Flywheel

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A **flywheel** is a rotating mechanical device that is used to store rotational energy. Flywheels have an inertia called the moment of inertia and thus resist changes in rotational speed. The amount of energy stored in a flywheel is proportional to the square of its rotational speed. Energy is transferred to a flywheel by the application of a torque to it, thereby increasing its rotational speed, and hence its stored energy. Conversely, a flywheel releases stored energy by applying torque to a mechanical load, thereby decreasing the flywheel's rotational speed.

Trevithick's 1802 steam locomotive used a flywheel to even out the power of its single cylinder

Common uses of a flywheel include:

- Providing continuous energy when the energy source is discontinuous. For example, flywheels are used in reciprocating engines because the energy source, torque from the engine, is intermittent.
- Delivering energy at rates beyond the ability of a continuous energy source. This is achieved by collecting energy in the flywheel over time and then releasing the energy quickly, at rates that exceed the abilities of the energy source.
- Controlling the orientation of a mechanical system. In such applications, the angular momentum of a flywheel is purposely transferred as a torque to the attaching mechanical system when energy is transferred to or from the flywheel, thereby causing the attaching system to rotate into some desired position.

G2 Flywheel Module, NASA

Flywheels are typically made of steel and rotate on conventional bearings; these are generally limited to a revolution rate of a few thousand RPM.[1] Some modern flywheels are made of carbon fiber materials and employ magnetic bearings, enabling them to revolve at speeds up to 60,000 RPM (1 kHz).[2]

Carbon-composite flywheel batteries have recently been manufactured and are proving to be viable in real-world tests on mainstream cars. Additionally, their disposal is more eco-friendly.[3]

Flywheel movement

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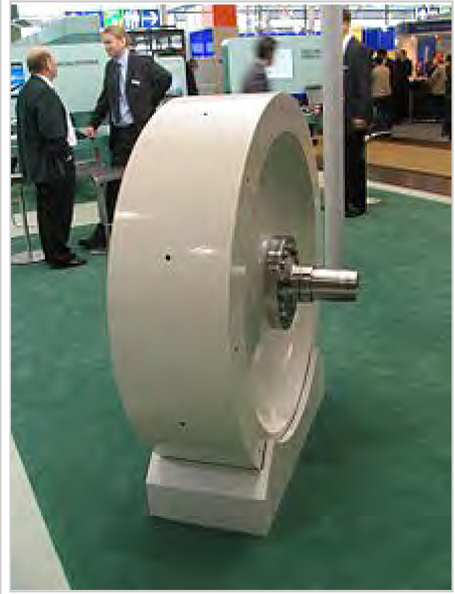
An industrial flywheel.


A Landini tractor with exposed flywheel.

Applications

Flywheels are often used to provide continuous energy in systems where the energy source is not continuous. In such cases, the flywheel stores energy when torque is applied by the energy source, and it releases stored energy when the energy source is not applying torque to it. For example, a flywheel is used to maintain constant angular velocity of the crankshaft in a reciprocating engine. In this case, the flywheel—which is mounted on the crankshaft—stores energy when torque is exerted on it by a firing piston, and it releases energy to the crankshaft when a piston is in the process of compressing a fresh charge of air and fuel. Other examples of this are friction motors, which use flywheel energy to power devices such as toy cars. In uses like this, the distribution of the mass of the flywheel toward the outside and away from the center is beneficial. Pushing the mass away from the axis of rotation gives it greater rotational inertia without increasing its total mass. This increases the efficiency of the flywheel, since it does not have as much difficulty driving its own weight forward as well as that of the payload.

A flywheel may also be used to supply intermittent pulses of energy at transfer rates that exceed the abilities of its energy source, or when such pulses would disrupt the energy supply (e.g., public electric network). This is achieved by accumulating stored energy in the flywheel over a period of time, at a rate that is compatible with the energy source, and then releasing that energy at a much higher rate over a relatively short time when it is needed. For example, flywheels are used in riveting machines to store energy from the motor and release it during the riveting operation.

