Paper ID: RT-05

Selection of Proper Materials and Optimization of Magnetic Circuit for Magneto-Rheological Brake to Get Better Magnetic Field Orientation: A Finite Element Analysis Based Investigation

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Abstract

Magneto-Rheological (MR) fluid-based braking systems are considered for the future automobile technology. Magneto-Rheological Brake (MRB) is a kind of mechanical frictionless and electromagnet-based braking system which uses MR fluid as a working fluid. MR brake system doesn't require mechanical force to apply the braking torque but the braking torque of MRB is not satisfied comparing to the conventional frictional brake. For this reason, thousands of researches have been conducted worldwide. In this paper, to select materials of structure of double disks MRB in 'ON state' for getting higher braking torque, a finite element model of double disks MRB is analyzed numerically in ANSYS® APDL software and magnetic circuit is also optimized for MR brake based on magnetic field orientation which is influenced by material's relative permeability and their geometrical structure.

Keywords: Smart fluid, Magnetorheological fluid, Bingham plastic, Finite element analysis (FEA).

1. Introduction

Magnetorheological fluid or MRF is a kind of smart fluid which changes its rheological properties when magnetic field is imposed on it [1]. There are three phases in MR fluid: solid phase, liquid phase and additives. Ferro magnetic particles are used as solid phase. Mineral oil, synthetic oil or vegetable oil is used as liquid phase. Oleic acid and grease are used as additives [2]. The MR fluid acts like Newtonian fluid when there is no magnetic field. When an external magnetic field is applied on the MR fluid, the Ferro magnetic particles get collinear with the imposed magnetic line of force and prohibit the liquid phase to flow. So that, the rotating part of MRB gets clung which results in the braking action. This is called 'ON state'. In this state, MR fluid follows the Bingham plastic model [2]. The MR brake system utilizes shear strength of MR fluid. The main contribution of this literature is to select the materials for MRB structure based on magnetic field orientation which can be controlled by the material's relative permeability and by the position of magnetic coil in MRB.

2. Finite Element analysis

In this research work, several finite element analyses have been done to optimize magnetic field orientation of MRB and to select the materials of MRB structure. Magnetic line of force should fall perpendicular on brake disc to get the maximum braking torque of a MR fluid disc brake system [3][4]. For this reason, a couple of simulations are performed on ANSYS to visualize the magnetic field orientation and to find the best orientation to develop the maximum braking torque. In shear mode, magnetic field is applied perpendicular to the stationary plate and MR brake disk then MR fluid acts like a solid body with two adjacent plates. Electromagnetics of ANSYS® APDL was used to simulate the proposed geometry of MRB. The equations of performed simulations are following [5]:

$$J_s = \nabla \times H \quad \text{(Ampère-Maxwell Law)} \tag{1}$$

$$\nabla \cdot B = 0 \quad \text{(Gauss's Law)} \tag{2}$$

$$J_s = (N_{coil} I)/A_{coil} \tag{3}$$

$$B = \mu H \tag{4}$$

Where,

J_s = Current Density
H = Magnetic Field Intensity
B = Magnetic field density
I = Current flow
$\nabla \times$ = Curl Operator
$\nabla \cdot$ = Divergence Operator
N_{coil} = Number of turns of the coil
A_{coil} = Cross-sectional area of coil

For the analysis of MR brake, a CAD model of MR brake is produced in SOLIDWORKS® software (Fig.1).

