor. Because of this reaction force the other end friction pad will also come in contact with disc rotor and thus causing the rotor either to reduce the speed or to completely stop it.

III. DESIGN PROCEDURE OF MAGNETOSTRICTIVE BRAKE

A. Disc specifications

Disc brake in general has three major components namely,

(i)Disc brake rotor (ii)Friction pads(iii)Calipers

The disc brake rotors are available in standard sizes. In selecting the material for disc brake rotor, it is necessary to consider the coefficient of friction and its thermal properties since heat is generated during braking. Depending on material properties, disc wear rates and coefficient of friction may vary. Few important friction pad material properties data can be found in [8].

B. Calculation of kinetic energy possessed by disc

In the brake system the conversion of kinetic energy into heat energy takes place. The kinetic energy possessed by the disc rotor is required to be calculated. This kinetic energy mainly depends upon the disc rotor mass, and the velocity with which the vehicle or machine is moving.

C. Calculation of axial force required to stop the rotating disc

Consider a typical brake pad in the form of a sector of a circular annulus ABCD as illustrated in "Fig. 2", having an inner and outer radius r_1 and r_2 respectively. $\delta/2$ is the angle subtended by the friction pads at the center of the disc rotor. The procedure for calculating the axial force required to stop the disc rotor used in motor vehicles is discussed in [9].

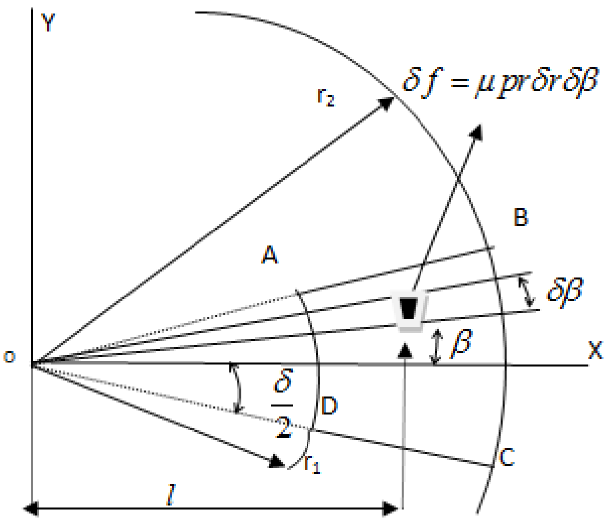

Figure 2. A typical brake pad sector of a circular annulus

In disc brake system the rotor is stopped by applying the force in perpendicular direction to the plane of disc i.e., parallel to the axis of rotation the disc from either sides. If p is the pressure acting on the unit area of the friction pad face then the torque T_1 acting on one pad is

$$T_1 = \int_{R_1}^{R_2}\int_{\frac{-\delta}{2}}^{\frac{\delta}{2}} \mu pr^2 dr d\beta = \int_{R_2}^{R_1} \mu pr^2 \delta dr \quad (1)$$

Resolving the forces acting on each element into two components R_x and R_y as

$$R_x = \int_{r_1}^{r_2}\int_{\frac{-\delta}{2}}^{\frac{\delta}{2}} \mu pr \sin\beta dr d\beta = 0 \quad (2)$$

$$\text{And } R_y = \int_{r_1}^{r_2}\int_{\frac{-\delta}{2}}^{\frac{\delta}{2}} \mu pr \cos\beta dr d\beta \quad (3)$$

Since the torque acting on a pad must equal the moment of the resultant R_y about the centre then

$$l = \frac{T_1}{R_y} \quad (4)$$

Where, l is the perpendicular distance from the centre to the line of action of the resultant reaction. There are two operating conditions applicable to disc brake system.

1. Uniform wear-applicable for practical brakes after a period of continuous usage

2. Uniform pressure-applicable for new brakes

D. For uniform pressure condition

When considering the capacity of a disk brake subjected to uniform pressure, every point on the brake face experiences the maximum design pressure for the friction material. This condition applies mainly to new brakes.

