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INERTIAL ENERGY STORAGE FOR SATELLITES

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ABSTRACT

The Charles Stark Draper Laboratory is developing a new system that performs satellite attitude control, attitude reference, and energy storage utilizing inertia wheels. The baseline approach consists of two counter-rotating flywheels suspended in specially designed magnetic bearings, spin-axis motor/generators, and a control system. The control system regulates the magnetic bearings and spin-axis motor/generators and interacts with other satellite subsystems (photovoltaic array, star trackers, sun sensors, magnetic torquers, etc.) to perform the three functions.

Existing satellites utilize separate subsystems to perform attitude control, provide attitude reference, and store energy. These functions are currently performed using reaction or momentum wheels, gyros, batteries, and devices that provide an absolute reference (sun sensors and star trackers). A Combined Attitude, Reference, and Energy Storage (CARES) system based on high energy density inertial energy storage wheels (flywheels) has potential advantages over existing technologies. Even when used only for energy storage, this system offers the potential for substantial improvements in life, energy efficiency, and weight over existing battery technologies. Utilizing this same device for both attitude control and attitude reference would result in significant additional savings in overall satellite weight and complexity.

SATELLITE INERTIAL ENERGY STORAGE

- POTENTIAL FOR COMBINING ATTITUDE, REFERENCE, AND ENERGY STORAGE SYSTEMS
- FUNCTIONAL PRIORITY
  1) ENERGY STORAGE (REPLACES BATTERIES)
  2) ATTITUDE CONTROL
  3) ATTITUDE REFERENCE
- APPROACH

  CONFIGURE A BASELINE SYSTEM BASED ON THE REQUIREMENTS OF:
  1) SMALL SATELLITE APPLICATION
  2) TYPICAL SPACE STATION

The small satellite system studied to date is sized to meet the requirements of the Solar Max Mission (SMM) configuration of the Multimission Modular Spacecraft (MMS) satellite. The components which would be replaced with the CARES system include the batteries, IRU, reaction wheels, and some functions of the power regulation unit. With minor modifications, the baseline system could be used to provide a subset of the CARES functions. In particular, the system could be configured to provide energy storage and attitude control, energy storage alone, or attitude reference alone.

