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A Spaceflight Magnetic Bearing Equipped Optical Chopper With Six-Axis Active Control

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ABSTRACT

This paper describes the development of an ETU (Engineering Test Unit) rotary optical chopper with magnetic bearings. An ETU is required to be both flight-like, nearly identical to a flight unit without the need for material certifications, and demonstrate structural and performance integrity. A prototype breadboard design previously demonstrated the feasibility of meeting flight performance requirements using magnetic bearings. The chopper mechanism is a critical component of the High Resolution Dynamics Limb Sounder (HIRDLS) which will be flown on EOS-CHEM (Earth Observing System-Chemistry).

Particularly noteworthy are the science requirements which demand high precision positioning and minimal power consumption along with full redundancy of coils and sensors in a miniature, lightweight package. The magnetic bearings are unique in their pole design to minimize parasitic losses and utilize collocated optical sensing. The motor is of an unusual disk-type ironless stator design.

The ETU design has evolved from the breadboard design. A number of improvements have been incorporated into the ETU design. Active thrust control has been added along with changes to improve sensor stability, motor efficiency, and touchdown and launch survivability. It was necessary to do all this while simultaneously reducing the mechanism volume. Flight-like electronics utilize a DSP (Digital Signal Processor) and contain all sensor electronics and drivers on a single five inch by nine inch circuit board.

Performance test results are reported including magnetic bearing and motor rotational losses.

INTRODUCTION

A breadboard rotary optical chopper was designed to meet preliminary performance requirements for the HIRDLS instrument prior to acquiring knowledge on it's mechanical interface. This magnetic bearing equipped mechanism successfully demonstrated the feasibility of meeting these requirements. The mechanism specifications were particularly demanding with regards to volume, mass, and power along with the necessity for full redundancy of sensors and windings. Approval was given for the development of an ETU

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magnetic bearing optical chopper and its electronics. The ETU mechanism and electronics are flight-like, designed to be as similar to flight as practical using commercial parts only when flight qualifiable counterparts are available and without the need for material certifications. The ETU mechanism and electronics are in the process of being qualified by means of vibration, thermal/vacuum, and performance testing. They will be integrated into the ETU instrument and undergo compatibility and performance testing.

ETU MECHANISM REQUIREMENTS

The requirements list (Table I) has been reduced from overall instrument requirements to applicable mechanism performance and environmental requirements. While the performance requirements are direct or derived requirements based on the science observation objectives and instrument design, the environmental requirements reflect a conservative estimate of the environments for launch, ascent, spacecraft separation from the launch vehicle, orbit transition and on-orbit operations.

Although some requirements and interfaces were undefined during the breadboard development, simplified requirements were assumed for progress to be made while there was full knowledge of the risk of potential redesign of the ETU when those requirements were fully defined. Other requirements, such as allowable envelope, have changed since the breadboard design necessitating a significant redesign to shrink mechanical packaging.

ETU DESIGN CHANGES

Significant changes and improvements have been incorporated into the ETU. An active magnetic thrust bearing and thrust axis sensor have been added. Touchdown bushings have been replaced by ball bearings. Design changes have been made to the motor to improve efficiency and reduce its volume. A separate commutation chopper has been eliminated with commutation now accomplished using the chopper blade. Sensor feedback has been incorporated to improve long-term stability affected by the radiation and thermal environment as well as IR diode degradation. The housing mechanical interface has been changed. More discussion will follow with regards to these changes.

DESCRIPTION

The magnetic bearing optical chopper mechanism spins a six-bladed chopper at 5,000 rpm to modulate incoming light. Refer to the cross section view (Figure 1) and note that it is a full scale drawing. The chopper blade is clamped to the shaft hub. Housing endcaps are removable, each of which contain ball bearings used to limit the shaft motion during inadvertent touchdown while spinning and under launch vibration. The bearings are held in place by Viton o-rings and elastomer sleeves used to provide damping. Radial motion is constrained by the front and rear bearings while axial motion is constrained only by the front bearing.