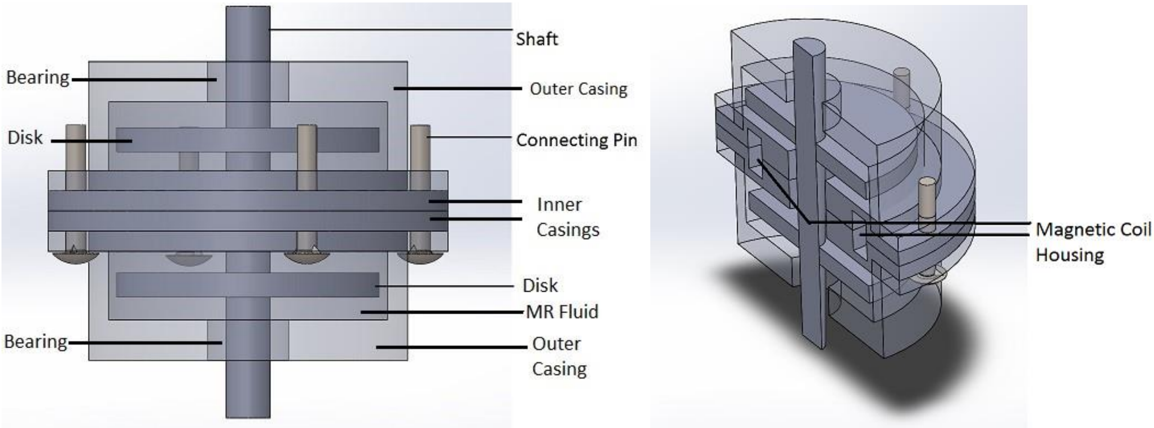

Fig. 1. Front view of CAD model of MR brake (left), Cross-sectional view of MR brake(right).

PLANE13 element of ANSYS APDL is used for 2D axisymmetric two-disc model of MR brake (Fig. 2) [6]. It is symmetric about the rotational axis. 2D axisymmetric modeling drastically reduces the computational time and cost [7]. Intensity of current through the coil represents the load of this analysis. The magnetic flux produced by the coil current is assumed to be so small that no saturation of the iron occurs. This allows a single iteration linear analysis. The flux leakage out of the iron at the perimeter of the model is assumed to be negligible. This assumption is made simple to keep the model small. The stranded, wound coil of 650 windings with 1 amp/turn supplies the predefined current. The current per winding is 1 amp. The length of edge of each

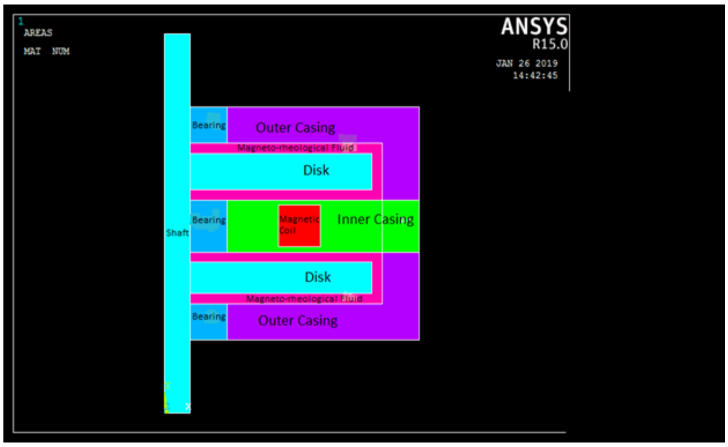

Fig. 2. 2D axisymmetric modeling of the MR brake in ANSYS® APDL.

meshed area is 0.25 times of the coordinates. Relation among braking torque, effective area of the disk and magnetic field density can be expressed by the following equation [8]:

$$T_{total} = \frac{2\pi}{3} N k H^{\beta} (r_o^3 - r_i^3) + \frac{\pi}{2h} N \mu \omega (r_o^4 - r_i^4) \tag{5}$$

Where:

T_{total} = Total braking torque
H = Magnetic field strength
B = Constant parameter
N = No. of disc
k = Constant parameter
h = Fluid gap between rotor and stator

r_o = Outer diameter of the disc
ω = Angular speed of the disc
r_i = Inner diameter of the disc
μ = Viscosity of MR fluid

First analysis

For the first analysis of magnetic flux density and magnetic field lines in MR brake, the materials of table-1 are chosen according to their relative permeability which has an effect to setup the direction of magnetic flux lines. For materials of table-1, the result of finite element analysis (FEA) of MRB is shown in Fig. 3.

Table 1. Relative permeability of the different part in first simulation

Parts	Materials	Relative Permeability
Disks	Aluminium	1
Outer Casings	Aluminium	1
Coil	Copper	1
Bearing	Low Carbon Steel	100
Fluid	MR Fluid (Basonetic 5030)	8
Inner Casings	Aluminium	1