If pad is new, p can be considered constant, and by integrating equations "(1)" and "(3)"

$$l = \frac{\delta}{3\sin\frac{\delta}{2}} \frac{\left(r_2^3 - r_1^3\right)}{\left(r_2^2 - r_1^2\right)} \quad (5)$$

The total torque output of the disc is $2\mu p_1 l$ which can be expressed as

$$T = \frac{4\mu p_1 \delta}{3\sin\frac{\delta}{2}}\left(\frac{r_1 + r_2}{2}\right)\left\{1 - \frac{r_1 r_2}{\left(r_1 + r_2\right)^2}\right\} = 2\mu P_1 K_1 R_m \quad (6)$$

$$\text{Where, } K_1 = \frac{2\delta}{3\sin\frac{\delta}{2}}\left\{1 - \frac{r_1 r_2}{\left(r_1 + r_2\right)^2}\right\}$$

When $\delta = 25^o$ and 45^o respectively and $r_2 = 1.5r_1$ the value of K_1=1.021 and 1.04. When $\delta = 45^o$ and $r_2 = 2r_1$, the value of K_1 is 1.064. P_1 is the load acting on each pad.

E. For uniform wear condition

In this condition, the wear at any location is assumed to be directly proportional to the pressure intensity and the corresponding relative velocity of the local ring of contact. In the final pad position, if the wear is proportional to the work done, then $pr = c$ where, c is a constant. Substituting $p_2 = \frac{c}{r}$ in equations "(1)" and "(3)" and integrating, l results in

$$l = \frac{\delta}{2\sin\frac{\delta}{2}}\left(r_1 + r_2\right) \tag{7}$$

The torque output of a disc brake is now by

$$T = 2\mu P_2 K_2 R_m \tag{8}$$

Where, $$K_2 = \frac{\delta}{2\sin\frac{\delta}{2}} \tag{9}$$

And K_2 =1.008 and 1.026 when $\delta =$ 25° and 45° respectively. The braking torque is equal to kinetic energy possessed by the wheel. From the above mentioned procedure, with the rotor size of ϕ 160 mm and vehicle speed of 16.67 m/s, the maximum axial force obtained is 12kN. Based on this force the dimensions of Terfenol D are calculated as follows.

F. Diameter of Terfenol-D for the required axial force

The average Young's modulus of Terfenol D is E =45 GPa [10]; The force capability of Terfenol D rod is given as

$$P = EA_t\lambda_{\max} \tag{10}$$

Where A_t is cross section area $= \frac{\pi}{4} \times d^2$;

d = diameter of Terfenol-D;

$\lambda_{\max}$, the maximum magnetostriction and in linear range for 1 ksi prestress is given as 800 ppm [3]. For both the operating conditions, d can be calculated by using

$$d = \sqrt{\frac{P \times 4}{\pi \times E \times \lambda_{\max}}} \tag{11}$$

The above mentioned procedure is followed and diameter of Terfenol-D is calculated by varying radius of the disc rotor and by varying the angle subtended by the friction pad at the center of the disc rotor. The dimensions obtained from both the conditions are approximately equal. In general for safe design, the maximum axial force is considered and hence the maximum diameter of Terfenol D. A code is written in Matlab7.5, which gives diameter of Terfenol D for a particular disc specification .the maximum diameter of Terfenol D thus obtained is 20 mm. As mentioned in [11] the Terfenol D rod with 20 mm diameter can generate 12 kN. Hence, it is concluded that it is liable to use giant magnetostrictive material -Terfenol D for actuation in brake systems.

G. Calculation of length of Terfenol-D

Generally the frictions pads are kept at a distance of around 1 mm away from disc rotor. The fluid displacement mechanism used here amplifies the displacement 10 times. Hence, the displacement need to be obtained from Terfenol D rod is 0.1mm.

$$\frac{\Delta l}{l} = \lambda_{\max} = 800 \text{ ppm} \tag{12}$$

$$l = \frac{\Delta l}{\lambda_{\max}} = \frac{0.1}{800 \times 10^{-6}} = 125 \text{ mm}$$

The length thus obtained is checked for buckling so as to ensure safe operating conditions. The Euler formula of the critical load for bucking for a bar fixed at both ends is given as

$$P_{cr} = \frac{EI\pi^2}{L_e^2} \tag{13}$$

Where, E is Young's modulus of Terfenol D, I is moment of inertia given as $\frac{\pi}{64} \times d^4$ m^4, L_e - the effective length for column which depends on the type of boundary condition. For bar with fixed end at both sides is given as $0.5L$, L -length of the rod.

