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MAGNETIC BEARING DEVELOPMENT FOR SUPPORT OF SATELLITE FLYWHEELS

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Abstract

The use of magnetic bearings (MB) for support of space based flywheels can provide significant improvement in efficiency due to reduction in drag torque. A NASA supported program directed through the Texas A&M Center for Space Power has been formed to advance the technology of MB's for satellite flywheel applications. The five areas of the program are: (a) Magnetic Field Simulation, (b) MB controller Development, (c) Electromechanical Rotordynamics Modeling, (d) Testing and (e) Technology Exchange. Planned innovations in these tasks include eddy current drag torque and power loss determination including moving conductor effects, digital (DSP) based control for high speed operation, MATLAB-based coupled flexible rotor/controller/actuator electromechanical model with fuzzy logic nonlinear control, and ultra high speed>100krpm measurement of drag torque. The paper examines these areas and provides an overview of the project.

INTRODUCTION

Satellite based flywheels may provide a very compact, durable an efficient replacement for batteries while also performing momentum control tasks. At 25-50 w. hr./lb, the target energy densities for flywheels are 5-10 times larger than for NiH batteries. Total target energies are between 1-5 kw-hrs. An intense effort has been launched by NASA to achieve these goals. One strategy is to minimize parasitic losses in the flywheel due to bearing drag. These losses are significantly reduced by using magnetic bearings (MB) instead of rolling element bearings. Genta (1985) shows a power loss reduction by approximately a factor of 8 between the two types of supports. In addition magnetic bearings may function in an adaptive mode to provide optimal control under various operating conditions. MB's also provide force sensing capability which is a more sensitive indicator of flywheel failure than vibration. This capability is exploited in a "virtual containment" plan to reduce flywheel speed at the earliest indication of wheel distress.

Magnetic bearing power losses arise from ohmic losses in the bearing coils and power amplifiers, eddy current losses and alternating and rotational hysteresis losses. Kasarda (1997) shows measured eddy current induced losses of approximately 0.5-1.0 kw for a 0.091m bore diameter MB at 30,000 rpm. These results provide a reason for developing low power loss MB's via test and simulation. Finite element modeling of the magnetic field has provided a means to accurately predict fringing, leakage and the effects of time harmonic impressed currents. The current research seeks to extend these capabilities to include effects of rotation induced eddy currents. These result from the Lorentz type force imposed on the rotor's electrons as they revolve through the field developed by the stator coils. A thorough search of commercially available software has failed to locate any package capable of modeling this effect for magnetic Peclet numbers:

$$\gamma = \mu\sigma Vh > 1.0 \tag{1}$$

where μ , σ and V are the rotor material's permeability, conductivity and velocity, respectively and h is the finite element's length in the direction of motion. For comparison, typical values may be 50,000 rpm, $\sigma = 2.0 \times 10^6 \Omega^{-1} m^{-1}$, $\mu_r = 3{,}000.$, $h = 1.mm$, $5.cm$ diameter, for which the Peclet at the rotor's surface is 980. Developing accurate and efficient means for including this effect and the effects of very thin (typically 0.1-0.4mm) laminates are important objectives of the current research. the former topic is addressed in the companion paper, "Flywheel Magnetic Bearing Field Simulation with Motion Induced Eddy Currents", by the same authors.

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The current research also focuses on MB controller/expert system development. Commercially available controllers typically consists of a PID stage cascaded in series with lead-lag compensation, low pass and notch filtering. Plant based/optimal control though demonstrated on small laboratory test rigs has not yet appeared in widespread commercial application. A supervisory (expert system) layer has been added to commercial controller in order to adaptively adjust gains and feedforward settings to shift critical speeds, reduce or increase damping at and above critical speeds and for synchronous current force and vibration cancellation. The controller transfer function design includes consideration of the rotor and housing's modal characteristics to insure low Q critical speeds and stability of supersynchronous frequency modes. The current research seeks to integrate the controller and mechanical designs and to develop new control strategies. The latter area is directed towards controller linearization of the MB actuator's force/deflection and force/current characteristics and in fuzzy logic based weighting of the PID gains. In addition expert system based supervisory control and health monitoring is also being pursued.