The phenomenon of precession has to be considered when using flywheels in vehicles. A rotating flywheel responds to any momentum that tends to change the direction of its axis of rotation by a resulting precession rotation. A vehicle with a vertical-axis flywheel, that is rigidly attached to the vehicle, would experience a torque applied to the body of the vehicle that would rotate with as the flywheel precesses. This would produce an alternating rolling and pitching of the vehicle body as it moved up the incline. The descent of the hill would produce the opposite effect and so it would zero out the pitching and rolling (roll momentum in response to a pitch change). Two counter-rotating flywheels may be needed to eliminate this effect. This effect is used in reaction wheels, a type of flywheel employed in satellites in which the flywheel is used to orient the satellite's instruments without the use of thruster rockets. Alternatively, the flywheel would be mounted in two yokes, with axes at mutual right angles, and so allow limited changes to the orientation of the vehicle body thereby eliminating precession.


Modern automobile engine flywheel

History

The principle of the flywheel is found in the Neolithic spindle and the potter's wheel.[4]

The use of the flywheel as a general mechanical device to equalize the speed of rotation is, according to the American medievalist Lynn White, recorded in the *De diversibus artibus* (On various arts) of the German artisan Theophilus Presbyter (ca. 1070–1125) who records applying the device in several of his machines.[4][5]

In the Industrial Revolution, James Watt contributed to the development of the flywheel in the steam engine, and his contemporary James Pickard used a flywheel combined with a crank to transform reciprocating motion into rotary motion.

Physics

A flywheel is a spinning wheel or disc with a fixed axle so that rotation is only about one axis. Energy is stored in the rotor as kinetic energy, or more specifically, rotational energy:

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


A flywheel with variable moment of inertia, conceived by Leonardo da Vinci.

where:

- ω is the angular velocity, and
- I is the moment of inertia of the mass about the center of rotation. The moment of inertia is the measure of resistance to torque applied on a spinning object (i.e. the higher the moment of inertia, the slower it will spin when a given force is applied).
- The moment of inertia for a solid cylinder is $I = \frac{1}{2} m r^2$,
- for a thin-walled empty cylinder is $I = m r^2$,
- and for a thick-walled empty cylinder is $I = \frac{1}{2} m ({r_{\mathrm{external}}}^2 + {r_{\mathrm{internal}}}^2)$,[6]

where *m* denotes mass, and *r* denotes a radius.

When calculating with SI units, the units would be for mass, kilograms; for radius, meters; and for angular velocity, radians per second and the resulting energy would be in joules.

The amount of energy that can safely be stored in the rotor depends on the point at which the rotor will warp or shatter. The hoop stress that develop within the rotor is a major consideration in the design of a flywheel energy storage system.

- $\sigma_t = \rho r^2 \omega^2$

where:

- σ_t is the tensile stress on the rim of the cylinder
- ρ is the density of the cylinder
- r is the radius of the cylinder, and
- ω is the angular velocity of the cylinder.

This formula can also be simplified using specific tensile strength and tangent velocity:

- $\frac{\sigma_t}{\rho} = v^2$

where:

- $\frac{\sigma_t}{\rho}$ is the specific tensile strength of the material
- v is the tangent velocity of the rim.

Material selection

Flywheels are made from many different materials; the demands of the application determine the choice of material. Small flywheels made of lead are found in children's toys. Cast iron flywheels are used in old steam engines. Flywheels used in cars to smooth power-transmission may be made of cast or nodular iron, steel or aluminum depending on the performance application.[7] Flywheels made from high-strength steel or composites have been proposed for use in vehicle power storage and braking systems.

The efficiency of a flywheel is determined by the amount of energy it can store per unit weight. As the flywheel's rotational speed or angular velocity is increased, the stored energy increases; however, the centrifugal stresses also increase. If the centrifugal stresses surpass the tensile strength of the material, the flywheel will break apart. Thus, the tensile strength determines an upper limit to the amount of energy that a flywheel can store.

In this context, using lead for a flywheel in a child's toy is not efficient; however, the flywheel velocity never approaches its burst velocity because the limit in this case is the pulling-power of the child. In other applications, such as an automobile, the flywheel operates at a specified angular velocity and is constrained by the space it must fit in, so the goal is to maximize the stored energy per unit volume. The material selection therefore depends on the application.[8]

The table below contains calculated values for materials and comments on their viability for flywheel applications. CFRP stands for carbon-fiber-reinforced polymer, and GFRP stands for glass-fiber reinforced polymer.

