Performance Analysis of the Eddy Current Braker with Multi-layer Rotor Considering Constant Braking Torque

Cherl-Jin Kim*, Kwan-Yong Lee*, Kyoung-Hee Han and Soo-Hyun Beak****

Abstract - Study of an accurate and robust braking control method is required as a technical improvement to the servo system. In particular, the braker exhibiting constant braking performance under speed variation conditions of the prime mover needs to be investigated. In this paper, the braking torque of the eddy current braker between the electromagnet stator and rotating disk is analyzed. The torque-speed characteristics and accurate disk construction are represented. From the computer simulation results, it was found that eddy current braking torque is linear or approximately constant over the desired speed range depending on the rotor material, disk construction, pole number and pole displacement of the stator. These relations are confirmed by experimental results.

Keywords: Constant braking torque, eddy current braker, eddy current distribution, finite element method (FEM), multi-layer rotor

1. Introduction

Along with the recent developments in the servo-system, namely the newly created motor and actuator, braking methods need to be scrutinized next for the purpose of accurate control. Braking torque is generated by the interaction between the magnetic flux and eddy current. In the case of the eddy current braker, the eddy current is induced by moving the disk through a time invariant magnetic flux interlink. The conventional braker using iron has high permeability, but carries the disadvantage of extreme heat dissipation due to high electrical resistance.

In this paper, an eddy current braker is proposed with a triple layer structure to promote smooth flow of the eddy current. The braker rotor is composed of a mix of aluminum (Al) /iron (Fe) /aluminum (Al) or copper (Cu) /iron (Fe) /copper (Cu) for low electrical resistance and high permeability. In the eddy current braker with solid rotor, the electromagnets can also be replaced by permanent magnets, but certain devices such as a mechanical clutch must be added to move the exciting magnetic field to the rotating disk. With electromagnets, the eddy current braker makes mechanical operation simple and it is easy to control the braking torque. The eddy current braking torque represents linear or approximately constant performance over the desired speed range depending on the rotor material, disk construction, pole number and pole displacement of the stator. In this study, we present the braking torque characteristics of the eddy current braker. The validity of the proposed braking method is confirmed by simulation and experimental results.

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2. Basic Model and Theory

2.1 Basic Structure and Motion Principle

The structure of the eddy current brake proposed in this paper is shown in Fig. 1. It consists of a mixed metallic disk rotating across an air gap from two fixed electromagnetic disks. The stator material used is comprised of an Fe plate, for reluctance reducing and the rotor material is triple layered, as $Al/Fe/Al$. It will be possible to substitute Cu for Al , in which case the rotor is connected in the axis of the prime mover. When the electromagnets of the stator supply a DC source magnetic flux occurs. Here, the eddy current is induced in order to move the disk through the time invariant magnetic flux interlink. The eddy current distribution in the triple layer rotor is mainly presented on the Al plate where the electric resistance is small. Magnetic flux passes the Fe plate of the rotor, forming the magnetic path. A 2D finite element model is used as an analysis model where the solution is found iteratively.

Fig. 2 shows the modified linear model used to interpret the proposed model to the 2 dimensional linear models. A summary of the assumptions and approximations comprising this model are as follows;

In the model, curvature is neglected and the slab geometry is invariant in the direction of the constant velocity motion. Saturation in the *Fe* regions is accounted for. However, the slab conductivity is assumed to be constant and isotropic. Based on these assumptions, the fields are planer (x, y) and static. [1]

