Engineering and Technology Journal
Journal homepage: https://etj.uotechnology.edu.iq

Effect of the material properties of the rotor-disc on the performance of eddy current braking systems

Ahmed M. Salman*, **Jamal A.-K. Mohammed**, **Farag M. Mohammed**

Electromechanical Engineering Dept., University of Technology-Iraq, Alsina'a street, 10066 Baghdad, Iraq.
*Corresponding author Email: eme.20.10@grad.uotechnology.edu.iq

HIGHLIGHTS

- Non-ferromagnetic rotor disc conductors were investigated for electromagnetic braking efficiency
- Copper braking force was 12.6% higher than aluminum and 34.6% higher than steel
- Highest braking torque was 1.30914 Nm for copper, versus 1.12914 Nm aluminum and 0.84914 Nm steel
- Highly conductive copper significantly improved braking efficiency
- Copper stopping time was 3.7% and 10% lower than aluminum and steel with higher braking torque

ARTICLE INFO

Handling editor: Sattar Aljabair

Keywords:
Electromagnetic brake; Braking force; Frictionless brake; Characteristics materials Magnetic flux density; Eddy Current Braking (ECB)

ABSTRACT

Failure of traditional brakes occurs due to raised temperatures and the formation of structural fractures caused by wear and strain. For resolving mechanical brake problems, consider employing contactless braking technology, also known as eddy current braking, which offers a smoother deceleration. This research aims to assess the suitability of multi-materials for designing brake discs (ECBs) for use in automobiles. The choice of material for the rotor disc is crucial in the design of eddy current brakes. Different material factors impact the performance of these brakes. Therefore, there is a need for a material that possesses superior mechanical properties, high electrical conductivity, and efficient power dissipation capabilities. An extensive analysis was conducted to identify the optimal materials for implementing this technology in lightweight vehicles to achieve maximum braking efficiency and reduce general brake issues. This study assesses the impact of three different non-ferromagnetic materials (copper, aluminum, and steel) on the performance of the ECB system. The operation of the (ECB) is meaningly influenced by material properties such as permeability, electrical Conductivity, and thermal Conductivity. The investigation was carried out by finite element analysis (FEA) simulation. Findings demonstrated that copper is the more conductive material for eddy current braking. Due to its good electrical conductivity, it creates eddy currents, leading to important braking force and efficiency. Moreover, copper exhibits a force of 116.130 N, aluminum shows a force of 104.6 N, and steel showcases a force of 94.25 N, as indicated by the statistics. The percentage increase in braking strength is higher for copper than aluminum and steel, with values of 10.3% and 18.9%, respectively.

1. Introduction

Automobile protection mostly depends on the braking system, which decreases or stops the vehicle's velocity. Classical frictional brakes can fail due to causes such as high temperature and pressure, cracking, and wear [1]. New technological brake advances are popularly used to improve braking performance. Electromechanical brakes (EMB) are a technology that provides quick braking, low fuel use, environmental sustainability, easy maintenance, and better safety design [2]. In addition, another method for deceleration systems exploits electromagnetic induction to achieve precise and effective braking. This type of brake has the potential to diminish wear on brake parts and improve safety across several applications [3]. The authors have employed the implementation of (ECB). The generation of electric currents on the plate is caused by a variation in the magnetic flux density brought about by the rotation of the rotor disc [4]. Maxwell's law applies electromagnetic induction to control the direction in which eddy currents are formed. The currents exhibit a counter-rotational movement, creating a force that reduces the velocity of the rotor disc. These currents result in thermal energy, gradually making the wheel's kinetic energy and causing it to stop.

The idea is to be made up of a magnet field and a rotating metal plate, as explained in Figure 1. Recent exploration has shown the finite element methodology's importance in engineering system analysis in the field of ECB [5] the electromagnetic phenomena have been examined employing (FEM). In the study [6] (3D), a finite element model was employed to estimate the braking operation of an (ECB) and electromagnetic field distribution. The study certain the precision of the (FEM) in forecast resist force. Also, it shows how the shape of the conductor and the strength of the magnetic field influence the operation of the

http://doi.org/10.30684/etj.2024.144221.1625
Received 27 October 2023; Received in revised form 10 January 2024; Accepted 15 January 2024; Available online 16 February 2024
2412-0758/University of Technology-Iraq, Baghdad, Iraq