$P_{cr} = 2180$ kN

In present work the force experienced by Terfenol D rod is around 12kN which is very much smaller than the critical load. Hence it can be concluded that the Terfenol D is safe in buckling conditions.

IV. Magnetic Circuit Design

Magnetic circuit design involves the following steps:

1) Calculation of equivalent reluctance offered by the component of actuator.

2) Based on the linear range of operation of magnetostrictive actuator, obtain the number of turns for the solenoid.

3) FEMM simulation is to be carried out and coil height and wire size has to be arrived at.

The axisymmetrical view of the magnetic circuit path as modeled in FEMM is as shown in "Fig. 3". The magnetic path consists of eight designated sections of components through which the magnetic flux passes.$\Re$1-reluctance offered by Terfenol D rod, $\Re$2-reluctance offered by plunger, $\Re$3-reluctance offered by top end plate, $\Re$4- reluctance offered by top end plate edge, $\Re$5-reluctance offered by housing thickness, $\Re$6-reluctance offered by bottom end plate edge, $\Re$7-reluctance offered by bottom end plate, $\Re$8-reluctance offered by the bottom support of Terfenol D.

The Ampere's law gives the relationship between the current and the magnetic field density (A/m) and can be represented in the integral from as

$$\oint Hdl = NI \tag{14}$$

Therefore
$$\oint Hdl_{GMM} = N_{GMM}I_{GMM} = H_1l_1 + H_2l_2 + H_3l_3 + H_4l_4 + H_5l_5 + H_6l_6 + H_7l_7 + H_8l_8 \tag{15}$$

Where, N_{GMM} number of turns of coil, I_{GMM} current input given to the coil, $H_1, H_2, H_3, H_4, H_5, H_6, H_7, H_8$ are the magnetic field magnitude and $l_1, l_2, l_3, l_4, l_5, l_6, l_7, l_8$ are length of the magnetic path in reference to "Fig. 4".

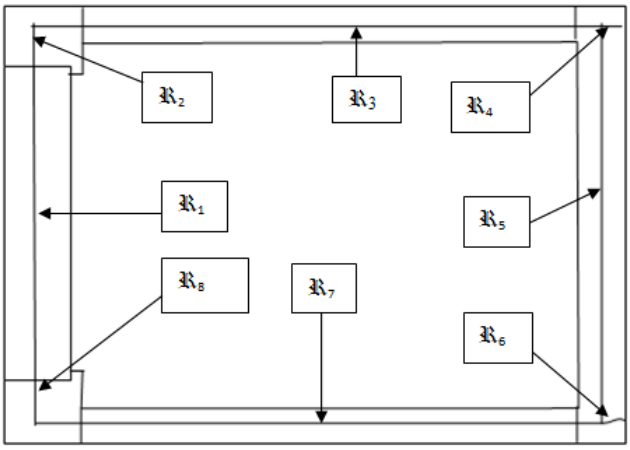

Figure 3.Axisymmetrical view of the magnetic path of the actuator

The individual reluctance along the path can be calculated by using the equation

$$\Re_i = \frac{l_i}{\mu_0 \mu_r A_i} \quad \text{Amp-turns per weber} \qquad (16)$$

