

Application of Eddy Current Braking in Automobile Using Rotating Magnetic Field From Stationary Poly-Phase Windings

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Abstract — Automobile braking by eddy current induction using rotating magnetic field has been studied. A conducting brake disc rotates between the poles of an electromagnet. There is no contact. The electromagnetic field comes on when the brake is applied and eddy current is induced in the conducting brake disc to effectuate retardation. The brake disc is coupled to the road wheel so that retardation of the brake disc transmits directly to the road wheel. The eddy current braking torque is a measure of the braking power. The braking torque varies directly as the relative speed between the conducting brake disc and the eddy current brake magnetic field. The braking torque is studied under three main conditions. These are when the brake disc and the magnetic field rotate in opposite directions, when the brake disc and the magnetic field rotate in the same direction and when the wheel is stationary with only the magnetic field rotating. Braking performance is studied in terms of stopping a vehicle, slowing and preventing motion. Results show that stopping and slowing down are achieved when the magnetic field rotates opposite the direction of the brake disc rotation. For stationary wheel, motion will not occur as long as the torque which tends to be tractive is counterbalanced by friction at the wheels and the vehicular mass inertia. Modelling and simulation in this study was done using Matlab – Simulink software.

Keywords— Automobile, disc braking, eddy current, electromagnetic, magnetic braking, rotating magnetic field.

1.0 Introduction

Eddy current brake came with a number of advantages. Having no contact between braking parts, it is quiet, frictionless, wear-free and odourless. Being wear-free, there is great savings from maintenance and replacement of worn-out parts that would have been, as compared to friction brakes. Requiring no brake fluids, there is no potential hazard of leakage of toxic fluids to the environment. Eddy current brakes achieve shorter braking distance due to faster response. They have higher braking torque at high vehicular speeds.

Nonetheless, eddy current braking has some notable drawbacks. Eddy current brakes are ineffective at low vehicular speeds. They require electrical power for the electromagnet types. Energy is wasted as heat dissipated in the brake conductor.

Research has been on-going to improve on eddy current brakes, to address the drawbacks associated with eddy current braking and to better adapt it to use in automobiles.

In an attempt at providing help to basic understanding of the application of eddy currents in automobile braking, a moderate-cost, eddy current brake experimental set-up was presented [1]. Basically, the functional dependence of power dissipated on brake disc velocity, on the sources of magnetic field, and sample resistivity were demonstrated by the experiments.

Three different materials that will be suitable for use as eddy current brake disc has been investigated, namely: aluminium, copper and zinc [2]. Aluminium was found to be the best of the three, followed by copper and zinc. Furthermore, two different series of aluminium (A16061 and A17075) were compared. The A16061 material produced greater braking torque due to its higher electrical conductivity. Additionally, it was observed that thicker brake discs produced higher braking torque. Also, smaller air-gaps produced greater braking torque. However, it was noted that the eddy current brake prototype that was studied performed better at high speeds [2].

To compensate for the poor performance of the eddy current brake at low vehicular speeds, a hybrid of eddy current braking (ECB) and electro-hydraulic braking (EHB) technology have been introduced [3]. The work of previous authors sought to capture the combined benefits of eddy current braking and electro-hydraulic braking while eliminating their stand-alone shortcomings. They also attempted to make-up for the poor performance of eddy current brakes at low vehicular speed in their "integrated electric motor and eddy current brake" design. It is for application in electric all-wheel drive cars [4].

At the inception, electromagnetic braking system belonged to a type of braking formally known as *electromechanical* braking. They are the type of brakes that actuate electrically but transmit torque mechanically through a magnetic field. Their later name – electromagnetic brakes – refers to their method of actuation [5] energy wastage, and electrical power requirement of electromagnetic braking [6].