SMM MISSION SPECS

POWER SYSTEM

BATTERIES: THREE 20-Ah Ni-Cd
WEIGHT: 158 lb
DOD: 2-yr MISSION 40%
CAPACITY: 806 Wh (2-yr MISSION)
POWER: 1200 W

ATTITUDE CONTROL SYSTEM

4 REACTION WHEELS
MAX TORQUE PER WHEEL: 0.15 N·m
MAX H PER WHEEL: 20 N·m·s
SLEW RATE: 5 min arc/30 s

MAG TORQUERS: 0.0035 –0.007 N·m

ATTITUDE REFERENCE SYSTEM

3 TWO-DEGREE-OF-FREEDOM GYROS
ACCURACY: 100 ppm DEVIATION
<1/2% ABSOLUTE
POWER CONSUMPTION: 7 W/AXIS

COMPONENTS REPLACED WITH CARES SYSTEM

BATTERIES

POWER REGULATOR

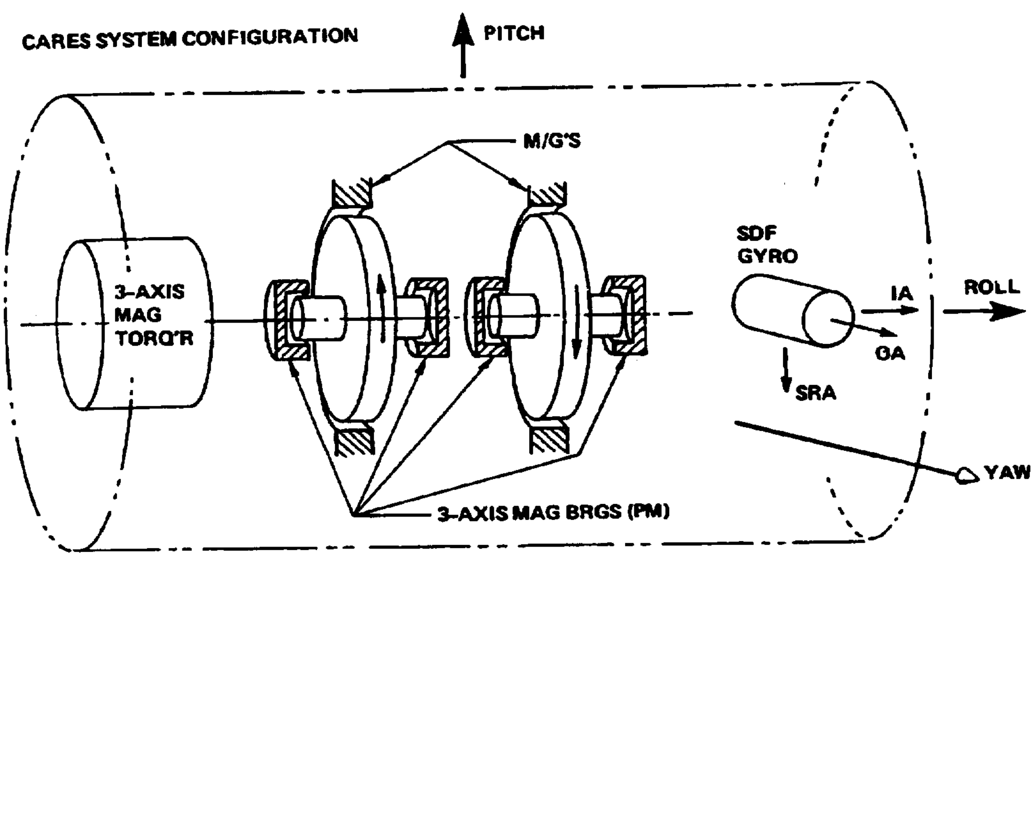
REACTION WHEELS

ATTITUDE CONTROL ELECTRONICS

IRU

The mechanical configuration of the baseline system is shown below. During periods of sunlight, motors accelerate the flywheels, thus storing the excess energy from the photovoltaic array (PVA) as kinetic energy. During periods of eclipse, these motors function as generators and provide power for satellite systems. The CARES system provides attitude control about the roll, pitch, and yaw axes. Control about the roll axis is obtained by differentially torquing the motor/generators. Control about the pitch and yaw axes is obtained by tilting the flywheels within the magnetic bearings at a controlled rate. Two axes, therefore, are controlled by utilizing the wheels as control moment gyros while the third axis is controlled by utilizing the wheels as reaction wheels. Attitude rate information about the pitch and yaw axes can be computed from bearing torque and gap information. Attitude rate information about the roll axis is provided with a gyro or other external sensor. In alternative configurations, three axes of rate information could be provided and all gyros could be eliminated.

