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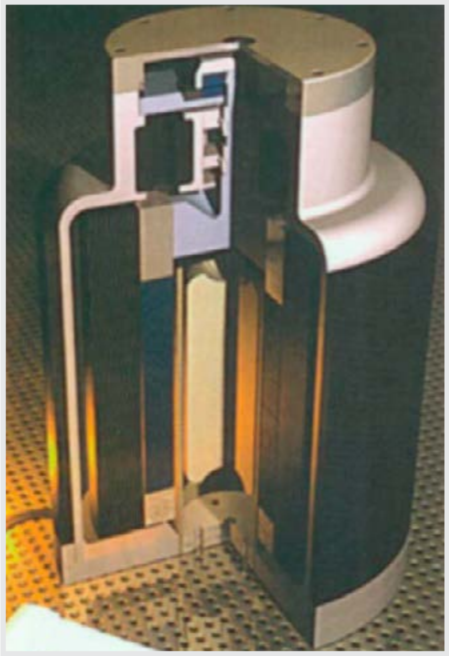
Test Devices by SCHENCK

Designing Safer Energy Storage Flywheels



Packed with power that is available on demand, a practical flywheel battery would go a long way toward making low-pollution, high-mileage hybrid electric cars, trucks, and trains a reality. Few other near-term technologies can foreseeably provide the load-leveling (power-averaging) capabilities necessary for rapid acceleration, speed maintenance on grades, and recovery of braking energy (regenerative braking).

But high energy density has its drawbacks. A high-performance composite flywheel rotor spinning anywhere from 30,000 to more than 100,000 revolutions per minute has lots of inertia. That's going to be tough to control, particularly when moving on rough roads. Another formidable technical challenge is designing a lightweight, cost-effective safety containment system that can resist the impact of burst fragments and transmission of high torque loads just milliseconds after wheel failure.

Fig. 1 — A prototype flywheel energy-storage system designed by Trinity Flywheels is being tested by Pacific Gas & Electric in an uninterrupted-power-supply application.

Several recent industrial developments have placed the issue of flywheel safety in question. Chrysler Corp. recently scrapped well-trumpeted plans to develop a 500 horsepower Patriot LeMans race car, with a flywheel-turbine power plant that would have propelled it to 200 miles per hour. "To make it viable, we needed an order of magnitude improvement in the container," said the project's executive engineer, Tom Kizer. Ford Motor Co., meanwhile, has displayed similar caution regarding flywheel-equipped cars. "An awful lot of energy is stored when a flywheel is spun up to maximum speed," said Robert Mull, chief engineer for Ford's Synergy 2010, a nonworking hybrid electric concept car that included a flywheel and a direct injection diesel. "To protect against failure, you would have to add so much weight and cost that it would not be viable."

Despite the concern, a composite flywheel is a difficult thing to break. Designed to withstand hundreds of thousands, even millions, of 'g's at the rim, fiber/epoxy flywheel rotors regularly resist fracture and de-lamination in overspeed spin ("spin-to-failure") tests conducted in heavily reinforced test cells.

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Fig. 2 — Engineers at the Center for Electromechanics developed this high performance, 2-kilowatt-hour, 150-kilowatt, 40,000-rpm flywheel rotor that will be used in a future hybrid electric transit bus.

Proven durability does not mean that high-performance flywheels pose no risk to operators, however. Last August, a German engineer was killed and two others were injured in an accident during a spin test of a composite flywheel that was designed to fail. The fatal mishap occurred during evaluations being conducted for the German automaker BMW at a laboratory in Ottobrunn run by the government-supported IABG testing authority.

Although details are hard to come by due to the ensuing legal tangle, the tragedy reportedly had several causes. According to one observer, the rotor "was loaded quite unrealistically and dangerously by installing soft iron segments on the inside of the composite rings to load them with very high compressive squeezing stresses." The idea was to cause it to fail at normal operating speeds. Technicians used a test rig designed to evaluate lightweight turbine components and other rotating devices. Unfortunately, the rig's vacuum seal did not provide sufficient closure strength to protect the operators from shrapnel escaping the containment system after the modified wheel broke.

Engineers are reluctant to speak about the incident, but one said it generated a good deal of concern in the flywheel research community. Most agreed that the accident implies no intrinsic insurmountable flywheel hazard but did reinforce the belief that more caution was necessary. Other flywheel researchers said they got religion about safety after seeing the results of their own catastrophic wheel failures.

