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ABSTRACT

The paper provides an overview of many areas of the flywheel magnetic suspension (MS) R&D being performed at the Texas A&M Vibration Control and Electromechanics Lab (TAMU-VCEL). This includes system response prediction, actuator optimization and redundancy, controller realizations and stages, sensor enhancements and backup bearing reliability.

INTRODUCTION

In 1997 the VCEL was tasked by NASA to develop a robust controller for magnetic suspension positioning of a 400 watt-hour flywheel battery spinning at 40,000 rpm. This effort resulted in a new approach to magnetic suspension control that has now been awarded a U.S. patent, and was subsequently utilized in the successful magnetic suspension of a 60,000 rpm flywheel. Although this accomplishment was remarkable, many other related areas require similar levels of innovation for practical implementation of a magnetic suspension for satellite and ISS (International Space Station) service. These areas include:

- lowering power loss due to eddy currents, hysteresis and ohmic losses in the magnetic bearing actuator
- providing for redundant (fail safe) operation
- minimizing susceptibility of position feedback sensors to switching power amplifier and adjacent sensor EMI, and to out-of-roundness and non-uniformity of the spinning target for the sensor.
- providing reliable means to protect the magnetic bearing actuators while operating the shaft on mechanical "catcher" bearings
- developing magnetic suspension control strategies that are effective in the presence of gyroscopic moments due to precessions applied to the flywheel housing for satellite attitude control service, i.e. a gyrostat.
- developing radiation-hardened hardware for controller realization
- developing effective means of thermal management for stationary and rotating sub-systems
- development of an expert system for detecting and correcting magnetic suspension anomalies and/or alerting the operators of an impending mal-function
- development of a new generation of magnetic suspension and rotordynamic design software including GUI's for ease of use by commercial flywheel vendors and NASA.

The remainder of this manuscript provides discussions of the TAMU-VCEL's response to these needs.

R&D AREAS

System Simulation and MS Control Laws

Classical rotordynamics relies on accurate models of passive components to describe the interaction forces between a spinning shaft and its suspension, that typically consists of ball, oil film, or foil bearings and seals. These components lack provision to adapt their force-based responses to the shaft's lateral and axial motion. In comparison to this, the MS may be designed to optimally stabilize the shaft's motion with minimum power loss. This benefit requires careful selection of a feedback control law that accounts for not only the structural responses of the shaft and flywheel housing but also of the sensor, power amplifier, MS actuator and controller I/O related dynamics. Thus the system model includes, structural, magnetic, electrical and optical (sensor) dynamics. For this reason classical "rotor" modes become influenced by all of the feedback system and structural dynamics.

Figure 1 shows a model of a flywheel battery whose housing is forced to precess by a motor, for the purpose of producing attitude control torques on a satellite. Table 1 shows the model parameter values. Figure 2 shows the response of the rotor to an imposed 11. degree/sec precession of the flywheel housing. The results show the shaft being forced into the catcher bearing by the gyroscopic torque and re-levitating when the imposed precession is removed. The MS control law typically has the stage-type structure shown in figure 3.

The pre-filtering stage is for anti-aliasing of the A/D operation and the exit filtering is to smooth the D/A output waveform. The input and output end coordinate transforms change the shaft positions and output force commands into forms that are required for the control strategy, and for the specific locations and directions of the force actuators, respectively. An example of the input transform is transformation from physical to modal coordinates. An example of the output transform is transformation of a desired control moment into the two forces of a couple. The "Digital Filters" stage is the heart of the controller and represents the central strategy of the control law, whether minimizing response to disturbance, achieving maximum stability, providing the highest efficiency or some combination of all of the above. This stage may be based on a state space or modal coordinate control strategy. Due to memory and speed limitations on rad-hardened controllers hardware, it is generally better to simplify (reduce the order of) the digital filter, while maintaining good stability, disturbance rejection and efficiency. The VCEL control strategy employs a unique extension of the nutation and precessional mode control laws presented by Ahrens (1, 2) and Okada (3), and results in significant reduction in runout and noise related voltages and currents. This approach is described in Palazzolo, et al. (4) and has been successfully employed with rigid and flexible hub flywheel rotors.

The feedback gain stage in figure 3 is utilized to optimize the control law, by on-site corrections for parameter uncertainties in the model. The "notch filter" stage in figure 3 provides a means to block the feedback of specific components of the sensor outputs. For instance shaft runout creates a false vibration so if conditions demand it, the runout components should be rejected from the feedback path.

Development of the control law requires an accurate model of all components in the system. This proceeds by building flexible shaft and housing models with finite elements, measuring transfer functions of sensor, controllers, power amplifiers and MS actuators, and assembling all feedback related states into a total system model.

