

KINETIC ENERGY FLYWHEEL ENERGY STORAGE

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“A journey of a thousand miles starts with a single step.”
Mao Tse Tung

“If you do not know where you are going, any road will take you there.”
The Cheshire Cat, Alice in Wonderland

INTRODUCTION

Flywheels can store electricity from the electric grid in the form of kinetic energy, and can dispense that energy back to the grid in quick bursts. They have potential as energy storage devices for renewable energy sources, which are intermittent and unpredictable. Solar and wind power in particular would become more promising as energy storage is used to capture and store their energy for later use.



Figure 1. Flywheel system. Source: Beacon Power.

A flywheel provides extremely fast response times and optimal grid behavior. The flywheel constitutes a very simple and robust system with reliable operation and long term spare parts supply such as ball-bearings. Wind energy using fast rotating flywheels can be used to store wind power.

Composite metallic and polyester resin materials can be used in flywheels with an efficiency:

$$\eta = \frac{\text{Restored energy}}{\text{Consumed energy}} = 80 \text{ percent.} \quad (1)$$



Figure 2. G2 flywheel with a rotational speed of 41,000 rpm. Source NASA.

APPLICATION TO WIND ENERGY



Figure 3. Enercon 200 kW of rated power and 5 kW.hr of energy storage capacity flywheel for use with a standalone wind power system. Source: Enercon.

Wind energy production fluctuations can be smoothed out by storage in a flywheel system, particularly for stand-alone installations.

With a flywheel rotating at 15,000 rpm on magnetic bearings in a vacuum chamber, it is theoretically possible to store 400 W.hr/kg for a period of 24 hours. A limitation shared with nuclear fuel enrichment centrifuges exists: beyond a certain critical rotational speed the centrifugal stresses would cause a catastrophic failure of the device.

ENERGY STORAGE IN A STRAIGHT ROTATING FILAMENT

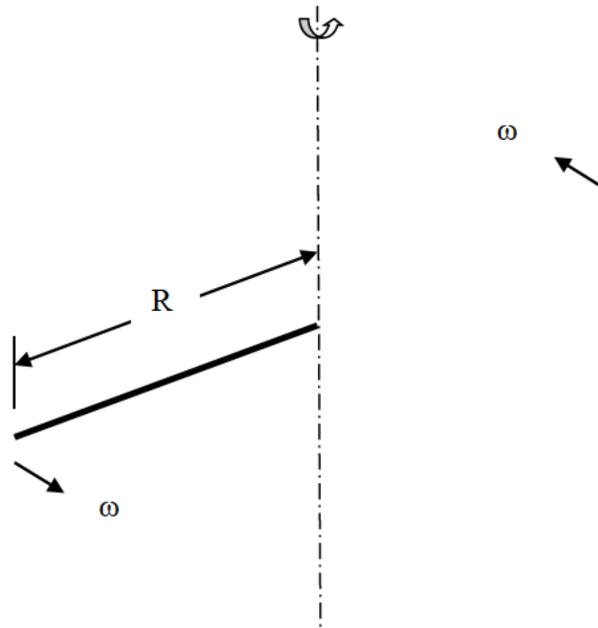


Figure 4. Rotating straight half-filament.

We consider the energy storage capability of a straight filament of length $2R$ rotating around a vertical axis at a rotational speed ω [radians/sec].

The kinetic energy of the rotating can be written as:

$$E = \frac{1}{2} I \omega^2 \text{ [in.lb]} \quad (2)$$

In this equation, I is the moment of inertia about the spin axis. For a thin rod of weight W , exclusive of the shaft and hub:

$$I = \frac{R^2 W}{3g} \left[\frac{\text{in}}{\text{lb.sec}^2} \right] \quad (3)$$

where $g = 386[\frac{in}{sec^2}]$, is the gravity acceleration constant.

Substituting from Eqn. 3 into Eqn. 2 yields:

$$E = \frac{1}{2} \frac{R^2 W}{3g} \omega^2 = \frac{1}{6} \frac{W}{g} R^2 \omega^2 [in.lb] \quad (4)$$

This suggests that the energy storage capability of the rotating filament is proportional to its weight W . It is also proportional to the square of its length and its rotational speed.

