Kufa Journal of Engineering
Vol. 17, No. 2, April 2026, P.P. 150-170
Article history: Received 21 October 2024, last revised 9 March 2025,
accepted 26 June 2025

STUDYING THE EFFECT OF FERROMAGNETIC MATERIAL TYPE ON HYSTERESIS BRAKE PERFORMANCE

Mahmood D. Jassam[1], Jamal A.-K. Mohammed[2], and Wisam E. Abdul-Lateef[3]

[1] College of Electromechanical Engineering, University of Technology, Baghdad, Iraq, Email:eme.22.31@grad.uotechnology.edu.iq.

[2] College of Electromechanical Engineering, University of Technology, Baghdad, Iraq, Email:50128@uotechnology.edu.iq.

[3] College of Electromechanical Engineering, University of Technology, Baghdad, Iraq, Email:50110@uotechnology.edu.iq.

https://doi.org/10.30572/2018/KJE/170210

ABSTRACT

Mechanical brake systems usually suffer from major defects such as friction, noise, high wear rate, lack of accuracy, and lack of smoothness, so it has become necessary to replace them with alternative braking technologies that address these problems. One such technology is the hysteresis brake. This brake is one of the unique and effective braking technologies that uses the principle of magnetic hysteresis to generate braking force. It has features such as powerful torque, silent operation, no wear parts or mechanical friction, precise control, and no need for regular maintenance. The most influential aspect of the performance of the hysteresis braking system is the material that is used to make the brake disk. In this study, the COMSOL Multiphysics platform was applied to analyze the impact of four types of magnetic materials: cobalt, nickel, neodymium, and iron on the performance of the braking system. This was achieved by studying the equations of the governing braking system. This system proves to be great in determining the braking parameters to ensure that a good choice in terms of coil, core, and magnet specifications is made to enable good performance. These parameters were determined after numerous experiments and watching the outcome. Effects of material properties, including permeability, electrical conductivity, and thermal conductivity, on the braking force and system efficiency were studied by simulation through the use of the finite element analysis (FEM) method. It was demonstrated that neodymium is the best core material used in this brake, due to its high magnetic permeability and excellent electrical conductivity.

Neodymium enhances the brake with maximum braking force superior to cobalt, nickel, and iron materials by 20, 100, 150%, respectively. The results also showed that using cobalt cores leads to improved design, as it generates the highest braking efficiency under load, with a value ranging between 90-98%.

KEYWORDS

Hysteresis braking system, ferromagnetic materials, Finite element analysis, COMSOL Multiphysics, Braking force.

1. INTRODUCTION

To stop or slow down a moving wheel, axle, or vehicle, mechanical devices known as braking systems employ the energy of the moving system. The braking action is often achieved by electromagnetic forces or friction. As technology has advanced, various brake types have been developed to meet the needs of different applications. There are many types of braking systems (Orthwein 2004; Goodnight N. and VanGelder 2019) including mechanical, hydraulic, pneumatic, electric, regenerative, power-assisted, vacuum, electromagnetic, magnetic particle, eddy current, and hysteresis.

Conventional (frictional) brakes (Al-Araji 2014; Huang et al. 2019; Abdulkareem et al. 2023; Chandane and Kulkarni 2023) are limited in their use in electric cars, even with the numerous efforts made by researchers to date to enhance their performance by refining the design or applying modern control methods. The primary constraint of these brakes is their severe wear and tear because of the considerable friction between the braking discs and pads. Brake component replacement and regular maintenance may result from this.

The most often used type of electromagnetic brakes (EMBs) (Mohammed et al. 2021; Faisal et al. 2022; Li et al. 2023) in the past were called electromechanical brakes, and they worked by using an armature and an electromagnet to initiate the braking action on a device called a "friction disc". A vehicle can be stopped or slowed down using an EMB system, which combines mechanical and electrical components. The EMB systems adopt the application of the electromagnetic principle, which reduces the value of friction and eliminates the need for lubrication to solve the slipping problem in traditional braking systems, thus increasing the lifespan and reliability of the brakes. Due to this, it is recommended to apply this technology in contemporary and hybrid vehicles. It is much smaller than conventional braking systems in comparison.

All three forms of brakes, magnetic particle brake (MPBs) (or powder brakes) (Liu et al. 2011; Nakamura and Motoi 2021), eddy current brake (ECBs) (Putra et al. 2021; Salman et al. 2024; Salman et al. 2025), and hysteresis brake (HBs) (Shyrokau et al. 2014; Donat and Kanoun 2016) have no worn components because the torque is produced by electromagnetic reactions rather than mechanical friction. For them to work, they need electronic controllers and a rectifier to supply direct current. Nevertheless, the word "electric brakes" is not typically used to describe them since it was formerly reserved for electromagnetically actuated friction brakes, which work by applying an electric current via a coil to create a magnetic field that contacts a shoe and drum.

The MPBs work on a different concept than conventional friction brakes, which rely on physical contact between components to create stopping force. They regulate torque and rotational speed by making use of the intriguing characteristics of magnetic particles floating in a fluid.

The ECBs are used to slow or stop moving objects by creating eddy currents that release the object's kinetic energy in the form of heat. In an ECB, friction between two surfaces that are compressed together does not produce a drag force. The drag force is caused by electromagnetic forces that exist between a moving conductive item and a magnet nearby. This is because the conductor's electromagnetic induction creates eddy currents. Permanent magnets and electromagnets may both produce the magnetic field needed for an ECB. Electric meters for electric utilities, stoppers for powered tools, semi-trailer vehicles to save brake wear and overheating, trains and roller coasters, and electric meters are all equipped with ECBs.

The HBs have several significant benefits over other brakes due to their better design. They have almost no wear and work based on a frictionless design. Benefits from this include a longer projected life, better torque repeatability, lower life-cycle costs, a wide speed range, high environmental stability, and smoother operation. The present study is particularly interested in the HBs, which generate braking force by using the magnetic hysteresis features of materials. The HBs operate mostly due to hysteresis, a phenomenon defined as the lag between an input and an output in a system. Hysteresis in magnetic materials is characterized by magnetization that remains after an external magnetic field is removed (Mörée and Leijon 2023). The HBs cannot function without this characteristic, and further investigation is needed to determine exactly how it impacts braking effectiveness, reliability, and performance.

