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Survey of Technology Developments in Flywheel Attitude Control and Energy Storage Systems

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Advances in microprocessors and composite materials in the past decade, along with limitations of chemical batteries for U.S. Air Force mission concepts, have caused a renewed interest in flywheel energy storage systems for space applications. This interest has also been driven in the past by the promise of using flywheel systems for energy storage and as attitude control actuators. The primary issues are power efficiency, mass and size, and long-term stability. Flywheels as one-to-one replacements for spacecraft batteries are competitive for only a few special missions. When flywheels replace components in two major bus subsystems, the potential mass and volume benefits are attractive. This especially benefits future small satellite missions that seek agile slewing with high peak power. The objective of this paper is to describe the progression of the flywheel technology state of the art for combined energy storage and attitude control systems in space applications and the current energy storage and attitude control systems efforts.

Nomenclature

K_s = shape factor
m = rotor mass
v = volume
ρ = rotor density
σ = allowable material stress

I. Introduction

MECHANICAL energy storage devices have been used for thousands of years in many applications. Interest in power-generating mechanical energy storage systems has followed a cyclical pattern. The primary components of power-producing flywheel systems are the rotor, bearings, and the spin motor/generator. An early example of a power-generating flywheel system is the Gyrobus, which was produced in Switzerland in the 1950s and was powered by a 1500 kg flywheel [1,2]. The modern era of high-efficiency flywheel energy storage began in the 1970s. Recently, terrestrial flywheel energy storage systems, such as high-capacity uninterruptible power supplies, have come into production, and hybrid electric vehicles using flywheel energy storage systems have been demonstrated in mass transit applications. One of the near-term terrestrial applications areas for flywheel power systems seems to be in power quality mitigation equipment [3]. In space applications, various component technologies have demonstrated flight heritage. The five French Satellite pour l'Observation de la Terre (SPOT) satellites, dating back to 1986, use magnetically suspended momentum wheels [4], as does the Amateur Radio Satellites (AMSAT) AO40 satellite, launched on 15 November 2000 [5]. Recent interest in space applications of flywheel energy storage has been driven by limitations of chemical batteries for U.S. Air Force and NASA mission concepts (including small satellites), advances in microprocessors and composite materials, and the promise of using flywheel systems for energy storage and as attitude control actuators. Flywheels as one-to-one replacements for spacecraft batteries are competitive for only a few special missions. Combining the functionality of two subsystems addresses the industry's continuing desire to improve efficiency and reduce spacecraft mass and cost. Unlike most terrestrial flywheel energy storage systems, space applications impose unique constraints. The primary issues are power efficiency, mass and size, and long-term stability. Flywheel systems in ground vehicles share some of these same challenges. Specific energy, safety, and reliability are important for both.

Flywheels in ground vehicles have to contend with base motion disturbances that can be higher in magnitude than those found on spacecraft. On the other hand, mass production and price are constraints on terrestrial flywheels that are not as critical in space applications. The concept of combining energy storage and power generation capability with spacecraft attitude control capabilities in flywheels is by no means new. Flywheels for energy storage in space systems were first discussed in 1961 [6], and a class of combined energy storage and attitude control systems (ESACS), integrated power and attitude control systems (IPACS) for satellites were first proposed in the 1970s [7,8]. Note that the term IPACS here refers to the case in which the attitude and power system are designed to control the flywheel speeds simultaneously. The more general ESACS case includes not only IPACS approaches but also the approach in which the electrical power subsystem (EPS) controls the wheels and the attitude control system rejects those wheel disturbances while tracking the desired attitude. Although progress has been made in many technical areas, there are still major hurdles to overcome before ESACS are realized for operational satellite missions. The objective of this paper is to summarize ESACS state of the art, describe the technology path that has led there, and describe

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recent work in the field, including ESACS advancements for small satellites. The main areas that are covered in the paper are rotor designs, which have evolved with material advances; bearings, which must react to axial loads when used for attitude control; dynamics and control methods; power distribution; and hardware testing.

II. Integrated Power and Attitude Control System and Flywheel History

The first reference to a mechanical energy storage system for space applications is the 1961 paper by Roes [6]. Roes describes a system design that stores energy in two counter-rotating magnetically suspended flywheels (Fig. 1). The system-level energy density is about 17 W · h/kg, with an operating speed range of 9500–19,000 rpm. With a 24-in.diam rotor, tip speeds of 306 to 612 m/s could be achieved. According to Hall [9], the term IPACS was first introduced by Anderson and Keckler in a 1973 paper [8]. NASA sponsored studies of IPACS around this time. In 1974, a two-volume NASA contractor report (CR) [7] described the results of an evaluation of the IPACS concept. This NASA CR considered IPACS for seven possible NASA spacecraft/missions and proposed conceptual designs for two of them. Two technology levels were considered: conventional technology that was based on ball bearings and steel rotors, and advanced technology that required the development of composite rotors and magnetic bearings for the high spin speed regime (Fig. 2). The study described technology performance crossover points (e.g., spin speed and mass for trading mechanical bearings against magnetic bearings). One conclusion was that a conventional technology IPACS was preferred for certain niche missions.

Two concurrent NASA Langley Research Center studies [10–12] presented experimental and simulation results of IPACS concepts for potential NASA missions. The objective of the experiments in [10] was to investigate the attitude control/power generation interactions.

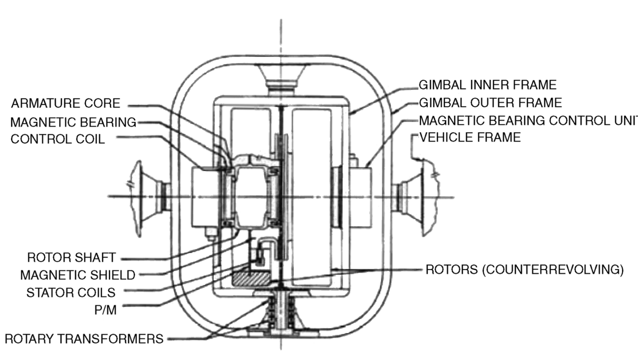

Fig. 1 Conceptual flywheel spacecraft battery, 1961 [6].

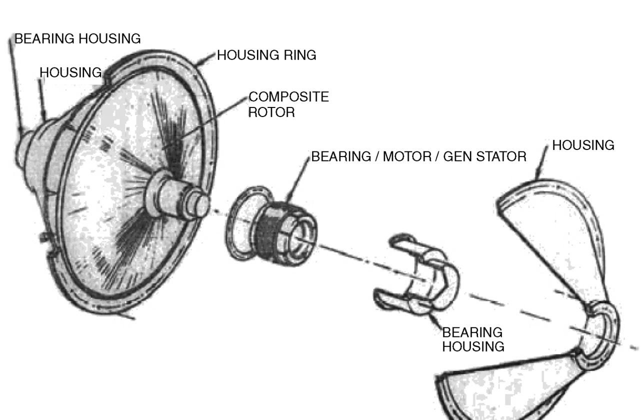

Fig. 2 Advanced technology flywheel concept, 1974 [7].

A double-rotor, double-gimbal IPACS configuration was assumed. The experiments employed an IPACS scaled model with control moment gyro (CMG) units with a maximum momentum capacity of 1.78 N · m · s. The report indicated that the experiment was essentially a tabletop hardware-in-the-loop (HWIL) simulation with a spacecraft flying in a computer. In the other effort, [11,12], a full-scale IPACS unit was built and tested. The unit had a titanium constant stress rotor, a unit level energy density of 19 W · h/kg, and an operating speed range of 17,500–35,000 rpm on ball bearings. The rotor diameter was 45.4 cm and the maximum rotor tip speed was 832 m/s at 35,000 rpm. These reports captured the IPACS state of the art/state of the experience in the mid-1970s. These works [10–12] are notable because they describe the first IPACS ground experiments. Until recently, these experiments were the most comprehensive, integrated laboratory tests performed. In the 1980s, the U.S. Department of Energy, U.S. Department of Transportation, NASA, and the U.S. Air Force were interested in flywheel systems.

NASA sponsored studies [13] to reassess the utility of the IPACS concept and the applicability of flywheel energy storage for space stations [14,15]. Rodriguez et al. [13] identified and prioritized critical technologies as 1) composite wheel development, 2) magnetic suspension, 3) motor/generator, 4) containment, and 5) momentum control. A significant section on power system aspects was presented, including a comparison of energy storage efficiencies of flywheels with electrochemical systems for a low Earth orbit (LEO) mission. Figure 3 shows a conceptual flywheel design [13]. The authors concluded that, for their assumed mission, a flywheel battery could be about 13 and 20% lighter than nickel–cadmium (Ni–Cd) and nickel–hydrogen (NiH_2) battery technology of the day, respectively, (including a 35% weight allowance for containment, but with no launch constraints.)

Gross [14] concisely addressed most of the promise of flywheel technologies circa 1983. The author concluded that the potential benefits of flywheel batteries on a space station significantly outweigh the disadvantages and that such a system could be more efficient than electrochemical batteries of the day. An IPACS for a space station was also considered in [14]. The analyses concluded that the integration of a space station attitude control system and energy storage in an IPACS was not advantageous. Some of the conclusions and projections in the report have turned out to be optimistic.

