Investigation of the Effect of Pole Shape on Braking Torque for a Low Power Eddy Current Brake by Finite Elements Method

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Abstract

The principle of electromagnetic braking involves the conversion of kinetic energy into thermal energy. When a non-magnetic or magnetic conductive material rotates into static magnetic field, eddy currents are induced in material. Paths of induced eddy currents depend on the geometrical configuration of moving conductive material and also its electromagnetic properties. However, due to electrical resistance of the conductive material, the eddy currents are disrupted into heat and braking torque occurs.

In practice, eddy current brakes are frequently used for motor testing because of the easiness of braking torque control. It is also used as supplementary retardation equipment in addition regular friction brakes on heavy vehicles. Mathematical analysis of the effects of eddy currents is almost impossible due to the complexity of electromagnetic problem. There is no obtained certain relationship which can explain output data in terms of input data since relation includes too many variables including conductive disk areas, conductive disk thickness, conductive disk radius, speed etc.

In this study, braking effects of two different eddy current brakes having different pole shapes are compared. Round and rectangular pole shape which have the same pole area are analysed where all numerical design constraints were kept unchanged to compare braking torque vs speed characteristics and total power dissipation on rotating disk. All mentioned designs are analysed by commercial software using finite element method (FEM)

1. Introduction

Eddy current braking uses typically the rotational movement of a conductive disk between two oppositely poled magnets to induce an emf in the conductive material [1]. When a rotating conductive material is exposed to a time-invariant magnetic flux density, eddy currents are induced around the pole projection area in conductive disk depending on rotation. According to Lorenz law, braking torque is generated by the action between the eddy current and time invariant magnetic flux density [2,3].

The time invariant magnetic flux density is produced by stationary electromagnets which are placed onto a yoke that is placed in front of a rotating conductive material, shaped as a disk connected to a shaft of a motor to be loaded. The stationary windings surrounding the poles are fed by direct current and this results in a time invariant magnetic field in the air gap. Although the magnetic flux density in the gap is unchanged according to time, rotation of the conductive disk brings about an alternating magnetic field inside the disk causing Eddy currents to be induced [4,5]. Magnetic field produced by Eddy currents opposes the applied magnetic field causing a braking torque to occur. Since there is current passing through the resistance of the conductive material, heat is produced over the disk. In other words, mechanical input energy of the rotating system is transformed into heat inside the rotating disk.

In 1975, Schieber analytically found the optimal size of a rectangular electromagnet for eddy current brake system. In this study he found that the optimal ratio of the length/width where the length is the direction of motion is approximately 0.5 for an infinitely large conductive disk [6].

In the whole study of the authors, effects of changes in design parameters are all analysed to extend the limits of the designed eddy current brake. Here in this study, only the effect of pole shape is investigated and two different eddy current brakes having rectangular or round pole are analysed by finite elements method (FEM). Remaining design parameters apart from pole shape such as conductive disk material, number of poles, excitation current, air gap length, poles area etc. are all kept unchanged. Several characteristics for two different pole shapes for all low, medium and high speed regions are obtained and presented.

2. General Theory of Eddy Current Brake

Eddy current brakes are composed of a stationary magnetic flux source like permanent magnet or electromagnet and a conductive disk connected to a rotating mechanical energy source. Depending on rotation, the conductive material exposed to a time varying magnetic flux density which can be expressed by Lenz's law where E is electric field intensity and B is magnetic flux density.

$$\nabla \times \vec{E} = -\frac{\partial \vec{B}}{\partial t} \tag{1}$$

Occurrence of electric field causes current, because of Ohm's law where J is current density and these currents are eddy currents which complete their path along the material as a loop.