system. Orderly to increase the efficiency of (ECBs) designs, the (FEM) method was employed, aiming to achieve a balance between maximizing braking force and decreasing the weight of the system [7]. The conductivity of the rotor disc greatly affects the operation and efficiency of (ECBs) it has been as stated by researchers [8,9]. Increased conductivity makes better (ECB) effectiveness. Choosing materials based on their conductivity and thermal properties is important because the eddy currents make up overheating in the rotor discs, leading to loss of the material properties [10]. Eddy's current distribution and enhancement braking operation have been carried out by precise design [11]. Based on an up-to-date investigation, the conductor material influences the braking torque, and ferrous materials carry out weakly due to their low conductivity level. Aluminum (nonferrous materials) are ideal for ECB conductors due to their low heat generation and high torque capabilities [12].

The project focused on the effect of different rotor disc materials on the overall effectiveness and operation of an (ECBs). The emulation was designed to discuss the system's operation and identify the best rotor plate materials to achieve maximum performance.

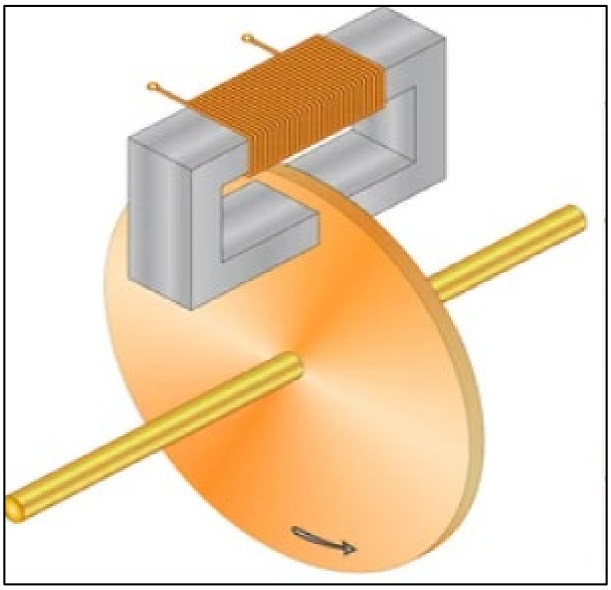

Figure 1: Working principle of eddy current brake

2. Mathematical model

The mathematical models are necessary for correctly representing and examining ECB principles. Maxwell's equations present the foundation of electromagnetic theory for modeling electromagnetic phenomena. Maxwell's equations have been adjusted properly for magnetic fields, electric currents, and conductive materials in (ECB) [13].

- Gauss's Law for Electricity:

$$\nabla \cdot \mathrm{E} = \frac{\rho}{\varepsilon 0} \tag{1}$$

- Gauss's Law for Magnetism

$$\nabla \cdot \mathrm{B} = 0 \tag{2}$$

- Faraday's Law of Induction:

$$\nabla \times \mathrm{E} = -\frac{\partial \mathrm{B}}{\partial t} \tag{3}$$

- Ampere's Law with Maxwell's Addition

$$\nabla \times \mathrm{B} = \mu_0 \mathrm{J} + \mu_0 \varepsilon_0 \frac{\partial \mathrm{E}}{\partial t} \tag{4}$$

The eddy current intensity was estimated by employing the equation [14]:

$$\mathrm{J} = \sigma\left(\frac{\partial \mathrm{B}}{\partial \mathrm{t}}\right) \tag{5}$$

The formula below calculates the force intensity vector. Force intensity offers the contact force per unit volume on the material [15] :

$$\mathrm{F} = \mathrm{J} \times \mathrm{B} \tag{6}$$

Integrating the force intensity (F) across the volume exposed to the magnetic field yields the braking force (Fb) applied to the material plate. The integral is expressed as [16]:

$$F_b = \int F dV \tag{7}$$

(F_b): brake force and (dV): differential volume (m^3).

