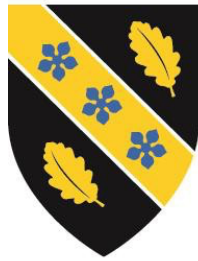


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Analyse and Simulate a Mechanical Energy Recovery System

ACMA5010 – Stress Analysis and Dynamics

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Executive Summary

This report will analyse the impact and origins of flywheel technology and its impact on modern energy production and retention systems. With fundamental energy recovery principles present in modern day flywheel applications, this technology remains relied upon for several important daily uses for all users.

This report will consider the how the findings throughout time in rotational kinetic energy impacted technology produced at the time, and how it has translated into modern engineering equipment and processes.

Calculations and analysis of Kinetic Energy Recovery Systems (KERS) will also be investigated, showcasing the modern applications that flywheel energy storage and retention is being optimised.

Introduction

The pursuit of sustainable energy production and storage has inspired development across the engineering industry, with newer concepts and technologies providing sustainable practises for future engineering systems and products. As energy storage systems become more complex and data-driven, the constant throughout time has remained the use of the flywheel. The mechanical principles of energy storage align with the behaviour of the flywheel, which has inspired innovation and new technologies to enhance the capabilities of energy storage.

With the initial technical findings about flywheels being published in the late 19th century, the technology at the centre of innovative solutions follows the basic first findings in this area. Throughout the last several hundred years, the inspection and analysis of such systems have allowed improved focus on maximising energy output and storage, whilst minimizing mechanical losses, such as vibration and heat.

In modern engineering innovations, the flywheel is relied upon as a key component and system in energy retention and production. Modern technologies such as kinetic Energy Recovery Systems (KERS), Off-grid energy production, and mechanical batteries are a few of the relied upon technologies for which the use of flywheel technology and principles are required.

Task 1**History of Flywheels**

The evolution of flywheel uses, and enhancement has been apparent from the early concepts of its use to modern day. Each of the attributes and findings have supported its ability to be adapted for wider use across engineering and basic common applications.

Potter's Wheels – ancient circa 3000 BCE

Mesopotamian Potter's wheels first acknowledged the concept of inertia as a key finding in the use of flywheel basis. Whilst the formal understanding of energy storage was not documented in technical terms in the 3000 BCE that flywheel basic discovery occurred, the core mechanical and energy storage knowledge is displayed in inertia and angular momentum findings. The findings focused on the conservation on angular momentum as shown below:

$$L = I\omega$$

L - angular momentum (kg m²/s)

I – moment of inertia

ω = angular velocity (rad/s)

Ancient Egyptians and craftsman understood that the moment of inertia was directly related to the angular momentum achieved in flywheel rotation, which favoured the use of heavier and larger rotating bodies to generate momentum. This was also true in regard to body symmetry for consistent rotational acceleration. (*Arabkoohsar, 2020*)

Greeks – water lifting mechanisms

Theoretical understanding was first developed by Archimedes in his study of fluid mechanics (approx. 286 BCE.) His work in fluid mechanics lent itself to development in the field of rotational kinematics, and thus adopting principles of flywheel use. (*Doherty, 2015*) The Archimedes screw was an innovation in which water was able to be transported from a lower place to a higher location using a design similar to that of a flywheel. Weighted handles and flywheel arrangements contributed to its original formula in usage:

$$h = p \cdot \sin (\theta)$$

p – screw pitch (rotation per turn)

θ – incline angle of the screw

h - height gained per revolution of screw

Whilst this area of innovation and theory contributed indirectly to the development of flywheel innovation, it held an important step in the history of flywheel adaptability and variety across several designs and theories in time.