In previous works, the authors explored the working principle of eddy current braking mechanism [7]. The study was based on eddy current braking (for high speed) to which linear Halbach magnetized mover was applied. The application of a (magnetized) mover suggests that permanent magnets, rather than electromagnets, were used [8]. This eliminates the need for external power supply to electromagnet coils. To address the drawback of eddy current brakes requiring an external power supply, the "self-excited eddy current brake" has been proposed [9].

Another work on the source of excitation for eddy current brakes, was carried out by different authors. They presented a *novel hybrid excitation eddy current braking system for high speed road and rail vehicles*. They strove to tap the advantages of both the electrical excitation magnet system and the permanent magnet system, and eliminated their individual disadvantages [10].

So far, reviewed literature has limited the application of eddy current braking in automobiles to use as secondary brakes that functioned effectively only in the high vehicular speed region. However, at least a patent for an invention has been found that claims to have adapted eddy current braking to effective use in the low vehicular speed region as well as in the high vehicular speed region. The invention, integrated a brake disc concentrically with the axle of a car inside wheel of the said car [11]. Two cores were arranged around an edge of the said brake disc with a

spacing of 90° between the cores. A coil was wound around each of the cores, forming electromagnets. The invention claimed to selectively apply a dc or an ac of calculated magnitude to the electromagnetic coils depending on the speed of the vehicle.

This study is based upon the type of circular eddy current brake that looks like the conventional disc brake. Instead of a friction brake pad, an electromagnet separated from the brake disc by an air-gap should be in place. The electromagnet, unlike the friction brake pad that rubs against the disc, induces eddy current in the disc when the brake is applied. Eddy current braking torque depends on the relative speed between the conducting brake disc and the magnetic field. This study seeks to address the ineffectiveness of eddy current braking at low vehicular speeds by the application of rotating magnetic field. It is known that whenever a set of poly-phase windings is supplied current by an equal number of poly-phase a.c. sources, a rotating magnetic field is generated [12]. The source of the rotating magnetic field will therefore be a set of poly-phase ac windings. The relative motion (between brake disc and field) that should be lost due to slowing of the disc in the case of static magnetic field will be enhanced and sustained when the field rotates.

2.0 Methodology

This study modelled and simulated eddy current braking torque based on three main conditions. These are when the brake disc and the magnetic field rotate in opposite directions; when the brake disc and the magnetic field rotate in the same direction and when the wheel is stationary with only the magnetic field rotating.

A. Braking Torque

The expression upon which the braking torque analysis will be based is given as in [2].

$$T_b = \sigma R^2 S d \omega \left(\frac{\mu_0 n}{l_g} \right)^2 t^2 \quad (1)$$

where

- = Eddy current braking torque
- = Brake disc electrical conductivity
- = Radial distance between the brake disc centre and the centre of the field winding core
- = Surface area of magnetic pole
- = Brake disc thickness

= Common angular speed of road wheel and brake disc

= Air gap permeability

= Number of turns of electromagnetic winding

= Air gap length

= Applied current

The above stated expression for braking torque (1) applies to the eddy current brake application where the magnetic field is stationary. Only the brake disc coupled to the road wheel moves (through the magnetic field) to produce relative motion between the magnetic field and itself, the conducting brake disc.

B. Modification to the Braking Torque Expression

This study proposes the use of rotating magnetic field rather than the relatively stationary field in earlier applications. A necessary modification here is that the angular speed will be given by the relative motion between the brake disc and the rotating magnetic field.

Hence,

$$\omega = \omega_w - \omega_f \quad (2)$$

where

ω = Road wheel or brake disc angular speed

ω_f = Rotating magnetic field angular speed

The direction of field rotation, with respect to the brake disc direction of rotation, is taken into account. Rotation in the direction of the road wheel is taken as positive.

The modelling and simulation in this study was done using Matlab/Simulink software.

C. Assumptions

- The brake is assumed to be applied at time $t = 0$.
- It is known that as soon as the driver steps-off the accelerator pedal, retardation sets in due to wind resistance, friction at the wheels and so on. It is assumed that the driver steps-off the accelerator and steps on the brake. The time lapse between both actions is ignored.
- The field speed cannot increase indefinitely. But it is assumed that for the purpose of braking, the maximum field speed will not be reached.