Table I - PRELIMINARY REQUIREMENTS FOR THE ROTARY CHOPPER

Environmental Conditions	
Vacuum	Operation in vacuum Operation in ambient air with degraded performance allowed
Gravity	1g operation in any orientation 0g operation on orbit
Mechanical loads (launch environment)	21 g (flight level sine burst at 20 Hz) 26 g (qualification level sine burst) 8 g peak (18-50 Hz sine sweep, 4 octave/minute sweep) 14.1 g-RMS (qualification random) 142.6 dB (flight acoustic, qualification level is 3dB higher)
On-orbit disturbance	0.015g while operating, disturbance frequency is TBD
Thermal	0°C to 40°C (flight level) -10°C to 50°C (qualification level)
Instantaneous power loss	Must not suffer degradation after instantaneous power loss
Performance	
Chopping frequency	500 Hz chopping (6 bladed chopper at 5000 rpm)
Synchronization Position & Velocity	To external clock
Velocity variation Repeatable Non-repeatable	0.001 (0.0005 goal) 0.0005 (0.0001 goal)
Runout Synchronous Asynchronous	<10 m (1 m goal) <1 m
Axial stability	20 m
Maximum blade lead/lag angle Repeatable Non-repeatable	(as synchronized to external clock) 1.5 mrad (0.25 goal) 0.5 (0.05 goal)
Blade flutter	<0.5 mrad
Maximum angualr blade tilt Repeatable synchronous Non-repeatable synchronous	1.5 mrad max (0.1 mrad goal) 0.5 mrad max (0.05 mrad goal)
Vibration exported to base	0.1N max (0.01N goal)
Anular momentum	TBD max
Radiation	10K rad total dose TBD high energy particles
Redundancy	All coils, sensors and electronics
Reliability	5 year operational life on orbit
Power	
Control electronics	10W max
Chopper assembly	<500mW max (<100mW goal) dissipated in radial and thrust bearings, sensors and motor
Dissipated in shaft	50mW (10mW goal)
Max fluctuation in shaft	10mW (1mW goal)

