Flywheel Energy Storage

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REPORT SUMMARY

Flywheels are under consideration as an alternative for electrochemical batteries in a variety of applications This summary report provides a discussion of the mechanics of flywheels and magnetic bearings, the general characteristics of inertial energy storage systems, design considerations for flywheel systems, materials for advanced flywheels, and cost considerations.

Background
Energy is stored in the rotating mass of a flywheel. Historically, flywheels have stored the energy of short impulses so as to maintain a constant rate of revolution in rotating systems. Steam and combustion engines have incorporated flywheels for that purpose from the time of their invention. The application of flywheels for longer storage times is recent. It has been made possible by developments in materials science and bearing technology.

Objective
To provide a brief introduction to the state-of-the-art in flywheel technology.

Approach
The project team researched available technical literature to produce a brief but comprehensive introduction to flywheel technology and to compile an up-to-date bibliography of published books, papers, and reports on flywheel research and development.

Results

Advanced flywheels require materials of high tensile strength, very light weight, and "benign" failure mode. The enabling development from materials science is fiber-reinforced polymers, a class of composite materials that is the best current candidate for flywheel applications. The comparable development in bearing technology is the magnetic bearing, which suspends a rotating shaft or rotor by magnetic forces. Owing to the absence of contacts between solid surfaces, drag torques are very low in magnetic bearings and lubrication is unnecessary. Other advantages include high reliability, absence of wear, high allowable peripheral speeds, and the capacity for controlling stiffness and damping in real time.

In principle, flywheel systems have load leveling capabilities that are matched by few near-term technologies. These capabilities are especially desirable for ground vehicles such as automobiles and locomotives, which benefit by rapid acceleration, speed maintenance on grades, and regenerative breaking. In the electric power industry, large flywheels may be useful for load management during peak hours, for storing electricity from base-loaded generators during low-demand periods, and for electricity storage from alternative power sources such as wind or solar.

EPRI Perspective

While government agencies, national laboratories, automobile companies, utilities, and manufacturers are investing in flywheel-related projects, flywheel energy storage remains in the R&D stage. For several reasons, commercialization may occur in the near future. Fiber-reinforced composites are becoming better and cheaper, and new rare earth-transition metal magnets have become available that can enhance the performance of magnetic bearings. Perhaps most importantly, concerns about flywheel safety are being addressed seriously by a consortium run under the aegis of the Defense Advanced Research Projects Agency.

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Interest Categories
Power conditioning
Applied science and technology
Energy storage

Key Words

Fly wheels
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1

INTRODUCTION

Storing mechanical kinetic energy for comparatively short times with flywheels has been known for centuries. Flywheels are now being considered for a variety of applications such as replacement of, or assists for, electrochemical batteries. A useful account of all aspects of flywheels, including their history, is given by Genta.[1]

Energy is stored in the rotating mass of a flywheel. Historically, flywheels have stored the energy of short impulses so as to maintain at a constant rate the revolutions of a rotating system; steam and combustion engines have incorporated flywheels for that purpose from the time of their invention. The application of flywheels for longer storage times is recent, and has been enabled by developments in materials science and bearing technology.

As will be seen, advanced flywheels require materials of high tensile strength, very light weight, and "benign" failure mode. The enabling development from materials science is fiber-reinforced polymers, a class of composite materials that is better suited for flywheel applications than any other now available. The comparable development in bearing technology is the magnetic bearing, which suspends a rotating shaft or rotor by magnetic forces. Owing to the absence of contacts between solid surfaces, drag torques are very low and there is no need for lubrication. Other advantages include high reliability, absence of wear, high allowable peripheral speeds, and the capacity for controlling stiffness and damping in real time.

This summary report provides very brief discussions of the mechanics of flywheels and magnetic bearings, general characteristics of inertial energy storage systems, design considerations for flywheel systems, materials for advanced flywheels, and cost considerations. Two appendices are included: a table of the organizations and key people engaged in development of flywheels and magnetic bearings; and a bibliography of published books, papers, and reports on flywheel R&D from 1947 to the present.

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BASIC MECHANICS

Flywheel Energy

The energy content of a rotating mechanical system is

$$W = 0.5\ I\omega^2$$

where I is the moment of inertia and ω is the angular velocity. The moment of inertia is determined by the mass and shape of the flywheel, defined by

$$I = \int x^2 dm_x$$

where x is the distance from the axis of rotation to the differential mass dm_x. If the mass of a flywheel of radius r is concentrated in the rim, i.e., x = r = constant,

$$I = x^2 \int dm_x = mr^2$$

and $$W = 0.5r^2 m\omega^2,$$

which shows that the stored energy depends on the mass of the flywheel and the square of the angular velocity. To store large amounts of energy, high angular velocity is much more important than the mass of the rotating system.

The energy density (amount of energy per kilogram) of a flywheel is simply

$$\frac{W}{m} = 0.5r^2\omega^2.$$

Likewise, the volume energy density is obtained by expressing the mass as the product of density, ρ, and the volume V

$$\frac{W}{V} = 0.5\rho r^2\omega^2.$$

The upper limit for angular velocity is determined by the tensile strength of the flywheel material. In the elementary example given above, the tensile (hoop) stress in the rim is

$$\sigma = \rho\omega^2 r^2,$$

so that the maximum energy per unit volume is

$$\left[\frac{W}{V}\right]_{max} = 0.5\sigma_u$$

and the maximum energy per unit mass is

$$\left[\frac{W}{V}\right]_{max} = 0.5\sigma_u/\rho$$

Thus, for fixed dimension, the main requirements for high energy storage are high tensile strength and low density.

The factor 0.5 in the expressions for energy and energy density applies only to a simple rim flywheel. A more general description for any flywheel constructed from material of uniform density is

$$\left[\frac{W}{V}\right]_{max} = K\ \sigma_u/\rho$$

where K is a shape factor that is a measure of the efficiency with which the flywheel geometry uses the material strength. That is, the value for K depends on the moment of inertia (I) and how the flywheel shape affects the magnitude of the restraining stresses set up by centrifugal forces. This is illustrated in Figure 2-1 for a number of flywheel shapes. The value of K for a constant-thickness disc, for example, is reduced by a central hole, which acts as a stress concentrator; a large central hole (i.e., a thin-rim disc) is less of a stress concentrator than a small central hole (pierced constant-thickness disc). However, it is also true that the large central hole detracts more from the energy capability of the flywheel since there is less rotating mass.