Where, l_i is length of the section of the component, A_i is cross-sectional area of the section of the component and $i = 1$, 2… 8. The dimensions for the housing are to be assumed based on the dimensions of the Terfenol D rod and the coil sizes it can accommodate in the housing. Here trial and error method is used for obtaining the housing dimensions. The dimensions assumed for the housing are: inner diameter 156 mm, thickness 7 mm and height of the housing as 139 mm. The corresponding lengths and cross-sectional areas of the sections of the components are given as follows:

l_1 is the length of the magnetic path in Terfenol D rod=125 mm, l_2 is the length of the magnetic path in plunger portion of housing=4.5 mm, l_3 is the length of the magnetic path in top end plate =60.25 mm, l_4 is the length of magnetic path at the top end plate edge=3.5 mm, l_5 is the length of the magnetic path in the thickness portion of the housing =134 mm, l_6 is the length of magnetic path at the bottom end plate edge =3.5 mm, l_7 is the length of the magnetic path in bottom end plate =60.25, l_8 is the length of the magnetic path in the bottom support of Terfenol D rod=4.5 mm; Thickness of the top end plate $w_t = 5$ mm; Thickness of the housing $w_h = 7$ mm;

The procedure mentioned in [6] is used for calculating individual reluctance offered by all the components of magnetic flux. The reluctance thus obtained are added to get the total reluctance of the system $\Re$. Hence the total system reluctance is given as

$$\Re = \Re_1 + \Re_2 + \Re_3 + \Re_4 + \Re_5 + \Re_6 + \Re_7 + \Re_8 \qquad (17)$$

$\Re = 5.070074293 \times 10^7$ Amp-turns per weber.

In any magnetic circuit the total flux, Φ (weber) remains constant throughout the path. The relationship between flux density, B (Tesla), and flux is equal to the flux density multiplied by the integral of cross-sectional area

$$\Phi = \int B dA \qquad (18)$$

Where ' A ' is cross sectional area of the individual component along the magnetic path. As the flux is constant throughout the path, the product of flux density and cross-sectional area must be constant for each material. Hence

$$\Phi_{Terfenol} = \Phi_{steel} \qquad (19)$$

Substituting "(18)" in "(19)"

$$B_{Terfenol} A_{Terfenol} = B_{steel} A_{steel} \qquad (20)$$

The flux density B depends on the properties of the medium and specially the relative μ_r and is given by the equation

$$B_{Terfenol} = \mu_0 \mu_{r(Terfenol)} H_{Terfenol} \qquad (21)$$

$$B_{steel} = \mu_0 \mu_{r(steel)} H_{steel} \qquad (22)$$

The reluctance, $\Re$ in the magnetic circuit is similar to the resistance in the electric circuit. The simple equation for calculating the reluctance of the circuit is given by

$$\Re = \frac{NI}{\Phi} \qquad (23)$$

Combining the equations from "(19)" to "(21)", and substituting in "(23)"

$$N = \frac{\Re \mu_0 \mu_{r(Terfenol)} H_{Terfenol} A_{Terfenol}}{I} \qquad (24)$$

The actuator is needed to be operated in linear range along the path by which there is a provision to predict the magnetic field induction for a given magnetic field as shown in "Fig. 4"

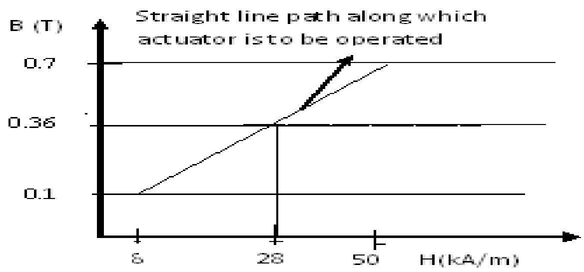

Figure. 4 Linear operating range of actuator

From the [10] for the prestress of 1ksi the linear range is found to be 0.1T to 0.7T at 6 kA/m to 50 kA/m respectively. Magnetic bias of 28 kA/m is given by DC coil and the rest 22 kA/m is given by AC coil so that the actuator is operated in the linear range. So, the magnetic field required for the present design is 50 kA/m out of which 28 kA/m is from DC and the rest 22 kA/m is from AC field. For most of the wires wound the current should not exceed 4 A. Hence by substituting the value of R in the "(17)" the total number of turns can be calculated as

