EDDY CURRENT BRAKING SYSTEM

B Tech Mini-Project Report

Submitted in partial fulfilment for the award of the Degree of
Bachelor of Technology in Electrical and Electronics Engineering

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CERTIFICATE

This is to certify that the thesis entitled “EDDY CURRENT BRAKING SYSTEM” is a bona fide record of the mini-project done by **Vishnu S** (*Roll No.*B160495EE), **Hari Bhaskar J** *(Roll No. B160546EE),* **Mebin Muhammed HS** *(Roll No. B160354EE)* and **Karthik Balasankar** *(Roll No. B160034EE)* under my supervision and guidance, in partial fulfilment of the requirements for the award of Degree of Bachelor of Technology in Electrical & Electronics Engineering from National Institute of Technology Calicut for the year 2020.

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ABSTRACT

Braking systems have been around for a long time since the time man invented vehicles. They have always been a subject of interest and a lot of research have been conducted to find out the most efficient system for the same. The traditional brakes of today have been plagued with a lot of energy loss along with a lot of wear and tear.

To overcome this problem, frictionless brakes have been developed and tested with good results. In our project, we simulated and created a working system to showcase an eddy current braking system. We have used an electromagnet to create the required magnetic field that is used to induce the eddy current in the aluminium disc. These eddy currents then produce a reverse magnetic field that opposes the cause of it. We used a current sensor to measure the current in the coils and a photoelectric encoder to measure the speed of the rotating disc. A 12V supply is given to the motor driver (Voltage Controller) whose output is controlled by the microcontroller (Arduino UNO). The braking torque produced by the eddy currents is proportional, to the speed of the rotating disc, and the current passing through the electromagnet.

Our project aims to bring down the rotating disc from its maximum speed to a specific lower speed, under constant load, in a given amount of time using a closed loop control system. If the mechanical components are manufactured to scale, it is a perfect example of how an eddy current braking system should work.

Contents

1. CHAPTER I: INTRODUCTION

Braking systems have been around since the time man invented vehicles. Over the course of the last couple of centuries, massive developments have been made in this front and the advent of electric vehicles in the 21st Century make it even more possible than before to utilize eddy currents to stop them. Our project aims to display a working model of a miniature version of the same, using eddy currents that are formed inside an electromagnet to stop a rotating aluminium disk.

1.1 History

The eddy-current brake has its origins in France, where it is sometimes known as the Frein linéaire à courants de Foucault. This commemorates Frenchman Jean Bernard Léon Foucault who discovered the underlying scientific principle in the 19th century. Foucault observed that a higher force was needed to make a vertical copper disc rotate between two magnetic poles, and at the same time the copper disc warmed up. In simple physics, the movement of a metal plate in a magnetic field induces a voltage, which in turn creates eddy currents. Thus, a second magnetic field is generated in opposition to the first, and the metal plate decelerates, transforming its kinetic energy into heat. The better the conductivity and permeability of the plate, the stronger the braking force.

Whereas some inventions are rapidly adopted, others take longer to become generally accepted, and this was the case with the eddy-current brake. It was nearly a quarter-century after Foucault's death before the first patent was issued in 1892.

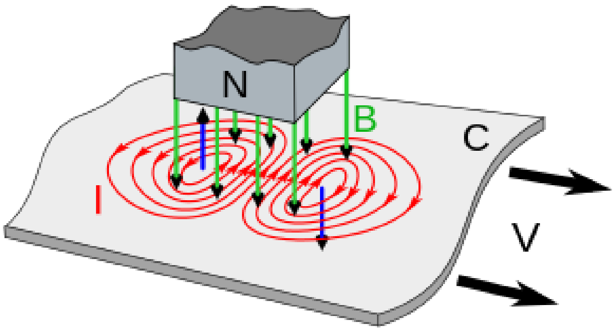
1.2 Why eddy current braking?

The traditional brakes found in commercial vehicles of today contain either a mechanical (disk or drum) brake or a hydraulic brake system to stop the moving vehicle. This causes a lot of wear and tear in the braking mechanism and will need regular maintenance to keep it in tip top condition to provide optimal performance all the time.

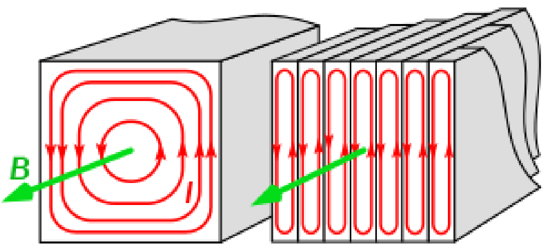
Meanwhile, Eddy-current braking technology offers the potential for frictionless braking at high speeds, thus taking out the physical contact between the braking system and the rotor. This results in minimum or no damage to the system, reducing the need for regular maintenance. The idea of a truly frictionless brake has great appeal, and railways have been experimenting with the use of eddy-current brakes for many years.

1.3 What are ''Eddy Currents''?

The term eddy current comes from analogous currents seen in water when rowing using an oar, causing localised areas of turbulence known as eddies give rise to persistent vortices. Somewhat analogously, eddy currents can take time to build up and can persist for very short times in conductors due to their inductance. Eddy currents are loops of electrical currents that are induced within the conductors on account of a varying magnetic field in a conductor. It works on the principle of Faraday's laws of electromagnetic induction. Eddy currents flow in closed loops in the conductor, in planes perpendicular to the magnetic field. They can be induced in conductors by virtue of a time varying magnetic field produced by an electromagnet or a transformer or by a moving magnetic coil/magnet as well. The strength of the induced current is directly proportional to the strength of the magnetic field, rate of change of flux, and inversely proportional to the resistivity of the material.



(Eddy currents (I, red) induced in a conductive metal plate (C) as it moves to right under a magnet (N).) Source: Wikipedia



((left) Eddy currents (I, red) within a solid iron transformer core. (right) Making the core out of thin laminations parallel to the field (B, green) with insulation between them reduces the eddy currents.) Source: Wikipedia

1.4 Braking Systems

A brake is a mechanical device which inhibits motion. Brakes use friction of brake shoes and drums to convert kinetic energy developed by the vehicle into heat energy. When we apply brakes, the pads or shoes that press against the brake drums or rotor convert kinetic energy into thermal energy via friction.

