Three-dimensional finite element magnetic simulation of an innovative multi-coiled magnetorheological brake

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Abstract. This research delivers a finite element magnetic simulation of a novel disk type multi-coil magnetorheological brake (MR brake). The MR brake axial design had more than one coil located outside of the casing. This design could simplify the maintenance process of brakes. One pair of coils was used as the representative of the entire coil in the simulation process, and it could distribute magnetic flux in all parts of the electromagnetic. The objective of this simulation was to produce magnetic flux on the surface of the disc brake rotor. The value of the MR brake magnetic flux was higher than that of the current MR brake having one coil with a larger size. The result of the simulation would be used to identify the effect of different fluids on each variation. The Magneto-rheological fluid MRF-132DG and MRF-140CG were injected in each gap as much as 0.50, 1.00, and 1.50 mm, respectively. On the simulation process, the coils were energized at 0.25, 0.50, 0.75, 1.00, 1.50, and 2.00 A, respectively. The magnetic flux produced by MRF-140CG was 336 m Tesla on the gap of 0.5 mm. The result of the simulation shows that the smaller the gap variation was, the higher the magnetic value was.

1. Introduction

Magnetorheological fluids (MRFs) have become a substitution privilege, since its rapid reaction for plenty x-by-wire applications, such as brakes, valves, dampers, clutches, and so on [1]. The novel design of a modular MR valve has been proposed by employing complicated flow path to enhance its performance [2]. MR elastomer possible utilization was investigated from three main points of view, such as its enforcement in automobile devices, prosthetic apparatus, and prospective purposes [3]. The magnetorheological brake (MR brake) is still extraordinary in the commercial markets [4].

Magneto-rheological (MR) brake is a type of MRFs application which is researchers feel strongly about. The fact is due to its various utilizations make MR brakes develop rapidly in several discipline area. It has been recently introduced by several automobile industries [5,6]. Analysis and optimal design have been investigated to enhance more capability of MR brakes, for instance, material selection, sealing, mixing scheme, and MR fluid selection [4,7]. Additionally, an MR brake which applied for prosthetic knee joint was carried out to gain its development by Gudmundsson et al. [8]. An optimal geometrical design of an MR brake considering.

It generates an interesting concern of MRFs implementation. The primary working mode of MRFs application in the MR brake is shear mode. The breaking effect is created from friction between idle
and rotate a component of magnetic field vulnerable viscosity. Thus, disc type, drum type, T-shaped MR brakes, multiple disks, and multiple layers are purposed and determined to become plenty types of MR brake [9]. However, it suggests to improving the more valuable field of magnetic flux by employing the shape and numbers of the coil [10].

MR brake with drum and disk brakes are simple to manufacture. It has a cylindrical shape of the rotor and the magnetic field is performed in the radial direction. However, the results are unsatisfied enough to apply in automotive industries [11]. The T-shaped rotor brake is most accessible than other MR brake above however it contains uneasy to manufacture. This design is still rare in the literature. York et al. [12] showed an initial example used as a torque load simulator system producing a massive torque amount. Other tools requiring high torque are clutches for automatic transmission [13]. Shiao and Nguyen [14,15] developed multi-coiled MR brake in recent years. It performed a promising brake torque due to its numbers of coils which produced much more magnetic field [14]. Its response was scrutinized beneath the free move inertial mass. The breaking time will be decreased when the boosting current exercised as the braking torque reaction [3].

Since the multi-coiled MR brake achieved an enormous amount of magnetic field, numerous researchers were desired to expand several brand new shapes. Shiao and Nguyen [14,15] built a drum brake MR brake and deliver with variations of outer and inner rotors. It managed yield resistance in the fluid, hence producing torque area for the brake [15]. Multi-coiled MR brake with disc brake performed valuable result which was firstly constructed by our group. It consists of six couples of coils and one disc brake. Due to its axisymmetric coils arrangement, it crossed much more rotor disc brake. As a result, a high value of the magnetic field was exhibited [16].

This study contributes on designing a unique type of multi-coiled MR brake for radial mode breaking system which has never been proposed before. It is that valuable for investigating the magnetic flux within the gap (breaking area) using the 3D approach of magnetic simulation. To looking after the flux density, three-dimensional of MRFs were incorporated in simulation a brief view of resulted prototype was also presented at the end of this paper.

