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HIGH EFFICIENCY MAGNETIC BEARINGS*

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SUMMARY

This paper reports on research activities concerning high efficiency permanent magnet plus electromagnet (PM/EM) pancake magnetic bearings at the University of Maryland.

The paper begins with a description of the construction and working of the magnetic bearing. Next, parameters needed to describe the bearing are explained. The paper then summarizes methods developed for the design and testing of magnetic bearings. Finally the paper discusses a new magnetic bearing which allows active torque control in the off-axes directions.

LIST OF SYMBOLS

A	magnetic bearing pole face area
B	magnetic flux density
c	control system sensitivity
F_A	active radial force
F_I	current force
F_X	passive radial force
g_0	width of airgap
i_{max}	maximum current in the electromagnetic coils
K_A	active radial stiffness
K_I	current force sensitivity
K_X	passive radial stiffness

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- N number of turns of wire in coils
- x_{oper} maximum operational width of airgap ($< g_0$)
- μ_0 permeability of free space

INTRODUCTION

Magnetic bearings evolved in the 1950s from the simple application of permanent magnets positioned to exert repulsive forces to electromagnets and then to present day magnetic bearings which utilize permanent magnets and electromagnets to achieve active control (ref. 1).

The magnetic bearings currently under development at the University of Maryland are of the permanent magnet plus electromagnet (PM/EM) type (ref. 2-5). These bearings use permanent magnets to provide bias flux and electromagnets to provide a modulating control flux so as to keep the clearance in the magnetic bearing constant. This modulation is necessary to provide active control in the radial direction and in the presence of unbalance or external forces. Control in the axial direction is passive. The bearing system consists of a central stator and a concentric rotor which in one application is a flywheel. The stator is made up of Samarium-Cobalt magnets which are contained between two bias flux plates. Four control coils are located at the top and bottom of the bias flux plates as shown in fig. 1. Bias flux produced by the magnets flows across the airgap and through the suspension ring in the flywheel (fig. 2); thus making the system unstable in the unpowered condition. Two feedback control systems one in the E-W and other in the N-S directions, are provided to stabilize the flywheel and hold the gap constant. When the rotor displaces radially, the motion is sensed by the position sensors and the control system responds by sending a measured current through the coils which results in the generation of a corrective magnetic flux. This flux adds to the permanent magnet flux on the side of the increasing gap and subtracts from the permanent magnet flux on the side of the decreasing gap as shown in fig. 3. The net result is a stabilizing force which moves the flywheel back to the central position.

There are three parameters which characterize the magnetic bearing. They are K_X , K_I and K_A . K_X is a measure of the destabilizing force produced by the permanent magnets and is measured in lbs./in. The amount of corrective force produced by the coils in response to a current is characterized by K_I which is measured in lbs./Amp. K_A represents the total stiffness of the stabilized magnetic bearing measured in lbs./in. These parameters are necessary in the design of magnetic bearings since they are directly related to stability, linear range of operation and load capacity of the bearing.

MAGNETIC BEARING DESIGN

Numerous computer programs have been developed as tools for the design of magnetic bearings. These programs are capable of simulating the working of the magnetic bearing for a given set of input dimensions (ref. 6,7). Theoretical predictions of K_X , K_I and K_A may be made in this manner. These programs also allow the user to observe the effects of various dimensional parameters on K_X , K_I and K_A and to select the optimal choices of bearing dimensions and permanent magnet size. Another useful feature of these programs is their capability to identify magnetic saturation in critical parts of the bearing and suggest ways to prevent it.

The general approach to designing a magnetic bearing is to compute the stiffness K_X based upon permeance modeling (ref. 7). Fig. 4 shows the half-plane representation of the permeance model. Magnetic flux produced by the permanent magnet is redistributed into useful flux and fringing flux based on this model. If B is the corresponding useful

flux density at the pole faces then K_X can be shown to be:

$$K_X = \frac{A * B^2}{g_0 * \mu_0}$$

If N is the number of turns of wire in the coils then the current force sensitivity K_I can be shown to be:

$$K_I = \frac{A * B * N}{\sqrt{2} * \pi * g_0}$$

This shows that a large radial flux (B) is beneficial for providing a large corrective force. This is an important and somewhat unexpected point. A large radial flux indicates the presence of a large destabilizing force. However, the nature of the control system is such that the destabilizing force is harnessed beneficially.

