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Structural Analysis and Validation of the Multi-pole Magnetorheological Brake for Motorcycles

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Abstract

Magnetorheological fluid (MR) has been developed and applied in various systems on vehicles such as suspension, engine mount and heavy-truck seat. However, due to its small maximum torque, conventional MR brake currently cannot be successfully applied on vehicles. In this paper, a multi-pole MR brake for motorcycle has been proposed. The targeted MR brake not only provides sufficient braking torque, but also maintains an acceptable size. With unique operation concept, two brake designs of the new MR brake, one has inner-rotor structure and another has outer-rotor structure, have been designed and analyzed for its application feasibility. For the ease of verification in braking performance, a comparison procedure was built in which braking torque is evaluated based on the torque-to-volume ratio. Magnetic simulation results show that the two designs can certainly reach the targeted torque while the one with outer-rotor structure has better compact design. This design proves its feasibility for using on motorcycle brake system.

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Keywords: Magnetorheological Fluid; Multi-pole MR Brake;, MR Brake for Motorcycle.

1. Introduction

Conventional MR brake consists of a round housing (stator) and a rotor inside. Several researches have proposed methods of torque enhancement for the conventional design of MR brake [1–3]. Common methods

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include reducing the MR fluid gap, extending the active area of the MR fluid and increasing the applied field strength under the magnetic saturation limit. The application of MR brake on motorcycle benefits by simple structure, easy maintenance, fast response and favorableness for torque control. However, there is less study focusing on this topic. Only in the study of Nguyen *et al* [4,5], a conventional MR brake was investigated for using on motorcycle. The major challenge of this application is the maximum brake torque required for motorcycle braking, normally over 300 Nm for each front/rear brake [6]. This value is usually over the reach of torque from a conventional MR brake. Therefore, this paper addresses a new MR brake design with solid and compact structure to enhance the magnetic field and its resulted braking torque. In the next sections, magnetic simulation and structure analysis have been carried out to validate the performance of proposed MR brake designs.

2. Concept and Mathematical Model

The concept of multi-pole MR brake initially proposed by Shiao study [7]. It is later improved and introduced in [8]. Both brake designs are structured by a stator covering an inner-rotor, and the performance is applicable for indoor applications only. In this paper, the multi-pole MR brakes are specifically designed for using on motorcycle. It mainly consists of magnetically permeable multi-pole stator and a rotor as in figure 1. It is noted that the poles are placed on stator while the rotor is a solid metal part only. Two MR brake designs, which have the same operation concept, are proposed for comparison. As in figure 1(a), the inner-rotor brake features with an inner rotor surrounded by outer stator, while in the outer-rotor brake the stator is placed inside a rotor as in figure 1(b). In both designs, magnetic flux travels following the red-line paths, and the direction of magnetic flux in each pole is opposite to that of its two adjacent magnetic poles. By that flux arrangement, the flux will travel in a closed loop: from one pole, through the MR fluid gap, to the rotor, back to the MR gap and into the two adjacent poles. As a result, all MR fluid in the channel between the cylindrical surface of the rotor and the stator will be orthogonally penetrated by magnetic flux. It then produces yield resistance in the fluid, thus creating field torque for the brake. From the operation concept, the head area of each pole will be affected to activate MR fluid in the channel. Depending on the size of rotor, winding and manufacture abilities, different arrangements and number of poles can be chosen. In this study, the performance of those two types of MR brake with 12 poles have been analyzed and verified for its harmonization between size constraints and braking performance to motorcycle brake system. Magnetic field strength in MR fluid can be enhanced by the influence of pole configuration as well as physical dimensions of the brake.

Since the same operation concept is used, these two inner-and outer rotor designs share the same mathematical models (but different parameters) for simulation. The effective working area of MR fluid in the two multi-pole MR brakes is the cylindrical surface of the rotor where the fluid is activated by applied magnetic field. Bingham-Plastic model has been used in this study to describe the shield characteristic of MR fluid [9]. MRF-140CG MR fluid from Lord Company was used in this design. Its detailed specification [10] is listed in table 1. According to Shiao *et al* study [8], the total braking torque produced by MR brake is

$$T = R_r^2 \int_0^z \int_0^{2\pi} \tau_y \, d\theta \, dz + \frac{2\pi\eta\omega}{g} R_r^3 z + T_{fr} \tag{1}$$

where R_r is the rotor radius and also the length of torque arm; θ and z are the cylindrical coordinates of the rotor as shown in figure 2; τ_y is the yield stress of MR fluid developed in response to the applied magnetic field; η is the viscosity of the MR fluid with no applied magnetic field; ω is the angular velocity of the rotor and g is the thickness of the MR fluid gap; T_{fr} is the friction torque.

