-

# A STUDY OF AUTO-REINFORCED MAGNETIC FLYWHEEL'S PERFORMANCE

by:

SYAFIQ BIN MOHD KHAIRAN

13496

Dissertation submitted in partial fulfilment of

the requirements for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

SEPTEMBER 2012

Universiti Teknologi PETRONAS

Bandar Seri Iskandar

31750 Tronoh

Perak Darul Ridzuan

## CERTIFICATION OF APPROVAL

# A STUDY OF AUTO-REINFORCED MAGNETIC FLYWHEEL'S PERFORMANCE

by

Syafiq Bin Mohd Khairan (13496)

A project dissertation submitted to the

Mechanical Engineering Program

Universiti Teknologi PETRONAS

in partial fulfilment of the requirement for the

Bachelor of Engineering (Hons)

(Mechanical Engineering)

Approved by,

________________________

(Dr Mokhtar bin Awang)

Date:

UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

SEPTEMBER 2012

# CERTIFICATION OF ORIGINALITY

This is to certify that I, Syafiq Bin Mohd Khairan (I/C No: 890825-14-6221), 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.

________________________________________

Syafiq Bin Mohd Khairan

Student ID : 13496

I/C No : 890825-14-6221

Date :

# ABSTRACT

Advance development of technologies such as composite material and active magnetic bearings enable flywheel, a kinetic energy storage a more viable energy storage solution compared to static energy storage such as battery and capacitors. Numerous researches made to increase the potential of flywheel such as the aforementioned material development. However, these research aims at increasing the operational limits of the flywheel itself. This research centres around a novel design of a flywheel which known as the Auto-reinforced magnetic flywheel (AMFLY). Designed by Radikal Akbar, AMFLY alter the basic operational principle solely by addition of a reinforcing flywheel to the flywheel energy storage system to boost the performance. This is made possible by the application of mecha-magnetic features to the system. The concept will be proven through several analysis and experimental testing of the AMFLY prototype and simultaneously determines the optimal configuration of the system.

## ACKNOWLEDGEMENT

Alhamdulillah, only with Allah's blessing, I am able to complete my Final year project. Here I would like to express my utmost gratitude and deepest appreciation to the individuals who had made this project a success.

First and foremost I would like to show my utmost appreciation to my supervisor, Dr Mokhtar bin Awang, for trusting me with this title in the first place. I put forward my appreciations for his advices, thorough guidance and endless encouragement throughout the project development.

Secondly, I would like to extent my deepest gratitude towards Mr. Radikal Akbar for the opportunity to work on this exceptional project and for the vast knowledge passed onto me. I would also like to thank him for the dedication of his time and effort, relentlessly teaching, guiding and entrusting me with multiple tasks covering a range of his project despite his many other obligations and responsibilities.

It has been a rewarding experience and an honour to work with these outstanding individuals.

Special thanks to Universiti Teknologi PETRONAS and staffs for providing excellent facilities and assistance to complete my project conveniently, mitigating most of my difficulty along the way. Also, my appreciation goes to family and friends for their undying supports.

**<u>CONTENTS</u>** **<u>PAGE</u>**

## List of Figures

## List of Tables

# 1.0 INTRODUCTION

## 1.1 BACKGROUND

The usage of flywheel concept had been adopted since the Neolithic period as a pottery wheel. Recorded by an American medieval, Lynn White, a German artisan, Theophilus Presbyter (1070-1125) used flywheel as a mechanical device in several of his machines [1]. However the true origin of flywheel is still disputable. Some scholar said that the Egyptian invented flywheel in the 15th century for shipbuilding. Modern flywheel on the other hand is developed mostly in 19th century prominently during the Industrial Revolution in Europe. One of the initial implementation of flywheel was for the first steam engine built by James Watt.

Over the century, flywheel technology had seen progressive development. The most popular application of modern flywheel is in reciprocating engine of automobiles. Due to irregular patterns of energy supply, flywheel is essential in providing continuity in energy supply to other components of the engine. Other application of flywheel is as energy storage device, popularly known as Flywheel Energy Storage System (FESS). Figure 1 shows a commonly used flywheel in a flywheel energy storage system. FESS widely finds application in power grids, space satellite, uninterruptible power supply (UPS) and also in industrial machinery. This is due to the fact that flywheel is one of the most efficient and possess high lifespan compared to other types of energy storage system such as LI-ION and CAES [2] as illustrated in Figure 2.

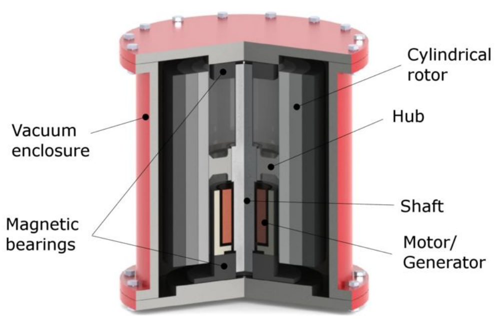



Figure 1: Example of a cylindrical flywheel

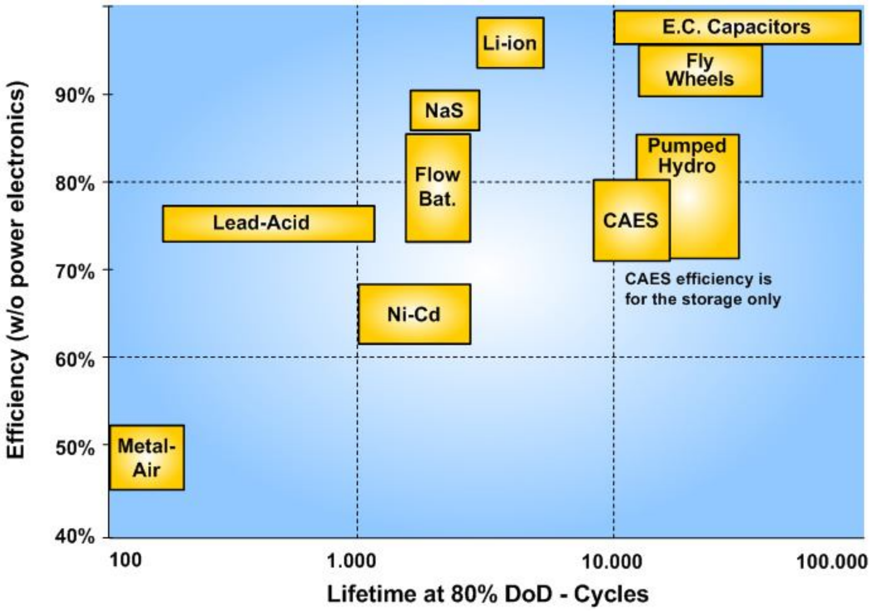



Figure 2 : Efficiency and lifetime of storage technologies [2]

The concept of flywheel mainly revolves around energy conversion and conforms to the principle of conversation of energy. Torque and moment of inertia are the important parameters involved in the operation of flywheel. Flywheel function is not only limited to energy storage. Flywheel is able enhance the performance energy transfer by smoothing the process by stabilizing the rotation caused by natural torque fluctuation [3]. In terms of energy storage, energy is stored in kinetic energy form or specifically rotational energy. This is done through accelerating the flywheel by application of torque. This part of process is also known as charging. Rotating of flywheel stores the energy. Subsequently, when load is applied and energy is channelled out, the flywheel will decelerate. Energy is released by applying torque to the load mechanically. This phase is referred to as discharging.

## 1.2 PROBLEM STATEMENT

Numerous researches were aimed at addressing drawbacks of flywheel technology however less focus on the effect of deceleration of flywheel. As aforementioned, deceleration occurs when the flywheel is subjected to a load during which discharging takes place. There are two possible consequences resulted by deceleration which are short discharge time and rate of deceleration. Short discharge time implicates that the flywheel has low performance as it represent the capacity of which energy can be stored within. High deceleration rate depicted in the velocity versus time graph through the steep gradient of line constitutes low area under the graph. Area under the graph represent low amount of displacement which is also the energy storage capacity. In this graph, load is applied at the point the line is descending where deceleration happens. Figure 3 shows the speed performance of a typical flywheel.

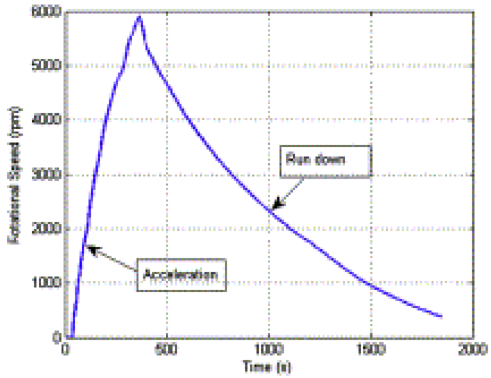



Figure 3 : Graph of Flywheel performance, velocity versus time. [4]

### 1.3 NOVEL DESIGN: AUTO-REINFORCED MAGNETIC FLYWHEEL (AMFLY)

Deceleration of flywheel during which load is applied affect the capacity of the energy storage. Therefore by decreasing the rate of deceleration and extending the discharge time, capacity of flywheel is increased thus the performance. One of the possible means to achieve this is by re-charging or "re-speed up" the flywheel at the point where deceleration begins or when load is applied. This concept is called auto-reinforced performance [4]. In order for a flywheel to achieve auto-reinforced performance, it must be equipped with a component which can provide a "kick back" of kinetic energy after load is applied to momentarily recharge the flywheel. The solution to this conundrum, which is also the essence and centre of this research, is permanent magnets [4]. This flywheel design adopts the concept of double flywheel where a smaller flywheel (primary) is fitted inside of a second bigger flywheel (secondary) centre hollow. Permanent magnets are mounted on both flywheels according to a structured orientation. Theoretically the movement/rotation of both flywheels will cause the magnet to react thus providing the kick back effect. This novel design (Figure 4) by Ahmad Radikal Akbar is named as Auto-Reinforced Magnetic Flywheel (AMFLY) [4].

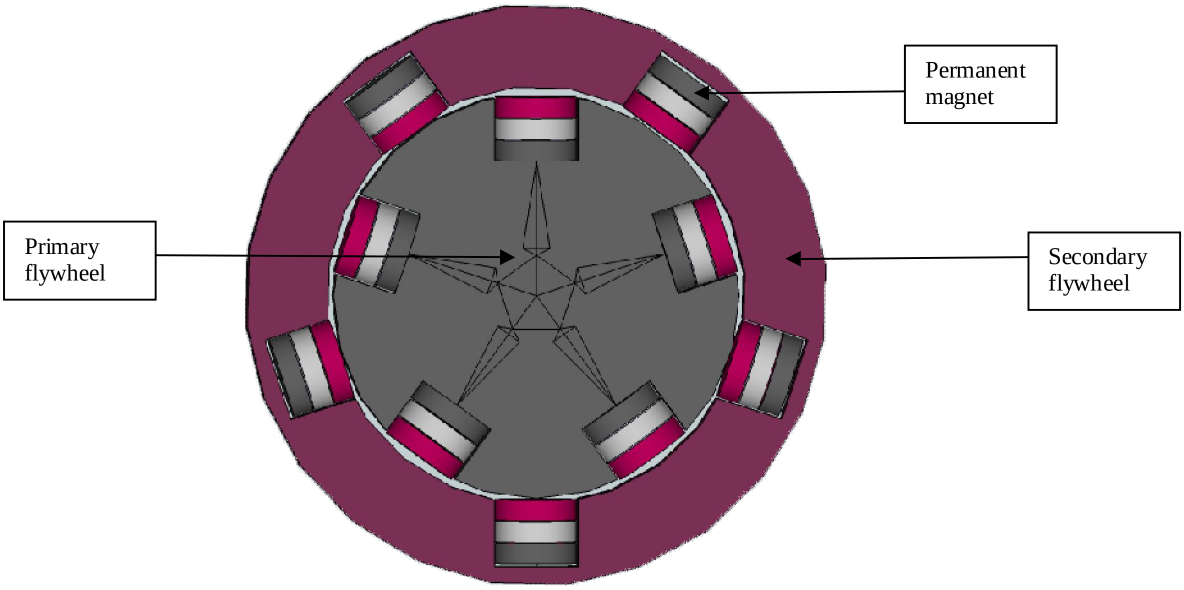



Figure 4 : The cross sectional view of the AMFLY design

The graph bellow illustrates the desired effect of the kickback to the AMFLY performance.

