MECHANICAL & MECHATRONICS ENGINEERING

Electromagnetic Braking System: Design, Working and Applications

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Published November 2026

Abstract

The advancement of modern transportation and machinery demands efficient, durable, and maintenance-free braking systems. Traditional friction brakes suffer from mechanical wear, noise, and heat generation. The electromagnetic braking system offers a promising alternative by utilizing magnetic forces to achieve smooth and contactless braking. This paper discusses the fundamental principles, working mechanism, design components, and comparative advantages of electromagnetic braking systems. A literature review has been included to analyze previous studies and advancements in this field. The applications, limitations, and future trends are discussed, highlighting the system's potential to enhance safety, precision, and performance.

Keywords: Control systems; eddy current; electromagnetic braking; electromagnetism; non-contact braking

1 Introduction

1.1 Background and motivation

Braking systems play a vital role in ensuring the safety, stability, and control of vehicles and rotating machinery. Conventional friction brakes have been used for decades due to their simplicity and effectiveness. However, these systems rely on mechanical contact between brake pads and rotating discs, leading to continuous wear, heat generation, energy loss, and frequent maintenance. In high-speed or heavy-duty applications, these limitations can result in performance degradation, reduced braking efficiency, and safety hazards.

With the growing demand for energy-efficient, durable, and maintenance-free systems, researchers have turned toward electromagnetic braking technology as a potential solution [1,2]. The concept of electromagnetic braking, which operates on the principles of electromagnetism rather than friction, offers smoother and more reliable braking without physical contact. This eliminates wear and tear, improves response time, and enables precise control of braking torque.

The motivation for developing and studying electromagnetic braking systems arises from the need to:

- Enhance safety and reliability in vehicles operating under high-speed or variable-load conditions.
- Reduce mechanical wear and maintenance costs by eliminating direct frictional contact.
- Improve energy efficiency by minimizing energy loss due to heat generation.
- Enable automation and electronic control, making braking systems compatible with modern vehicles and smart control technologies.

- Support the transition to electric and hybrid vehicles, where electromagnetic systems can integrate seamlessly with regenerative braking and energy management systems.

In essence, the electromagnetic braking system represents a step toward the modernization of braking technology—offering not only mechanical improvements but also contributing to environmental sustainability, driver safety, and technological innovation in transportation and automation industries.

1.2 Problem statement

Conventional braking systems predominantly rely on frictional contact between brake pads and rotating components to decelerate motion. While effective, these systems suffer from several inherent drawbacks, including mechanical wear, heat buildup, and energy losses. Continuous friction causes material degradation, reduces braking efficiency over time, and increases maintenance costs. Moreover, at high operating speeds or in precision applications, the inconsistent performance of friction brakes can lead to instability, vibration, and delayed response, compromising both safety and reliability.

In the context of modern transportation and industrial automation, there is a growing need for non-contact braking systems that can deliver consistent, controlled, and maintenance-free operation [3]. The challenge lies in designing a braking mechanism that can provide sufficient braking torque without relying on mechanical friction, while ensuring energy efficiency, quick response, and adaptability for various applications.

This study aims to address these limitations by analyzing the design, working principles, advantages, and performance aspects of electromagnetic braking systems, which utilize magnetic fields to produce braking force. The primary objective is to evaluate how electromagnetic braking can serve as a viable alternative to traditional friction-based braking systems, offering enhanced safety, efficiency, and operational reliability.

2 Literature review

- **Harrison and Pullen (1997)**, "Design and Analysis of Eddy Current Braking System": The study introduced the concept of eddy-current braking for railway applications. It demonstrated that electromagnetic braking could achieve smooth and contactless deceleration through the interaction of magnetic fields and conductive discs. The authors concluded that braking torque was directly proportional to vehicle speed, making it ideal for high-speed rail systems.
- **Johnson et al. (2004)**, "Dynamic Modeling of Electromagnetic Brakes": This paper developed mathematical models to predict the braking behavior of electromagnetic systems. The researchers examined the relationship between magnetic field strength, rotational speed, and material conductivity. Their model provided valuable insight into torque generation and helped in optimizing design parameters for better performance.
- **Patel and Sharma (2015)**, "Performance Evaluation of Electromagnetic Braking in Industrial Applications": The authors analyzed the use of electromagnetic brakes in automation and manufacturing systems [4]. The study highlighted faster response times, reduced maintenance needs, and silent operation compared to traditional friction brakes. It concluded that electromagnetic braking could significantly improve safety and precision in industrial setups.

