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OVERVIEW OF MAGNETIC BEARING CONTROL AND LINEARIZATION APPROACHES FOR ANNULAR MAGNETICALLY SUSPENDED DEVICES

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INTRODUCTION

The purpose of this paper is to present an overview of magnetic bearing control and linearization approaches which have been considered for annular magnetically suspended devices. These devices include (Fig. 1) the Annular Momentum Control Device (Ref. 1) and the Annular Suspension and Pointing System (Ref. 2).

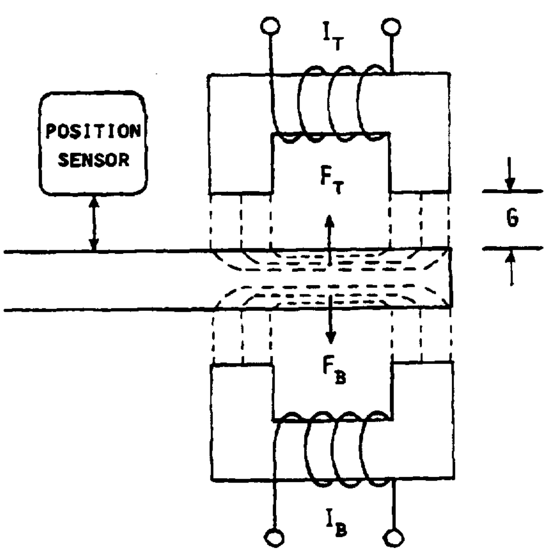
ANNULAR MAGNETICALLY SUSPENDED DEVICES FOR CONTROL AND POINTING APPLICATIONS

- ANNULAR MOMENTUM CONTROL DEVICE (AMCD)
  - Momentum Storage Device
- ANNULAR SUSPENSION AND POINTING SYSTEM (ASPS)
  - Auxiliary Pointing System

Figure 1

CONTROL AND LINEARIZATION APPROACHES

In order to define the basic type of magnetic bearing actuator being discussed, the simplified schematic diagram of Figure 2 is introduced. Shown are two electromagnets, with currents I_T and I_B, producing forces F_T and F_B on a suspended element positioned at a gap distance G from the top electromagnet pole face. A position sensor is shown and is required both for some of the linearization approaches to be discussed and for the magnet suspension control system. Under ideal assumptions, the force produced by a given electromagnet is directly proportional to the square of the coil current and inversely proportional to the square of the electromagnet gap. Since the electromagnet produces an attractive force only, two are required to produce a bidirectional force capability. Two approaches have been investigated for controlling this type of magnetic actuator. One approach involves controlling the upper and lower electromagnets differentially about a bias flux. The bias flux can either be supplied by permanent magnets in the magnetic circuit or by bias currents. In the other approach, either the upper electromagnet or the lower electromagnet is controlled depending on the direction of force required. One advantage of the bias flux approach is that for small gap perturbations about a fixed operating point, the force-current characteristic is linear. However, if a requirement for a linear force characteristic over a wide gap range exists, as for example in the ASPS, bias currents which are varied as a function of measured gap are used. Linearization approaches investigated for individual element control include an analog solution of the nonlinear electromagnet force equation and a microprocessor-based table lookup method.



$$F = K\frac{I^2}{G^2}$$

MAGNETIC BEARING CONTROL APPROACHES

- BIAS FLUX
- INDIVIDUAL ELEMENT CONTROL

MAGNETIC BEARING LINEARIZATION APPROACHES

- BIAS FLUX
  - PERMANENT MAGNETS
  - FIXED BIAS CURRENTS
  - VARIABLE BIAS CURRENTS
- INDIVIDUAL ELEMENT CONTROL
  - ANALOG SOLUTION OF BEARING ELEMENT FORCE EQUATION
  - MICROPROCESSOR CONTROL (TABLE LOOKUP)

