Flywheel Technology

Past, Present, and 21^{st} Century Projections

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ABSTRACT

This paper describes the present status of flywheel energy storage technology, or mechanical batteries, and discusses realistic future projections that are possible based on stronger composite materials and advancing technology. The origins and use of flywheel technology for mechanical energy storage began several hundred years ago and was developed throughout the Industrial Revolution. One of the first "modern" dissertations on the theoretical stress limitations of rotational disks (isotropic only) is the seminal work by Dr. A. Stodola [1] whose first translation to English was made in 1917. The next big milestones were during the 1960s and 1970s when NASA sponsored programs proposed energy storage flywheels as possible primary sources for space missions. However, it was not until the 1980's when microelectronics, magnetic bearing systems and high power density motor-generators became enabling technologies. The next decade proved that a mechanical battery could surpass chemical batteries for many applications.

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INTRODUCTION

Flywheel energy systems are now considered as enabling technology for many applications including space satellite low earth orbits, pulse power transfer for hybrid electric vehicles, and many stationary applications. Typical mechanical batteries consist of a high speed inertial composite rotor, magnetic bearing support and control system, integral drive motor/generator, vacuum support housing and containment, compact heat removal and exchangers, instrumentation monitoring and control, and power electronics for electrical conversion. The design life has no degradation during its entire cycle life unlike chemical batteries. Current testing indicates that flywhyeels are not damaged by repetitive very deep discharge. The present designs at US Flywheel Systems (USFS) have been tested and show power densities of their permanent magnet synchronous motor/generator operating at its designed speed of 110,000 rpm will exceed 11.9 kW/kg continuous, with in or out efficiencies of 93%.

Projections of flywheel energy storage technology into the 21^{st} Century shall advance by more inexpensive and stronger fiber materials and resin systems. Increases in tensile modulus also improve system performance with stiffer rotors and housing structures. This is significant, since energy density is proportional to tensile strength. The cost and performance of magnetic bearing technology is advancing flywheel systems with lower operational power, higher load capacity, and faster response.
Micro-miniaturization of electronics with increased

reliability and lower costs also provide for significant advancement of flywheel systems. Current test data indicates that upward of 40,000 deep discharge cycles can be anticipated which is not possible for any known chemical battery system in the world today. In summary, flywheel systems have exceedingly high power and energy density with no fall-off in capacity under repeated charge/discharge cycles. Uniquely they can provide satellite and space systems with renewable energy storage in conjunction with attitude control. This is the only type of energy system that can accomplish both functions.

FLYWHEEL ORIGINS

Flywheel origins, initiated over 100 years ago, were solely to keep machinery running smoothly from cycle to cycle, as is the case of every automobile engine ever built. The first real breakthrough in analyzing flywheel rotor shapes and rotational stress was the seminal book by Dr. A. Stodola [1] whose first translation to English was made in 1917 in a two-volume series, and is still today a credible reference in the later editions. The next big milestones occurred during the early 1970s when flywheel energy storage was proposed as a primary objective for electric vehicles and stationary power back-up. In the years immediately following, fiber composite rotors were built and tested in the laboratory by US Flywheel Systems and other organizations. However, it was not until the 1980s when relatively low speed magnetic bearings and motor-generators made their advanced appearance. The next decade proved that "mechanical battery" flywheels could surpass chemical batteries for many applications.

The "Stodola Period" showed that with technical finesse a rotating mass supported by a shaft could store energy mechanically. Dr. Stodola's extensive stress analysis showed that special shapes for isotropic flywheels yield uniform stress distributions throughout the rotor material; thus "optimizing" the rotor design. This concept was initially put into practice even before his time and made possible the industrial revolution, where every piece of rotating machinery had to carry out its kinetic cycle smoothly without intolerable vibration. These optimized shapes and analyses are still valid and used today for certain isotropic applications. However, the same designs are not optimum with composite materials where stress distributions anisotropic strength variations vary with fiber, rotor design, and construction.

PRESENT FLYWHEEL STATUS

The current decade has made tremendous strides in flywheel energy storage technology. For the first time, a complete systems approach has been adopted by serious investigation teams. This means that all subsystems are optimally integrated, i.e., each are brought to an equal level of sophistication. The end result yields a mechanical battery system that can have electrical power fed in, store it as kinetic energy, and release electrical power out upon demand. A weak link in any subsystem cannot be tolerated. This mechanical battery is comprised of composite rotor, a magnetic (or mechanical) bearing support of the rotor, a motor-generator, miniaturized control and power electronics, backup bearings, health monitoring instrumentation, heat exchanger, vacuum and safety containment, and benign failure detection.

Current rotor designs today have usable energy densities of 45 to 90 Whrs/kg. To this we have to add the remaining parts of the system weight which can be 30% to 60% of the rotor mass. Thus, the net system energy density can range from 34.5 to 69 Whrs/kg for a 30% additional system weight, and 28 to 56 Whrs/kg for a 60% additional system weight. A flywheel can cyclic discharge to zero energy without any degradation whatsoever, unlike the failings of all chemical batteries. However, electronic conversion efficiency tends to fall off at 95% depth of discharge (DOD) and above. Recent design projections indicate near term advances above these values. The limitation is optimizing the values of radial stress and hoop stress (which differ by as much as two orders of magnitude) to their design levels.