The characteristics of materials used to make the parts of the HB system are subject to different design parameters, the most important of which is the performance of the HB system. The material properties of the components, especially those of the rotor material, which will be a determining factor in the performance of HB, are also to be known. The HBs utilize the magnetic properties of magnetic materials to release the force needed to brake. In fact, these materials are capable of amazing magnetic properties, which are applicable to any task that requires a significant amount of braking force, precision, and no noise. The engineers can enhance HB to suit different industrial needs by employing a good selection of materials.

This creates magnetic fields due to the magnetization of the magnetic core, and a strong magnetic field is created when an electric current is conducted through the coil. It is important to have an understanding of the reasons behind the intensity of the magnetic field generated by the electromagnets. Its strength is highly dependent on the permeability of the magnetic material that it is made up of, the number of coil turns, and the current that is passing through the coil. (Basu and Dhasmana 2023). The type of magnetic material employed in the rotor plays a major role in the effectiveness of an HB. All these features are essential since a rotor with a high magnetic permeability can become magnetized more easily and hence has higher stopping power (Orthwein 2004).

The ability of a substance to retain its magnetism even when not subjected to an external magnetic field is referred to as magnetic retention. Due to the long period of time, the braking force does not reduce once the magnetism has disappeared. The strength of a magnetic field that is needed to demagnetize a substance is known as the coercive force. A low coercive rotor is demagnetized easily, and therefore it results in minimum energy loss when braking.

The literature includes studies that have been relevant in giving background to this research. (Yangyang et al. 2016) have shown a special way to improve the tribological characteristics of the braking materials by developing the magnetic particles into the matrix material, and showed their influence on the wear and friction performance. The work has led to the creation of a new magnetic braking material with nano-Fe3O4 and Nd-Fe-B. (Lijesh et al. 2017) proposed that when dealing with Magneto-Rheological (MR) brakes, it is better to rely on varying levels of hardness of the brake disc. High disc hardness enhanced the braking effect. To examine the influences of various rotor materials on the performance of the ECB in terms of torque, (Ulucak et al. 2017) constructed a device to research the topic. The outcomes also showed that galvanized steel produced the least amount of torque, and low-carbon steel produced the most amount of torque. The study (Putra et al. 2021) was about an ECB design. They found that the iron brake disc material was not the most suitable for the performance of these brakes. There is a need to employ aluminum as a disc in the ECB or a combination of the two kinds of materials. Batista, et. al. (Morree and Leijon 2023) explained both the design and the operation of an EMB with an emphasis on the hysteresis effects using both a simulation and experimental data. (Salman, et al. 2024) tested different materials in the design of the rotor disk of the ECB system, which is used by vehicles. Results proved that copper is a more appropriate material to use in ECB as compared to aluminum and steel because of its good electrical conductivity. Moreover, (Salman et al. 2024) studied the impact of the type of permanent magnet selected on the performance of the ECB system. The results of the overall performance indicated that permanent magnets made of neodymium, iron, and boron always offered the greatest braking capability.

The importance of HBs in industrial processes has become the focus of attention, and international companies are racing to manufacture and develop them. There are several studies (Shyrokau et al. 2014; Lee et al. 2012; Shiao and Gadde 2021) in the literature that have studied the phenomenon of hysteresis effect in rotating mechanisms, and others (Donat and Kanoun

2016; Tarte et al. 2006; Caruso et al. 2020) have utilized the HBs for loading, calibrating, and measuring torque or load of rotating mechanisms. However, there is no research in the literature to date that has exclusively studied and analyzed the behavior of these brakes and the effect of changing variables on their performance. The present paper aims to study the effect of changing the type of material that makes up the hysteresis brake rotor disk on the braking behavior concerning braking force, torque, and efficiency. Structural analysis will be combined with magnetic simulation to gain a deeper understanding of brake behavior and determine the influence of design factors on performance.

2. CONSTRUCTION AND WORKING PRINCIPLES OF THE HYSTERESIS BRAKE

Magnetic hysteresis in ferromagnetic materials is the basis for how the HB functions. As shown in Fig. 1, the HB is composed of two main parts: a rotor composed of soft magnetic material with strong hysteresis qualities and a stator, typically consisting of an electromagnetic coil or permanent magnet (Orthwein 2004). The HB comes in the form of gears inside a magnetic field aperture to turn the rotor. These parts are fitted together but not in direct contact to use the hysteresis effect in magnetism for torque control. Because there is no wear or adjustment due to the braking torque being generated without any physical contact between the brake elements, the system has a longer lifespan, good stability with high repeatability, and operates entirely silently.

The creation of a magnetic field initiates the process. A powerful magnetic field is created in the stator when an electric current is supplied to the coil. The magnetic material undergoes cyclic variations in magnetization as the rotor rotates inside this field, which causes the material to continuously cycle through hysteresis. The waste of energy during the hysteresis cycle is the fundamental component of the braking process. When this energy loss is transformed into heat, it creates a braking torque that prevents the rotor from rotating.

The ability of the HB to regulate the braking force depending on the coil current may be considered one of the fundamental product features. Increased braking torque is the result of an increased, powerful magnetic field, which is generated upon an increase in current. Some of the performance qualities of HB brakes that differentiate them from other brakes include the relatively constant braking torque over a wide variety of speeds and the smooth and quiet operation. Those characteristics make HBs especially more useful when it comes to their application to devices that need tension control to be precise and constant, like wire winding machines. The research will be aimed at close attention to such issues as the selection of the materials to work with, the design of the magnetic circuits, and the thermal management.

