Optimal Design and Analyses of T-shaped rotor Magnetorheological Brake

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Abstract. Magnetorheological (MR) brakes, belonging to the class of electromagnetic brakes, have a potential to replace conventional hydraulic brakes owing to reversible, rapidly controllable torque characteristics. In this study, T-shaped rotor MR brake was considered due to their higher braking torque capability and compactness compared to other configurations of brake. Optimal design of the brake was performed considering brake rotor radius, rotor thickness, flange length, casing thickness, coil height and coil width. Magnetostatic analyses were performed for different combinations of parameters of the brake dimensions to compute the magnetic flux density generated in the MR fluid region and the torque ratio and mass were calculated. The optimum dimensions of the brake were determined based on maximization of torque ratio and minimization of mass of the brake using multi-objective Genetic algorithm optimization technique. Further, magnetostatic analyses of the T-rotor brake with optimal dimensions were performed and torque characteristics were compared with those obtained for brake with simple disk rotor. It was concluded that T-rotor brake produces higher braking torque compared to simple disk rotor type MR brake for similar dimensions.

1. Introduction

A MR brake comprises of single or few revolving disks surrounded by MR fluid inside a casing embedded with electromagnet. By supplying current to the electromagnet coil, the iron particles in the MR fluid aligns with the generated magnetic field and its viscosity and yield stress increases in a fraction of a second. This yield stress which is controllable, generates torque due to shear friction on the revolving disk. Thus, the MR brakes when compared to conventional hydraulic brakes have quicker response, easier implementation of a new controller, lesser maintenance since there is no material wear and lower weight as it does not require additional auxiliary components. Based on the shape of the brake rotor, there are five designs of MR brake proposed by researchers namely drum, inverted drum, disk, T-shape rotor and multiple disks brake. T shaped rotor brake produces higher torque due to larger area of MR fluid subjected to MR effect at the periphery of rotor. However, it is complex and hence difficult to manufacture [1]. The performance of an MR brake is measured primarily in terms its torque characteristics.

A lot of research work has been performed by several researchers to design and enhance the torque characteristics of MR brake. Assadsangabi et al. [2] performed finite element analysis of MR brake with simple disk to analyse the magnetic field intensity distribution and then optimized braking torque capacity using Genetic Algorithm to obtain optimal dimensions. Nguyen and Choi [3] determined the optimized dimensions of several forms of brakes such as simple disk, drum, hybrid and T shaped types...
by maximizing the braking torque with the torque ratio higher than desired value. Further, the selection of MR brake based on radial and axial dimensions have been proposed. Nguyen and Choi [4] determined optimal dimensions of single and multiple disk MR brake for three types of commercial MR fluid supplied by the Lord Corporation for a passenger vehicle depending on the desired braking torque, temperature due to friction of MR fluid in the absence of magnetic field, mass of the brake and important dimensional parameters. Hung and Bok [5] determined optimal dimensions of a MR brake with T shaped rotor considering braking torque, availability of space, mass and heat generated by friction torque of the MR brake in the absence of magnetic field. Nguyen and Choi [6] designed three different configurations of MR brake with T shaped stationary drum embedded with two coils based on three different commercial Lord MR fluids and compared their size, mass and power consumption. Nguyen et al. [7] determined optimal dimensions of disk, drum, single-coil and double coil with and without combination of magnetic and non-magnetic materials for casing and T-type MR brakes with the aim of minimizing the mass of the MR brake needed to provide necessary braking torque. The selection of MR brake types was discussed depending on the mass of the brake, power consumption and braking torque. However, multi-objective optimization considering several objective functions such as mass of the brake, maximum braking torque and compactness have not been performed.

In this study, optimal dimensions of T-rotor MR brake were determined using multi-objective genetic algorithm optimization method. Initially, L-27 orthogonal array was used to analyse the effects of different parameters of the brake on the magnetic flux density generated in the MR fluid gap which was computed using magnetostatic analyses using ANSYS workbench software. The on state torques were calculated analytically based on the magnetic flux density in different portions of the MR fluid. The optimum dimensions of the brake were determined based on maximization of torque ratio and minimization of mass of the brake. Further, magnetostatic analyses of the T-rotor brake with optimal dimensions were performed and results were compared with those obtained for brake with simple disk rotor of similar dimensions.

