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MAGNETIC BEARINGS AT DRAPER LABORATORY

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ABSTRACT

Magnetic bearings, unlike traditional mechanical bearings, consist of a series of components mated together to form a stabilized system. The correct design of the actuator and sensor will provide a cost effective device with low power requirements. The proper choice of a control system utilizes the variables necessary to control the system in an efficient manner. The specific application will determine the optimum design of the magnetic bearing system including the touch down bearing. Draper for the past 30 years has been a leader in all these fields. This paper summarizes the results carried out at Draper in the field of magnetic bearing development. A 3-D radial magnetic bearing is detailed in this paper. Data obtained from recently completed projects using this design are included. One project was a high radial load (1000 pound) application. The second was a high speed (35,000 RPM), low loss flywheel application. The development of a low loss axial magnetic bearing is also included in this paper.

INTRODUCTION

The present state-of-the-art magnetic bearings are a result of continuing development. Operational units are emerging for large pipeline and refinery gas compressors where safety, reliability and low maintenance are a high priority. Commercial applications include high speed spindles for precision machining, sealed pumps and compressors for safety and environmental concerns, turbomolecular vacuum pumps for elimination of oil systems and high speed flywheels for energy storage. A large number of prototype systems have been developed to meet these specialized needs. From these applications, many side benefits have been recognized. One such benefit is in equipment monitoring and diagnostics from both on-site and remote locations. Failure prediction and analysis are the by-products. The feedback data from the field equipment has resulted in improved new equipment designs. *A close relationship between equipment maker, magnetic bearing supplier and user is required to develop the full potential of this technology.* The present off-the-shelf magnetic bearing systems are large compared to the mechanical bearings they replace. This has led to their use in equipment where size and weight are not of primary importance. Momentum is building for commercial use, but the high initial cost

has limited magnetic bearings to niches where there is significant cost/benefit improvement. The keys to greatly expanded use of this technology is a reduction in size, weight, power and cost of the total system.

Draper has been developing magnetic suspensions for over 30 years, initially for inertial instrument suspensions and later for other military and space applications. The emphasis in recent years at Draper has been the investigation and proto-typing of active magnetic bearing systems for main shaft support in gas turbine engines. Off-the-shelf magnetic bearings were unsuitable for this application because of their excessive size and weight. Their limitations on operating temperature, speed range and the high power requirements and inefficient and expensive controllers were also a draw back. Draper has addressed all of these issues. *We have made significant advances in digital controllers, reduced the size, weight and power requirements of the actuator and have reduced the eddy current losses in the actuator which limits the rotational speed of the system.* Bearing actuator designs are simple and the control methodologies have been developed and simplified using low cost mass produced electronics. Patent applications have been filed for the actuator designs and the control techniques.

BACKGROUND

Initial work at Draper on magnetic suspensions was applied to floated inertial instruments. The first of these suspensions was an active suspension developed in the early fifties. In 1953 it was discovered that passive suspensions using tuned AC fields were possible and the technology was applied to floated instrument designs. These passive suspensions have been a mainstay in all precision inertial instruments for the last 30 years. In parallel, work has continued at Draper on active magnetic suspensions. In 1975, Draper began to apply this technology to a flywheel energy storage problem (low loss bearings) under a grant from the National Science Foundation (NSF). Since 1975, both analytical and hardware development activities have been continued toward developing actuators and associated controls with emphasis on a total magnetic suspension system.

Five-Axis Active Flywheel Bearing

This project in the mid 1970's resulted in a system which magnetically suspended a twelve pound flywheel at operating speeds to several thousand rpm's. The magnetic bearing system actively controlled five degrees of freedom during operation. The actuators chosen for this system were permanent magnet biased electromagnets. Analog circuitry provided the control.

Electromagnetic Isolator

This 1970's program produced two major results. The first was the understanding of the performance limits of a system based on electromagnetic isolation (e.g., sensors, modeling, actuators, power). The second was to examine actuator performance in a single degree of freedom system. The single degree of freedom system allowed experiments to be run more directly. This system

suspended a ten pound mass using pure electromagnetics. Both analog and digital controls were evaluated.

Flywheel Energy Systems

The CARES project was organized in the early 1980's for the development of a system that simultaneously stored energy in a flywheel and was capable of transferring the associated stored momentum for attitude control. A Lorentz force large angle magnetic suspension (LAMS), motor-generator, power electronics, flywheel, and controls were developed. A hybrid analog/digital controller actively controlled the five degrees of freedom. Draper also conducted extensive work on rotor dynamics on this project. Emphasis on the ability of magnetic bearings to change their dynamic performance in providing forces to the rotor was examined. Benefits from this approach include: suppression of whirl-mode instabilities, reduction of synchronous (mass imbalance) vibrations and eliminating gyroscopic torque couplings.

Slew Actuator-Isolator Development

This 1987 program was to determine the feasibility of using a large angle magnetic suspension system to meet the high torque, low noise requirements for a retarget and slew application. A result from this program was the development of a permanent magnet axial bearing actuator and the demonstration of the torquing and the vibration isolation capabilities of a magnetic bearing system.

