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Design & Theoretical Study of Electromagnetic Braking System

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Abstract: *An electromagnetic braking system uses magnetic force to engage the brake, but the power required for braking is transmitted manually. The disc is connected to a shaft and the electromagnet is mounted on the frame .When electricity is applied to the coil a magnetic field is developed across the armature because of the current flowing across the coil and causes armature to get attracted towards the coil. As a result it develops a torque and eventually the vehicle comes to rest. The behavior of two different materials to be used as brake disc which are aluminum & copper was studied. The experiment also aimed to see the effects of increasing the current induced into electromagnet which produce drag force that will slow down the motion. A few graph been presented to show the best material to be used as the brake disc for electromagnetic braking system using eddy current project. The variation in braking time & braking torque with respect to variation in air gap & current was studied & graphs were plotted to show the results.*
Keywords: *Aluminum, Braking, Copper, Eddy Current, Electromagnetic*

I. Introduction

With the technological enhancement a lot of new technologies are arriving in the world. Many industries got their faces due to the arrival of these technologies. An automobile technology is one of them. As a part of automobile, there are also innovations in brake. The commonly used types of brakes used in automobiles are drum and disc brakes. Various types of braking system used are hydraulic, pneumatic etc. Magnetic braking forms the basis of growing technology. Braking system is generally classified based upon the principle of operation. The two major type of brake are frictional and electromagnetic retarder. The principle of braking in road vehicles involves the conversion of kinetic energy into thermal energy (heat).When stepping on the brakes, the driver commands a stopping force several times as powerful as the force that puts the car in motion and dissipates the associated kinetic energy as heat. Ineffective braking results in a lot of accidents. Brakes must be able to arrest the speed of a vehicle in a short period of time regardless how fast the speed is. As a result, the brakes are required to have the ability to generating high torque and absorbing energy at extremely high rates for short periods of time. Brakes may be applied for a prolonged periods of time in some applications such as a heavy vehicle descending a long gradient at high speed. Brakes must have the mechanism to keep the heat absorption capability for prolonged periods of time.

The frequency of accidents is now-a-days increasing due to inefficient braking system. Hence braking system needs to be enhanced for effective and efficient braking. Electromagnetic brake is as new revolutionary concept. It is found that electromagnetic brakes can develop a negative power which represents nearly twice the maximum power output of a typical engine, and at least three times the braking power of an exhaust brake. These performance of electromagnetic brakes make them much more competitive candidate for alternative retardation equipments compared with other retarders. In this research work, with a view to enhance to the braking system in automobile, a prototype model is created and analyzed. It aims to minimize the brake failure to avoid the road accidents. It also reduces the maintenance of braking system. An advantage of this system is that it can be used on any vehicle with minor modifications to the transmission and electrical systems.

Electromagnetic brakes operate electrically, but transmit torque mechanically. This is why they used to be referred to as electro-mechanical brakes. Over the years, EM brakes became known as electromagnetic, referring to their actuation method. Since the brakes started becoming popular over sixty years ago, the variety of applications and brake designs has increased dramatically, but the basic operation remains the same. Single face electromagnetic brakes make up approximately 80% of all of the power applied brake applications. Electromagnetic brakes have been used as supplementary retardation equipment in addition to the regular friction brakes on heavy vehicle.

II. Methodology

- The electromagnetic brake is a relatively primitive mechanism, yet it employs complex electromagnetic and thermal phenomena. As a result, the calculation of brake torque is a complex task.
- However precise mathematical models of the brakes are important for the purpose of simulation and control.
- There are three models proposed in the literature on eddy current brakes:
  - ➢ W.R. Smythe's Model

