Design, Fabrication and Testing of Electromagnetic Braking System

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Abstract - *This technical article concerns the study of electromagnetic braking system integrated with conventional friction braking mechanism and its experimentation and testing on a GO-KART vehicle. Electromagnetic braking system is used along with friction brakes to improve the system in terms of brake efficiency, user convenience, maintenance cost, human safety and environmental impact. The integrated braking system is designed such that electro-mechanism will be used to retard the vehicle first and then friction braking will be applied to bring the vehicle to complete rest. The study has been done in three major parts: design, numerical analysis and experimentation. Design of the basic structure like core of electromagnet, number of turns, and current to be supplied is done using software like SolidWorks, MATLAB, etc and various parameters that are deterministic in the design of electromagnetic braking system are analyzed numerically and experimentally. The study aims to mitigate the problem of braking inefficiency and high maintenance cost of conventional braking system.*

Key Words: Electromagnetic braking system, friction braking, automobile, mechanical design

1. INTRODUCTION

Different types of braking system are being used in different types of vehicles such as disk brake, drum brake, pneumatic brakes, and so on. Different approaches are being made for enhancing the effectiveness of braking system. But, still results are not obtained as expected.

Conventional braking system has the problem of heat dissipation due to its excessive use. It requires frequent maintenance which consequently increases the maintenance costs. Likewise, conventional braking system has environmental impacts as its components are made of the substances like asbestos which is really harmful to our health causing diseases like lung cancer, mesothelioma, asbestosis, etc.

Lots of people are losing their life due to the diseases caused by the exposure to asbestos particles. We have tabulated the deaths of American people caused by asbestos related diseases.

Table-1: Number of deaths due to asbestos related diseases

Year	Mesothelioma	Asbestosis
2007	2606	1393
2008	2709	1341
2009	2753	1255
2010	2745	1308
2011	2832	1243
2012	2874	1208
2013	2686	1229

Source:(http://www.asbestosnation.org/facts/asbestos-kills-12000-15000-people-per-year-in-the-u-s)

Also, one of the major causes of road accidents in Nepal is found to be poor mechanical condition of vehicles in which improper functioning of brakes also lies.

Table-2: Number of accidents along with deaths in a particular year

S.N.	Fiscal Year	No. of Accident	Fatalities	Serious Accidents
1	065/66	4770	147	246
2	067/68	4672	143	229
3	069/70	4999	133	233
4	071/72	5568	166	275
5	073/74	5530	188	201

Source:(https://traffic.nepalpolice.gov.np/index.php/news/traffic-activities/425-annually-accidental-descriptions)

Electromagnetic braking system can be a great asset for automobile industry which can address the above mentioned issues and hence, can enhance the effectiveness of the braking system. Electromagnetic braking system along with the conventional braking system can be used as a dual braking mechanism which will bring a new revolution in the field of braking system. Electromagnetic braking system will be used first to reduce the speed of vehicle and then friction braking system will be used to bring the vehicle to complete rest.

2. METHODOLOGY

2.1 Selection of Materials

Components of different materials were fabricated and tested in the system. After multiple failures, following materials were found to be most effective for the proposed mechanism.

2.1.1 Electromagnetic Core

Fig-1: Electromagnetic Core 3D Design

Iron was used for the fabrication of electromagnetic core. Iron was chosen due to its high relative permeability which is one of the most crucial elements while selecting the material for electromagnetic core. Also, it is readily available and cheap compared to other materials.

2.1.2 Winding Wire

Insulated copper wire of 18gauge was used for winding the electromagnetic core. Copper wire was selected due to its chemical, physical and mechanical property which best suits the requirement of solenoid for electromagnets.

Fig-2: Insulated copper wire

2.1.3 Rotor

Aluminum disc of 6mm thickness and 260mm diameter was used for the rotor. Initially, steel rotor disc of traditional friction braking mechanism was used which didn't perform as expected due to its ferromagnetic nature.

Fig-3: Aluminum rotor

2.2 Working Principle

The rotor is kept close to the electromagnet so as to cut the lines of force and thus a varying flux is cut by a rotating disc. From Faraday's law of induction, this field induces a flow of electric current by setting up a primary induced EMF on a conducting rotor plate This induced EMF is called Eddy current.

