Flywheel Batteries Come Around Again

Kinetic energy storage will propel applications ranging from railroad trains to space stations

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"What goes around comes around" is not just a popular expression and the title of a Bob Marley song, it is also a good description of what is happening these days with flywheel energy storage. The technology is coming around again after undergoing a round of improvements in materials, magnetic bearing control, and power electronics.

Of course, scientific and technical advances by themselves are not enough to renew interest in a technology, however good it may be. The advanced wizardry must also serve a genuine need. Today's flywheel batteries, which depend on a rotating mass to store energy, score well in both areas: they embody several exciting technological advances, and they are serious contenders for a variety of important energy-storage applications. They are, for example, competitive with chemical batteries in applications like transportation or improving power quality, which involve many charge-discharge cycles and little in the way of long-term storage.

Progress in power electronics, particularly in high-power insulated-gate bipolar transistors (IGBTs) and field-effect transistors (FETs), underlies higher-power flywheel operation. While the stored energy is determined by the speed, mass, and geometry of the wheel, the limits on input and output power are in general set by the power electronics. With these higher-power devices, fewer individual components are needed, so the power electronics package can be comparable in size to the flywheel plus motor-generator combination.

The growing density of energy storage is to be attributed mainly to advances in fibers, resins, composite manufacturing techniques, and manufacturing quality control. Together, these have made it possible to construct flywheels strong enough to operate reliably at high speed [see photo, opposite]. Exploiting such developments, US Flywheel Systems (Pasadena, Calif.) has operated a composite flywheel at 60 000 r/min with a corresponding rim speed of about 1 km/s. On the lifetime reliability front, the University of Texas at Austin has subjected a composite flywheel spinning at about 48 000 r/min to more than 90 000 charge-discharge cycles with no loss of functionality.

In an increasingly electrical world, the need to store electric energy is growing, both to help improve power quality and to accommodate distributed generation. Most schemes for realizing those goals involve the storage of energy near the load, which, as shall be shown, makes flywheel batteries prime candidates for the job.

Nor are grid-connected applications the only likely beneficiaries. In transportation, hybrid vehicles need to store power. While an internal combustion engine supplies them with constant power, an electric motor powered by a temporary store (today most often a nickel metal-hydride battery) supplies extra energy for acceleration, deceleration, and (in the future) electrically actuated active suspensions. Flywheels are also finding a place in hybrid gas-turbine/electric trains, where battery banks would be too large and heavy.

Space vehicles, especially those in orbit around the earth, should also make a good home for flywheel batteries. In earth orbit, after all, the sun is the prime energy source, so that energy must be stored for the parts of the orbit when the satellite is in darkness.

In military affairs, the recently released modernization plans for both the U.S. Navy and the U.S. Army indicate their intention to depend more heavily on electricity for the propulsion of both ships and manned and unmanned ground vehicles, as well as for the weapons, navigation, communications, and intelligence systems they carry. This multipurpose use of electric energy tends to call for more energy storage because the various systems often use energy at different rates—that is, at different power levels. With appropriate energy storage, the primary power source may be absolved from handling the peak power load.

