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SYSTEM CHARACTERIZATION OF A MAGNETICALLY SUSPENDED FLYWHEEL

PROGRESS REPORT ON NASA GRANT NAG 5-396

BY

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For the period

February 1988 thru October 1988

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I. INTRODUCTION

The purpose of flywheel energy storage is to provide a means to save energy during times when the satellite is in sunlight, and then return the energy during the time when the satellite is in darkness. Typically, an energy storage device operates cyclically, where for satellites in Low Earth Orbit the typical period is 60 minutes of sunlight followed by 30 minutes of darkness. If a lifetime of 17 years is required the energy storage system must be capable of sustaining approximately 10^5 cycles.

The work presented in this report covers the recent developments at the University of Maryland and how these progressions apply to a 500 Watt-hour magnetically suspended flywheel stack energy storage system. The work includes hardware testing results from a stack flywheel energy storage system, improvements in the area of non-contacting displacement transducers, and performance enhancements of magnetic bearings. The experimental results show that a stack flywheel energy storage system is a feasible technology.

II. GOALS OF THE PROJECT

For Low Earth Orbit Satellites (LEO), including space station, the energy storage cycle is approximately 60 minutes of sunlight followed by 30 minutes of darkness. Typically, the Nickel-Cadmium battery (at 1.3 volts per cell) is used for energy storage. To achieve the necessary bus voltage, cells are placed in series, and the resultant system has a cyclical energy density of, perhaps, 6-7 Wh/Kg.

For future applications, where satellite bus voltages are expected to approach 200 volts, batteries present difficulties because of limited cycle lifetimes, reliability problems of numerous cells in series, and difficulties in measuring the state of charge. Because of these difficulties with batteries, NASA has a modest ongoing effort at the University of Maryland to look into a magnetically suspended composite flywheel energy storage system. The goals for the University of Maryland effort are directed towards achieving a working energy storage system suitable for unmanned satellites.

The specific design goals of the University of Maryland project are as follows:

1. A system energy density greater than 20 Wh/Kg.
2. A round trip cycle efficiency of 80%.
3. Bus voltages of 150 volts D.C.
4. Demonstrated cycle testing to 1000 cycles.

III. PROGRESS DURING THE REPORTING PERIOD

This progress report focuses on several laboratory developments during the past year. The major development being improvements in the current stack system in the laboratory. Two further developments, which will be discussed in greater detail in this progress report, are non-contacting position transducers and performance parameters of magnetic bearings. Other work performed at the University of Maryland in the past year but not included in this progress report can be found in references 25,26,27, and 28.

A. STACK IMPROVEMENTS

A stack prototype was built approximately two years ago at the University of Maryland, see figure 1. This stack consisted of two pancake magnetic bearings of 7.62 cm (3 in.) outside diameter. Also included in this preliminary design were touchdown bearings and an aluminium flywheel. For this initial design the intention was to prove the stack concept, therefore such technologies as composite material flywheels and brushless motor/generator were not incorporated with this initial design. Although this stack configuration magnetically suspended the flywheel, some further development of the stack system was necessary. In the following paragraphs a description of these developments is presented.

Before suspension of the stack system can be achieved, the two magnetic bearings, which makeup the stack system, must be positioned concentrically relative to each other. This is because the linear range of the control system for the stack system is 0.254 mm (0.010 in.). If the magnetic bearings are not concentric relative to each other this could produce a situation where the amount by which the bearings are not concentric is greater than the linear range of the control system. Such a case would be impossible to suspend magnetically. This positioning is accomplished in the mechanical design of the stack system. The current magnetic bearing design consists two bias flux plates sandwiching permanent magnets and two control flux plates sandwiching electromagnets, see figure 2. To this design dowel pins were added to the bias flux plates to secure these plates from shifting relative to each other. Stricter mechanical tolerances were applied to ensure the positioning of the magnetic bearings and other stack parts. The net effect of these changes produced a stack system which can be assembled and disassembled while retaining its original position.

The original stack system had its bottom magnetic bearing fixed to a base plate and the top magnetic bearing was not fixed. With this arrangement, vibrations of the stack system were noticeable. These vibrations of the stack system were the result of the flywheel producing oscillatory forces on the stator portion of the stack system. The corrective action to alleviate the noticeable vibrations was to provide the stack system with a rigid support structure, see figure 3. This support structure fixes both magnetic bearings so not to produce a cantilever effect as with the previous setup. An added benefit to the support structure, seen in figure 3, is that upon failure of the rotor the support structure doubles as a containment facility.