- D. Schieber's Model
- J.H. Wouterse's Model
- Smythe's approach is to treat the problem as a disc of finite radius and obtained a closed-form solution of torque calculation by means of a reflection procedure (the magnetic field due to eddy currents which appears from either side of the sheet, is modeled by a pair of images receding with uniform velocity) specifically suited to the geometry of the problem. The first step is to calculate the magnetic induction, B, produced by the eddy currents induced in a rotating disk by a long right circular cylinder pole piece.
- Schieber adapted a general method of solution to a rotating system which is different from Smythe's approach. This formula is for low speed only. Schieber found out that his result is very close to Smythe's result at low speed and that it is valid for a linearly moving strip as well as a rotating disc. Schieber did not investigate the high speed region.
- Based on the works of Schieber and Smythe, Wouterse tried to find the global solution for the torque in the high-speed region as well as the low speed region. Following results are obtained by Wouterse's Method:
- At very low speeds, the field differs only slightly from the field at zero speed.
- At the speed at which the maximum dragging force is exerted, the mean induction under the pole is already significantly less than B0.
- At higher speeds, the magnetic induction tends to further decrease.
- The analysis of electromagnetic brake is done according to Schieber's method as it is a general method and it is also applicable for a rotating disc.
- Aluminum and Copper are the preferred materials for the disc due to their electric, thermal and magnetic properties.
- Discs of two different thickness and three different air gaps for the electromagnets are taken for purpose of comparison and design of experimentation.
- Maximum Braking torque, Maximum Braking force and Stopping Distance are calculated.
- Design of electromagnetic braking system is done based on the calculations.

III. Design Of Electromagnetic Brakes

3.1 Material Selection

The material of the rotor disc must also be optimized in order to minimize the time constant, τ and minimize the disc's moment of inertia, I. There are two strong candidates in our selection of material which are copper and aluminum. This evaluation is based on the qualitative result of Equation. In order to minimize the time constant, we must choose the smallest ratio of density, ρ to conductivity, σ from all the materials available. We have evaluated the ratios for a number of possible commercial materials. We find that copper and aluminum rank top. The ratio for copper is calculated to be 1.5*10-4 kgm2/S and for aluminum is 0.76*10-4 kgm^2/S. Therefore, we plan to use aluminum as the material for our rotating disk in the prototype in order to achieve better brake performance.

$$\tau = \frac{I}{b} = \frac{2\rho R^2}{n\sigma D^2 B^2} \quad (1)$$

$$b = n\frac{\pi\sigma}{4} D^2 d B^2 R^2 \quad (2)$$

$$I = \frac{1}{2}\rho d \pi R^2 \quad (3)$$

Table 1: Comparison between copper & aluminum as the material for the rotating disk.

	Density [kg/m3]	Specific Conductivity [S/m]	Ratio [kgm2/S]
Copper	8.9*103	58.0*106	1.5*10-4
Aluminum	2.7*103	35.5*106	0.76*10-4

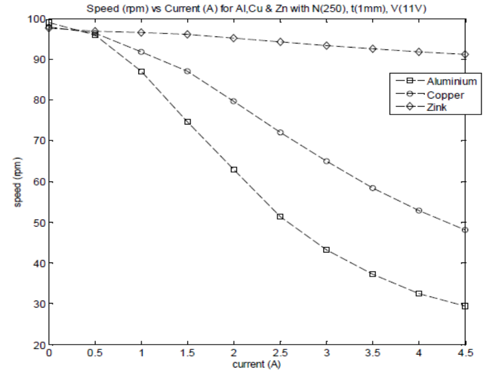

Figure 1: Speed (rpm) versus current (A) for aluminum, copper and zinc N (250), thickness (1mm) and V (11V).

3.2 Selection of Disc Thickness

The thickness of the rotor disc, *d*, must also be optimized in order to minimize the time constant, τ and minimize the disc's moment of inertia, *I*. The inertia of the disc is linearly proportional to the thickness, so minimizing the disk radius minimizes the disk inertia. The time constant does not depend on the disc thickness. Thus, the optimization problem reduces to minimizing disc thickness while maintaining enough structural rigidity.

$$I = \frac{1}{2}\rho d \pi R^2 \qquad (4)$$

$$\tau = \frac{I}{b} = \frac{2\rho R^2}{n\sigma D^2 B^2} \qquad (5)$$

3.3 Disc Radius

The radius of the rotor disc, *R*, must also be optimized in order to minimize the time constant, τ and minimize the disc's moment of inertia, *I*. The inertia of the disc is proportional to the radius to the fourth power, so minimizing the disk radius minimizes the disk inertia. The functionality of the time constant on the disc radius isn't as clear. Equation that the time constant is proportional to the radius squared, however the magnetic flux, $\phi(R)$, is also a function of the disc radius because the larger the radius the more magnets can be mounted and thus the stronger the magnetic field. This functionality of the magnetic field on the disc radius is unknown and may only be evaluated experimentally. Thus, optimization of the rotor disc radius possess a design challenge due to incomplete governing mathematical relations.

