AEROSPACE APPLICATIONS OF MAGNETIC BEARINGS

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ABSTRACT

Magnetic bearings have traditionally been considered for use in aerospace applications only where performance advantages have been the primary, if not only, consideration. Conventional wisdom has been that magnetic bearings have certain performance advantages which must be traded off against increased weight, volume, electric power consumption, and system complexity. These perceptions have hampered the use of magnetic bearings in many aerospace applications because weight, volume, and power are almost always primary considerations.

This paper will review progress on several active aerospace magnetic bearing programs at SatCon Technology Corporation. The magnetic bearing programs at SatCon cover a broad spectrum of applications including:

(1) a magnetically-suspended spacecraft integrated power and attitude control system (IPACS)
(2) a magnetically-suspended momentum wheel
(3) magnetic bearings for the gas generator rotor of a turboshaft engine
(4) a vibration-attenuating magnetic bearing system for an airborne telescope
(5) magnetic bearings for the compressor of a space-rated heat pump system
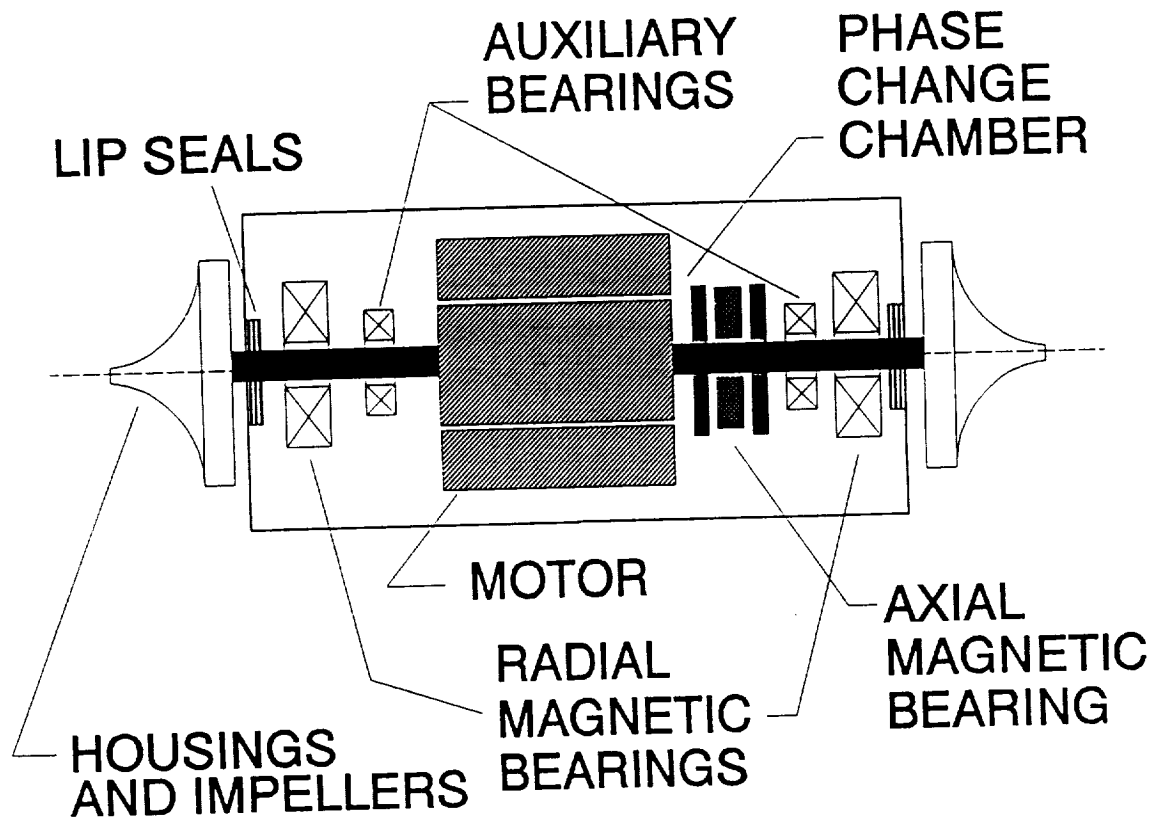
The emphasis of these programs is to develop magnetic bearing technologies to the point where magnetic bearings can be truly useful, reliable, and well tested components for the aerospace community.

- SatCon has three current programs involving magnetic bearings, two in fabrication/testing stage, one in final design.

- Usual disadvantages:

  More expensive hardware

  Complicated controller

  Backup bearings

- Usual advantages of magnetic bearings:

  Vibration control

  No lubrication

  High speed

  No wear
      Extended life
      Less heat

THE FREON COMPRESSOR (PHASE II, SDIO)

- Rationale: Heat pump/thermal management system shown to be more efficient in reducing mass and radiation area.

- Goal: Develop with Mainstream Engineering, integrated freon heat pump capable of 5 year lifetime.

- Sensors, actuators, and auxiliary bearings integrated in a small package with a high-speed induction motor.

- Design Specifications:

Operating speed:	24 krpm
Rotor mass:	≈ 5 kg
Overall mass:	15 kg
Required motor output:	7 hp
Rotor 1st flexible mode	> 500 Hz
Environmental conditions:	
Temperature Range:	230 K - 400 K

Magnetic bearing loads up to 2 g's + Compressor Axial load

Components must operate in Freon 113

- **Schematic of system:**

AUXILIARY BEARINGS

PHASE CHANGE CHAMBER

LIP SEALS

MOTOR

RADIAL MAGNETIC BEARINGS

AXIAL MAGNETIC BEARING

HOUSINGS AND IMPELLERS

Freon Compressor Schematic

- Two radial bearings and one axial bearing.

- Bearing geometry dictated by flexural consideration.