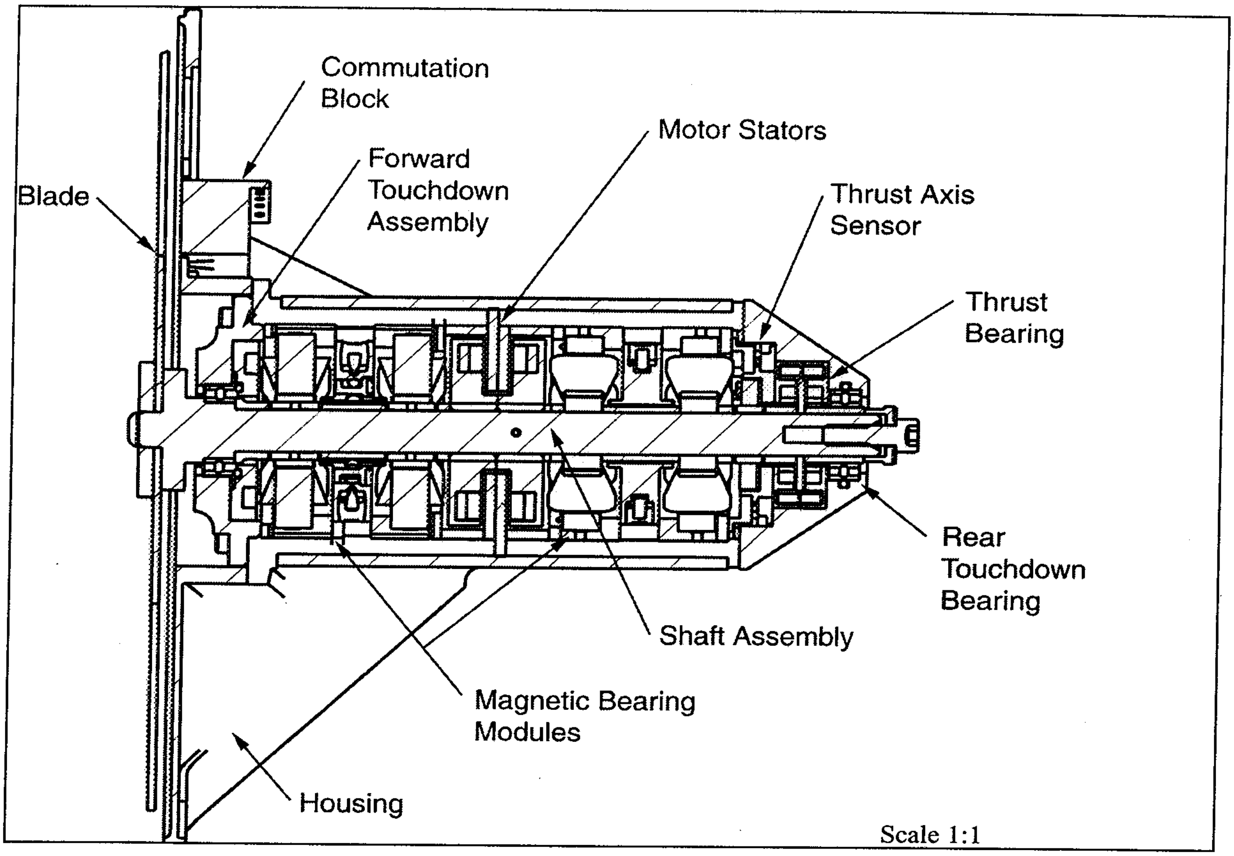

Figure 1 - HIRDLS ETU MAGNETIC BEARING CHOPPER

The following components are contained inside the housing: a front radial magnetic bearing module (which includes an integrated radial position sensor), a dual stator motor assembly, a rear radial magnetic bearing module, a thrust axis sensor, and a thrust magnetic bearing. Ribbon cables are connected at the outer diameters of the components and are recessed into grooves in the housing inner diameter. One hundred and six conductors exit behind the chopper blade and from the rear end cap. Each radial magnetic bearing module is composed of two laminated stators each with a non-laminated flux ring around its outer diameter, an optical sensor disk between the stators contained by the flux rings, and four samarium-cobalt magnets feeding bias flux to the flux rings. The magnetic bearing rotors, mounted on the rotating shaft, are also laminated. Two disk shaped motor stators are clamped by aluminum sleeves in the housing inner diameter. The motor rotor consists of two 12-pole samarium-cobalt ring magnets each with a Hiperco back-iron together which pass magnetic flux through the two stators. These ring magnet assemblies are encapsulated into a two section aluminum housing all of which rotates and is keyed with the mechanism shaft. The thrust disk is located near the end of the shaft within the thrust stator. A 4-40 screw and belleville washer at the end of the shaft clamps all the shaft components together. Likewise, both endcaps clamp all the appropriate housing components together. With the endcaps removed, the internal components can be slid out of the front of the housing as a unit.

The magnetic bearings provide for two axes of control near each end of the shaft. The fifth axis, the thrust axis, is actively controlled by the magnetic thrust bearing. The sixth axis, the rotational axis is controlled by means of a PLL (Phase-Locked Loop) using commutation signals for feedback. Commutation sensors located on the chopper shroud sense chopper blade transitions. The mechanism mounts to the instrument by three fasteners to a blade shroud which is kinematically supported.

MAGNETIC BEARINGS

The homopolar radial magnetic bearings are virtually unchanged as compared with the breadboard unit. Loss measurements prove the design to have outstanding rotational efficiency. This can be attributed to careful attention to the design to prevent flux variations around the rotors. Magnetostatic analysis called for a pole-to-pole gap of 0.25 mm (0.010 in) for this design. Printed circuit boards now serve as bearing module wire terminators and routers and significantly reduce bearing assembly time while improving system reliability.

Active thrust axis control is accomplished using the thrust magnetic bearing. The breadboard design lacked axial stiffness and could only operate in orientations with the shaft horizontal. Dual windings in the thrust bearing are used for primary and redundant operation. Two axially magnetized ring magnets provide the bias flux.

POSITION SENSORS

IR (infrared) diode/phototransistor pairs are used to sense x and y axes for each of the radial magnetic bearings. Both primary and redundant IR diode/phototransistor pairs are installed in a sensor housing which is located between two eight-pole stators forming a magnetic bearing module. Position detection is accomplished utilizing the cylindrical surface of each sensor sleeve to vary IR light blockage to the position phototransistors. A similar arrangement is used for thrust axis sensing. In this case, the flat surface of a thrust sensor disk is used to vary IR light blockage.

Feedback phototransistors, which were not part of the breadboard design, have been incorporated to maintain constant intensity of the IR diodes. The radial sensor housings make use of small mirrored surfaces machined on 0.078 inch pins to reflect some waste IR light to their respective feedback phototransistors. The thrust sensor geometry accomplishes this without the use of mirrored surfaces. This feedback scheme minimizes sensor drift caused by temperature variation and IR diode degradation due to aging and radiation exposure.

MOTOR

The motor is an ironless-stator brushless design similar to the breadboard motor. The stator windings are manufactured as a printed circuit board. Modifications to the breadboard design were made to improve the motor efficiency. The operational torque to drive the chopper mechanism is only a function of eddy-current losses when operated in a vacuum. Testing of the breadboard revealed that eddy-current losses were much more dominant in the motor than in than the magnetic bearings. For highest efficiency when operating in a vacuum, motor and magnetic bearing losses should be equal. Optimization of the design to minimize motor power consumption actually called for reducing the copper volume of the motor stators. This allowed combining both stators within a single rotor. Further eddy-current loss reduction has been accomplished by reducing the trace width from 0.008 inches to approximately 0.003 inches. Also, concentrating the radial traces to the center of each pole location has further improved efficiency by improving commutation accuracy. The number of poles have been reduced from sixteen to twelve in order to commutate off of the main chopper blade which has six blades. A separate commutation chopper has been eliminated thus saving precious volume.