$$I = \frac{1}{2}\rho d \pi R^2 \qquad (6)$$

$$\tau = \frac{I}{b} = \frac{2\rho R^2}{n\sigma D^2 B^2} \qquad (7)$$

$$\phi(R) = BD(R)n(R) \qquad (8)$$

3.4 Design of Electromagnet

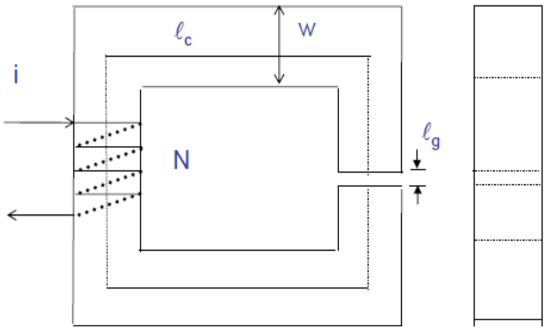

Figure 2: Schematic diagram of electromagnet.

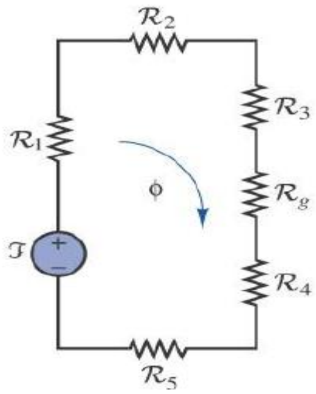

Figure 3: Equivalent electrical circuit.

$$R_c = \frac{l_c}{\mu_c A_c} \qquad (9)$$

$$R_g = \frac{l_g}{\mu_g A_g} \qquad (10)$$

$$\varphi = \frac{N_i}{R_c + R_g} \qquad (11)$$

$$\varphi = \frac{N_i}{\Sigma R} = \frac{N_i}{(R_1+2R_2+2R_3+2R_g+R_d)} \quad [Wb] \qquad (12)$$

$$B = \frac{\varphi}{A} = \frac{N_i}{A(R_1+2R_2+2R_3+2R_g+R_d)} \quad [T] \qquad (13)$$

$$A = \frac{\tau}{4} d_p^2 \qquad (14)$$

According to our application,

$r_d = 100mm$

$r_e = 75mm$

$d_p = 40mm$

3.4.1 Dimensions of Electromagnet

Table 2: Dimensions of electromagnet.

Dimensions of Electro-magnet						
(All dimensions are in mm)						
l1	l2	l3	l4	l5	lg	t
55	50	25	25	50	1	4
57	50	25	25	50	3	4
59	50	25	25	50	5	4
56	50	25	25	50	1	5
58	50	25	25	50	3	5
60	50	25	25	50	5	5

Table 3: Standard values of Relative Permeability & Absolute Permeability.

Permeability of vacuum	
0.000001256637	
Relative permeability	
Soft Iron	5000
Aluminium	1.000021
Copper	0.99904
Absolute permeability	
Soft Iron	0.006283
Aluminium	1.26E-06
Copper	1.26E-06

3.4.2 Result Table for Values of Magnetic Field for Aluminium Disc

Table 4: Values for magnetic field for Aluminium disc with thickness 4mm & 5mm.

Air gap(mm)	Rg	R1	R2	R3	R4	R5	Rd	∑R	B
1	636619.8	7003.024	6366.385	3183.19	3183.19	6366.385	2546425.615	3209147.559	0.124048
3	1909859	7257.679	6366.385	3183.19	3183.19	6366.385	2546425.615	4482641.754	0.088807
5	3183099	7512.335	6366.385	3183.19	3183.19	6366.385	2546425.615	5756135.95	0.069159
1	636619.8	7130.35	6366.385	3183.19	3183.19	6366.385	3183032.018	3845881.288	0.103511
3	1909859	7385.07	6366.385	3183.19	3183.19	6366.385	3183032.018	5119375.555	0.077761
5	3183099	7639.66	6366.385	3183.19	3183.19	6366.385	3183032.018	6392869.69	0.062271

3.4.3 Result Table for Values of Magnetic Field for Copper Disc

Table 5: Values for magnetic field for Copper disc with thickness 4mm & 5mm.