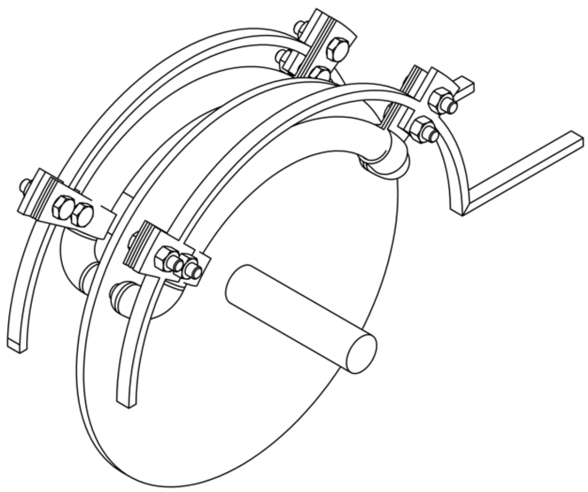

Fig-4: Electromagnetic core fixed on rotating circular disc

Each of these circular currents creates a counter magnetic field, which due to Lenz's law opposes the change in magnetic field, causing a drag force on the disk which is the braking force exerted by the brake. This braking force exerted by an eddy current brake is directly proportional to the speed of the disk.

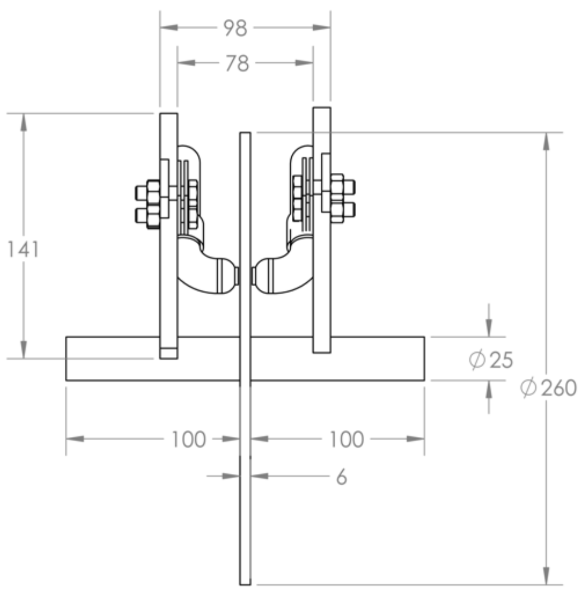

Fig-5: Electromagnetic braking system design

2.3 Numerical Analysis

As per the measurement, following data was obtained from the system:

Coefficient of friction between the brake pad and the disk, $\mu = 0.7$

Radius of the brake rotor, $r = 0.13m$

Mass of the vehicle, $m = 150kg$

Acceleration due to gravity, $g = 9.81m/s^2$

Wheel base, $L = 1.28m$

$$a = b = 0.64m$$

Height of C.G. from the ground level, $h = 0.55m$

Moment of inertia of wheel,

$$I = \frac{MR^2}{2} = \frac{9 \times (0.19)^2}{2} = 0.1444kg.m^2$$

2.3.1 Braking Torque

The braking torque that can be gained from the eddy current braking system is given by

$$T_b = \sigma R^2 sd \left(\mu_0 \frac{Ni}{l_g}\right)^2 \cdot \omega$$

Assuming the initial velocity of the vehicle to be at 50km/hr and final velocity to be 0km/hr i.e. complete stop and braking distance to be 23m, braking torque required can be calculated as follows:

Initial angular velocity,

$$\omega_1 = \frac{50000}{3600 \times 0.2032}$$

$$= 73.099\ rad/s$$

Final angular velocity,

$$\omega_2 = 0\ rad/s$$

Angular displacement travelled,

$$\theta = \frac{23}{0.19} = 121.052rad$$

Let t be the time to stop the vehicle completely and α be the angular deceleration or the wheel of the vehicle.

