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Design and Analysis of Magneto-rheological Brake Envelope

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Abstract: The aim of this work is to understand the performance variations of magneto-rheological brake system by considering the different shapes of brake envelopes. The shapes selected for brake envelopes are rectangular, dumbbell, shell type and 7-segment and find out the most suitable shape or geometry. MR brakes of different shapes were modelled and the braking torque for each envelope was found out. By using ANSYS Mechanical APDL optimization of MR brakes with different shapes is performed. From the results most suitable MR brake system were identified and discussed.

Keywords: Magneto-rheological fluid (MR fluid), MR brake, Shape of envelope, braking torque.

I. INTRODUCTION

A conventional brake system has many disadvantages and creates lot of environmental problems. The particles emanating because of wear of the brake pad pollute the environment. In addition to pollution caused by wear particles, the friction-induced noise between the brake pad and the disc is also a major concern. Also, localized heating occurs in a conventional disc brake [1, 2]. To avoid both of these problems, conventional disc brakes can be replaced with magneto rheological fluid brakes. Magneto rheological fluids are materials having a shear yield stress which is a function of the magnetic field. On the application of a magnetic field, magneto rheological particles become aligned and increase the shear resistance between relatively moving surfaces.
MR fluids have great potential in many applications that require an electromechanical interface such as clutches, brakes, valves, dampers and robotics [3, 4].

MR damper or MR shock absorber is a damper filled with MR fluid, which is controlled by a magnetic field, usually using an electromagnet. This allows the damping characteristics of the shock absorber to be continuously controlled by varying the power of the electromagnet [5]. This type of shock absorber has several applications, most notably in semi-active vehicle suspensions which may adapt to road conditions, as they are monitored through sensors in the vehicle, and in prosthetic limbs [6].

The U.S. Army Research Office is currently funding research into using MR fluid to enhance body armor [7]. In 2003, researchers stated they were five to ten years away from making the fluid bullet resistant. In addition, HMMWVs, and various other all-terrain vehicles employ dynamic MR shock absorbers or dampers [8, 9].
MR Finishing, a MR fluid-based optical polishing method, has proven to be highly precise. It was used in the construction of the Hubble Space Telescope's corrective lens [10].

Many types of MR brakes have been developed and evaluated such as;

- Disc-type MR brakes [11, 12]
- Drum-type MR brakes [13]
- Hybrid-type MR brakes (a combination of disc- and drum-type MR brakes) and
- T-shaped rotor MR brakes

There are many research programs for obtain the most suitable MR brakes by changing number of discs, type of MR fluid, changing current in the magnetic circuit etc..But these researches give the little importance on the brake shape or envelope geometries of MR brake system. Our work has been pointed towards in this direction. The conventional MR brake envelope consists of Rectangular envelope, which is simple and most compatible type envelope and also a rectangular envelope is convenient for design and manufacturing. But the braking torque developed by these MR brakes becomes significantly low. The rectangular shape causes an uneven distribution of magnetic density resulting in local '**bottle-neck**' problems with MR brake magnetic flow, which reduces the braking torque. In addition, the rectangular shape of the envelope may result in the MR brake being heavy [14].

In this work we consider different types of other envelopes for MR brake assembly and their relative change in the braking torque with geometric changes in the envelopes. The shapes of envelopes considered in this work include;

- Conventional rectangular
- Dumbbell shaped

- Shell type
- 7-segment polygonal

This study limited only to disc type MR brakes, but these results can be applicable any other MR brake forms. By developing the four MR brake geometries, we are able to calculate the braking torque for each shapes based on the characteristics of MRF-132 DG (Table I) [1]. A finite element analysis has been performed for obtaining results with high degree of accuracy. The 2D magneto static analysis is conducted in ANSYS mechanical APDL.