2. Torque analyses of MR Brake
The MR brake consists of T-shaped rotor, stationary casing, MR fluid between rotor and casing and electromagnetic coils enclosed in the casing. Upon application of current to the electromagnet coil, the generated magnetic field lines increase the viscosity and hence the yield stress. This causes generation of braking torque due to resistance to the rotation of rotor. The schematic diagram of a T-rotor MR brake is shown in figure 1.

![Figure 1. Schematic diagram of T-rotor Magnetorheological Brake.](image-url)
The total torque generated in MR brake is the sum of on-state and off state torques. The braking torques were derived by modelling the rheological properties of the MR fluid using Herschel-Bulkley model. The off-state torque due to viscosity of MR fluid \( T_g \) is given by equation (1), [6]

\[
T_g = \frac{4\pi \mu_{eq} y \Gamma_{11}}{g} \left[ 1 - \left( \frac{r_1}{r_{11} + t} \right)^{n_{11} + 1} \right] \omega + \frac{4\pi \tau_{y1}^{11}}{3} (r_{11} + t)^3 - r_1^3 + 2\pi \tau_{y1}^{11} r_1^2 L_g' + (r_1 + t)^2 L_g' \right] + 2\pi K_{11} \left( \frac{\omega}{g} \right)^{n_{11} + 1} \left[ r_1^{2n_{11} + 1} L_g' + (r_1 + t)^{2n_{11} + 1} L_g' \right]
\]

(1)

The on-state torque which is due to the application of magnetic field is the sum of the torque in the inner \( T_{i} \) and outer \( T_{o} \) portions of rotor flange and in the leg \( T_{l} \) of the rotor and is given by equations (2) to (6), [6]

\[
T_h = 2T_i + T_{o} + T_{l}
\]

(2)

\[
T_i = \frac{2\pi \mu_{eq} r_1^{n_1}}{g} \left[ 1 - \left( \frac{r_1}{r_{1}} \right)^{n_1 + 1} \right] \omega + \frac{2\pi \tau_{y1}^{1}}{3} (r_1^3 - r_1')
\]

(3)

\[
T_{o} = 2\pi r_1^2 L_g' \tau_{y1}^{1} + K_{o1} \left[ \frac{\omega r_{1}}{g} \right]^{n_{1}}
\]

(4)

\[
T_{o} = 2\pi (r_1 + t)^2 L_g' \left\{ \tau_{y1}^{1} + K_{o1} \left[ \frac{\omega (r_1 + t)}{g} \right]^{n_{1}} \right\}
\]

(5)

\[
\mu_{eq} = K_{i1} \left( \frac{r_{1} \omega}{g} \right)^{n_1 - 1}
\]

(6)

where, \( L_{o} \) is the effective length of outer portion of rotor flange, \( L_{i} \) is the effective length of the inner portion of the rotor flange, \( \omega \) is the angular velocity and \( \mu_{eq} \) is the equivalent viscosity at the required location of rotor. The rheological properties of Lord MRF 140CG fluid at different magnetic fields were calculated based on the equation (7), [6]

\[
Y = Y_0 + (Y_0 - Y_{\infty}) \left( 2 e^{-B \alpha_{sy}} - e^{-2B \alpha_{sy}} \right)
\]

(7)

where, \( Y \) is the rheological parameter which could be yield stress \( \tau_{y1} \), consistency index \( K \) or flow behaviour index \( n \). \( Y \) ranges from value at zero magnetic field, \( Y_0 \) to that with magnetic field at saturation, \( Y_{\infty} \). \( \alpha_{sy} \) is the saturation moment index and \( B \) is the magnetic flux density. The rheological parameters of MRF 140CG can be obtained by curve fitting the experimentally determined flow and viscosity curves of the fluid to Herschel-Bulkley model. The parameters obtained are \( K_0 = 0.65 \text{ Pa} \cdot \text{s}^n \), \( K_\alpha = 5400 \text{ Pa} \cdot \text{s}^n \), \( \alpha_{\alpha} = 5 \text{T}^{-1} \), \( \tau_{y0} = 25 \text{ Pa} \), \( \tau_{y\infty} = 39000 \text{ Pa} \), \( \alpha_{\omega} = 2 \text{T}^{-1} \), \( n_0 = 0.915 \), \( n_\omega = 0.24 \), and \( \alpha_{\omega} = 35 \) [6].

