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Analysis of Mechanical Energy Recovery Systems

Stress Analysis and Dynamics

ACMA5010

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1 Introduction

From the ancient potter's wheel, to modern energy recovery systems, flywheels have been integral to the development and facilitations of mankind's way of life from time immemorial. The technological progression of flywheels has seen them used in advanced applications such as kinetic energy recovery systems (KERS), regenerate braking, and mechanical batteries.



Figure 1, Töpferscheibe, O. Kurmis,. (2005)

This essay aims to cast a light on the adaptability of flywheel technology, and potential uses in the future, by exploring the development and usage of flywheels, their modern implementations, and comparing between mechanical and chemical energy storage.

2 Evolution of the flywheel

The flywheel's earliest progenitor is thought to be the potter's wheel, usually as a heavy disc upon which clay is shaped. The inertia of a heavy wheel smooths out rotational velocity, especially useful when the object is rotated with intermittent applications of force. A potter's wheel exhibits the core elements of a flywheel, storing kinetic energy in a rota



Figure 2, Noria, D. Bainbridge,. (2025)

With the passage of time, the implementations of flywheels became more sophisticated. The introduction of flywheels to noria, a waterwheel intended to supply water to aqueducts at higher elevations than the height of the stream, by ibn Bassal improved the delivery of power.

The adoption of the steam engine before and during the industrial revolution made a perfect scenario for the integration of flywheels. Steam engines drive a shaft back and forth by directing high pressure steam through valves. As such, power isn't applied continuously, but rather in short bursts. By increasing the inertia of the system with a flywheel, the power output smooths out, reducing fatigue on components from sudden changes in force. The inertia of a spinning flywheel results in stable force during low pressure intervals in the steam engine cycle, resulting in a more reliable power transmission.

Aside from locomotive uses, flywheels were used to provide short bursts of power. Certain machinery, such as punch presses, relies on high amounts of force for a split second. Rather than building a big powerful engine to supply this power intermittently, a smaller and cheaper engine can be used to rotate a heavy flywheel, and the latter can power the machinery when needed.

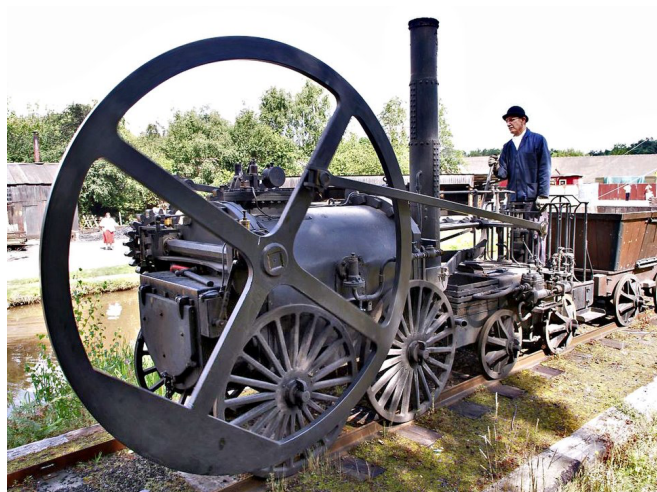


Figure 3, Trevithick's Locomotive, BMT,. (2025)

3 Principles of Rotational Kinetic Energy

Flywheels store kinetic energy according to the equation:

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

where:

I is the moment of inertia

ω is the angular velocity

In other words, increasing either the moment of inertia or the angular velocity of a flywheel will result in a higher kinetic energy stored. It is worth noting that an increase in angular velocity yields a bigger increase in kinetic energy.

The moment of inertia can be ascertained with the following equation:

$$I = mr^2$$

where:

m is the mass of the flywheel

r is the radius of the flywheel

This applies specifically to thin-ringed flywheels, wherein a majority of the mass is concentrated on the circumference of the flywheel, whereas for a uniform cylindrical flywheel the total inertia would must be halved.

As the formula shows, an increase in the radius of the flywheel results in a far higher moment of inertia when compared to an increase in mass. It is no surprise then that examples in industry of high-end flywheels push the envelope on max rotational velocity and the radius of the flywheel.

4 Mechanical Batteries

4.1 Impact on energy grid

Global focuses are increasingly shifting towards electrification and the integration of renewable energy. As of 2023, 91.6% of the world's population has access to electricity (WorldBank, 2024), and demand increases year by year., with energy demand forecasted to double within the next 25 years (Fernande, M.I, et al. 2024). Wind and solar are the most widely used renewable power source, and both suffer from great power output variance.