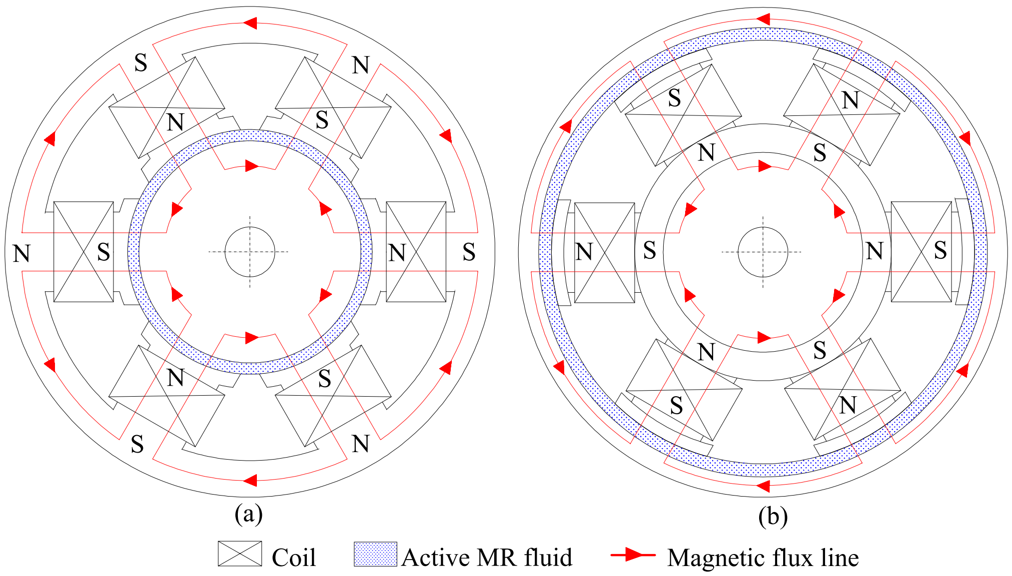


Fig. 1. Operation concept of the Multi-pole MR brake: (a) inner-rotor brake and (b) outer-rotor brake

Table 1. Properties of MRF-140CG MR fluids [10].

Property	MRF-140CG
Carrier liquid	Hydrocarbon
Density (g/cm^3)	3.64
Yield strength (kPa) at 100 kAmp/m	38
Yield strength (kPa) at 200 kAmp/m	57
Plastic viscosity (mPa-s) at $40^oC,\ \gamma > 500s^{-1}$	280
Operating temperature (^oC)	-40 to +130
Thermal conductivity[a] (W / m^oC) at 25 ^oC	0.28 – 1.28
Coefficient of thermal expansion 0-50 ^oC	5.0 x 10^{-4}

[a] Values were calculated with and without magnetic field applied

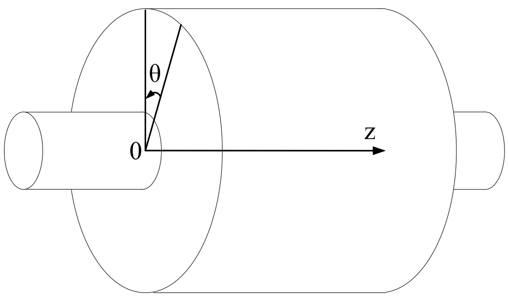


Fig. 2. The cylindrical coordinate system applied to rotor

In right side of equation (1) two parts below can be recognized as the field torque component T_f and viscous torque component T_v:

$$T_f = R_r^2 \int_0^z \int_0^{2\pi} \tau_y d\theta dz \tag{2}$$

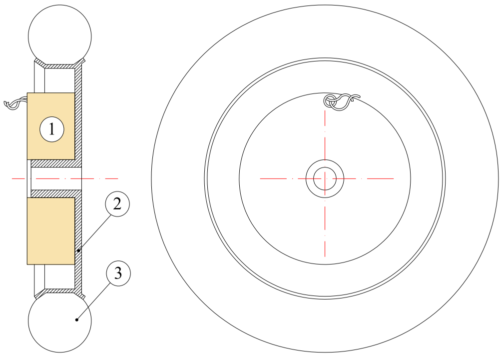
$$T_v = \frac{2\pi\eta\omega}{g} R_r^3 z \tag{3}$$

The torque in equation (1) majorly depends on the yield characteristics of active MR fluid and rotor structure (R_r, z). This paper mainly focuses on the torque improvement for two types of MR brake designs. In the following section, detailed investigation about this issue is discussed.

