Flywheel Energy Storage
Energy Storage via Rotational Inertia

by Christopher Reed – xchrisrx@gmail.com

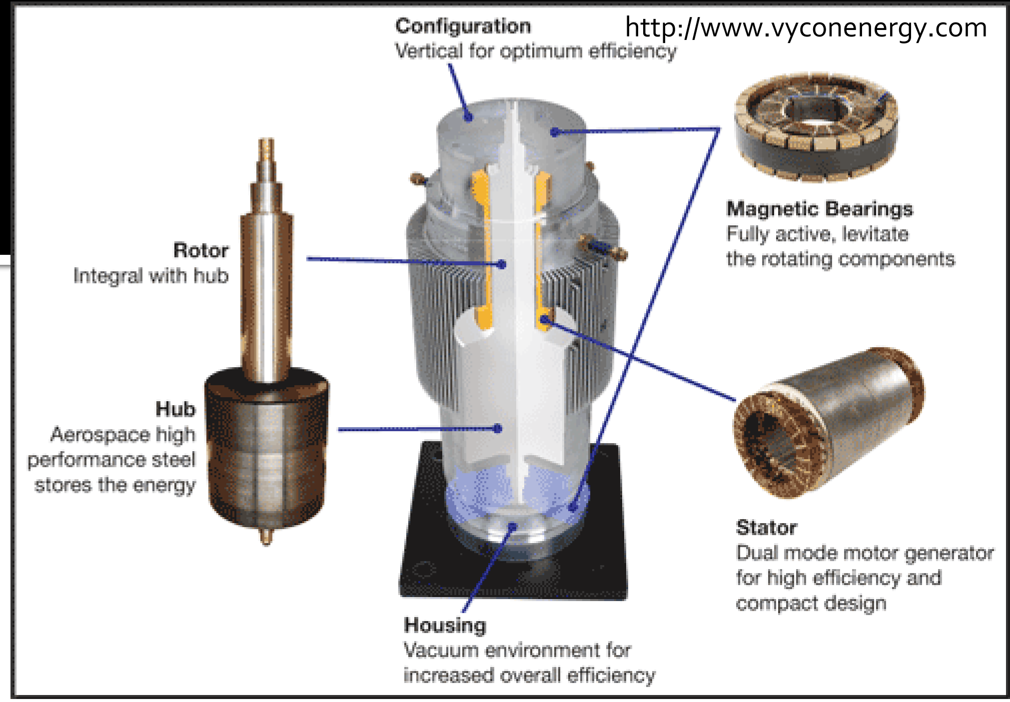
Overview

- Definition
- Components
- Calculations
- Advantages
- References
- Videos & Applications
- Practice Problem

Definition

- A flywheel is a mechanical device that stores energy within the inertia of mass, particularly rotational inertia
- Some flywheels are designed intentionally to store energy, while others may not be
  - ex: a wheel on a bike
- While flywheels store energy in the form of kinetic energy, the energy is often input into or taken out of the system in the form of electrical energy via electric motor-generator combo
  - But doesn't have to be!