Jet Engine Magnetic Bearing Effort

In 1987, a joint effort with MIT's Gas Turbine Laboratory and Draper was formed to investigate the feasibility of using magnetic bearings for main shaft support in gas turbine engines. Included here was an assessment of then state-of-the-art magnetic bearing technology to quantify load carrying capability and maximum operating temperatures.

Magnetic Bearing Test Bed

The objective of this 1988 project was to develop magnetic bearing technology for larger rotating machinery, as a means to control and minimize transmitted vibration. An approach to centralized control design methodology, involving de-coupling algorithms was developed. This Adapted Force Balancing (AFB) algorithm demonstrated significant vibration reduction. A low power radial actuator was developed and constructed with an integrated sensor assembly.

MAGNETIC BEARING SYSTEM

A magnetic bearing is comprised of a number of components when mated together form a suspension system. The major components are the Magnetic Bearing Actuator, the Magnetic Bearing Controller, the Sensor System and the Touchdown Bearing. The difficulty in the design of a total system is the determination of where and when to use magnetic suspensions. Figure 1 shows a graph of rotor speed vs. rotor support weight. The figure shows low speeds and small shaft diameters are an area where mechanical bearings are better suited for support than a magnetic bearing system. As the speeds increase, the load the shaft can support decreases because of the internal loads generated in the

bearings. To increase the load carrying capacity, a larger bearing is required which in turn lowers the speed limit of the shaft. At a point, mechanical bearings become unsuitable. Table I lists area comparisons and the support system suitable for these areas.

ACTUATOR SIZING - FIRST STEP

The basic design equation used to determine the amount of pole area required to magnetically support an object is:

$$\text{Pole Force (F)} = 57 * \text{Pole Area (A)} * B^2 \quad (1)$$

where F is in pounds, A is in inches and B is in Tesla. If the B in the air gap and the B in the material is the same, then the following equation holds:

$$N * I = B * g_o / \mu_o \quad (2)$$

where g_o is the air gap length (meters), $\mu_o = 4\pi * 10^{-7}$ (MKS), N is the number of turns and I is the current (amps). To determine the inductance of a coil, the following holds:

$$L = N^2 \mu_o A / g_o \quad (3)$$

where L is in Henry. The last of the basic equations is

$$V / L = di / dt \quad (4)$$

where V is in volts and t is in seconds.

These four equations when used together are the first steps in determining the size of a magnetic actuator. These equations also show that while all the equations are independent, when some parameters are chosen, then others become dependent. As an example, if the pole force and the maximum flux density are chosen, then the pole area is calculated (equation 1). For a given air gap and flux density, the required NI is calculated (equation 2). Given a maximum current, the number of turns is determined (equation 2), as well as the inductance of the coil (equation 3). For a maximum voltage, the maximum slew rate of the actuator is calculated (equation 4).

If the above equations were all that were necessary when designing a magnetic actuator, everyone would be doing it. The fact that more is involved can be seen in Figure 2. This figure shows a typical B-H curve for a soft magnetic material. Point P is where B becomes more difficult to obtain from a change in H. How much to the right of P an actuator is designed is one of the main design considerations. If the internal design is not correct, then areas of saturation will occur and the operation of the device will be further to the right of point P than expected. This point will also change depending on the heat treatment of the material. Internal magnetic leakage is also not accounted for with these equations and it can be as high as 20% in some designs.

PARAMETRIC STUDIES

The primary objective to any magnetic bearing design is to produce the maximum force in the minimum volume which will still be controllable over the

entire operational range. In order to accomplish this goal, extensive use of electromagnetic finite element codes are used. While the answers these codes produce are precise for the objects modeled, they do not lend themselves well in the initial design stage. At this initial stage, after the above equations are used, trade-off studies are required which FEM codes do not handle well. By using the traditional approach of a lumped parameter reluctance network, a simple linear model of the magnetic circuit is possible. Figure 3 shows a flux plot of one half of an 8 pole bearing. Figure 4 shows the same plot in cylindrical coordinates. Figure 5 shows the lumped parameter reluctance network for this same model. Using standard field equations, the reluctance values for the resistors can be calculated and the network solved using any standard electronic package. Table II shows a comparison of the results for the FEM and the lumped models. By varying the parameters in the lumped model, optimizing the actuator for maximum force for minimum volume is possible. Refining the linear analysis to include nonlinear effects due to varying parameters is also possible with this technique. The resulting model can then be used as the transfer function for interface with the control system.

DRAPER RADIAL MAGNETIC BEARING ACTUATOR (FOUR POLE-3-D)

Present off-the-shelf radial magnetic bearing actuators use motor-like configurations having two dimensional flux paths with 8 or 12 poles. These designs have two major drawbacks. The first is their high reluctance flux paths which require high input power to the control coils during operation. The second is the large number of poles create high frequency flux cycling in the rotor at rotational speed producing high eddy current loss and heating of the rotor. Both of these conditions limit the rotational speed and efficiency of the suspension system. *Draper has developed and built a radial actuator which produces high force at low power and with low rotational losses at high operating speed.*

Figure 6 shows a magnetic bearing we developed for a 1000 pound static radial load. It is a four pole design with endplates providing a continuous 360 degree return path for the three dimensional flux flow between poles, rotor and end plates. The end plate air gap area is large compared to the main pole area which provides a low reluctance return path for the bias flux. Control coils produce attractive forces at the pole gaps in two perpendicular axes. The reduced pole count, reduces the frequency of rotor currents and biasing the poles at the same magnetic polarity (Homo-Polar) reduces the cyclical flux density peak-to-peak amplitude in the rotating rotor. Both of these conditions reduce eddy current heating. The reduction of eddy currents in the rotor is an increase in efficiency of the bearing.

