

**Modelling and Motion Analysis of a Cylindrical Steel-Rod under Very Close
Distance between Electromagnets with Alternating Polarities**

By

Muhammad Haziq Hassani Bin Hassan

24760

Dissertation submitted in partial fulfilment of
the requirements for the
Bachelor of Engineering (Hons)
(Mechanical)

JANUARY 2020

Universiti Teknologi PETRONAS,
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CERTIFICATION OF APPROVAL

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Approved by,




(AP. Ir. Dr. Masri Bin Baharom)

UNIVERSITI TEKNOLOGI PETRONAS
BANDAR SERI ISKANDAR, PERAK
JANUARY 2020

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.



MUHAMMAD HAZIQ HASSANI BIN HASSAN

ABSTRACT

Electromagnetism has many properties and one of it is the electromagnetic force. Based on Coulomb's Law, forces between electromagnets and forces between permanent magnets, the force is inversely proportional to the distance between one another. Due to this, a prototype is built by a postgraduate student which will be used to study the attraction force and response characteristics between ferrous metal and electromagnets especially at a very close distance. This is because the information for attraction force between ferrous metal and electromagnet under a very close distance is limited. Moreover, the response characteristics is yet to be known towards ferrous metal-rod.

In methodology, the prototype built by a postgraduate student will be used to conduct as an experimental study where the gap between 0.1mm until 0.6mm act as a manipulative variable. Based on the results, it is concluded that the line graph of position over time is best fit with a polynomial function of degree 2. Subsequently, further analysis by differentiating produces linear velocity graph and constant acceleration. In case of velocity graph, the response characteristics for reduction of initial velocity trend will occur when the position is beyond 0.5 mm. Another remark is force becomes constant since constant acceleration is produced by differentiation. Then, 0.6 mm has the highest result in acceleration, force, work done and power. As interval time increases, power output gradually reduces. To simplify, the behaviour of dynamic case is constant whereas static case is linear.

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CHAPTER 1: INTRODUCTION

1.1 Background Study

Electromagnetism has many properties and one of it is the electromagnetic force. By definition, it is a force that occurs between electrically charged particles which known as electrons. This can be described in electrostatics as being either positive or negative. According to a website named Sciencing, electromagnetic force is the second strongest force in nature behind strong nuclear force. The formula that describes this behaviour was derived by James Clerk Maxwell where nowadays, it is known as Maxwell's equation. Since this force is based on two electric charged particles, the equation is given by:

$$F = \frac{kq_1q_2}{r^2} \quad eq. (1)$$

Where,

F = Force (N)

k = Coulomb's constant ($\frac{Nm^2}{C^2}$)

q_1, q_2 = Magnitude of charge (C)

r = Distance between charged particles (m)

Interestingly, equation (1) is similar to Coulomb's Law and the equation of force between two magnetic poles. Based on this equation, force is inversely proportional to the distance squared. Hence, when the distance between the charges is halved, the magnetic force between them will increase up to 4 four times than its initial value. However, when the distance is approaches to zero, the value of magnetic force will be infinite. Due to this, the plotted graph of force against distance between magnets will have a very high force value for the region of very close distance. As distance increases, the value of force will decrease until it reaches to a constant force value (Vokoun et al, 2009). This graph description is fully depicts based on Figure 1.

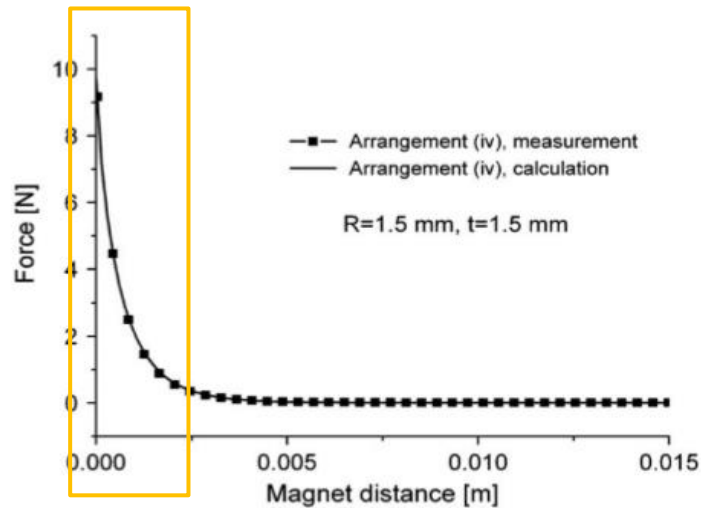


Figure 1.1: A plotted graph of calculated and measured attraction forces versus distance of the magnets

From here, this paper is interested of investigating the relationship of electromagnetic force when the distance between magnets is very close as referred to orange highlighted in Figure 1.1. With that being said, a master student has designed a modelling (based on Figure 1.2) led by Dr. Masri that can study this behaviour as well as other findings. From this modelling, a moveable cylindrical steel-rod is placed in between the fixed electromagnets and this steel-rod will be examined to analyse the electromagnetic attraction force, motion that is being created when electromagnets are subjected to alternating polarities, speed development and how the response characteristic of electromagnetic reaction time is developed during motion analysis.

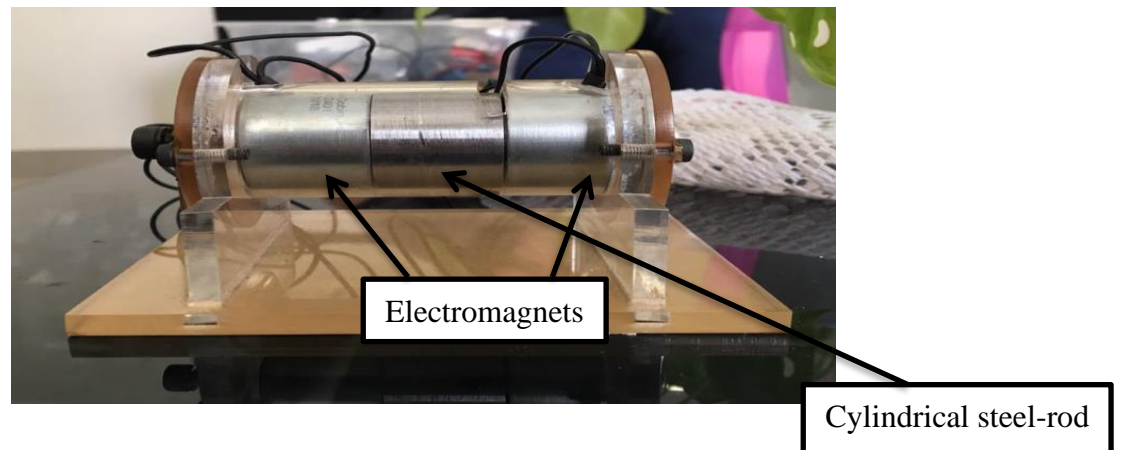


Figure 1.2: Prototype of the project

1.2 Problem Statement

- i. The information for attraction force of ferromagnetic material under a very close distance between electromagnets is limited. In addition, Maxwell equation especially relating to Coulomb's Law is unable to calculate the electromagnetic force for a very close distance because when the gap approaches to zero, the force value becomes infinite. Due to this, this paper is interested in determining the attraction force between ferrous metal and electromagnets under very close distance.

- ii. The response characteristics of electromagnetic reaction time are yet to be determined for electromagnets against a moveable ferrous metal. When it comes to disadvantage, electromagnets need time to energize and becomes fully magnetization. Due to this, there is a chance a delay time will occur during on/off period. Once there is a delay time in the experiment, the expectation of producing a smooth linear motion will be unlikely. Hence, the ferrous metal will have difficult time to produce a desired momentum continuously.

1.3 Objective

The main objectives to carry out this research are:

- i. To investigate the attraction force and speed of steel-rod under very close distance between electromagnetic forces.
- ii. To investigate the response characteristics of electromagnetic reaction time towards the moving cylindrical steel rod.

1.4 Scope of Study

The scopes and boundaries of this study are as follows:

- i. Set up the modelling and conduct the experiment with the following set up parameters:
 - Each round of experiment is conducted and analysed starting with a gap of 0.1mm until 0.6mm. This gap represents the air gap distance of cylindrical steel-rod between the electromagnets.
 - Frequency is applied at 2 Hz whereas the applied current and voltage to the electromagnets are 0.3 A and 12 V respectively for prototype configurations purpose.
 - Observe the speed and motion of the cylindrical steel-rod when electromagnet is switched on.
- ii. Retrieved the images and select among the frames taken before proceeding to measure the distance travelled of cylindrical steel rod.
- iii. Further analyse once the experimental results (the measurement of the motion) has completed.
- iv. Other phenomena such as hysteresis and aspect ratio are not put into consideration when conducting this project.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction of Electromagnetism

Over the years, electromagnetism has become an increasingly important to scientific and technological applications especially in electrical components. Electromagnetism theory is introduced by the merge of electricity and magnetism. The relation between them is that a change of electrical field can produce a magnetic field and vice versa, changing magnetic field can produce an electric field. What differentiates electromagnetism from the phenomena of magnetism is the additional study associated with both magnetic fields and electric fields. Anything with the solely relation of magnetic fields has a similar concept of magnetism.

Based on the concept of electromagnetism, there are two different poles of magnet, North Pole and South Pole. Usually, North Pole represents positive and South Pole represents negative to differentiate with one another. When two magnets with same polarity are made in contact, it will experience repulsion. In contrast, opposite polarity will experience an attraction force.

2.2 Attraction Force of Magnetism

As of now, there are application that uses the concept of magnetic dipole-dipole interaction such as the force between two electromagnets, permanent magnets and a combination of electromagnet and permanent magnet. Adding up the dipole interaction for both electromagnets will determine the net force between those electromagnets. For example, magnetic field strength has to be opposite between both of them in order the attracting effect is accomplished. Otherwise, the field strength should be similar for the case of repelling effect. In addition, the dimension and type of electromagnetic core should be comparable to one another in order to avoid non-uniform magnetization. In this project, both electromagnets are used the same product which has similar specification and capabilities.