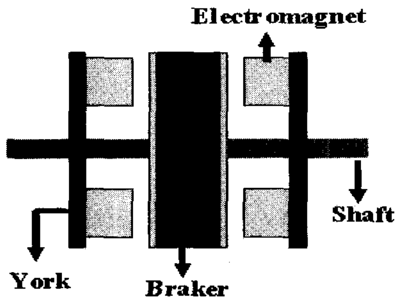


Fig. 1 Structure of eddy current braker

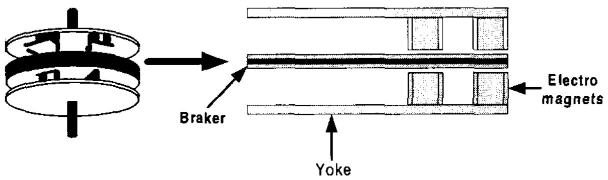


Fig. 2 Linear model of eddy current braker

The total force per pole is then the sum of the eddy current forces contributed by the *Al* and *Fe* layers ($F_{Al} + F_{Fe}$), for in the rotor of the triple layer structure, the electromagnets produce a flux line going straight through the air gap and the lower permeability rotor layer (Al), as leakage is neglected. The magnetic flux enters the *Fe* layer and flows towards the neighboring pole. The reluctance of the rotor *Fe* layer as well as that of the *Fe* behind the magnets is neglected. These assumptions are suitable for the large permeability difference between *Al* and *Fe* . Given these assumptions and the flux density $\vec{B}$ in the electromagnets, we arrive at the following equation (1), which is uniform.

$$\vec{B} = \mu_0 \frac{(NI)}{(l_g + l_{Al})} \tag{1}$$

N : Turns/pole, I : exciting current, l_g : air gap length

l_{Al} : Thickness of the Al

$$\vec{F}_{Al} = \sigma \mu_0{}^2 \frac{(NI)^2}{(l_g + l_{Al})^2} (s l_{Al}) \vec{V} \tag{2}$$

σ : Conductivity of Al

$\vec{V}$: Velocity

The eddy current density $\vec{J}$ is uniform and is primarily distributed throughout the eddy current *Al* layer. The braking torque is solved by equations (1) and (2). The force in equation (2) is the maximum, when $l_g = l_{Al}$. Maxwell's equations for solving the electromagnetic field are given by following the equation; where $\vec{J}$ is the impressed source current density due to the electromagnets.

$$\nabla \times \vec{H} = \vec{J} + \vec{J}_{ec} \tag{3}$$

$$\nabla \cdot \vec{B} = 0 \tag{4}$$

$$\vec{J}_S = \frac{N}{S} I \tag{5}$$

N : Turns/pole, I : exciting current, S : pole area

The second current density term $\vec{J}_{ec}$ is the velocity induced eddy current density; which is a function of the slab conductivity: σ , velocity: $\vec{v}$ and flux density: $\vec{B}$

$$\vec{J}_{ec} = \sigma \vec{v} \times \vec{B} \tag{6}$$

These equations are solved in terms of the magnetic vector potential:

$$\vec{B} = \nabla \times \vec{A} \tag{7}$$

Notice that this definition of flux density automatically satisfies the solenoid nature of equation (4). Substituting this expression into (3) yields the standard curl-curl equation for magnetostatic as follows:

$$\nabla \times (\frac{1}{\mu} \nabla \times \vec{A}) = \vec{J}_S + \sigma \vec{v} \times \nabla \times \vec{A} \tag{8}$$

3. Performance Analysis

The analysis of the proposed model is solved by the finite element method iteratively and analyzed in transient-on mode (constant speed) or transient-off mode (variable speed).

3.1 Rotor Material

The comparison of the rotor configuration with $Al/Fe/Al$ and simple substance *Fe* only is shown in Fig. 3. The eddy current braking torque is represented linearly or is approximately constant over the desired speed range depending on the rotor material. In the case of the rotor configuration with *Fe* only, braking torque is proportional to continuous speed. The rotor with mixed configuration (*Al / Fe / Al*) has the advantage that the servo driving system requires constant braking torque.