Controller Hardware

The interdependence of the controller hardware and system simulation model becomes clear through considering

- the hardware is based on its effectiveness as demonstrated in the simulation model
- the algorithm must fit (execute) in the memory and speed limits of the controller board, i.e. each stage of a control takes execution time and the control algorithm programmed into it, therefore the entire stream of control actions must occur in less than one time sample. In addition, I/O filters for anti-aliasing and smoothing must be accounted for in the control law design.

The VCEL has employed the following digital signal processors (DSP) for MS control:

(1) Innovative Integration SB32-50 Mhz processor speed
(2) Innovative Integration SB67-150 Mhz processor speed

These DSP's provide versatility for developing and testing control algorithms and fine tuning them "on the fly" during actual operation of the flywheel. Their limitation is the risk incurred by employing non-rad hardened equipment in a space environment. The scarcity of high speed rad-hardened controller hardware has motivated the VCEL's efforts to develop non-DSP means to realize the controller algorithms. The three approaches being developed are:

- complete analog realization
- Field Programmable Gate Array (FPGA) based realization
- hybrid analog/FPGA realization

These approaches employ existing COTS rad-hardened devices. A challenge encountered is to provide the required shaft spin speed dependent control logic with analog or FPGA circuitry. Significant progress has been made in this area and added benefits have been discovered such as virtually zero "processing" time with analog circuitry.

Shaft Position Sensors

The good news about shaft sensors whether reluctance, eddy current, capacitance or optical is their generally high bandwidth. This is desirable in the closed loop control to improve phase margins for stability. The challenges for sensors are:

(a) high susceptibility to EMI from switching power amplifiers, except for optical sensors
(b) high susceptibility to shaft surface imperfections and non-uniformity around the

circumference of the shaft at the sensor locations, especially for optical sensors.
(c) DC drift due to thermal environment changes.

Tests at the VCEL shows that an eddy current position sensor near to a coil that is suddenly powered up with a PWM power amplifier (P.A). produces an output noise floor that suddenly jumps by about 30 dB. This phenomena may cause high current slew rate commands that saturate the power amplifiers. One fix for this is post filtering the P.A. output.

Optical sensors perform best with a highly polished target requiring a 5-10 micron uniformly polished surface. This surface quality is difficult to achieve typically yielding large runout. Our present recommendation is to utilize eddy current sensors and P.A. post filters for position feedback since they exhibit the least susceptibility to noise and shaft runout. A sensor rig as shown in figure 3 will be utilized for sensor development.

Fault Tolerance Actuators

Backup systems are very important for space application of flywheel batteries. Fault tolerance of critical components can provide a far less expensive substitute for entire module backup. Magnetic bearing actuators may experience coil or power amplifier failures, which would normally cause the shaft suspension to fail leading to operation on the mechanical catcher bearings. Fault tolerance actuators instead continue to provide uninterrupted levitation forces in spite of coil failures. This is accomplished for heteropolar MB's as described in Na and Palazzolo (5,6). Recent efforts in the VCEL have shown similar fault tolerant capabilities for homopolar magnetic bearings.

The six pole homopolar MB shown in figure 4 has shown an ability to produce invariant forces even with up to 4 of the poles failed. This MB is presently being built and its capabilities will be tested shortly.

Thermal Modeling

Limiting hot spot temperatures on the rotor and stator is a key objective of MS design for flywheel batteries. Losses at the magnetic bearings provide heat inputs to the magnetically suspended rotor, which cause high temperatures due to the vacuum environment.

Two-dimensional and 3D heat transfer models of the MB's and rotor provide valuable guidance for reducing rotor and stators hot spot temperatures. Figure 5 and 6 show a 3D thermal model of the rotor and 2D model of the MB, respectively. A practical application of the thermal model is its ability to identify tolerable levels of MB power loss in terms of the resulting temperatures on the shaft, hub and composite rim. For example, figure 5 is the steady state temperature response of a flywheel rotor due to 5 watt inputs at each MB.

Auxiliary B (Catcher Bearings)

The intrinsic redundancy in the MS is the mechanical backup bearings, which catch and suspend the shaft in the event of a complete MS failure. Operation on the catcher bearings (CB) excites transient vibration response that may be benign or severe leading to failure of the CB's and possibly the MB's. It follows that careful design of the CB's and their support system is a critical step in the MS design process. VCEL developed codes are utilized to predict forces, temperature changes, internal clearance changes and motions for ball bearings utilized as CB's. Figure 7 represents a simulation model for a flywheel battery that include two catcher bearings (CB1 and CB2). Figure 8 illustrates the detailed CB model that includes nonlinear, speed dependent stiffness, heat sources from lubricants friction and from sliding contact of the shaft on the bearing's inner race, and a squeeze film damper. The MS power-off condition response of the shaft is shown in figure 9. Note that the vibrations indicate a short period of high frequency backward whirling at 0.2 seconds after MS "power-off". This is followed by a more benign low frequency bouncing of the rotor on the CB's .

