Integrated Spacecraft Power and Attitude Control Systems Using Flywheels

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Chapter 1

Introduction

The power and energy engineering community has been investigating the use of high performance kinetic energy storage systems since the 1960s, with significant research and development activity throughout the subsequent decades. A wide variety of applications have been proposed, and the list includes primary storage for automobiles, electromechanical actuators for aerospace vehicles, uninterruptible power supplies for critical facilities such as hospitals and computer centers, and secondary battery replacement for satellites. In this last application, the flywheels can perform the additional functions of some of the attitude control sensors and actuators. Both NASA and the USAF are developing programs related to the use of high-speed flywheels in “integrated power and attitude control systems,” or IPACS. This multiple-use application is the focus of this report. Specifically, we aim to provide a review of the relevant literature in sufficient detail to allow the reader to understand the basic concepts and to plan for further research leading to the implementation of flywheels in this application. In this chapter, we describe the basic concept of integrated power and attitude control systems, and conclude with an overview of the report.

1.1 Concept

To describe the use of flywheels for integrated power and attitude control in satellites, we begin by discussing the configuration of a typical Earth-orbiting satellite power system, then describe the use of flywheels as a storage element of the power system. We then discuss typical satellite attitude determination and control systems (ADCS), and describe how high-speed flywheels are used as sensor and actuator elements of this spacecraft subsystem.

Figure 1.1 is a simplified block diagram of a generic satellite power system. The power source is typically an array of solar cells, either attached to the spacecraft exterior (for spin-stabilized satellites), or to articulated solar panels (for three-axis stabilized satellites). The solar arrays provide primary power whenever the satellite is in sunlight. However, most satellites experience periodic eclipses during which the satellite passes through the Earth's shadow. During these eclipse periods, a backup power source is required. Furthermore, solar arrays are typically sized to handle nominal power loads, but not to handle peak power loads. A backup power source is also required to augment the solar arrays during peak power demand. The backup power source typically comprises a "secondary" battery made of electrochemical cells, such as nickel cadmium, nickel hydrogen or lithium ion cells.* The power demand and eclipse duration, along with the allowable depth of discharge (DOD) of the batteries and number of required cycles, are used to size the backup battery energy storage system. Power demand is a spacecraft-dependent function, whereas eclipse depends on the orbit and is therefore mission-dependent. Allowable depth of discharge depends on the type of batteries employed and the mission lifetime. Thus the design of an energy storage system depends on the mission, the spacecraft design, and the choice of energy storage device.

After an eclipse, when the spacecraft returns to sunlight, excess power from the solar arrays is used to recharge the secondary batteries. The solar arrays must be sized to be able to handle the nominal power requirement and to recharge the batteries during the sunlit period of the orbit.

The basic idea of chemical batteries is to convert electrical energy to chemical energy for storage, then reconvert the chemical energy to electrical energy when needed. As with any technology, there are some limitations associated with chemical batteries. The number of charge-discharge cycles is limited, and in general, this is the limiting factor on satellite lifetime. It is also difficult to sense the state of charge of batteries, although with some batteries, such as NiH_2, it is possible to measure the state of charge accurately by measuring the pressure of the H_2 gas.

The basic idea for using flywheels as batteries is to convert electrical energy to rotational

*Note that the term "primary batteries" refers to non-rechargeable batteries used in "one-shot" applications such as activating the deployment of appendages, whereas the term "secondary batteries" refers to the rechargeable batteries used in the storage system.