TYPES OF BRAKES

- Mechanical Brakes
- Hydraulic brakes
- Electric/Magnetic Brakes

Mechanical Brakes

Mechanical brakes as the name suggests, uses a mechanical approach to stop the rotating wheel. It may use a disk brake type or a drum brake. Disc brakes consist of a brake rotor which is attached directly to the wheel. Hydraulic pressure from the master cylinder causes a caliper to squeeze the brake pads on either side of the rotor. Drum brakes consist of a brake drum attached to the inside of the wheel. When the brake pedal contracts, hydraulic pressure presses two brake shoes against the brake drum. The friction between these causes the rotor to slow down and eventually stop.

Hydraulic Brakes

Hydraulics is the use of a liquid under pressure to transfer force or motion, or to increase an applied force. The pressure on a liquid is called hydraulic pressure. The brakes which are operated by means of hydraulic pressure are called hydraulic brakes. These brakes are based on the principle of Pascal's law.

Magnetic Brakes

Magnetic brakes are non-contact brakes that use magnetic fields to actuate the braking components. The magnet in the backing plate has 2 wires which tap directly into the wiring. When electricity is on, it magnetizes the brake magnet coil. The magnet is attracted to the drum face. When it contacts this area, the friction causes it to rotate, which moves the actuating arm, and pushes the shoes out against the drum. Those shoes have a special brake pad material on them that resists the heat caused by that friction. When the shoes press against the inside of the drum, they prevent the hub, and consequently the wheel that's touching the ground from spinning.

1.5 Eddy current braking

Lenz's law : Lenz’s law states that when an emf is generated by a change in magnetic flux according to Faraday’s Law, the polarity of the induced emf is such, that it produces a current whose magnetic field opposes the cause that produces it.

The negative sign used in Faraday’s law of electromagnetic induction, indicates that the Induced emf (ε) and the change in magnetic flux (dφ) have opposite signs.

$$\varepsilon = - N\frac{d\phi}{dt}$$

Where,

ε = Induced emf

$d\phi$ = change in magnetic flux

N = No of turns in coil

In an eddy current braking system, the conductor is rotated within a magnetic field due to which circular currents (eddy currents) are induced in the conductor. These currents in turn produce their own magnetic field in such a way that it opposes the cause that produced It (ie rotation of the conductor). The conducting disc (aluminium) thus experiences a braking torque that slows it down and eventually stops it.

$$\tau_B = r\,X\,F$$

$$F = I_{ed}(l\,X\,B) = BI_{ed}l \quad (sin\Theta = 1) \qquad \text{(eq 1)}$$

Where,

B= magnitude of magnetic field in the air gap

I_{ed}= eddy current formed in the aluminium disc (Inversely proportional to ρ)

l=Length of the eddy current path

r = Radius of rotating aluminium disc (assuming eddy currents are formed at the edge of the disc)

τ_B= Braking torque developed

Net torque acting on the disc after the power has been switched off,

$$\tau_{net} = \; -\tau_f - \tau_B = J\alpha_{net} \qquad \text{(eq 2)}$$

Where,

τ_f = Frictional torque

τ_B = Magnetic braking torque

α_{net} = Net deceleration

J= Moment of inertia of the system

In eq 1,

$$B = \mu_0(1 + k)H = \mu_0(1 + k)\left(\frac{B}{\mu}\right)$$

$$B = \frac{\phi}{A} \qquad \varphi = \frac{mmf}{Reluctance} = \frac{NI}{R_m}$$

Where

k= relative permeability of electromagnet core

H= Magnetic intensity

N= number of turns of electromagnet

I = current through the electromagnet

ϕ= Magnetic flux passing through the disc

R_m= Reluctance of the flux path

$$I_{ed} = \frac{V}{R} = \frac{\frac{d\phi}{dt}}{R}$$

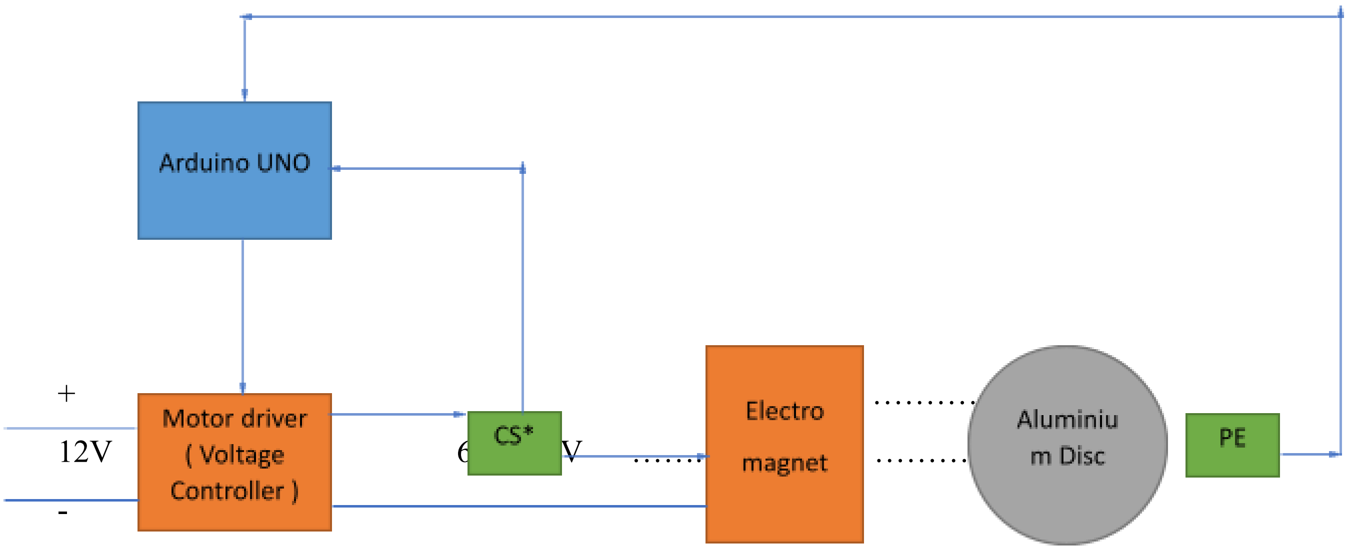
Here the flux "φ" varies when a specific portion of the disc moves away and comes back into the region of magnetic field during rotation. When that specific portion moves away from the region of magnetic field, it creates a negative change in flux and thereby, an eddy current in one direction. And at the same time, another portion of the disc moves into the region of magnetic field, has a positive change in flux and thereby causing eddy currents in the opposite direction. These eddy currents produce tangential forces which in turn produce torques that gets added up to give us magnetic braking torque.

