APPLICATION OF ADVANCED FLYWHEEL TECHNOLOGY FOR ENERGY STORAGE ON SPACE STATION

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Summary

In space power applications where solar inputs are the primary thermal source for the power system, energy storage is necessary to provide a continuous power supply during the eclipse portion of the orbit. Because of their potentially high storage density, flywheels have been given consideration for use as the storage system on the proposed orbiting space station.

During the past several years graphite fiber technology has advanced, and this has led to significant gains in flywheel storage density. The tensile strength of current fibers is a factor of two to three higher than previous materials. Use of the improved fibers in experimental flywheel rims has resulted in ultimate storage densities of 878 kJ kg^{-1} being achieved.

With these high-strength fibers, operational storage densities for flywheel storage modules applicable to the space station storage need could reach 200 kJ kg^{-1}. This module would also be volumetrically efficient, occupying only about 1 m^3. Because the size and mass of the flywheel storage module are controlled by the storage density, improvements in fiber strength can have a significant impact on these values. With improvements in fiber strength that are anticipated within the next five years, operational storage densities of the order of 325 kJ kg^{-1} may be possible for the flywheel module.

Introduction

Space power systems using a solar primary energy source require an energy storage component to maintain operation of the platform during the eclipse portion of the orbit. Flywheels offer a number of advantages that make them attractive for such systems. They possess relatively high energy storage densities; this results in a low storage system mass. Also, the power density of the flywheel is independent of the energy density and is fixed by the output device rather than by the flywheel. This results in a storage system whose charging and discharging rates can differ greatly without affecting its performance. In addition, the rotating mass of the flywheel can provide for attitude control of the space platform, while also fulfilling its

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energy storage role. Because of these valuable operating characteristics, NASA has sponsored several flywheel workshops [1, 2] and has investigated a concept that integrates energy storage and attitude control functions [3] in a single flywheel module.

In this paper, advances in flywheel performance are detailed and potential improvements estimated. A flywheel energy storage module suitable for the needs of the space station is described. Performance of the module, in terms of energy storage density, is estimated using demonstrated flywheel performance. In addition, anticipated improvements in flywheel storage densities are used to determine potential performance increases for the storage module.

Flywheel development

Flywheel rotor materials

In space power applications, minimization of system mass is a critical design parameter. For the flywheel designer, this translates into a requirement that the storage system possess the highest possible storage density. As shown in Table 1, this necessitates that the flywheel rotor be constructed of composite material.

Early composite flywheel performance

Composite flywheel technology was initially established in the Mechanical Energy Storage Technology (MEST) Program conducted by the Oak Ridge National Laboratory [4]. In the initial stages of the program, a number of rotor designs (configurations and materials) were fabricated and

TABLE 1

Characteristics of materials used in flywheels

Material	Ultimate tensile strength (σ) (MPa)	Density (ρ) (g cm^{-3})	σ/ρ (kJ kg^{-1} (W h kg^{-1}))
Steels			
4340	1517	7.7	197 (54.7)
18 Ni (300)	2070	8.0	259 (71.8)
Composites			
E-glass/epoxy	1379	1.9	726 (201.6)
S-glass/epoxy	2069	1.9	1089 (302.5)
Kevlar[a] epoxy	1930	1.4	1379 (382.9)
Graphite epoxy	1586	1.5	1057 (293.7)
Other			
METGLASS[b]	2627	8.0	328 (91.1)

[a]Kevlar is a trademark of Du Pont.
[b]METGLASS is a registered trademark of the Allied Corporation, Morristown, NJ.

tested. The purpose of these initial tests was to determine the performance limits of the design and verify rotor failure mechanisms. Thus, the testing regime was limited to ultimate speed evaluations. The performance results of these initial ultimate speed tests are given in Table 2. The energy density and stored energy figures represent the rotor's capability at the maximum speed attained in the test. Actual operational values would, of course, be lower. The highest ultimate energy density achieved was 266 kJ kg^{-1} with a subcircular Kevlar rim design. Following closely, at 233 kJ kg^{-1}, was a disk/ring design made of graphite and S-glass. The highest stored energy, 7.67 MJ, was achieved with a graphite overwrap configuration.