2. Design and working principle

The coils configuration of MR brake system is displayed in Figure 1(a). Either using single or multiple coils arrangements in the earlier design is typically located inside of MR BRAKE body. Nevertheless, the suggested layout in the current MR BRAKE installs the coils on the outside of the cover. It is expected to construct more intensive magnetic flux in the radial field. The outer coils are seated on the magnetic core hubs to contact its two adjacent magnetic poles. Subsequently, the flux will pass from one pole via the magnetic core hubs, to another pole with a particular characteristic. Formerly, it will travel into the MR fluid gap, across the rotor. Finally, it will be back to the MR fluid gap and into the two adjacent poles as can be seen in Figure 1(b). By such an innovative design, the rotor disk will be entered with various coils that associated to others.

Figure 1. A model of axial multiple MR brake: (a) Isometric view, (b) Top view.
In Figure 1(b), the magnetic flux spreads over all around the disk surfaces. The result is that an appropriate shear stress will be exhibited, hence producing an area torque for the brake. From the operating concept, the head area of each pole will be triggered with an official current to stimulate the MR fluid area in the channel. Depending on the capacity of the rotor, windings (coils) and manufacture abilities, particular adjustment, and numerous of poles can be selected, from the small number, for instance, four or six poles or more. The earlier research that is integrating radially multi-coiled MR brake was founded by Shiao and Nguyen [14]. Meanwhile, the performance of 12-poles of the MR brake has been evaluated and documented in this study due to its balance between size constraints and braking performance in our future operations. The magnetic field strength in the MR fluid can be enlarged by accommodating the pole arrangement and the rotor’s radial and axial dimensions. Finally, the analogous shear stress on the cylindrical surface is expanded significantly, which supports to increase the braking torque.

The components for MR brake device can be clearly seen in Figure 2 through partial cross section mode. The materials that applied in the brake have a crucial impact on the magnetic field as well as the anatomical and magnetic characteristics. Since the magnetic field simulation has a key effect on the MR brake performance, the components selection is mandatory. Considering the cost, permeability, and availability, AISI 1018 steel was preferred as the magnetic component in the MR brake. The magnetic properties of AISI 1018 are displayed in Table 1. The aluminum alloy was exploited as the non-ferromagnetic material to build the shaft and the MR BRAKE covers. The AWG-21 copper wire was employed for the coils. The polyethylene was utilized for the bobbins for the electrical insulation property.

![Figure 2. Exploded view of the MR brake.](image)

| Part                  | Material   |
|-----------------------|------------|
| Bobbin                | Aluminum   |
| Support Bobbin        | Steel      |
| House Bearing         | Bronze     |
| Bean Shaped Plate     | Steel      |
| Circular Plate        | Aluminum   |
| Hollow Circular Plate | Aluminum   |
| Disc                  | Steel      |

### 3. Magnetic circuit analysis
Simulation process was used electromagnetic induction thus Maxwell equation (1) is necessary:

$$\nabla \times E = \frac{\partial B}{\partial t}
$$

(1)
where, $\nabla \times$ is curl operation, $E$ is an electric field, and $B$ is a magnetic field. On the following equation is functioned of $t$ (time). A simulation based on finite element model is necessary to trim the error computation of the MR brake. ANSOFT Maxwell 14 is operated to cultivate the magnetic field patterns of the expected design in a 3D environment. The electric circuit analogy of the multipoles MR brake as displayed in Figure 3 was promoted. Figure 3 also demonstrates the magnetic flux flow within the device. The magnetic device mainly consists of two coil bobbin sets, connector, and the rotor disc. The coils generate magnetic flux density to almost every part of the MRFs.

