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Effect of Rotational Mass Radius as Energy Storage on a Flywheel (Conceptual Stage)

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Abstract

This project focuses on the design and development of a small-scale dynamometer test rig integrated with a variable mass flywheel for motorcycle applications. The main objective is to evaluate the influence of mass distribution on rotational speed, input voltage, and acceleration time in order to enhance energy efficiency and engine performance. The system consists of a 24 V DC motor, a rotating disc mounted on a shaft, and an adjustable flywheel that allows mass to be positioned at different radial distances. Rotational speed is measured using a tachometer, while acceleration time and input voltage are recorded under various load and test conditions. By altering the radial position of the load and the target speed, the effect of mass distribution on the moment of inertia can be systematically evaluated. The dynamic behaviour of the system is analysed based on the relationship between acceleration time and applied voltage. Experimental results show that changes in mass distribution significantly influence the acceleration response and overall system performance. The prototype provides a controlled platform to study rotational energy characteristics prior to the final flywheel design. Overall, this study supports the development of cost-effective and efficient variable mass flywheel systems for optimized energy utilization and improved drivetrain performance.

1. Introduction

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Recent developments in Internal Combustion Engine (ICE) technology have improved engine efficiency, with some systems achieving more than 60% thermal efficiency [1][2]. However, ICEs still produce harmful emissions such as Nitrogen Oxides (NOX), Particulate Matter (PM), Carbon Monoxide (CO), and Hydrocarbons (HC) due to energy losses during combustion [3]. A large portion of fuel energy is lost as heat, friction, and exhaust losses, and only a small amount is converted into a useful mechanical power [4][5]. Therefore, improving ICE efficiency is important to reduce fuel consumption and environmental impact [5].

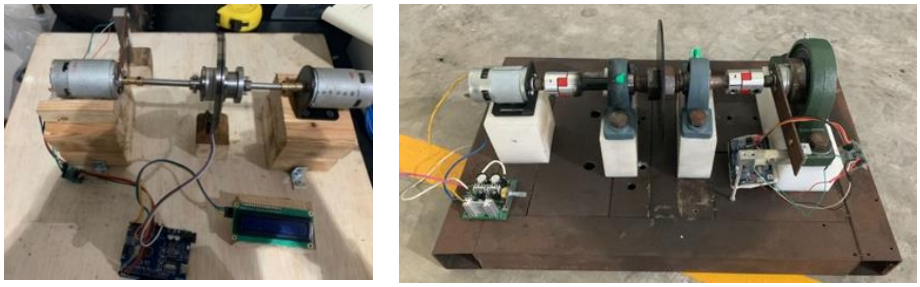
One possible method to reduce energy losses is the use of a variable mass flywheel. The flywheel stores rotational kinetic energy during the power stroke and releases it during other strokes to maintain smooth engine operation [6]. It helps reduce speed and torque fluctuations and supports stable energy flow during the operation within the drivetrain. By adjusting the flywheel mass or radius of load attached, the moment of inertia can be changed according to operating conditions. A lighter flywheel can improve startup response, while a heavier flywheel can store more energy during operation, helping to reduce deceleration and fuel consumption, it also maintains rotational momentum for a longer period, resulting in smoother engine performance and reduced speed fluctuations, especially under varying load conditions [7].

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Previous studies, including flywheel-based Kinetic Energy Recovery Systems (KERS), have shown that flywheels can capture and reuse energy that would otherwise be lost during braking. These systems improve fuel efficiency and offer a cost-effective alternative to battery-based hybrids [7]. However, traditional flywheels have fixed mass and limited flexibility. Therefore, this research investigates how changes in flywheel mass and radius affect rotational behaviour and energy storage. The aim is to experimentally evaluate the potential of a variable mass flywheel as a simple and practical solution for improving efficiency in low-capacity vehicle powertrains.