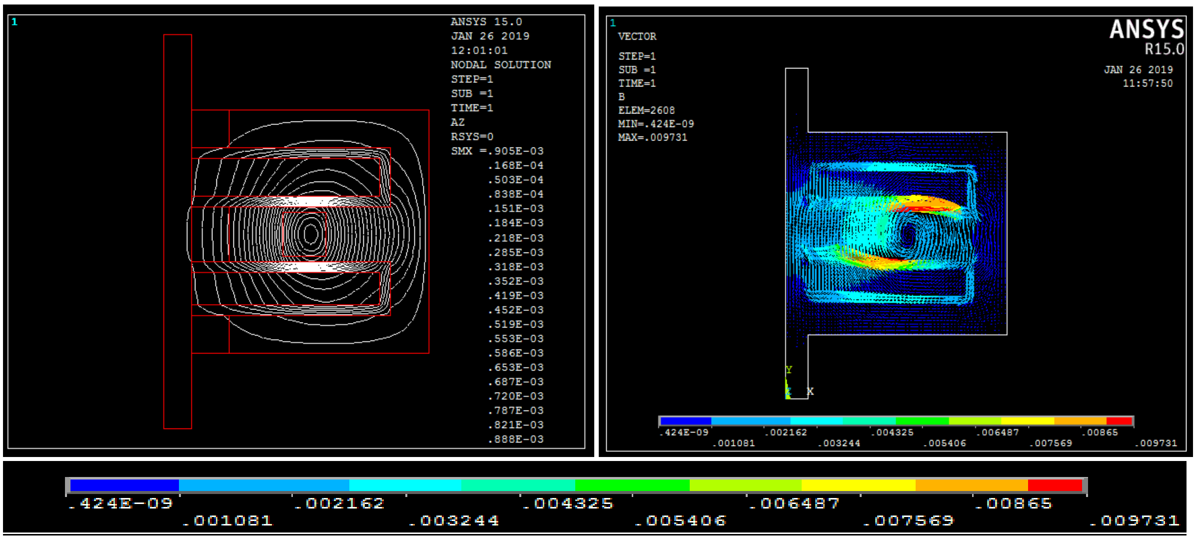

Fig. 3. Distribution of magnetic flux density (Tesla) in vector form (left), Line representation of magnetic field density for better visibility (right), Extended view of the result(magnetic field density) of FEA (below).

Second analysis

For the second analysis of magnetic flux in MR brake, the materials of table-2 are chosen according to their relative permeability which has different effect than previous materials to setup the direction of magnetic flux lines. The result of FEA of MRB in ANSYS for materials in table-2 is shown in Fig. 4.

Table 2. Relative permeability of the different parts in second simulation.

Parts	Material	Relative Permeability
Disks	Iron 99.8% Pure	5000
Outer Casings	Aluminium	1
Coil	Copper	1
Bearing	Low Carbon Steel	100
Fluid	MR Fluid (Basonetic 5030)	8
Inner Casings	Aluminium	1