For the second stage of testing in the MEST Program, the field of candidate rotors was narrowed, and the testing regime expanded to include cyclic fatigue tests. Results of these tests are given in Table 3. The disk and disk/rim rotors completed the full 10 000 cycle test. Subsequent ultimate speed tests of these rotors yielded energy densities of 175 and 229 kJ kg^{-1}, respectively. The disk/rim results were particularly instructive, because ultimate speed data were obtained for rotors with no cycles and with 10 000 cycles. Comparison of the energy density achieved in the two tests (233 kJ kg^{-1} and 229 kJ kg^{-1}) indicated that there was no degradation in performance through 10 000 cycles.

TABLE 2

Performance results for initial ultimate speed configuration tests

Manufacturer	Wheel type	Material[a]	Energy density at maximum speed (kJ kg^{-1})	Energy stored (MJ)
ORNL	Overwrap	K49	178	2.02
Brobeck	Rim	SG/K49	229	2.55
Garrett/ AiResearch	Rim	K49/K29/SG	266	4.43
Rocketdyne	Overwrap rim	G	143	7.67
APL-Metglass	Rim	M	81	0.14
Hercules	Disk (contoured pierced)	G	135	3.06
AVCO	Disk (pierced)	SG	158	1.44
LLNL	Disk (tapered)	C	225	1.12
LLNL	Disk (flat)	SG	242	0.58
GE	Disk (solid/ring)	SG/G	233	2.37
Owens/Lord	Disk	SMC	63	0.61
	Disk/ring	SMC/G	90	1.01
		SMC/G	100	1.30
		SMC/G	132	1.44

[a]Material legend: SG = S-glass; K49 = Kevlar 49; K29 = Kevlar 29; G = Graphite, M = Metglass; SMC = S-glass sheet molding compound.

TABLE 3

Fatigue and ultimate speed test results from MEST program

	Flywheel design			
	Disk	Disk/rim	Subcircular rim	Bidirectional weave
Material	SGL[a]	SGL[a]/G	K49	K49
Completed 10 000 cycle test	Yes	Yes	No[b]	—[c]
Ultimate energy density (kJ kg^{-1})	175[d]	229[d]	237	134
Total stored energy (MJ)	1.86	2.32	2.24	1.50
Speed at failure (rpm)	40 638	47 058	30 012	27 575

[a] S-glass laminate.
[b] Rotor failed at 2586 cycles.
[c] Rotor was not cycle tested.
[d] Rotor had previously completed cyclic test.

Advances in flywheel performance

The MEST Program was phased out in 1983, and flywheel technology was essentially frozen at these performance levels. Flywheel development activities resumed at Oak Ridge in 1985, and significant advances in rotor performance were achieved through precision fabrication of carbon fiber/epoxy material [5]. The fibers used were Hercules IM6 and AS6. The Hercules IM6 fiber came to the market in 1985 and represented a significant improvement in fiber strength. Previous graphite fibers had ultimate tensile strengths of the order of 2640 MPa (383 ksi). The IM6 fiber at 5340 MPa (775 ksi) more than doubled this strength and led to significant advances in flywheel performance.

The focus of this effort was the design, fabrication, and spin testing of carbon/epoxy flywheels using the advanced high-strength fibers. The first series of rims to be tested (the only ones to be tested to date) was designated the Demo 1 series. To construct the rotors, fibers were wet wound and cured on a mandrel to form a thick-walled cylinder. The fabricated cylinder was then sectioned to form the test rims. In this design, the lower-modulus, higher-strength material (IM6) was used for the outer portion of the rim and AS6 for the inner portion.

