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A Microprocessor-Based Table Lookup Approach for Magnetic Bearing Linearization

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Information Branch

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SUMMARY

An approach for producing a linear transfer characteristic between force command and force output of a magnetic bearing actuator without flux biasing is presented. The approach is microprocessor based and uses a table lookup to generate drive signals for the magnetic bearing power driver. An experimental test setup used to demonstrate the feasibility of the approach is described, and test results are presented. The test setup contains bearing elements similar to those used in a laboratory model annular momentum control device (AMCD).

INTRODUCTION

This paper describes an approach for producing a linear transfer characteristic between the force command and force output of a magnetic bearing actuator. The approach, which is microprocessor based and uses a table lookup to generate drive signals for the magnetic bearing actuator power driver, was investigated for application to a laboratory model annular momentum control device (AMCD). The laboratory model (described in ref. 1) was built to investigate potential problem areas in implementing the AMCD concept and is being used as part of an AMCD hardware technology development program. The basic AMCD concept is that of a rotating annular rim, suspended by a minimum of three magnetic bearing suspension stations and driven by a noncontacting electromagnetic spin motor. A detailed discussion of the rationale for the AMCD configuration and of some of its potential applications is presented in reference 2.

As described in reference 1, the magnetic-bearing linearization technique used in the original laboratory model AMCD magnetic suspension was to differentially control sets of magnetic bearing elements about a permanent-magnet bias flux. Preliminary tests indicated that this approach (permanent-magnet flux biasing) presented a problem from a control system standpoint (ref. 3). For a given equivalent permanent-magnet stiffness, a minimum bearing servo bandwidth is required for stability. The existence of structural modes in the area of the laboratory model bearing servo crossover restricted the amount of bearing servo damping that could be achieved.

Because of the limitations of permanent-magnet flux biasing encountered with the laboratory model AMCD, a decision was made to explore an alternate approach to the design of the magnetic suspension system (ref. 4). As a result, a new magnetic suspension system for the laboratory model has been designed, fabricated, and tested (ref. 5). The new system uses a zero bias flux approach for the magnetic bearing actuators. Analog multiplier and square root modules produce a direct solution to the ideal magnetic actuator force equation to provide a linear force-current characteristic. (For further discussion of magnetic bearing actuator control approaches, see ref. 6.) The accuracy of this approach is limited by the accuracy with which the ideal force equation approximates the actual characteristics of the actuator and by the accuracy of the analog components. This paper presents a zero bias flux linearization approach which is digital and which uses a lookup table constructed from measured actuator characteristics. An experimental test setup that was used to develop this approach is described, and test results are presented.

SYMBOLS

Dimensional quantities are presented in both SI Units and U.S. Customary Units. Measurements were made in U.S. Customary Units.

F_B	force produced by bottom electromagnet
F_C	force command for magnetic bearing actuator
$F_C(m)$	value of force command associated with mth line segment
F_T	force produced by top electromagnet
f_s	microcomputer system sample rate
ΔF_C	$= F_C(m+1) - F_C(m)$ for all m, where $m < N$
δF_C	$= F_C - F_C(m)$, where $F_C(m) \leqq F_C < F_C(m+1)$
G	displacement of suspended element with respect to centered position in magnetic bearing actuator gaps
G_B	gap of bottom electromagnet
G_O	magnetic bearing actuator gap with suspended element centered
G_T	gap of top element
I_B	current in bottom electromagnet
I_C	current command for magnetic bearing actuator
$I_C(m)$	stored value of current command associated with mth line segment
I_T	current in top electromagnet
K	electromagnet constant
N	number of line segments
SLOPE(m)	slope of mth line segment from $(F_C(m), I_C(m))$ to $(F_C(m+1), I_C(m+1))$

Abbreviations:

A/D	analog-to-digital converter

AMCD	annular momentum control device
D/A	digital-to-analog converter
dc	direct current
emf	electromotive force

APPROACH

Magnetic Bearing Control Approach

The magnetic bearing control approach is one which uses zero bias flux. Figure 1, a schematic representation of a magnetic bearing element pair, is

