Received: 19 October 2023 | *Revised: 17 November 2023* | *Accepted: 25 November 2023*
DOI: 10.37917/ijeee.20.2.18 *Vol. 20 | Issue 2 | December 2024*

Open Access

Iraqi Journal for Electrical and Electronic Engineering
Original Article

Analysis of Permanent Magnet Material Influence on Eddy Current Braking Efficiency

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Abstract
Traditional friction brakes can generate problems such as high braking temperature and pressure, cracking, and wear, leading to braking failure and user damage. Eddy current brake systems (contactless magnetic brakes) are one method used in motion applications. They are wear-free, less temperature-sensitive, quick, easy, and less susceptible to wheel lock, resulting in less brake failure due to the absence of physical contact between the magnet and disc. Important factors that can affect the performance of the braking system are the type of materials manufactured for the permanent magnets. This paper examines the performance of the permanent magnetic eddy current braking (PMECB) system. Different kinds of permanent magnets are proposed in this system to create eddy currents, which provide braking for the braking system is simulated using FEA software to demonstrate the efficiency of braking in terms of force production, energy dissipation, and overall performance findings demonstrated that permanent magnets consisting of neodymium, iron, and boron consistently provided the maximum braking effectiveness. The lowest efficiency is found in ferrite, which has the second-lowest efficiency behind samarium cobalt. This is because ferrite has a weaker magnetic field. Because of this, the PMECBS based on NdFeB magnets has higher power dissipation values, particularly at higher speeds.

Keywords
Eddy current Barking, Magnetic flux density, Braking efficiency, Permanent Magnetic.

I. Introduction

The safety of motorized vehicles heavily relies on brakes, which are responsible for reducing or stopping the vehicle's speed when needed. However, traditional friction brakes can cause issues such as excessive temperature and pressure, cracking, and wearing out, resulting in brake failure and harm to the user. Alternative braking technologies are in high demand to improve braking performance. One such technology is Electromechanical brakes (EMB), which offers quick-response braking, efficient fuel consumption, environmental sustainability, simple maintenance, and enhanced safety design [1–3]. Additionally, Eddy's current braking systems use electromagnetic induction for precise and effective braking, potentially improving energy efficiency, reducing wear on brake components, and enhancing safety in various applications [4]. In Fig. 1, the concept consists of a powerful magnet and a rotating metal plate. As the magnetic flux changes due to the rotation, eddy currents are generated on the wheel [5]. These currents move toward the wheel's rotation and create a force that opposes the rotation, causing a decrease in the wheel's speed. ECs are generated by Lenz's law, and electromagnetic induction is used to identify the direction of induced current [6]. The resulting current dissipates the kinetic energy of the wheel, converting it into heat and eventually bringing it to a halt. With permanent magnet eddy current braking (PMECB) systems, permanent magnets generate eddy currents in a conductive braking material, eliminating the need for a power source [7]. PMECB systems are more reliable and require less maintenance than conventional friction-based braking systems [8]. In [9], the electromagnetic theory be-

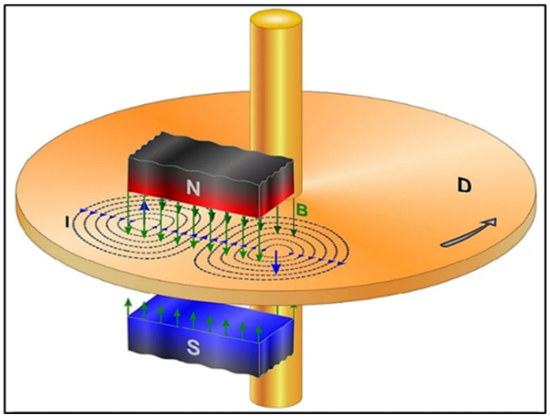

Fig. 1. Illustrates the operational principle of the PMECB

hind PMECB is explored, including the equations determining braking force and design details. The impact of various permanent magnet configurations, magnet strengths, and brake plate designs on braking performance and efficiency was investigated in a study [10]. [11] to study and forecast the behavior of PMECB systems. The many benefits of PMECB systems make them desirable for various applications, as stated by researchers' study [12]. Researchers explored new ways to optimize deceleration profiles through hybrid braking systems that combine PMECB with other technologies [13].
This paper examines a model of an eddy current braking system using FEM. This modeling study aims to demonstrate the effectiveness of PMECB in producing braking force, dissipating energy, and enhancing overall braking performance. The findings from this study will be used to support further research in this area.