Based on a research by Azhar's group (2016), an investigation in comparing the performance of Permanent Magnet Linear Motor (PMLM) was conducted. From this research, it stated that those PMLM which has larger magnetic gap will result a lower magnetic flux density in the air gap. Thus, producing lower thrust density denoted as F compared to those with smaller magnetic gap (Azhar et al 2016). In this finding, the thrust density represents magnetic force. It can be said that the magnetic gap plays an important role in defining the magnetic force. This finding can also be found in other researches like Mohdeb's group (2019) where calculating the attraction force in cylindrical permanent magnets arrays is investigated. Another research found that the disk of permanent magnets has strong deviation from dipole-dipole interaction (Belenggia, Tandon, Zhu & Graef, 2014).

Moreover, the shape of the magnet or electromagnetic core can also determine the magnetic field strength. A magnet interaction with the shape of cylinder -cylinder and cube-cube produces fairly high attraction force acting between permanent magnets as refer to Figure 2.1 (Vokoun & Belenggia, 2014). Even Mohdeb’s group (2019) uses cylindrical magnet to investigate the attraction force when it comes in array condition. In addition, increasing the magnet set in array form produces better attraction force when the gap distance approaches to zero.

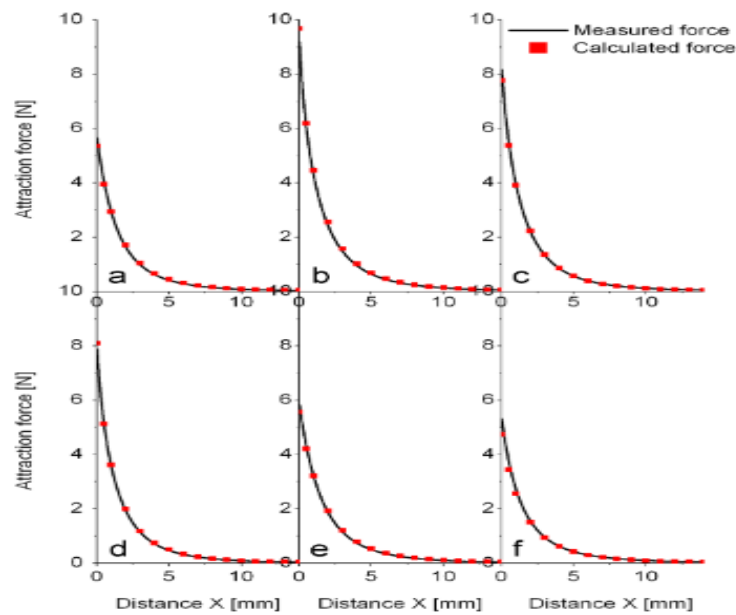


Figure 2.1: Diagram of attraction force against gap distance, X for interaction (a) cylinder-sphere, (b) cube-cube, (c) cylinder-cube, (d) cylinder-cylinder, (e) cube-sphere, (f) sphere-sphere.

Besides that, there is an experiment where it calculates the attraction force between two permanent magnets of different shapes in a static condition and planned a numerical method to calculate the forces at close distance (Vokoun, 2011). The experimental and computational results are presented in Figure 2.2. It is observed that the behaviour is approaching to linear for magnetic force between the distance from 0.1 mm to 0.5 mm.

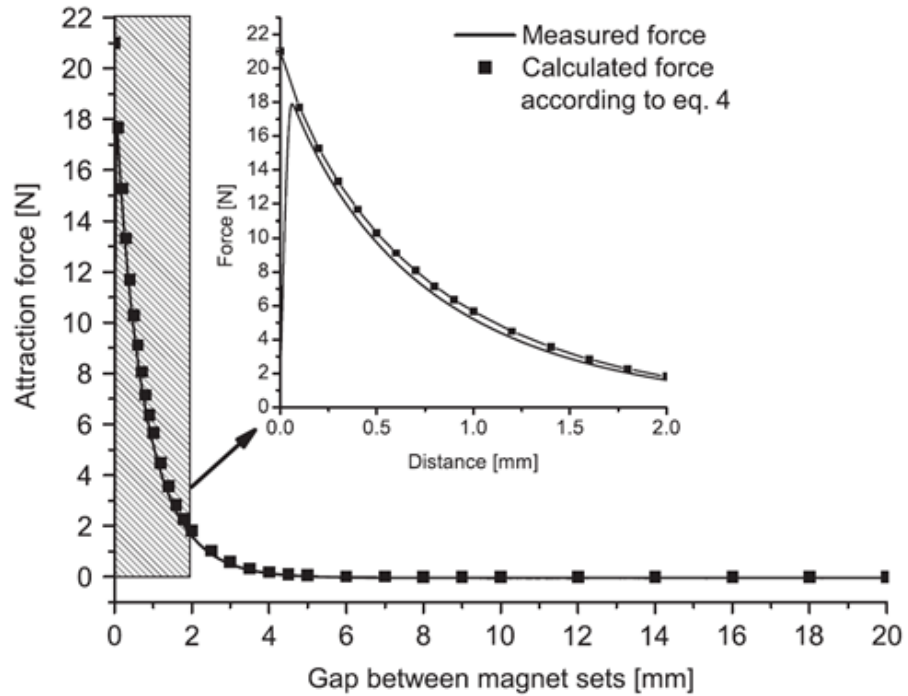


Figure 2.2: Graph of experimental and computational results of attraction force

Another similar experiment with Vokoun's study where it conducts the electromagnetic force between two electromagnets at a very close distance (Mushtaq, 2018). This was done by experimental method where it uses load cell to detect the voltage. This voltage value will convert to electromagnetic force. The experimental graph is represented in Figure 2.3. Based on this graph, it is found that the electromagnetic force against position of the electromagnets has a similar pattern as Vokoun's experiment in 2011. This indicates that both experiments have a linear characteristic when the gap begins at a very close distance until it approaches to zero.

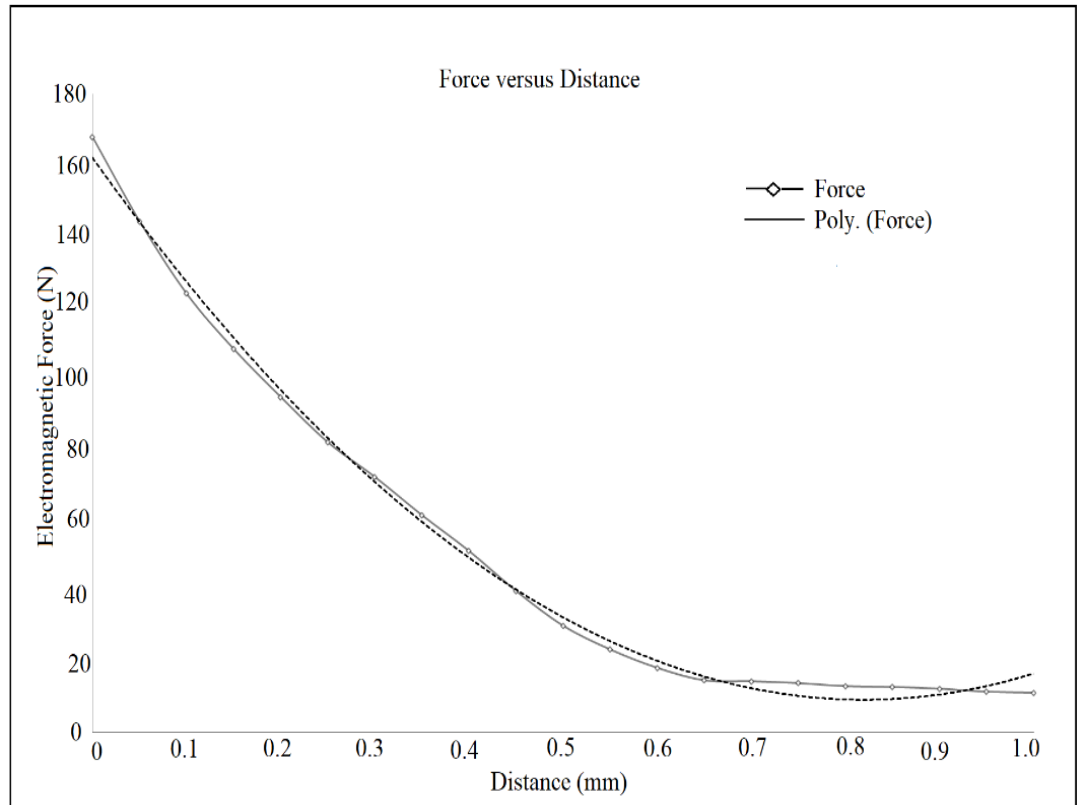


Figure 2.3: Attraction force versus position of electromagnet

However, most researchers only noted the relation of force and the magnetic gap. There are little findings that focus on calculating the attraction force when two magnets are at a very close distance. Also, there are no investigations that specify on the attraction force between electromagnet and ferrous metal. Therefore, this project is interested in findings those value and the relation of attraction force occurred between electromagnet and ferrous metal. Moreover, the author is curious whether the results of this project will have a similar pattern as in the past literature.

2.3 Response Characteristic of Electromagnetic Reaction Time

Electromagnet is a device that creates a magnetic field when a current flowing through a coiled wire is presented, either from a battery or any electrical sources. This helps to magnetize the metal that is wrapped around by a coil wire creating a similarity as permanent magnet. In addition, unlike permanent magnet, electromagnet has its own usefulness where it can be switched on and off in order to complete or interrupting the circuit, respectively. This indicates that whenever the electric current is flowing, a magnetic field will only be then existed temporarily. Hence, anyone can control the electromagnet whenever the user wishes to do so.

Apparently, electromagnet has its own setback where it may require time to energize and become fully magnetize. Energizing an electromagnet can be depended on certain aspects. According to a research by Li, Su and Zhang (2017), it is found driving current can be a factor that influence the opening and closing response characteristics of solenoid valve. Solenoid valve is one of many applications that use the concept of electromagnetism. In further description, when the coil current increases, the time taken for electromagnetic force obtained decreases. Hence, the opening response of solenoid valve becomes faster. However, this group of researchers also found that the closing time of solenoid valve would require a longer time. This is because electromagnets need time to de-energize and lose its ability of magnetization. Even more so, another researcher named Ule (1975) stated that increased electrical current is required in order to obtain a given electromagnetic force when the magnetic gap is open. By then, a significant amount of magnetic energy would be able to accomplish before desired force is obtained for open gap situation. So, there is a high expectation that this information itself can probably occur to the project.