Figure 2

PERMANENT MAGNET FLUX-BIASED MAGNETIC ACTUATOR

In order to describe the operation of a permanent magnet flux-biased magnetic actuator, the simplified schematic drawing of Figure 3 is introduced. The figure shows a single actuator, for control along a single axis, which consists of a pair of magnetic bearing elements with permanent magnets mounted in the cores. The bearing elements are connected in a differential configuration. That is, for a given input the amplifier driver shown in the figure produces current in a direction to aid the permanent-magnet-produced flux in one element while at the same time producing equal current in a direction to subtract from the permanent-magnet-produced flux in the other element. This results in a net force produced on the suspended mass in a direction dependent on the polarity of the input to the amplifier driver.

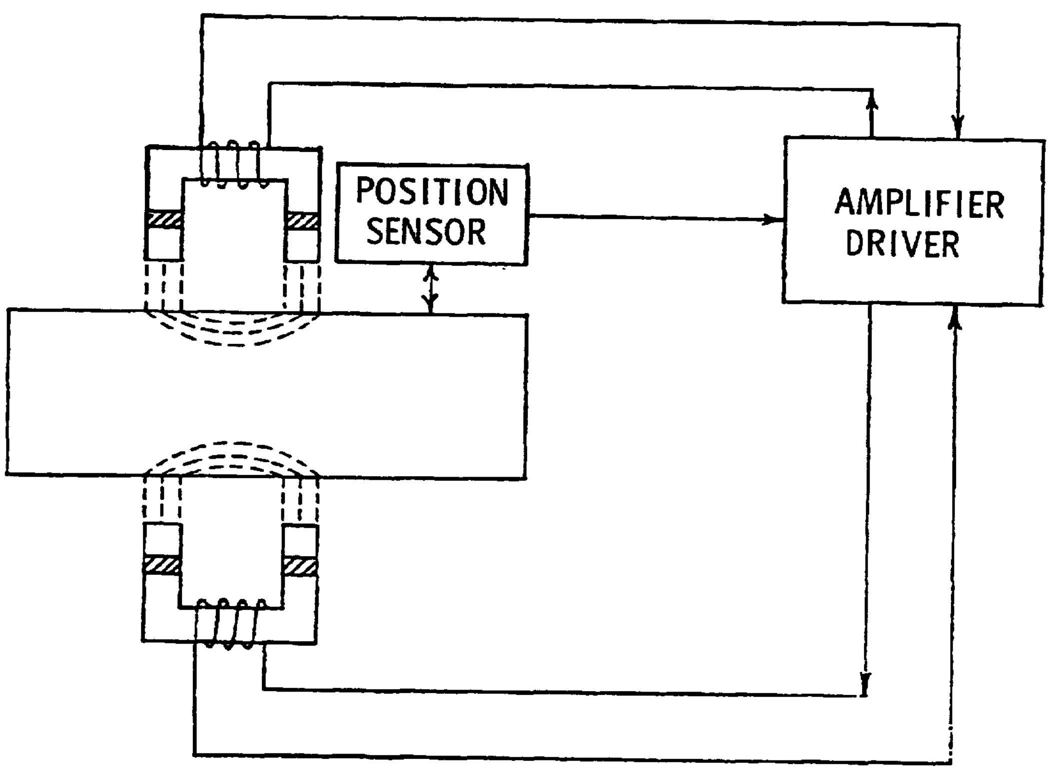


Figure 3

FLUX-BIASED MAGNETIC ACTUATOR FORCE CHARACTERISTIC

The composite force-current characteristic of a flux-biased magnetic actuator with the suspended mass centered in the actuator gaps is shown in Figure 4. This figure illustrates a linear electromagnet gain of the actuator at a given gap position. By performing a first order linearization of the actuator force equation about a fixed operating point the actuator force as a function of differential coil current and displacement can be written as

$$F = K_B I + K_M G$$

where K_B is an equivalent electromagnet gain and K_M is an equivalent bias flux stiffness. These gains would be different for different operating points. Permanent magnet flux-bias was the control approach used in the original magnetic suspension system for the laboratory test model AMCD (Ref. 3).