II. Formulas for the PMECB System in Mathematics

The PMECB system's mathematical formulations are derived from electromagnetic principles and Maxwell's equations [14], providing information on braking forces and energy dissipation. According to Faraday's law, a changing magnetic field passing through a conductor creates an electromotive force (EMF) in a closed loop

$$\mathrm{EMF} = -\frac{\mathrm{d}\Phi}{\mathrm{dt}} \tag{1}$$

where EMF is the induced voltage, (dΦ) is the magnetic flux linked with the material, and (dt) is the period. The braking force (F) produced by the interplay of induced eddy currents and the magnetic field can be estimated as follows [15]

$$\mathrm{B} = \mu \mathrm{H} \tag{2}$$

$$\mathrm{J} = \alpha \cdot \mathrm{EME} \tag{3}$$

$$\mathrm{F} = \mathrm{J} \times \mathrm{B} \tag{4}$$

The symbol (J) represents eddy current density, while (σ) is used to denote the electrical conductivity of the material. By using the material's permeability (μ) and magnetic field inte nsity (H) to calculate the magnetic flux density (B).

The power dissipated in the eddy current braking system is a crucial parameter [16].

$$P_{in} = (I_{eddy})^2 R \tag{5}$$

The power output of the braking system represents the energy absorbed to slow down a moving object.

$$P_{\text{out}} = T \cdot \omega \tag{6}$$

The symbol (T) represents braking torque, while (ω) refers to rotational speed. The efficiency of the eddy current braking system is the ratio of output power to input power, which can be calculated using a specific equation [17]:

$$\eta = \frac{\text{Pout}}{\text{pin}} \tag{7}$$

III. Design Considerations and Simulation

Choosing the right permanent magnet type is crucial for creating an efficient PMECB system. The magnets used directly affect the strength of the magnetic field, which in turn impacts the braking force produced by the system. Proper selection of magnet materials is essential when designing efficient PMECB systems. Neodymium Iron Boron, Samarium Cobalt, and Ferrite (Ceramic) are commonly used magnet materials for PMECB applications [18]. The arrangement of permanent magnets in the PMECB system is crucial in determining the distribution of magnetic fields and the effectiveness of the braking force. The magnet must be positioned correctly to distribute force evenly and optimize energy conversion. Simulation software like FEA tools allows designers to develop virtual models of efficient and reliable PMECB systems using critical simulation and optimization methods [19]. These models demonstrate the interaction between magnets, conductors, and magnetic fields, displaying information on force distribution and eddy current effects. Table I displays the design aspects of PMECB. Numerical simulations can predict braking system behavior and analyze the effects of conductive materials. Simulation and analysis of the braking system are

TABLE I.
GEOMETRY DESIGN OF THE PMECB

Parameter	Value	Unit
Conductivity of Copper disk	58.0×10^6	S/m
Copper density	2.7×10^3	kg/m3
Disc brake thickness	8	mm
Disc brake diameter	200	mm
Length of air gap	0.8	mm
Relative permeability of copper	0.99904	
Resistivity of Brake Disc [p]	100E – 9	ghm.m
Mass disc	2.21	kg
Speed range	0 – 1500	rpm

critical phases, as shown by the Solid Works EMS flowchart in Fig. 2. Fig. 3 shows PMECB components. Fig. 4 illustrates the use of SolidWorks in simulating the model for this research. The simulation software incorporates conductive materials and measures key parameters such as electrical conductivity, permeability, and intensity. As illustrated in Fig. 4, the FE analysis discretizes the permanent magnetic material into tiny elements, allowing numerical assessment of the integral based on the force intensity and magnetic field distribution at each element. For real-world applications, this technique gives a more precise and practical answer. To begin PMECB production, the electromagnetism specialist was employed for 3D analysis and optimization. Table II shows the electrical conductivity of recommended materials [20].