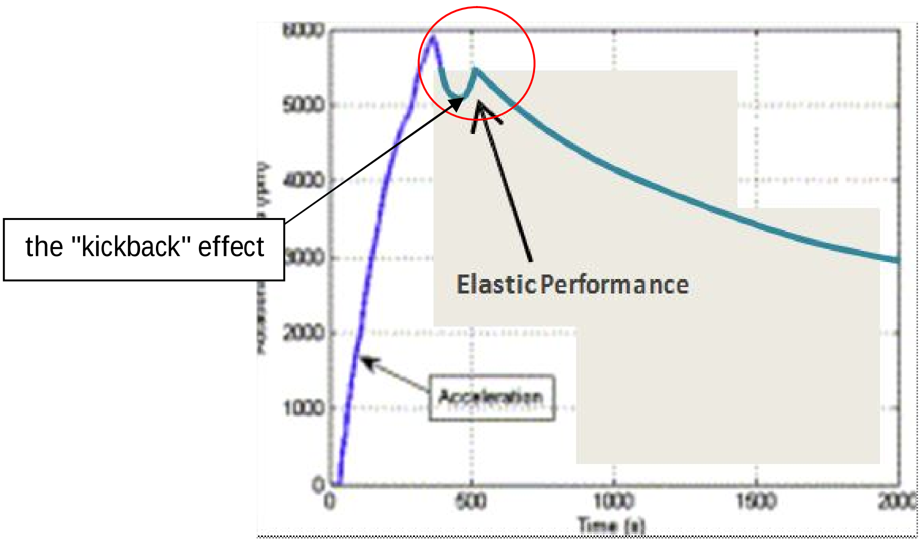



Figure 5 : Theoretical/desired velocity versus time performance graph of AMFLY [4]

Through Figure 5, the kickback effect can be clearly observed just after the line start to descend (in circle). Note that the area under the graph is larger than the previous graph (figure 3) of conventional flywheel as the gradient of the line during which deceleration occurs is less steep. This indicates that deceleration rate is slower and discharge time is longer. Bigger area under the graph signifies a bigger capacity of energy storage and better performance. Through the graphs, AMFLY evidently shows greater performance from the conventional flywheel.

## 1.4 OBJECTIVE

There two main aims of this research:

1. To conduct performance assessments and tests to prove the novel concept of Auto - Reinforced Magnetic Flywheel (AMFLY) experimentally.
2. To conduct a quantitative and qualitative study of comparison between the AMFLY and conventional flywheel performance.

## 1.5 SCOPE OF STUDY

The research covers several areas of studies which are:

I. **Mechanical energy performance of a flywheel**: It comprises of kinetic energy, inertial energy, energy density and torque during the operational rotating energy charging and discharging process. Mechanical properties such shape factor and tensile strength are rudimentary to flywheel performance.

II. **Magnetism**: the study of magnetic reaction of a magnetic source which are fairly popular in the field of energy as well as electrical. This research will assess the effect of magnetic force relative to various configuration of magnet orientation. Comparison between repulsive force and attractive force is essential in determination of the AMFLY performance

III. **Mecha-magnetism**: the study of mechanical behaviour induced by magnetism properties of a magnetic source. The reinforcement feature of the flywheel adopts the principle of mecha-magnetism which is scarcely researched on. This research is intended to further contribute to the understanding of this area of study.

# 2.0 LITERATURE REVIEW

## 2.1 FLYWHEEL PERFORMANCE

Since the Auto-reinforced Magnetic Flywheel (AMFLY) is a novel, the level of performance can be theorized based on the performance of conventional flywheel as the AMFLY adopt the same concept.

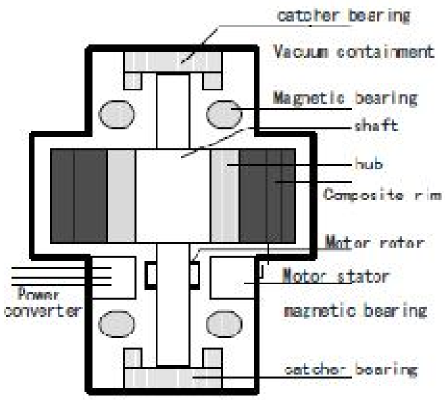



Figure 6: cross section of a typical flywheel [5]

A typical flywheel consist of the flywheel itself, a disk or rotor commonly made of steel which rotate around the shaft connected to motor or power converter. Magnetic bearings are usually used to ensure the fluidity of the rotation and also enable the flywheel to rotate at high speed up to 60000 RPM [6]. Figure 6 represent a configuration of a typical flywheel.

The performance of flywheel is mainly determined by three aspect which are material strength, cross-section geometry and rotation speed [7]. These are the rudimentary aspects which directly affect the torque and inertia which constitutes the performance of a flywheel. Kinetic energy stored in a flywheel equals to the squared value of its rotational velocity where:

$$E_k = \frac{1}{2} I \omega^2 \qquad (1)$$

$\omega$ = the angular velocity

$I$ = the moment of inertia of the mass about the center of rotation.

Moment of inertia is essential as it is relative to mass. The moment of inertia is the reaction force of torque produced by rotating object. Therefore higher moment of inertia will result in slower rotational speed. The moment of inertia of a cylinder is governed by this equation:

$$I = \frac{1}{2}mr^2$$

m= mass (kg) r = radius (m) (2)

From the equation, it is clear that mass affects the performance of flywheel. Light weight flywheel will produce smaller moment of inertia which will result in higher rotational speed of flywheel. Light weight and low density material such as carbon-fibre and graphite are usually used for advanced high energy flywheel [2]

Material properties such as maximum tensile strength and shape factor influenced the maximum stored energy of flywheel through the following expression [8]:

$$E_{sp} = k_s \frac{\sigma_m}{\rho} \tag{3}$$

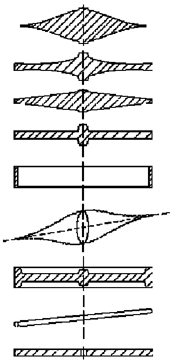
$E_{sp}$ = Maximum specific energy density $\sigma_m$ = maximum tensile strength

$k_s$ = Shape factor $\rho$ = density

Geometrically, the shape or cross section is one of the factors relative to flywheel performance. Different types of cross section are represented by different shape factor which affect the maximum energy stored in flywheel. The shape factor is relative to planar stresses and described in the table below [8]:

Table 1: Shape Factor and types of cross section [8]

| Fly wheel geometry | Cross section | Shape factor K |
|---|---|---|
| Disc | | 1.000 |
| Modified constant stress disc | | 0.931 |
| Conical disc | | 0.806 |
| Flat unpierced disc | | 0.606 |
| Thin firm | | 0.500 |
| Shaped bar | | 0.500 |
| Rim with web | | 0.400 |
| Single bar | | 0.333 |
| Flat pierced bar | | 0.305 |



The value of K ranges from around 0.3 to approximately below 1. The higher the value of K (near to 1) indicates the better performance [8]. However it impossible for a cross section to possess a shape factor of 1 except for the theoretical constant-stress disc geometry [9]. Further analysis such as Finite Element analysis had confirms K properties shown in Table 1 [8].

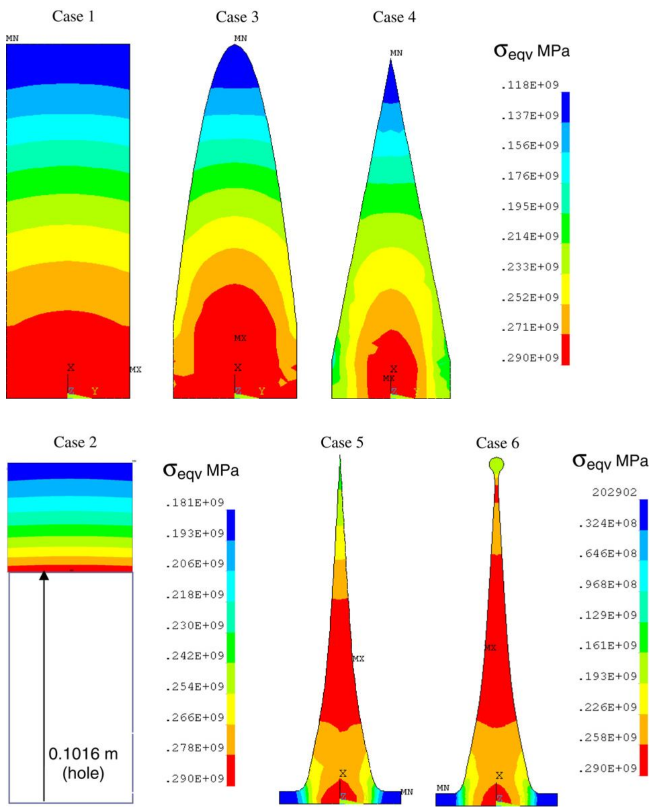



Figure 7 : Equivalent stress distribution for 6 different geometries of flywheel [8].

Table 2 : Comparison of FEA results on 6 different geometries of flywheel [8].

| | Case 1 | Case 2 | Case 3 | Case 4 | Case 5 | Case 6 |
|---|---|---|---|---|---|---|
| Max. rotational speed (rpm) | 19325 | 13140 | 23860 | 27220 | 31560 | 29900 |
| Mass (kg) | 26.798 | 13.8296 | 16.0264 | 10.035 | 3.2926 | 3.5202 |
| Kinetic energy (J) | 582,180 | 207,922 | 403,198 | 256,115 | 103,772 | 113,758 |
| Max. $\sigma_{eqv} = \sigma_Y$ (MPa) | 290 | 290 | 290 | 290 | 290 | 290 |
| $E_k$/mass (kJ/kg) | **21.7248** | **15.03** | **25.1584** | **25.521** | **31.517** | **32.316** |
| $E_k$/mass (W-h/kg) | **6.038** | **4.175** | **6.988** | **7.089** | **8.755** | **8.977** |
| Best performance rank | 5 | 6 (worst) | 4 | 3 | 2 | 1 (best) |

Figure 7 and Table 2 indicates higher strength enable flywheel to perform at a higher level. In short, mechanical performance of a flywheel can be represented by a performance triangle (Figure 8).

