DESIGN AND PERFORMANCE IMPROVEMENTS OF THE PROTOTYPE OPEN CORE FLYWHEEL ENERGY STORAGE SYSTEM*

D. Pang
Hua Fan College of Humanities and Technology
Shihtin, Taiwan

D. K. Anand
Professor of Mechanical Engineering
University of Maryland

J. A. Kirk
Professor of Mechanical Engineering
University of Maryland
College Park, MD 20742 USA

ABSTRACT

A prototype magnetically suspended composite flywheel energy storage (FES) system is operating at the University of Maryland. This system, designed for spacecraft applications, incorporates recent advances in the technologies of composite materials, magnetic suspension, and permanent magnet brushless motor/generator. The current system is shown in Figure 1 and is referred to as an Open Core Composite Flywheel [OCCF] energy storage system.

This paper will present design improvements for enhanced and robust performance. The control aspects of the OCCF magnetic bearings are discussed in a separate paper, "Parameter Design And Optimal Control Of an Open Core Composite Flywheel Energy Storage System."

Initially, when the OCCF prototype was spun above its first critical frequency of 4,500 RPM, the rotor movement would exceed the space available in the magnetic suspension gap and touchdown on the backup mechanical bearings would occur. On some occassions it was observed that, after touchdown, the rotor was unable to re-suspend as the speed decreased. Additionally, it was observed that the rotor would exhibit unstable oscillations when the control system was initially turned on. Our analysis suggested that the following problems existed:

1. The linear operating range of the magnetic bearings was limited due to electrical and magnetic saturation,

2. The inductance of the magnetic bearings was affecting the transient response of the system,

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3. The flywheel was confined to a small movement because mechanical components could not be held to a tight tolerance,

4. The location of the touchdown bearing magnifies the motion at the pole faces of the magnetic bearings when the linear range is crucial.

In order to correct these problems an improved design of the flywheel energy storage system was undertaken. The magnetic bearings were re-designed to achieve a large linear operating range and to withstand load disturbances of at least 1 g. The external position transducers were replaced by a unique design which were resistant to magnetic field noise and allowed cancellation of the radial growth of the flywheel at high speeds. A central rod was utilized to ensure the concentricity of the magnetic bearings, the motor/generator, and the mechanical touchdown bearings. In addition, the mechanical touchdown bearings were placed at two ends of the magnetic bearing stack to restrict the motion at pole faces. A composite flywheel was made using a multi-ring interference assembled design for a high specific energy density. To achieve a higher speed and better efficiency, a permanent magnet DC brushless motor was specially designed and fabricated. A vacuum enclosure was constructed to eliminate windage losses for testing at high speeds.

With the new improvements the OCCF system was tested to 20,000 RPM with a total stored energy of 15.9 WH and an angular momentum of 54.8 N-m-s (40.4 lb-ft-s). Motor current limitation, caused by power loss in the magnetic bearings, were identified as causing the limit in upper operating speed.

INTRODUCTION

A magnetically suspended composite flywheel energy storage (FES) system was developed, for spacecraft applications, incorporating recent advancements in the technologies of composite materials, magnetic suspension, and permanent magnet brushless motor/generator. Kirk and Anand [1] suggested that a magnetically suspended composite flywheel energy storage system is a viable and superior alternative to batteries for spacecraft applications. The system can easily achieve the specific energy density (SED) of 20 WH/kg, which exceed a typical 14 WH/kg of the electrochemical system and has a long lifetime of 10 to 15 years. The proposed system was designed for a low earth orbit (LEO) satellite with a 90-minute cycle. The flywheel is accelerated during a 60-minute interval (charge cycle) when the satellite is exposed to sunlight. The flywheel is spun down during a 30-minute interval (discharge cycle) when the satellite is exposed to darkness. The system during this darkness must supply power at a constant voltage of 150±2% volts DC. With efficient power electronics, the system can accomplish an efficiency of 90% for each cycle. The FES system utilized an open core flywheel made of multi-ring graphite/epoxy composites which was interference assembled to maximize the specific energy density (SED). Two permanent magnet/electromagnet (PM/EM) magnet bearings were stacked in the center for magnetic suspension of the flywheel. The motor/generator mounted between two magnetic bearings was used to provide power transfer into and out of the system.

The overall design of the FES system was based on a pancake-shaped PM/EM magnetic bearing and a spokeless composite flywheel proposed by Kirk and Studer [2]. They described general design requirements for a magnetically suspended composite flywheel energy storage system. Anand, Kirk, and Iwaskiw [3] developed a detailed design of a 500 WH magnetically suspended composite flywheel energy storage system for a low earth orbit (LEO) satellite. A prototype of this design was constructed at the University of Maryland's Magnetic Bearing Laboratory and is shown in Fig. 1.

