Design and Fabrication of Eddy Current Braking System

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***Abstract*— The design of an eddy current disc brake system requires a multidisciplinary approach. Eddy Current braking utilizes electronic and magnetic power based on the principle of relative motion between a magnetic source and a metal. This braking system is an upcoming alternative to the traditional braking systems which utilize friction forces to transform the kinetic energy of a moving body into heat, and proves to have remarkable safety features and applications along with reasonably low maintenance cost. In this research work, with a view to enhance the overall efficiency and effectiveness of the braking system, a prototype model for eddy current braking system is be designed, fabricated and analysed.**

***Keywords*— Eddy Current Braking, Auxiliary Braking system, Brake Disc Design, Self-Aligning Vice, Magnetostatic Analysis, SIMULINK Modelling**

I. Introduction

Eddy currents are loops of electrical current induced within conductors by a changing magnetic field in the conductor, due to Faraday's law of induction. By Lenz's Law, the direction of induced eddy currents is such that the magnetic field generated due to it, opposes the source of induction. Thus, this phenomenon inspires its application in the field of braking and is known as eddy current braking system. In this type of braking, deceleration is achieved by eddy currents produced by the relative motion between the magnet and the metal, which induces a reverse magnetic field. The magnetic field may be created by a permanent magnet or an electromagnet, so the braking force may be varied by adjusting the electric current in the electromagnet's windings. The motive of modelling eddy current brakes is to investigate the performance of non-ferrous rotating disc and estimate the braking torque. Contactless eddy current brakes have scope in a wide range of applications such as automobiles, locomotives, roller coasters, aeronautical industries, hydraulic and turbomachinery, emergency shut-off systems, machine tools, robots, elevators, etc. They can be used either as a replacement for mechanical brakes or as an auxiliary braking system.

The aim of this paper is to design and fabricate a test rig on eddy current braking system and estimate the braking torque obtained by eddy currents produced on a rotating non-ferrous disc. The disc is placed between a pair of permanent magnets, with opposite poles with respect to the distance between the magnets and the disc. This is achieved by selecting a mathematical model to assess the behaviour of the system and performing simulations for experimental validation. Magnetostatic analysis was carried out to determine the total magnetic field intensity. Furthermore, a self-aligning vice was fabricated to adjust the air gap accurately.

II. Design and Analysis

A model of eddy current braking system has been designed with all its components and necessary analysis has been performed.

A. Brake Disc

The material of the brake disc or rotor must be optimized in order to minimize the time constant (τ) and the disc's moment of inertia (I). In order to minimize the time constant, we must choose the smallest ratio of density (ρ) to specific conductivity (σ) from all the materials available. It was found that copper and aluminium rank amongst the top. The ratio for copper was calculated to be 1.5*10-4 kgm^2/S and for aluminium, it was 0.76*10-4 kg��/S. Therefore, we have used aluminium AISI 6061 as the material for our rotating disc in order to achieve better brake performance. Also, aluminium has the highest speed reduction compared to other materials such as copper and zinc.

The thickness of the disc (t) and the radius of disc (r) must also be optimized in order to minimize the time constant (τ) and minimize the disc's moment of inertia (I). The time constant does not depend on the disc thickness. Thus, the optimization problem reduces to minimizing disc thickness, which in turn decreases the inertia, while maintaining enough structural rigidity and avoiding undesired disc vibrations while maintaining straightness. Therefore, the thickness of the disc had been kept as 3 mm and the diameter of the disc was selected to be 130 mm. A slotted disc has not been used as the slots will be occupied by air, which has very high resistance to electric currents, thus resulting in the formation of weaker eddy currents.

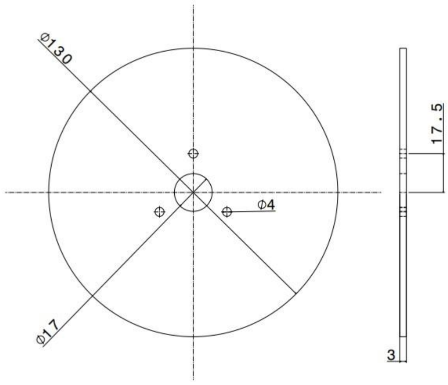


Figure 1 Brake Disc

Static structural analysis was not performed as eddy current brakes are contactless brakes, thus stress is not developed. On the other hand, thermal analysis of the brake disc was performed to analyse the temperature generated due to eddy currents for a maximum braking time of 3 secs for 5 cycles. The input parameters included convective film coefficient of 64 W/m^2 ^{0}C for aluminium and average heat flux generated, which was calculated to be around 890 W/m^0. The ambient temperature was taken as 22 ^{0}C. The maximum temperature attained by the disc was 49.3 ^{0}C.