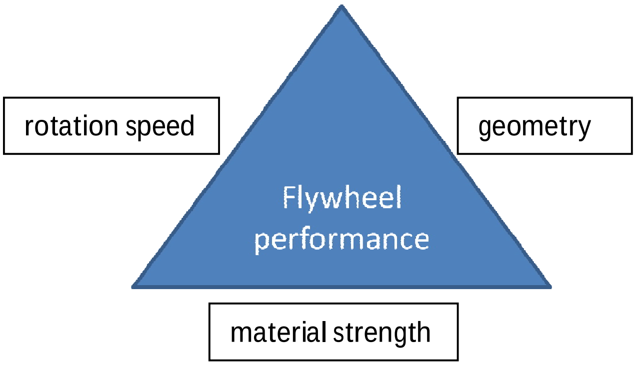



Figure 8: Flywheel performance triangle

Analogous to fire triangle, performance triangle indicate that the three component are equally crucial in constitution of a flywheel performance.

## 2.2 MECHA-MAGNETISM

Auto-Reinforced Performance is the novel concept which set AMFLY apart from conventional flywheel. Auto-Reinforced Performance is a result of mounting permanent magnets in certain configurations on two parallel flywheels. The fundamental nature behind the reactions of these permanent magnets is plainly the attraction force of permanent magnets themselves. After the charging process, the primary flywheel will rotate and due to the mounted permanent magnet, the secondary magnet will subsequently rotate and eventually match the speed of the primary flywheel. The mounted permanent magnets on the secondary flywheel were attracted to the permanent magnets on the already rotating primary flywheel thus inducing the secondary flywheel to also rotate.

Permanent magnets are chosen to act as the main magnetic field source over electromagnetic application due to cost, reliability and ease of operation [4]. Electromagnet might have better depth of field and able to carry more loads than permanents magnets, however it need a source of electricity to be activated and furthermore the short range between both flywheel in AMFLY system deem it unnecessary.

Thus in order to achieve best performance, the choice of permanent magnets in the design is important. There are three common type of permanent magnets which are relevant to its application on AMFLY:

1. Neodymium

   Made of the rare earth element magnet alloy; the neodymium. The neodymium magnet is the strongest permanent magnet which can be physically harmful. It has large amount of potential energy.
2. Ferrite

   Also known as ceramic magnet, it is made of sintered composite of iron oxide with barium or strontium. It has a relatively low magnetic strength and possess a plastic like physical properties
3. Samarium Cobalt

   A type of rare earth magnet which is made of samarium-cobalt alloy. It is the second strongest permanent magnet, not as strong as neodymium magnet. However it possesses higher coercivity and temperature rating.

In this research, only Neodymium magnet and ferrite would be used. It is to compare the performance induced by both type of magnets and the feasibility of their usage. Furthermore, they are commercially and widely available rather than the other.

These are some of the permanent magnets properties to be focused on in determining the best choice [4]:

- **Magnetomotive Force (Ampere)**

  Analogous to electromotive force, it is the key of mecha-magnetism where it is the force responsible to physical force of a magnet, produces magnetic flux and increase magnetic field.
- **Field Flux (Weber)**

  It is the quantity of magnetism where flux denotes the strength of magnetic interaction with other material
- **Field Intensity**

  It is the amount of field force of electromagnets. It is also referred as Magnetizing Force
- **Flux Density**

  Commonly known as magnetic field, it is the quantity of magnetic flux per unit area
- **Reluctance**

  It is the resistance in magnetic field flux through a specific volume. It is analogous to electrical resistance
- **Permeability**

  It is the measure of magnetic flux acceptance. Closely to electrical permittivity, it is a measure of "magnetic conductivity". Material with high permeability such as ferromagnetic metals reacted easily with magnetic flux as opposed to low permeability material such as wood and air.
- **Magnetic Energy**

  it is the potential energy stored in a permanent magnet

Table 3 shows the properties of magnets; symbols used, unit of the properties and etc.

Table 3 : Magnetic properties and units

| UNIT | SYMBOL | CGS SYSTEM | SI SYSTEM | ENGLISH SYSTEM |
|---|---|---|---|---|
| Flux | ø | maxwell | weber (Wb) | maxwell |
| Flux Density | B | gauss (G) | Tesla (T) | lines/in² |
| Magnetizing force | H | Oersted (Oe) | ampere turns/m (At/m) | ampere turns/in (At/in) |
| Magnetomotive Force | F | gilbert (Gb) | ampere turn (At) | ampere turn (At) |
| Permeability in air | $\mu_o$ | 1 | 4 pi x $10^{-7}$ | 3.192 |
| susesptibilitas | $\chi$ | dimensionless | | |
| Permeance | Λ | | webers per ampere-turn | |
| Reluctance | R | | Ampere turn/Wb | |

| CGS KE SI | | | SI KE CGS | | |
|---|---|---|---|---|---|
| 1 Oe | = | 7.962 x 10 A/m | 1 A/m | = | 1.256 x $10^{-2}$Oe |
| 1 G | = | 1 x $10^{-4}$ T | 1 T | = | 1 x $10^{4}$G |
| 1 Gb | = | 0.796 At | 1 At | = | 1 .265 Gb |
| 1 maxwell | = | 1 x $10^{-8}$ Wb | 1 Wb | = | 1 x $10^{8}$ maxwell |
| 1 G Oe | = | 7.962 x $10^{-3}$ J/m³ | 1 J/m³ | = | 1.256 x $10^{2}$ G Oe |

AMFLY adaptation of magnetism involved the interaction between to magnet. Interaction of two permanent are only in two orientations, it is either attractive or repulsive. According to previous research by Akbar [10], the magnetic energy density increase during attractive interaction and decline during repulsive interaction. Theoretically, this is due to vector characteristic of flux, where two opposing vector of flux will cancel each other magnitude and vice versa. However in AMFLY application, a definite justification on this characteristic is still undetermined due to the difference in of operation mode between AMFLY and Flux Collider machine which are used to experiment this effect [10].

In this research, magnetic properties affect the behaviour of AMFLY. The most important magnetic values to obtain the magnitude of magnetic energy are flux density, B and magnetizing force, H. Magnetic energy is a function of B and H and they are directly proportional. The magnet maximum energy product is described in the following equation which can be derived through experimental data [9]:

$$(BH)_{max} = \frac{B_r^{\,2}}{4\mu_{rec}} \qquad (gauss \bullet oersted) \tag{4}$$

$B_r^2$ = Residual Flux Density

$\mu$ rec = Recoil permeability

The magnetic force of two nearby cylindrical magnets (which is similar to the mounted magnets on the AMFLY system) [9]

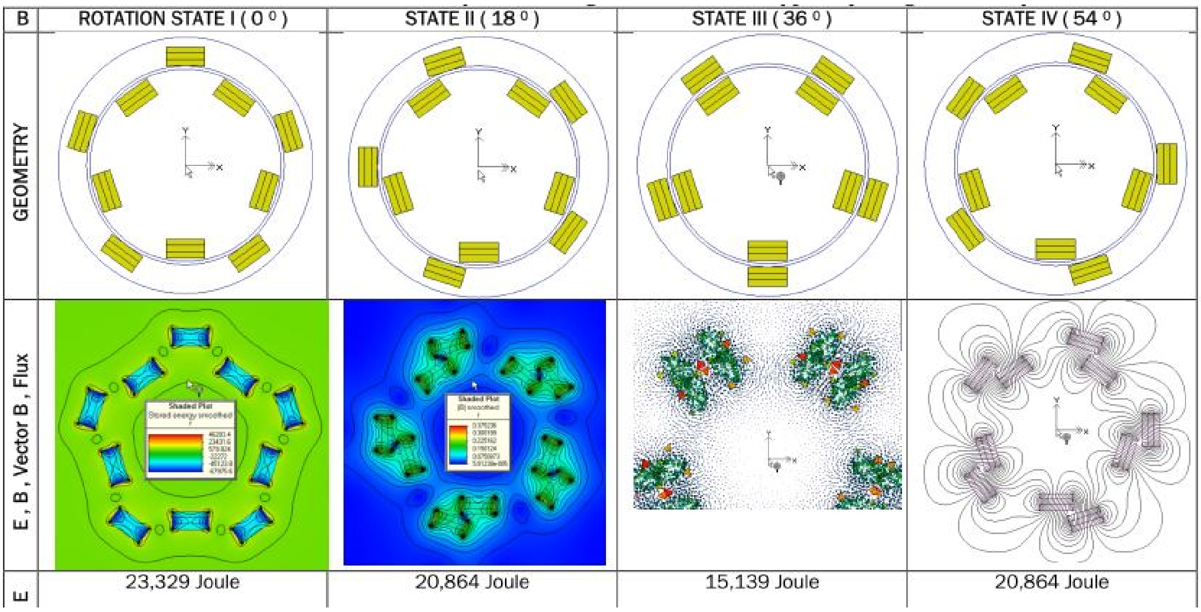
$$F = \left[\frac{B_0^2 A^2 \left(L^2 + R^2\right)}{\pi \mu_0 L^2}\right] \left[\frac{1}{x^2} + \frac{1}{(x+2L)^2} - \frac{2}{(x+L)^2}\right] \tag{5}$$

$\mathbf{B_0}$ = magnetic flux density very close to each pole, in T,
**A** = area of each pole, in m2,
**L** = length of each magnet, in m,
**R** = radius of each magnet, in m, and
**x** = separation between the two magnets, in m.
$\boldsymbol{\mu_0}$ = permeability of space, which equals 4π×10−7 T•m/A

## 2.3 SIMULATION STUDIES

The Auto-reinforced magnetic flywheel utilizes a principle which is unprecedented to the technology of flywheel which is magnetism. Magnetism act as a connection or binder between two flywheels and exploited its contactless and unique energy generation to yield momentum to gain extra performance. Therefore it is obvious that magnetism is the key to the mechanism of AMFLY. Several simulations had been made by Akbar to overview the behavior of permanent magnets on the AMFLY during the operation of AMFLY.

Table 4: simulation of AMFLY by Magnetic Infolytica [4]




This simulation shown in Table 4 is done using Magnet Infolytica software and utilizes the finite element magnetic method. The simulation is not in dynamic basis but only static through positional placement between magnets. As seen in the table above, there are four position simulated statically to see the effect of flux **φ**, the vector of it and the flux density **B**, and stored energy **E** of permanent magnets on respective positions. In the first row is the positions simulated, the second row is the visualization of each parameters stated; (from left: stored energy, flux density, flux vector and Flux) and the third row is the energy accumulated in the positions established in the first row. This configuration is in repulsion position where the same poles face each other. Repulsion is chosen for this project as it gives more momentum than in attractive configuration

Through row number 2, reaction between magnets is shown to be continuous at all positions thus proving the magnetic auto-reinforced mechanism is plausible. Shown in row 2 column 1, stored magnetic energy engulfed the whole permanent magnets configuration mounted indicating reactions. Therefore movement is expected in the system.

As shown through the table, highest energy is accumulated at position 1, where the greatest torque will be generated. This shows that energy from magnet is greater when the two magnets are far from each other after reaction with each other.