Just as early auto engineers learned to minimize the substantial fire hazard inherent in a tank of gasoline, their modern counterparts expect to address concerns about flywheel safety successfully, but they acknowledge that much research remains to be done. Little information has been published about the failure modes of graphite and glass fiber Epoxy flywheels and the data that exist are considered proprietary by various flywheel developers.

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The Flywheel Safety Project

To determine the effects of typical composite wheel failures and develop systems that mitigate those failures, the Defense Advanced Research Projects Agency (DARPA) in Arlington, VA, established the Flywheel Safety Project, a cooperative research program, in 1995. The multimillion-dollar collaboration is part of DARPA's ongoing Electric Hybrid Vehicle Program. Besides civilian applications, the Defense Department envisions flywheel batteries fulfilling the demanding power-averaging needs of next-generation combat vehicles equipped with electromagnetic guns, suspensions, and countermeasures.

The Southern Coalition for Advanced Transportation (SCAT), an Atlanta-based nonprofit consortium of 50 businesses, universities, and government agencies engaged in developing advanced transportation technology, serves as the project's administrative lead. The DARPA project couples the country's top commercial flywheel spin-test facility, Test Devices by Schenck in Hudson; VA, with several leading flywheel developers, including the Center for Electromechanics (CEM) of the University of Texas at Austin; Trinity Flywheels Inc. in San Francisco; and US. Flywheel Systems in Newbury Park, CA.

CEM engineers are developing two flywheel energy storage systems under U.S. government contract: a 2 kilowatt-hour, 150-kilowatt, 40,000-rpm unit for a hybrid electric transit bus; and a 165-kilowatt-hour, 3 megawatt, 15,000-rpm system for a locomotive. Trinity is working on stationary and mobile flywheel applications. Mike Bowler, vice president for manufacturing, said that the initial public demonstration of the Trinity unit will take place this month. Pacific Gas & Electric will test a flywheel based uninterrupted-power supply system at its San Ramone Modular Generation Test Facility. Bowler added that the company is building 10 test and evaluation units for customers in the United States, Europe, and Japan. US. Flywheel is working with a 4.1-kilowatt-hour, 100,000-rpm flywheel prototype that the company hopes will be used eventually in banks to drive an all flywheel-powered car.

The idea was to pool the collective resources and assemble the combined expertise of the U.S. flywheel community, said John Gully, assistant director for land systems in DARPA's Tactical Technology Office. "After hosting two flywheel workshops at Oak Ridge National Laboratory in Oak Ridge, TN, we realized that the 10 or so competing flywheel development groups were doing pretty much the same things in parallel." The competitors clearly considered the bearing, rotor, and motor/ generator technologies to be too proprietary for open cooperation, but, Gully said, "no one was working on containment even though everybody needed it."

The DARPA managers deemed the safety containment issue a key pre-competitive technology appropriate for a cost-shared cooperative research effort. "We picked a neutral site (Test Devices), got SCAT on board as the lead, and invited the flywheel teams to join," Gully said. CEM, Trinity, and later US. Flywheel complied. While both United Technologies and Satcon were initially interested, they eventually declined to join. Today, however, interest among program non-participants is said to be growing. The program has been integrated with similar programs sponsored by the Department of Energy.

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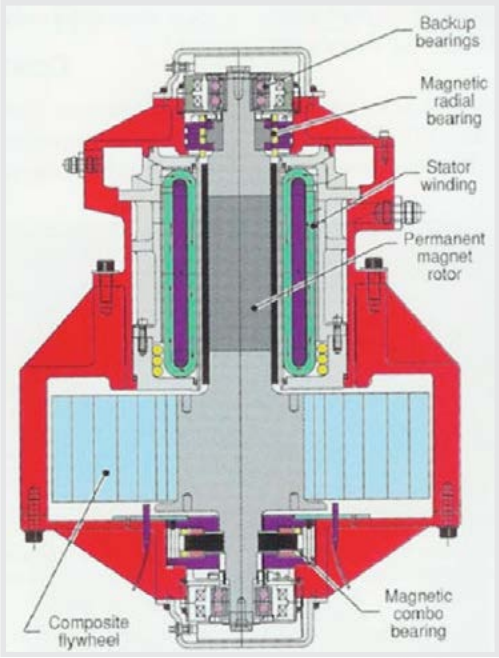

Fig. 3 — The University of Texas' design for a transit-bus flywheel battery includes a composite flywheel, a magnetic-levitation bearing system, and a motor/ generator unit.