2. Methodology

This research applied an experimental and practical methodology to assess the functioning of a variable mass flywheel system. This included designing, building, and testing a small-scale dynamometer for assessing how changing the mass of a variable mass flywheel would affect the way a flywheel rotates and how efficiently its energy is used. The first step in building the dynamometer was to create a working proof of concept, or Proof-of-Concept (PoC), that could confirm the basic measurements of torque and speed as shown in **Fig 1 (a)**. All system designs were developed using Computer Aided Design (CAD) software, and laboratory testing was conducted under controlled conditions to gather consistent and replicable information.



(a) (b)

Fig 1: (a) PoC Dynamometer small-scale prototype (b) Upgraded version of Dynamometer small-scale prototype

Once fulfilling the PoC requirements, a revised version of the dynamometer prototype was produced to provide a more structurally stable and accurate testing platform as shown in **Fig 1 (b)**. This new system would allow for the controlled modification of a flywheel's mass with external weight systems that could be mounted to the system at varying radial locations, as shown in **Fig 2**. The selected radius are Rad 35, Rad 45, Rad 55, and Rad 65 which correspond to the distance of mass at 35 mm, 45 mm, 55 mm, and 65 mm from the center of flywheel.

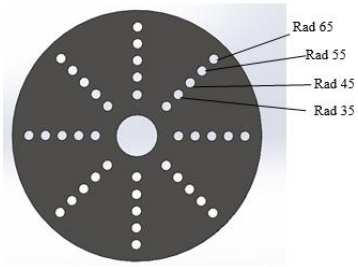


Fig 2: Flywheel

Two experiments were conducted to study the effect of rotating mass on the flywheel. The first test was a coast-down test, where the flywheel was accelerated to specific rotational speeds and then allowed to coast to a complete stop naturally after being disconnected from the power source. The recorded deceleration time provided data on the rotational inertia of the flywheel and the dissipated energy. During this test, eight 10-gram masses were attached at specified radii. The second test evaluated the system's acceleration response to reach target speeds under a constant supply voltage. Both experiments initially began with an unloaded flywheel, after which loads were incrementally applied at different radial distances. The data collected from both tests forms the foundation for the analysis and discussion presented in the following section.

3. Results and Discussion

The experimental results are tabulated in Table 1, showing the supplied motor voltage and average duration across various rotational speeds and load radii.

Table 1: Time measurement and voltage at variable speed and load radius

Speed (rpm)	Supplied Voltage to Motor (V)					Average of Duration (s)				
	Zero Load	Rad 35	Rad 45	Rad 55	Rad 65	Zero Load	Rad 35	Rad 45	Rad 55	Rad 65
500	1.66	1.9	1.73	1.96	1.82	1.32	1.32	1.68	1.75	2.02
1000	2.73	3.03	2.71	2.83	2.55	2.75	3.18	3.14	3.15	3.35
1500	3.17	3.57	3.55	3.31	3.38	3.83	4.20	4.24	4.33	4.86
2000	3.83	4.14	4.22	4.22	4.06	4.75	5.15	5.26	5.30	5.77
2500	4.63	5.18	5.18	4.77	4.64	5.64	6.09	6.11	6.23	6.73
3000	5.25	5.84	6.00	5.38	5.58	6.46	7.19	7.12	7.52	7.86

Based on the results that were obtained from both experiments, the mechanical energy and parameter were calculated to find the angular velocity (ω), moment of inertia (I), Kinetic Energy (KE) and Potential Energy (PE) using equations as follow:

Angular velocity (ω):

$$\omega = (2\pi \times N) / 60 \quad (1)$$

Where; N is revolution of flywheel per minute.

Moment of Inertia (I):

$$I = \tfrac{1}{2}mr^2 \quad (2)$$

Where; m is mass and r is radius of mass.

Kinetic Energy (KE):

$$KE = \tfrac{1}{2} I \omega^2 \quad (3)$$

Where; I is moment of inertia.

Potential Energy (PE):

$$PE = mgr \quad (4)$$

Where; g is gravity.