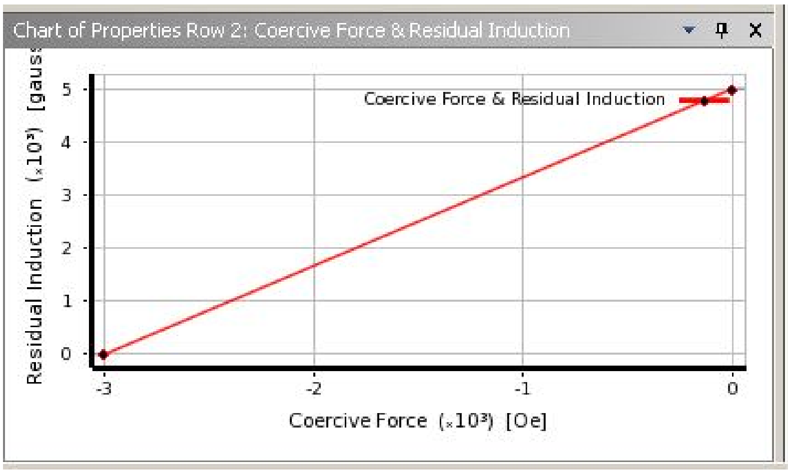



Figure 9 : ANSYS Magnetostatic simulation

When magnets react to each other whether it is repulsive or attractive, there will be residual induction in the body of the magnet in forms of flux. Magnetic force is larger when the presence of residual induction in a body is smaller as shown in Figure 9 above. This explains that distance (post reaction resultant distance) will reduce the residual induction in the body of the magnets which are shown in the previous Magnet Infolytica simulation. Subsequently it will enable it to generate more energy when they are closer again.

This simulation confirms that the repulsive mode is the better configuration to be used in the following model as repulsion will give more momentum and subsequently torque. On the other hand, attractive configuration will result to distance between magnets to be smaller at all time due to attractive force of both magnet.

## 3.0 METHODOLOGY

### 3.1 CONCEPT METHODOLOGY

The Auto-Reinforced Magnetic Flywheel (AMFLY) consists of two flywheels which movement are independent of each other. As stated before, the interior flywheel is called primary flywheel while the exterior flywheel is the secondary flywheel. Both primary and secondary flywheels have distinct role in the operation AMFLY. The primary flywheel acts as the core where energy is stored while the secondary flywheel provides support as a reinforcing flywheel as well as the power enhancer [4]. In AMFLY, besides the outlined performance factors; strength of material, geometry and size, the numbers and the orientation of mounted permanent magnets are essential in determining its performance. Figure 10 illustrate the future possible prototype to test the performance of the system.

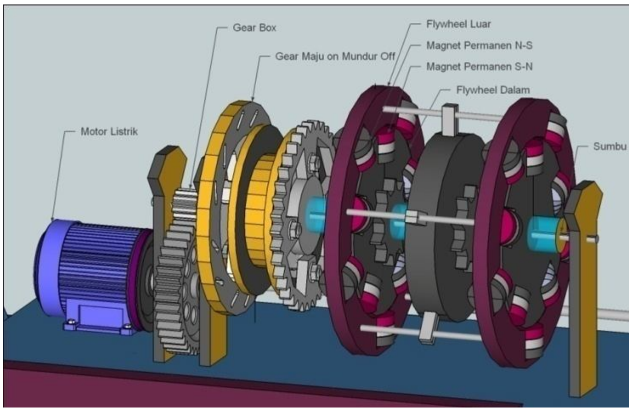



Figure 10 : 3D view AMFLY [4]

The operation of AMFLY started as the primary and secondary flywheel are charged, where torque are supplied to the system. The flywheels will accelerate to a maximum velocity and remain constant for a period of time indicating energy being transferred. In conventional flywheel the amount of energy saved can be determined by the value of flywheels total mass m (kg), diameter d (m), and the rotation velocity ω (rad/s). When load is applied, energy stored will then be transmitted to the load causing the primary flywheel to decelerate. At this stage, the secondary flywheel will provide a momentary boost in acceleration to the primary flywheel which was previously mentioned as the "kickback" effect. The amount of acceleration and energy increased are governed by multiple factors relative to the properties of the mounted permanent magnets. They are the type/strength, size and mounting position of the permanent magnets.

## 3.2 PROJECT ACTIVITIES

This research is based on the research done by Ahmad Akbar Radikal entitled "The Novel Design of Flywheel Using Permanent Magnet Energy" [4] and act as a parallel research simultaneously. Figure11 below basically explains the flow of this research:

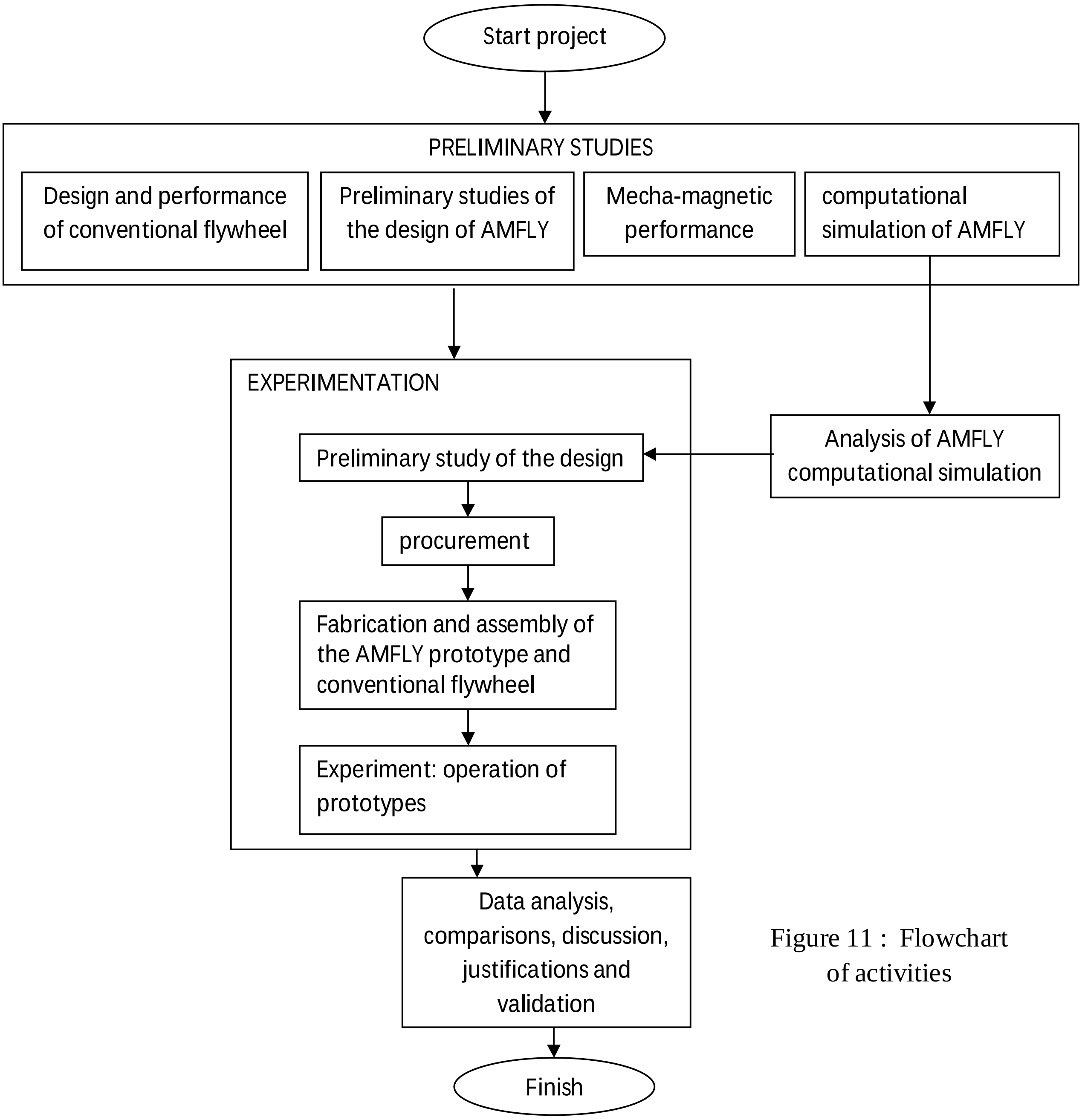



Figure 11 : Flowchart of activities

In order to achieve the outlined objectives, an experimental approach is selected to yield the best result. The experiment involves the operation of the AMFLY. Throughout the operation, several parameter will be measured and noted . Subsequently, an analytical study will be carried out on the performance of the AMFLY and the conventional flywheel based on the data obtained.

**KEY MILESTONE**

Table 5: Project Key Milestone

| Date | Expected Result | Progress |
|---|---|---|
| 31 July 2012 | - Research on conventional flywheel and AMFLY design conducted.<br>- Drawings and models of AMFLY analyzed<br>- AMFLY Prototype fabrication planned.<br>- Work on specification and dimension of prototype begun. | 10 % |
| 31 August 2012 | - Specification and dimension is determined.<br>- Simulation study complete | 30 % |
| 30 September 2012 | - All materials are procured and obtained. | 50 % |
| 31 October 2012 | - Fabrication of AMFLY prototype completed.<br>- Experiment completed.<br>- The prototype is optimized with the best configuration of permanent magnet.<br>- Experimental data assessed and interpreted.<br>-The experiment result is validated by other similar experiment through comparison. | 70 % |
| 30 November 2012 | - Discussion and analysis made based on data interpretation<br>- Comparison between AMFLY and conventional flywheel analyzed. Final justifications made. | 80 % |
| 15 December 2012 | - The AMFLY concept is proven and validated.<br>- Conclusion and summary of project substantiated. | 100 % |

**GANTT CHART**

Table 6 : Project Gantt Chart

| Month / Activities | JUN 6 | JULY 7 | AUG 8 | SEP 9 | OCT 10 | NOV 11 | DEC 12 |
|---|---|---|---|---|---|---|---|
| Flywheel and AMFLY Research | ■ | ■ | ■ | | | | |
| Simulation studies | | | ■ | ■ | | | |
| Fabrication planning & Procurement | | | ■ | ■ | | | |
| Fabrication | | | | ■ | ■ | | |
| Experiment & Testing | | | | | ■ | | |
| Evaluation and data interpretation | | | | | ■ | | |
| Data analysis and comparison | | | | | ■ | | |
| Discussion and justifications | | | | | | ■ | |
| Documentation | ■ | ■ | ■ | ■ | ■ | ■ | ■ |

## 3.3 EXPERIMENTAL MODEL DESIGN DEVELOPMENT

As one of the utmost significant objective, this project is intended to prove that the concept works and subsequently to prove that it perform better than conventional flywheel. Therefore after receiving positive overview given by the simulations done, a physical prototype is necessary to further fortify the foundation made by the simulations: it is plausible. Hence, this calls for a proof of concept prototype. In order to design the prototype, a thorough study is made on conceptual designs made by Akbar himself as it projects the vision of the concept itself. The main objective and target of the proof of concept prototype is to proof the very fundamental mechanism of the auto-reinforced magnetic flywheel (AMFLY) which is mecha-magnetic in nature. The design of the prototype is made based on the available materials and limited budget in order to save for future prototypes. It is also made with minimum number of parts to keep it as simple as possible and more focused on the flywheels mechanism. The prototype must consist of three parts: the motor, flywheels and loading mechanism.

