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PM based Eddy Current Braking for Automobile Applications

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***Abstract*—Of late, there is overwhelming growth of the e-mobility sector and hence, growing interest in integrating automotive electronics. In this context, the present paper discusses Eddy Current Braking (ECB) Systems. Electrification of the braking systems would aid in gaining electronic control and total integration of electrical and electronic components in an automobile. Electrical eddy-current braking is a prominent type of braking systems used in textile, oil rigs and locomotive sectors. Potential of incorporating ECB with existing frictional braking to form Integrated braking systems for automotive braking applications is explored. ECB provide retardation, while frictional components are required to halt the brake disc. Development of analytical model and a preliminary hardware model are carried out in the present paper.**

***Index Terms*— Eddy Current Braking, electrical braking systems, permanent magnets.**

I. INTRODUCTION

Brakes have changed considerably from traditional wooden log blocks to present day Automatic braking systems. For more than 100 years, braking systems have evolved to adapt with improving automotive capabilities and road conditions. Throughout history, the mechanical friction type of braking mechanism has been favored, with little to no advocation towards Electrical or electromagnetic braking. With the exponential growth of e-mobility sector and interest of electrifying automotive components, the focus on electric braking is gaining prominence.

In the present paper, Eddy Current Braking (ECB) Systems are looked into as a prospect for application in automotive braking. Integrated ECB systems which incorporate existing frictional braking components and employ Permanent Magnets (PMs) are explored to fulfil the needs of automotive braking.

A brief review on evolution of braking systems and current status of ECB is done in Section II. In section III, ECB is designed using Permanent Magnets incorporating brake disc. Section III covers a simple analytical model is developed to validate the expressions and plot characteristic graphs of an ECB. In section V, a preliminary hardware model is designed to validate the fundamental working principles of an ECB employing PMs. Subsequent results obtained and inferences observed are elaborated in section VI, followed by concluding remarks in section VII.

II. LITERATURE SURVEY

A. Evolution Of Braking Systems

The earliest brakes were wooden log blocks used on steel rimmed cart wheels. They were primarily used in

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steam powered vehicles and horse drawn carriages. However, Rubber tyres were introduced by Michelin brothers in late 1890s [1], which made wooden braking obsolete. The drum braking systems were a huge upgrade from wooden braking in terms of usability and braking force. Mechanical drum braking consists of a cam, brake linkage, brake shoes and a drum anchored to the vehicle's chassis. They were designed to be used in early rubber wheeled automobiles. Louis Renault, a French automobile pioneer, developed this model around 1902 [2].

A 4-wheel brake system using hydraulics was first used in Model A Duesenberg car in 1921 [3]. In Hydraulic braking, when a pedal is pressed, fluids are used to transfer the pressure to the brake shoe. Cylinders and tubes are used to achieve the desired pressure.

The first vehicle to commercially adapt to disc braking was Chrysler Imperial in 1949 [4]. This method employs calipers with brake pads, which pinches a rotor or disc, mounted on the wheel shaft.

Anti-lock Braking Systems (ABS) was first installed in 1966 in FF sports sedan, produced by Great Britain Jensen. ABS was meant to be used in airplanes [5]. It prevents vehicles' brakes from locking up. This technology particularly senses when the brake is about to lock up and then responds by stimulating the valves to reduce brake pressure.

A production car by Pierce-Arrow's was the first to integrate power braking in 1928 [6]. In this method, the intake-manifold vacuum is used to reduce the magnitude of effort required to apply brakes.

Automatic braking technology has been on the rise since 2006 with Mercedes leading and implementing the technology in their higher-end models. Automatic Emergency Braking Systems (AEBS) employ short-range radar and long-range radar that can bring a car to a stop even if the driver does not touch the brake pedal.

Electrical dynamic braking is the use of an electric traction motor as a generator for slowing down a rotor. It is termed "rheostatic" if the generated electrical power is dissipated as heat in brake grid resistors, and "regenerative" if the power is returned to the supply line. Other spectrum of Electrical braking is Electromagnetic brakes, which slow or stop motion using electromagnetic force to apply mechanical resistance (friction).

