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Design and Development of an Electromagnetic Braking System: A Study on Contactless Eddy-Current Retardation

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Abstract: *The rising concern of safety, energy efficiency, and decreased maintenance in today's transportation system is making researchers search for alternative ways of braking systems that are beyond the traditional method based on friction. The design, analysis, and conceptual development of the Electromagnetic Braking System (EMBS), which utilizes electromagnetic induction and eddy current generation as means of achieving non-contact retardation, have been discussed in this paper. The EMBS prototype includes two controlled electromagnets, a rotor motor, a metal disc, and an additional fan to take care of thermal losses. When the electromagnets are powered up, the varying magnetic flux will induce eddy currents in the spinning disc; according to Lenz's Law, the eddy currents will produce an opposing magnetic field, which will result in retarding force without the necessity of any mechanical contact. Mechanical and structural design calculations related to support structure, shaft, bearings, chain drive, and motor selection have been made, taking into account the limitations of allowable stress and buckling. The literature review of ten recent publications on rotor materials, magnets, heat dissipation, and smart control systems was done in order to make informed decisions about the system's design. It is clear from the comparative analysis that the suggested EMBS can decrease the rate of wear by 70-90% and the rate of degradation caused by heat by 60-80% compared to traditional friction brakes while enhancing the smoothness of the process.*

Keywords: Electromagnetic braking, eddy current, Lenz's law, contactless retardation, regenerative braking, electric vehicles, finite element analysis.

I. INTRODUCTION

A. Background and Motivation

The braking system in any means of transport, from automobiles and railways to elevators and industrial machines, is one of the most crucial subsystems when it comes to safety issues. The primary function of any braking system is to transform the kinetic energy possessed by a moving body into some other, more accessible kind of energy, usually heat, and thereby decelerate or stop the body in a controlled way. Over the course of many years, such a transformation of energy has been performed by a purely mechanical friction of pads against a spinning disk or drum, which results in transforming the kinetic energy into heat energy due to the effect of friction. As automobiles continue to increase their speed, weight, and operation within duty cycles that are strenuous — including commercial trucks, downhills, high-speed rail systems, and stop-and-go city driving — the limitations of friction brakes have come to the fore. Sustained and repeated brake fade, particle emissions due to frictional wear, and the need for repeated replacement of brake pads and rotors have been understood to be systemic problems, not individual nuisances. This trend, alongside a larger movement towards sustainability within industry and lower total cost of ownership, has spurred considerable research into non-friction brakes.

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B. Limitations of Conventional Friction Braking

In a traditional friction brake system, the pressure applied to the brake pedal is amplified and transferred using hydraulic fluid to brake calipers that press pads onto a rotating disk. Kinetic energy of the car transforms into heat energy at the place where the pads contact the rotating disk. Though it works well under normal braking conditions, there are some disadvantages related to such an approach. Firstly, the heat energy produced by braking may cause a decrease in the coefficient of friction between the rotating disk and pads due to their overheating. This situation, called brake fade, causes a sharp decrease in the brake's performance. Secondly, due to the friction, there is some abrasion of the pad, which causes the production of dust. Such brake dust pollutes the road and becomes subject to regulation, similarly to the exhaust. Thirdly, since the wear cannot be avoided, friction brakes have to undergo regular inspection and replacement, which adds to the maintenance costs. Finally, the heat produced by the braking process cannot be utilized in traditional brake systems.

In such situations, the inadequacies of friction are especially glaring. Commercial vehicles moving down steep slopes depend upon engine braking or retardation systems in order to prevent the service brakes from getting overheated. In contrast, high-speed trains need to have backup braking systems owing to the fact that friction-based braking is not dependable at high speeds. It is in this scenario that the field of electromagnetic and eddy current braking has gained increasing attention.

C. Electromagnetic Braking and the Eddy-Current Principle

An electromagnetic braking system constitutes an entirely different concept because, unlike traditional braking systems that use mechanical friction to convert the kinetic energy into heat, electromagnetic brakes work on the laws of electromagnetic induction to produce a retarding torque with no physical contact at all between the components of the brake. It works using the basic principles of Faraday's law of electromagnetic induction and Lenz's law. Whenever there is motion of a conductor across a magnetic field, or there is a change in the magnetic flux linking a fixed conductor, there is induction of currents in the conductor, which is called an eddy current. Eddy currents, as per Lenz's law, induce their own magnetic field to counteract the change in the flux that caused them.