"As research efforts toward flywheel batteries progressed, safety emerged as a serious consideration," said Joe Beno, CEM program manager. "People in the flywheel community realized that more resources needed to be devoted to the problem, because we really don't yet understand the failure properties of flywheels. For years there has been this folklore that flywheels are very safe, that rather than burst they would just unravel into a ball of fluff or cotton candy in a long-duration, low-power event. Truth is, it has been difficult to make them burst, period." Beno noted that there have been some rather spectacular composite flywheel failures, particularly at Oak Ridge in the mid-1980s.

"A lot of groups operate their wheels at a tip speed around 800 meters per second," Gully said. (Tip speed is a general "figure of merit" or normalizing factor that allows comparison between rotors of different diameters.) "At 800 meters per second, flywheels do come apart like cotton candy, but at some level above that, say 1,400 to 1,600 meters per second, they tend to come apart rather dramatically," he said. "From a containment standpoint, there is a key design trade-off between tip speed, which is directly related to energy density, and the size and mass of the containment system. Somewhere there is an optimum. That is one of the things we hope to determine."

The stated objectives of the joint research effort includes developing burst test technology, conducting a combined theoretical and experimental program to gain a fundamental phenomenological understanding of failures, and devising a basic methodology for designing containment structures and systems. "How they come apart determines the containment scheme," said one engineer.

As part of the project, new flywheel test techniques, instrumentation, dedicated test apparatus, and advanced safety approaches will be developed. They will be applied in a modified turbine disk test cell at Test Devices, said company president Eric Sonnichsen. Test data produced by accelerometers, strain gauges, and thermocouples will be gathered by high speed data-acquisition systems, tape recorders, and a new Kodak ultrahigh-speed video camera that shoots 10,000 frames per second. "The camera and a synchronized-pulse laser illuminator, which are mounted at view ports at the bottom of the spin pit, will image spinning flywheels every 5 to 10 degrees of rotation, to record failure sequences and related phenomena," he said.

A set of subscale and full-scale flywheels are being individually designed and fabricated by the project members, according to SCAT. The sample rotors will include most varieties of flywheel design: tall and short aspect ratios; mass-loaded, pre-stressed, and strain-matched designs; and plain bore construction, polar-weave, prepreg tow, and wet-wound systems. Some wheels will be designed to burst prematurely at normal operating speeds to study containment performance. Later in the project, flywheels will be burst in candidate containment structures in the spin facility. The results will be used to conduct modeling, simulation, and theoretical development. A final report will document the likely failure scenarios, and make design and procedural recommendations.

Filament-wound composite rotors are different from their widely used metal counterparts. Manual transmission cars, for example, use metal flywheels as power-smoothing devices, an application in which they operate in close proximity to driver and passenger.

As flywheel failure modes are both design- and material dependent, accepted design rules have not yet been established for composite units, according to CEM researchers. A flywheel's energy-storage potential is proportional to its mass moment of inertia and the square of the rotational speed. For a specific rotor configuration, speed is limited by the material's strength-to-density ratio. For this reason, flywheel engineers selected high-strength, lightweight composite materials. CEM engineers observed that composite flywheels are operated at stresses near the material's ultimate strength to maximize energy storage.

"The range of current flywheel designs are in some sense bounded by mass-loaded types on one end and preloaded on the other," said Richard C. Thompson, CEM research associate. There are various kinds of intermediate types. Different rotor designs have a propensity for different types of failures. The nuances of operation and fabrication also has an effect. Despite the design differences, "at comparable tip speeds, their stress and strain states look generally the same," he said.

Fig. 4 — Engineers at the Center for Electromechanics fabricated this composite flywheel (left) with weakened graphite fibers so it would burst at a specified rotational speed. Fragments from the wheel failure are shown on the right.

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Mass-loaded flywheels have a radially increasing specific stiffness or modulus to generate radial compression with increasing speed, which creates a large force gradient across the weak direction of the composite. "You need the radial compression to hold it together," Thompson said. Generally, this design can be more susceptible to burst (a failure of the fiber/matrix material in the hoop direction), especially if the loss of the outer ring results in hoop failure of all the inner rings. Bursts can be catastrophic because they are accompanied by a significant energy release. Burst failure is considered the most extreme challenge to a containment system. Mass-loaded units are said to be easier to fabricate than preloaded wheels.