D. Braking Torque Model

If torque coefficient,

$$T_i = \sigma R^2 S d \left(\frac{\mu_0 n}{l_g} \right)^2 i^2 \quad (3)$$

The braking torque expression of (3) can be rewritten as

$$T_b = T_i \omega i^2 \quad (4)$$

Using (2) in (4),

$$T_b = T_i (\omega_w - \omega_f) i^2 \quad (5)$$

The Matlab/Simulink models for the eddy current braking torque used in the study simulations were built from the mathematical model of (5). Generally, T_i was taken as 5units and i^2 as 10units, arbitrarily, so that $T_i i^2$ is 50units all through the simulations. The wheel speed is assumed to reduce from 400units and the rotating magnetic field speed assumed to increase from zero. All simulations were run for one hundred seconds, hence, $t = 0:1:100$, where 't' is simulation time.

2.1 Field rotation opposite wheel rotation

(a) Wheel speed decreases, field speed increases both at the same rate.

The study assumed the wheel speed decrease rate to be 10units and the field speed (opposite) increase rate to be 10units as well.

Hence,

$$\omega_w = 400 - 10t$$

$$\omega_f = 0 - 10t$$

(b) Wheel speed decreases, field speed increases more.

The study assumed the wheel speed decrease rate to be 10units and the field speed (opposite) increased rate to be 15units.

Hence,

$$\omega_w = 400 - 10t$$

$$\omega_f = 0 - 15t$$

(c) Wheel speed decreases faster than field speed increases

The study assumed the wheel speed decrease rate to be 15units and the field speed (opposite) increase rate to be 10units.

Hence,

$$\omega_w = 400 - 15t$$

$$\omega_f = 0 - 10t$$

(d) *Wheel speed decreases, field speed steady*

The study assumed the wheel speed decrease rate to be 10units and the field speed (opposite) to be steady at 40units.

Hence,

$$\omega_w = 400 - 10t$$

$$\omega_f = -40$$

Table 1: Summary- Field rotation opposite wheel rotation

	Time(t)	$\omega = \omega_w - \omega_f$	$T_b = 50\omega$
A	0:1:100	400	20,000
B	0:1:100	$400 + 5t$	$20,000 + 250t$
C	0:1:100	$400 - 5t$	$20,000 - 250t$
D	0:1:100	$440 - 10t$	$22,000 - 500t$

2.2 Field and wheel rotate in the same direction

(a) *Wheel speed decreases, field speed increases; both at the same rate.*

The study assumed the wheel speed decrease rate to be 10units and the field speed increase rate to be 10units as well. Hence,

$$\omega_w = 400 - 10t$$

$$\omega_f = 0 + 10t$$

(b) *Wheel speed decreases, field speed increases more*

The study assumed the wheel speed decrease rate to be 10units and the field speed increase rate to be 15units.

Hence,

$$\omega_w = 400 - 10t$$

$$\omega_f = 0 + 15t$$

(c) *Wheel speed decreases faster than field speed increases*

The study assumed the wheel speed decrease rate to be 15units and the field speed increase rate to be 10units.

Hence,

$$\omega_w = 400 - 15t$$

$$\omega_f = 0 + 10t$$

(d) *Wheel speed decreases, field speed steady.*

The study assumed the wheel speed decrease rate to be 10units and the field speed to be steady at 40units.