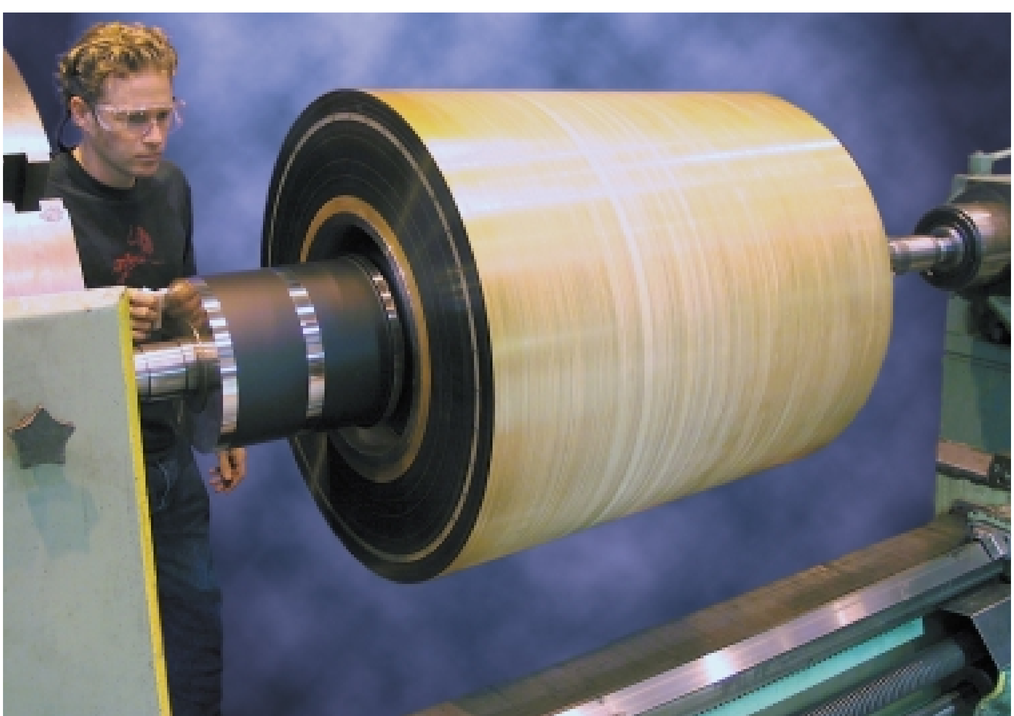
Alternative forms of storage

Flywheel energy storage systems are attractive for the types of applications for which a designer might also consider conventional electrochemical batteries or superconducting magnetic energy storage (SMES). With the latter, energy is stored in the magnetic field surrounding a coil of superconducting wire. When cooled to cryogenic temperatures, superconducting wires exhibit zero resistivity, which means that a current circulating in such a coil can persist for a very long time without loss. Of course, keeping the coil at cryogenic temperature itself consumes energy, which is one reason why SMES systems are not considered suitable for long-term energy storage [see table comparing lead-acid batteries, flywheel batteries, and SMES systems, middle of next page].

Given the state of development of both flywheel batteries and SMES systems, it is to be expected that costs for both can be lowered with further technical development. On the other hand, electrochemical batteries, above all the lead-acid variety, already have a tremendous economy of scale that has driven costs down about as far as they are likely to go. The comparison table suggests that lead-acid batteries and flywheel systems are competitive on the basis of life-cycle cost for some applications today.

In all probability, all three technologies will remain viable. Each has attributes different enough from those of the others to maintain a market niche unless a disruptive technological breakthrough occurs in one area.

Modern flywheel batteries have been designed for a variety of applications [see bottom table, next page]. Their initial niche will be for individual flywheels capable of storing approximately 1–500 megajoules. As the table shows, the peak power ranges from kilowatts to gigawatts, with the higher powers aimed at pulsed-power applications. All these systems are in



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A flywheel rotor for a railroad locomotive is being wound with a composite material under the watchful gaze of Robert L. Sledge, a research engineer at the University of Texas at Austin's Center for Electromechanics.

use, in testing, or under construction, except that the one for the hybrid combat vehicle is still in the design phase.

A steady source of power

Another role for which flywheel energy storage has been enlisted is to supply highly reliable electric power for seconds to minutes at a time. This is the most mature commercial application to date of flywheel storage for electricity. Companies in both Europe and the United States have developed systems and are distributing them worldwide. For example, Piller GmbH (Osterode, Germany) has installed flywheel energy storage in the combined heat and power station that supplies an AMD semiconductor fabrication facility in Dresden, Germany. The three-year-old plant has an overall power rating of 30 MW; its multiple-flywheel storage subsystem can supply or absorb 5 MW for 5 seconds—that is, it can store 25 MJ, or about 7 kWh. The facility can be powered by the utility grid or local generators. The 5-second storage interval is enough for the plant to switch smoothly between one power source and the other when necessary.

Similarly, Active Power (Austin, Texas) announced that it is delivering 17 flywheels with a combined power rating of 4.75 MW to a plastics product manufacturer, which needs them for power conditioning and to protect against outages. Flywheels integrated with generators from Caterpillar store sufficient energy to power the load while the generators are brought into service.

