Flywheel Technology Development At The NASA Glenn Research Center

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Abstract

With the advent of high strength composite materials and microelectronics, flywheels are becoming attractive as a means of storing electrical energy. In addition to the high energy density that flywheels provide, other advantages over conventional electrochemical batteries include long life, high reliability, high efficiency, greater operational flexibility and higher depths of discharge. High pulse energy is another capability that flywheels can provide. These attributes are favorable for satellites as well as terrestrial energy storage applications. In addition to energy storage for satellites, the several flywheels operating concurrently can provide attitude control, thus combine two functions into one system. This translates into significant weight savings.

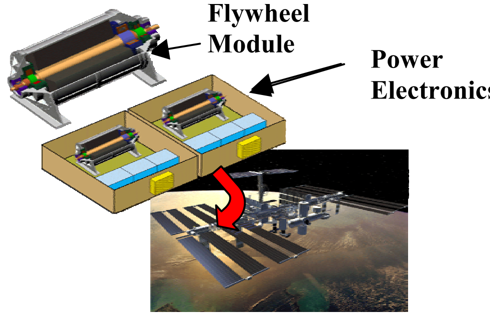

Figure 1- Flywheel Location On the Space Station

The NASA Glenn Research Center in Cleveland Ohio is involved in the development of this technology for space and terrestrial applications. Because of the multidisciplinary nature of flywheels, NASA GRC is well suited for this research. The disciplines include power electronics design, rotor dynamics, composite material research, magnetic bearings and motor design and control, all of which NASA GRC has world class expertise. NASA GRC is proposing a Flywheel Energy Storage System (FESS) concept to replace the current Nickel Hydrogen batteries in the International Space Station (ISS) Electrical Power System. Due to the longer design life (15 years vs. 5 years for the current batteries), the FESS project will realize a life cycle savings of about $450 Million. The FESS project will also space qualify a high speed composite rotor design, necessary to prove the concept for the satellite industry.

To support the FESS and other space applications, NASA is funding a Flywheel Technology Development Program. The purpose of this program is to design, fabricate and test an Attitude Control/Energy Storage Experiment (ACESE). Two flywheels will be integrated onto a single power bus and run simultaneously to demonstrate ISS energy storage and control. It will also demonstrate single axis attitude control on an air bearing. The ACESE test bed can facilitate the assessment of various motor generator and magnetic bearing architectures and will eventually be used to demonstrate the FESS prototype, currently under construction. Other applications for flywheels, such as a power source for magnetically levitated launch vehicles and distributed electrical actuation for aircraft, are also being investigated. In addition to this test bed, NASA GRC has flywheel technology component test facilities for individual component design and evaluation.

This paper presents details on the Flywheel Technology Demonstration Program as well as discuss the various flywheel test facilities. Flywheels have been used to store and dissipate energy for a very long time, however the technology has not been cost competitive compared to batteries. With major advances in advanced materials and electronics technologies have enabled the emergence of flywheels as a cost-competitive energy storage alternative to batteries and ultracapacitors in high-pulsed power applications. State-of-the-art flywheel technology currently being developed by NASA for energy storage applications on spacecraft provide many advantages over electrochemical energy conversion devices, including:

- Higher efficiencies, 85-90% versus 65-70%
- Longer life, 15-20 years, versus 5 years (for low earth orbit applications)
- Higher energy densities
- No toxicity, no safety impacts or environmental impacts upon disposal
- Higher pulse power capabilities while maintaining constant bus voltage upon discharge

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• Lower depth of discharge capabilities, which adversely affect battery life
• Operate efficiently over larger temperature ranges
• Easily measurable state of charge, simply the rotational speed of the rotor.

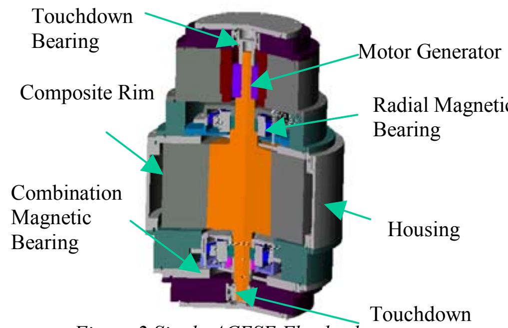

Figure 2 Single ACESE Flywheel Module

Flywheel devices require an electric motor/generator to convert the rotational energy into electrical energy, and vice versa. Advanced flywheel systems typically consist of magnetic bearings, a composite rotor, power electronics and advanced control software algorithms. Magnetic bearings levitate the rotor for low frictional losses at high speeds. The composite rotor provides high strength for faster rotation capability. The power electronics condition the energy into and out of the system to meet the electrical bus characteristics and the control algorithms provide seamless interfacing with the electrical bus.