When this prototype was spun slightly above its first critical frequency of 4,500 RPM, the magnetic suspension would fail and touchdown would occur. It was sometimes observed that the system failed to self-suspend or exhibited unstable oscillations when the control system was initially turned on. Analysis suggested that the following problems existed:

1. the linear operating range of the magnetic bearings is limited due to electrical and magnetic saturation,

2. the inductance of the magnetic bearings affects the transient response of the system,

3. the flywheel is confined to a small movement because mechanical components could not be held to a tight tolerance,

4. the location of the touchdown bearing magnifies the motion at the pole faces of the magnetic bearings when the linear range is crucial.

In order to correct these problems an improved design of the flywheel energy storage system was attempted [4,5,6]. The magnetic bearings were re-designed to achieve a large linear operating range and to withstand load disturbances of at least 1 g. The external position transducers were replaced by the inner ones to cancel the radial growth of the flywheel at high speeds. A central rod was utilized to ensure the concentricity of the magnetic bearings, the motor/generator, and the mechanical touchdown bearings. In addition, the mechanical touchdown bearings were placed at two ends of the magnetic bearing stack to restrict the motion at pole faces. A composite flywheel was made using a multi-ring interference assembled design for a high specific energy density. To achieve a higher speed and better efficiency, a permanent magnet DC brushless motor was specially designed and fabricated. A vacuum enclosure was constructed to eliminate windage losses for testing at high speeds. A final prototype was built along with a display panel, which includes all control electronics and a data acquisition system. This has been reported in earlier literature [7,8].

The FES system was tested to 20,000 RPM with a total stored energy of 15.9 WH and an angular momentum of 54.8 N-m-s (40.4 lb-ft-s). Additional specifications are shown in Table 1. Motor current limitation, caused by power loss in the FES system, prevented testing to a higher speed. The spin-down test and magnetization tests have indicated that the major power losses are due to eddy currents in the magnetic bearing return rings. The test results and theoretical analysis are discussed in [9]. This work shows that the performance was not robust and several critical improvements are necessary.

The objective of this continued research is principally to analyze the magnetic bearing system for nonlinear effects in order to increase the region of stability, as determined by high speed and large air gap control. This is achieved by four tasks: (1) physical modeling, design, prototyping, and testing of an improved magnetically suspended flywheel energy storage system, (2) identification of problems that limits performance and their corresponding solutions, (3) development of a design methodology for magnetic bearings, and (4) design of an optimal controller for future high speed applications.

This paper is concerned with an improved design methodology leading to system improvements for enhanced and robust performance. The control aspects are discussed in a separate paper.

IMPROVED DESIGN

Central to the design methodology is an appropriate model. The mathematical model of the PM/EM magnetic bearing can be represented by both a reluctance model and a stiffness model. In the reluctance model, magnetic circuit theory and bearing geometric dimensions are used to analyze the magnetic flux in the bearing. In the stiffness model, stiffness and force equilibrium equations are utilized to describe the bearing characteristics. By combining the two models, the performance of the bearing can be predicted given the geometric dimensions, the power electronics, the permanent magnets, and the electromagnetic coils.

The linear range is determined not only by the maximum control current to the EM coils but by the current/displacement ratio C of the control system as well. The active stiffness and the maximum restoring force are also dependent on the current/displacement as illustrated in Fig. 2.

The EM coil design is based on the stability and the force slew rate considerations, which determine the number of turns for the coils, and the power amplifier voltage and current. The stability consideration is derived from a nonlinear control system analysis, which is used to remove the limit cycle oscillation and to improve the robustness of the bearing. The force slew rate consideration is derived from the dynamic requirements of the magnetic bearing under either the external force or mass unbalance condition. From both experimental results and theoretical analysis, the power amplifier voltage and the number of turns of the EM coils have greater roles in stabilizing the bearing and responding to any disturbance.

It was found that when the power of the magnetic bearing was turned on, the flywheel not only failed to self-suspend but often broke into self-sustaining oscillations unless the mechanical touchdown gap was well adjusted. Also, the magnetic bearing flywheel system broke into a limit cycle oscillation due to a large disturbance. It has been shown that the oscillation is due to the combined effects of the power amplifier saturation, the passive radial stiffness, the touchdown gap, and the inductance of the EM coil. The mathematical representation of the model has been developed in detail in [9] and is used in the design procedure discussed further.

The flowchart for the new design methodology of the PM/EM bearing is shown in Fig. 3. The design procedures start with performance requirements for the magnetic bearing including the mass of the flywheel, axial force, radial force, and linear operating range. There are some initial inputs such as the saturation flux density of the magnetic material, the recoil permeability of the PM material, the operating flux density of the permanent magnet, the useful flux ratio, and power amplifier voltage. These values can be updated or changed with the choice of the specific materials and designs. The bearing design is an iterative process so the number of steps just shows a possible sequence.