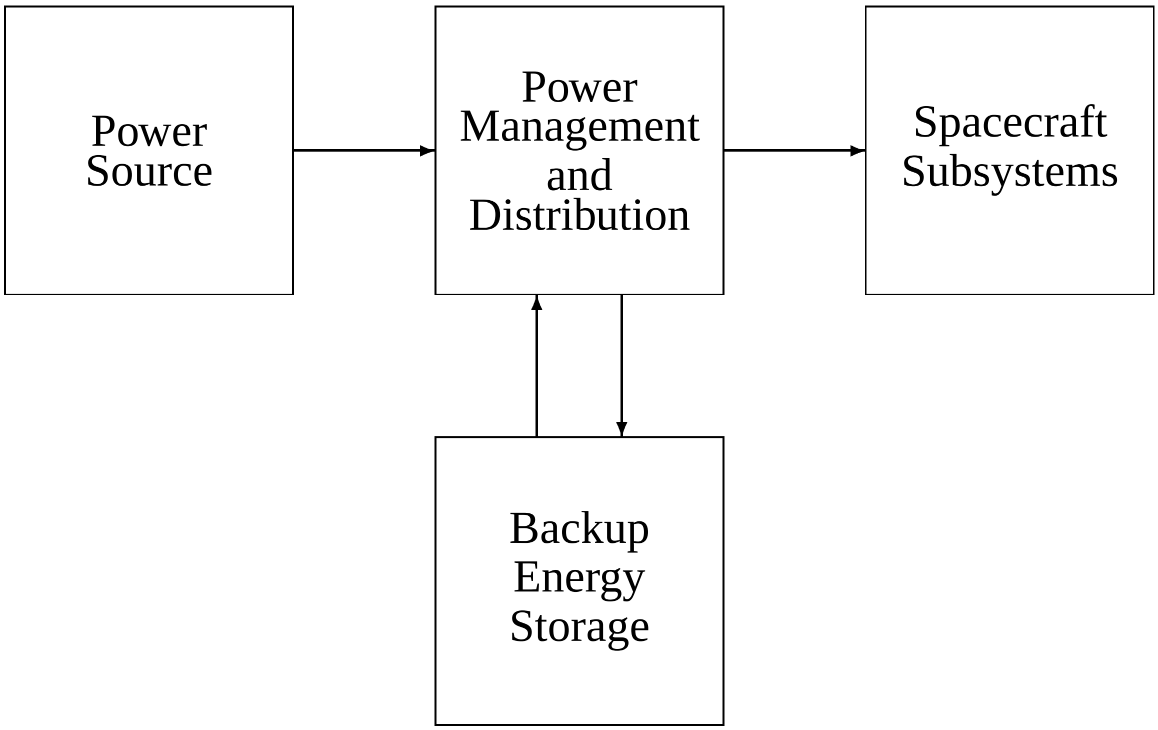

Figure 1.1: Generic Satellite Power System

mechanical (kinetic) energy for storage using a motor to spin up the flywheel. Then when electrical energy is needed, the flywheel runs a generator to convert the mechanical energy to electrical energy. Note that the motor and generator may be the same unit. The cycle life of flywheel batteries is limited by the life expectancy of the electronics and the rotor material, and it is expected that the cycle life will eventually exceed that of chemical batteries. The state of charge may be easily determined by using a simple tachometer to determine the angular velocity of the flywheel. Since a tachometer is required in any case to synthesize the control torques required to spin up and despin the flywheel, the tachometer represents no additional complexity.

Note that the straightforward replacement of chemical batteries with flywheels may be a reasonable design decision when based on the energy storage capability for a given storage system mass. In fact, several studies in the 1960s and 1970s indicated that the use of steel flywheels on mechanical bearings would be competitive with the chemical batteries of the time. In 1997, lightweight composite flywheels and virtually frictionless magnetic bearings have led to the apparent inevitability of the use of flywheels for energy storage.

However, there are additional advantages to using flywheels. The first of these is based on the fact that most spacecraft use some form of rotating flywheels for attitude control (*e.g.*, momentum wheels and control moment gyros), and some spacecraft use flywheels for attitude rate sensing (*e.g.*, rate gyros). By integrating the energy storage and attitude control functions, significant mass savings may be possible. The second additional advantage is that a flywheel energy storage system can accept a higher charge/discharge rate than chemical batteries, so that the power management and distribution system (PMAD) can be simpler and less massive than with a battery system. For example, when a spacecraft comes out of eclipse, the solar panels are cold and thus quite efficient. In systems with chemical batteries, some of the excess power must be shunted to heat dissipation units because batteries are sensitive to charge rate. Flywheels are less sensitive to rate of charge/discharge, so, at least in some cases, this power would not be wasted in a flywheel system. Exploitation of this fact should lead to mass savings in the PMAD system, as well as making it possible to use smaller solar arrays.

There are, however, some potential obstacles to success in implementing IPACS systems. The high rotational speeds required mean that either the rotors must operate in the supercritical regime, or the rotor designs must have extremely high lowest critical speeds. The former will lead to reduced lifetime of the rotors, and the latter will increase the cost associated with design, development, and manufacture. In order to reach and maintain these high speeds (on the order of 50,000 to 100,000 rpm), magnetic bearings will be required. Although the magnetic bearing technology is reasonably mature, there are still some problems to be anticipated in implementing the technology with the IPACS application. At least some of the failure modes for high-speed flywheels could be characterized as “explosions,” and the ability to predict, contain, and/or control these failures is critical to the success of these systems.

1.2 Overview of the Report

The purpose of this report is to provide useful information to the Phillips Laboratory program manager, and to the AFIT space operations, systems engineering, and astronautical engineering students involved in related research, as well as to outline a research program.

In Chapter 2, we present a summary of the key results related to the use of flywheels in general, with particular attention paid to those elements that make it possible to consider using high-speed flywheels on spacecraft. In Chapter 3, we describe the attitude determination and control and power subsystems, focusing on the established use of spinning wheels in the attitude control systems of spacecraft, including spin-stabilization, reaction wheels, momentum wheels, and control moment gyros. In Chapter 4 we describe a variety of approaches that have been suggested for simultaneously providing power and attitude control using flywheels. In Chapter 5 we give recommendations for planning future R&D activities.