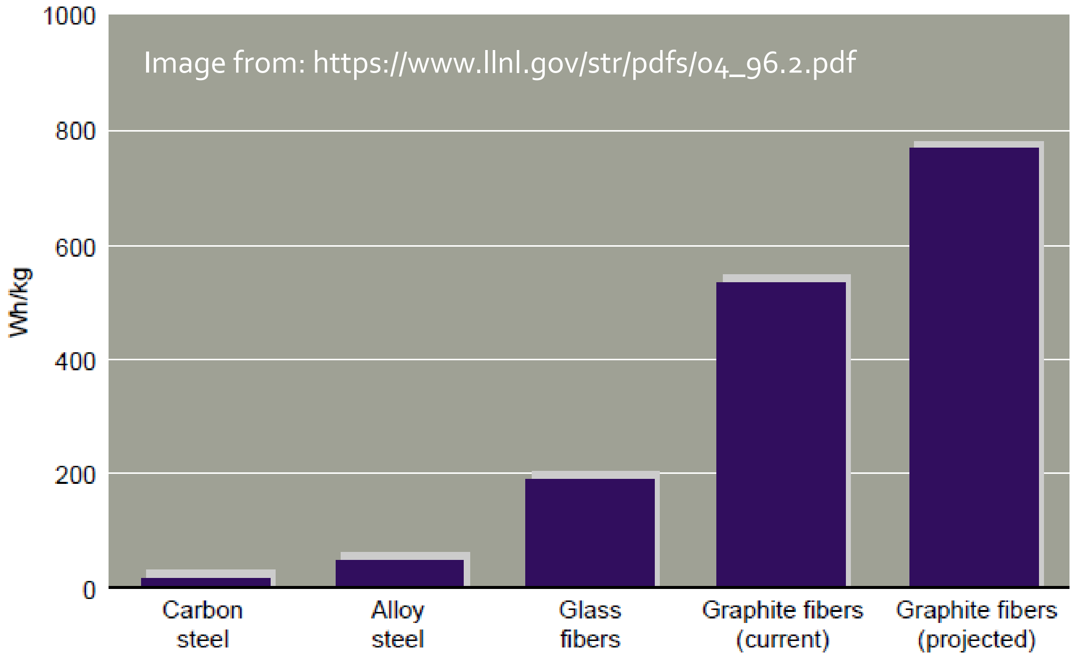
Components



- All flywheels include:
  - Rotor – a Rotating Mass
- Most flywheels designed for energy storage include:
  - Bearings
  - Encasing
    - For protection from failure
  - Vacuum contained
    - Reduces air resistance on the rotor, improving the efficiency
  - Electric Motor-Generator Combo

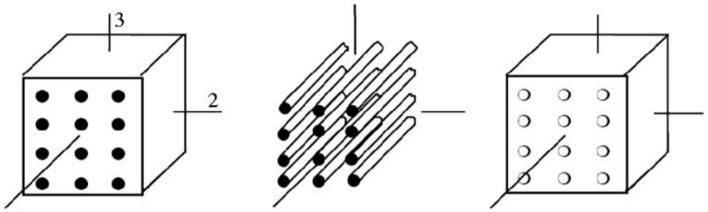
Rotor

- Must endure high tensile stress
- Composites are often safer because they break-up or disintegrate upon failure



Composites

- Subscripts
  - c: composite
  - m: matrix phase
  - r: reinforcing phase



http://www.emeraldinsight.com

$$\rho_c = \frac{m_m + m_r}{V_c} = f_m \rho_m + f_r \rho_r = \frac{V_m}{V_c} \rho_m + \frac{V_r}{V_c} \rho_r$$

Composite Density

$$E_c = f_m E_m + f_r E_r$$

Modulus of Elasticity Parallel with Reinforcing Fibers

$$E_c{}' = \frac{E_m E_r}{f_m E_r + f_r E_m}$$

Modulus of Elasticity Perpendicular to Reinforcing Fibers

Stress Analysis

- Find the stress in a cylinder rotating about its longitudinal axis as a function of x from the center, C.