Moreover, another factual that influences the response characteristics is the voltage supplied to electromagnets. Voltage has the same behaviour as current when applying to the solenoid valve or any application that uses the concept of electromagnetism. The main reason is that voltage is directly proportional to current and this is based on the basic equation of Ohm's Law, $V = IR$. In the experiment of Li, Su and Zhang (2017), there are two set-up conditions that are being conducted, the voltage supplied of 25V and 13.5V. From this experiment, the voltage supplied at 25V has the shortest time to achieve the maximum electromagnetic force produced by solenoid valve unlike 13.5V. Since voltage has a direct relation with current, higher voltage carries higher current. Hence, more time is needed for high current to reduce zero value. So, setting the voltage at 25V is a disadvantage for closing response time compared to 13V despite its capability to achieve shorter time for opening response characteristics of solenoid valve (Li, Su & Zhang, 2017). All those findings can be concluded that voltage cannot be simply increased or reduced in order to improve the response characteristic of electromagnetic reaction time. In addition, two researches from Zhang's group (2019) and Dong's group (2012) have similar findings as Li's group (2017). This shows that all these findings are supported and convincing.

Next, the aspect that can influence the response characteristics is the frequency (Li, Su & Zhang, 2017). In Figure 2.2 shows the different response characteristic of solenoid valve when working frequency changes. It is seen that the response characteristics improves as the frequency applied increases. However, if the working frequency is too much, it can cause the current rise unable to create a saturated magnetic field. Thus, controlling the working frequency in a certain range is necessary. Moreover, a very high working frequency can also cause a disruption to circuit of the products including electromagnets. With that being the case, the response characteristics can be fundamentally irrelevant to the action frequency if the working frequency is below the maximum action frequency (Zhang et al, 2019).

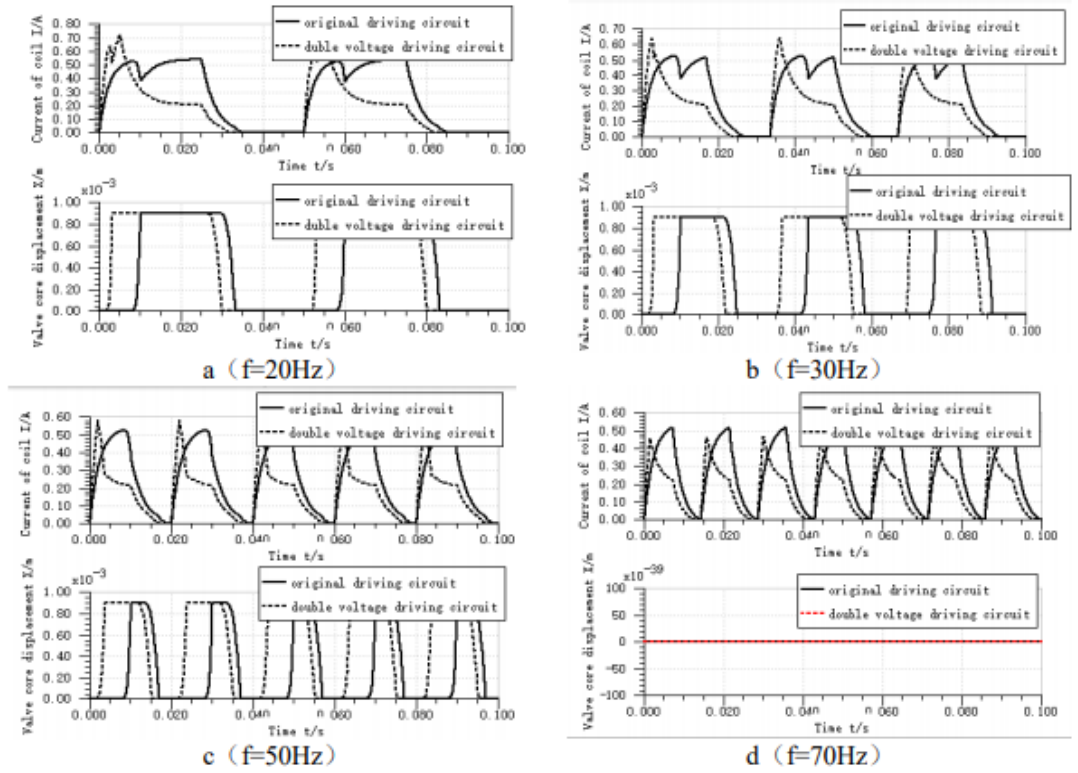
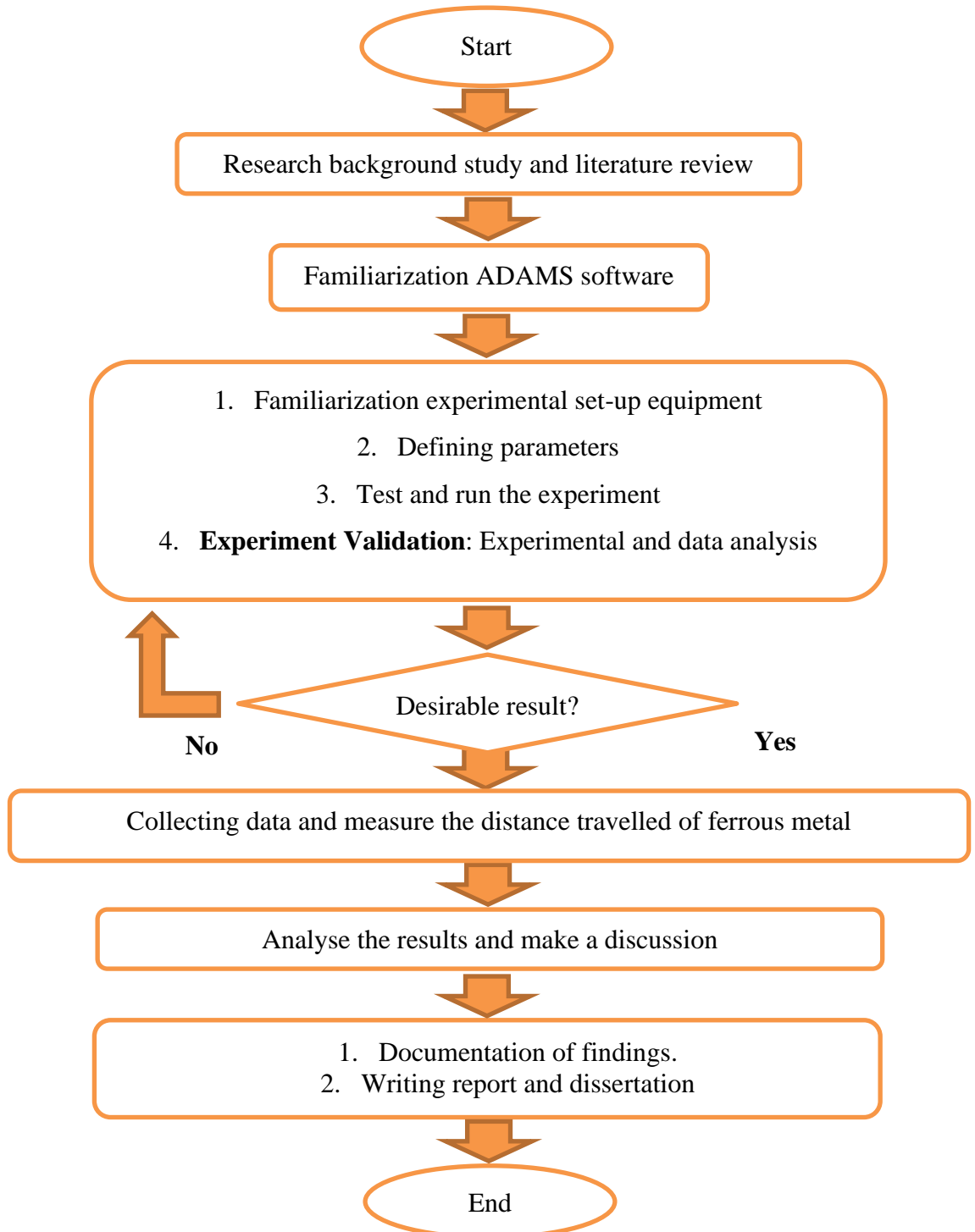


Figure 2.4: the influences of different driving circuits on the valve response when changes the working frequency.

CHAPTER 3: METHODOLOGY

3.1 Process Flow Chart



3.2 Equipment and Tools for Prototype Set-up

Figure 3.1 shows a prototype built by a postgraduate student, Ms. Atira which will be used to study the motion and interaction between ferromagnetic materials and electromagnets especially at a very close gap situation. In this prototype, it consists of base, holder, cover, wirings which connect to electromagnets at both ends, and a cylindrical shape of steel-rod. This cylindrical steel-rod is placed in between electromagnets.

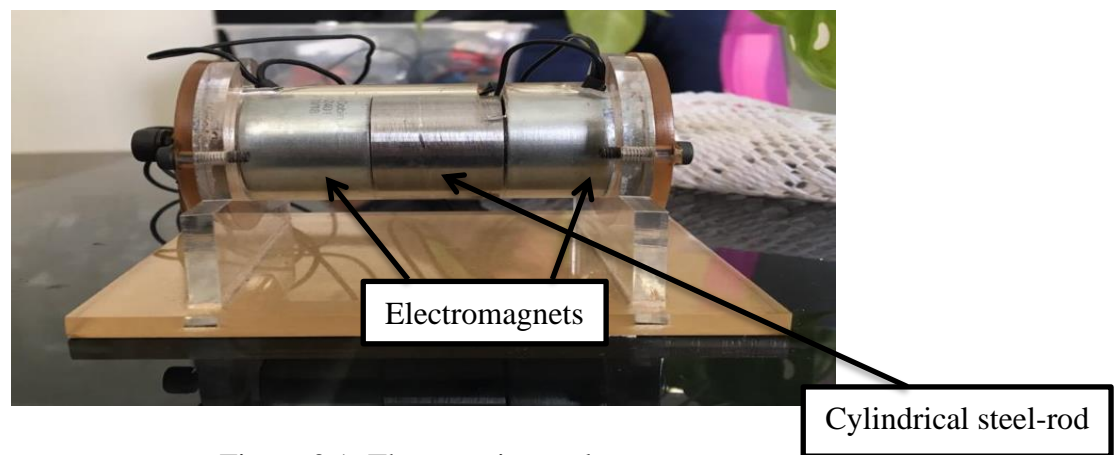


Figure 3.1: The experimental prototype

As for set-up procedure, the prototype wirings will connect to a power supply as shown in Figure 3.2. This creates a current flow to the electromagnet to excite its magnetization. Next, a high-speed camera is set up in front of the prototype to record the motion. This set up will be positioned between the gap of electromagnet and the ferrous metal. Note that, this can be focused on one sided only for recording purpose. The camera brand is known as Phantom Miro M310. This camera and its specification can be seen in Table 3.1. This high-speed camera will be connected to a laptop to control the device by using a software application called Phantom Camera Control (PCC). From there, the user can adjust the parameters such as the frame rate, the time taken and many more before proceeding to run the experiment.