During the past four years US Flywheel Systems has been developing an integrated flywheel energy system, along with an optimization of each of the major subsystems described earlier. The primary objective has been oriented towards satellite use for lower earth orbit (LEO). In this context, hundreds of fiber composite rotors of primarily high tensile strength graphite were designed by extensive finite element analysis (FEA), followed by in-house fabrication in our specially designed winding laboratory. These rotors were spin tested with experimental results recycling back to corrective FEA and more fabrication and testing. This process allowed the rotors to be optimized for high energy density, limited only by maximum allowable fiber tensile strength and benign non-destructive spin test failure. Similar iterative testing has been applied to all of the other subsystems until an integrated design was achieved. A general schematic of this flywheel module system is shown in Figure 1, on next page.

USFS has a life cycle test program sponsored in part by DARPA to evaluate four flywheel module systems similar to those shown in Figure 1.

A completely automated data acquisition system has been designed and fabricated comprising over a hundred channels of sensors to continuously record, on a real-time basis, all subsystem performance during the continuous charge/discharge cycles. Full spin up and spin down (charge/discharge) to 90% DOD is accomplished by the integrated motor generator in 20 minutes. Target life is anticipated to be somewhere between 10,000 and 50,000 cycles without degradation of performance. This high number of cycles at 90% DOD is not possible for chemical batteries. In addition, the proposed configuration will provide 3-axis attitude control for satellites.

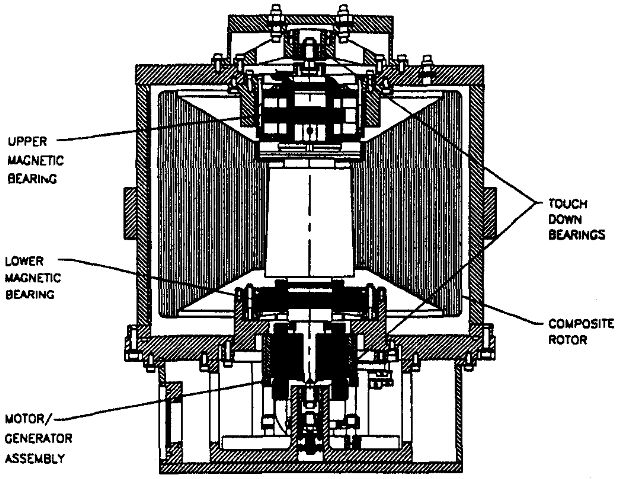

Fig. 1. USFS Integrated System Design

21st CENTURY PROJECTIONS

There are two major advancements that are considered for the next decade. These are higher specific power density kW/kg and higher specific energy density Whrs/kg. The former is almost wholly dependent upon the motor/generator. Based on current technology projections, it is not unreasonable to expect up to 30 kW/kg. This can take place by higher rotational spin speeds, better heat exchangers to accommodate intermittent double or more over-rating, and predictable design enhancements. The more difficult prediction for flywheel systems is higher specific energy over and above near term values. As a comparison, great increases in chemical battery performance are unlikely unless an unknown major breakthrough occurs in the future. However, even if this does occur, it is unlikely that electrochemistry can also reach higher specific powers.

The energy density E_ρ is a useful figure of merit for comparing how composite or metal flywheel rotors of differing materials relate to two parameters; namely, the maximum achievable hoop stress of the rotor, σ_θ, and the rotor material density ρ. An approximation for the flywheel energy density $E\rho$ is given by:

$$E_\rho = 1.57E-5\left(\frac{\sigma_\theta}{\rho}\right)\xi_{Stress}\xi_{Design} \quad (1)$$

where

E_ρ = energy density (W-hrs/lb)
σ_θ = hoop stress (psi)
ρ = material density (lbs/in^3)
ξ_{Stress} = safety stress reduction factor (typically 50%-75%)
ξ_{Design} = non-ideal design reduction factor (typically 50%-80%).

From this we can see that the specific energy in watt hours/lb is a constant times fiber tensile strength divided by fiber density. This applies to any material selected for the rotor. One would normally think a heavier rotor would be better, but this is not the case. Better performance (specific energy) is obtained by high tensile strength combined with low material density. Table 1 summarizes the theoretical thin rim limit based on differing rotor materials. These values are arranged in ascending order of performance where steel is the lowest at the bottom of the table. Note that in the following table, a value of 100% was used for the safety stress reduction factor ξ_{Stress} and the non-ideal design reduction factor ξ_{Design}.