Hence,

$$\omega_w = 400 - 10t$$

$$\omega_f = 40$$

Table 2: Summary – Field and Wheel rotate in the same direction

	Time(t)	$\omega = \omega_w - \omega_f$	$T_b = 50\omega$
A	0:1:100	$400 - 20t$	$20,000 - 1,000t$
B	0:1:100	$400 - 25t$	$20,000 - 1,250t$
C	0:1:100	$400 - 25t$	$20,000 - 1,250t$
E	0:1:100	$360 - 10t$	$18,000 - 500t$

2.3 Wheel stationary

(a) *Wheel stationary, field speed steady at 40 units, say.*

$$\omega_w = 0$$

$$\omega_f = 40$$

(b) *Wheel stationary, field speed increasing at a rate of 10units, say.*

$$\omega_w = 0$$

$$\omega_f = 0 + 10t$$

Table 3: Summary – Wheel Stationary

	Time(t)	$\omega = \omega_w - \omega_f$	$T_b = 50\omega$
i	0:1:100	-40	-20,000
j	0:1:100	-10t	-500t

3.0 Results and Discussion

The purposed braking system is categorized into three:

- Stopping
- Slowing
- Prevention of motion

The analysis of the results of the several braking torque models presented here follow the three categories just listed. Sections 2.1 and 2.2 each

addresses stopping and slowing. Prevention of motion is addressed in section 2.3.

With the magnetic field rotating opposite the direction of the road wheel, stopping and slowing can be achieved. Braking can be achieved in variable time, as the braking torque is variable according to the relative speed between the rotating magnetic field and conducting brake disc. This finding is from section 2.1.

Having the magnetic field rotate in the same direction as the brake disc will not stop a vehicle. This follows from the findings all through section 2.2. All four graphs in the said section have negative slope. The braking torque falls to zero before the wheel stops, and the braking torque further goes negative while the wheel is still in motion. When the braking torque goes negative, it becomes tractive rather than retarding. The implication is that motion of the wheel becomes augmented rather than retarded from the point where the braking torque goes negative. The wheel never stops. It only slows for a while, and then continues in motion. For slowing the wheel, having the magnetic field rotate in the same direction as the brake disc will not be ideal. Retardation occurs only till the point where the braking torque changes sign. And the retardation occurs with decreasing braking torque. This does not provide for progressive reduction in braking distance, which is required in emergency slowing.

Application of the brake when the wheel is stationary generates a tractive torque, section 2.3. It is tractive in that it tends to initiate motion. So long as the said torque does not overcome friction at the wheels, inertia and other opposing forces; the vehicle remains stationary. The model with simulation result shown in Fig. 10 can be used in combination with the model with result of Fig. 9 to restrict a vehicle from rolling down when parked on an incline. The tractive torque should be made to act up the incline. First, the tractive torque is increased from zero until it reaches a value that stops the vehicle from rolling down. The torque is then held constant at the so attained value. The same model combination can be used to restrict a vehicle from moving under the "idle propulsion" of automatic transmission system. The magnetic field should be made to rotate opposite the direction of propulsion.

A. Field rotation opposite wheel rotation

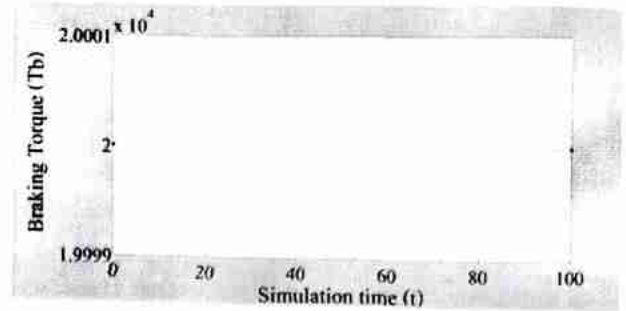


Fig. 1 Wheel speed decreasing, field speed increasing; both at the same rate but opposite.

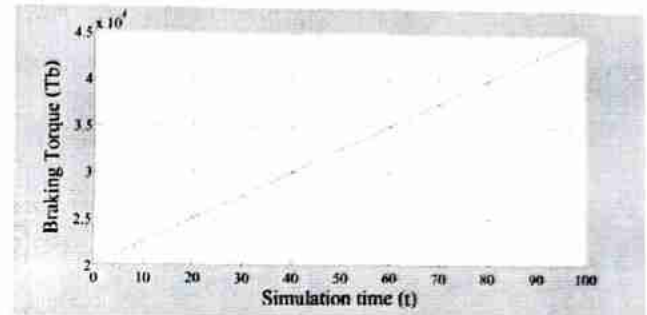


Fig. 2 Wheel speed decreasing, field speed (opposite) increasing more.