The specific energy storage capability of the rotating filament is given by:

$$\frac{E}{W} = \frac{1}{2} \frac{I \omega^2}{W} = \frac{1}{2} \frac{\frac{R^2 W}{3g} \omega^2}{W} = \frac{R^2 \omega^2}{6g} \quad (5)$$

It is also expressed in terms of the material properties as:

$$\frac{E}{W} = \frac{\sigma^2}{3\rho} \quad (6)$$

where: $\sigma [psi]$, is the stress at the rotational speed ω

$\rho [\frac{lb}{in^3}]$, is the material weight density

To obtain a high value of the specific energy storage E/W for a flywheel, high rotational speeds and high strength, low density material are chosen.

FLYWHEEL APPLICATIONS

Flywheels are an old and familiar technology. Flywheels have been used in the potter's wheel since 6,000 years ago, as a stone tablet with enough mass to rotate smoothly between the kicks on a foot pedal. Flywheels were an essential component in the steam engine at the dawn of the industrial revolution.

Flywheels are used in cars with manual transmissions. Internal combustion moves the pistons up and down within the bore, regulated by spark timing. The flywheel is used to transfer engine torque to a friction disc, a throw-out bearing and finally the clutch. Once these are turning at the same speed as the engine, the clutch is released and the motion is carried through the gear assembly in the transmission in the rear wheel drive vehicles to the drive shaft, or in a transaxle vehicle to the axles.

In a pull-start lawn mower or any pull-start motor the pulley that the rope is wound around is attached to a weighted flywheel. When the rope is pulled, it moves the pulley, and engages the flywheel. At the end of the rope pull, the pulley disengages from the flywheel, which continues to momentarily turn allowing the pistons to compress the

fuel vapors and start the combustion process. The energy applied to the flywheel allows it to turn the motor mechanisms for operation faster and easier than one could do by hand.

MODERN FLYWHEEL TECHNOLOGY

The true potential of the flywheel is recently being realized. When spun up to very high speeds, a flywheel becomes a reservoir for a massive amount of kinetic energy, which can be stored or drawn back out at will acting as an electromechanical battery.

A lead acid battery cell stores energy with specific energy of 30-40 Watt-hours/kg; enough to power a 100 Watt bulb for about 20 minutes. A flywheel-based battery, on the other hand, can reach specific energies 3-4 times higher, at around 100-130 Watt-hours/kg.

The flywheel can also store and discharge the stored kinetic energy rapidly without being damaged. It can charge up to full capacity within minutes instead of hours and deliver up to one hundred times more power than a conventional battery.

Table 1. Candidate materials for flywheel materials.

Material	Density [gm/cm ³]	Maximum peripheral speed [m/s]	Tensile Strength [Newton/mm ²]	Tensile strength to density ratio
Carbon fiber composite	1.7	>800	2,000	1176.47
Glass fiber composite	2.0	600	700	350.00
Maraging steel, superhard alloy	8.0	525	2,250	281.25
High strength steel	8.0	455	1,700	212.50
Titanium	4.6	440	920	200.00
High strength aluminum alloy	2.8	425	520	185.71

In addition, it is unaffected by extreme temperatures, boasts an efficiency of 85-95 percent, and has a lifespan measured in decades rather than years.

Modern flywheels function by using electricity to accelerate a carbon fiber rotor inside a vacuum. When the power grid needs a burst at peak demand times, that kinetic energy is released, and the flywheel slows down. When more energy is being generated, it can be sent to the flywheel, which will speed up.

Electrical utilities use flywheels for electrical load leveling purposes to maintain a steady flow of electricity between power generation peaks, or storing surplus energy during low-demand periods to prevent brownouts later on. Flywheels can maintain the balance between supply and surging demand. Currently, utilities use natural gas power plants to maintain that balance.

Laboratory experiments that require huge amounts of electricity are sometimes powered by a flywheel, which can be gradually charged up over time rather than placing a massive drain on the power grid all at once.

The National Aeronautic and Space Administration, NASA is developing flywheel systems as a replacement to batteries in space applications. Other than a marked superiority in energy density and lifespan, flywheels have the unique advantage of providing energy storage and attitude control for a spacecraft or satellite in one easy package. When two flywheels aboard a satellite spin in opposite directions at equal speeds, the satellite will maintain its attitude; when energy is transferred between the wheels to speed one and slow the other, the satellite will rotate.