Air gap(mm)	Rg	R1	R2	R3	R4	R5	Rd	∑R	B
1	636619.8	7003.024	6366.385	3183.19	3183.19	6366.385	2536749.66	3199471.604	0.124423
3	1909859	7257.679	6366.385	3183.19	3183.19	6366.385	2536749.66	4472965.799	0.088999
5	3183099	7512.335	6366.385	3183.19	3183.19	6366.385	2536749.66	5746459.995	0.069276
1	636619.8	7130.35	6366.385	3183.19	3183.19	6366.385	3170937.075	3833786.345	0.103837
3	1909859	7385.07	6366.385	3183.19	3183.19	6366.385	3170937.075	5107280.612	0.077945
5	3183099	7639.66	6366.385	3183.19	3183.19	6366.385	3170937.075	6380774.747	0.062389

3.5 Calculations for Braking Torque

For the braking torque analysis, we've followed the analysis that has been done by Lee. The iron core shape use in this study was a round shape in diameter of 60 mm. For this analysis, n, i, lg, µ, represent the number of electromagnet turns, applied current, air-gap and permeability of air,respectively.

Here, the µbeen taken as 12.568 x 10 -7 N.A-2 . For the electrical conductivity, it was 2.73 x 10 7 Ω.m-1 and 1.92 x 10 7 Ω.m-1 for Al6061 and Al7075, respectively.

$$B = \frac{\mu_0 ni}{l_g} \quad (15)$$

While the current density, J that been induced at center of the pole as,

$$J = \sigma(R\dot{\theta} \times B) \quad (16)$$

where σand θare the electrical conductivity and angular velocity of the brake disc.

If all the power dissipated by the eddy current, Pd which is the power dissipation assumed to be converted to generate braking torque Tb , which can be expressed as,

$$T_b = \frac{P_d}{\dot{\theta}} \quad (17)$$

The total power dissipation, Pd can be described as,

$$P_d = \rho J^2 \times \text{Volume} = \sigma R^2 S d\dot{\theta}^2 B^2 \quad (18)$$

Here, ρindicates the disc resistivity. For the braking torque calculation as in Eq., S, R, θ and represent the pole area, distance between center of the disc and pole center, and angular speed,respectively. The braking torque can be expressed in the form of,

$$T_b = \sigma R^2 S d\dot{\theta} i^2 \left(\frac{\mu_0 n}{l_g}\right)^2 \quad (19)$$

3.5.1 Results of Braking Torque of Aluminium Disc

Table 6: Braking torque for aluminium disc of thickness 4mm & air gap 1mm.

Pole Area	N	Air gap (mm)	∑R
0.001256	250	1	3209147.559
Current (A)	MMF	B(T)	Tb(max)
0	0	0.0000	0.0000
0.25	62.5	0.0155	0.0293
0.5	125	0.0310	0.1172
0.75	187.5	0.0465	0.2637
1	250	0.0620	0.4689
1.25	312.5	0.0775	0.7326
1.5	375	0.0930	1.0549
1.75	437.5	0.1085	1.4359
2	500	0.1240	1.8754
2.25	562.5	0.1396	2.3736
2.5	625	0.1551	2.9303

2.75	687.5	0.1706	3.5457
3	750	0.1861	4.2197
3.25	812.5	0.2016	4.9523
3.5	875	0.2171	5.7434
3.75	937.5	0.2326	6.5932
4	1000	0.2481	7.5016
4.25	1062.5	0.2636	8.4686
4.5	1125	0.2791	9.4943

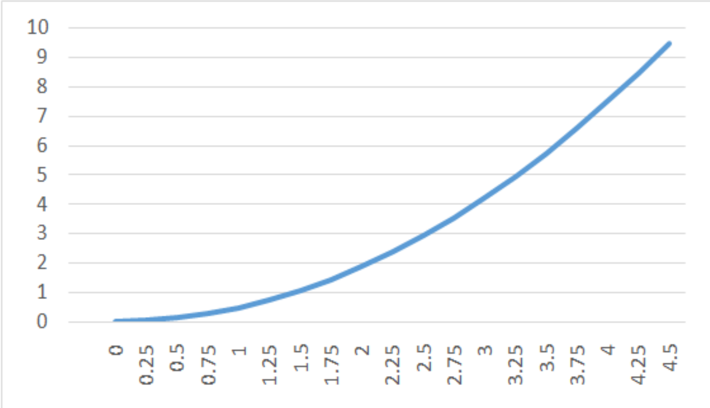

Figure 8: Braking torque vs Current for aluminium disc of thickness 4mm & air gap 1mm.