Chapter 2

Flywheel Technology

Flywheels have been in use for millennia, as described in Genta's excellent monograph.[1] In this chapter, we discuss the flywheel technology developments that are relevant to the IPACS application. We first discuss the modern research and development activities and the applications that have been proposed, and then focus on the developments that have made the IPACS application a possibility. In particular, the use of composites has decreased the mass of flywheels, whereas the use of magnetic bearings has increased the achievable rotation speeds.

2.1 Modern Applications

The idea of using flywheels for energy storage on spacecraft appears to have originated in 1961 with a paper by Roes,[2] and Adams[3] studied the use of flywheels for space systems in 1972. The 1970s saw a burst of enthusiasm for the use of flywheels in a variety of applications. A 1974 energy bibliography[4] cited only eight sources on flywheels, including Adams' 1972 NASA report.[3] A 1974 Sandia report[5] includes several references. In 1976 Hagen and Erdman[6] published "a comprehensive listing of [428] papers and articles that discuss 'flywheels' in the period 1965 to 1975." Evidently the compilers of Ref. 4 did not consider flywheels to be a significant energy topic. In 1979, Mallon and Kuhn[7] published a bibliography that included "555 selected references ... through December 1977," including the 1961 paper by Roes.[2]

Flywheels were the subject of at least two symposia in the 1970s. The first[8] took place in 1975, sponsored by Lawrence Livermore National Research Laboratory (LLNRL), and, according to the *Proceedings* Introduction, was the first conference devoted to flywheels. It included 37 technical papers and concluded with a panel discussion. Some of the papers are directly relevant to the subject of this report. Rabenhorst[9] mentioned spacecraft as a typical maximum performance application, but only for energy storage. Schlieben[10] discussed the important consideration that energy flywheels must be considered as components of systems that include "the motor/generator, suspension system, vacuum and safety housing, support structures, gimbals and power conditioning unit." He mentioned that RCA Astro-Electronics Division (now Lockheed-Martin Astro Space Division) has a long history of flywheel technology development in the way of "momentum wheels, reaction wheels, and control moment gyros." His paper focused on other applications and did not mention the possibility of the standard spacecraft wheels evolving into energy storage devices. A paper by Notti[11] was submitted, but only the abstract appeared in the *Proceedings*. The abstract reported a 1480 W hr flywheel operating between 17,500 and 35,000 rpm. Andeen[12] articulated the fundamental differences between a momentum wheel and an energy wheel. Torossian[13] described the development of magnetically suspended momentum wheels for spacecraft applications at ESA and COMSAT. He described the "great interest for simultaneous use of the wheel as an energy storage device and actuation element," but gave no references to support this statement.

The second flywheel symposium[14] was held in 1977, and included some 56 technical papers on topics ranging from the performance of wooden flywheels to the various flywheel development programs that were ongoing at the time. The symposium ended with four panel discussions, mainly on ways that flywheel technology could be advanced by government and industry efforts. Only one paper at the symposium specifically mentioned space applications (Poubeau[15]), although at least one of the other papers (Schlieben *et al.*[16]) was based on research sponsored by NASA's Goddard Space Flight Center. Poubeau[15] described a 24,000 rpm flywheel for satellite applications including both energy storage and attitude control; however emphasis was on energy storage and flywheel construction, not attitude control. Schlieben *et al.*[16] described a Goddard-sponsored design study, but no space applications were discussed. Their design used an all-axis active magnetic bearing and had an estimated system energy density of $>$ 18 W hr/kg. Eisenhaure *et al.*[17] described Draper Lab efforts in design of brushless dc motors for flywheels, but no satellite applications were discussed.

A third symposium on flywheel technology was held in 1980,[18] with 53 technical papers presented. These papers presented important results on a variety of topics involving fundamental research on construction and control, and applied research relevant to specific energy storage applications. However, none of the papers specifically addressed space systems.

There were other studies conducted during the 1970s. A 1975 Rockwell report[19] briefly mentioned a spacecraft flywheel energy storage system application (on p. 2-4) that was "rated at [5.6 W hr/kg] at 10^5 cycles." This report also included a list of more than 150 flywheel applications (App. G). Lawson[20] conducted an extensive study of the use of flywheels for energy storage in buses. Kirk[21] and Kirk and Studer[22] gave a presentation of the fundamentals of using flywheels for energy storage. They included a performance comparison of flywheels using a variety of materials. In Ref. 22, they focused on the concept of a composite flywheel supported by magnetic bearings, and described in detail a proposed 10 kW hr system with energy density of 90 W hr/kg. Brobeck *et al.*[23] also did a system-level study.