NASA reevaluated IPACS utility for space stations in [15] because space station concepts evolved and technology panels recommended flywheel energy storage technology. This study concluded that an IPACS has significant advantages over separate energy storage wheels and CMGs; however, the study did not include electrochemical batteries in the trade. An array of five double-gimballed flywheel units (Fig. 4) was preferred. The suggested design is notable because recent IPACS configurations have preferred single-gimbal units. Four composite material systems were

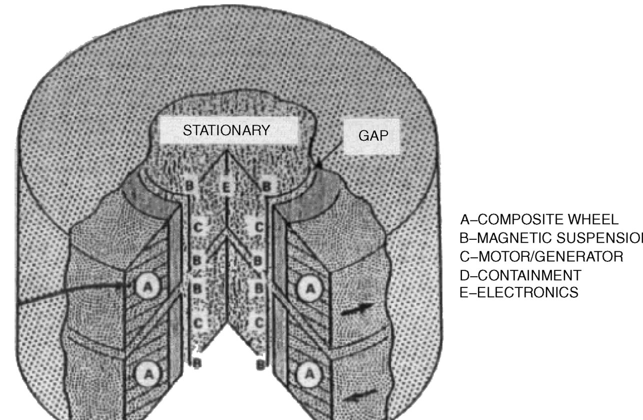

Fig. 3 Conceptual flywheel design for a spacecraft power system, 1983 [13].

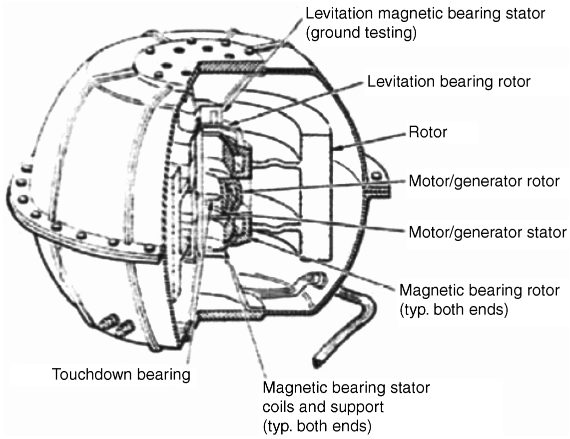

Fig. 4 IPACS unit design concept, 1985 [15].

identified for the rotor: 1) boron/epoxy, 2) graphite/epoxy, 3) boron/aluminum, and 4) silicon carbide/aluminum. A large-angle magnetic bearing was proposed. The report also contains an excellent literature survey covering developments from the early 1970s. According to Oglevie and Eisenhaure [15], a 1983 U.S. Air Force sponsored study [16] concluded that flywheel energy storage for spacecraft was not advantageous. Because none of the studies discussed involved actual hardware or missions, their conclusions depended on initial assumptions, including wheel geometry, material strength, various efficiencies, and mission characteristics. In spite of all the promising study results, most government funding for flywheel energy storage systems was withdrawn in the mid-1980s, but work continued on a smaller, research-level scale. NASA's research support was continued primarily in magnetic bearings and also in flywheel momentum configurations [17].

In the mid-1990s, there was renewed interest in flywheel energy storage and IPACS concepts, based on advances in magnetic bearings and high-strength composite fibers, which evolved independently. In 1994, the NASA Glenn Research Center (GRC) (then the Lewis Research Center) began new efforts to develop flywheel systems on satellites. A cooperative effort was initiated with the Space Vehicles Directorate of the U.S. Air Force Research Laboratory (then Phillips Laboratory) to develop flywheel technology for satellite applications. Collaboration with the TRW Company also was initiated [18], and yet another study of space station flywheel energy storage viability was performed [19]. The objective of this study was to examine the overall feasibility of using electromechanical flywheel systems on the space station. The report included a conceptual design and deployment plan of a flywheel demonstrator experiment leading to a battery replacement option, life cycle cost analysis, and a top-level development plan for critical flywheel technologies.

For the past decade, the NASA GRC has been interested primarily in developing the flywheel energy storage (FES) capability, with a secondary interest in the attitude control potential. NASA's development efforts focused on producing an FES system suitable as an energy storage replacement for the nickel–hydrogen secondary batteries on the International Space Station (ISS) [20]. Two FES development units were built by U.S. Flywheel Systems for GRC and optimized for energy storage. The attitude control capability of these units was minimal at best (i.e., about $\sim$1 $N \cdot m$ of control torque). One of these development units was able to achieve the technology goal of achieving the maximum design speed for the units of 60,000 rpm. Unfortunately, NASA funding cuts, especially for the ISS, resulted in the ISS program office dropping the flywheel replacement option. However, NASA continues to develop these units in-house for a potential flight experiment on an ISS express pallet (Fig. 5).

The NASA GRC has been instrumental in advancing various flywheel technologies, including composite rotor design and analysis methods, rotor nondestructive engineering techniques, power system designs, and rotor standards. Recently, the NASA

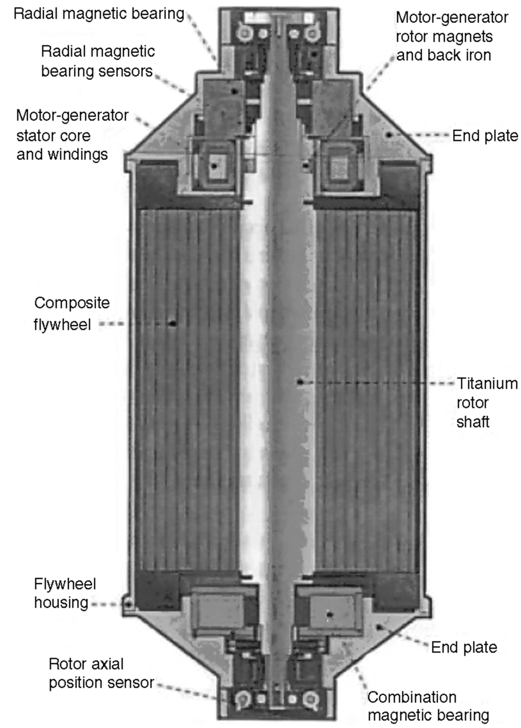

Fig. 5 Flywheel battery for space station experiment [61].

GRC has been performing system-level experiments to develop multiwheel systems and demonstrate the ability to cycle while controlling torque, define impacts of flywheel disturbances on attitude control, and address failure modes on both the attitude control and power systems at the spacecraft level. The experiments involve single-axis, air-table tests of two counter-rotating flywheel modules, and two-axis, three-module tests [21]. Although the NASA GRC's interest is primarily in research and the system-level demonstration of flywheel energy storage, the current U.S. Air Force interest is primarily in the potential high-end attitude control capability of the high-speed flywheels in conjunction with their energy storage capability (i.e., an IPACS). Realizing that developing a flywheel system capability for agile satellite attitude control while simultaneously providing energy storage for the satellite power bus is a high-risk endeavor, the U.S. Air Force Research Laboratory (AFRL) has focused its attention on a risk-reducing ground demonstration. Development of the flywheel units, under the Flywheel Attitude Control, Energy Transmission, and Storage (FACETS) program, was initiated with Honeywell Engines, Systems & Services Division, Tempe, Arizona. The Honeywell FACETS units, such as the one in Fig. 6, were designed to balance attitude control and energy storage requirements instead of emphasizing one or the other. In parallel with the Honeywell development effort, AFRL originally planned a ground demonstration of the FACETS units at its Space Vehicles Directorate. The test was envisioned to test three flywheel units on the Agile, Multipurpose Spacecraft Simulator (AMPSS) testbed. In fact, one prototype FACETS unit was completed and delivered to the AFRL. Unfortunately, a depletion of funding cancelled FACETS before the conclusion of the first unit tests and before three-actuator tests in three axes could take place.

III. Lithium–Ion Batteries

For flywheel systems to be successful, they must be competitive with electrochemical batteries, as indicated by the numerous studies already discussed. Over the past 20 years, $Ni–H_2$ batteries have been used for nearly all space applications with some Ni–Cd and silver–zinc applications. For the most part, $Ni–H_2$ batteries have performed reliably with the largest negative being the large volume required. On the other hand, lithium–ion (Li–Ion) batteries represent the future of spacecraft electrochemical energy storage because of their much

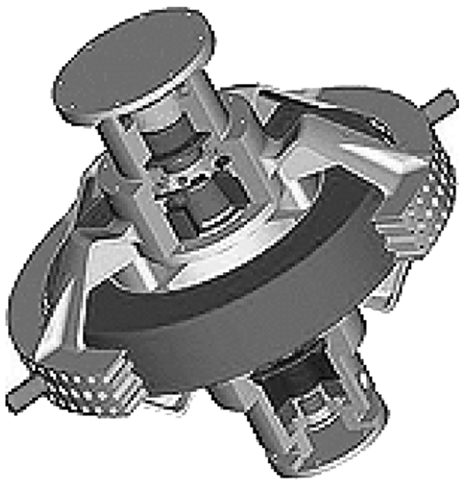

Fig. 6 AFRL energy storage VSCMG.

higher specific energy. Li–Ion batteries are in production, and laboratory life cycle data on Li–Ion cells have been positive. More than 16,000 LEO cycles at 30% depth of discharge (DOD) have been demonstrated [22]. Currently, the specific energy of spacecraft Li–Ion batteries is around 100 $W \cdot h/kg$. This value assumes 100% DOD, which is unattainable in actual applications; however, battery engineers insist that this approach gives them a consistent number with which to compare different technologies. In practice, it is typical to assume 60–65% DOD for geosynchronous Earth orbit missions for which there are a few thousand cycles and 30–40% DOD for LEO applications for which there are tens of thousands of cycles. This leads to effective specific energies between 30 and 65 $W \cdot h/kg$. The exact limits for Li–Ion are still being defined, but these values provide a reference for the system-level specific energy that flywheel systems will need to exceed and to be competitive. Two issues with Li–Ion systems are tight thermal control requirements and the taper charge profile required in LEO. Thermal control is required in all electrochemical batteries and is a major contributor to their complexity and life. The accepted charge profile uses constant current until a cell voltage near 4 V is reached, at which time the charge current tapers down until 100% energy capacity is returned to the battery. For Li–Ion batteries the taper charge region is not well defined yet, but the longer the taper charge, the higher the current required in the constant current region, which increases the required solar array power output. Another limiting factor is that Li–Ion batteries are limited to a $C/2$ charge rate, for example, a 10 Ah battery can be charged at a maximum of 5 A. This affects the power system design, the DOD, and the resulting system efficiency.