Magnetic bearings are operated in the biased mode to linearize the control function. This operation is the condition where the pole gaps contain one half the flux density that is required at the maximum operating condition. At no load, with all poles attracting the rotor with equal force, a state of equilibrium exists. Biasing may be achieved by either the use of permanent magnets (PM) in the magnetic

circuit or by current in coils (EM). Each of these methods have advantages. With PM biasing, the no load power requirements will be limited to the power loss due to eddy currents in the magnetic circuit. This is a desired condition where input power is at a premium, applications like space based flywheels or range extender systems. EM biased designs are attractive where the static forces are high or are desired to be adjustable during operation of the actuator.

An inside-out radial magnetic bearing actuator was developed at Draper in 1993 based on a PM biased design. This actuator was to be a part of a range extender flywheel system which was to operate up to 35,000 rpms. Figure 7 shows the rotor and stator components of the actuator. Figure 8 shows a plot of the control current vs. pole force for this design.

AXIAL MAGNETIC BEARING

A double acting axial magnetic bearing actuator was developed in 1993 as part of a range extender flywheel system. The performance goal of the axial bearing was to support a static flywheel weight of 53 Lbs. under dynamic loads of +/-120 Lbs. The design was satisfied with the unique actuator shown in Figure 9. Static load capacity was achieved using a P.M. biased design provided by high energy neodymium iron boron magnets supported by a titanium structure. The low loss actuator design contributed towards an overall high system bandwidth. Figure 10 shows the plot of control current vs. axial force for one of the delivered units.

MAGNETIC BEARING CONTROL SYSTEM

The control system is one of the features which makes the Draper Magnetic Bearing system unique. A computer based fault tolerant system can be constructed about either a Texas Instrument C40 or an Analog Device 21020 processor. The control frequency required for rotor speeds up to 60,000 rpms is 40 to 50 KHz. This assumes a bandwidth of the power amplifiers to be 4 KHz. The control system would be designed to operate in a "centralized" configuration. Past analysis at Draper has shown a magnetic bearing run in a "decentralized" configuration is subject to bandwidth limitations which makes it unacceptable to a moving platform system. Analysis has also shown the "centralized" approach produces a system with significant bandwidth and thereby performance improvements over the "decentralized" approach. One technique used at Draper for control of a magnetic bearing system was with an approach called "Linear Quadratic Regulator with Loop Transfer Recovery (LQG/LTR).

A sub-topic of control was one which dealt with synchronous vibration compensation, referred to as auto balancing. Notch filters are one such technique, but this is bandwidth limited. A Draper patented technique called "Adaptive Force Balancing" effectively compensates for synchronous vibrations over the entire control system bandwidth without producing any de-stabilizing effects. This adaptive algorithm simultaneously tracks and compensates mass

unbalance amplitude, phase and frequency, forcing the rotating shaft to spin about its center of mass rather than the geometric center. This saves enormous amounts of power during high speed operations.

An additional topic in the control system for magnetic bearings is in the use of the suspended mass to damp out vibrations at a remote location. This innovative approach to do active control of tonal vibrations is shown in Figure 11. The information from a remote vibration sensor is supplied to the controller along with tone sensor and tracker information which can be gained from the position sensors in the suspension system. The use of a phase shifter and variable gain algorithm is superimposed on the control amplifiers to vibrate the mass with the magnetic actuators. The phase, frequency and amplitude of the vibration is such, that it cancels out the vibration at the desired remote location. This remote location can be a sensitive piece of instrumentation for sighting or data collection. This approach does not require "a priori" knowledge of the sensor / actuator transfer function. This low bandwidth loop has been demonstrated at Draper. The use of this technique requires no additional hardware to the basic magnetic suspension system, but only some additional code to the control system.

In applications where high reliability is essential, such as an aircraft engines, fault tolerant controllers are necessary. Draper has been a leader in this field for over twenty years. In 1990 a prototype single board fault tolerant controller, based on Transputer Technology was designed and built.

TOUCHDOWN BEARINGS

Draper has been a leader in the design and development of precision bearing assemblies since the 1950's. This includes ball bearings, gas bearings and journal bearings. At this time, over one million space based hours have been accumulated on Draper built ball bearing assemblies without a failure. Hemispherical gas bearings assemblies designed and built by Draper into precision inertial instruments have an estimated MBTF of over 250,000 hours. A Draper designed journal bearing is contained in a pump 2 inches long by two inches in diameter which runs at 20,000 rpm's and produces 90 watts of hydraulic power. Draper has developed machining techniques and technologies which enable the wide spread use of ceramics to be utilized in precision roller bearing designs. The development of a touchdown bearing comprised of a ceramic material with a dry lubricant base has been researched at Draper.