### PERMANENT MAGNETS POLES ORIENTATIONS

Another rudimentary factor affecting the performance of the systems is the orientation of the permanent magnets. When the poles of the magnets are aligned in an orientation where the same poles (i.e. North-North, South-South) are facing each other, there will be a repulsive force in the interaction between the permanent magnets of both flywheel. In the other hand, different poles which interact will induce attraction force between magnets. The effects of these two configurations are different.

In attractive mode, when the primary flywheel rotates, the secondary flywheel will rotates in the same direction with the primary flywheel due to the attraction force between the permanent magnets mounted on both flywheels. The secondary flywheel magnets will try to reduce their distance to the permanent magnets in the primary flywheel. When the primary flywheel is starting to decelerate, using the attraction between magnets, the primary flywheel speed will rise slightly to catch-up with the rotational speed of the secondary flywheel which is now higher than of the primary flywheel due to inertia. This creates the auto-reinforced magnetic effect.

In the repulsive mode, where the same poles of the mounted permanent magnets are facing each other, the flywheel will push each other away and they will rotate in a different direction.. This phenomenon gives this configuration an advantage where momentum is created at the moment the magnets repulse each other. Flywheel mode of operation is fundamentally based on inertia which proves that momentum would be significant to the performance.

The magnetostatic simulations suggest that the presence of magnetic energy density in attractive mode is higher than of the repulsive mode [4]. However through the physical experiment, repulsive mode proves to be a better configuration as it yields greater momentum for the rotation of the flywheels when they interacts thus providing greater rotational speed. At this time of writing, the effect of the magnetic energy density to the performance of AMFLY is still under research by Akbar [4]. For the purpose of this research, repulsive mode is chosen to be used in the proof of concept model as it is physically proven to be superior backed by the aforementioned simulation which is relative to the residual induction in magnets. However these hypothesis is going to be tested in the experiment.

**PREVIOUS CONCEPTUAL MODELS.**

These are the designs made by Akbar during the conception phase:

<u>MODEL 1.</u>

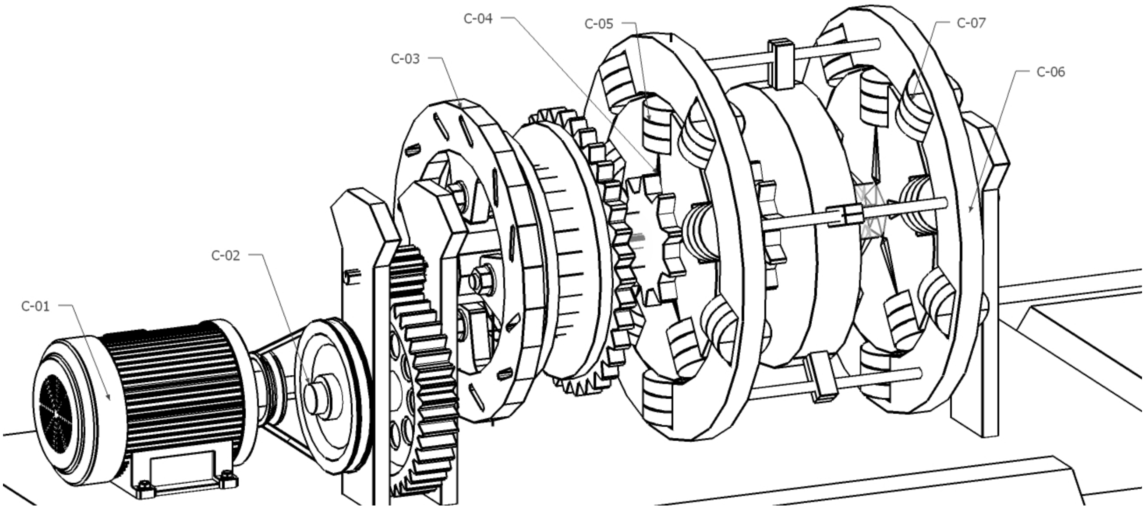



figure 12: the first model of AMFLY prototype

Model 1 is taken from the Akbar project proposal. The model consists of two set of flywheels. This model is made based on an automotive basis where common components such as the gears as seen in this prototype. This model is made as to illustrate one of the future applications of the AMFLY; in the engine. However the loading mechanism where loads are to be applied is not present. The flywheels as seen in figure 3 are simple disk shaped without any profile on the surface to ease procurement. The reason for simple disk shape is to ease the fabrication of permanent magnets on the flywheels. In the model the magnet are depicted to be cylindrical.

MODEL 2

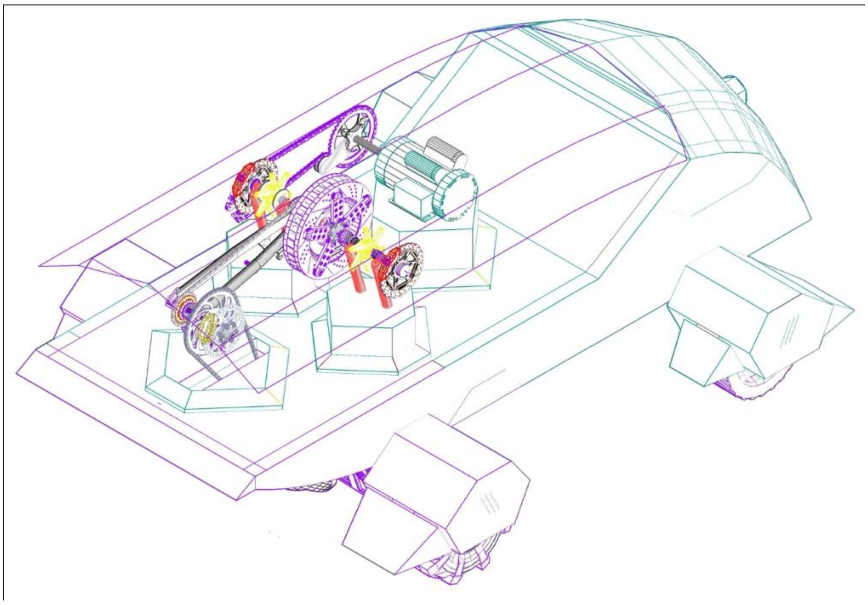


Figure 13: 2nd model of AMFLY prototype

The second model which is used as a reference in the process to design the proof of concept model is Akbar's initial model of his final prototype. The model is also made on an automotive nature as proved by the presence of the vehicle shaped chassis and wheel. In this prototype model, the mechanism is seen simpler than the initial model made. This model only consists of the main component as opposed to the first model. This model can be classified into 3 parts. They are the motor/generator, flywheel system and the loading system, where the conserved energy from the flywheel system will be used. The generator part consists of the motor which is then connected to part 2 which is the flywheel system by a gear and chain system. In part 2, the flywheels are mounted on two independent rod respectively. The chain from motor is connected to the rod which the primary flywheel is mounted. Parallel to the aforementioned rod, a second with the secondary flywheel is located. The loading mechanism is connected to the rod which the primary flywheel is mounted on. The loading mechanism in this model is the vehicle wheel. The movement of the wheel be the load exerted on the system. In this prototype, the rods are held by holders which are similar to the bicycle wheel holder. In fact the prototype is made with the idea of recycling unused bicycle part due to its availability and cost effectiveness