The braking force in Equation (6) is used to calculate the braking torque (Tb) as a function of the rotor radius (r):

$$T = F . r \tag{8}$$

In addition, the braking Efficiency (η_b) of the ECB is estimated by:

$$\eta_b = \frac{Useful\ Input\ Power}{Braking\ Power} \times 100 \tag{9}$$

where Pin= (Ieddy)2 R, and Pout=T·ω , (εo): Free space permittivity, J: Eddy Current intensity (A), (μo): Free space permeability, $\partial B/\ \partial t$:magnetic field rate of change, (T/s), (∇): Gradient operator, (ρ): charge density, (B): magnetic field strength (T), ω: Rotational speed (rad/sec), R: Resistance (Ohm)

3. Simulation and design consideration

To optimize the performance of an eddy current braking system, it is essential to simulate the effects of varying its rotor disc materials. The right program must be employed to perform precise and successful modeling. ANSYS Electronics is the ideal simulation program for this assignment. It is a solid framework for designing and simulating difficult physical systems using finite element analysis. This program uses Maxwell's equations to portray electromagnetic processes in eddy current braking systems correctly [17]. The software's skill to model real-world events accurately captures the system's behavior. It is possible to forecast performance accurately and optimize design parameters. Simulating eddy current braking systems in a virtual environment with good results is possible. The fundamental elements of numerical experiments utilized to simulate eddy current braking have been defined in the Simulation Configuration. By following this critical procedure, it is guaranteed that the simulations faithfully depict practical circumstances and offer significant observations regarding the operation of the braking system. The geometric representation was produced through (ANSYS) tool using geometry modeling. The dimensions and configurations of various elements within the system, such as the brake disc, magnetic field source, and structure system, have been established.

The geometrical design of the suggested ECB can be seen in Table 1. After the geometric model has been generated, as illustrated in Figure 2, the next stage involves identifying the material characteristics and boundary circumstances corresponding to each part of the system. This gives the materials used in the plate disc and magnetic field source adequate electrical and magnetic characteristics. The choice of materials for conductors is a vital topic that impacts the overall performance of ECB systems. Various substances have varying degrees of electrical conductivity. The thermal characteristics and magnetic permeability have a direct impact on braking efficiency. As a result, conducting a thorough theoretical study to investigate the impacts of various conductive materials on the operation of the (ECB) system is critical. This study is critical for improving the system's architecture and increasing the braking efficiency of the mechanism. Table 2 describes steel, copper, and aluminum attributes, including their properties.

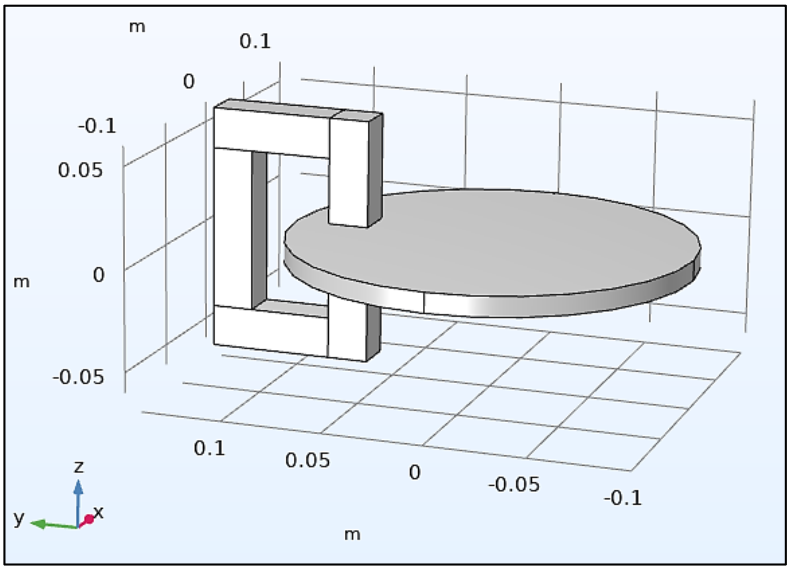

Figure 2: Show 3D Design For the rotor and Stator of ECB

Table 1: Design Consideration of ECB

Parameter	Value	Unit
Thickness of Rotor Disc	8	mm
Diameter of Rotor Disc	200	mm
Excitation current	0-10	A
Length of air gap	1	mm
Mass	1.5	Kg
No. of Coils turns	360	
Coil Width	150	mm
Coil Length	500	mm

Table 2: Characteristics that define non-ferromagnetic substances [9]