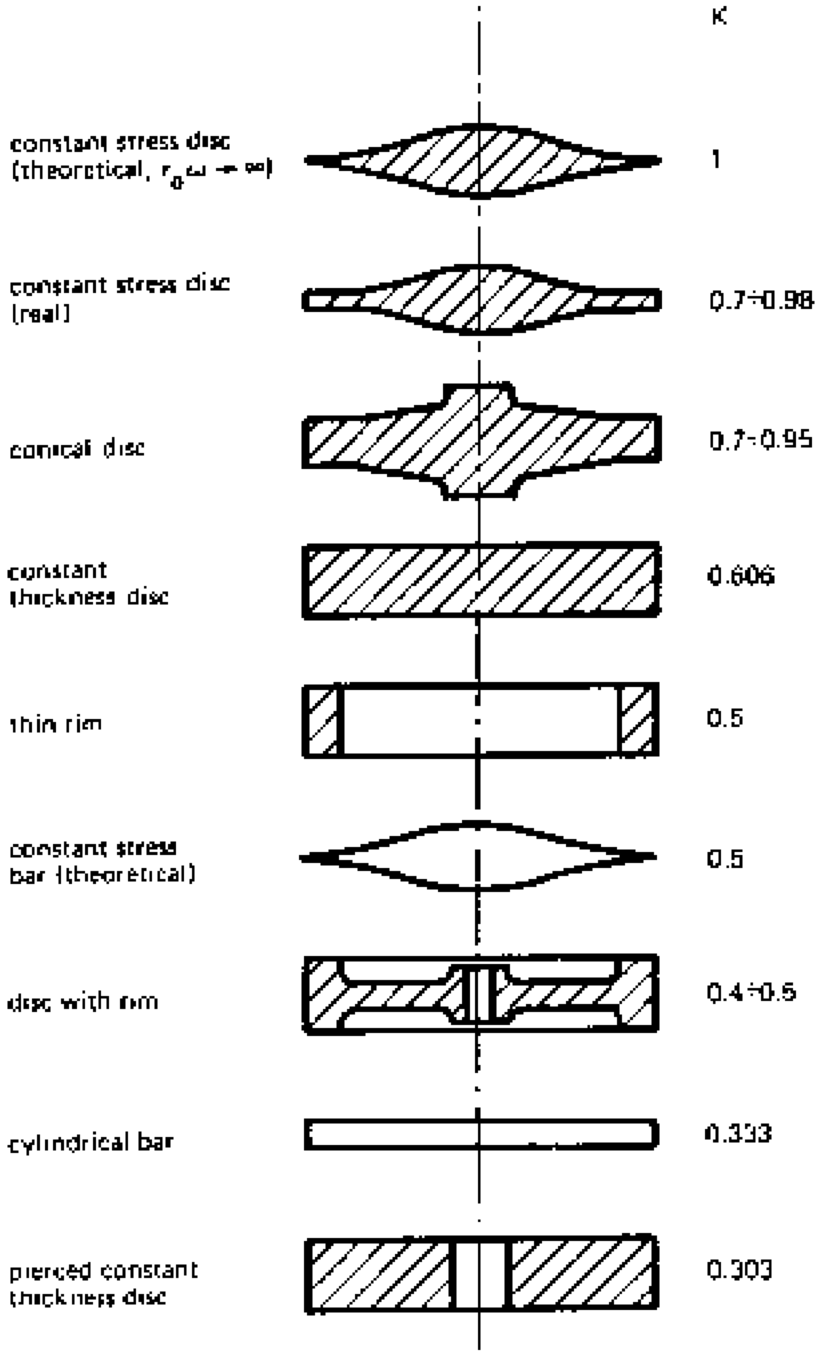


Figure 2-1
Shape factor K for some flywheel shapes.
Source: adapted from Genta[1]

Gyroscopic Moments of Flywheels

A flywheel reacts with a gyroscopic moment, **M,** to any angular motion of its rotation axis. For a flywheel spinning about one of its principal axes of inertia with angular velocity ω, a movement of the rotation axis at angular velocity **Ω** produces a moment (in vector notation)

$$\overline{M} = I\,\overline{\omega} \times \overline{\Omega}$$

This means that a torque about an axis perpendicular to the spin axis causes a moment around a third axis perpendicular to the other two. In the case of a flywheel-powered vehicle with the flywheel spinning around the vertical (yaw) axis, a torque in the plane of the vertical-longitudinal (roll) axis will result in an overturning moment around the longitudinal axis. For road vehicles, the highest angular velocities experienced during normal operation are around the vertical (yaw) axis; therefore, when the flywheel rotation axis is vertical, such maneuvers do not result in a gyroscopic reaction.

Returning to the moment equation, it is seen that the gyroscopic moment depends on the first power of the rotational speed, the first power of the mass, and the square of the radius of the rotating part. In terms of the stored energy,

$$\overline{M} = \frac{2W\,\overline{\omega} \times \overline{\Omega}}{2\omega^2}$$

Thus, for a given stored energy, gyroscopic moments are minimized by high-speed, small-diameter, low-mass flywheels. Gyroscopic moments can also be much reduced or effectively eliminated by clever designs, as will be seen.

Magnetic Bearings

The maximum axial and radial loads, F_{ax} and F_{rad}, that can be withstood by magnetic bearings can be estimated from the following relationships:

$$F_{ax} = 2\pi p_a d_b w_r$$

and

$$F_{rad} = p_r d_b w_s,$$

where d_b is the outer diameter of the shaft bearing or plate bearing, and w_r and w_s are the width of the magnetic field. The coefficients p_a and p_r, measured in pressure units, are materials dependent: for Fe-3% Si, $p_a = 50 \times 10^4$ Pa and $p_r = 25 \times 10^4$ Pa, whereas for high saturation Fe-45% Co-2%V, $p_a = 100 \times 10^4$ Pa and $p_r = 50 \times 10^4$ Pa.

The stiffness of active magnetic bearings depends on the control system. An order of magnitude stiffness can be estimated from

$$k = m(2\pi f)^2,$$

where m is the suspended mass and f is the natural frequency for the control system. Frequencies of 100-500 Hz are suggested for the amplifiers, which give high values of stiffness.

Although magnetic bearings are virtually frictionless, small losses occur from three sources: eddy currents generated in the rotating shaft; leakage flux (stray flux paths); and hysteresis in the rotor material. The sum of these losses, known as the drag torque, can be estimated from

$$M = mg(3.2 \times 10^{-5} + 1.3 \times 10^{-8}\, b\omega)$$

for a horizontal rotor of mass m. The constant b, which depends on the number of poles, ranges from b=2 for small machines to b=6 for larger machines. For vertical rotors, the torque is even smaller.

3

GENERAL CHARACTERISTICS OF INERTIAL ENERGY STORAGE

All flywheel energy storage systems have high power densities. They can be charged at high rates and they can deliver their energy in very short times (high power); the main limits on power delivery are the transmission system, or overheating of the motor-generator if the power is withdrawn as electricity, and the torque that the flywheel itself can withstand. In contrast, electrochemical batteries depend on a chemical reaction that becomes increasingly irreversible as the discharge rate is increased. This can be seen in Table 3-1, which compares the energy densities and power densities of two common electrochemical batteries with those projected for flywheel systems. A more extensive comparison among energy systems is shown in Figure 3-1.