The technology used for a touchdown bearing is dependent on the application. If fluid is present, a journal bearing may be the most cost effective approach. If vapors are present, then a gas bearing may be the design of choice. If these options are not practical then a roller element bearing would be necessary. Draper has and continues to maintain the expertise in all these fields to properly design and manufacture an optimum touchdown bearing for most applications.

CONCLUSIONS

To produce a cost effective magnetic bearing requires a full systems approach to the problem. Having just the actuator on hand will not provide a magnetic bearing. The mating of the magnetic actuator technology with control techniques and touchdown bearing designs will produce the desired effect of having a cost effective long life, low power magnetic bearing. Other important issues for the successful application of magnetic bearings include power drive systems, digital control computers and sensors which are light weight, fault tolerant and compact. Draper has been and continues to be a leader in the pioneering fault tolerant systems. Draper has the unique ability to apply these critical technologies to the design and development of magnetic bearings.

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**Table I
Rotor Support System Trade-off**

GROUND BASE SYSTEMS	VEHICLE BASE SYSTEMS	SPACE BASED SYSTEMS
Medium Production Volume	High Production Volume	Low Production Volume
Large Supported Mass	Small to Medium Mass	Small to Medium Mass
Low Env. Input	Large Env. Input	Large at Launch Small During Mission
Size Secondary	Size & Power Prime	Size & Power Prime
Magnetic Suspension System of Choice	Mechanical Suspension System of Choice	Magnetic Vs Mechanical Suspension Trade-off: Power, Speed, Size, Life

**Table II
Comparison of FEM & Lumped Parameter Model**

B in Gap	Lumped Parameter Model	Finite Element Model
Pole 1	1.71	1.74
Pole 2	.51	.55
Pole 3	.08	.10