CARES SYSTEM CONFIGURATION



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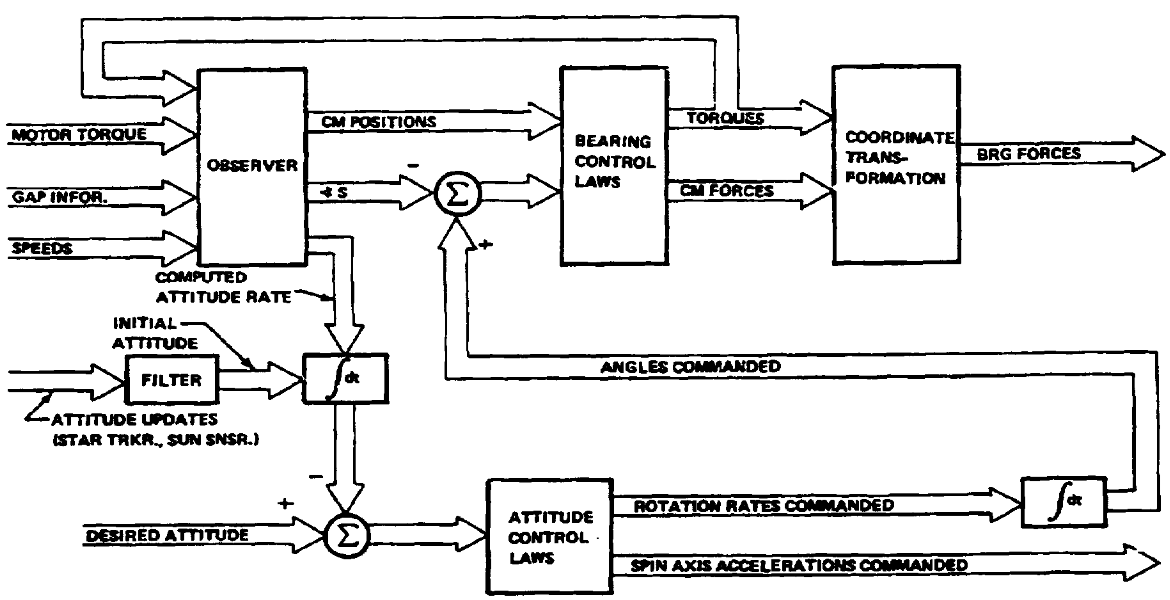
The magnetic suspension produces net torques about the pitch and yaw axes of the satellite in response to either commanded attitude changes of the satellite or external disturbances. For example, consider a commanded rotation of the satellite about its pitch axis. The control system would initially command a rate of tilt (with respect to the satellite) of the flywheels about the yaw axis. In order to affect this tilt rate, the magnetic suspensions exert torques about the pitch axis of the satellite. The satellite will continue to accelerate about the pitch axis until one or both of the flywheels have reached their maximum allowed angle of tilt. At this point, the inclinations of the flywheels remain fixed, and the satellite continues to rotate about its pitch axis at a constant rate. While the satellite is rotating about its pitch axis, the control system automatically supplies equal and opposite torques to each wheel. These torques cause the wheels to precess at the satellite rate but yield no net torque on the satellite. When the satellite nears completion of the desired motion, the control system commands an oppositely directed rate of tilting of the flywheel spin axes. This removes the satellite angular momentum and brings the attitude of the satellite to its desired value.

CARES SYSTEMS CONTROL CONFIGURATION



The magnetic suspension functions as a bearing, torquer, and inertial rate sensor. Because of its multiple uses, the suspension must have negligible cross-axis coupling, gain that is independent of rotor position, and stable torque characteristics. These are all characteristics in which magnetic bearings have traditionally had deficiencies. The baseline system utilizes an "ironless" 3-axis magnetic suspension concept employing high energy product samarium cobalt permanent magnets. This suspension has the potential for overcoming many of the deficiencies in existing magnetic bearings.

CANDIDATE ROTOR MATERIALS—75% DOD

	WHEEL SPEED (r/min)	RADIUS (in.)	WEIGHT (lb)	VOLUME (in.^{3})	Wh/lb	Wh/lb @ BURST
STEEL VASCO MAX 300	25,292	5.6	80	280	6.7	12.2 (21.2 demonstrated)
TITANIUM Ti 6Al-4V	26,320	6.2	61	378	8.85	9.6
BORON/ALUMINUM	40,760	5.71	29.3	298	18.31	26 BASELINE
BORON/EPOXY	38,400	6.19	28	380	19.1	38.2
GRAPHITE/EPOXY	35,250	6.41	31.6	421	16.7	33.4 (28.4 demonstrated)