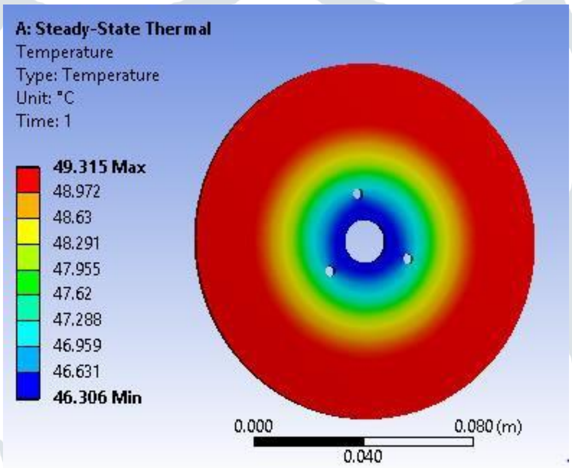


Figure 2 Thermal Analysis of Brake Disc

B. Brake Disc Mount

A separate mount disc has been designed to provide support for the brake disc on the shaft. Also, it ensures provision for mounting other discs with different materials and dimensions, as a future scope, instead of integrating the disc on the shaft. The material used for the mount disc was mild steel with 16 mm thickness and 45 mm diameter.

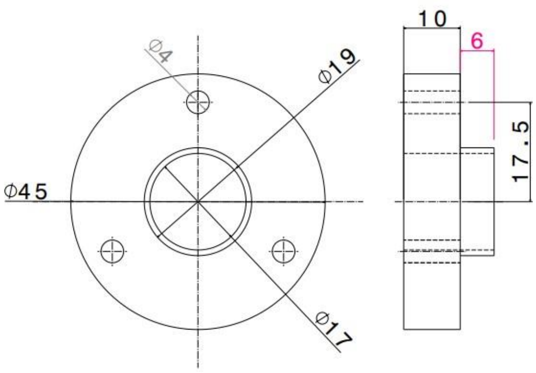


Figure 3 Brake Disc Mount

C. Base Plate and Supports

A mild steel plate with 12 mm thickness has been used as base plate, as it was essential to provide rigid support to the entire set up. The dimensions of the plate are 250 mm by 300 mm. Integrated with the base plate, are the shaft supports with required dimensions at desired positions. Mild steel square bars are used as shaft supports. The height of the support was maintained at 90 mm, while 30 mm diameter holes have been provided to incorporate ball bearings. The motor mounting plate has a thickness of 10 mm, a width of 80 mm, a height of 115 mm and is integrated with the base plate. Another 80 mm by 80 mm square mount plate has been designed to mount the motor with precision.

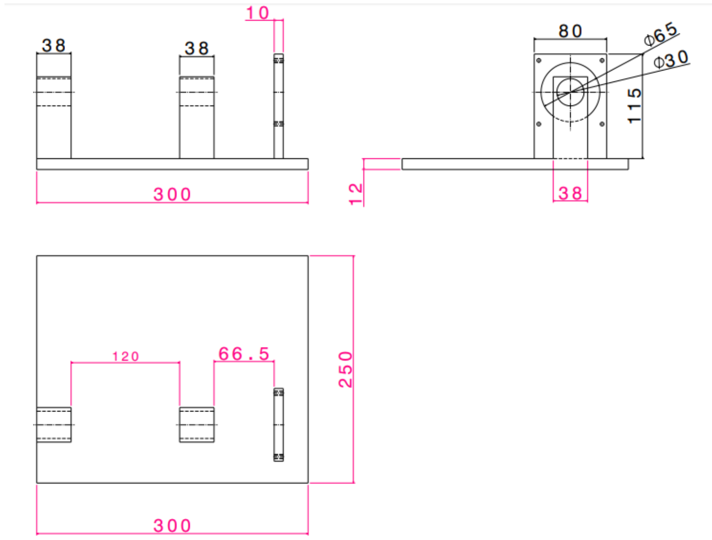


Figure 4 Base Plate, shaft Supports and Motor Support

D. Magnet Selection and Magnet Mounts

Permanent magnets have been chosen, since they are effective means for achieving low maintenance braking, without utilizing external power source. Thus, the magnet selected was 12 mm in diameter and 10 mm in thickness. The strength of the magnet is 0.35 Tesla.