Most power line disturbances—more than 80 percent of them—last for less than a second. A market therefore exists for an uninterruptible power supply that reacts reliably to occasional, relatively low-energy loads—voltage sags lasting less than a second—but can also store sufficient energy and deliver sufficient power to on occasion carry the entire load for 15 seconds or so, while a standby motor-generator powered by hydrocarbon fuel is brought on line. This application has generally been regarded as the province of either chemical batteries or flywheels; SMES units have been viewed as too costly or complex in this power range. The application is well suited to flywheel batteries for two reasons:

- First, flywheel life is almost independent of the depth of discharge. Flywheel systems can operate equally well on frequent shallow discharges and on very deep discharges. This type of load variation is usually challenging to batteries because the combination of low- and high-power loads makes their design difficult to optimize. With the flywheel battery, the power is limited by the power electronics rather than electrochemistry, which yields a wider range of application.
- Second, the state of charge of a flywheel battery (how much energy it contains and therefore what kind of load variations it can handle) is readily determined from its rotational velocity. Determining the state of charge for an electrochemical battery is more difficult.

How Flywheel Batteries Compare to Lead-Acid and Superconducting Types

	Lead-acid battery	Flywheel battery	SMES
Storage mechanism	Chemical	Mechanical	Electrical
Life (years in service)	3–5	>20	~20
Technology	Proven	Promising	Promising
Number of manufacturers	~ 700	~ 10	~1
Annual sales (in US $millions)	~ 7000	~ 2	A few
Temperature range	Limited	Less limited	Controlled
Environmental concerns	Disposal issues	Slight	Slight
Relative size (equivalent power/energy)	Larger	Smallest	In between
Practical time to hold a charge	Years	Hours	Days
Price, per kilowatt	$50–$100	$400–$800	>$300

SMES = Superconducting magnetic energy storage.

Source: University of Texas

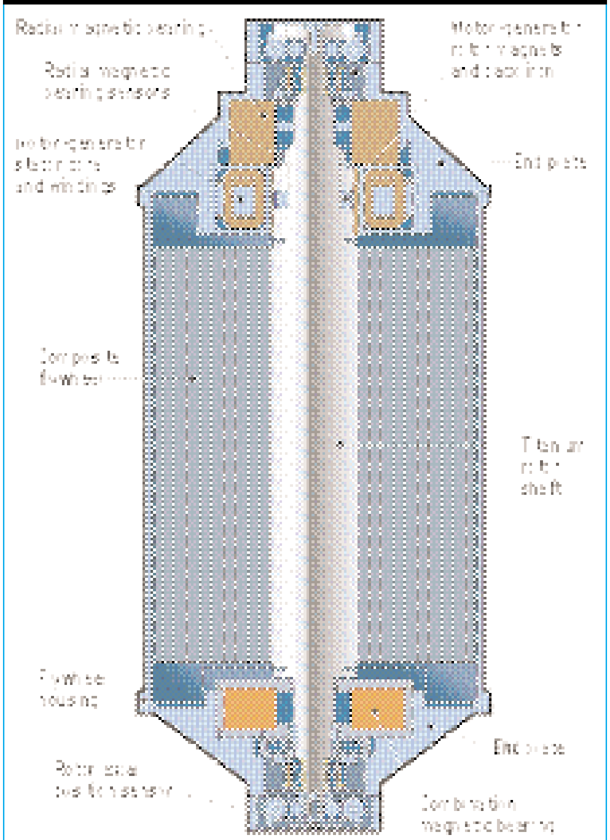
Application-Specific Flywheel Battery Designs

	Peak power	Stored energy, MJ (kWh)	Maximum rotational velocity, rpm	Rim speed, m/s	Rotor material	Rotor mass, kg
Satellite	2 kW	1.4 (0.4)	53 000	900	Composite	30
Power quality	400 kW	4.7 (1.3)	10 000	400	Steel	1400
Hybrid bus	150 kW	7 (2)	40 000	900	Composite	60
Space station	3.6 kW	13 (3.7)	53 000			75
Hybrid combat vehicle	11 MW pulsed; 350 kW continuous	25 (14)	18 000	540	Composite/ metallic	280
Electromagnetic launcher	5–10 GW	50–150 (14–42)	10 000	450	Composite	4000
Train	2 MW	470 (130)	15 000	950		2500

Source: University of Texas

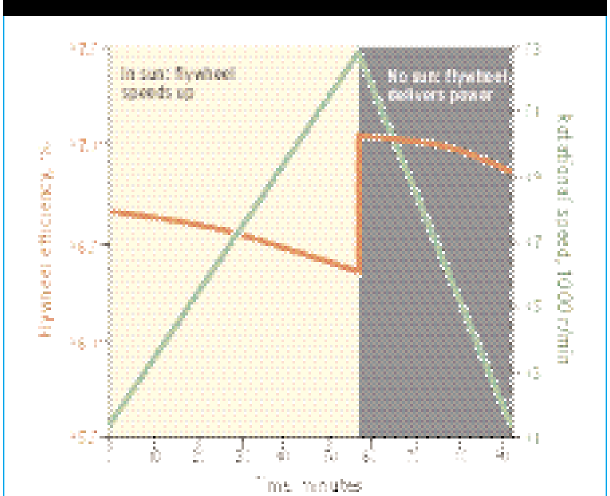
Really Reliable...

