Development of a High Specific Energy Flywheel Module, and Studies to Quantify Its Mission Applications and Benefits

Tim Dever / NASA GRC
Topics

• How Flywheels Work
• Flywheel Applications for Space
  – Energy Storage
  – Integrated Power and Attitude Control
• Flywheel Module Design
  – What are the major components of a flywheel?
  – GRC Flywheel Performance Progress
  – G3 Performance Metrics
• Flywheel Mission Study
  – International Space Station
  – Lunar 14 day eclipse energy storage system
Flywheels: How the Technology Works

A flywheel is a chemical-free, mechanical battery that uses an electric motor to store energy in a rapidly spinning wheel - with 50 times the Storage capacity of a lead-acid battery.

As the flywheel is discharged and spun down, the stored rotational energy is transferred back into electrical energy by the motor — now reversed to work as a generator. In this way, the flywheel can store and supply power where it is needed.
Flywheel Applications For Space
Flywheels For Energy Storage

- Flywheels can store energy kinetically in a high speed rotor and charge and discharge using an electrical motor/generator.

Benefits
- Flywheels life exceeds 15 years and 90,000 cycles, making them ideal long duration LEO platforms like ISS or national assets like the Hubble telescope.
- Flywheels have flexible charge/discharge profiles, so solar arrays are more fully utilized.
- Flywheels can operate over extended temperature ranges, reducing thermal control requirements.
- Flywheel state of charge is precisely known.
Integrated Power & Attitude Control System Options

- **Body Mounted Reaction Wheel**
  - Momentum vector of wheels are fixed w.r.t. spacecraft
  - Wheel speed is determined by simultaneously solving the bus regulation and torque equations.

- **Variable Speed Control Moment Gyro.**
  - Momentum vector of wheels are rotated w.r.t. spacecraft to produce torque
  - Wheel speeds are varied for bus regulation

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Fausz, J.; Richie, D., “Flywheel Simultaneous Attitude Control and Energy Storage Using a VSCMG Configuration”, 2000

Flywheel Module Design
What are the major subcomponents of a flywheel?

**Auxiliary Bearings** – Capture rotor during launch and touchdowns.

**Magnetic Bearings** – Used to levitate rotor. These non-contact bearings provided low loss, high speeds, and long life.

**Housing** – A structure used to hold the stationary components together. Can also act as a vacuum chamber.

**Composite Rotor** – Stores energy. High energy density is achieved through the use of carbon composites.

**Motor/Generator** – Transfers energy to and from the rotor. High efficiency and specific energy is required.
## System Metrics

The G3 Flywheel Module is the first module designed to meet the Near Term IPACS program metrics of the Aerospace Flywheel Technology Program.

### AFTP Near Term IPACS Metrics

<table>
<thead>
<tr>
<th>Metric</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Energy –</td>
<td>25 Whr/kg</td>
</tr>
<tr>
<td>Efficiency –</td>
<td>85%</td>
</tr>
<tr>
<td>15 Yr LEO Life</td>
<td></td>
</tr>
<tr>
<td>Temperature Range –</td>
<td>-45 to 45 °C</td>
</tr>
</tbody>
</table>

Specific Energy is at the system level. The system is defined to include the flywheel modules, power electronics, sensors and controllers.

Efficiency is measured at the system level as the ratio of energy recovered in discharge to energy provided during charge.

Fifteen year life is required in a Low Earth Orbit (LEO).

The ambient temperature range outside of the system is specified.
### Rotor Development

<table>
<thead>
<tr>
<th>Flywheel</th>
<th>HSS</th>
<th>Dev1</th>
<th>D1</th>
<th>G2</th>
<th>FESS</th>
<th>G3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Features</td>
<td>Steel Hub</td>
<td>Single Layer Composite</td>
<td>Multilayer Composite 750m/s</td>
<td>Multilayer Composite 750m/s</td>
<td>Multilayer Composite 950m/s</td>
<td>Composite Arbor 1100m/s</td>
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<td>Energy (W-Hr)</td>
<td>17</td>
<td>300</td>
<td>350</td>
<td>581</td>
<td>3000</td>
<td>2136</td>
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<td>23</td>
<td>20</td>
<td>26</td>
<td>40</td>
<td>80</td>
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<tr>
<td>Life</td>
<td>?</td>
<td>&lt; 1 yr</td>
<td>1 yr</td>
<td>1 yr</td>
<td>15 years</td>
<td>15 years</td>
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<tr>
<td>Temperature</td>
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<td>+25 to +75</td>
<td>+25 to +75</td>
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<td>-45 to +90</td>
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</table>
Flywheel Mission Study
Flywheel Mission Studies

• ISS
  – Efficiency and Charge Profile Effects
  – Mass Estimates
  – Proposed Configuration
  – Upmass Benefits

• Lunar 14 day eclipse energy storage system
Efficiency and Charge Profile Effects

Excess Solar Array Capacity Due to Taper Charge

Excess Capacity Due to Efficiency

-3500
-2500
-1500
-500
500
1500
2500
3500

0 20 40 60 80 100

Power (W)

Time (min)

13 min
1995 W

-2300 W

Flywheel Nominal Orbit
Flywheel Charge Limit
Ni-H ORU Nominal Orbit

1995 W
1485 W

-2300 W
Flywheel Module Mass Estimates

- GRC has completed a detailed design of the G3 flywheel module which stores 2100 W-hr at 100% DOD and has a power rating of 3300W at 75% DOD.