Table 3-1
Typical Energy Densities and Power Densities for Energy-Storage Systems

System	Energy Density, Wh/kg	Power Density (50% DOD), W/kg
Lead-Acid	30-50	60-90
Nickel-Cadmium	40-70	160-185
Flywheel	100-250	500-5000

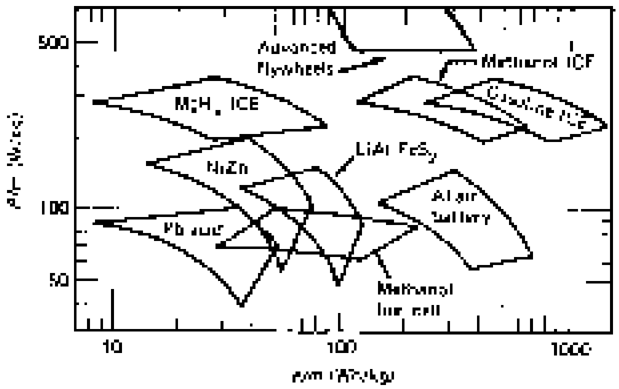


Figure 3-1
Power density versus energy density for energy accumulators.
Source: adapted from Genta[1]

The volumes of flywheel-energy storage systems are not much different from those of electrochemical batteries. If 30 kWh of stored energy is required for a vehicle with a range of 200 miles at 60 mph, a modular flywheel system would occupy about 0.36 m^3 (0.012 m^3/kWh), compared to about 0.4 m^3 for lead-acid batteries. The weights, however, are very different: 300 kg for the flywheel system versus 725 kg for the lead-acid batteries.

The flywheel itself has very high efficiency. For short-time storage the efficiency can be almost 100%, which decreases progressively for medium- and long-time storage. Operation in vacuum is required to reduce such losses to acceptable levels, since flywheels cannot store energy for more than a short time at atmospheric pressure. Also, special bearing systems (e.g., magnetic bearings) are needed for high efficiency. An advanced flywheel, operating in high vacuum ($3x10^{-5}$ torr) and suspended on magnetic bearings, can maintain a high efficiency for long periods (weeks or months), but such systems are still in the development stage.

Some disadvantages of flywheels are partly a matter of perception. An example is the concern about safety, which stems from catastrophic bursts of large rotating machines such as combustion turbines. For large monolithic flywheels, this concern is real. However, advanced flywheels constructed of fiber composites do not explode into two or three chunks that fly apart at high velocity. Flywheels that are designed to operate at tip speeds of up to 800 m/s (corresponding to just over 50,000 rpm for a 0.3 m (12 in) diameter rotor) fail by delamination, which is a pulverizing process. Housings able to withstand atmospheric pressure are adequate containments. Genta has performed more than 50 burst tests on advanced rotors without breaching the casing. However, failure modes of composite flywheels rotating at the substantially higher tip speeds contemplated for the most advanced designs have not yet been adequately defined.

A major disadvantage derives from the very concept of kinetic energy storage, which involves at least one fast-moving piece of machinery with all the associated problems of fatigue, wear, and vibration. A properly designed flywheel system, however, has a much longer fatigue life than a lead-acid battery does, particularly when deep and fast discharges are required. Nevertheless, it is true that advanced flywheels are usually highly deformable, difficult to balance, and the balance can change over the useful life. Design must account for such dynamic characteristics. It is fortunate that designers can rely on very extensive studies of similar problems with high-speed turbines. Experience with turbines suggests that the problems of vibration, balance, and wear can be overcome for fiber-composite flywheels as well.

4

DESIGN CONSIDERATIONS

Flywheels

The classical configuration of flywheels for steam engines is a hoop connected by spokes to a hub. It will be readily appreciated that the stored energy density of this configuration is too low for modern applications, inasmuch as most of the volume (between rim and hub) is empty space and therefore useless. Filling up that space, to make a disk with a central hole, does not solve the problem because centrifugal forces set up restraining stresses within the disk. These stresses are higher than those in a thin rim rotating at the same speed, with the highest stress at the inner hole (Figure 4-1).

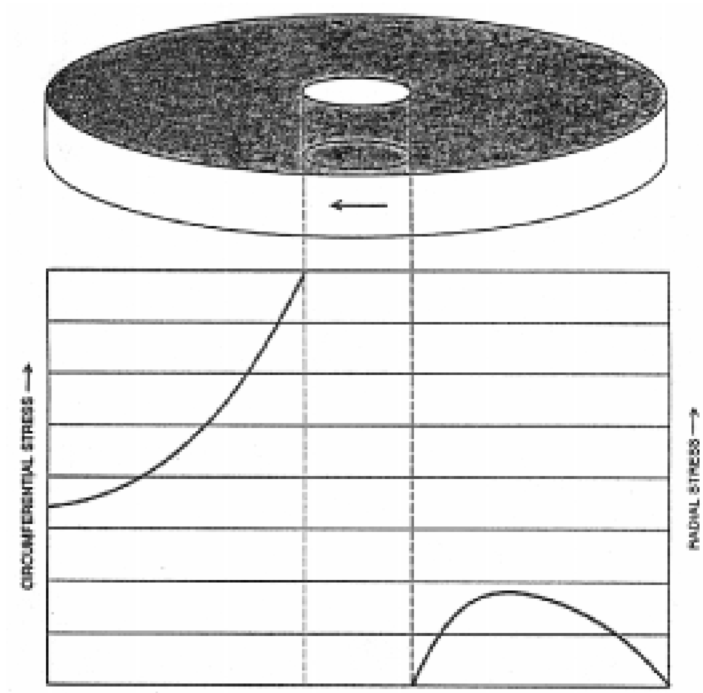


Figure 4-1
Operating stresses (arbitrary units) in a thick-rim flywheel.
Source: Post and Post[2]

For one-piece disks made of homogeneous material, it has been known for a long time that the concentrated stresses near the center can be alleviated by making a tapered disk, thickest at the center. High-speed turbine wheels are configured this way. However, the tapered design is unsuitable for construction with fiber composites, which have the potential to maximize the benefits of high strength with low density.

Fiber composites are anisotropic materials; maximum strength is obtained when all the fibers are aligned in the direction of the tensile stress. The bonding material, typically an epoxy resin, can only transmit relatively weak forces between adjacent fibers. Strength perpendicular to the fibers is on the order of only a few percent of the strength parallel to the fiber direction. Radial delamination causes flywheels made from fiber composites in solid disk or thick ring configuration to fail at rotational speeds far below those corresponding to the tensile strength of the fibers. Design must take into account this disparity between longitudinal and transverse strength.