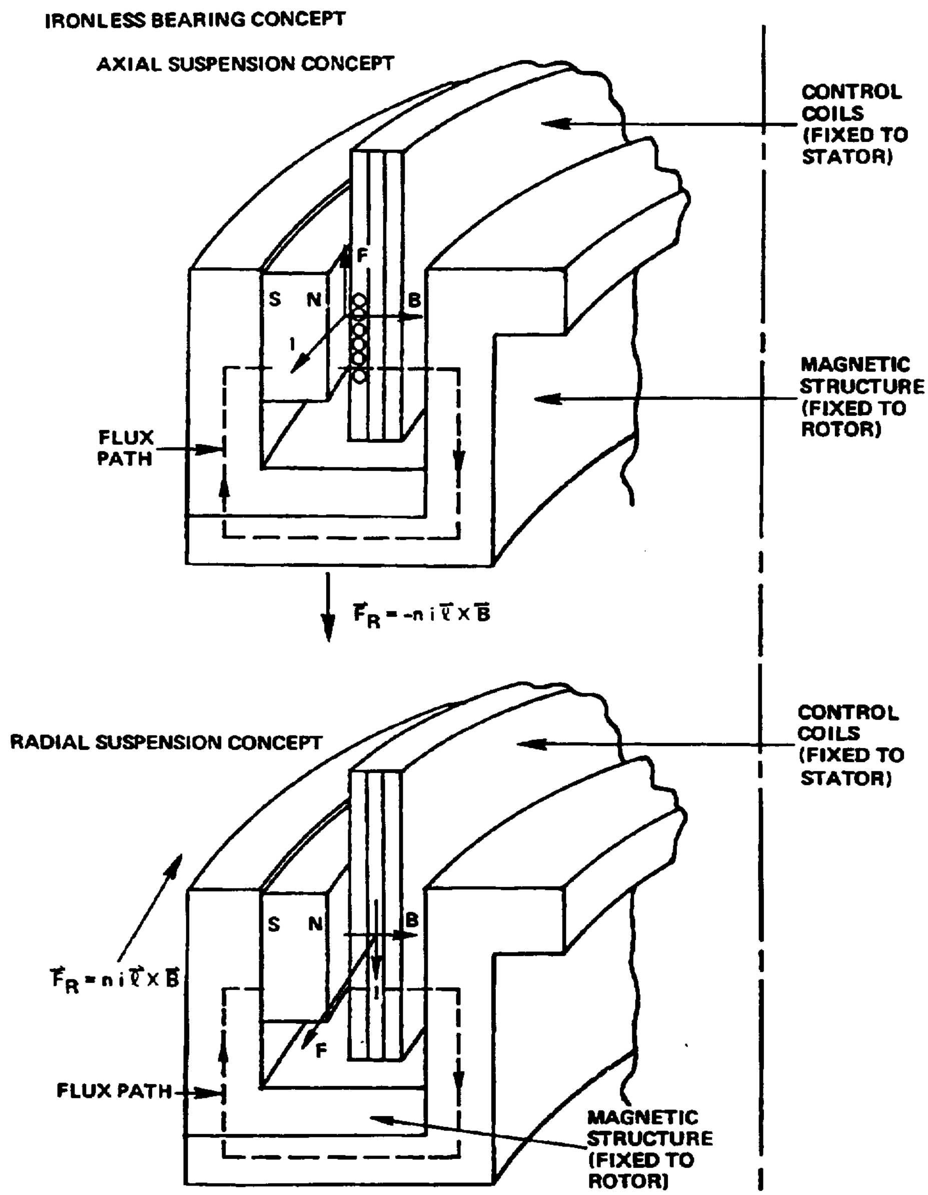
FACTORS AFFECTING MAGNETIC BEARING DESIGN

- WHEEL ANGULAR MOMENTUM
- REQUIRED SLEW RATES OF SATELLITE
- REQUIRED SATELLITE TORQUE
- WHEEL IMBALANCE
- WHEEL SPEED
- STRUCTURAL COMPLIANCES AND INTERACTIONS

