Design optimization of magnetorheological brake using structural parameter: evaluation and validation

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Abstract. Magneto-rheological (MR) brake is one of the most promising smart systems, which transmit torque with the applied magnetic field. This process is reversible in the absence of magnetic field. In this paper, the most common disk type MR-Brake (MRB) design is selected to optimize for the desired range of torque transmission without changing the diameter of the MRB. The theoretical torque transmission equation is deduced and using that power index dependency is studied for each structural MRB parameter. Three structural parameters (outer radius of the disk, fluid gap, and coil width) are selected, for three levels and analysis has performed using Minitab software to understand percentage contribution of the structural parameters. Then by varying fluid gap and fixing the other two MRB parameters, FEMM analysis has performed to understand magnetic flux concentration at the fluid gap. After confirming the MRB design, MRB is developed having two different MR-fluid working gaps. Later, maximum torque transmission of the MRB having different MR-fluid working gaps are studied at applied current value. The experimental data confirms with theoretical calculation.

1. Introduction

Magnetorheological (MR) fluid is considered in the category of smart material due to its phase change (fluid to quasi-solid) process in the presence of a magnetic field (MF). This process is reversible when MF is removed and the time required is in milliseconds. The MF tune the rheological properties over three to four orders of magnitude. The MF induces a yield-stress in fluid; this property is used in many applications [1-5]. One such application is rotary MR-Brake (MRB). The MRB transmits torque by the shear resistance of an MR-fluid. In developing MRB, important aspects that should be considered carefully are size and braking torque. Using the different configurations of MRB braking torque can be enhanced. The disk-type MRB is the most common configuration, which is also the pioneer configuration described by Jacob Rabinow in 1951 [6]. Nevertheless, for development and improvement of MRB performances several quality research work has been done [7-9]. These research works substantial efforts are made to improve brake design.
The primary input of this study is to optimize the rotary-disk MRB for practical application and validate the same. The developed MRB design is selected from available literature and the targeted application is for mid-sized motorcycle [10]. To optimize the same the comprehensive suite of data analysis and process development tools were used. The percentagewise contribution of the effective structural parameter is determined by the Minitab software [11]. FEMM [12] analysis performed to understand magnetic flux concentration and leakage in the MRB design, which facilitated a lot in choosing the MRB material right. Grounding on these, MRB is developed and its performance is evaluated.

2. MRB Theory

The rotary disk type MRB involves three components for total torque (T) transmission. These component followed as, (i) fluid viscosity, (ii) friction, and (iii) field-dependent yield stress [13]. Therefore, total torque is represented by,

\[ T = T_{viscosity} + T_{friction} + T_{yield-stress} \]  

\[ (1) \]

The Herschel-Buckley model is used for MR-fluid under applied MF condition for high shear rate applications. It is represented with shear stress (\( \tau \)), in the MRBs it can expressed as [14],

\[ \tau = \tau_{yd} + K \gamma^n \]  

\[ (2) \]

\( \tau_{yd} \) is yield stress of the MR-fluid, \( \gamma \) is shear rate, \( n \) and \( K \) are flow behaviour index and consistency parameter respectively. Researchers [15, 16] have given the mathematical expression for the torque transmission of the single disk rotary MRB based on equation (1) and (2). The mathematical form for the same is expressed as equation (3).

\[ T_{total} = 2\pi R_{OD}^2 b_D K_0 \left( \frac{\omega R_{OD}}{h_{duct}} \right)^{n_0} + \frac{4\pi \gamma y}{3} \left( R_{OD}^3 - R_{ID}^3 \right) + \frac{4\pi \mu_{eq} R_{OD} \omega}{(n+3) h} \left[ 1 - \left( \frac{R_{ID}}{R_{OD}} \right)^{n+3} \right] \]  

\[ (3) \]

Where, \( R_{ID}, R_{OD} \) = inner and outer disk radii respectively, \( \omega \) = rotary disk angular velocity, \( h \) = fluid gap, \( h_{duct} \) = gap of the annular duct, \( b_D \) = thickness of the disk, \( n_0, K_0 \) = flow behaviour index and constancy at zero MF, \( \mu_{eq} \) = equivalent viscosity. Each brake parameter’s effect on torque has been estimated. The power index dependency of the MRB parameters are shown in figure 1a. The torque of the MRB is majorly governed by two parameters. First is the \( \tau_{yd} \) and second is the \( R_{OD} \) of the MRB. These two parameter dominates the other parameter. So, the performance of the MRB can be improved by enhancing yield stress of MR-fluid and optimizing outer radius of the disk. The yield stress of MR-fluid is the function of the MF intensity (Figure 1b). So, to enhance MR-fluid yield stress, MF intensity can be optimized without changing fluid property. However, the MF intensity explicitly depends on coil width and MR-fluid working gap. So, keeping this in mind, in next section MRB design, its effective parameters, and its optimization are discussed.
3. MRB Design

In MRB, the electromagnetic coil (EM-coil) encloses the rotary disk in the central casing. MR-fluid region is energized by EM-coil. Each side is bolted with a side casing. MR-fluid is occupied in the space formed by the side casing and rotary disk. Figure 2 depicts the cross-sectional view of the MRB. Table 1 shows the MRB parameters (except $R_{ID}, R_{OD}, h, b_D$).