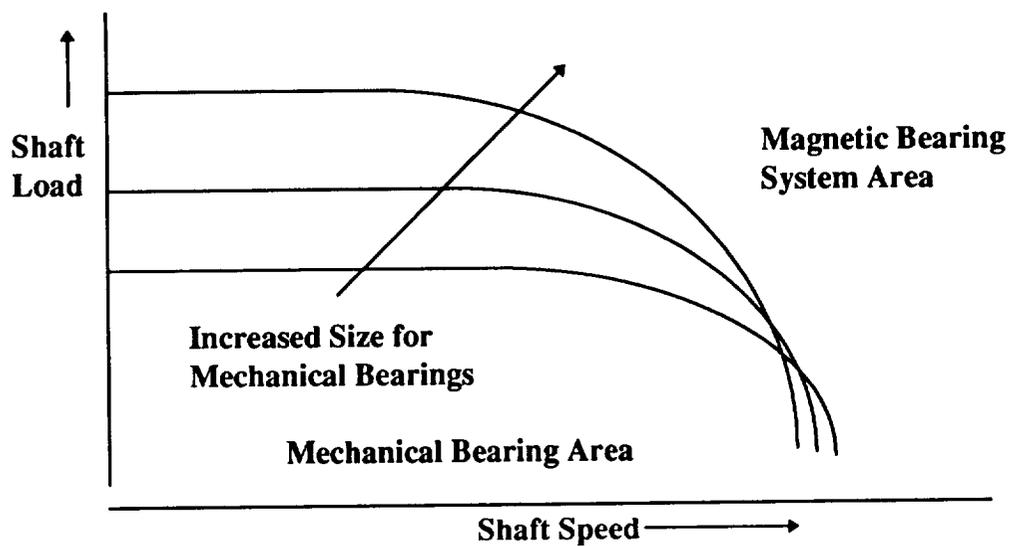


FIGURE 1

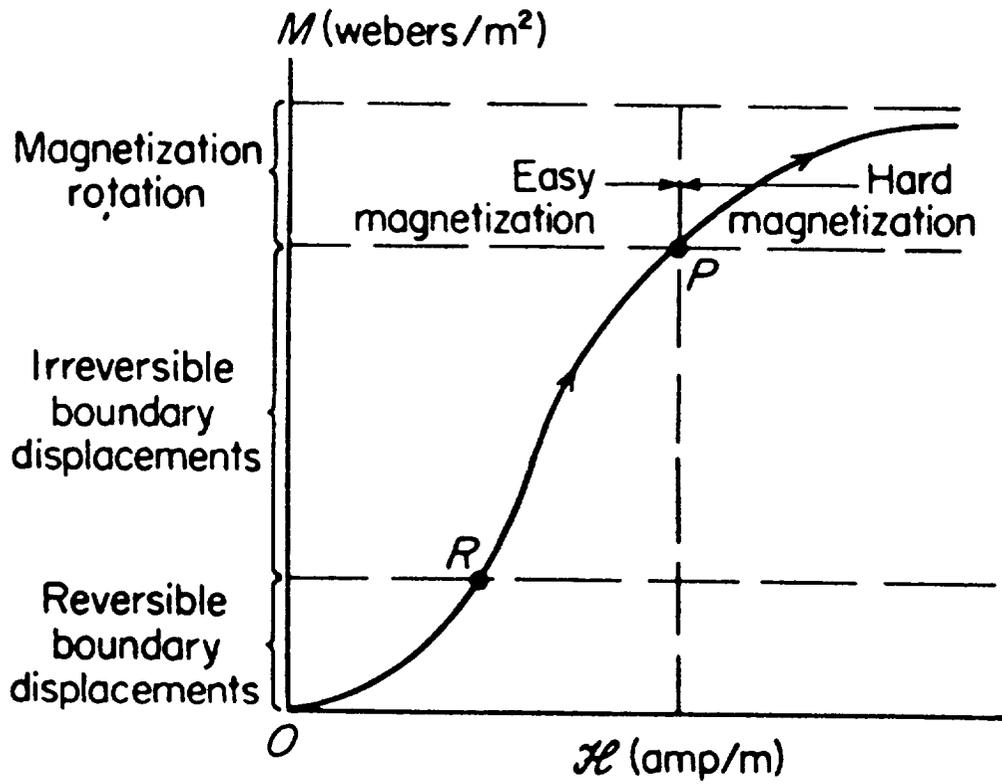


FIGURE 2