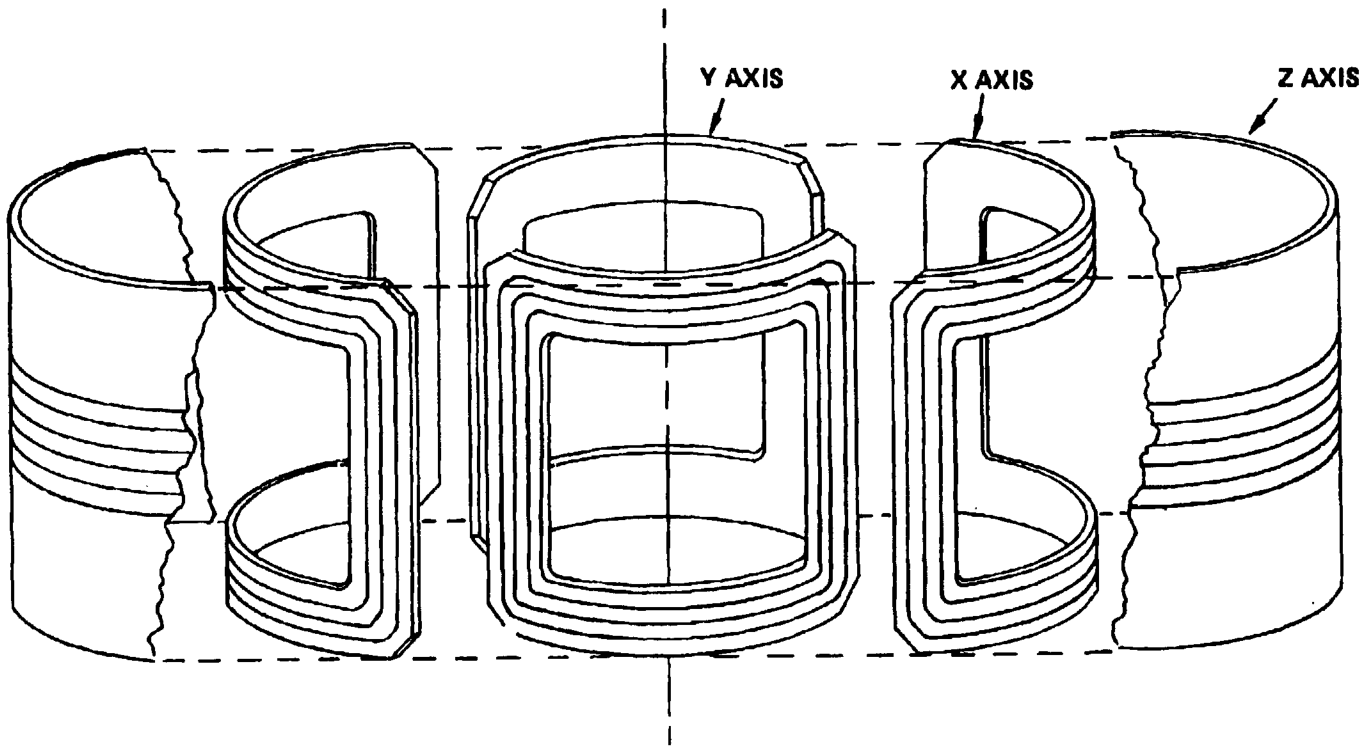
FUNCTIONS PERFORMED

- BEARING
- TORQUER
- RATE SENSOR

Forces are exerted on the flywheel due to the interaction of rotating permanent magnets and stationary control coils. The figure shows the configuration required to produce these forces. The windings of the control coil structure are shown assembled and in exploded form. Rotor position is determined by a 3-axis capacitive position sensor. Flywheel motion is detected by the change in capacitance of several electrical paths between the flywheel and housing.



CONTROL COILS DETAILED



A flywheel energy storage system for a satellite might consist of a photovoltaic array (PVA), a peak power tracker (PPT), and a pair each of regulatcrs, motor/generators (M/G), and flywheels as shown. The two motors would require two control loops -- one a differential loop for roll axis stabilization, the other a common mode loop such that the bus voltage is maintained.