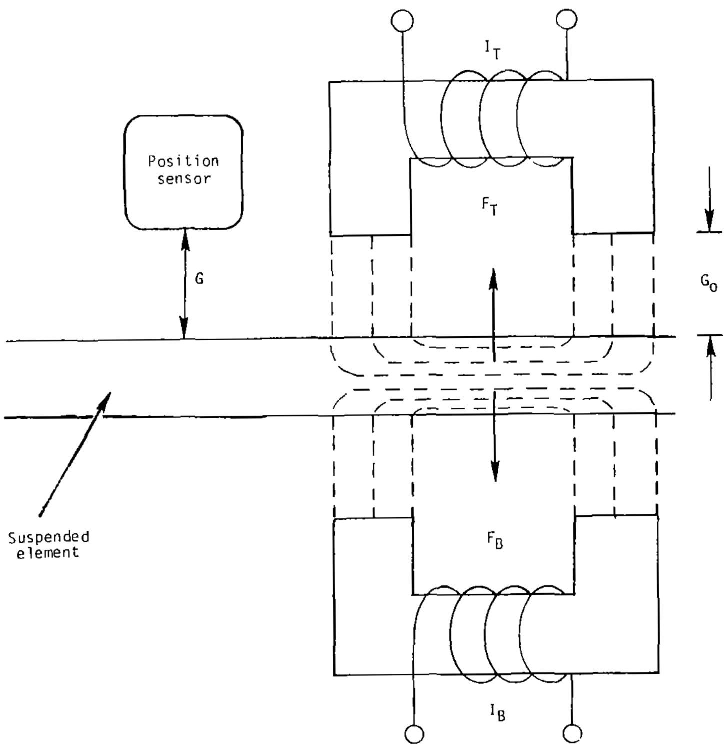

Figure 1.- Magnetic bearing actuator.

presented in order to describe this approach. Included in the figure are top and bottom electromagnets, with currents I_T and I_B, respectively; a portion of the suspended element which is centered between the electromagnets; and a position sensor which measures the displacement G of the suspended element with respect to the centered position G_o. In the zero bias flux control approach, one electromagnet at a time is controlled; the top electromagnet is controlled for an upward force and the bottom electromagnet is controlled for a downward force (since each electromagnet can physically produce only a unidirectional force). Figure 1 indicates that if up is taken as the positive direction, the electromagnet gaps are

$$G_T = G_O - G \tag{1}$$

and

$$G_B = G_O + G \tag{2}$$

Assuming negligible fringing and ignoring nonlinear core effects, the force produced by each electromagnet is given by (ref. 4)

$$F_T = K\left(\frac{I_T^2}{G_T^2}\right) \tag{3}$$

and

$$F_B = K\left(\frac{I_B^2}{G_B^2}\right) \tag{4}$$

The composite force-current characteristic of a zero bias flux actuator with the suspended element centered is shown in figure 2.

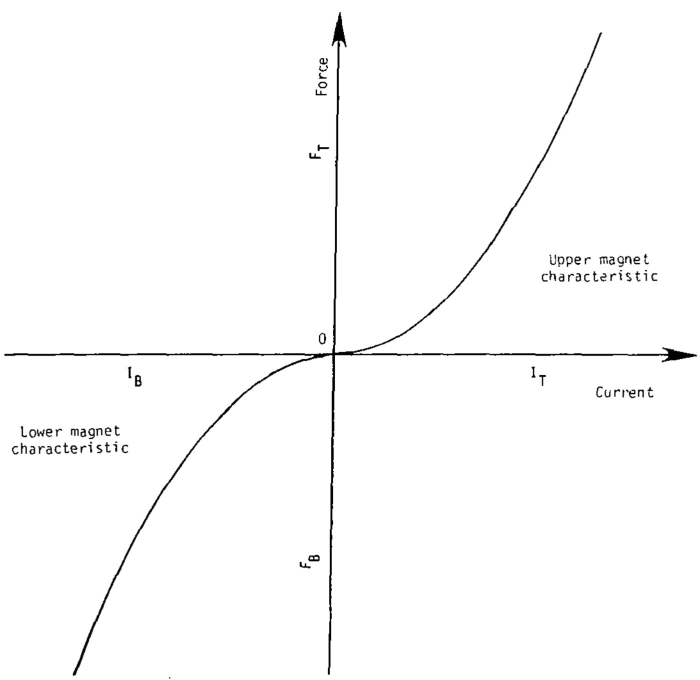

Figure 2.- Composite force-current characteristic of a zero bias flux magnetic actuator.