Magnetostatic analysis was performed to determine the total magnetic flux density and total magnetic field intensity of the selected permanent magnets.

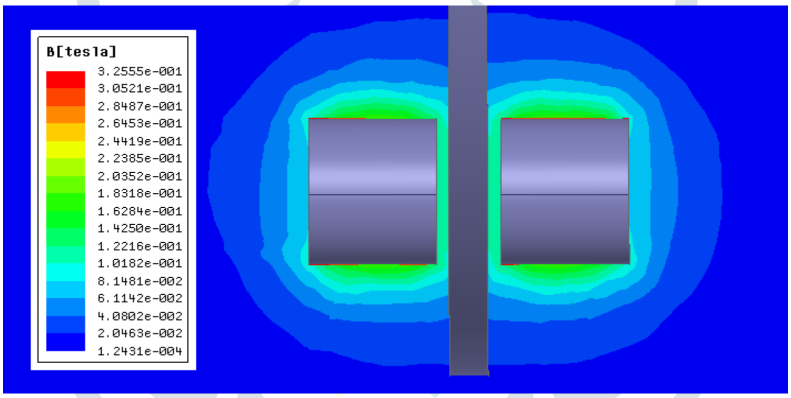


Figure 5 Total Magnetic Field Intensity Distribution

Magnet mounts in form of cantilever beams have been designed, in which the magnets will be press fit, so as to avoid any problems due to pole attraction or repulsion during experimentation. Aluminium, due to its paramagnetic nature, was selected as was selected as the material for the square beams.

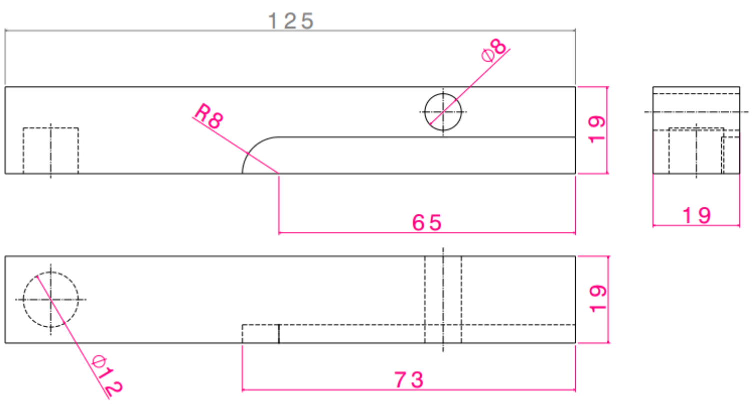


Figure 6 Magnet Mount

E. Self-Aligning Vice

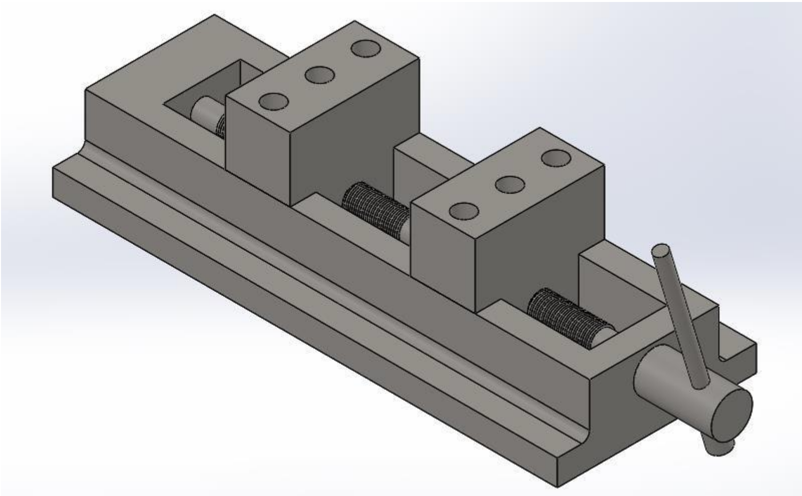


Figure 7 Self-Aligning Vice

In order to achieve the desired air gap between the brake disc and the magnets, at symmetrically equal distances, a self-centering vice has been designed. Mild steel was selected as the material as it is readily available and its material properties suffice for the application. Thread configuration for the lead screw was selected to be M10*1.5, single start ACME threads, from the standard catalogue. Two jaws have been used with internal threads that mate with the lead screw. The function of the jaws is to support the cantilever magnet mounts.