Table 3.1: Specification of Phantom Miro M310

Phantom Miro M310	
	
Specialties	3.2 Gigapixels/second (Gpx/s) throughput
Max resolution	1280 x 800 @ 3260 fps
Max frame rates (fps)	650,000

The following set up is having two spotlight lamps to brighten up towards the prototype in order to have a better image when recording the motion. Hence, these two spotlight lamps will be placed near to the prototype. After completion, the model is ready to run for the experiment. The main goal of this prototype is to produce a attraction force and linear motion.

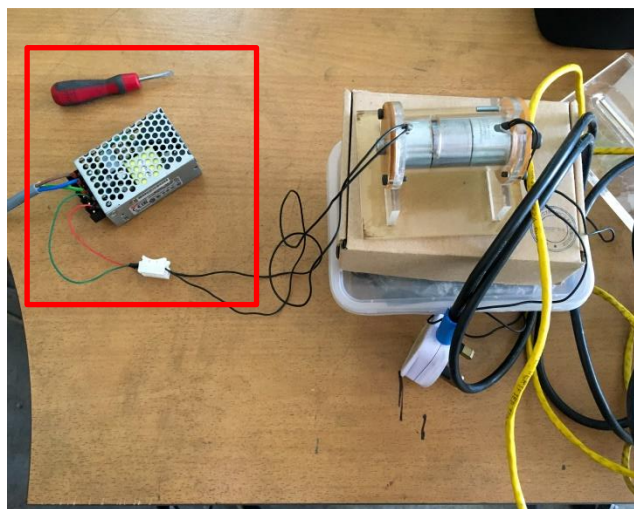


Figure 3.2: power supply (red box) connecting with the prototype

Moreover, IRF520 MOSFET Driver Module is used to control the power supply voltage to both electromagnets and the equipment is shown in Figure 3.3.



Figure 3.3: IRF520 MOSFET Driver Module

Figure 3.4 represents how all equipment and tools will be set-up accordingly at the CAREM laboratory. This experimental set-up is including with high speed camera and a laptop. As for Table 3.1, it signifies the specification and the capabilities of electromagnets that will be used in this project.

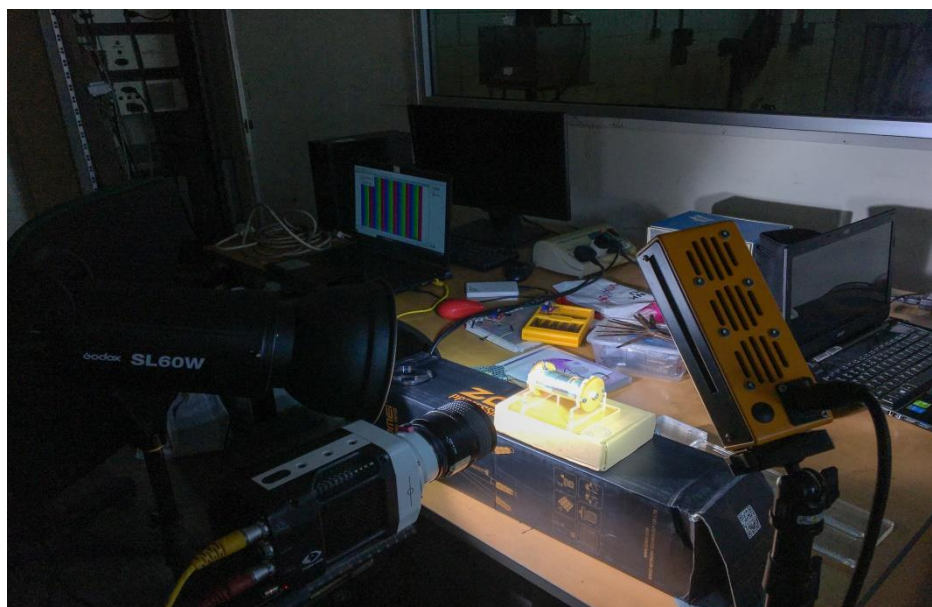



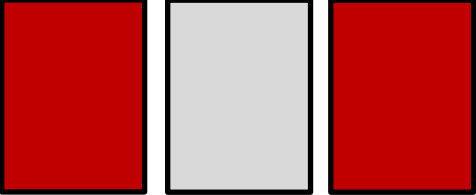
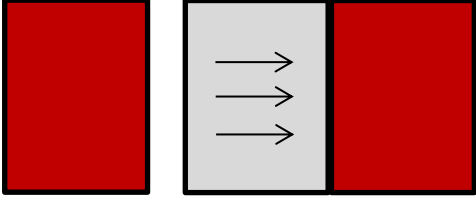
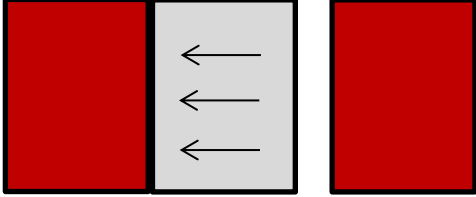
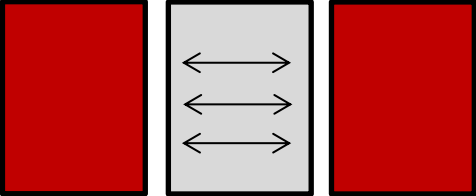
Figure 3.4: Experiment set-up including with high speed camera

In Table 3.2, it represents the specification of the electromagnet that is being used in the prototype. Both electromagnets used in the prototype are identical. This 0.47 kg of electromagnet is capable producing a maximum force of 140 N according to the manufacturer's data. The dimension of this electromagnet is a diameter of 20.5 mm and length of 25.0 mm. As for magnetic field, it is measured at the center of $B = 31.1 \text{ mT}$.

Table 3.2: Specification of electromagnet TYPE 58

Electromagnet TYPE 58				
				
Specification				
Brand	Axial Force (N)	Magnet Weight (Kg)	Armature Weight (Kg)	Operating Voltage
SG Transmission	140	0.07	0.01	12V/24Vd.c

3.3 Working Principle of the Modelling

<p>1) This setup situation is a two-dimensional (2D) view of the actual modelling. This is a reference on how the motion will occur to both simulation and experimental method. Note that the gap of cylindrical steel-rod between the electromagnets is very close.</p> <ul style="list-style-type: none"> • Red = cylindrical electromagnets • Silver = cylindrical steel-rod 	
<p>2) When the right electromagnet is firstly switched on, it will excite the magnetization. Once it has reached the magnetic energy requirement, it creates an attraction force to cylindrical steel-rod. This will eventually move towards to the right electromagnet.</p>	
<p>3) Next, left electromagnet is switched on and right electromagnet switched off. After excitation has surpassed the magnetic energy, left electromagnet will produce an attraction force which causes steel-rod to move towards to the left electromagnet. Note that, the magnetic energy on the right electromagnet is reduced to zero which will reduce the attraction force.</p>	
<p>4) Then, this sequence of alternating polarities to the electromagnets is repeated numerous times to observe cylindrical steel-rod creating a linear motion by moving right-to-left-to-right continuously.</p>	

3.4 Experimental Study

A complete prototype will be set-up and tested in a CAREM laboratory to run its feasibility before proceeding with an actual experiment. From this experimental set up, the author will retrieve its data and result for further analysis. Generally, there are a few methods that can be conducted from this prototype to learn different cases. As for this case, the study that will be measured is the distance travelled of cylindrical steel-rod to the attraction force from the excitation of the electromagnet. This measurement will be done by using a high-speed camera.

Before obtaining the desirable results, the frequency is applied at 2 Hz whereas the applied current and voltage to the electromagnets are 0.3 A and 12 V respectively. All those parameters mentioned in the previous statement are required to be distinguished for prototype configuration purpose and these will be known as a constant variable. Then, the air gap between the cylindrical steel-rod (moveable ferrous metal) and fixed electromagnet is varied between 0.1mm to 0.6mm. This parameter alone is considered as a manipulative variable. Once all these configurations have been set up, the working principle of the project can finally be demonstrated.

This idea itself is in hopes of achieving an attraction force from the moveable ferrous metal in a very close distance condition. The attraction force produced by the electromagnet will then make the moveable ferrous metal moves from right to left continuously. A linear motion is observed and expected. Moreover, different linear motion results with different air gap set-up are also expected. All these linear motions will also be recorded by a high-speed camera to investigate the motion analysis using an image processing sequence. An AutoCAD software will be used as a technique for image processing sequence for these data which later can obtain the results.

3.5 High Speed Camera

High speed camera is used to record the motion of cylindrical steel-rod in the experimental study. This equipment is available in the CAREM laboratory. It can capture the motion by using frame-by-frame analysis. There are many options that can impact on the quality of video image but in this case, the frame rate is chosen to compute the manipulated variable. Frame rate is the number of images (frames) per second that a camera can capture specifically for video recording. This generally expressed in frames per second or fps. From a practical perspective, frame rate can be viewed as individual images taken per second. In addition, the motion that will be recorded is a 2D motion (in X-axis). Due to this, only one camera is needed to conduct the experiment and positioned it perpendicular to the motion of the prototype.