Once K_X and K_I are known the suspension operating range may be found from the following inequality.

$$K_I * i_{\max} > K_X * x_{\text{oper}}$$

The physical meaning of this condition is that the stabilizing force produced by current through the electromagnet coils should exceed the destabilizing force generated by the permanent magnets.

Current in the coils is produced by the control system in response to displacement sensed by the position sensors. If c denotes the amount of current in the coils for a unit displacement at the position sensors then K_A can be written as

$$K_A = c * K_I - K_X$$

c , which is measured in Amps/inch is dependent on the control system. It must be noted that this equation for K_A is valid only in the linear range of operation of the control system and under steady state conditions.

An important characteristic is the maximum axial force carrying ability. Both the maximum axial force, and the curve shape (axial force vs. displacement) are important parameters. To prevent excessive sag, it is desirable to have a large slope at smaller displacements. Also, a large peak axial force prevents the loss of suspension under external axial overloads.

TESTING OF MAGNETIC BEARINGS

Theoretical formulation of K_X , K_I and K_A have been developed at the University of Maryland. Therefore there existed a need to verify theory with experiment. This was accomplished via an experimental apparatus developed by Frommer at the University of Maryland. The apparatus is shown in fig 5. In this apparatus the stator is held stationary on the bearing support while the rotor is clamped to the mounting plate which is allowed to move on a set of linear bearings. Force is measured via a strain ring and displacement is read as voltage from the position sensor. A more detailed description of the apparatus is presented in reference 8.

TESTING AND SIMULATION RESULTS

Fig 6 is a typical set of curves of radial force vs. displacement for different values of bias current. The linearity of the curve especially around the centered position suggests an absence of magnetic saturation. The slope of the force curve at 0 amps bias current is the K_X of the bearing. Fig 7 shows the variation of F_A which is the total restoring force produced by the bearing, with displacement. F_A can be shown to be a combination of two forces, F_I which is the stabilizing force produced by the coils and F_X which is the destabilizing force produced by the permanent magnets. This

is clearly seen in fig 7. The variation of F_x with displacement is fairly linear at smaller values of displacement, however the F_y curve clearly shows the effect of magnetic saturation and current limit of the control system. Current limit and magnetic saturation are to be avoided as far as possible so that the complete system is linear. A large linear range assures a larger range of controllability leading to a stable magnetic bearing. Tests on magnetic bearing led to an improved understanding of the working of the bearing and these were reflected in the simulation programs. Changes were made to account for saturation and magnetic flux paths were revised so as to arrive at theoretical predictions which were consistent with test results (ref. 9).

OFF-AXES TORQUE CONTROL MAGNETIC BEARING

Another configuration of EM/PM magnetic bearing currently under development is an off-axes torque control magnetic bearing (ref. 10). The arrangement of permanent magnets and electromagnet coils in this bearing gives it an added degree of control i.e. capability of controlling the tilt in the off-axes direction. Bias flux at the air gap is provided by two sets of permanent magnets as shown in fig 8. Modulation of the control flux is provided by electromagnetic coils. These coils are capable of controlling the radial position as well as the off-axes tilt of the flywheel with respect to the bearing. Radial control is possible when radial-control electromagnetic coils at opposite ends of the central permeable disk introduce magnetic flux. This flux aids the bias flux of the magnets on one side while opposing it on the other resulting in radial movement of the flywheel. The angular-control electromagnetic coils on the upper and lower permeable disk quadrants are connected to produce a magnetic flux circulating around the periphery of the magnetic path. When this flux circulates in the clockwise direction as shown in fig 8, it aids the permanent magnet flux at the upper-right and the lower-left airgaps and opposes the permanent magnet flux at the upper-left and the lower-right airgaps. This flux pattern does not introduce a net right or left force, but the inequalities of forces at the corner airgaps produce a net torque on the rotor, tilting it counterclockwise about the y-axis. Similar arrangement exists in the y-z plane of the stator to control the rotor motion along the y-axis and rotor tilt about the x-axis. Control along the z-axis is passive.

Fig 9 illustrates a feedback control system for one plane of the bearing. The control circuitry varies the currents in the radial- and angular-control coils in response to the outputs of the radial- and angular- position sensors. An angular command bias to the angular differential amplifier sets the equilibrium angular position.