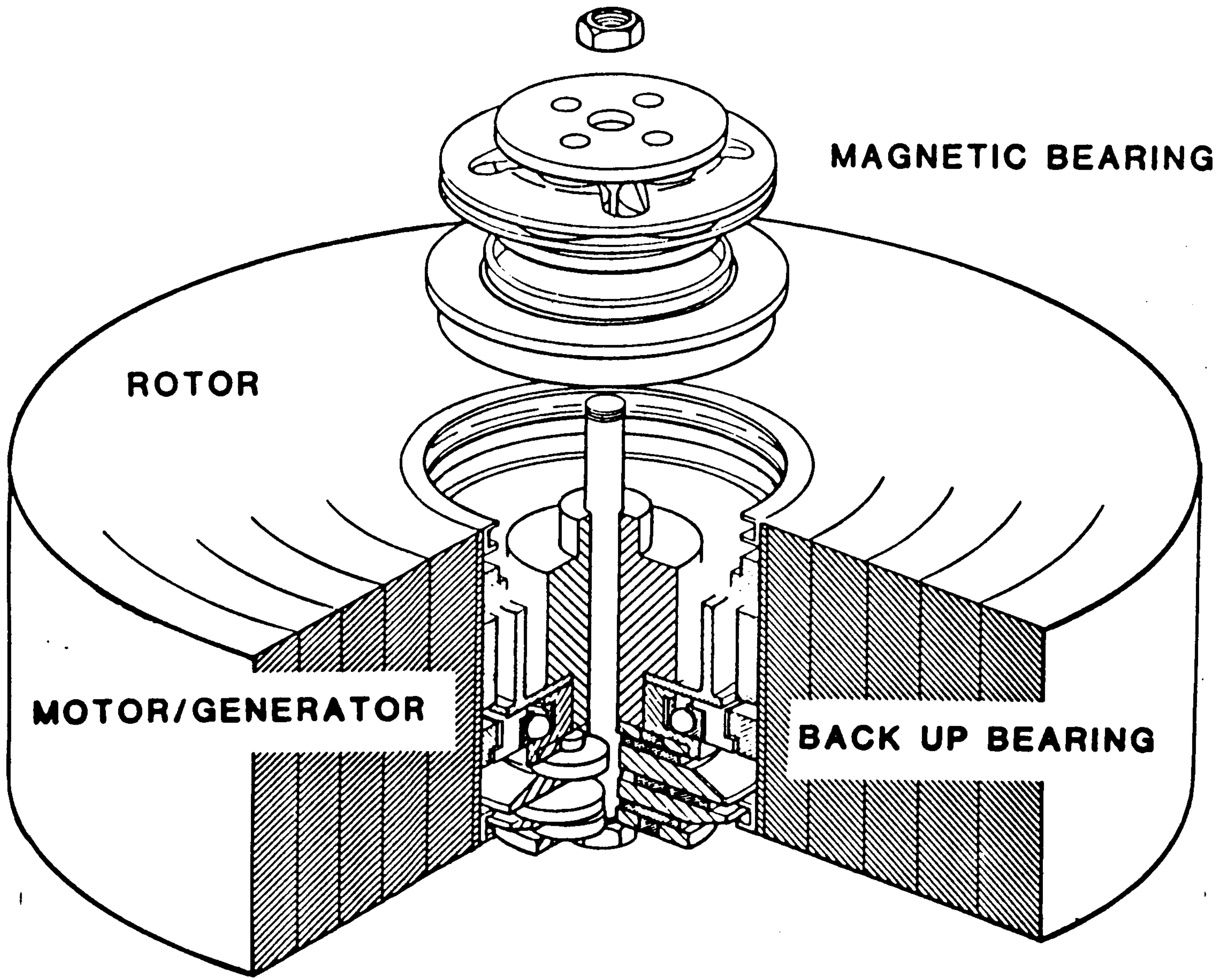

Figure 1. Cut away sectional View of the Flywheel Energy Storage System.

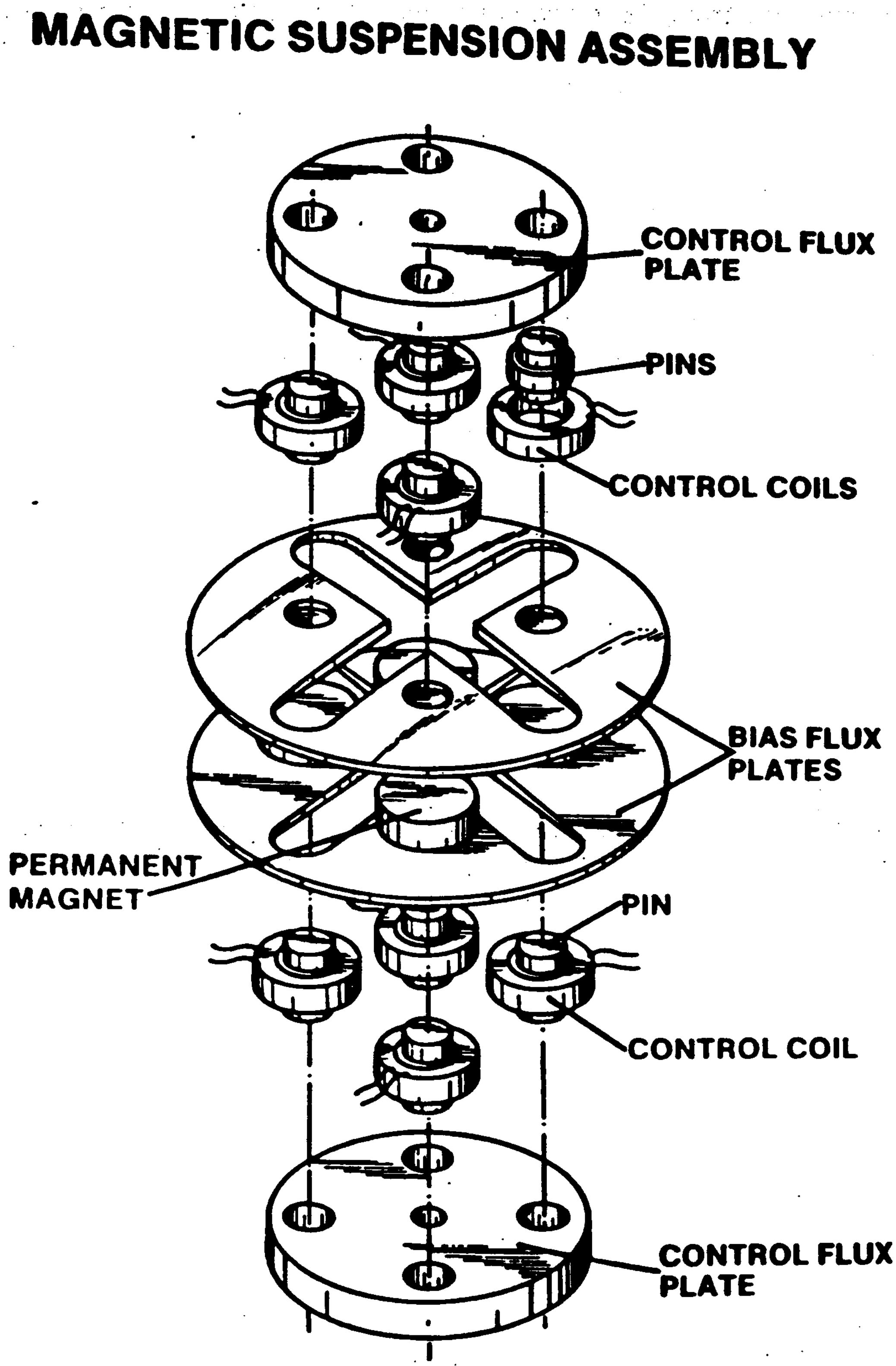

Figure 2. Exploded view of the Permanent Magnet + Electromagnet Pancake Magnetic Bearing assembly.

