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Effective Eddy Current Braking at Low and High Vehicular Speeds – A Simulation Study

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Author's contributions

This work was carried out in collaboration between all authors. Author ALO designed the study, performed the statistical analysis, wrote the protocol, and wrote the first draft of the manuscript. Authors AOA and NEC managed the analyses of the study. Author NEC managed the literature searches. All authors read and approved the final manuscript.

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ABSTRACT

Conventional eddy current braking is limited in effectiveness to only the high vehicular speed region. As the vehicle slows, the conventional eddy current brake loses effectiveness. This inherent drawback is due to the use of static/stationary magnetic field in the brake system. This study presents a solution - the use of rotating magnetic field in the brake system. By the study design, the conducting brake disc rotates between the poles of an electromagnet. A constant air-gap separates the disc from the poles on either side. The electromagnet windings (each with a core) are made poly-phase so that when an equivalent poly-phase source supplies ac to the electromagnet windings, a rotating magnetic field is obtained. The rotating magnetic 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

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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 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. Modeling and simulation in this study are done using Mat Lab – Simulink software.

Keywords: Automobile braking; braking; disc braking; eddy current braking; electromagnetic braking; magnetic braking; rotating magnetic field.

1. 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. Conventional eddy current brakes, which employed stationary magnetic fields, are ineffective at low vehicular speeds. Eddy current brakes 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 an aid to basic understanding of the application of eddy currents in braking, Gonzalez presented a moderate-cost, eddy current brake experimental set-up [1]. Basically, the functional dependence of power dissipated on brake disc velocity, on the sources of magnetic field, and sample resistivities were demonstrated by the experiments.

Studying materials that will be suitable for use as eddy current brake disc, Baharom et al. [2] investigated three different materials of aluminium, copper and zinc. Aluminium was found to be the best of the three, followed by copper and zinc. Furthermore, two different series of aluminiun (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.

To compensate for the poor performance of the eddy current brake at low vehicular speeds, He et al introduced a hybrid of eddy current braking (ECB) and electrohydraulic braking (EHB) technology [3]. The work of He et al sought to capture the combined benefits of eddy current braking and electrohydraulic braking while eliminating their stand-alone shortcomings.

Scalon also attempted to make-up for the poor performance of eddy current brakes at low vehicular speed in his “integrated electric motor and eddy current brake” design. It is for application in electric all-wheel drive cars [4].

Puttewar et al described an electromagnetic braking system that belongs 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].

Kishore addressed energy wastage in, and electrical power requirement of, electromagnetic braking [6].

Maurya et al. [7] explored the working principle of eddy current braking mechanism. 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.

Addressing the drawback of eddy current brakes requiring an external power supply, Jeong et al proposed the “self-excited eddy current brake” [9].

Another work on the source of excitation for eddy current brakes was done by Kou et al. They presented *a novel hybrid excitation eddy current braking system for high speed road and rail vehicles.* Kou et al strove to tap the advantages of both the electrical excitation magnet system and the permanent magnet system, and eliminate 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 was found that claims to adapt eddy current braking to effective use in the low vehicular speed region as well as in the high vehicular speed region. The invention, which was by Park and Lee, integrates a brake disc concentrically with the axle of a car inside a wheel of the said car [11]. Two cores are arranged around an edge of the said brake disc with a spacing of 90^0 between the cores. A coil is wound around each of the cores, forming electromagnets. The invention claims to selectively apply a dc or an ac of calculated magnitude to the electromagnet 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. Only, 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 ac source, 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.

Schematic of the Brake Design

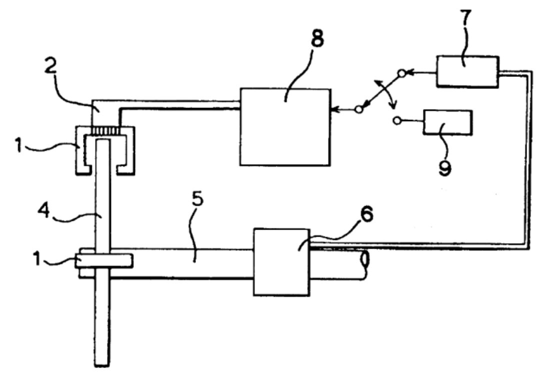

Fig. 1A. A typical schematic diagram of the proposed eddy current brake system
Drawing source: Park, Kyi Hwan; Lee, Kap Jin [11]