GYROBUS, ELECTRICAL VEHICLES

Despite decades of development, a practical electric automobile seems as far away as ever because of the limitations of current batteries. They are lacking in power, storage capacity, charge speed, durability, and lifespan. Flywheel energy storage could well be the solution.

The Gyrobus was a public transportation vehicle that saw service in Switzerland, Zaire, and Belgium during the 1950s. Electric buses were already common at the time, but they were restricted to traveling along a grid of overhead electric lines. The idea behind the Gyrobus was to free a bus from connection to the wires.

Instead of a conventional engine, the bus carried a 3-ton rotating steel wheel attached to an electric motor. When the bus was parked at a charging station, the motor would accelerate the flywheel up to around 3,000 rpm. To take off, the motor was used as a generator, converting the flywheel's kinetic energy back into electricity which drove the bus's wheels.

The charging process took between 30 seconds and 3 minutes. Once charged a Gyrobus could travel 3-6 miles at speeds of 30-40 mph.

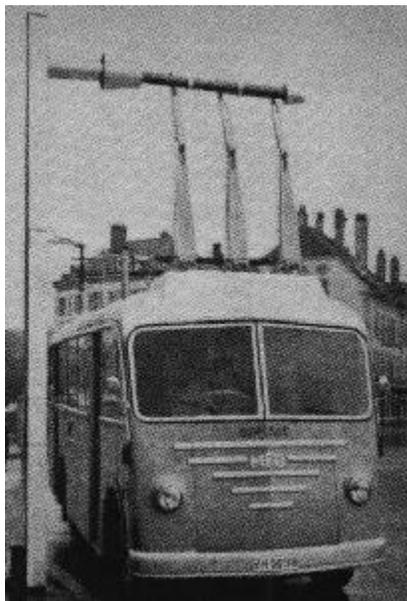


Figure 5. The Gyrobus used a flywheel in the 1950s in Switzerland.

Problems were encountered with the design. The flywheel sat on a standard bearing which frequently broke under the strain, and which rapidly drained the wheel's energy through friction. A need to recharge the bus every few stops proved to be a hassle. The massive wheel made it heavier and less efficient than a regular bus design.

The justification for the bus's massive steel wheel is that the heavier a rotating object is, the more kinetic energy it holds. Increasing the object's rotational speed, which raises its energy-quadratically rather than linearly is a more efficient way to add energy. But spinning a steel wheel faster would tear it apart. The designers were stuck with favoring size over speed.

In the 1970s, materials both stronger and lighter than steel were developed. Carbon fiber flywheels exist that can be spun fast enough to hold 20 times more energy than steel wheels of equal mass.

Flywheel energy systems use magnetic bearings, which levitate the wheel within a vacuum enclosure so that it spins in a nearly friction-free environment.

Flywheels under experimental conditions some have spun for up to two years without outside influence. If friction is present, the flywheel can be kept at full charge indefinitely by trickling in just enough energy to overcome it.

BITTERLY'S FLYWHEEL

Jack Bitterly, chief engineer for the company US Flywheel Systems in the 1990s used a combination electric motor/generator to add and draw power from a flywheel made of computer-molded carbon fiber and spun silently on magnetic bearings at 100,000 rpm.

Enclosed in a reinforced vacuum container, it weighed less than 100 pounds and could deliver a steady 20 horsepower, or 50 HP in shorter bursts. Bitterly's idea was to put 16 of these units into a regular-sized car, which would generate 800 hp and travel 300 miles on a single charge resulting in the same range as a tank of gasoline at a cost of around 5-10 dollars.

One important element of Bitterly's system is the way a computer was used to design a custom pattern for winding the carbon fiber that makes up their flywheel. The result is that it has the highest possible fiber to epoxy ratio, and as the carbon fiber is much stronger than the epoxy, the wheel can safely withstand much greater rotational speeds than normal high-strength carbon fiber.

A number of obstacles face a practical flywheel car. Magnetic bearings are not yet up to the task demanded by a moving vehicle. Keeping a flywheel spinning in a laboratory or in the weightless vacuum of space is simple. Spinning a flywheel within a speeding car contending with swerves, stops, and bumps is a difficult task. The magnetic bearings must adjust on-the-fly to the sizable g-forces produced by ordinary driving in order to prevent energy loss and damage from a flywheel "touchdown."