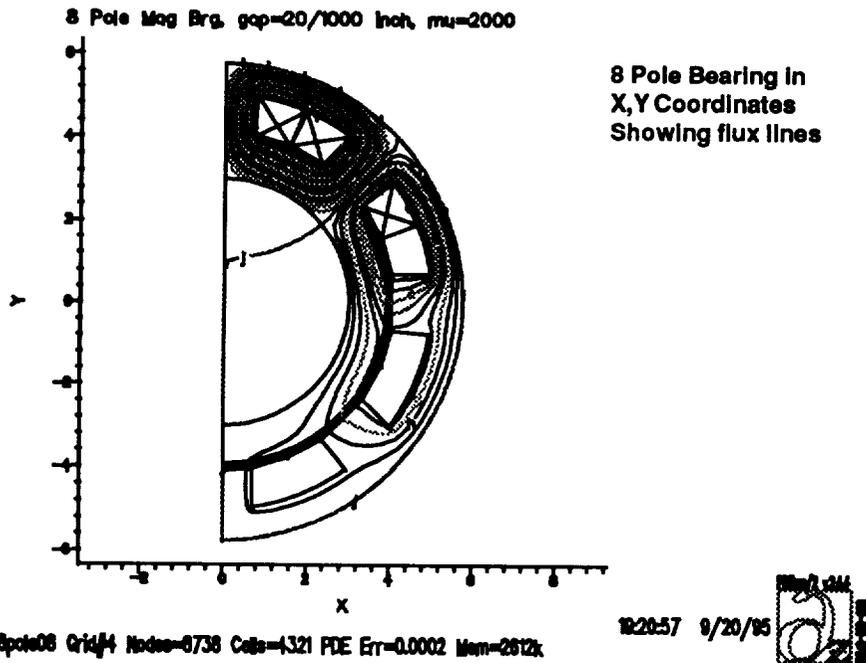


FIGURE 3

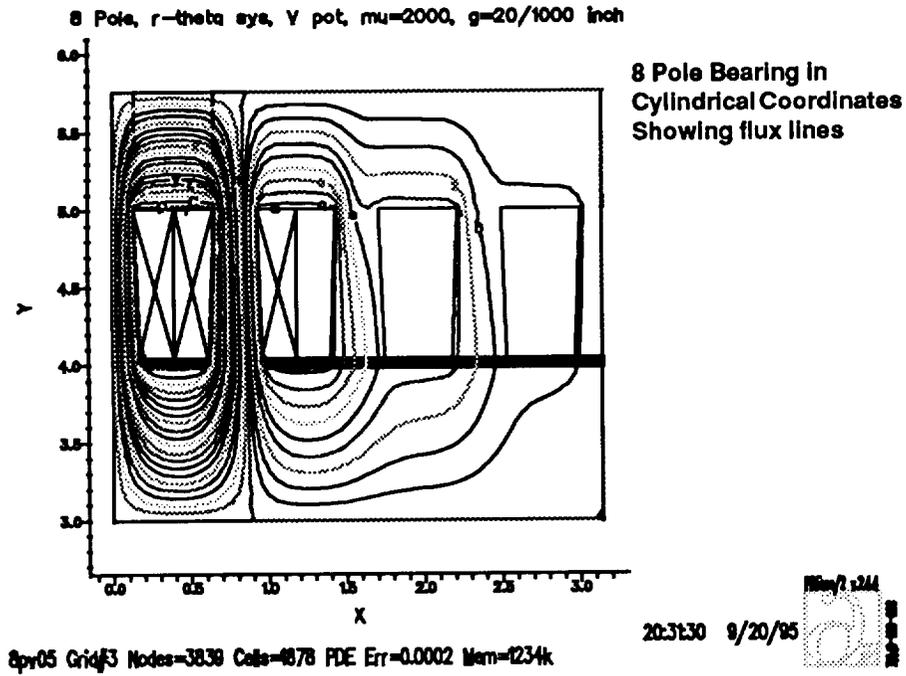
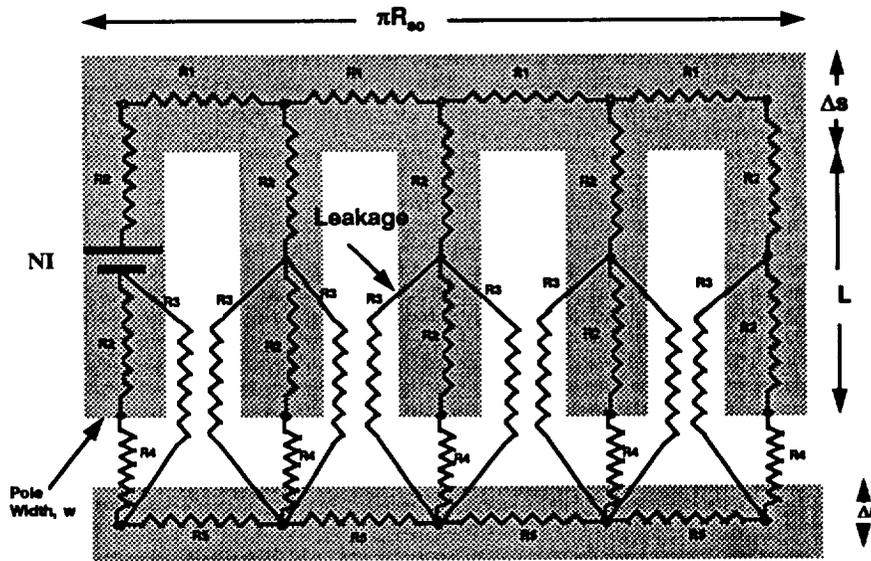