IV. Rotor Designs

The ideal rotor for an IPACS depends on the assumed operating condition. Four constraints must be considered: 1) allowable material stress, 2) loading conditions, 3) rotor size and shape, and 4) spin speed. These constraints apply to all types of flywheels, not just to those used in IPACS applications. For space applications, the specific energy and volume energy density are important, because of weight and volume constraints. The equation relating specific energy and specific stress is

$$E/m = K_s(\sigma/\rho) \tag{1}$$

This equation applies to all types of rotors, regardless of composition. The shape factor, K_s, is a measure of the shape efficiency of the rotor in the stress-limited case. The maximum value is 1 for the ideal isotropic rotor with the Stodola shape. The Stodola rotor has a constant stress profile and infinite radius. The maximum for practical isotropic rotors is approximately 0.8. The minimum value is 0.3 for a thick isotropic rim with a vanishingly small center hole. Titanium is a high specific stress material based on approximate yield strength. Titanium flywheels can be expected to have a working specific energy of no more than 30 $W \cdot h/kg$, based on shape factor (0.8) and stress safety factor (1.3), and a lower system-level energy density. Keckler [12] includes a description of an IPACS experiment that used a titanium rotor with an effective rotor specific energy of 30 $W \cdot h/kg$ and a unit-level specific energy of 19 $W \cdot h/kg$. In terms of energy density, this is not competitive with Li–Ion electrochemical batteries. If the operating mode is speed limited, not stress limited, then Eq. (1) does not apply, and the ideal rotor shape is determined by the rotor's polar moment of inertia. The most efficient shape for an isotropic rotor in this case is the ideal rim, because the mass is maximally displaced from the spin axis. This is also the optimal shape for momentum storage. For ideal composite rotors, the analysis is more complicated because the maximum stress depends not only on the rotor shape, but also on the composite material system(s), fabrication process, loading conditions, and other factors such as failure modes. The maximum shape factor for anisotropic rotors is $K_s = 1$ [23]. As in the isotropic case, this represents a constant stress rotor. However, because composite material systems combine materials with greatly different strengths (e.g., resin and fiber), a constant stress anisotropic rotor does not take full advantage of high-strength fibers and is impractical. Laminated (e.g., hoop-wound) rotors have a theoretical maximum shape factor of 0.5 [23]. A number of papers (e.g., [23–26]) have shown that $K_s = 0.45$ seems to be the upper bound for practical designs. This is achieved by the interference fitting of concentric rings with variable ply angles [26]. The high allowable specific stress of composite materials dominates the design space and hinders the fabrication effort required to maximize K_s in composite rotors. Although an isotropic metal rotor can easily be made with a shape factor twice that obtainable with a composite rotor, composite material specific strengths are almost an order of magnitude greater. This means that the theoretical energy densities of ideal composite rotors are about 5 times that of ideal metallic ones. The energy density is the ratio of kinetic energy to flywheel volume. The energy density is a function of the allowable material stress:

$$E/v = K_s\sigma \tag{2}$$

Equation (2) is strictly valid for homogeneous rotors, but can be applied to composite rotors if average density is used. Like Eq. (1), this equation is quite general and can be used for rotor efficiency (total stored energy and rotor volume) or system-level efficiency (usable energy and flywheel unit volume). Composite rotors that carry the allowable stress along the fiber direction can have up to a fivefold advantage in volume energy density over metallic rotors. Filament winding is the dominant fabrication method for thick flywheels because it puts the fiber in the highest stress direction (i.e., the hoop direction), is the most economical for low-volume production, and affords a large range of the design flexibility. In filament-wound rotors, the radial strength is dominated by the matrix and is much lower than the circumferential strength. Because the matrix is weak, radial tension loads can cause rotor failure and must be avoided. This is generally done through the interference fitting of multiple rings to preload the rotor in radial compression or through a so-called growth matching design in which rings with different moduli (i.e., materials) are fitted so that they expand consistently under centrifugal loading.

The preceding discussions have focused on ideal rotor shapes; however, almost all rotors are attached to a metal shaft through a hub, which is usually metallic. Hub design therefore also affects rotor efficiency. The fundamental design issue in a metal hub/composite rim rotor is placing the maximum operating stresses in the strong rim, away from the relatively weak hub, that is mitigated by introducing compressive preloads through the interference fitting of the rim on the hub. Hubs for flywheels are usually webs or spokes. Spoke hubs have to deal with stress concentration issues at the shaft and bending stresses in the rim between the spokes. Genta [2] provided an excellent exposition on the stress equations for different types of rotors and, although the discussion is restricted to isotropic materials, it can be easily extended to hoop-wound rims. Of course, any detailed design will be based on a finite element analysis to determine the

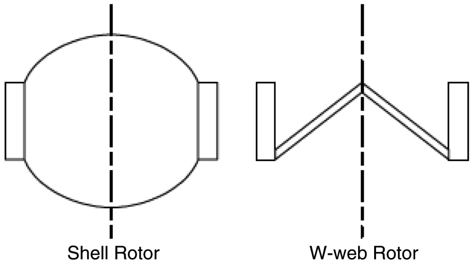

Fig. 7 CMG rotor types.

stress field. Recent experimental designs have included shell hubs, flexible expanding hubs, conical hubs (like the W web in Fig. 7) [27], and multidirectional composite rims [28]. For momentum storage devices such as CMGs and reaction wheel assemblies (RWAs), which are used for angular momentum storage not energy storage, the optimum steel rotor shape is a thin rim. Two common CMG and RWA hub geometries are shown in Fig. 7. The W-web rotor, a variant of the standard rim and straight web, is used in RWAs and relatively small CMGs. The shell rotor is used for large CMGs because of the stability it provides against lateral loads. Most published stress analyses of composite flywheels address centripetal loads, deceleration loads, and thermal loads, but neglect axial loads as they are not relevant to systems with no base motion. Such loads will occur when the flywheel is gimbaled. The implications for rotor design and testing may be significant if the IPACS units must produce large torques, like large CMGs (e.g., >1000 ft · lb). However, currently there are no IPACS rotor concepts for high-torque applications. For example, the FACETS units designed for the AFRL experiments had a torque requirement of only 50 N · m (37 ft · lb) [29].

V. Bearing Technology

The spinning rotor must be supported on bearings. Initially, both ball bearings and magnetic bearings were considered. Ball bearings fell out of favor for flywheel energy storage applications because of their limited life and high drag losses. However, there are mass, complexity, and thermal penalties associated with magnetic bearings compared with ball bearings. Magnetic bearings also require power, which the IPACS units must provide during eclipse times; during the in-sun portion of the orbit, the magnetic bearings are powered from the solar arrays as any other spacecraft load. Launch loads may pose a problem, and touchdown or auxiliary bearings are required in case the magnetic bearings fail.

Magnetic bearings have advantages, too. Magnetic bearings are preferred because they can accommodate high spin speeds and have theoretically unlimited life and low losses. If designed properly, the electronics can sense imbalance changes that may indicate structural problems with the rotor and can also isolate rotor imbalance-induced vibrations. The important parameters in assessing the use of ball bearings or magnetic bearings for IPACS applications are weight, power consumption, static capacity, and stiffness. In general, an upper bound on the spin speed exists above which magnetic bearings are better. Below this bound, ball bearings have a weight advantage because the drag losses are relatively low. This bound is application dependent, but generally falls between 20,000 and 40,000 rpm for low-torque units. Most flywheel systems aim to operate at much

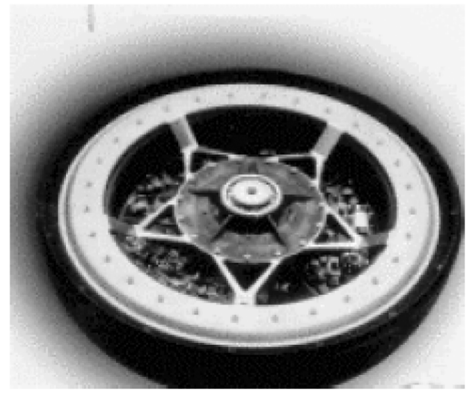

Fig. 8 ESA/Teldix magnetically supported momentum wheel, 1995 [64].

higher speeds, and so they must rely on magnetic bearings. The weight, power, and complexity penalties for magnetic bearings increase as static capacity (i.e., lateral load capability) requirements increase. Large radial static capacity magnetic bearings have been applied in terrestrial applications such as turbocompressors; however, these bearings have relatively large-diameter shafts. In spacecraft applications, for which the shaft diameter is relatively small compared with the static capacity, magnetic field variations due to bearing curvature and gap control are two sources of power and complexity penalties. These power and complexity penalties increase with IPACS torque requirements and render magnetic bearings impractical for high-torque-output (e.g., >1000 ft · lb) IPACS flywheels. A comparison of ball bearing and magnetic bearing static capacities is given in Table 1. The ball bearing radial static capacity is the load at which the bearing steel suffers load-induced indentations. Because ball bearings have to support a rotor during launch, launch loads often drive the bearing selection. Operating radial loads (i.e., gimbaling loads) are usually much lower.

In satellite applications, magnetic bearings have been used in momentum wheels on the SPOT satellites and the AMSAT AO40 spacecraft. In 1995, the ESA supported development of low-noise magnetic bearing momentum wheels (Fig. 8). Ball bearings have benefited greatly from material advances, such as ceramics and very hard steels. The main life issues are not material fatigue life, but rather lubricant life. Lubricant life depends primarily on temperature. Bearing life is essentially unlimited if temperatures are kept low and the lubricant does not deteriorate.