Even under perfect conditions, current magnetic bearings are expensive, unreliable, and drain excess energy through eddy currents which are random electrical flows in the system.

A problem unique to flywheel designs is the gyroscopic effect, which causes spinning objects to resist changes to their orientation. This is not a desirable trait when a vehicle is attempting to turn corners.

SAFETY ISSUES

Safety is a concern. A compact flywheel system carries roughly the kinetic energy of a military tank traveling at highway speed, all of which must be released very quickly if the flywheel breaks apart or falls off its axle. Numerous deaths have resulted from just such failures throughout the history of modern flywheel design.

This safety issue caused the demise of the Chrysler “Patriot,” a hybrid racing vehicle built in the early 1990s. The car featured a 58,000 rpm flywheel as part of its drive system, but the power of the wheel could never be safely and practically contained.

The difference between a potentially deadly failure and a harmless disintegration is the strength of a flywheel’s container. Designers must balance strength with mass in order to keep a vehicle’s weight down. The perfect materials and design for such a container remain a challenge.

Flywheels “bursting” when they had reached their limits of energy storage can be remedied with “wound” flywheels. Where a steel disc would burst, the “wound” wheel would come apart and fill up the housing and come to a stop.

Carbon fiber wheels are also wound from filament that will come apart and fill up the housing in much the same way. Whereas the wound steel flywheels could be “re-wound”, the carbon wheels turn into “fluff.”

A liquid could easily be encapsulated in such a way that it would be the mass of the flywheel yet designed to fail much more safely.

If the housing is also made of carbon filament, it also reacts to the flywheel running into it by turning into the same “fluff” and slowly bring the wheel to a stop.

Magnetic bearings have plenty of potential for improvement and cost reduction: the biggest advance might come from passive magnets made out of superconducting materials, which would eliminate the problems with energy drain and most of the control hardware.

The gyroscopic effect can be largely canceled by mounting the flywheel enclosure on a gimbal or by pairing each flywheel with a counter-rotating partner.

The risk of flywheel failure can be managed much like gasoline as a chemical energy storage medium.

RECENT APPLICATIONS

A flywheel plant at Stephentown, New York, will help the natural gas plants meet the grid's power demands. It would provide about 10 percent of frequency-regulation services in New York for a typical day.

Flywheels are slowed down by mechanical friction in the bearings, and air friction on the flywheel itself. For this reason modern flywheels are enclosed in a drum evacuated of air, as close to solid vacuum as is possible with current technology.

The bearings use magnetic levitation system which has zero measurable friction, thus allowing the system to theoretically be 100 percent efficient. The limiting factor in the storage efficiency of the system is the motor/generator. Some of the electrical energy

added to the system is converted to heat by the motor, and some of the energy pulled out will do the same through the generator, adding two inefficiencies.

This system loses miniscule amounts of energy throughout the storage period, effectively losing no energy at all for a day to day peak and valley draw that this system is being used for.

A limiting factor is the ratio of the tensile strength of the flywheel material to its density. With current state of the art fused silica materials one can get up to almost 1 MJ per kg of flywheel material. This is useful for power conditioning on the grid and for replacing lead-acid batteries for backup power at data centers.

It needs to be better than this to compete with lithium ion batteries for use in vehicles of various kinds.

The speed at the surface of the flywheel is Mach ~4. A hefty vessel is needed to prevent the flywheel from becoming a missile if it fails. It is not clear that increasing the energy density of the flywheel itself will increase overall energy density in vehicles. For stationary uses one cannot cover the flywheel with enough dirt or emplace it behind enough concrete as a shield material.

For systems that are buried outside of buildings, a foot or so of sand surrounding the normal containment structure should do wonders for absorbing the released kinetic energy.

A flywheel made out of carbon nano-tubes one could store as much energy into the flywheel as exists in an equivalent mass of gasoline or about 40 MJ/kg. The speed at the surface of the flywheel would be about Mach ~25.