![Figure 3. Magnetic circuit of a coupled coil.](image)

One loop of differentiated Kirchhoff Laws was used to calculate magnetic circuit as portrayed in Figure 3. The reluctance of the core 1, reluctance of the core 2, reluctance from the connector, reluctance from the disc, and the reluctance of the MR fluid is personified by the symbols $R_{coil_1}$, $R_{coil_2}$, $R_{connector}$, $R_{disc}$, $R_{MR\ fluid}$, respectively. The reluctance of each section can be determined by the following equation below,

$$R = \frac{L}{\mu A} \quad (2)$$

where, $L$, $\mu$, $A$ represent the effective length, magnetic permeability, and effective area of the magnetic flux, correspondingly. While, the equation below displays the total magnetomotive force is the summation of the magnetomotive force produced by all of the parts in one loop. The magnetomotive force is directly proportional to the magnetic flux and reluctance as declared in below (Equation (3)),

$$\Phi_1 + \Phi_2 - R_{coil_1} - R_{MRF}\ fluid - R_{disc} - R_{MRF}\ fluid - R_{coil_2} - R_{connector} = 0 \quad (3)$$

The magnetic flux $\phi_1$ and $\phi_2$ rely on the number of coil turns and electric current pass through the coils. As a result, Equation (3) can be rewritten as the following form (Equation (4)),

$$N_1I_1 + N_2I_2 - R_{coil_1} - R_{MRF}\ fluid - R_{disc} - R_{MRF}\ fluid - R_{coil_2} - R_{connector} = 0 \quad (4)$$

where, $N$ and $I$ are numbers of wire turns in each coil and electric current passing through the coils, subsequently.

4. Simulation setup

CAD was employed to create the 3D design of proposed prototype. Then, it is converted to ANSOFT MAXWELL to perform the magnetic simulation. Nonmagnetic components were assigned as aluminum and polyethylene, while others were attributed as steel AISI 1008 for magnetic objects. Two types of MRFs i.e. MRF-132DG and MRF140CG were applied by using B-H curve from LORD technical data sheet in FIGURE. Several currents were attached to the 3D simulation, 0.25, 0.50, 0.75, 1.00, 1.50, and 2.00 A for each varied MRFs. Also, 0.50 mm, 1.00 mm, and 1.50 mm gap were operated to chase the optimum design. The measurement line was added in the middle of the gap...
which is located beneath of the core. For this reason, it is a proper spot to earn the magnetic flux result. Table 2 below shows the properties of each MRFs.

| Properties        | MRF-132DG   | MRF-140CG   |
|-------------------|-------------|-------------|
| Carrier Liquid    | Hydrocarbon | Hydrocarbon |
| Filling particle  | Carbonyl iron | Carbonyl iron |
| Density g/cm³     | 3.09        | 3.64        |
| Viscosity, Pa-s @ 40 | 0.112 ± 0.02 | 0.280 ± 0.070 |
| Solids content by weight, % | 80.98 | 85.44 |
| Flash point, °C (°F) | >150 (>302) | >150 (>302) |
| Operating Temperature, °C (°F) | -40 to +130 (-40 to + 266) | -40 to +130 (-40 to + 266) |

5. Results and discussion
The straight line in Figure 4 illustrates the position to measure the magnetic flux value. The measuring line was placed at the center position of the fluid MRFs used with 40 mm and it divided into 40 points. The position of the measuring line is located along the core diameter is pulled straight in the direction of at a central point.

Figure 4 shows the direction of the magnetic flux generated by the coil pair. Clearly demonstrated, the distribution is done at the center of a copper coil then passes through the components that are in one loop. The highest magnetic flux is shown located at the center of the copper windings, while the lowest value was achieved when the magnetic flux passing through the disc after previously passing MRFs.
Results directions of magnetic flux obtained using two-dimensional directions as shown in Figure 5. Same as depicted in Figure 4, the greatest value lies at the core of the copper windings and magnetic flux smallest value contained on the disk is used. In two dimensions is obvious leaps magnetic flux. Leaps the magnetic flux looking for the nearest magnetic material to be passed.

![Magnetic Flux Directions](image1)

- (a) Current 0.25 A
- (b) Current 0.50 A
- (c) Current 0.75 A
- (d) Current 1.00 A
- (e) Current 1.50 A
Magnetic fluxes were produced by every variation of the MRFs at 0.50 mm gap is shown in Figure 6. The highest value of magnetic flux is about 339 mT was created by MRF 140 CG at 0.50 mm gap which is placed on measurement line along core diameter. That result was the best value in this simulation. Flux magnetic of MRF-140 CG is always placed higher than other MRFs. It can be caused by MRF-140 CG has greater magnetic permeability than the others. Magnetic permeability is influenced by the volume fraction of contained particle of MRFs itself. Carbonyl iron is a particle which is used to fill MRFs. The more number it contained on MRFs, the greater magnetic conductivity.