Table 1 Simulation condition

Mode	Speed	Exciting Current	Rotor
Transient-on	150 [rpm]	2 [A]	10/10/10 [mm]

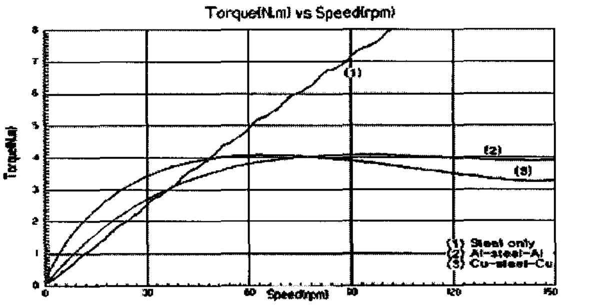
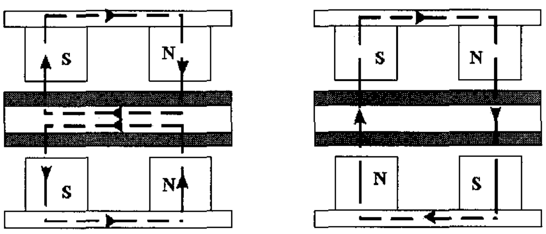


Fig. 3 Torque speed characteristics by each material respectively

From the comparison of the *Al/Fe/Al* structure with the *Cu/Fe/Cu* structure, it is found that the former case maintains a rather constant braking torque at higher speeds. The reason for this is due to the conductivity affected by resistance variation and skin effect.

(*Al*: $\sigma_{Al} = 3.40\times10^7$ and *Cu*: $\sigma_{Cu} = 5.80\times10^7$).

3.2 Magnetic Path and Pole Number



<<Horizontal magnetic path>> **<<Vertical magnetic path>>**

Fig. 4 Configuration of magnetic path

Fig. 4 depicts both horizontal and vertical magnetic paths.

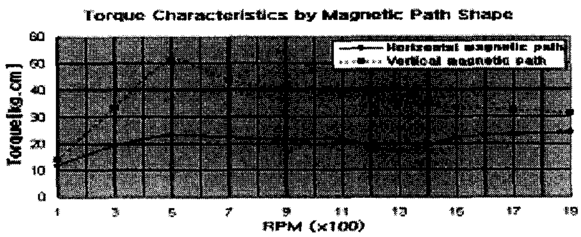


Fig. 5 Torque characteristics to magnetic path shape (Horizontal/Vertical magnetic path)

Table 2 Simulation condition

Mode	Speed	Exciting Current	Rotor
Transient-off	0~1900[rpm]	1 [A]	3/10/3[mm]

The horizontal path has two closed magnetic paths, while the vertical path is configured with one closed magnetic path. In the two closed horizontal magnetic paths, the magnetic flux is concentrated at the *Fe* region of the rotor. Therefore, the horizontal path favors constant torque more than the vertical path.

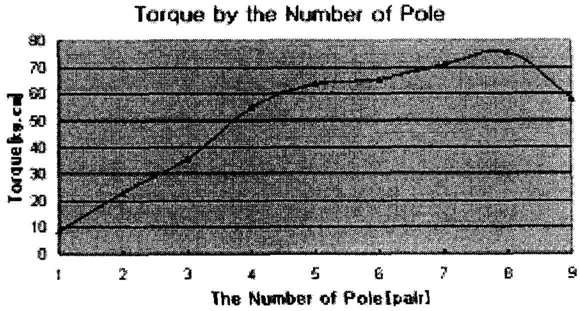


Fig. 6 Torque to pole number

Pole number is an important design parameter and it is generally proportional to output torque, as shown in Fig. 6. When there are only a few poles, the reluctance of the main magnetic flux path is large; therefore the magnetic flux density of the rotor is lower. As the pole number is changed from 4 to 8 poles, the torque is increased by more than 2 times according to the fact that the total magnetic flux is multiplied by almost 2 times. As shown in Fig. 6, it is suitable to have 4 to 14 poles in this system for representing the linear region.
In case the pole pair number is increased from 3 to 5 pole pairs, the torque is increased nearly 1.6 times. However, in case of an even pole number increase such as 2 to 4 pole pairs, the torque is increased almost 2.8 times. Therefore, we discern that an increase in odd-numbered poles represents the concentrating magnetic flux to a few poles as well as increased reluctance.