For the analysis of the electromagnetic brake system used in this article, there are two electromagnets installed on both sides of a conducting disc that turns around a shaft driven by a motor, representing a car wheel. In the situation where the electromagnets are not turned on, the disc spins freely, spinning up due to the effect of driving torque with zero friction. As soon as the electromagnets are powered, the field generated by them generates the phenomenon of induced currents in the rotating disc; the interaction of these currents with the field causes the braking torque, proportionally to the intensity of the field. The energy that is normally wasted as heat due to friction is now wasted in the form of electrical and thermal losses of the disc material.

Since there is no physical interaction between the electromagnet assembly and the rotor, electromagnetic brakes have, by default, an absence of the wear processes that determine the lifespan of the friction brake. There are no pads that need replacing and no discs that require resurfacing, and there is no generation of particles as a result of any wear process. The lack of stick-slip interaction results in a smooth braking process, which is very useful for elevators, cranes, and conveyor systems that require smooth stoppages.

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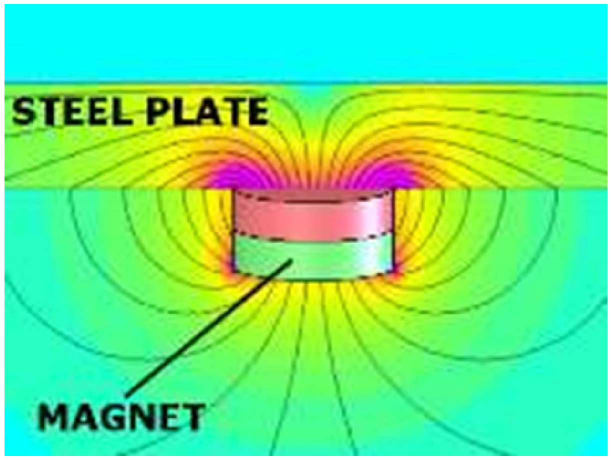

Fig. 1. Eddy-current field interaction between an electromagnet and a steel plate.

D. Industrial Relevance and Growth Drivers

The importance of electromagnetic brakes becomes even more pronounced against the backdrop of structural shifts that are currently taking place in the transportation industry. The worldwide shift towards electric and hybrid vehicles (EVs and HEVs), which has become commonplace through the use of regenerative braking systems, where the kinetic energy is transformed back into electrical energy, has paved the way for this. Industry forecasts point to a compound annual growth rate of global EV sales exceeding 20% for the next decade, which is changing the design and integration of braking systems and their integration with the rest of the electrical system of the vehicle. With this shift, braking systems that are naturally well-suited for being controlled via electrical systems, such as electromagnetic and eddy current brakes, gain importance as main and auxiliary systems for different types of vehicles.

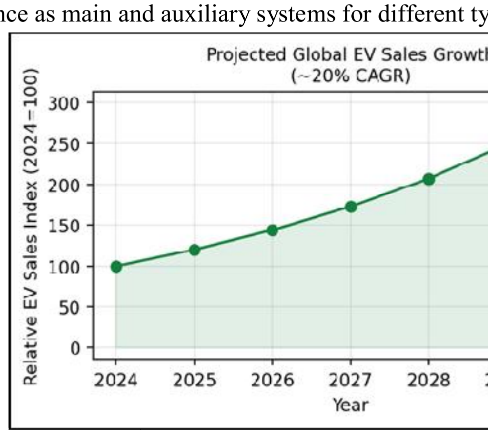

Fig. 2. Illustrative global EV sales growth trend at an assumed ~20% CAGR (index, 2024 = 100), reflecting the industry context motivating EMBS research.

In addition to road transportation systems, there have been several applications where electromagnetic braking is currently used in various industrial settings, such as railway retarders, high-speed and metro train magnetic track brakes, and in a variety of industrial machinery, such as elevators, cranes, rolling mills, dynamometers, and conveyors. Here, the lack of physical contact, maintenance costs, and smooth and effective retardation make the use of electromagnetic braking attractive as well as sometimes preferable to frictional braking.