Each ACESE module is sized for approximately 350 whr (10% of the ISS FESS capability), with a speed range between 60,000 and 20,000 rpm. Composite, carbon wound rims provide the bulk of the rotating mass. Other components include a 2-pole permanent magnet synchronous machine, magnetic bearings and a vacuum housing as shown in Figure 2. Along with the power electronics, single ACESE flywheel modules will be tested in a containment test chamber as shown in Figure 3. Operations and control are performed in the Flywheel Control Room which contain the inverter and other power processing components as well as the computers which operate the magnetic bearing and motor generator controls. Standard Commercial-Off-The Shelf components are used where possible, with modifications as necessary.

Figure 3- Low Energy Flywheel Facility

The integrated ACESE testing will occur in the High Energy Flywheel facility, shown in Figure 4. This is a unique test bed in that the containment is provided by water rather than a steel chamber. The adequacy of this approach was verified by firing composite samples into water containers via a high pressure gun, used for testing materials in jet engines. There are significant fabrication savings as well as the ability to readily configure the test bed to facilitate other flywheel configurations. An air bearing is mounted at the bottom of the test bed, causing the flywheel modules to rotate in a circular manner, thus evaluating the adequacy of proposed attitude control algorithms.

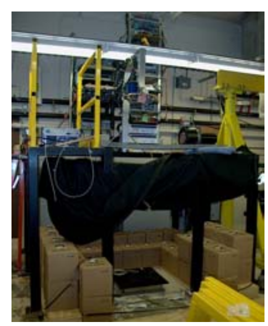

Figure 4- High Energy Flywheel Facility

Other facilities exist at NASA that can support various flywheel development activities. Included are:

- Next Generation Launch Vehicle Actuator Test Facility
- Fault Tolerant Magnet Bearing Test Facility
- Electrical Interface Simulator
- Cyclic Spin Facility.
- Touchdown Bearing Test Facility

These facilities combined with other expertise and capabilities located at the NASA GRC, provide excellent potential for significant flywheel development for aerospace and terrestrial energy storage, power and attitude control applications.

Flywheel Energy Storage System For International Space Station

The Flywheel Energy Storage System (FESS) program was a NASA International Space Station (ISS)-funded flight program The goal was to design, fabricate, qualify, launch and operate a flywheel as a direct replacement for the Nickel Hydrogen batteries in the ISS Electric Power System (EPS). It was to demonstrate the ability to operate a flywheel on-orbit seamlessly with the ISS EPS, in other words it has to operate like a battery and be capable of being installed and replaced by robotics and astronaut spacewalks as an Orbital Replacement Unit (ORU). The benefits derived by utilizing this technology include: reduction of ISS operating costs (>$450 million), lower maintenance costs (15 year life vs. 5 years for the batteries), and greater contingency power (2 orbits versus 1 orbit, defined as the power required to maintain power to the ISS loads without any solar array power generation). Repeated depth of discharges as low as 90% will not affect life. The effort concluded with the final design of the flywheel module, delivery of prototype hardware to NASA GRC for testing and preliminary overall systems architecture. Unfortunately due to the budget constraints of the ISS, this program has been cancelled. However, great interest remains at NASA Headquarters because of the potential for significant operational cost savings. Participants in this project include the following table.

Table 1 FESS Participants and Responsibilities

Participant	**Responsibility**
NASA Glenn Research Center	Program Management, Configuration Management, Risk Reduction Testing, Systems Engineering, Safety, Reliability and Quality Assurance
The University of Texas at Austin- Center for Electromechanics (UT-CEM)	Flywheel Module, Development and Testing
TRW- Space and Electronics Group	Integrating Contractor, Flywheel Electronics and Control
University of Toledo	Systems Engineering, Risk Reduction Testing

Each FESS consists of two Flywheel Modules and associated electronics and the ORU box for packaging and handling. Some performance characteristics of the FESS are listed in Table 2