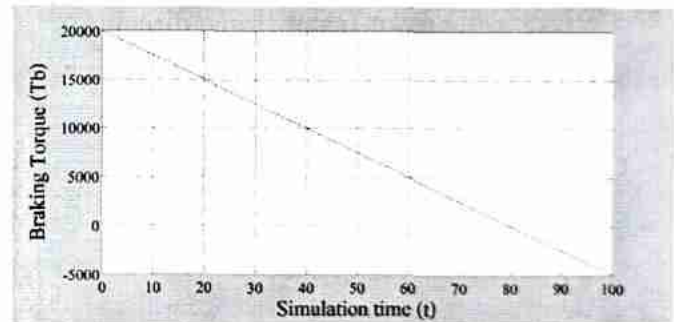


Fig. 3 Wheel speed decreasing faster than field speed (opposite) is increasing.

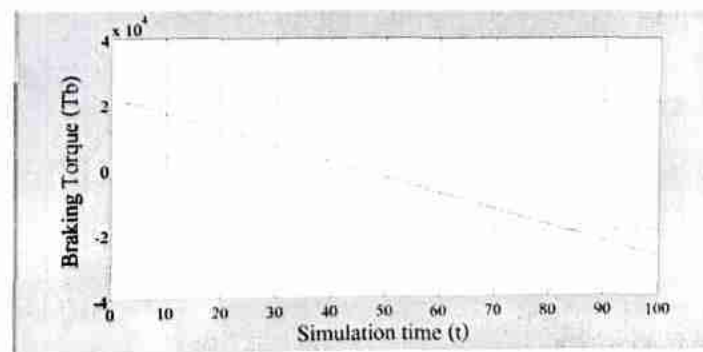


Fig. 4 Wheel speed decreasing, field speed steady.

B. Field and wheel rotate in the same direction

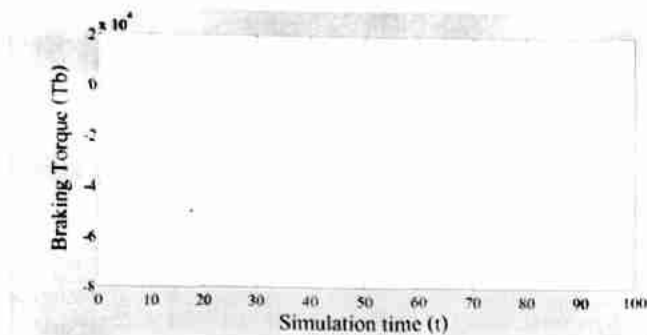


Fig. 5 Wheel speed decreasing, field speed increasing, both at the same rate and in the same direction.

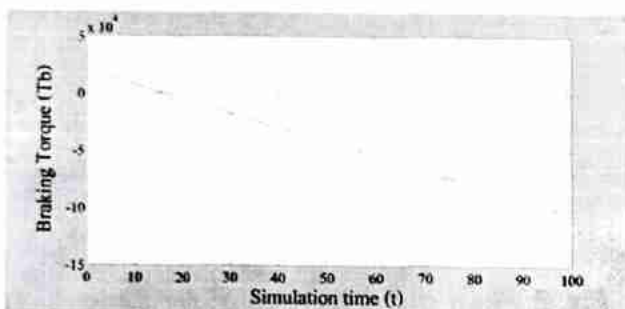


Fig. 6 Wheel speed decreasing, field speed increasing more/faster (same direction).