3. Simulation of the Multi-pole MR Brake

3.1. Structural Analysis

The MR brake is placed inside the rim of motorcycle wheel and constrained by the rim dimensions as in figure 3. From the point of view of structure, advantages and disadvantages of two brake designs are listed in table 2. It is noted that the outer-rotor brake has potential application advantage for motorcycle.



1 – Multi-pole MR brake 2 – Rim 3 – Tire

Fig. 3. The assembly of MR brake and motorcycle wheel

Table 2. The structural characteristics of two MR brake designs

	Inner-rotor brake	Outer-rotor brake
Advantage	• using smaller volume of MR fluid than outer-rotor brake • larger space for winding	• easy winding by automatic winding machine • bigger rotor radius than one of inner-rotor brake if both have the same overall size. • easy to fit with structure of commercial motorcycle rim
Disadvantage	• smaller rotor radius than that of outer-rotor brake if both have the same overall size. • difficult winding by automatic winding machine	• using larger volume of MR fluid • less space for winding • difficult sealing inner stator from MR fluid

3.2. Simulation of two designs

The 3D models of two designs have been built. Detailed dimensions of inner-rotor brake and outer-rotor brake are shown in figure 4(a) and 4(b), respectively. It is noted that the overall dimensions of two designs are the same. It is referred to the overall dimensions to fit the space of motorcycle rim. Due to the available space, a 12-pole design is preferred for both designs. However, the other dimensions can be considered based on optimized solution. The optimization method is discussed in study of Shiao et al [8]. The magnetomotive force (NI – where N is number of turns per coil and I is the input current) is kept at 700 amp-turn per coil for both cases.

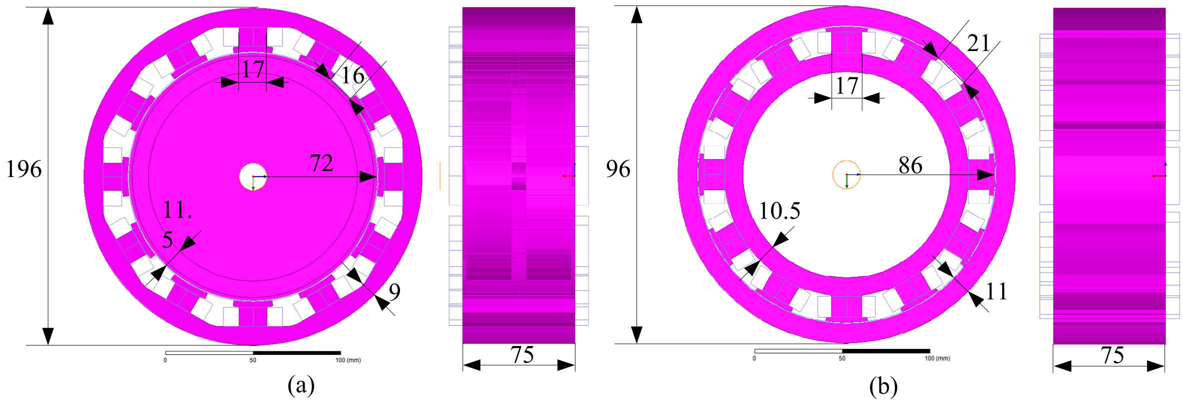


Fig. 4. Simulation models of two designs, (a) Inner-rotor brake and (b) Outer-rotor brake

To compare the performance of two designs of the multi-pole MR brake, the torque to volume ratio R_{TV} [11] is used. It is defined by the ratio of maximum brake torque to the overall geometrical volume of the brake. In this study, simulated brake torque is also used for comparison.

4. Results and Discussions

4.1. Magnetic simulation results

The simulated magnetic results of two designs are shown in figure 5 to 8. It is obvious that in both designs most of the MR fluid in cylindrical surface of the rotor is penetrated orthogonally by magnetic flux from 12 surrounding poles. In inner-rotor brake, the coils produce a higher magnetic field strength than one of outer-rotor brake. It is due to the shorter travel path in inner-rotor brake compared with outer-rotor brake. Figure 6 and 8 provide a closer look on the formation of magnetic field of one pole and its adjacent poles. The results agree with the operation concept shown in figure1, in which the flux travels in a closed loop.