3.3 MMF and Air Gap

The useful flux is decided by exciting current of electromagnets and the length of air gap between the stator and rotor, as well as by the braking torque of the eddy current braker. Fig. 7 represents the result of MMF to air gap length, which is solved under the conditions in Table 3.

Table 3 Simulation condition

Mode	Magnetic Path	Exciting Current	Rotor
Transient-on	horizontal	1 [A]	3/3/3[mm]

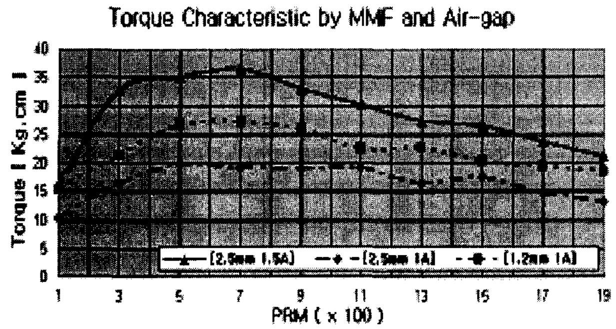


Fig. 7 Torque characteristic by MMF and air gap

As air gap increases from 1.2[mm] to 1.5[mm], the useful flux decreases and the maximum torque decreases almost 0.7 times. Also, as exciting current increases from 1[A] to 1.5[A], the maximum torque increases almost 1.9 times at a 2.5[mm] air gap. In the case of 1[A] exciting current, the constant torque region is longer than the 1.5[A] case, as in Fig. 7.

3.4 Thickness of Rotor

In the transient-on mode, various conditions of *Al*/*Fe*/*Al* structure are simulated; (3/3/3[mm], 3/10/3 [mm], 3/3/3[mm], 1/3/1[mm], 1/10/1[mm]). Simulation results are represented in Fig. 8. From the analysis results, it is discovered that the resistance of conductors (*Al*) determines the eddy current distribution that is to affect the braking force, and the torque is increased substantially in the inner thickness.

Table 4 Simulation condition

Mode	Magnetic Path	Exciting Current	Rotor
Transient-on	horizontal	1 [A]	variable

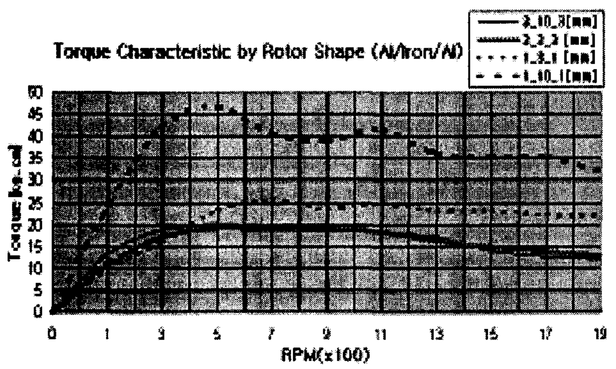


Fig. 8 Torque characteristic by rotor shape (*Al*/*Fe*/*Al*)

As shown in Fig. 8, in this case the *Al*/*Fe*/*Al* structure is selected as 3/10/3[mm], 3/3/3[mm], 1/3/1[mm] and 1/10/1 [mm]. The torque characteristics to air gap variation are represented, and the resulting maximum torque exists in the 5[kg.cm]~27[kg.cm] range. The braking torque is decided by rotor thickness, physical composition, air gap, conductor (*Al*) resistance, magnetic flux path, etc.