$$N_{DC}=\frac{5.070074293\times10^{7}\times4\pi\times10^{-7}\times4\times4.9087\times10^{-4}\times28\times10^{3}}{I}$$

$$N_{DC}=874.6753\simeq875 \text{ turns}$$

$$N_{AC}=\frac{5.070074293\times10^{7}\times4\pi\times10^{-7}\times4\times4.9087\times10^{-4}\times22\times10^{3}}{I}$$

$$N_{AC}=687.3478\simeq688 \text{ turns.}$$

Hence in order to generate a DC and AC magnetic field of 28 kA/m with the assumed dimensions of housing, a solenoid with 875 turns and 688 turns respectively is required. The optimum height of the coil can be calculated by simulating the actuator in FEMM software and finding the optimum value by considering its circuit properties. In case of magnetostatic problems, the fields are time-invariant. In order to solve magnetostatic problems with a non-linear $B-H$ relationship, FEMM utilizes the following governing equation

$$\vec{\nabla}\left(\frac{1}{\mu\left(\vec{B}\right)}\vec{\nabla}\times\vec{A_m}\right)=\vec{J} \qquad (24)$$

Where, $\vec{\nabla}$ is gradient operator, $\vec{B}$ is magnetic induction vector, $\vec{A_m}$ is magnetic vector potential, $\vec{J}$ is current density and μ is absolute permeability.

FEMM magnetic simulations were carried out with 875 and 688 turns for DC and AC coil respectively, for a particular SWG wire with different heights such as 105, 110, 115, 120 and 125 mm. After finding the optimized coil height with a particular SWG (Standard wire gauge) wire, again simulation was carried out with different SWG sizes. The optimized coil dimensions for the required field are obtained with coil height of 120mm and with 17 SWG wire gage.

V. Experiment on Solenoid

For the purpose of verifying the above theoretical calculations with regards to the AC and DC coils for the solenoid, separate calculations were carried out for a solenoid

Figure 5. Solenoid for actuation of Terfenol D.

details which could generate 100kA/m for input current of 9 amps. This particular solenoid was fabricated using a 17 SWG wire and it is as shown in "Fig.5". The coil has a height of 80 mm and 972 turns are wounded which gives coil thickness of 26 mm.

A. *Testing of coil*

The fabricated coil was tested by passing low frequency current and DC current as well.

1) For AC current input

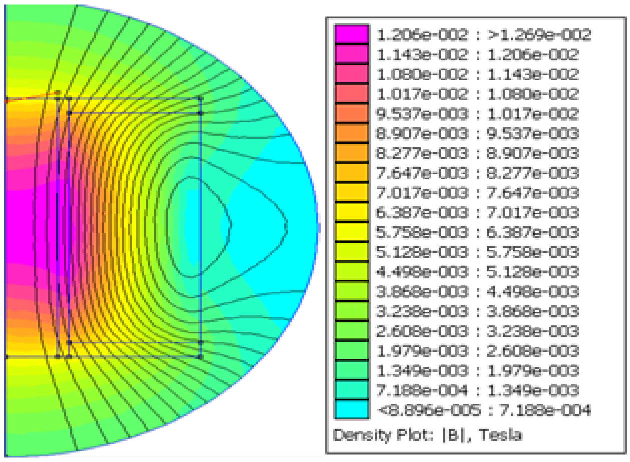

Figure 6. Simulation results of coil in free air at unit AC drive current

The experimental setup as shown in "Fig.7"consists of a computer loaded with LABVIEW software and data acquisition system called PXI (Peripheral Component Interface extensions for Instrumentation) card in it, BNC (Bayonet Neil-Concelman) 2120 module, Techron amplifier, guassmeter and multimeter. For low frequency current input, the signal is generated using BNC module and given to power amplifier as input. The amplifier ensures required voltage output through it. The output of the amplifier was connected to the coil ends through a crocodile connector.