So, from the equation of motion in rotational direction,

$\omega_2 = \omega_1 - \alpha t$

Or, $0 = 73.099 - \alpha t$

Or, $\alpha t = 73.099$

Again, we know that,

$\theta = \omega_1 t - \frac{1}{2}\alpha t^2$

Or, $121.052 = 73.099\, t - \frac{73.099\, t}{2}$

Or, $t = 3.31\, s$

And, $\alpha = 22.07 rad/s$

From braking torque basic equation,

Braking torque on the front wheel,

$$T_f = \mu rmg \frac{b + \mu h}{L}$$

$= 0.7 \times 0.19 \times 150 \times 9.81 \times \frac{0.64 + 0.7 \times 0.55}{1.28}$

$= 156.72\, Nm$

Similarly, braking torque on the rear wheel,

$$T_r = \mu rmg \frac{a - \mu h}{L}$$

$= 0.7 \times 0.19 \times 150 \times 9.81 \times \frac{0.64 - 0.7 \times 0.55}{1.28}$

$= 38.99\, Nm$

Wheel torque,

$T_i = I\alpha$

$= 0.14 \times 22.07$

$= 3.19 Nm$

Total braking torque for one wheel,

$T_{bf} = \frac{T_f}{2} + T_i$ (Braking torque for one front wheel)

= 81.55 Nm

$T_{br} = \frac{T_r}{2} + T_i$ (Braking torque for one rear wheel)

= 22.68Nm

This is the amount of torque that must be applied by the braking system constantly in order to stop the vehicle with initial velocity of 50 km/hr within the distance of 23m.

2.3.2 Number of Turns

The value of number of turns in the electromagnetic coil was calculated using the following equation:

$$n := \sqrt{\frac{T \cdot l^2}{\mu^2 \cdot R^2 \cdot i^2 \cdot s . \sigma \cdot d \cdot \theta}}$$

Distance between center of disc and center of pole, $R = 0.06m$

Thickness of the disc, $d = 0.006m$

Surface area of the pole, $s = 3.14 \times 10^{-4} m$

Relative permeability of the air, $\mu_0 = 12.56 \times 10^{-7}$

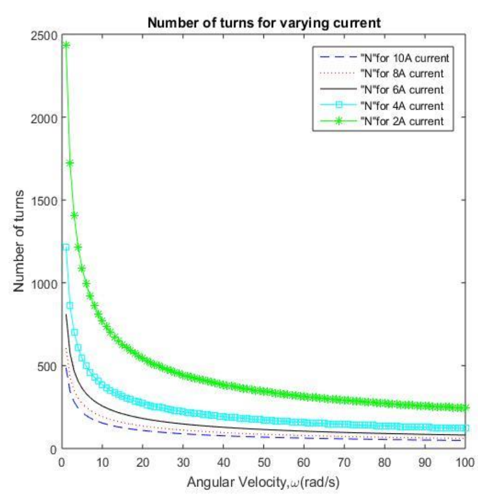

Chart-1: Number of turns vs. angular velocity

For optimized number of turns in the solenoid coil, our assumptions:

Minimum speed of vehicle upto which eddy current brake is effective = 10km/hr

Average current drawn from the battery = 2A

Number of turns in the solenoid coil is calculated using the equation as

$N =$

$$\sqrt{\frac{22.68\times0.002^2}{(12.56\times10^{-7}\times0.1135)^2\times16\times3.14\times10^{-4}\times10^7\times0.06\times14.61}}$$

$= 424.50$

Considering leakage of magnetic flux from the solenoid, eccentricity of the disc and the change in the air gap between the disc and the pole, we use leakage correction factor as 4.

So, the number of turns becomes:

4*424.5=**1698**.