CONCLUSIONS

Both 3" and 4" diameter EM/PM magnetic bearings have been successfully designed and tested at the University of Maryland. Under initial tests the 3" magnetic bearing flywheel was maintained at a speed of 2000 rpm for a total time period of 200 hours. In addition this bearing was successfully spun to a maximum rpm of 10,000.

During the commissioning of these bearings many problems were encountered both with the actuator and the control system. These problems centered around magnetic saturation in the metallic parts and the modeling of permanent magnet leakage fluxes. The development of testing procedures helped shed light and alleviate many of the problems.

Continuing work includes the use of Vanadium Permendur which is a material with an extremely high saturation level (2.3 Teslas) as compared to Nickel Iron (1.5 Teslas) which is currently used. There is also a need to improve bearing performance with superior position transducers and power amplifier systems. Newer bearing configurations such as the one described in this paper are also being developed.

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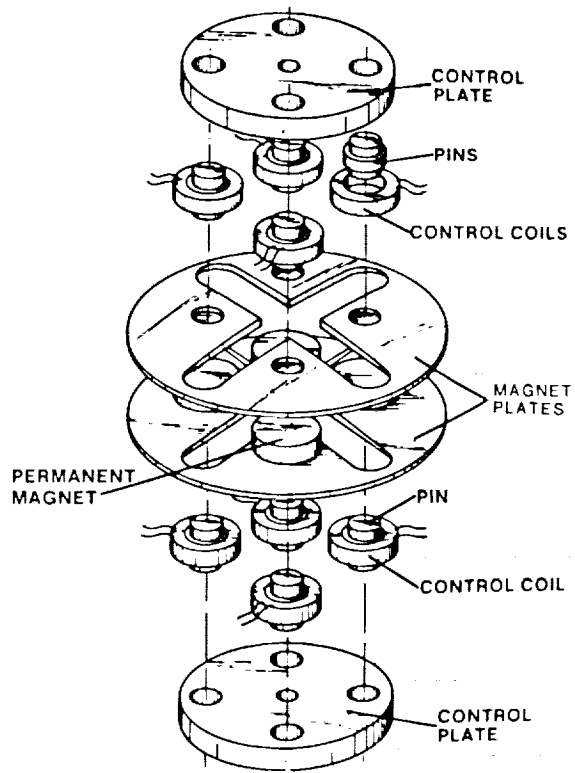