B. Eddy Current Braking Systems: Advancements and Current Status

Currently, eddy current brakes are used in various domains like oil rigs, textile industry, trains and selected automotives. With respect to the automotive domain, they are employed in some of the commercial trucks and buses and are referred to as "electric retarder" or "electromagnetic retarder". It is an auxiliary braking system to the basic friction brake system, aiding in scenarios like downhill driving and overheating. It is usually mounted on the drive-shaft.

Several architectures [7-12] are developed to vary the magnetic field in case of permanent magnets and several architectures are developed to control excitation in terms of electromagnets. However, architectures which vary the magnetic field by mechanical movement of the magnet itself have not been studied extensively.

An auxiliary braking system which uses electromagnets (EM) is proposed in [13, 14]. PMs are used as a source of magnetic field as opposed to EMs used in the previous configurations [15]. The magnetic circuits are designed to vary magnetic fields. In recent years, permanent magnet technology has evolved, with magnets having increased energy density and reduced costs. Extensive study using new permanent magnets to use in Eddy current braking is to be carried out.

Stand-alone type of braking systems or retarder type of braking systems are predominantly designed [16,17]. Integrated braking configurations [18] i.e., eddy-current braking which incorporates the already existing components of a traditional frictional brake is not efficiently realized. However, including magnets in the existing caliper of the brake is not explored extensively.

Simple Analytical models [17, 18] and comparatively more complex FEA analysis models [19,20,21] are among the common simulation models used. The difference between the models in terms of performance and the parameters affected is explored. However, subsequent ways to reduce the gap between the models in terms of results by improving the simpler analytical model is to be attempted.

An experimental test set-up is employed to validate the Finite-Element Analysis (FEA) results and numerical results in [22]. Models not necessarily designed to be implemented on the vehicle, but to verify the results and equations are to be developed. An effective experimental model to fill the gap between prototype model and mathematical results is to be realized.

Gaps in Research:

At present, ECB is not commercially implemented in passenger vehicles. Towards this end, prominent research and development of prototype models for Integrated braking systems which make use of existing mechanical frictional braking components are not realized.

Keeping these in minds, the scope for further research work is inferred to be:

- Development of an end-to-end model which uses a simple analytical method taking into consideration the new PMs.
- This analytical model's equations and results are to be validated by a simple working hardware model. The architecture of mechanically moved magnets to control the braking can be explored and the setup is to be realized incorporating already present components of traditional frictional braking.

III. DESIGN OF ECB

The Eddy Current Braking model employed consists aluminum brake disc rotating with velocity v_m, through an inhomogeneous magnetic field created by magnet placed facing the disc. Fig. 1 represents the arrangement of the Brake disc and the Magnet.

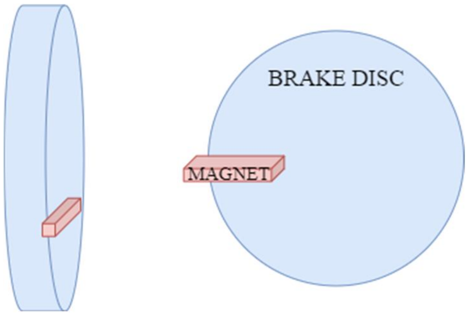


Fig. 1. Basic ECB Model with brake disc and magnet

In the model, we can either employ Permanent Magnet (PM) or Electro-magnets (EMs) to generate the magnetic field. In case of PMs, air-gap distance is varied to gain control over braking force, whereas excitation current is varied in case of EMs.

Permanent Magnets

During the rotation of brake disc with velocity v_m, the induced voltage u_i in the disc can be calculated using Faraday's law of induction,

$$\oint_s \vec{v} \times \vec{B}\, dS = (B^+ - B^-)0.5 l v_m \qquad (1)$$

where l is the width of the disc [23]. The resistances along axis of eddy current path, namely R_1 and R_2 is calculated. Disc physical and material properties are taken into consideration.

$$R_1 = C_r \frac{2l}{\sigma t_{ec} \tau} \qquad (2)$$

$$R_2 = C_r \frac{\tau}{\sigma 2 l t_{ec}} \qquad (3)$$

The total resistance of one eddy current path is,

$$R = 2C_r(R_1 + R_2) \qquad (4)$$

The correction factor C_r is used, as the eddy currents are considered of only one eddy current streams.