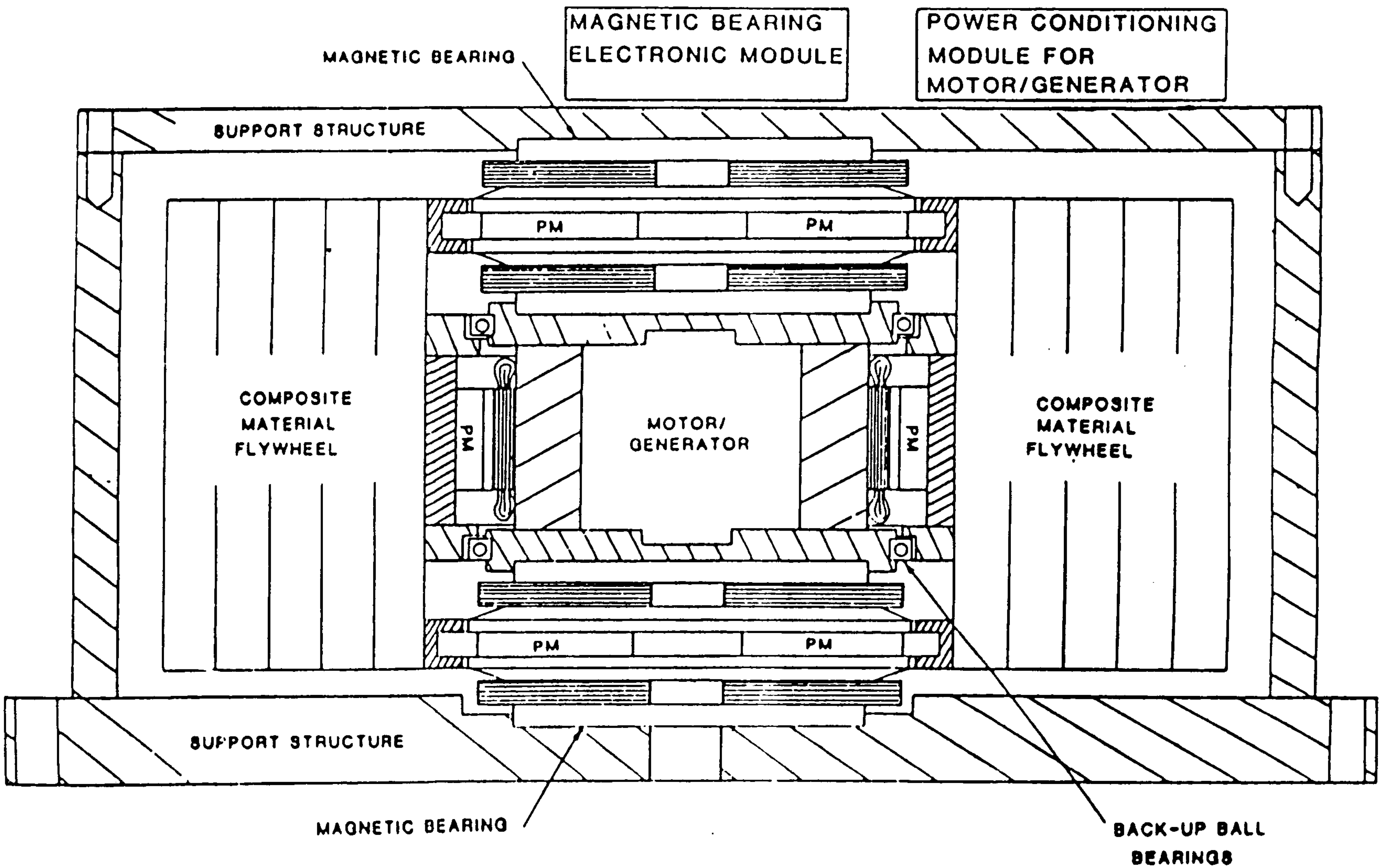

Figure 3. Cross section view of the University of Maryland Flywheel System.

To protect the magnetic bearing, suspension ring and brushless motor/generator when failure of the magnetic suspension occurs, back-up ball bearings are used, see figure 4. The outside portion of the touchdown bearings is set just beyond the linear control range of the magnetic bearing, this range has been mentioned previously and is typically 0.254 mm (0.010 in.).

With the above inclusions the stack system was rotated to a speed of 5630 rpm. At this speed the flywheel became unstable do to the flywheel reaching a natural frequency. A need to pass through these natural frequencies while remaining stable became apparent. The natural frequency of a stack system is a function of active stiffness produced by the magnetic bearings. The active stiffness can be varied through the control system electronics, hence the natural frequency can be adjusted electronically. With this theory in mind a control system switch was developed to vary the natural frequency of a magnetic bearing system. This adjustment of gains is accomplished by placing a switch at the linear adjust gain block, see figure 5, in the control system. There are two positions on the switch with a two to one ratio of the gain. This ratio of the linear adjust gain theoretically produces a two to one ratio of the natural frequencies of the magnetic bearing system. The switch was tested using a 7.62 cm (3 in.) single magnetic bearing system equipped with a brushless motor/generator. The results of this test are presented in figure 6. As seen in figure 6, a natural frequency was encountered with the switch up, which is the lower gain value, at approximately 2000 rpm. With the switch in the down position no natural frequencies were encountered in the test, although the theoretical value was predicted at 4500 rpm. Therefore, to avoid the natural frequency at 2000 rpm the flywheel was spun up from 0 rpm to 2500 rpm with the switch in the down position. Then at 2500 rpm the switch was placed to the up position for the remainder of the test. There were also no problems experienced with changing the switch from the up to down positions. The control system switch proved to be successful in avoiding natural frequencies during spin up of the flywheel. Currently at the University of Maryland we are developing a control system switch for a stack flywheel system.

