Calculation of the Eddy Current Loss and Braking Characteristic Analysis of the Eddy Current Brake

Sooyoung Cho[1], Ju Lee[1], Dong-Woo Kang[2], and Hyungwoo Lee[3]

[1]Hanyang University, Seoul, Korea (the Republic of), jsy0593@naver.com
[1]Hanyang University, Seoul, Korea (the Republic of), julee@hanyang.ac.kr
[2]Keimyung University, Daegu, Korea (the Republic of), dwkang@kmu.ac.kr
[3]Korea National University of Transportation, Uiwang, Korea (the Republic of), krhwlee@ut.ac.kr

The eddy current brakes are operated at various speeds when the vehicle is braking. In order to increase the eddy current loss, drum is composed of iron with conductivity. As a result, the eddy current brake exhibits a skin effect and an armature reaction phenomenon, and the skin depth and the air-gap flux density vary depending on the braking speed. In this paper, the eddy current loss equation of the eddy current brake with a copper coating inside the drum is newly presented and compared with the finite element analysis(FEA) results. Also, the change of the speed-torque curve according to the conductivity value of drum and inner coating material are shown. Finally, a prototype experiment was conducted to compare and verify the characteristic curve of the eddy current brake obtained from the newly derived equations.

***Index Terms*— Eddy currents, eddy currents brake, eddy current loss, braking torque, conductivity, magnetic materials.**

I. Introduction

THESE DAY, many countries are using eddy current brakes as auxiliary braking devices for commercial vehicles and railway vehicles. [1]-[4] This is a non-contact type brake, which is easy to maintain due to no wear, and has the advantage that the response speed is fast. The eddy current brake has a winding type [1],[2] and a permanent magnet type [3],[4] depending on the structure of the magnetic field source. This paper is designed as the winding type eddy current brake which can easily control the magnetic field of the windings and have no demagnetization problem due to high temperature and armature reaction.

The eddy current brakes are made of the non-laminated iron to generate large eddy currents in the drum. As a result, skin effect and armature reaction are shown. However, there are few papers that analyze the skin effect and armature reaction phenomenon of the eddy current brake. In addition, the paper that obtains the output power by calculation considering the skin effect and armature reaction is composed of one layer of the drum part. [5] In this paper, a new braking torque equation is obtained in a structure with a copper coating inside the drum to improve the braking force. Through this equation, the change of the speed-torque curve according to the conductivity variation of the drum was predicted and compared with the FEA result. In addition, the output characteristics according to the coating material and thickness were analyzed. Finally, the prototype's experimental results were compared with the induced equation results.

II. The Eddy Current Brake Model

Fig. 1 shows the eddy current brake model presented in this paper. Drum is composed of the non-laminated iron to provide eddy current generation and flux path.

Since the eddy current brakes operate at various speeds when the vehicle is braking, a skin effect occurs. In the cylindrical rotor structure, the skin depth is as follows.

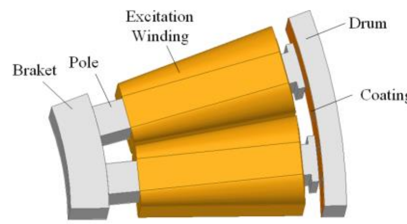


Fig. 1. The eddy current brake model.

$$\delta = \sqrt{\frac{2}{\sigma\omega\mu}} \tag{1}$$

where σ is conductivity, ω is angular speed, μ is permeability.

Also, the current density of the eddy current brake is as follows.

$$\vec{J} = \sigma\vec{E}e^{((r-R_{drum})/\delta)} = \sigma\left(\vec{v}\times\vec{B}\right)e^{((r-R_{drum})/\delta)} \tag{2}$$

where r is the distance from the center of the rotor to an arbitrary position and R_{drum} is the radius of the drum. The air-gap magnetic flux density is expressed as follows. [5]

$$B = B_0 e^{-R_m} = B_0 e^{-\sigma\mu_0\omega R_{drum}} \tag{3}$$

where B_0 is the air-gap flux density at zero speed and R_m is the magnetic Reynolds number.

Therefore, as the speed of the eddy current brake increases, the skin depth, current density, and air-gap flux density decrease.

III. Calculation of The Eddy Current Loss and Torque

The eddy current loss of the eddy current brakes is all used as braking forces. Therefore, the braking performance can be predicted by calculating the eddy current loss occurring in the drum and coating.

The eddy current loss is as follows.

$$P_e = \int_V \frac{J^2}{\sigma} dV \tag{4}$$

The total eddy current loss is the sum of the eddy current losses generated in the drum and coating. When the distance of

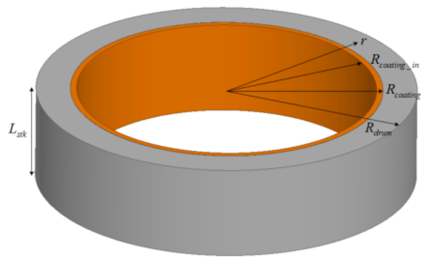


Fig. 2. The rotor structure of the eddy current brake.

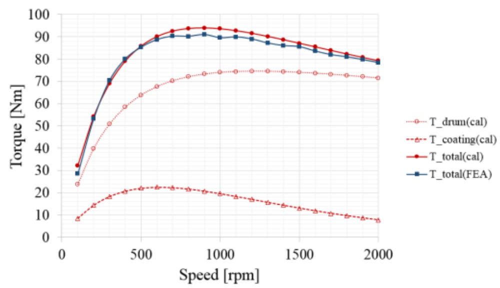


Fig. 3. The speed-torque curve of the eddy current brake by induced equation and FEA.