Drag Torque Test Rig.

Successful magnetic suspension of a flywheel battery requires that its magnetic bearing, eddy current induced drag torques are very small in order to improve efficiency and present overheating of the rotor. A specialized test rig for measuring MB drag torques in the equivalent power loss range of 2-5 watts at 60,000 rpm is nearing completion in the VCEL (figure 10). This will provide a means to measure the effects of modifications on power loss in the search for ultra-low loss MB's and motor/ generators. The rig will also provide a means to improve the accuracy of modeling approaches for MB hysteresis and eddy current losses.

Pre-Load Loss Monitor Test Rig.

Loss of radial preload between the concentric rings of a composite rim flywheel may cause harmful effects on its operation. The University of Texas at Austin-Center for Electromechanics have developed a means to indicate inter-ring radial preload loss. Figure 11 depicts a soon to be completed VCEL test rig which will be utilized to determine if the magnetic suspension's position and current signals provide reliable detection of the UTA-CEM preload-loss effect.

MS Expert System (ES)

The MS may operate more reliably and efficiently with an expert system to adapt it to anomaly occurrences and operating conditions (OC). Some OC's include host rocket launch, battery mode, attitude control mode, facing sun or eclipsed by sun, low speed or high speed, etc. The ES adapts the MS controller to varying degrees of these operating conditions via a fuzzy logic constructed rule base. In addition the ES rule base is developed to detect anomalies and if possible mitigate their effects. Figure 12 shows a typical LabView based panel for the ES.

SUMMARY

Flywheels for energy storage (batteries) and attitude control promise significant efficiency and environmental benefits. Magnetic suspensions significantly enhance these benefits. The TAMU-VCEL is presently leading efforts to optimize design of the Flywheel MS's via the tasks described herein.

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(5) Na, U.J and Palazzolo, A., "Optimized Realization Of Fault Tolerant Heteropolar Magnetic Bearings", ASME J. of Vibrations and Acoustics, Vol.122, No.3, July 2000, pp 209,221.

(6) Na, U.J and Palazzolo,A., "Fault Tolerance of Magnetic Bearings with Material Path Reluctances and Fringe Factors," IEEE Trans. On Magnetics, Vol.30, No.6, Nov. 2000.

TABLE 1.—SIMULATION MODEL PARAMETERS FOR FIGURE 1

Model Parameter		Values
Weight [lb]	Flywheel	28.64
	Housing	114.55
Ip [lb-in-s^2]	Flywheel	193
	Housing	965
It [lb-in-s^2]	Flywheel	233
	Housing	1165.1
DC Motor	Kt [lb-in/A]	5
	Ke [V/rpm]	5.3944
	L [mH]	50
	R [Ohm]	20
	Bandwidth [Hz]	63.7
	Damping [lb-in-s]	0.001
Table 1: (Continued)		
MB Load Capacity [lb]		50
CB Clearance [mil]		10
CB Friction Coefficient.		0.1
Housing Target Precession Rate [deg./sec]		11

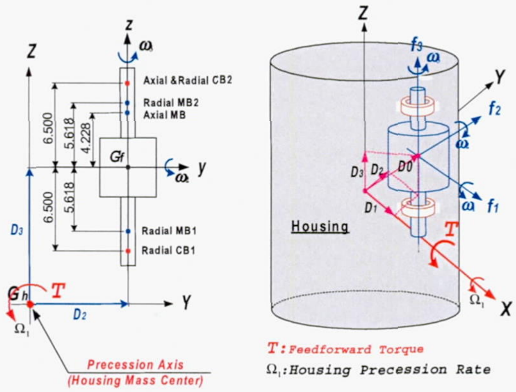

FIGURE 1.—MODEL OF FLYWHEEL FOR COMBINED ENERGY STORAGE/ATTITUDE CONTROL SERVICE.

