Design and analysis of magneto rheological fluid brake for an all terrain vehicle

Luckachan K George¹
Tamilarasan N²
Thirumalini S³

1. PG Student, Department of Mechanical Engineering, Amrita school of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India
2. Assistant Professor, Department of Mechanical Engineering, Amrita school of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India
3. Professor, Department of Mechanical Engineering, Amrita school of Engineering, Coimbatore, Amrita Vishwa Vidyapeetham, Amrita University, India

E-Mail: ¹ luckachankgeorge@gmail.com ² n_tamilarasan@cb.amrita.edu ³ st_malini@cb.amrita.edu

Abstract. This work presents an optimised design for a magneto rheological fluid brake for all terrain vehicles. The actuator consists of a disk which is immersed in the magneto rheological fluid surrounded by an electromagnet. The braking torque is controlled by varying the DC current applied to the electromagnet. In the presence of a magnetic field, the magneto rheological fluid particle aligns in a chain like structure, thus increasing the viscosity. The shear stress generated causes friction in the surfaces of the rotating disk. Electromagnetic analysis of the proposed system is carried out using finite element based COMSOL multiphysics software and the amount of magnetic field generated is calculated with the help of COMSOL. The geometry is optimised and performance of the system in terms of braking torque is carried out. Proposed design reveals better performance in terms of braking torque from the existing literature.

Keywords: Smart materials, Magneto-rheological brake, All Terrain Vehicle (ATV), COMSOL

1. Introduction

This paper introduces a design of single disk magnetorheological fluid brake for automobile application. Automobile industry is changing every day. Billions of dollars are put as resources in to innovative work for building more secure, less expensive and better performing vehicles. One such speculation is the “x by wire” point which has been acquainted with enhancing the current mechanical frameworks in automobiles. Conventional friction brakes (FB) is the commonly used brakes in the recent years. However, it is incorporated with the down sides such as periodic replacement due to wear, vast mechanical time delay, brake noise due to metal to metal friction and also size required for the brake is more due to the auxiliary components such as fluid pump, fluid reservoir, hydraulic lines etc. Electromechanical brake (EMB) is a suitable option to reduce some of these drawbacks.

In this work we propose a design for EMB using Magneto rheological fluid (MR Fluid) for All terrain vehicles (ATV). As the ATVs are designed mainly for off roads and transportation through inaccessible areas, much higher significance is given to the designing of proper brake system. As of now the ATV is associated with conventional brakes. The important characteristics of MR fluids are of response time and stiffness, latter which is directly proportional to the applied magnetic field. Figure 1 shows the behaviour of MR fluid in the presence of magnetic field. Response time of MR fluid is less than a millisecond whereas in the case of conventional hydraulic brakes response time is around 200 – 300 milliseconds.
MR fluids are those fluids which varies their rheological behaviour on the application of magnetic field. This change is caused by the development of yield stress that increases with the applied field. In the absence of magnetic field, MR fluids act like Newtonian fluid. Jacob Rabinow at the US National Bureau of Standard discovered MR fluids [1].

Jolly et al. [2] describes that MR fluids consist of magnetically permeable micron-sized particles which are dispersed throughout the carrier medium. The carrier medium is either a polar or non-polar fluid, which influences the viscosity of the MR fluids. On the other hand, MR fluids are controllable fluids that exhibit dramatic reversible change in rheological properties (elasticity, plasticity or viscosity) either in solid-like state or free-flowing liquid state depending on the presence or absence of a magnetic field. When magnetic field is applied particles acquire dipole moment aligned with magnetic field to form linear chains parallel to field. The flow resistance (apparent viscosity) of the fluid is intensified by the particle chain. When the magnetic field is removed, the particles are returned to their original condition, which lowers the viscosity of the fluid. Sedimentation problem is the disadvantage of MR fluids, Fang et al. [3] developed single walled carbon nano tube (SWNT) in the MR fluid. Shetty and Prasad [4] synthesized MR fluid with a non edible vegetable oil as a carrier liquid and they reported that the yield stress produced is only 25 kPa.