Properties	Types of Materials		
	Copper	Aluminum	Steel
Electrical conductivity (σ)	≈ 5.96×10^7 S/m	≈ 3.77×10^7 S/m	≈ 6.99×10^6 S/m
Relative Magnetic Permeability (μ)	0.99904	≈1	1.000021
Electrical Resistivity	0.00000170 ohm-cm	0.00000366 ohm-cm	0.0000015 ohm-cm
Thermal Conductivity	≈ 401 W/m·K	≈ 237 W/m·K	(15 to 50) W/m·K
Specific Heat Capacity (c)	0.385 J/(g·K)	0.897 J/g·K	0.460 (J/g·K)
Tensile Strength	210 - 370 (MPa)	170 - 570 (MPa)	300 to 600 (MPa)
Yield Strength	50 - 220 (MPa)	70 - 500 (MPa)	250 MPa
Young's Modulus (E)	≈ 117 (GPa)	≈ 69 (GPa)	≈190 (GPa)
Intensity (ρ)	8.96 (g/cm³)	2.70(g/cm³)	7.85 (g/cm³)
Melting Point	1083.2-1083.6 °C	582-651.7 °C	1370 °C to 1530 °C

4. Results and discussion

The program's results show how the metal characteristics affect disc braking performance. Numerous materials, such as copper, aluminum, and steel, were applied in simulations as conductive braking components. Table 3 displays the braking force for conductive metals. (Cu) has a better braking force than aluminum and steel. The resist force of copper is greater than that of aluminum and steel. This is due to copper's high electrical conductivity and uniform eddy current distribution.As a consequence, copper is more effective in braking [18]. Furthermore, aluminum has weak conductivity but still offers an important braking force; steel has the smallest. The amount of resist force is proportional to the intensity of the current, which in turn is determined by the conductivity of the metals used. This relationship is described by a mathematical Equation (5).

Figure 3 illustrates the braking torque values for several conductive materials. The braking torque was theoretically estimated using Equation (8); Cu has been found to have a higher braking torque than (Al and steel). Copper has the greatest braking torque value (1.50914 Nm), whereas aluminum and steel have values (1.102914 Nm and 0.86914 Nm, respectively). The conductivity (σ) of aluminum and copper is greater than steel's. Increased conductivity enhances eddy current production efficiency when exposed to a changing magnetic field. The magnetic permeability (μ) of steel is greater in magnitude when compared to that of aluminum and copper. The concentration of magnetic flux may be enhanced by increasing permeability; however, it is essential to note that this can also result in magnetic saturation, which can restrict the efficiency of eddy current production. Compared to steel, aluminum, and copper, they are anticipated to produce more powerful eddy currents due to their greater conductivities, consequently leading to greater braking forces. The improved braking efficacy can be attributed to the more uniform distribution of eddy currents caused by the lower magnetic permeability of these non-ferromagnetic materials.

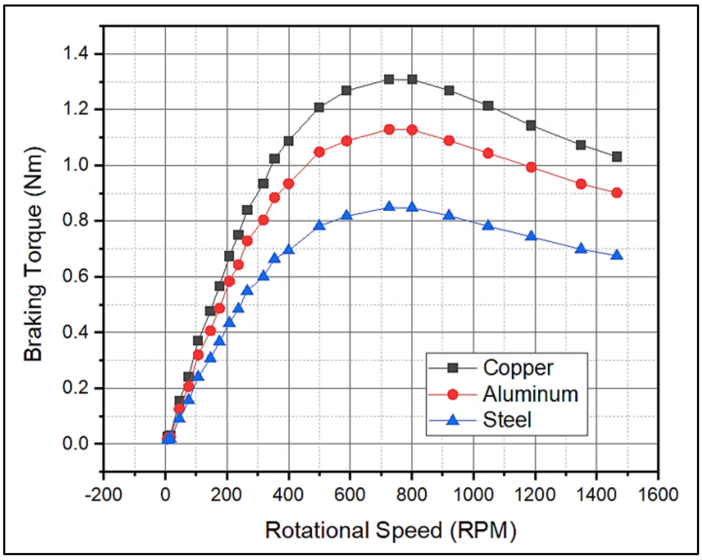

Figure 3: Braking torque with rotational speed

Table 3: Braking force values for conductive materials

Steel	Aluminum	Copper
26.6778177	29.61237765	32.86973919
35.1990546	39.07095061	43.36875517
41.8681122	46.47360454	51.58570104
49.0927803	54.49298613	60.48721461
54.8350878	60.86694746	67.56231168
60.9480909	67.6523809	75.0941428
68.1702948	75.66902723	83.99262022
73.7263554	81.83625449	90.83824249
79.2812838	88.00222502	97.68246977
87.4244103	97.04109543	107.7156159
91.8618462	101.9666493	113.1829807
94.2543624	104.6223423	116.1307999
94.0598127	104.4063921	115.8910952
92.0061351	102.12681	113.3607591
88.0980471	97.78883228	108.5456038
83.6323284	92.83188452	103.0433918
79.1639235	87.87195509	97.53787014
75.6278853	83.94695268	93.18111748