TABLE I PROPERTIES OF MRF 132-DG

Property	Value/limits
Base fluid	Hydrocarbon
Operating temperature	-40 to 130°C
Density	3090 kg/m³
Colour	Dark gray
Yield stress	45kPa
Weight percent solid	81.64%
Specific heat at 25°C	800 J/kg K
Thermal conductivity at 25°C	0.25-1.06 W/m K
Flash point	>150°C
Viscosity at 40°C	0.09(±0.02)Pa s
K(MR fluid dependent constantparameter)	0.269 Pa m/A
β(MR fluid dependent constantparameter)	1

II. ENVELOPES AND THEIR CHARACTERISTICS

In this section we discuss about the characteristics of each MR brake envelopes under our consideration. Fig. 1 shows the typical rectangular MR brake system. Rotary disc, MR fluid, Magnetic coil, Shaft and Stationary housing are the major components of the MR brake assembly. When a current is applied across the magnetic coils, a magnetic field is induced. Due to this magnetic field the MR fluid present in the gap between the rotary disc and envelope solidifies. This causes a shear friction to develop between the rotary disc and solidified MR fluid and braking torque is developed, which slow down the shaft [14, 15].

The most widely used MR brake uses rectangular envelop due to its simplicity in design and manufacturing. But it has certain limitations as we discussed earlier, in order to avoid these problems MR brakes with envelopes having dumbbell, dumbbell type and 7-segment polygonal shapes are considered in our work.

Fig.2 and Fig. 3 shows geometric cross section of dumbbell and shell type envelopes. These are designed according to the housing thickness, housing radius, coil width and height, outer and inner radius of the disc, thickness of disc, shaft radius. The 7-segment envelope MR brake has been developed according to their respective geometric variations in these parameters, cross section of that one shown in Fig. 4.