Produced for NASA for use in space, this flywheel battery has a composite rotor that spins in a vacuum, supported by magnetic bearings. The one at the bottom is a combination axial and radial bearing; a radial bearing is at the top. Also at the top is the motor-generator through which electric energy enters and leaves the battery.



...And Really Efficient

The NASA flywheel wastes little energy, as shown by a plot of efficiency versus time [below]. Note how it speeds up in sunlight and slows in shadow over a complete earth orbit.



TOP: STEVE STANKIEWICZ BOTTOM: UNIVERSITY OF TEXAS

In general, flywheel batteries are used just like conventional electrochemical batteries: they are connected electrically to chemically fueled engine-generators. For pulsed-power applications, though, where it is important to have as much energy as possible stored (and immediately available) in the rotor's motion, it may be advantageous to couple them mechanically; putting both the flywheel battery and the engine-generator on the same shaft can then minimize overall system size and complexity.

On a smaller scale, staff members at Clarkson University (Potsdam, N.Y.) and the University of South Africa (Pretoria) are developing flywheel storage with a view to helping the nearly one-third of the world's population without access to an electricity grid. Solar power, wind power, or diesel generators can supply these people with some electricity for refrigerating food and medicine and for communication. Renewable sources, though, cannot by themselves ensure a continuous supply of electricity. Storage is also needed. Today that storage almost always takes the form of banks of lead-acid batteries. If the cost of flywheel systems can be lowered for these smaller systems, they may provide a more environmentally benign solution than batteries.

Flywheels in space

One application to which energy storage is of great concern is on the International Space Station. The primary power source is the sun, but the station must continue to operate while in eclipse. The initial design uses battery storage, but an alternative system is under development by NASA.

The flywheel battery [see figure at left, top] has attributes that make it attractive on the space station. It fits in the same space and weighs about the same as the chemical batteries that it would replace, but seems likely to last three to ten times longer. It can power the load for twice as long as a chemical battery without recharging. Finally, the state-of-charge of the flywheel battery is always known from a measurement of its rotational velocity.

Each set of two NASA flywheel units will store in excess of 15 MJ and can deliver a peak power of more than 4.1 kW. Replacing all the battery boxes will take 48 flywheels together capable of producing more than 150 kW. NASA estimates that more than US $200 million will be saved if flywheels replace the first generation of space station batteries.

The system has a net (charge-discharge) efficiency of 93.7 percent [see diagram at left]. The losses in cycling through a charge-discharge cycle are largely due to eddy-current and hysteresis losses in the magnetic bearings and the motor-generator. These losses include all motor, generator, and flywheel losses, but exclude the power electronics. For comparison, the chemical batteries used today are no more than 80 percent efficient. As the chemical and flywheel batteries use comparable power electronics, the flywheel system is more efficient overall.

Besides the efforts in civilian space vehicles, the U.S. Air Force is funding research into flywheel-based systems that store energy and supply attitude control. For the International Space Station, the flywheel batteries are controlled as pairs, so that a change in flywheel rotor speed produces no net torque.

In the Air Force program, a more sophisticated control algorithm is envisioned, such that the same set of flywheels can store energy and provide torque to the spacecraft for attitude control as the flywheel batteries are charged or discharged. This program is coordinated with, and complementary to, the NASA program and is targeted at military satellites.

Research led by staff at Honeywell International (Tempe, Ariz.) aims to develop what the Air Force calls the flywheel attitude control, energy transmission and storage (Facets) system. This system, whose components are being tested today, is to combine all or part of the energy storage, attitude control, and power management and distribution subsystems into a single assemblage, decreasing bus mass and volume. Further, the Facets system is intended to be more efficient than those it replaces—greater than 90 percent—and to be capable of higher rates of charge or discharge than electrochemical batteries. It is designed to provide up to 7.2 MJ of usable energy with a specific energy greater than 150 kJ/kg (42 Wh/kg). It will exploit the gyroscopic action of the energy-storing flywheels to provide three-axis attitude control with maximum control torques greater than 50 N·m on each axis.