Upendra S. Gupta provides an in-detail description of the design considerations, static & dynamic analysis and mathematical data involved in the design of a ATV Vehicle [5]. Edward J. Park developed a design of magneto rheological fluid brake for automotive application [6]. L shaped disk was developed by Hajiyen et al [7] and obtained a better performance in terms of braking torque. Tamilarasan N depicts a detailed study about the ferro fluids and developed a ferro fluid based Braille systems [8] and Ajith describes a detailed study about the finite element analysis and optimisation using DOE [9].

2. Magneto rheological Fluids (MR fluids)

The MR fluid is characterised by mainly three components, carrier fluid, iron particles and additives. Carrier fluids are chosen in view of their viscosity, their temperature steadiness and their similarity with different materials in the device. Mainly used carrier fluids are silicone oil, synthetic oil, water, kerosene etc. The most broadly utilized material for MR fluid particle is carbonyl iron, on account of its high magnetic saturation and is acquired by the process of thermal decomposition of iron pentacarbonyl. (Fe(CO)5). The additives are used for particle settling, agglomeration, preventing the particle from oxidation and wear.

The Bingham plastic model is used to describe the MR fluid characteristics, which is illustrated in figure 2. In this model, the amount of total shear stress (τ) developed is given by the equation

\[ \tau = \tau_y (H) + \eta \gamma^n \]

Where \( \tau_y (H) \) the dynamic yield stress due to the applied magnetic field, \( \eta \) is the plastic viscosity which is same as that of no field viscosity and \( \gamma \) is the shear strain rate. The slope shear stress and shear strain curve gives the plastic viscosity of magneto rheological fluid. Several models are used to describe behaviour of MR fluids. One such model is Herschel Bulkley model for which accommodate shear thinning and shear thickening effects can be accommodated. In this work we focus simple Bingham plastic model to analyse the behaviour fluid.
Mainly two types of MR fluids are used in brake applications, MRF 132DG and MRF 241 ES. These fluids use synthetic oil and water based fluids as carriers. Graph of magnetic field vs yield stress of MRF 241 ES is shown in figure 3 and MRF 132 DG is shown in figure 4. The main properties of two fluids are shown in the table 1.

![Bingham plastic model](image)

**Figure 2. Bingham plastic model**

| Properties                     | MRF 132DG         | MRF 241ES        |
|--------------------------------|-------------------|------------------|
| Fluid base                     | Synthetic oil     | Water            |
| Operating temp range (deg C)   | -40 to 140        | 0 to 70          |
| Density (g/cc)                 | 3.055             | 3.818            |
| Viscosity (Pa sec)             | 0.09 ± .02        | 2.2 ± .02        |

![Yield stress vs Magnetic field of MRF 241 ES](image)

**Figure 3. Yield stress vs Magnetic field of MRF 241 ES**
3. Design of MR brake

Figure 5 depicts the two dimensional illustration of MR fluid brake. The actuator consists of a disk (2) immersed in the MR fluid surrounded by an electromagnet. The MR fluid is enclosed in the static casing and the disk is attached to the shaft (1). With the rotation of shaft, disk also rotates. The braking torque can be controlled by applying DC current to the electromagnet. In the presence of magnetic field, the fluid transforms to semi solid by aligning magnetic particles in a chain like structure, thus increasing the viscosity.

From equation 1 and the above geometrical configurations, the braking torque is caused by the friction between disk and the MR fluid. The equation for calculating the braking torque is given by

\[ T_b = \frac{4}{3} \pi \tau (r_o^3 - r_i^3) \]  

(2)

Where \( n \) is the number of surfaces are in contact with the fluid, for this two surfaces are in contact with the fluid. \( \tau \) is the total shear stress developed in the MR fluid due to the application of magnetic field and \( r_o, r_i \) are the outer and inner radius of disks.
4. Methodology

For MR brake, the analysis consists of simply running the desired geometrical configuration with known dimensions and materials. In order to design a suitable MR brake we need to optimise the geometry to get an improved design. The standard dimensions of disks are obtained from readily available data and by measuring the dimensions of existing ATV brakes. Comparing both set of values, the desired dimensions of ATV MR brake is chosen. For optimising the geometry, Taguchi’s method is used. In this paper, preliminary design, optimisation, selection of MR fluid and analysis is carried out.