FIGURE 4



$\Delta s=.75''$ $L=1''$ $\Delta r=1''$ $W=1.4''$ $R_{oo}=5.75''$ $\mu_r=2000$ $\mu_o=4\pi e-7$

FIGURE 5

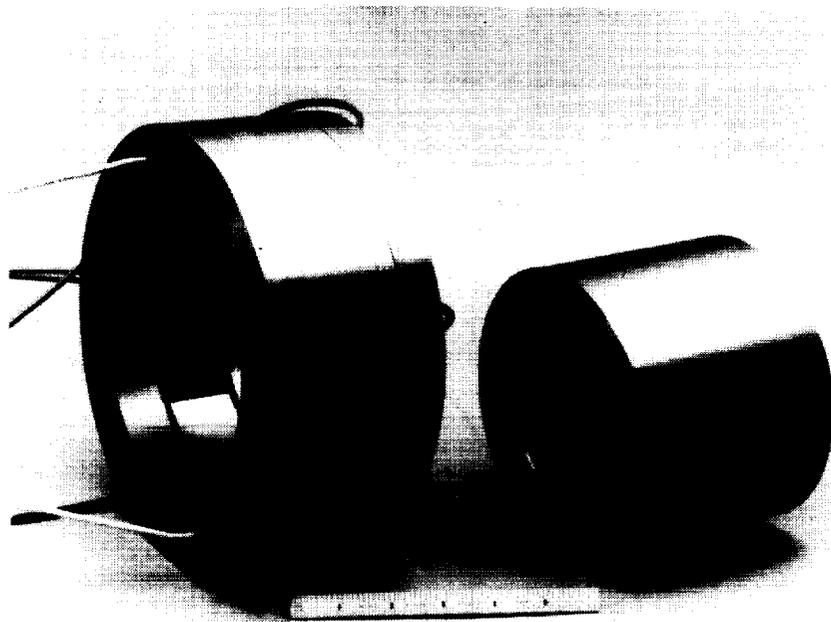


FIGURE 6

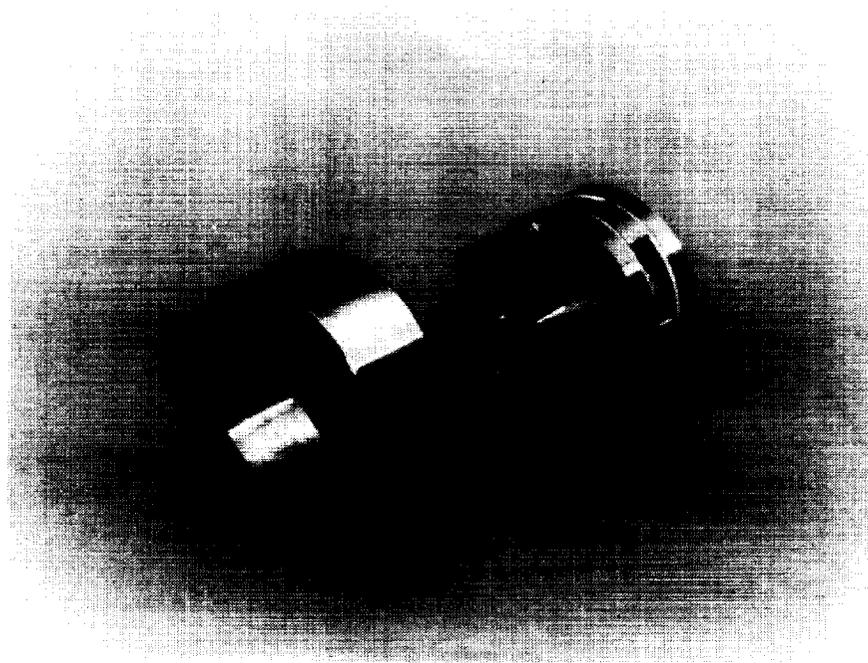