The part labeled 4 (Fig. 1A) is the conducting brake disc which is coupled to the road wheel via a central axle labeled 5. The part labeled 1 is the electromagnetic core separated from the brake disc by an air gap on either side of the brake disc. Such cores are three in number (three phase) oriented about the brake disc 120 electrical degrees apart. The part labeled 2 is the electromagnet winding that magnetizes the core when ac flows in it. The part labeled 9 represents the brake pedal. When the brake pedal is pressed, signals of pedal pressure and travel go into the control unit labeled 7. The control unit upon signals from the pedal, activates variable frequency three phase ac supply via the part labeled 8 to the three phase ac windings. The part labeled 6 is the frequency sensor. It senses frequency of the coil current as a function of the rotating magnetic field speed and reports to the control unit.

2. METHODOLOGY

This study models and simulates 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.

2.1 Braking Torque

The expression upon which the braking torque analysis will be based is given as

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

(Source: Baharom, M.Z., Nuawi, M.Z., Priyandoko, G., Hari S.M. [2]; Kyi Hwan Park and Kap Jin Lee, [11]

Where

T_b = Eddy current braking torque
σ = Brake disc electrical conductivity
R = Radial distance between the brake disc centre and the centre of the field winding core
S = Surface area of magnetic pole
d = Brake disc thickness
ω = Common angular speed of road wheel and brake disc
μ_0 = Air gap permeability
n = Number of turns of electromagnetic winding
l_g = Air gap length
i = Applied current

The above stated expression for braking torque, Eq. (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.

2.2 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_w = 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 modeling and simulation in this study is done using MatLab/Simulink software.

2.3 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 e.t.c. 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.
- Effects of road conditions, presence of foreign material or proximity to other vehicle metallic parts on the brake performance are neglected.

2.4 Braking Torque Model

If torque coefficient,

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

The braking torque expression of Eq. (1) can be re-written as

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

Using Eq. (2) in Eq. (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 are built from the mathematical model of Eq. (5). Generally, T_i was taken as 5 units and i^2 as 10 units, arbitrarily, so that $T_i i^2$ is 50 units all through the simulations. The wheel speed is assumed to reduce from 400 units and the rotating magnetic field speed assumed to increase from zero. All simulation is run for a hundred seconds, hence, t = 0:1:100. Where 't' is simulation time.

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 10 units and the field speed (opposite) increase rate to be 10 units 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 10 units and the field speed (opposite) increase rate to be 15 units.
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 15 units and the field speed (opposite) increase rate to be 10 units.
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 10 units and the field speed (opposite) to be steady at 40 units.
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) Field and wheel rotate in the same direction

e. Wheel speed decreases, field speed increases; both at the same rate.
The study assumed the wheel speed decrease rate to be 10 units and the field speed increase rate to be 10 units as well. Hence,
$\omega_w = 400 - 10t$
$\omega_f = 0 + 10t$

f. Wheel speed decreases, field speed increases more.
The study assumed the wheel speed decrease rate to be 10 units and the field speed increase rate to be 15 units.
Hence,
$\omega_w = 400 - 10t$
$\omega_f = 0 + 15t$

g. Wheel speed decreases faster than field speed increases.
The study assumed the wheel speed decrease rate to be 15 units and the field speed increase rate to be 10 units.
Hence,
$\omega_w = 400 - 15t$
$\omega_f = 0 + 10t$

h. Wheel speed decreases, field speed steady.
The study assumed the wheel speed decrease rate to be 10 units and the field speed to be steady at 40 units.
Hence,
$\omega_w = 400 - 10t$
$\omega_f = 40$

Table 2. Summary – field and wheel rotate in the same direction

	Time(t)	$\omega = \omega_w - \omega_f$	$T_b = 50\omega$
e	0:1:100	400 – 20t	20,000 – 1,000t
f	0:1:100	400 – 25t	20,000 – 1,250t
g	0:1:100	400 – 25t	20,000 – 1,250t
h	0:1:100	360 – 10t	18,000 – 500t

3) Wheel stationary

i. Wheel stationary, field speed steady at 40 units, say.
$\omega_w = 0$
$\omega_f = 40$

j. Wheel stationary, field speed increasing at a rate of 10 units, 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	-2,000
j	0:1:100	-10t	-500t

3. RESULTS AND DISCUSSION

3.1 Field Rotation Opposite Wheel Rotation

Simulation results for the four sub-conditions are presented in Figs. 1, 2, 3 and 4.