Table 2 FESS Performance Characteristics

Parameter	**Value**
Total Energy Stored, kWhr	5.5
Power Output. Kw	6.6
Round Trip Efficiency, %	88
No. Of Contingency Orbits	2
Maximum Normal Operating Speed, rpm	53,000
Minimum Normal Operating Speed, rpm	41,000
Maximum Depth of Discharge, %	90
Cycle Time, min: - Charge - Discharge	 57 35
Total Weight, lb	900
No. Design Cycles	350,000 (60 year life)

Flywheel Express Pallet Experiment

The Flywheel EXpedite the PRocessing of Experiments to Space Station (EXPRESS) Pallet Experiment (FEPE) was conceived to demonstrate the ability of flywheels to operate in a Low Earth Orbit (LEO) environment. It will build upon the legacy of the FESS design and incorporate two flywheels providing power to and from each other with the ISS providing the small amount of power to make up for the losses. This flight experiment was proposed since a total LEO environment cannot be simulated in a ground facility without excessive facility development costs. It also is focused on commercialization of flywheel technology for satellite applications, one of the missions that Congress has mandated NASA to perform on the ISS. The three objectives of this program are:

1. Static testing of composite rotor materials on the ISS.
2. Flight test of the flywheel module and avionics for ISS applications.
3. Flight test of a flywheel module for satellite applications.

For the first flight experiment, a scale-down version of the FESS flywheel module is being proposed. Since the limiting factor on the EXPRESS Pallet is thermal rejection, each flywheel module was designed to store 650 wHr of energy This resulted in a smaller rotor design and slightly lower speed. Total makeup power to the system is 120 W. The existing magnetic bearing, end caps and motor generator design from the FESS program will be used as well as a similar avionics set. The system will simulate a full orbital cycle, 57 minutes, charge, 35 minutes, discharge). The experiment is proposed to be launched in 2006 and fly for one year before returning for examination.

The second flight experiment will build upon the experience gained from the first with the exception of a high performance flywheel that will utilize a strain-matching hub. The existing end caps, bearings and motor generator will be utilized after refurbishment from the first experiment. The straining matching composite hub will increase the energy density of the wheel with a focus on the high performance satellite market. It will have slightly lower energy storage capacity (~500 wHr). The aim is to demonstrate the ability of flywheels to provide the life that can be achieved in Geosynchronous Orbit (GEO) in Low Earth Orbit (LEO). This program is receiving considerable support by NASA Headquarters and industry because of the potential ISS savings as well qualifying flywheel technology for satellite applications.
Table 3 lists the participants of this proposed program.

Table 3 FEPE Participants and Responsibilities

Participant	**Responsibility**
NASA GRC	Program Management, Configuration Management,Risk Reduction Testing, Systems Engineering, Safety, Reliability and Quality Assurance
UT-CEM	Flywheel Module, Development and Testing
TRW- Space and Electronics Group	Integrating Contractor, Flywheel Electronics and Control
Commercial Space Center for Engineering- Texas A&M University	EXPRESS Pallet Integration
University of Toledo	Systems Engineering, Risk Reduction Testing

Flywheel Technology Demonstration Program

NASA Code R (Research) has an ongoing flywheel technology development program. The flywheel testbed at GRC is being used to demonstrate a two axis Attitude Control and Energy Storage Experiment (ACESE) system and to test prototype electronics for the FESS and FEPE programs on the International Space Station (ISS). The hardware configuration for the NASA ACESE experiment consists of two flywheel modules with parallel spin axis vertically mounted on an air-bearing table. The electronics to support the magnetic bearing and motor/generator controls are a combination of commercial and brassboard hardware with rapid prototype software using Simulink. The NASA ACESE has three objectives:

1. Demonstrate two flywheel modules operating in a lightly constrained mounting system. This will verify an analytical modeling effort, which is exploring the effect of mount stiffness on magnetic bearing stability.

2. Demonstrate momentum and energy control in charge mode with the flywheels on separate power buses. This will verify the ability to control charge rate and net torque between the two flywheels.

3. Demonstrate full momentum and energy control in charge and discharge on a single power bus. This will verify that in discharge the controller will regulate the bus voltage and the net torque of the two-wheel system.

After completing the NASA ACESE work, the same hardware will be used to support development for ISS applications. The ACESE flywheels stored 10% of the energy required for ISS. Since normal orbit cycles cannot be demonstrated with smaller flywheels, two extremes will be tested. First, the system will run at normal charge and discharge power levels, completing an orbit cycle in nine minutes. Second, the system will be run the full ninety minutes at 10% power. The synergy between the NASA ACESE and the ISS work has allowed GRC to focus resources and provide value to each program at a reduced cost.