It is possible, in principle, to avoid the delamination problem while taking advantage of fiber composite properties to obtain high volumetric efficiency. Such a flywheel would consist of multiple rings assembled concentrically.[2] Small gaps between adjacent rings would be filled with an elastomer to hold the flywheel together and allow for relative expansion of the rings under circumferential stresses. Individual rings are thin (approximately 10% of their radius) to minimize internal radial stresses.[3] However, centrifugal forces are lower and less energy is stored in the inner rings (small radii) if all the rings are made of the same materials. Dimensional stability and efficiency can be preserved by making the rings progressively more dense or of lower elastic modulus from the outside to the inside. This could be accomplished with either dense loading materials, or by fibers with graded elastic moduli, or by a combination of both approaches.[3] A schematic of such a construction is shown in Figure 4-2.

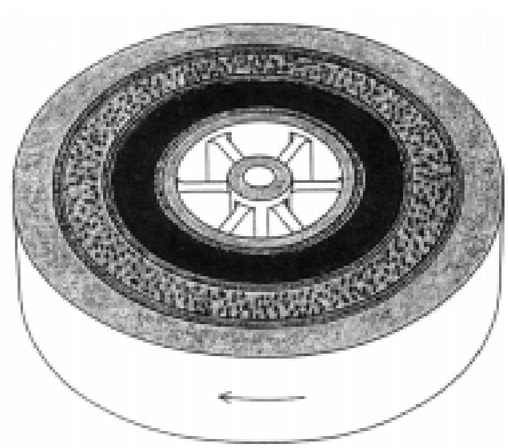


Figure 4-2
Schematic of a flywheel built with concentric rings of fiber composite separated by thin layers of elastomer.
Source: adapted from Post and Post[2]

In the multi-ring rotor design, unstable resonances can arise from transverse oscillations of the shells with respect to each other. Analysis has shown that instability can be avoided if the lowest mode of oscillation (determined by the effective spring constants of the separators) is constrained to lie above the highest operating speed of the flywheel.[3] Likewise, dissipative losses and consequent out-of-phase torques can occur within the rotor. It is anticipated that these "whirl" instabilities will be eliminated by compliant and/or dissipative elements in the magnetic-bearing supports.[3] Finally, synchronous rigid-body modes and critical speeds associated with bending modes can be avoided by designing for a rotor length to diameter ratio of less than one.[4]

Energy Input and Extraction

Charging and discharging can be accomplished mechanically or electrically, in any combination. The flywheel can be spun up mechanically, for instance, by direct coupling with a shaft or through a gearbox and discharged electrically by means of a generator. This was mostly the case in past designs, in which one end of the flywheel shaft was connected to the charging system and the other end was coupled to the output device. Modern high-performance flywheel systems are almost always all-electrical; a single motor-generator (motor-alternator) spins the flywheel up to full operating speed and extracts energy by generating electricity. In today's designs, the motor-generator is integral with the flywheel. Rare-earth permanent magnets mounted on the innermost shell of the rotor rotate past stationary coils, either to generate electricity or to energize the flywheel. The entire assembly is "ironless" for low standby losses (no hysteresis losses) and the motor-generator is electronically commutated.

Flywheels in Vehicles

For flywheels to be applied in vehicular propulsion, two other concerns confront design: dynamic loads (road shock) and gyroscopic forces. Designs currently being developed isolate transitory loads from the rotor with shock-absorbing or elastomeric systems. In addition, it is envisaged that the bearings (preferably of the magnetic type) will provide the restraint necessary to counteract inputs not damped out by the shock- and vibration-isolation systems. The gyroscopic effect is diminished with flywheels of small diameter, since the angular momentum varies as the square of the radius. Post states that a 1 kWh flywheel has a gyroscopic moment comparable to that of the flywheel in a typical automobile engine.[5] Moreover, current designs embody either counterrotating rotors that inherently cancel gyroscopic forces or an even number of flywheel modules that ameliorate much of the gyroscopic effect. Again, it should be borne in mind that many detailed analytical studies of gyroscopic effects have been performed for high-speed rotating machinery in aircraft.

Magnetic Bearings

Magnetic bearings can be of the *passive* or *active* variety. A passive magnetic bearing depends on a system of permanent magnets, whereas active bearings employ electromagnets under electronic control via feedback circuits.

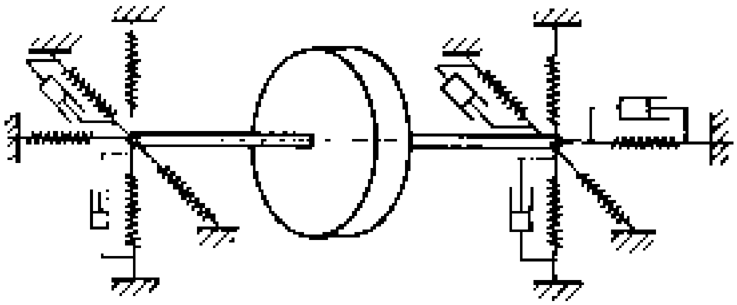


Figure 4-3
Schematic of five axes magnetic suspension; springs and dashpots represent stiffness and damping of the magnetic bearings.
Source: Genta[1]

Since five out of the six rigid-body degrees of freedom of a flywheel rotor must be restrained by the suspension system (the unrestrained degree of freedom is rotation about the rotor axis), various kinds of magnetic and conventional bearings can be combined in many ways. Arrangements range from a simple magnetic thrust bearing with conventional bearings for the other four degrees of freedom, to five-axis magnetic systems. In a complete five-axis system, shown schematically in Figure 4-3, a typical layout embodies two active radial bearings, Figure 4-4, and two active axial bearings. Less complicated systems can be devised with the rotor suspended either on two passive radial bearings and one active axial bearing[6] or on radially active and axially passive bearings. The latter arrangement is illustrated in Figure 5-1.[7] A cutaway schematic of a passive radial bearing is shown in Figure 5-2.[8] CAD programs for design of magnetic bearings are readily available.[7]

Note that EPRI has undertaken two projects aimed at applying magnetic bearings in boiler feed pumps and recirculating fans.[9]