$$\vec{J} = \sigma \cdot \vec{E} \tag{2}$$

The action between eddy currents and magnetic flux density creates a braking force (F) and induced braking torque can be expressed as below, where r is the radius of the disk;

$$\vec{F} = \vec{J} \times \vec{B} \tag{3}$$

$$\vec{T} = \vec{F} \cdot r \tag{4}$$

3. Finite Element Equations

Eddy current brakes include stationary poles creating the magnetic field which are excited by excitation current or permanent magnets and moving conducting disk. In practise, eddy current brakes have non-conducting and conducting regions to be modelled by using magnetic scalar potential ϑ and magnetic vector potential A where H_T is total magnetic field intensity [7,8].
In non-conducting regions (5) is used.

$$H_T = -\nabla.\vartheta \tag{5}$$

This total magnetic field intensity has two components including ϕ as reduced magnetic scalar potential and H_S as the magnetic field intensity of source.

$$H_T = -\nabla.\phi + H_S \tag{6}$$

The relation between H_S and J_S, source current density is as shown below.

$$\nabla \times H_S = J_S \tag{7}$$

The Laplacian type equation is below where μ is the permeance;

$$\nabla.\mu.\nabla.\vartheta = 0 \tag{8}$$

In eddy current or conducting regions, magnetic flux density (B) and electric field intensity (E) can be expressed as below where V is scalar electric potential, ϖ is speed [9].

$$B = \nabla \times A \tag{9}$$

$$E = -\frac{\partial A}{\partial t} - \nabla.V + \varpi \times \nabla \times A \tag{10}$$

In order to obtain an equation where V is omitted, equation 2,10 and Ampère's law can be used;

$$\nabla \times \frac{1}{\mu} \times \nabla \times A = \sigma\left(-\frac{\partial A}{\partial t} - \varpi \times \nabla \times A + \nabla.V\right) \tag{11}$$

Eq. 12 is attained by obtaining the divergence of (11).

$$\nabla.\sigma\left(-\frac{\partial A}{\partial t} - \varpi \times \nabla \times A + \nabla.V\right) = 0 \tag{12}$$

Scalar electric potential can be expressed in terms of A and ϖ as in (13).

$$V = A.\varpi \tag{13}$$

By substituting (13) into (11),

$$\nabla \times \frac{1}{\mu} \times \nabla \times A = \sigma\left(-\frac{\partial A}{\partial t} - (\varpi.\nabla)A - (A.\nabla)\varpi - A \times (\nabla \times \varpi)\right) \tag{14}$$

is obtained.

4. 3D Transient Magnetic Model

In this study, an eddy current brake is analysed to investigate the effect of the pole shape on braking torque. An optimised design previously obtained by the authors is used during the analysis where all design parameters are kept unchanged while the rectangular pole shape is changed with round pole. For each chosen pole shape, different angular speed values are used between 50 rpm-7500 rpm in 25 steps.

Optimal Eddy current brake design [9] properties are given in Table 1. The design has two separated air gaps divided by the conductive disk facing 8 poles on each side. Copper is used in wiring, 7075 aluminium for the conductive disk and steel 1010 as the magnetic material for the yokes. All other design and operational parameters are all kept unchanged.

The problem solved by considering skin and proximity effect, motion induced eddy currents and time diffusion of magnetic fields as in previous parts of the study [9]. To simulate this problem, 3D transient optimized design parameters of Eddy current brake magnetic model was used. Only ¼ of the geometry is modelled so as to solve the each problem quicker. One side of 3D transient magnetic model of the each Eddy current brakes which has different pole shape are given below in Fig. 1 [5,7,8] and Fig. 2.