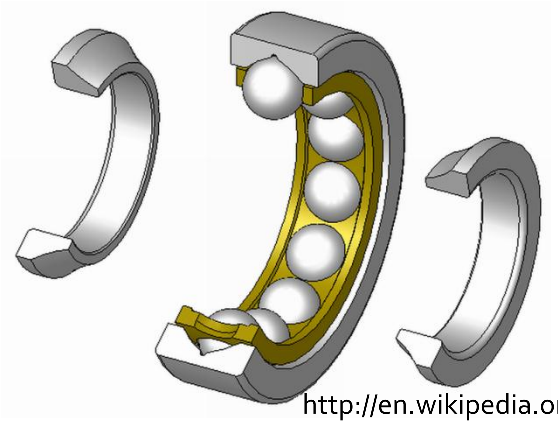
$$\sigma = \frac{F}{A}$$

$$\tau = F \cdot x$$

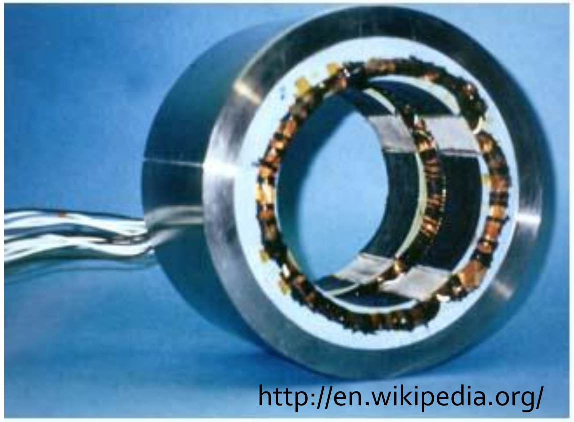
$$E = \frac{\Delta\sigma}{\Delta\epsilon}$$

Bearings

- Magnetic bearings are advantageous over mechanical because the friction drops significantly, resulting in an increased efficiency
- High Temperature Superconductors (HTSC) bearings often used
- Hybrid systems use permanent magnets for maintaining the load, and HTSC for stabilizing, therefore saving on operation (electrical) costs



http://en.wikipedia.org/



http://en.wikipedia.org/

Calculations for Rotation

- Moment of Inertia

$$I = \int r^2 dm = \sum m_i {r_i}^2$$

for a mass rotated off-center:

$$I = I_{cm} + md^2$$

  - Cylinder rotating about longitudinal axis

$$I_{cylinder} = \frac{1}{2} m r^2$$

- Kinetic Energy

$$\boldsymbol{KE} = \int \frac{1}{2}\omega^2 r^2 dm = \frac{1}{2}\omega^2 \int r^2 dm = \boldsymbol{\frac{1}{2}\omega^2 I}$$

- Work

$$\boldsymbol{W} = \int_{\theta_i}^{\theta_f} \tau \, d\theta = \Delta KE = \boldsymbol{\frac{1}{2} I({\omega_i}^2 - {\omega_f}^2)}$$

Advantages

- Little to no affect due to temperature changes
- No memory effect (often seen in batteries)
- Quick charge and discharge time
  - Minutes as opposed to hours
- High Efficiency, depends on storage time
- Long lifetimes, often designed for 20+ years of no maintenance