THE PROOF OF CONCEPT DESIGN 1

3D VIEW

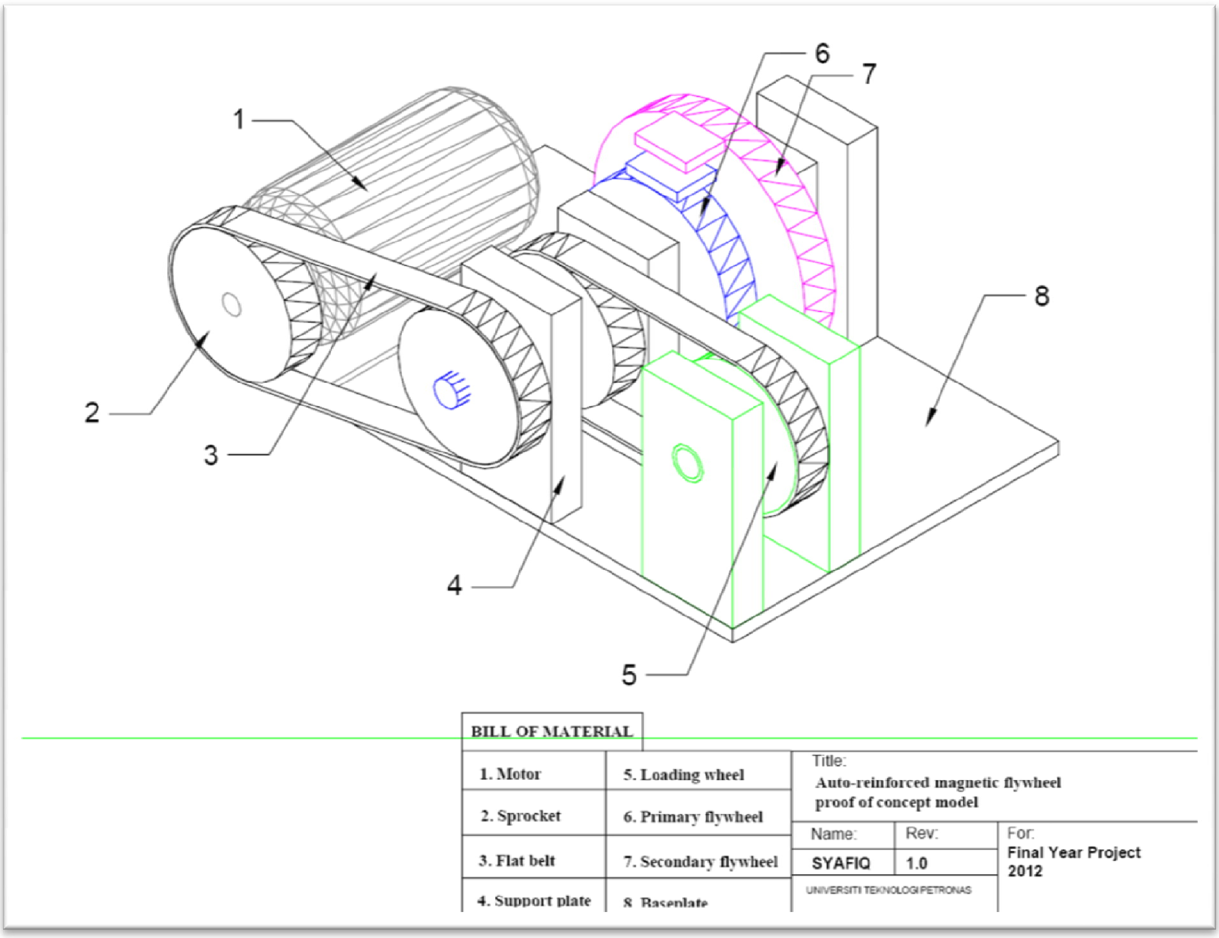



Figure 14: AMFLY proof of concept 1 technical drawing

**Drawing is attach in the appendix section*

SIDE VIEWS

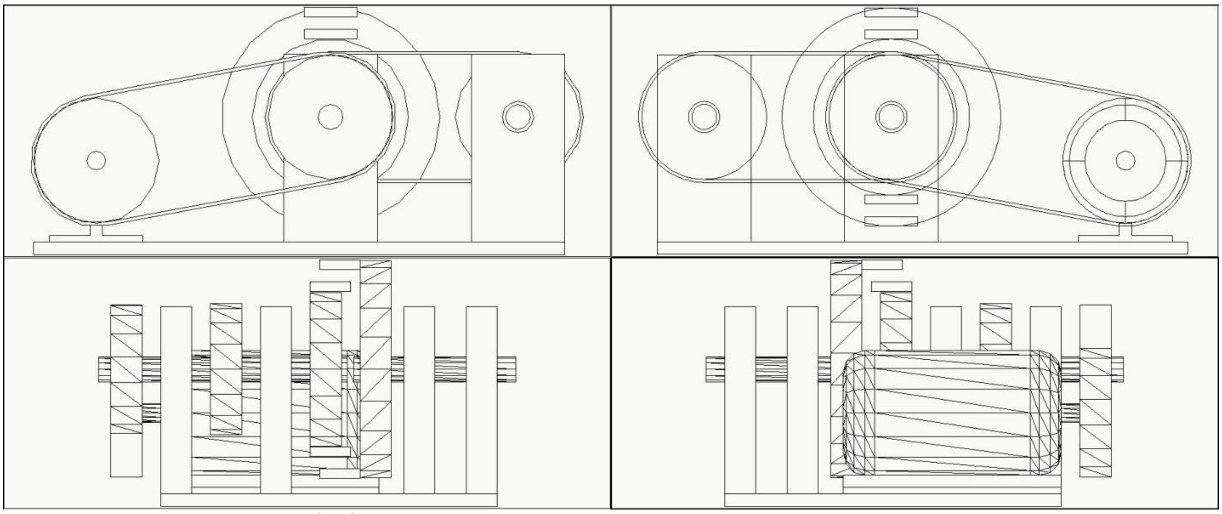


Figure 15: AMFLY proof of concept, side views

The proof of concept design is made based on Akbar second model (Figure 4). It consists of three parts which are also similar to the prototype: generator, flywheels and load mechanism. However due to the shortage of budget and availability of material this model is further simplified to be a laboratory experimental model. Instead of a full body chassis, all components are mechanically mounted on a metal plate.

Compared to initial model of AMFLY (Figure 13), both flywheels in this model are not in line of each other. As seen in Figure 16, there are two separate cylindrical flywheel, where the secondary flywheel is larger than the primary flywheel, both independently on separate shafts. The magnets however are mounted on each flywheel to be line in with each other to give the same effect presumed on the initial design of AMFLY flywheels.

The transmission between systems is changed to flat belt. The holder is made of thick metal plates with bearing installed in each plate. The main different with the prototype is the loading mechanism. The loading mechanism consists of a wheel which will then be connected to a torquemeter or newtonmeter through a rope. When the flywheel is rotating and the motor is shut down, the rope will be pulled manually and the load exerted on the flywheel as well as the torque generated are then indicated.

Another important part of the design is the material of the flywheel. The permanent magnets are to be mounted on the flywheels which cause a reaction between them. Therefore it is important the material of the flywheel is not ferritic or in other words, does not react with magnet. Convention flywheel uses steel which is affected by magnets and although metal such as aluminium is not affected, there is still a possibility of eddy current development on the surface of it which would be hazardous to the operation. Therefore, in order to keep the project within the budget, concrete prove to be the best alternative.

**DISCLAIMER:** DUE TO TECHNICAL DIFFICULTIES IN PROCUREMENT, LACK OF RESOURCES AND TIME, THE PROOF OF CONCEPT MODEL COULD NOT BE COMPLETED THUS THE EXPERIMENT INVOLVING THIS MODEL COULD NOT BE CARRIED OUT.

HOWEVER THIS REPORT WILL INCLUDE MOCK-ANALYSIS OF THE POSSIBLE RESULT IF THIS EXPERIMENT IS COMPLETED FOR FUTURE REFERENCES.

IN THE NEXT SECTION, THE EXPERIMENT IS CARRIED OUT WITH A DIFFERENT PROOF OF CONCEPT MODEL WHICHIS INTENDED TO PROVE THE CONCEPT AS WELL AS TO TEST ON DIFFERENT ASPECT OF AMFLY'S PERFORMANCE.

**PROOF OF CONCEPT MODEL 2**

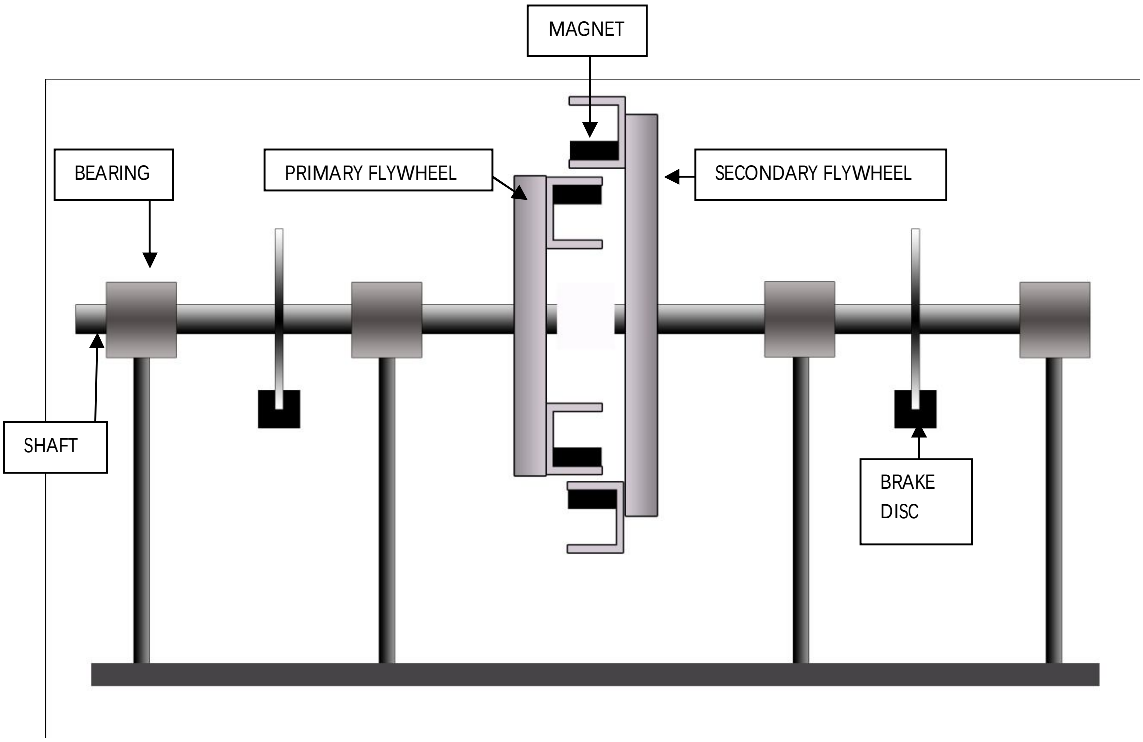



Figure 16: AMFLY proof of concept model 2 schematic diagram.

Due to some issues during procurements, lacks of resources and time, the prototype or proof of concept design is changed to aimed to only prove the auto-reinforcing ability of the magnets configurations. The weight of each flywheel is minimized obtain the minimum system mass for the auto-reinforced performance to work. The proof of concept model is made of two light wheels on an independent shaft respectively. Brake disks are equipped on each shaft and a rod is attached perpendicular to the shaft to add additional weight in future testing. Magnet holders which are mounted on each flywheel are adjustable to adjust the distance between two magnets on different flywheels. This is essential as the distance determine the strength of magnets attraction. Figure 17 shows the picture of the completed proof of concept model of AMFLY and Figure 18 indicate the magnets which are mounted on the flywheels.

Figure 17: Proof of concept model 2 of AMFLY     Figure 18: Mounted permanents Magnets

Attractive configuration is used as repulsive configuration does not gives enough force for the system. However, this does not write off repulsive configuration potential as the problem lies in the prototype itself as it does not have enough mass to gain more torque and inertia.

These are the specifications/configurations of the AMFLY proof of concept model made:

1. Flywheel Mass:
    a. Primary Flywheel (including mounted magnets): 1 kg
    b. Secondary Flywheel (including mounted magnets) : 2kg
2. Flywheel material: Polypropylene (Bicycle wheel)
3. Flywheel diameter:
    a. Primary Flywheel : 30 cm
    b. Secondary Flywheel : 40 cm
4. Magnet strength: 100 mT (militesla)

5. Magnet type: Ferritic Magnets
6. Magnet dimensions: 1.5cm x 8.5cm x 6.5cm (t x l x w)

This prototype also is unable to prove the performance of the AMFLY to be compared with conventional flywheel performance. Therefore, this prototype will be used only to:

1) Prove the workability of AMFLY concept as a preliminary step for further research.

2) Identify minimum properties/requirements i.e.; minimum mass, radii, and magnets strength for an AMFLY to work as future reference or datum for future prototype.

## 3.4 EXPERIMENTAL PROCEDURES

**Part 1: Concept proving**

1) The AMFLY proof of concept model is connected to the motor which is connected to a regulator as shown in Figure 19.

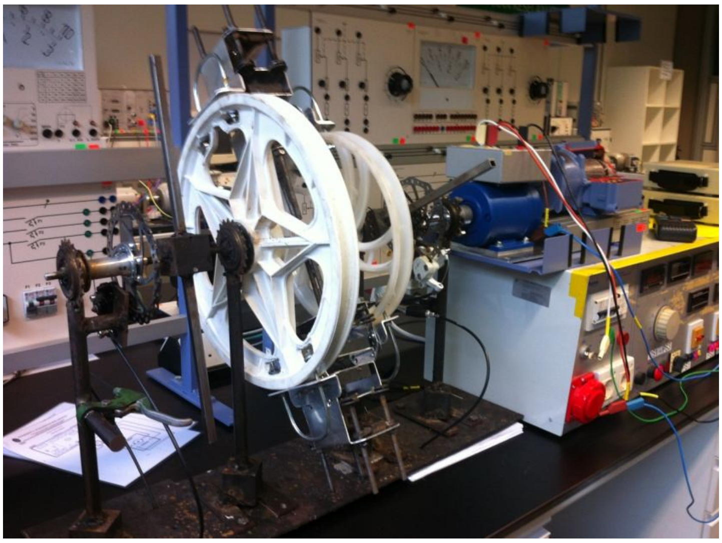


Figure 19: Experimental configuration for AMFLY proof of concept model 2.

2) The motor is switched on and using the regulator, the speed of the system is controlled

3) After reaching a certain speed, the motor is shut down and brake is applied. the subsequent reaction is observed and noted.

**Part 2: The identification of minimum operating configuration to achieve auto-reinforced performance.**

1) The AMFLY proof of concept model is connected to the motor which is connected to a regulator as shown in Figure 19.

2) The motor is switched on and using the regulator, the speed of the system is controlled

3) By using the tachometer (Figure 20), the rotational speed is noted and through regulator, the system rotational speed is to be maintained at 30 rpm.