High-performance flywheel systems continued to be investigated throughout the 1980s, with a significant number of papers being published in the *Proceedings* of the annual Intersociety Energy Conversion Engineering Conference. In 1980, Davis and Csomor[24] presented a survey paper on flywheel energy storage systems, but only briefly mentioned the IPACS concept.

In NASA's Forecast of Space Technology: 1980–2000,[25] published in 1976, flywheels were briefly discussed on p. 4-29, where a system energy density of nearly 200 W hr/kg was projected for the year 1980, and nearly 300 W hr/kg was projected for the year 2000. In 1992, another NASA Special Publication[26] projected only 100 W hr/kg, and noted that

> Although these systems may be capable of long lives, this capability has not yet been demonstrated, nor have all failure modes and safety needs been identified.

Evidently the authors of the earlier report were overly optimistic.

Researchers at MIT have studied related problems. For example, Larkin's thesis investigated the design of the motor/generator component of a flywheel energy storage system for spacecraft.[27] Foley's thesis investigated the design of the support structure for an integrated energy storage and attitude control system.[28]

Lawrence Livermore National Laboratory has an active program in "electromechanical batteries," as described by Post *et al.*[29] They described an envisioned system of 1–5 kW hr modules with 10 kW/kg specific power from flylwheels spinning at 200,000 rpm.

2.2 Magnetic Bearings

Magnetic suspension systems have generated significant interest in the past few decades. Magnetic suspension applications are typically grouped into two types: spinning rotors, and suspended platforms. Both applications are relevant to spacecraft design; however, the spinning rotor application is most relevant to the IPACS concept. A NASA-sponsored workshop[30] was held in 1988, featuring 24 technical papers. Kroeger[31] gave a concise description of the fundamentals, as well as more details regarding the platform suspension application. Swann[32] gave a useful historical background for the spinning rotor application. Weise[33] considered the lessons learned and their applicability to space systems. The use of magnetic gimbals was described in detail by Stuart.[34] Hockney and Hawkey[35] gave some good references. Maslen *et al.*[36] gave good "practical" discussion. Downer *et al.*[37] gave good discussion of space applications. Nikolajsen[38] described a magnetic bearing for flywheel energy storage systems in space. Downer and Eisenhaure[39] discussed superconductivity for control moment gyros.

Another symposium was held in 1995,[40] and included 55 technical papers on magnetic suspension systems. A paper by Kondoleon *et al.*[41] described the relevant work at Draper Laboratories, and gave an excellent overview of the issues associated with magnetic bearings. Samuel *et al.*[42] described in detail the space-related applications developed by their company. Of particular interest in this article is the fact that these systems have been flight-proven on successful spacecraft.

There were other studies in the 1970s and 1980s. Poubeau[15] described the problem of optimizing magnetic bearings for satellite flywheel applications and kinetic storage of energy for satellites. Downer's master's thesis investigated the dynamics of a single axis magnetic suspension system,[43] as did Basore's.[44] Bucciarelli and Rangarajan[45] also studied the dynamics of magnetically suspended flywheels, and Eisenhaure *et al.*[46] considered the related control problem. Poubeau[47] gave an overview of the use of magnetic bearings for flywheel energy storage systems.

Murakami *et al.*[48] developed a magnetically suspended gimbal momentum wheel for use in spacecraft attitude control systems. Their momentum wheel spins stably at 10,000 rpm (70 Nms) with a total mass of 5.5 kg. This amounts to an energy density of about 1.85 W hr/kg. Bangham[49] investigated the design of a magnetic bearing for flywheels. Downer *et al.*[50] presented a design of a large-angle magnetic suspension system for LEO applications. Anand *et al.*[51,52] presented a design of a 300 W hr system of an aluminum flywheel with magnetic suspension and usable energy density of 35 W hr/kg. Jayaraman *et al.*[53] studied the rotor dynamics of a flywheel energy storage unit with magnetic bearings.

Superconducting bearings for energy storage systems have also been of interest.[54,55] Because of the temperature requirements for superconducting bearings, it is unlikely that they will be applicable for space systems in the near future. However, since infrared systems typically require cryogenic cooling systems, it is possible that space-based infrared systems may eventually take advantage of superconducting bearings for flywheel energy storage.

2.3 Composites and Containment

Evidently composite materials technology is at a level of maturity to enable high speed flywheels to be manufactured for the IPACS application. While there is a substantial body of literature on composite materials properties, we only cite a few sources that are specifically relevant to flywheels. Golovkin *et al.*[56] conducted an analysis of the stiffness and resonant frequencies for composite flywheels. Portnov *et al.*[57–62] conducted a substantial study of composite flywheels specifically for the energy storage application. Coppa *et al.*[63] investigated the technology for containing flywheels during failure, but this report is nearly 2 decades old. Kulkarni[64] evaluated containment for composite flywheels with a failure energy density of 88 W hr/kg, and an operational energy density of 44 to 55 W hr/kg. The system he described had an energy storage capacity of approximately 1 kW hr. Sapowith[65] conducted a burst containment study for Lawrence Livermore Laboratory. Mohr and Walter[66] described flywheel energy storage systems with 0.7 kW hr capacity and energy densities of more than 70 W hr/kg, apparently based on the flywheel mass (1 kg rotors). Their study included evaluation of containment structures.