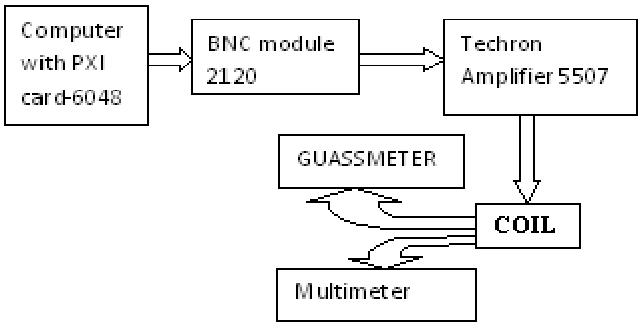

Figure 7. Experimental set up testing of solenoid with AC current as input.

The resistance of the wire was measured at no load conditions by using multimeter. The resistance reading from the multimeter was obtained as 1.9 ohms. The flux density produced by the coil in free air was measured using gauss meter. Using FEMM simulation for DC current input is also carried out as shown in "Fig. 6" and the results obtained by experimental and simulation results are compared in Table 1.

Table 1 Experimental flux density for AC current input

Voltage (V)	Current (A)	Flux density B (gauss)		Percentage difference
		Experimental reading	FEMM	
1.9	1	30	45	33.3
3.8	2	62	85	27.05
5.7	3	98	120	18.33
7.6	4	130	150	13.33

2) For DC current input

The experimental set as shown in "Fig.8"up here consists of APLAB DC power amplifier, multimeter, guassmeter. The DC voltage input of required magnitude can be given to the coil by amplifier. the amplifier terminals are connected to the coil and corresponding magnetic field is measured using guassmeter.

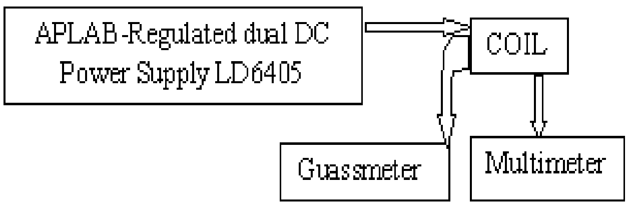

Figure 8.Experimental set up for testing of solenoid with DC current as input.

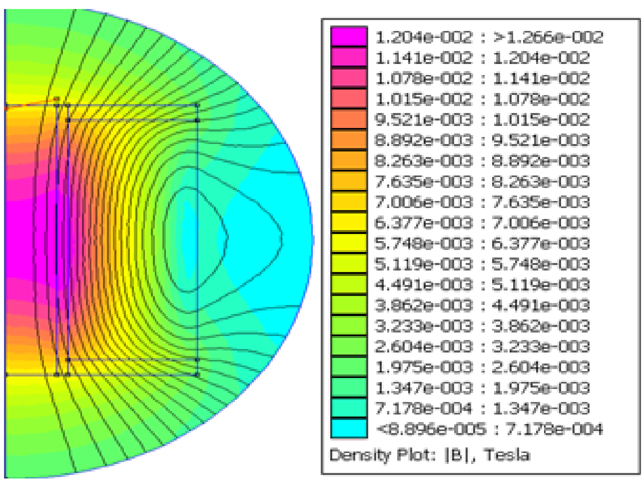

Figure 9.Simulation results of coil in free air at unit DC drive current

Table 2 Experimental flux density for DC current input

Voltage (V)	Current (A)	Flux density B (gauss)			Percentage difference
		Trial1	Trial2	FEMM	
1.9	1	54	55	60	10
3.8	2	104	104	115	9.56
5.7	3	170	170	180	5.5
7.6	4	233	230	240	3.75

Using FEMM simulation for DC current input also is carried as shown in "Fig.9" and the results obtained by experimental and simulation results are compared in Table 2.

B. Results

It is inferred that the flux density produced by the coil in free air experimentally is in good agreement with the theoretically required flux density.

VI. CONCLUSION

This paper has focused on the design aspects of the magnetostrictive disc brake. The magnetic circuit details for actuation of Terfenol d rod are discussed. Experimental results with regard to the flux density are obtained to verify the design detail of the solenoid.

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