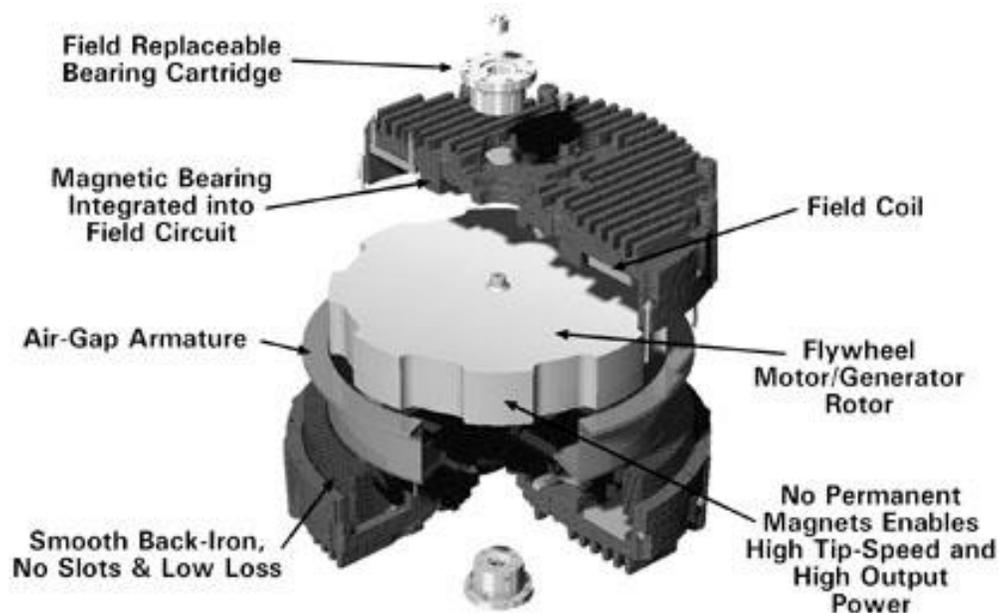


Figure 6. Flywheel motor-generator. Source: CleanSource.

MAGNETIC BEARINGS

Magnetic bearings offer a host of advantages, including high speed capabilities and the ability to operate lubrication-free and in vacuum environments. They generate no friction, experience minimal wear, and operate contamination free with extremely low vibration.

Magnetic bearings can precisely control shaft position, measure external forces acting on the shaft, and monitor a machine's operating condition. Magnetic-bearing systems electromagnetically suspend shafts by applying electric current to a bearing's ferromagnetic materials. The systems have three main elements: bearing actuators, position sensors, and controller and control algorithms.

Typical units consist of two magnetic radial bearings and one magnetic thrust bearing. They control the shaft along five axes: two axes for each radial bearing and a fifth axis along the shaft. The radial stator is formed by a buildup of laminations, each of which is shaped with poles. The laminations stack together, and coils of wire are wound around each pole.

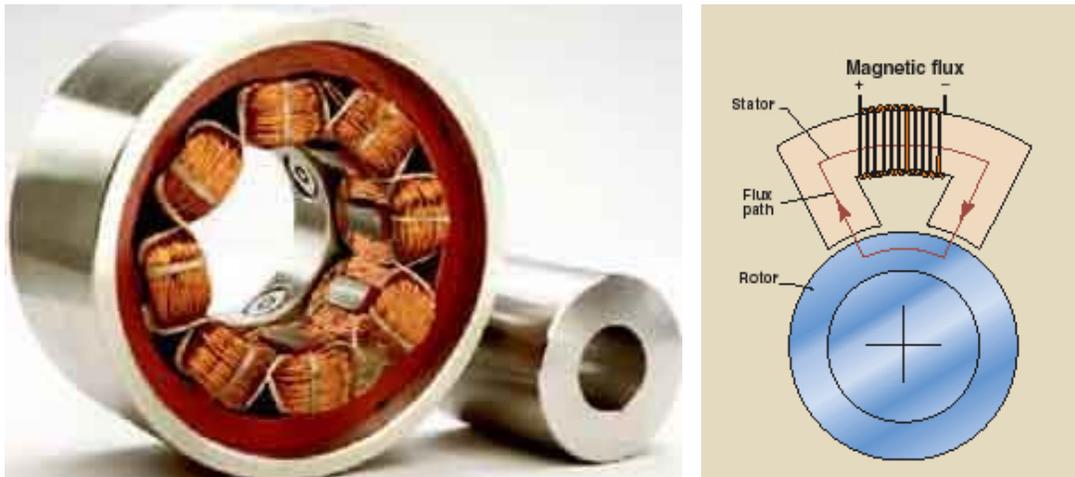


Figure 7. Magnetic bearing stator and rotor.