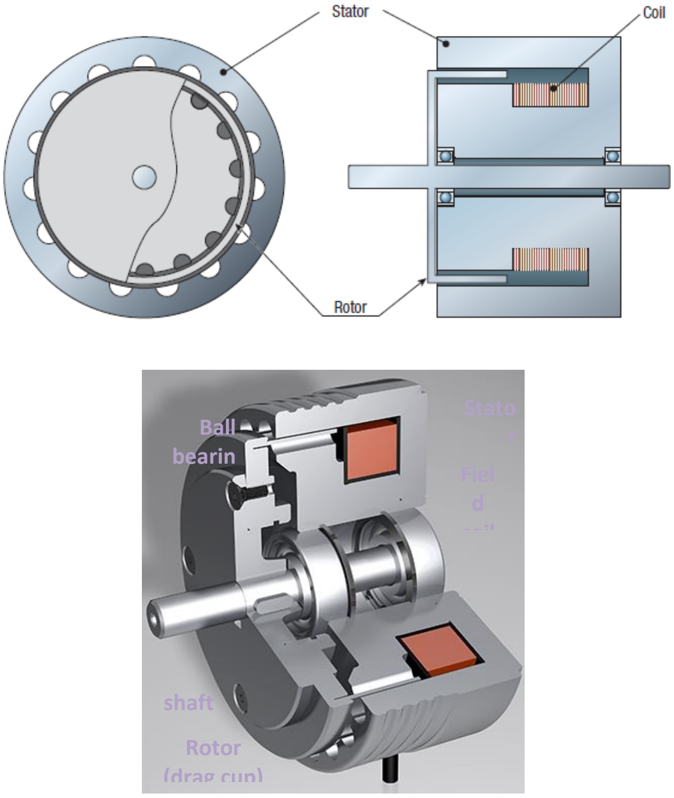

Fig. 1. Structure of the hysteresis brake

2. MATHEMATICAL MODEL OF THE HYSTERESIS BRAKE

The development of HB takes advantage of the magnetic hysteresis properties of materials in their fabrication. To analyze the performance of this brake, it has to be modeled mathematically. It is a model that attempts to analyze the governing equations of the braking system by modelling the relationship between the inputs (say, an applied magnetic field or electrical current) and the outputs (say, the resultant torque or braking force).

2.1. Governing equations

The behavior of any electromagnetic brake can be mathematically modeled using the following governing equations (Orthwein 2004; Lee et al. 2012; Hwang et al. 2016):

Gauss's Law for the Electric Field:

$$\nabla \cdot E = \frac{\rho}{\varepsilon_o} \tag{1}$$

Gauss's Law for the magnet field:

$$\nabla . B = 0 \tag{2}$$

Faraday's law of induction:

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

Ampere's Law:

$$\nabla \times B = \mu_0 \left(J + \varepsilon_o \frac{\partial E}{dt} \right) \quad (4)$$

Hysteresis power loss density:

The hysteresis loss per unit volume in the ferromagnetic material can be given as:

$$P_h/m^3 = k_h f B_{max}^n \quad (5)$$

Where n is the empirical exponent, in the range 1.5-2.5.

Hysteresis braking force density:

$$F_h = \frac{1}{2}\mu_o \frac{dH}{dx}(B - \mu_o H) \quad (6)$$

Hysteresis (or breaking) torque (Lee et al. 2012):

$$T_h = \frac{P_h}{\omega} \quad (7)$$

Braking efficiency:

It is the efficiency of converting electrical power to braking torque:

$$\eta = \frac{P_h}{P_{in}} \quad (8)$$

Where E is the electric field, B is the magnetic flux density, ρ is the charge density, ε0 is the permittivity of free space, μ0 is the permeability of free space = 4π×10-7 T.m/A, J is the electric current density, ε0 is the permittivity of free space, kh is the hysteresis constant, f is the frequency of reversals of magnetization, $\frac{dH}{dx}$ is the gradient of magnetic field strength (A/m2)along the direction x, kh is the Steinmetz or hysteresis constant, Bmax is the maximum value of the magnetic flux density, V is the volume of magnetic material, ω is the rotational speed, and Pin is the electric input power.

2.2. Finite element (FE) formulation

The HB model proposed in this study is built, simulated, and optimized using the FE method in COMSOL. The model may be implemented through the following steps:

- Define the type of problem by specifying the mathematical equations and describing the properties of four selected ferromagnetic materials.
- Create the HB model (Bottauscio et al. 2000; Hadžiselimović et al. 2008).
- Describe in detail the magnetic potential using nodal basis functions.
- Integrate the discretized Preisach model.
- Use electromagnetic coupling by calculating the joint magnetic energy.
- Calculate the time steps.
- Continue to improve the network to ensure accuracy and thus analyze the results with high accuracy.

Fig. 2 explains the use of the FE method in a simplified manner in COMSOL.

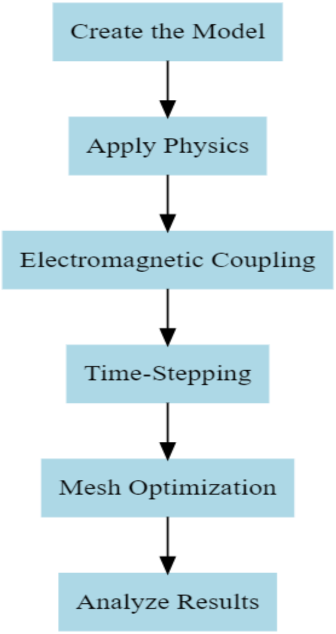

Fig. 2. Flowchart of the proposed HB model using the FE method in COMSOL

3. SIMULATION AND DESIGN CONSIDERATION

COMSOL Multiphysics software is well-suited for 3D simulation of the HB system and studying its behavior to optimize design parameters. COMSOL's application of Maxwell's equations will realistically capture the electromagnetic phenomena that control hysteresis braking. This allows predicting the behavior of the system in virtual simulation experiments before creating physical prototypes.

Properly setting up the simulation by creating test conditions and geometries consistent with real-world braking components will yield meaningful and transferable results. Changing material parameters, such as those in the rotating disk via simulations, as originally proposed, is a logical approach. Output metrics such as magnetic flux distributions, torque generation, and thermal profiles can provide valuable insight to optimize designs for maximum efficiency. Parameter sweeps can systematically explore the design space. What's more, post-processing features enable analysis of outputs such as magnetic flux distributions, torque generation, heat transfer, and stresses/strains. Parameter scans can optimize designs efficiently. By modifying the geometric and material parameters in the simulation, the design can be optimized for better performance. Here are some suggested values to use:

Coil parameters:

Coil radius: 1-2 cm (adjusted as needed for desired size)
Number of turns: 50-100 (more turns provide higher inductance)
Wire gauge: 28-32 AWG (balanced resistance and inductance)
Coil length: 3-5 cm (longer coil cuts more magnetic flux)

Core parameters:

Core material: Ferrite or the best choice is silicon steel (high permeability).