B. DISPLACEMENT TRANSDUCER DEVELOPMENT

Displacement transducers are used to detect flywheel movement and convert this movement into a voltage level which is proportional to displacement. This voltage is then utilized in the feedback loop of the control system. Current magnetic bearing systems at the University of Maryland use inductive (eddy current) type sensors. These position sensors use the outside surface of the flywheel as a target, see figure 7. All of the current flywheels are aluminium and provide the inductive type sensor with an appropriate sensing surface. For a 500 Wh energy storage system composite material flywheels must be used. The inductive type sensor can not be used in the current arrangement with a composite material. For this reason inserting the displacement sensors on the inside of the magnetic bearing to sense the suspension ring was investigated.

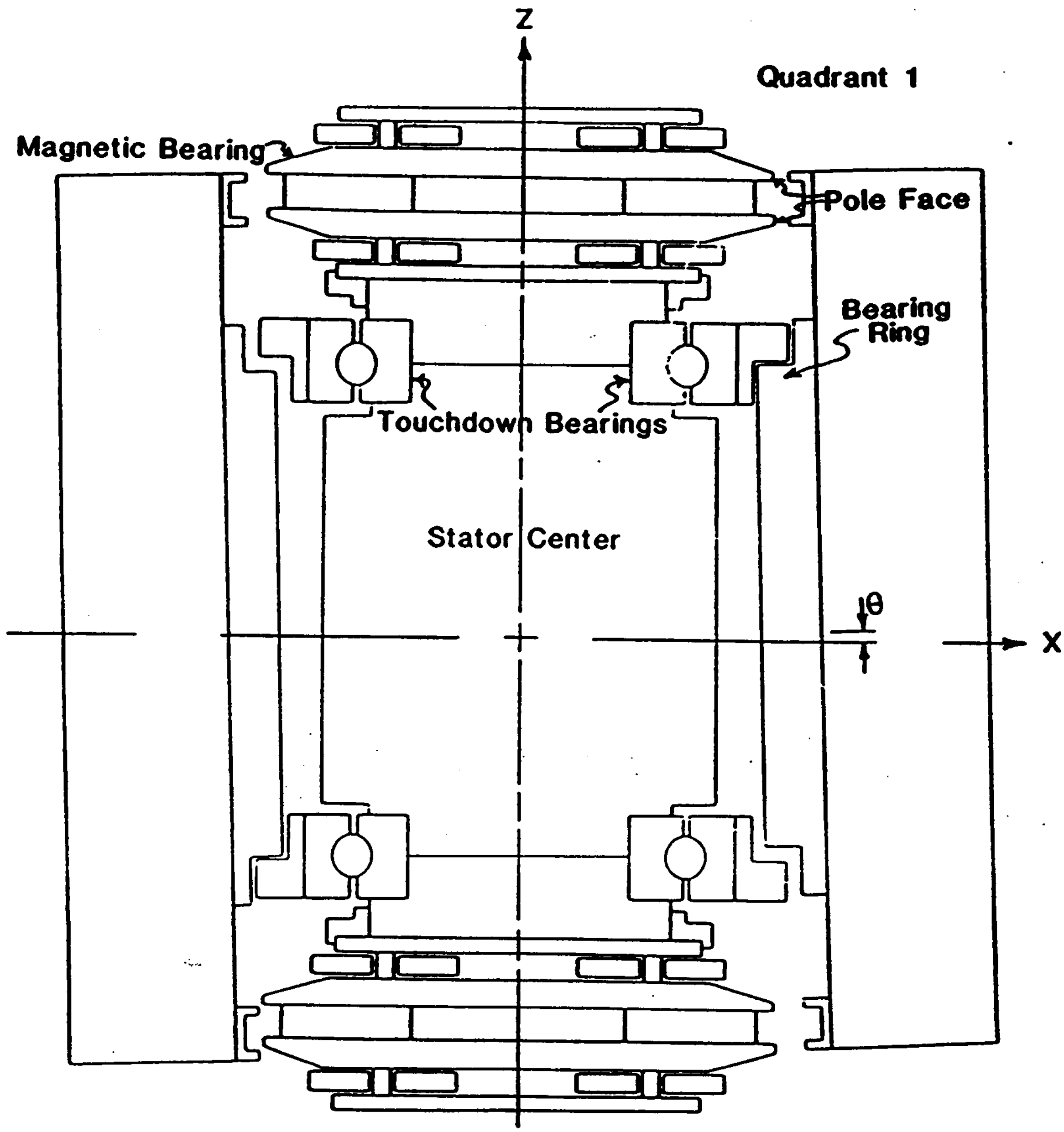

Figure 4. Touchdown Bearing design for the University of Maryland Flywheel System.