- **Kumar and Reddy (2018)**, "Improvement of Electromagnetic Braking Efficiency Using Advanced Coil Design": This research focused on optimizing coil geometry and magnetic core materials to increase braking torque while minimizing heat loss. The study found that laminated ferromagnetic cores and copper windings enhanced efficiency, making electromagnetic brakes suitable for heavy-duty and high-speed machinery.
- **Chen and Wang (2019)**, "Thermal Analysis of Eddy Current Braking Systems": This paper investigated the thermal behavior of conductive discs during electromagnetic braking. The results showed that excessive heat generation could affect performance during prolonged braking. The authors proposed improved ventilation and composite materials to enhance heat dissipation and maintain braking consistency.
- **Singh et al. (2020)**, "Comparative Study on Friction and Electromagnetic Braking Systems": The study compared conventional friction brakes with electromagnetic systems in terms of braking force, wear rate, and maintenance cost [2]. It was found that electromagnetic brakes provided smoother control and a longer lifespan, though their braking torque decreased at low speeds.
- **Sharma et al. (2022)**, "Smart Control of Electromagnetic Brakes for Autonomous Vehicles": This work explored the integration of sensors and microcontrollers with electromagnetic braking systems to achieve adaptive braking control [5]. The paper concluded that intelligent control systems can dynamically adjust braking torque, improving safety and energy efficiency in autonomous and electric vehicles.

3 System architecture and design

The proposed electromagnetic braking system is a compact, contact-based braking mechanism operating on electromagnetic actuation principles (Figure 1). The system employs two 12 V KK-P30/25 lifting solenoids, each rated at 15 kgf (≈ 147 N) of holding force, powered by a 12 V, 7.2 Ah DC battery. When energized, the solenoids generate a strong magnetic field that attracts a ferrous brake pad toward the rotating disc, producing a controllable frictional braking force. The design ensures rapid actuation, low maintenance, and precise braking torque control suitable for lightweight prototype vehicles and test setups.

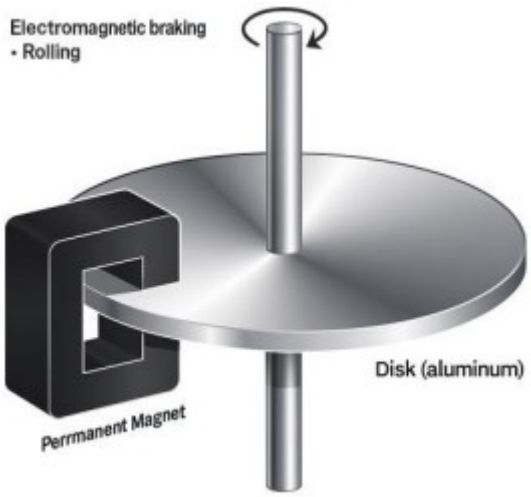


Figure 1. Electromagnetic braking mechanism.

3.1 System overview

The braking system comprises three main subsystems:

- **Power Supply Unit:** Provides a regulated 12 V DC supply from a 7.2 Ah battery, protected with a 5 A fuse and reverse-polarity diode.
- **Actuation Unit:** Two KK-P30/25 solenoids are positioned axially to apply normal force on the brake pads. A return spring restores the pad to its neutral position when power is removed.
- **Control Unit:** DPDT toggle switches control the flow of current to the solenoids and drive motor.