These modifications have reduced motor power consumption in a vacuum by a factor of three with little effect upon motor power consumption during ambient pressure operation. Motor volume has been reduced by a factor of two.

TOUCHDOWN BEARINGS/LAUNCH SURVIVAL

The breadboard unit used Vespel bushings to protect the mechanism from damage in the event of a touchdown or when subjected to launch vibration. This configuration does not allow for a graceful touchdown due to inherent high friction. Also of concern is the generation of debris during touchdown or launch. The ETU uses touchdown ball bearings at each end of the housing. The forward bearing constrains radial and axial motion of the shaft while the aft bearing constrains only radial motion. Both bearings are held in place at each endcap through pre-compressed Viton o-rings and elastomer sleeves (uralane 5753) which provide damping. Total radial motion is constrained to $\pm$ 0.0035 inches and axial motion is constrained to $\pm$ 0.0065 inches.

ELECTRONICS AND CONTROL

Figure 2 is the functional block diagram of the electronics for the chopper control. There are five controllers for the magnetic bearing control and one controller for the motor velocity. The entire 6-axis controllers are being built on a 5" x 9" board using all military parts. The heart of the controllers is the SMJ320HFHM40 Digital Signal Processor (DSP) whose function is to handle all command and telemetry interfaces, compensation algorithms for the 6 controllers, and CPU health and safety. Also, the DSP will handle the levitation/spin sequence, touchdown sequence, and sensor calibration. The A/D and D/A conversions, multiplex channel selection, and CPU interrupt for I/O read /write are handled by a Field Programmable Gate Array (FPGA). The throughput rate including 16 analog I/O channel sampling and CPU computation time is expected to be 20 KHz.

The motor controller employs a Phase-Locked Loop (PLL) scheme with a lock frequency of 500 Hz. The closed loop bandwidth is about 6 Hz. Figure 3 shows the measured closed loop frequency response of the motor controller. Both the Pulse-Width Modulated (PWM) and linear drivers have been built and tested for the motor operation. The PWM motor