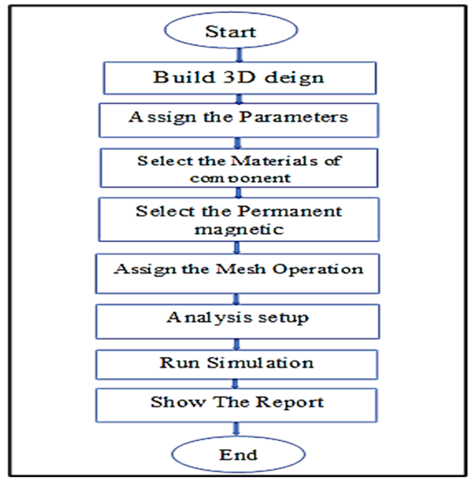

Fig. 2. Flowchart of the PMECB design

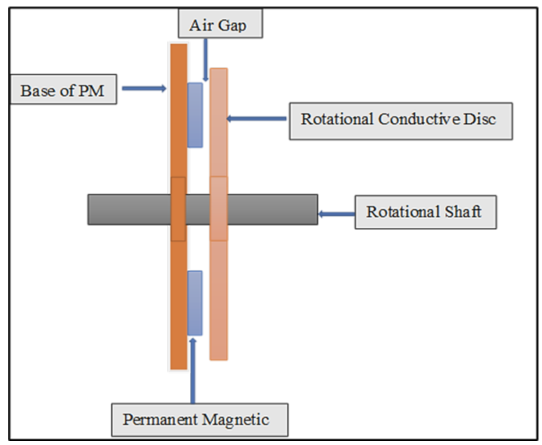

Fig. 3. Schematic diagram of the PMECB components

IV. RESULTS AND DISCUSSION

The study provided valuable insights into how ferromagnetic permanent magnetic materials impact the performance of ON (ECB) systems. Numerical simulations were conducted using several ferromagnetic PM materials as braking components to evaluate key performance parameters such as braking force, efficiency, and thermal behavior. The graph in Fig. 5 illustrates the braking force values for each material as a function of rotational speed. This sentence compares different magnetic materials to understand how their properties affect braking performance. The strength of eddy currents is directly proportional to the rate of change of magnetic flux and the Conductivity of the conductor. This leads to a more significant interaction between the eddy currents and the permanent magnetic field, which results in stronger braking forces. As the speed of the conductor increases, the force applied to the brakes also increases. Higher conductance materials generate stronger eddy current interactions, leading to greater braking forces. Conversely, lower conductivity materials produce weaker eddy currents and exhibit lower braking forces. Neodymium iron boron magnets are distinguished from other permanent magnets by their superior electrical conductivity. Neodymium Iron Boron magnets can produce stronger braking forces than other materials due to their higher magnetic flux density [21]. Samarium Cobalt magnets offer high magnetic fields and thermal stability, while Ferrite magnets can be a cost-effective alternative with lower braking forces for certain applications.

TABLE II.
THE MATERIALS' ELECTRICAL CONDUCTIVITY

Material	Conductivity (S / m)
Neodymium Iron Boron	6.3×10^6
Samarium Cobalt	1.2×10^6
Ferrite(Ceramic) Magnet	1.0×10^3

Fig. 6 shows. The braking power generated in an eddy current braking system involving different PM materials at various rotational speeds is influenced by the interaction between the magnetic field induced by the permanent magnets and the conductive materials in the brake disc. The actual values for brake disc power depend on the magnets' characteristics, the braking system design, and operational conditions. Neodymium Iron Boron (NdFeB) is the strongest magnetic material, producing high power at any speed. Due to its high magnetic characteristics, it induces greater eddy currents in the conductive brake disc. Samarium Cobalt generates less power than Neodymium Iron Boron but more than Ferrite (Ceramic) due to its slightly lower magnetic strength. Ceramic magnets have a weaker magnetic strength when compared to Neodymium Iron Boron and Samarium Cobalt because the magnetic field of this magnet interacts weakly with conductive brake discs, which generates less power. The study shows a direct relationship between the magnetic properties of PM materials and their power output in eddy current brake systems.

Fig. 7 illustrates how the efficiency of braking varies at different rotational speeds for the three magnet materials. The braking efficiency decreases as power losses increase due to the dissipation of input power within the braking system. As power losses increase, less input power generates braking force. Neodymium magnets display lower power loss at low speeds due to their high coercivity and remanence. However, the increase in rotational speed may cause moderate power dissipation due to eddy current losses.

