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Research Article

Conceptual Design of Magnetorheological Brake using TK Solver

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Abstract

The aim of this paper is to design a magnetorheological brake (MRB) system, which has potential to replace the existing automobile mechanical shoe-pedal brake system. The proposed brake system consists of rotary disks immersed in a MR fluid and enclosed in an electromagnet. The yield stress of the fluid varies as a function of magnetic field created by electric current passing through the electromagnet. The instantaneous increase in yield stress of fluid significantly increases the friction on the surfaces of rotating disks; thus generating a retarding braking torque. Unfortunately, MR fluids do not show linear increment in shear strength with increase in applied magnetic field, and finally shear strength gets saturated. Therefore in the present study, the non-linear behavior of shear strength and its saturation limits to estimate the braking torque exercised by MR brake have been incorporated. A parametric study considering various configurations of rotating disk and MR gap has been presented. Finally, based on analysis, merits of the multidisc MR brake have been highlighted.

Keywords:MR fluid, MR brake, Multi disk MR Brake.*

1. Introduction

Magnetorhelogical (MR) suspensions are known for dramatic change in their apparent viscosity. Due to their variable viscosity, MR fluids are used in engineering applications requiring controllable dynamic performance. One such application is magnetorheological brake in which MR fluid is treated as a brake lining material. This material does not wear-away and provides desirable friction resistance by just controlling the magnetic field passing through it. As MR brake involves electromagnetism and magnetisable friction material, this system can be named as "electromagnetic brake" (Gupta and Hirani, 2011).

A typical MR fluid consists of 20-40 volume percentage of pure-iron (purity > 99%) particles (size: Ø3-10 micrometers), suspended in a carrier liquid such as mineral oil, synthetic oil, water or glycol. A variety of proprietary additives to avoid gravitational settling, to elude wear and to promote particle suspension, are added to MR fluids. To model the behavior of MR fluids, the Bingham plastic model (Ginder and Davis, 1994) is used. MR fluids exhibit maximum yield strengths of 50-100 kPa for applied magnetic fields of 150-250 kA/m. The performance of MR-based devices is relatively insensitive to temperature over a broad temperature range (Ginder and Davis,1994).

The design of MR brake starts with the maximum shear strength, τ_{max}, achievable by the available MR fluid. The control on the shear stress (between zero to τ_{max}) of MR fluid is achieved by regulating the magnitude and direction of the magnetic field. The field density is a function of permeability and saturation of materials through which magnetic field passes, brake geometry, number of turns in electromagnetic coil, and current supplied to electromagnetic coil (Sarkar and Hirani, 2015), (Sarkar and Hirani, 2013), (Sukhwani, *et al*, 2009), (Sukhwani and Hirani, 2008), (Sukhwani and Hirani, 2008), (Hirani and Manjunatha, 2007), (Sukhwani, *et al*, 2007), (Sukhwani, *et al*, 2006), (Gupta and Hirani, 2011), (Muzakkir and Hirani, 2015), (Muzakkir, *et al*, 2015). Unfortunately, MR fluids do not show linear increment in shear strength with increase in applied magnetic field, and finally shear strength gets saturated. Therefore in the present study, the non-linear behavior of shear strength and saturation limits to estimate the braking torque exercised by MR brake have been incorporated.

2. Conceptual Design and Development of MR Brake

The MR brake consisting of MR fluid, disk and brake pad as shown in figure 1. Four configurations of MR Brake, considered in the present study, are shown in figure 2.

In configuration 1, brake pad inner radius is r1, its outer radius is r2. The brake pad material is ferromagnetic. When the electric current is supplied to

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the central electromagnet, the MR fluid in the hollow cylindrical area having bore-radius as r1 and outer radius as r2 gets magnetized. The configuration 2 is similar to configuration 1, but the only the difference is radius of rotor is almost equal to the bore radius of housing. This especially is required to minimize the leakage of MR fluid from the brake. In configuration 3, along with the presence of MR fluid at side surfaces of disk, MR fluid is placed on the periphery of the rotating disk. Therefore, when the magnetic field is applied, additional braking due to the MR fluid in the annular region o defined by radius r2, (r2+h) and width w1 is achieved. The configuration 4 shows multi-disk MR brake. Here three rotating disks have been used, which increase the MR effect in the presence of magnetic field.