To take into consideration the field repression, the resistances are calculated across the thickness of the brake disc. But, due to presence of fictive current in eddy current paths, effective thickness, t_{ece} for eddy current paths is calculated as,

$$t_{ece} = \delta(1 - e^{-\frac{t_{ec}}{\delta_p}}) \qquad (5)$$

$$\delta_p = \sqrt{\frac{\tau}{\pi \sigma \mu_0 \mu_{co} v_m}} \qquad (6)$$

Where, σ is the conductivity of eddy current material, δ_p is the penetration depth and μ_{co} is the relative permeability.

As eddy currents of only one stream are taken into consideration, an inductance L is applied to eddy current path. Inductance is the result of magnetic resistance present in the air gap. It is calculated by,

$$L = \frac{\mu_0 C_L \tau l}{8 t_{ece}} \qquad (7)$$

where, C_L is the inductance fitting parameter and τ is the length of the magnet. The respective reactance can be calculated by,

$$X = \frac{L2\pi v_m}{\tau} \quad (8)$$

Due to the impedance Z and voltage induced in the disc, the eddy current can be estimated as,

$$I = \frac{u_i}{\sqrt{R^2+X^2}} \quad (9)$$

The drag force produced in an eddy current brake can be approximated by,

$$F = RN_{ec}\frac{\Delta B^2 l^2 v_m}{4(R^2+X^2)} \quad (10)$$

Where, N_{ec} is the number of eddy current paths. All parameters used for the calculations are presented in Table 1 including brake disc and magnet parameter values.
The Effective flix density at an air gap distance l_g is calculated by,

$$B_T = \frac{B}{2}\left(\frac{l+lg}{\sqrt{\left(\frac{d}{2}\right)^2+(l+\mathrm{lg})^2}} - \frac{lg}{\sqrt{\left(\frac{d}{2}\right)^2+lg^2}}\right) \quad (11)$$

where, d is the Disc diameter.
The aim of the design is to find the physical parameters of the ECB which ensure maximum braking torque. Fig. 2 shows the Torque-speed curve of an ECB with its characteristic values.

TABLE I. PARAMETERS USED FOR PM DISC BRAKING

Parameter	Value
Disc thickness (t_{ec})	4 mm
Disc diameter (d)	20 mm
Disc material	Aluminium
Length of magnet (l)	80mm
Magnetic Inductance of PM (Bx)	1.2 T
Number of eddy current paths (N_{ece})	8
Resistance Correction Factor (C_r)	2.02
Inductance Correction Factor (C_L)	0.21
Permeability Correction Factor (μ_{co})	8.2

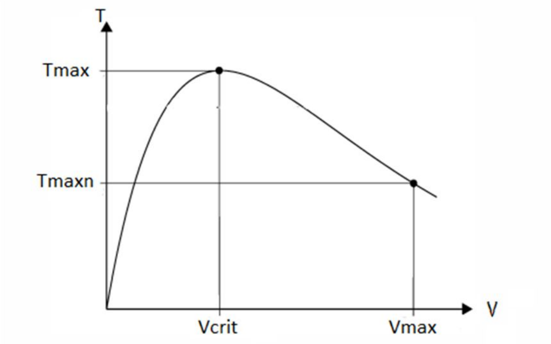


Fig. 2. Characteristic torque curve of an ECB

Torque axis and Speed axis correspond to Braking Torque of the ECB and Speed of the Brake disc respectively. It can be observed that the Torque of an ECB increases up to its critical speed V_{Crit}, where it reaches Maximum torque T_{max}. As the speed increases past Critical speed, the torque decreases.

IV. DESIGN OF ANALYTICAL MODEL

A simple analytical model to assess the equations of ECB using permanent magnets is developed. The analytical model takes disc parameters, magnet parameters and other physical parameters like air gap as input. It calculates the Braking force and torque generated, with respect to brake disc speed.
The results of the analytical derivations are implemented and computed using MATLAB®. The braking torque is computed for a broad speed range. Fig. 3 shows the algorithm used for calculations.
After the calculations, the characteristics 'Braking Force-Speed' and 'Torque-speed graph' are plotted.
Fig. 4 shows the Braking Force vs Speed plot of Eddy-Current Braking system. The Brake disc speed V_m is plotted against the produced Braking Force. In our application of Eddy Current Braking system to automobiles, the region of characteristic plot where, braking force is increasing with increase in speed is taken into account.
Fig. 5 corresponds with the Braking Torque-Speed characteristics of the Eddy Current Braking system. Brake disc speed is plotted against corresponding Braking Torque. It can be observed that Braking torque is increasing in magnitude with increase in speed.
Fig. 6 shows the Braking force as a function of different air gaps lg. It can be seen that increasing air gap between the permanent magnet and disc decreases the magnitude of braking force.