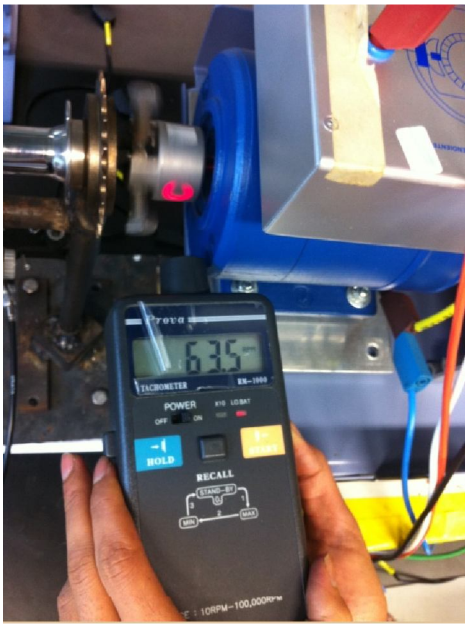



Figure 20: Rotational speed rating using tachometer.

4) After reaching the 30 rpm and maintaining for a period of time, the motor is shut down and brake on primary flywheel is applied as shown in Figure 21. Stop watch is started the moment the primary flywheel start to accelerate back.

Figure 21: Application of brake on AMFLY system

5) The stop watch is stopped the moment the system stop rotating. The time is noted.

6) Step 3 to step 5 is repeated for two more times and repeated for rotational speed of 40 rpm, 50 rpm, 60 rpm, 70 rpm, 80 rpm, 90 rpm, and 100 rpm.

7) Result is tabulated.

**Part 3: Magnets torque measurement**

1) A rope is tied to the primary flywheel.

2) The rope is connected to a mass of a known weight which is 5 kg which is placed on a weight scale.

3) The primary flywheel is manually rotated slowly by pulling the rope and the secondary flywheel is ensured to rotate together by the magnets attraction force as shown in Figure 22 below.

Figure 22: AMFLY proof of concept torque measurement procedures.

4) The decrement in weight reading of the mass just before the moment the attraction force dispersed is noted (when the secondary flywheel stop rotating together).

5) Test is repeated for another three times for confirmation

**4.0 RESULT.**

**Part 1: Concept proving**

Observation:

From the start, both flywheel is observed to move at a same speed. After the motor is shut down, the secondary flywheel still moves together with the primary flywheel at a relatively same speed. When the primary flywheel brake is applied, a drastic decrease in speed can be observed on the primary flywheel but the secondary flywheel drastically decelerate. Subsequently, the primary flywheel speeds up to follow the secondary flywheel speed which is now faster. The re-acceleration is not continuous however. Finally both flywheel stop after some time. The highest speed detected by tachometer here is over 120 rpm.

**Part 2: The identification of minimum operating configuration to achieve auto-reinforced performance.**

The time taken in this part of experiment is the time the secondary flywheel act as re-inforcer to the primary flywheel.

Table 7: Time of reinforcement to flywheel rotational speed

| Rotational Speed (rpm) | Time (s) | | | |
|---|---|---|---|---|
| | 1 | 2 | 3 | Average |
| 30 | 0 | 0 | 0 | 0 |
| 40 | 0 | 0 | 0 | 0 |
| 50 | 3.4 | 3.0 | 3.5 | 3.3 |
| 60 | 3.7 | 4.3 | 4.5 | 4.1 |
| 70 | 6.1 | 5.4 | 5.9 | 5.8 |
| 80 | 4.9 | 6.9 | 6.5 | 6.1 |
| 90 | 8.1 | 8.3 | 8.0 | 8.1 |
| 100 | 8.8 | 9.0 | 8.4 | 8.7 |

**Part 3: Magnets torque measurement**

The mass decrement obtained is 1.2 kg.

Therefore the force to which the magnetic attraction could sustained is 1.2kg x gravitational acceleration (9.81 $m/s^2$) which is 11.77N. The permanent has been rated to have a magnetic strength of 11 mili-Tesla each. Torque which is evaluated as T = Fr in this case is **2.05 N.m**.

## 4.0 DISCUSSION

### Part 1: Concept proving

From the observation, it is proven that the AMFLY concept is workable. The secondary flywheel had clearly induced movement in terms of acceleration to the primary flywheel as it is decelerating. However, as aforementioned, the reinforcement is not solid as the primary flywheel's rotation fluctuate during the reinforcement period. In some instances, the primary flywheel slow down and speed up again repeatedly.

However this is believed to be the apparatus inability rotate smoothly. The prototype is fabricated with recycled parts and most of the components are joined lightly through welding. Physically, parts clearly are not fabricated with precision as they were used in different machine previously. Furthermore, the model is not accounted for having sufficient mass. This has caused the system to vibrate violently during operation and it can be clearly observed when the rotational speed is low. Therefore the model is believed to be subjected to high magnitude of mechanical loss.

Another conclusion made is that the magnets is not strong enough to attract the other magnet in high speed which in short indicates that the magnetic strength is insufficient for a rotational speed as high as 120 rpm.

However, through the test run, the result is positive as the model is able to produce the auto-reinforced performance.

### Part 2: The identification of minimum operating configuration to achieve auto-reinforced performance.

From the table, the auto-reinforced performance is achieved when the rotational speed of the system is above 40 rpm. On 40 rpm and lower, the system rotate with great vibration and when the brake is applied, it nearly stop and the secondary flywheel is unable to reinforce the speed of the primary flywheel. This indicates that in order to achieve auto-reinforcement performance, there is a minimum speed to be surpassed. However, the true minimum speed is also dependant on the system mechanical loss which is believed to be high in this experiment. Less minimum loss would lower down the minimum speed to achieve the auto-reinforced performance.

When the rotational speed is above 40 rpm, the secondary flywheel successfully induce acceleration in primary flywheel while it is decelerating. And the higher the rotational speed, the longer the secondary flywheel could reinforce the speed of the primary flywheel. Therefore speed is directly proportional to time of reinforcement.

Through this experiment, a basic equation on the relation of speed and reinforcement time can be worked out. From the data obtain, a scatter plot is made and a linear trend line is drafted as shown Figure 23.

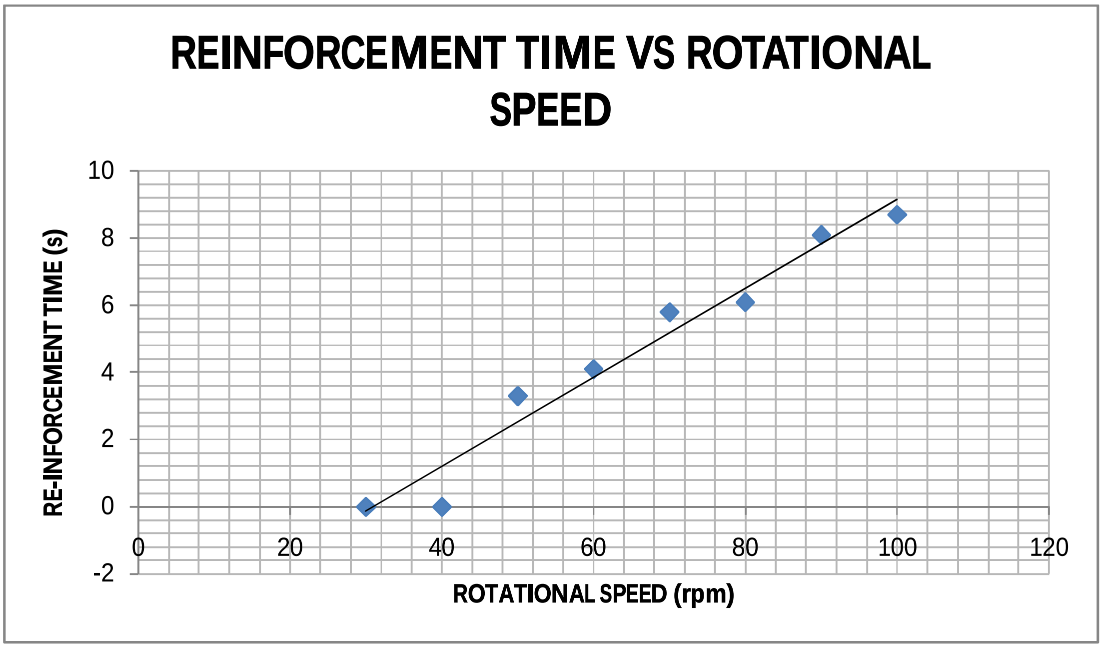



Figure 23: Reinforcement time against rotational speed.

From the trend line, the gradient is calculated and we obtained the gradient to be:

0.125

Since y = mx +c , the equation for this graph would be y = 0.125x - 3.7

This equation reflect the relationship between reinforcement time to rotational speed for this configuration (with this magnetic strength, flywheel size and mass). This could be useful in estimating reinforcement time and speed relation in other configuration. However further experiment must be made with the same model with different configurations to estimate the scaling factor.

As flywheel is an inertial device, mass plays an important role in a flywheel design. With more mass, the flywheel would be able to build up more momentum and able to store more energy. In the future, mass would be added to the system by attaching it on the steel rod on the shaft. Further testing will confirms the effect of mass on the reinforcement time which is believed to boost the performance.

**Part 3: Future Experiments**

This section outline the original plans for this project and explains to how the result can be obtained through the original design of the AMFLY proof of concept model (Figure 15, page 26)

The proof of concept model 1 (POCM1) is aimed to evaluate the performance of the AMFLY system and also the conventional flywheel system, where the later is done by mechanically locking the flywheels together. The rotational speed will be evaluated against time from the moment the motor is switched on. The expected data would be expected to form a trend such as shown in the Figure 24 and Figure 25 below:

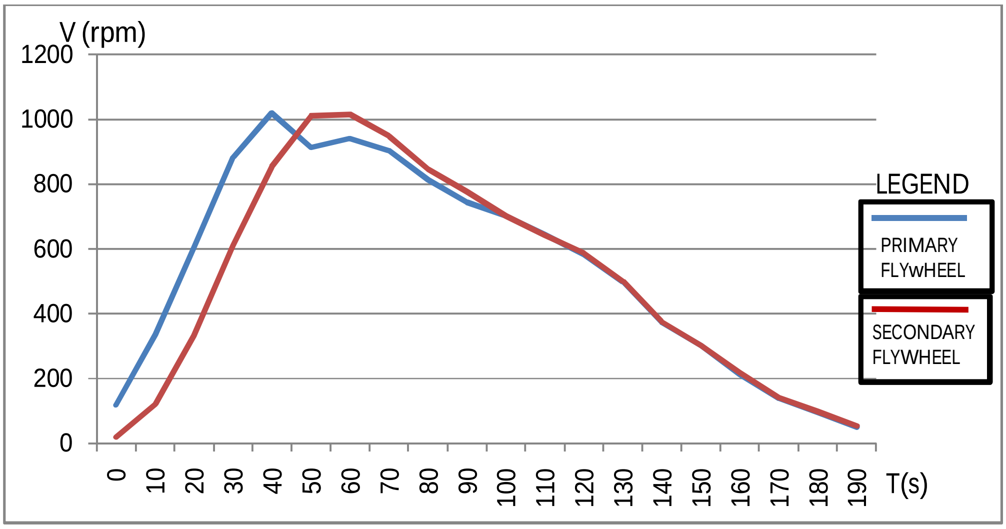



Figure 24: Velocity versus time graph of the AMFLY.