BEARING ACTUATOR

Radial

- Real time force control requirements: 2 g of shaft acceleration for both the radial and thrust systems and capability of the thrust bearing to compensate the thrust load from the compressor (450 N)

- Separated bias and control coils: reduces power amplifier number to four and single bias supply.
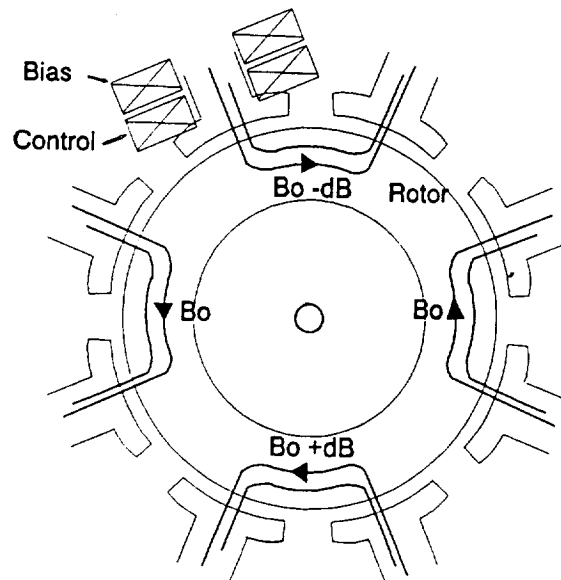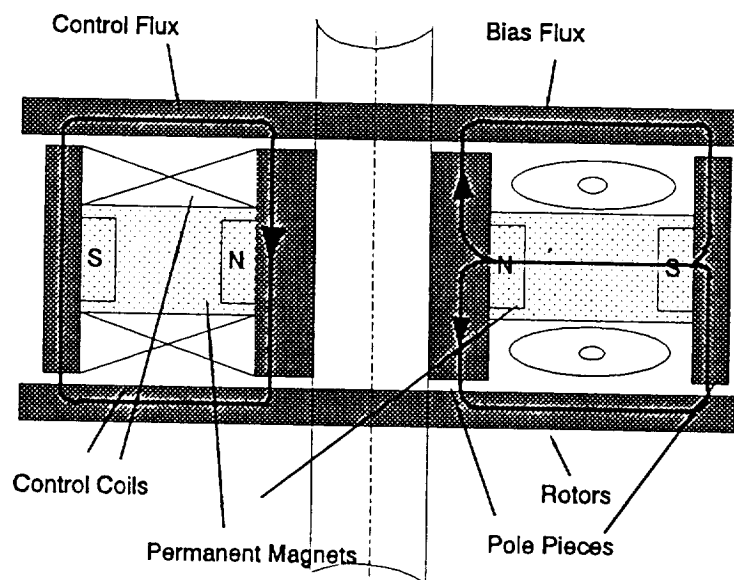

Magnetic configuration of eight pole radial bearing showing flux paths and coil arrangement.
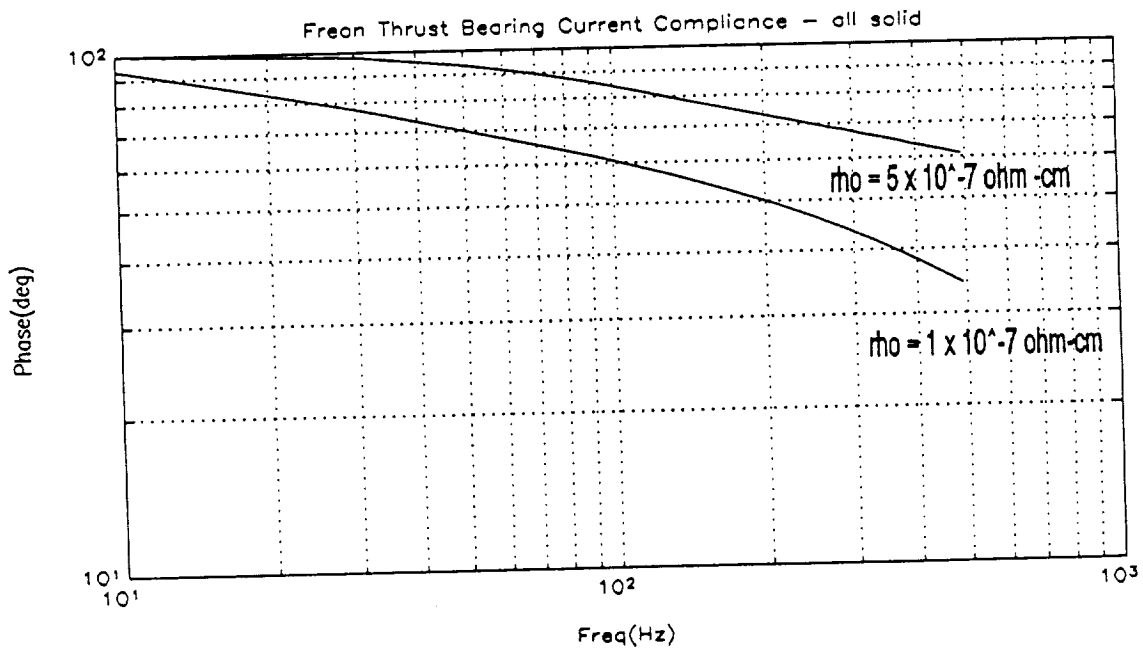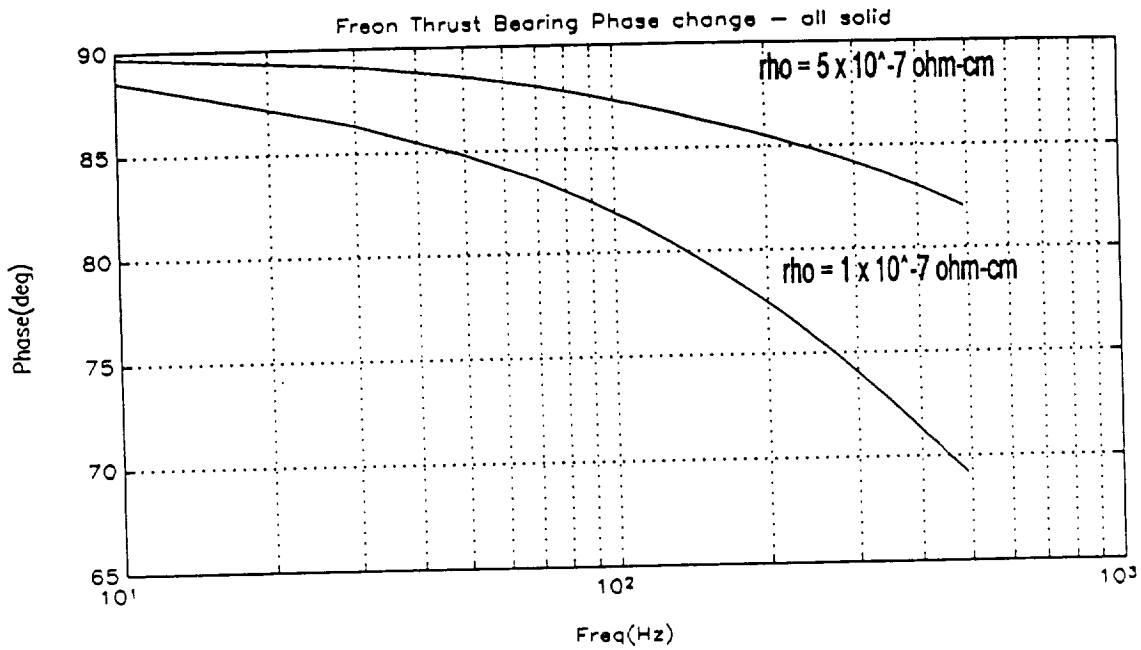
Copper
end turns