The flux densities in any section of the magnetic bearing are limited by the saturation value of the magnetic material so the combined flux densities from the PM and EM are less than the saturation value. If there are equal flux densities from the PM and EM, the bearing can generate a maximum force. For a linear attractive force, the flux density from the PM is greater than that from the EM.

There are a few constraints on the geometric dimensions of the bearings due to physical limitations and engineering considerations. For example, the size of the permanent magnets is limited to a quadrant of the magnetic plate. Since our PM/EM bearing is a small gap suspension design, the linear range is expected to be less than 15% of the air gap. To avoid large leakage flux between the pole faces of the return ring and two magnet plates, the pole face thickness is at least 3 times that of the air gap.

The magnetic bearing can be designed to satisfy the force requirements by using the flux densities and the geometric dimensions. Because of our radial active bearing design, the load capability in the axial direction is weaker than the radial direction. If the bearing is used to handle the same force in both directions, the axial force requirement becomes dominant.

To avoid the possibility that a larger axial drop may worsen the magnetic properties of the bearing, the ratio of the axial drop and the pole face thickness is limited to 20%.

After satisfying the performance requirement and physical constraints, a feasible design is chosen which includes the flux densities from the PM and EM, the mean radius, the air gap, the pole face thickness, and other dimensions.

Using the information from the previous step, the parameters of the permanent magnet design such as the magnet strength, thickness, and cross section area can be determined. Based on the stability and force slew rate considerations, the number of turns for the EM coils as well as the voltage and current for the power amplifier can finally be determined.

An optimization model was developed and in order to keep the design problem manageable, the scope of the optimization is concentrated on the most important design variables of the bearing.

The design goals for the magnetic bearings in the flywheel energy storage system are that the bearing has a 2 g axial load capacity, can withstand 2 g radial force, the axial drop is less than 10% of the pole face thickness and that the stable range of the bearing is maximized. The magnetic bearings are expected to handle a 2 g load from the flywheel at both the axial and radial directions. The axial drop ratio requirement is based on past work showing that the large axial drop will reduce the useful magnetic flux and affect all the magnetic properties of the bearing. The last requirement seems to be hard to observe because the bearing should be designed for a large linear range, a higher active stiffness and a greater radial force. Notice that the linear range, active stiffness, and radial force are dependent on the control system design and impose conflicting requirements. For example, a control system with a large linear range will have a lower active stiffness. In order to fundamentally improve the properties of the bearing, the stable range, which is independent of the control system, should be as large as possible. The objective of the optimization design is to maximize the stable range of the bearing, and select 12 design variables.

The equations for the objective function and the design constraints are developed in [9]. In these equations there are parameters in the model that most be specified by the designer. These parameters include the weight of the flywheel, the axial force, the radial force, the maximum mean radius of the bearing, the axial drop ratio, the useful flux ratio, the operating flux density of the permanent magnet, the saturation value of the magnetic material, the maximum current output, the maximum numbers of turns for the EM coil and the minimum air gap. The model can be further simplified by eliminating 6 equality constraints so that the 12 design variables become 6 independent variables.

Three optimization methods, the Monotonicity analysis, the Generalized Reduced Gradient (GRG) method and the Augmented Lagrange Multiplier (ALM) method, have been developed to find the optimal magnetic bearing design. The monotonicity analysis can check if the optimization model is well bounded. If all design variables are bounded, the model is well defined. This analysis can improve the modeling of the problem and satisfy the necessary condition of existence of a solution before trying to compute the solution. The GRG and ALM methods are used to solve the nonlinear constraint problems numerically. A commercial software package GRG2, developed by Lasdon [10], is used in the optimization process. The ALM method is a kind of penalty algorithm to solve a constrained optimization problem as an unconstrained problem. A computer program is developed using the ALM method, the Fletcher-Reeves conjugate direction method, and the golden section method to find the optimal point of the pseudo-objective function.

The results from these three methods [9] are remarkably close. They show the constraints of the axial force, the axial drop, the control current, the number of turns for the EM coil, the space for the permanent magnet, and the bearing diameter are active constraints. It comes as no surprise that the axial performance requirements are dominant for the radial active bearing, because the axial direction has passive control and its performance is limited. The control current output is restricted by the existing power amplifier but the objective function can be improved by relaxing this constraint. The number of turns for the EM coil is restricted by the stability and force slew rate considerations. The geometric limitations for mean radius of bearing and the permanent magnet are inherited from the design of the flywheel system so the restrictions are hard to ease physically.

SYSTEM IMPROVEMENTS

During the development of a magnetically suspended FES system, many system performance limitations were identified and corrected. The problems limiting system performance include magnetic bearing perturbation force, third harmonic noise, power amplifier voltage saturation, structure vibration, mass imbalance, electronic unreliability, impedance mismatch between motor controller and motor/generator, and time delay of motor commutation sensors. Although all these are discussed in detail in [9], two of the areas of investigation are discussed here.