FUNCTIONS PERFORMED BY POWER DISTRIBUTION SYSTEM

- BUS VOLTAGE REGULATION
- SPIN-AXIS ATTITUDE CONTROL
- PEAK POWER TRACKING

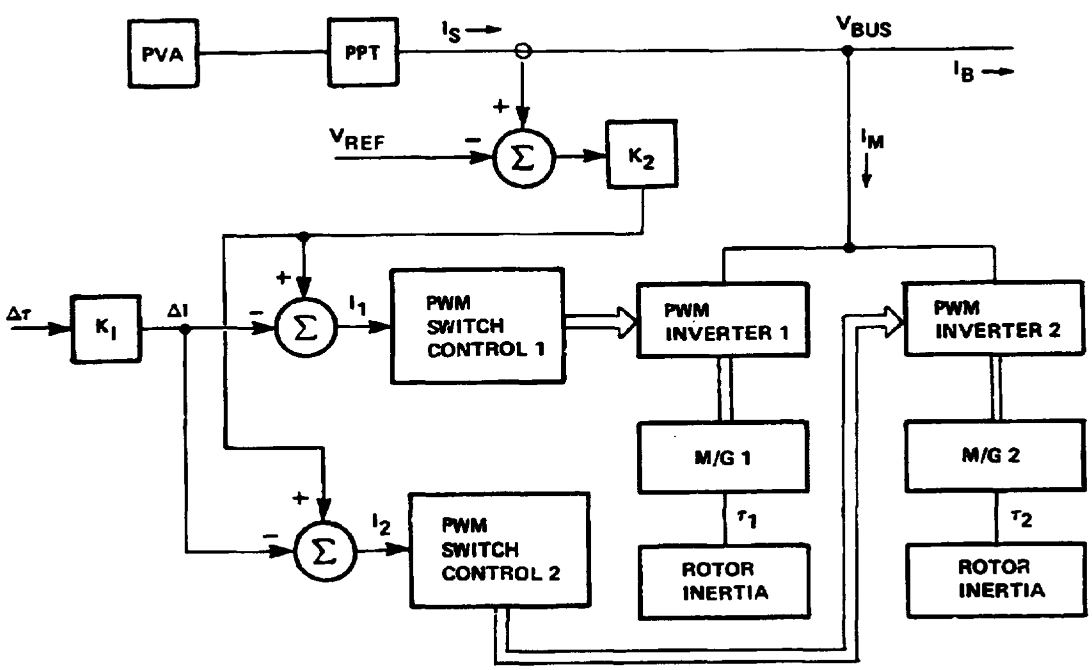
POWER HANDLING COMPONENTS

- SOLAR ARRAY
- PEAK POWER TRACKER
- PWM dc/ac MOTOR DRIVES (2)
- IRONLESS PM MOTOR/GENERATORS (2)

A power distribution system for satellites typically provides the functions of peak power tracking of the PV array and voltage regulation of the satellite's power bus(ses). In the CARES system, the power distribution system components are also used for roll axis attitude control.

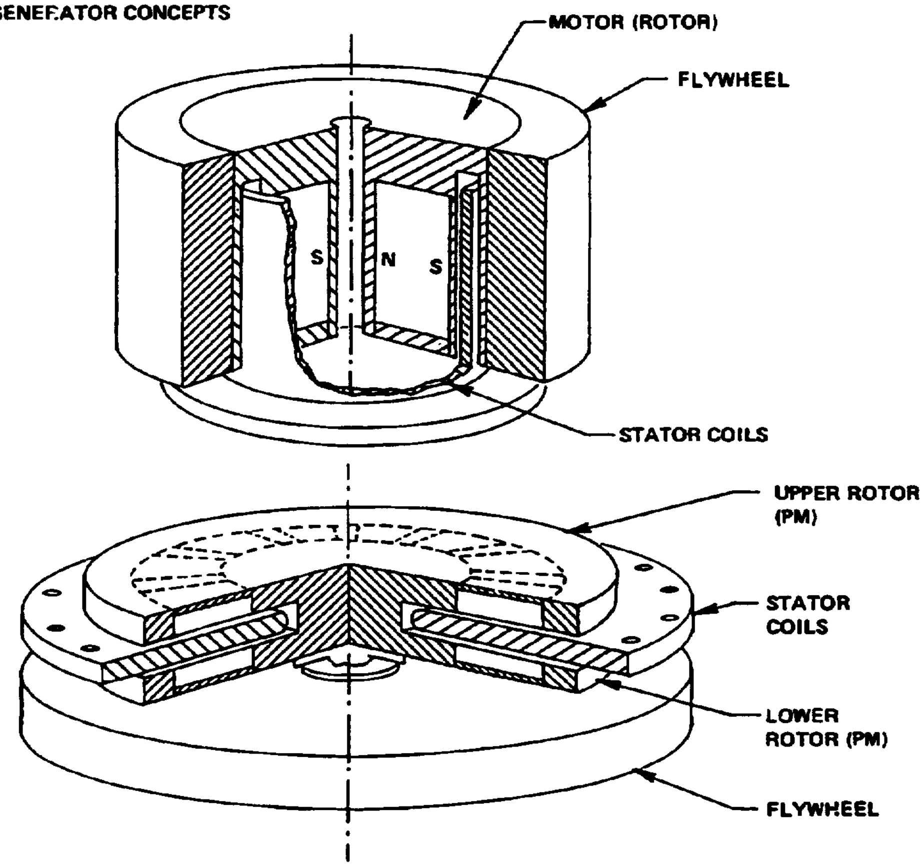
The roll axis of the satellite is stabilized by feeding back an error signal proportional to the difference between the desired roll axis torque and the actual applied torque ($\Delta\tau$). The M/G control system performs the function of torque regulation about a desired set point. To decouple the functions of attitude control and energy storage (provide a subset of the CARES functions), the torque set point is made equal to zero. Note that the regulators and meters consist of pulse width modulated (PWM) inverters and permanent magnet (PM) motor/generators.