Table 1. Theoretical Flywheel Energy Comparison

(Assumption: ξ_{Stress} = 100% and ξ_{Design} = 100%)

Rotor Material	Max Tensile Strength (psi)	Material Density (lbs/in^3)	Energy Density (W-hrs/lb)
T-1000 Graphite	1,000,000	0.065	241.5
T-700 Graphite	700,000	0.065	169.1
Spectra 1000	435,000	0.035	195
Technora T220	598,000	0.050	188
Kevlar 49	525,000	0.052	159
S2-Glass	600,000	0.092	102.4
E-Glass	450,000	0.092	76.8
4340 Steel	260,000	0.283	14.4

This table clearly shows the potential benefits from composite flywheel rotors compared to steel flywheel rotors. Taking steel as a material, its theoretical specific energy is 14 Whrs/lb (30.8 Whrs/kg) which is coincidentally only slightly better than lead acid batteries. If we go "up the ladder" the highest value is graphite fiber at an ultimate tensile strength of about 1,000,000 psi.

Now let us do some projections, without going to some organic long chain molecules that may be found in the future, and stick with graphite. Consider that its density will remain relatively unchanged while its ultimate tensile strength will increase over the next decade. The author has had private communications with carbon fiber manufactures [2] relative to tensile strength possibilities. They indicate that short fiber lengths (limited to several feet) have strengths of 2,000,000 psi to 3,000,000 psi in actual laboratory samples, and that higher values are theoretically possible.

Figure 2, on next page, shows a three dimensional plot of Equation 1 with material density and tensile strength as independent variables. The surface shows the theoretical limit of kinetic energy storage without design limitations. Also depicted are reasonable "system" energy densities including 50% safety margins and a 50%

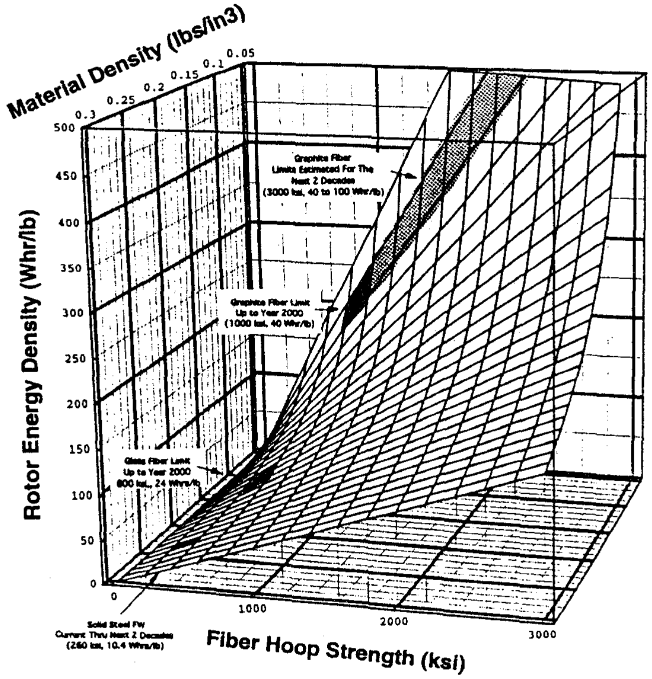

Fig. 2. Theoretical Material Dependent Energy Density Projections

reduction assuming real rotors rather than thin rims. Both these reduction factors are within today's current design limits. As material strengths increase, especially graphite, one can project flywheel battery energy densities approaching 100 Whrs/lb.

CONCLUSIONS

During the last century, flywheel mechanical energy storage has advanced from simple inertial rotating machines operating at low speeds to fully integrated electro-mechanical batteries. These systems are now becoming enabling technologies for many applications like LEO satellite energy storage and pulse power for hybrid electric vehicles. Based on increases in fiber strengths over the last two decades, and assuming continued increases in graphite fiber strengths over the next two decades, we can project energy densities approaching 100 Whrs/lb (220 Whrs/kg). Therefore, future flywheel systems are projected to have the following performance characteristics:

1. Specific Energy = 200 Whrs/kg; (possible projections)
2. Specific Power = 30 kW/Kg; (reasonable projection)

REFERENCES

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[2] Private communication with Toray and Hercules carbon manufactures, 1997.

Letter

Editor

Henry Oman asked "Why Do Empires Fall?" in your December 1997 issue. To answer that, one must ask "Fundamentally, why should they succeed and what does that imply for maintenance?"

Empires succeed because they are better at using force, at producing, or at providing some value to individuals.

Henry's examples are of force, through the Roman and British empires did provide a specific value to people – a rule of law (an early form of a justice system).

Societies whose existence depends on force will eventually fail, because it is not the best method to ensure productivity. That is why the USSR failed, ironically being unable to achieve the end used to justify its oppressive means – feed its own people.

While many technical inventions were made in China centuries ago, their society was unable to effectively make use of them. Why not? Probably because the need to both think and act was not fully recognized. In contrast, the Industrial Revolution in Britain combined new knowledge with action focused on usefulness to people's lives. A substantial part of that action involved "business" aspects.

Notice the elements involved: thinking, rational action, trade. They were important factors in the survival of one of the most enduring and free societies – Britain, which spawned others including a very productive society that improved on freedom: the United States.

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