3.5.2 Results of Braking Torque of Copper Disc

Table 7: Braking torque for copper disc of thickness 4mm & air gap 1mm.

Pole Area	N	Air gap (mm)	∑R
0.001256	250	1	3199471.604
Current (A)	MMF	B(T)	Tb(max)
0	0	0.0000	0.0000
0.25	62.5	0.0156	0.0626
0.5	125	0.0311	0.2505
0.75	187.5	0.0467	0.5637
1	250	0.0622	1.0021
1.25	312.5	0.0778	1.5658
1.5	375	0.0933	2.2548
1.75	437.5	0.1089	3.0690
2	500	0.1244	4.0085
2.25	562.5	0.1400	5.0733
2.5	625	0.1555	6.2633
2.75	687.5	0.1711	7.5786
3	750	0.1866	9.0192
3.25	812.5	0.2022	10.5850
3.5	875	0.2177	12.2761
3.75	937.5	0.2333	14.0925
4	1000	0.2488	16.0341
4.25	1062.5	0.2644	18.1010
4.5	1125	0.2800	20.2931

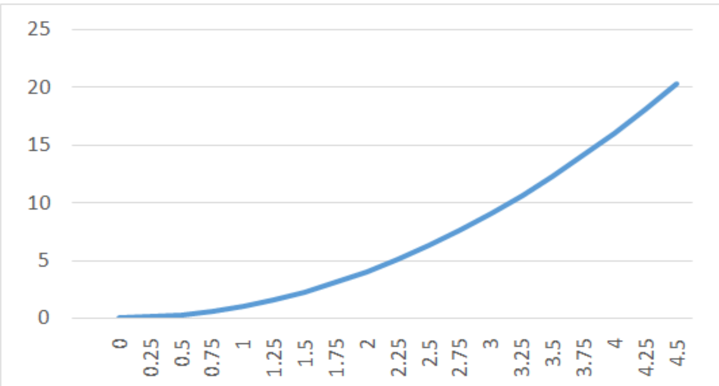

Figure 9: Braking torque vs Current for copper disc of thickness 4mm & air gap 1mm.

3.6 Calculations for Braking Time

The free response of the rotating disk at a certain initial condition can be modeled in a second-order differential equation by Newton's Second Law:

$I\ddot{\theta} + b\dot{\theta} = 0\,,\quad \text{with } \theta = 0 \text{ and } \dot{\theta} = \omega_0$ (20)

Here b represents the integration of variables before the angular velocity term in Equation as a damping coefficient and, I is the moment of inertia of the disk. Explicitly, they are:

$b = n\frac{\pi\sigma}{4}D^2 dB^2R^2$ (21)

$I = \frac{1}{2}\rho d\pi R^2$ (22)

When formulating the above equation, we overlook any other viscous or static frictions existing in the system because they are only secondary effects. By solving the equation of motion, the angular velocity can be obtained to be:

$\dot{\theta} = \omega_0 e^{-(b/I)t} = \omega_0 e^{-(1/\tau)t}$ (23)

The time constant, τ[s] is therefore the ratio of the moment of inertia of the disk to the effective damping coefficient:

$\tau = \frac{I}{b} = \frac{2\rho R^2}{n\sigma D^2 B^2}$ (24)

It not only captures the brake performance, but also shows the tradeoffs that maximize the damping for the smallest inertia. A small value is expected for the time constant which means it takes less time for a wheel to stop rotating. Equation 6 gives the ideal design guideline that qualitatively helps us optimize the brake performance before any experimental verification.

3.6.1 Results of Braking Time of Aluminium Disc

Table 8: Braking time for aluminium disc of thickness 4mm & air gap 1mm.