The rotordynamic response of a magnetic bearing supported shaft cannot be accurately predicted by considering the bearings as passive springs and dampers. This approach neglects the non-ideal characteristics, e.g. dynamics, of the feedback path components: sensors, filtering, controller, power amplifiers and the actuator itself. Total system , coupled electromechanical modeling is therefore essential for the successful analysis and design of magnetic bearing supported machinery. This task may require simulation of casing dynamics along with shaft dynamics. A MATLAB based preprocessor has been developed for the purpose of providing a systematic means to model generically defined magnetic bearing/flexible shaft systems. This code provides an easy means to model and analyze a system along with providing access to the powerful control features of MATLAB. The rotor model is defined using a finite element structures approach while feedback components are defined by their measured or calculated transfer functions. Time transient response may be performed to determine vibrations due to imbalance including a nonlinear bearing model. Linear analysis is also being developed to examine the effects of gain changes on closed loop stability.

A test rig is being designed to measure the drag torque developed by magnetic bearings due to eddy currents. The rig has a 150,000 rpm drive turbine and will house the MB in a 0.01-0.1 torr vacuum chamber. The rig will accommodate MB's with outer diameters to 0.2m and lengths to 0.1m. The measured flux densities, drag torques and temperatures on this rig will be correlated between other MB's and with theoretical results.

Technology transfer/exchange is also an important task of the overall project. Hence, in the past companies have received our assistance in the areas of measurements, controls and system modeling.

ELECTROMAGNETIC FIELD MODELING

The companion paper "Flywheel Magnetic Bearing Field Simulation with Motion Induced Eddy Currents" has a detailed explanation of our theoretical developments in this area. The thrust of this effort is to develop an accurate means to predict the field drag torque, power loss and static/dynamic force characteristics for a generically defined MB. This will be accomplished either with a new stand-alone code or by integrating new features such as the velocity induced eddy current effects, or distributed calculation of hysteresis loss, into an existing commercial code. The ANSOFT-EMASS code has widespread use in industry of electromagnet and electro-mechanical modeling. This code has demonstrated excellent agreement with static B field measurements on a homopolar MB in our lab. Figure 1 shows a drawing of this MB which has 4 poles at each of its two axial planes.

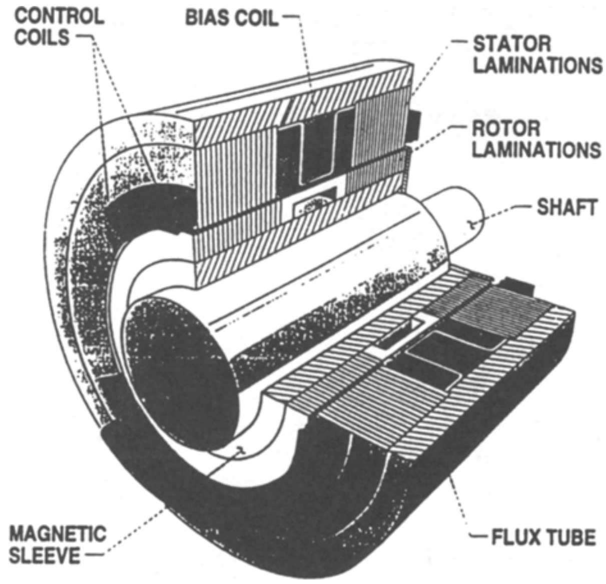


FIGURE 1. Homopolar Magnetic Bearing for Test/ Theory Correlation

Figure 2 shows a grey scale plot of the predicted flux density due to a one hz harmonically varying control coil current (shown as large arrows). The B vectors are seen to be concentrated in the pole of the excited coil, and from there flow to other poles in the same plane or to the 2nd axial plane. Tables 1-4 show the test/theory correlation for this case. In table 4 (Control Coil) the excitation current is 2A DC, relative permeability of rotor and stator is 10000, and relative permeability of back iron is 5000. In table 4 (Bias Coil) the excitation current is 1.5, relative permeability of rotor and stator is 5000, and relative permeability of back iron is 1000.