Test results for the Demo 1 series are summarized in Table 4 and compared with the MEST results in Fig. 1. Since the purpose of the program was to demonstrate advances in rotor technology, no attempt was made to optimize the web structure. In these tests, the web structures were relatively

TABLE 4

Test results for advanced flywheel rotors

1985 date	Demo unit	Velocity ($m\ s^{-1}$)	Rim specific energy ($kJ\ kg^{-1}$ ($W\ h\ kg^{-1}$))	Result
Oct. 17	1A	1055	495 (138)	Web failure, small crack. No rim damage.
Nov. 8	1B	1173	605 (168)	Stopped for inspection. No damage.
Nov. 12	1C	1221	663 (184)	Stopped for inspection. No damage.
Dec. 9	1C	1405	878 (244)	Intentional failure test.

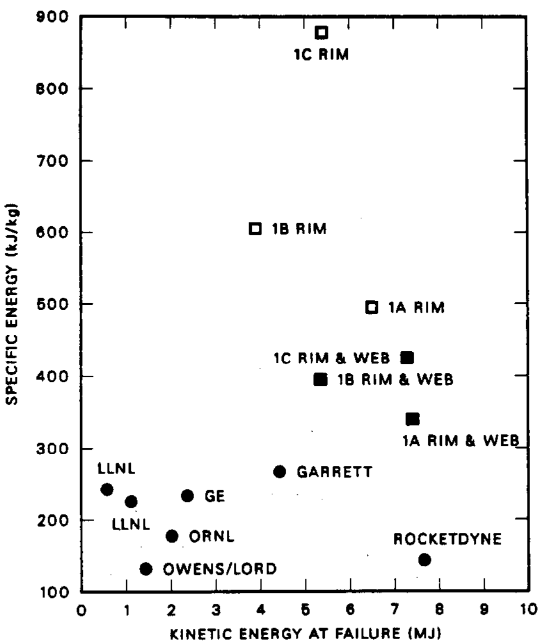

Fig. 1. Comparison of rotor performance.

heavy, being about equal to the rim weight. In an optimized system, the web would be much lighter (potentially of the order of 20% of the rim weight). Consequently, the data points for "rim + web" do not reflect a typical design.

The most dramatic result was obtained with Demo 1C. This rotor was intentionally accelerated until failure occurred at a peripheral speed of 1405 $m\ s^{-1}$. At this speed, the energy density of the rim only was 878 kJ

kg^{-1}. The total kinetic energy stored by the unit (rim + web) was 7.28 MJ. The 1405 m s^{-1} peripheral velocity was an increase of ~40% over previous spin tests. The demonstrated failure speed of 1405 m s^{-1} provides firm experimental evidence for a safe flywheel design operating speed in the range 1100 - 1200 m s^{-1}.

Space station flywheel storage module

Module configuration

A schematic for a flywheel energy storage concept applicable to the needs of the space station is shown in Fig. 2. This concentric configuration was chosen because it is highly efficient in its volumetric characteristics. The flywheel module would consist of two such flywheels. Energy is stored in the two counter-rotating flywheel rotors, which are aligned on a common axis. This results in the momentum vectors of the two flywheels cancelling and the platform experiencing a zero momentum vector. A highly efficient (of the order of 96%), lightweight (specific power of 5 kW kg^{-1}), axial gap permanent magnet motor/generator is used for charging and discharging the flywheel. The suspension system uses magnetic bearings to achieve very low drag and minimize standby losses. This also allows the bearing stiffness to be adjusted during operation of the system.

Estimated system performance

Mass estimates were prepared for the flywheel storage module illustrated in Fig. 2. In performing the analysis, it was assumed that the required module output power was 87.5 kW. The time available for charging (solar time during orbit) was set at 55 min, and the discharge time (eclipse portion of the orbit) was assumed to be 36 min.

The flywheel operational storage density was governed by several major assumptions. The maximum operating speed of the flywheel was limited to 80% of the burst speed. A 2:1 speed ratio was used resulting in a 75% depth of discharge (on an energy basis). For efficiency in material use, a relatively thin rim was used; the ratio of inner to outer radius was set at 0.85.