R= resistance of the eddy current path

2. CHAPTER II : WORKING

2.1 Block diagram

So, the basic functioning of the eddy current braking system is as explained above. From this, we can understand that braking torque τ_B decreases with decrease in speed of the disc, if B remains constant. So, in our project, we aim to produce a uniform magnetic braking torque throughout the decay of disc speed. For this purpose, we designed a 2-loop control system to vary the current through the electromagnet so that magnetic braking torque remains constant.



BASIC CONTROL AND POWER FLOW DIAGRAM

CS*:- Current Sensor (Hall Effect)

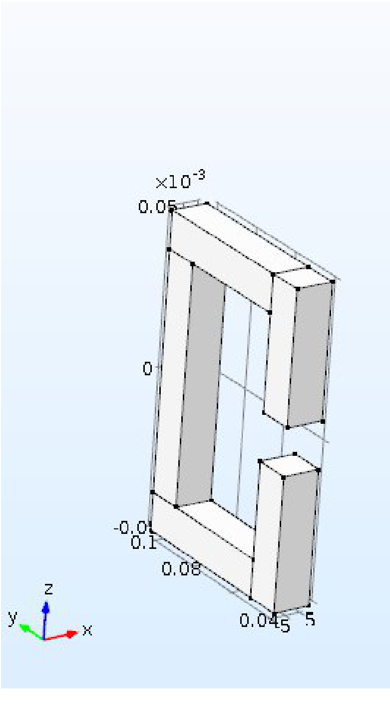
PE:- Photoelectric Encoder

*The Current Sensor is not employed in this particular model of our eddy current braking system. This is based on the assumption that the source voltage remains constant at 12V and that the electromagnet coil resistance remains constant. So, we can assume that the correct change in voltage produces the desired change in current. This takes out the need for a current feedback from the output line of the voltage controller. But, in real life situations, where supply voltage might fluctuate and the precision of braking torque is very much important, a closed loop control system with the current sensor is necessary to obtain the exact magnitude of excitation current for the electromagnet.

3. CHAPTER III : DESIGN AND HARDWARE

3.1 DESIGN

We first started off the project work, by testing a transformer core and winding to act as the electromagnet. We first dismantled the transformer (core type) core and rearranged the stampings in an 'E' shape. But that couldn't provide us with enough flux linkage with the aluminium disc, to give us the required range of braking torque. We further tried with a transformer of higher current rating, in the same fashion. That didn't yield us any results either. So, we decided to make an electromagnet of our own. We got square iron bars of 1.2x1.2 cm^2 cross section welded into a 'C' structure as shown:



We used 26 SWG Copper wire to wind the coil around this structure. We used around 102 m of wire that gave us approximately 1200 turns (N=1200). It has current rating of 1.4A. It has a resistance per metre of 0.105Ω. So, our coil has a resistance of 10.71Ω. But experimentally, its resistance was found out to be R=11.4Ω. This error is due to the approximation in length of copper wire, as it was purchased at the rate per kg.

The reluctance of the flux path was calculated as follows:

$$R_i = \frac{l}{\mu A} = \frac{0.286}{4000\mu_0 * 1.44 * 10^{-4}} = 395124.2511\ H^{-1}$$

$$R_g = \frac{l_g}{\mu_0 A} = \frac{0.012}{\mu_0 * 1.44 * 10^{-4}} = 66314559.62\ H^{-1}$$

$$R_t = R_i + R_g = 66709683.87\ H^{-1}$$

So, flux φ, magnetic field B, and magnetic intensity H, are calculated as follows:

$$\phi = \frac{mmf}{R_t} = \frac{NI}{R_t} = \frac{1200I}{R_t} = 1.79884 * 10^{-5} * I\ \ Wb$$

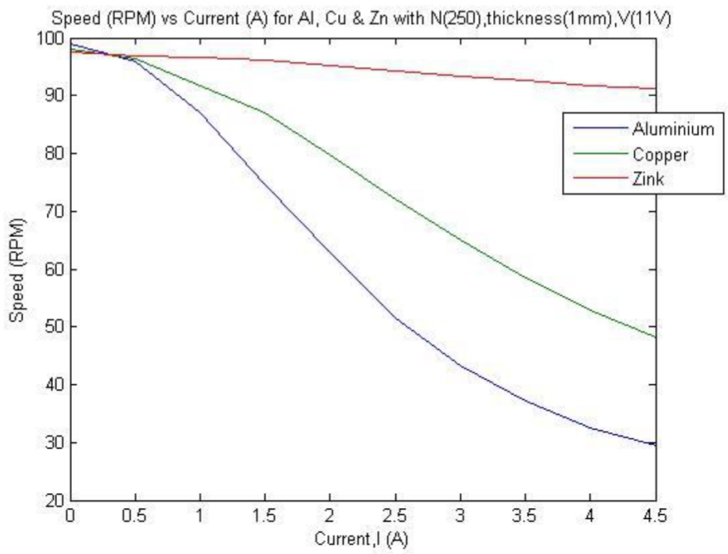
$$B = \frac{\phi}{A} = 0.12492 * I\quad T$$

$$H = \frac{B}{\mu} = 24.85 * I\quad ATurns/m$$

Therefore, $$H_{max} = 24.85 * I_{max} = 24.85 * \frac{12}{R} = 26.158\quad ATurns/m$$

$$H_{min} = 24.85 * I_{min} = 24.85 * \frac{6}{R} = 13.079\ \ ATurns/m$$

Also, the inductance of the electromagnet was found to be 3.473 H, which is pretty high.



(Speed (RPM) versus Current (A) for Aluminium, Copper and Zinc)

The above graph was obtained as the result of a study conducted by Universiti Kebangsaan Malaysia. From it, for the same increase in electromagnet current, the best braking effect is produced in an Aluminium Disc.