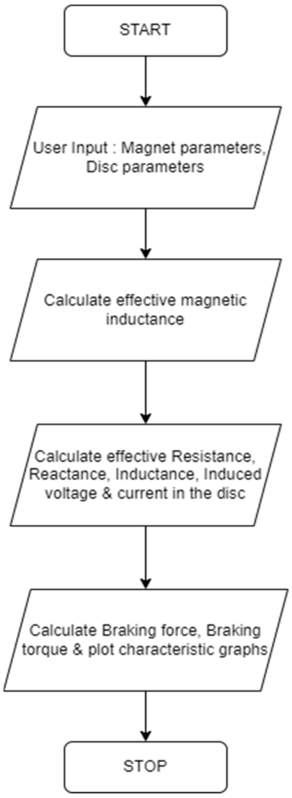
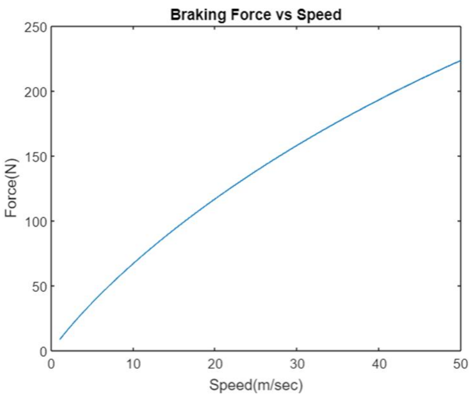


Fig. 3. Algorithm implemented in MATLAB to solve for Braking parameters of ECB



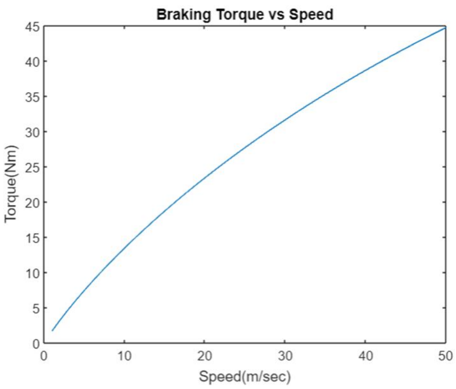


Fig. 4. Braking Force – Speed curve of Eddy Current Brake Fig. 5. Braking Torque – Speed curve of Eddy Current Brake

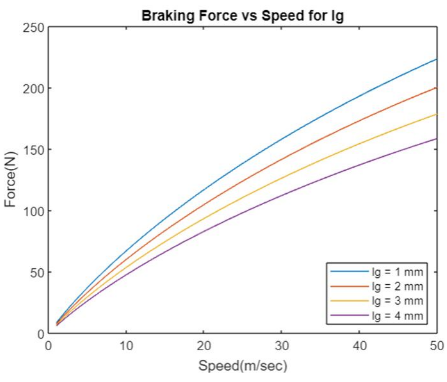


Fig. 6. Braking force – speed curve for different air-gap distance l_g

V. Hardware Design and Preliminary Realization

A preliminary hardware model is designed to test our hypothesis on fundamental physics and working of an Eddy Current Braking model employing Permanent Magnets. Neodymium Circular disc magnets, which possess high magnetic flux density are chosen to decelerate an Aluminium disc of a similar dimensions to that of an automotive brake disc. Suitable drive type to actuate the disc is designed and motor sizing is carried out. Fig 7.shows the CAD model of the designed system.

TABLE II. HARDWARE MODEL SPECIFICATIONS

Disc	
Material	Aluminum
Dimensions	20 cm OD
Magnet	
Type	Neodymium disc magnets
Magnetic Induction (B)	1.2 T
Dimensions	50*20*20 mm
Motor	
Motor type	PMSM Motor
Torque	5-8Nm
Speed	1500 RPM
Type	Variable speed type
Drive	
Type	Direct coupling with shaft
Shaft	8mm aluminum
Bearings	Ball bearings
Mountings	Weld mountings
Body	Cast Iron

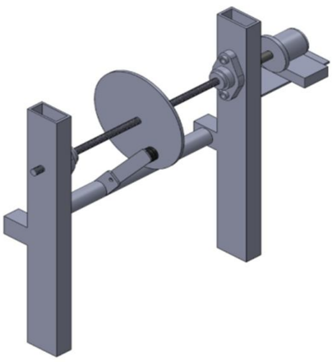


Fig. 7. Model of preliminary Braking test system using PM

A preliminary hardware working model is realized to test out the theoretical assumptions and to ensure the fundamental understanding of working of an ECB using PM are validated.