Laminated Rotor

Insulation

Laminated Rotor
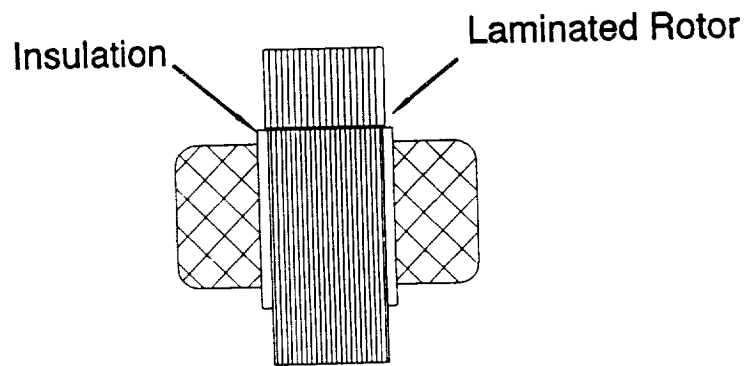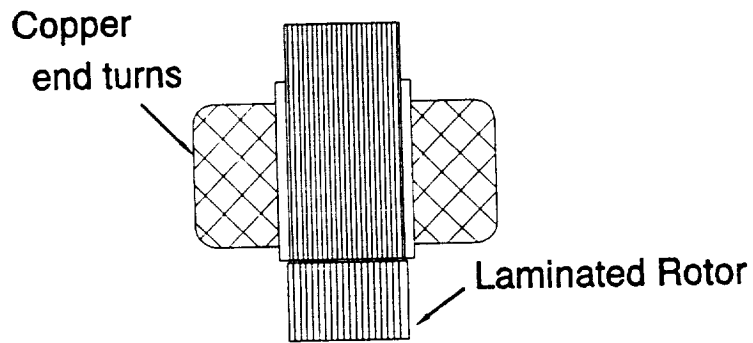
Radial actuator side view to scale.

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Thrust

- Require 450 N bi-directional with ±2g superimposed

- Startup requirement mandates ramping capability under closed loop control.

- Geometry: dual rotor/single geometry (fewer components and less V-A capability but greater mass)

- P-M Magnetic Bias.

- Un-laminated. Core losses acceptable.

Permanent magnet biased geometry for thrust actuator with flux paths indicated.

Freon Thrust Bearing Phase change — all solid

rho = 5 x 10^-7 ohm-cm

rho = 1 x 10^-7 ohm-cm

Phase(deg)

Freq(Hz)

Freon Thrust Bearing Current Compliance — all solid

rho = 5 x 10^-7 ohm-cm

rho = 1 x 10^-7 ohm-cm

Phase(deg)

Freq(Hz)

Phase and compliance as a function of frequency for axial actuator. The two curves are for different core resistivities.

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- Precision journals on center shaft as targets for the radial inductive sensors.

- Unit is designed to run in zero-g; it must be tested with the shaft oriented both vertically and horizontally.

- Auxiliary Bearings:

  - Momentary support during failures and startup.

  - Two sets of duplex angular contact bearings integrated into the end housings and pre-loaded.