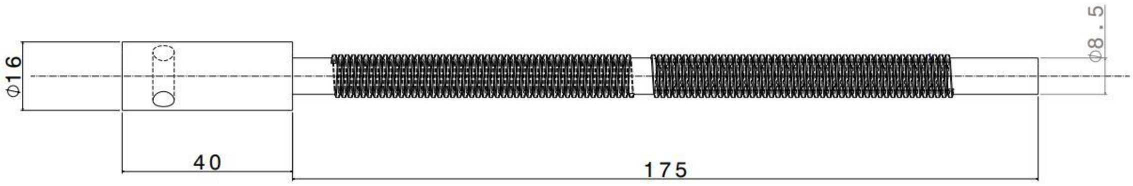


Figure 8 Lead Screw

Static structural analysis was performed on the lead screw to check the stress concentration and to analyse the structural rigidity.

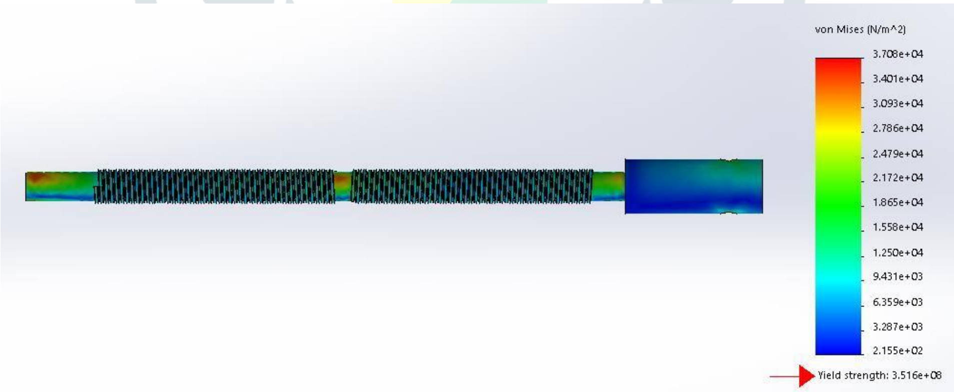


Figure 9 Static Analysis of Lead Screw

F. Final Assembly

The DC motor used is 65 mm in diameter and 100 mm in length. The diameter of the motor shaft is 8 mm, while the diameter of the main shaft is 17 mm. A spring coupling has been designed to couple the main shaft with the motor shaft. The purpose of the coupling is to overcome the misalignment of the motor with respect to the shaft. The distance of the main shaft from the base plate is 90 mm.

The self-aligning vice has been placed in reference with the brake disc position. The centre of the brake disc is in line with the midpoint of the lead screw in the vice, i.e. they are part of the same plane and are equidistant from the aluminium disc. This ensures the setting up of precise and equal distances between the magnet mounts and the brake disc.