SPIN AXIS CONTROL LOOP



The system can be implemented using a variety of configurations. Minimization of interactions between the drives and the suspension, however, suggests the use of ironless PM motor/generators such as those shown. The PM configuration requires the feedback of rotor position to the PWM in a minor loop. The PWM configuration should be implemented with output current used as the control variable, since this control variable is convenient for both the attitude control system ($I \propto T$) and bus voltage control loops.

IRONLESS MOTOR/GENERATOR CONCEPTS

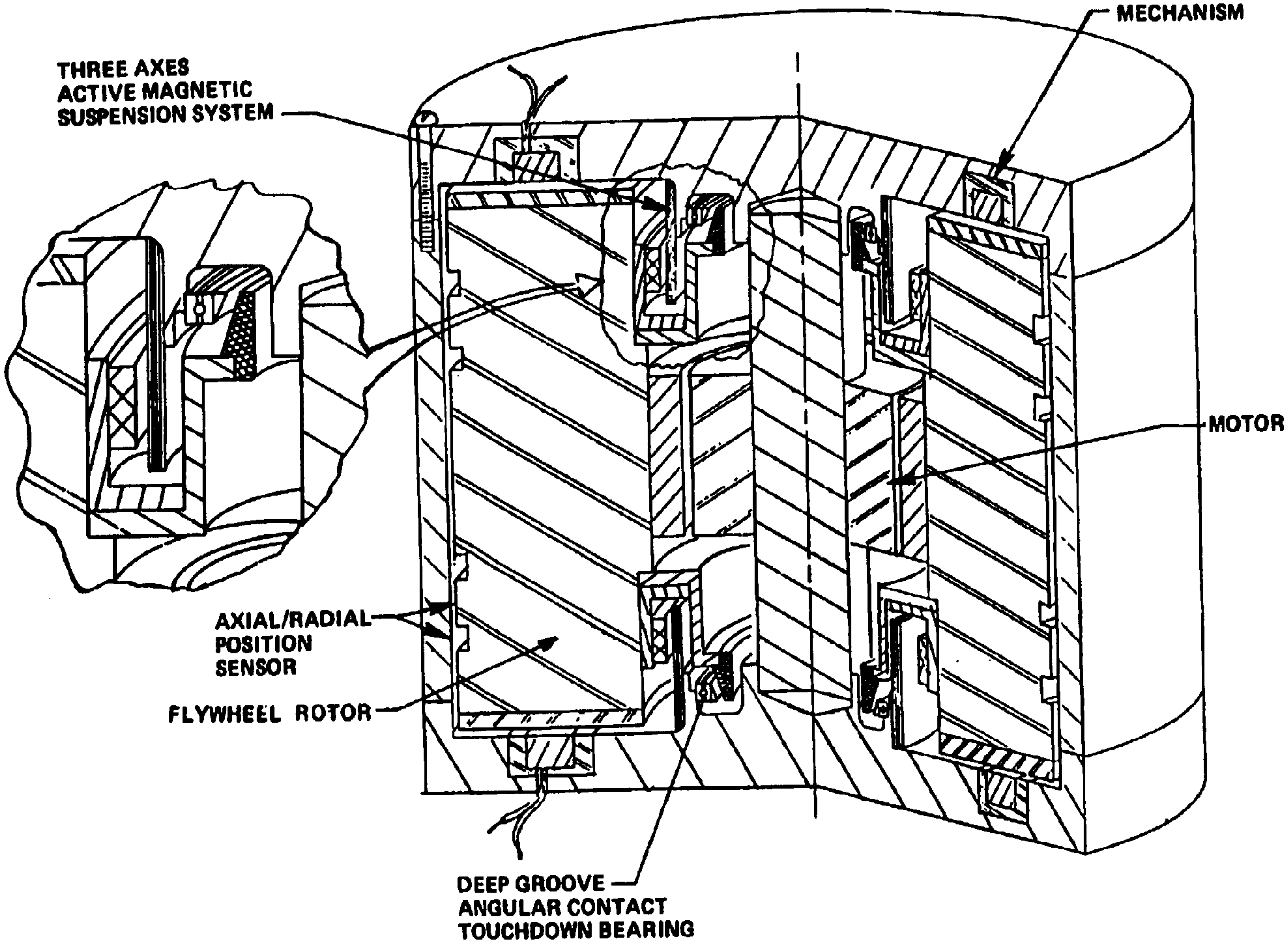


There are several advantages of the CARES approach over conventional approaches. First, storage weight and volume are greatly reduced; second, storage life is substantially extended; third, and perhaps most important, the extremely high potential efficiencies can have substantial impact on satellite PV arrays and radiators.

SYSTEM COMPARISON

FLYWHEEL SYSTEM 75% DOD		FLYWHEEL SYSTEM 50% DOD		CONVENTIONAL 2 YEAR		CONVENTIONAL 5 YEAR	
ROTORS (2)	58.6 lb	ROTORS (2)	88 lb	BATTERIES	158 lb	BATTERIES	252 lb
MOTOR/GEN	10 lb	MOTOR/GEN (2)	10 lb	IRU	37.2 lb	IRU	37.2 lb
MAG BEARINGS	13.3 lb	MAG BEARINGS	20 lb	REACTION WHEELS (4)	79.2 lb	REACTION WHEELS	79.2 lb
GYRO (1)	3 lb	GYRO (1)	3 lb				
STRUCTURE	17 lb	STRUCTURE	23 lb				
101.9 lb		144 lb		274 lb		368.4 lb	
1192 in.^{3}		1792 in.^{3}		4282 in.^{3}		6140 in.^{3}	

MAGNETIC BEARING FLYWHEEL ASSEMBLY



CONCLUSION

Over the last ten years, the government has funded the design and development of a large number of composite flywheel rotors. This research, which received early support from NSF-RAND, has recently been funded almost exclusively by DOE and its predecessor, ERDA. This program has