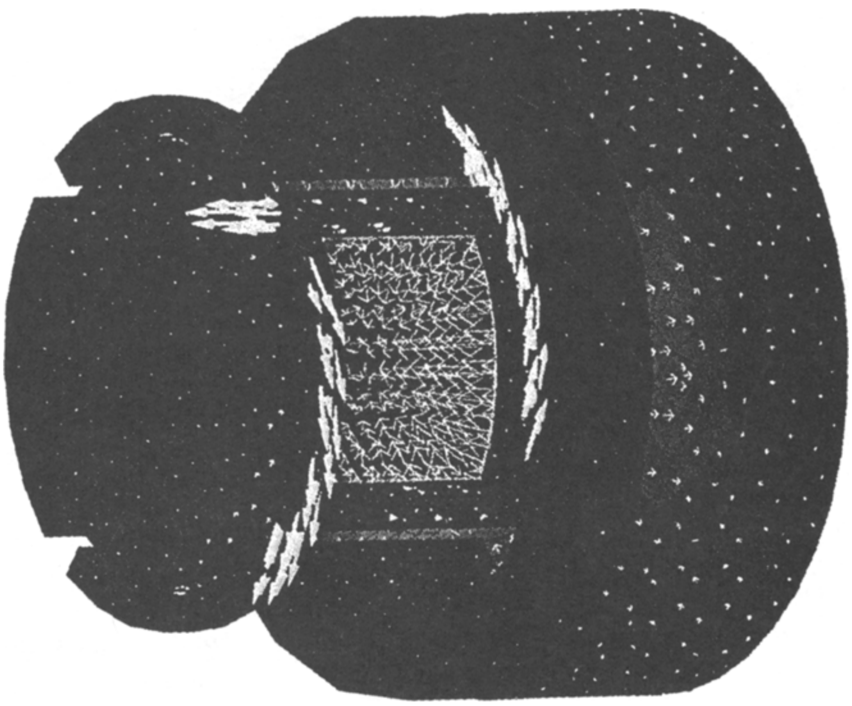


FIGURE 2. Grey Scale Flux Density Plot - Grey in Gap (0.09Tesla)

TABLE 1. Effect of Permeability on Flux in Gap Under Control Coil as Determined By Finite Analysis. The Measured Flux is .34T.

Part	Relative Permeability	Flux Density
Back Iron	268	.21T
Rotor & Stator	1412	
Back Iron	5000	.30T
Rotor & Stator	10000	

TABLE 2. Uncertainty in Measure and FEA Gap Flux Value

Item	Uncertainty
Residual Magnetism Uncertainty	+/- .017T
Accuracy Uncertainty	+/- .025T
FEA Adjacent Node Variation	+/- .03T

TABLE 3. Comparison Between Measured and FEA Results for Flux Due to Control Coil Excitation of 2A

Item	Flux Density
Measured Flux Under Excited Control Coil	.33T
FEA Flux Under Excited Control Coil	.30T
Measured Flux Under Adjacent Control Coil on Same Stator	.06T
FEA Flux Under Adjacent control Coil on Same Stator	.044T
Measured Flux Under Adjacent Control Coil on Opposite Stator	.035T
FEA Flux Under Adjacent Control Coil on Opposite Stator	.040T

TABLE 4. Effect of Number of Elements on Solution

Control Coil Excitation		Bias Coil Excitation	
Case	Gap Flux T	Case	Cap Flux T
Actual Measurement	.33T	Actual Measurement	.57T
FEA 7000 Elements	.29T - .31T	FEA - 7000 Elements	.57T
FEA - 17800 Elements	.28T - .29T	FEA - 114500 Elements	.69T
FEA - 56000 Elements	.29T - .31T		