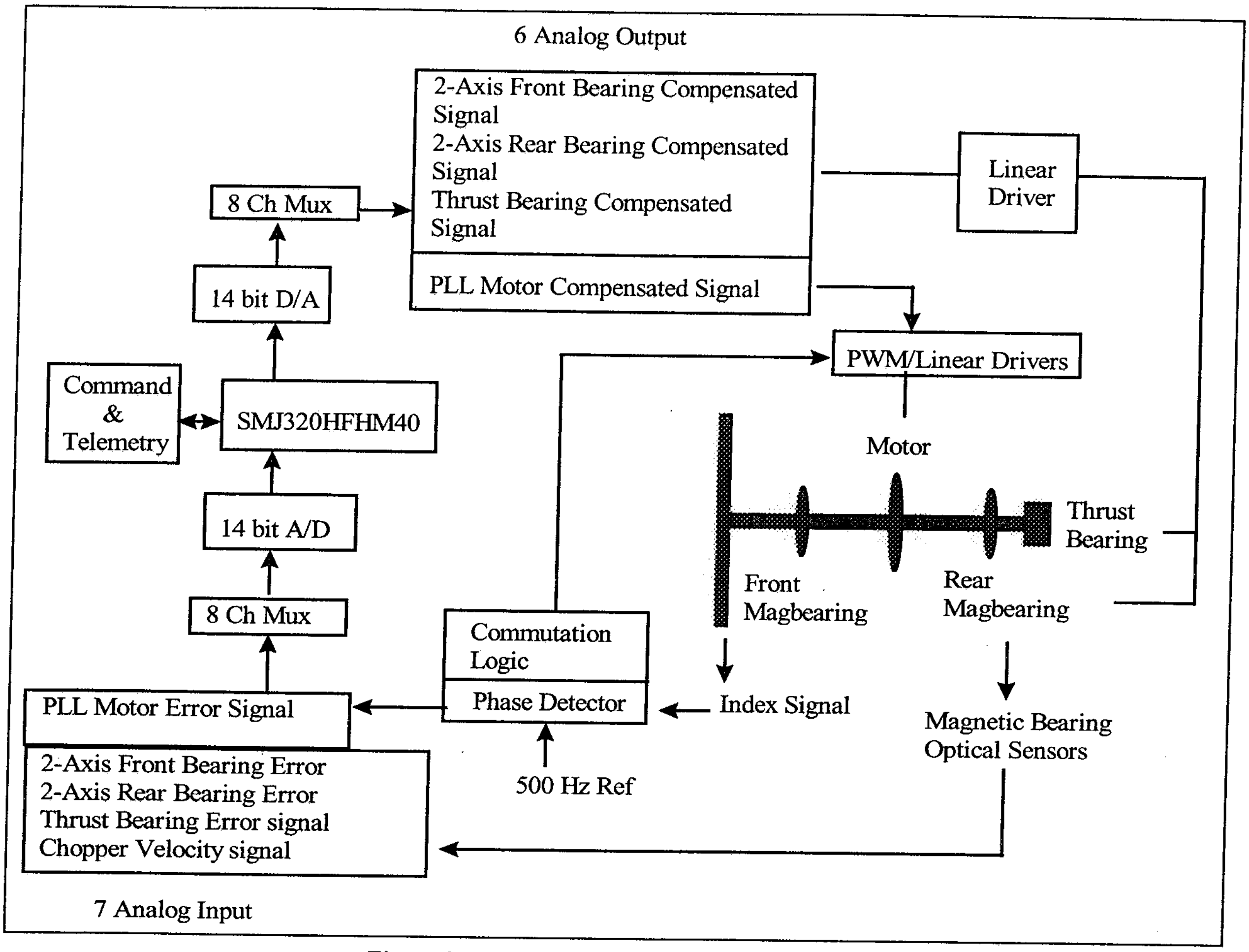

Figure 2 - FUNCTIONAL BLOCK DIAGRAM

drivers minimize power consumption, especially for the operation in air, however, they exhibit EMI problem and possibility of exciting the structural modes. The linear drivers are the push-pull type and therefore the high motor drive currents are returned to the power supply, not to the ground. This will keep the ground relatively quiet. Also, the absence of high frequency pulsing reduces the Electro-Magnetic Interference (EMI) concern. For these reasons, linear drivers were chosen for the final design. The phase detector, commutation logic, and all other necessary logic circuits necessary for the motor control are generated inside the FPGA.

The magnetic bearings are controlled using PID technique. The drivers for the magnetic bearings are also linear for the same reason as for the motor drivers. The measured closed loop bandwidth for each controller is between 100 and 200 Hz range. Achieving high closed loop bandwidth is crucial for high tolerance toward external disturbances such as the mass imbalance of the spinning components and disturbances from the spacecraft. Also, fast step and settle response is important for levitation to be achieved due to non-linearity caused by the bias flux. The frequency response of one of the magnetic bearing control loops is shown in Figure 4. The plot shows the position deviation of the shaft from its nominal position due to external disturbance applied at the housing mount. An important requirement is that the mechanism must meet its performance criteria while subjected to a 0.15g input disturbance. The projected disturbance rejection profile of the magnetic bearing system is depicted in Figure 5. Based on the projection, even at the most sensitive frequency (i.e., 50 ~ 70 Hz) the magnetic bearing controllers should withstand the required external disturbance level.