Braking torque is related to eddy current magnitude and varies linearly with speed. The critical speed is when the braking torque is highest, and the eddy current's reaction field decreases the magnetic field. As the speed increases, so does the braking force, which peaks at the critical speed. On the other hand, the reaction field formed by eddy currents develops faster than speed, resulting in a decrease in the combined influence of flux density and eddy currents. As a consequence, the braking torque is constantly decreasing [19]. Figure 4 demonstrate the efficiency of (ECB) performance for plate materials. The efficacy and efficiency of the performance of (ECB) were calculated using Equation (9) the braking efficiency improves as the current intensity increases. Nevertheless, the development starts to decline and reach a saturation point. Increasing the current intensity will not improve braking efficiency at this stage. This is because it is influenced by other factors, such as heat production and limitations of the materials. Depending on the findings, it is clear that using a highly conductive material like copper improves the system's braking efficiency significantly. The figures show that copper has the maximum braking efficiency of 85.43%. This efficiency falls steadily to 83.26%. Steel has the lowest efficiency at 77.73%, whereas aluminum has an adequate efficiency of 81.83%. Other metals, such as aluminum and steel, have magnetic permeability, which may restrict their capacity to generate powerful eddy currents, resulting in decreased braking effectiveness.

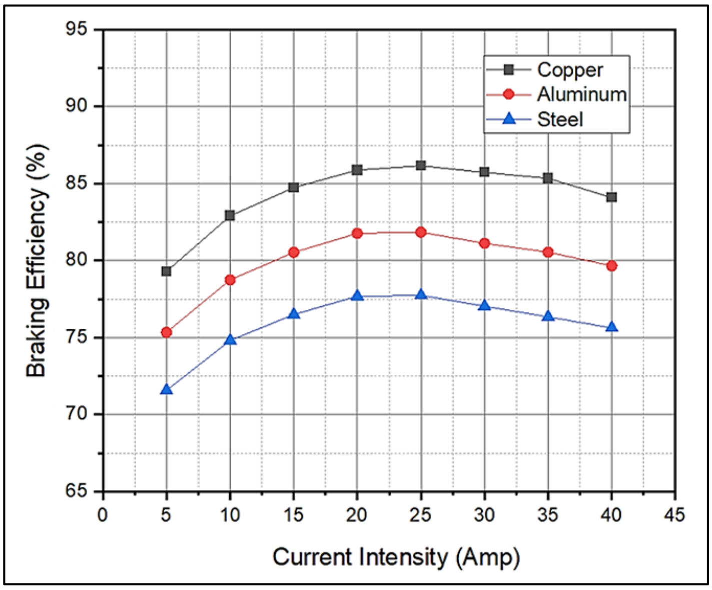

Figure 4: Current intensity and braking efficiency for three materials

Figure 5 shows the stopping times of three conductive materials at varying rotational speeds. The time required to stop a revolving part is proportional to its rotational speed. According to the research, the (ECB) is more successful at specific critical rotational speeds. This could be due to eddy currents formed by the rotor's relative speed and magnetic field, resulting in braking torque. Copper has a 4.1% shorter stopping time than aluminum and an 11% shorter stopping time than steel. Copper has a stronger braking torque than aluminum and steel. The rate at which the magnetic flux going through the conductor changes increases as the rotation rate of an item increases. According to Faraday's equation, the electromotive force (EMF) created on a conductor is proportional to the magnetic flux rate. Consequently, the induced electromotive force (EMF) increases when the rotating speeds rise, resulting in quicker eddy current production [20].