Comparison

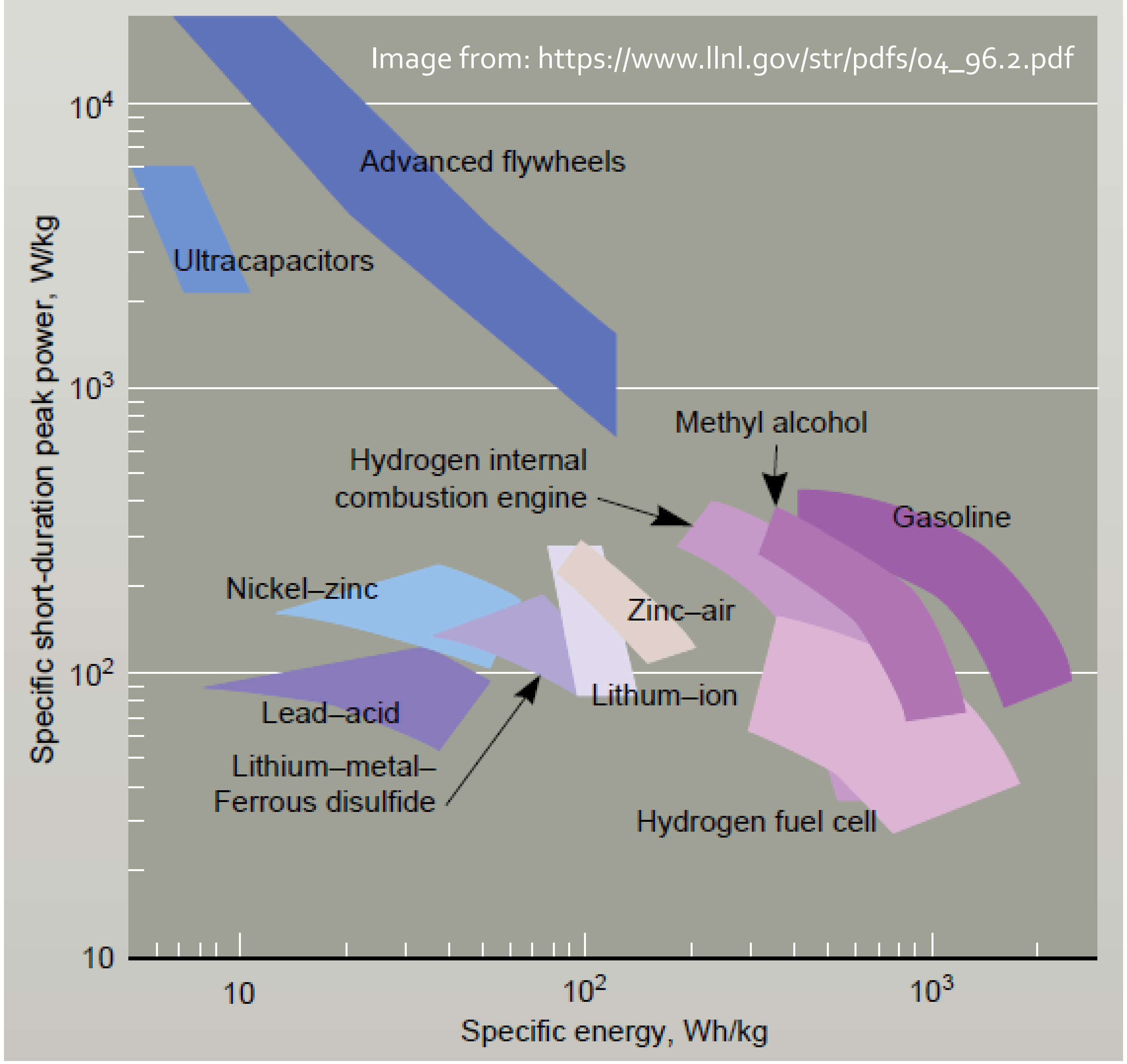


Image from: https://www.llnl.gov/str/pdfs/04_96.2.pdf
Advanced flywheels
Ultracapacitors
Methyl alcohol
Hydrogen internal combustion engine
Gasoline
Nickel–zinc
Zinc–air
Lithum–ion
Lead–acid
Lithium–metal–Ferrous disulfide
Hydrogen fuel cell
Specific short-duration peak power, W/kg
10
10²
10³
10⁴
Specific energy, Wh/kg

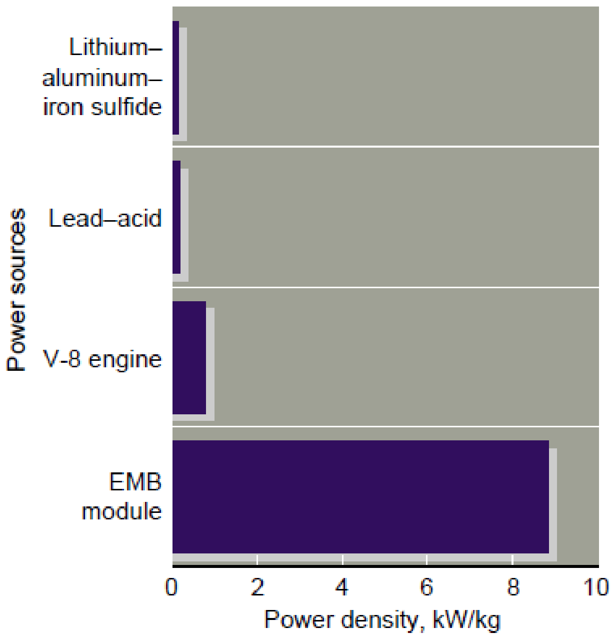
Comparison

Table 1. Comparison of attributes for battery modules.