Linearization Approach

The linearization approach is microprocessor based and uses a lookup table. The most straightforward approach for producing a linear transfer characteristic between force command and force output would be to solve equations (3) and (4) for the electromagnet current required to produce the desired force. That is,

$$I_T = G_T\left(\frac{|F_C|}{K}\right)^{1/2} \qquad (F_C > 0) \qquad (5)$$

and

$$I_B = G_B\left(\frac{|F_C|}{K}\right)^{1/2} \qquad (F_C < 0) \qquad (6)$$

where F_C is the commanded force. Implementing the solutions of equations (5) and (6) digitally could produce a more computationally accurate result than the analog solution but would not account for deviation of the actual bearings from the ideal model. This solution would also require that considerable computing power be dedicated to a relatively minor portion of the total control system.

The table lookup approach, which employs a one-to-one correspondence between force command F_C and output current command I_C permits the output/input function to conform, within the limits of quantization error, to the actual bearing characteristics. However, this form of table requires considerable memory space. The minimum memory requirement is obtained by selecting the minimum set of straight line segments which approximate the output/input relationship within the desired tolerance. The major disadvantage of this choice of line segments is that considerable time may be spent searching for the appropriate line segment.

Since in this application computational time is more critical than memory size, an approximation was selected which requires more memory but eliminates the search time. The minimum set of equally spaced line segments N are selected so that $N = 2^n$, and the $N + 1$ points defining the line segments are separated by equal force command steps ΔF_C. If the range of F_C is scaled to a B bit binary word ($B > n$), the n most significant bits of F_C uniquely identify the N line segments. In actual computation these bits identify the lookup table data associated with the mth force command data point $F_C(m)$ such that $F_C(m) \leqq F_C < F_C(m+1)$. The $B - n$ least significant bits of F_C represent the difference δF_C between F_C and $F_C(m)$. (See fig. 3.)

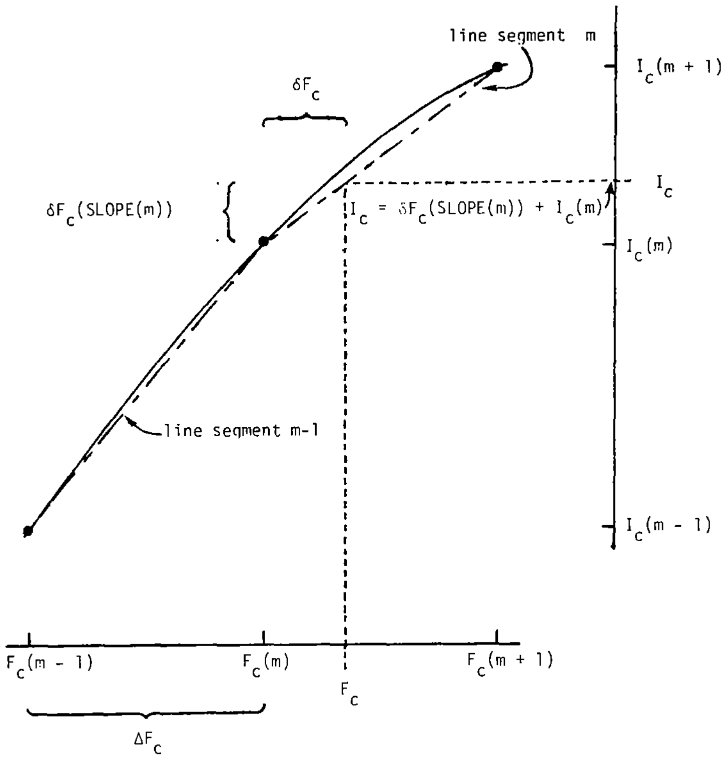

Figure 3.- Table lookup approach.