The major parts of ATV MR brakes are shaft, disk, coil, fluid gap and casing. Selection of material is a crucial part for the analysis. The materials have to be selected on the basis of thermal, structural and magnetic properties. The magnetic characteristics of the material depend on the permeability of the material, which is the ratio of magnetic field intensity (B) to the magnetic flux density (H). The materials for shaft and disk are selected on the basis of structural considerations. The temperature affects the permeability of the ferromagnetic material, hence the generated heat should be quickly removed as soon as possible in order to maintain the viscosity of MR fluid. To remove the heat from the magnetic disk, the non magnetic materials having high conductivity and high convection coefficient are chosen. AISI 4340 is chosen as non magnetic material and AISI 1010 as magnetic material for brake application considering cost, permeability, availability and yield stress. For selecting the material for coil, American wire gauge standards are identified. The properties and conductor size is also taken into account. The thicker wires have a capability of conducting greater amount of current but take more space. Hence, the number of turns of the coil is reduced. The selected material for coil is AWG 24. The materials used in MR brake is shown in table 2.

Table 2. Materials used in MR brake

| Parts       | Material             |
|-------------|----------------------|
| Magnetic    | AISI 1010            |
| Non magnetic| AISI 4340            |
| MR fluid    | MRF 241ES,MRF 132 DG |
| Coil        | Copper coil          |

Initially, for designing ATV MR brake we need to consider the physical limitations. The brake should be placed within the brake rim. The dimensions of brake should not go beyond the rim. The overall diameter of the brake must be fit in that area. For automotive brake application, a clearance of 3mm exists between the brake and the wheel rim. For ATV’s, the maximum diameter of the rim is taken as 34 cm. Maximum acceptable diameter of brake is calculated as 34 cm - 2 x 0.3 cm = 33.4 cm. ie; maximum acceptable radius of MR brake is 16.7 cm. The initial dimensions are calculated using Taguchi method and 3D model is generated using COMSOL multi-physics.

For the selection of better MR fluid two cases were considered and dimensions used are given below in table 3.

Table 3. Basic geometry of MR brake

| Parameters      | Dimensions (cm) |
|-----------------|-----------------|
| Disk radius     | 14              |
| Coil width      | 1               |
| Fluid gap       | 0.1             |
| Thickness of casing | 0.25           |
| Thickness of disk | 0.5            |

5. Design optimisation

Optimization is the process of finding the best suitable solution from the given feasible solutions. For better employment of MR fluid brake, optimal brake design should be considered. Taguchi’s method is employed for optimising the brake geometries. Figure 6 shows the various optimising parameters for the MR brake.
The key factor to be considered for brake design is braking torque. The main objective of MR brake is to achieve a desired amount of braking torque within the available geometrical dimensions. The input parameters and their range are shown in Table 4. Orthogonal array is generated using Minitab software and 27 set of combinations are generated which is shown in Table 5. For each combination, braking torque is calculated.

Table 4. Input parameters and their range

| Parameter                  | Upper Range (cm) | Middle Range (cm) | Lower Range (cm) |
|---------------------------|------------------|-------------------|------------------|
| Length of the disks       | 5                | 5.5               | 6                |
| Thickness of the disks    | 0.5              | 0.6               | 0.7              |
| Axial thickness of casing | 0.5              | 0.6               | 0.7              |
| Radial thickness of coil  | 1                | 1.2               | 1.4              |
| Radius of disks           | 14               | 15                | 16               |