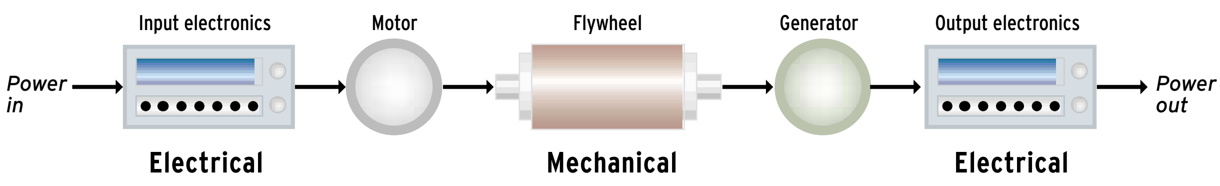
On the road

Hybrid electric vehicles (HEVs) are coming into use to reduce pollution and extend the use of hydrocarbon fuels. The vehicles use both an internal combustion engine and an electric motor for propulsion. The basic idea is that the average power needed to propel the vehicle should be supplied by the engine, which can therefore operate at a nearly constant, optimum speed, reducing fuel consumption, air and noise pollution, and engine maintenance requirements, and extending engine life. Short bursts of power, for climbing hills and acceleration, are taken from an energy store (a battery of one sort or another), which is replenished directly by the engine or by regenerative braking when the vehicle is slowed down.

Unlike friction brakes, which turn kinetic energy into waste heat, regenerative braking changes it into electricity, which is then used to speed up the flywheel, effectively storing more energy for subsequent acceleration. The conversion is done by reversing the motor drive circuitry, which causes the drive motors to act as generators.

A flywheel battery should be a more attractive energy store than a chemical battery for several reasons. It has a longer life, is free from depth-of-discharge effects, and can accept and deliver large amounts of energy in a very short time (higher power and energy density—on both a mass and a volume basis). Because of the current cost of flywheels, they are initially being considered for large vehicles where the battery costs in any case are high. For example, a flywheel to replace the battery pack in a hybrid electric bus is being tested at the University of Texas at Austin. The unit can accelerate a fully loaded bus to

Flywheel Fundamentals



The phrase "flywheel battery" describes a system consisting of a flywheel, a motor-generator, and control electronics for connection to a larger electric power system. What it does is take electric energy from a source, store it as kinetic energy of rotation, and deliver it to a load at the time, and in the form, that the load needs [see drawing above].

The input power may differ from the output power in its temporal profile, frequency, or other attributes. It is converted by the input electronics into a signal appropriate to efficiently driving a variable-speed motor. The motor spins the flywheel, which stores energy mechanically, speeding up as it accumulates energy, and slowing down as it delivers energy to a load. That decrease in mechanical energy is converted into electrical form by the generator. A challenge facing the motor and generator designer is to size the system for the amount of storage (energy) and delivery rate (power) required and to minimize losses. The output electronics convert the variable-frequency output from the generator into the electric power required by the load. Since the input and output are typically separated in time, many approaches combine the motor and generator into a single machine, and the input and output electronics into a single module, to reduce weight and cost.

Modern high-speed flywheels differ from their forebears in being lighter and spinning much faster. Since the energy stored in a flywheel increases only linearly with its moment of inertia (the rotational equivalent of mass) but goes up as the square of its rotational speed, the tradeoff is a good one. But it does raise two issues: flywheel strength and losses due to air friction (windage).

To keep from flying apart, modern flywheels are complex structures based on extremely strong materials like carbon fibers.

Windage losses are addressed by housing flywheels in evacuated containers, the level of vacuum being determined by whatever value of windage loss is tolerable in a particular application. Today's systems typically operate somewhere between atmospheric pressure (100 kilopascals) and 0.1 Pa, with the highest-speed devices operating at the lowest pressure. Lower-speed flywheels are larger, but can be operated in air with acceptable losses.