  - Unlubricated, since incompatible with Freon 113
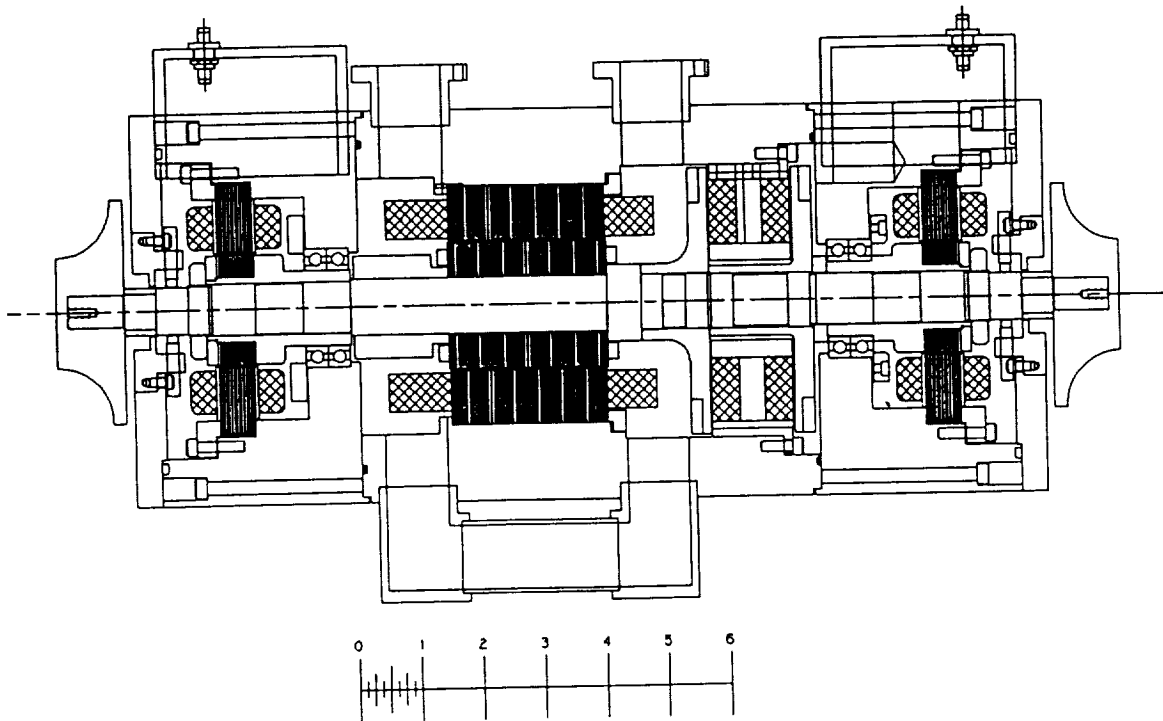
Complete compressor showing positions of magnetic bearing actuators.

Status

- Thrust loop has been closed.

- One directional radial loop shakedown underway, non-zero bias from complementary actuators complicates testing.

- Compressor impellers not yet designed.

MOMENTUM WHEEL (SBIR PHASE II, NASA, GODDARD)

- Rationale: Vibrations of momentum wheel bearings in spacecraft degrade instrument and pointing performance.

- Standard Approaches: Design structure to separate modal from vibrational frequencies, minimize residual mass imbalance, passive isolators.

- Alternately: Use magnetic bearings to eliminate vibrations and mass imbalance by use of bearings with programmable compliance.

- Goals: Design and fabricate magnetically suspended momentum wheel and test for operation in 1g ground experiment.

SPECIFICATIONS

Base line TELDIX DR-68 momentum wheel

|	
Momentum	68 Nms (92.2 ft-lb) at 6000 rpm
Speed range	3500 - 6600 rpm
Inertia	0.1082 kgm^2
Run Up time	19 min (1140 sec)
T_{min} (designed)	0.06 Nm
T_{min} (measured)	0.092 Nm

Critical design criteria for SatCon Momentum Wheel

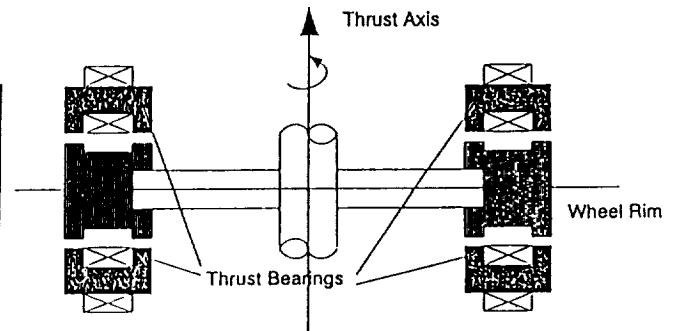|	
Nominal op. speed	6000 rpm
Nominal Stored Momentum	68 Nms at 6000 rpm
Motor Peak Torque	0.1 Nm
Maximum bus power available	120 W
Torque for precessing wheel	0.57 Nm

DESIGN ISSUES AND QUALITATIVE GUIDELINES

- Must operate in 1 g

- Spins about inertial axis

- Concentrate mass at periphery to maximize inertial

- Touchdown bearings fabricated with conventional technology

- Magnetics with overcapacity in terms of forcing and torquing

- Actuators to utilize large lever arms for precessional torque
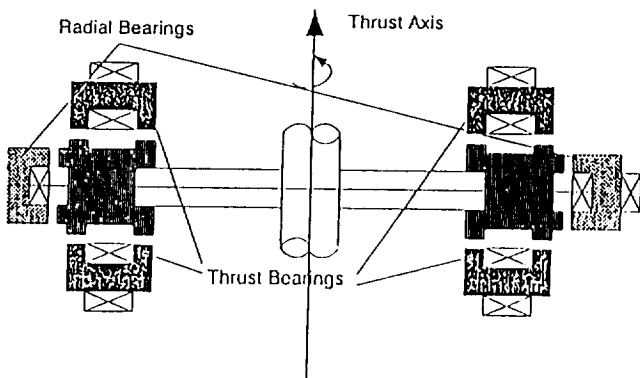
- Sensor gaps measured at pole faces (collocated).

Thrust Axis

Radial Magnetic Bearings

Wheel Rim
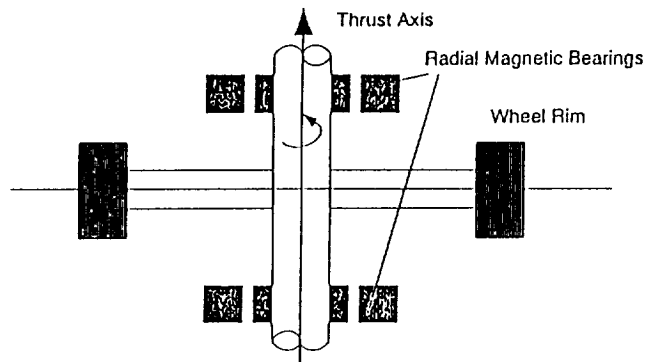
Active Radial Control. Passive Thrust Control