DIGITAL CONTROLLER

Both 2 and 4 axis digital controllers have been developed and are currently being employed by a company for development of a MB supported flywheel. We have developed various controller architectures for MB's. These include 3rd order type PID paths, first Order PID paths followed by low pass and notch filtering and a non-PID, linearization type algorithm. Feedforward control is also included in these controllers for suppression of synchronous vibration amplitude or transmitted shaking force. Figures 3 and 4 show a typical PID transfer function (TF) with low pass filtering and a notch filter transfer function, respectively. These capabilities provide phase lead compensation, and plant and disturbance offset and high frequency noise rejection. The DSP board employed has a TI-TMS 320 C32 D, 60 mhz processor. A graphical user interface was developed for the feedback/feedforward controller. This slider bar controlled GUI was programmed in National Instrument - Labview G language. Feedback and feedforward gains phase angle settings, setpoints and path TF coefficients are easily adjusted with this GUI.

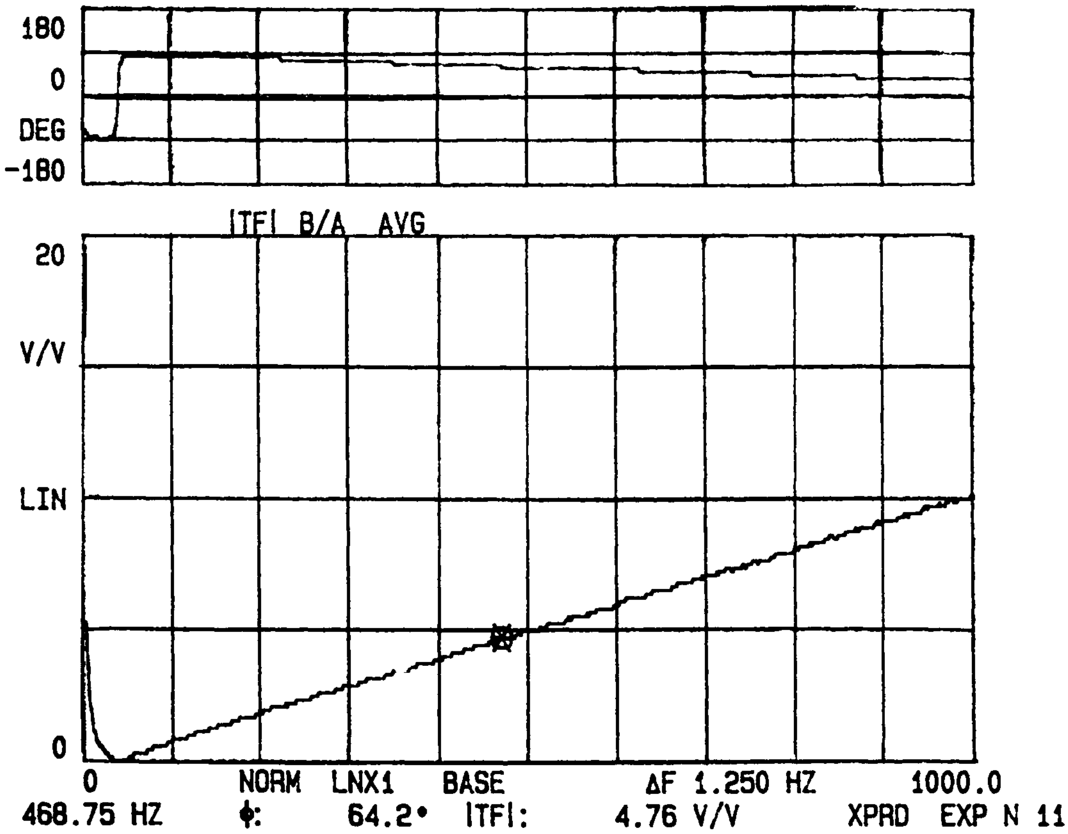


FIGURE 3. Typical PID Transfer Function for Digital Controller

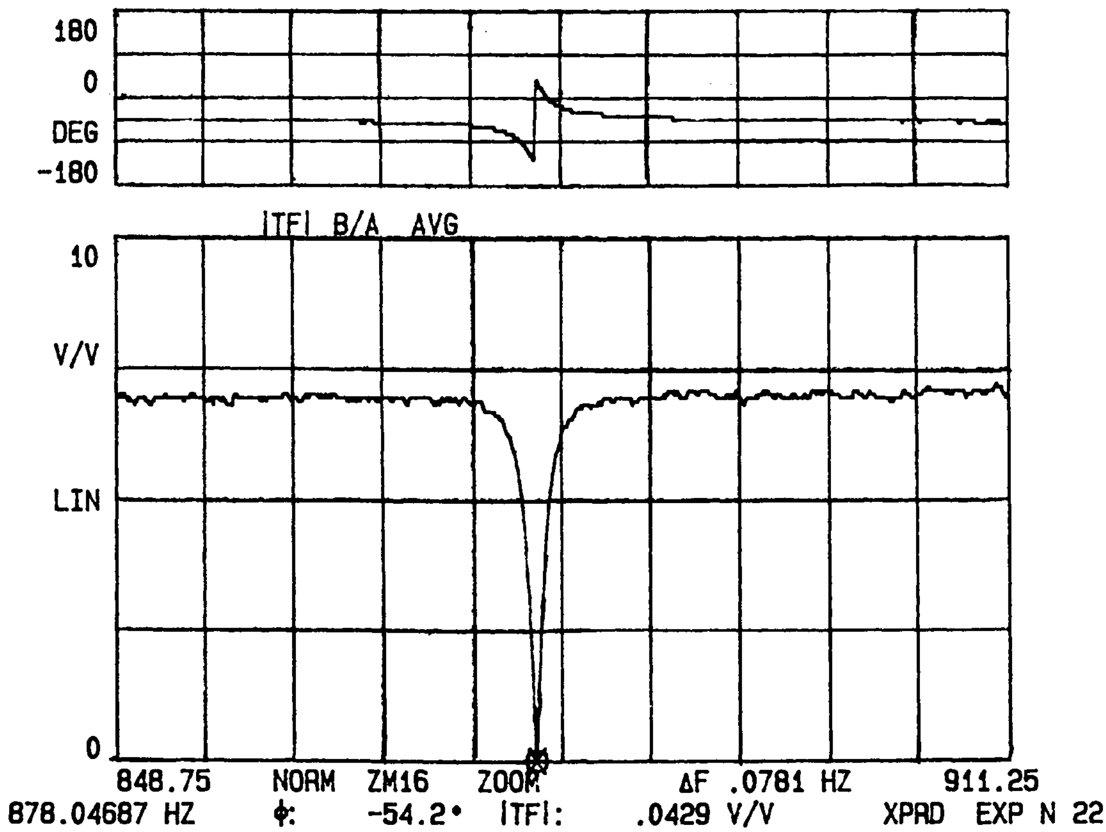


FIGURE 4. Notch Filter Transfer Function