Core length: 5-10 cm

Core width: 2-5 cm

Core thickness: 1-2 cm

Magnet parameters:

Magnet type: Neodymium or samarium cobalt (high flux density)

Magnet size: Adjust width/length/thickness based on core size

Air gap: 1-3 mm, the best (1 mm)

Other parameters:

Applied voltage: 12-24V DC (depends on coil resistance/inductance)

Angular velocity: 0-3000 rpm

After several trial and test options, here are recommendations for selecting coil, core, and magnet specifications that provide good performance while balancing cost and efficiency:

For the Coil:

Coil radius: 1.5 cm

Number of turns: 75 turns (higher inductance without excessive resistance)

Wire gauge: 30 AWG (reasonable resistance for 12-24V operation)

For the Core:

Core material: Ferrite (inexpensive and high permeability)

Core length: 7 cm

Core width: 3 cm

Core thickness: 1.5 cm

For the magnets:

Magnet type: Neodymium

Magnet size: 1 × 1.5 × 1 cm (sufficient flux with compact size)

Air gap: 2 mm

Once the geometric model is made, then would subsequently need to define the material properties and boundary conditions of all the system components. This is achieved by providing the materials used in the braking disk with the required electrical and magnetic properties and the source of the magnetic field. The choice of materials is another crucial aspect that significantly affects the work of the HB system in general. The magnetic effects of various materials vary. The thermal characteristics and the magnetic permeability have a direct effect on the braking efficiency. To this effect, there is a need to thoroughly analyze the theoretical effects of different materials on the effectiveness of the HB system. This analysis is essential in order to optimize system design and the efficiency of the braking mechanism in general. Table 1 below (Coey and Parkin 2021) lists all the characteristics of the features of all types of ferromagnetic materials, including cobalt, neodymium, nickel, and iron. Precise characteristics of any given element can be different regarding its purity, processing, and others.

Table 1. Overview of the properties of different magnetic materials

Feature	Cobalt (Co)	Neodymium (Nd)	Nickel (Ni)	Iron (Fe)
Atomic number	27	60	28	26
Atomic mass (u)	58.933195(5)	144.242(3)	58.6934(2)	55.845(2)
Electron configuration	[Ar] 3d7 4s2	[Xe] 4f4 6s2	[Ar] 3d8 4s2	[Ar] 3d6 4s2
Density (g/cm³)	8.9	7.01	8.908	7.874
Melting point (°C)	1495	1021	1455	1538
Boiling point (°C)	2927	3074	2913	2862
Magnetic permeability	250	1.5	600	5000
Electrical conductivity (MS/m)	16.8	1.6	14.3	10
Thermal conductivity (W/m·K)	100	16.5	90.7	80.4

3.1. Meshing the boundaries

Here is the boundary mesh of the coil, core, and magnet with attention to the sizes of the elements:

For the coil boundary (radius of 1.5 cm, thickness of 0.8 cm):

- Use a boundary layer mesh with 10 layers through the thickness
- First layer has a thickness of 0.08 cm and a growth rate of 1.2
- Circumference swept mesh with 100 divisions
- Refine at edges and corners with a maximum size of 0.1 cm

For the core boundary (length of 7 cm, width of 3 cm, and thickness of 1.5 cm):

- Free tetrahedral mesh on outer surfaces
- The maximum size of the element with a range of 0.3-0.5 cm in central regions
- Reduce to 0.1 cm near air gap edges/corners
- (5-10) layers through the thickness with 0.15 cm for the 1st layer

For the magnet boundaries (size of 1×1.5×1 cm):

- Block mesh structure to match geometry
- Elements no larger than 0.1 cm at air gap interfaces
- Gradually increases to 0.3-0.5 cm away from the air gap
- Ensure at least 8 elements across each dimension

3.2. Estimating the total number of mesh elements

Based on the meshing guidelines provided, the following is an estimate of the total number of mesh elements required:

For the coil:

- Boundary layers: 10 layers × 100 circumferential divisions = 1000 quadrilateral elements
- Sweep divisions: 100
- Total coil elements: 1000

For the core:

- Outer surfaces: 7 × 3 × 1.5 cm block
- Estimating 0.3-0.5 cm tetrahedral elements
- Elements per dimension = 7/0.3 = 23
- Total = 23 × 23 × 23 =12,167 tetrahedral elements
- Through thickness layers: 5-10 layers × estimated 30 elements per layer = 150-300 elements
- Total core elements: 12,167 + range of (150-300) = 12,317 to 12,467

For the magnets:

- (1 × 1.5 × 1 cm) block
- Estimating 0.1 cm tetrahedral elements
- 10 elements per dimension
- Total per magnet = 10 × 10 × 10 = 1000 tetrahedral elements
- With 2 magnets, total magnet elements = 2000

The grand total estimated elements are:

- Coil: 1000
- Core: 12,347 to 12,467
- Magnets: 2000

Total elements = 1000 + (12,317 to 12,467) +2000 = 15,317 - 15,467) elements

Fig. 3 shows the 3D FE mesh model of the proposed brake in the COMSOL program.

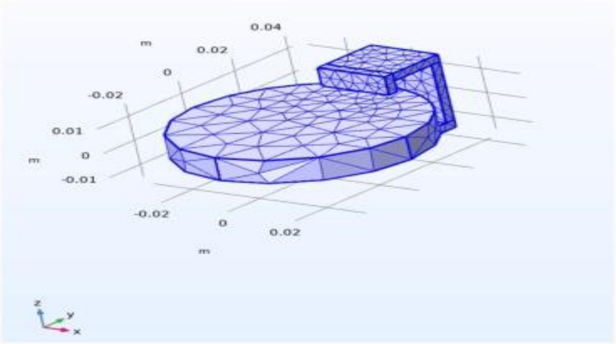

Fig. 3. 3D FE Mesh model of HB in COMSOL

4. RESULTS AND DISCUSSION

In this section, the COMSOL simulation results of the HB model are implemented and analyzed using a variety of magnetic materials. The magnetic field of rotating systems is simulated. The performance of the brake with core using different magnetic materials will be analyzed, compared, and discussed. The predicted simulation results are arranged in Table 2 to facilitate comparison of braking performance using different core ferromagnetic materials.