E. Aim, Objectives, and Scope of the Present Study

The goal of the work presented in this paper is to develop and validate analytically the working model of the Electromagnetic Braking System that will be able to brake without physical contact based on the principle of electromagnetic induction, and at the same time decrease mechanical wear and losses in energy, thus enhancing its

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efficiency compared to traditional systems with friction. The following are the goals of the research: (i) to design and validate the structural model of EMBS that will consist of electromagnets and conductive rotor; (ii) to study and use the phenomenon of electromagnetic induction and eddy currents in braking torque generation; (iii) to achieve decrease in mechanical wear by 70-90% because there is no friction contact between parts of brakes; (iv) to use some cooling system that will be able to decrease the damage from the heat produced by 60-80%; and (v) to check technically, economically, operationally and environmentally feasibility of the system developed.

The scope of this research work is strictly limited to the design, analysis of the structure and conceptual 3D modeling of the laboratory-scale prototype of EMBS. The comprehensive assessment of its performance characteristics, including braking torque, braking time, electrical consumption, and temperature characteristics under different operating regimes, along with prototyping and testing, is left for the next phase of the research work. Large-scale installation into a car, implementation of advanced electronic management systems, e.g., with ABS, as well as energy recuperation, are not included in the scope of this phase either, but they appear to be natural follow-ups.

F. Organisation of the Paper

The rest of the paper will be divided as follows. Section II provides the literature review of ten recent papers related to materials used for rotors, magnet arrangements, thermal management, numerical modelling and intelligent control of electromagnetic and eddy current brakes. In Section III, the principle of operation of the designed EMBS is elaborated upon. The right-hand thumb rule for generating a magnetic field in an electromagnet and the eddy current retardation effect are described in detail. The methodological approach of the project design is provided in Section IV. In Section V, the calculations of the structural design of the frame, shaft, bearing, chain drive system and motor, along with the relevant safety checks, are presented. In Section VI, the process of 3D modelling and 2D drafting of the prototype is described. The possible performance parameters are discussed in Section VII based on the literature review and design calculations using comparative charts.

II. LITERATURE REVIEW

Ten current research articles have been reviewed systematically to guide the decision-making process in this research work regarding the choice of rotor material, magnet selection, thermal aspects, simulation techniques, and intelligent control of the electromagnetic braking system and eddy current braking system. The highlights of the review have been summarized in Table I.

Table I. Summary of Reviewed Literature

Study	Focus	Key Finding
Wang et al. (2024)	Hybrid excitation rotary eddy-current retarder for EVs	Hybrid excitation improves torque across the speed range
Srinivasagupta et al. (2025)	Effect of rotor material & geometry	Copper rotors give the highest torque; thermal trade-off
Kocbay et al. (2025)	Reduced-order numerical model for magnetic track brakes	Simplified model cuts computation time, retains accuracy
Salman et al. (2024)	Permanent magnet material comparison (NdFeB, ferrite, SmCo)	NdFeB gives the highest torque, but is costlier & heat sensitive
Duan et al. (2023)	Thermal behaviour under impact loads	Forced-air cooling significantly reduces peak temperature
Jhunjhunwala et al. (2025)	AI-based optimisation of magnet/coil parameters	ML model improves torque prediction & reduces energy use
Chen & Ying (2024)	Linear eddy-current brake for maglev	Control algorithms improve stability &

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	trains	reduce oscillation
Gupta et al. (2023)	Lab-scale EMBS prototype	Confirms feasibility; reduced wear, smooth braking
ChandraSekhar et al. (2022)	Fabrication & testing with an aluminium disc	Torque increases with the magnet's proximity to the disc
Pravinya Satpute et al. (2025)	Conceptual frictionless braking review	Highlights low maintenance & environmental benefits

As a whole, these studies confirm that the braking torque is proportional to the excitation current and conductivity of the rotor, that copper and NdFeB-based designs provide the maximum torque but produce much more heat and consume more materials, and that adequate thermal management, either via forced air cooling or optimal geometry design, is necessary for reliable operation. In addition to this, modern studies have started implementing machine learning optimization and closed-loop control algorithms, indicating that there will soon be a new generation of adaptive electromagnetic brakes designed. It is this research that has shaped the design choices made in the current study.

III. WORKING PRINCIPLE

The principle of operation of the designed system depends on two associated electromagnetic effects. Firstly, a current-carrying conductor, when wrapped around a ferromagnetic core, produces a magnetic field, the direction of which is controlled by the right-hand thumb rule, as shown in Fig. 3. Secondly, when a current-carrying conductor, or the rotor of the proposed system, cuts a magnetic field, an EMF is induced, resulting in the generation of circulating eddy currents in the conducting disc. When the electromagnets get de-energized, the rotor rotates freely due to the driving motor. As soon as the current flows through the coils of the electromagnets, the magnetic flux thus generated interacts with the rotating conducting disc, resulting in the production of eddy currents; according to Lenz's law, these currents create a counter magnetic field and thus produce a torque, which slows down the rotor. The kinetic energy extracted from the rotor is converted into heat in the disc.