Kirk *et al.*[67] conducted a stress analysis of a composite multiring/multiwheel flywheel system for space applications. They showed how to increase the energy density, and how to distribute the radial stresses in a way that causes the outer flywheel rings to separate at their interfaces during failure, thereby potentially reducing the mass of the containment structure. Their work is continued in Refs. 68 and 69.

Olmsted[70] described the development of a 16 kW hr system with system energy densities on the order of 15 W hr/kg. Olszewski and O'Kain[71] described in detail a program aimed at developing a flywheel energy storage system for space applications with a total stored energy on the order of 300 kW hr. Olszewski[72] described further details of this program.

Chapter 3

Spacecraft Attitude Determination and Control and Power Subsystems

The development of satellites is closely related to the study of spinning objects. Although the dynamics of tops and gyroscopes was already well-advanced before the 1950s,[73,74] the first two artificial satellites (Sputnik I and Explorer I) led directly to a fundamentally new principle of satellite spin stabilization, namely the "Major Axis Rule".[75] This rule states that a spacecraft can only be spin-stabilized about its major axis, due to the internal energy dissipation which is present in any physical system. This was the first of many important results regarding the practical stability of the attitude motion of spacecraft that either spin or contain spinning components. There are numerous texts that deal with the various attitude dynamics and control problems. Thomson's early text[76] (still available as a reprint) included unusually precise treatments of a variety of problems, including spin stabilization, despinning satellites, energy dissipation effects, and the effects of varying mass configuration. The handbook edited by Koelle[77] (§ 14.2) included substantial treatment of the problems of stability and control of launch vehicles, upper stages, and satellites. Purser *et al.*[78] discussed attitude stabilization and control systems in Ch. 21, including momentum wheels and a brief discussion of control moment gyros. The monumental treatise edited by Wertz[79] included a wealth of information on all aspects of spacecraft attitude dynamics, determination, and control. It remains practically the only book source of information on attitude determination.

The texts of Kaplan,[80] Hughes,[75] and Chobotov[81] treated many standard attitude dynamics and control problems. Hughes[75] in particular, provided a consistent treatment of many of the rotational stability results mentioned above, including the effects of energy dissipation and environmental torques. The space system design-oriented texts by Larson and Wertz,[82] Griffin and French,[83] and Pisacane and Moore,[84] all included substantial coverage of the details of attitude control systems.

3.1 Basic Requirements

The attitude determination and control system (ADCS) of a spacecraft serves the spacecraft mission by providing accurate determination of the current or past orientation of the spacecraft relative to a known reference frame, by providing the capability to control the spacecraft orientation accurately, and in some cases, by providing the capability to maneuver the spacecraft from one orientation to another. The last of these is important for surveillance and remote sensing satellites.

Spinning rotors are used to carry out all of these functions. Rate and integrating gyroscopes provide angular velocity and angular rotation measurements, but are subject to drift errors, are massive, and have high power requirements. For these reasons, the attitude determination function usually involves a combination of gyros and non-gyroscopic instruments, such as magnetometers, and sensors that detect the Earth horizon, the sun, or specific star patterns. Attitude control is often effected using reaction wheels, momentum wheels, or control moment gyros. Some spacecraft use thrusters to provide attitude control, but these have the disadvantages of using expendable fuel, generating contaminants that may degrade the performance of sensitive instruments such as optical systems, and generating a vibrationally noisy environment. The various wheel configurations are superior to thrusters in all these respects. Magnetic torquer rods are also used but generally do not provide the accuracy available with the various flywheel configurations.

3.2 Spin and Dual-Spin Stabilization

The earliest spacecraft were spin-stabilized. That is, the spacecraft were designed to spin about the major axis. This type of attitude control has two disadvantages. Because the spacecraft is spinning, it is not possible to keep any part of it pointing at the Earth. Large, cylindrical spacecraft with the symmetry axis as the major axis may be too large to fit into a launch vehicle's payload shroud. Dual-spin stabilization overcomes both of these disadvantages. The addition of a despun platform with sufficient energy dissipation leads to a new type of "major-axis" rule that makes it possible for a minor-axis dual-spinner to be stabilized. The "despun" platform can be made to spin at a relatively slow rate of one revolution per orbit so that it remains Earth-pointing, whereas the spinning rotor provides the gyric stability.