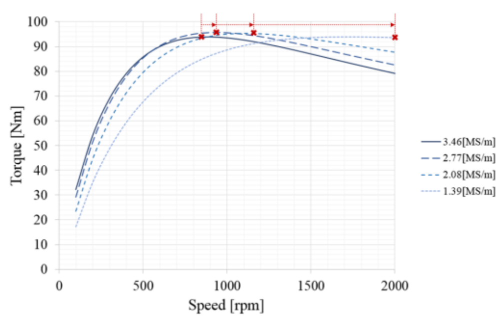
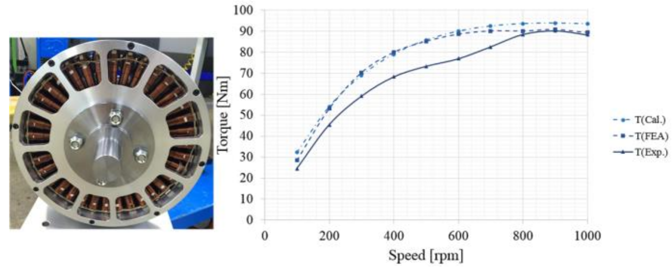


Fig. 4. The speed-torque curve of the eddy current brake according to conductivity change of drum.

the drum and the coating are specified as shown in Fig. 2 and the conductivity of the drum and the coating material is designated as σ_1 and σ_2, the eddy current loss equation is derived as follows.

$$
\begin{aligned}
P_e &= P_{e\_drum} + P_{e\_coating} \\
&= \pi L_{stk} \sigma_1 \omega^2 B_0^2 e^{-2R_{m1}} \delta_1 \left[R_{drum}^3 - e^{\frac{2\left(R_{coating} - R_{drum}\right)}{\delta_1}} R_{coating}^3 \right. \\
&\quad - \frac{3\delta_1}{2} \left(R_{drum}^2 - e^{\frac{2\left(R_{coating} - R_{drum}\right)}{\delta_1}} R_{coating}^2 \right) \\
&\quad + \frac{\delta_1^2}{2} \left(R_{drum} - 3e^{\frac{2\left(R_{coating} - R_{drum}\right)}{\delta_1}} R_{coating} \right) \\
&\quad \left. - \frac{3\delta_1^3}{4} \left(1 - e^{\frac{2\left(R_{coating} - R_{drum}\right)}{\delta_1}} \right) \right] \\
&\quad + \frac{\pi}{2} L_{stk} \sigma_2 \omega^2 B_0^2 e^{-2R_{m2}} \left(R_{coating}^4 - R_{coating\_in}^4 \right)
\end{aligned}
\tag{5}
$$

The output torque equation can be obtained by dividing equation (5) by angular speed as follows.



(a) (b)

Fig. 5. (a) Prototype of the eddy current brake, (b) Experimental result of the eddy current brake.

$$T = \frac{P_e}{\omega} \tag{6}$$

Fig. 3 compares the speed-torque curve obtained through the derived equation with the speed-torque curve obtained through FEA. This figure shows that there is some error between the equation and FEA results, but it is almost the same.

In addition, the speed-torque curve according to the conductivity value of the drum is shown in Fig. 4. That is, as the conductivity of the drum decreases, the speed at which the maximum torque is generated increases.

IV. Experiment

The prototype was fabricated and tested to verify the torque equations obtained from the calculations and FEA results.

Fig. 5 shows that there is some error between the actual experimental results and the calculated equation results. This is due to the fact that the initial temperature of the drum is slightly different at each speed in the experiment.

V. Conclusion

In this paper, a new torque equation has been obtained in consideration of the skin depth and current density in the drum shape with 2-layer structures. In order to verify the torque equation, it is compared with the actual FEA results, and confirmed the change of the speed - torque curve when the material of the drum changed. Also, the torque equation was verified through a prototype experiment. In the future, full paper will be additionally discussed about the phenomenon of changing the material and thickness of the coating.

References

[1] R. Yazdanpanah and M. Mirsalim, "Axial-flux wound-excitation eddycurrent brakes: Analytical study and parametric modeling," *IEEE Trans.Magn.*, vol. 50, no. 6, pp. 1–10, Jun. 2014.

[2] A. Zamani, "Design of a controller for rail eddy current brake system," *IET Electrical Systems in Transportation*, vol. 4, pp. 38-44, 2013.

[3] S. E. Gay and M. Ehsani, "Parametric analysis of eddy-current brake performance by 3-D finite-element analysis," *IEEE Trans. Magn.*, vol.42, no. 2, pp. 319–328, Feb. 2006.

[4] H. J. Shin, Y. Y. Choi, H. W. Cho, and S. M. Jang, "Analytical torque calculations and experimental testing of permanent magnet axial eddy current brake," *IEEE Trans. Magn.*, vol. 49, no. 7, pp. 4152–4155, Jul. 2013

[5] S. Sharif, J. Faiz, and K. Sharif, "Performance analysis of a cylindrical eddy current brake," *IET Electr. Power Appl.*, vol. 6, no. 9, pp.661–668, Nov. 2012.