In terrestrial applications, this can be accomplished by continually flushing filtered oil through the bearings. In space applications, the ball bearings are sealed. Over time, the oil in the bearings breaks down or evaporates because of the vacuum of space. However, grease acts as an oil reservoir, external oilers provide an additional reservoir, and good thermal designs keep bearing temperatures low enough to prevent lubricant degradation. There have been no recent studies comparing new hybrid bearings and magnetic bearings for projected applications on the basis of power, weight, volume, life, vibration, rotor size, and spin speed. At the system level, ball bearings may do surprisingly well in the trade space. Recent experiments with 101-size hybrid bearings using Si_3N_4 ceramic balls and REX-20 (a very hard, low CTE steel) races demonstrated promising endurance results on a small CMG class rotor. Over three

Table 1 Example of magnetic and ball bearing properties

Bearing	Bearing ID, mm	Bearing OD, mm	Bearing height, mm	Radial static capacity, N	Max. speed, rpm
MB-R-25-205	25	98	52	205	58,000
MB-R-280-25555	280	478	312	25,555	8000
101 hybrid[a]	12	28	8	$>10,675$	40,000[b]
204 hybrid[a]	20	47	14	$>32,472$	25,000[b]
305 hybrid[a]	25	62	17	$>73,396$	6600[b]

[a]Hybrid are ball bearings with Si_3N_4 balls and REX-20 races; ball bearing radial capacity is for bearing pairs
[b]Achieved in test

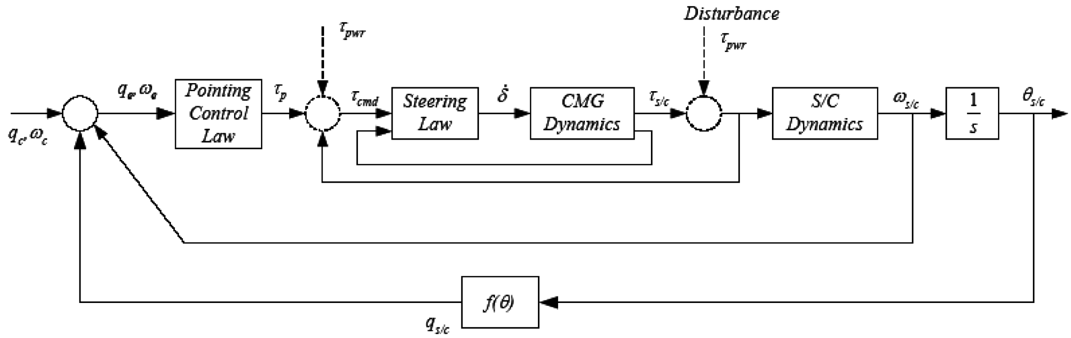

Fig. 9 Simplified IPACS attitude control system model.

months of continuous operation at 40,000 rpm and another 3 months at 30,000 rpm have been achieved to date. The average power consumption was less than 50 W.

VI. Integrated Power and Attitude Control System Dynamics and Control

An IPACS must perform two functions simultaneously: attitude control and power tracking. It must provide commanded torques for attitude control and generate power, accumulate energy, and store energy. A flywheel produces or absorbs power by changing its wheel speed. Attitude control torques are produced by changes in the net angular momentum vector, H. This can be done by operating the flywheel units as an RWA or a variable speed control moment gyro (VSCMG) array. The RWA assembly is mechanically simpler because no gimbals are required. On the other hand, an RWA has less torque-producing capability.

For an RWA design, the flywheels can be grouped in an array of counter-rotating pairs or individual units. The systems are sized with excess angular momentum to provide the attitude control capability after the energy and power requirements are satisfied. At least four wheels or three wheel pairs are needed to provide simultaneous three-axis control and power tracking. Usually spacecraft have at least one redundant RWA to prevent a wheel failure from degrading the mission. In practice, then, the spacecraft would need five wheels or four counter-rotating pairs. The counter-rotating pair array has the advantages that each pair has a zero momentum bias and the angular momentum vector can be oriented using the relative spin rates of the wheels. Therefore, power can be generated with no net torque output; conversely, torques can be imparted with minimal energy losses. With an array of individual flywheel units, the attitude control and power generation functions are highly coupled. To provide power without changing the net angular momentum, wheel speed changes must be coordinated. To provide torque without generating power requires tightly coupled power and control torque algorithms.

The single-gimbal VSCMG configuration can be the more challenging control and dynamics problem if the power and maneuver functions are not decoupled. Single-gimbal CMG control without the additional energy storage and power generation requirement is an interesting problem in and of itself. There have been many papers written on the subject (e.g., [30–41]) but few experimental results are available in the open literature other than those described in Sec. VIII. The lack of experimental results is due to the fact that CMGs have historically been large, expensive, and, thus, incompatible with most terrestrial test beds. This dogma was challenged with novel developments in mini-CMGs at the University of Surrey's Space Research Centre (SSC) [42], but this was one rare exception to the conventional norm. Nevertheless, CMGs are typically less common than RWAs because fewer missions require them. Finally, spacecraft manufacturers whose satellites use CMGs have proprietary control strategies tailored to specific missions.

The VSCMG IPACS array provides attitude control torques by gimbaling the rotor (i.e., rotating the H vector) and discharges energy by changing the wheel spin speed. Changing the wheel speed also generates a torque because the magnitude of H changes. The power-tracking-operation torques can be treated as actuation torques or disturbances on the satellite, depending on the system design. There are two ways to approach this problem. When viewed as actuation torques, the residual torques generated by the power-tracking operation can be subtracted from the commanded torque and essentially absorbed by the gimbal commands. When the power-tracking and attitude control functions are decoupled and the power-tracking torques are small, they can be treated as disturbances. This approach is further investigated in [29]. Power-tracking wheel speed changes required to generate or absorb power can be coordinated to minimize disturbance torques. Figure 9 shows a simplified block diagram for an IPACS pointing attitude control system using only the CMG mode. The commands identify the target location and body rate. A pointing control law transforms th e attitude and rate error into torque. The torque generated by power-tracking operations can be introduced in either of two places depending on the approach chosen, as already discussed. If the power tracking is performed in a no-net-torque mode, the attitude control loop can treat it as either a known or random disturbance. If power tracking is allowed to generate a residual torque, it must be taken into account when forming the command torque vector. A steering law, such as that discussed in [29,31–41,43–45], is used to generate gimbal rates that command the flywheel units as CMGs. Because the wheel speed is not constant, the IPACS control loop needs to account for the changing angular momentum of the wheels. Information required by the steering law, such as wheel speed and acceleration, gimbal angle, and gimbal rate, are fed back from the CMG dynamics. The CMG creates torques that act on the spacecraft. The spacecraft dynamics block can represent the satellite as a rigid body or can include critical bending modes because they affect the measured body rates.

A simplified, independent power-tracking block diagram is shown in Fig. 10. It is based on a standard RWA control loop. The power command is distributed to the individual units where it is converted to a motor torque command that accelerates or decelerates the rotor depending on whether the unit is charging or providing power. The τ_d block accounts for system losses. Because the block diagrams are simplified, many things, such as coordinate transformations, saturation, overspeed, and gimbal angle limit logic, are omitted. Also, some liberties are taken with respect to operations that do not easily fit into a block-diagram structure, such as the calculation of attitude-error quaternions. In the FACETS experiments, the power-tracking loop will command the three flywheels in response to a voltage draw from the power bus. The individual wheel speeds will be matched so that power draws and charging are shared equally among the three wheels (i.e., load leveling). This decouples the power-tracking operation from the attitude control loop. Power-tracking torques will be small and can be treated as disturbances, and so the pointing control loop will be similar to Fig. 9. The main issue with sizing CMGs is the presence of singularities in the momentum space. A singularity is a gimbal angle configuration in which no torque can be generated in the commanded direction [30]. The extra degree of freedom in VSCMGs makes it possible to traverse through most singularities while limiting the pointing error. In IPACS applications, a subset of CMG singularities are also power singularities, that is, gimbal angle configurations in which the array cannot simultaneously generate a torque in the commanded direction and provide the required power. An IPACS needs at least three

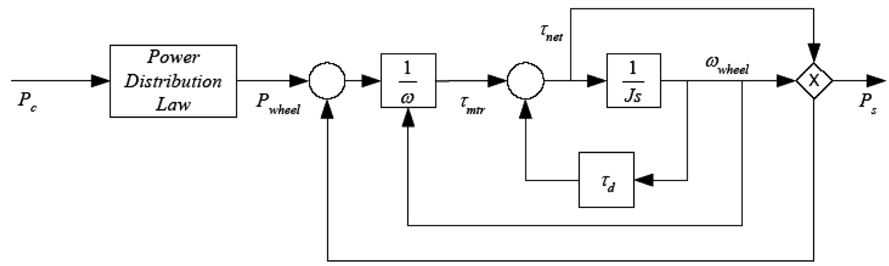

Fig. 10 Simplified IPACS power command model.

VSCMGs to provide simultaneous three-axis control and power tracking. Because a VSCMG can generate torque in two axes, limited three-axis control could be maintained after a wheel failure; however, torque capability in one axis will be limited. Usually, CMGs are sized and oriented so that singularities are never encountered. In missions that make flywheels attractive as energy storage devices, the angular momenta of the wheels are expected to be much greater than the required CMG momenta for attitude control even at minimum wheel speed, which means that gimbal rates can be low and gimbal travel limited, which will make encountering any singularities very unlikely.