Therefore, high speed camera is chosen because the motion of the experiment occurs at a very close distance and this requires a lot of images to be captured between those distances. Hence, the equipment used is capable to record a motion with a frame rate of up to 650,000 fps. So, the chances of capturing at the targeted area are increased as the frame rates increases. However, due to its wide range of fps capability, the author decides to record it with 30000 fps as it is sufficient to achieve the desired data and results. Based on a previous finding, Ms. Atira clarified that 1000 fps and 2000 fps is insufficient to achieve it as the amount of frame captured at the targeted area (linear slope graph) is around the range of 2 to 4 frames. Hence, it is difficult to analyse the slope properly. Due to this, 30000 fps is the minimum set-up for high speed camera to record the motion after a discussion with Ms. Atira and Dr. Masri.

Once this experiment has been conducted, these experimental data will be transferred to the computer. According to Garhammer and Newton's findings, all those data can be analysed through frame-by-frame measurement of the location of image points (body segments or implements). Later, these will convert into digitization. Using a digitizing software packages, it can calculate the motion paths and kinematic analysis such as linear and angular position, velocity and acceleration (Pueo, 2016).

3.6 AutoCAD software

AutoCAD is a commercial computer-aided design (CAD) software where engineers, architects, construction professionals, or any users can access to create detailed 2D and 3D drawings. It was developed in the year 1982 by Autodesk and now, it has widely marketed in many fields of industry which involves manufacturing, wiring and construction (Kennedy, 2014). Because of this, many institutions of higher learning have introduced this CAD software in their education system to ensure students get an exposure of this highly job-market demand (Awang, 2000). Generally, users can use this software for a variety purpose which are:

- 1) Creating and modifying 2D and 3D plans for professional drafting as well as modelling.
- 2) Customizing the software with add-on apps depending on the project requirements.
- 3) Annotating drawings with dimensions, text, tables, and leaders.
- 4) Includes with specialized toolset to assess and design product in surface modelling and wireframe.

Therefore, this CAD software is chosen as it has the ability to annotate with dimensions onto imported images thanks to the updated specialized toolset that Autodesk has installed into its latest version. All those images captured from the high-speed camera will initially examine to locate which frames that the moveable ferrous metal is currently in motion. This step is important as it would be tedious and time consuming for the author to annotate the dimensions on all images captured since every run of experiment has 30000 frames in each take. Then, those selected images will later be imported to AutoCAD software for measurement purpose. Once is completed, all measurements taken will proceed for further analysis by using Microsoft Excel

3.7 Gantt Chart








Gantt chart and its key milestone of FYP 1 and upcoming FYP 2 have been illustrated in Table 3.3 and Table 3.4 respectively.




Table 3.3: Gantt chart of FYP 1

Planning & Activities	Week													
	FYP 1													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Project title confirmation & project discussion with SV	■													
Project discussion with SV's team	■	■												
Literature review on related topics		■	■	■	■	●								
Preparation of extended proposal & proposal submission						■	■	◆						
Familiarization with experimental study							■	■	■					
Determining parameters required for experimental study							■	■	■	●				
Progress evaluation & proposal defence										■	◆			
Preparation and submission of draft report										■	■	■	◆	■
Final report submission														◆

Process	■
Project Milestone	●
FYP 1 Milestone	◆

Table 3.4: Gantt chart of FYP 2

Planning & Activities	Week													
	FYP 2													
	1	2	3	4	5	6	7	8	9	10	11	12	13	14
Test and run the experiment														
Experimental and data analysis														
Preparation and submission of progress report														
Critical analysis														
Submission of Final Progress or Draft Report														
Viva														
Submission of Dissertation														

Process	
Project Milestone	
FYP 1 Milestone	

3.8 Key Milestones

Table 3.5 represents the key milestones that have been identified as shown in the Gantt chart (refer Table 3.3). This representation is to highlight the progress of the project.

Table 3.5: Key Milestones of FYP 1





FYP 1		
Week	FYP Markers	FYP Activities
7		Preparation of extended proposal & proposal submission
11		Progress evaluation & proposal defence
13		Preparation and submission of draft report
14		Final report submission
Week	Project Markers	FYP Activities
6		Literature review on related topics
10		Determining parameters required for experimental study

Table 3.6: Key Milestones of FYP 2

FYP 2		
Week	FYP Markers	FYP Activities
5		Test and run the experiment
7		Preparation and submission of progress report
11		Submission of Final Progress or Draft Report
14		Submission of Dissertation
14		Viva
Week	Project Markers	FYP Activities
6		Experimental and data analysis
10		Critical analysis

CHAPTER 4: RESULTS AND DISCUSSION

4.0 Introduction

In this section, the author will display and explained all the information relating to result obtained from the experimental study. As for certain analysis, there will be comparison with the past literature for confirmation purposes.

4.1 Minimum Number of Frames Captured during Motion

Since the setting for the frame rate is 30000 fps, the calculation to estimate number of frames that can be captured during the motion from 0.6 mm to the contact position is shown in below:

Based on manufacturer's data, the maximum force exerted by the electromagnet is 140 N and the weight of it is 0.47 kg. When the motion is occurring in one direction (X-axis), force is computed using the following equation:

$$F = ma$$

$$140 = 0.47a$$

$$a = 297.872 \text{ m/s}^2$$

This acceleration is assumed to be the maximum value for ferrous metal to move. Based on derivation method, velocity is derived by distance over time whereas acceleration is derived by velocity over time. From here, the time taken for ferrous metal to reach the certain destination can be calculated by using this derivation method. Assumed 0.1mm is used in this sample calculation.

$$v = \frac{dx}{dt} \text{ \& } a = \frac{dv}{dt} = \frac{dx}{dt^2}$$

$$a = 297.872 \text{ m/s}^2 = \frac{dx}{dt^2} = \frac{0.1}{\frac{1000}{t^2}}$$

$$t^2 = \frac{0.0001}{297.782} = 3.357 \times 10^{-7}$$

$$t = \sqrt{3.357 \times 10^{-7}} = 5.794 \times 10^{-4} s$$

The time taken to reach 0.1mm is $5.794 \times 10^{-4} s$. For frame rate of 30000 fps, the time taken for 1 frame is $3.333 \times 10^{-5} s$. Then, the calculation for the number of frames captured in this distance is shown in below:

$$\text{Number of frames captured} = \frac{5.794 \times 10^{-4}}{3.333 \times 10^{-5}} = 17.382 \approx 17 \text{ frames}$$

Thus, 17 frames can be captured by setting up the frame rate at 30000 fps. Note that this is considered an assumption because acceleration is constant over time as per mentioned above. It means that the ferrous metal will not have any delay issue and occurs at maximum acceleration throughout the motion. So, this assumption may differ with the result of completing the experiment. However, this quantity is adequate to plot a better graph and determine its polynomial behaviour. Table 4.1 represents the number of frames that can capture in an experiment testing with the incremental value of 0.1 mm until it reaches 0.6 mm.

Table 4.1: Estimation number of frames captured for each experiment testing

Position	0.0001	0.0002	0.0003	0.0004	0.0005	0.0006
Time taken	5.794E-04	8.194E-04	1.004E-03	1.159E-03	1.296E-03	1.419E-03
Number of frames	1.738E+01	2.458E+01	3.011E+01	3.476E+01	3.887E+01	4.258E+01
Rounded off the number of frames	17	24	30	34	38	42

4.2 Images Processing


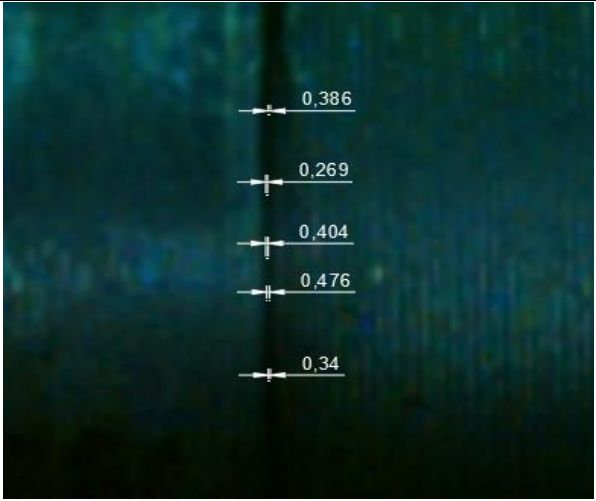
After completing the experiment, all images captured for every repetitive experimental testing with the incremental value of 0.1 mm are observed and analysed using the computer. Since there is an estimation of at least 30000 images for each experiment, the selection process to cut down unnecessary images is initially done by using a software named Phantom Camera Control. This software is mainly used to control the high-speed camera (Phantom Miro M310) and visualize the prototype which needs to adjust into a right position before proceeding to capture the images. After editing out into smaller range of images, these selected images will transfer into the computer.

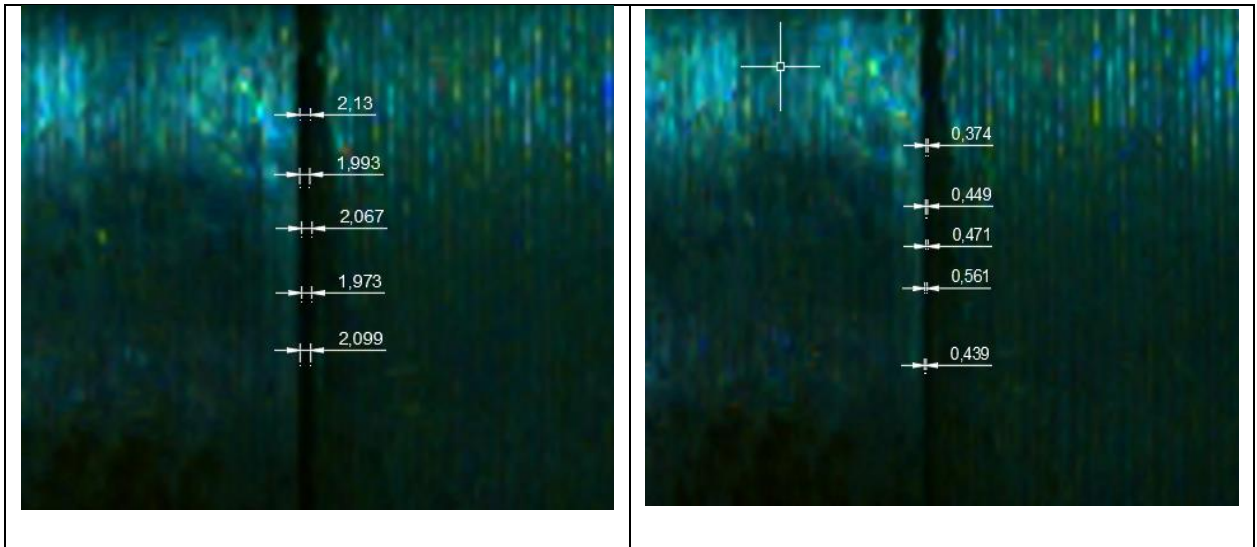
Based on the specification of high-speed camera used, it can achieve a maximum resolution of 1200 X 800 at 3260 fps. However, as the frame rate increases, the resolution will decrease. Thus, the resolution for 30000 fps has reduced of up to 320 X 240. This gives the images smaller which creates a limitation to see the full view of ferrous metal in motion. Despite that, this resolution is sufficient to measure the distance travelled of ferrous metal in several location.