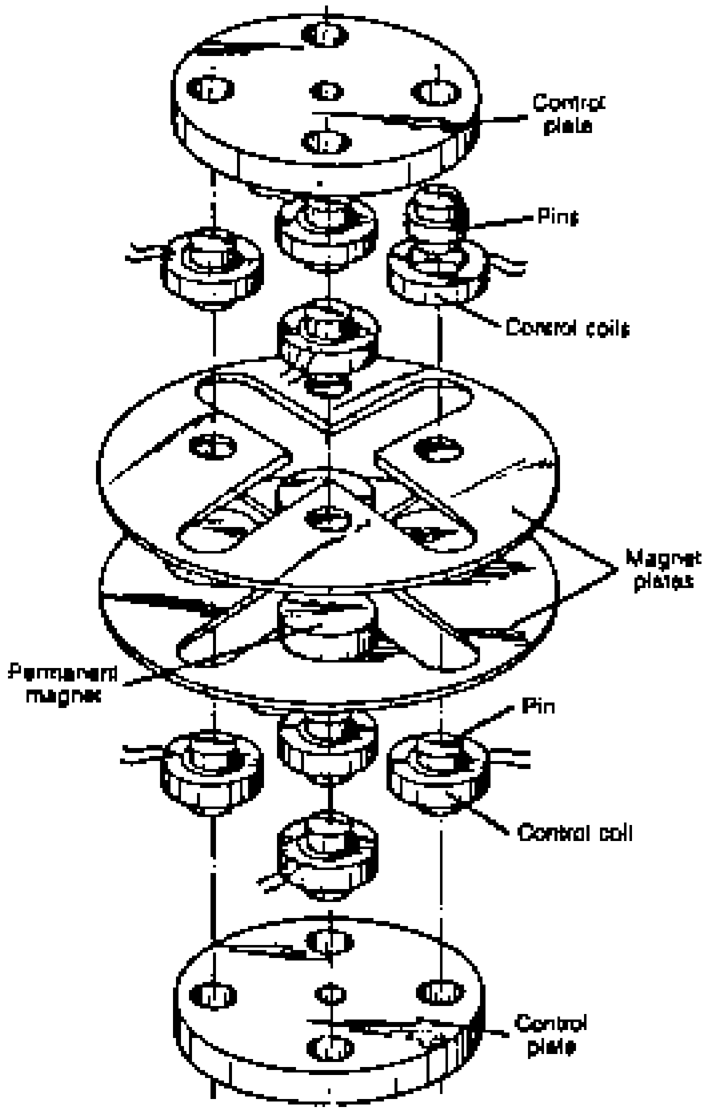


Figure 4-4
Exploded view of magnetic bearing with active control in two orthogonal radial directions and passive control of all other degrees of freedom (except flywheel spin).
Source: Anand, *et al.*[7]

5

MATERIALS CONSIDERATIONS

Flywheels for engines have traditionally been made of isotropic materials in monolithic forms. High-strength steels were a common choice: AISI 4340, 18Ni-maraging steels, or 9Ni-4.5Co-1Mo steel. Although their specific strengths are relatively low and their failure modes are not favorable for flywheels with high energy densities, they can be readily produced in shapes with high values of the shape factor (see Figure 2-1). Other conventional materials such as aluminum, magnesium, or titanium alloys are also characterized by the same deficiencies of low specific strengths and unfavorable failure modes.

As has already been pointed out, the performance of flywheels depends on high rotational speed, which is limited by the tensile strength and density of the flywheel material. In this respect, modern composite materials, i.e., polymers reinforced with high-strength fibers, are clearly indicated as the preferred materials of construction. The advantage of fiber composites is apparent in Table 5-1, in which the listed properties are for purposes of comparison and are not meant to represent the best achievable material in any of the categories. However, fiber-reinforced polymers are highly anisotropic, and their low strength perpendicular to the fiber direction does not permit the use of shapes with high shape factors. Hence, the suggested design of Figure 4-2 that consists of thin (about 10% of radius) concentric rings with densities or moduli that are graded from the rim to the hub.[3]

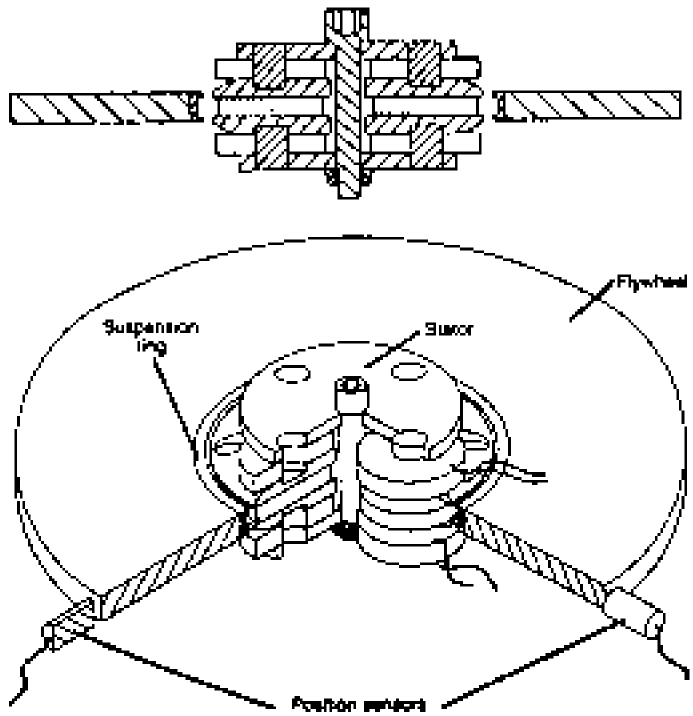


Figure 5-1
Radially active and axially passive pancake magnetic bearing.
Source: Anand, *et al.*[7]

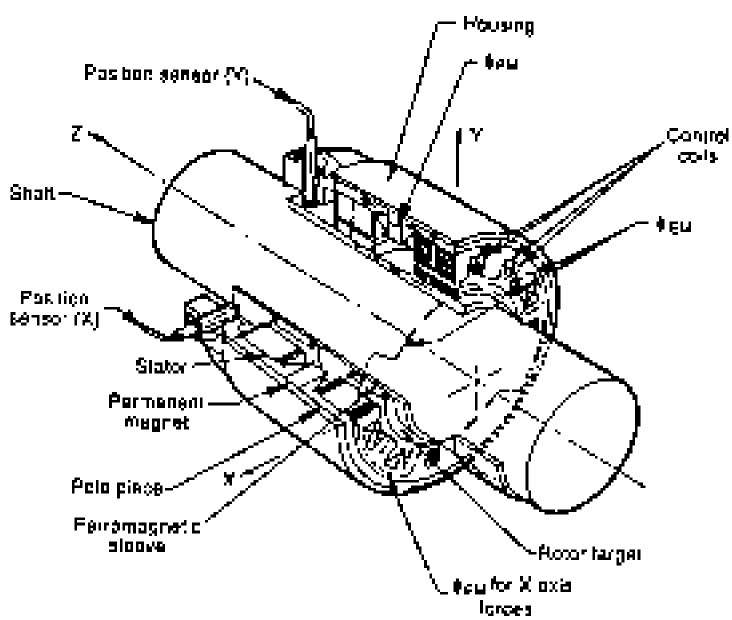


Figure 5-2
Cutaway of combination passive-active magnetic bearing.
Source: O'Connor[8]