Higher electrical resistivity materials like samarium cobalt may result in higher eddy current losses in the conductor. Energy may be wasted as heat instead of being converted adequately to braking force, resulting in reduced efficiency. High temperatures can cause demagnetization or reduce braking efficiency in magnets with temperature sensitivity.

Fig. 8 illustrates how permanent magnets and magnetic flux density affect the eddy currents induced in the brake connector by a variable magnetic field. The strength of the braking force is directly related to the magnetic flux density. Higher eddy currents result in stronger magnetic flux densities and, therefore stronger braking forces.

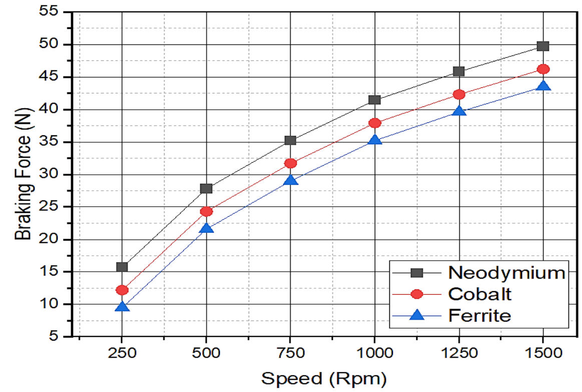

Fig. 5. Braking power disc with rotational speed for several types of PM materials

Fig. 9 examines the term "mesh," which describes the interplay between the magnetic field and conductor components in a PMECB setup. The mesh arrangement plays a crucial role in the braking force, efficiency, and overall performance of a system. An adequately designed mesh ensures that force is distributed evenly and energy is converted effectively, making it a vital component in the optimization and design of the PMECB system. There are 177393 elements and 36105 nodes in the arrangement.

V. Conclusions

The exciting advancement in braking technology known as the PMECB system combines the principles of eddy currents

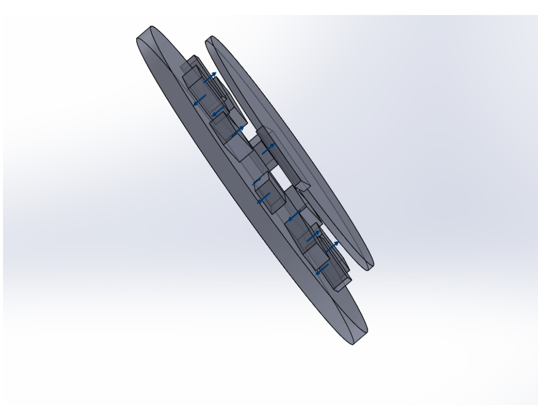

Fig. 4. 3D CAD diagram of the PMECB components

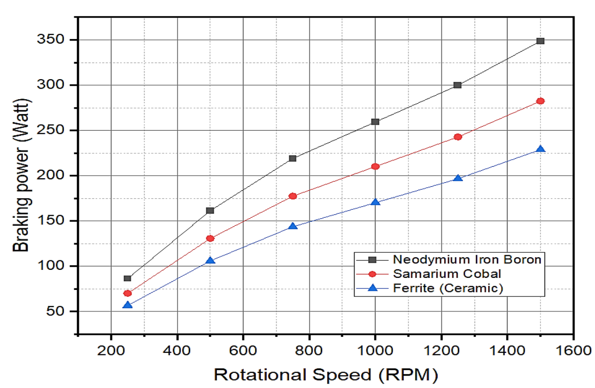

Fig. 6. Braking power disc with rotational speed for several types of PM materials

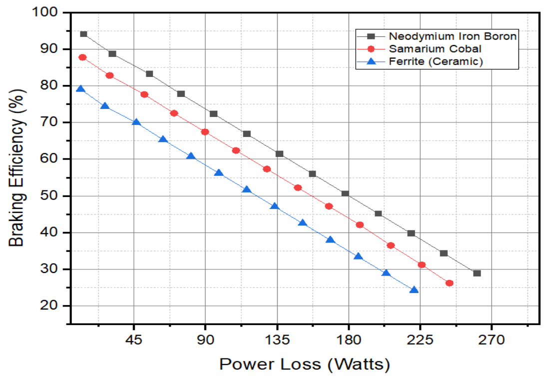

Fig. 7. The braking efficiency with rotational speed for several types of PM materials