3.1 Coast-Down Time Measurement at Variable Speeds and Load Radius

In order to understand how a flywheel system slows down under different factors affecting inertia, coast-down experiments were conducted with varying rotational speeds and load attached at the different radius of the flywheel. As the speed of rotation increased, coast down times grew longer regardless of test configuration since rotating at higher speeds means storing more kinetic energy. During coast down, mechanical friction bearings, and aerodynamics will take longer to deplete that stored energy due to the increased duration of coast down at high speeds.

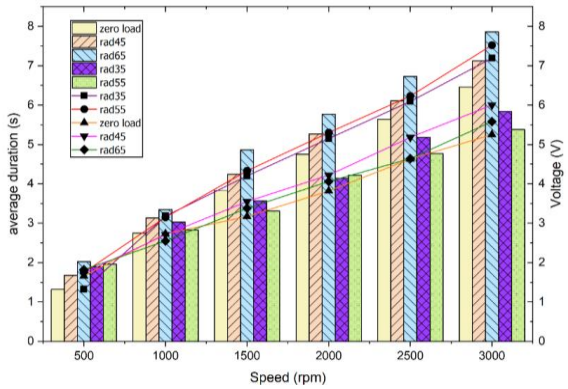


Fig 3: Average Duration and Voltage Response at Various Speeds and Radius

The coast-down time associated with the zero-load condition exhibited a steady and progressive increase with rotational speed, rising from approximately 1.32 seconds at 500 rpm to about 6.46 seconds at 3000 rpm, as illustrated in **Fig 3**. This trend indicates that at higher initial angular velocities, the flywheel retains a greater amount of kinetic energy, resulting in a longer duration required for the system to decelerate to rest under minimal resistive forces. When external loads were introduced, the measured coast-down times were consistently longer than those recorded for the unloaded condition at the same rotational speeds. This behaviour confirms the influence of additional inertia on the deceleration process, as the presence of external mass increases the system's resistance to changes in rotational motion. Furthermore, an increase in the weight radius led to a noticeable extension in coast-down duration, demonstrating the significant role of mass distribution relative to the axis of rotation. By positioning mass farther from the rotational centre, the moment of inertia is increased, allowing the flywheel to store and sustain rotational energy for a longer period. These findings collectively reinforce the fundamental principle that both added mass and its radial placement are critical factors governing the inertia characteristics and energy retention capability of the flywheel system.

3.2 Acceleration Time Measurement under Controlled Voltage Input

This acceleration time test was conducted at a controlled voltage of six volts to measure the dynamic response of the flywheel system under no load and a loaded condition. It is evident that as the rotational speed of the system was set at increases, so did the acceleration time across all configurations indicating that in order to achieve higher rotational velocities, the input energy amount required to accelerate will also be higher than at lower speeds, Under Zero Load condition, when the flywheel was accelerated from Zero rpm to 500 rpm, it took approximately 0.420 seconds. When accelerating The flywheel to a rotational speed of 3000 rpm, however, it took a total of approximately 6.070 seconds, When placing external load on The flywheel, the acceleration times increased progressively as the radial load increase (35 mm, 45 mm, 55 mm, and 65 mm). Therefore the respective acceleration times measured at 3000 rpm were 7.840 seconds, 7.880 seconds, 8.350 seconds and 8.770 seconds (for each load radius). Thus, based on these acceleration time trends, it is clear that mass distribution contributes to the rotational dynamic behaviour of the flywheel, i.e., that the greater the distance mass is placed away from the centre of mass (moment of inertia), the more it will resist changes in angular velocity (decreasing acceleration at speeds greater than 0 rpm) and the more required torque to accelerate at higher speeds.

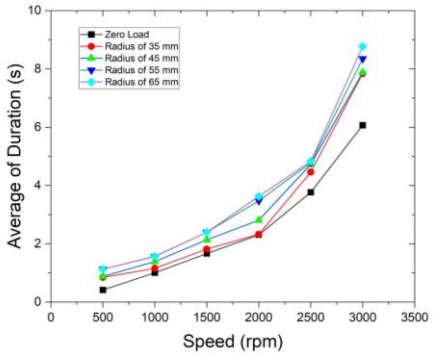


Fig 4: Average Duration versus Speed for Different Load Radius at Constant Voltage of 6 V