Material	Specific tensile strength $(\frac{kJ}{kg})$	Comments
Ceramics	200-2000 (compression only)	Brittle and weak in tension, therefore eliminate
Composites: CFRP	200-500	The best performance—a good choice
Composites: GFRP	100-400	Almost as good as CFRP and cheaper
Beryllium	300	The best metal, but expensive, difficult to work with, and toxic to machine
High strength steel	100-200	Cheaper than Mg and Ti alloys
High strength Al alloys	100-200	Cheaper than Mg and Ti alloys
High strength Mg alloys	100-200	About equal performance to steel and Al-alloys
Ti alloys	100-200	About equal performance to steel and Al-alloys
Lead alloys	3	Very low
Cast Iron	8-10	Very low

[9]

The table below shows calculated values for mass, radius, and angular velocity for storing 500 J. The carbon-fiber flywheel is by far the most efficient; however, it also has the largest radius. In applications (like in an automobile) where the volume is constrained, a carbon-fiber flywheel might not be the best option.

Material	Energy storage (J)	Mass (kg)	Radius (m)	Angular velocity (rpm)	Efficiency (J/kg)
Cast Iron	500	0.0166	1.039	1465	30121
Aluminum Alloy	500	0.0033	1.528	2406	151515
Maraging steel	500	0.0044	1.444	2218	113636
Composite: CFRP (40% epoxy)	500	0.001	1.964	3382	500000
Composite: GFRP (40% epoxy	500	0.0038	1.491	2323	131579

[10]

Table of energy storage traits

Flywheel purpose, type	Geometric shape factor (k) (unitless – varies with shape)	Mass (kg)	Diameter (cm)	Angular velocity (rpm)	Energy stored (MJ)	Energy stored (kWh)	Energy density (kWh/kg)
Small battery	0.5	100	60	20,000	9.8	2.7	0.027
Regenerative braking in trains	0.5	3000	50	8,000	33.0	9.1	0.003
Electric power backup[11]	0.5	600	50	30,000	92.0	26.0	0.043

[12][13][14][15]

For comparison, the energy density of petrol (gasoline) is 44.4 MJ/kg or 12.3 kWh/kg.

High-energy materials

For a given flywheel design, the kinetic energy is proportional to the ratio of the hoop stress to the material density and to the mass:

- $E_k \propto \frac{\sigma_t}{\rho} m$

$\frac{\sigma_t}{\rho}$ could be called the specific tensile strength. The flywheel material with the highest specific tensile strength will yield the highest energy storage per unit mass. This is one reason why carbon fiber is a material of interest.

For a given design the stored energy is proportional to the hoop stress and the volume:

- $E_k \propto \sigma_t V$

Rimmed

A rimmed flywheel has a rim, a hub, and spokes.[16] Calculation of the flywheel's moment of inertia can be more easily analysed by applying various simplifications. For example:

- Assume the spokes, shaft and hub have zero moments of inertia, and the flywheel's moment of inertia is from the rim alone.
- The lumped moments of inertia of spokes, hub and shaft may be estimated as a percentage of the flywheel's moment of inertia, with the majority from the rim, so that $I_{\text{rim}} = K I_{\text{flywheel}}$

For example, if the moments of inertia of hub, spokes and shaft are deemed negligible, and the rim's thickness is very small compared to its mean radius (R), the radius of rotation of the rim is equal to its mean radius and thus:

- $I_{\text{rim}} = M_{\text{rim}} R^2$

See also

- Dual mass flywheel
- Flywheel energy storage
- Diesel rotary uninterruptible power supply
- List of moments of inertia
- Clutch

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External links

- Flywheel batteries (http://itotd.com/articles/332/flywheel-batteries/) on *Interesting Thing of the Day*.
- Flywheel-based microgrid stabilisation technology. (http://reneweconomy.com.au/2015/darwin-made-outback-tested-energy-storage-system-to-be-used-in-remote-africa-88338), ABB
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