Table 2. Comparison of performance using different core ferromagnetic materials

Property	Cobalt	Neodymium	Nickel	Iron
Peak braking torque (Nm)	1.5-2.5	2-3	1-1.5	0.8-1.2
Torque constant (Nm/A)	0.7-1.2	1-1.5	0.5-0.8	0.4-0.7
Back EMF constant (mV/rad/s)	60-110	70-120	50-80	40-70
Inductance (mH)	60-110	70-120	50-80	40-70
Resistance (Ω)	3-5	3-5	3-5	3-5
Max. energy regeneration (J)	25-35	30-40	20-25	15-20
Temperature rise after 1 min (°C)	25-30	30-40	20-25	15-20
Magnetic flux density (Tesla)	0.7-1.2	0.8-1.3	0.6-1	0.5-0.8
Flux linkage (mWb-turns)	12-25	15-30	10-20	8-15
Braking efficiency (%)	90-98	87-97	80-90	75-85
Force factor (N/A)	0.12-0.22	0.15-0.25	0.1-0.18	0.08-0.15
Braking factor (N)	15-25	20-30	10-15	8-12

When reviewing these simulation results for the HB system using different core materials, some of the following key conclusions stand out: Neodymium performed the best overall, with the highest braking torque, energy regeneration, efficiency, and flux density/linkage. However, it also saw the highest temperatures, which could pose reliability issues over long-term use. Cobalt was the second strongest performer. It also offers a very good balance between high torque/EMF and temperatures only slightly higher than Nickel. This implies that it can be the optimal fabric in terms of performance and safety. Nickel core was good, but in comparison to Cobalt and Neodymium, it was way behind in most measures. It would probably be enough to work with lighter-duty applications that do not need optimum torque/power levels. Iron core was the poorest of the lot, having braking capabilities that were lower than those of Nickel. It would only appear appropriate when the braking capacity is seconded to the lowest cost.

Neodymium seems to be the best alternative when considering the need to apply more force in braking without the need to compromise on the heat generation. Cobalt would also be effective in case cooling is done to cool its unwanted temperatures. Nickel would do less exalted purposes. In general, it is evident that the material has a high impact on the braking system's abilities, and therefore, the choice of the appropriate one plays a role in ensuring the performance specification.

On comparing the data in the table to each other, it is observed that: Cobalt core exhibited the best braking efficiency with load, ranging between 90-98%. This is perceived considering the fact that it has performed better in other measures, such as torque. Neodymium core provided a very small range of efficiency of 87-97% only. It retains extremely competitive skills. Nickel core efficiency was around 80-90, which was evidently a step lower than Cobalt and Neodymium, but still good. The iron core possessed the least braking efficiency of 75-85 as per its torque and other factors. Neodymium and Cobalt once again topped the group in terms of force factor, which is the ratio of the torque output to the electrical current. This added to their advantage in case of the need for increased braking forces. Nickel and Iron cores were also lower, though not highly.

Overall, the results demonstrate that Cobalt and Neodymium are the best options where maximum force braking is critical, whilst Nickel and Iron are lesser.

Fig. 4 shows the distribution of total heat over braking (stopping) time for four ferromagnetic elements: cobalt, neodymium, nickel, and iron. The stopping time is the time it takes for the brake to stop rotating after the power is turned off. Neodymium generates the largest amount of total heat, followed by cobalt, nickel, and iron. The total amount of heat generated for each element varies due to its different physical properties, such as thermal conductivity and electrical resistance. Knowing the relationship between the total temperature and braking time for different elements is important in many applications.

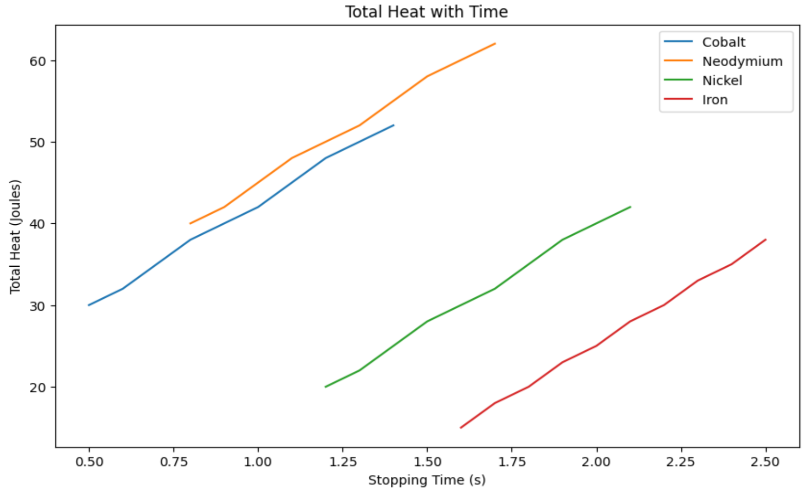

Fig. 4. Total heat vs. stopping time for different ferromagnetic materials

Fig. 5 displays two interesting graphs analyzing the braking torque over time and the angular velocity for each of the four materials studied. The upper graph is the relationship between braking torque and angular velocity. The braking torque of all materials decreases with increasing speed. Here, neodymium shows the highest braking force, followed by cobalt, nickel, and finally iron. The lower graph shows the braking torque decreases with time for all materials, and here again, neodymium shows the highest braking torque, followed by cobalt nickel, and iron is the last metal. Through these results, the high performance of neodymium in braking applications is highlighted when compared to other materials.

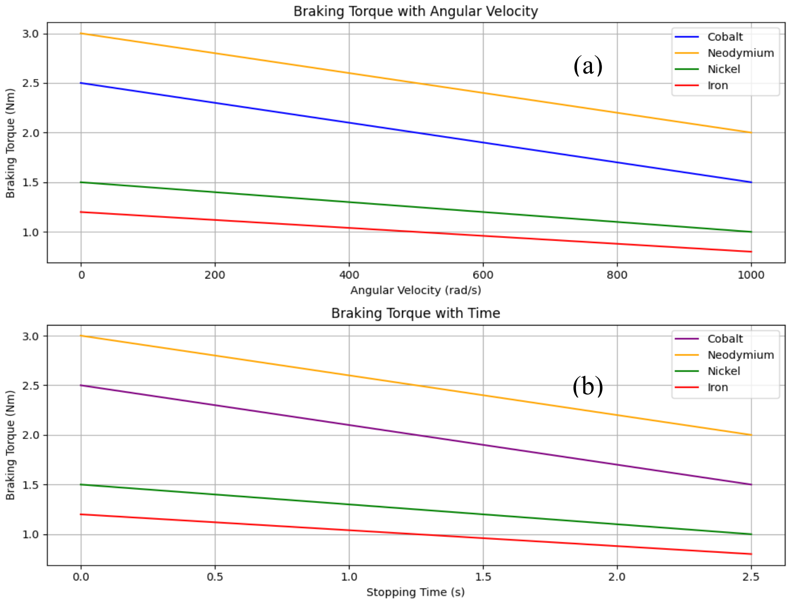

Fig. 5. Braking torque vs. a) angular velocity, b) stopping time.