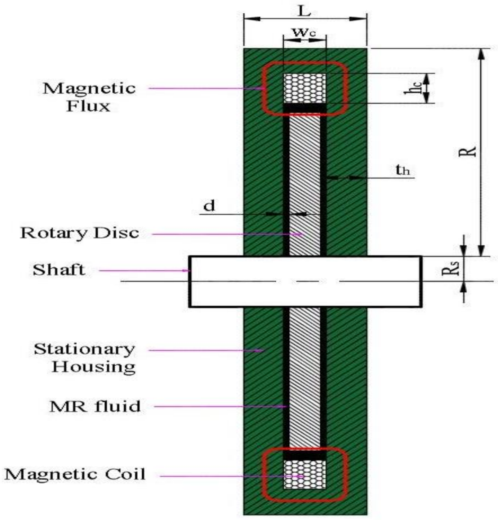


Fig 1

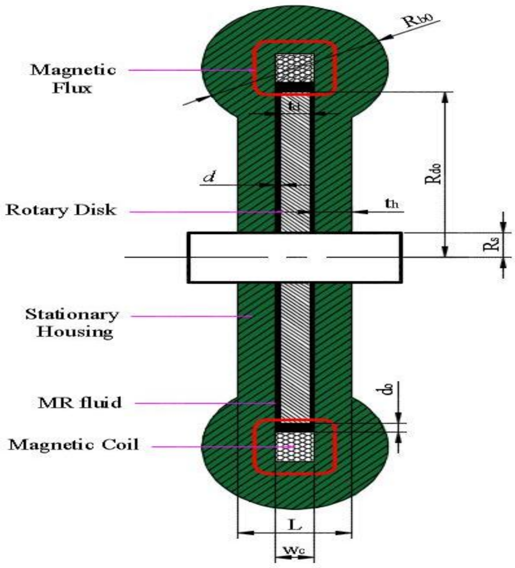


Fig 2

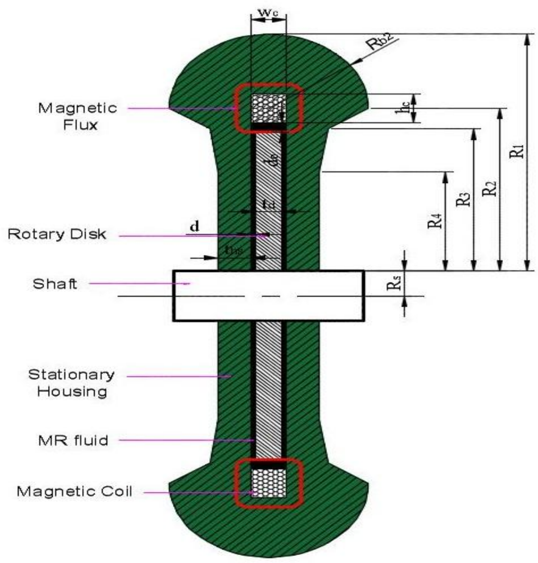


Fig 3

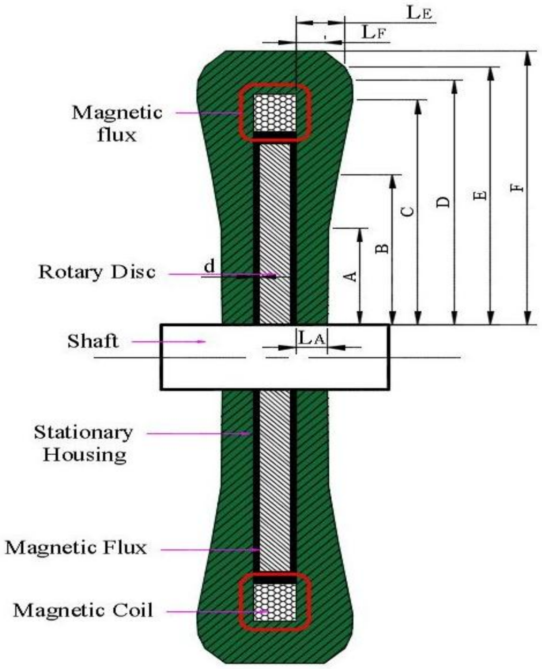
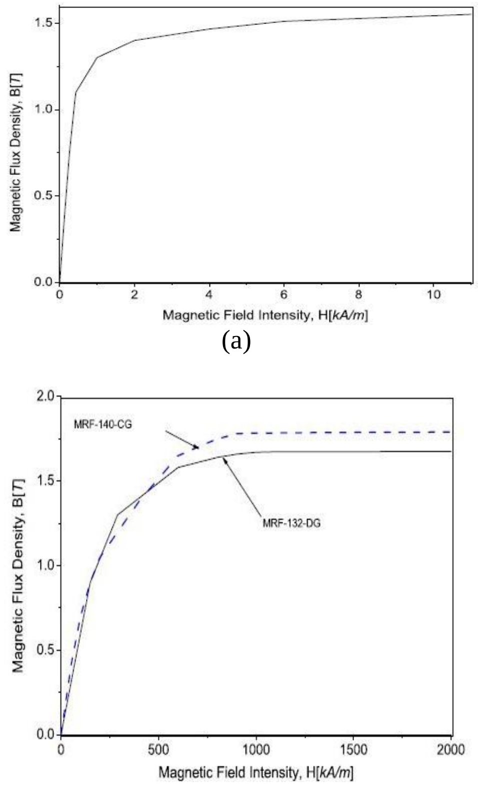


Fig 4

Configuration of a disc-type MR Brakes- Rectangular type, Dumbbell shape, Shell type, 7-Segment



(a)

(b)

Fig. 5: Magnetic properties of silicon steel and MR fluids: (a) B–H curve of silicon steel and (b) B–H curve of MR fluids

III.FEA MODELLING AND OPTIMISATION

It is assumed that commercial silicon steel is used for the magnetic components of the MR brake such as the MR brake housing and disc. The coil wires are sized as 23-gauge (diameter D 0.573 mm) and a maximum current of 2.5 A is applied to the coil. Two-dimensional (2D)-axisymmetric couple element (Plane 13) is used to solve the magnetic circuits of the MR brakes;the element edge length is specified as 0.0002mm for accurate result. The characteristics of disc and housing are defined based on the BH curve shown in the Fig. 5(a), also B-H curve of MRF 132 DG is given in Fig. 5(b) [1]. Copper coils have the relative permeability of 1(B/H).The applied boundary condition refers that the magnetic flux is confined within the envelope.