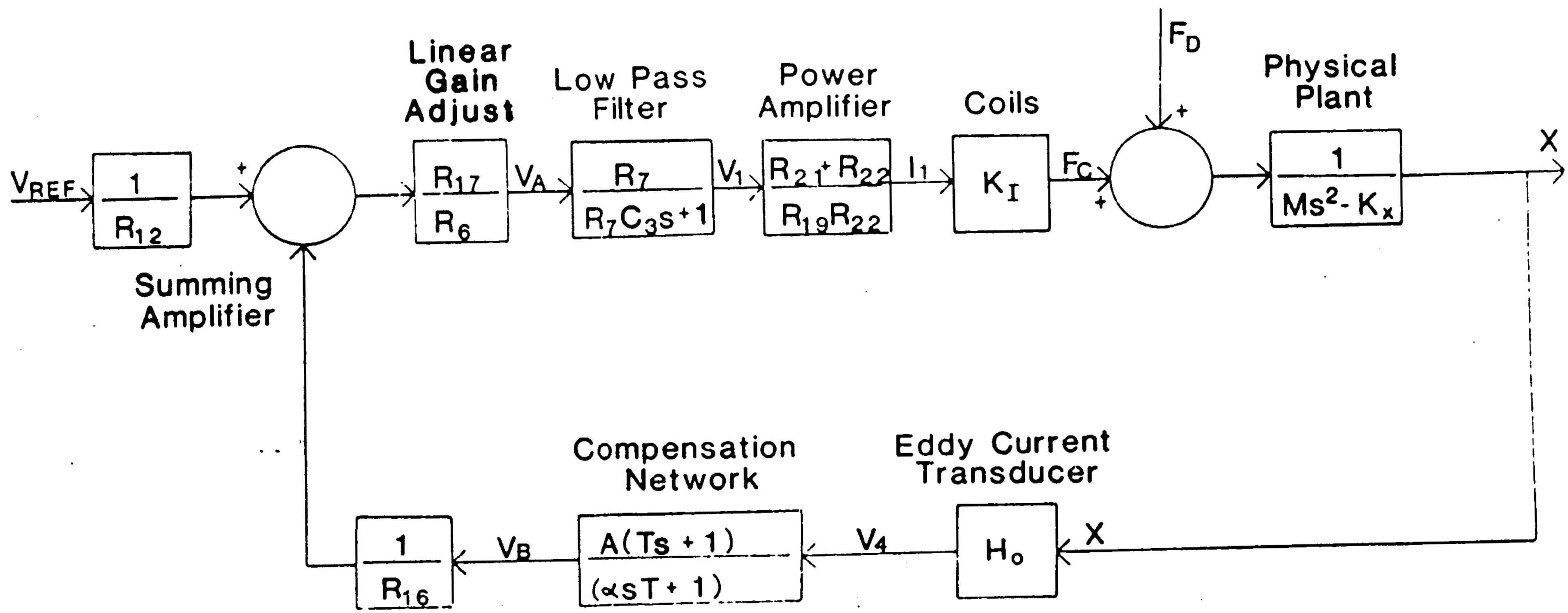

Figure 5. Control System for the Magnetic Suspension.

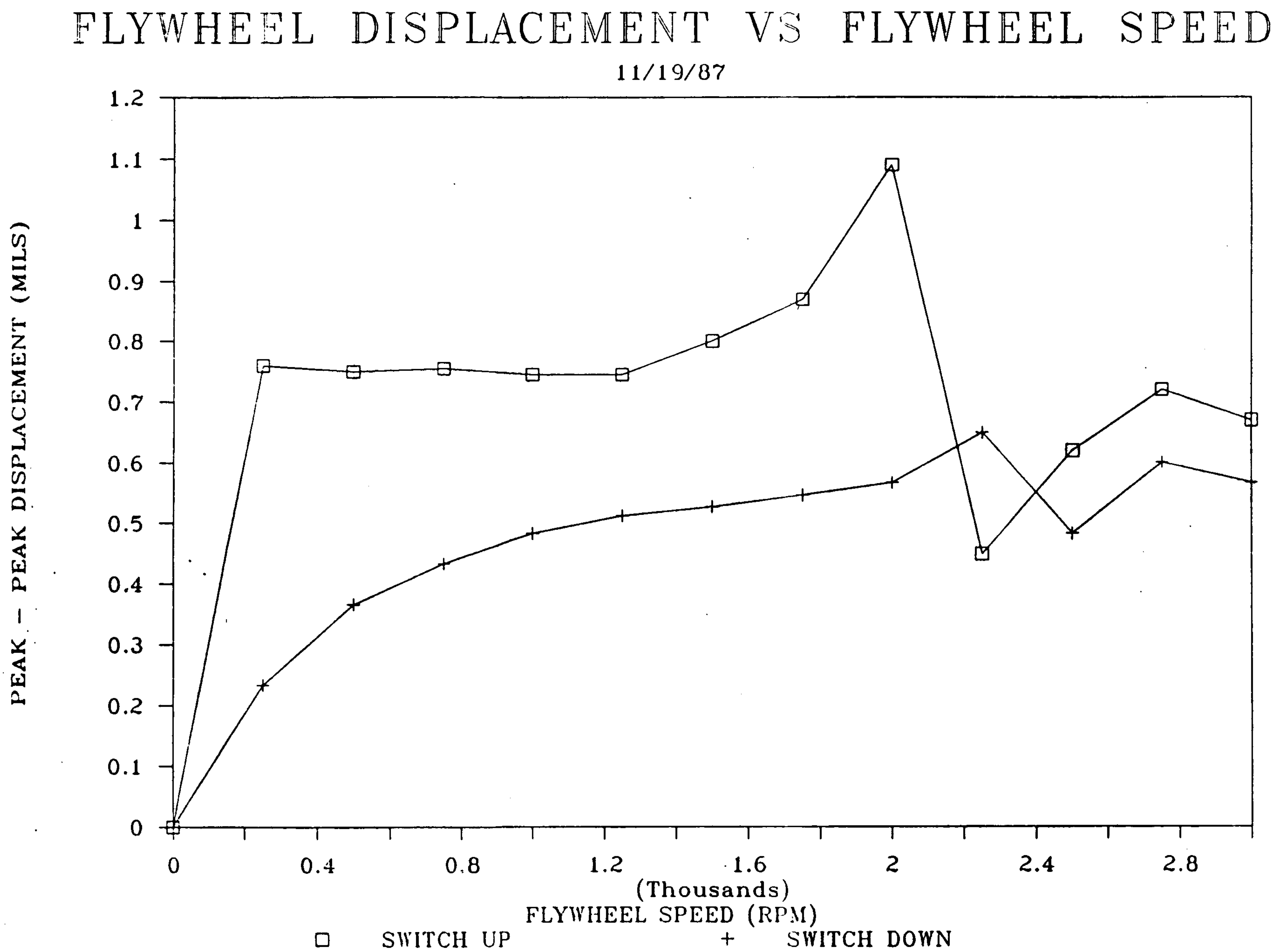

Figure 6. Control System Switching Test for evaluating Gain Switching to alter bearing stiffness.