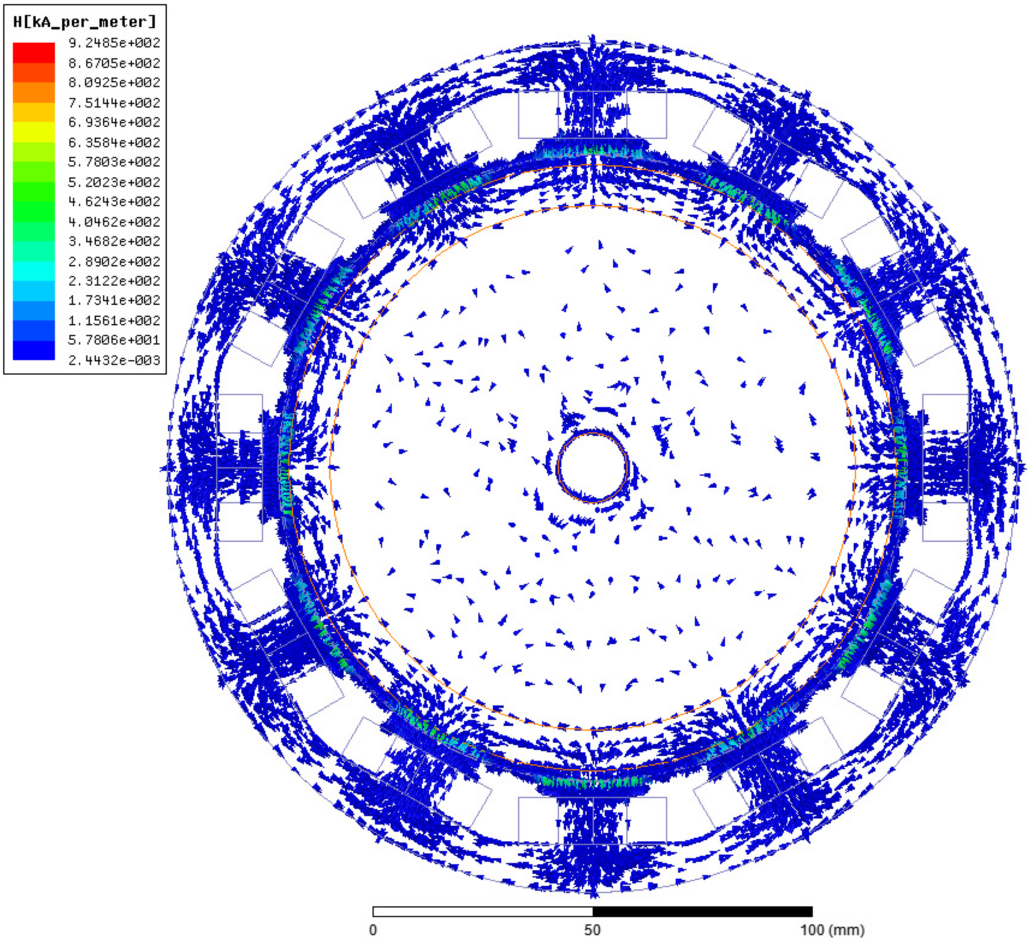


Fig. 5. The formation of magnetic flux on cross section of inner-rotor brake