Then, a second round of selecting images is needed because the results only needs to be analysed when the moveable ferrous metal has travelled from right to left. So, this second round of selection process is done by viewing manually to every single image that has been transferred to the computer. Based on observation, it is estimated of up to 50 images that captures the motion of the ferrous metal

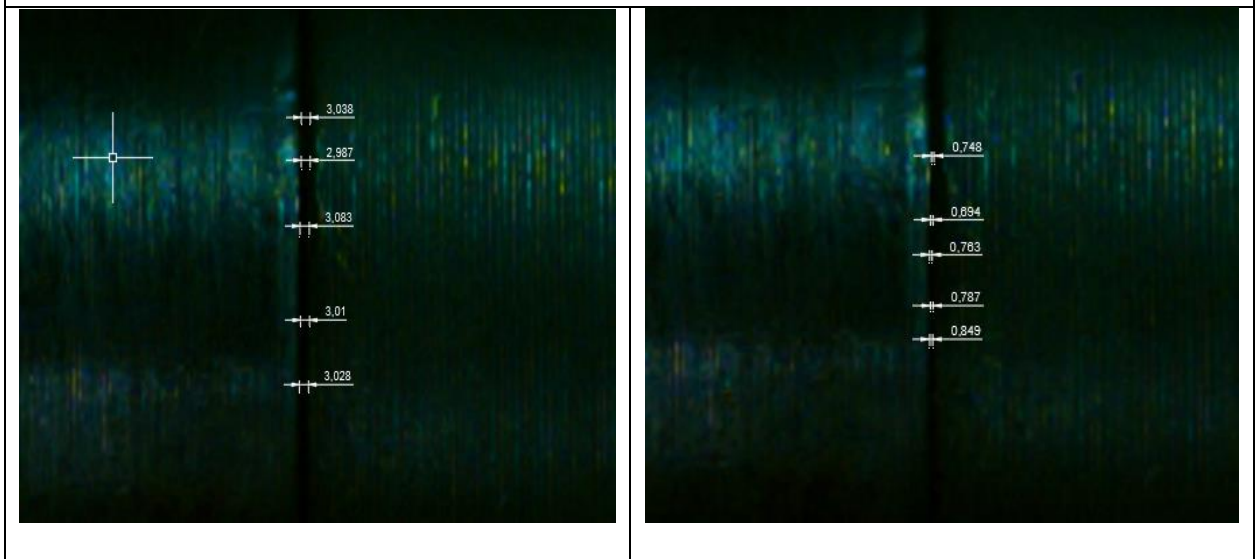
Once the second round of selection process is completed, these images are imported into AutoCAD software to measure the air gap when ferrous metal rod is in motion from right to left. Due to lack of lighting effect onto the surrounding of the prototype, the images still give a difficult time to achieve an accurate measurement. Hence, this measurement is taken five attempts at different location for each image in order to achieve an average measurement. Table 4.2 shows how the annotation with dimensions is carried out on every images of all experiment. The images shown below is only consists of before and after the motion of ferrous metal has gone through.

Table 4.2: Before and after images of every experiment

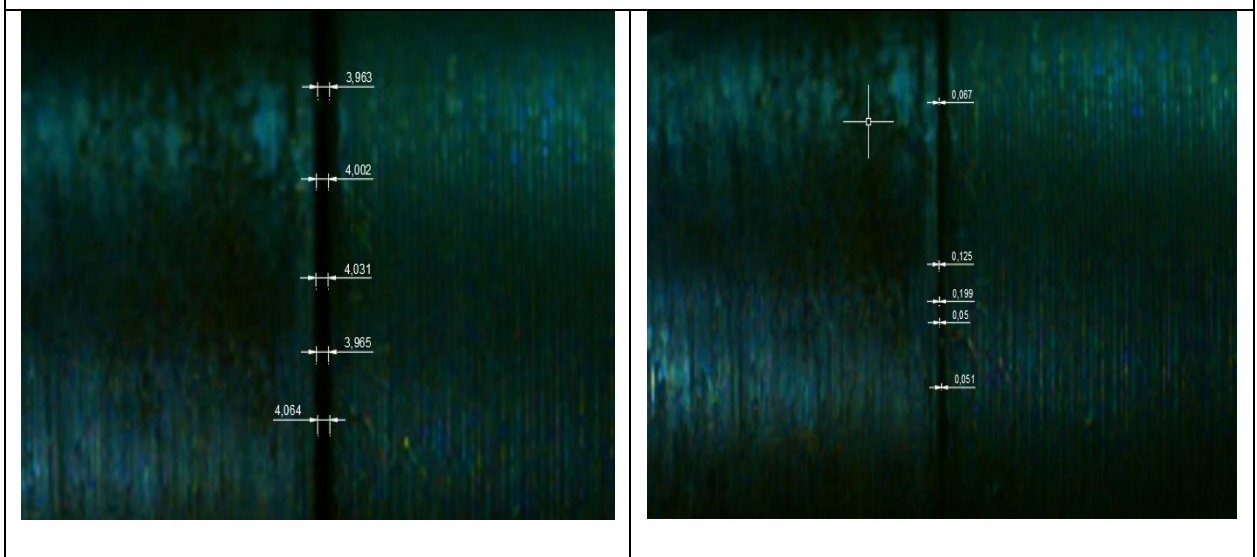
Annotate Images with Dimensions (mm) using AutoCAD	
Before motion begins	After motion ends
0.1 mm experiment	
	
0.2 mm experiment	

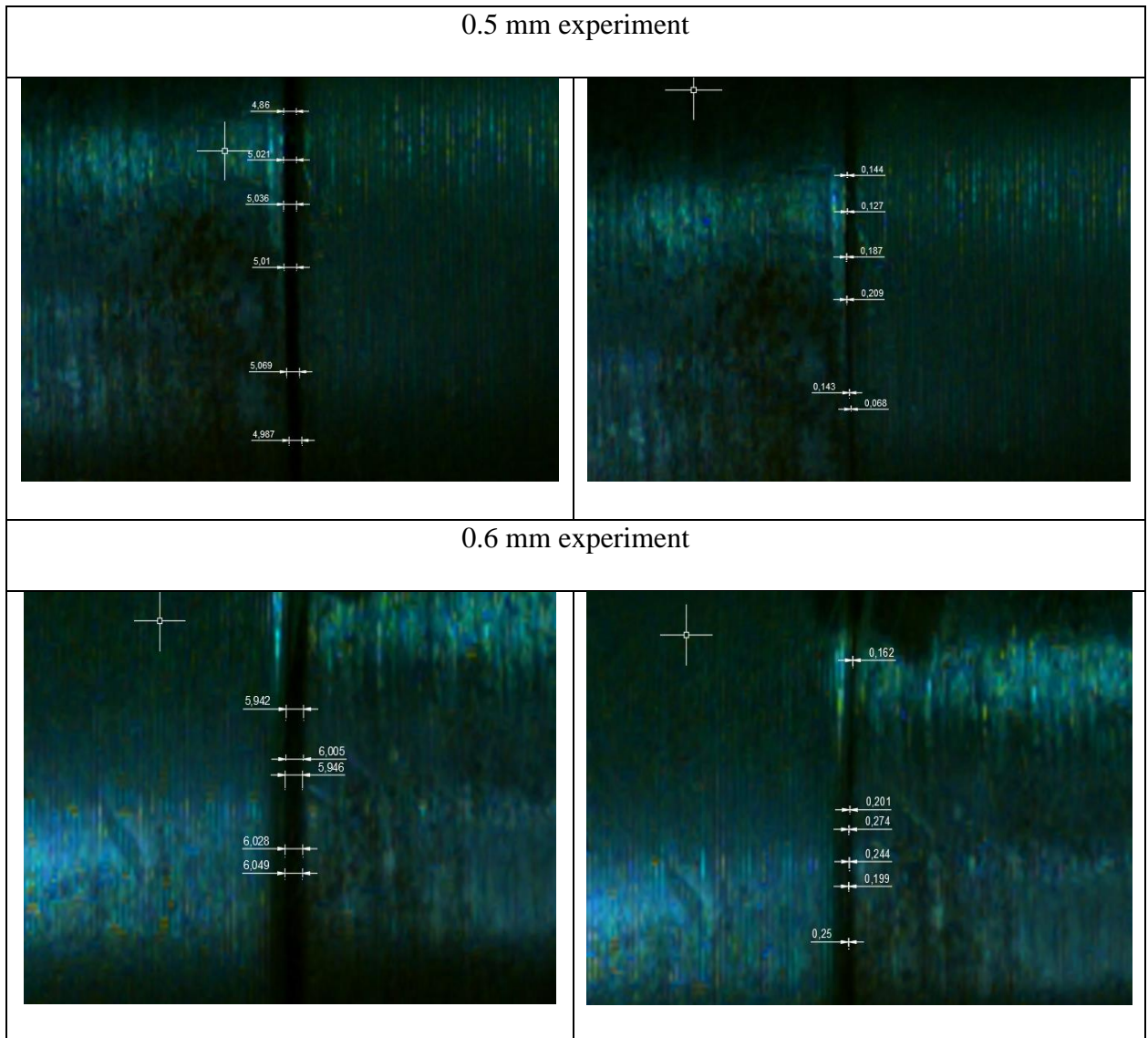


0.3 mm experiment



0.4 mm experiment





Next, all these measurements are recorded into Microsoft Excel spreadsheet to plot a scatter line graph entitled position of ferrous metal-rod over time. Since there is six repetitive experiment, six scatter line graphs are expected. After plotting the graph, there is a need of rescaling process to the images so that it achieves the actual dimension as in the experiment. Afterwards, these updated graphs are verified using a curve fitting functions with the intention of finding the best function to these plot lines. Curve fitting functions are based on the regression correlation square values. Among all functions used, it is found that the best fit to these data would be the polynomial of degree two. These plotted graphs from case 0.1 mm to 0.6 mm are shown in Figure 4.1.