2.3.3 Current Supply

The braking distance and stopping time of the vehicle with varying current is demonstrated on the graphs below:

Braking distance of the vehicle:

From raking distance of a vehicle is given by,

$$Braking\ distance = \frac{\omega_1 - \omega_2}{K} + \frac{{\omega_2}^2 r^2}{2a}$$

Taking maximum allowable acceleration as 4.2m/s² and 1698 as the number of turns,

We get the plot of braking distance for various values of braking current as:

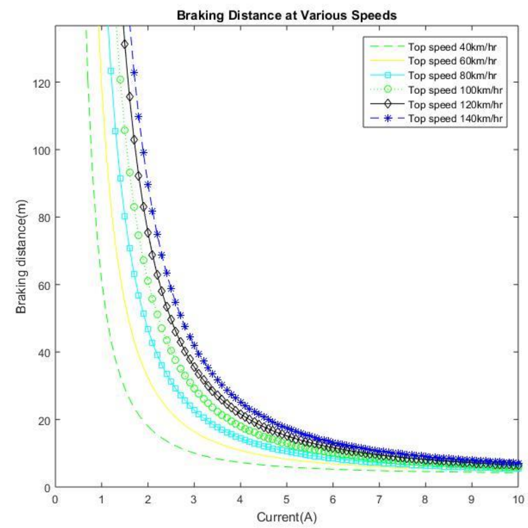

Chart-2: Braking distance at various speeds

Stopping time of vehicle:

Stopping time of the vehicle is given by,

$$stopping\ time = \frac{1}{2K}\cdot(ln\omega_1 - ln\omega_2) + \frac{\omega_2}{\alpha}$$

Taking maximum allowable acceleration as 4.2m/s² and 1698 as the number of turns,

We get the plot of braking distance for various values of braking current as:

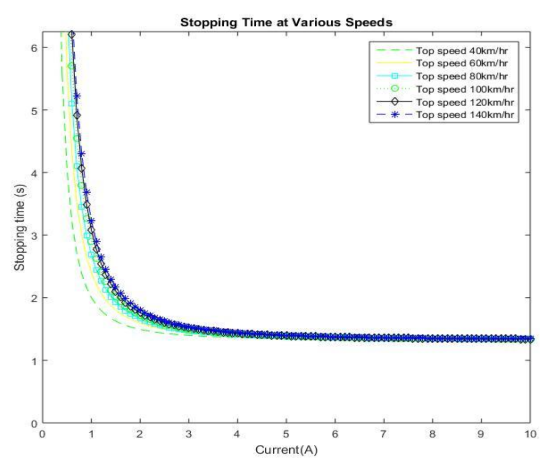

Chart-3: Stopping time at various speeds

2.4 Fabrication

The electromagnet set was installed on GO-KART. Firstly, the place where electromagnet was to be located was fixed. Housing for the electromagnet was made by using aluminum sheets for support and adjustment, and iron structures were made for welding it with the chassis. The wheel and rotor disc of the vehicle was removed and the electromagnet set was installed. The clearance between the electromagnet surface and brake disc was maintained 1mm to 3mm. This distance could be altered using the adjustment mechanism in support system. The electromagnet was excited using 12V battery through probes. 1ohm resistance was used to maintain the current flowing through the system. The aluminum rotor disc and wheel were reassembled in the axle.

Fig-6: Installation of electromagnetic brake

3. RESULTS AND DISCUSSION

3.1 Testing

The braking mechanism was tested by lifting the wheel above ground level on some support i.e. with no vehicle weight consideration. The axle of the vehicle was driven and brake was applied for retarding the speed and finally deceleration within a short time was observed. Tachometer was used to measure the speed of the wheel and digital multimeter was used to measure the current in the solenoid coil before the eddy current brake was applied.

3.2 Experimental Data

Top speed of the vehicle: 620 rpm

Table-3: Speed Measured At Different Interval after Application of Brake

S.N.	Current (A)	Speed (after brake application for)		
		1s	**2s**	**3s**
1.	1.4	486	331	255
		442	350	258
		446	360	239
		448	379	249
2.	1.9	430	367	230
		414	303	249
		416	367	250
		418	346	253
3.	2.9	386	285	153
		356	298	166
		360	299	157
		352	306	159
4.	3.6	346	288	145
		336	293	128
		375	294	144
		352	299	141
5.	5	278	195	99
		251	162	95
		261	173	91
		247	175	96
6.	8	237	137	88
		214	127	75
		231	128	79
		249	154	92