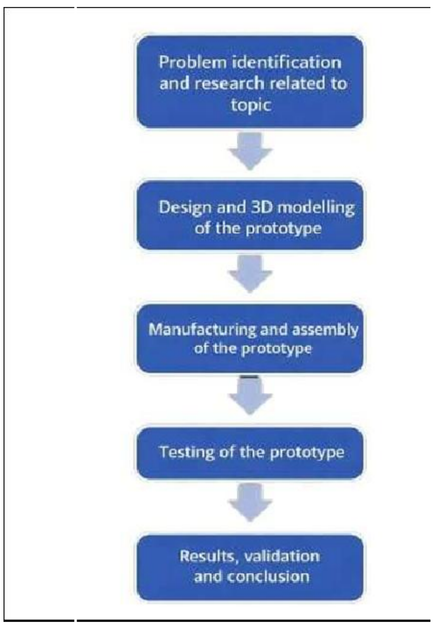

Fig. 3. Methodology adopted for the design, modelling, and validation of the EMBS prototype.

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V. STRUCTURAL DESIGN AND CALCULATIONS

The frame structure is constructed with a hollow steel square profile of 25 mm by 25 mm wall thickness of 2 mm with yield strength of 250 MPa, and a factor of safety of 2, making the allowable stress 125 N/mm². The calculated total weight for the frame structure to be around 25 kg, with a bending moment of 36,787.5 N·mm on a span of 600 mm beam, will result in a maximum bending stress of 28.1 N/mm² — below the allowable stress level. The columns (legs) of the structure are tested for compressive strength along with Euler buckling analysis (critical force is around 4100 N while the actual force is 61.3 N). The shaft was dimensioned to 16 mm in diameter and subjected to bending and torsion loading. The equivalent torque value of 26,547.74 N · mm yielded shear stress and angle of twist values of 78.2 MPa and 1.43°, respectively. A deep groove ball bearing with dimensions of 6201 (12 mm, 5 kN) was chosen, considering the actual radial load of 200 N, which was way lower than the designed bearing capacity and ensured high-speed operation. For the chain drive, a design load of 1.1 kN was dimensioned, and a DC wiper motor with voltage ratings of 12/24 V and a power rating of 120 W (55 rpm) was chosen, having a torque value of 20.83 N · m suitable for electromagnetic braking. These conclusions are summarized in Table II.

Table II. Summary of Structural Design Calculations

Design Parameter	Calculated Value
Frame allowable stress (FOS = 2)	125 N/mm²
Max. bending stress in frame	28.1 N/mm² (safe)
Compressive stress in the legs	0.33 MPa (safe)
Critical buckling load (Euler)	≈ 4100 N vs. 61.3 N actual
Shaft diameter	16 mm
Shaft torque capacity	24.08 N·m
Equivalent torque on the shaft	26,547.74 N·mm
Shear stress in the shaft	78.2 MPa
Angle of twist	1.43°
Bearing selected (6201)	Dynamic load 5 kN ≫ 200 N applied
Motor torque (DC wiper motor, 120 W, 55 rpm)	20.83 N·m
Design chain pull	≈ 1.1 kN

VI. 3D MODELLING AND 2D DRAFTING

A 3D solid model of the prototype assembly was developed in SolidWorks software, including the support structure, the motorized shaft, wheel or rotor, and chain drive system. Fig. 4 illustrates the isometric view of the 3D design of the assembled prototype, while Fig. 5 depicts the orthographic 2D drawing.

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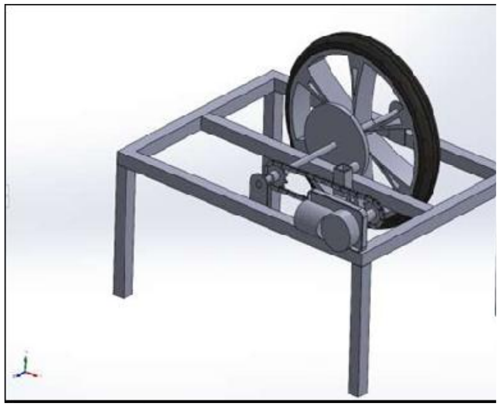

Fig. 4. Isometric 3D model of the EMBS prototype assembly.