TABLE II DIMENSIONS USED DURING MODELING

MR brake	Dimensions (mm)
Rectangular	MR fluid gap: d =0.8 Coil width: W_c=6.35 Shaft radius:R_s =6 Coil height: h_c =2.2 Disc thickness:t_d =5 Housing thickness: t_h =6 No. of coil turns: 68, Disc radius:R_{do} =46 Mass: 1.21 kg Outer radius: R =55

IV.RESULTS AND DISCUSSION

In this section, we discuss about the braking torque developed by each MR brakes due to changes in their magnetic flux density variations.

A. Current Density

Current density is calculated using equation;

$$\rho = \frac{n \times I_c}{A_c}$$

Where, ρ = Current density, n = Number of coils (72), I_c= Current per coil (2.5A), A_c= Coil area. The current density is applied in the coil. Figure 6 shows that the applied current density is limited only to the coil area.

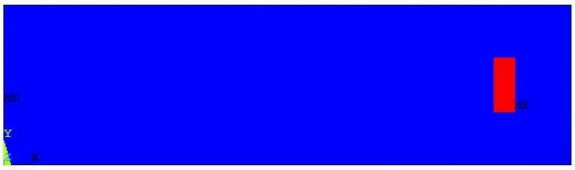


Fig. 6: Current density was applied across the coils (rectangular envelope)

B. Magnetic Flux Lines

The magnetic flux lines show lines of constant AZ (or constant radius-times-AZ for axisymmetric problems).

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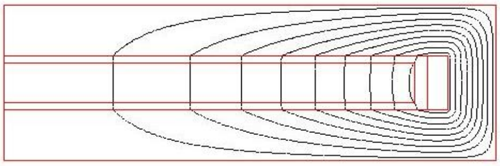
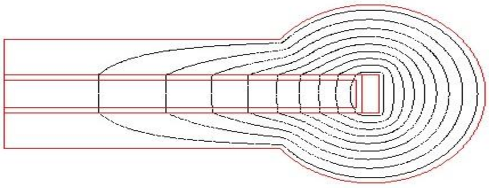
The flux lines for different envelopes are as shown in figure 7. It is evident from the figure that the 7-segmented shape gives the desired output when compared with the other models.



(a)



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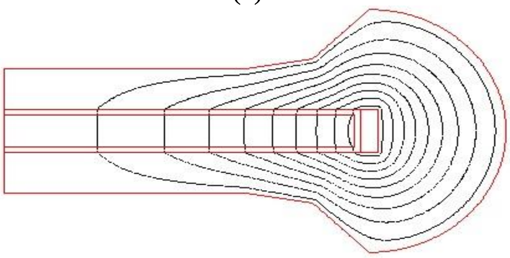
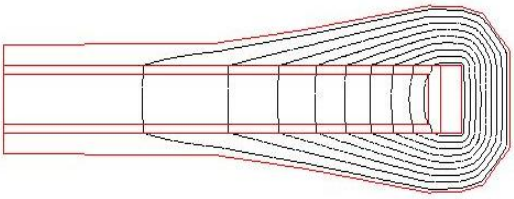


(c)

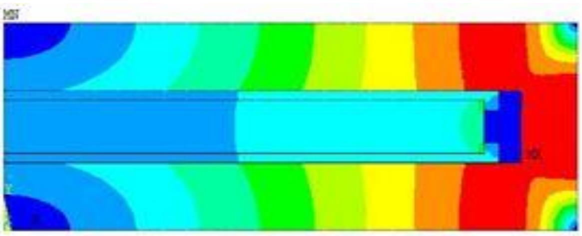


(d)

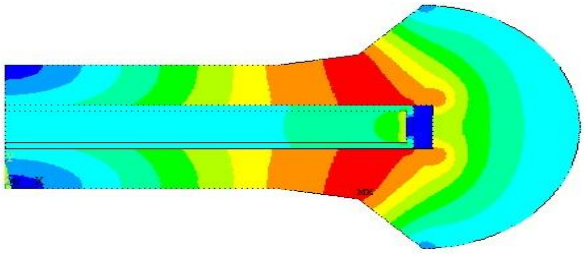
Fig. 7: Magnetic flux lines distribution of (a) Rectangular, (b) Dumbbell, (c) Shell type, (d) 7-segment