James Watt's steam engines- industrial revolution

The implementation of flywheel theory in the industrial revolution was key in its efforts to increase energy output and adaptability in key application. This was especially apparent in its adoption into James Watt's steam engine design. Watt's developed systems that converted reciprocating motion into rotational motion. Whilst this breakthrough proved innovative, issues were presented in uneven rotations and inconsistency due to the steam engine's uneven pressure fluctuations. The adaptation of the system to incorporate a flywheel design ensured a steady and continuous rotation, fixing the issues presented in the fluctuating nature of the pressure differences. (Landels, 1981).

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

E_k – kinetic energy stored in flywheel (J)

ω – angular velocity (rad/s)

I - moment of inertia (kg * m²)

$$I = \frac{1}{2} M R^2$$

M – mass of flywheel

R – radius of flywheel

The lessons learnt from James Watt's implementation of the flywheel within his work have transcended into modern advantages and reasoning for their widespread use across the automotive industry. Advantages such as stable rotational motion, improved energy and fuel efficiency, and increase component lifespan are serious factors in modern manufacturing and design of systems.

Regenerative Braking

The use of regenerative braking has been adopted industry wide in motor-vehicle production, along with several other roles across several industries and applications. As a technical concept, the simplicity of the regenerative braking system is its main advantage. The concept being that the energy produced from deceleration or breaking can be used as rotational energy to turn a flywheel and use this rotational energy to charge a battery or power unit, to them be reused to power the driven wheels. Due to the lack of conversion required from rotational energy to any other form of movement, the energy losses in this system are substantially lower than that of other systems providing energy conversion.

Despite its conception being prior to the development of modern hybrid and electric cars, its use in the design of these vehicles has been of great success in providing more energy efficient and effective drive trains.

The electric flywheel first developed as part of the Williams Hybrid Power unit was a pioneering concept at its conception in 2009, achieving global recognition and interest into the capabilities of an effective regenerative braking system. This was an innovation in Formula 1 at the time, which has continued its use into a global market whereby the technology is now widely used in mass car manufacturing and public transport, specifically on services such as buses and trams where there is a repeated acceleration and stopping.

Off-grid Energy Storage Systems

Flywheels are often adopted for off-grid energy storage systems across areas and industry. Their efficiency and reliability make them especially suited to applications where infrastructure is limited, such as remote communities, and renewable powered systems.

The flywheel system is able to use surplus electrical energy to spin and then convert the energy back into usable electricity for distribution via a motor generator system. This simple, yet effective, set up requires limited maintenance and cost for its application. (*Przemyslaw Komarnicki, Pio Lombardi and Zbigniew Styczynski, 2017*).

Development in technology used for energy storage applications has created innovative ways of improving the systems used as fluctuation monitors. Carbon fibre materials, magnetic bearings, partnered with vacuumed sealed flywheel chambers.

Kinetic Energy Recovery Systems (KERS) – Applied to Road-going vehicles

The Kinematic Energy Recovery System (KERS) is an important technology that is now adopted industry-wide in the automotive industry. This innovation uses the key principles of energy recovery and uses from flywheel understanding. The aim of the KERS system is to minimise waste in energy production within a reciprocating or rotating mechanical battery.

To design and develop an effective KERS system, several key areas must be tested and researched to achieve peak performance of the system. Three of the most important areas for attention are:

- **Precision balancing**
- **Containment**
- **Materials**

Precision balancing refers to the dynamic balancing of the flywheel whilst subject to high revolutions per minute and irregular angular velocity. Ensuring that the rotating mass is stable during its operation ensures that less wasted energy occurs, improving its efficiency. This is also vital in ensuring reduced vibration and bearing loads, which would result in increased wear and potential for component failure. (*Boretti, 2013*).

Measures can be put in place to improve the balancing of the KERS system in road going applications. This includes dynamic balancing rigs, that can be controlled via onboard computers to make micrometre adjustments to achieve the correct balance in the rotating flywheel.

The containment of the KERS system refers to the safe collection and dissipation of large amounts of kinetic energy within the flywheel set-up. With such high amounts of energy being generated in the system, ensuring that the system has the correct material and capacity to safely use and disperse the energy is required to meet vehicle safety standards.