Fig. 1 Exploded View of Stator of Magnetic Bearing

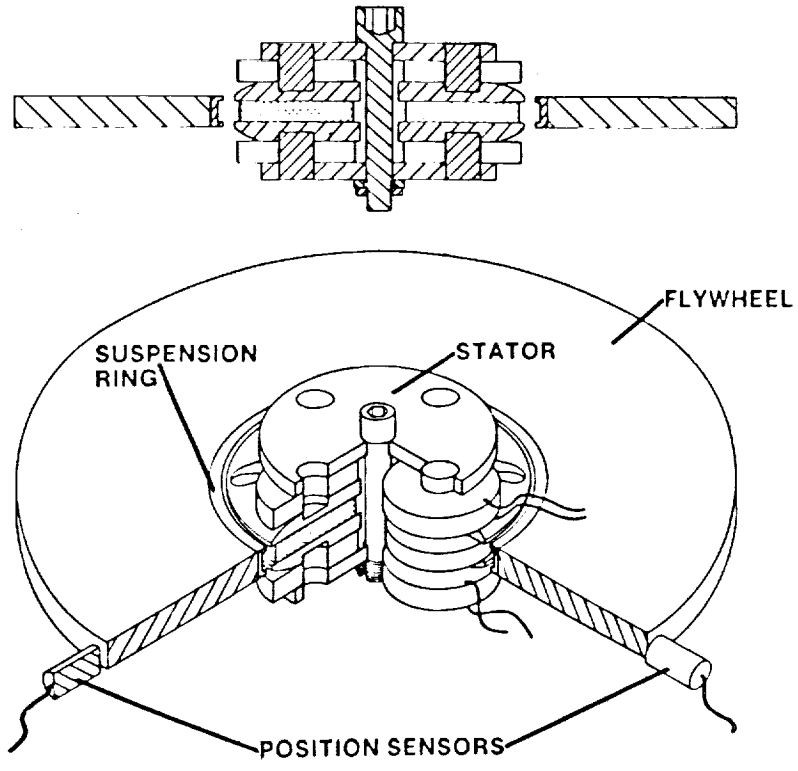
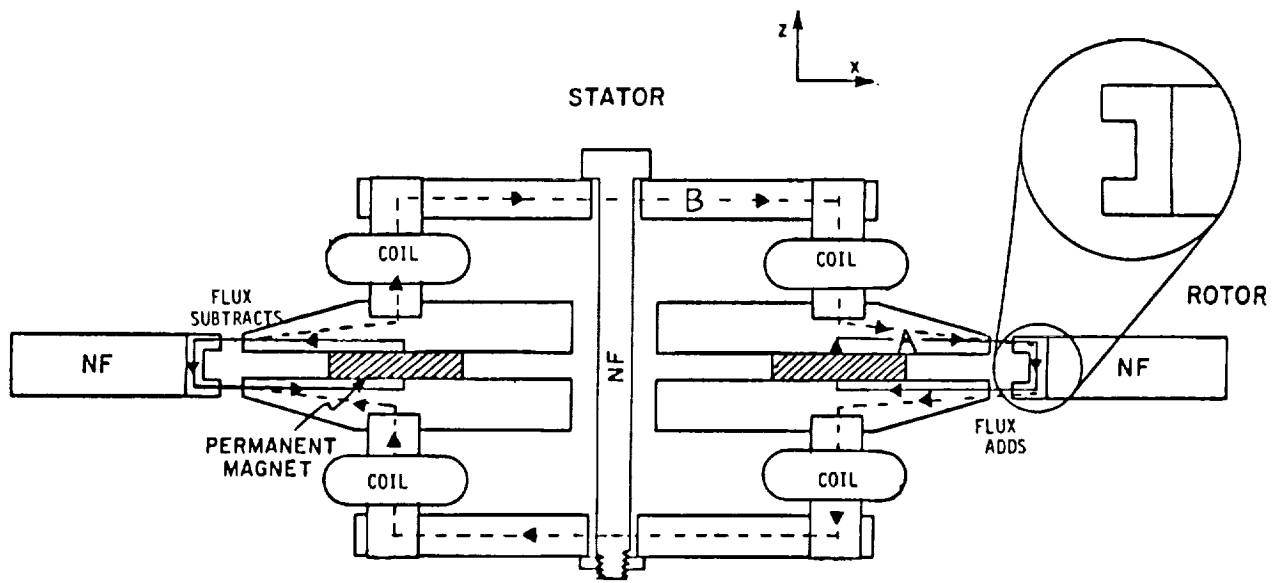


Fig. 2 Pancake Magnetic Bearing



* All materials are Ni-Fe unless marked NF (non-ferromagnetic)