Flywheel Test Facilities

Significant investment was made to construct several facilities that are currently being used for component and system testing.

Low Energy Flywheel Facility

The Flywheel Test Facility consists of a test cell and a control room. The test cell, known as the Low Energy Flywheel Facility (LEFF) is located in the Power System Facility (PSF) Building 333, Room 123, at NASA GRC and is physically separate from the control room for safety purposes. The control room is located in the same building, Room 114. The present flywheel under test, NASA ACESE consists of a 2 pole permanent magnet synchronous machine, high strength composite rotor, magnetic bearings and a housing structure which is sealed and pumped to a low vacuum with water cooling capability. The flywheel module itself is housed in a containment structure that is closed during operation. Power for the motor is derived from a standard six switch, three-phase inverter with a DC power supply source. The inverter is a commercial off the shelf intelligent power module (gate drive circuitry included in the unit) rated at 600 volts, 200 amps. DC Power supplies as well as resistive power dissipating load banks are contained in this test cell. The control room has independent stations for various functions: magnetic bearing control, motor/generator control, DC power supply control, and temperature monitoring. The motor/generator control function is implemented digitally using a commercially available microprocessor board. The control algorithms are written in a high-level block diagram simulation language and converted to the necessary microprocessor code via software by the manufacturer of the microprocessor board. Currents and voltages are measured in the control room and fed back to the control room to support the motor generator control functions. The control room contains oscilloscopes, chart recorders, software emulators and data acquisition systems.

High Energy Flywheel Facility

The High Energy Flywheel Facility (HEFF) is located in the PSF, Building 333, Room 123. Its purpose is to test two integrated flywheel modules for combined energy storage and two axis attitude control. An air bearing is located at the bottom of the HEFF, which allows for circular articulation. The mezzanine contains power electronics and instrumentation. Overall control monitoring is provided by the same control room as described above. Containment is provided by water enclosures, which has been verified to absorb failure of the rotor by testing at NASA GRC. This facility is currently under construction but will be operational by February, 2002. ACESE flywheel for testing as a combined energy storage and attitude control configuration integrated on a simulated spacecraft bus.

Electrical Interface Simulator

The Electrical Interface Simulator (EIS) is used to test and validate the motor generator control algorithms. It is located in the PSF, Room 108. It consists of back-to-back motor generators, one of which simulates the electrical loads and a computer that manages the motor generator control algorithms The EIS is shown in Figure 5.

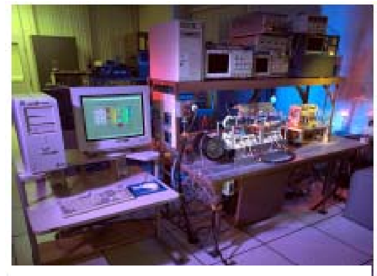

Figure 5- Electrical Interface Simulator

Cyclic Spin Facility

The Cyclic Spin Facility is located behind Building 333 and accommodates the safe-life testing activities for the composite rotor rim. It is built in an underground bunker and has a remote control room with video feed. It has the capability of rotating to a steady state of 60,000 rpm with short bursts to 66,000 rpm. The motive drive is provided by an air turbine. This facility will be used to support the man-rated composite rotor certification.

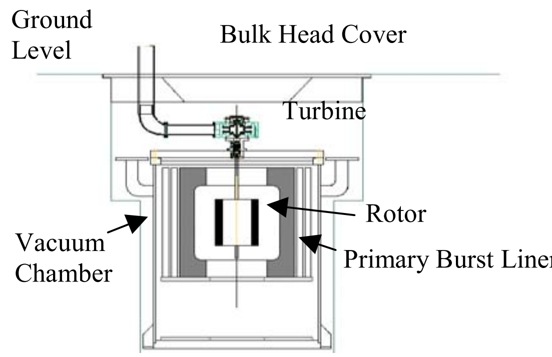

Figure 6- Cyclic Spin Facility

Summary

The NASA GRC is a leading center in flywheel research. Although the focus is on flywheels for space applications, this knowledge can be readily adaptable to terrestrial uses. Some of the uses under consideration include distributed energy sources for all-electric aircraft and ships, uninterruptible power systems and pulse power and power peaking applications. These test facilities along with other facilities and expertise residing at NASA GRC would be useful in development of flywheels for these applications.