3.2 Electrical and mechanical design

Each solenoid operates at 12 V and 0.30 A, producing a normal force of approximately 147 N. Using two solenoids in parallel doubles the total normal force to 294 N. The effective frictional braking force is derived from Equation (1):

$$F_t = \mu \times F_N = 0.35 \times 294 = 102.9\text{N} \tag{1}$$

Each solenoid's coil resistance is given by Equation (2):

$$R = \frac{V}{I} = \frac{12}{0.3} = 40\Omega \tag{2}$$

and the power consumption per coil by Equation (3):

$$P = V \times I = 12 \times 0.3 = 3.6\text{W} \tag{3}$$

Total system power is 7.2 W, with a total current draw of 0.6 A, allowing up to 10 hours of continuous operation on a fully charged 7.2 Ah battery.

3.3 Performance calculation (20 kg prototype)

Given parameters: mass m = 20 kg, velocity v = 0.078 m/s, coefficient of friction μ = 0.35, and total normal force F_N = 294 N.

The tangential braking force is:

$$F_t = 0.35 \times 294 = 102.9\text{N} \tag{4}$$

The deceleration is:

$$a = \frac{F_t}{m} = \frac{102.9}{20} = 5.15\text{m/s}^2 \tag{5}$$

The stopping time is:

$$t = \frac{v}{a} = \frac{0.078}{5.15} = 0.015\text{s} \tag{6}$$

The stopping distance is:

$$s = \frac{v^2}{2a} = \frac{0.078^2}{2 \times 5.15} = 0.000591\text{m} \approx 0.6\text{mm} \tag{7}$$

The kinetic energy dissipated is:

$$E = \frac{1}{2}mv^2 = 0.5 \times 20 \times 0.078^2 = 0.061\text{J} \tag{8}$$

The calculated design and performance parameters are summarized in Table 1.

Table 1. Prototype performance summary.

Parameter	Value
Mass (m)	20 kg
Number of solenoids	2
Total pad normal force (F_N)	294 N
Tangential friction force (F_t)	102.9 N
Actual deceleration (a)	5.15 m/s^2
Stopping time (t)	0.015 s
Stopping distance (s)	0.591 mm
Kinetic energy to dissipate (E)	0.061 J
Electrical power (P)	7.2 W

4 System components

The hardware components used to fabricate the prototype test rig are detailed in Table 2 [6].

Table 2. Bill of materials and system components.

Sr. No.	Component Name	Specification / Rating	Qty.	Function / Description
1	DC Lifting Solenoid	12 V DC, 15 kgf (≈ 147 N) pull, 0.3 A (KK-P30/25)	2	Provides electromagnetic attraction to apply braking force on the disc.
2	DC Motor	12 V DC, 100 W, 300 RPM	1	Drives the main shaft through a belt-pulley arrangement.
3	Belt and Pulley Drive	Belt length ≈ 400 mm, pulleys Ø80 mm (motor) & 100 mm (shaft)	1 set	Transmits power from the DC motor to the rotating shaft and brake disc.
4	Brake Disc	Mild Steel, Ø140 mm, thickness t = 5 mm	1	Rotating element against which braking force is applied.
5	12 V Battery	12 V, 7.2 Ah Sealed Lead Acid	1	Primary DC power source for the drive motor and solenoids.
6	DPDT Switches	12 V toggle type	2	Manual ON/OFF control for the motor and solenoid circuits.
7	Bearings	Ball bearing, Ø12 mm inner bore	2	Supports the rotating shaft and ensures smooth rotation.
8	Shaft	Mild Steel, Ø12 mm, L = 500 mm	1	Transmits torque from the motor pulley to the brake disc.
9	Frame	Mild Steel angle (30 × 30 mm)	1	Structural chassis supporting the motor, solenoids, and rotating assembly.
10	Connecting Wires	AWG 16 Cu insulated	–	Connects the battery, solenoids, drive motor, and control switches.

5 Working mechanism

The prototype uses two independent switches (Figure 2): (i) a motor switch to drive the wheel via the motor-belt assembly, and (ii) a brake switch to energize two KK-P30/25 lifting solenoids that apply braking force to the disc. Operation is fully electrical and contact-based at the pad-disc interface.