Innovations such as containment rings can be incorporated into the system to provide protection in the event of rotor degradation or breaking. Design inspiration has also been incorporated from aerospace technologies in turbine containment, aiding in the design becoming more effective in preventing large scale damage and error.

Development in the research and procurement of specialist materials has aided the performance of KERS systems via the introduction of carbon fibre reinforced polymers (CFRP) as a replacement to previously used steels in flywheel manufacturing. Whilst the first iteration of KERS systems used steel due to its toughness and low cost, its higher density hinders rotational speed and its energy to weight ratio.

CFRP has been used in advanced KERS systems for manufacturers worldwide, including the likes of Volvo and Porsche. The low-density characteristic of the material lends itself to higher angular velocities compared to steel. This paired with a low density and having a high tensile strength allowed for its use industry wide.

An increase in cost of production and material was necessary to improve the KERS effectiveness in modern vehicle usage. (*Boretti, 2013*).

Mechanical batteries and Chemical Batteries.

The use of mechanical and chemical batteries across applications worldwide has encouraged development in both technologies to increase energy efficiency and product effectiveness. The use of compressed air systems and flywheels as mechanical batteries have been theorised and used for millennia, proving its effectiveness in producing and storing energy.

The electrochemical reactions used to generate energy in chemical batteries have dominated industries that rely on large energy output with limited infrastructure and area. Its use in technology and IT settings has allowed for continuous development in both industries, unhindered by lack of portable power available. (*Nehme, 2025*).

The efficiency and power density of both types of batteries is clearly calculated and understood from testing and data analysis, showing a clear difference in levels of efficiency and power density in favour of mechanical batteries. Whilst lithium-ion cells have a round-trip efficiency of 70-90%, flywheels experience efficiency of approximately 90-95%. The loss of heat and return of energy is often apparent in chemical batteries, leading to higher levels of energy loss.

$$E = 1/2 I\omega^2$$

E – kinetic energy stored in flywheel (J)

ω – angular velocity (rad/s)

I - moment of inertia (kg * m²)

Due to the degradation rate of chemical batteries due to electrode corrosion and dendrite formation, their lifespan is often limited to a low number of chemical reactions created energy from the battery. High-cycle and lifespan applications require mechanical batteries for their durability and ability to reach a component lifespan of up to 20 years. This makes them especially capable of working at an optimum level required for grid frequency regulation and KERS systems in motor vehicles.

The environmental impact of both types of batteries is also widely considered before their use, with an increased importance being placed on sustainable power. Ensuring that batteries can adhere to industry sustainability standards is vital and is why mechanical batteries are often chosen.

With mechanical batteries using materials such as steel, carbon fibre, and aluminium, the end-of-life recyclability of components is close to all of the components used. This makes it a sustainable type of battery to use.

Mechanical batteries should be used in applications that allow for its size and cost. Their advantages outweigh those of a chemical battery in their efficiency and ability to create large amounts of energy storage.

Task 2

Gross mass = 2,080 kg

Initial breaking speed = 55 mph

Re-acceleration occurs from rest using only the stored KERS energy.

KERS flywheel specification:

Mass = 6.5 kg

External dia = 300mm

Max rotational speed = 50,000 RPM

Combined efficiency = 80% (braking and acceleration)

Vacuum sealed enclosure

Geometry can be analysed as a 'thin ring' design.