3.2 Field and Wheel Rotate in the Same Direction

Simulation results for the four sub-conditions are presented in Figs. 5, 6, 7 and 8.

3.3 Wheel Stationary

Simulation results for the two sub-conditions are presented in Figs. 9 and 10.

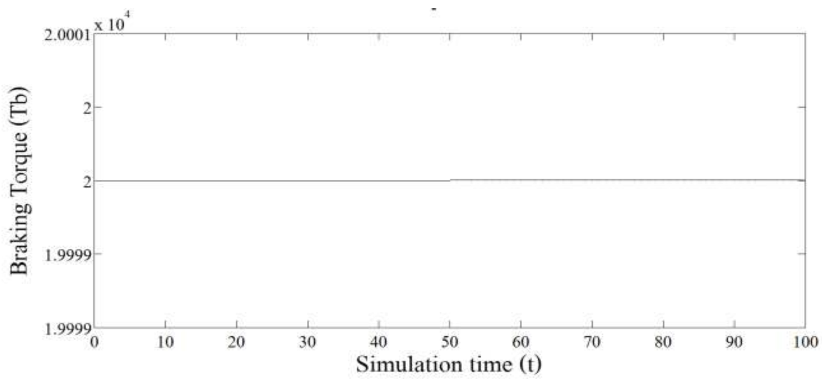

Fig. 1. Wheel speed decreasing, field speed increasing; both at the same rate but opposite