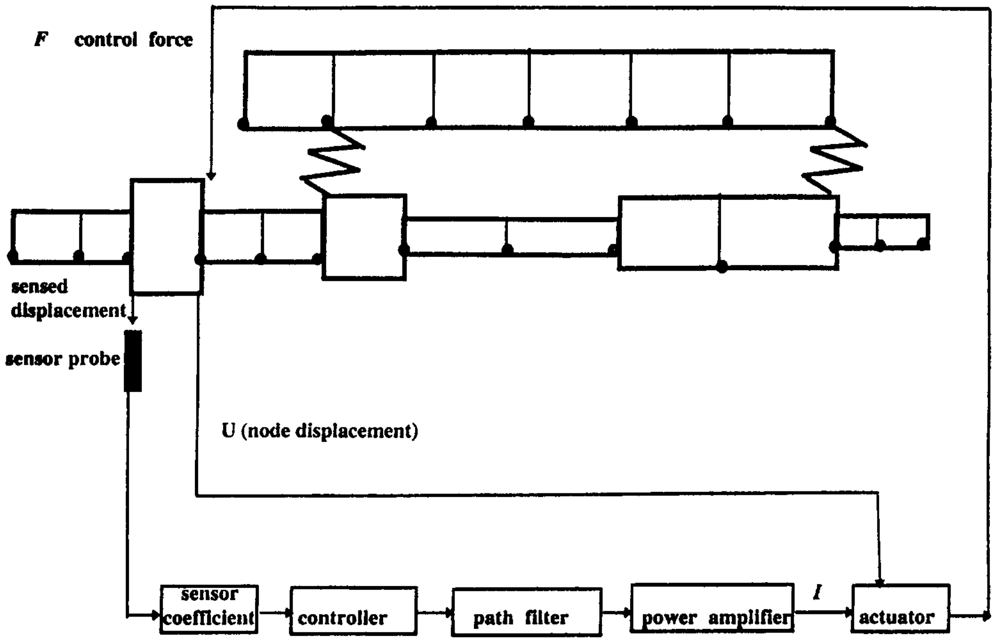


FIGURE 5. Model for Generic Flexible Shaft/Feedback Path Simulation

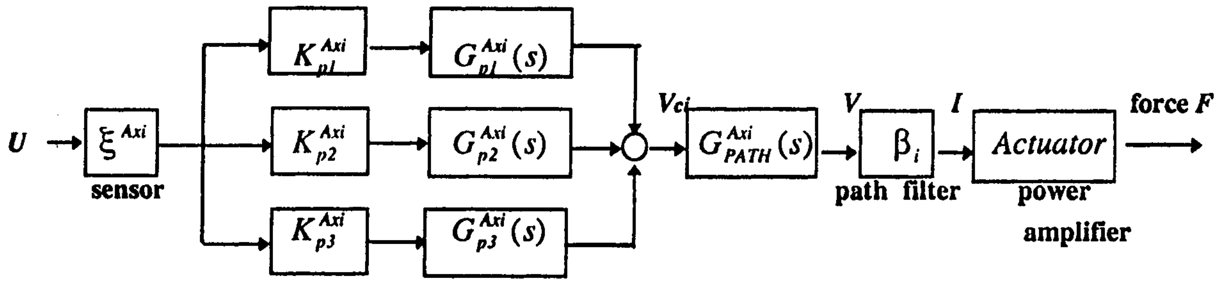


FIGURE 6. Feedback Path TF's and Component Blocks

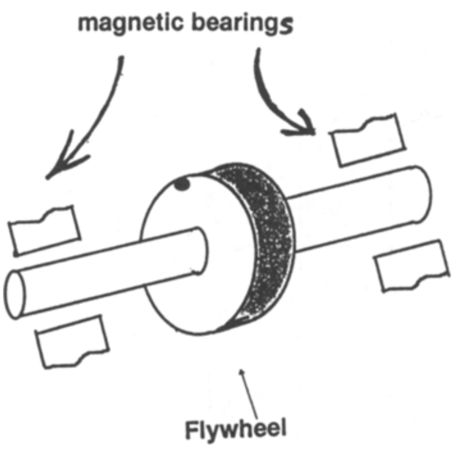


FIGURE 7. Simple Flywheel Model for Electromechanical Code Demonstration

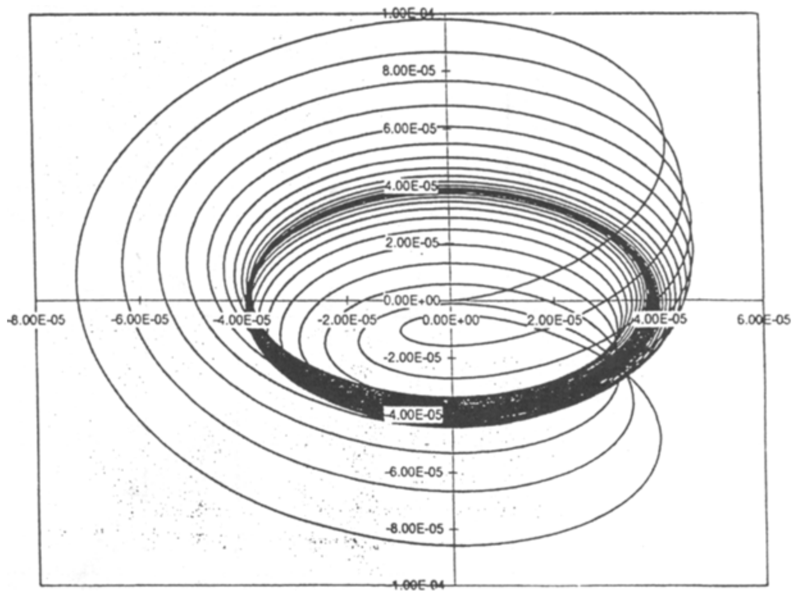
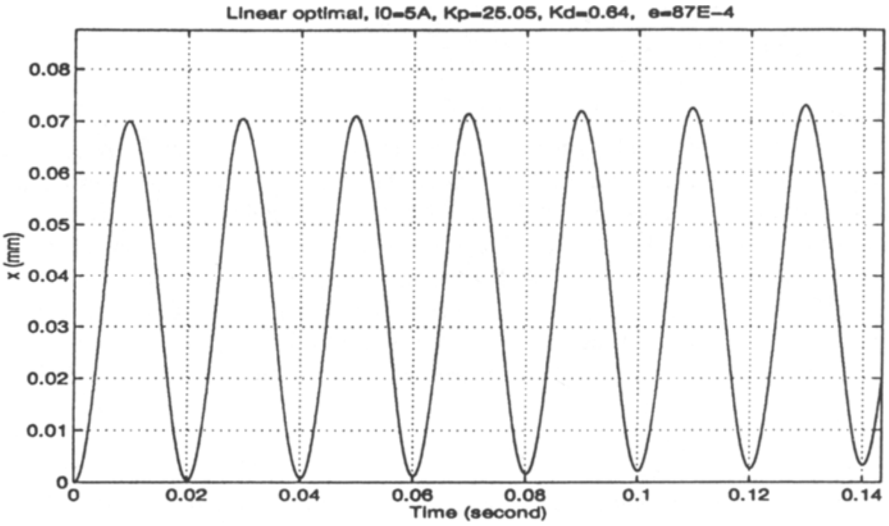
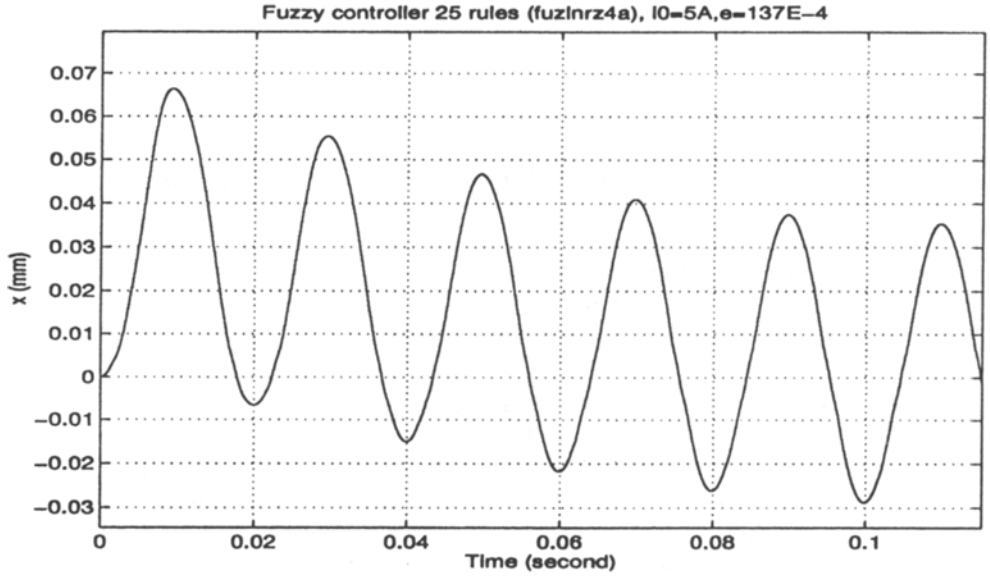