OPTION A

Thrust Axis

Wheel Rim

Thrust Bearings

Active Thrust Control. Passive Radial Control

OPTION B

Radial Bearings

Thrust Axis

Thrust Bearings

OPTION C

Thrust Axis

Radial Magnetic Bearings

Thrust Bearings
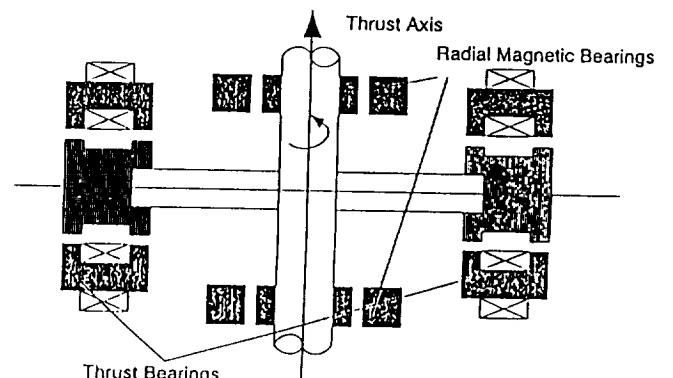
OPTION D

Alternate Magnetic Bearing Actuator Configurations in Momentum Wheel.

ACTUATOR GEOMETRY

- Four bearings at periphery for torques (τ_x, τ_y, and forces F_z)

- Radial bearing at hub (F_x, F_y)

- Non-laminated.

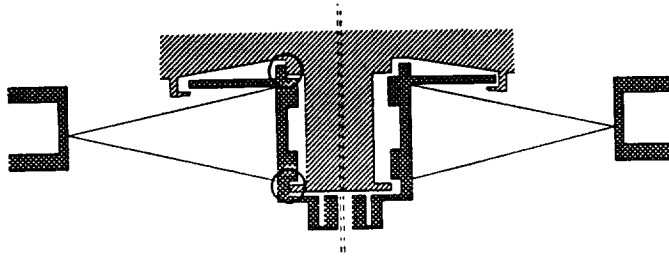- Drive motor at center of hub

MECHANICAL DESIGN

- Rotor

- Housing structure
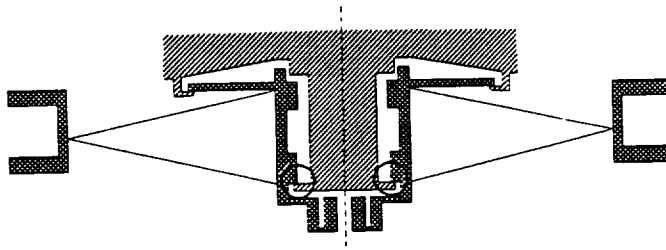
- Inertial rings

- Bearing actuators

- Motor drive

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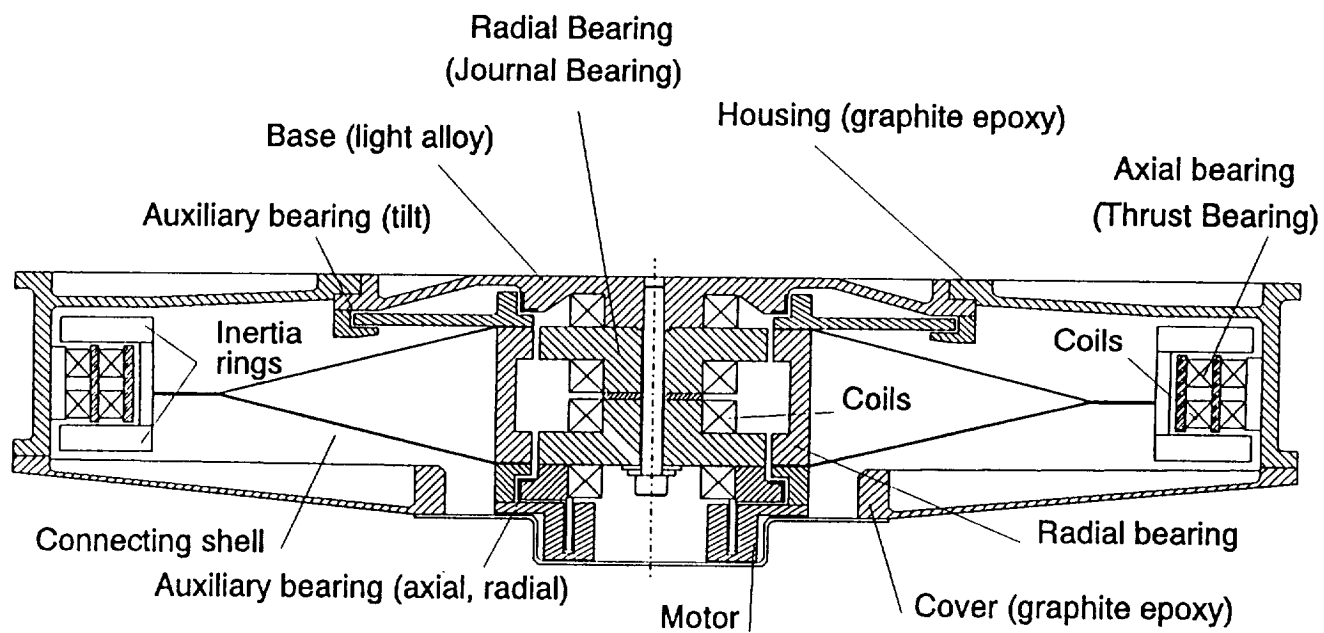
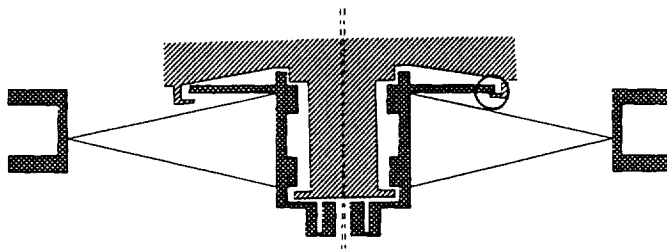Thrust and radial bearing placement in the low noise momentum wheel design