Increasing the thickness of the disc decreases resistance of Eddy Current path (R). So, we decided to use a 6mm thickness disc. Also increasing the radius of disc gives better braking for the same rpm, because tangential velocity and thus dφ/dt increases.

The aluminium disc is machined from a 6mm thick plate, in a lathe machine. It has a radius of 5.45 cm. It is fixed onto the centre of a stainless-steel rod, suspended within two ball bearings at the ends, housed in two vertical plywood pieces fixed onto a plywood base. This allows us to freely rotate the aluminium disc with minimum friction. This helps in magnifying the observation of the eddy current braking effect. Enough length of rod is provided at one end to attach loads, and the photoelectric encoder is attached to the other end of the rod, to measure the speed of rotation.

Basically, the aim of our project was to design an eddy current braking system to provide uniform braking torque throughout its entire duration of speed decay.

$$\tau_B = rBI_{ed}l$$

Where

r= radius of disc = 5.45 cm (assuming that the eddy currents are formed at the edge of the disc)

B= magnetic field in the air gap

I_{ed}= Eddy current formed

l = length of eddy current path

$$\tau_B = r * \mu_0(1 + k)H * I_{ed}l = r(1 + k)H * \frac{d\phi}{dt} * \frac{l}{R_e} = r\mu_0(1 + k)H\frac{d\phi}{dt} * \frac{A}{\rho}$$

$$\tau_B = r\mu_0(1 + k)H * k_e v_{rpm} * \frac{A}{\rho}$$

$$\tau_B = r\mu_0(1 + k)Hv_{rpm} * k_e^{'} = 0.0503rk_e^{'}Hv_{rpm}$$

$$\tau_B = k_B Hv_{rpm}$$

Where, k_e = eddy current constant

$$k_e^{'} = k_e * \frac{A}{\rho}$$

$$k_B = 0.0503 * k_e^{'} * 0.0545 = 2.74 * 10^{-3} * k_e^{'} \quad (Braking\ Constant)$$

So, for τ_B to be constant, $H * v_{rpm}$ needs to be constant. That is, $I * v_{rpm}$ needs to be constant. So, in the microcontroller (Atmega328), we can find the new current to be supplied by the equation: $I_2 = I_1 * \frac{v_1}{v_2}$

The net decelerating torque acting on the disc, once its source of power is removed:

$$\tau_{net} = \tau_f + \tau_B \qquad \left(\tau_f \; is\; frictional\; torque\right)$$

Therefore. $\tau_B = \tau_{net} - \tau_f$

$$\tau_B = k_B H v_{rpm} = J\alpha_{net} - k_f v_{rpm}$$

$$(k_f = frictional\; constant) \qquad (J = Moment\; of\; Inertia\; of\; setup)$$

So, to find out the braking torque produced by the eddy current braking system, we will either have to know the values of J and k_f , or the value of k_B . Equations to experimentally find out the values of these constants, have been derived in the 'Future Possibilities' section.

The net deceleration α_{net}, when eddy current braking is applied:

$$\alpha_{net} = \frac{\tau_f + \tau_B}{J} = \frac{k_f * v_{rpm}}{J} + \frac{k_B * (H v_{rpm})}{J}$$

When τ_B is made constant using our control strategy,

$$\alpha_{net} = \frac{\tau_f + \tau_B}{J} = \left(v_{rpm} * \frac{k_f}{J} \right) + k$$

The graph of α_{net} vs v_{rpm} will be a straight line with slope $\frac{k_f}{J}$ and y-intercept k.

When $H = H_{max}$,

$$\alpha_{net} = \frac{k_f * v_{rpm}}{J} + \frac{k_{max} * v_{rpm}}{J} = v_{rpm} * \left(\frac{k_f}{J} + \frac{k_{max}}{J} \right)$$

The graph of α_{net} vs v_{rpm} will be a straight line with slope $\frac{k_f + k_{max}}{J}$ and passing through the origin.

When $H = H_{min}$,

$$\alpha_{net} = \frac{k_f * v_{rpm}}{J} + \frac{k_{min} * v_{rpm}}{J} = v_{rpm} * \left(\frac{k_f}{J} + \frac{k_{min}}{J} \right)$$

The graph of α_{net} vs v_{rpm} will be a straight line with slope $\frac{k_f + k_{min}}{J}$ and passing through the origin. This slope value will be lesser than that of the one right above.

When eddy current braking system is switched off,

$$\alpha_{net} = \frac{\tau_f}{J} = v_{rpm} * \frac{k_f}{J}$$

The graph of α_{net} vs v_{rpm} will be a straight line with slope $\frac{k_f}{J}$ and passing through the origin. This slope value will be lesser than that of all the ones above.

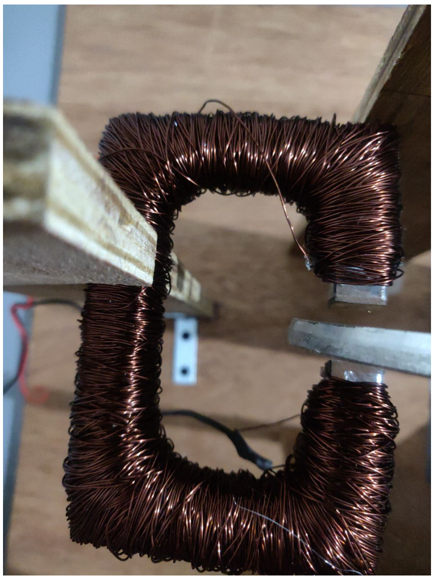
3.2 Components Used

3.2.1 Conductor Disc

- Material: Aluminium
- Radius: 5.45 cm
- Thickness: 6 mm

3.2.2 Electromagnet

Regarding the electromagnet, even though we tried various combinations of transformer windings, to act as the electromagnet, we could not get enough flux to pass through the disc. So, we wound an electromagnet for ourselves on a C shaped iron flux path, with a 12 mm air gap to accommodate the free rotation of the 6 mm thick Aluminium Disc.



Following are the specifications:

- Core: Iron (k=4000)
  - Area=1.2x1.2 cm^2
- Winding Wire: 26 SWG Enamel Coated Copper wire (102 m)
  - Resistance=11.4 Ω
  - Current Rating: 1.4 A
- Number of Turns=1200 (approx.)