Fig. 6(a) refers to the relationship between braking efficiency and angular velocity for all proposed materials. The figure shows that neodymium has the highest efficiency among materials. It is noted that the braking efficiency for all materials decreases with increasing angular velocity. Fig. 6(b) shows the relationship between force factor and angular velocity. The highest of the materials is neodymium. Thus, the braking efficiency of neodymium shows the highest strength factor, followed by cobalt, nickel, and iron, which is considered the least efficient, making it less effective in applications that require high efficiency.

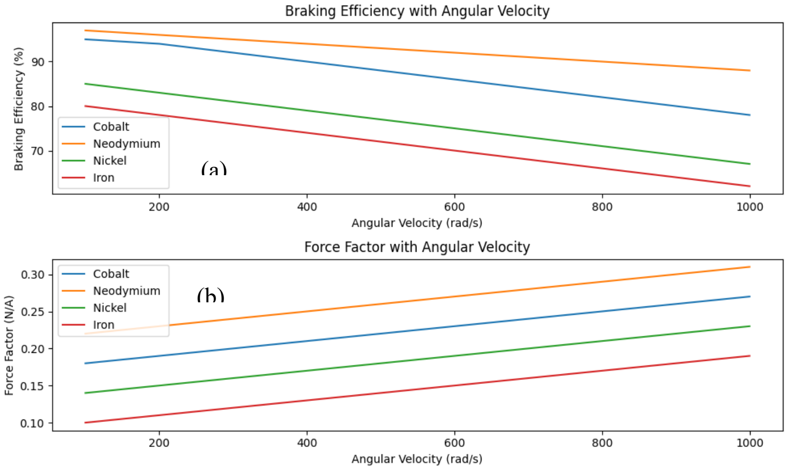

Fig. 6. Braking efficiency (a) and force factor (b) vs. angular velocity

From the shapes shown in Fig. 6, the relationship between the braking efficiency and force factor shown in Fig. 7 can be deduced. By analyzing this graph for four materials, it is noted that neodymium has the highest braking efficiency over the force factor range.

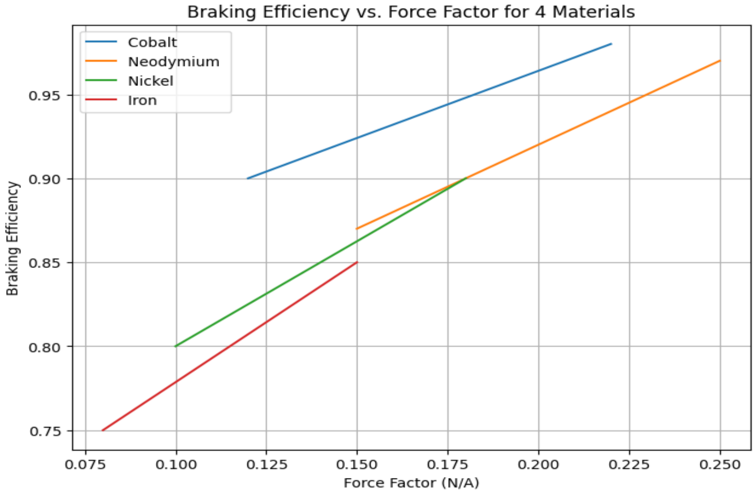

Fig. 7. Braking efficiency vs. force factor for different ferromagnetic materials

Fig. 8 shows the relationship between the torque constant and the stopping time of the brake. The torque constant is a measure of the brake's ability to produce torque. It is noted that this ability inversely decreases over time.

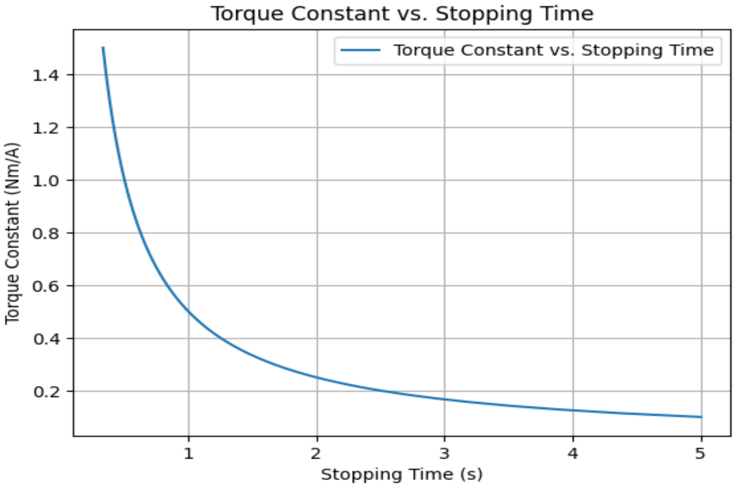

Fig. 8. Torque constant vs. stopping time

Fig. 9 shows the temperature rise as a function of braking torque for the ferromagnetic materials. Through the analysis, the following conclusions can be drawn. It is observed that the temperature rise of cobalt does not change much with increasing braking torque. It means that cobalt is quite a good heat dissipater, which does not allow high temperatures to be reached during high braking torque. In the case of the neodymium, the temperature is much higher as a result of an increase in braking torque. Although neodymium has good magnetic properties, it seems to be less capable of dissipating heat than cobalt, making it generate more heat when a large amount of braking torque is reached. There is moderate growth in the rise in temperature with increasing braking torque in nickel. It possesses moderate thermal conductivity, hence the explanation of its lower temperature increase as compared to neodymium but higher than iron.

Finally, using iron, the temperature rise is small with the increase in braking torque. Iron, which is not as efficient as iron in regard to magnetic properties, can dissipate heat moderately, thus causing a slight rise in temperature if a braking torque is applied.