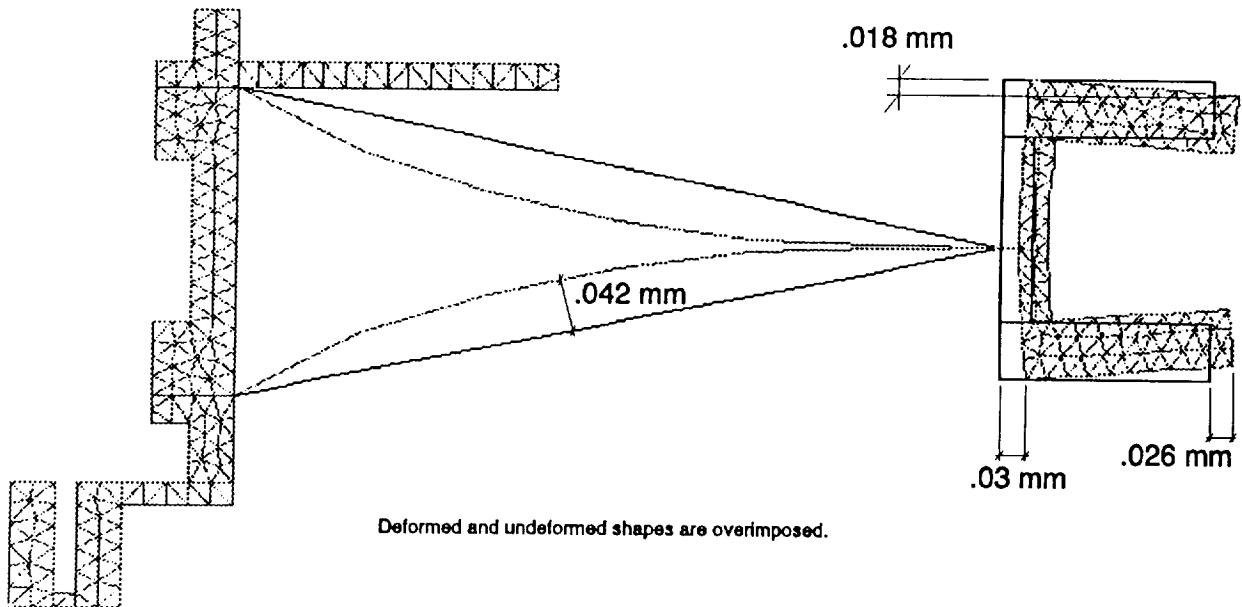- **Touchdown surfaces:**

Radial Touchdown

Axial Touchdown

Tilt Touchdown

Auxiliary Bearing Operation
- Use 'Vespel' (DuPont) - dimensional stability, low friction, high PV limit.

- **Stress loading at 6000 RPM:**

.018 mm

.042 mm

.03 mm
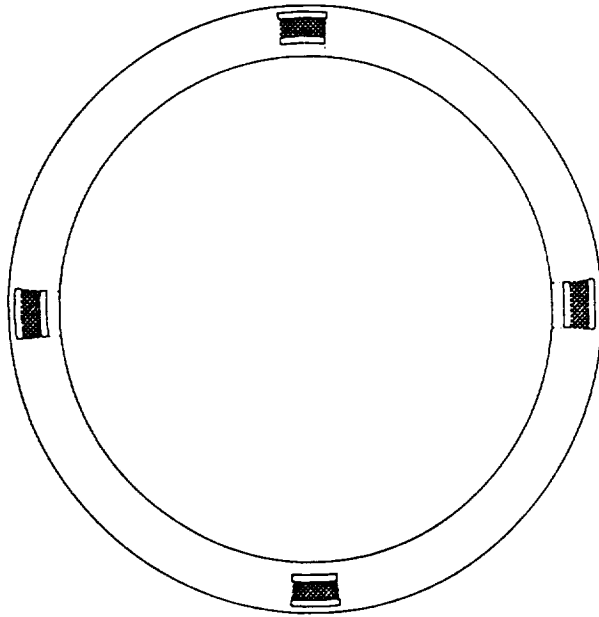
.026 mm

Deformed and undeformed shapes are overimposed.

Deformation of the Rotor Under Centrifugal Loading
- **Thrust Sensors Operate in Pairs to Reject Common Mode Signals**