Table 1. The design parameters which are constant during the analysis

Symbol	Quantity	Value
I	Excitation Current	*10A*
N	Number of Turns per pole	*300*
p	Number of Pole Pairs	*8*
τ	Pole Width	90^o
g	Air-gap Width	*2mm*
A_{mag}	Electromagnet surface area	$1250mm^2$
R	Conductive Disk Radius	*380mm*
μ_r	Relative permeability of Conductive Disk	*1*
σ	Conductivity of Disk	$58000000\Omega^1$

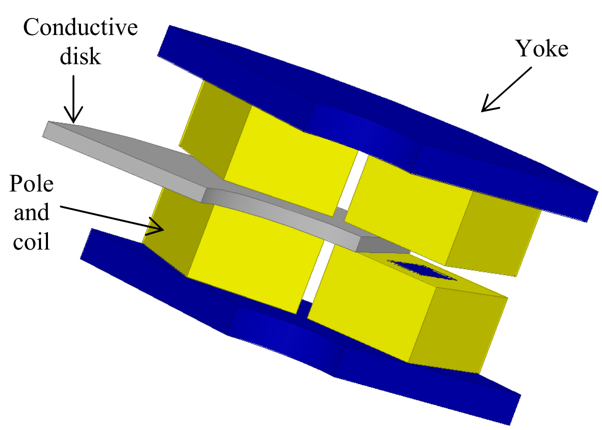

Fig. 1. ¼ geometry including the rectangular poles of the 3D transient magnetic model

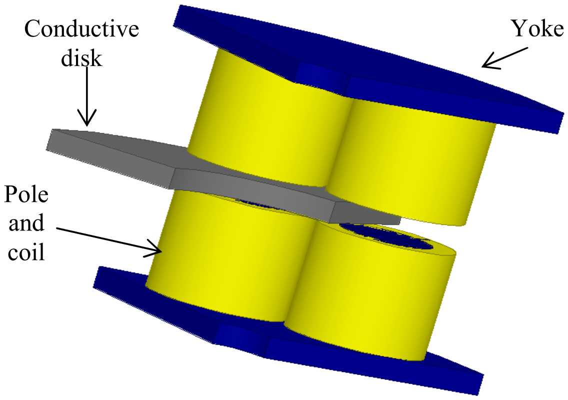

Fig. 2. ¼ geometry including the round poles of the 3D transient magnetic model

Mesh inside the conductive disk is chosen to be non-uniform since moving eddy current regions need more mesh than non-conducting region as in Fig. 2 [5].

The time step in transient magnetic problems is very crucial to increase the accuracy of the calculated eddy current. Finite element algorithm uses nodal solution, so time step and mesh size play an important role in obtaining a correct and stable solution and eventually the time step is chosen 0.5ms.

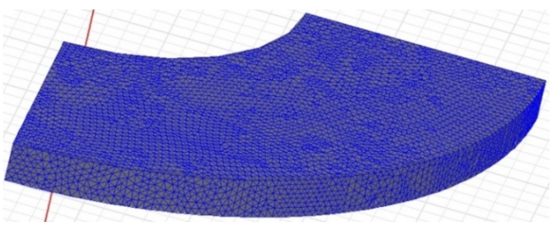

Fig. 3. The mesh of the models for both designs

5. Results

Since the aim of the study is to obtain characteristics for different speed values for two different models, numerous simulations are needed. 25 different speed levels between 50 and 7500 rpm are used to determine the characteristics. .

In order to determine the effect of pole shape, more than 50 different simulations are completed. Combined characteristics of the brake are presented for rectangular and round pole eddy current brake at a certain speed value. The chosen visual output given in Fig. 4-9 are for 1500 min^{-1}. Magnetic flux density inside the conductive disk is given in Fig. 4 and Fig. 5 for both designs. Representations of vectorial display for Eddy current density inside the conductive disk and magnetic flux density over the pole surface are given in Fig. 6, 7, 8, 9 respectively.