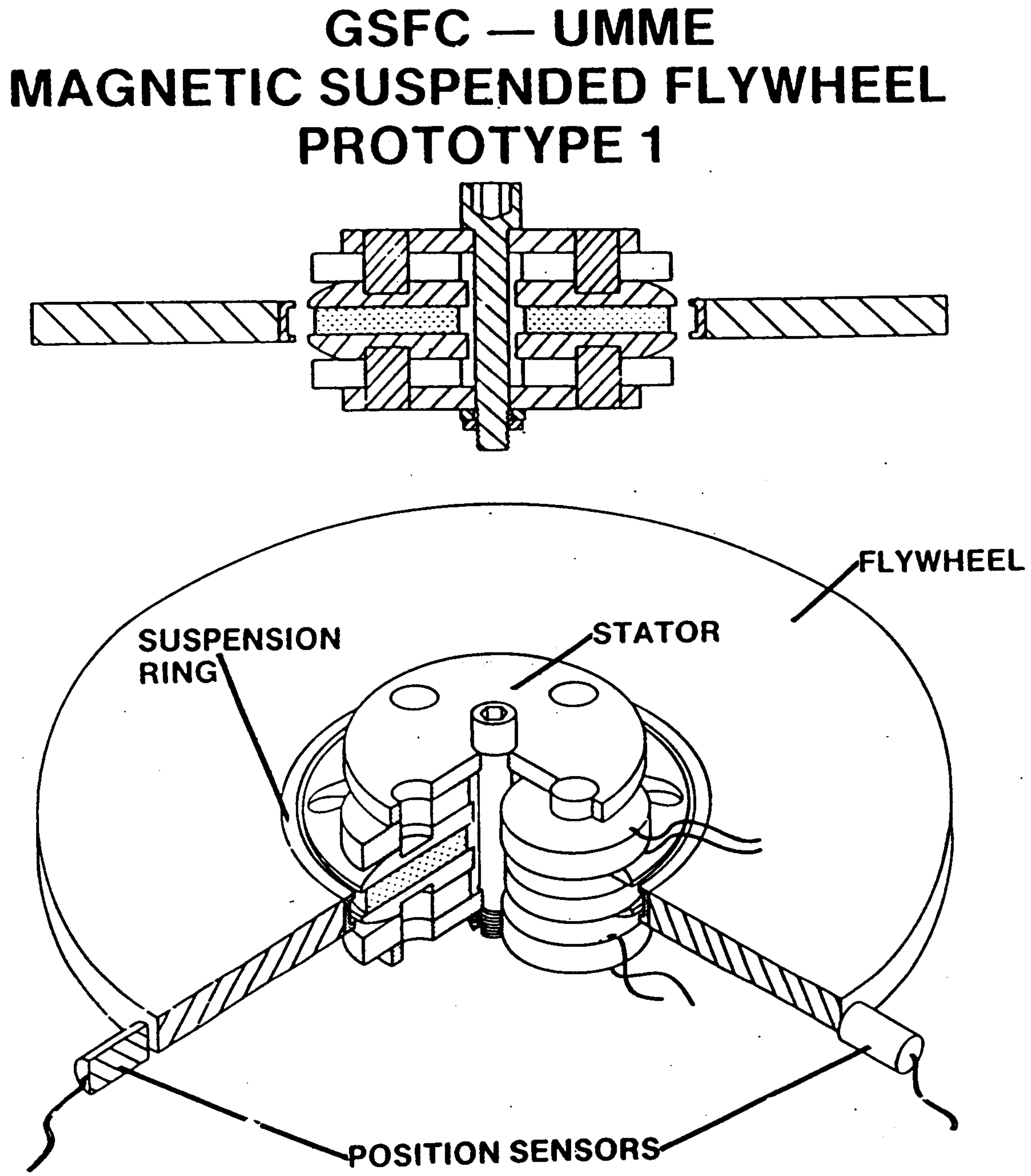

Figure 7. Pancake Magnetic Bearing.

The investigation produced several requirements of which the most important is the size limitation of the displacement transducer's probe. As can be seen in figure 2, the sensor must be placed between the bias flux plates. Most of the volume between the bias flux plates is occupied by the permanent magnets. Since these sensors must reside between iron material bias flux plates, the sensors must be able to operate in large varying magnetic fields, typically 1 to 1.5 Tesla. At flywheel speeds of 60,000 rpm radial growth of the inside diameter of a composite material flywheel is predicted at 0.483 mm (0.019 in.). This radial growth will cause the sensors to detect false displacements. Therefore four displacement sensors will be needed per magnetic bearing, two sensors per axis in a bridge network arrangement. Other requirements include the linear range and offset distance, the sensitivity in volts per inch, and the frequency response and the phase response of the sensor.

With the above specifications a survey of the non-contacting displacement transducer market was conducted. The result of this survey produced several possible displacement transducers which could be used in our magnetic bearings. The types of displacement transducers included inductive, capacitive, and optical. In addition, two sensors, inductive and optical, were constructed at the University of Maryland. The capacitive type sensor proved to be very adaptive to the size limitation problem, but had a low frequency response and was very costly. The optical sensor was quite promising with high frequency response (flat from 0 to 100kHz), linearity over large distances, very small size with the use of fiber optics, and very low cost since we could build this sensor in house. There existed one problem with the optical sensor which could not be remedied at this time which was a problem of target nonuniform surface reflectivity. The inductive sensor passed all the necessary requirements and was ultimately used as the displacement transducer for the magnetic bearing system. Referring to figures 2 and 4, the sensors can be placed between the bias flux plates in an off-axis sensing position. Currently at the University of Maryland we are developing the necessary electronics to compensate for off-axis displacement sensing.

C. MAGNETIC BEARING PERFORMANCE DATA

To improve the theoretical understanding of magnetic bearings the University of Maryland has performed numerous experimental tests during the past few years. Two such experiments are the passive stiffness variance as a function of axial drop and the weight capacity of our magnetic bearings. A figure of the experimental setup is shown in figure 8. For the passive stiffness variance as a function of axial drop experiment the flywheel is biased axially, then the flywheel is displaced radially and radial force, Fx, developed in the in the air gap is recorded. This force is then plotted versus displacement to obtain the passive stiffness for the current axial bias. The results of this experiment are shown in figure 9. Notice that the passive stiffness deceases by half its original amount at approximately the pole face dimension, a. Referring once again to figure 8, the experimental setup for the second experiment, weight capacity of the magnetic bearings, is performed by adding weight to the flywheel and recording the axial drop of the flywheel via the displacement sensor shown. A graph of the axial force versus the axial drop is