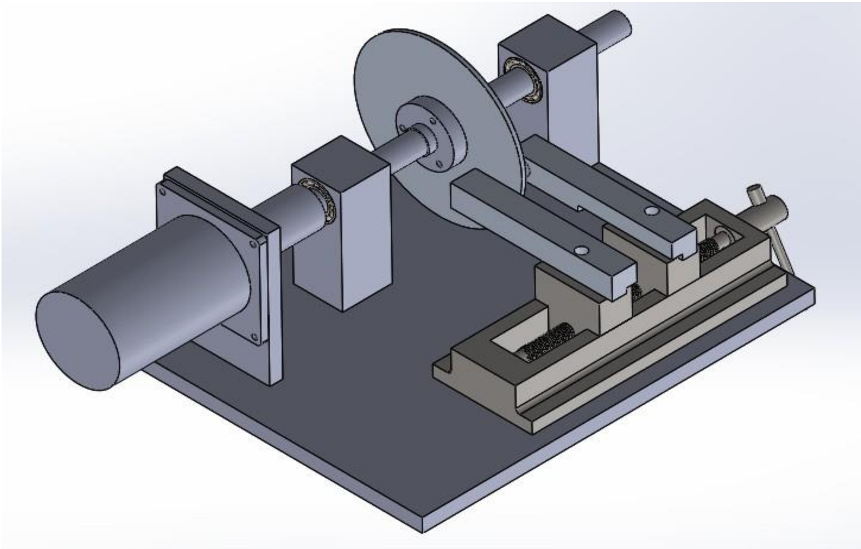


Figure 10 Assembly of Eddy Current Braking System Setup

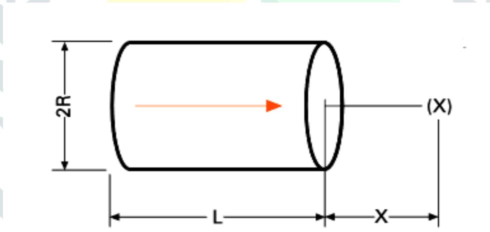
III. Simulation

As the general theory relating to eddy current braking is based on Faraday's law of induction, i.e. when a conducting element moves through a constant magnetic field, a current is induced, this current reacts with the magnetic field to produce a force which counters the motion of the disc. At low speeds, the basic expression for this force is given by,

$$F=0.5 * B^2 \sigma A tv \qquad (1)$$

Where,
σ is the conductivity of the disc in S/m,
A is the area of the magnetic footprint of the magnet in m^2,
t is the disc thickness in m,
v is the translational velocity of the disc in m/s^2

Here, the value of B, the magnetic flux density in T, varies with the air gap between the magnets and the disc.
For circular disc,



gure 11 Permanent Magnet Dimensions

$$B_x(X) = \frac{B}{2}\left[\frac{L+X}{\sqrt{R^2+(L+X)^2}} - \frac{X}{\sqrt{R^2+X^2}}\right] \qquad (2)$$

TABLE I
Values for Various Parameters

Parameters	Meaning	Value
σ	Conductivity of the rotor material (Al)	$3.5*10^7$ S/m
a	Distance measured from the centre of pole shoe area to the disc centre	49.5 mm
r	Radius of a circle with the same area as the pole face	6.5 mm
t	Disc thickness	3 mm
B	Magnetic Flux Density	0.35
ω	Angular velocity at a point under the influence of magnetic field	1600 rpm

The basic expression for braking torque is derived to be,

$$T=F*a \qquad (3)$$

Where,
a is the distance measured from the centre of pole shoe area to the rotating disc centre.

The SIMULINK model is modelled for the above-mentioned equation of braking force for the permanent magnet. Keeping all the other parameters constant, as mentioned in Table I, the air gap is given a Ramp signal which varies from 1mm to 20mm.