TC(s)	8.352018529
t(s)	w(rad/s)
0	158.7302
2	124.9287
4	98.3251
6	77.3868
8	60.9073
10	47.9371
12	37.7289
14	29.6946
16	23.3711
18	18.3943
20	14.4772
22	11.3943
24	8.9679
26	7.0582
28	5.5551
30	4.3722
32	3.4411
34	2.7083
36	2.1316
38	1.6777
40	1.3204

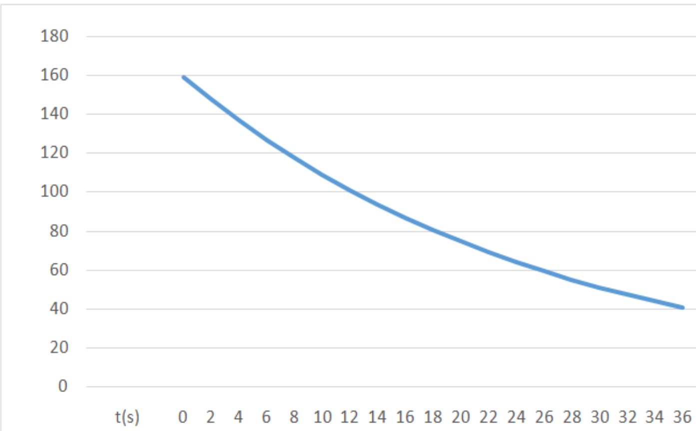

Figure 10: Speed vs Braking time for aluminium disc of thickness 4mm & air gap 1mm.

3.6.2 Results of Braking Time of Copper Disc

Table 9: Braking time for copper disc of thickness 4mm & air gap 1mm.

TC(s)	5.081187506
t(s)	lg=1mm
0	158.7302
2	107.0822
4	72.2396
6	48.7341
8	32.8769
10	22.1794
12	14.9626
14	10.0940
16	6.8096
18	4.5939
20	3.0991
22	2.0907
24	1.4104
26	0.9515
28	0.6419
30	0.4330
32	0.2921
34	0.1971
36	0.1330
38	0.0897
40	0.0605

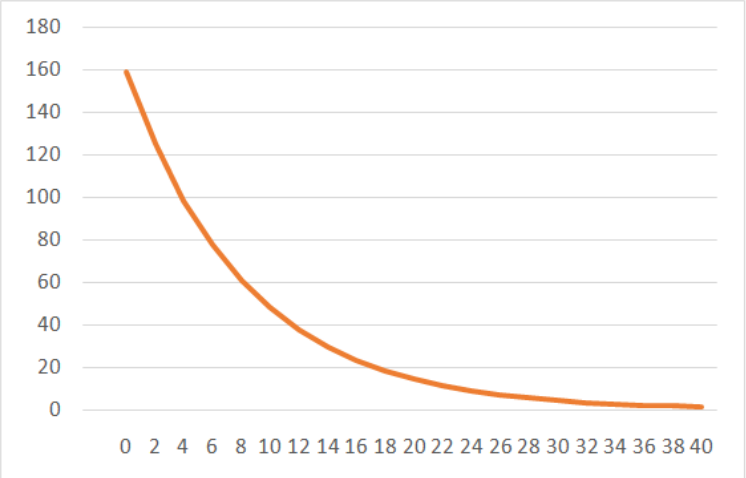

Figure 11: Speed vs Braking time for copper disc of thickness 4mm & air gap 1mm.

IV. Cad Model Of Experimental Setup

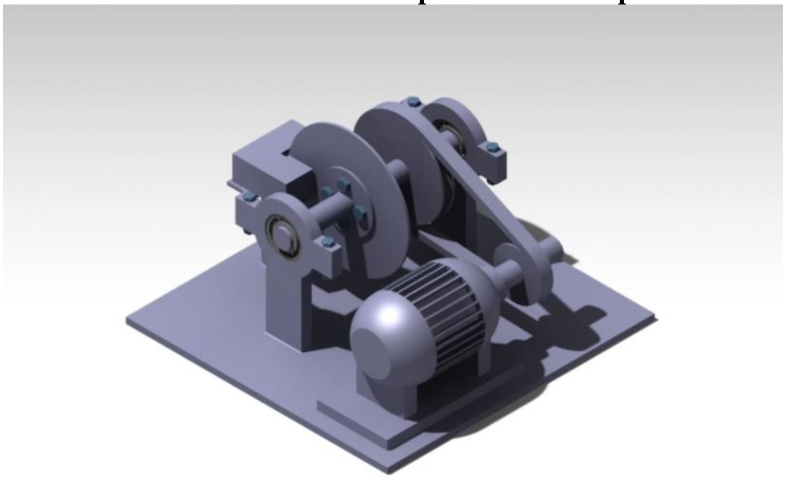

Figure 12: CAD model of experimental setup of electromagnetic braking system.