The torque ratio \( (K_T) \) is defined as ratio of on-state torque \( (T_h) \) to the off-state torque \( (T_g) \) and is given by equation (8),

\[
K_T = \frac{T_h}{T_g}
\]

(8)
3. Magnetostatic analyses of MR Brake
Magnetostatic analyses were carried out in ANSYS workbench to determine the magnetic flux density in the MR fluid region for different combination of dimensions of the brake whose values are listed in table 1.

| Lower level | 30 | 5 | 50 | 10 | 10 | 10 |
| Second level | 50 | 10 | 75 | 15 | 15 | 15 |
| Upper level | 70 | 15 | 100 | 20 | 20 | 20 |

One fourth of MR brake was modelled and the material properties of their components were specified as input in the ANSYS software. Low carbon SAE1020 steel was chosen as material for rotor and casing and the B-H curve of this material was taken from ANSYS materials library. Bobbin is made of aluminium having a relative permeability of one. The B-H curve of Lord Corporation’s MRF 140 CG is specified as per the material data sheet [8]. The analyses were performed at constant voltage of 12 V and current of 1 A. Angular velocity of 100 rad/s was considered for the analysis. The L27 orthogonal array was used for performing the magnetostatic analysis to examine the effects of variation in the dimensions of the brake on the magnetic flux density generated in the MR fluid gap. The response factors for the different combination of dimensions of the brake are shown in table 2. The values of magnetic flux densities in the MR fluid gap were substituted in equations (7) to calculate requisite properties of the fluid which are required to calculate on-state torque using equations (2) to (6).

| Sl. No. | Rotor Radius (mm) | Rotor Flange Length (mm) | Rotor Thickness (mm) | Casing Thickness (mm) | Coil Width (mm) | Coil Height (mm) | On-State Torque (Nm) | Off-State Torque (Nm) | Torque ratio | Mass (Kg) |
|--------|---------------------|--------------------------|----------------------|-----------------------|-----------------|-----------------|---------------------|---------------------|-------------|-----------|
| 1      | 30                  | 50                       | 5                    | 10                    | 10              | 10              | 42.99               | 0.79                | 54.18       | 5.48      |
| 2      | 30                  | 50                       | 5                    | 10                    | 15              | 15              | 49.78               | 0.79                | 62.73       | 6.55      |
| 3      | 30                  | 50                       | 5                    | 10                    | 20              | 20              | 52.78               | 0.79                | 66.52       | 7.73      |
| 4      | 30                  | 75                       | 10                   | 15                    | 10              | 15              | 68.36               | 1.45                | 75.77       | 11.36     |
| 5      | 30                  | 75                       | 10                   | 15                    | 15              | 15              | 81.62               | 1.45                | 65.30       | 13.21     |
| 6      | 30                  | 75                       | 10                   | 15                    | 20              | 20              | 86.24               | 1.45                | 59.49       | 15.21     |
| 7      | 30                  | 100                      | 15                   | 20                    | 10              | 10              | 98.11               | 2.43                | 40.36       | 20.05     |
| 8      | 30                  | 100                      | 15                   | 20                    | 15              | 15              | 122.16              | 2.43                | 50.25       | 22.84     |
| 9      | 30                  | 100                      | 15                   | 20                    | 20              | 20              | 129.56              | 2.43                | 53.29       | 25.83     |
| 10     | 50                  | 50                       | 10                   | 20                    | 10              | 15              | 156.22              | 3.78                | 41.28       | 18.64     |
| 11     | 50                  | 50                       | 10                   | 20                    | 15              | 20              | 170.74              | 3.78                | 45.12       | 20.83     |
| 12     | 50                  | 50                       | 10                   | 20                    | 20              | 20              | 162.02              | 3.78                | 42.81       | 23.02     |
| 13     | 50                  | 75                       | 15                   | 10                    | 10              | 15              | 201.64              | 6.19                | 32.56       | 17.46     |
| 14     | 50                  | 75                       | 15                   | 10                    | 15              | 20              | 227.64              | 6.19                | 36.75       | 19.64     |
| 15     | 50                  | 75                       | 15                   | 10                    | 20              | 10              | 218.16              | 6.19                | 35.22       | 21.83     |
| 16     | 50                  | 100                      | 5                    | 15                    | 10              | 15              | 210.10              | 6.35                | 33.10       | 21.09     |
| 17     | 50                  | 100                      | 5                    | 15                    | 15              | 20              | 252.21              | 6.35                | 39.73       | 23.87     |
| 18     | 50                  | 100                      | 5                    | 15                    | 20              | 10              | 227.61              | 6.35                | 35.85       | 26.72     |
| 19     | 70                  | 50                       | 15                   | 15                    | 10              | 20              | 325.07              | 10.59               | 30.69       | 24.69     |
| 20     | 70                  | 50                       | 15                   | 15                    | 15              | 10              | 309.45              | 10.59               | 29.22       | 26.96     |
| 21     | 70                  | 50                       | 15                   | 15                    | 20              | 15              | 344.75              | 10.59               | 32.55       | 29.44     |
| 22     | 70                  | 75                       | 5                    | 20                    | 10              | 20              | 422.40              | 13.18               | 32.04       | 32.14     |
| 23     | 70                  | 75                       | 5                    | 20                    | 15              | 10              | 386.29              | 13.18               | 29.30       | 35.25     |
| 24     | 70                  | 75                       | 5                    | 20                    | 20              | 15              | 448.38              | 13.18               | 34.01       | 38.61     |
| 25     | 70                  | 100                      | 10                   | 10                    | 10              | 20              | 453.96              | 18.24               | 24.89       | 30.29     |
| 26     | 70                  | 100                      | 10                   | 10                    | 15              | 10              | 431.03              | 18.24               | 23.63       | 33.39     |
| 27     | 70                  | 100                      | 10                   | 10                    | 20              | 15              | 503.29              | 18.24               | 27.60       | 36.73     |
The mass of the brake for different configurations was calculated based on the product of volume and density of individual components. It can be observed that with increase in the dimensions of the brake there is significant increase in the on-state, off-state braking torques and mass though the torque ratio varies. The torque ratio is high for smaller dimensions of the brake which could be attributed to the smaller off-state torque.