Since these spacecraft do not normally contain any "small" flywheels, it is unlikely that these configurations will be candidates for using flywheels energy storage.

3.3 Reaction Wheels and Momentum Wheels

Reaction wheel (RW) and momentum wheel (MW) attitude control systems use flywheels whose spin axes are fixed in the spacecraft. The bearings have typically been mechanical, but magnetic bearings have been used. Scharfe *et al.*[85] described the design of magnetic-bearing momentum wheels for attitude stabilization of an amateur satellite (AMSAT's Phase 3-D).

The primary difference between RW and MW systems is in the nominal spin rate of the flywheels. Reaction wheels typically have zero nominal angular velocity, which slowly changes in response to small environmental torques. Once the maximum operating speed is reached, external torques must be applied to the spacecraft in a "momentum unloading" maneuver. These torques are typically applied using thrusters or magnetic torquer rods. Momentum wheels typically have a momentum bias, and spin at a large angular velocity, which slowly changes to absorb small environmental torques. Momentum unloading maneuvers are also required.

Momentum wheel systems can also be used to perform large-angle rotational maneuvers. The control laws to perform such maneuvers are reasonably simple, since the relationship between the inputs (spin axis torques) and the outputs (spacecraft rotational motion) is simple, albeit highly nonlinear. Furthermore, with four or more momentum wheels, it is possible to change the spin rates of all the wheels without affecting the motion of the spacecraft. This result was first reported in Ref. 86.

3.4 Control Moment Gyros

Control moment gyro (CMG) attitude control systems use flywheels mounted in gimbal frames that can be rotated about the gimbal axis. The spin rate is held constant relative to the gimbal frame, and the gimbal axis is perpendicular to the spin axis. The attitude control is effected by changing the gimbal angles to absorb external environmental torques or to produce a large-angle rotational maneuver. Two types of CMGs have been used: single-gimbal CMGs and double-gimbal CMGs. The double-gimbal variety may experience gimbal lock, and are not as frequently used. The single-gimbal variety produces more output torque, does not experience gimbal lock, and is evidently the CMG of choice. Momentum unloading maneuvers are required when the gimbal angles reach limiting values defined by the mechanical design. With large-angle magnetic bearings, it may be possible to reduce the requirement for momentum unloading, but not to eliminate it altogether.

The control laws to perform large-angle rotational maneuvers are quite complex, and the dynamics and control issues associated with using CMGs are not completely understood.[87] Note also that the CMG studies that have been performed were based on constant-speed flywheels, and the generalization to variable-speed flywheels that would be required for IPACS is non-trivial. The attitude dynamics and control of spacecraft with variable-speed "gimbaled momentum wheels" (GMWs) is addressed by Ford.[88]

3.5 Power Subsystems

Discussions of spacecraft power subsystem fundamentals are available in a variety of sources. Koelle[77] (Ch. 15) described spacecraft electrical systems and power plants from the point of view of the designers of the earliest space systems. No mention was made of flywheels, although other rotating power supply systems were discussed, including Sterling engines. The author of §15.2 (Huth) noted that "compared with rotating equipment, batteries have the obvious advantage of inducing absolutely no vibrations and gyroscopic torques, while they themselves can withstand high shocks." Purser *et al.*[78] discussed power systems in Chs. 18 and 19, making no mention of flywheels for energy storage. The more recent space system handbooks provide extensive material on the approaches to designing power subsystems for spacecraft. These include Larson and Wertz,[82] Pisacane and Moore,[84] and Griffin and French.[83] Larson and Wertz[82] is particularly useful in that it provides simplified formulas for sizing space power system requirements. The annual Intersociety Energy Conversion Engineering Conference (IECEC) regularly includes sessions on space power systems, including generation, management and distribution, storage, and simulation, as well as new technologies relevant to one or more of these subtopics.

Szego *et al.*[89] developed a related optimization problem for space energy storage systems. Specifically, they looked at the optimal configuration of electrical storage (batteries) and thermal storage (latent heat of phase change). They showed that there are cases where the optimal configuration is a combination of the two storage systems.

The early (1961) paper by Roes[2] evidently presented the earliest suggestion that flywheels might be useful as energy storage devices on spacecraft. The author's concept included a pair of magnetically-suspended, counter-rotating flywheels with specific energy density of 7 W hr/lb. Roes[2] did not mention the possibility of attitude control using the flywheels.