Considering these findings, one can say that cobalt is the best option in the context of braking applications when efficient heat dissipation is needed, and overheating is to be avoided, whereas neodymium is used in areas where a substantial braking force is needed, and overheating should be controlled. A compromise on thermal and braking comes in nickel and iron.

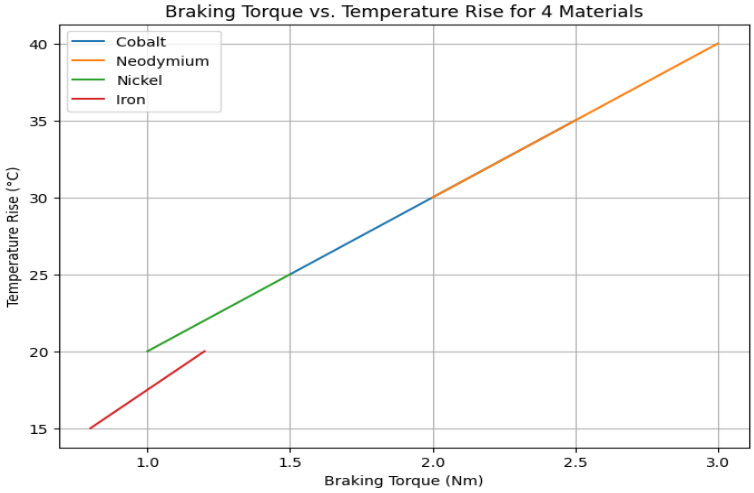

Fig. 9. Temperature rise vs. braking torque for different ferromagnetic materials

Here is an analysis of the potential plots that could be generated from the simulation. The subplots with braking force versus angular velocity and braking force versus braking time would allow useful comparisons of how the different materials perform under varying rotational speeds and over the duration of braking. Some insights that may emerge:

Neodymium and Cobalt are likely produce higher forces across most speeds/times due to their magnetic properties.

Nickel and Iron may lag at higher velocities due to weaker braking capacity.

Over time, materials like cobalt that generate excess heat may experience greater force degradation faster than others. The total heat versus time plot could reveal important longevity and safety implications.

Key aspects:

Cobalt would likely rise much quicker in temperature than the rest. This could cause reliability issues if not properly cooled.

Neodymium should see only a modestly higher heating rate than Nickel. Making it safer to use but still very capable.

Iron may warm up the slowest but offers little braking power to begin with.

Evaluating heating slopes could predict long-term durability differences between cores. Together, these simulations would provide insight into both the dynamic performance variations and thermal operating limits of the materials. Such comparisons are invaluable for selecting an appropriate core based on the key design priorities and duty cycle of a given braking application.

5. CONCLUSIONS

Based on the received results, it is possible to make the following conclusions:

The neodymium core offers sufficient levels of high braking torque/force output with comparatively low temperatures, such as nickel core between 30-40 °C, which is highly advantageous in general-purpose medium-duty hysteresis braking system design.

The core material cobalt exhibited good hysteresis braking properties with a high measured value of braking torque, 1.5-2.5 N.m. Its sensitivity to high temperatures of heating rates of 25-30 °C, however, can restrict its use to those applications where thermal management is able to accommodate such temperatures.

The nickel core was decent as compared to the cobalt and neodymium cores, and as a result, should be used to reduce the power braking requirement when operating at 20-25 °C.

The lowest temperatures which the iron core experienced in the braking torque range are those between 15-20 °C.

Simulation and testing of braking force with speed and thermal profile versus numerical simulation and testing of braking force with respect to speed and thermal profile give valuable information on performance and limitations to base material selection, depending on the application duty cycle and thermal dissipation capacity of the application.

When developing hysteresis braking systems, proper attention should be paid to the impact of the core composition on the main braking performance indicators such as torque, efficiency, temperature, life, and safety.

The above comparisons are quite useful in deciding on a core that is appropriate based on the duty cycle and other significant design specifications of a given brake application.

Through this study, more is known about the hysteresis braking process, and thus, in the future, a better design can be made with a higher efficiency.

6. REFERENCES

Abdulkareem, A.Q., Humod, A.T., Ahmed, O.A. (2023) 'Fault Detection and Fault Tolerant Control for Anti-lock Braking Systems (ABS) Speed Sensors by Using Neural Networks', Eng. & Tech. J., 41 (2), 333-344, https://doi.org/10.30684/etj.2022.135106.1259

Al-Araji, A.S. (2014) 'Designing a Nonlinear PID Neural Controller of Differential Braking System for Vehicle Model Based on Particle Swarm Optimization', Eng. & Tech. J., 32 (1A), 197-214, https://doi.org/10.30684/etj.32.1A.15

Basu, P.K. and Dhasmana, H. (2023) 'Electromagnetic Theory, Switzerland AG 2023. https://doi.org/10.1007/978-3-031-12318-4

Bottauscio, O., Chiampi, M., Chiarabaglio, D. and Repetto, M. (2000) 'Preisach-type hysteresis models in magnetic field computation', Physica B: Condensed Matter, 275 (1-3), 34–39, https://doi.org/10.1016/s0921-4526(99)00692-4

Caruso, M. Tommaso, A.O.D. Lisciandrello, G., Mastromauro, R.A., Miceli, R., Nevoloso, G., Spataro, C. and Trapanese, M. (2020) 'A General and Accurate Measurement Procedure for the Detection of Power Losses Variations in Permanent Magnet Synchronous Motor Drives, Energies, 13 (21) 5770. https://doi.org/10.3390/en13215770

Chandane, G. and Kulkarni, S. (2023) 'The Impact of Friction Material on Disc Brake Performance: A Review', Int. J. Eng. Resear. & Tech. (IJERT), 12 (9), https://doi.org/10.17577/IJERTV12IS090049

Coey, J.M.D. and Parkin, S.S.P. (2021) Handbook of Magnetism and Magnetic Materials, Springer Nature Switzerland AG 2021, https://doi.org/10.1007/978-3-030-63210-6_31

Donat, K. and Kanoun, O. (2016) 'Torque calibration with hysteresis brakes', 2016 13th IEEE Inter. Multi-Conf. on Syst., Signals & Devices (SSD), https://doi.org/10.1109/SSD.2016.7473669

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

Goodnight, N. and VanGelder, K. (2019) Automotive Braking Systems, 1st Edition, Jones & Bartlett Learning.