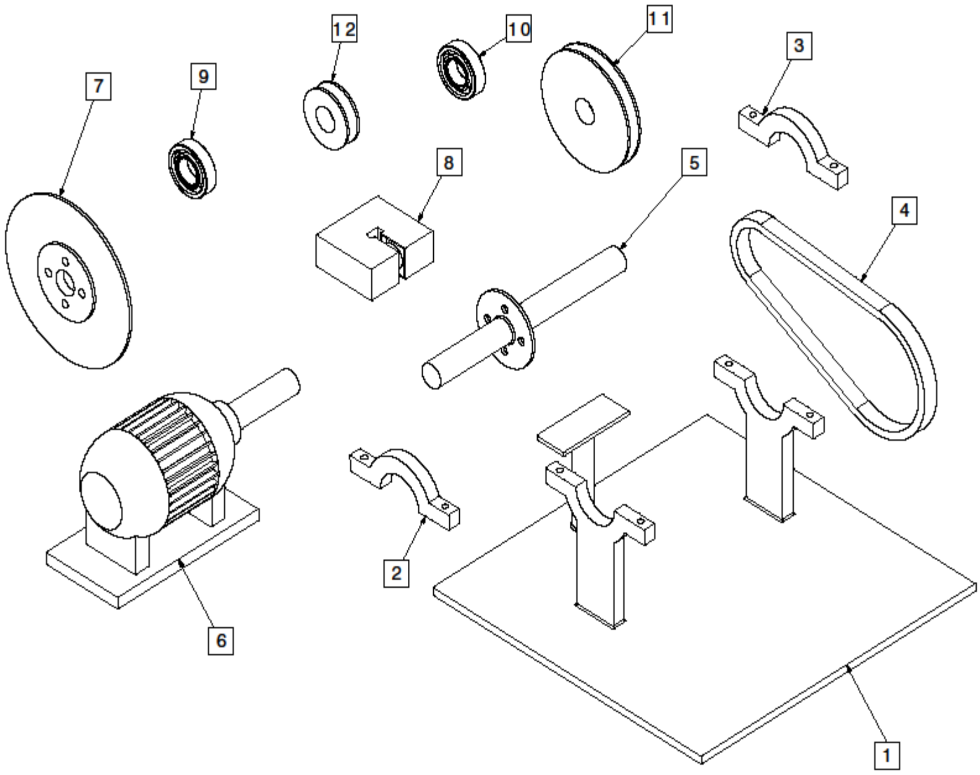

Figure 13: Exploded view of CAD model of experimental setup.

Table 10: List of different parts in the exploded view of CAD model of experimental setup.

PART NO.	PART NAME
1	Setup Base
2,3	Bearing support
4	V belt
5	Disc carrying shaft
6	Motor
7	Aluminium Disc
8	Electromagnet
9,10	Bearing
11	Driven pulley
12	Drive pulley

V. Conclusions

- Advantages and Disadvantages of electromagnetic braking system over conventional braking system has been studied.
- Electromagnetic brakes have higher performance than conventional brakes in high speeds but it cannot be used at low speeds. Hence it must be used as an auxiliary brake during high speeds.
- Aluminium and Copper have the most suitable properties for Rotor Material.
- With decrease in Air Gap there is increase in Magnetic flux passing through the rotor resulting in increased Braking Torque and hence reduced Braking time.
- With increase in thickness of rotor the magnetic flux passing through the rotor decreases resulting in lower value of Braking torque and hence increased of Braking time.
- Braking torque increases with increase in current passing through the Solenoid. But the value of current is limited due to heating of copper wire and an optimum value of current density of 2.5-3.5 A per sq.m is used.
- The optimum value of current is found to be 2A.
- Aluminium disc of thickness 4mm having an air gap of 1mm provides the best results amongst the 2 aluminium discs with maximum braking torque of 1.904Nm.
- The speed of the disc reduces from 80kmph to 40kmph in 5.96s and stopping distance is calculated by Simpsons 3/8th rule.
- The stopping Distance is found to be approximately 108.13m.

- Copper disc of thickness 4mm having an air gap of 1mm provides the best results amongst the 2 Copper discs with maximum braking torque of 3.99Nm and shows maximum retardation.
- The speed of the disc reduces from 80kmph to 40kmph in 3.6s and stopping distance is calculated by Simpson's 3/8th rule.
- The stopping Distance is found to be approximately 89m.

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