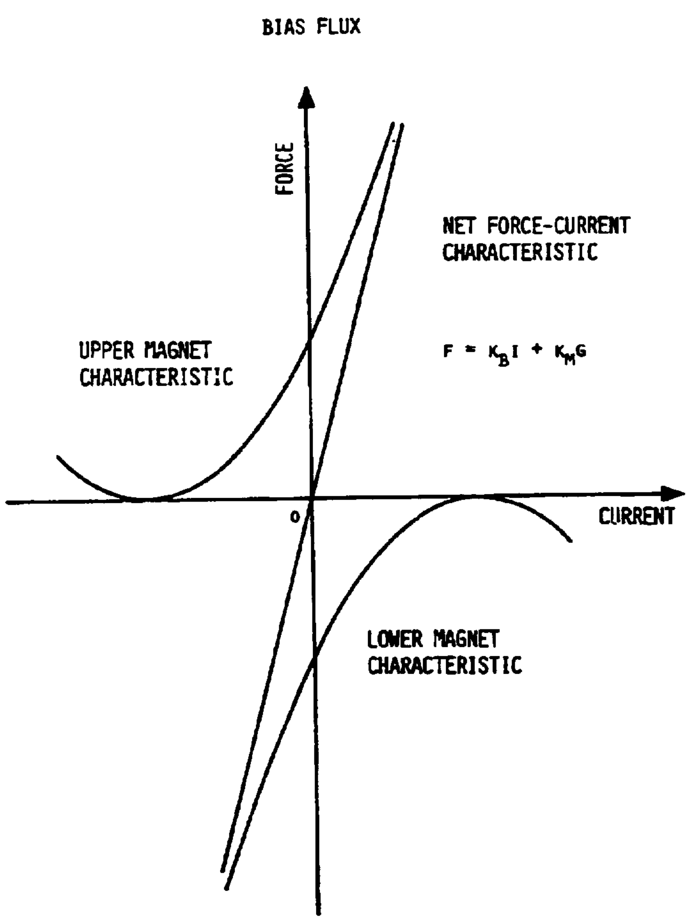


Figure 4

VARIABLE BIAS CURRENT APPROACH

Figure 5 is a simplified block diagram of a variable bias current approach which was implemented for the ASPS. As can be seen by working through the block diagram, the bias current and control currents of the upper and lower electromagnets are adjusted so that the bias force produced by each and the net force produced by a given command force are equal no matter where the suspended mass is in the gap. The unbalanced bias flux stiffness is thus eliminated and the electromagnet gain is constant. For more detail on the implementation of this approach, see Reference 4.