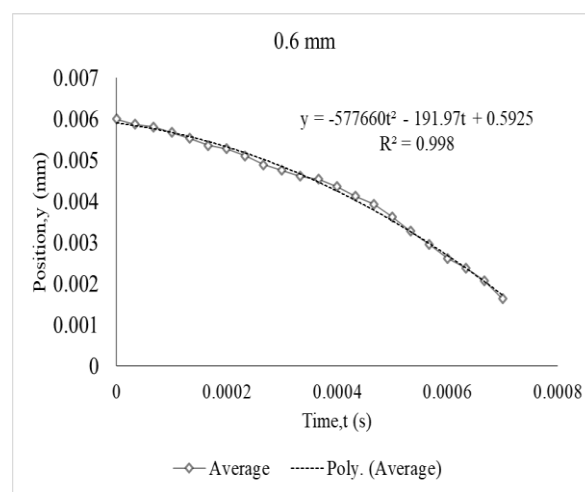
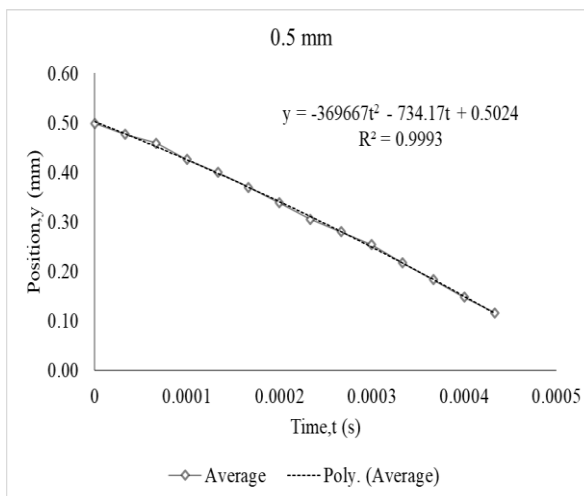
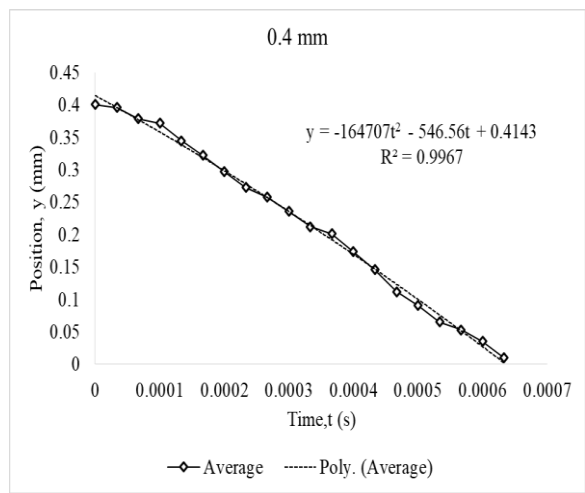
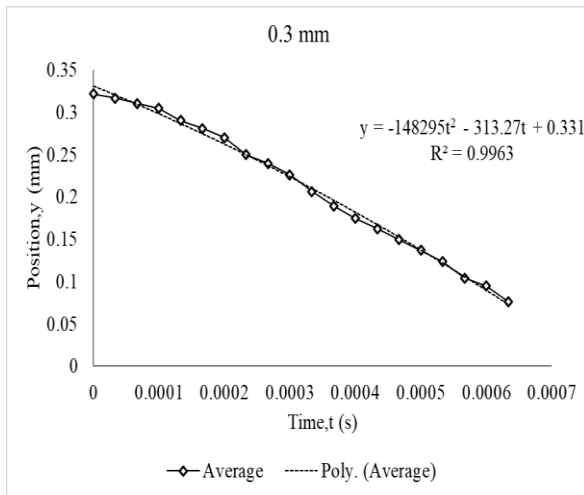
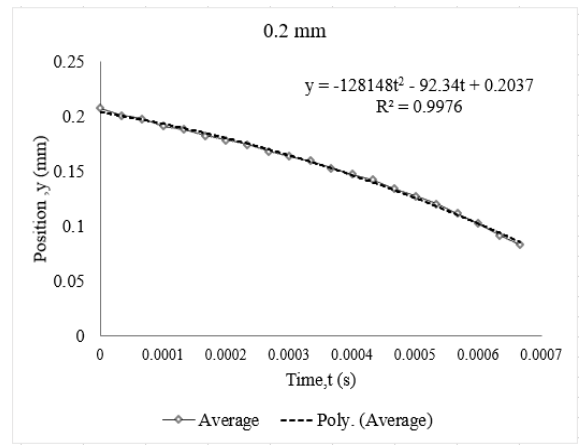
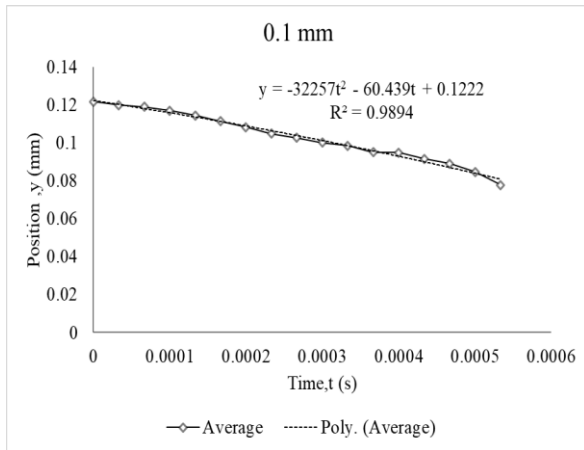


Figure 4.1: Graph of position of ferrous metal-rod against time

Based on Figure 4.1, it is observed that the polynomial of degree 2 or quadratic function has the best fit with the data measured where all cases from case 0.1 mm to 0.6 mm have the values of squares of regression coefficients, r^2 approaches to 1. In a research of Henseler's group (2009), the group proposed a rule of thumb where the acceptable r^2 for 0.25, 0.50 and 0.75 are labelled as weak, moderate and substantial respectively. Consequently, all those six cases have surpassed the minimum requirement value of r^2 where the lowest value among all cases is around 0.98.

Since it is polynomial function of degree 2, this can be further analysed by differentiating the equation of the graph for every case. The result of this differentiation is a plot graph of velocity against time as shown in Figure 4.2. It is a graph which comprises data from cases 0.1 mm until 0.6 mm. A noticeable observation from this graph is all lines have linear characteristics with respect to time. This is because polynomial function has reduced to degree 1 after differentiating.

Next, another remark can be made where the initial speed for cases from 0.1 mm to 0.5 mm has a cumulative trend. In spite of that, cases 0.6 mm has a lower value of initial speed which lies between 0.2 mm and 0.3 mm cases. The reason behind this phenomenon is relating to the duration for electromagnetic force or field to be fully developed. As soon as the distance between two objects are very close, the magnetic field has little amount of time to develop the full force. Subsequently, less attraction force is in contact with the ferrous metal-rod. If the position is set further from the contact position, force can be increased up to its full potential because longer time allows it to develop. In contrast, if the distance is exceedingly far, the required time to fully developed will surpass the allowable time taken which creates unnecessary dissipative force to the surrounding. Thus, initial attraction force towards the ferrous metal-rod becomes lesser. This clarification has caused the occurrence of lower initial velocity for case 0.6 mm. In support to this phenomenon, Vokoun (2011) also found that the force decreases as the distance between the two magnets increases when it is tested in static condition. Therefore, it can be said that the reduction of initial velocity trend will occur when the position is beyond 0.5 mm.

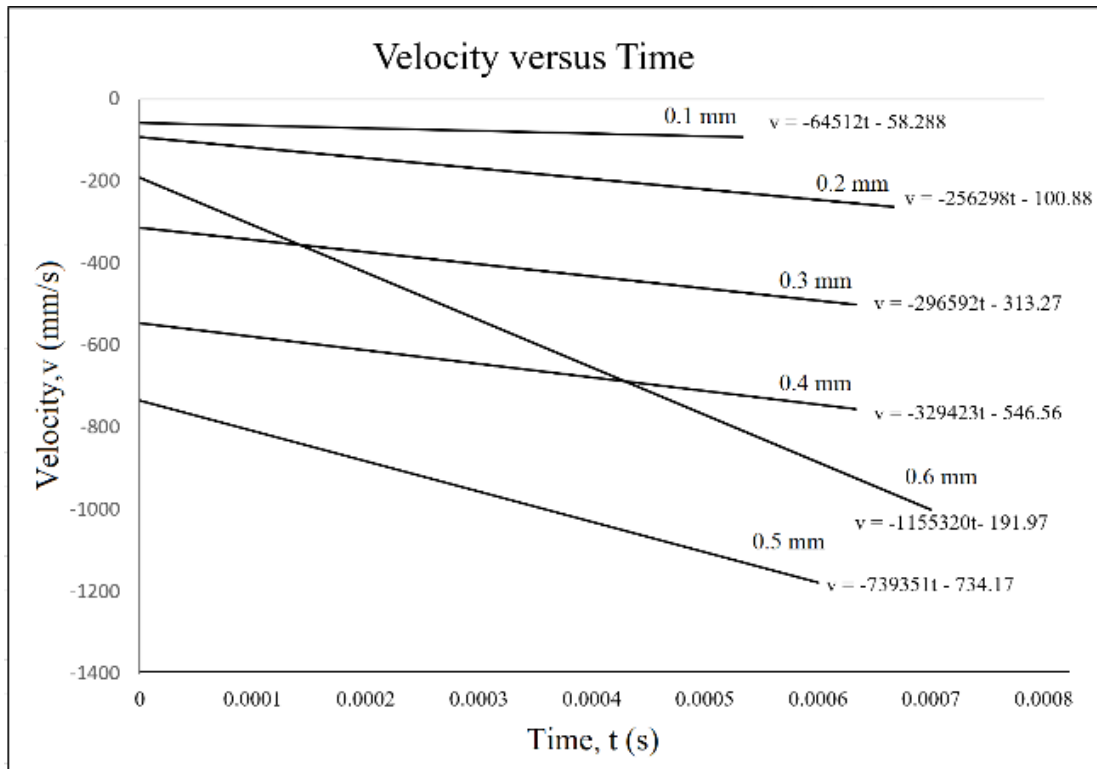


Figure 4.2: A compilation graph of velocity against time for all cases

This linear curve can be differentiated once more into a plot graph of acceleration against time. This means that the degree of function has reduced to zero which implies to be a constant function. Hence, acceleration is constant over time. Due to this, the author decided to plot the graph of acceleration against position from 0.1 mm to 0.6 mm instead. It is to create a clearer picture on the projection of acceleration in each position and this graph can be seen in Figure 4.3. One of the main findings in this case is that force becomes a constant over time. This is because in terms of its equation ($F = ma$), the mass of ferrous metal-rod remains the same and the only left behind for force to be depended on is the acceleration. Since it is constant acceleration, force will also be constant.