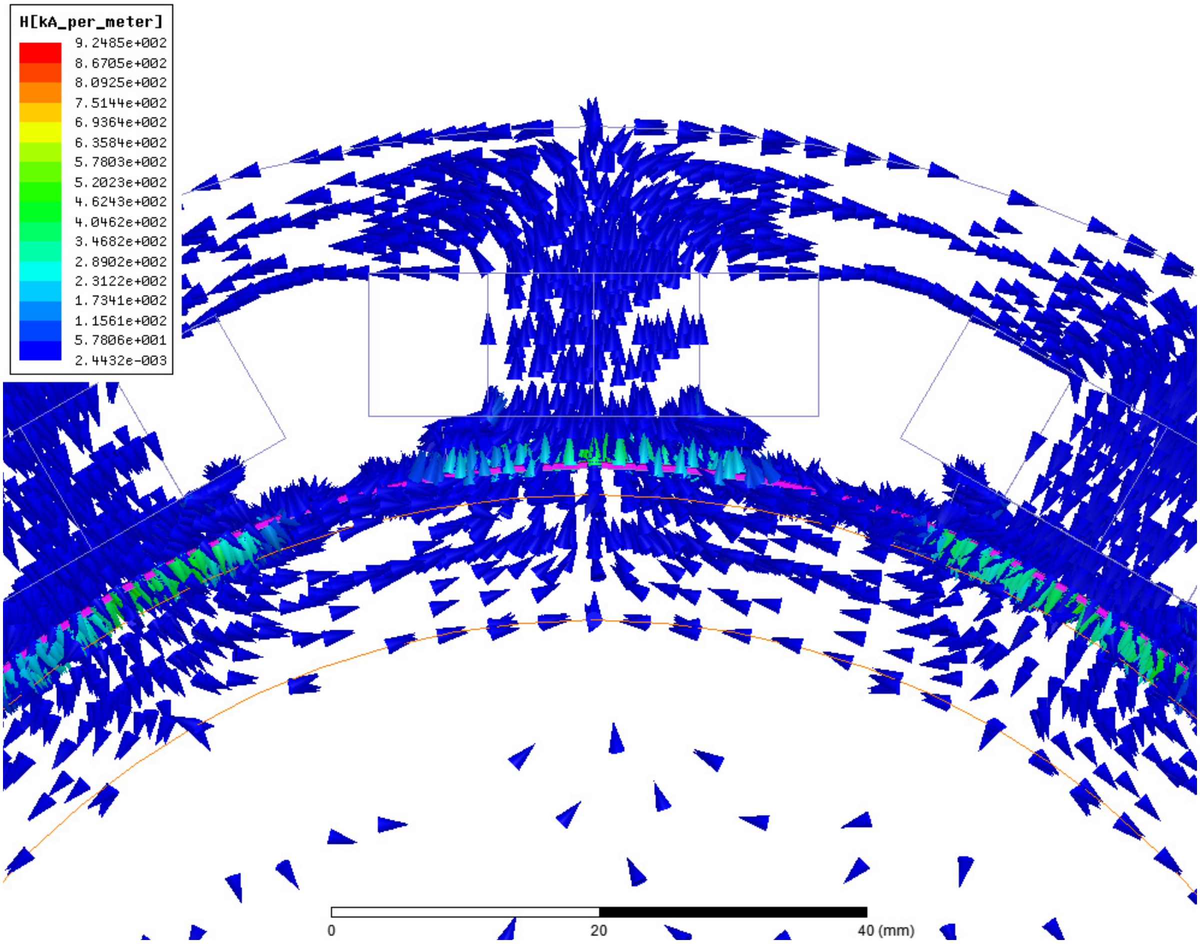


Fig. 6. A close view of the direction of magnetic flux on cross section of inner-rotor brake