The torque characteristics of the 1/3/1[mm] disk maintain constant torque in a longer range than the 1/10/1 [mm] disk. This is related to the saturable flux density. (1/10/1 [mm]: 5.5[T], 1/3/1[mm]: 2.3[T])

4. Experimental Results

4.1 Experimental Devices

The eddy current braker is composed of rotor and stator parts. In the case of the rotor, the average diameter is 15[cm] and the structure is triple layered containing two material *Al* (1[mm]) and *Fe* (1[mm]). The stator with 4 poles is fixed to the two back-irons in both sides to maintain a 2.5[mm] air gap. Fig. 9 shows the features of the experimental constitution.

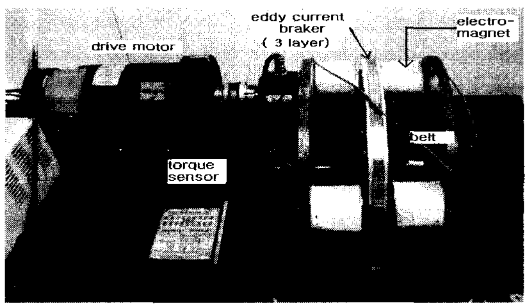


Fig. 9 Braking system for experiment

The braking system for experimental purposes is constituted of drive motor, eddy current braker (3 layer), electromagnets, back-iron, belt, torque sensor and so on.

Sensed torque values are communicated via PC for data processing through a communication port (RS232). The measured data are received 10 times for a constant period, and they are arithmetically averaged for higher accuracy.

4.2 Pole Pitch and Magnetic Path

Fig. 10 represents the speed-torque test results of the horizontal magnetic path N-N(S-S) and vertical path N-S(S-N) based on the opposite direction pole of the stator in the electromagnets. In case of the former, torque remains almost constant with 27[kg.cm] in the range of 900 to 1300 [rpm], and the latter maintains nearly 29[kg.cm] from 900 to 1500 [rpm].

Finally, the horizontal magnetic path with N-N(S-S) is used at higher speeds of about 200[rpm] with constant

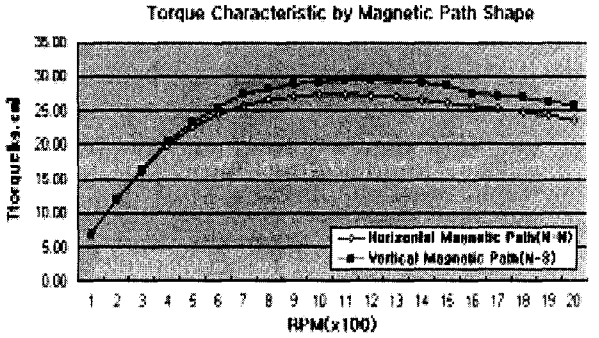


Fig. 10 Torque characteristics by magnetic path shape

torque than in the case of the vertical magnetic path with N-S(S-N). Fig. 11 shows the test results of speed-torque characteristics regarding pole placement variation to 36° and 144° between two electromagnets. By comparing two cases, the braking torque is nearly constant continuously from 900 to 1300 [rpm] in inter-pole 36° , but torque is kept constant from 900 to 1450 [rpm] in 144° inter-pole placement. We recognize that a case of 144° has the advantage of constant torque over the 36° case at a higher speed region.

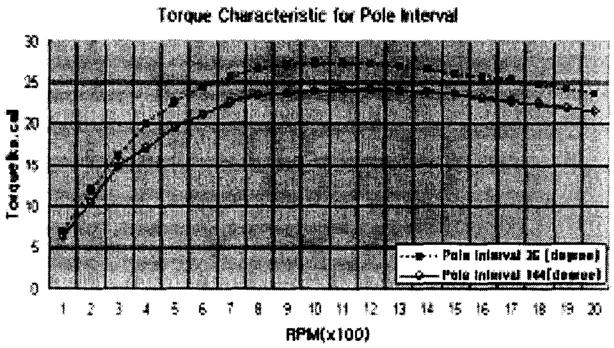


Fig. 11 Torque characteristics to pole pitch

4.3 MMF and air gap

Fig. 12 shows the torque characteristics according to MMF and air gap of the eddy current braker. The composition of the eddy current braker is 3/3/3[mm], 4-pole and horizontal magnetic path, and each pole interval is 144°. In the air gap of 2.5[mm], the maximum braking torque is confirmed, which increases by almost 11.49 [kg.cm] according to the exciting current increasing from 1[A] to 1.3[A]. The exciting current of 1[A] continues over a greater time with constant torque than that exciting current with 1.5[A]. As air gap increases from 1.2[mm] to 2.5[mm], the useful flux is decreased and the maximum torque is decreased also, but a 2.5[mm] air gap is optimal for constant torque.