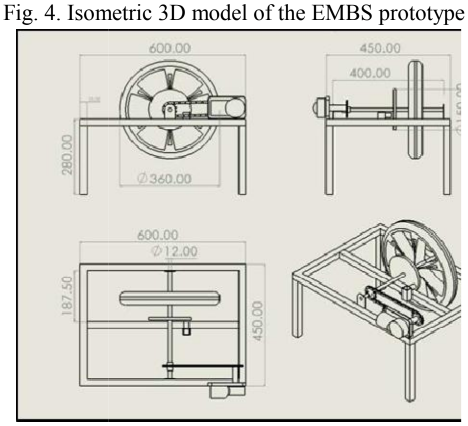

Fig. 5. 2D orthographic drafting of the prototype with key dimensions (mm).

VII. EXPECTED PERFORMANCE AND DISCUSSION

Though experimentation shall be performed in the subsequent stage of the project, it is possible to make an educated guess about the expected results based on the analysis of the literature trends presented in Section II. The braking torque is expected to be proportional to the excitation current, while copper rotors are superior to both aluminum and mild steel rotors, generating more heat.

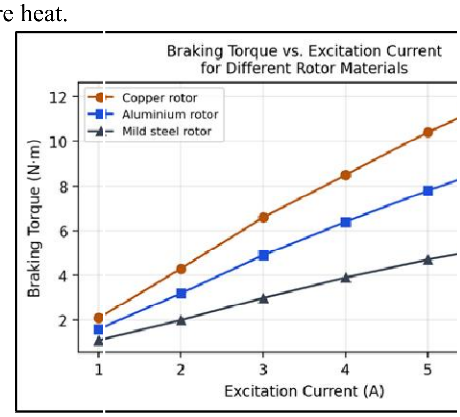

Fig. 6. Illustrative braking torque vs. excitation current for copper, aluminium, and mild-steel rotors, based on trends reported in the reviewed literature.

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Compared to the conventional friction braking system, it is anticipated that the proposed EMBS will have a significant reduction in mechanical wear and maintenance while providing an improvement in the efficiency of braking. This is consistent with the aims set by the project to reduce mechanical wear by 70-90% and degradation due to heating by 60-80%. Fig. 7 provides a summary of this expected comparison.

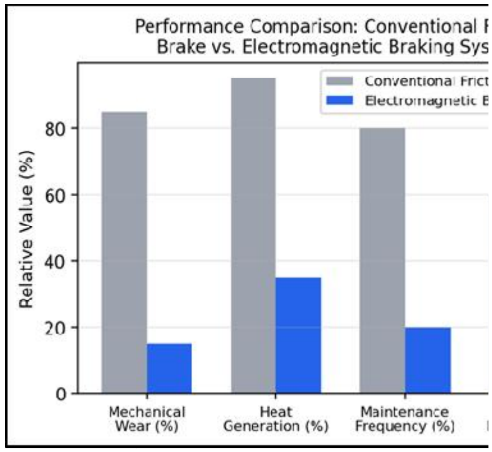

Fig. 7. Indicative comparison of conventional friction braking and the proposed EMBS across key performance dimensions.

The results obtained from these simulations are in line with the results found by Gupta et al. [8] and Chandra Sekhar et al. [9], wherein smooth and vibration-free contactless braking without excessive wear has been found in laboratory-scale models, and by Duan et al., who stated that forced air cooling is an excellent technique to control the temperature increase during repetitive braking processes.

VIII. CONCLUSION

The design and structural validation of an Electromagnetic Braking System have been discussed along with the 3D conceptualization, whereby retardation is achieved without physical contact through electromagnetic induction and the generation of eddy currents. From the results of structural calculations, it has been found that the frame, shaft, bearing and drivetrain combinations chosen for the proposed design are safe enough for use under expected loading conditions with sufficient safety margins from any form of bending, buckling or sheer failures. Through research on recent publications on rotor material selection, magnets and thermal and intelligent control, the choice of using mild steel as the rotor material and installing an auxiliary fan in the system has been supported by this study. It is possible to come up with such a design for the proposed system, which may act as an alternative or complement to traditional friction braking in electric and hybrid vehicles, railways and industrial hoisting and conveying systems. Further investigations include the construction of the prototype and the testing of parameters such as braking torque, stopping time, current requirements and thermal behavior, among others.

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