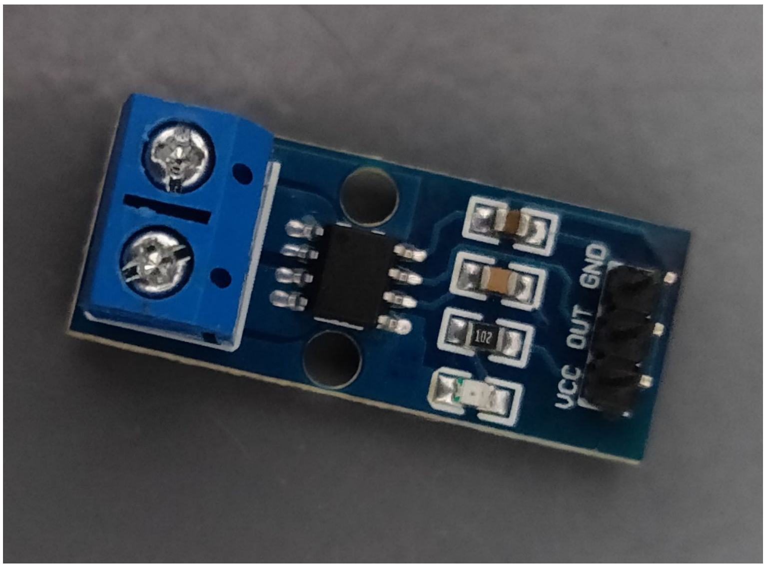
3.2.3 Motor Driver (Voltage Controller)

We used a DC motor driver here, as a voltage controller, which in conjunction with the current sensor act as a current controller. It is used to increase the current to the electromagnet as the disc speed decays. The motor driver used is Cytron 13A.

It is designed to drive high current brushed DC motors, bi-directionally up to 13A continuously. It supports motor voltage ranges from 5V to 30V, and a peak current of 30A for 10 secs. It uses a full NMOS H-Bridge for better efficiency and so no heat sink is required.

The Cytron 13A, 5-30V Single DC Motor Controller is an enhanced version of the MD10B which is designed to drive high current brushed DC motor up to 13A continuously. It offers several enhancements over the MD10B such as support for both locked-antiphase and sign-magnitude PWM signal as well as using full solid-state components which result in faster response time and eliminate the wear and tear of the mechanical relay.

3.2.4 Current sensor



The current sensor is used here measure the current sent by the voltage controller and thereby control the current flowing to a desired value.

ACS712 current sensor operates from 5V and outputs analog voltage proportional to current measured on the sensing terminals. You can simple use a microcontroller ADC to read the values.

Sensing terminal can even measure current for loads operating at high voltages like 230V AC mains while output sensed voltage is isolated from measuring part.

Provides up to 3000 VRMS galvanic isolation. The low-profile, small form factor packages are ideal for reducing PCB area over sense resistor op-amp or bulky current transformer configurations. The low resistance internal conductor allows for sensing up to 20 A continuous current. Providing typical output error of 1%.

Features:

- 100 mV/A output sensitivity
- 5.0 V, single supply operation
- Output voltage proportional to AC or DC currents
- Extremely stable output offset voltage
- Nearly zero magnetic hysteresis
- Low-noise analog signal path

- 5 μs output rise time in response to step input current
- 80 kHz bandwidth
- Total output error 1.5% at TA = 25°C
- 1.2 mΩ internal conductor resistance
- 2.1 kVRMS minimum isolation voltage from pins 1-4 to pins 5-8

3.2.5 Photoelectric Encoder

The photoelectric encoder is used to measure the speed of rotation of the disc in rpm so that, as speed decreases current to the electromagnet can be increased to provide a constant braking effect throughout speed decay.

Features:

- Wide voltage, high resolution, short response time
- Working voltage: 4.5~5.5V
- Launch tube pressure drop: V_f=1.6V
- Launch tube current: If<20mA
- Signal output: A, B two lines
  - TTL power level
  - Resolution: 0.01mm
- Measurement frequency: 100KHz
- Disc diameter: 24mm
- Encoder resolution: 20 lines

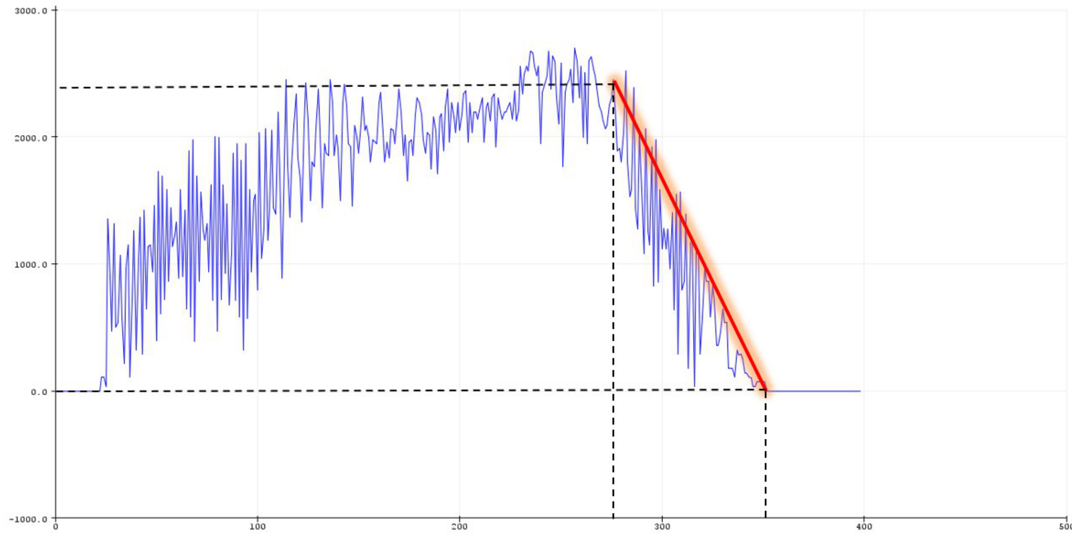
3.2.6 Mechanical System

Here, we tightly fixed the Aluminium disc onto the centre of a stainless-steel rod and attached ball bearings of the same inner diameter on both the sides of the rod. Those bearings were housed in pieces of plywood erected on a plywood base, such that the rod and thus the disc are free to rotate. The electromagnet was fixed onto a groove made on another piece of plywood and raised at the correct height such that the edge of the disc would completely be inside the region of magnetic field and wouldn't touch the edges of the air gap during rotation.