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100 km/h, stores about 7.2 MJ, and has a peak power capability of 150 kW, as well as a specific energy of more than 120 kJ/kg of rotating mass and a specific power of 2.5 kW/kg of rotating mass. It is smaller and lighter than the batteries it replaces. Moreover and more importantly, the flywheel battery is expected to have three to five times the life of the earlier battery pack. That expectation is based on models and component tests. Verification of the longer life will take in-service testing.

On a spacecraft, the same set of flywheels can store energy and also provide torque for attitude control

If this flywheel battery system continues to operate according to the design, an obvious extension would be to make a smaller system appropriate for an automobile. Further development would probably be required, though, because an automobile would require a smaller flywheel than can be constructed economically today.

A natural concern with flywheel batteries for mobile applications, in close proximity to people, is safety. For a few years now, several safety projects have been funded in the United States by the Defense Advanced Research Projects Agency, the Houston (Texas) Metro Transit Authority, and NASA. Together, they have advanced the safe design and operation of flywheel batteries, developing a three-pronged approach to built-in safety. First, the flywheel is designed not to fail by flying apart. Design margins are verified, largely through spin tests, to failure at speeds well above the rated speed. The second prong is to monitor, generally through the magnetic bearing controller, the dynamic behavior of the flywheel batteries so they can be shut down safely if an abnormal condition should arise. Third is containment. Housings have been developed that can safely absorb the energy of a disintegrating rotor while themselves remaining intact.

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Not only are flywheel batteries being developed for bus applications, but the U.S. Federal Railroad Administration also has a program to develop flywheel batteries for high-speed rail applications. Diesel-powered trains are regarded by many in the industry as too heavy for operation at speeds above about 180 km/h. Electric trains, conversely, are well suited for high-speed operation but electrification of the right-of-way costs millions of dollars per kilometer.

The solution: a hybrid approach in which a gas turbine driving a high-speed generator supplies the average power, while a flywheel battery handles power leveling and storage applications. A generator being developed for this application has a continuous-power rating of 3 MW and fits in a cylinder less than 1.5 meters long and 0.75 meter in diameter.

A flywheel battery for a high-speed passenger train with nine cars would store 470 MJ and would provide 2 MW of peak power. The power and energy requirements are set by the desired speed and the maximum weight of the train sets. Although the flywheel is useful in power leveling for the turbine in grades, the primary design driver is stopping and starting the train set at stations.

This attribute does open up an interesting possibility that has been investigated in a preliminary set of tests reported by London Underground, Urenco Power Technologies, Balfour Beatty Rail Power Systems, and Seeboard Powerlink. They found that by installing three flywheels, provided by Urenco, in a substation supplying a test track, they could reduce the voltage drop at the substation from 180 V to 100 V. They also reported that they could recover about 30 percent of the braking energy. Siemens has reported similar results on a light rail line in Cologne, Germany.

Flywheel-powered combat vehicles

Hybrid electric power is an essential enabling technology for many future combat vehicles, given the number of electrically powered subsystems planned for those conveyances. The U.S. Department of Defense envisions likely future combat vehicles as having electric propulsion as well as suspension, communications, weapons, and defensive systems—all needing electric power. The hybrid electric power system will consist of an engine/alternator, sized for average power demand; fuel cells and their associated small batteries for stealth (quieter) operation; other power-averaging energy-storage components, like flywheels and supercapacitors, to provide both continuous and pulsed power for the various systems on the vehicle; distribution networks; subsystem controls; and power-conditioning devices.

This approach promises to maximize system life by operating the prime power sources at nearly constant power levels. It also reduces the overall vehicle weight because the prime power units are sized for only the average (not the peak) power demand. For those combat systems that must be provided with power in less than about 10 μs, the flywheel batteries would first charge a bank of supercapacitors, which would then power the high-speed systems.

A flywheel designed for this application stores 25 MJ and produces 5–10 MW of pulsed power and 350 kW of continuous power. A system that can store 60 MJ and produce 6 GW is not much larger, being about 1.5 meters high and less than 1 meter in diameter.

Another likely application of flywheel batteries is in the launching of aircraft from carriers. Today, launch catapults are driven by steam systems, which use steam accumulators to store enough energy for the job. The U.S. Navy is developing electromagnetic systems in which flywheels could replace the steam accumulators so that the power-generating system would not have to be sized for the peak power load.

Clearly, flywheel batteries are an emerging technology. Commercial versions are available for limited applications today, but the research and development now under way may stimulate much wider use. ●

Michael J. Riezenman, *Editor*