Table 5. Orthogonal array

| Length of disk(cm) | Thickness of disk(cm) | Axial thickness of casing(cm) | Radial thickness of coil(cm) | Radius of disk(cm) | Torque(Nm) |
|--------------------|-----------------------|-------------------------------|------------------------------|---------------------|------------|
| 5                  | 0.5                   | 0.5                           | 1                            | 14                  | 259.60     |
| 5                  | 0.5                   | 0.5                           | 1                            | 15                  | 306.00     |
| 5                  | 0.5                   | 0.5                           | 1                            | 16                  | 356.00     |
| 5                  | 0.6                   | 0.6                           | 1.2                          | 14                  | 255.39     |
| 5                  | 0.6                   | 0.6                           | 1.2                          | 15                  | 301.02     |
| 5                  | 0.6                   | 0.6                           | 1.2                          | 16                  | 350.45     |
| 5                  | 0.7                   | 0.7                           | 1.4                          | 14                  | 234.29     |
| 5                  | 0.7                   | 0.7                           | 1.4                          | 15                  | 276.11     |
| 5                  | 0.7                   | 0.7                           | 1.4                          | 16                  | 321.50     |
| 5.5                | 0.5                   | 0.6                           | 1.4                          | 14                  | 255.46     |
| 5.5                | 0.5                   | 0.6                           | 1.4                          | 15                  | 301.97     |
| 5.5                | 0.5                   | 0.6                           | 1.4                          | 16                  | 352.40     |
| 5.5                | 0.6                   | 0.7                           | 1                            | 14                  | 289.00     |
| 5.5                | 0.6                   | 0.7                           | 1                            | 15                  | 341.00     |
| 5.5                | 0.6                   | 0.7                           | 1                            | 16                  | 397.00     |
| 5.5                | 0.7                   | 0.5                           | 1.2                          | 14                  | 252.70     |
Optimization of MR brake is carried out using design of experiments software from the above listed geometric parameters and their levels. The main goal of this optimization is to maximise the braking torque. The main effect plots of SN ratio generated from the software is shown in figure 7. From which, optimum geometrical configuration is obtained. Table 6 gives the optimum geometrical values of MR brake for all terrain vehicles.

![Main Effects Plot for SN ratios](image)

**Figure 7.** Plot for SN ratio

Optimum design is generated from the main effects plots SN ratio and is shown in table 6. The fluid gap is taken as 0.1cm and is not optimised in this case because the increase in fluid gap causes the excessive heat generation in fluid, thus damage to the system.

**Table 6.** Optimum design parameters

| Parameter               | Optimum value(cm) |
|-------------------------|-------------------|
| Length of disk          | 6                 |
| Thickness of disk       | 0.6               |
| Axial thickness of casing | 0.7          |
| Radial thickness of coil | 1               |
| Radius of disk          | 16                |
6. Numeric simulations
The proposed design is analysed using finite element based COMSOL multi-physics (AC/DC) module. 2D axisymmetric section is selected for the simulation purpose to reduce simulation time. The optimised geometry is shown in figure 8. The initial step in the analysis is to find out the magnetic field intensity across the shear surfaces, which is performed using magneto statics analysis. Figure 9 depicts the mesh generated in the simulation. COMSOL’s automatic mesh generator with extremely fine mesh size is used for generating the mesh geometry. A number of 7427 triangular elements are used for solving the following electromagnetic equations.

![Figure 8. Axisymmetry geometry of MR brake](image1)
![Figure 9. Mesh geometry of MR brake](image2)

7. Results and discussion

7.1 Fluid selection
For the purpose of finding a better MR fluid two different fluids which are commonly used for the brake applications were compared. Two different cases were considered, in case 1 MRF 132 DG and in case 2 MRF 241 ES and the magnetic field for both the cases were simulated using COMSOL software. With the help of those results the braking torque for both the cases were calculated to conclude which fluid is better for braking application.

![Figure 10. Case 1 MRF 132 DG](image3)
![Figure 11. Case 2 MRF 241 ES](image4)

There is a huge difference between the braking torque values obtained from both the cases. The braking torques value for case 1 is 103 Nm and for the case 2, an amount 234 Nm is developed. From this MRF 241 ES is selected for the brake application.
7.2 Optimised geometry of the design

Figure 12 shows the surface plot magnetic field generated in the simulation for the application of 2A current. The dynamic yield stress is computed from this graph. From this the maximum amount of magnetic field generated is $4.69 \times 10^4$ A/m. The magnetic flux density graph is taken from the post processor AC/DC module. The proposed design produces a maximum magnetic flux density of 0.67 T. Figure 13 gives the flux density profile.