1

$$E_k = \frac{1}{2}mv^2$$

$m = 2080\text{kg}$

$v = 55\text{mph}$

$$55 \div 2.237 = 24.5872 \text{ m/s}$$

$$\begin{aligned} E_k &= \frac{1}{2} \times 2080 \times (24.5872)^2 \\ &= 628,711.62 \text{ J} \end{aligned}$$

2.

$$E_{\text{Stored}} = \eta \times E_k$$

$\eta = \text{Efficiency}$

$$\begin{aligned} E_{\text{Stored}} &= 0.8 \times 628711.62 \\ &= 502,969.30 \text{ J} \end{aligned}$$

3.

$$\begin{aligned} I &= mr^2 \\ I &= 6.5 \times 0.15^2 \\ &= 0.14625 \text{ kg/m}^2 \end{aligned}$$

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

$$\omega = \sqrt{\frac{2E}{I}}$$

$$\omega = \sqrt{\frac{2 \times 502969.3}{0.14625}}$$

$$\omega = 2624.33 \text{ rad/s}$$

$$RPM = \frac{\omega \times 60}{2\pi}$$

$$RPM = \frac{2624.33 \times 60}{2\pi}$$

$$RPM = 25044.32$$

4.

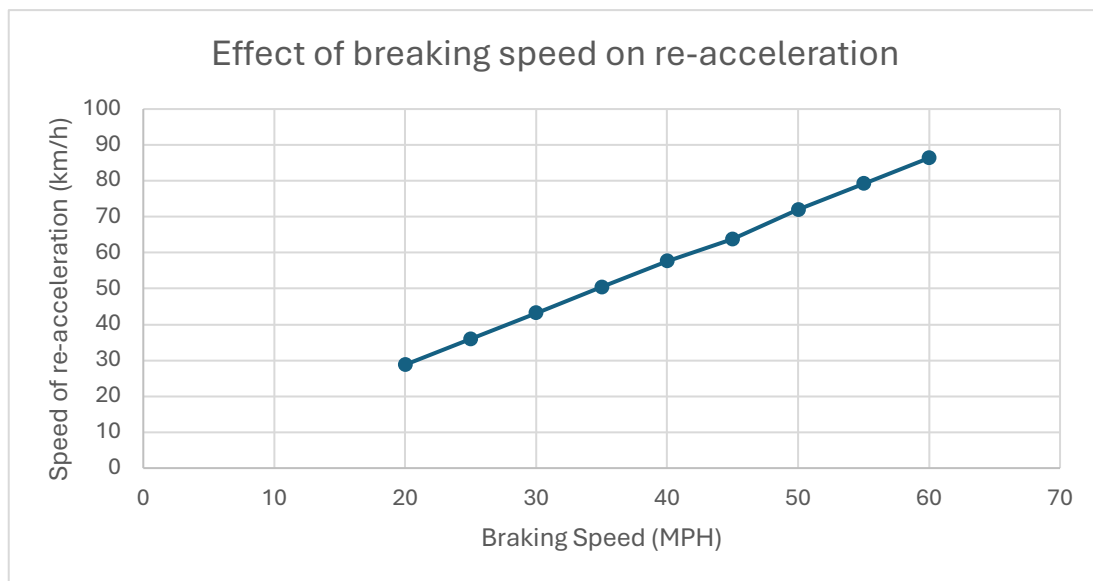
$$v = \sqrt{\frac{2E}{m}}$$

$$v = \sqrt{\frac{2 \times 502969.3}{2080}}$$

$$v = 21.99 \text{ m/s}$$

$$v = 79.2 \text{ km/h}$$

5.



6.

$$a = \frac{v}{t}$$

$$a = \frac{23.99}{6.5}$$

$$a = 3.69 \text{ ms}^{-2}$$

7.