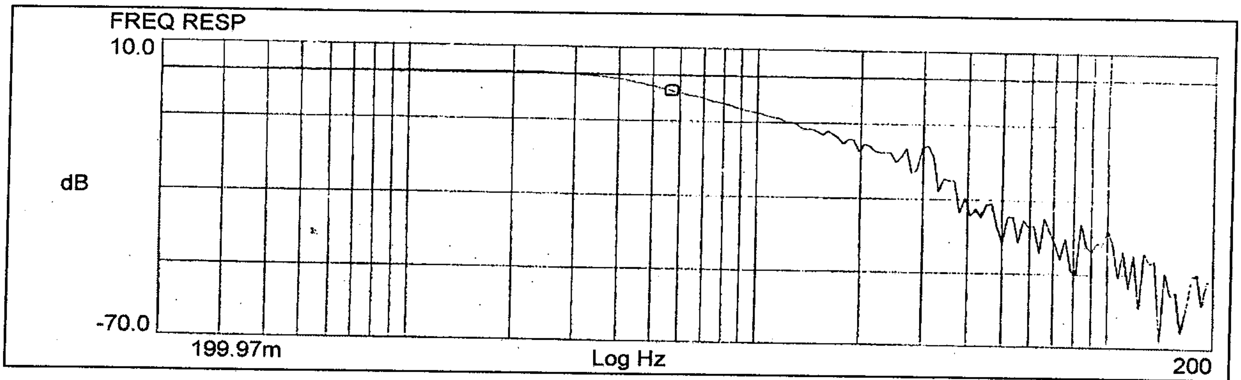

Figure 3 - FREQUENCY RESPONSE OF THE MOTOR CONTROLLER, CLOSED LOOP

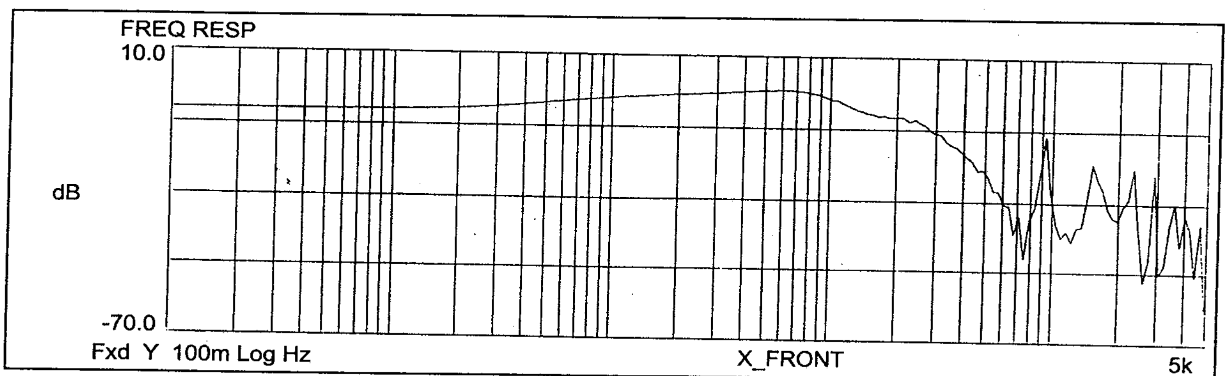

Figure 4 - FREQUENCY RESPONSE OF A RADIAL MAGNETIC BEARING AXIS, CLOSED LOOP

ROTATIONAL LOSSES

Predictions for rotational losses in the motor and magnetic bearings were made based upon measurements taken using the breadboard unit. Since the motor load consists of only magnetic bearing rotational losses, motor rotational losses, and aerodynamic losses, determining these losses is crucial for sizing the motor for maximum efficiency. Rotational losses consist primarily of eddy-current and hysteresis losses in magnetic bearing rotors, and only eddy-current losses in motor stators. Motor current measurements were made with a single stator energized. This measurement was repeated with one stator physically removed. Since motor parameters were known and verified with back-emf measurements, the eddy-current losses of the single removed stator was calculable based upon the change in current. These measurements were performed at 500 rpm with the chopper blade removed so that aerodynamic losses would be negligible. With the eddy-current losses of each stator known and aerodynamic losses considered to be zero, the remaining load to the motor is the magnetic bearing rotational loss. Since we were interested in losses at 5000 rpm and eddy-current losses are a function of velocity squared, a factor of 100 was included. Table II summarizes the rotational losses.