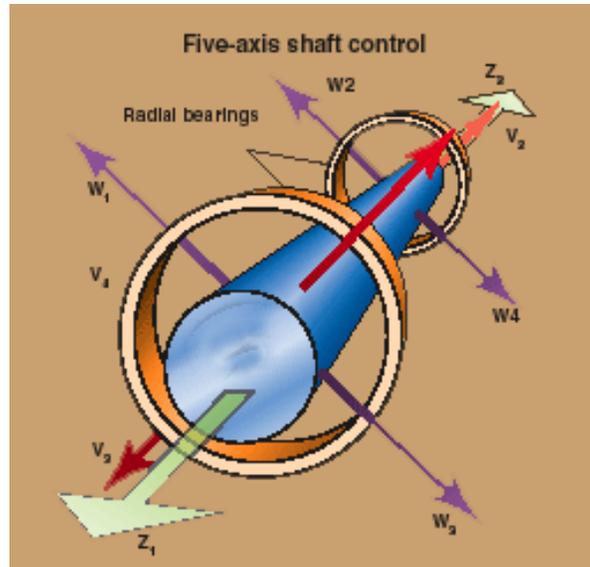


Figure 8. Five axes control of magnetic bearing: Two axes for each axial bearing and one running along the shaft axis. Source: machinedesign.com.

Controlled electric currents passing through the coils produce an attractive force on the ferromagnetic rotor and levitate it within an air gap. The gap usually measures about 0.5 mm but, in some applications, can be as large as 2 mm. The rotor fits over the shaft, which is in the air gap but need not be centered.

A magnetic thrust bearing provides axial control. The thrust-bearing rotor is a solid steel disk attached to the shaft and positioned at a preset distance from the stator on one or both sides. During operation, electromagnetic forces produced by the stator act on the rotor and control axial movement.

Magnetic bearing arrangements include touchdown or auxiliary bearings. Their main function is to support the shaft when the machine is idle and protect machine components in case of power outage or failure. The touchdown bearing's inner ring is smaller than the magnetic-bearing air gap to prevent potential damage if the shaft delevitates.

USE ON TRAINS

Most electrical commuter trains run with miles of overhead wire. When one of those wires goes down, the train cannot operate.

Flywheels can be installed on wireless trains. One can speed up with the flywheel array, recapture the energy when the brakes are applied, and top off at each station along the way.

A train would not experience the same stop and go chaotic activity that plagues the idea of flywheel automobiles; with a train you know where you're starting and stopping and doing it however fast you please. There are no unexpected or sharp turns, no potholes, no banking.

The reduction in infrastructure required could more than make up for the added cost of the flywheel array. Tracks would no longer need the overhead wires anywhere except the stations and perhaps booster runs along extended stretches.

FLYWHEEL DESIGN CONSIDERATIONS

RELIABILITY

Multiple flywheels about the size of a standard auto wheel must be used to provide a redundant system. Should any fail, power will still be available.

SAFETY

A smaller flywheel loses its kinetic energy faster than a larger one. Should one ever get loose, the smaller ones would cause less damage than say a massive car-sized one.

It is easier to move and replace any parts on say a 150-pound metal wheel than a one-ton plus metal wheel.

However, the more parts to a system, the higher the maintenance cost and the more components that can and will fail.

CONTROLLED ENVIRONMENT

The system must be stored in a so climate controlled area to ensure a longer life span for the various components since rust and dirt cause friction which decreases the system's efficiency.

A hardened concrete structure would be best with a positive pressure system with filtered air blown into the structure so that any dust/dirt is blown out.

If a mount failure occurs, and the friction/magnetic safety brake failed to slow/stop the flywheel, it would just rebound within the enclosure.

Each flywheel would have its own enclosure to decrease chances of it damaging the other ones.

AVAILABILITY

The system must be designed so that the power usage will never cause the flywheels to drop below a certain rotational speed since the initial cost in energy to start the flywheel moving from a dead stop is over 3 times what is needed to keep them spinning.

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