VII. Safety and Containment

A major design consideration for high-speed rotating machinery (flywheels, turbines, etc.) is containment of the test article in the event of a catastrophic failure. If such a failure occurs without containment, pieces of the rotor, or the whole rotor itself, may interfere with the test assembly and pose a great danger to the system setup and/or personnel. Certainly, if a catastrophic failure occurred on orbit, the spacecraft would become space debris.

A. Safety Procedures

High-energy flywheels are still largely developmental, and the industry is addressing containment and safety specifications and procedures. Containment during testing and evaluation is fairly straightforward: one should use a spin pit or test cell. Ground transportation systems and space applications pose unique operational challenges because of the disturbance environment and or weight/volume constraints. In these applications, large containment structures are not feasible, even in ground tests. The failure mode effects and criticality analyses (FMECA) process is an appropriate framework for working through risks and mitigation strategies. The highest risk comes from failure of the rotor, which can occur due to any number of events. One of the main objectives of the FMECA is to identify these events and prevent their occurrences. Generally, the main interest has been in understanding rotor failure from wheel-speed-related stresses; however, other faults, such as magnetic bearing failure, can lead to rotor failure. Possible failures must be mitigated in the flywheel unit design and experiment procedures.

B. Failure Modes

Failure modes of metal rotors are different than those of composite rotors and, although metal rotors tend to break into large pieces, there is considerably more practical experience with metal rotors than composite ones. Because metals are homogeneous isotropic materials, they are predictable. The weak areas in metal rotors tend to be at machined interfaces (i.e., fillets) and weld-affected zones. CMG and RWA manufacturers have a high degree of confidence in their designs and modeling and simulation tools. Although current CMGs and RWAs operate at relatively low speeds (below 10,000 rpm), the modeling and simulation tools are applicable at higher speeds. Furthermore, the community has confidence in the validity of safety factors. One RWA manufacturer regularly operates its products in evacuated bell jars on laboratory bench tops. Recently, an experimental high-speed CMG unit (with ball bearings) operated at 20,000–40,000 rpm while simultaneously gimbaling at 2–4 rad/s in a test cell with no integral containment system [42]. Composite rotors, on the other hand, are more complex than metal rotors, and they contain multiple materials (i.e., metal, fiber, resin, adhesives) that make them anisotropic. Material properties can vary, and the manufacturing process can introduce flaws unless great care is exercised. Failures can occur in unexpected places and at unexpected speeds; however, recent experience has shown that properly manufactured composite rotors are tough to break, even intentionally for test purposes.

Generally speaking, a composite rotor rim may fail in one of two ways: 1) circumferential delamination, or 2) rim disintegration (i.e., burst). In the first case, the composite rim delaminates into two or more circumferential rings, which may or may not disintegrate further. If a portion of the rim rubs against the housing, the result may be numerous irregular fragments, shredded clumps of fiber, powder, and a burst housing. Less likely is a rotor burst, in which case many fibers fail rather spectacularly, leaving a mass of shredded composite fibers. A by-product of composite rotor failure can be the generation of fine carbon powder (dust) that can be very flammable. Matrix cracking and hub–rim interface failure are two additional failure modes. These modes depend on the specific hub design. For many failure modes, the rotor may give some indication of a problem, such as imbalance-induced vibration. If proper instrumentation is in place, it may be possible to shut the system down and prevent a catastrophic failure. Bounding analyses of rotor failure are relatively straightforward if the failure modes are known. Colozza [46] performed a containment analysis based on three failure modes: 1) triburst, in which the rotor breaks into three pieces; 2) outer ring disintegration, which produces uniform radial pressure; or 3) containment lid impact, which produces axial pressure loads on the lid. The analysis was intended to be a bounding one for determining if the containment can withstand a worst-case failure. No justification that the three assumed failure modes bound the range of possible forces generated by a rotor failure is given. Lawrence Livermore National Laboratory (LLNL) sponsored the development of rotor failure modeling techniques. Coppa [47] developed a method called “crushing fragment containment analysis” (CFCA) for radial burst failure. It assumes that an axisymmetric distribution of fragments is released upon rotor failure. Upon contact with the containment wall, the fragments crush and the containment wall deforms. CFCA was also adapted for axial loads. A better understanding of the forces released during rotor failure (e.g., asymmetrical transient loads and initial momenta of flywheel debris) is needed to improve modeling, analysis, and design methods. Tests are always needed to validate the analyses and determine empirical terms, such as safety factors. Especially challenging is the characterization of composite material properties over the service life, both analytically and empirically, and the assessment of the implications for composite rotor failures.

C. Testing and Development Phase

During testing and development, experiments are conducted in special test facilities. Many test facilities take the form of spin pits, containment chambers, or test cells. Spin pits are a common method of containment. Usually, a spin pit is a pit in the ground with a reinforced floor and walls. The pit is covered with a steel or concrete lid. Spin pits do not provide easy access to the test subject because the lid has to be removed and the test subject has to be lifted out. There is also a preferred operating orientation (i.e., the spin axis of the wheel

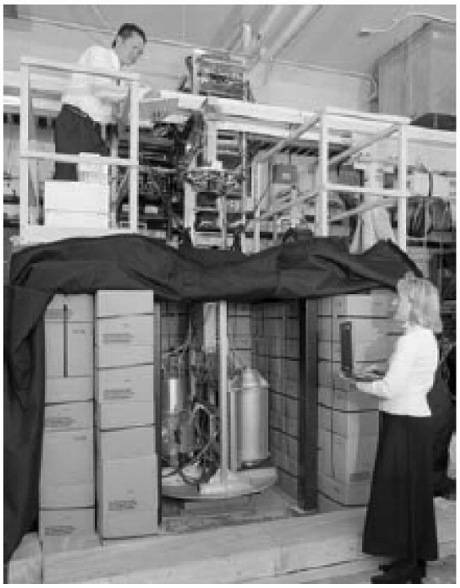

Fig. 11 NASA GRC high-energy flywheel facility water containment facility [25,56].

perpendicular to the lid), which makes testing gimbaled wheels or wheel performance in other orientations difficult. Containment chambers are essentially aboveground spin pits, and they take the form of one or multiple cylinders or walls that fit around the test subject and confine a catastrophic rotor failure. Recently, NASA GRC completed construction on an innovative low-cost containment chamber made of water-filled blocks (Fig. 11). Test cells are above ground facilities, usually concrete-reinforced rooms or buildings. Test cells are not typically used for initial testing. A test cell would be used for testing complete flywheel units after considerable confidence has already been developed. At the point when test cells are used, the engineering and test teams may need easy access to the test subject and have a high level of confidence that the subject will not fail catastrophically. However, test cells cannot house large, system-level performance tests in which an IPACS is mounted on a spacecraft or model structure.

D. Operational Phase

Once unit testing is completed and the IPACS is applied to a system, the engineering team must guarantee with some level of confidence that a flywheel failure will not destroy the system to which the flywheel supplies power. In service, flywheel energy systems cannot support heavy containment structures, except perhaps in a few terrestrial applications, such as uninterruptible power supplies. Because spacecraft are ground tested before launch, flywheels will be spun up and cycled. A practical containment methodology, not relying on spin pits or test cells, is needed that leaves a flywheel design and integration team with some options: 1) a fail-safe rotor; 2) an engineered failure mode, also known as virtual containment, 3) a reduced-weight containment system; and 4) no containment system.

A fail-safe rotor is essentially overdesigned and cannot fail under operating conditions. In the virtual containment concept, a “mechanical breaker” is designed into the rotor to indicate a problem well before catastrophic failure so that the flywheel system can shut itself down gracefully. Of course, the mechanical breaker failure must be repeatable and must include a sufficient safety factor. This will reduce the operational efficiency of the flywheel. In space applications, for which weight and volume constraints are severe, a containment system is impractical. However, if an operational containment system is needed, it can be integrated with the vacuum housing. Compared with a metal flywheel rotor (and steel turbine), a composite rotor should not have the structure or material properties to puncture a containment system. However, when a composite flywheel fails and rubs against the containment housing, the sudden transfer of energy can increase the temperature of the housing in a fraction of a second. Therefore, the temperature dependence of the mechanical properties of the containment materials must be considered. Also, due to the high speeds of the rotors, a failure event can cause containment failure due to shock loading (causing brittle fracture modes even in ductile materials) if not properly accounted for in the design. In the early 1980s, LLNL was prominently involved in the study of operational containment systems, and a number of concepts were developed. Three prototype containment systems developed at LLNL in the 1980s are described in [48] and at least one of them was tested. Although it contained some of the energy of the failed rotor, the containment was destroyed and “a substantial amount of residual energy remained to be absorbed by the spin test enclosure” [48]. The failure was attributed to large axial loads and asymmetric burst conditions [47]. A number of companies and research organizations have been working on operational containment of flywheel energy storage systems for both terrestrial and nonterrestrial applications. United Technologies has proposed a system based on a single chamber with a honeycomb layer inside to trap any loose fibers and dust particles that may come off the flywheel [49]. The Regents of the University of California [50] received a patent for a lightweight containment system composed of a combination of layers of various materials that absorb the energy of a flywheel structural failure. The various layers of material act as a vacuum barrier, momentum spreader, energy absorber, and reaction plate. According to the patent, the system has been experimentally shown to contain carbon fiber fragments with a velocity of 1000 m/s and has an areal density of less then 6.5 g/cm^2 The containment systems in [49,51] are conceptually similar to the one described in [48].

The proposed containment systems did not address the axial loads that are generated by the interaction of the radial energy of a failed rotor with the containment system. Pentadyne Corporation has continued the development of a flywheel containment system that was originally developed by the now-defunct Rosen Motors. This flywheel containment system is a two-chamber system [52]. The first chamber is the vacuum housing, and the second chamber contains any material that the vacuum wall does not. A suitable liquid is placed between the two walls. This containment system has survived 24 burst tests. The University of Texas Center for Electromechanical Research performed containment load analyses and tests on a composite containment liner [53,54]. The liner is free to rotate to absorb the kinetic energy of the rotor failure.