Due to restrictions not limiting to financial, availability and time restrictions, some variation has been made from the designed model.

A mild steel disc of 20mm outer diameter was procured instead, and appropriate light-weight shaft has been used to enable rotation of the disc. The shaft is directly coupled with a PMSM motor to eliminate any drive losses. Neodymium circular disc magnets are mounted on a retractable flat member which oscillates the magnet in and away from the disc. Ball bearings are installed at both ends of the shaft to ensure there is no other load other than the disc itself. The whole frame for the model has been constructed with Iron square members to ensure strength and rigidity.

Fig. 8 and Fig. 9 contains the images of realized ECB model using PMs.

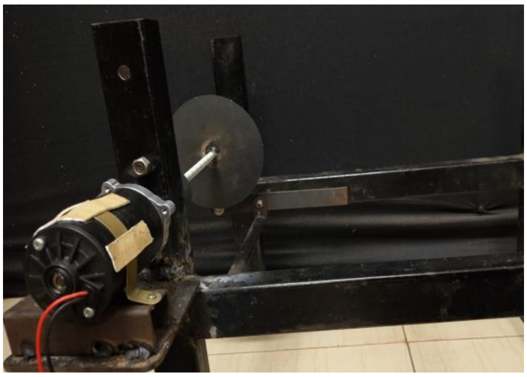


Fig. 8 Realized working model of preliminary Braking system using PMs

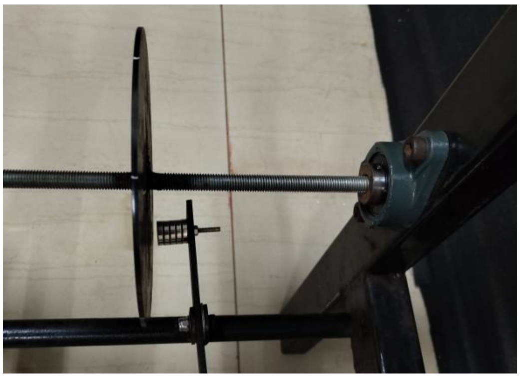


Fig. 9. View of PMs in vicinity of the Brake disc

VI. RESULTS AND DISCUSSIONS

Several test cases have been performed on the set-up to aid the understanding of basic principles related to ECB. Disc speed has been measured in RPM.

In the first set of experiments, PM is brought in the vicinity of the disc without cutting off the motor power supply. The readings are taken for two cases, 330 RPM and 860 RPM as initial speeds. In the next set of experiments, motor power is cut off when the magnets are brought in. Same two cases of speed are measured. Air gap lg of 2 mm has been fixed throughout the entirety of the experiments undertaken.

Fig. 10 shows case 1, when the disc is initially rotating freely at 330 RPM. When the permanent magnet is brought in the vicinity of the disc, the speed of the brake disc drops to 280 RPM. Speed of the disc is reduced by 50 RPM and remains constant as the motor is powered throughout the time period.

Fig. 11 shows case 2, where the disc is rotating freely at 860 RPM. When the permanent magnets are brought closer to the disc, the speed of the brake disc drops to 780 RPM and remains constant as motor is still live.