Fig. 3 Flux Paths in Magnetic Bearing

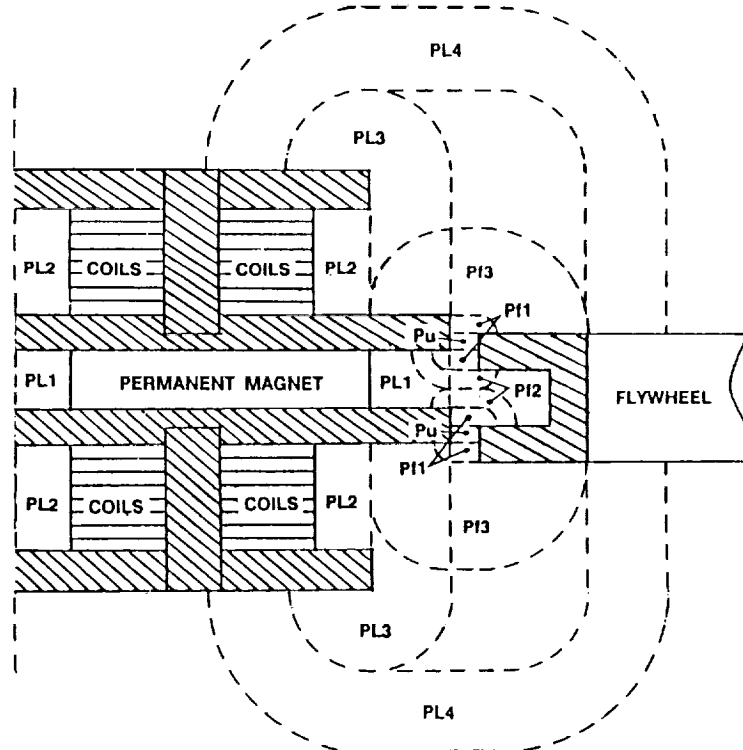


Fig. 4 Flux Paths in Permeance Model

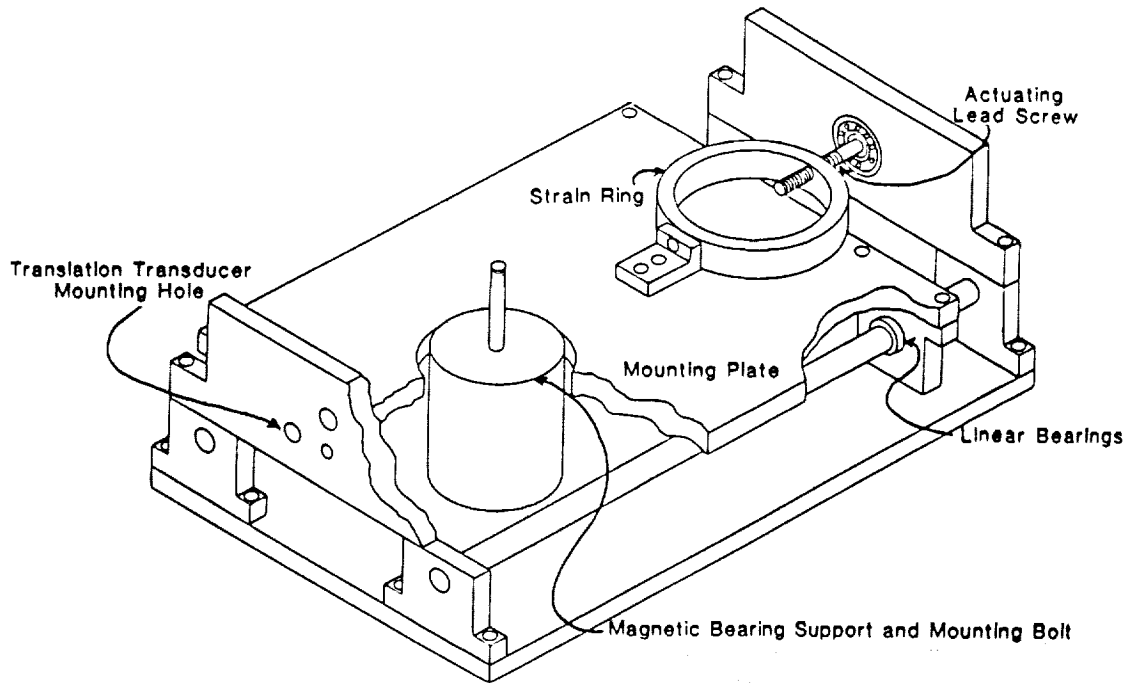