The concepts discussed herein are not intended to be an exhaustive list; rather, they give a flavor of the work on containment systems.

VIII. Integrated Power and Attitude Control System Power Distribution

A flywheel energy storage system must work well with the spacecraft power system. Because spacecraft EPSs incorporate chemical batteries and flywheels are mechanical systems, some differences must be considered. Batteries can deliver power almost instantaneously, while acting as excellent transient filters. Batteries require thermal management and a charge–discharge controller. Flywheels require a generator and power converter to output a regulated dc bus voltage. The flywheels also have parasitic loads if magnetic bearings are used. These loads represent a loss in efficiency. The only additional hardware for a battery is a charge–discharge controller. In nominal operation, the flywheel control electronics control the wheel speeds and accelerations in response to a voltage draw from the power bus. Because flywheels are complex mechanical systems with multiple failure modes, a circuit breaker is needed to allow the removal of a flywheel from the power bus. The control electronics must have separate spin up and shutdown control modes. The transient response of the flywheels may be longer than that of batteries, and so a capacitor may be needed between the flywheel units and the power bus to mitigate the voltage drop as power is switched from solar arrays to the flywheels. The capacitor would be integrated into the flywheel electronics and not part of the spacecraft power system explicitly. On the other hand, if flywheels operate at voltages higher than the power bus voltage, the power converter may take up any voltage drop. Then there would be a current drop rather than a voltage drop on the low-voltage power bus.

Flywheel energy storage systems are expected to have higher energy conversion efficiency than batteries. Because of the higher energy conversion efficiency, the parasitic loads associated with flywheels may not be a significant factor in the decision of using flywheels or batteries, which is application dependant and more of a factor for systems that are not continually charging or discharging. Many flywheel power system interaction design issues are discussed in [50,55–60].

IX. Hardware Testing

With the recent advances in microelectronics, the practical design and testing of IPACS is becoming more feasible [61–65]. IPACS are even being considered for small satellite missions with high peak power requirements, such as those using spotlight synthetic aperture radar and precision Earth imaging [29,66–68]. Richie et al. [29,68] discussed the preliminary design of a HWIL setup for an IPACS for small satellites using VSCMGs. Kenny et al. [69,70] described a power-oriented hardware test setup to try novel control algorithms for the charge and discharge modes of operation of a flywheel energy storage system. The charge and discharge portion of the algorithm uses command feed-forward and disturbance decoupling, respectively, to achieve a fast response with low gains. Simulation and experimental results are presented demonstrating the successful operation of the flywheel control up to the rated speed of 60,000 rpm. Meanwhile, simultaneous control strategies in [29,32–34,43,45] were experimentally validated by Jung and Tsiotras [44]. In [44], the gimbals and wheels operated per these algorithms to slew a test article on a hemispherical air-bearing structure, yet the actual storage and drain of power to run a load was not achieved.

Next, the aforementioned FACETS program aimed to realize the first practical and full-scale HWIL implementation of an IPACS. It was designed to use the AMPSS, which rests on a hemispherical air bearing and employs three Honeywell-built energy storage CMGs (ESCMGs) as ESACS actuators [71,72]. Figures 12 and 13 illustrate the ESCMGS and AMPSS. Each ESCMG contains a 0.6-m-diam, magnetically levitated rotor and provides $1.4\ \mathrm{kW \cdot h}$ of usable energy. Interestingly, the FACETS program's genesis dates back to the late 1980s and early 1990s with the Strategic Defense Initiative (SDI). Advancing from a space-based laser concept developed under the SDI, the Advanced Structures Experiment (ASTREX) conducted at Edwards Air Force Base, California, was used by AFRL to test the control of large space structures. In 1992, the initial experiments at Edwards Air Force Base ceased. Eventually, the dormant ASTREX structure moved to the Space Vehicles Directorate at Kirtland Air Force Base, New Mexico. By 1997, it became the foundation for the FACETS concept. As addressed in Sec. II, only one of the three planned FACETS ESCMGs was delivered, and it did not complete single-unit testing due to a lack of sustained project funding. Thus, as the FACETS program was cancelled, it did not realize its goal of being the first three-axis, spacecraft-scale, mission-traceable ground demonstration of a combined ESACS [71,72].

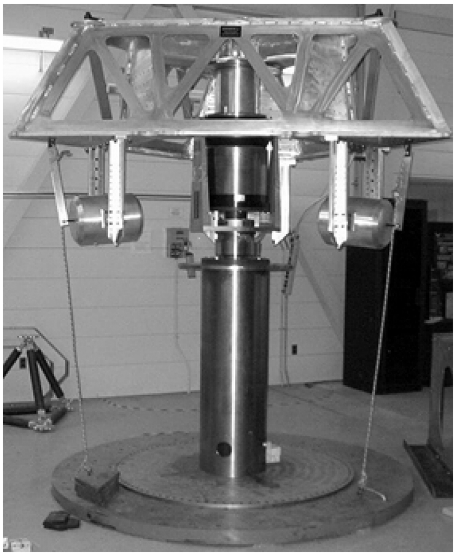

Fig. 12 AFRL/VSS AMPSS.

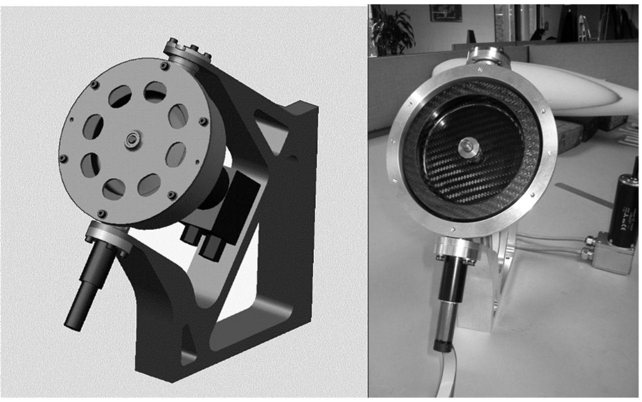

Fig. 13 Surrey Space Centre ESACS VSCMG CAD model and as-built prototype.

Recent efforts by the SSC, located at the United Kingdom's University of Surrey, have led to the first practical design and experimentation of a micro-ESCMG. This work employed a single VSCMG as part of an ESACS that was built from commercial off-the-shelf software (COTS) components and experimentally tested on a hemispherical air-bearing test article. Designs and images of the SSC prototype and air-bearing structure are captured in Figs. 13–15. The SSC effort has centered on storing and draining energy in a ESCMG (variable speed) carbon-fiber rotor while slewing the test article in three dimensions. Storage power is supplied to a wheel motor parallel to a simulated spacecraft load (light bulbs) in simulated sunlight. Then, in a simulated eclipse, the power is cut from driving the wheel and the wheel energy is ported to the load until the flywheel energy is depleted. Meanwhile, the ESCMG is gimbaled and the test article rotates, demonstrating successful test operation. The micro-ESCMG has been subjected to extensive HWIL testing and is the first such actuator/power system to be able to demonstrate power storage and energy conversion with direct and round trip transmission efficiencies of 58 and 60%, a depth of discharge rate of 84%, and an energy index of $0.029\ \mathrm{W \cdot h/kg}$ at flywheel speeds of 10,000 rpm and gimbal rates of $10\ \mathrm{deg/s}$. These performance outputs demonstrate that an ESACS built from COTS components can bring significant mass savings and performance benefits to small satellites [29]. Follow-on work will add more ESCMGs to form a full pyramid cluster and concentrate on assessing

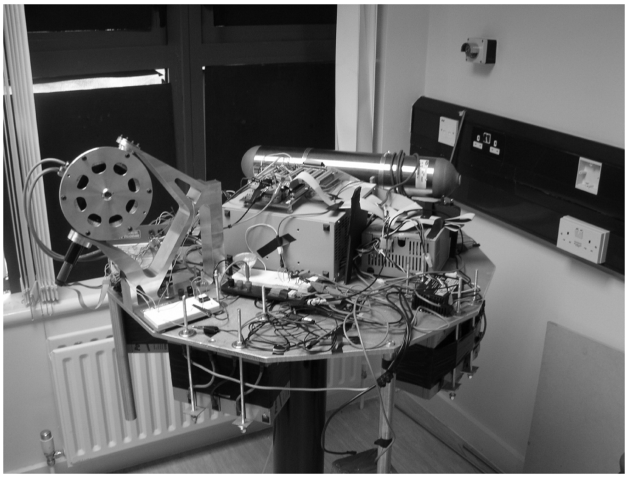

Fig. 14 Surrey Space Centre hemispherical air bearing.

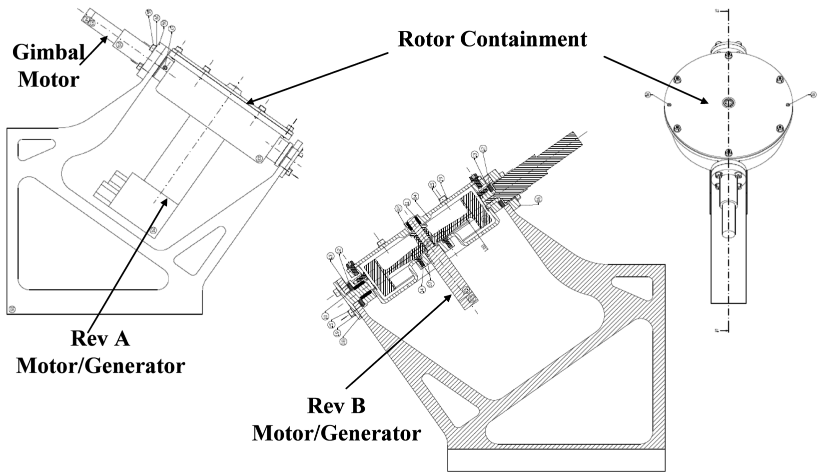

Fig. 15 Surrey Space Centre ESACS VSCMG assembly design.

attitude performance. Preliminary results show attitude pointing errors of less than 1–2 deg for open-loop attitude control tests. This work demonstrates the mass savings compared with a conventional RWA plus Ni–Cd battery approach of about 15 kg for a 400 kg minisatellite [29].