Preloaded designs, by contrast, are fabricated to exhibit constant or near-constant specific modulus (stiffness). They are characterized by a tendency to delaminate before experiencing a burst, especially when they incorporate lower-modulus graphite composites. Delamination is a physical separation of a localized portion of the flywheel due to loss of radial compression, leading to a debond between hoop fiber layers. De-bonds can also be initiated by creep of the matrix or matrix degradation due to elevated temperature. It typically produces an imbalance caused by the shifting mass that can quickly overcome bearing load capacity, requiring flywheel shutdown. Polar-woven flywheel designs are resistant to de-laminations due to the inclusion of radially oriented fibers.

In preloaded designs, the flywheel typically contacts the shaft with no coupling component or hub, Thompson said; the flywheel is assembled from two or more wound fiber rings pressor shrink-fit together. "At assembly you put in enough radial pre-compression such that radial compression is maintained throughout the speed range.

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Spin Tests

In recent spin tests at Test Devices, CEM engineers failed a multi-ring, preloaded wheel with a design that was altered by substituting weakened graphite in the fabrication of the outer ring. The objective was to demonstrate a controlled failure and “soft capture” of the fragments using a Kevlar catch ring.

“The outer ring was wound from graphite fiber with 40% reduced strength rather than the IM7 fiber in the rest of the wheel,” Thompson said. The engineers designed the rotor system using Patran pre- and post-processing software, the ABACUS finite-element analysis package, and LAMP A T software developed by the Army Research Labs that performs ply-by-ply analysis. These analytical codes were used to predict the speed range in which the wheel would fail.

At first the wheel was run at lower speeds to demonstrate the consistency of its mass balance. During the high-speed run, the wheel was shut down when the instrumentation registered the loss of mass balance.

The modified wheel stored 5.8 megajoules at burst speed and released 1.1 megajoules during the burst event. It failed at 35,200 rpm, which was within the predicted range. Thompson reported that 9.4 pounds of the wheel was lost during the failure, and 57% of the failed ring material was recovered following the test.
“80% of the recovered material was in the catch ring,” he said. The debris ranged in size from dust to fragments as long as 8 inches.

This spin test helped establish both the induced and allowable load limits of the wheel structure, which correlates analytical tools for designing safe wheels. The modified rotor also showed that an altered flywheel design can be tailored to deliver specific burst energy levels to candidate containment designs.

Another spin test is scheduled for later this year at Test Devices, said Richard J. Hayes, CEM project engineer. “This will be a de-lamination test using the inside portion of the wheel burst in the first test. We’ll re-machine it, place a new ring on the outside, and spin it up until it delaminates, then shut it down.” This relatively benign failure mode is called a mechanical fuse.

A third test, he said, will be conducted “inside a steel ring that behaves elastically on impact.” The ring will be instrumented to measure radial, axial, and torque loading. Hayes said that the surrounding ring could be mounted to a torque tube or to strain-gauged arms that extend out radially. By measuring the radial, axial, and torque levels, the engineers will be able to calculate the magnitude and duration of the load placed on the ring.

A fourth run, Hayes said, will be a loss-of-vacuum test, which is “bound to happen sometime on a vehicle. As the air enters, the wheel should heat up as it slows down. We want to see whether it will cause failure.” The other participating flywheel companies, Trinity and US. Flywheel, plan to perform similar spin tests on their rotor designs.

Containment Schemes

Once the test data are in, engineers hope to come up with some innovative concepts that will lead to a feasible and reliable containment system, DARPA's Gully said. According to CEM research engineer Mark Pichot, there are several classes of containment schemes. "First is the brute-force approach using heavy-walled pressure vessels." The rigid structure will handle the high forces, but difficulties in limiting torque loads on the mounting systems and the high weight make them less than optimal for vehicles, he said.

Another concept is a rotatable ring that spins to soak up energy when impacting flywheel fragments transmit their high torque. "By spreading the torque over time, this approach limits the forces that must be contained," Hayes said. The other general containment design would rely on an energy-absorbing liner; "this is the soft-catch approach-something like a catcher's mitt," Pichot said.

According to Pichot, some sort of hybrid or combination approach may finally end up being used in commercial applications.

"Flywheel developers are clearly concerned about safety containment," said Test Devices' Sonnichsen. "Lots of people believe that flywheels can't be accepted widely until the safety problem is addressed. But they could not afford the effort necessary to research it because they are focused on making the wheels themselves work. Now, with the DARPA cooperative research project, they can develop containment systems they need."

—END