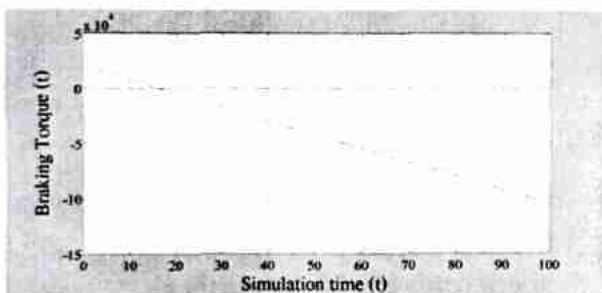


Fig. 7 Wheel speed decreasing faster than field speed is increasing (same direction).



Fig. 8 Wheel speed decreasing, field speed steady (same direction).

C. Wheel stationary

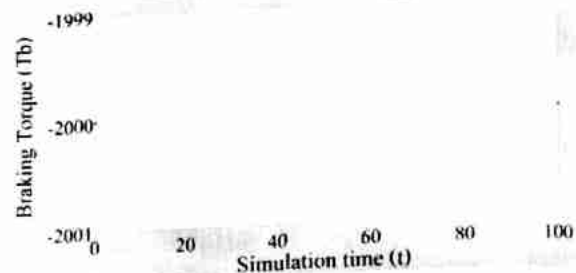


Fig. 9 Wheel stationary, field speed steady.



Fig. 10 Wheel stationary, field speed increasing.

4.0 Validation of Results

Foucault, who is credited with the discovery of eddy currents, found that the force required to rotate a metal (conducting) disc became greater when the disc is made to rotate with its rim between the poles of a magnet. There was a retarding force. An experiment (project) designed by Newsome, D., a Clemson Electrical Engineering Student, demonstrates the use of electromagnetic principle of eddy current to produce a braking device [8]. An aluminium disc was made to rotate through the field of a permanent magnet. With the relative motion thus created between the conducting aluminium disc and the magnetic field, eddy current is induced in the disc (Faraday's law of electromagnetic induction). By Lenz's law this induced current produces a magnetic field that acts to oppose the said relative motion. The disc is hence retarded. Notably, the higher the speed of the said relative motion, the more eddy current induced – and the more the retarding force.

In automobiles, the aluminium disc in Newsome's project could replace traditional brake discs (rotors). When the vehicle accelerates, the disc spins with the rotation of the wheels. The magnet used to stop the rotor should be an electromagnet that comes on with the application of the brake. And the electromagnet should have poly-phase windings supplied by equivalent poly-phase ac, so as to produce a rotating magnetic field [12]. In terms of typical braking

power, it is found that electromagnetic brakes (e.g. eddy current brake) can develop a negative power which represents nearly twice the maximum power output of a typical automobile engine, and at least three times the braking power of an exhaust brake [5].

5.0 Conclusion

Performance of eddy current braking using rotating magnetic field has been simulated and studied. With stationary magnetic field in earlier eddy current brake applications, braking torque reduced as vehicular speed reduced. Such eddy current brakes were ineffective at low vehicular speeds. But with rotating magnetic field as presented in this study, effective eddy current braking can be achieved at low vehicular speeds.

Stopping a vehicle will be achieved by having the brake magnetic field rotate opposite the brake disc rotation. Having the brake magnetic field rotate in the same direction as the brake disc will not achieve stopping. Also, slowing a vehicle is better achieved when the brake magnetic field rotates opposite the brake disc than when both the field and brake disc rotate in the same direction.

The need to prevent motion hints that there is a force tending to initiate motion, which force must be counterbalanced if motion must not occur. This force could be due to gravity, observed when a vehicle parked unrestricted on an incline rolls down the incline. To prevent this motion, the brake magnetic field should be made to rotate up the incline. Rotation up the incline is opposite the direction in which the brake disc will rotate if the wheels are not restricted. On a level ground, the continuous idle propulsion of automatic transmission systems is another force that may initiate motion if the wheels are not restricted. To prevent this motion, the brake magnetic field should be made to rotate in the direction opposite the impending motion. The field should rotate at a speed that generates a torque that counterbalances the —idle propulsion.

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