Table-4: Calculation of mean and standard deviation for different speed

Current (A)	Mean Speed (after)			Standard Deviation (after)		
	1s	**2s**	**3s**	**1s**	**2s**	**3s**
1.4	455.5	355	250.2	20.4	20.0	8.38
1.9	419.5	345.7	245.5	7.19	30.1	10.4
2.9	363.5	297	158.7	15.3	8.76	5.43
3.6	352.2	293.5	139.5	16.5	4.50	7.85
5.0	259.2	176.2	95.2	13.8	13.7	3.30
8.0	232.7	136.5	83.5	14.5	12.5	7.85

3.3 Graphs and Plots

Taking N = 1698 according to the design, following plots were obtained from MATLAB:

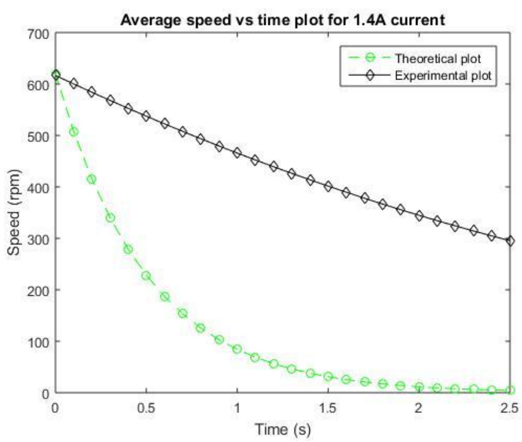

Chart-4: Average Speed Vs. Time Plot for 1.4A Current

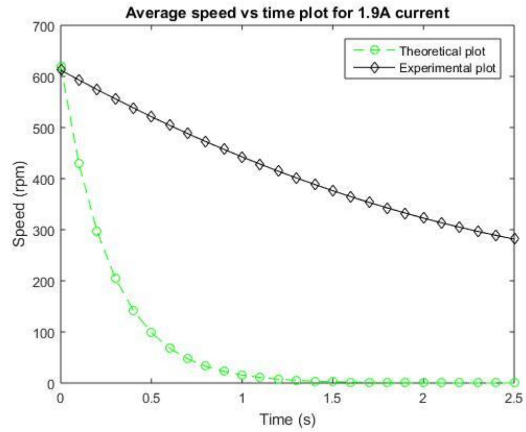

Chart-5: Average Speed Vs. Time Plot for 1.9A Current

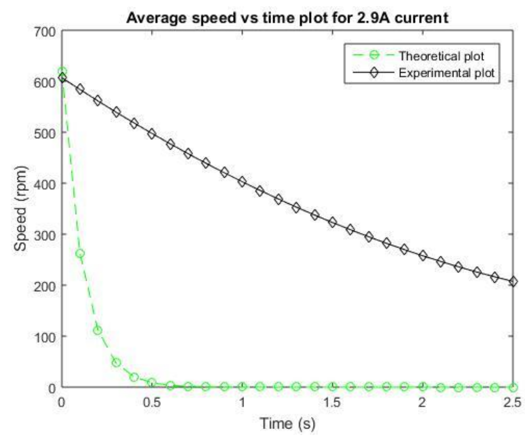

Chart-6: Average Speed Vs. Time Plot for 2.9A Current

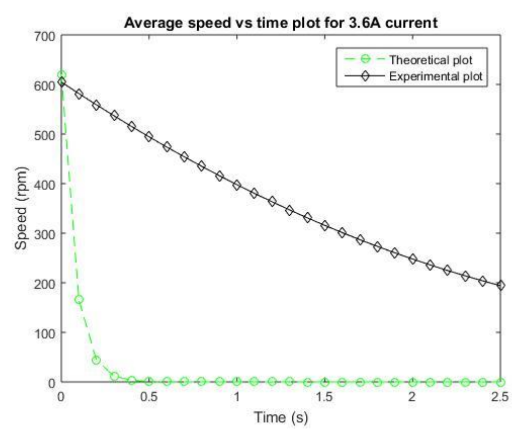

Chart-7: Average Speed Vs. Time Plot for 3.6A Current

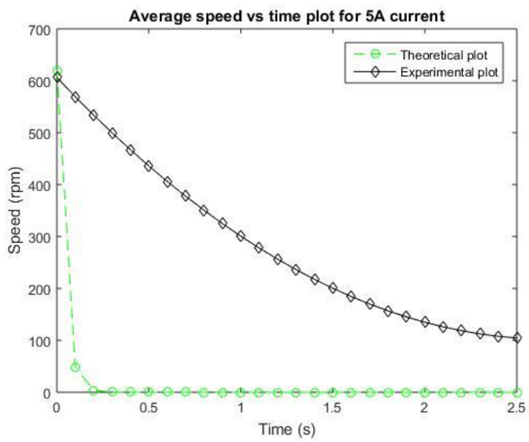

Chart-8: Average Speed Vs. Time Plot for 5A Current

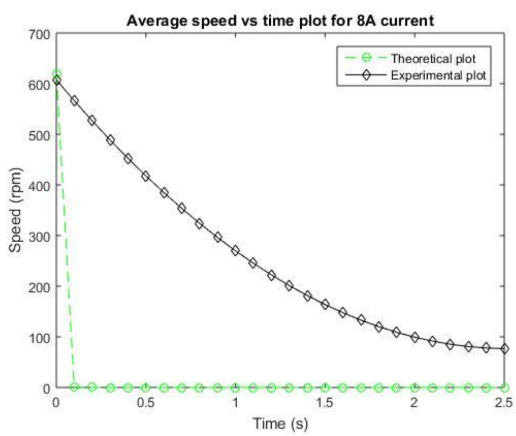

Chart-9: Average Speed Vs. Time Plot for 8A Current

3.4 Findings and Discussions

From the charts above, following observations were made:

- The braking effect was found to be higher when the current passed through the solenoid was more i.e. the velocity was reduced to 250.25 rpm after three seconds when the current was 1.4 amp and it was reduced to 83.25 rpm after three seconds when the current in the solenoid was 8 amp, where initial speed for both the conditions were 600rpm.

- The performance of the system was analyzed in terms of speed for various values of current (1.4A, 1.9A, 2.9A, 3.6A, 5A and 8A) and its duration of supply which revealed that speed decreases exponentially with time.

- The feasibility analysis showed that it is economically and technically viable as the electromagnetic brake reduces the use of friction brake almost by 66.7% which is about three times.

4. CONCLUSIONS