Fig. 5 Magnetic Bearing test apparatus

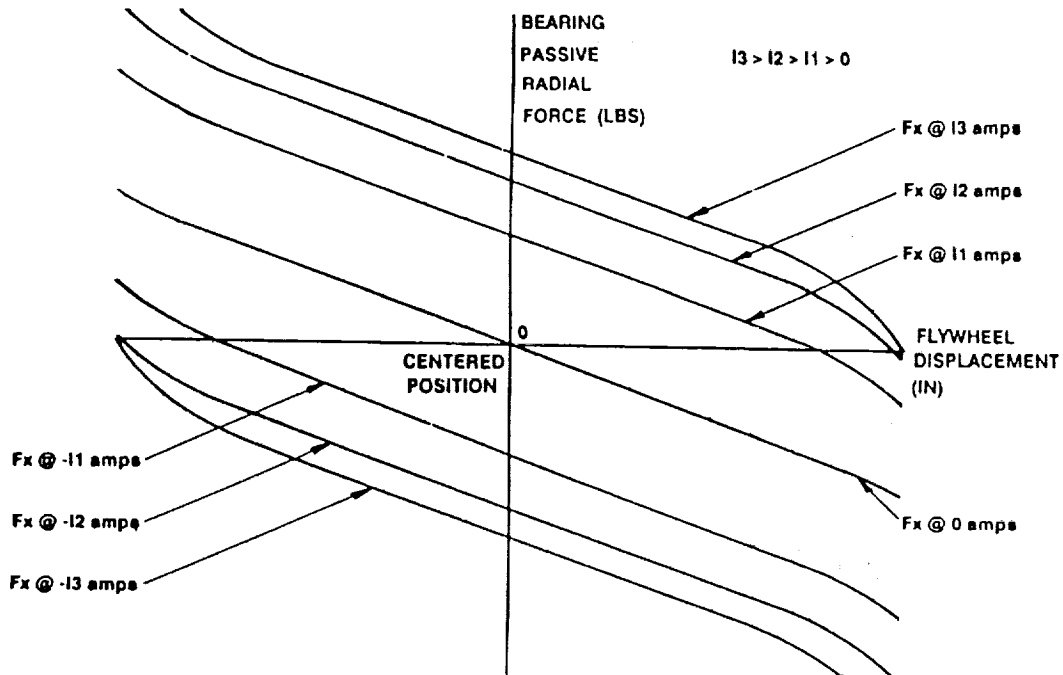


Fig. 6 Radial Bias Force vs. Displacement

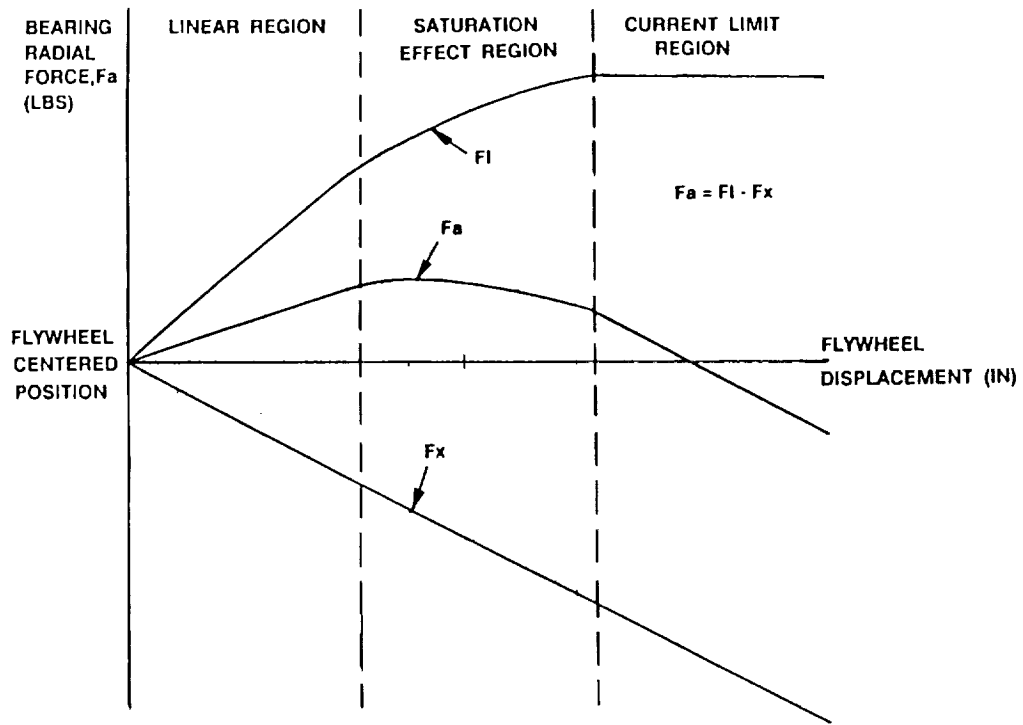