MAGNETICS DESIGN

- ## Axial Bearing: 80 N, maximum, 0.6 N-m

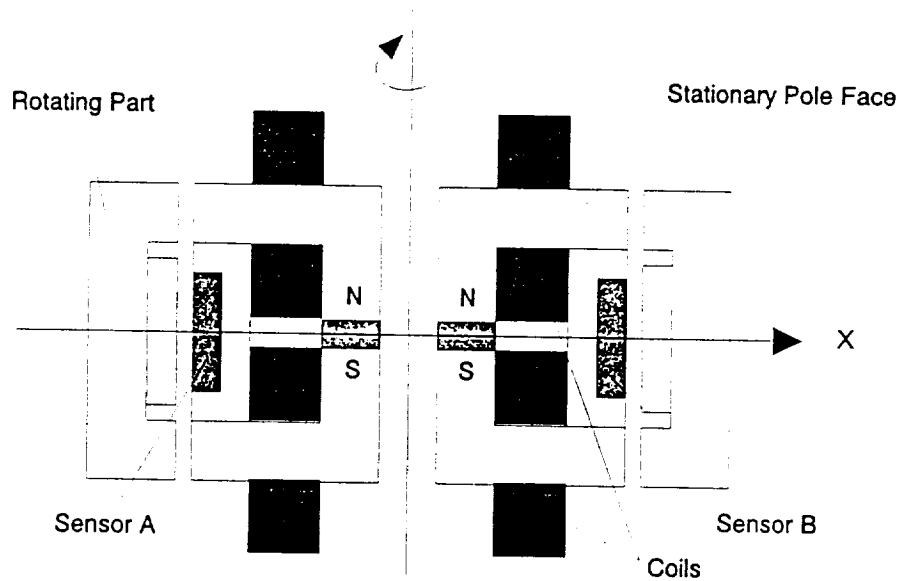Pole Pieces

Coils

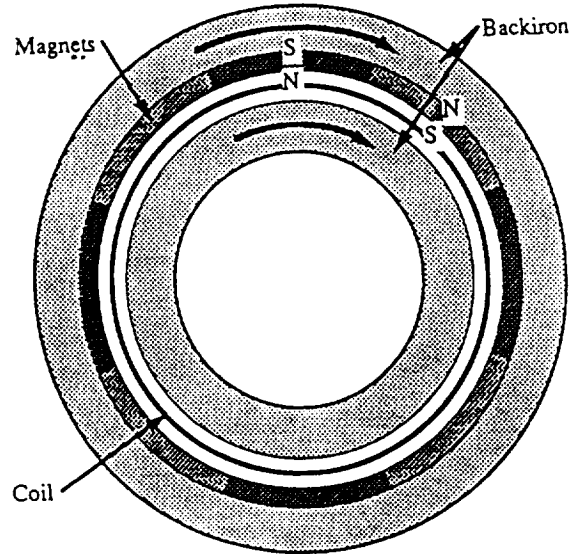Momentum Wheel
Backiron

Permanent
Magnet
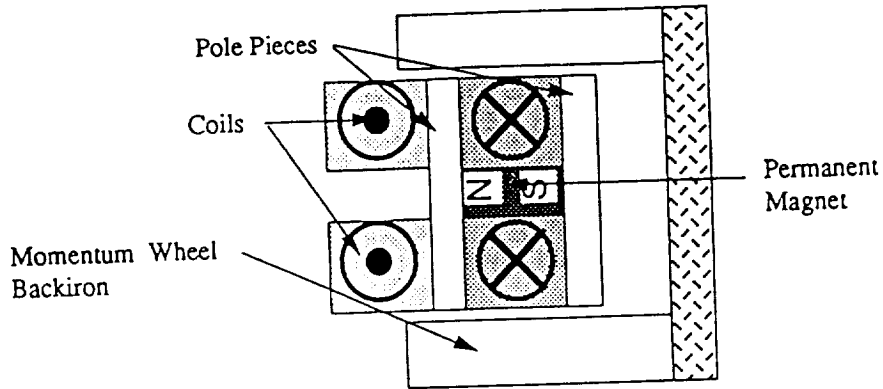
Thrust Actuator Configuration

Thrust Actuator Location

- Radial Bearing Actuator: 80 N max, Bias at .26 T, 400 A-T/coil, Tandem Sets of Four Poles

Rotating Part   Stationary Pole Face

N   N

S   S   X

Sensor A   Sensor B

Coils

Radial bearing gap measurement with 2 sensor heads

- **Torque Motor: Lorentz Force, 0.1 N/m, 3-phase, Ironless Armature, 4-pole**

Torque Motor Configuration

CONTROLLER IMPLEMENTATION

- **Designed to compensate for mass unbalance (rotation around mass center vs. geometric center)**

- **Elimination of synchronous disturbances**

	TELDIX DR-68 Momentum Wheel	SatCon Low Vibration Momentum Wheel
Total Mass	8 Kg	8.3 Kg
Dimensions	350 mm Diameter 120 mm Height	384 mm Diameter 88 mm Height
Steady State Power	< 26.5 Watts	< 10 Watts in 1g < 5 Watts in 0g
Maximum Wheel Precession Rate	-	0.03 rad/sec in 1g 0.08 rad/sec in 0g (min required 7.6×10^{-3})
Torque Vibration at GOES spacecraft mass center	Forces at 6000rpm with 0.75 gm cm residual static imbalance F = 4.7 N Measured at 6000rpm Tx = 7.46 Nm Ty = 6.83 Nm Tz = 7.46 Nm	Forces at 6600 rpm assuming 0.75 gm cm static imbalance F = 0.27 N Simulated including measurement error Tx=Ty=Tz < 0.7 Nm

MAGNETICALLY-SUSPENDED SPACECRAFT INTEGRATED POWER AND ATTITUDE CONTROL SYSTEM (SBIR PHASE II, NASA, MARSHALL).

• Rationale:

Spacecraft utilizing solar power generation use batteries as energy storage elements.