![Figure 12. Magnetic field distribution](image1)

![Figure 13. Magnetic flux density distribution](image2)

The next step is to find out the braking torque developed in the system for the application of 2A current. Braking torque is given by eqn. (2).
By Bingham plastic model the total shear stress is given by

$$\tau = \tau_y(H) + \eta \omega \frac{r}{h}$$  \hspace{1cm} (3)

The dynamic yield stress is calculated from the figure 4, from this the dynamic shear stress $\tau_y(H)$ developed is 24000 kPa

Outer radius $r_o$ = 16 cm  
Inner radius $r_i$ = 10 cm  
Fluid gap (h) = 0.1 cm  
Radial distance (r) = 6 cm  
Angular velocity ($\omega$) = $2\pi N/60$ = 52.35 rad/sec

By using the equation (3) the total shear stress ($\tau$) generated is 30910 N/m². The braking torque ($T_b$) is calculated using the equation (2) and as an amount of 400 Nm is obtained.

8. Conclusion

Magneto rheological fluid brake with single disk for all terrain vehicles is designed as an alternative to the current conventional hydraulic brakes. The proposed system utilizes Bingham plastic model to calculate the total shear stress developed in ATV brakes. It is found that MRF 241 ES is better for brakes compared to MRF 132 DG. The geometry of MR brake is optimised using Taguchi method and designed using COMSOL multi-physics. This brake design converts the conventional braking system to a controllable braking system, thus eliminating the drawbacks of conventional braking system. The proposed design reveals better performance in terms of braking torque compared to conventional braking system.

This work can be extended on different fronts. One interesting and important way is to perform the dynamic analysis of the new design in order to determine its expected service life. Optimization with respect to cost considerations can also lead to easier implementation of MR brakes in ATVs.

9. References

[1] Rabinow, (1948). The Magnetic Fluid Clutch, Transactions of the AIEE, Vol. 67, 1308-1315.
[2] Jolly, M. R., Bender, J. W., & Carlson, J. D. (1999). Properties and applications of commercial magnetorheological fluids. Journal of intelligent material systems and structures, 10(1), 5-13.
[3] Fang, F. F., Jang, I. B., & Choi, H. J. (2007). Single-walled carbon nanotube added carbonyl iron suspension and its magnetorheology. Diamond and related materials, 16(4), 1167-1169.
[4] Prasad, P. S. S. (2011). Rheological properties of a honge oil-based magnetorheological fluid used as carrier liquid. Defence Science Journal, 61(6), 583.
[5] Gupta, U. S., Chandak, S., & Dixit, D. Design & Manufacturing of All Terrain Vehicle (ATV)-Selection, Modification, Static & Dynamic Analysis of ATV Vehicle. International Journal of Engineering Trends and Technology (IJETT)–Volume, 20.
[6] Park, E. J., Stoikov, D., da Luz, L. F., & Suleman, A. (2006). A performance evaluation of an automotive magnetorheological brake design with a sliding mode controller. Mechatronics, 16(7), 405-416.
[7] Hajiyan, M., Mahmud, S., & Abdullah, H. Magnetorheological Fluid Based Braking System Using L-shaped Disks. School of Engineering, University of Guelph, 50.
[8] Tamilarasan, N., Thirumalini, S., Nirmal, K., Ganapathy, K., Murali, K., & Srinath, H. (2016, December). Design and simulation of ferrofluid tactile screen for braille interface. In Robotics and Automation for Humanitarian Applications (RAHA), 2016 International Conference on (pp. 1-7). IEEE.
[9] Ramesh, A., Sumesh, C. S., Abhilash, P. M., & Rakesh, S. (2015). Finite element modelling of orthogonal machining of hard to machine materials. International Journal of Machining and Machinability of Materials, 17(6), 543-568.