Since the old magnetic bearing from the earlier prototype did not meet the radial load requirement in the linear operating range, a new magnetic bearing was designed following the design methodology proposed here. In order to improve the bearing performance in the radial direction, the design must maximize the bearing stable range for a fixed control current. Due to the constraints (magnetic bearing diameter, the number of turns for EM coils, maximum control current, and permanent magnet material), the pole face thickness and the permanent magnet diameter were identified as the two most important design parameters. In order to improve the bearing performance, the new pancake bearing was built using the pole face thickness of 3.05 mm (0.12 in) and permanent magnet diameter of 31.75 mm (1.25 in), compared to 1.65 mm (0.065 in) and 34.29 mm (1.35 in) for the old bearing. The experimental testing results for the old magnetic bearing and new pancake bearing are discussed in detail in [9] but it is suffice to say that considerable improvements in bearing performance is noted. Specifically

1. The new pancake bearing can stand at least 1 g load of 36 N (8 lb) in axial and radial directions.

2. When both bearings have almost the same linear range due to the same gain in the control system, the new pancake bearing exhibits a higher active stiffness and a greater radial force.

3. Both bearings show a similar active stiffness when the new pancake bearing has a gain at 125 KΩ and the old bearing at 250 KΩ. The linear range of the new pancake bearing is almost doubled.

4. Both bearings have a similar axial drop around 20% of the pole face thickness at 1 g load.

The new pancake bearing was tested using a single magnetic bearing setup and was spun up to 3400 RPM with a runoff error of less than 0.02 mm (0.0008 in). The new pancake showed impressive performance in the radial direction and is satisfactory in the axial direction. It was therefore chosen for the final prototype of the magnetically suspended flywheel energy storage system.

The rotor orbit in the FES system can be observed using an X-Y plot of two perpendicular displacement sensor outputs. Because of eccentricities and disturbances, a circular shaped orbit was expected similar to the one shown in Fig. 4 using a single pancake bearing setup. When the flywheel supported by two stack bearings was spun, rectangular and diamond shaped orbits from the top and bottom stack bearings were observed as shown in Fig. 5.

These orbits are caused by a third harmonic superimposed on a first harmonic. The third harmonic noise was observed at all speed ranges. Sometimes, the third harmonic component becomes very large and the orbit had sustained loops. The third harmonic noise is undesirable because it demands unnecessary voltage and current outputs from the control system.

For a bearing stiffness of 350 N/mm (2000 lb/in), the third harmonic noise is very small but it distorts the flywheel motion. Also, the third harmonic noise demands unnecessary control voltage and current, and causes extra difficulties for mass balancing of the flywheel. Because the first harmonic from the magnetic bearing force is superimposed by mass imbalance, sensor error, and geometric error, there are different shaped orbits for the top and bottom stack bearings throughout the speed range.

Mathematical modeling and experimental analysis confirmed that the magnetic bearing return ring operating in the nonlinear region caused the third harmonic noise. The pancake return ring has the best performance because it does not cause any third harmonic noise at either the pancake bearing or the top stack bearing. The return ring causes a large third harmonic noise at either bearing. The different characteristics of the return rings were possibly due to the batch variation of the magnetic materials since all the rings follow the same machining and heat treatment processes.

In order to find out the best return rings for the magnetic bearing stack, the return rings were assembled into a one-ring composite flywheel for spinning test and frequency analysis. The one-ring composite flywheel did not have the permanent magnet ring so the motor/generator did not affect the testing. Because there are less third harmonic noises generated using the pancake return rings this arrangement was chosen for the final prototype of the FES system. Results of a variety of improvements in the final prototype are given in Table 2.

For flywheel energy storage applications, the power loss of the magnetic bearing system is very important. Unexpected large power losses during spin down tests prompted further theoretical analysis and experimental studies.

Considering the experimental tests and theoretical analysis [9] we conclude:

1. The major power loss is caused by the skin effect of the eddy currents in the magnetic bearing return rings.

2. Non-laminated return rings have similar DC magnetic properties as the manufacturer's laminated specimens but differ greatly from AC magnetic properties. Because of the skin effect, the return rings have a large magnetic field, a low peak permeability, and a huge core loss at the same flux density level and cycling frequency.

3. If the flux density distribution is uniform throughout the cores, the hysteresis and eddy current losses are proportional to the frequency and the square of the frequency of the magnetic field. The hysteresis and eddy current components of the core loss can be separated by testing at different frequencies and the knowledge of their relative magnitude can be used to reduce the power loss.

CONCLUSIONS

The problems limiting performance of the magnetically suspended flywheel energy storage system were identified. With the improvements done on the magnetic bearing, motor/generator, composite flywheel, system electronics, and system mechanical structure, the FES system achieved a maximum speed of 20,000 RPM with a total stored energy of 15.9 WH and a DN number greater than 2.1 million which exceeds the capability of most mechanical bearings.