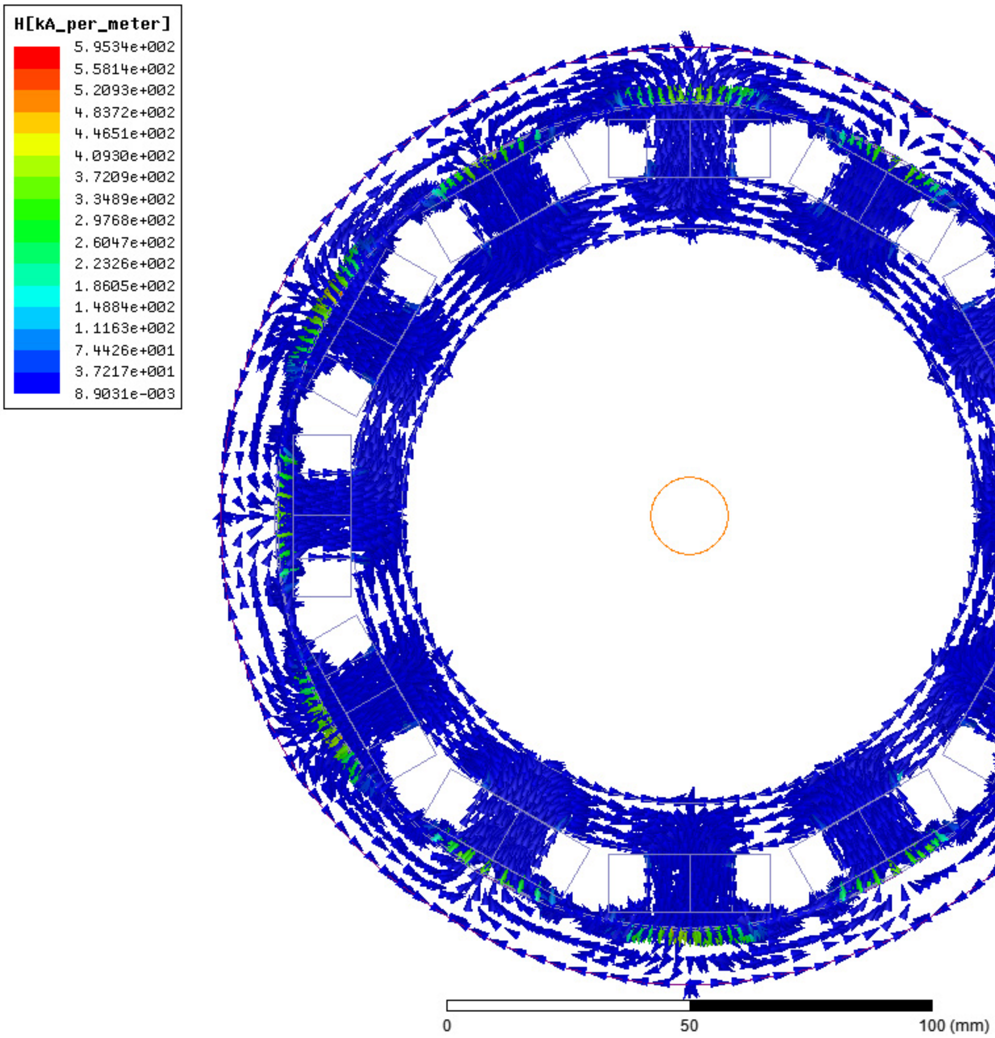


Fig. 7. The formation of magnetic flux on cross section of outer-rotor brake

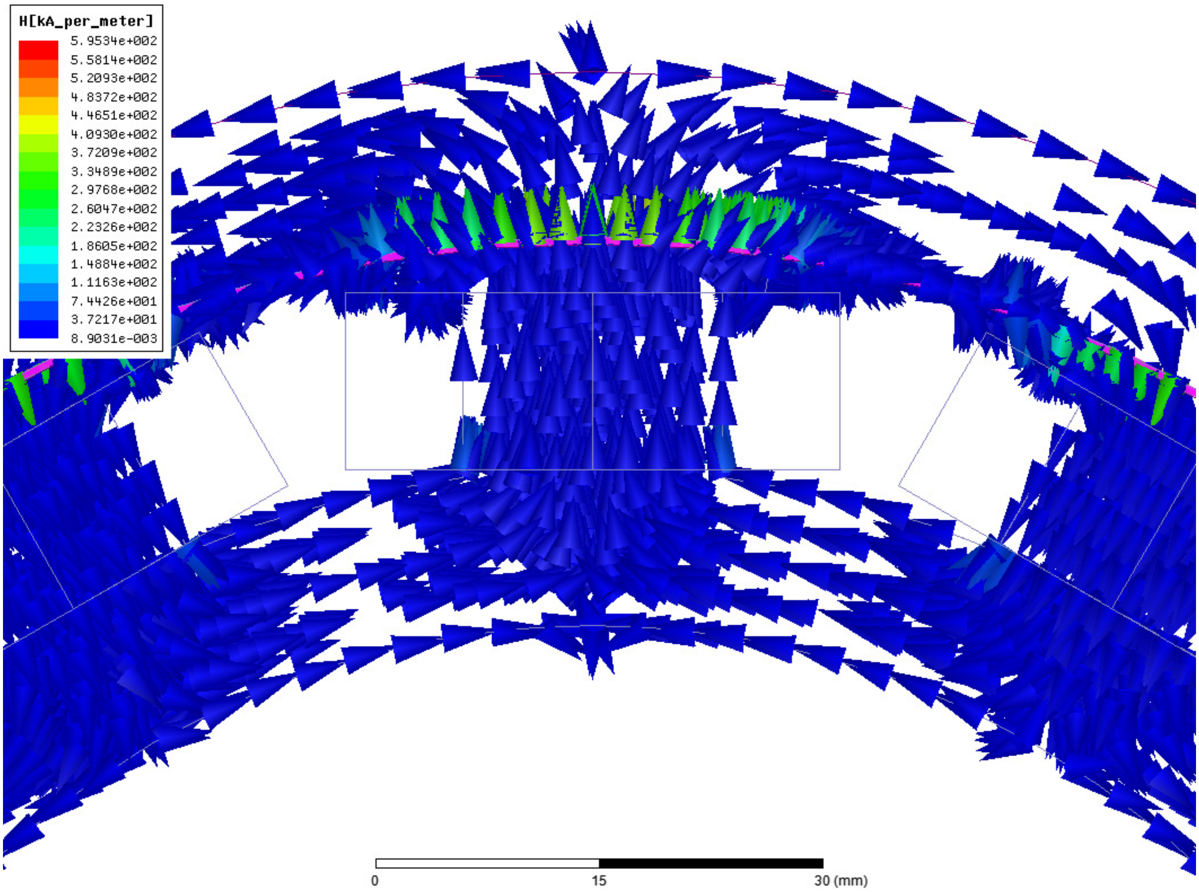


Fig. 8. A close view of the direction of magnetic flux on cross section of outer-rotor brake

4.2. Torque simulation results

Figure 9 shows the simulation results of brake torques of the two designs with different NI. The torque increases nearly linearly with the raise of NI. The maximum brake torque for inner-rotor and outer-rotor brakes are 426 Nm and 525 Nm, respectively. The output torque of two brakes is then applicable for motorcycle braking. As in equation (1), the higher maximum torque of outer-rotor brake is due to its bigger rotor radius R_r while still maintaining a compact structure.

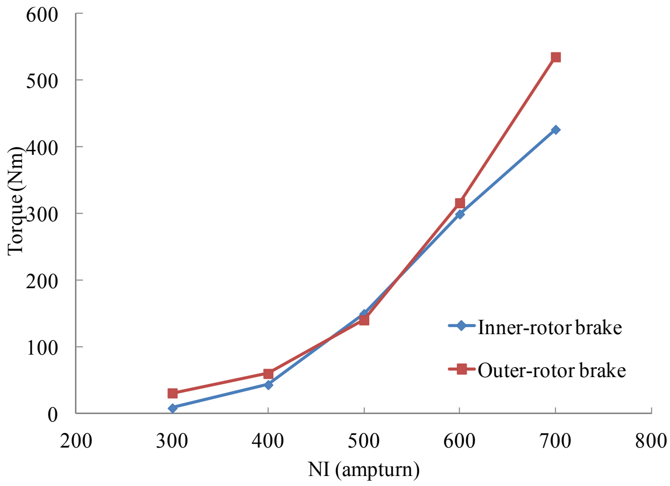


Fig. 9. Simulated torque results of two designs

4.3. Results of Torque to Volume Ratio