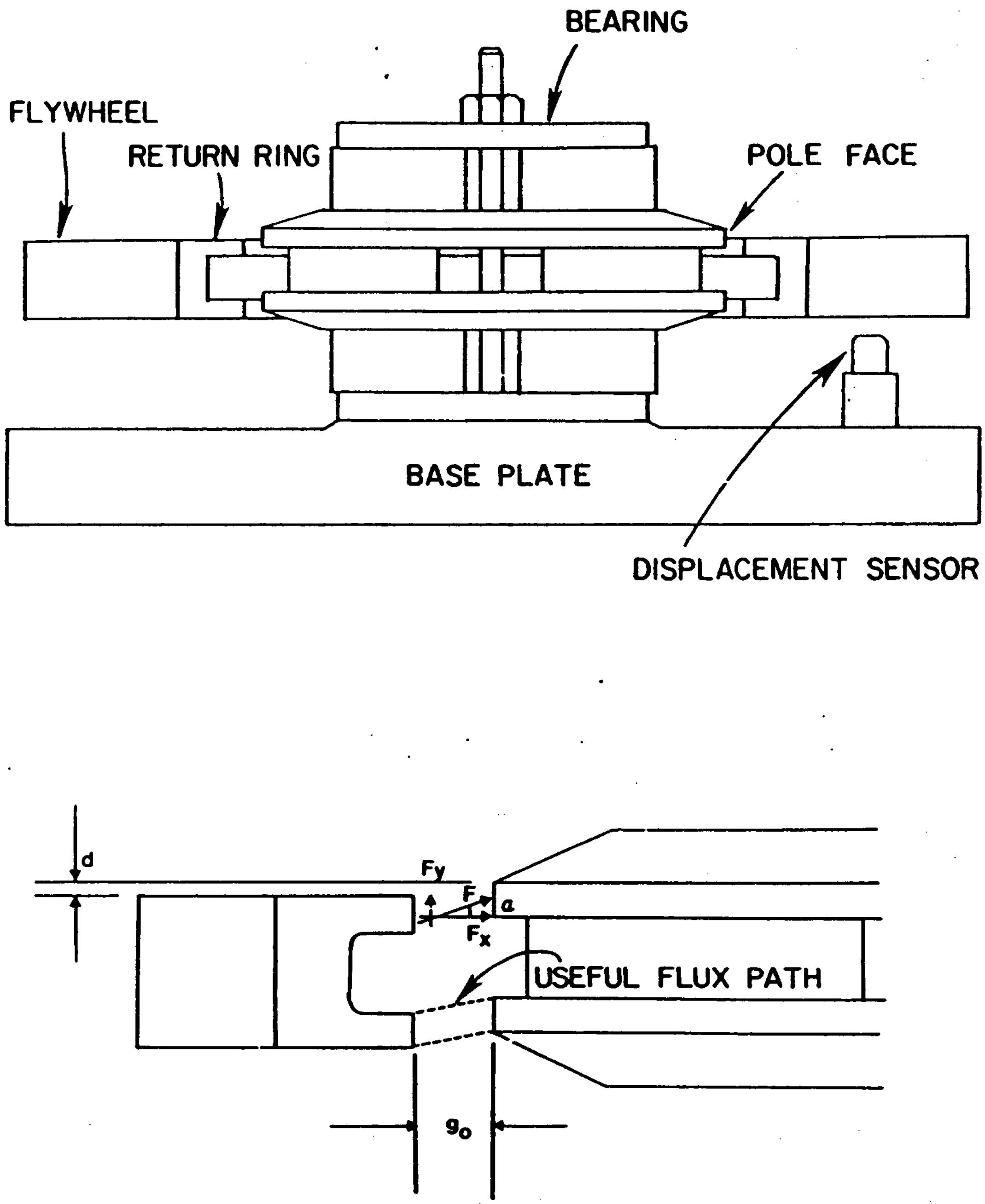

Figure 8. Experimental Test setup for Force versus displacement results for the magnetic bearing.