It was concluded that the speed of the rotor decreases exponentially with time after the application of electromagnetic brake. It was also observed that the brake is efficient only in high velocity region. The cause for this deviation of experimental curve from theoretical curve may be variation of air gap, flux leakage from the solenoid, eccentricity of the disc and some inaccuracy in the simultaneous measurement of time and speed. It was also observed during the study that the braking efficiency of electromagnetic braking system depends on following major entities:

Number of turns: Magnetic flux produced is directly proportional to the number of turns of wire in electromagnet. Hence, higher number of turns results in higher magnetic flux which implies higher braking force.

Rotor disc: Traditional friction braking mechanism uses steel rotor disc which is ferromagnetic in nature and is perforated with number of holes on its surface. These holes resist the loop of induced eddy current loop on rotor surface. Hence, non-ferromagnetic material such as aluminum with no perforated holes is required.

Core geometry: The core of electromagnet should not have sharp edges and sudden changes in cross-sectional areal which can result in leakages through edges and corners.

Air gap: Magnetic force experienced by an object decreases exponentially with increase in distance. Hence, air gap between the electromagnet and rotor surface should be maintained minimum.

5. LIMITATIONS AND RECOMMENDATIONS

The braking mechanism was found to have certain limitations which can be addressed in further research in the field.

- Due to residual magnetism present in electromagnets, the brake shoe takes time to come back to its original position.

- The installation of an electromagnetic brake is very difficult if there is not enough space between the gearbox and the rear axle.

- Electric braking cannot be used for holding the machine after coming to the rest, so a mechanical braking is required additionally. For example in the case of the train going uphill, after the train is stopped using electric brakes, it has to be prevented from moving down hill.

- Battery charge consumption rate will be higher than previous system.

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