![Cross-sectional view of the MRB with its structural parameter.](image)

Figure 2. Cross-sectional view of the MRB with its structural parameter.

![Power index dependency of MRB parameter on torque transmission](image)

Figure 1. (a) Power index dependency of MRB parameter on torque transmission (b) The yield stress variation with MF intensity for MR-fluid. The line is fit to proposed Fang et al. [17] empirical relation of yield stress versus field.

Table 1 shows the MRB parameters (except $R_{ID}, R_{OD}, h, b_D$).

| Parameter                  | Value |
|----------------------------|-------|
| MRB Parameter              | Value  |
| $R_{ID}$                   | Value  |
| $R_{OD}$                   | Value  |
| $h$                        | Value  |
| $b_D$                      | Value  |

Yield Stress $\tau_y$, Equivalent Viscosity $\eta_{eq}$, Rotary Disk Thickness $b_D$, MR Fluid Working Gap $h$, Annular Duct Gap $h_{دق}$, Outer Radius of the Rotary Disk $R_{OD}$, Inner Radius of the Rotary Disk $R_{ID}$.
As discussed in the earlier section, MRB performance can be enhanced by improving fluid yield stress and optimizing essential structural parameters. By keeping the aforementioned optimization parameter of MRB, brake performance is optimized using FEMM (Finite Element Method Magnetics) software considering parameter as in table 2. There are seven basic structural parameters (bearings and oil seal dimensions are not considered) of an MRB which contributes to the performance of the torque transmission. Grounded on power index dependency, three structural parameters are selected for optimization which dominates the torque transmission among all. The selected parameters are the outer radius of rotating disk ($R_{OD}$), EM-coil width ($C_b$) and MR-fluid working gap ($h$). By using these three parameters in Minitab software, the full factorial design of experiment table 3 is prepared. In that outer radius, coil width and MR-fluid gap are input parameters, and braking torque and power requirement (current supplied to EM-coil) are considered as output parameters. For this analysis, the current supply to the magnetic coil is 1 A so, power is calculated based on the resistance of the coil using equation $P=I^2R$.

The analysis is performed (EM-coil current=1.0 A) to find out the torque and power in FEMM software for different combinations of radius, coil width, and gap. The values of torque and power are shown in table 3. For statistical analysis, Minitab software is used. To find, effect of outer radius of disk, coil width and MR-fluid gap on the torque and power main effect plot is used. By using the main effect plot as shown in figure 3a the torque increases with coil width and disk radius. As higher coil width produces higher MF which results in enhanced $\tau_{yd}$ and based on equation (3) higher the radius maximum torque will be produced. However, as the MR-fluid working gap increases the torque decreases due to decrement in the magnetic flux which leads to lower $\tau_{yd}$. Figure 3b shows the main effect plot for power. The plot shows that with increase in radius and coil width power requirement increases while with the gap it is unchanged. With the change in the coil width and radius, the number of turns wound in the coil changes. Nevertheless, coil configuration is independent of the MR-fluid gap, thus power requirement remains constant.

### Table 1. MRB parameter

| Sr. No. | Parameter Symbol | Parameter       |
|---------|------------------|-----------------|
| 1       | $R_B$            | Radius of Bearing |
| 2       | $R_O$            | Radius of oil-seal |
| 3       | $R_C$            | Central casing radius |
| 4       | $R_S$            | Side casing radius |
| 5       | $C_b$            | EM-coil width |