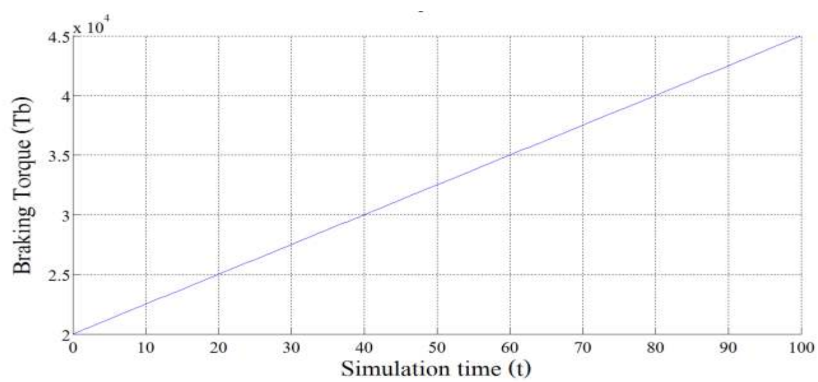

Fig. 2. Wheel speed decreasing, field speed (opposite) increasing more

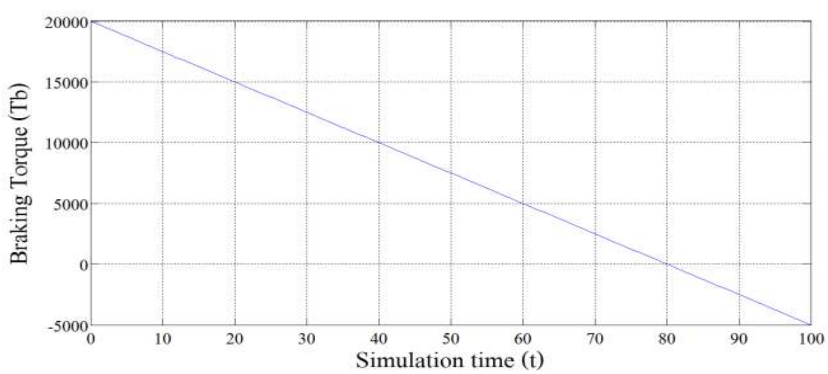

Fig. 3. Wheel speed decreasing faster than field speed (opposite) is increasing

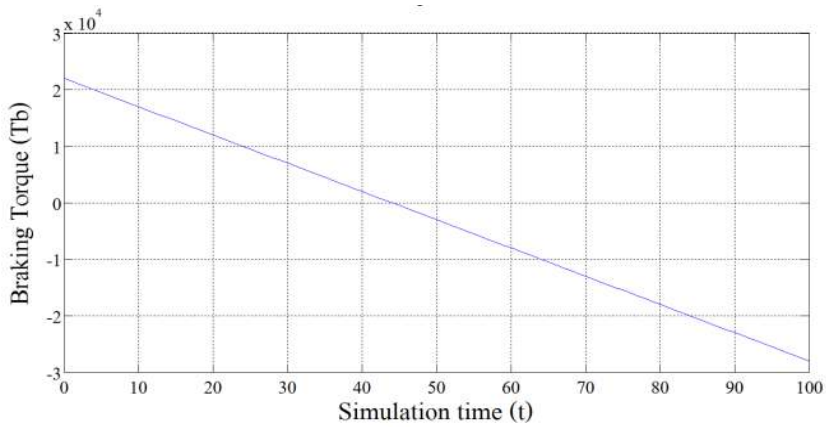

Fig. 4. Wheel speed decreasing, field speed steady

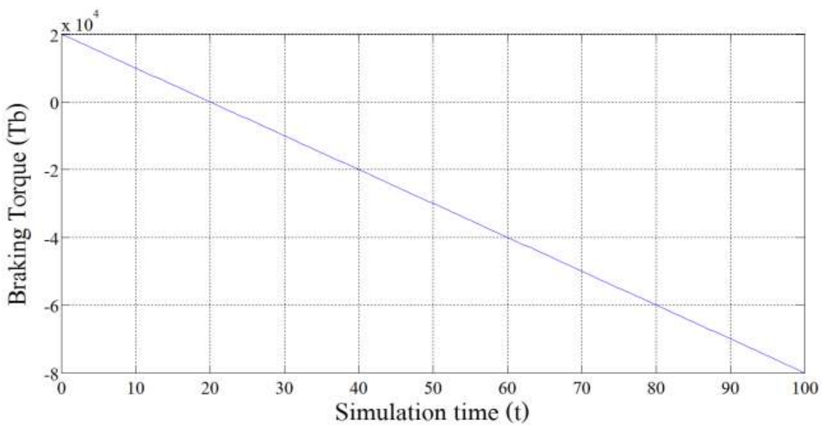

Fig. 5. Wheel speed decreasing, field speed increasing, both at the same rate and in the same direction

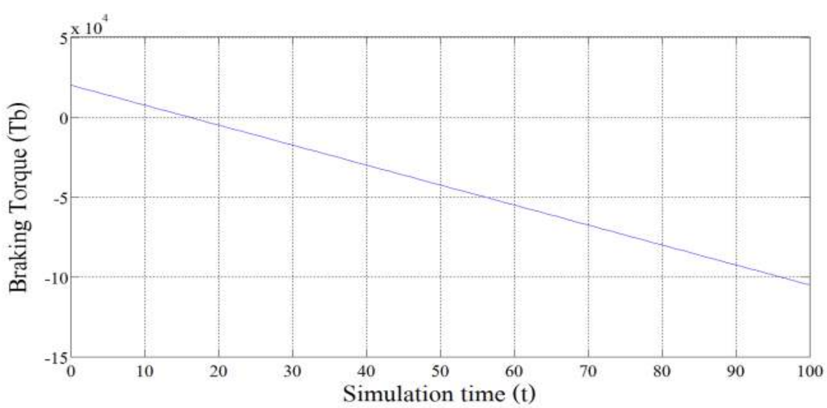

Fig. 6. Wheel speed decreasing, field speed increasing more/faster (same direction)

3.4 Discussion of Results

The purpose of braking 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 3.1 and 3.2 each addresses stopping and slowing. Prevention of motion is addressed in section 3.3.

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 3.1.

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 3.2. 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.

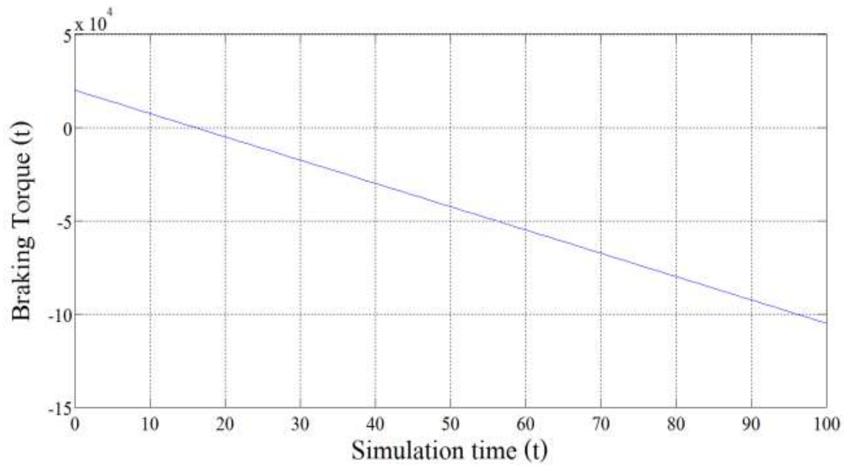

Fig. 7. Wheel speed decreasing faster than field speed is increasing (same direction)