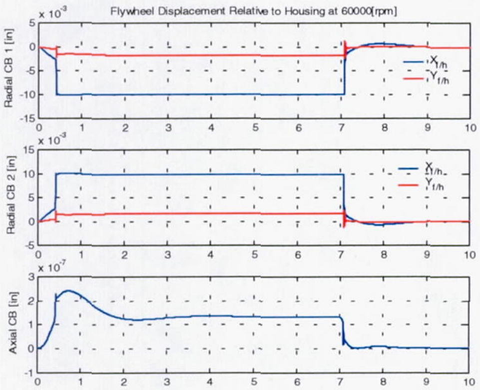

FIGURE 2.—FLYWHEEL DISPLACEMENT RELATIVE TO HOUSING AT CATCHER BEARING LOCATIONS.

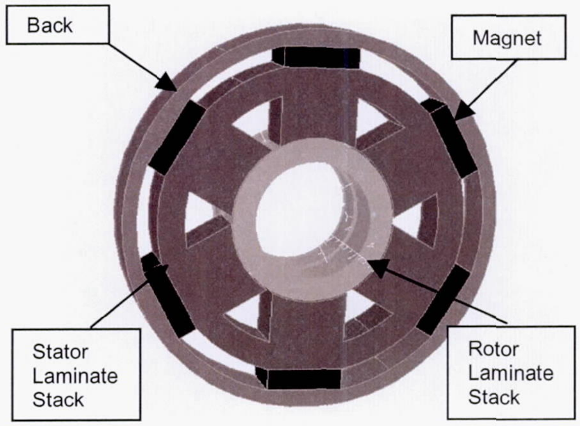

FIGURE 4.—PARTIAL VIEW OF 6 POLE HOMOPOLAR FOR REDUNDANT SERVICE.

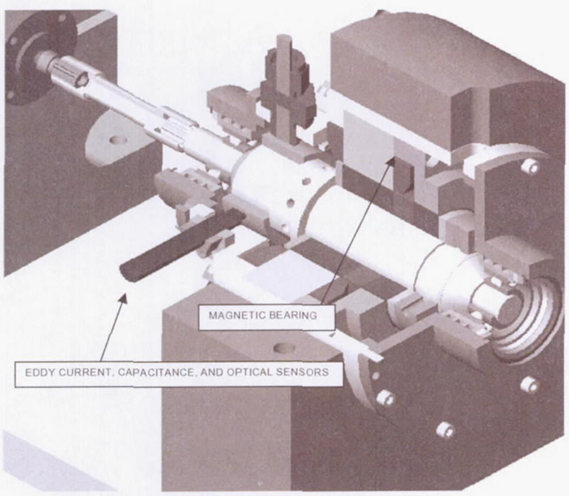

FIGURE 3.—HIGH SPEED (60,000+ rpm) TEST RIG FOR POSITION FEEDBACK SENSOR DEVELOPMENT.

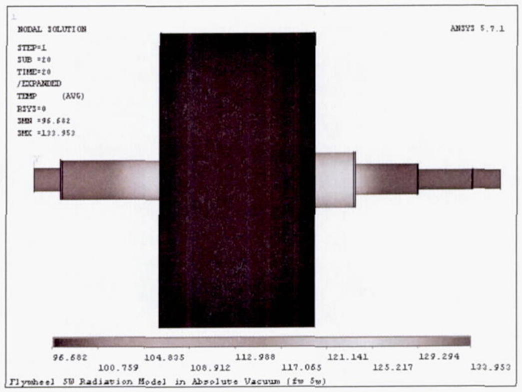

FIGURE 5.—THERMAL MODEL RESULTS FOR A FLYWHEEL WITH MB HEAT SOURCES.

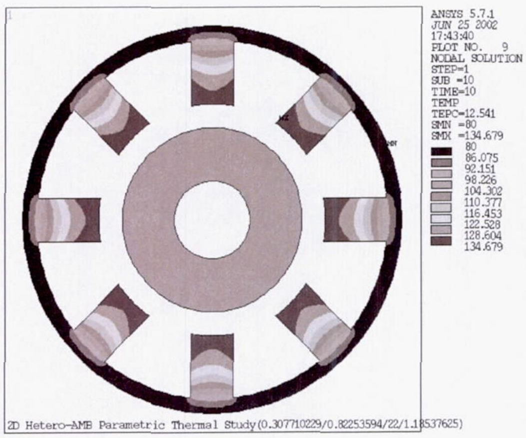

FIGURE 6.—2D THERMAL MODEL OF MAGNETIC BEARING ACTUATOR WITH GAPS INTENTIONALLY ENLARGED.