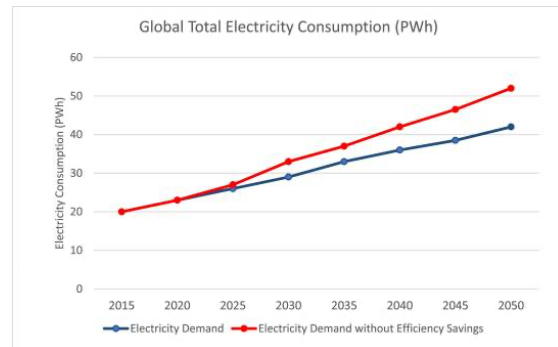


Figure 4, Global Total Electricity Consumption, Fernandez M.I, et al., (2024)

Mechanical flywheel batteries utilize excess power generated by flywheels, during troughs in power generation, or just when demand outpaces supply in general, the flywheels drive generators, feeding power back into the grid.

4.2 Comparison to chemical batteries

Modern flywheel energy systems consist of clusters of flywheels each contained within a vacuum enclosure, and suspended on magnetic bearings. This leads to very low friction in the system, increasing efficiency and allowing the flywheels to rotate at tens of thousands of rotations per minute. The role of a mechanical or chemical battery is primarily to smooth out the variance between supply and demand of power. With the variance from renewables, potentially these energy batteries will be cycling power in or out thousands of times a day. Mechanical batteries require very little maintenance, due to the vacuum within the enclosure, and the absence of physical attachments, a mechanical battery can handle millions of charge-discharge cycles within its lifetime without significant degradation. Comparatively, lithium-ion batteries for professional industrial applications handling at most a few thousand cycles (Han, X, et al., 2019) before there is noticeable degradation in storage capacity.

Flywheels can operate at any temperature without degradation in performance, the lack of friction within the enclosure mitigates any heat accumulation, lithium-ion batteries require a temperature within -20°C to 60°C , preferably 10°C to 45°C , to function properly (Rezvanizani, S.M. et al., 2014).

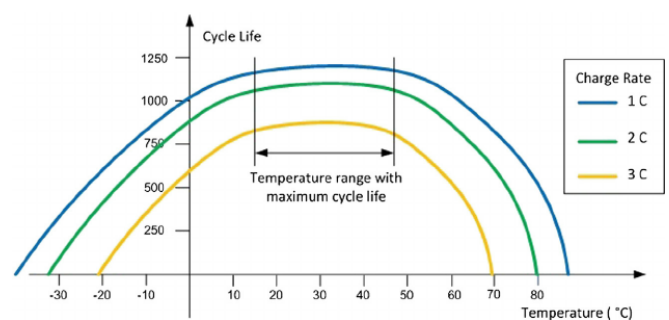


Figure 5, Lithium ion battery life vs. temperature and charging rate, Rezvanizani, S.M. et al., (2014)

Modern flywheels are often made of complex materials, due to the high centripetal forces from the high rpm, but these are largely available and inert. Most of the lithium harvested today comes from rich brines, which are fed into shallow pools to evaporate the liquids, surface brine evaporation has been known to contaminate drinking water, cause respiratory problems, and degrade ecosystems.

Although inert, mechanical batteries do require complex systems to support their upkeep and production. Maintaining a vacuum in a massive enclosure is not easy, and the quantity and quality of magnets needed to keep a flywheel of this magnitude does not come cheap.

5 Kinetic Energy Recovery Systems

5.1 Impact on vehicles

Regenerative braking replaces the normal braking method of applying friction to the wheels of a vehicle to retard speed with applying the load back to a generator, thereby charging a battery or capacitor. KERS works in a similar way, but instead of charging a chemical battery, a flywheel is accelerated during braking. By capturing some of the energy that would've been lost as heat during braking, both KERS and regenerative braking improve fuel efficiency. Further, for combustion engine vehicles the high torque of the flywheel can be desirable for accelerating from standstills, where the inertia of the vehicle is hardest to overcome.

Today, many vehicle applications benefit from the implementation of KERS. Although originally designed for formula 1 cars (Racecar Engineering, 2008), KERS has been implemented on double decker buses (Uk, I. 2015), rail vehicles with only intermittent access to power rails, consumer cars. The benefits are most obvious for vehicles that often go through frequent start stop cycles, such as public transport, and commuters within cities.

5.2 Design Implications

Modern flywheels, enclosed within vacuums and held onto magnetic bearings, can achieve thousands of rotations per minute, even slight imperfections can cause the flywheel to oscillate, potentially with catastrophic consequences. As such, the tolerances and build quality required for them is extremely high.