X. Conclusions

From a systems-level perspective, the SSC ESACS must advance to a demonstrable maturity to overcome the inherent conservatism in space programs. New technology, even if better, is risky to a satellite program manager and will not be used unless the mission requires it, which means that ESACS have some hurdles yet to overcome. First, they are a satellite bus component, and the payload dominates a satellite program, which means new bus components are harder to introduce than new payload technologies. There must be a tangible mission benefit. Second, new components need some demonstrated legacy to gain acceptance. For CMGs and RWAs, risk mitigation has meant life tests, which cannot be accelerated because of the mechanical bearings. A multiyear life test means that the technology will be frozen long before it will be flown. Third, the IPACS implementation of ESACS combines two complicated subsystems, attitude control and power distribution, into one, which implies a single point of failure for two subsystems. IPACS also challenges the historical project structure of satellite programs, whereas decoupled ESACS approaches benefit from existing EPS designs.

This paper has summarized the current state of the art and the path that led here. Most of the system-level work has been theoretical studies, not experiments. Component- and unit-level research has largely been performed separately, not in an integrated way. The system studies have shown that ESACS have competitive advantages, and advances have been made that indicate ESACS and flywheel energy storage alone can be practical. Research will continue in component areas, but the critical step is evolving the system feasibility demonstration to several actuators. ESACS technology will be successful only if it is brought to a level of maturity at which satellite programs no longer consider it new and unproven. Development does not require the most technologically aggressive components, but it does require a complete ESACS and dynamic (agile) structure, which only continued practical experiments can provide.

Acknowledgments

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References

[1] "The Oerlikon Electrogyro," *Automobile Engineer*, Dec. 1955, pp. 559–566.
[2] Genta, G., *Kinetic Energy Storage-Theory and Practice of Advanced Flywheel Systems*, Butterworths, London, 1985.
[3] Babuska, V., Beatty, S., deBlonk, B., and Fausz, J., "A Review of Technology Developments in Flywheel Attitude Control and Energy Transmission Systems," *Proceedings of the IEEE Aerospace Conference*, Vol. 4, Inst. of Electrical and Electronics Engineers, New York, 2004, pp. 2784–2800.
[4] Anstett, P., Souliac, M., Rouyer, C., and Gauthier, M., "SPOT—The Very First Satellite to Use Magnetic Bearing Wheels," *Proceedings of the 33rd IAF Congress*, International Astronautical Federation, Paris, 1982.
[5] Scharfe, M., Meinzer, K., and Zimmermann, R., "Development of a Magnetic Bearing Momentum Wheel for the AMSAT Phase 3-D Small Satellite," *Proceedings of the International Symposium on Small Satellites*, ESA, Paris, 1996.
[6] Roes, J. B., "An Electro-Mechanical Energy Storage System for Space Application," *Energy Conversion for Space Power*, Vol. 3, Progress in Astronautics and Rocketry, Academic Press, New York/London/Orlando, FL, 1961, pp. 613–622.
[7] Notti, J. E., Cormack, A., and Schmill, W. C., "Integrated Power/Attitude Control System (IPACS) Study, Vols. 1 & 2," Rockwell International Space Division NASA-CR-2383, Downey CA, April 1974.
[8] Anderson, W. W., and Keckler, C. R., "An Integrated Power/Attitude Control System (IPACS) for Space Application," *Proceedings of the 5th IFAC Symposium on Automatic Control in Space*, International Federation of Automatic Control, Laxenburg, Austria, 1973, pp. 121–128.
[9] Hall, C. D., "High Speed Flywheels for Integrated Energy Storage and Attitude Control," *Proceedings of the American Control Conference*, Vol. 3, Inst. of Electrical and Electronics Engineers, New York, June 1997, pp. 1894–1898.
[10] Will, R. W., Keckler, C. R., and Jacobs, K. L., "Description and Simulation of an Integrated Power and Attitude Control System Concept for Space-Vehicle Application," NASA Langley Research Center NASA-TN-7459, April 1974.
[11] Cormack, A., and Notti, J. E., "Design Report for the Rotating Assembly for an Integrated Power/Attitude Control System," NASA Langley Research Center NASA-CR-172317, Sept. 1974.
[12] Keckler, C. R., "Integrated Power/Attitude Control System (IPACS)," *Proceedings, Integrated Flywheel Technology Workshop*, NASA Goddard Space Flight Center, Greenbelt, MD, Aug. 1983, pp. 5–22.
[13] Rodriguez, G. E., Studer, P. A., and Baer, D. A., "Assessment of Flywheel Energy Storage for Spacecraft Power Systems," NASA Goddard Space Flight Center NASA-TM-85061, May 1983.
[14] Gross, S., "Study of Flywheel Energy Storage for Space Stations," The Boeing Company NASA-CR-171780, Seattle, WA, Feb. 1984.
[15] Oglevie, R. E., and Eisenhaure, D. B., "Advanced Integrated Power and Attitude Control System (IPACS) Study," Rockwell International Corp., Downey, CA, and Charles Stark Draper Laboratory, Cambridge, MA, NASA-CR-3912, 1985.
[16] Marcoux, "High Energy Density Rechargeable Battery for Satellite Applications," Air Force Wright Aeronautical Laboratories