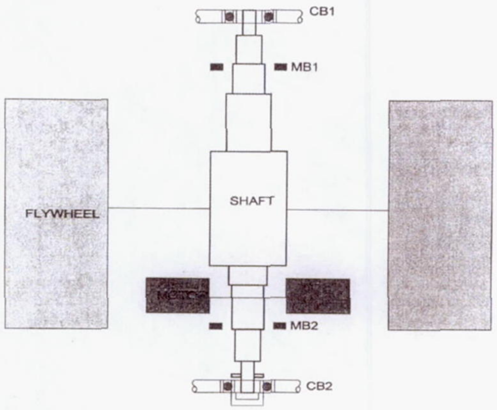

FIGURE 7.—VERTICAL ROTOR SHAFT WITH FLYWHEEL, MOTOR AND MAGNETIC AND CATCHER BEAGINGS.

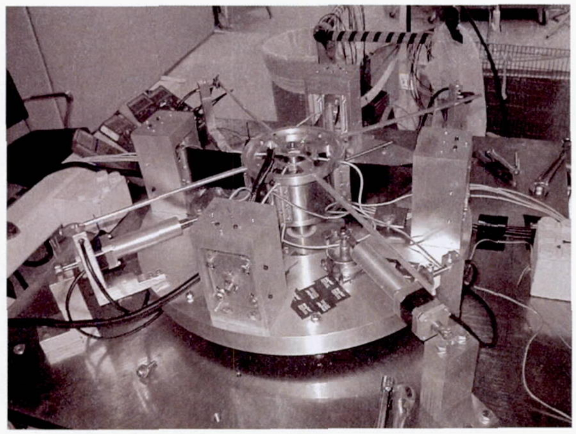

FIGURE 10.— DRAG TORQUE MEASUREMENT TEST FIXTURE.

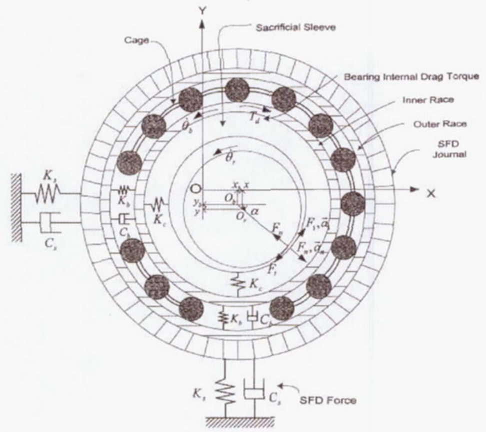

FIGURE 8.—DETAILED CATCHER BEARING MODEL SUPPORTED ON SQUEEZE FILM DAMPER.

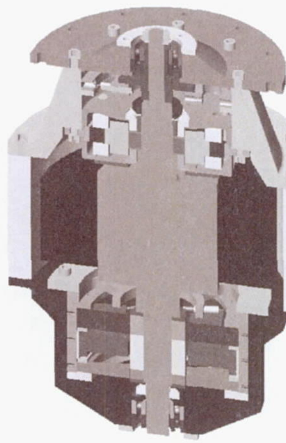

FIGURE 11.—VCEL TEST RIG FOR INDICATING UTA-CEM PRELOAD LOSS MONITOR EFFECT.

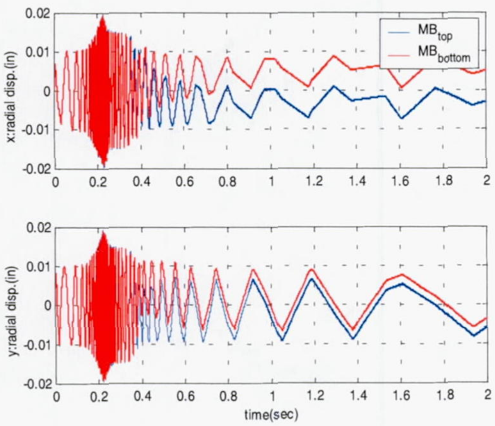

FIGURE 9.—RADIAL DYNAMIC RESPONSE OF THE SHAFT AT MB LOCATIONS.

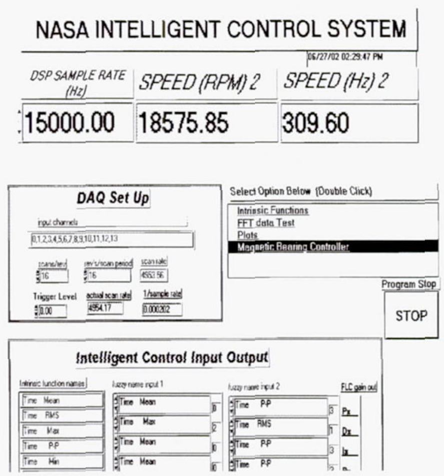

FIGURE 12.—TYPICAL PANEL FOR MAGNETIC SUSPENSION ES.

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