- A sizing code has been designed which can be used to estimate the mass of a G3 type design as a function of energy stored and power.

- The five major components: rotor, motor, housing, and magnetic bearings are linearly scaled based on the requirements.

<table>
<thead>
<tr>
<th>G3 Rotor</th>
<th>G3 Motor</th>
<th>G3 Stator</th>
<th>G3 Radial MB</th>
<th>G3 Combo MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rotor Mass</td>
<td>32.3</td>
<td>3.21</td>
<td>27.3</td>
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<tr>
<td>Rotor Inertia</td>
<td>0.560113</td>
<td>0.9185</td>
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<td>0.0147</td>
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<tr>
<td>Rim Mass</td>
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<td>1.57</td>
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<td>Hub Mass</td>
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<tr>
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<td>Rim Mass/Length</td>
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</table>

<table>
<thead>
<tr>
<th>G3 Motor</th>
<th>G3 Stator</th>
<th>G3 Radial MB</th>
<th>G3 Combo MB</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overall Mass</td>
<td>3.21</td>
<td>60.1</td>
<td>4.59</td>
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<tr>
<td>Active Length</td>
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<tr>
<td>Stator Active Mass</td>
<td>1.57</td>
<td>4.59</td>
<td>1.314</td>
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<tr>
<td>Rotor Active Mass</td>
<td>1.15</td>
<td>1.57</td>
<td>0.53</td>
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<tr>
<td>Mass/meter of Active Length</td>
<td>147.9</td>
<td>125.4</td>
<td>147.5</td>
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<tr>
<td>Power @ 50,000 RPM</td>
<td>7600</td>
<td>20086</td>
<td>285</td>
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<tr>
<td>Mass in Non Active Area</td>
<td>0.473</td>
<td>0.466</td>
<td>0.466</td>
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<tr>
<td>Active Mass / Power</td>
<td>0.000360</td>
<td>0.000649</td>
<td>0.000649</td>
</tr>
</tbody>
</table>

Note: G3 Rotor - CDR DESIGNED INFO
G3 Motor - CDR DESIGNED INFO
G3 Stator - CDR DESIGNED INFO
G3 Radial MB - CDR DESIGNED INFO
G3 Combo MB - CDR DESIGNED INFO
Proposed Configuration

• A single flywheel system will replace three strings of Ni-H batteries on the IEA

• This configuration allows three options after the flight demonstration phase
  – Flywheels only
  – Flywheels paralleled with Ni-H to extend life (rotor size reduced)
  – Flywheels paralleled with Li-Ion (rotor size reduced)

• The flywheel system will interface with the existing mounting hardware.
Upmass Benefit To ISS

- **General Assumptions**
  - One flywheel ORU replaces six Ni-H ORUs
  - One Li-Ion replaces two Ni-H ORUs
  - No BCDU replacements for Li-Ion
  - All BCDUs launched prior to flywheel flight demo

- **Life Assumptions**
  - Flywheel Life = 15 years
  - Ni-H & Li-Ion Life = 7 years

- **Mass Assumptions**
  - Li-Ion ORU – 394 lbm
  - Ni-H ORU – 375 lbm
  - BCDU – 235 lbm
  - FESS-E – 993 lbm
Benefits of 14 day Lunar Eclipse Flywheel System

- **Safety, Reliability, and Redundancy**
  - Flywheel infrastructure will not need to be replaced during the first 15 years of lunar exploration.
  - Flywheels do not degrade when not in use. If program milestones slip, the deployed hardware will not suffer.
  - Flywheels can provide complete electrical isolation between a power source and load. A low voltage motor charges the flywheel from the solar array and a separate high voltage motor provides power to the lunar base.
  - Since reliability is achieved at the component level within a flywheel module, a system with 100 flywheel modules would provide tremendous redundancy.

- **Performance**
  - Flywheels can charge and discharge quickly and can be used as outposts for rover or EVA suit recharging.
  - Flywheels can accommodate very high peak loads, reducing constraints and planning requirements for operations.
  - Flywheels can operate over extreme temperature ranges without maintenance.
Summary

• Flywheels have been experimentally shown to provide bus regulation and attitude control capability in a laboratory.

• The G3 flywheel can provide 25W-hr/kg system specific energy, 85% round trip efficiency for a 15 year, LEO application

• A sizing code based on the G3 flywheel technology level was used to evaluate flywheel technology for ISS energy storage, ISS reboost, and Lunar Energy Storage with favorable results.