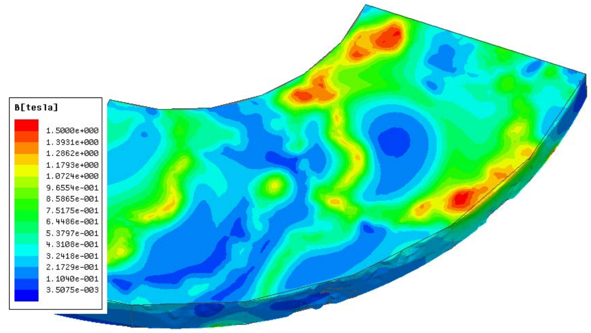

Fig. 4. Magnetic flux density distribution of the conductive disk for the eddy current brake with round poles

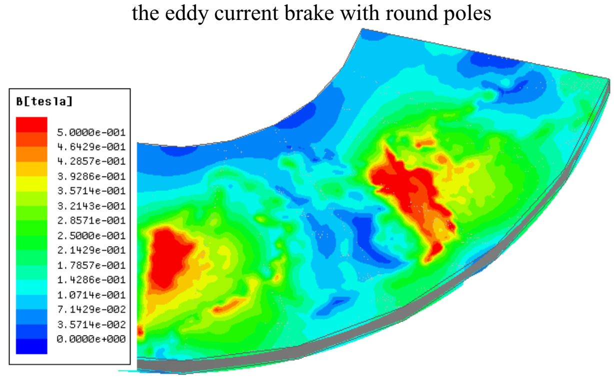

Fig. 5. Magnetic flux density distribution of the conductive disk for the eddy current brake with rectangular poles

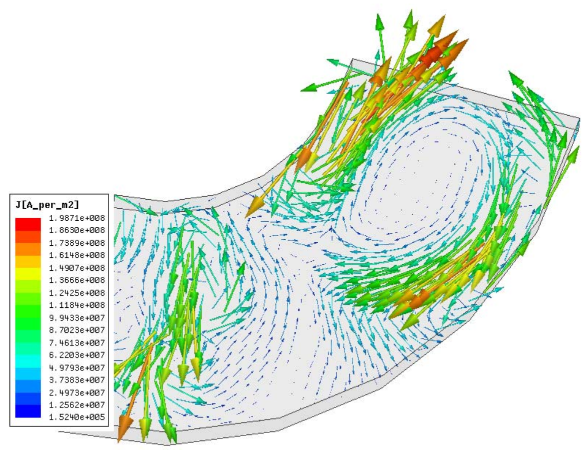

Fig. 6. Eddy current density vector display inside the conductive disk for the eddy current brake with round poles

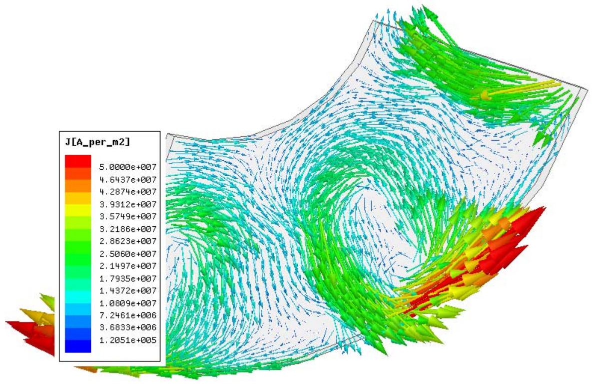

Fig. 7. Eddy current density vector display inside the conductive disk for the eddy current brake with rectangular poles

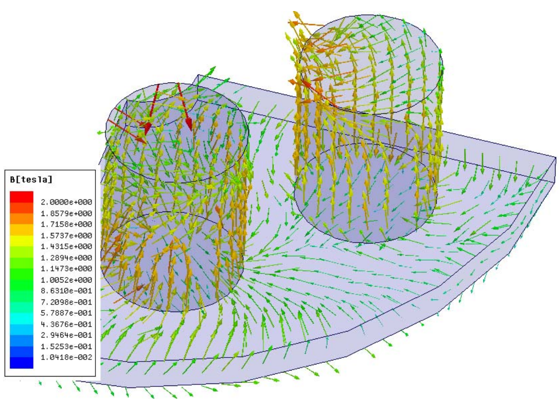

Fig. 8. Magnetic flux density vector display of the pole surfaces for the eddy current brake with round poles