The high rotational speeds create enormous centrifugal forces on the flywheel. Commonly modern flywheels will be constructed with expensive composites such as carbon fibre, to improve the strength of the flywheel, and allow faster rotation.

In the event of a catastrophic failure, the flywheel, or parts of it could release from the container at high velocity. To prevent threat to life, these enclosures must be extremely robust.

To achieve speeds of thousands of rotations per minute, the enclosure must be kept at a vacuum, potentially requiring follow ups to account for air leaching in through the seals. Further, magnetic bearings are expensive and require very strong magnets, which can be dangerous if handled improperly.

6 Conclusion

Flywheels present a unique engineering implement in human history, having stood the test of time from the humble potter's wheel, to modern energy recovery systems, and more likely than not there will be numerous applications in the future that engineers will adapt and develop them for.

Today's high speed composite flywheels, housed within vacuum enclosures and suspended on magnetic bearings, represent thousands of years of human ingenuity and progress. Today, they provide a robust means of cycling power in and out of a system, making them ideal for stabilizing the grid, or harnessing power otherwise lost to braking.

While chemical batteries hold the limelight for the time being in the energy storage sphere, mechanical batteries pose as great competitors, offering flexible and environmentally friendly alternatives to lithium-ion batteries.

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8 TASK B

8.1 Variables

8.1.1 Vehicle Specs

$$m_{vehicle} = 2080 \text{ kg}$$

$$v_{vehicle} = 55 \text{ mph or } 24.5872 \frac{\text{m}}{\text{s}}$$

8.2 KERS Flywheel Specs

$$m_{flywheel} = 6.5 \text{ kg}$$

$$\theta_{flywheel} = 300 \text{ mm}$$

$$\omega_{flywheel} = 50,000 \text{ rpm or } 1833.33\pi \frac{\text{rad}}{\text{s}}$$

$$\eta_{combined} = 80\%$$

Thin Ring

8.3 Task 1

$$\text{KE} = \frac{1}{2}mv^2$$

$$\text{KE} = \frac{1}{2}2080 \cdot 24.5872^2$$

$$\text{KE} = 628711.62 \text{ J}$$

8.4 Task 2

$$\eta_{rt} = 0.8$$

$$\eta_b = \eta_d = \sqrt{0.8} = 0.8944$$

$$E_{stored} = \text{KE} \cdot \eta_b$$

$$E_{stored} = 562336.77 \text{ J}$$

8.5 Task 3

$$I = 6.5 \cdot 0.15^2$$

$$I = 0.14625 \text{ kg} \cdot \text{m}^2$$

$$\omega = \sqrt{\frac{2 \cdot 562336.77}{0.14625}}$$

$$\omega = 2773.1 \text{ rad/s}$$

$$\omega = 26481.14 \text{ rpm}$$

8.6 Task 4

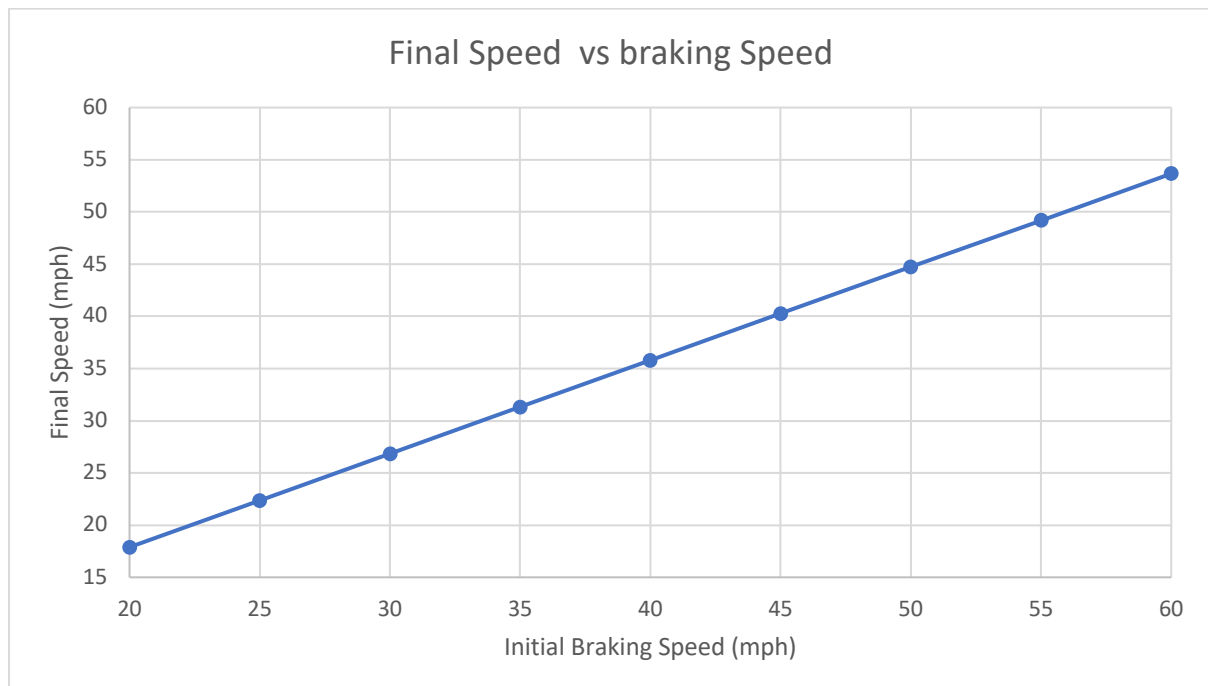
$$E_{\text{returned}} = 562336.77 \cdot 0.8944$$