$$Ek = \frac{1}{2} \times 1510 \times (26.8224)^2$$

$$= 543,383.5 \text{ J}$$

$$543,383.5 \times 0.8$$

$$E_{\text{stored}} = 434,706.8 \text{ J}$$

$$E = \frac{1}{2} I \omega^2 = \frac{1}{2} m f r^2 \omega^2$$

$$\omega = \sqrt{\frac{2E}{mfr^2}}$$

$$RPM = \frac{\omega \times 60}{2\pi}$$

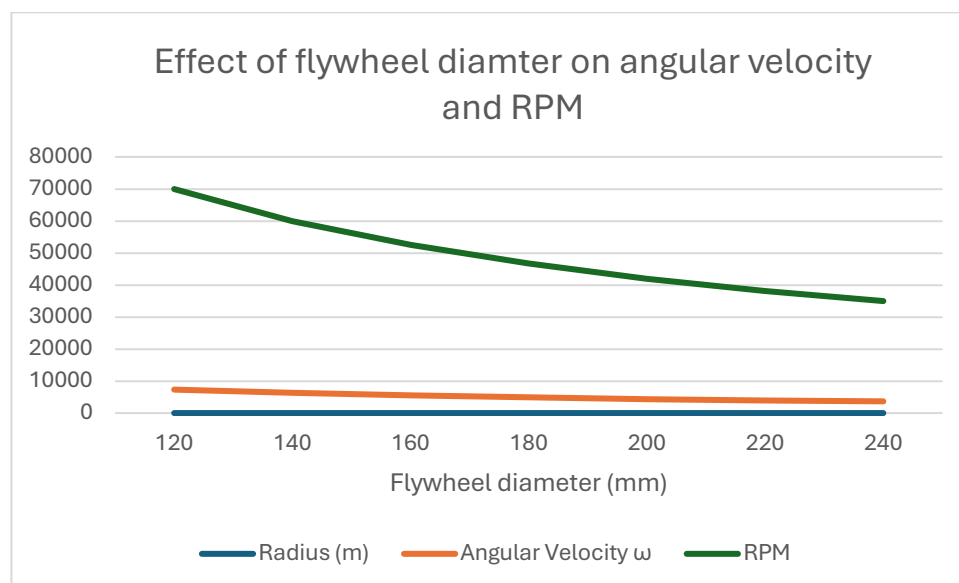
$$\omega = \sqrt{\frac{2 \times 434,706.8}{4.5 \times 0.06^2}}$$

$$\omega = 7322.7$$

$$RPM = 69942.1$$

As the diameter of the flywheel increases, the moment of inertia is directly impacted, with the increase in its moment of inertia. This means that the larger radius stores energy at a lower angular velocity. The revolutions per minute is then lowered due to the reduction in angular velocity.

Diameter (mm)	Radius (m)	Angular Velocity ω	RPM
120	0.06	7325.81	69956.3
140	0.07	6279.27	59962.6
160	0.08	5494.36	52467.3
180	0.09	4883.87	46637.6
200	0.1	4395.49	41973.8
220	0.11	3995.9	38158
240	0.12	3662.91	34978.2



8. Several assumptions were made throughout the calculations of task 2 to complete the equations to a fair and effective solution. The efficiency of the drivetrain and rolling resistance were idealised, both would be lower in a real-world application. The energy transfer efficiency remains at 80% during the task, which is inaccurate to real world application, where the efficiency would vary under different loads and speeds. The thin ring flywheel is assumed to be geometrically perfect, with no deviations in the shape to introduce additional losses during use. It was also assumed the vacuum sealed nature of the flywheel introduced no drag or air resistance at all, something that would be especially difficult to achieve. And finally, the KERS system assumed no driver input of modulation. The re-acceleration phase has the KERS full energy being delivered straight away, something that would be undesirable in a practical setting.

Conclusion

This assignment has highlighted the wide and varied use of the flywheel in general and specialist applications. Its use has inspired innovation and widespread adoption of mechanical batteries as opposed to chemical batteries in several applications. The constant development of the technology lends itself to the engineering industry having the opportunity to create new and innovative methods of energy storage, something that is important as the industry moves away from traditional energy production and storage methods.

This assignment has analysed several flywheel systems, focusing on Kinetic Energy Recovery Systems (KERS). This includes research about the technology, partnered with an effective analysis and example of calculations. The KERS system continues to show the effectiveness of partnering flywheel technology with drive trains to encourage road-going efficiency for users.

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