### Table 2. Effective MRB parameters for optimization

| Sr. No. | Parameter Symbol | Parameter Name                | Lower Range (1-level) | Mid Range (2-level) | Upper Range (3-level) | Dimensions (mm) |
|---------|------------------|-------------------------------|-----------------------|---------------------|-----------------------|-----------------|
| 1       | $R_{OD}$         | Outer radius of rotating disk | 40                    | 45                  | 50                    |                 |
| 2       | $C_b$            | EM-coil width                 | 8                     | 11                  | 14                    |                 |
| 3       | $h$              | MR-fluid working gap          | 1                     | 1.5                 | 2                     |                 |
Table 3. Structural Parameters of MRB and its response

| Sr. No. | ROD (mm) | Cb (mm) | h (mm) | T (Nm) | R (Ω) |
|---------|----------|---------|--------|--------|-------|
| 1       | 50       | 14      | 2      | 4.89   | 32.8  |
| 2       | 50       | 14      | 1.5    | 5.38   | 32.8  |
| 3       | 50       | 14      | 1      | 5.80   | 32.8  |
| 4       | 50       | 11      | 2      | 4.27   | 23.9  |
| 5       | 50       | 11      | 1.5    | 5.39   | 23.9  |
| 6       | 50       | 11      | 1      | 6.60   | 23.9  |
| 7       | 50       | 8       | 2      | 2.94   | 17.5  |
| 8       | 50       | 8       | 1.5    | 4.10   | 17.5  |
| 9       | 50       | 8       | 1      | 5.69   | 17.5  |
| 10      | 45       | 14      | 2      | 4.22   | 30    |
| 11      | 45       | 14      | 1.5    | 5.23   | 30    |
| 12      | 45       | 14      | 1      | 5.81   | 30    |
| 13      | 45       | 11      | 2      | 3.15   | 21.8  |
| 14      | 45       | 11      | 1.5    | 4.11   | 21.8  |
| 15      | 45       | 11      | 1      | 5.34   | 21.8  |
| 16      | 45       | 8       | 2      | 2.32   | 15.9  |
| 17      | 45       | 8       | 1.5    | 3.07   | 15.9  |
| 18      | 45       | 8       | 1      | 4.38   | 15.9  |
| 19      | 40       | 14      | 2      | 3.03   | 27.2  |
| 20      | 40       | 14      | 1.5    | 3.88   | 27.2  |
| 21      | 40       | 14      | 1      | 4.54   | 27.2  |
| 22      | 40       | 11      | 2      | 2.25   | 19.8  |
| 23      | 40       | 11      | 1.5    | 2.97   | 19.8  |
| 24      | 40       | 11      | 1      | 4.07   | 19.8  |
| 25      | 40       | 8       | 2      | 1.65   | 14.3  |
| 26      | 40       | 8       | 1.5    | 2.20   | 14.3  |
| 27      | 40       | 8       | 1      | 3.20   | 14.3  |

Analysis of variance (ANOVA) is executed to find the contribution of these three parameters on torque and power. Table 4 shows the percentage contribution of each parameter for torque. Where DF represents the amount of information in a data point. SS shows the sum of the square and the adjusted sum of a square is represent as Adj SS. Adj MS shows the adjusted mean square for the given data point. F value shows the response of the input parameters on torque. P values show a significant level of input parameters. In table 4 P-value is less than 0.05 so all the input parameters are considered as significant for the torque. The percentage contribution is calculated from the Adj MS values. The R² value is 95.06%.

From table 4, the maximum contribution in the torque is 39.27% for radius followed by a gap of the fluid and coil width. The percentage contribution for the gap of the MR-fluid is 36.62% and the coil width is 23.58%.
Table 4. Percentage contribution of MRB parameter on Torque

| Source            | DF | Seq SS  | Adj SS  | Adj MS  | F      | P   | Contribution |
|-------------------|----|---------|---------|---------|--------|-----|--------------|
| Outer radius      | 2  | 16.6772 | 16.6772 | 8.3386  | 76.02  | 0   | 39.27        |
| Coil Width        | 2  | 10.0159 | 10.0159 | 5.008   | 45.66  | 0   | 23.58        |
| MR-fluid gap      | 2  | 15.5536 | 15.5536 | 7.7768  | 70.9   | 0   | 36.62        |
| Error             | 20 | 2.1938  | 2.1938  | 0.1097  |        |     | 0.005        |
| Total             | 26 | 44.4404 |         | 21.2331 |        |     |              |

Table 5. Percentage contribution of MRB parameter on Power

| Source            | DF | Seq SS  | Adj SS  | Adj MS  | F      | P   | Contribution |
|-------------------|----|---------|---------|---------|--------|-----|--------------|
| Outer radius      | 2  | 83.21   | 83.21   | 41.6    | 188.53 | 0   | 8.44         |
| Coil width        | 2  | 902.13  | 902.13  | 451.06  | 2044.09| 0   | 91.51        |
| MR-fluid gap      | 2  | 0       | 0       | 0       | 0      | 1   |              |
| Error             | 20 | 4.41    | 4.41    | 0.22    |        |     |              |
| Total             | 26 | 989.75  |         | 492.88  |        |     |              |

Similarly, the percentage contribution in power is due to coil width, which is a maximum of up to 91.51%. The percentage contribution of the radius is nearly 8.44% (table 5), which is very less compared to the coil width. The gap is not a significant parameter, so it does not contribute to power. The $R^2$ value
for the power is 99.55%. From the aforementioned study and analysis, an MRB design was selected keeping mid-sized motorcycles brake parameters. In the next section, design parameters and test results are discussed.