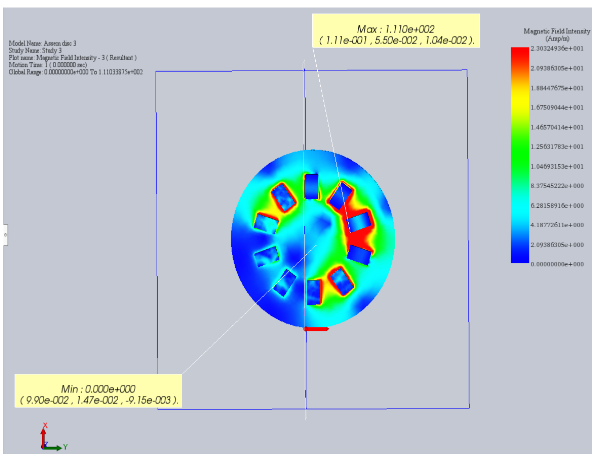

Fig. 8. The distribution of magnetic flux in the rotating disc

with permanent magnets to offer a unique, innovative, and dependable solution for a variety of industrial applications. The current study reached some conclusions, which are as follows:

With their high electrical conductivity, Neodymium Iron Boron magnets exhibit higher eddy current interactions and greater braking forces, setting them apart from other permanent magnet kinds.

Neodymium Iron Boron magnets create stronger braking forces, Samarium Cobalt balances high fields and thermal stability, and Ferrite magnets offer lower braking forces but are cost-effective.

From investigation, the braking efficiency decreases with increasing rotational speed, particularly in higher electrical resistivity materials like Samarium Cobalt. This leads to severe eddy current losses, resulting in heat loss and decreased efficiency.

From another side, higher magnetic materials like Neodymium Iron Boron and Samarium Cobalt generate stronger magnetic fields, causing larger eddy currents and increased power dissipation, compared to weaker materials like Ferrite magnets.

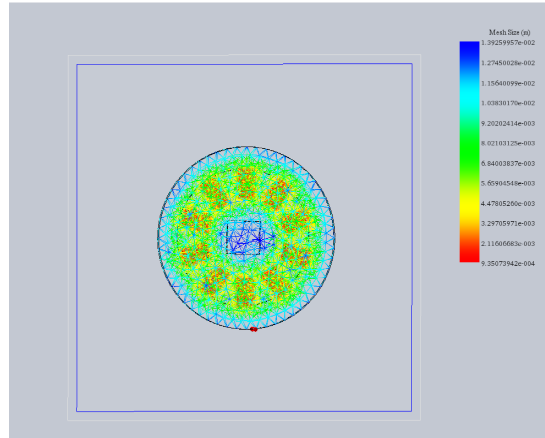

Fig. 9. Mesh process of the PMECB system

Acknowledgments

I would like to express my deep gratitude to Dr. Jamal A.-K. Mohammed and Dr. Farag M. Mohammed, the research supervisors, for their guidance, enthusiastic encouragement, and constructive criticism of this research work.

Conflict of Interest

The authors have no conflict of relevant interest to this article.

References

[1] A. Q. Abdulkareem, A. T. Humod, and O. A. Ahmed, "Fault detection and fault tolerant control for anti-lock braking systems) abs) speed sensors by using neural networks," *Engineering and Technology Journal*, vol. 41, no. 2, pp. 333–344, 2023.

[2] H. N. Faisal, F. M. Mohammed, and J. A. Mohammed, "Design and implementation of an electromechanical brake system," *Engineering and Technology Journal*, vol. 40, no. 1, pp. 31–39, 2022.

[3] F. M. Mohammed, J. A.-K. Mohammed, and H. Faisl, "Modeling and simulation of an electromechanical brake system," in *IOP Conference Series: Materials Science and Engineering*, vol. 1105, p. 012051, IOP Publishing, 2021.

[4] J. Liu, W. Li, L. Jin, G. Lin, Y. Sun, and Z. Zhang, "Analysis of linear eddy current brakes for maglev train using

an equivalent circuit method," *IET Electrical Systems in Transportation*, vol. 11, no. 3, pp. 218–226, 2021.