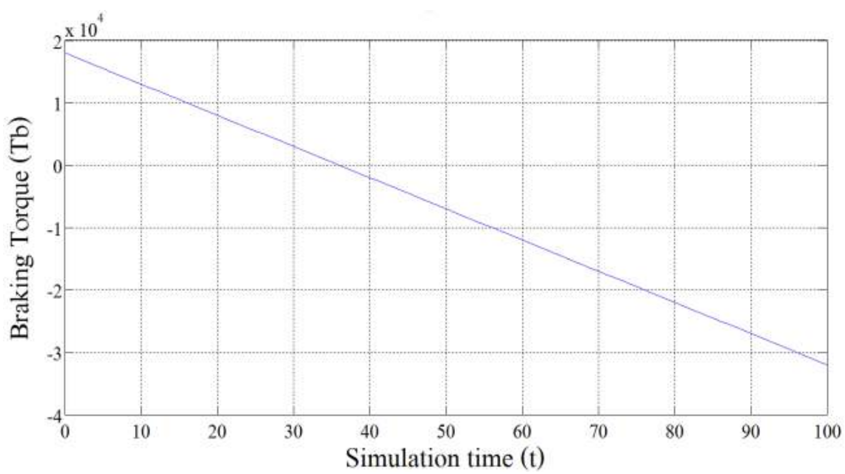

Fig. 8. Wheel speed decreasing, field speed steady (same direction)

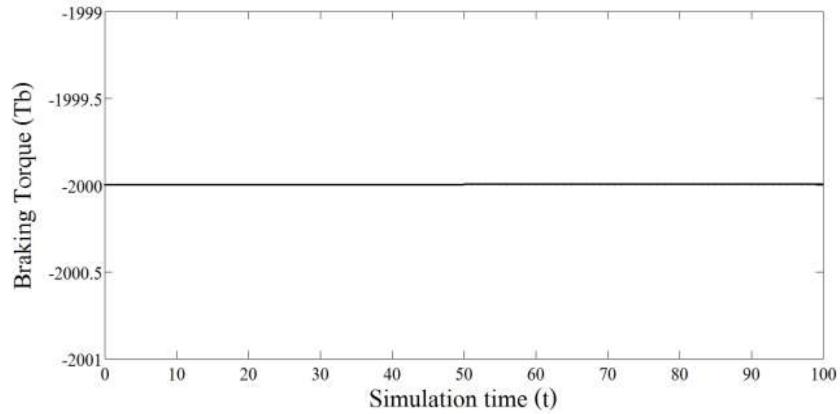

Fig. 9. Wheel stationary, field speed steady

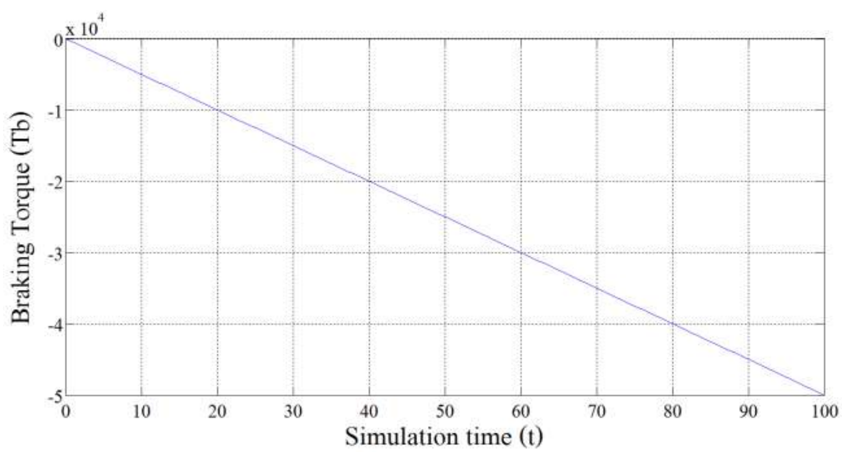

Fig. 10. Wheel stationary, field speed increasing

Application of the brake when the wheel is stationary generates a tractive torque (section 3.3). 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.

3.5 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].

4. 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, as well as in high, 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".

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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