$$E_{\text{returned}} = 502969.3 \text{ J}$$

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

$$v = 22.09 \text{ m/s}$$

8.7 Task 5



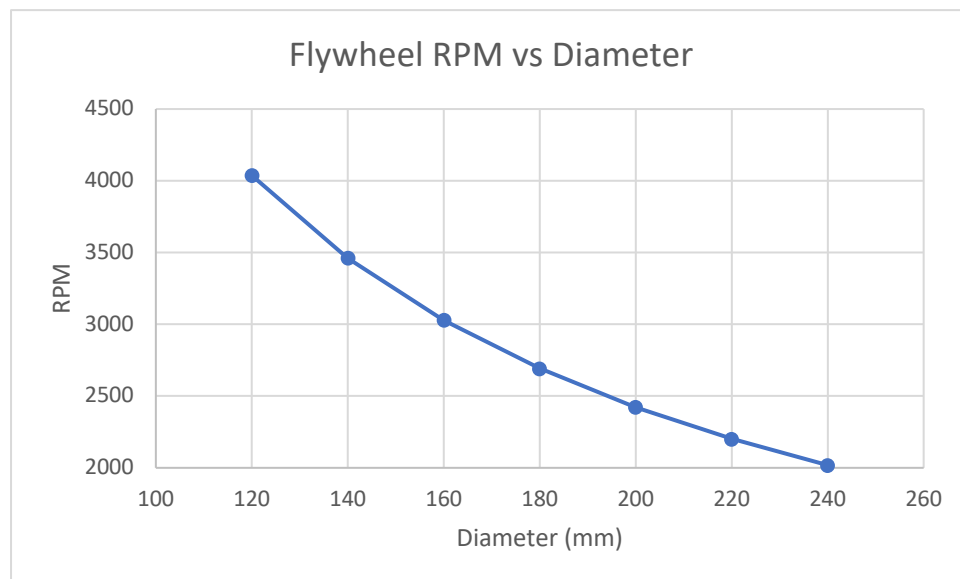
The plot shows an almost linear relationship between initial braking speed and final speed after using KERS. This is due to the round-trip efficiency of 80%. Should the initial braking speed be increased, it can be expected to have a final speed of that value x 0.8.

8.8 Task 6

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

$$\alpha = 3.69 \frac{m}{s^2}$$

8.9 Task 7



The relationship between RPM and Diameter is somewhat inversely proportional. As the diameter increases, the required rotations per minute to store X amount of kinetic energy decreases. In other words, of two flywheels rotating at the same rpm, the bigger one will hold more energy.

8.10 Task 8

No rolling resistance is accounted for; in reality there would be some tyre rolling resistance.

Aerodynamic drag is ignored during braking and acceleration.

Terrain incline is assumed to be 0, and terrain is assumed to be even and flat.

Acceleration and deceleration are treated as if they are constant. Ignoring that often brake pressure and drivetrain drag vary.

Vehicle is treated as rigid mass, no account for suspension absorbing energy, weight transfer between the front and rear.

From round trip efficiency, we assume braking and acceleration efficiency are perfectly even, in reality could be asymmetric.

Efficiency remains constant, no account for potential efficiency differences at different gears, flywheel rpm.

Assumed that all of the braking is done by kers, none handled by traditional braking systems.

Assumed that no energy is lost as heat (bar the miscellaneous 20% per round trip)

Flywheel is treated as idealistic thin ring, in reality there would be an inner and outer diameter, lowering the moment of inertia

Lossless transmission assumed

Flywheel and tyres assumed to rotate perfectly, no oscillating laterally.