DIFFERENTIAL CONTROL OF ELEMENTS ABOUT BIAS FLUX

VARIABLE BIAS CURRENT APPROACH

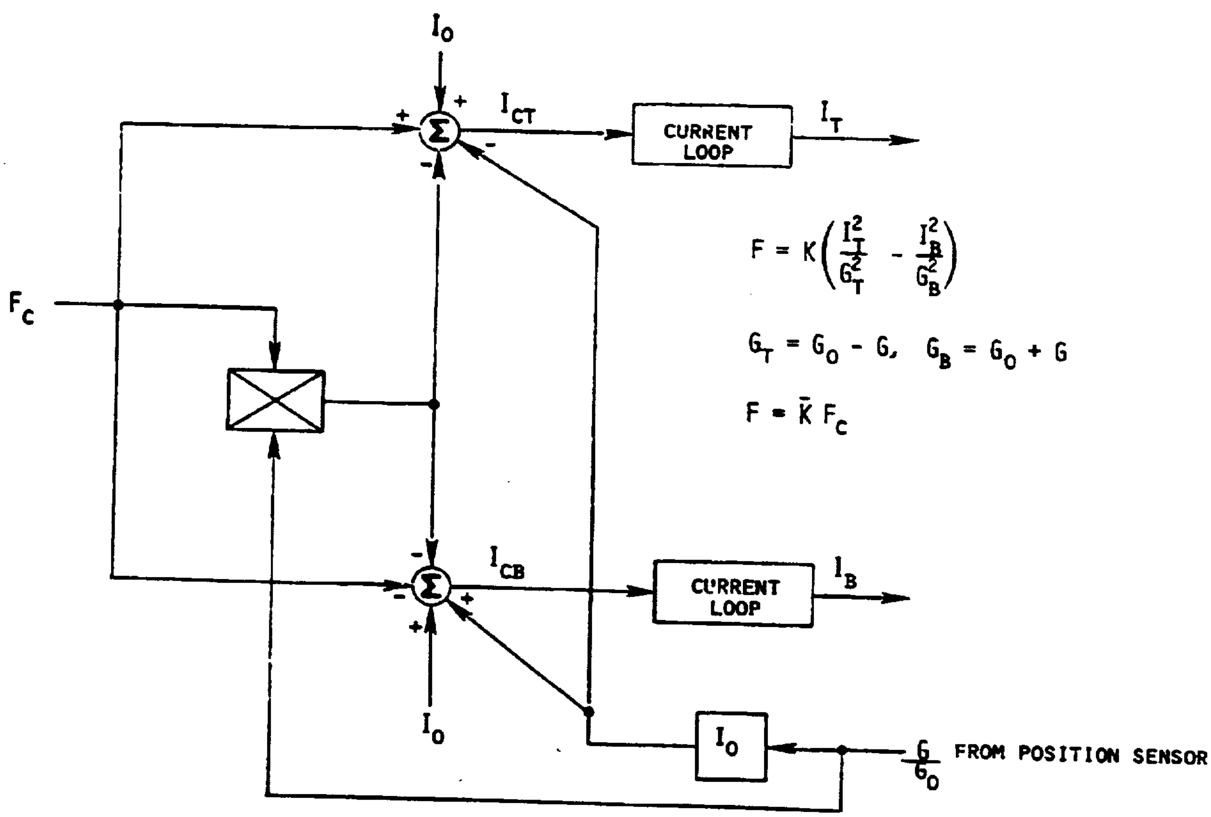


Figure 5

INDIVIDUAL ELEMENT CONTROL FORCE CHARACTERISTIC

The composite force-current characteristic of a magnetic actuator with individual element control and with the suspended mass centered in the actuator gaps is shown in Figure 6. This figure illustrates the highly nonlinear force characteristics of an uncompensated actuator.