4. CHAPTER IV : RESULT

The following data were obtained in the Arduino plotter when the rotational speed vs time were plotted under different conditions.

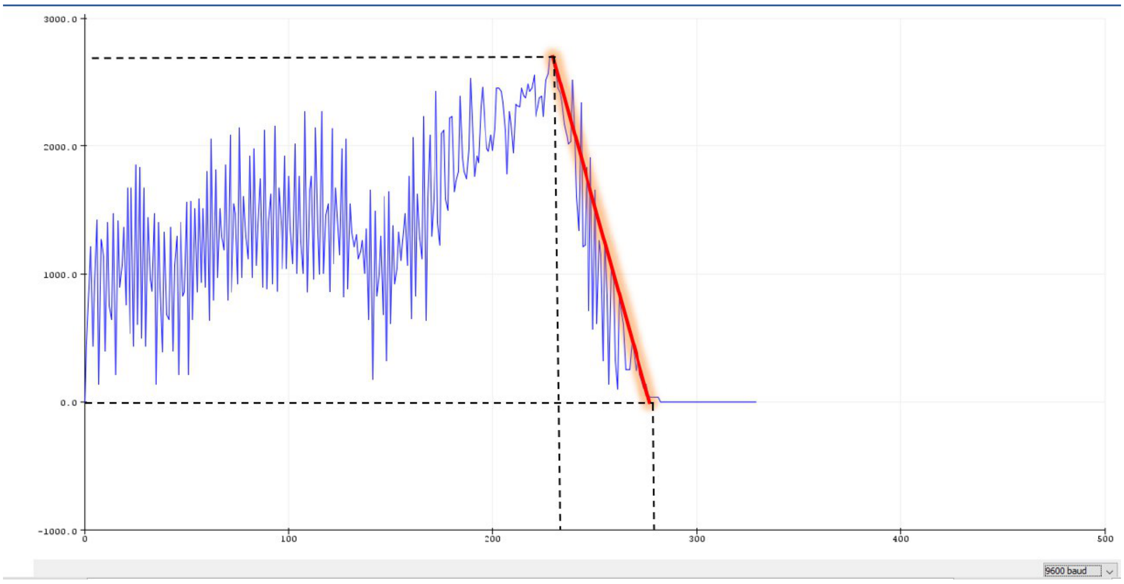
4.1 When eddy current braking system is switched off