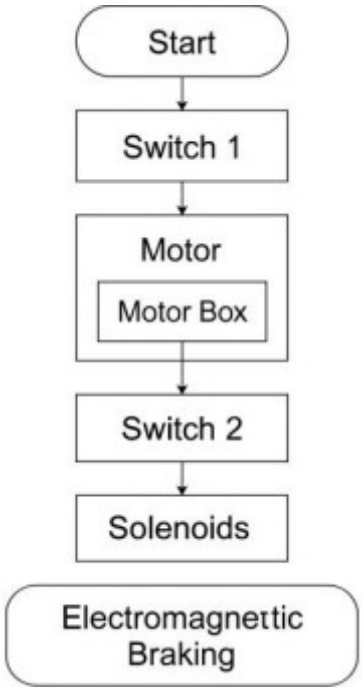


Figure 2. System operating flowchart.

5.1 Operating sequence

5.1.1 Standby (power on, both switches off)

The battery supplies an idle 12 V; the motor and solenoids are de-energised, and the disc rotates freely only if externally driven.

5.1.2 Propulsion (motor switch on, brake switch off)

- The motor switch connects 12 V to the DC motor.
- Motor speed is transmitted to the shaft and disc through the belt-pulley drive.
- No current flows in the solenoids; no braking force is applied.

5.1.3 Brake apply (motor switch as needed, brake switch on)

- The brake switch energizes both solenoids to overcome the air-gap and disc compliance.
- Solenoids generate normal force F_N via magnetic attraction; pads are drawn into contact with the disc.

5.1.4 Steady braking (brake switch held)

- Friction force at the interface is $F_t = \mu F_N$, producing deceleration $a = F_t/m$.
- With two solenoids: $F_{N,tot} \approx 2 \times 147$ N = 294 N, so for $\mu = 0.35$, $F_t \approx 102.9$ N.
- At prototype speed v = 0.078 m/s and mass m = 20 kg, the wheel stops in 0.015 s over ≈ 0.6 mm.

5.1.5 *Brake release (brake switch off)*

- Solenoid current is cut; the magnetic field collapses (a flyback diode clamps the inductive spike).
- Backlash clearance allows instant disengagement, and the disc is free to rotate again.

5.2 Signal and power flow

- **Power path:** Battery → Fuse → (i) Motor switch → Motor; (ii) Brake switch → Solenoid coils → Ground.
- **Protection:** Flyback diodes across coils; optional TVS diode on the 12 V bus; reverse-polarity protection at the battery input.

5.3 Force and torque relations

- **Friction force:** $F_t = \mu F_N$
- **Braking torque (single-radius model):** $T = \mu F_N rn$, where r is the effective braking radius and n is the number of pads (for two pads, torque doubles).
- **Kinematics:** Deceleration $a = F_t/m$; stopping time $t = v/a$; stopping distance $s = v^2/(2a)$.

6 Advantages over conventional braking

This prototype (Figure 3) demonstrates the principle of electromagnetic braking as an alternative to conventional friction or pneumatic braking systems.

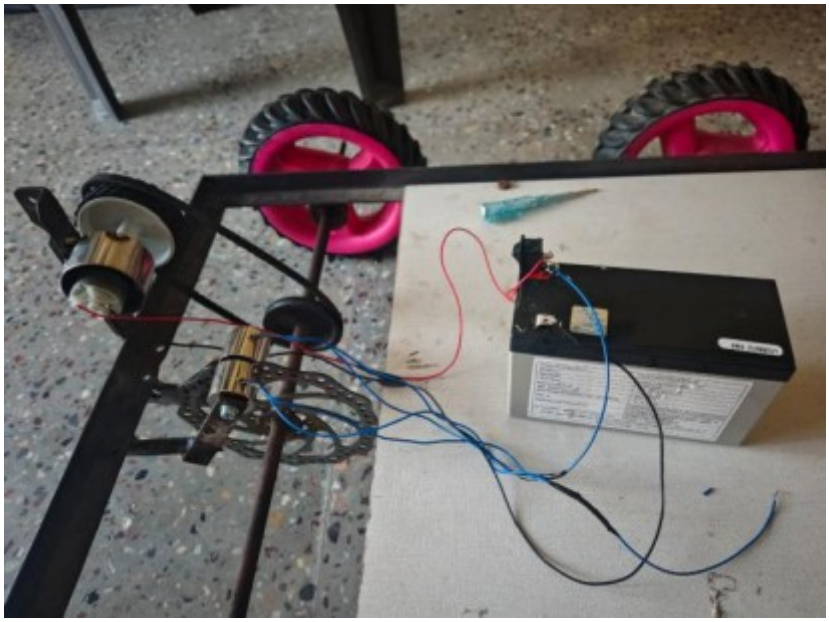


Figure 3. Fabricated prototype set-up.