Fig. 7 Bias, Coil and Restoring Force vs. Displacement

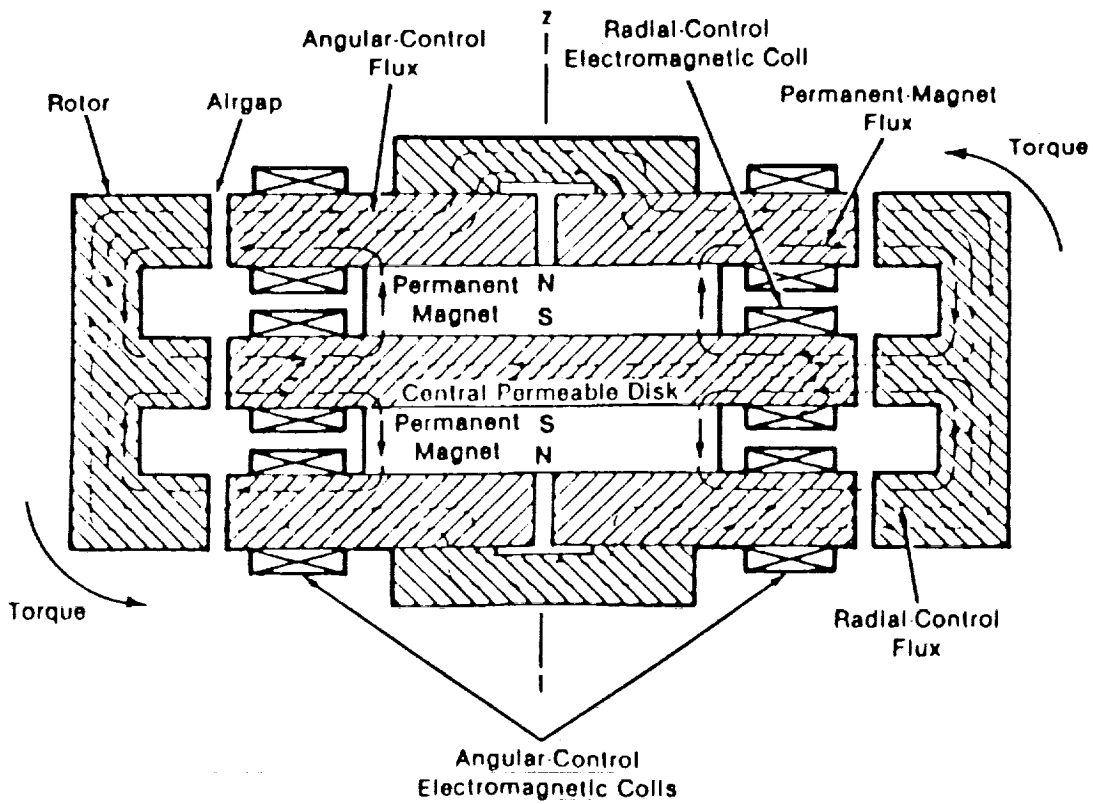
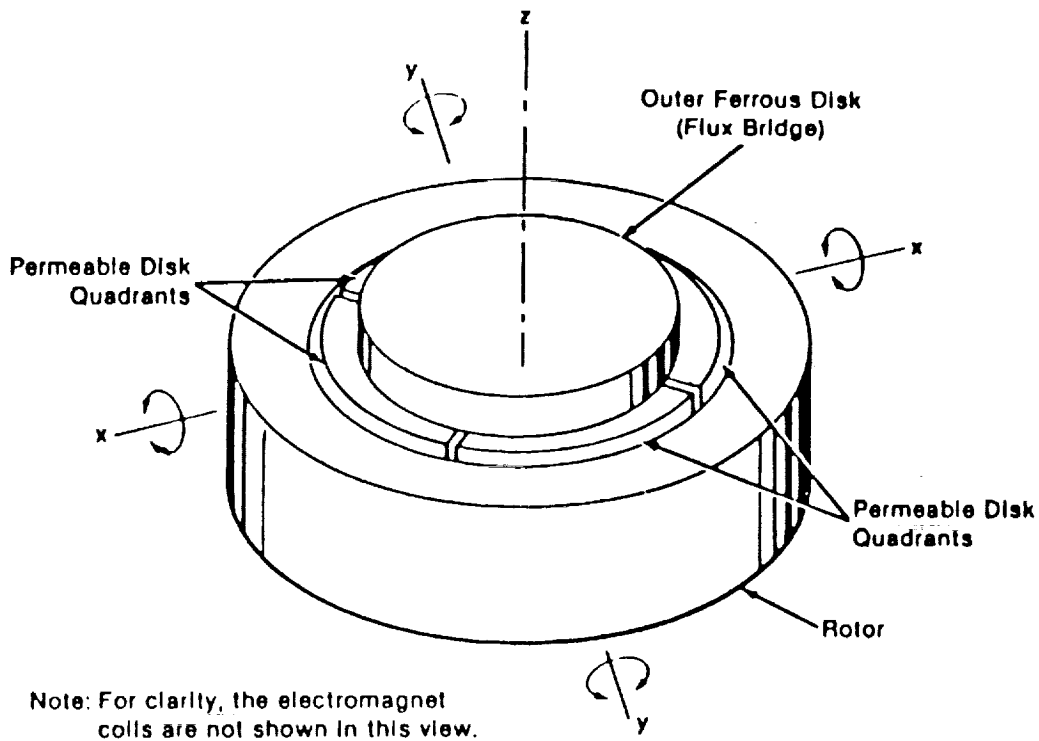