[5] M. I. González, "Experiments with eddy currents: the eddy current brake," *European journal of physics*, vol. 25, no. 4, p. 463, 2004.

[6] S. Cho, H.-C. Liu, J. Lee, C.-M. Lee, S.-C. Go, S.-H. Ham, J.-H. Woo, and H.-W. Lee, "Design and analysis of the eddy current brake with the winding change," *Journal of Magnetics*, vol. 22, no. 1, pp. 23–28, 2017.

[7] S. Zhou, H. Yu, M. Hu, and L. Huang, "Design of permanent magnet eddy current brake for a small scaled electromagnetic launch model," *Journal of Applied Physics*, vol. 111, no. 7, 2012.

[8] D. Zheng, X. Guo, Y. Li, W. Cong, and S. Jiang, "Torque analysis of axial-flux permanent magnet couplers with skewed slots using electromagnetic-thermal semi-analytical model," in *2020 Chinese Control And Decision Conference (CCDC)*, pp. 4077–4081, IEEE, 2020.

[9] E. Galardi, E. Meli, D. Nocciolini, L. Pugi, and A. Rindi, "Development of efficient models of magnetic braking systems of railway vehicles," *International Journal of Rail Transportation*, vol. 3, no. 2, pp. 97–118, 2015.

[10] K. Karakoc, A. Suleman, and E. J. Park, "Analytical modeling of eddy current brakes with the application of time varying magnetic fields," *Applied Mathematical Modelling*, vol. 40, no. 2, pp. 1168–1179, 2016.

[11] J. A. Doe and B. C. Smith, "Electromagnetic theory of permanent magnetic eddy current braking," *Journal of Applied Physics*, 2014.

[12] R. Sattarov and D. Garafutdinov, "Simulation of a self-regulating eddy-current brakes with permanent magnets," in *2021 International Ural Conference on Electrical Power Engineering (UralCon)*, pp. 587–591, IEEE, 2021.

[13] K. J. Lee and S. H. Park, "Enhancing reliability and safety of industrial machinery through permanent magnetic eddy current braking," *Mechanical Systems and Signal Processing*, 2016.

[14] O. Taqavi and N. Taghavi, "Development of a mixed solution of maxwell's equations and magnetic equivalent circuit for double-sided axial-flux permanent magnet machines," *IEEE Transactions on Magnetics*, vol. 57, no. 4, pp. 1–11, 2021.

[15] T. Tong and D. Wang, "Analytical modeling and optimal design of disk permanent magnet eddy current coupler," in *2023 2nd Conference on Fully Actuated System Theory and Applications (CFASTA)*, pp. 900–905, IEEE, 2023.

[16] C. Chen, J. Xu, and X. Wu, "Analytical calculation of braking force of super-high speed maglev eddy current braking system," in *2019 22nd International Conference on Electrical Machines and Systems (ICEMS)*, pp. 1–5, IEEE, 2019.

[17] K. Karakoc, A. Suleman, and E. J. Park, "Analytical modeling of eddy current brakes with the application of time varying magnetic fields," *Applied Mathematical Modelling*, vol. 40, no. 2, pp. 1168–1179, 2016.

[18] K. Filipecka, P. Pawlik, A. Kozdraś, J. Filipecki, K. Pawlik, and J. Wysłocki, "Magnetic properties and phase constitution of the nanocrystalline fe 65 pr 9 b 18 w 8 alloy ribbons.," *Acta Physica Polonica A*, vol. 131, no. 5, pp. 1207–1211, 2017.

[19] M. Hano, T. Miyamura, and M. Hotta, "Finite element eddy current analysis by novel mixed-order vector elements," *International Journal of Applied Electromagnetics and Mechanics*, vol. 14, no. 1-4, pp. 19–22, 2002.

[20] M. Gulec and M. Aydin, "Modelling and analysis of a new axial flux permanent magnet biased eddy current brake," in *2016 XXII International Conference on Electrical Machines (ICEM)*, pp. 459–465, IEEE, 2016.

[21] R. W. Johnson and S. P. Brown, "Application of permanent magnetic eddy current braking in public transportation," *Transportation Research Part C: Emerging Technologies*, 2015.