Rept. TR-83-2055, Hughes Aircraft Co., 1983.
[17] Christopher, D. A., and Beach, R., "Flywheel Technology Development Program for Aerospace Applications," *IEEE Aerospace and Electronic Systems Magazine*, Vol. 13, No. 6, June 1998, pp. 9–14. doi:10.1109/62.683723
[18] Decker, D. K., Spector, V. A., and Pieronek, T. J., "An Overview of Flywheel Technology for Space Applications," *Space Technology & Applications International Forum, Part 1*, CP 397, American Institute of Physics, New York, Jan. 1997, pp. 257–261.
[19] Santo, G. E., Gill, S. P., Kotas, J. F., and Paschall, R., "Feasibility of Flywheel Energy Storage Systems for Applications in Future Space Missions," NASA Lewis Research Center NASA-CR-195422, Jan. 1995.
[20] Christofer, D., and Fausz, J., "Overview of the AFRL/NASA Flywheel Program," *NASA/USAF Aerospace Flywheel Workshop*, Oct. 1998.
[21] McLallin, K., "AFRL/NASA Flywheel Program Overview," *2003 Flywheel Workshop Presentation*, Aug. 2003.
[22] Schautz, M., Olsson, D., and Dudley, G., "PROBA, The First Flying ESA Spacecraft Flying Lithium-Ion," *NASA Aerospace Battery Workshop*, NASA, Washington, D.C., Nov. 2001.
[23] Acebal, R., "Shape Factors for Rotating Machines," *IEEE Transactions on Magnetics*, Vol. 33, No. 1, Jan. 1997, pp. 753–762. doi:10.1109/20.560109
[24] Acebal, R., "Effect of Shape Factor, Operating Stresses, and Electrical Conductors on the Energy Density of Rotating Machines," *IEEE Transactions on Magnetics*, Vol. 32, No. 2, March 1996, pp. 421–425. doi:10.1109/20.486527
[25] Acebal, R., "Energy Storage Capabilities of Rotating Machines Including a Comparison of Laminated Disk and Rim Rotor Composite Designs," *IEEE Transactions on Magnetics*, Vol. 35, No. 1, Jan. 1999, pp. 317–322. doi:10.1109/20.738424
[26] Sung, K. H., Jeong, H-M., and Cho, Y-S., "Optimum Design of Thick-Walled Composite Rings for an Energy Storage System," *Journal of Composite Materials*, Vol. 32, No. 9, 1998, pp. 851–873.
[27] Thompson, R. C., "Integrated Composite Arbor and Flywheel Rim Technology Development," *2003 Flywheel Workshop Presentation*, Aug. 2003.
[28] Abdel-Hady, F. et al. "Multi-Directional Composites Flywheel Rotors," *2003 Flywheel Workshop Presentation*, Aug. 2003.
[29] Richie, D., "Combined Attitude Control and Energy Storage for Small Satellites Using Variable Speed Control Moment Gyroscopes," Ph.D. Dissertation, School of Electronics and Physical Sciences, Univ. of Surrey, Guildford, U.K., July 2008.
[30] Margulies, G., and Aubrun, J. N., "Geometric Theory of Single-Gimbal Control Moment Gyro Systems," *Journal of the Astronautical Sciences*, Vol. 26, No. 2, 1978, pp. 159–191.
[31] Costic, B. T., de Queiroz, M.S., Dawson, D. M., and Fang, Y., "Energy Management and Attitude Control Strategies for Flywheels," *Proceedings of the 40th IEEE Conference on Decision and Control*, Inst. of Electrical and Electronics Engineers, New York, Dec. 2001, pp. 3435–3440.
[32] Tsiotras, P., Shen, H., and Hall, C., "Satellite Attitude Control and Power Tracking with Energy/Momentum Wheels," *Journal of Guidance, Control, and Dynamics*, Vol. 24, No. 1, 2001, pp. 23–34. doi:10.2514/2.4705
[33] Yoon, H., and Tsiotras, P., "Spacecraft Adaptive Attitude and Power Tracking with Variable Speed Control Moment Gyroscopes," *Journal of Guidance, Control, and Dynamics*, Vol. 25, No. 6, 2002, pp. 1081–1090. doi:10.2514/2.4987
[34] Fausz, J. L., and Richie, D. J., "Flywheel Simultaneous Attitude Control and Energy Storage Using a VSCMG Configuration," *Proceedings of the 2000 IEEE Conference on Control Applications*, Inst. of Electrical and Electronics Engineers, New York, Sept. 2000, pp. 991–995.
[35] Bedrossian, N. S., Paradiso, J., and Bergmann, E. V., "Steering Law Design for Redundant Single-Gimbal Control Moment Gyroscopes," *Journal of Guidance, Control, and Dynamics*, Vol. 13, No. 6, 1990, pp. 1083–1089. doi:10.2514/3.20582
[36] Vadali, S. R., Oh, H-S., and Walker, S. R., "Preferred Gimbal Angles for Single Gimbal Control Moment Gyros," *Journal of Guidance, Control, and Dynamics*, Vol. 13, No. 6, 1990, pp. 1090–1095. doi:10.2514/3.20583
[37] Bedrossian, N. S., Paradiso, J., and Bergmann, E. V., "Redundant Single Gimbal Control Moment Gyroscope Singularity Analysis," *Journal of Guidance, Control, and Dynamics*, Vol. 13, No. 6, 1990, pp. 1096–1101. doi:10.2514/3.20584
[38] Oh, H-S., and Vadali, S. R., "Feedback Control and Steering Laws for Spacecraft Using Single Gimbal Control Moment Gyros," *Journal of the Astronautical Sciences*, Vol. 39, No. 2, 1991, pp. 183–203.
[39] Schaub, H., Vadali, S. R., and Junkins, J. L., "Feedback Control Law for Variable Speed Control Moment Gyros," *Journal of the Astronautical Sciences*, Vol. 46, No. 3, 1998, pp. 307–328.
[40] Ford, K. A., and Hall, C. D., "Singular Direction Avoidance Steering for Control-Moment Gyros," *Journal of Guidance, Control, and Dynamics*, Vol. 23, No. 4, 2000, pp. 648–656. doi:10.2514/2.4610
[41] Wie, B., Bailey, D., and Heiberg, C., "Singularity Robust Steering Logic for Redundant Single-Gimbal Control Moment Gyros," *Journal of Guidance, Control, and Dynamics*, Vol. 24, No. 5, 2001, pp. 865–872. doi:10.2514/2.4799
[42] Lappas, V., "A Control Moment Gyro (CMG) Based Attitude Control System (ACS) For Agile Small Satellites," Ph.D. Dissertation, School of Electronics and Physical Sciences, Univ. of Surrey, Guildford, U.K., Oct. 2002.
[43] Yoon, H., and Tsiotras, P., "Singularity Avoidance of Variable Speed Control Moment Gyros," *Journal of Guidance, Control, and Dynamics*, Vol. 27, No. 3, 2004, pp. 374–386. doi:10.2514/1.2946
[44] Jung, D., and Tsiotras, P., "An Experimental Validation of Spacecraft Attitude and Power Tracking with Variable Speed Control Moment Gyroscopes," American Astronautical Society Paper 07-130, Feb. 2007.
[45] Richie, D., Tsiotras, P., and Fausz, J., "Simultaneous Attitude Control and Energy Storage using VSCMGs: Theory and Simulation," *Proceedings of the American Control Conference*, American Automatic Control Council, New York, 2001, pp. 3973–3979.
[46] Colozza, A. J., "High Energy Flywheel Containment Evaluation," Dynacs Engineering Company, Inc., NASA-CR-210508, Brook Park, OH, Oct. 2000.
[47] Coppa, A. P., "Flywheel Containment and Safety Considerations," *An Assessment of Integrated Flywheel Technology*, CP-2346, NASA, Washington, D.C., 1984, pp. 243–264.
[48] Mohr, P. B., and Walter, C. E., "Flywheel Rotor and Containment Technology Development-Final Report," Lawrence Livermore National Laboratory Technical Report UCRL-53448, Sept. 1983.
[49] Miller, R. M., "Flywheel Containment Device," United Technologies Corporation, U.S. Patent No. 5,387,451, July 1993.
[50] Salim, A. A., "In-Orbit Performance of Lockheed Martin's Electrical Power Subsystem for A2100 Communications Satellites," AIAA Paper 2000-2809, 2000.
[51] Smith, J. R., "Lightweight Flywheel Containment," The Regents of the University of California, U.S. Patent No. 6,203,924, Feb. 1998.
[52] Rosen, H. R., "Safety System for Flywheel System for Mobile Energy Storage," Rosen Motors, L. P., U.S. Patent No. 61357611, Aug. 1997.
[53] Dulaney, K. A., Beno, J. H., and Thompson, R. C., "Modeling of Multiple Liner Containment Systems for High Speed Rotors," *IEEE Transactions on Magnetics*, Vol. 35, No. 1, Jan. 1999, pp. 334–339. doi:10.1109/20.738427
[54] Strubhar, J. L. et al. "Lightweight Containment for High-Energy Rotating Machines," *IEEE Transactions on Magnetics*, Vol. 39, No. 1, Jan. 2003, pp. 378–383. doi:10.1109/TMAG.2002.806410
[55] Truong, L. V. et al. "Simulation of the Interaction Between Flywheel Energy Storage and Battery Energy Storage on the International Space Station," NASA TM-2000-210341, 2000; also AIAA Paper 2000-2953.
[56] Truong, L. V., Wolff, F. J., and David, N. V., "Simulation of Flywheel Electrical System for Aerospace Applications," AIAA Paper 2000-2908, 2000.
[57] Hockney, R. L., "High-Efficiency Power Conversion Options for Flywheel Energy Storage Systems," *An Assessment of Integrated Flywheel Technology*, CP-2346, NASA, 1984, pp. 349–367.
[58] Nola, F., "Motor/Generator and Electronic Control Considerations for Energy Storage Flywheels," *An Assessment of Integrated Flywheel Technology*, CP-2346, NASA, 1984, pp. 389–405.
[59] Ratner, J. K. H., Chang, J. B., and Christopher, D. A., "Composite Flywheel Rotor Technology—A Review," *Composite Materials: Testing and Design Fourteenth Volume*, STP 1436, edited by C. E. Bakis, ASTM International, West Conshohocken, PA, 2003.
[60] Ratner, J. K. H., Chang, J. B., and Christopher, D. A., "Flywheel Rotor Safe-Life Technology Literature Search Summary," NASA CR-2002-211810, July 2002.
[61] Hebner, R., Beno, J., and Walls, A., "Flywheel Batteries Come Around Again," *IEEE Spectrum*, Vol. 36, No. 4, April 2002, pp. 46–51. doi:10.1109/6.993788

[62] Henderson, T., and Dennehy, N., "Attitude Control and Energy Storage (ACES) Flywheel Demonstration Testbed," Charles Stark Draper Laboratories Rept. P-3730, 1999.
[63] Peczalski, A. et al. "Micro-Wheels for Attitude Control and Energy Storage in Small Satellites," *Proceedings of the IEEE Aerospace Conference*, Vol. 5, Inst. of Electrical and Electronics Engineers, New York, March 2001, pp. 2483–2492.
[64] Stickel, H., "Space Qualification Testing of the TELDIX Magnetic Bearing Wheel MWX," *Proceedings of the 1st International Workshop on Spacecraft Attitude and Orbit Control Systems*, ESA, Paris, 1997, pp. 221–228.
[65] Trase, L. M., "The Evaluation and Implementation of a Water Containment System to Support Aerospace Flyhweel Testing," *Proceedings, 37th IEEE Intersociety Energy Conversion Engineering Conference (IECEC)*, Inst. of Electrical and Electronics Engineers, New York, July 2002; also NASA TM-2002-211722.
[66] Varatharajoo, R., and Fasoulas, S., "Methodology for the Development of Combined Energy and Attitude Control Systems for Satellites," *Aerospace Science and Technology*, Vol. 6, No. 4, 2002, pp. 303–311. doi:10.1016/S1270-9638(02)01157-4
[67] Varatharajoo, R., and Fasoulas, S., "The Combined Energy and Attitude Control System for Small Satellite Earth Observation Missions," *Acta Astronautica*, Vol. 56, 2005, pp. 251–259. doi:10.1016/j.actaastro.2004.09.027
[68] Richie, D., Lappas, V., and Palmer, P., "Sizing/Optimization of a Small Satellite Energy Storage and Attitude Control System," *Journal of Spacecraft and Rockets*, Vol. 44, No. 4, 2007, pp. 940–952. doi:10.2514/1.25134
[69] Kenny, B., Kascak, P., Jansen, R., and Dever, T., "A Flywheel Energy Storage System Demonstration for Space Applications," NASA TM 2003-212346, June 2003.
[70] Kenny, B., Kascak, P., Jansen, R., Dever, T., and Santiago, W., "Control of a High Speed Flywheel System for Energy Storage in Space Applications," NASA TM 2004-213356, Nov. 2004.
[71] Wilson, B., "Power System Design of a Spacecraft Simulator Using Energy Storage Flywheels," *Aerospace Corporation, Space Power Workshop*, April 2005.
[72] Wilson, B., Babuska, V., Potter, C., and Fausz, J., "Power System Design for a Spacecraft Simulator Using Energy Storage Flywheels," *Proceedings of the 3rd International Energy Conversion Engineering Conference*, AIAA, Reston, VA, Aug. 2005, pp. 1–13.