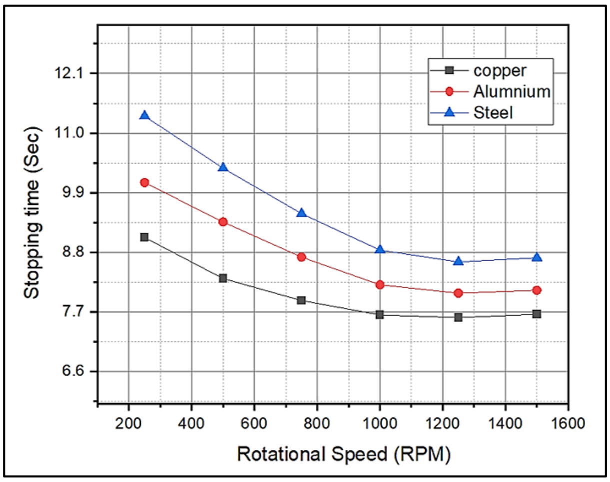

Figure 5: Stopping time with rotational speed for three materials

Figure 6 explores the word "mesh," which characterizes the interaction between the magnetic field and the arrangement of conductor materials. The mesh configuration is critical to a system's braking force, efficiency, and overall performance. A well-designed mesh ensures that force is distributed uniformly and energy is successfully converted, making it a critical component in the optimization and design of the ECB system. The arrangement has 177393 elements and 36105 nodes.

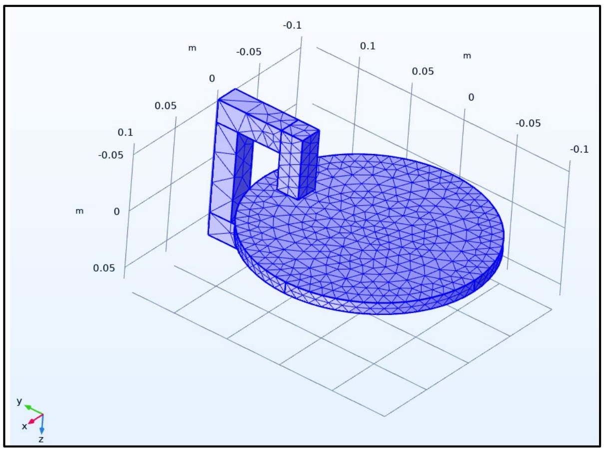

Figure 6: Meshing process of ECB

5. Conclusion

The study of the influence of conductivity material selection on the efficacy of eddy current braking systems yielded interesting results.

1) (Cu) exhibited the most relevant braking force compared to the other materials tested. The moving object decelerated more efficiently due to higher eddy currents because of its greater electrical conductivity.
2) Copper had the lowest temperature increase during braking. Its enhanced electrical conductivity aided heat dissipation, improving thermal behavior and system reliability, it outperformed aluminum and steel during braking.
3) Aluminum is best suited for less demanding braking criteria in cost-sensitive applications, whereas copper is best suited for strong braking forces, high efficacy, and minimum heat problems.
4) The amount that an (ECB) is proportionate to its intensity. Stronger eddy currents give the spinning system more braking force at higher rotational speeds. Accelerating the brakes causes the spinning object to slow down more quickly.

Author contributions

Conceptualization, A. Salman. J. Mohammed. and F. Mohammed; writing—original draft preparation, A. Salman. J. Mohammed. and F. Mohammed.; writing—review and editing, A. Salman. J. Mohammed. and F. Mohammed.; supervision, J. Mohammed. and F. Mohammed. All authors have read and agreed to the published version of the manuscript.

Funding

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] H. N. Faisal, F. M. Mohammed, J. A.-K. Mohammed, Design and Implementation of an Electromechanical Brake System, Eng. Tech. J., 40 (2022) 31–39. https://doi.org/10.30684/etj.v40i1.2150

[2] F. M. Mohammed, J. A.-K. Mohammed, H. N. Faisal, Modeling and Simulation of an Electromechanical Brake System, IOP Conf. Ser.: Mat. Sci. Eng., 1105 (2021) 1–13. https://doi.org/10.1088/1757-899X/1105/1/012051

[3] M. I. González, Experiments with eddy currents: the eddy current brake, Eur. J. Phys., 25 (2004) 463. https://doi.org/10.1088/0143-0807/25/4/001