FIGURE 7

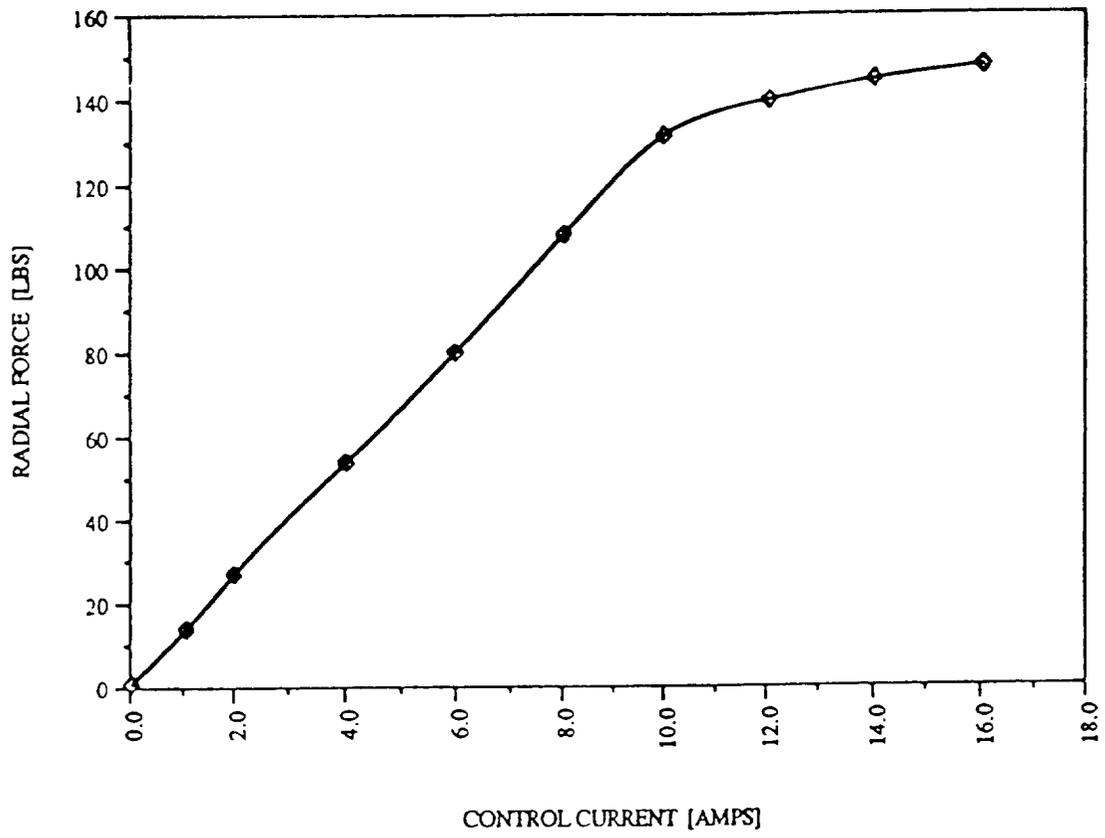


FIGURE 8



FIGURE 9

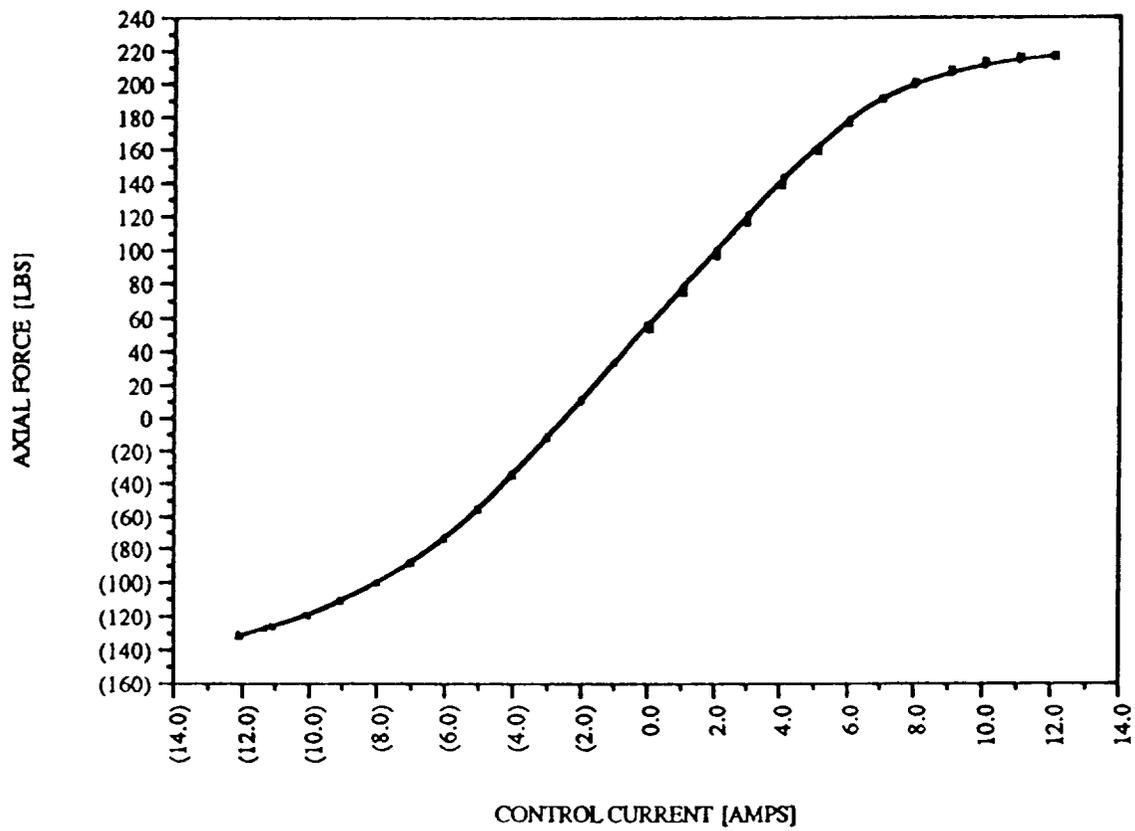


FIGURE 10

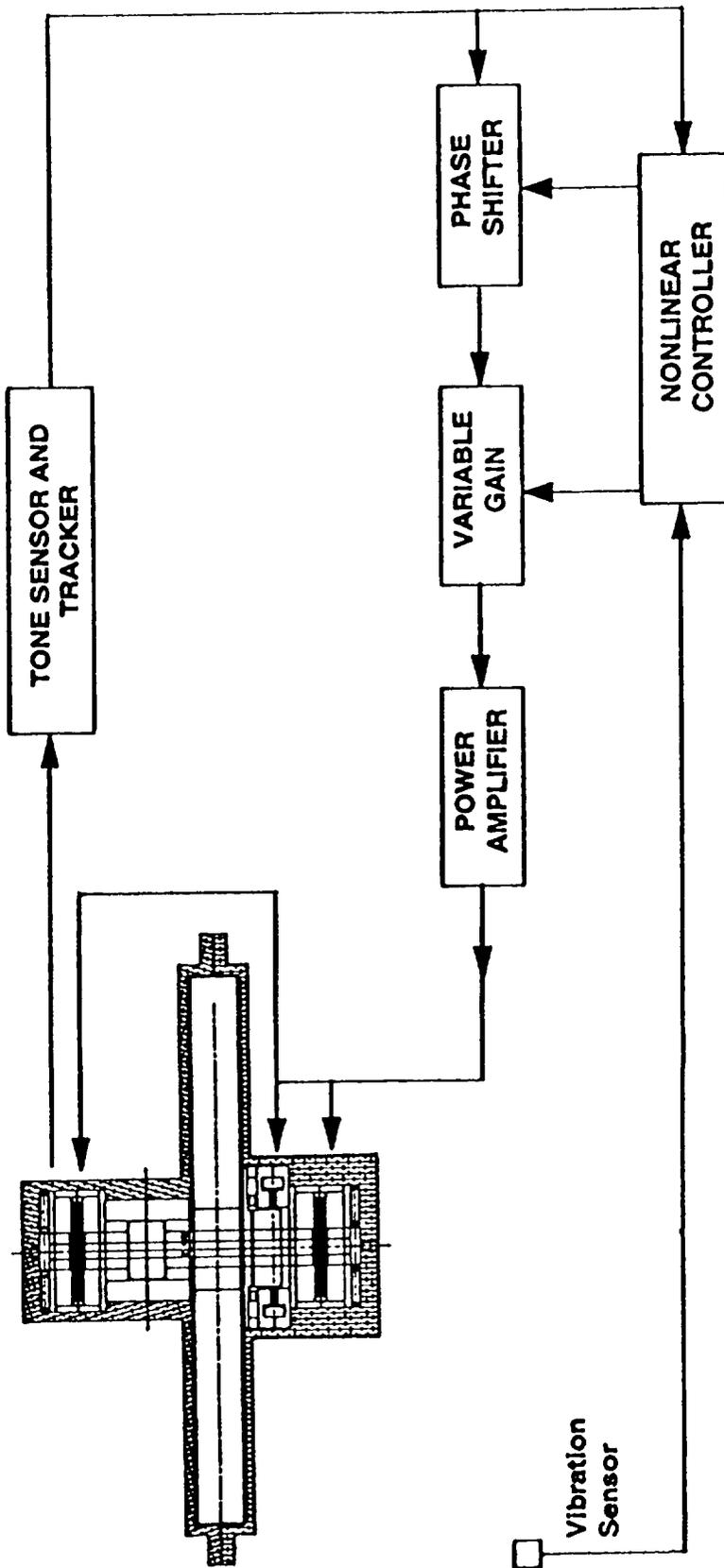


FIGURE 11