In order to improve bearing performance, a new magnetic bearing with larger load capability has been designed and manufactured. The improved magnetic bearing can handle at least 1 g load in both axial and radial directions, and has a linear operating range over the mechanical touchdown gap. Because the third harmonic noise affects the stability of the FES system, theoretical analysis and experimental testing were conducted. The results showed that the third harmonic noise is caused by the magnetic bearing return ring operating in the nonlinear region. In order to eliminate the noise, all the return rings were tested and the best return rings were selected in the final prototype of the FES system.

The research has been primarily concerned with nonlinear effects of a magnetically suspended flywheel energy storage system in order to increase the region of stability at high speed and large air gap.

The FES system was unable to reach a higher speed because power losses in the magnetic bearing exceeded the power capability of the motor controller. Experimental and theoretical studies have shown the major power loss is due to the skin effect of the eddy currents in the non-laminated return rings.

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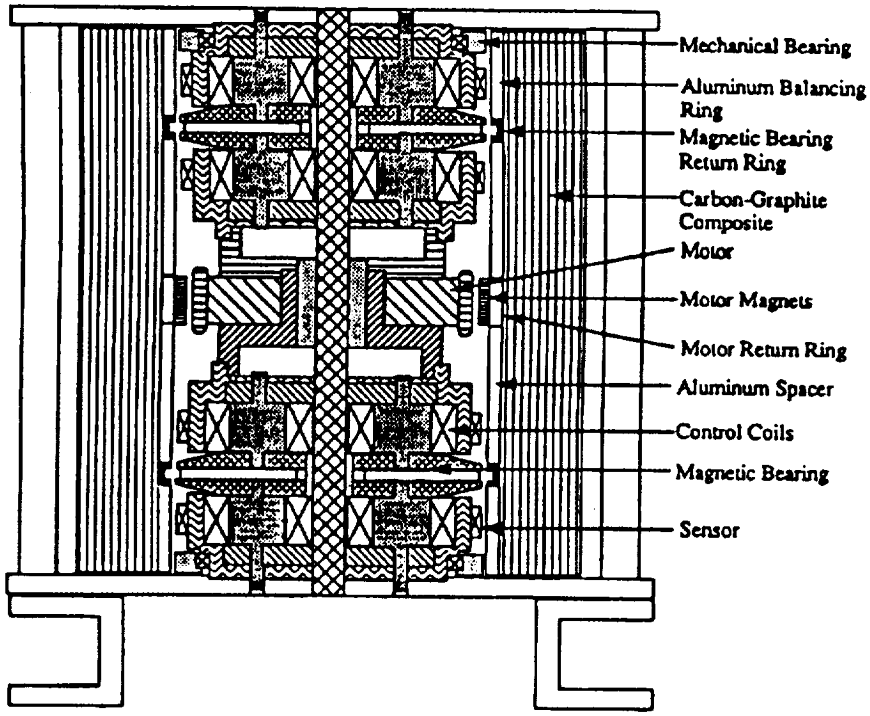