[4] C. Sooyoung, et al., Design and analysis of the eddy current brake with the winding change, J. Magn., 22 (2017) 23–28. https://doi.org/10.4283/JMAG.2017.22.1.023

[5] S. E. Guy and M. Ehsani, Parametric analysis of eddy-current brake performance by 3-D finite-element analysis, IEEE Trans. Magn., 42 (2006) 319–328. https://doi.org/10.1109/TMAG.2005.860782

[6] S. -M. Jang, S. -S. Jeong, and S. -D. Cha, The application of linear Halbach array to eddy current rail brake system, IEEE Trans. Magn., 37 (2001) 2627–2629. https://doi.org/10.1109/20.951256

[7] M. Hecquet, et al., A linear eddy current braking system defined by finite element method, IEEE trans. Magn., 35 (1999) 1841–1844. https://doi.org/10.1109/20.767391

[8] M. Z. Baharom, Electromagnetic Braking System Using Eddy Current for Brake Disc of Al6061 and Al7075, Int. Rev. Mech. Eng., 6 (2012) 588–592.

[9] M. I. Munyaradzi and R. S. Tomar, Evaluation of Materials Suitable for Use in Eddy Currents Non-Contact Brakes Disc in Automobile Application, Int. J. Sci. Res., 5 (2016). https://doi.org/10.21275/v5i4.nov163002

[10] L. Gorjan, M. Boretius, G. Blugan, F. Gili, D. Mangherini, X. Lizarralde, M. Ferraris, T. Graule, A. Igartua, G. Mendoza, J. Kuebler, Ceramic protection plates brazed to aluminum brake discs, Ceram. Int., 42 (2016) 15739–15746. https://doi.org/10.1016/j.ceramint.2016.07.035

[11] A.A. Agbeleye, D.E. Esezobor, S.A. Balogun, J.O. Agunsoye, J. Solis, A. Neville, Tribological properties of aluminum-clay composites for brake disc rotor applications, J. King Saud Univ. Sci., 28 (2017) 21–28. https://doi.org/10.1016/j.jksus.2017.09.002

[12] K. Karakoc, E. J. Park, and A. Suleman, Improved braking torque generation capacity of an eddy current brake with time-varying magnetic fields: A numerical study, Finite Elem. Anal. Des., 59 (2012) 66–75. https://doi.org/10.1016/j.finel.2012.05.005

[13] Y. Liao, Overview of Numerical Analysis and Optimization Methods for Eddy Current Retarders, Acad. Sci. Technol., 3 (2022) 6–9. http://dx.doi.org/10.54097/ajst.v3i2.2079

[14] J. Li, et al. Calculation and Characterization of Braking Performance for Rail Eddy Current Brake With AC Excited Ring-Winding Armature, IEEE Trans. Ind. Appl., 59 (2022) 1614–1625.http://dx.doi.org/10.1109/TIA.2022.3227140

[15] P. Min-Gyu, et al., Torque analysis and measurements of a permanent magnet type Eddy current brake with a Halbach magnet array based on analytical magnetic field calculations, J. Appl. Phys., 115 (2014). https://doi.org/10.1063/1.4862523

[16] S. Cho, H. C. Liu, H. Ahn, J. Lee, and H. W. Lee, Eddy Current Brake with a Two-Layer Structure: Calculation and Characterization of Braking Performance, IEEE Trans. Magn., 53 (2017) .https://doi.org/10.1109/TMAG.2017.2707555

[17] M. N. Ahamad and S. A. Jumaat, Analysis of Eddy Current Density using ANSYS MAXWELL Software, J. Electron. Voltage Appl., 1 (2020) 37–45.

[18] R. K. Srivastava and S. Kumar, An alternative approach for calculation of braking force of an eddy-current brake, IEEE Trans. Magn., 45 (2009) 150–154.https://doi.org/10.1109/TMAG.2008.2006993

[19] J. H. Wouterse, Critical torque and speed of eddy current brake with widely separated soft iron poles, IEE Proc. B Electr. Power Appl., 138 (1991) 153–158. https://doi.org/10.1049/ip-b.1991.0019

[20] J. Liu, W. Li, L. Jin, G. Lin, Y. Sun, Z. Zhang, Analysis of linear eddy current brakes for maglev train using an equivalent circuit method, IET Electr. Syst. Transpo., 11 (2021) 218–226. https://doi.org/10.1049/els2.12016