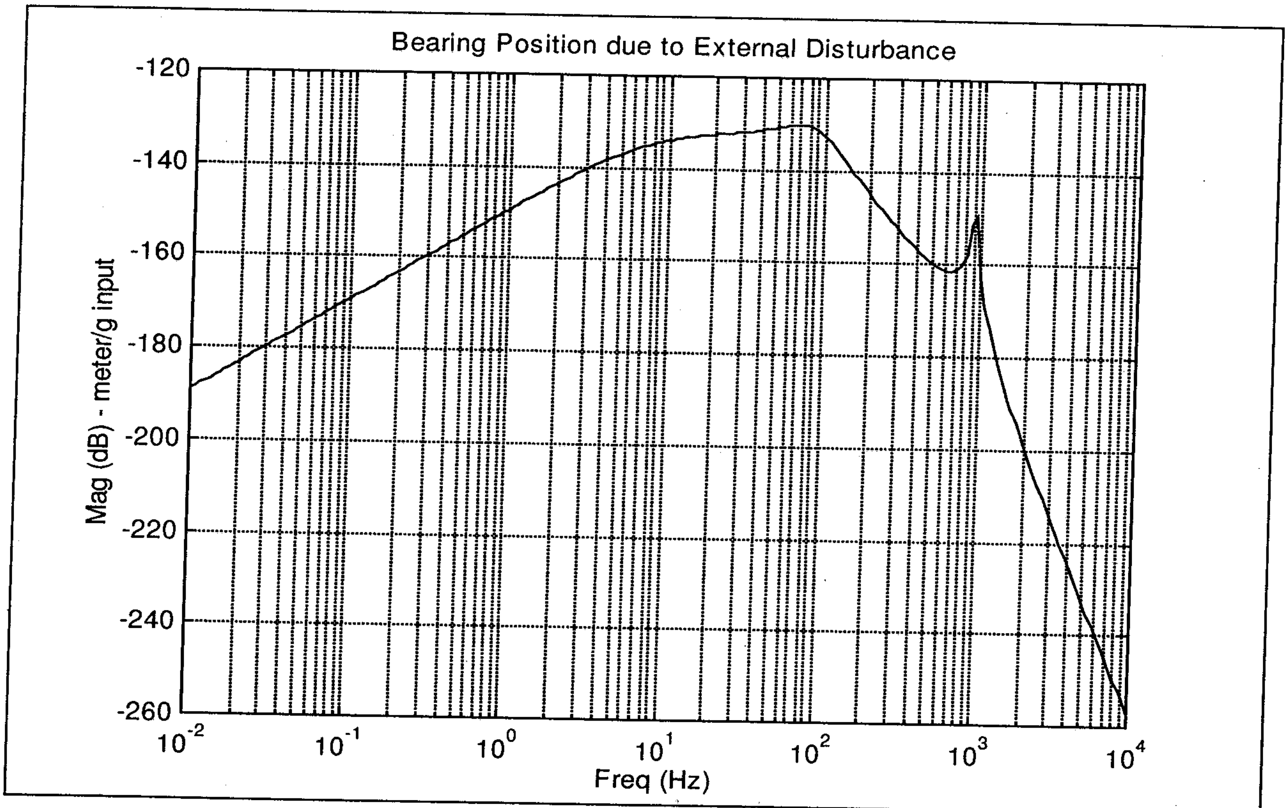

Figure 5 - MAGNETIC BEARING POSITION DUE TO EXTERNAL DISTURBANCE

Table II - MOTOR STATOR AND MAGNETIC BEARING ROTATIONAL LOSSES AT 5000 RPM

BREADBOARD MOTOR STATOR	238 mW
ETU MOTOR STATOR (PREDICTED)	44 mW
MAGNETIC BEARING	51 mW

PERFORMANCE AND ENVIRONMENTAL VERIFICATION

A critical process in the engineering efforts that comprised the design of the mechanism and electronics was to establish baseline performance and environmental requirements and plan for verification of those requirements. Standard environmental tests for space applications including vibration, thermal/vacuum, EMC (electromagnetic compatibility) and AC/DC magnetic field strength will be performed. Of particular concern are potential damage to the mechanism due to touchdown while spinning and overall mechanism life, so specific tests are planned in these two areas as well.

Mechanism stand-alone performance and environmental verification tests are described in Table III, below. Future mechanical tests and their associated level of assembly in planned chronological order are described in Table IV.

Table III – Currently Planned Mechanism Tests

Test	Configuration
Vacuum performance test	Mechanism at speed (5000 RPM) Radial and axial test directions
Qualification random vibration test	20-2000 Hz 14.1 g RMS Radial and axial test directions Mechanism power off
Touchdown test	Mechanism power on and at speed Radial and axial tests
Vacuum disturbance rejection test	0.015g disturbance input, 5-50Hz sweep Mechanism at speed Radial and axial tests
Thermal/vacuum performance test	-10°C to +50°C 4 hours soaks at temperature, 4 hour transitions 8 temperature cycles Mechanism at speed
Magnetic field	TBD Mechanism powered off and at speed
EMC	Mechanism and electronics Mechanism at speed TBD Levels
Life test	Mechanism at speed in vacuum and electronics 5 years continuous operation

Table IV – Future Mechanism Tests

Test	Parameters	Level of Assembly for Test
Sine burst test	26g each axis	Instrument level[1]
Sine sweep test	8g peak each axis 18-50 Hz at 4 octaves/minute	Instrument level[1]
Acoustic	142.6 dB	Spacecraft level[2]
Pyrotechnic shock	TBD	Spacecraft level[2]

Note: 1. ETU tests at the instrument level will be performed to qualification loads which are 25% greater than flight loads.
2. Spacecraft level tests are performed with the flight mechanism to flight loads.

CONCLUSION

A flight-like ETU magnetic bearing chopper and associated electronics have been designed and optimized and are in the process of being qualified. It is expected that both qualification and performance criteria will be met.