Figure 1 - Cross section of OCCF Components

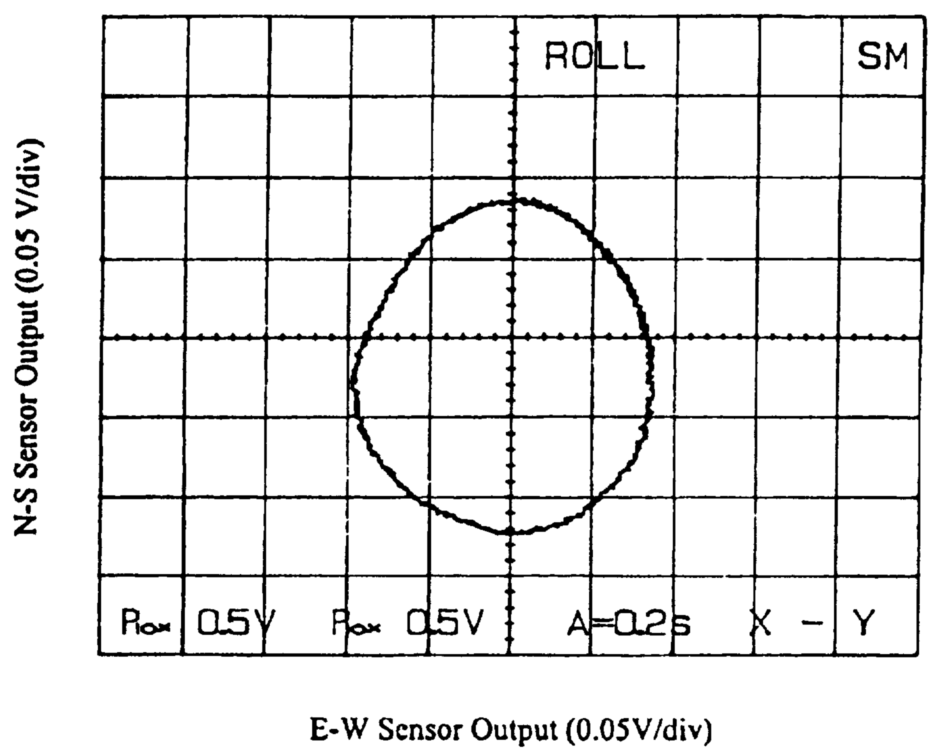

Figure 4 - Pancake Magnetic Bearing Displacement Output

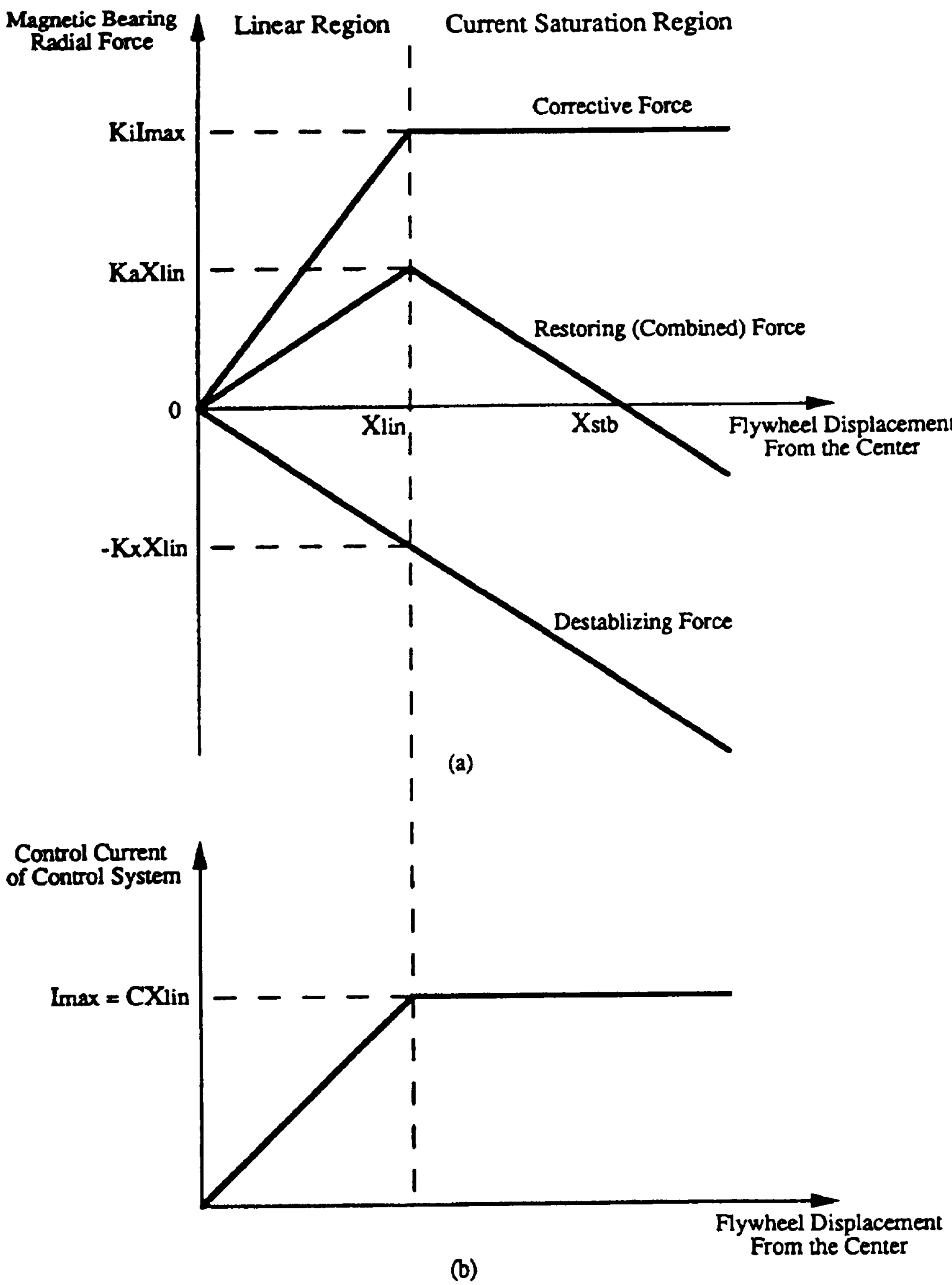

Figure 2 - Radial Forces and Control Current Output of Magnetic Bearing

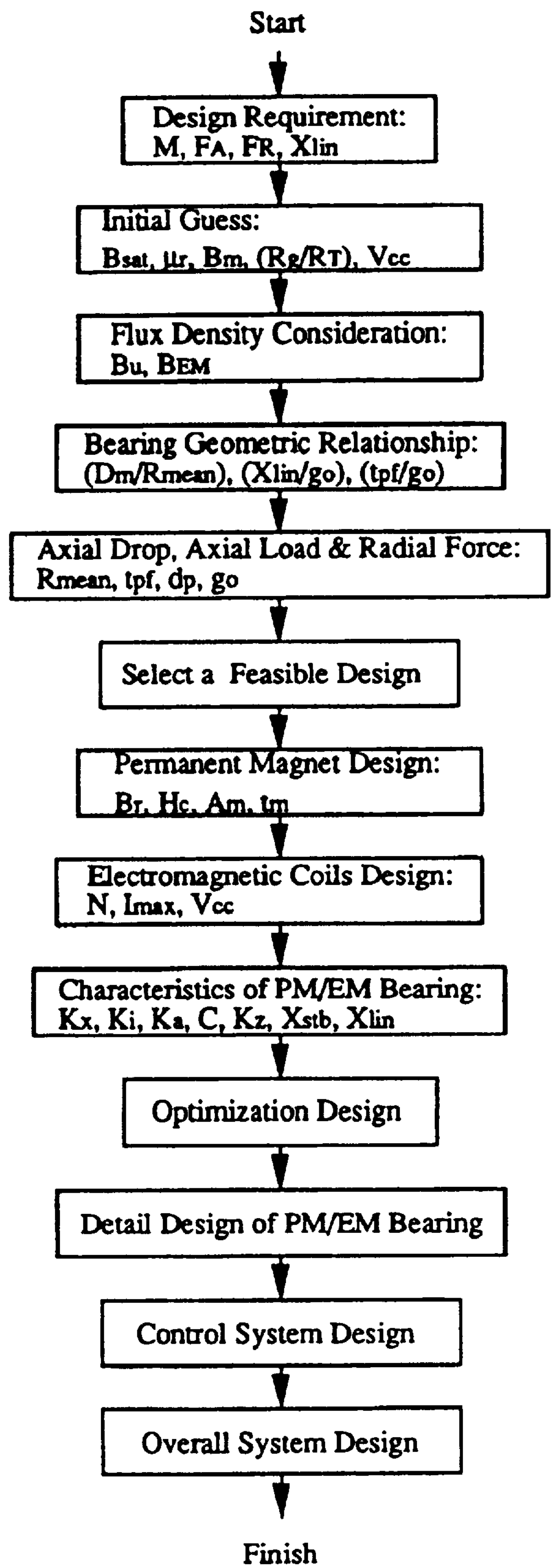

Figure 3 - Design Methodology Flowchart of PM/EM Magnetic Bearing

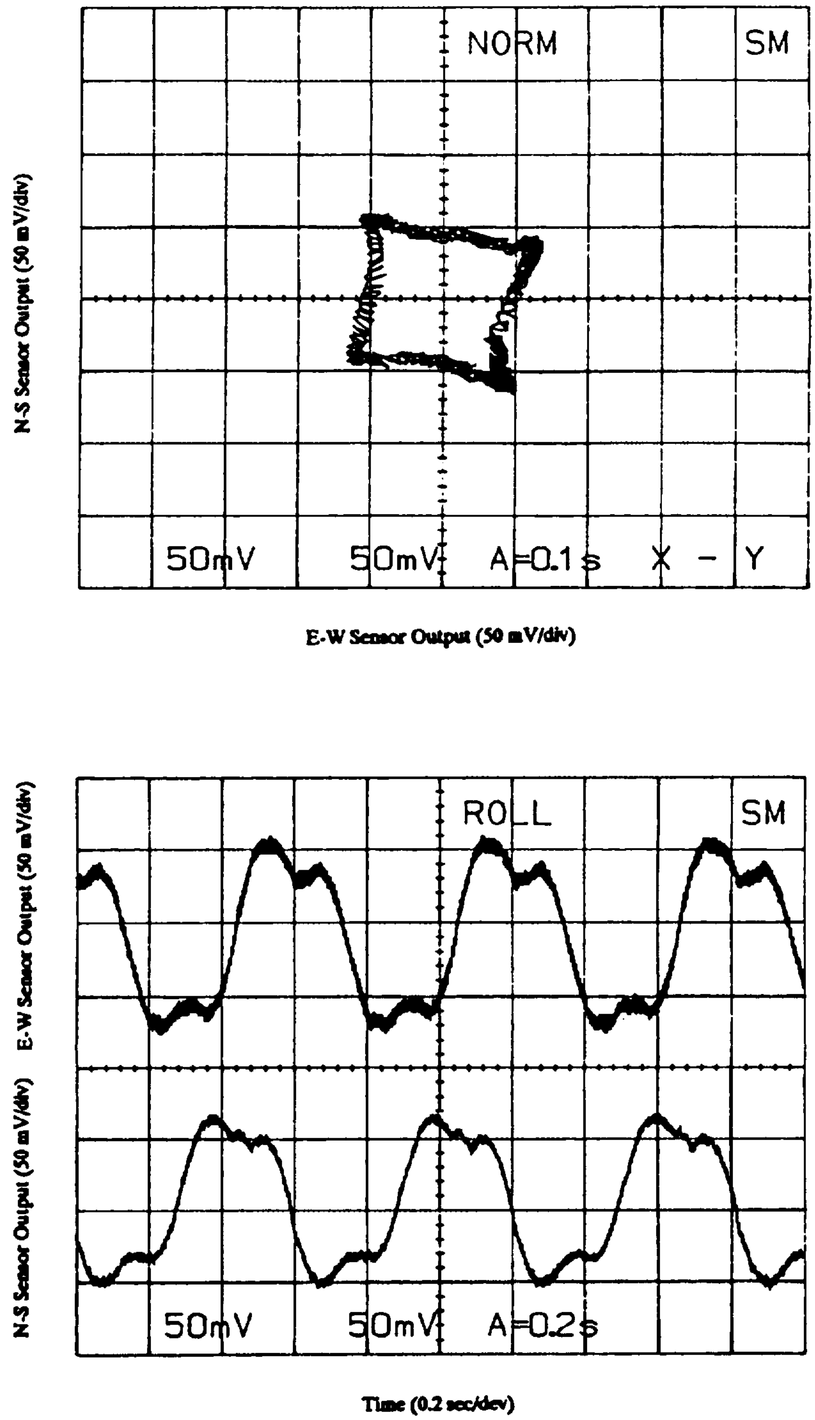

Figure 5 - Top Stack Bearing Displacement Sensor Output

TABLE 1

SPECIFICATIONS OF MAGNETICALLY SUSPENDED FLYWHEEL ENERGY STORAGE SYSTEM

FES Systems Designs Specifications

Deliverable Energy:	171 Wh
Useful Flywheel S.E.D.:	30.2 Wh/Kg
Operating Speed:	37,875 - 75,750 RPM
Cycle Period:	90 Minutes (60-minute Charge Cycle, 30-minute discharge cycle)
Power Line Output:	150±2 V DC
System Efficiency:	85%

FES System Specifications

Max. Operating Speed:	20,000 RPM
Stored Energy:	15.9 Wh at 20,000 RPM
Angular Momentum:	54.75 N-m-sec (40.38 lb-ft-sec) at 20,000 RPM