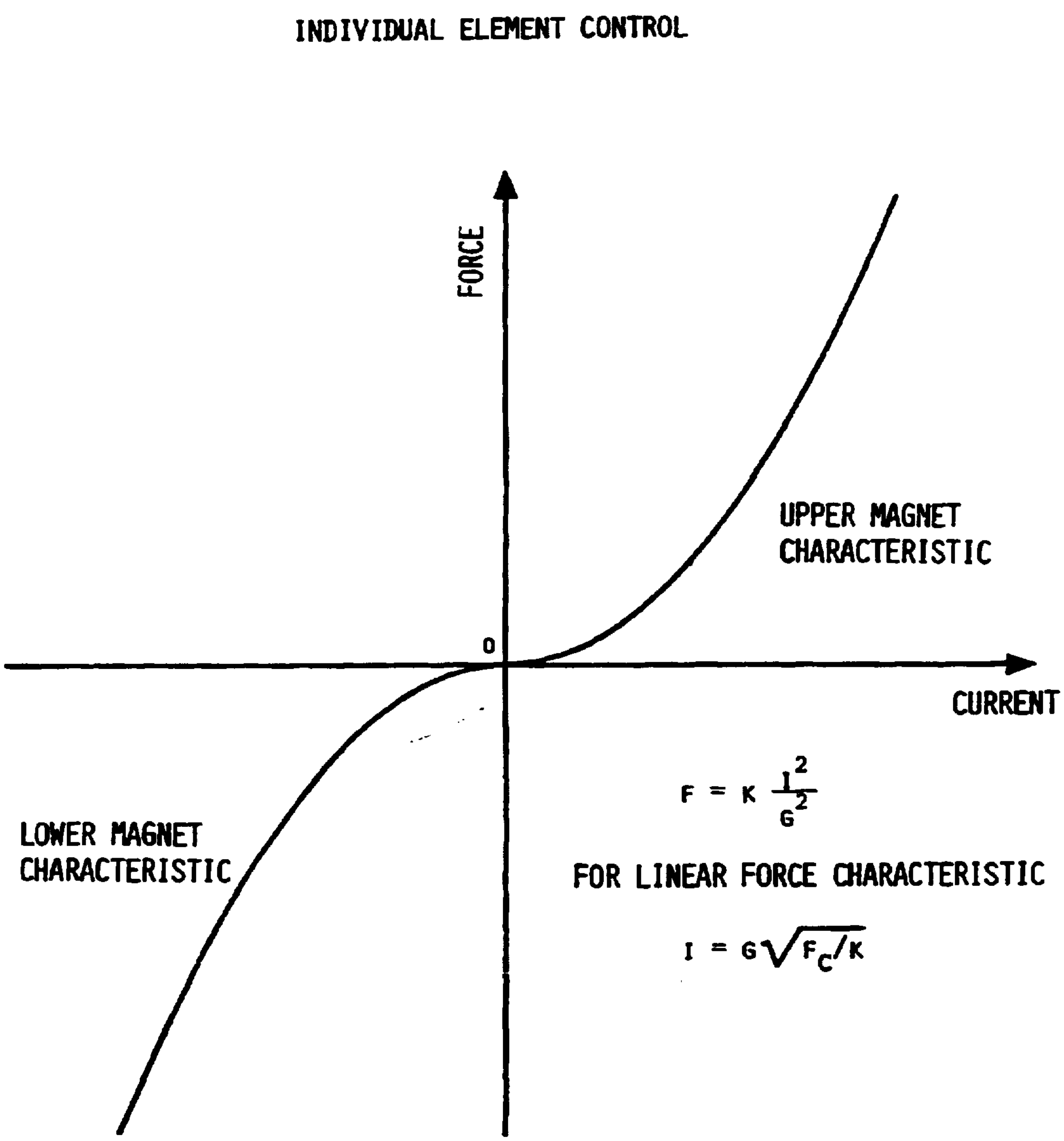


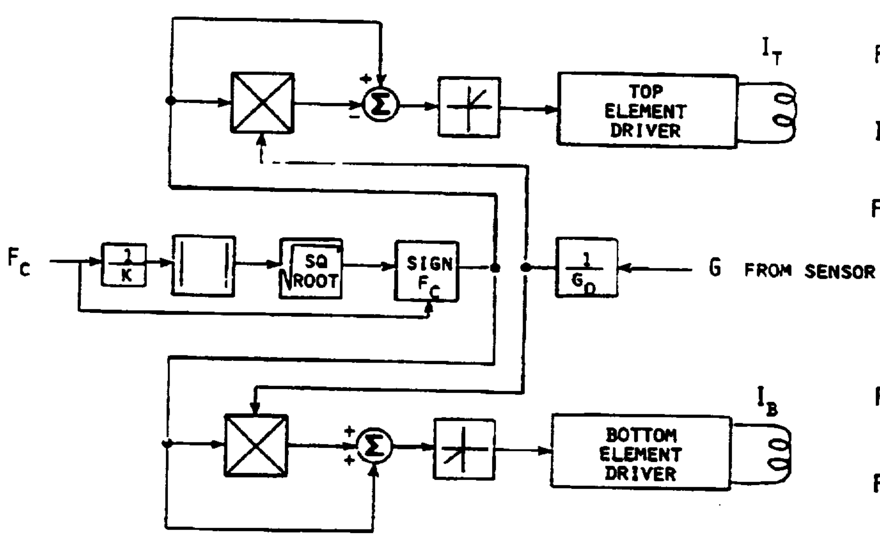
Figure 6

ANALOG SOLUTION OF FORCE EQUATION FOR INDIVIDUAL ELEMENT CONTROL

Figure 7 is a simplified block diagram of an analog implementation of the solution of the force equation for a magnetic actuator with individual element control. This approach was implemented for a magnetic suspension system for the laboratory test model AMCD. For more detail on the implementation of this approach, see Reference 5.