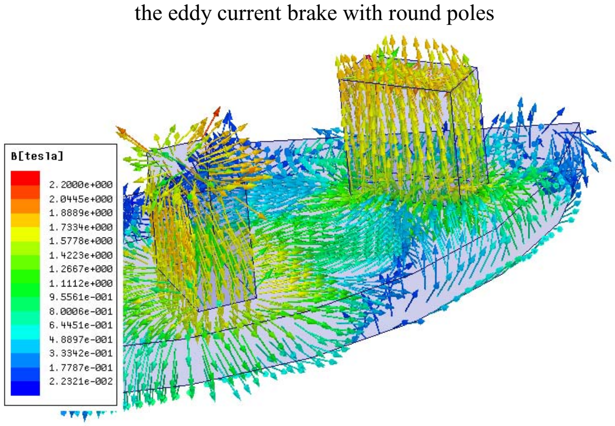

Fig. 9. Magnetic flux density vector display of the pole surfaces for the eddy current brake with rectangular poles

Braking torque versus speed characteristics for both pole shapes are obtained by processing the separated output data of 50 simulations and combined characteristics are given in Fig 10-11 for all low, medium and high speed regions.

Fig. 10 represents the comparison of braking torque change according to mechanical speed. Total power dissipation for each design related to shaft speed is given in Fig. 11. It can be seen from Fig. 10, critical speed remains substantially same as the pole shape changes.

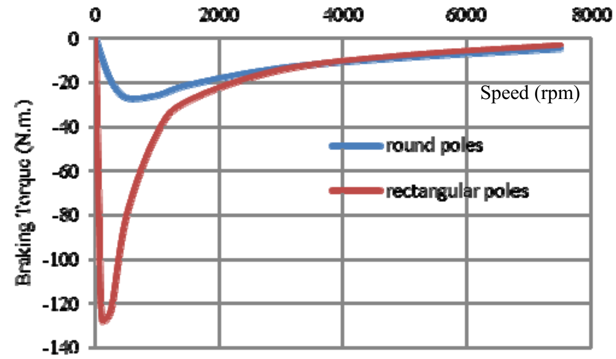

Fig. 10. Braking torque versus mechanical speed

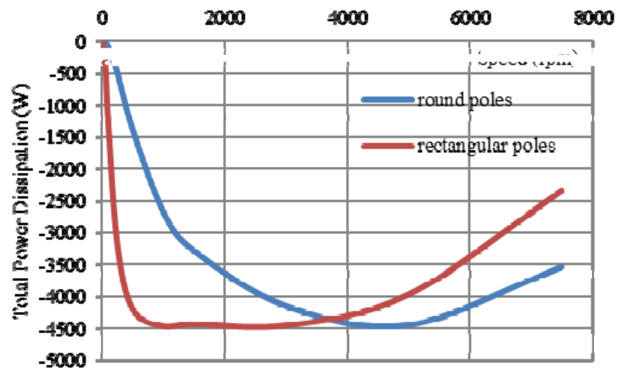

Fig. 11. Total power dissipation versus mechanical speed

6. Conclusion

In this paper, basic design parameters for two different optimised double-side excited eddy current brakes having different pole shapes are given. The effect of change of pole shape over braking torque is investigated. All other numerical design parameters are all kept constant. Each design having two different pole shapes is then analysed for 25 different speed values. 50 simulations for the specific design are completed. All output data is processed by computer to obtain integrated characteristics. Several figures including different electrical and magnetic quantities are given distribution for one of the 50 simulations. Braking torque vs speed, total power dissipation vs speed curves are given in comparison.

Obtained results showed that the rectangular pole shape increases maximum braking torque value while the critical speed remains nearly unchanged. Also total power dissipation of rectangular pole shape is greater than round pole shape at low and critical speed region.

7. Acknowledgement

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8. References

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