Chapter 4

Integrated Power and Attitude Control Systems

One of the earliest descriptions of the IPACS concept is in the NASA Technical Note by Will *et al.*,[90] based on research at NASA Langley. The authors modeled an IPACS system using a pair of two-rotor, double-gimbaled CMGs. It is worth noting that the IPACS system described in this TN is based on using mechanical bearings and (presumably) non-composite flywheels. Their simulations were based on linearized equations of motion, and addressed a specific application to a LEO solar observatory mission with attitude control requirements of 1.0 arcsecond pointing accuracy, 0.25° pointing stability about the pointing axis, and 0.02 arcsecond pointing stability about the transverse axes during operational observation periods of up to 45 minutes. Another NASA Langley report by Shaughnessy[91] presented essentially the same material, with somewhat more detail. Apparently the authors of these two reports were aware of each others' work, but neither report cites the other.

A two-part report by Notti *et al.*[92,93] was sponsored by NASA Langley and published in 1974. Passani[94] described the use of a flywheel for satellite energy storage, claiming that "the gyroscopic effect of the flywheel [has] no significant effect on the pilot-ability of the satellite." His study showed that the use of flywheels improved several performance measures for typical satellites, when compared to using NiCd batteries.

Slifer[95] presented a design study for a a 5 kW-hr flywheel component operating at 50

% DOD, capable of supporting an average load of 3 kW, and a peak load of 7.5 kW for 10 percent of the low earth orbit cycle. Studer and Evans[96] described the results of two studies investigating a magnetic bearing "mechanical capacitor" design, including the design details of the bearing, motor/generator, power conditioning, and the rotor.

Two NASA workshops,[9798] were held to evaluate the feasibility of using flywheels on spacecraft. The first was essentially limited to NASA researchers and featured 21 presentations and four panel workshop summaries. Several papers were presented on the IPACS concept. Keckler[99] presented an overview of the concept, and Rodriguez[100] presented an overview of GSFC research activities. Rice,[101] Nicaise,[102] and Elam,[103] gave an evaluation of space station requirements for IPACS systems. Brandon[104] discussed technology issues. Keckler and Groom[105] presented the status of ACAPS. Elam[103] described the sizing of flywheel systems for meeting attitude control requirements. The second had substantial industry participation and included 25 presentations and four workshop summaries. Eisenhaure[106] described a CARES system (Combined Attitude, Reference, and Energy Storage) using a large-angle magnetic bearing suspension system for the flywheel. This approach is unique in that the integrated system also acts as a rate gyro system, using bearing torque and magnetic gap information to estimate the attitude rates. Giudici[107] described a comparison of flywheel systems to NiCd batteries and regenerative fuel cells. The report by Gross[108] focused primarily on the use of flywheels as energy storage devices, with emphasis on space station applications. The report was summarized at the second NASA IPACS workshop.[109]

Loewenthal *et al.*[110] described a 0.87 kW-hr flywheel energy storage module, but did not discuss the integration of attitude control. Their paper focused on the experimental investigation of an actual flywheel, including the losses associated with ball bearings and aerodynamic drag. Flatley[111] investigated the use of a four-flywheel system for integrated energy storage and attitude control, including the relationships between current, voltage, and motor/generator torques. This appears to be the only paper recommending a "momentum wheel" approach to the IPACS concept.

Keckler and Groom[112] described the IPACS concept. Van Tassel and Simon[113] described the system level issues associated with IPACS for space station applications. O'Dea *et al.*[114] described a CARES system (Combined Attitude, Reference, and Energy Storage) using a large-angle magnetic bearing suspension system for the flywheel. The authors provide detailed specifications for the system, based on space station requirements. Rodriguez *et al.*[115] performed a detailed study of flywheel systems for energy storage and briefly mentioned that "differential speed control can be used to provide attitude control functions." Their study focused on a LEO application with a 3-kW power system with a 250 VDC bus using peak-power tracking. Even without the additional potential for attitude control, they concluded that the system could outperform NiCd or NiH2 battery systems. Studer and Rodriguez[116] gave a brief description of the ACES concept (Attitude Control and Energy Storage). Burke[117] conducted an analysis of the size of gimbals required for an IPACS system, using double-gimbaled gyros and mechanical gimbals.

Oglevie and Eisenhaure[118] conducted a NASA-sponsored study of the IPACS concept for space station. Their report includes an excellent review of the earlier literature, with 90 citations. A broad range of system-level issues are investigated, including the trade-offs involving the wheel configuration. Their fundamental conclusion on this issue is that, for space station, the "preferred wheel array configuration ... is the 'planar' arrangement employing five double-gimbaled wheels." The gimbaling approach involves the use of a spherical large angle magnetic bearing. A conference paper[119] summarized this report. Studer[120] patented a design for a satellite attitude control system using magnetic bearing-supported flywheels. He also discussed the use of an energy recovery system to be used during flywheel deceleration, but did not perform any detailed study of this function.

Bichler[121] described an "intelligent" flywheel energy storage system that combines energy storage, attitude control, voltage generation, and structural vibration damping. A master's thesis at the Hartford Graduate Center considered integrating energy storage and attitude control for missile roll dynamics.[122] Santo *et al.*[123] conducted a recent study on flywheel energy storage systems for space systems.