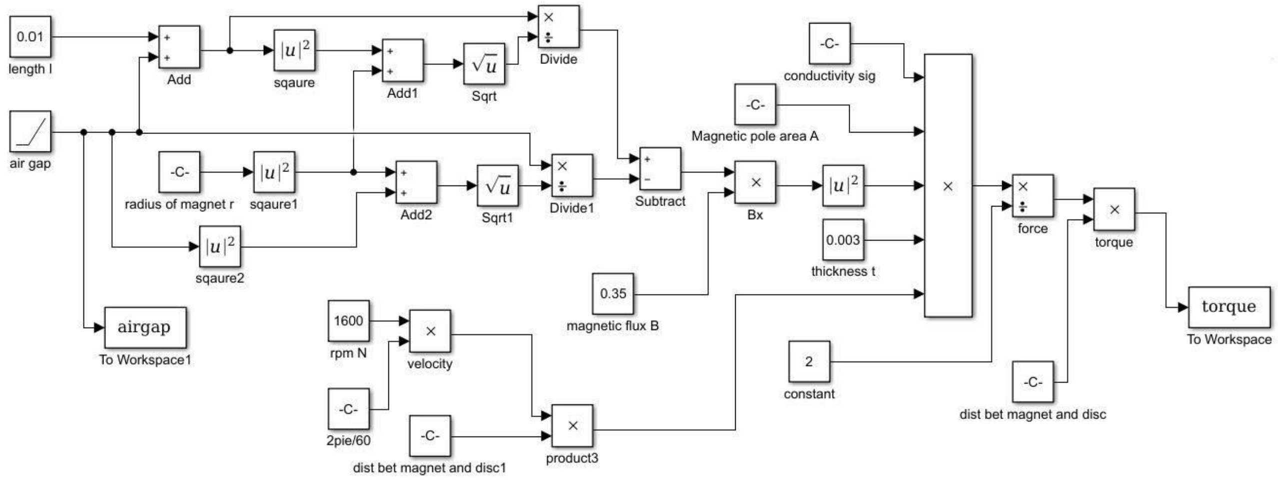


Figure 12 SIMULINK Model for Permanent Magnets

IV. Fabrication and Experimentation

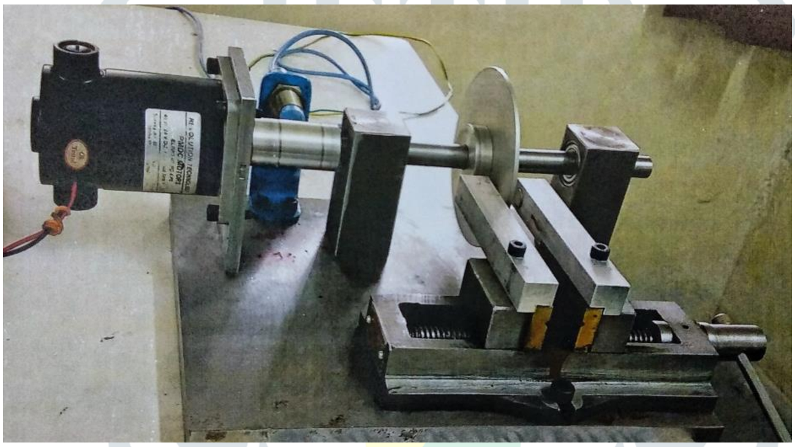


Figure 13 Experimental Setup

The manufactured prototype model has been shown in the above figure. The setup has been manufactured in close tolerances of 50 microns to avoid the probability of whirling of shaft and disc running out axially.

In the self-aligning vice, the jaws were machined to 50 microns tolerance with tapped blind holes for M4 Allen bolts to rigidly hold the cantilever magnet mounts and adjust the distance from the disc to the beam end. Two brass plates of 10 mm were also mounted in front of the jaws to maintain a minimum of 20 mm distance between the jaws, so as to prevent the lead screw from reaching the initial threads. Three pairs of aluminium magnet mounts have been manufactured to provide adjustable magnetic flux density.

Figure 14 Regulated Power Supply 0-30 V DC, 20 W

The square motor plate was fixed on the motor mounting support through M6 Allen bolts through 4 holes provided on the support. The tightening of the motor mounting bolts was adjusted by revolving the shaft manually and maintaining 20 microns run out recorded on dial gauge at three positions, i.e. one at the end of the shaft, one at mid of the shaft and one near the spring coupling.

The prime mover to rotate the disc carrying shaft was selected to be a PMDC motor. To change the voltage applied to the motor, a variable 0-30 V DC regulated power supply of 20 W was used. The power supply limits the current going to the motor to less than 2 A DC.

The angular velocity of the disc i.e. relative velocity between magnets and the disc was required to be varied to investigate the effect. Thus, an RPM indicator was interfaced with an inductive proximity sensor to indicate the angular velocity. The height of the inductive proximity sensor is maintained to 75 mm from the base plate of the setup. The frequency of pulses provided by the inductive pick up was 1 per revolution. So, the RPM indicator was selected to show the rpm scale factor of 1. The response time of the rpm indicator is 30 seconds. Therefore, the readings had to be taken 2 minutes after the distance was set.

A. *Procedure for Experiment*

The three parameters that have been taken into consideration are, distance between magnets and disc i.e. air gap, voltage applied to the motor i.e. power input for the DC motor and magnetic field strength of magnets. The air gap is adjusted by self-aligning vice, the power to DC motor is adjusted through adjustable regulated DC supply and the magnetic field strength or the magnetic flux density can be changed by mounting aluminium square bars carrying one, two and three magnets, on both sides of the disc, respectively.

Detailed Procedure:

- Initially, aluminium bars with one magnet are mounted on the vice.
- The current is set to the desired value, i.e. initially 0.5A.
- The air gap is set step by step, beginning from 20 mm to 1 mm.
- The angular velocity displayed in the rpm indicator is recorded after 2 minutes of setting up of air gap.
- The indicated voltage in the regulated power supply is also recorded along with the current reading.
- The angular velocity recorded and the applied power give the initial torque.
- The reduced speed in presence of magnetic field is recorded which gives the additional eddy current torque applied.