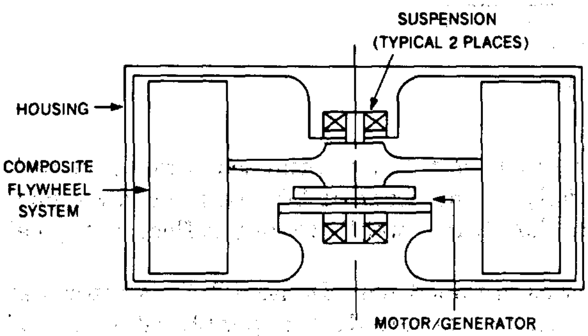

Fig. 2. Schematic of flywheel module for space station application.

The flywheel rotor was examined at three technology levels. With currently available fibers, a burst speed of 1405 m s^{-1} has been demonstrated. This yields a maximum operating speed of 1125 m s^{-1} and an operational storage density of 410 kJ kg^{-1} for the rim only. Within the next several years it is anticipated that fiber strength can increase by about 13%. This would raise the maximum operational speed to 1190 m s^{-1} and produce an operational storage density of 460 kJ kg^{-1} (rim only). Within the next five years, fibers may be available that would permit operational maximum speeds to reach 1400 m s^{-1}. With these fibers the flywheel operational storage density would be 650 kJ kg^{-1} (again, rim only).

Previous analysis of flywheel storage modules designed for low power (of the order of 100 kW) applications with charge/discharge time ratios near unity have indicated that the module operational storage density is about half that of the rim only value [5]. Using this relationship results in the flywheel module operational storage densities shown in Table 5. As indicated, the module operational storage density, using current fibers, would be 205 kJ kg^{-1}. A modest 10% improvement is anticipated within the next several years, resulting in a module storage density of 230 kJ kg^{-1}. With fiber technology advances anticipated within the next five years, the module storage density could be raised to 325 kJ kg^{-1}.

Since the concentric design has all power components within the bore of the flywheel, the module volume is fixed by the size and shape of the flywheel rotor. In sizing the rotor, it was assumed that the rotor length was equal to the rotor diameter. This criterion was used to determine the volume occupied by the modules designed to meet the storage needs of the space station. As indicated in Table 5, the storage module, using current fibers, would occupy 1.07 m^3. Within two years, advances in fiber technology would result in the volume being reduced to under 1 m^3. With the longer term advances, the module volume could potentially be reduced to 0.67 m^3.

Another measure of the volumetric storage efficiency is given by the volumetric storage density. As shown in Table 5, with present technology levels the module stores 177 MJ in one cubic metre. This could rise to 199 MJ m^{-3} within two years and 282 MJ m^{-3} within 5 years if the anticipated increases in fiber strength are realized.

TABLE 5

Flywheel energy storage module characteristics

Fiber technology	Operational storage density (kJ kg^{-1})	Volume (m^3)	Volumetric storage density (MJ m^{-3})
Demonstrated	205	1.07	177
Within 2 years	230	0.95	199
Within 5 years	325	0.67	282

Conclusion

The flywheel module appears to be an attractive energy storage option for the space station application. With current fibers, the system operational energy storage density is expected to be 205 kJ kg^{-1}. This compares favorably with battery and fuel cell systems, which are anticipated to be in the range 25 - 75 kJ kg^{-1} [1, 2]. In addition, the flywheel module is volumetrically more efficient than the competing systems. The flywheel volumetric storage density of 177 MJ m^{-3} is about an order of magnitude higher than that of battery systems (from ref. 1 the volumetric density of Ni–Cd batteries is about 25 MJ m^{-3}).

If anticipated increases in fiber strength are realized, the performance of the flywheel storage module would increase substantially. If fiber strength increases are fully realized, it will be possible to raise the storage density (on a mass basis) to 325 kJ kg^{-1} with a volumetric density of 282 MJ m^{-3}.

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