Figure 6. Flux Distribution to MRFs Variations on 0.50 mm of Gap.
Figure 7. Flux Distribution to MRFs Variations on 1.00 mm of Gap.

Figure 7 shows magnetic flux was exhibited by gap 1.00 mm for every variation of MRFs. MRF-140 CG produced exactly 298.923 mT on measurement line of 1.0 mm gap variation which was given 2.00 A applied current. The value of the magnetic flux generated increases with the applied current. The value of the magnetic flux MRF-132DG always is lower when compared to other fluid. This is caused by the magnetic conductivity (magnetic permeability) MRF-132DG smaller than the other MRFs. The volume fraction of filler particles affects the size of the magnetic conductivity MRFs. It has the smallest volume fraction causes the magnetic flux produced the lowest.
The value of the magnetic flux generated by MRFs variation in the gap of 1.5 mm is shown in Figure 8. The best value magnetic flux generated by MRF-140CG amounted to 270.444 mTesla with the applied current of 2.00 A on variations in the gap of 1.5 mm along the measuring line. The increase in the provision resulted in an increased flow of magnetic flux generated value. The value of the magnetic flux MRF-140CG is always higher when compared to other fluid. Magnetic conductivity (magnetic permeability) MRF-140CG greater than MRFs are other causes magnetic flux value is.

Figure 8. Flux Distribution to MRFs Variations on 1.50 mm of Gap.
always higher. The value of the magnetic flux is influenced by the volume fraction of particles in the MRFs. Carbonyl iron is used as filler particles in MRFs. The more the iron particles used in MRFs, the greater the magnetic conductivity and magnetic flux generated.

![Figure 9. Magnetic Flux Density Versus Applied Current.](image)

Current distribution result graphs were delivered has the same pattern for all variations of MRFs, MRF-132DG, and MRF140CG. It distinguishes on every gap variations are shown in Figure 9. Comparison of current to the magnetic flux of MRF-132DG for any variations gap which was used is shown in Figure 9(a). It is apparent that it produces a linear graph. The magnetic flux density for all of three variations at 0.25 A was given tends to equal at 40 mT. However, the differences seen at the time
line on 0.75 A. The distinguished of the magnetic flux started to occur although not too significant at 99-110 mT. The highest value of the magnetic flux was exhibited by 0.5 mm at 2.00 A was located at 280 mT. The larger the gap is used, the smaller the magnetic flux generated.

Figure 9(b) shows magnetic flux density MRF-132DG which was delivered at each variation. It provided 300 mT at 0.5 mm which lies in the middle of the MRFs along the core diameter. The comparison of current to the magnetic flux of 0.5, 1.0, and 1.5 mm for MRFs MRF-140CG is clearly displayed in Figure 9(c). The graph results in a linear curve. The greater the current supplied to the coil, the greater the magnetic flux developed. The smaller gap is used, the greater the magnetic flux actualized.

Magnetic flux increased as long as the current added. The gaps and MRFs were stimulated the increasing of magnetic flux. The larger the gap was used, the smaller magnetic flux would be obtained. MRF-140CG performed the biggest magnetic flux due to a magnetic conductivity. Volume fraction was affecting the magnetic conductivity of MRFs. Magnetic flux earned by MRF-132 and MRF-140 was slightly different since volume fraction of both MRFs is not much contrast. The magnetic flux total at whole cores in the simulation is 2.4 T. The magnetic flux is greater than the study by Shiao and Nguyen [14], which was mounted 2.3 T. The magnetic flux in the simulation is enough for application on static bicycles.

6. Conclusions
This paper has addressed several variations of magnetostatic simulation from an innovative multi-coiled disk type MR brake. Its procedure approach and dimensional are the same from a previous study. The results display that some modification can exhibit acceptable magnetic flux value which validates the performance of proposed device. Magnetic permeability placed MRF-140CG became the best MRFs for magnetic flux distribution. The smallest gap produces the most sophisticated amount. Therefore, it can be used for next study on the MR brake system for medical device purposes.

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