Owing to the motivation primarily from the aerospace industry, development of fiber-reinforced composites is proceeding at a rapid pace.[11] Epoxy composites made with "high strain" graphite fibers, for instance, have been fabricated into prototype flywheels with ultimate hoop strengths of about 3200 MPa.[10] Recent introduction of boron-graphite hybrid composites[12] with the properties listed in Table 5-2 is another example; tension and bend strengths of these hybrids are claimed to be higher than any other material. The fatigue resistance of fiber-reinforced polymers, particularly those made with graphite, aramid (Kevlar), and boron fibers, is likewise excellent, as shown in Figure 5-3. Notice that composites made with glass fibers have much lower fatigue resistance than the other composites shown in Figure 5-3. Nevertheless, cyclic tests of high-energy, prototype flywheels constructed of S-glass sheet molding compound, both with and without graphite fibers, showed that the rotors suffered no degradation in performance after 10000 cycles.[10]

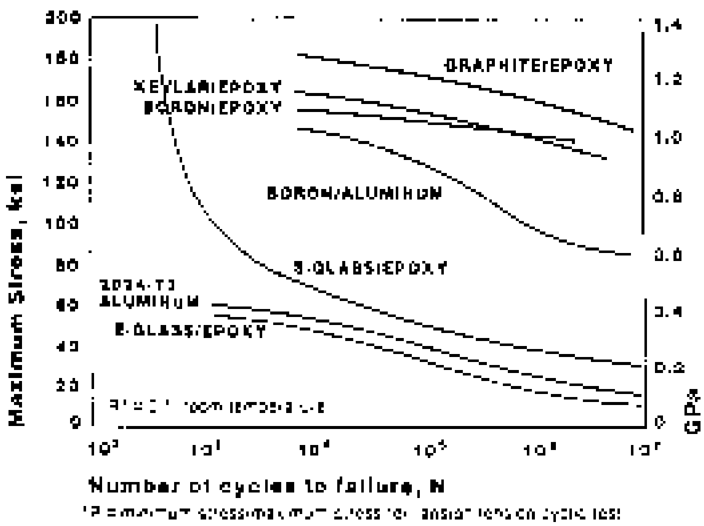


Figure 5-3
S-N curves for various composites in tension-tension cycling.
Source: Chung[11]

Other ongoing developments in fiber-reinforced composites include compressive prestressing to improve fatigue resistance, co-polymerizing epoxy with elastomers to increase transverse strength, and hybridizing with inexpensive glass fibers to reduce costs. In summary, the outlook for application of fiber-polymer composites in advanced flywheels is considered to be outstanding. A conceptual schematic embodying some of the configurational features and materials discussed in the foregoing, is shown in Figure 5-4. Note that modern designs are quite compact; the main feature of a 3 kWh module tested at Lawrence Livermore National Laboratory, for example, is a rotor only 25.4 cm in diameter and 25.4 cm high.[5]

Table 5-1
Materials for Flywheels

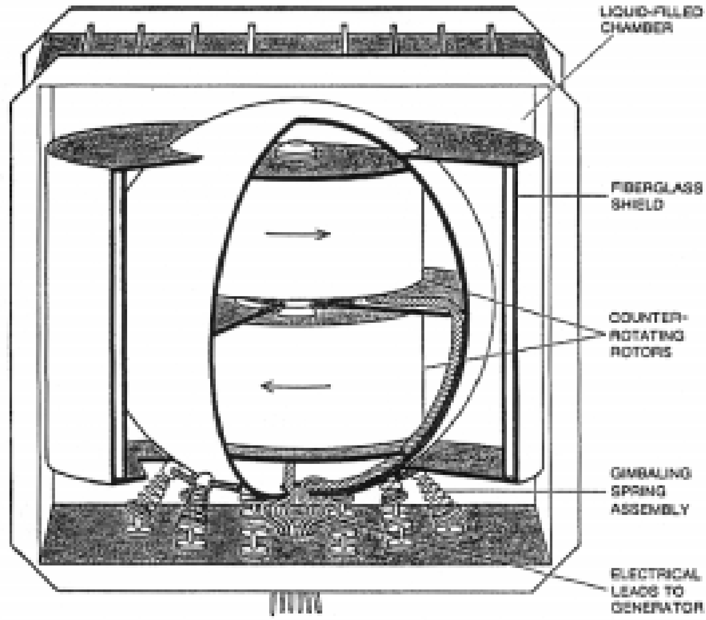
Materials	Ultimate Tensile Strength, σ_u MPa	Density, ρ g/cm^3	σ_u/ρ kJ/kg (Wh/kg)
Monolithics			
7075-T6 Aluminum	572	2.76	208 (57.8)
Ti-6Al-4V Titanium	1103	4.43	249 (69.2)
4340 Steel	1517	7.7	197 (54.7)
18 Ni Maraging Steel	2070	8.0	259 (71.8)
Composites			
E-glass/epoxy	1034	2.10	492 (136.8)
S-glass/epoxy	1751	1.99	880 (244.4)
Kevlar/epoxy	1241	1.39	893 (248.0)
Graphite/epoxy	1586	1.54	1030 (286.1)
Other			
Metglass	2627	8.0	328 (91.1)

Table 5-2
Boron-Graphite/Epoxy (Hy-Bor*) Composites

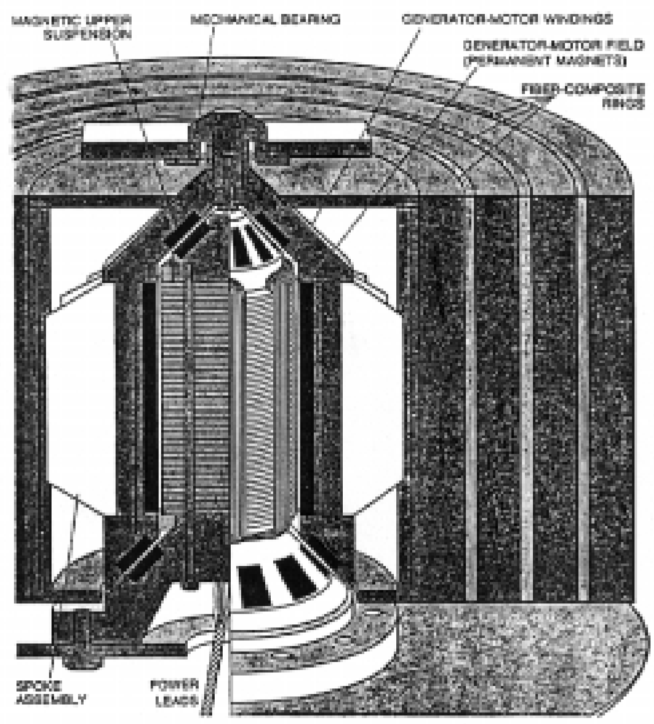
Boron fiber size Graphite fiber type Resin system	0.1 mm IM-7 3501-6	0.1 mm T-300 SG100	0.076 mm T-300 SG100	0.1 mm T-650 SG100	0.076 mm T-650 SG100
Tensile strength, MPa	2206	1793	2275	2000	2413
Tensile modulus, GPa	269	234	228	255	255
Flex strength, MPa	2965	2413	2827	2689	3103
Flex modulus, GPa	255	228	221	248	241
Interlaminar shear strength, MPa	116.5	93.8	95.2	94.5	93.1
Fiber volume, %	77	77	73	75	72

*Textron Specialty Materials, Lowell, MA

Source: Adapted from ref. 12



(a) Counter-rotating rotors, enclosure, and suspension system.