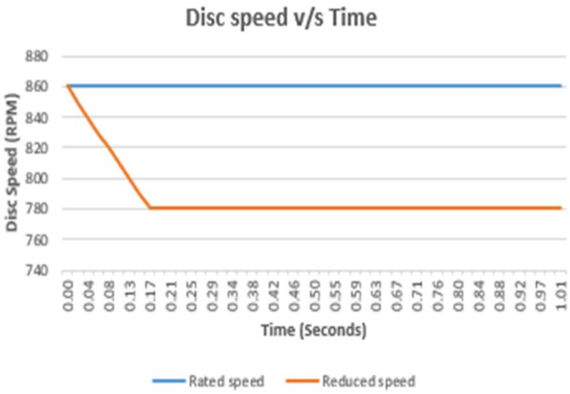


Fig. 10 Disc speed – Time graphs of initial speed 330 RPM

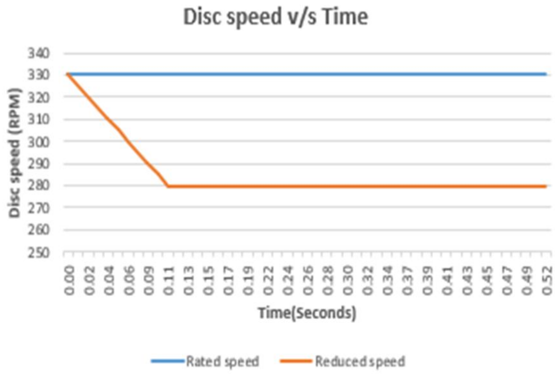
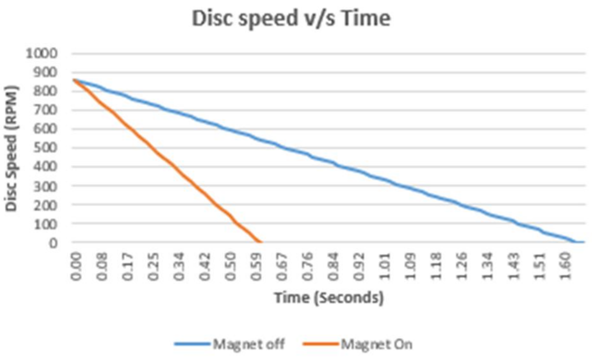


Fig. 11 Disc speed – Time graphs of initial speed 860 RPM

In the next set of experiments, the motor power is taken off to simulate accelerator pedal being taken off in case of an automobile. Subsequently, readings of time taken by the disc coming to halt, with magnet in its vicinity and magnet without in its vicinity are taken. This corresponds to braking effect and the deceleration rate of the brake disc.

Fig. 12 shows the graph of Brake disc speed versus time, with magnet in discs vicinity and without magnet in discs vicinity. It can be observed that the disc naturally decelerates at the rate of 11 RPM/s from 330 RPM to 0 RPM in 0.5 seconds. When the permanent magnet is brought in to produce brake torque, the disc now decelerates at increased magnitude of 18.33 RPM/s and takes only 0.3 seconds to stop.

In another case when the initial speed of the disc is 860 RPM, the disc naturally decelerates at 8.9 RPM/s to come to a halt at 1.60 seconds. When the braking as a form of bringing in the permanent magnets is applied, the disc decelerates at increased magnitude of 23.8 RPM/s and takes 0.6 seconds to stop. It is illustrated in Fig. 13.



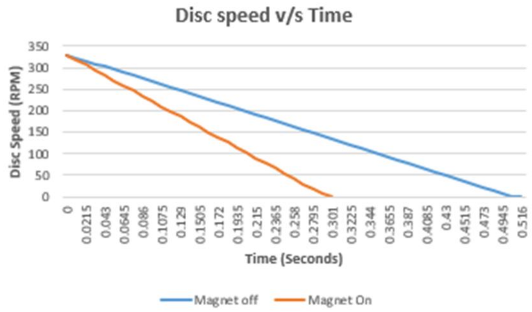


Fig. 12 Deceleration graph of initial speed 330 RPM

Fig. 13 Deceleration graph of initial speed 860 RPM

VII. CONCLUSION

With the exponential growth of e-mobility sector and the increasing interest in automotive electronics, focus on electric braking is gaining prominence. In this context, the present work was taken up to explore the realization of Eddy current braking using Permanent Magnets for automobile braking application.

Evolution of braking system was studied, leading to exploration of current state Eddy Current Braking Mechanisms. Eddy Current Brake is designed with Permanent Magnets incorporating already present frictional braking component of brake disc. Simple analytical model is developed to validate the equations and plot the characteristic graphs of an Eddy Current Braking System. Preliminary hardware system to validate the understanding of fundamental working of ECB was designed and realized.

Usage of ECBs in passenger vehicles has advantages like gaining electronic control over the braking mechanism and complete Electrical-Electronic integration of all the components in an automobile. It can be concluded that the presented work aims to aid the transition from traditional frictional braking to Integrated ECB systems.

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