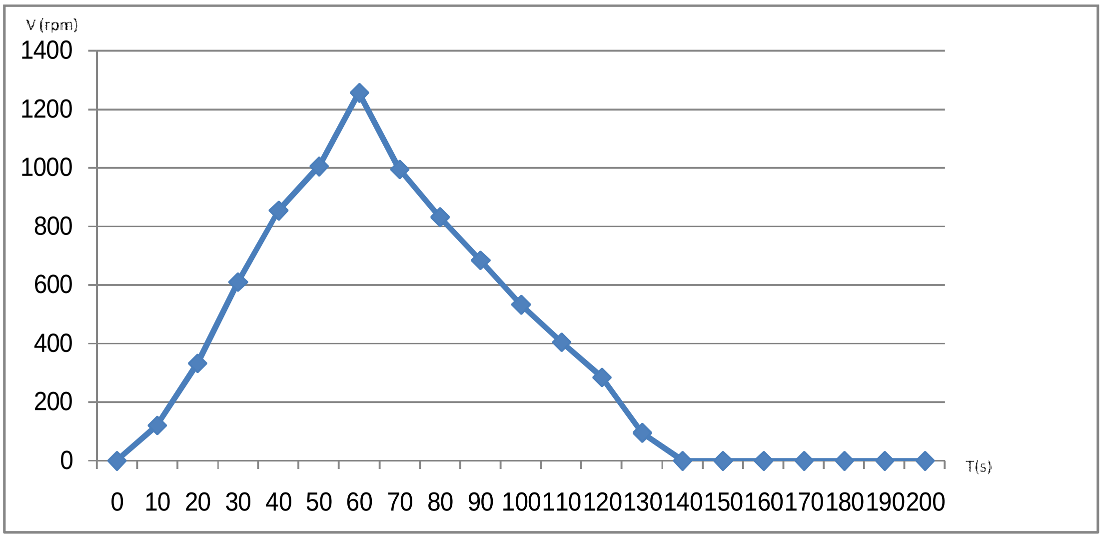



Figure 25: Velocity versus time graph for the conventional flywheel.

In the first graph, speed over time of both flywheels; primary and secondary through both charging and discharging stages are shown. The speed of primary flywheel is represented by the blue graph and the red line represents the secondary flywheel speed over a period of 200 seconds.

From the blue line (primary flywheel), from 50 to 70 seconds, after the decline in speed, there is a slight rise. Simultaneously, the secondary flywheel is at peak point. This is an indication of the coveted auto-reinforced magnetic performance.

On the other hand, in figure 18; the conventional flywheel graph of speed, the speed increase and decrease at the time load is applied. This trend is a normal trend to a flywheel. The top speed/peak point in this graph is lower than of the AMFLY graph.

Subsequently from the rotational speed data obtained, we can calculate the kinetic energy through equation:

$$E_k = \frac{1}{2} I \omega^2$$

The kinetic energy data is then tabulated and displayed in a graph which is expected to be similar to Figure 26:

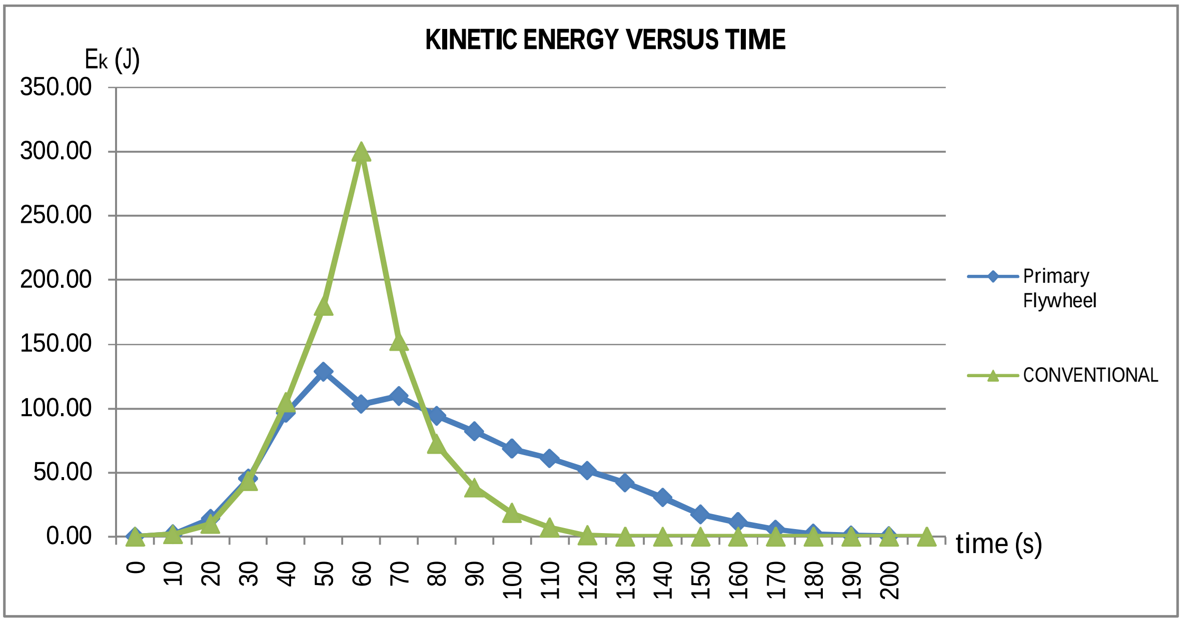



Figure 26: Kinetic energy versus time graph for the both system

Through graph in Figure 26, the performance's evaluation of this system depends on only the primary flywheel performance as it is the only one connected to the load. Since the number of revolution of flywheel reflect the capacity of the energy stored in a flywheel, the area under the graph constitutes the capacity of the flywheel. The area under the graph of the time versus Kinetic energy (Figure 26) is the energy capacity of the flywheel. The area under the graph will be evaluated through graphical method and compared. The area under the graph indicates the storage capacity of each system.

The auto-reinforced magnetic performance resemble the “spring effect” where elastic behaviour can be observed during which the speed of the primary flywheel increase again after it starts to drop. Similarly, a spring retracts or bounces back after pressure was released from it. In this scenario, the spring releases the energy which was given to it initially. Relatively, the secondary flywheel’s magnets release back energy which in turns accelerate the primary flywheel for an instant. This explains the behaviour of the magnetic energy during the permanent magnets’ interaction for that brief moment when the primary flywheel’s speed starts to rise again after dropping at the initial moment of discharging.

**Part 4: Experimental Errors**

As the proof of concept model is not fully optimized for performance yet, most components used are recycled from other used material such as bicycle wheel and measurement methods mostly involve are usually made manually. Therefore the experiments might be subjected to some errors along the process.

I. Human error: Error occur during the manual operation of the model and also through process of measurement taking such as recording the time and speed which are done fairly at a fast pace. Error might occur during procedures such as the torque measuring procedure which requires manual rotation of the flywheel and handling of tachometer.

II. Machine error: the model is not optimized for performance. Some parts might be worn out such as the bearing which might explain loss in the output speed. The two flywheels are manually aligned which might constitutes misalignment problem. The measurement apparatus might not be calibrated accordingly.

## 6.0 CONCLUSION

Magnetism had benefitted mankind through numerous area and most popular of all, energy generation. However this research set to look into the other side of its prowess, which is the mechanical capability. The Auto-reinforced Magnetic Flywheel's inception which is built on the very basis of mecha-magnetism itself, intends to harness the potential of the unpopular side of magnetism.

Throughout this project, it can be basically deduced that the Auto-reinforced Magnetic Flywheel (AMFLY) concept is a viable concept in expanding flywheel technology especially in energy storage capability. Magnetism interaction evidently increases the mechanical aptitude of a flywheel. This concept is firmly proved to be a stepping stone towards unlocking the existing limitation of flywheel technology especially in terms of capacity.

However, the objectives of the project are only partially achieved. The second objective initially established is still yet to be achieved. Comparison to a conventional flywheel is essential to further strengthen the practicability of this concept.

Development of the proof of concept model must be constructed in near future to further confirms the expected result predicted in the previous section. For the existing model, more optimization is needed to decrease the mechanical loss in order to obtain more credible result.

Though the research just prove the workability of the concept, as a promising technology to the advancement of energy storage system, there are still a lot of aspect need to be taken into consideration to ensure its practicability and a place in the future of modern technology. The original inventor of this concept, Radikal Akbar is currently working on optimizing the performance of the AMFLY to compete with current technology of flywheel such as double mass flywheel.

In the near future, more complex and optimized prototypes should progress to continue the pursuit of a breakthrough. Components such as magnetic bearings, vacuum container and dampener are needed to reduce mechanical loss in energy transmission.

In terms of material, the flywheel components must be made of a sturdier, heat resistant and non-ferritic material to operate in a more volatile condition or at a higher level of application. Dynamic magnetic simulations are needed to study the interaction of the permanent magnets further in order to improve the function of them as the connector between the flywheels more effectively. A more improved design might elevate the chances to achieve better performance such as triple magnetic flywheels system where another flywheel is added to increase the system reinforcement capacity. In terms of comparison study, it should broaden the list of contender such as the currently popular flywheel system dual mass flywheel in hopes to gain more credibility to the AMFLY concepts.

**7.0 REFERENCES**


1. Lynn White, Jr., *"Theophilus Redivivus"*, Technology and Culture, Vol. 5, No. 2. (Spring, 1964), Review, pp. 224–233 (233)
2. San Martín, J. I., Zamora, I., San Martín, J. J., Aperribay, V., Eguía, P., *Energy Storage Technologies for Electric Applications*, Department of Electrical Engineering - University of the Basque Country, 2011.
3. Gopinath, K., & Mayuram, M., *Machine Design II*, Indian Institute of Technology, Madras.
4. Akbar, A.R., *The Novel Design of Flywheel Using Permanent Magnet Energy Utilization*, Universiti Teknologi PETRONAS, 2012.
5. Meeker,N., Walker, B., *Flywheel Technology for Energy Storage*, RIT, February 2010.
6. Zhang, C., Tseng, K.J., Nguyen, T.D., Zhang, S., *Design and Loss Analysis of A High Speed Flywheel Energy Storage System Based on Axial Flux Flywheel-Rotor Electric Machines*, pp 886-891, 27-29 October 2010.
7. Arslan, M.A., *Flywheel geometry design for improved energy storage using finite element analysis*, Material and Design, Vol. 29, pp 514-518, January 2007
8. Bolund, B., Bernhoff, H., Leijon M., *Flywheel energy and power storage systems.* Renewable and Sustainable Energy Reviews, Vol. 11, pp 235–258, (2007)
9. Genta, G., *"Some considerations on the constant stress disc profile."*, Meccanica Vol. **24**, pp 235-248, 1989.
10. Akbar, A.R., *Energy Balance Assessment of Permanent Magnets and Formulation of Mecha- Magnetic Energy*. Surabaya: ITS. 2011.
11. Rodriguez, G.E., Studer, P.A., Baer, D.A., *Assessment of Flywheel Energy Storage for Spacecraft Power Systems*, NASA Technical Memorandum 85061, May 1983
12. Ahrens,M., Kucera,L., Larsonneur,R., Performance of a Magnetically Suspended Flywheel Energy Storage device, IEEE Transaction on Control Sytems Technology, Vol 4, No.5, September 1996.
13. Bitterly,J.G., *Flywheel Technology; Past, Present, and 21st century projections, U.S. Flywheel Systems*, Energy Conversion Engineering Conference, 1997. IECEC-97., Proceedings of the 32nd Intersociety, pp 2312 - 2315, vol 4, 27 Jul-1 Aug 1997

# APPENDIX