(b) Multi-ring construction, bearings, and motor-generator.

Figure 5-4
Conceptual schematic of a flywheel energy system for vehicular propulsion.
Source: Post and Post[2]

6

COST CONSIDERATIONS

Costs of flywheel-energy storage systems are difficult to obtain, since most of the extant examples are experimental and therefore were built only in ones and twos. Here, we rely on an analytical study of flywheel-energy storage for wind turbines[4] that appears to be thorough, sensible, and not unduly optimistic. A modular approach was taken in which each flywheel module was capable of storing 277 kWh (1 GJ). Table 6-1 lists the specifications for each flywheel module and Table 6-2 itemizes the capital costs.

Table 6-1
277 kWh (1 GJ) Flywheel Design

Speed	12500 rpm
Flywheel radius	0.84 m (33 in)
Flywheel inside to outside radius ratio	0.7
Shaft diameter	0.2 m (8 in)
Mass of composite	2060 kg
Mass of arbor plates (2)	100 kg
Tip speed	1120 m/s
Length	1.12 m (44 in)
Shaft bore	0.075 m (3 in)
Hoop stress	1900 MPa (276 ksi)
Mass of shaft	237 kg

Source: Headifen[4]

Table 6-2
Cost Breakdown for 277 kWh (1 GJ) Flywheel

Component	Quantity	Unit Price	Fabrication Price	Total Cost
Composite	2270 kg	$28/kg	$6/kg	$77,040
Arbor plates	110 kg	$18/kg	$1,800 each	5,580
Shaft	260 kg	$2.5/kg	$1,800	2,450
Motor-gen rotor	190 kg	$22/kg	$ 900	5,010
Permanent magnets	64 kg	$220/kg	$2,000	16,100
Motor-gen stator	75 kg	$2.5/kg	$3,600	3,800
Housing	2750 kg	$2.5/kg		10,500
Magnetic bearings	2	$25,000		50,000
Power electronics	300 kW	$100/kW		30,000
Other items, bolts, etc.		$10,000		10,000
Installation		$10,000		10,000
			Total	$220,500

Source: Headifen[4]

For comparison purposes, the corresponding cost of an equivalent chemical battery bank was estimated on the basis of existing systems. It was also estimated that the chemical batteries would have to be replaced every four years (1500 cycles) and maintained at an annual cost of $235/kWh capacity. Comparable annual maintenance costs for the flywheel system were assumed to be $10,000/flywheel. Table 6-3 summarizes the results.

Table 6-3
Cost Comparison of Flywheel and Chemical Energy Storage

Category	5 Flywheel Modules	Lead-Acid Batteries	Ratio of Flywheel: Chemical Batteries
Capital costs	$1.10 million	$1.55 million	0.71
20-year costs	$2.60 million	$4.37 million	0.59

Source: Headifen[4]

7

A SNAPSHOT OF CURRENT STATUS

In principle, flywheel systems have load-leveling capabilities that are matched by few near-term technologies. These capabilities are especially desirable for ground vehicles (automobiles, trucks, buses, and locomotives), which are benefitted by rapid acceleration, speed maintenance on grades, and regenerative braking. In the electric power industry, large flywheels can be envisaged for load management during peak hours, for storing electricity from base-loaded generators during low-demand periods, and for electricity storage from alternative power sources (e.g., wind or solar power).

In recognition of these qualities, government agencies, national laboratories, automobile companies, utilities, and manufacturers are evincing serious interest in flywheel energy storage by making resources available for R&D (see Appendix 1). Just how much is being spent on flywheel R&D is not known because a significant amount is in the private sector and considered proprietary. On the basis of published information about CRADAs and limited descriptions of industrial activities, it is estimated that the expenditure is $15-25 million per year.

As can be seen from the bibliography (Appendix B), the elements of flywheel design and materials have been known for more than twenty years. In spite of that, flywheel energy storage is still in the R&D stage; it is not yet ready for the mass market. What has changed in the last few years that would convince the various funding organizations that the technical and economic impediments to commercialization can be overcome?

The changes listed below have been evolutionary rather than revolutionary.

- Fiber-reinforced composites are more capable and less costly. For example, a joint venture between Dow Chemical and United Technologies Corp. has developed a proprietary resin-transfer molding process for flywheel rotors. In addition to filament-wound hoop fibers, reinforcement fibers are aligned in the radial direction by a "polar weaving" method. This permits a significant fraction of the graphite filaments in the hoop direction to be replaced by high performance but much less costly E-glass fibers.

- Rare earth-transition metal magnets (e.g., neodymium-iron-boron), which provide much higher flux intensities than were available twenty years ago, enhance the performance of magnetic bearings and motor-generator units.

- Flywheel motor-generators deliver electricity of variable frequency and voltage, which must be conditioned to match the load or charging system. Advanced controls will also be needed for active magnetic bearings and the motor-generator. Solid-state power electronics and controls have been getting steadily smaller and cheaper, allowing them to fulfill the required functions economically.

- Twenty years ago magnetic bearings were laboratory curiosities; now they are articles of commerce, with a number of very competitive suppliers.

- Flywheels are now regularly employed for attitude control in orbiting satellites and in space probes. A great deal of experience was gained from the space program over the last twenty years. Experience with high-speed combustion turbines for aircraft has been equally valuable in matters of dynamic balance and in designs to cope with gyroscopic moments.

Perhaps the most important issue to emerge in the last year or two is a renewed concern about safety. Most of the past development work had concentrated on improving the bearing, rotor, and motor-generator technologies. Relatively little effort was devoted to containment, owing largely to the assumption that failure of filament-wound, composite rotors would occur by a pulverizing process and that the debris would be easily contained. At tip speeds of 800 m/s, a common design feature, purposely weakened flywheels do, in fact, come apart "like cotton candy." However, at tip speeds of 1400 to 1600 m/s, the failures can be rather more dramatic bursts.[14]

As a consequence of this new information, in 1995 the Defense Advanced Research Projects Agency (DARPA) established the Flywheel Safety Project, a consortium consisting of the Southern Coalition for Advanced Transportation (administration), Test Devices Inc. (spin-test facility), and flywheel developers Center for Electromechanics (University of Texas), Trinity Flywheels Inc., and U.S. Flywheel Systems. The project will develop new test techniques, instrumentation, dedicated test apparatus, and advanced safety approaches. Flywheels will be individually designed and fabricated by the project members, and then burst in candidate containment structures. Results will be used for modeling, simulation, and theoretical development. A final report will document the likely failure scenarios, and make design and procedural recommendations.[14]

8

QUESTIONS AND UNRESOLVED ISSUES

Proponents of inertial energy storage imply that all the technologies for a high-performance, flywheel-energy system are now available; the challenge is to integrate them effectively.[5] Some of the constituents of that challenge are itemized below.