Flywheel Storage: Potentially longer operational life-time, lower maintenance requirements, higher energy densities, and peak power capability.
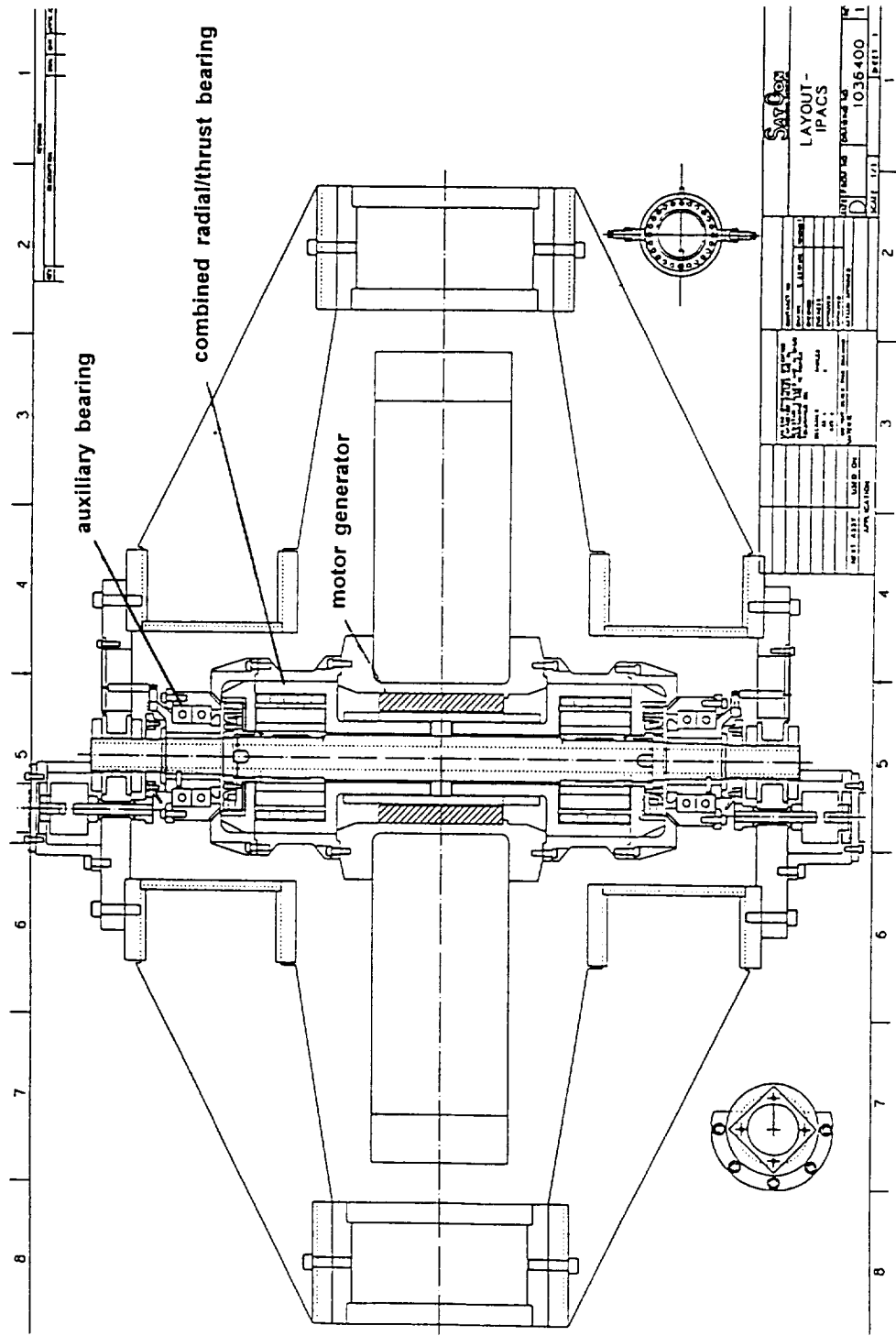
• Goal:

Integration of all current technology advances into working model.

Design, build, and evaluate system capable of 2 kW-hr at 40 W-hr/kg and 2 kW and charge/discharge efficiency greater than 85% all in 1 g.

Schematic of Fabricated Device:
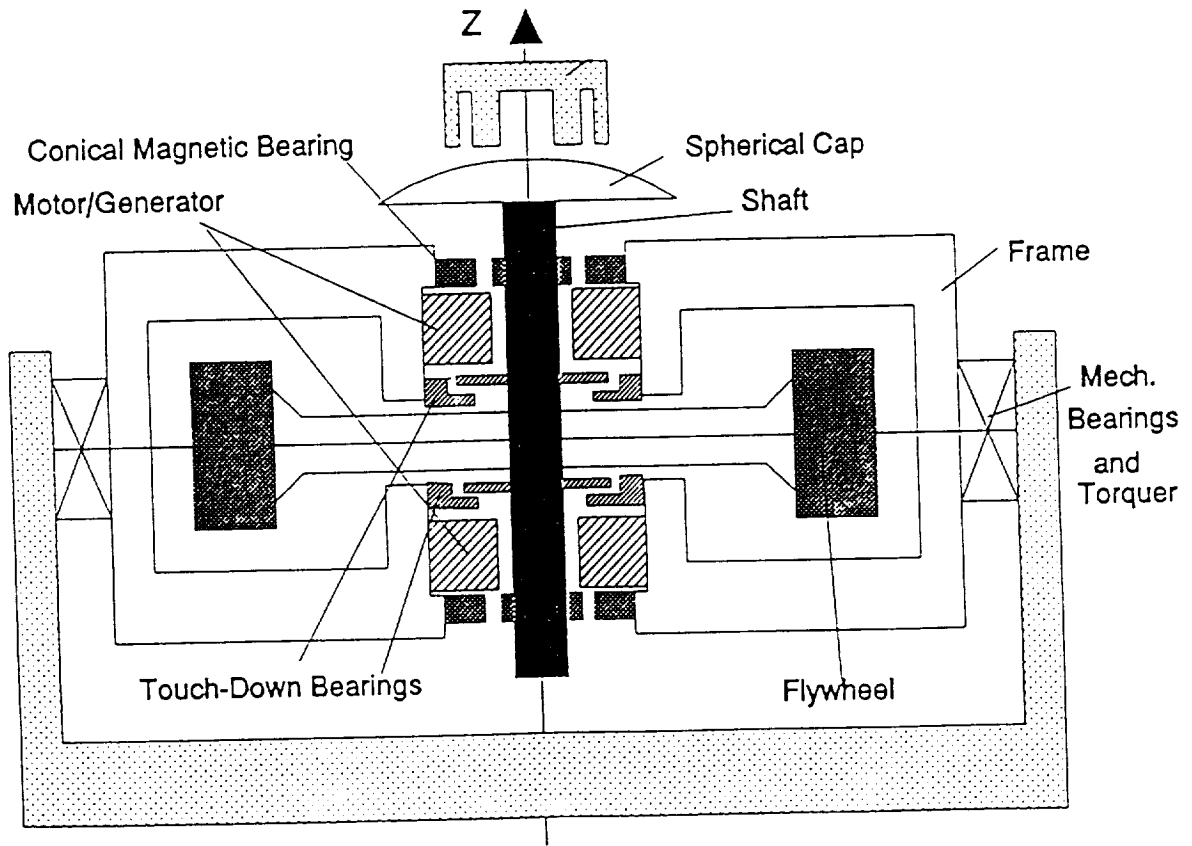
- **Actual Geometry:**

- **Status:**

  - **Assembly complete**

  - **Ready for testing**

  - **Instrumentation in progress**