The results of R_{TV} of two designs are shown in figure 10. Outer-rotor brake obtains better R_{TV} compared with that of inner-rotor brake. It is confirmed that the structure with outer rotor covering and inner stator is the most suitable structure for MR brake system used in motorcycles.

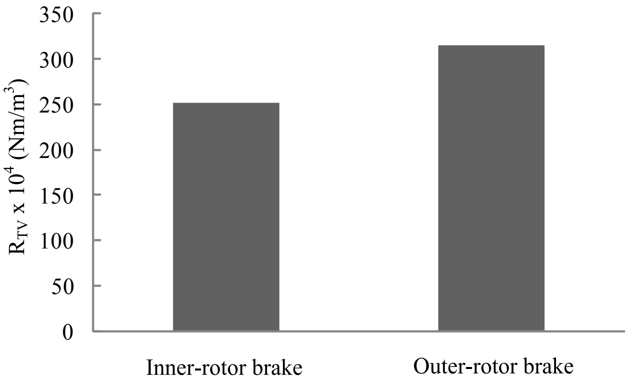


Fig. 10. The results of torque to volume ratio of two designs

5. Conclusion

This paper proposes two designs of new multi-pole MR brake. Mathematical models as well as structural analysis and magnetic simulation have been done to analyze the application feasibility of those designs. The results show that both two designs can produce appropriate amount of brake torque, which proves the ability of application on motorcycle brake system. The outer-rotor brake presents a better torque to volume ratio, which can be used for further research on the MR brake system for motorcycles.

Acknowledgements

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