INDIVIDUAL ELEMENT CONTROL

ANALOG APPROACH (SOLUTION TO FORCE EQUATION)



$$F_T = K \frac{I_T^2}{G_T^2}, \quad G_T = (G_0 - G)$$

$$I_T = \frac{1}{G_0} \sqrt{\frac{F_c}{K}} (G_0 - G)$$

$$F_T = \bar{K} F_c$$

$$F_B = K \frac{I_B^2}{G_B^2}$$

$$F_B = K \frac{I_B^2}{G_B^2}, \quad G_B = (G_0 + G)$$

$$I_T = \frac{1}{G_0} \sqrt{\frac{F_c}{K}} (G_0 + G)$$

$$F_B = \bar{K} F_c$$

Figure 7

TABLE LOOKUP APPROACH FOR INDIVIDUAL ELEMENT CONTROL

The last magnetic bearing linearization and control approach to be discussed is a microprocessor-based table lookup linearization approach for individual bearing element control and is shown in Figure 8. This approach was bench tested but has not been used in the AMCD laboratory model suspension system to date. In this approach, actual calibration data for a given bearing element pair are used to build a lookup table which is stored in the memory of a microprocessor system. Using the force command and gap position as input data, the correct value of current input to the coil, for the suspended element centered in the actuator gaps, is obtained by using a table lookup routine. This current is compensated for displacement from center by multiplying by the calculated gap. This approach is described and test results from bench tests are presented in Reference 6.

INDIVIDUAL ELEMENT CONTROL
MICROPROCESSOR APPROACH (TABLE LOOKUP)

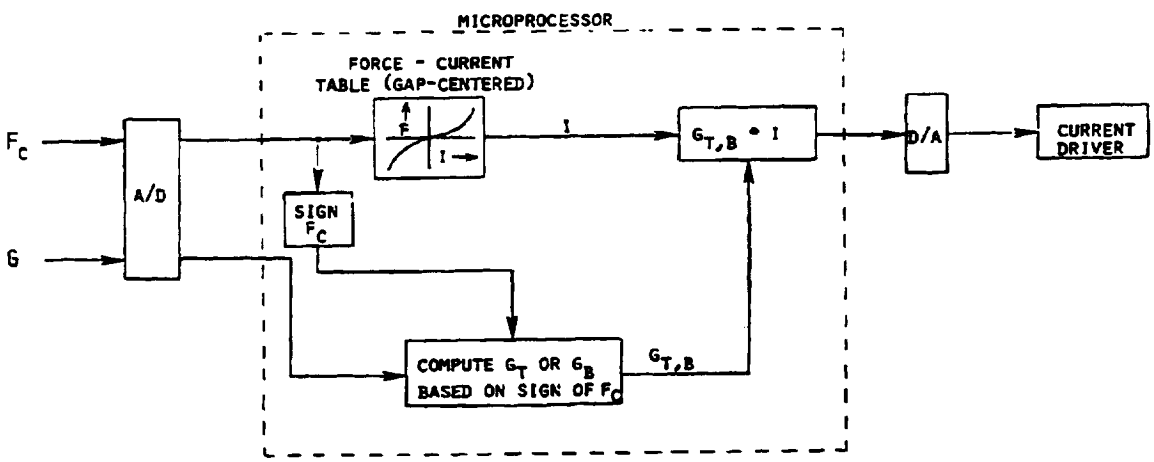


Figure 8

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