Slope is approximately=4.3

Electrical Power Input to the brake $= VI = 0$ W

4.2 When $H = H_{min}$

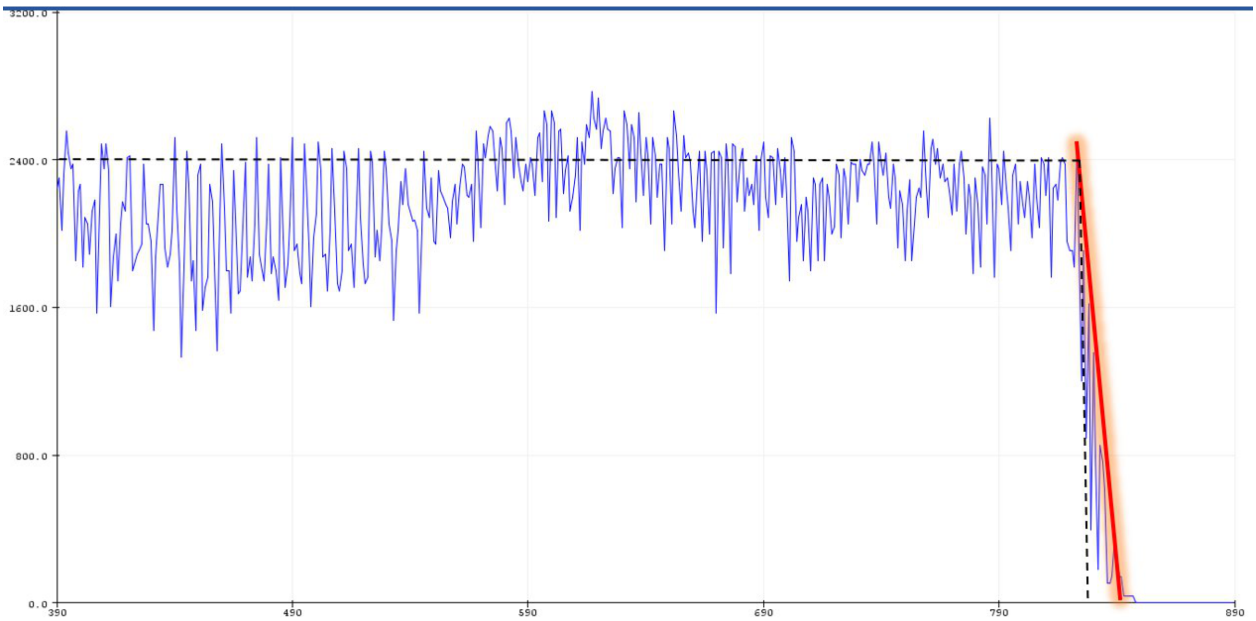


Slope is approximately=5.6

Electrical Power Input to the Brake = $VI = 6 * 0.526 = 3.16$ W

Electrical Energy used by the brake= $3.16 * 500 = 1580\, unit$

4.3 When $H = H_{max}$

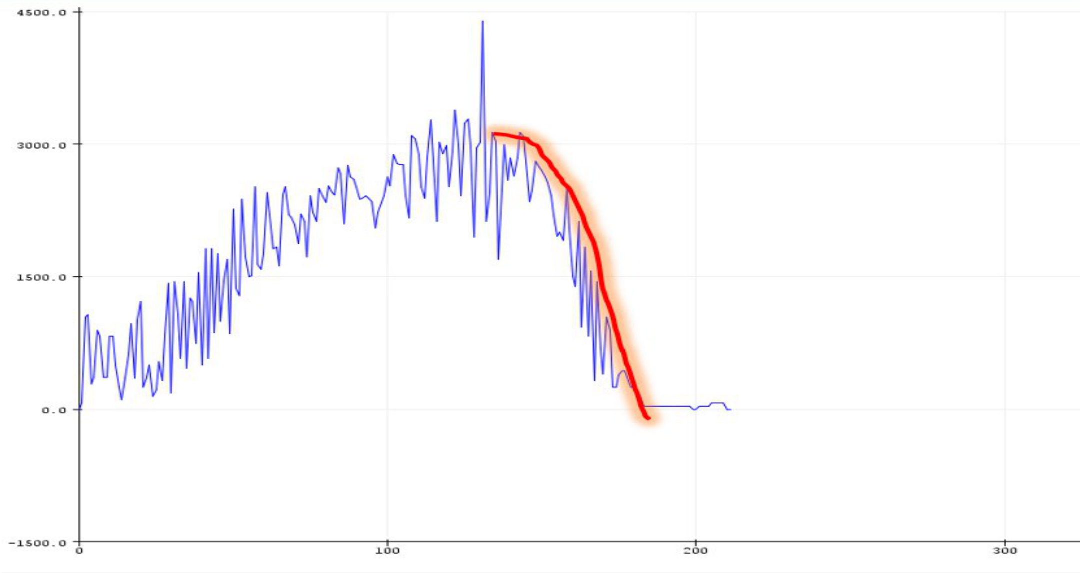


Slope is approximately=160

Electrical Power Input to the Brake = $VI = 12 * 1.052 = 12.624$ W

Electrical Energy used by the brake= $12.624 * 15 = 189.36\, unit$

4.4 When τ_B is made constant using our control system



Slope of linear part is approximately=83.33
Electrical Energy used by the brake (approx.) =441 unit

4.5 DISCUSSION AND INFERENCE

- From the above graphs, it is clear that, they do not exactly match with the graphs predicted by the equations described in the 'Design' section. This is because of the errors in measurement and lack of precision of the photoelectric encoder and motor driver. The high value of inductance and thus the high time constant of the electromagnet can also contribute to the error, because we ignored the transient analysis of the electromagnet.

- Specifically, the graph obtained when we apply our control strategy, deviates from the linear character. This is probably because of the inaccuracy and lack of precision of the encoder and motor driver, which leads to errored currents being supplied to the electromagnet. This takes away the constant nature of τ_B. So, the equation for α_{net} in this case:

$$\alpha_{net} = \frac{\tau_f + \tau_B}{J} = \left(v_{rpm} * \frac{k_f}{J} \right) + \frac{\tau_B}{J}$$

So, on differentiating the above equation, you do not get a constant. That means acceleration is not always constant. So, that's probably why this graph showed deviation from linearity.

- From the values of energy used by the eddy current brakes in these different cases, it can be concluded that applying full voltage (maximum current) to create a faster braking, is more energy efficient than applying minimum current to brake in a longer time. Also, braking using our control strategy uses more energy than the case where maximum current is always applied. But it uses less energy compared to the case where minimum current is always applied.

- Even though the controlled braking is slower and is less energy efficient when compared to the case where maximum current is always applied, in applications that require smoother breaking, or with a variable limit on maximum deceleration acceptable, this control strategy can be employed, which will give the most energy efficient eddy current braking system to meet the needs.

5. CHAPTER V: CONCLUSION AND FUTURE POSSIBILITIES

5.1 Alternate Control Strategy

Another control strategy that can be employed in this eddy current braking system is to slow down the disc from any value of speed (v) to a particular lower value of speed (v_0) in a fixed reaction time (T) .

- The equation for H (parameter to be controlled) can be derived as:

$$\alpha_{net} = \frac{\tau_f + \tau_B}{J} = \frac{dv}{dt}$$

$$\frac{dv}{dt} = \frac{k_f v + k_B H v}{J}$$

$$\frac{dv}{v\left(k_f + k_B H\right)} = \frac{dt}{J} \text{.....................} Integrating\ both\ sides$$

$$\left(\frac{1}{k_f + k_B H} \right) * \ln ln \left(\frac{v}{v_0} \right) = \frac{T}{J}$$

$$H = \frac{J}{Tk_B} * \ln ln \left(\frac{v}{v_0} \right) - \frac{k_f}{k_B}$$

So, we require to find out the values of constants $J,\ k_f,\ k_b$. That can be done with the help of the current sensor and the encoder.

- The equation for J can be derived as:

(assuming that magnetic losses are negligible)

$$\frac{1}{2} * J\left(v_1^2 - v_2^2\right) = \left(VI - I^2R\right)t$$

$$J = \frac{2t\left(VI - I^2R\right)}{\left(v_1^2 - v_2^2\right)}$$

- The equation for k_f can be derived as:

(electromagnet is turned off)

$$J\alpha = k_f v = J * \frac{dv}{dt}$$

$$\frac{dv}{v} = \frac{k_f}{J} * dt \text{..................} Integrating\ Both\ Sides$$

$$ln\left(\frac{v_1}{v_2}\right) = \frac{k_f}{J} * t$$

$$k_f = \frac{J}{t} * ln\left(\frac{v_1}{v_2}\right)$$

- The equation for k_B is:

$$H = \frac{J}{Tk_B} * \ln ln\left(\frac{v}{v_0}\right) - \frac{k_f}{k_B}$$

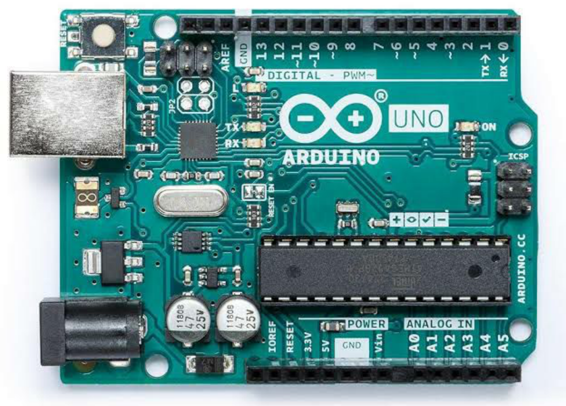
$$k_B = \frac{J}{tH} * \ln ln\left(\frac{v}{v_0}\right) - \frac{k_f}{H}$$