Hadžiselimović, M. Virtič, P. Štumberger, G. Marčič, T. Štumberger, B. (2008) 'Determining force characteristics of an electromagnetic brake using co-energy', J. of magnet. & magnet. Mater., 320 (20), 556-561, https://doi.org/10.1016/j.jmmm.2008.04.013

Huang, S., Bao, J., Ge, S., Yin, Y. and Liu, T. (2019) 'Design of a frictional–electromagnetic compound disk brake for automotives', J. Automob. Eng. 234 (4), https://doi.org/10.1177/0954407019864210

Hwang, S.-W., Lim, M.-S. and Hong, J.-P. (2016) 'Hysteresis Torque Estimation Method Based on Iron Iron-loss Analysis For Permanent Magnet Synchronous Motor', IEEE Transactions on Magnetics, 52 (7), https://doi.org/10.1109/TMAG.2016.2528998

Lee, J.-J., Kim, Y.-K., Rhyu, S.-H., Jung, I.-S., Chai, S.-H. and Hong, J.-P. (2012) 'Hysteresis Torque Analysis of Permanent Magnet Motors Using Preisach Model', IEEE Transactions on Magnetics, 48 (2), 935-938, https://doi.org/10.1109/TMAG.2011.2174435

Li, C., Zhuo, G., Tang, C., Xiong, L., Tian, W., Qiao, L., Cheng, Y. and Duan, Y. (2023) 'A Review of Electro-Mechanical Brake (EMB) System: Structure', Contr. & Applic., Sustain., 15 (5) 4514, https://doi.org/10.3390/su15054514

Lijesh, K.P., Kumar, D. and Hirani, H. (2017) 'Effect of disc hardness on MR brake performance', Eng. Fail. Analysis, 74, 228-238. https://doi.org/10.1016/j.engfailanal.2017.01.009

Liu, J.L., Wang, S.K. and Wang, J.Z. (2011) 'The Experimental Research of Magnetic Powder Brake Loading Characteristic in Rotary System', Appl. Mechan. & Mater., 130-134, https://doi.org/10.4028/www.scientific.net/AMM.130-134.3237

Mohammed, F.M., Mohammed, J.A.-K. and Faisl, H. (2021) 'Modeling and Simulation of an Electromechanical Brake System', IOP Conf. Ser.: Mater. Sci. Eng., 1105 (012051), http://doi.org/10.1088/1757-899x/1105/1/012051

Mörée, G. and Leijon, M. (2023) 'Review of Hysteresis Models for Magnetic Materials', Energies, 16(9) 3908, https://doi.org/10.3390/en16093908

Nakamura, S. and Motoi, N. (2021) 'Development of exoskeleton haptic device using powder brake and constant torque spring, Electr. Eng. in Jap., 214 (2), 651–661, https://doi.org/10.1002/eej.23311

Orthwein, W.C. (2004) Clutches and Brakes Design and Selection, 2nd Edition, Marcel Dekker, Inc. New Yourk, https://doi.org/10.1201/9780203026236

Putra, M.R.A., Nizam, M. and Tjahjana, D.D.D.P. (2021) 'Design of eddy current brake for electric motorcycle braking system', Int. J. Power Electron. & Drive Sys. (IJPEDS), 12 (1), 41-50, https://doi.org/10.11591/ijpeds.v12.i1.pp41-50

Putra, M.r.a., Nizam, M., Tjahjana, D.D.D.P. and A.R. Prabowo (2021) 'Mini Review on Eddy Current Brakes Parameter', 2021 IOP Conf. Ser. Mater. Scie. & Eng., 1096 (1) 012027, https://doi.org/10.1088/1757-899X/1096/1/012027

Salman, A.M., Mohammed, J.A.-K. and Mohammed, F.M. (2024) 'Analysis of Permanent Magnet Material Influence on Eddy Current Braking Efficiency', Iraqi J. Electr. and Electro. Eng., 20 (2), 220-225, https://doi.org/10.37917/ijeee.20.2.18

Salman, A.M., Mohammed, J.A.-K. and Mohammed, F.M. (2024) 'Effect of the material properties of the rotor-disc on the performance of eddy current braking systems', Eng. & Tech. J. 42 (8), 1061-1067, https://doi.org/10.30684/etj.2024.144221.1625

Salman, A.M., Mohammed, J.A.-K. and Mohammed, F.M. (2025) 'Investigation of the impact of conductive disk thickness on the electromagnetic efficiency of eddy current brakes', AIP Conf. Proceed., 3350 (1) (020011). https://doi.org/10.1063/5.0301545

Salman, A.M., Mohammed, J.A.-K. and Mohammed, F.M. (2025) 'Investigation of the impact of air gap length on the electromagnetic efficiency of eddy current brakes', AIP Conf. Proceed., 3350 (1) (060031). https://doi.org/10.1063/5.0301544

Shiao, Y. and Gadde, P. (2021) 'Investigation of hysteresis effect in torque performance for a magnetorheological brake in adaptive knee orthosis', Actuators, 10 (10) 271. https://doi.org/10.3390/act10100271

Shyrokau, B., Wang, D., Augsburg, K. and Ivanov, V. (2014) 'Vehicle dynamics with brake hysteresis, Proceedings of the Institution of Mechanical Engineers, Part D: J. of Autom. Eng., 227 (2), 139–150, https://doi.org/10.1177/0954407012451961

Tarte, Y., Chen, Y.Q., Ren, W. and Moore, K. (2006) 'Fractional Horsepower Dynamometer - A General Purpose Hardware-In-The-Loop Real-Time Simulation Platform for Nonlinear Control Research and Education, 2006 Proceed. of the 45th IEEE Conf. on Decis. & Contr., 3912-3917. https://doi.org/10.1109/CDC.2006.377021

Uluocak, I., Yavuz, H. and Gürsul, M. (2017) 'Effects of Rotor Material on Eddy Current Brake Performance, Europ. Mech. Scien., 1 (4), 129-132, https://doi.org/10.26701/ems.357456

Yangyang, J., Bao, J., Tuttle, M.E. and Hu, D. (2016) 'Influence of magnetic powders on the tribological performance of a novel magnetic brake material', Composite Interfaces, 24 (4), 1-17. https://doi.org/10.1080/09276440.2016.1218737