Due to renewed interest in the IPACS concept, primarily at NASA and the U.S. Air Force Phillips Laboratory, a special session on flywheel energy storage was held at the 1997 National Aerospace and Electronics Conference (NAECON) in Dayton, Ohio. Several relevant papers were included in this session (Refs. 124, 125, 126, 127, and 128). There was also a flywheel workshop at the 1997 Space Power Workshop, and a Flywheel Workshop held at NASA Lewis Research Center in September 1997.

Chapter 5

Recommendations for Future Research and Development

The IPACS concept has been investigated by numerous researchers over the past 20+ years. Early studies focused on the use of pairs of double-gimbaled mechanical control moment gyro assemblies, whereas later studies focused on the use of magnetic bearings and clusters of single-gimbal CMG assemblies. Most researchers have discounted the possibility of using momentum wheel clusters to perform the IPACS functions.

In this chapter, we suggest topics for further study. As mentioned in the Introduction, there are several potential obstacles to the success of flywheel energy storage systems on spacecraft. To establish a sound program for integrated attitude control and energy storage, the Air Force should push each of these areas. The current design study at the Air Force Institute of Technology will address some of these areas, and will help to demonstrate the potential of IPACS for Air Force programs.

5.1 Configuration

As noted above, most studies have assumed a gimbaled wheel approach to implementing IPACS systems. The motivation for this appears to be the higher power requirement for producing torque using the momentum wheel approach. This does not appear to be a reliable measure of the effectiveness of the system, and we believe that the momentum wheel approach has advantages over the gimbaled wheel approach. Specifically, the MW approach is simpler than the GMW approach, and the minimal MW configuration (4 MWs) allows energy storage to take place without affecting the attitude dynamics, whereas the minimal GMW approach (3 GMWs) requires attitude control whenever energy storage operations take place. A systematic comparison between the two approaches should include other measures of effectiveness such as reliability. The AFIT Systems Design Study will include such a comparison, and preliminary results indicate that the MW approach is superior to the GMW approach.

Within the gimbaled wheel approach, there are two possibilities for accomplishing the gimbaling: magnetic gimbaling and mechanical gimbaling. In the magnetic gimbaling configuration, the magnetic bearing is capable of rotating the rotor within the rotor housing, potentially providing for unrestricted gimbaling of the flywheels. In the mechanical gimbaling configuration, a mechanical gimbal or hinge is used to rotate the flywheel housing about an axis perpendicular to the spin axis. Should the gimbaled approach be preferable to the momentum wheel approach, a detailed trade study between the two gimbaling configurations should be conducted.

A further issue in configuration is the question of whether to spin the flywheels during launch. If the flywheels do not spin during launch, then some batteries will be required to power initial deployment activities. If the flywheels do spin on launch, then the mechanical bearings must be designed to withstand the launch loads. It appears to be unreasonable to design the magnetic bearings to withstand the launch environment. This issue has apparently received no significant engineering study, and should be addressed.

5.2 Attitude Determination

The CARES approach included attitude rate sensing using the flywheel system. Other researchers have not considered this additional function, and it deserves further attention. Specifically, analysis should be performed to determine the minimal configuration in the gimbaled and non-gimbaled approaches to perform all three functions: energy storage, attitude determination, and attitude control. Note that attitude determination cannot be reliably performed using only gyros, since drift occurs. Therefore, additional attitude sensors will be required in any system.

5.3 Containment

The potential for catastrophic failure with flywheel energy storage systems is substantial, and further research and development activities are required in this area. Specifically, the ability to manufacture composite rotors which have specific failure characteristics seems promising. System analysis, design, and testing should focus on integrating the rotor, hub and shaft design with the housing design.

5.4 Magnetic Bearings

This field is reasonably mature, and magnetic bearing momentum wheels have logged a significant number of spaceflight hours. However, these operational systems have used significantly lower rotor speeds than are needed for IPACS systems. Also, the speeds have been more or less constant during operation, rather than the continual spinup/despin that is expected with energy storage and retrieval. Important issues that should be addressed include the effects of higher speeds on the control of the magnetic bearings, and the effects of cycling and wide variation of speeds on the bearing performance.

5.5 Power Bus

Typical spacecraft power buses have used relatively low-voltage dc power, usually 28 V and less than 2 kW. For higher power systems, higher voltage buses may be superior, and ac designs may be appropriate. We recommend a study be performed to investigate the advantages and disadvantages of moving away from the 28 Vdc standard.

Appendix A

Alphabetized Bibliography

This appendix contains an alphabetized version of the Bibliography, which is sorted in order of citation. The superscripts preceding each entry provide an index into the Bibliography. The citation numbers in the main text refer to the numbering used in the unsorted Bibliography.

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