C. Magnetic Flux Density

To find magnetic flux density variations, we used nodal solution to obtain our results. It establishes the values at each node instead of looking at the element in general (element solution). For each envelopes the magnetic flux densities($BSUM_{AVG}$) in Tesla are: Rectangular=0.654031, Dumbbell=0.67433, Shell type=0.71006, 7-Segment =0.75533



(a)



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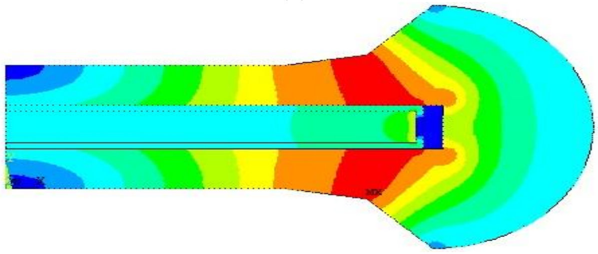

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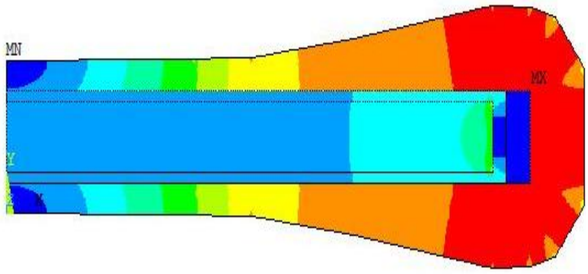

(d)

Fig. 8: Magnetic flux density variation of (a) Rectangular, (b) Dumbbell, (c) Shell type, (d) 7-segment

D. Braking Torque

The MR fluids behave rheologically as Bingham-plastic fluids. By taking into account of this assumption, the induced braking torque of single disc-type MR brake is determined by,

$$T_b = \frac{4\pi\mu_0 {R_0}^4}{(n+3)d}\left[1-\left(\frac{R_i}{R_0}\right)^{n+3}\right]\Omega + 2\pi {R_0}^2 b_d K_0 \left[\frac{\Omega R_0}{d_0}\right]$$

where R_i andR_0 are the inner and outer radius of the disc, d is the gap between disc and envelope, d_0 is the gap between outer cylinder of disc and envelope, b_d is the thickness of the disc, Ωis the angular velocity of rotor, K_0 is the MR fluid dependent constant parameter, μis the viscosity of the MR fluid and n is the number of coils.

For each models the calculated braking torque (Nm) are shown in table III;

TABLE III BRAKING TORQUES FOR EACH GEOMETRIES

Geometry	Braking Torque (Nm)
Rectangular	18.365
Dumbbell	20.685
Shell type	23.832
7-Segment	24.325

The difference between the increasing braking torque percentage of dumbbell and shell type MR brakes is no more that 2.4%.

V. CONCLUSION

In our work, different geometries of MR brake envelopes such as rectangular, dumbbell, shell type and 7-segment geometry, were considered from which the most suitable shape was identified. FEA integrated with an optimization tool is used to obtain optimal geometric dimensions of the MR brake constrained in a specific volume in order to maximize the braking torque. The braking torque calculated using the equation, depends on the properties of MR fluid, dimensions of the envelope and number of coils in the magnetic circuit. From our work, we found that magnetic flux density and magnetic field intensity has its own effect on the magnitude of braking torque. The results show that the braking torque of conventional rectangular MR brakes can be significantly increased by using a 7-segment type envelope. The results also show that the braking torque of the MR brakes using a shell type and 7-Segment envelope with is almost the same. Therefore, the manufacturing cost and the piece-wise smoothness are the important issues in deciding whether a shell type or a 7-Segment envelope should be used.

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