REFERENCES

Blumenstock, K., Lee, K., 1997. "A Magnetic Bearing Equipped Optical Chopper for a Spaceflight Radiometer," Proceedings of MAG '97, Alexandria, VA, pp. 185-195.

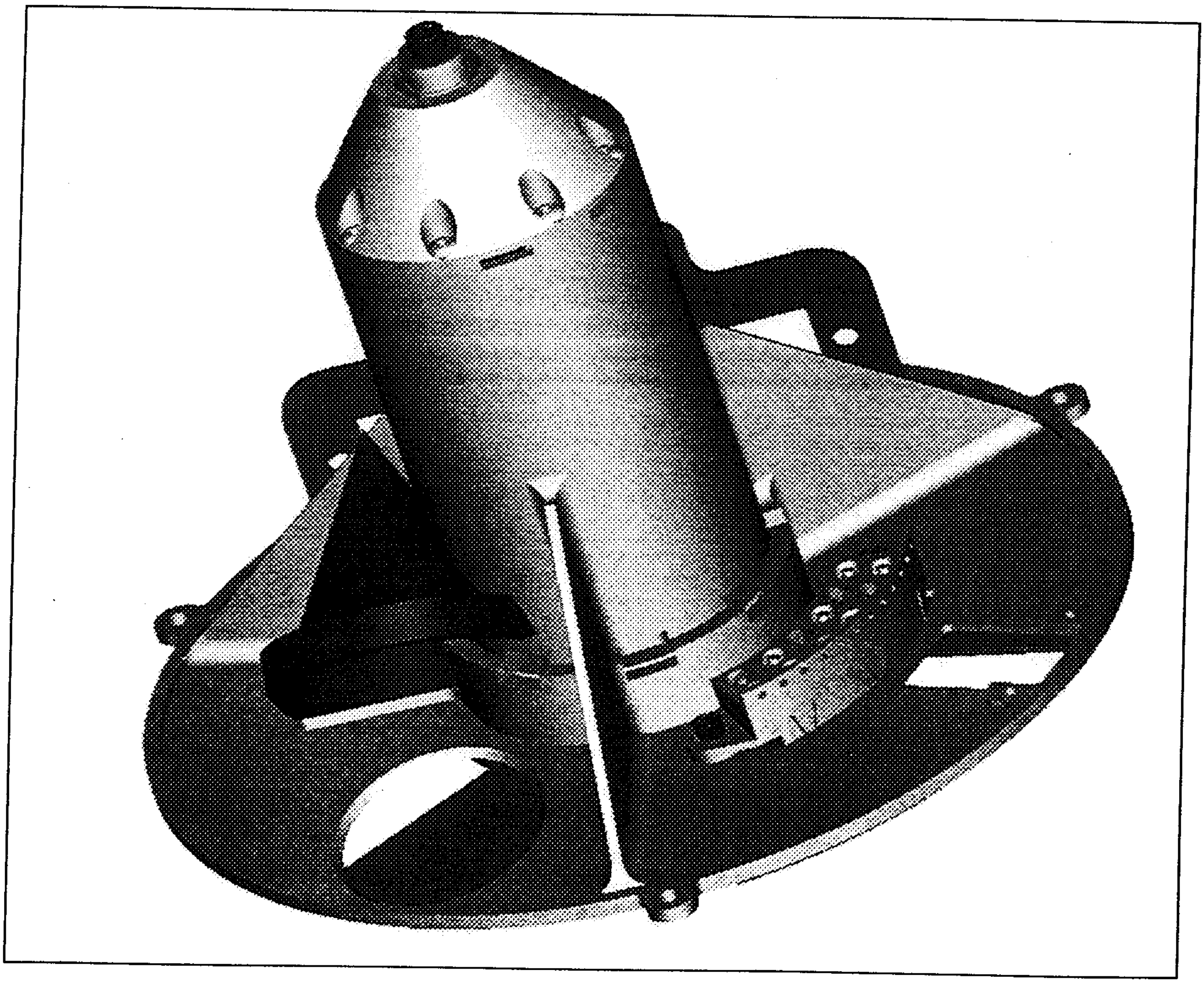

Figure 6 - HIRDLS ETU MAGNETIC BEARING CHOPPER

PATENT APPLICATION INFORMATION:

U.S. Patent Application Ser. No. 60/097,083
Filing Date: August 10, 1998
Title: Shaft Position Optical Scanner
Inventors: Ken Blumenstock, Claef F. Hakun and Clarence Johnson.
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