REFERENCES

- https://www.comsol.com/model/download/384881/models.acdc.magnetic_brake.pdf
- https://en.wikipedia.org/wiki/COMSOL_Multiphysics
- M.Z Baharom, Mohd Zaki Nuawi, Sallehuddin Mohamed Haris, Gigih Priyandoko " Braking torque analysis on electromagnetic braking study using eddy current for brake disc of Al6061 and Al7075" Universiti Kebangsaan Malaysia.
- M.Z.Baharom, M.Z.Nuawi, G.Priyandoko, S.M.Harris, L.M. Siow "EDDY CURRENT BRAKING STUDY FOR BRAKE DISC OF ALUMINIUM, COPPER AND ZINK" National University of Malaysia, Malaysia.
- https://www.bnl.gov/magnets/staff/gupta/scmag-course/uspas03/RG03/lecture05.pdf

APPENDIX

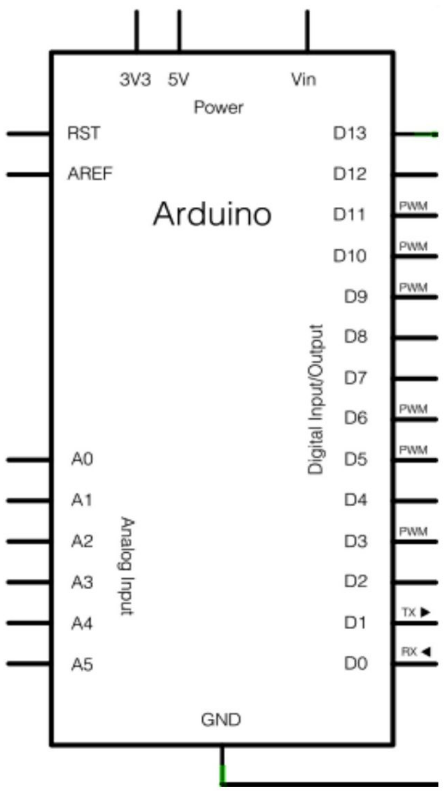
A.1 Arduino UNO



The Arduino Uno is a microcontroller board based on the ATmega328. The Arduino Uno has 14 digital input/output pins (of which 6 can be used as PWM outputs), 6 analog inputs, a 16 MHz crystal oscillator, a USB connection, a power jack, an ICSP header, and a reset button. It contains everything needed to support the microcontroller; simply connect it to a computer with a USB cable or power it with a AC-to-DC adapter or battery to get started.

Features of the Arduino UNO:
• Microcontroller: ATmega328
• Operating Voltage: 5V
• Input Voltage (recommended): 7-12V
• Input Voltage (limits): 6-20V
• Digital I/O Pins: 14 (of which 6 provide PWM output)
• Analog Input Pins: 6
• DC Current per I/O Pin: 40 mA
• DC Current for 3.3V Pin: 50 mA
• Flash Memory: 32 KB of which 0.5 KB used by bootloader
• SRAM: 2 KB (ATmega328)
• EEPROM: 1 KB (ATmega328)
• Clock Speed: 16 MHz

ADDITIONAL SPECIFICATIONS
• It also supports I2C communication required to interface IMU
• 6 analog inputs



A.2 ARDUINO IDE

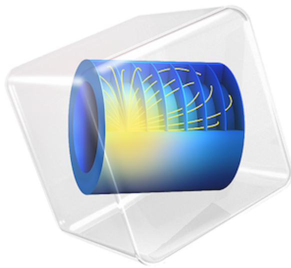
The open-source Arduino Software (IDE) makes it easy to write code and upload it to the board. It runs on Windows, Mac OS X, and Linux. The environment is written in Java and based on Processing and another open-source software.

Arduino IDE is an open source computer hardware and software company, project, and user community that designs and manufactures single-board microcontrollers and microcontroller kits for building digital devices and interactive objects that can sense and control objects in the physical and digital world. The project's products are distributed as open-source hardware and software, which are licensed under the GNU Lesser General Public License (LGPL) or the GNU General Public License (GPL), permitting the manufacture of Arduino boards and software distribution by anyone. Arduino boards are available commercially in preassembled form, or as do-it- yourself

(DIY) kits. Arduino board designs use a variety of microprocessors and controllers. The boards are equipped with sets of digital and analog input/output (I/O) pins that may be interfaced to various expansion boards or Breadboards(shields) and other circuits. The boards feature serial communications interfaces, including Universal Serial Bus (USB) on some models, which are also used for loading programs from personal computers.

The microcontrollers are typically programmed using a dialect of features from the programming languages C and C++. In addition to using traditional compiler toolchains, the Arduino project provides an integrated development environment (IDE) based on the Processing language project.

A.3 COMSOL Multiphysics



COMSOL Multiphysics is a cross-platform finite element analysis, solver and Multiphysics simulation software. It allows conventional physics-based user interfaces and coupled systems of partial differential equations (PDEs). COMSOL provides an IDE and unified workflow for electrical, mechanical, fluid, and chemical applications. An API for Java and Live Link for MATLAB may be used to control the software externally, and the same API is also used via the Method Editor. COMSOL contains an App Builder which can be used to develop independent domain-specific apps with custom user-interface. Users may use drag-and-drop tools (Form Editor) or programming (Method Editor). Specific features may be included from the model or new features may be introduced through programming. It also contains a Physics Builder to create custom physics-interfaces accessible from the COMSOL Desktop with the same look-and-feel as the built-in physics interfaces. COMSOL Server is the software and engine for running simulation apps and the platform for controlling their deployment and distribution. User developed apps can be run in COMSOL Server through web browsers or a Windows-installed client.

Features of COMSOL Multiphysics

- Fully parametric and ready-to-use parts for coils and magnetic cores
- Electric currents and Joule heating in thin, layered structures
- More than 40 new substrate materials for printed RF, microwave, and millimetre-wave circuits
- New boundary conditions for thin metallic layers and antireflective coatings
- *Schrödinger-Poisson Equation* interface for semiconductor simulations
- New and updated Part Library for ray optics
- More powerful STOP analysis
- Optical dispersion models for ray optics