Fig. 8 Off-Axes Torque Control Magnetic Bearing

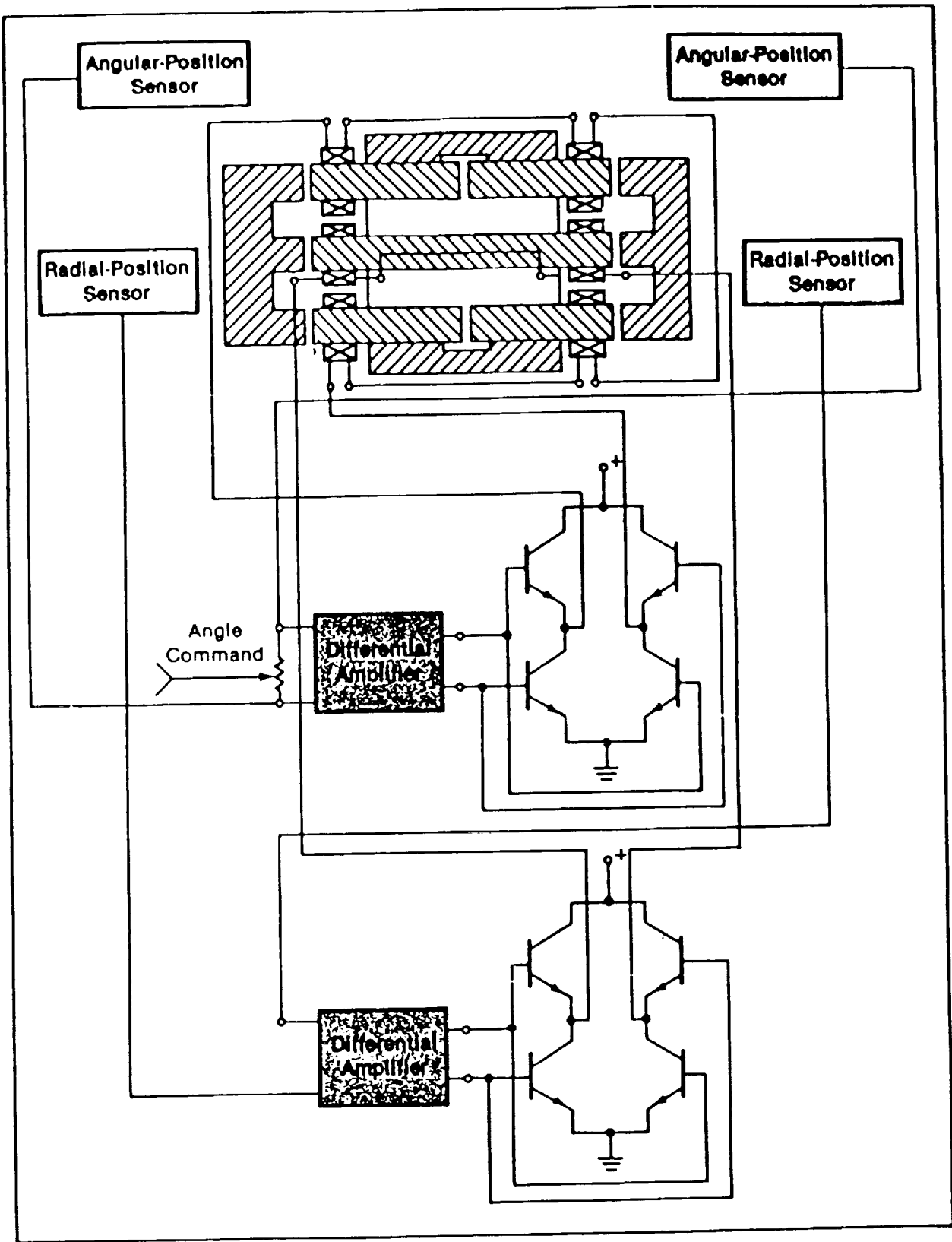


Fig. 9 Control System for Off-Axes Torque control Bearing