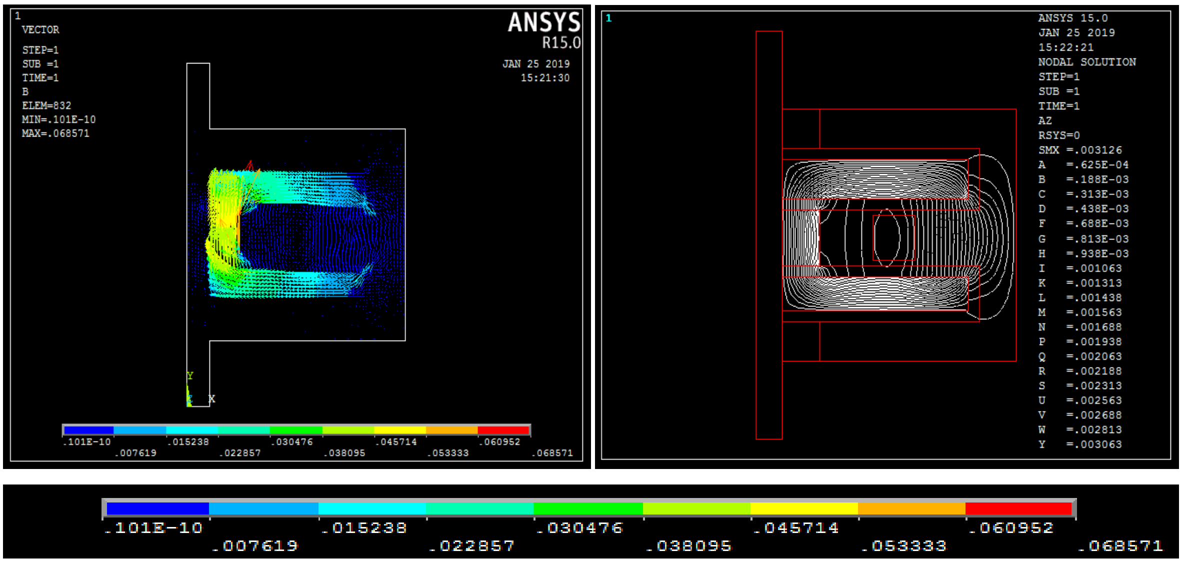

Fig. 4. Distribution of magnetic flux density (Tesla) in vector form (left), Line representation of magnetic field density (right), Extended view of the result (magnetic field density) of FEA (below).

Third analysis

For the third analysis of magnetic flux in MR brake the following different materials are chosen according to their relative permeability.

Table 3. Relative permeability of the different part in third simulation

Parts	Material	Relative Permeability
Disks	Aluminium	1
Outer Casings	Iron 99.8% Pure	5000
Coil	Copper	1
Bearing	Low Carbon Steel	100
Fluid	MR Fluid (Basonetic 5030)	8
Inner Casings	Aluminium	1

For materials of table-3, the result of finite element analysis (FEA) of MRB is shown in Fig.5.

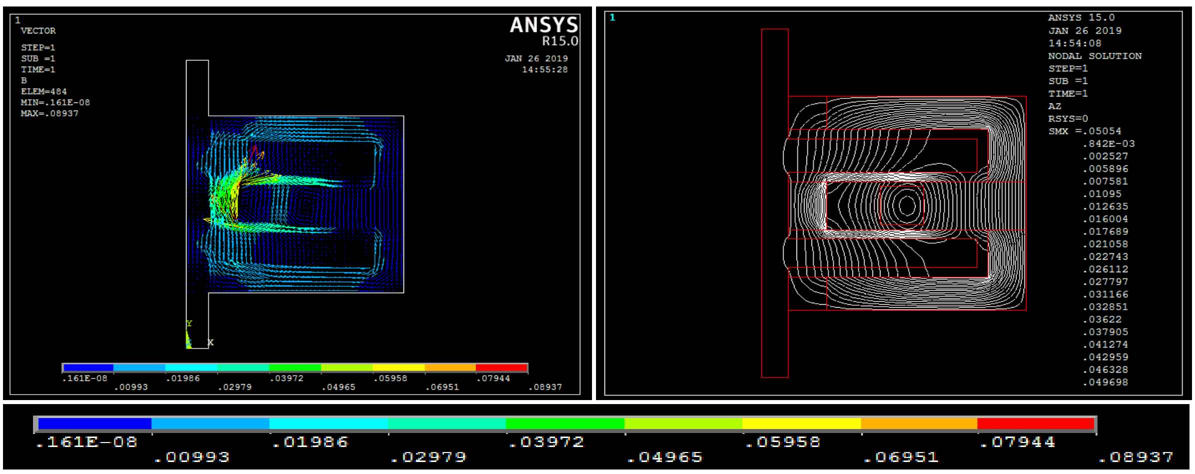

Fig. 5. Distribution of magnetic flux density (Tesla) in vector form (left), Line representation of magnetic field density (right), Extended view of the result (magnetic field density) of FEA (below).

Fourth analysis:

For the fourth analysis of magnetic flux in MR brake the following different materials (Table-4) are chosen according to their relative permeability and output of FEA of MRB is displayed in Fig.6.

Table 4. Relative permeability of the different part in fourth simulation.

Parts	Material	Relative Permeability
Disk	Low Carbon Steel	100
Outer Casings	Iron 99.8% Pure	5000
Coil	Copper	1
Bearing	Low Carbon Steel	100
Fluid	MR Fluid (Basonetic 5030)	8
Inner Casings	Aluminium	1