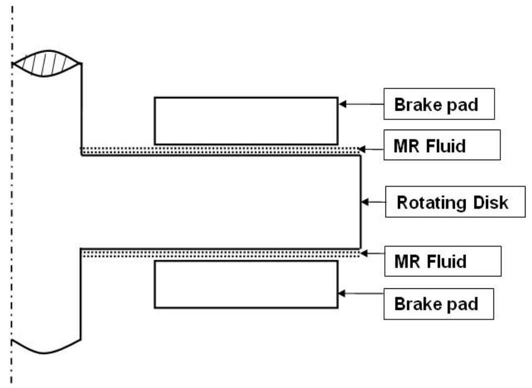
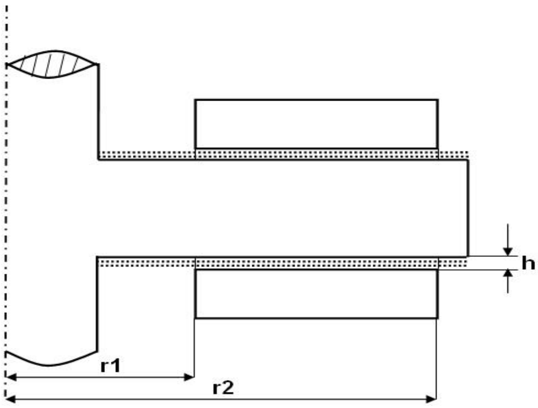
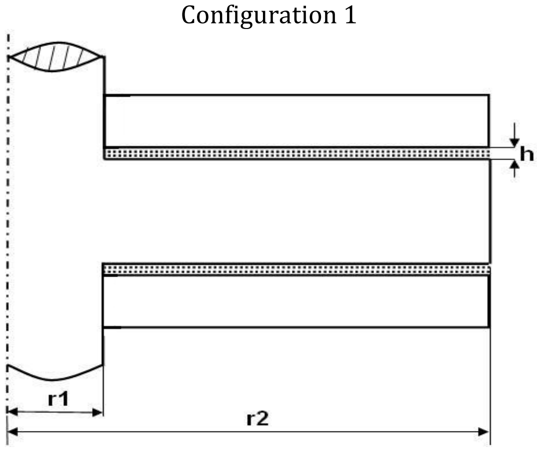


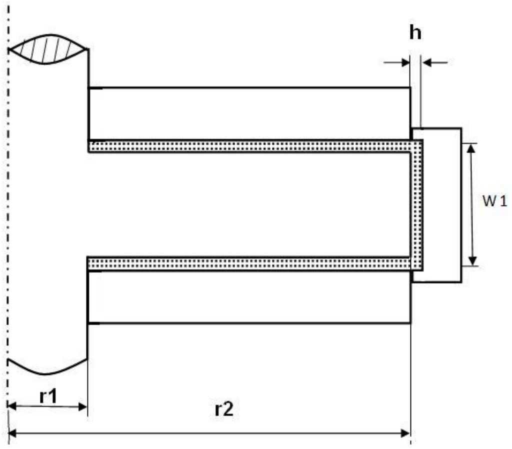
Fig.1 Block diagram of MR Brake



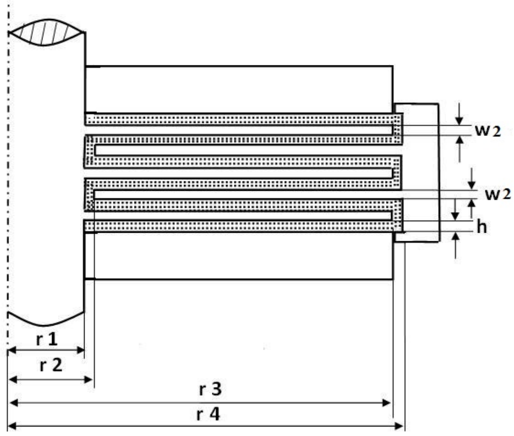
Configuration 1



Configuration 2



Configuration 3



Configuration 4

Fig.2 Four Different Configurations of MR brake

3. Mathematical Modeling

The shear stress of MR fluid is often modeled using Bingham model equation,

$$\tau = \tau_{yd} + \eta\dot{\gamma} \quad (1)$$

Where, $\tau_{yd}$is field induced yield stress, η is viscosity of the MR Fluid and Shear rate, $\dot{\gamma} = \frac{\omega^{*}r}{h}$.
Here h is gap between disk and brake pad, r is radius and $\omega$is angular speed. Therefore,

$$\tau = \tau_{yd} + \eta\cdot\frac{\omega^{*}r}{h} \quad (2)$$

Expression of brake torque for MR brake configuration 1 and configuration 2 are same and can be expressed as

$$T_1 = T_2 = 2\pi h(r_2^2 - r_1^2)\tau_{yd} + \frac{4}{3}\eta\pi\omega(r_2^3 - r_1^3)(3)$$