4. MRB test setup and evaluation

To validate the optimized parameters, two sets of MRB designs are considered by varying the MR-fluid working gaps \((h=1\text{mm} \text{ and } 2\text{mm})\). MR-fluid working gap has no effect on power but contributes 37\% on torque. The outer radius is not varied as it is fixed for mid-sized motorcycle. So, the outer radius of the disk \((R_{OD}=45\text{mm})\) and coil width \((C_{o}=11\text{mm})\) kept the same. The detailed MRB parameter values are mentioned in table 6.

Table 6. Dimensions of the fabricated MRB

| Sr. No. | Component               | Values (mm) | MRB-I | MRB-II |
|---------|-------------------------|-------------|-------|--------|
| 1       | Rotary disk- inner radius| 10          | 10    |        |
| 2       | Rotary disk- outer radius| 45          | 45    |        |
| 3       | Rotating disk thickness  | 12          | 10    |        |
| 4       | MR-fluid working gap    | 1           | 2     |        |
| 5       | Radius of Bearing       | 18.5        | 18.5  |        |
| 6       | Radius of oil-seal      | 18.5        | 18.5  |        |
| 7       | Central casing radius   | 85          | 85    |        |
| 8       | Side casing radius      | 85          | 85    |        |
| 9       | EM-coil width           | 11          | 11    |        |

The MF intensity distribution attained from FEMM for MRB-I and MRB-II is shown in figure 4. The analysis shows that the flux lines remain uniform in the MR-fluid working gap. As the MR-fluid working gap decreases the MF intensity increases. The increased field intensity leads to the robust yield stress of MR-fluid.

The fabricated components of the MRB and MRB assembly are shown in figure 5a and 5b separately. The MRB test rig schematic diagram (figure 6) which contains 2hp AC motor coupled with a gearbox. The MRB is connected to the torque sensor (rotary type), supported by rod-end bearings and jaw couplers. The EM-coil in an MRB is controlled by the DC power supply (30V and 5A).

The performance of the MRB-I and MRB-II has been examined for synthesized MR-fluid (for MR-fluid synthesis, refer [18]). The braking torque variation with the applied current at 300 rpm is shown in figure 7 for MRB-I and MRB-II. Torque value increases with the application of current, the response to applied current is different for MRB-I compared to MRB-II. The line is a theoretical fit to the experimental data using MRB braking torque equation (equation (3)). It is to be noted here that MRB-I has a smaller MR-fluid working gap and produces higher torque values than the MRB-II. This is due to the higher MF intensity concentration at MR-fluid working gap (figure 4). In MRB-I, shaft speed tends to zero after the applied current value reaches 0.6A while for MRB-II it is 0.8A. The torque value in MRB-I is increased by 91.67\% compare to MRB-II at 0.6A current. The value of torque obtained for MRB-I and
MRB-II, from equation (3), using $\tau_y$ versus H curve at 1 A agrees well with optimized values given in table 3.

Figure 4. MF distribution of MRB using FEMM (left side) and variation of MF intensity with MR-fluid length (right side). Field remains uniform in the MR-fluid working gap and decreases at the annular duct.

Figure 5. (a) MRB components, (b) Assembled MRB
Figure 6. MRB test setup (Schematic Diagram)

Figure 7. Variation of braking torque with applied current for MRB-I and MRB-II. The line is calculated using equation (3) and $\tau_y$ value obtained from figure 1b at different value of current (or MF intensity).

5. Conclusion

The effect of the structural parameters of MRB on torque transmission and its optimization is studied in the present work. Power index dependency of MRB parameters was obtained, which helped to zero down the most effective structural parameters of MRB. From this, three parameters were selected for three different levels and analyses were performed using Minitab software. ANOVA was carried out to find out the contribution of three parameters on torque and power.

Two sets of MRB design was considered by a varying working gap (MR-fluid) and keeping the outer disk radii and coil width constant. The torque value in MRB-I (having gap 1mm) was increased by 91.67% compare to MRB-II (having gap 2mm) at 0.6A. Experimental data were fitted to the theoretical equation of torque transmission. The torque value was increased as the MR-fluid working gap decreases.
The effect of variation in the outer disk radius and the coil configuration should be explored further in future studies according to the real-life applications.

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