Flywheel Tip Speed:	165 m/s at 20,000 RPM
Runoff Error:	<0.038 mm (0.0015 in)
Vacuum Condition:	~10^{-4} Torr
Power Loss:	~70 W at 16,000 RPM

TABLE 2

DEVELOPMENT OF FLYWHEEL ENERGY STORAGE SYSTEM

Rotating Speed (RPM)	Test Conditions	Limiting Factors	Corrective Actions
	Old FES System	Poor Magnetic Bearing Performance	Design of New Magnetic Bearings & FES System
All Speed Range	Magnetic Saturation of Return Rings	3rd Harmonics Affecting Stability	Selection of Return Rings with Minimum Magnetic Saturation
4,000	±24 V Power Amplifiers & 750-turn EM Coils	Magnetic Bearing Power Amplifier Voltage Saturation	(1) ±90 V Improved Howland Bridge Amplifier Installed, (2) Use of 500-turn EM Coils to Reduce Inductance
6,000	Undamped Structure	Structure Vibration	Rubber Vibration Isolators Installed
6,000	Flywheel as Manufactured	Mass Unbalance	Balancing Flywheel Using Displacement X-Y Orbit
8,000	FES System Operating in Air	Windage Loss	Vacuum System Implemented
10,000	PM DC Brushless Motor Controller	Motor Current Limitation due to Impedance Mismatch Between Motor and Motor Controller	(1) Use of Variac to Adjust Motor Controller Input Voltage, (2)Dummy Inductors Added to Motor Inputs
12,000	Hand Wired Electronics Boards for Controllers, Sensors, & Power Amplifiers	(1) Inconvenient to Adjust Stiffness & Damping of Magnetic Bearings (2) Reliability	(1)Adjustable Stiffness & Damping Controller Implemented, (2)Use of Print Circuit Boards for All Electronics
15,000	Phototransistor Reflective Optical Sensor with 1 ms Response Time	Time Delay of Motor Commutation Signal	Photodarlington Reflective Optical Sensor and Schmitt Trigger Installed with 0. I ms Response Time
20,000	Existing FES System with Improved Components	Motor Current Limitation	(1) Power Loss Analysis Suggesting Lamination of Magnetic Bearings, (2) Future Improvements on Motor & Motor Controller