Expression of brake torque for MR brake configuration 3 can be expressed as

$$T_3 = 2\pi h\tau_{yd}(r_2^2 - r_1^2) + \frac{4}{3}\pi\eta\omega(r_2^3 - r_1^3) + \pi w_1\tau_{yd}(r_3^2 - r_2^2) + \frac{2\pi w_1\eta\omega}{3h}(r_3^3 - r_2^3)(4)$$

Expression of brake torque for MR brake configuration 4 can be expressed as

$$T_4 = 6\left\{2\pi h\tau_{yd}(r_3^2 - r_1^2) + \frac{4\pi\eta\omega}{3}(r_3^3 - r_1^3) + \pi w_1\tau_{yd}(r_4^2 - r_3^2) + \frac{2\pi w_1\eta\omega}{3h}(r_4^3 - r_3^3) + \pi w_1\tau_{yd}(r_2^2 - r_1^2) + \frac{2\pi w_1\eta\omega}{3h}(r_2^3 - r_1^3)\right\} \quad (5)$$

As, with increase in magnetic field, the yield stress MR fluid increases, the logarithmic relation (Sarkar and Hirani, 2013)between the yield stress (τ_{yd}) and magnetic field (H) is as follows.

$$\log(\tau_{yd}(B)) = A_1(\log(H))^3 - B_1(\log(H))^2 + C_1\log(H) - D_1 \quad (6)$$

In this equation (6) coefficients A_1, B_1, C_1 and D_1 are specific to the MR fluid.

Equations (3) to (5) show the brake torque output of MR brake of given configuration increases with increase of yield stress but the maximum value of yield stress is governed by saturation magnetization of magnetic material as given by Equation (6) and will put an upper limit on the maximum value of braking torque. Therefore magnetic saturation should be accounted while calculating brake torque output. In this research work, LORD MRF-336AG silicone-based MR fluid (Lord, 2006) (Sukhwani and Hirani, 2008)has been taken for theoretical torque calculations of the MR brake. The magnetic field intensity (H) generated by an electromagnet (17) of MR brake can be expressed by Equation (7).

$$H = \frac{NI}{2h} \quad (7)$$

4. Results and Discussion

For configuration 1, torque in terms of control current and speed has been derived by substituting values of τ_{yd} (Eq. 8) in Equation (3).Here, N=1000,$r_1 = 0.121\,m, r_2 = 0.206\,m, \omega = 43.77\,\frac{rad}{sec}, \eta = 0.09\,Pas$.
The perform parametric study three values of h 0.25 mm, 0.75 mm and 1.25 mm were selected. The variation in torque T as function of gap h and control current is plotted in the Figure 5. To consider the saturation, the maximum value of $\tau_{yd}$was restricted to 56 kPa. Torque values obtained using this constraint $\tau_{yd} \leq 56$ kPa is plotted in Figure 6.These results indicate on accounting saturation, the braking torque increases with increase in MR gap.

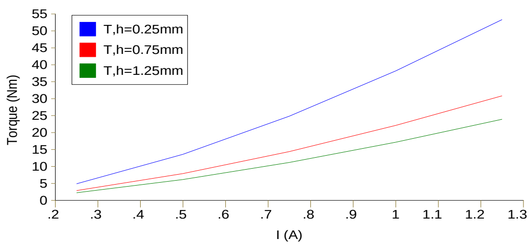


Fig. 5 Torque vs. Current for configuration 1 without saturation

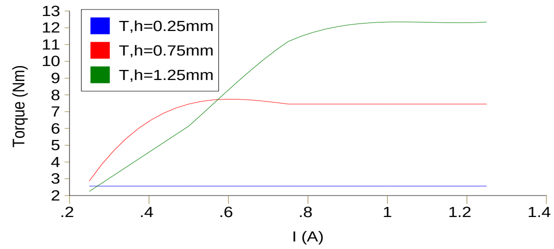


Fig. 6 Torque vs. Current for configuration 1 withsaturation

In configuration 2, r_1 = 0.063 m and r_2 = 0.2135 m. The MR gap, h varies from 0.50 mm to 1 mm. The variation of torque T with the gap h atdifferent control currents is listed in the Table 1. The braking torque saturates at 7.38 Nm and 14.67 Nm for MR gap (h) 0.5 mm and 1 mm respectively.