B. *Observation Table*

According to the given procedure of experimentation, trials were conducted and the following observations were noted.

TABLE II
FOR SINGLE MAGNET ON BOTH SIDES AND 0.5A MOTOR CURRENT

Air Gap (mm)	Current, I_m (A)	Voltage, V_m (V)	Angular Velocity (RPM)
20	0.5	9.3	1433
19	0.5	9.2	1420
18	0.5	9	1390
17	0.5	8.7	1345
16	0.5	8.5	1300
15	0.5	8.1	1245
14	0.5	7.7	1160
13	0.5	7.2	1080
12	0.5	6.6	985
11	0.5	6.0	875
10	0.5	5.3	760
9	0.5	4.9	685
8	0.5	3.9	532
7	0.5	3.2	400
6	0.5	2.6	298
5	0.5	2.1	210
4	0.5	1.8	155
3	0.5	1.4	98
2	0.5	1.2	61
1	0.5	1	40

V. Result

The results of the SIMULINK model for permanent magnets, which are theoretical output, were plotted and compared with the experimental results.

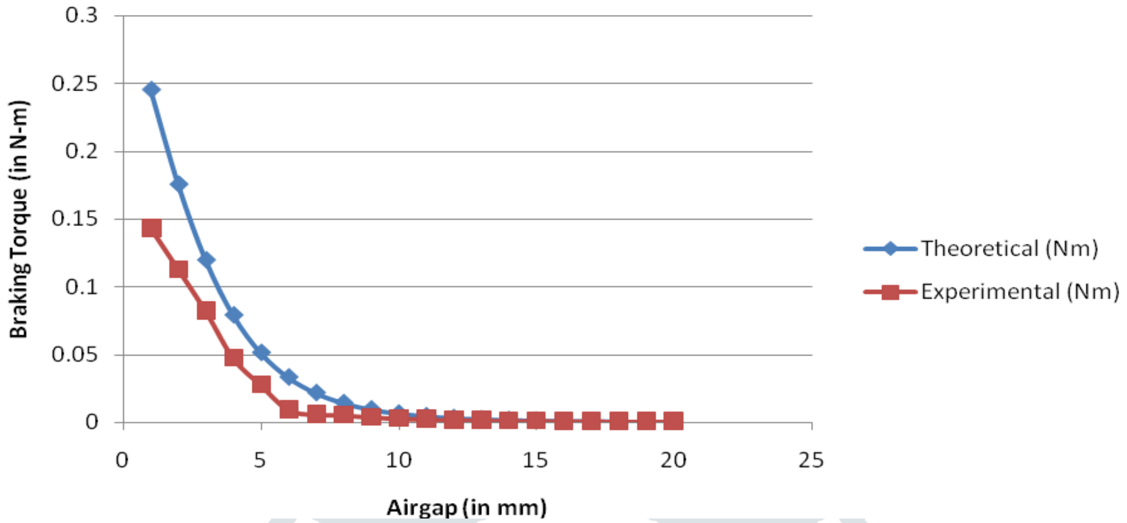


Figure 15 Braking Torque Vs Air Gap

As the air gap is decreased gradually, the measured velocity waveform of the conductor disc is observed to reduce. Therefore, a smooth variation of Braking torque vs air gap is obtained. Also, the experimental results are in good agreement with theoretical results. Hence, the proposed design is found to be effective and the results have been validated.

VI. Conclusion

The prototype set-up was designed and manufactured to validate the results of the SIMULINK model of Permanent magnet Eddy Current Brakes. The prototype is functional and intended braking is observed on the set-up. Thus, the results verify the torque obtained by the eddy currents, produced by pair of permanent magnets placed on either side of rotating disc with opposite poles, with respect to angular velocity, motor power, and air gap. Also, magnetostatic analysis has been successfully performed in ANSYS Maxwell 15.0, for permanent magnets and the total magnetic field intensity around the magnets and disc has been analysed.

Further modifications can be done on the set-up to explore various results by changing the disc material or dimensions, and varying the input motor characteristics along with a change in magnetic flux density by increasing the number of magnets on both sides of the disc.

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