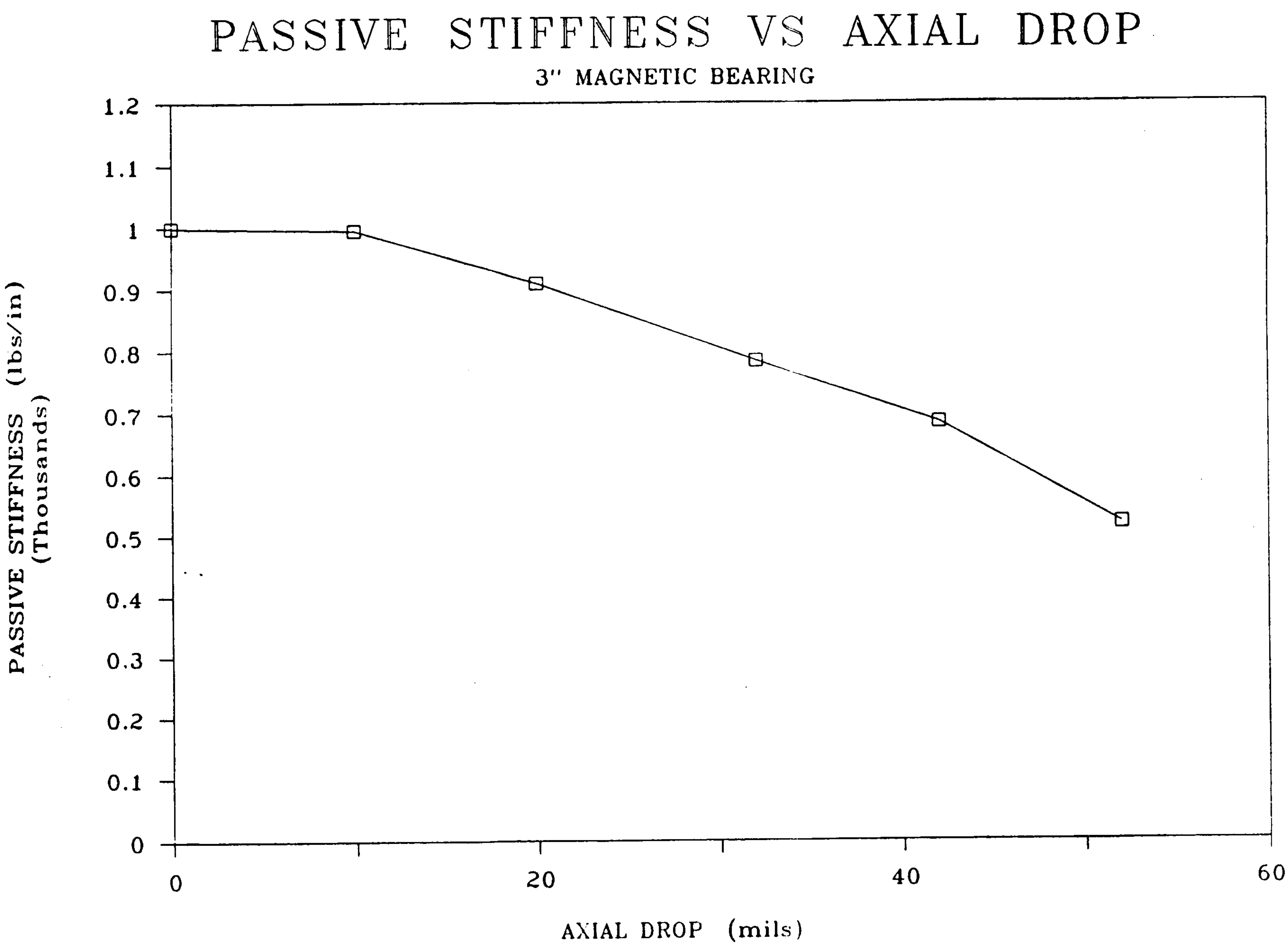

Figure 9. Passive [Axial] stiffness of the magnetic bearing as a function of axial drop.

shown in figure 10. The maximum weight that a 7.62 cm (3 in.) diameter magnetic bearing is approximately 5.45 kg (12 lbs) and for a 10.16 cm (4 in.) diameter magnetic bearing is approximately 10 kg (22 lbs). The weight capacity of the magnetic bearing is quite important because this determines the maximum energy that can be stored in a particular magnetic bearing.

IV. CONCLUSIONS

The performance of the stack flywheel energy storage system has been improved through a variety of mechanical design additions, which are more fully documented in David Plant's M.S. thesis [see Section VI]. Additional design improvements are continuing to be made and will be reported upon in the next progress report.

A control system gain switch [to change the active stiffness of the magnetic bearing] is necessary to avoid natural frequencies during spin up of the flywheel. The application of this switch has been demonstrated experimentally and the flywheel system was observed to operate without difficulties.

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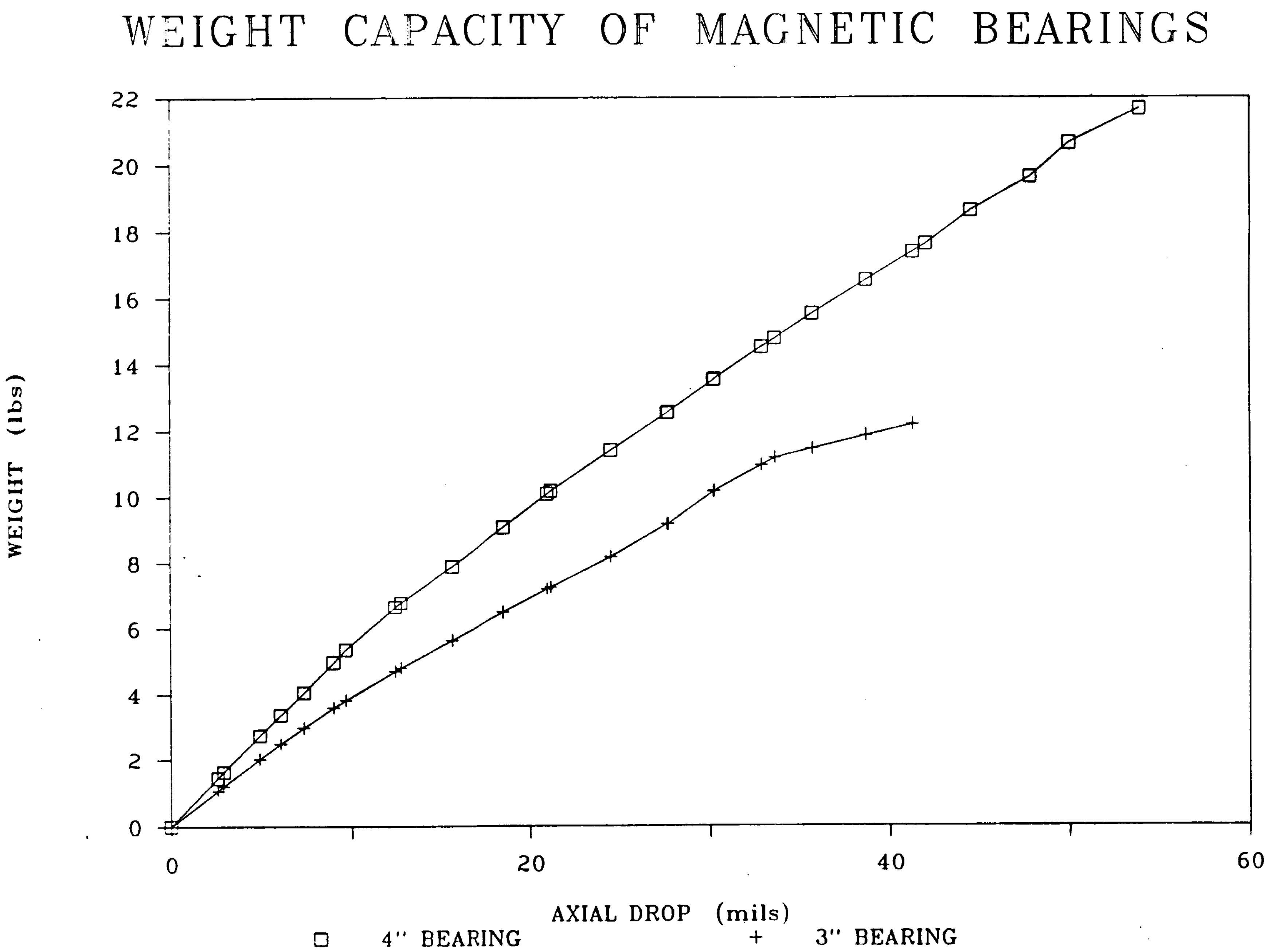

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VII. APPENDIX I - LIST OF FIGURES