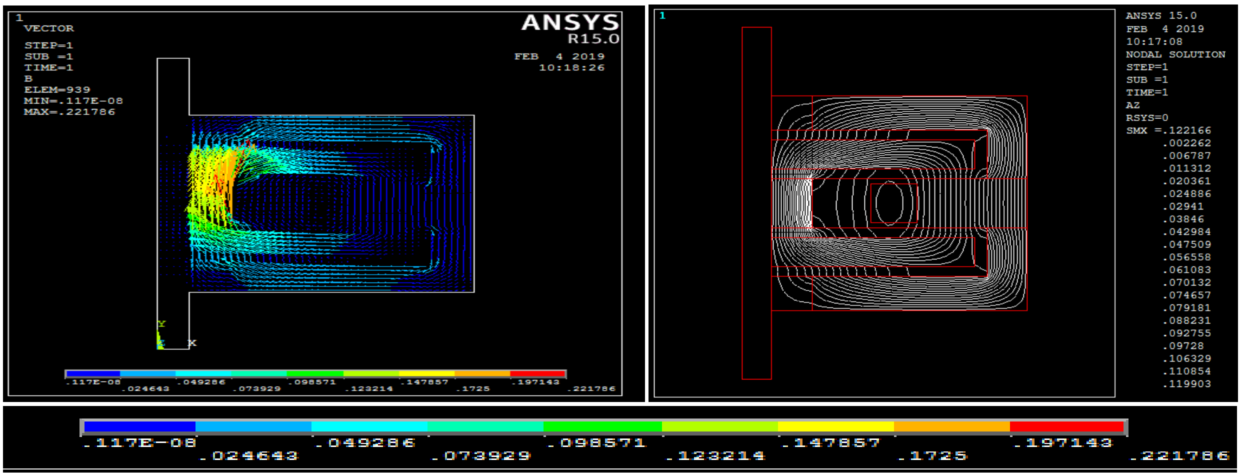

Fig. 6. Distribution of magnetic flux density (Tesla) in vector form (left), Line representation of magnetic field density (right), Extended view of the result (magnetic field density) of FEA (below).

3. Result and Discussion

In the first analysis, magnetic lines of force are found on the both flat and curved surface of the disk (Fig. 3). But the lines of force are parallel to the disk surface both on the flat and curved sides. So, no significant amount of braking torque could be found from the first analysis as this condition is not favorable to create high shear stress in MR fluid. If 99.8% pure iron is used for the disk material instead of aluminum, as it is for the second analysis, then it is seen that magnetic line of force is found perpendicular on the inner flat side of the disk but there is no line of force on the outer flat side of the disk (Fig. 4). Third analysis is also dissatisfying, as the inner surfaces of the disks do not have perpendicular line of force on the flat surfaces of disks (Fig. 5). In the fourth analysis all the lines of force are perpendicular on the both sides of flat surfaces of the disk (Fig. 6). The materials of 4th analysis can be selected to construct the MRB to get better braking torque. Any alternative material is possible to use for the respective parts of MRB if the alternation has the same relative permeability mentioned in the table-4.

So, we can summarize the output in the following tables:

Table 5. Comparisons among performed simulations.

No. of analysis	Maximum magnetic field density (T,tesla)	Shear mode of MR fluid
1st	0.0097	Almost no shear mode in outer MR fluid region
2nd	0.068	No magnetic flux in outer MR fluid region
3rd	0.089	Good shear mode in outer MR fluid but poor shear mode in inner MR fluid
4th	0.22	Good shear mode in outer and inner MR fluid

Table 6. Selected materials with relative permeability to get the best braking torque.

No.	Name of the part	Materials to be used	Relative Permeability
1	Disks	Low Carbon Steel	100
2	Outer casings	Iron 99.8% Pure	5000
3	Inner casings	Aluminium	1
4	Coil	Copper	1
5	Bearing	Low carbon steel	100

According to the relation between braking torque and effective surface area of the disk (Equation -5) the above combination will result in better braking torque.

4. Conclusion

A finite element model of double disks MR brake is analyzed numerically in ANSYS® APDL software to select proper materials mentioned in table-6 and the position of magnetic coil is fixed in the inner casing of MRB based on magnetic flux direction in MR fluid which is influenced by material's relative permeability and their geometrical structures. The outer casing material's relative permeability should be 5000 and inner casing material's relative permeability should be 1 for double disk MRB and disk material's relative permeability should be 100 to make magnetic flux lines perpendicular to the disk to create highest breaking torque. This literature will help to manufacture MR brake with better braking torque and energy efficient by reducing the waste of magnetic flux which will make enable to replace the conventional braking system of the vehicles or other possible applications.

5. References

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