The graphical representation of the relationship between acceleration time and target speed for the various load radius, as shown in **Fig 4**, demonstrates a strong correlation and offers clearer insight into the interaction between load radius and the system's acceleration behavior. As observed from the plotted curves, the separation between the profiles becomes increasingly pronounced as the target speed approaches the maximum operating speed of the flywheel. This trend indicates that the additional moment of inertia introduced by increasing the flywheel mass and load radius has a more significant influence on system dynamics at higher rotational speeds compared to lower target speeds. At elevated speeds, the motor is required to overcome greater inertial resistance, resulting in longer acceleration times for configurations with larger load radii. Consequently, variations in load radius lead to increasingly distinct acceleration responses, highlighting the sensitivity of acceleration performance to changes in inertia. Overall, the acceleration time versus target speed profiles provide clear evidence that load radius is directly correlated with acceleration performance, enabling a systematic comparison of the dynamic response of different load radii under various test conditions.

3.3 Mechanical & Energy Parameters

With the use of acceleration and deceleration experimental data, mechanical and energy parameters such as the angular velocity, moment of inertia, kinetic energy, and potential energy describe how the flywheel system behaves dynamically under various loading conditions. The angular velocity was determined from the data obtained from measuring the flywheel's rotational speeds, while the moment of inertia is dependent on the mass being applied to the flywheel and its radial distance from the flywheel's axis. Kinetic energy and potential energy were determined from known relationships regarding how these values relate to each other in a mechanical sense. By calculating these five parameters, it is possible to quantify the effects of load mass distributions on the amount of resistance that the flywheel must change in rotational speed and the amount of energy that can be stored by the flywheel.

Table 2: Mechanical and Energy Parameters at Different Load of Radius

Mass (kg)	Radius (m)	Angular velocity (rad/s)	Inertia (kg. m^2)	K. Energy (J)	P. Energy (J)
0.150	0.150	52.36	1.6875×10^{-4}	2.313	0.221
0.230	0.035	104.72	1.4088×10^{-4}	0.772	0.079
0.230	0.045	157.08	2.3288×10^{-4}	2.873	0.102
0.230	0.055	209.44	3.4788×10^{-4}	7.629	0.124
0.230	0.065	261.79	4.8588×10^{-4}	16.649	0.146

4. Conclusion

This study successfully developed and validated a small-scale dynamometer prototype for investigating the behavior of a variable mass flywheel. The experimental results demonstrated that increasing the load radius increased the flywheel's moment of inertia, resulting in longer coast-down times and improved rotational

energy retention. The longest coast-down time recorded was 7.86 s at a load radius of 65 mm, indicating that positioning the mass farther from the centre enhances the flywheel's ability to sustain rotational motion. Conversely, the increased moment of inertia also increased the acceleration time, with the maximum acceleration time of 8.77 s recorded when accelerating from 0 to 3000 rpm at the largest load radius. The calculated mechanical parameters further showed that increasing the load radius increased the moment of inertia, kinetic energy, and potential energy, confirming that mass distribution plays a significant role in the flywheel's energy storage capability. Overall, the findings demonstrate that variable mass distribution significantly influences the dynamic behaviour and energy storage characteristics of the flywheel, highlighting its potential for improving energy efficiency in small powertrain applications.

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Conflict of Interest

Authors declare that there is no conflict of interests regarding the publication of the paper.

Author Contribution

The authors confirm contribution to the paper as follows: ***study conception and design:*** *Dang Ra'il Zulaikha Sanusi; Muammar Mukhsin Ismail* ***data collection:*** *Dang Ra'il Zulaikha Sanusi;* ***analysis and interpretation of results:*** *Dang Ra'il Zulaikha Sanusi; Muammar Mukhsin Ismail* ***draft manuscript preparation:*** *Dang Ra'il Zulaikha Sanusi. All authors reviewed the results and approved the final version of the manuscript.*

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This guide contains examples of common types of APA Style references. Section numbers indicate where to find the examples in the Publication Manual of the American Psychological Association (7th ed.).

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