Table1 Maximum Torque produced at different current at configuration 2.

I, current (A)	Maximum torque at configuration 2			
	Without saturation		With saturation	
	h = 0.5mm	h = 1.0mm	h = 0.5mm	h = 1.0mm
0.25	5.1944	3.7118	5.1944	3.7188
0.50	14.4061	10.2325	7.3479	10.2325
0.75	26.3349	18.6674	7.3479	14.6689
1.0	40.4608	28.6559	7.3479	14.6689
1.25	56.4835	39.9857	7.3479	14.6689

In configuration 3, width W_1 is taken as $0.045m$. The values of torque T as a function of h and control currents are plotted in Figure 7. Figure 8 shows the saturation at h=0.25mm, 0.75mm and 1.25 mm. Therefore, the values of maximum braking torque are 144.01 Nm, 60.51 Nm and 42.49 Nm for MR gap (h) 0.25 mm, 0.7 mm and 1.25 mm respectively. The braking torque saturates at 7.84 Nm, 14.73 Nm and 21.96 Nm for the corresponding MR gaps. These results indicate that the braking torque increases with increase in MR gap.

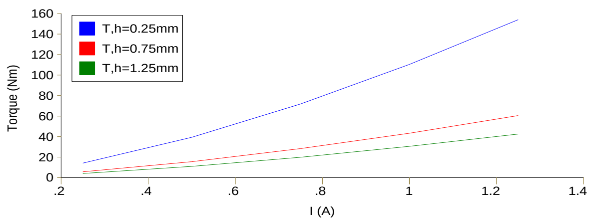


Fig.7 Torque vs. Current for configuration 3 without saturation

In case of configuration 4, $w_2 = 0.003m, r_1 = 0.063m, r_2 = 0.064m, r_3 = 0.213m, and\ r_4 = 0.215m$. The variation of torque T with the gap h for different control currents is shown in Table 2. It shows the saturation of braking torque for MR gaps, h = 0.5mm and h = 1 mm. The braking torque saturates at 43.10 Nm and 86.20 Nm for MR gap (h) 0.5 mm and 1 mm respectively. Theoretical estimations show that the multi disk MR brake provides better torque as compared to single disk MR brake.

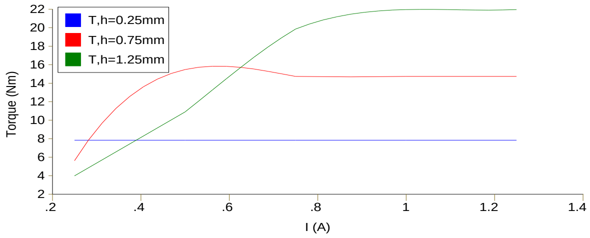


Fig.8 Torque vs. Current for configuration 3 with saturation

Table 2 Maximum Torque produced at different current at configuration 4.

I, current (A)	Maximum torque at configuration 4			
	Without saturation		With saturation	
	h = 0.5mm	h = 1.0mm	h = 0.5mm	h = 1.0mm
0.25	32.4710	22.7973	32.4710	22.7973
0.50	90.0481	62.7273	43.1000	62.7272
0.75	164.6077	114.4345	43.1000	86.2000
1.0	252.9000	175.6660	43.1000	86.2000
1.25	353.0495	245.1195	43.1000	86.2000

Conclusions

- In this study performance of a MR fluid brake has been evaluated to investigate its brake torque characteristics. Following conclusions can be drawn from this study:
- Analytical equation to estimate torque resistance offered by brake in terms of direct current and rotational speed has been derived.
- Multidisc MR brake is the best conceptual design as far as maximum torque is concerned.
- It is necessary to account the saturation of MR fluids. MR fluid having high saturation magnetic value shall be selected for the design of MR brakes.

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