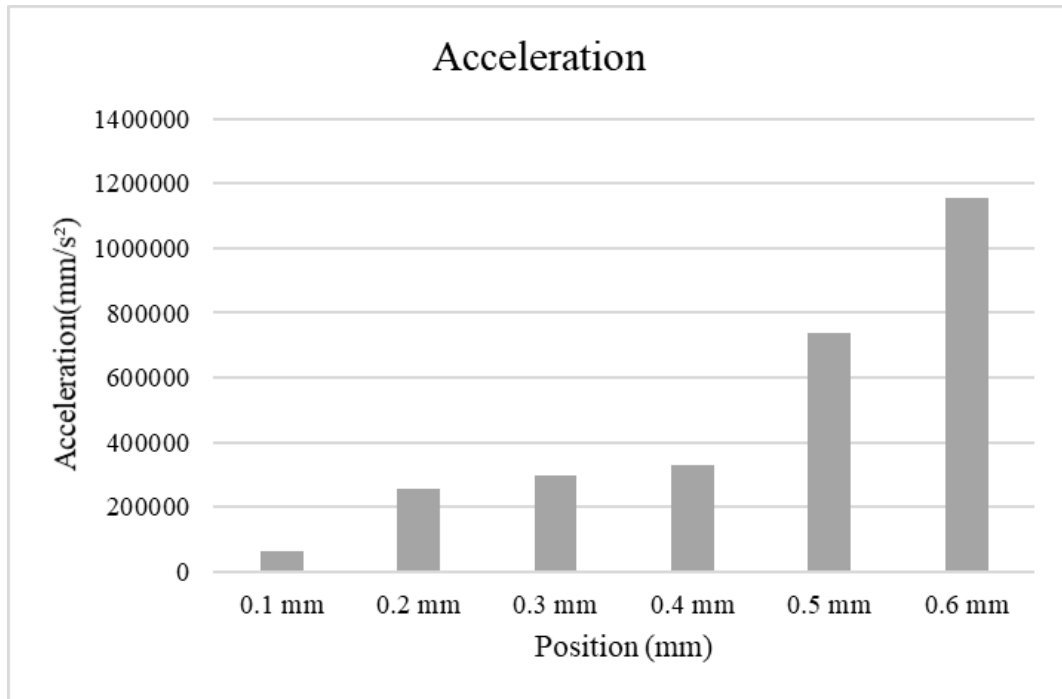


Figure 4.3: A compilation graph of acceleration against position for all cases

Besides that, this graph also has an increasing trend for the experimental positions from 0.1 mm to 0.6 mm. Since the highest value of acceleration among all cases is 0.6 mm and thus, it also makes the computation force at a highest value. Then, this can be further calculated to find the work done for every case. The sample calculation of work done is as shown below:

Let say that at position 0.6 mm is used. Note that the mass of ferrous metal-rod is 0.047 kg and the acceleration at 0.6 mm is 1155320m/s².

$$F = m \times a \quad \text{eq. (2)}$$

$$F = 0.047 \text{ kg} \times 1155320 \text{ m/s}^2$$

$$F = 54300.04 \text{ N} \approx 54300 \text{ N}$$

$$W = F \times d \quad \text{eq. (3)}$$

$$W = 54300 \text{ N} \times 0.0006 \text{ m}$$

$$W = 32.58 \text{ Nm}$$

Furthermore, power output can be computed by using the value of work done as stated above divided by time taken of ferrous metal-rod in motion. This time taken can be selected at any given time as long as it is within the journey of ferrous metal-rod moving from right to left. This is because acceleration is constant throughout the time, but power is varied at different value as every millisecond passed. In this case, the time selection is 0.0001 s. So, the calculation of power is as shown below:

$$P_{out} = \frac{W}{\Delta t} \quad eq. (4)$$

$$P_{out} = \frac{32.58 Nm}{0.0001 s}$$

$$P_{out} = 325800 W \approx 325.8 kW$$

Thus, the power output produced when $\Delta t = 0.0001$ s is valued at 325.8 kW. When Δt increases, the value of power output decreases. Power is inversely proportional to time. As for other cases, all values relating to acceleration, force and work done have been inserted into Table 4.3 as shown in below.

Table 4.3: Value of acceleration, force and work done for every case

	Position of experimental testing (<i>mm</i>)					
	0.1	0.2	0.3	0.4	0.5	0.6
Acceleration (<i>m/s²</i>)	64514	256296	296590	329414	739334	1155320
Force (<i>N</i>)	3032.16	12045.91	13939.73	15482.46	34748.70	54300.04
Work Done (<i>Nm</i>)	0.303	2.409	4.182	6.193	17.374	32.580

When referring to Table 4.3, 0.6 mm case leads ahead from other cases for resulting the highest in acceleration, force and work done. Meanwhile, it is also an increasing trend as the position of experimental testing increased. Once this table has been completed, the power output can be computed with different Δt for every experimental testing. All those power outputs from all cases are compiled in Table 4.4. It is observed that the power would be reduced as the interval time, Δt increases and this impacts to all cases. This may indicate that as time passed, power losses are expected. So, if the position is further from the contact position, the amount of time is increased for ferrous metal-rod needed to move from right to left. Note that, each position of experimental testing has its own time to reach its destination which means the length of interval time will be depended on the position. In a way, it creates higher power initially but gradually reduced over time until the ferrous metal-rod has reached to contact position.

Table 4.4: Power output at different Δt for every case

Interval time, Δt (s)	Position of experimental testing (mm)					
	0.1	0.2	0.3	0.4	0.5	0.6
	Work Done, W (Nm)					
	0.303	2.409	4.182	6.193	17.374	32.580
	Power Output by the ferrous metal-rod, P (W)					
0.0001	3030	24090	41820	61930	173740	325800
0.0002	1515	12045	20910	30965	86870	162900
0.0003	1010	8030	13940	20643.33	57913.33	108600
0.0004	757.5	6022.5	10455	15482.5	43435	81450
0.0005	606	4818	8364	12386	34748	65160
0.0006	505	4015	6970	10321.67	28956.67	54300

As for power input, the formula relates to voltage and current supplied to the electromagnet for energizing its electromagnetic force. So, the formula of power input is computed as below:

$$P_{in} = I \times V \quad eq. (5)$$

$$P_{in} = 0.3 A \times 12 V$$

$$P_{in} = 3.6 V$$

So, an important highlight from this trend of results are that the conservation of energy analysis is applied to it. Note that the value of current and voltage have kept it constant for each experiment. This dynamic condition experiment is considered different from the static condition. It is because in static condition, when the distance becomes closer, higher force is projected as if the energy is not conserved. Despite that, there is no information to retrieve and analysed from this experiment. Besides that, the phenomenon in velocity graph may occurred due to nature of magnetic fields at close distance which no researchers have discovered this information yet as of now.

CHAPTER 5: CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The purpose of this project is to investigate the attraction force and speed of moveable ferrous metal in very close distance. Another investigation is relating to response characteristics towards ferrous metal-rod. Experimental study is carried out by recording the movement of prototype using high-speed camera. In terms on experimental results, it can be concluded that when the moveable ferrous metal-rod is subjected to dynamics loading of electromagnetic force at a very close distance, the line graph of position over time is best fit with a polynomial function of degree 2. Subsequently, further analysis by differentiating produces linear velocity graph and constant acceleration. In remarks to velocity graph, the initial speed for cases from 0.1 mm to 0.5 mm has a cumulative trend whereas the initial speed of 0.6 mm case has drop significantly. This phenomenon is caused by the duration for the development of electromagnetic force. If distance becomes closer, magnetic field has little time to develop the full force. Therefore, the response characteristics for reduction of initial velocity trend will occur when the position is beyond 0.5 mm. Another remark is force becomes constant since constant acceleration is produced by differentiation. Next, 0.6 mm has the highest result in acceleration, force, work done and power. As interval time increases, power output gradually reduces. In brief, the behaviour of dynamic case is constant whereas static case is linear.

5.2 Recommendations

Firstly, recommendation that can be improved on this project is to have an experiment that can determine the definite value of attraction force between electromagnet and a ferrous metal at a very close distance under static condition. The purpose of this experiment is to validate whether the value of attraction force has the similar pattern with the previous results in the past literature especially to Vokoun and Mushtaq's case study. Both authors have conducted their own research in 2011 and 2018 respectively. This finding will then be able to compare the behaviour of electromagnetic forces under static case against dynamics loading.

Besides that, another possible challenge is to measure the image point using frame-by frame analysis as it requires time to finalize the experimental results and further analysis. One of the many options that can overcome this issue is by using image processing toolbox under MATLAB application. This method alone can give a better image of the gap and with that, this may achieve a better accuracy for the measurement. Hence, these results will produce a better linear graph of distance over time and as for further analysis, the expectation result for graphs of velocity over time and acceleration over time with a better version are high.

Lastly, a simple simulation study using ADAMS software can be added into this project which can simulate similar phenomenon of the prototype. Then, a comparison between simulation study and experimental study would help to improve the critical analysis.

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