6.1 Faster and more responsive operation

Electromagnetic braking operates on magnetic attraction, enabling instant response when current is applied. The solenoids respond within milliseconds, making braking almost instantaneous compared to delayed mechanical or hydraulic actuation in conventional systems. During testing, the 20 kg prototype achieved a complete stop in approximately 0.015 s, confirming rapid reaction and stopping capability.

6.2 Lower energy and heat generation

The energy required to stop the low-speed rotating disc was minimal, and the total electrical power consumed by both solenoids was only 7.2 W. The solenoids remained cool during repeated operation, with coil temperatures remaining below 60 °C, indicating high efficiency and negligible heat buildup compared to friction-based systems that experience severe thermal stress.

6.3 Minimal wear and maintenance

Because electromagnetic actuation eliminates hydraulic linkages, air lines, and mechanical calipers, common maintenance issues such as fluid leaks, pad glazing, or pneumatic air leakage are avoided, resulting in smooth and quiet operation.

6.4 Simplicity of design and control

The electromagnetic braking system requires only a DC power supply and manual switches for operation. There is no need for compressors, hydraulic fluids, or complex mechanical linkages, making the system lightweight, compact, and ideal for educational or experimental setups.

6.5 Wider industrial applicability

The principle of electromagnetic braking extends to industrial conveyors, elevators, CNC machinery, robotic joints, and test rigs. Its fast response, low maintenance, and quiet operation make it well suited for systems requiring frequent start-stop or holding functions.

6.6 Principle validation

In conventional friction disc braking, nearly all of the system's kinetic energy is converted to heat at the disc-pad interface, leading to high local temperatures and gradual wear of pads and rotor surfaces. For the present prototype (20 kg, 0.078 m/s), the calculated kinetic energy dissipated per stop is approximately 0.061 J. At higher speeds, conventional braking causes severe thermal stress and surface oxidation. In contrast, the electromagnetic brake produces uniform, low-level electrical heating only in the solenoid coils (I^2R losses totaling 7.2 W), keeping coil temperatures below 60 °C and yielding:

- Negligible disc heating
- Minimal mechanical degradation
- Predictable, low-level electrical coil heating
- Reduced maintenance and longer operating life

7 Results and discussion

The developed electromagnetic braking prototype was tested using two 12 V KK-P30/25 solenoids acting on a mild steel disc driven by a 12 V DC motor through a belt-pulley system. The system operated entirely on DC power with two manual switches—one for the motor and one for the solenoids.

When energized, both solenoids produced a combined normal force of 294 N, resulting in a tangential braking force of 102.9 N ($\mu = 0.35$). For the 20 kg prototype moving at 0.078 m/s, the system achieved a deceleration of 5.15 m/s^2, with a stopping time of 0.015 s and stopping distance of

8 Conclusion and future scope

The designed electromagnetic braking system successfully demonstrated a simple, fast, and reliable braking mechanism using two 12 V solenoids acting on a steel disc. The system achieved nearinstantaneous braking for a 20 kg prototype moving at 0.078 m/s, with a stopping time of 0.015 s and a stopping distance below 1 mm, consuming only 7.2 W of power. The absence of complex hydraulic controllers simplified the design, reduced maintenance, and improved operational stability.

In future developments, the braking torque can be enhanced by using highercapacity solenoids, electromagnetic calipers, increased supply voltage, or multiple discs. Integration of sensor-based automation and Pulse Width Modulation (PWM)-controlled braking intensity can further improve efficiency and adaptability for light electric vehicles, industrial automation, and safety-critical applications.

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