Protection Against Wheel Failure. A lightweight, cost-effective containment system is the No. 1 unresolved issue that is currently inhibiting acceptance of the most advanced flywheel designs.

Magnetic Bearings. Has an advanced flywheel device of 1 kWh capability or larger been built with magnetic bearings and tested? If so, what was the cost of the magnetic bearings? This is probably the No. 2 unresolved issue confronting the widespread application of flywheel energy systems.

Mechanical Stability. Internal vibrations (mechanical resonances) are intrinsic to rotating machines. Post states that the multiring construction can be configured so that all critical speeds are well above the highest operating speed.[2] Is this prescription consistent with the statement that supercritical operation (above the first critical speed of the rotor) will avoid the necessity for balancing,[3] which would be difficult (if not impossible) for a fiber-composite rotor? Does extraction of maximum power, a cited advantage of flywheels, cause speed reductions into the critical ranges?

Gyroscopic Moments. Clearly, there are design approaches for minimizing or eliminating gyroscopic effects. Still, prudence dictates that such designs be evaluated by way of analytical models to ensure that violent maneuvers (such as can occur in road accidents) do not produce dangerously high angular velocities.

Vacuum Operation. How will long-term vacuum be ensured? Will a sealed chamber containing polymeric components remain at pressures less than 10^{-4} Torr for long enough that vacuum maintenance does not inhibit vehicular application?

Electrical Components. The motor-generator, power electronics, and controls for an inertial energy storage system must be of a size, efficiency, and cost consistent with an advanced flywheel and with the constraints imposed by commercial application. This combination is still to be demonstrated.

9

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A

ORGANIZATIONS (ALPHABETICALLY) AND KEY PEOPLE ENGAGED IN R&D ON FLYWHEEL ENERGY SYSTEMS

ORGANIZATION	KEY PERSON(S)	CAPABILITY/SPECIALTY	PARTNER(S)/ ASSOCIATE(S)	LOCATION
Advanced Controls Technology, Inc. (AVCON)	Crawford Meeks, Pres & CEO	Homopolar bearings; hybrid-permanent-magnet/ electromagnet bearings	Allied-Signal is part owner	Northridge, cA
Allied-Signal, Inc.		Magnetic bearings; super-conducting passive bearings	Part owner of AVCON	Morristown, CA
American Flywheel Systems	Edward Z. Zorzi, VP Engng; Edward W. Furia, Chrm & CEO	Dual rotor, counter-rotating flywheel systems; magnetic bearings	ARPA; Sacramento MUD; joint venture with Honeywell Satellite Systems	Medina, WA
Argonne National Laboratory		Superconducting magnetic bearings	United Technologies Research Center	Argonne, IL
Aura Systems, Inc.		Producer of magnetic bearings		Los Angeles, CA
Dow-United Technologies Composite Products, Inc.	David Maass	Graded composites with radial strength, made by resin-transfer molding	CRADA with Dept. of Commerce (NIST) to develop composite rotor	Wallingford, CT
Energy Research Unit, Rutherford-Appleton Laboratory	Dr. Simon Watson, contact; Dr. J. Halliday, head of ERU	Flywheel energy storage systems for wind energy		UK
Flywheel Energy Systems, Inc.	Ralph Flanagan, Pres	Biannular flywheel design with aluminum flex-ring hub and concentric composite rings	Thortek, Inc.; MTI	Ottawa, Ontario Canada
General Motors Corp.	Larry Oswald, GM/DOE Hybrid Vehicle Propulsion Program; Don Bender (LLNL)	Entire vehicular propulsion system: flywheel, bearings, motor-generator	CRADA with DOE (via NREL) LLNL	Detroit, MI

ORGANIZATION	KEY PERSON(S)	CAPABILITY/SPECIALTY	PARTNER(S)/ ASSOCIATE(S)	LOCATION
Honeywell Satellite Systems		Attitude-control gyroscopes and control electronics for U.S. space program	Joint venture with American Flywheel Systems	Phoenix, AZ
IfR with Institute of Electrical Machinery (ETH), Chair of Power Electronics (ETH), and Swiss Federal Railways	Peter von Burg Markus Ahrens	Joint project to develop kinetic energy storage system with 1 kWh energy and 250 kW power		Zurich, Switzerland
Lawrence Livermore National Laboratory	Richard F. Post, Senior Scientist	Experimental flywheel energy storage systems; nested thin-wall composite rings of fiber-epoxy; permanent-magnet motor generator	CRADAs with General Motors, Westinghouse, and Trinity Flywheel Batteries	Livermore, CA
Magnetic Bearings, Inc.	Frank Pinckney, Director Engng.	Producer of magnetic bearings for large machines		Roanoke, VA
Mechanical Technology, Inc.	Paul Lewis, Mgr. Core Technol.; Jos. Reinhart, Mgr. Corp. Dev.	High-speed rotating machinery; magnetic bearings	Flywheel Energy Systems; Waukesha Bearings Corp.	Latham, NY
Oak Ridge National Laboratory	John Coyner, Progr. Mgr. Flywheel & Composite Technol.	Composite rotors; high-specific-power, axial-gap electric motors and generators		Oak Ridge, TN
SatCon Technology Corp.	David Eisenhaure	Innovative drive-train components for vehicles	Chrysler Corp.	Cambridge, MA
Thortek, Inc.	Douglas Thorpe, Pres	Integrating existing kinetic energy storage components into demonstration	Flywheel Energy Systems	Knoxville, TN
Trinity Flywheel Batteries, Inc.			CRADA with LLNL	San Francisco, CA
Unique Mobility	David Patch	Flywheel energy system designs, especially motor-generators	Previously associated with Flywheel Energy Systems	Golden, CO

ORGANIZATION	KEY PERSON(S)	CAPABILITY/SPECIALTY	PARTNER(S)/ ASSOCIATE(S)	LOCATION
United Technologies Research Center		Superconducting passive magnetic bearings	ANL	East Hartford, CT
University of Maryland	James A. Kirk, Prof. Mech. Engng.	Design and testing of flywheel components and systems	Baltimore Gas & Electric	College Park, MD
University of Texas at Austin	R. N. Headifen	Analysis of flywheel systems	Southwestern Public Service	Austin, TX
U.S. Flywheel Systems, Inc.	Bruce Swartout, Chairman	High-speed composite rotors and magnetic bearings; 4 kWh prototype	Calstart	Laguna Hills, CA
VistaTech Engineering, Inc.	R. N. Headifen	Design studies for flywheel energy storage in wind turbines	Southwestern Public Service	
Westinghouse Electric Corp.		Power-generating machinery; motors; switchgear	CRADA with LLNL	Pittsburgh, PA

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