4. Optimal Dimensions of MR brake
A magnetorheological brake should possess high torque ratio which means on-state torque should be high and off-state torque should be low. Also, mass of the brake is another important issue in the design of brake and should be as low as possible for given torque requirement. In this work, optimal dimensions were determined by maximization of torque ratio and minimization of mass using multi-objective Genetic algorithm optimization method using MATLAB and the Pareto front results is shown in figure 2. The selected optimized dimensions are mentioned in table 3.

![Figure 2. Pareto front of MOGA optimization.](image)

| Parameters         | Optimized dimensions (mm) |
|--------------------|---------------------------|
| Rotor radius ($r_1$) | 30.01                     |
| Rotor thickness ($t$)   | 5.07                      |
| Flange length ($L_1$)  | 50.02                     |
| Casing thickness ($t_c$) | 10.58                    |
| Coil height ($h$)       | 17.65                     |
| Coil width ($w$)        | 14.93                     |

5. Comparative analyses of T-shaped and disk shaped rotor MR brakes
Magnetostatic analyses of T-rotor MR brake having optimized dimensions and simple disk shaped MR brake of same dimensions were performed in ANSYS workbench software. The magnetic flux density distribution in the T-shaped and simple disk MR brake are depicted in figures 3(a) and 3(b) respectively. The magnetic flux density is higher in case of T-rotor MR brake. At 1A current, the total braking torque of T-rotor and simple disk MR brakes are 44.1 Nm and 11.8 Nm respectively. Thus, the total braking torque of T-rotor brake is 3.74 times than that of simple disk brake. The mass of T-rotor and simple disk MR brakes are 6.78 kg and 6.39 kg respectively. The torque to mass ratio of T-rotor and simple disk MR brakes are 6.5 and 1.8 respectively.

![Figure 3. Magnetic flux density distribution in the (a) T-rotor and (b) Simple Disk MR brakes.](image)
Further, magnetic flux density and subsequently braking torques for both the MR brake configurations were determined at different current magnitudes of 0.1A, 0.2A, 0.5A, 1A and 1.5 A which are plotted as shown in figure 4. Beyond 1A current, there is not much increase in the magnitude of torque which is due to saturation of magnetic flux in the MR fluid region.

![Figure 4. Comparison of torque of MR brakes at different applied currents.](image)

6. Conclusions
In this study, magnetic flux generated in the MR fluid region was determined for different combinations of parameters of the brake dimensions to calculate on-state torque. The optimum dimensions of the brake were determined with the objective of maximization of torque ratio and minimization of mass of the brake using multi-objective Genetic algorithm optimization technique. Further, magnetostatic analyses of the T-rotor brake with optimal dimensions were performed and results were compared with those obtained for brake with simple disk rotor. It was observed that T-rotor MR brake produces significantly higher braking torque at all current magnitudes compared to simple disk rotor MR brake. Thus, T-rotor MR brakes are compact and have superior torque to mass characteristics for similar dimensions.

7. References
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