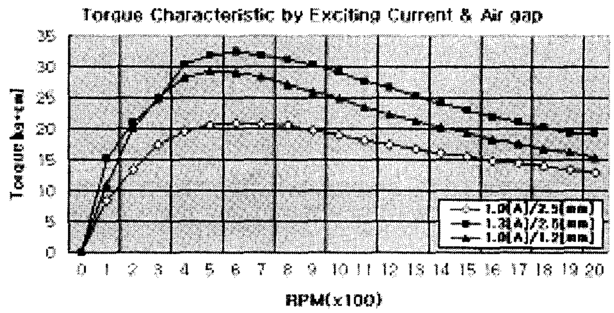


Fig. 12 Torque characteristics by exciting current and air gap

4.4 Thickness of rotor

Fig. 13 shows the torque characteristics according to rotor thickness. The structure of the eddy current braker is composed of the following parameters. (4-pole, air gap: 2.3[mm], inter-pole angle: 144°, horizontal magnetic path, exciting current: 1.0[A]. We have experimented using various kinds of layer thickness of the braker such as 3/10/3[mm], 3/3/3[mm] and 1/3/1[mm], 1/10/1 [mm]. In doing so we have found that $Al/Fe/Al$ thickness 1/3/1[mm] manifests the best constant torque characteristics and the case of 3/3/3[mm] and 3/10/3[mm] show relative constant torque performance at lower speeds from the experimental results.

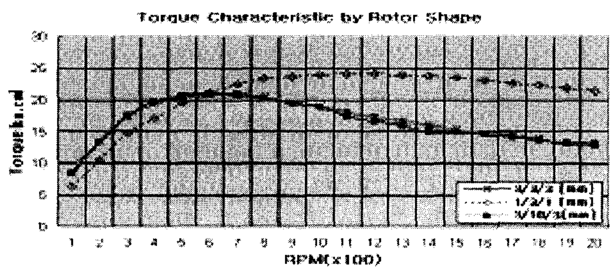


Fig. 13 Torque characteristics by rotor shape

Under comparison with simulation results, experimental results are almost identical. However, minor errors occurred as a result of the 2 dimension linear model assumption.

5. Conclusion

In this paper, the triple layer structure rotor of the eddy current braker is proposed to achieve constant torque. Generated braking torque is dependant on the material. The triple layer rotor of the $Al/Fe/Al$ structure is more favorable to obtain constant braking torque than the simple structure of Fe only. In this case, the braking torque is represented approximately constant over the desired speed range. From the viewpoint of rotor thickness, proper determination is needed to consider things such as magnetic material (Fe) and conductor (Al) parameters, magnetic path, air gap, etc. The best performance for constant braking torque are the following conditions resulting from this study; (disk thickness: 1/3/1[mm], magnetic path: horizontal, stator inter-pole displacement: 144°).

Generally, experimental results are in good agreement with theoretical analysis except for some minor errors that are included in the 2 dimensional linear model approximations.

In this study, it was found that the triple layer eddy current has an advantage in regards to maintaining constant torque and relatively fine braking performance without a feedback circuit. Therefore, the eddy current braker of mixed structure is expected to be used in many industrial applications in the near future.

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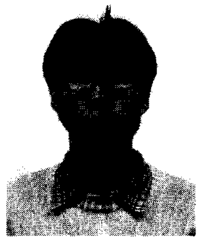

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