resulted in the development and test of many composite rotor systems. In addition to the DOE developed systems, a number of promising composite systems exist, which DOE ruled out for consideration based on either high cost or unavailability. These systems include metal matrices such as boron/aluminum or silicon carbide/aluminum, together with more conventional composites such as boron/epoxy.

In recent years, a number of organizations, including CSDL, MIT, Cambion, Sperry, Aerospatiale, and Teldix have built and demonstrated magnetic bearings. These developments were enhanced or even made feasible by advances in permanent magnetic materials, improved magnetic iron, and new semiconductor concepts.

Advances in recent years in magnetics (e.g., samarium cobalt magnets) and power semiconductors (e.g., MOSFET's) have made possible very efficient, high-power-density power conversion systems. These new conversion systems allow for the design of flywheel systems which are expected to have significantly higher storage efficiencies than batteries or other storage technologies.

The above advances in component technology allow CARES systems to be designed for space applications ranging from small satellites to large space stations. Utilizing a CARES system will result in significant savings in overall spacecraft weight and complexity over more conventional approaches.

- SIGNIFICANT WEIGHT AND VOLUME REDUCTIONS ACHIEVED THROUGH THE USE OF ENERGY STORAGE FLYWHEELS
- ADDITIONAL SAVINGS DUE TO CONSOLIDATION OF CRITICAL FUNCTIONS
  - ENERGY STORAGE
  - ATTITUDE CONTROL
  - ATTITUDE REFERENCE
- KEY COMPONENT TECHNOLOGIES HAVE BEEN DEMONSTRATED
  - ROTOR
  - MAGNETIC SUSPENSION
  - MOTOR/GENERATOR
  - POWER CONVERSION

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