FIGURE 8. Transient Imbalance Response of Flexible MB Controlled Rotor



simulation results with maximum unbalance offset *e=137E-4 (m)*



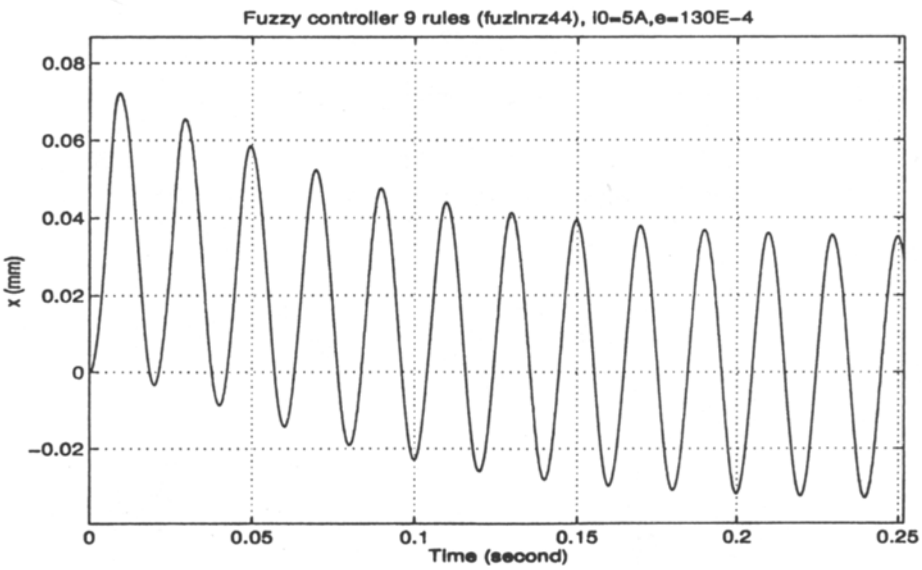


FIGURE 9. LQR vs. Fuzzy Logic Response Comparison for Instability Threshold

ELECTROMECHANICAL MODELING

Figures 5 and 6 show drawings of a generic rotor with a flexible wheel attached by interconnecting stiffnesses, and the general S-domain feedback paths along the ith axis of control (i=1,2,...,5), respectively. The flexible wheel and main rotor have gyroscopic moments and internal friction damping. The parallel control paths have arbitrary order TF's and independent gains. Inputs to the MATLAB based code consists of descriptions of the rotor and wheel structures, actuator parameters and controller TF coefficients. Figures 7 and 8 show a typical flywheel mode and it transient response to sudden imbalance. A fuzzy logic (FL) based non linear controller is also being incorporated into the MATLAB pre/post processor. It has been found that the FL controller maintains stable control for significantly higher levels of imbalance than a linear optimal controller (LQR). Figure 9 shown results of the previous model with maximum controllable imbalance eccentricities up to 8.6mm for LQR and 13.7mm for FL.

TEST RIG

As previously described the test rig will be capable of spinning rotors to 150,000 rpm. Drag torque will be measured directly by instrumenting the MB support for torque measurement as contrasted to previous approaches which rely on a curve fit of the speed vs. time coastdown data. The rig will also have the capability to provide two axis - single MB levitation capability to develop controllers for ultra high speed applications. A companion rig capable of measuring MB static and dynamic force has already been designed, fabricated and delivered to NASA Lewis by the authors. Nine inch diameter bearings may be tested in that rig.

TECHNOLOGY EXCHANGE

Satellite application of flywheels for energy storage and momentum control is requiring a high level of synergism between MB, flywheel and satellite researchers and government and industry sponsors. Our mission is to aid this process by supplying the necessary MB expertise, test results and tools to these development partners. This has been thus far performed on an immediate need basis, however plans are made to form a MB/Flywheel Consortium to foster and support projects addressing long term development. NASA Lewis Space Power Division has been very instrumental in supporting this efforts both technically and with funding.

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