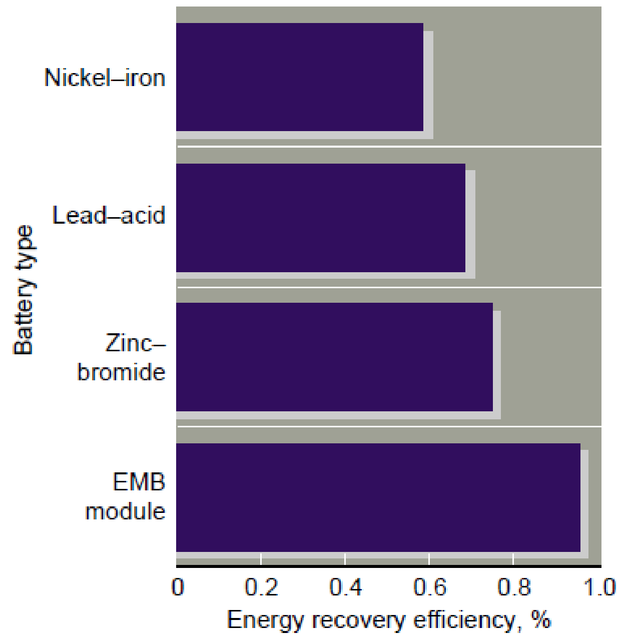
	EMB	Lead-acid battery
Specific power	5–10 kW/kg	0.1–0.5 kW
Energy recovery	90–95%	60–70%
Specific energy	100 Wh/kg	30–35 Wh/kg
Service lifetime	>10 years	3–5 years
Self-discharge time	Weeks to months	Many variables (temperature, usage, etc.)
Hazardous chemicals	None	Lead, sulfuric acid

Images from: https://www.llnl.gov/str/pdfs/04_96.2.pdf

(a)



(b)



Risks

References

- Beacon Power Corporation
  http://www.beaconpower.com/
- Modern Flywheel Technology, Oregon State
  http://www.physics.oregonstate.edu/~demareed/313Wiki/doku.php?id=modern_flywheel_technology
- Vycon
  http://www.vyconenergy.com
- Lawrence Livermore National Laboratory
  https://www.llnl.gov/str/pdfs/04_96.2.pdf
- Wikipedia
  http://en.wikipedia.org
- *Fundamentals of Modern Manufacturing, 3e* by Mikell Groover
- *Essential University Physics, Volume 1, 1e* by Richard Wolfson

Videos

- From Flywheel to Full-Scale Plant

  http://www.beaconpower.com/includes/videos/flywheel-video.html
- A Virtual Tour of Our Headquarters

  http://www.beaconpower.com/includes/videos/virtual-tour-video.html
- Flywheels and Frequency Regulation

  http://www.beaconpower.com/flash/video_large.asp?vid=VID_FLYWHEELS
- Frequency Regulation: How the Market Works

  http://www.beaconpower.com/flash/video_large.asp?vid=VID_REGULATION
- DIY Project

  http://www.youtube.com/watch?v=mV_b50Mqc2M

Practice Problem

- Find the kinetic energy in units of joules (J) of a rotor spinning at 16,000 rpm. The rotor is composed of:
  - an inner steel shaft (ρ=8 g/cm^3) with a length of 2.5 m, and a diameter of .08 m
  - an outer carbon fiber composite hub (ρ=1.7 g/cm^3) with a length of 1.8 m, and an outer diameter of 1.25 m