The data contained in the lookup table consist of the slope SLOPE(m) of each line segment m between $(F_C(m), I_C(m))$ and $(F_C(m+1), I_C(m+1))$ and of the current command $I_C(m)$ corresponding to $F_C(m)$. The location of the appropriate data is obtained directly from the force command word by masking and shifting. Calculation of output current command I_C at $G = 0$ requires a single multiplication of δF_C by SLOPE(m) and addition of this result to $I_C(m)$. Since actual variation of electromagnet current with gap was observed to be linear, as indicated by equations (5) and (6), calculation of I_C for other values of G is accomplished by multiplying I_C by the appropriate bearing gap. For a more detailed description of the table lookup algorithm, see appendix A.

HARDWARE TESTS

Description of Test System

The test system consisted of a magnetic bearing test fixture connected to a microcomputer system as shown in figure 4. This system was used to obtain the data required to develop the lookup table and to obtain data on the performance of the proposed approach. A description of the current driver shown in figure 4 is given in appendix B.

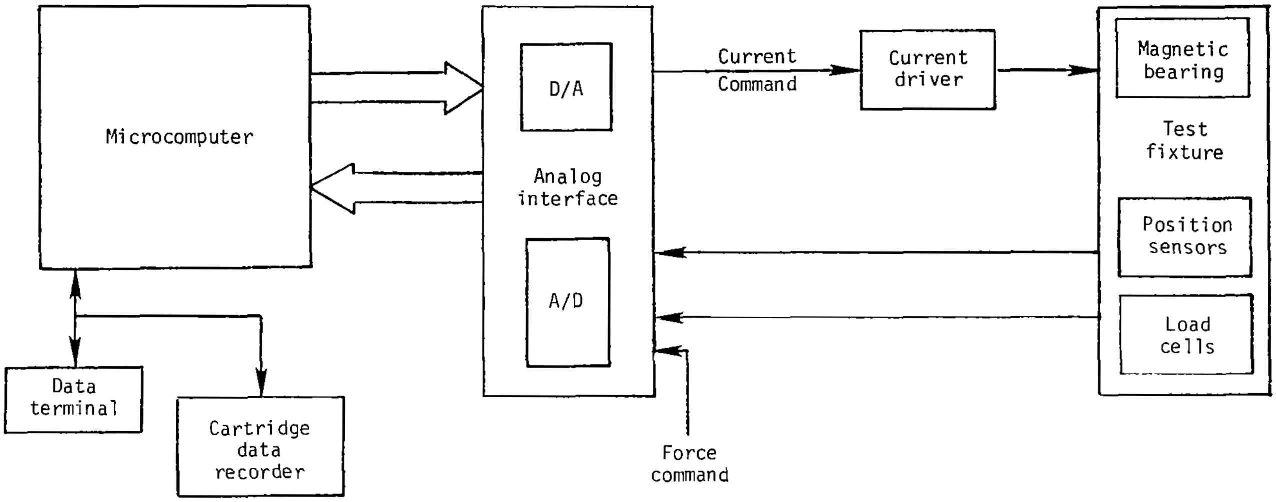

Figure 4.- Magnetic bearing test system.

Magnetic bearing test fixture.- The magnetic bearing test fixture shown in figure 5 consists of a magnetic bearing element pair; an equivalent "suspended" element, which is connected through a pair of load cells to the base of the fixture; and a pair of position sensors. The suspended element can be set to any desired vertical position in the magnetic bearing gap using the adjusting screws mounted on the load cells. The position sensors are used to measure the bearing gaps. The magnetic bearing elements have the same dimensions as the original magnetic bearing elements delivered with the laboratory model AMCD which is described in reference 1. Two main differences exist between the test fixture bearing elements and the original laboratory model elements: (1) the core material of the test fixture bearing elements is SAE 1010 soft steel (as opposed to a lower loss silicon core iron used in the original elements), and (2) the test fixture bearing elements contain no permanent-magnet material.

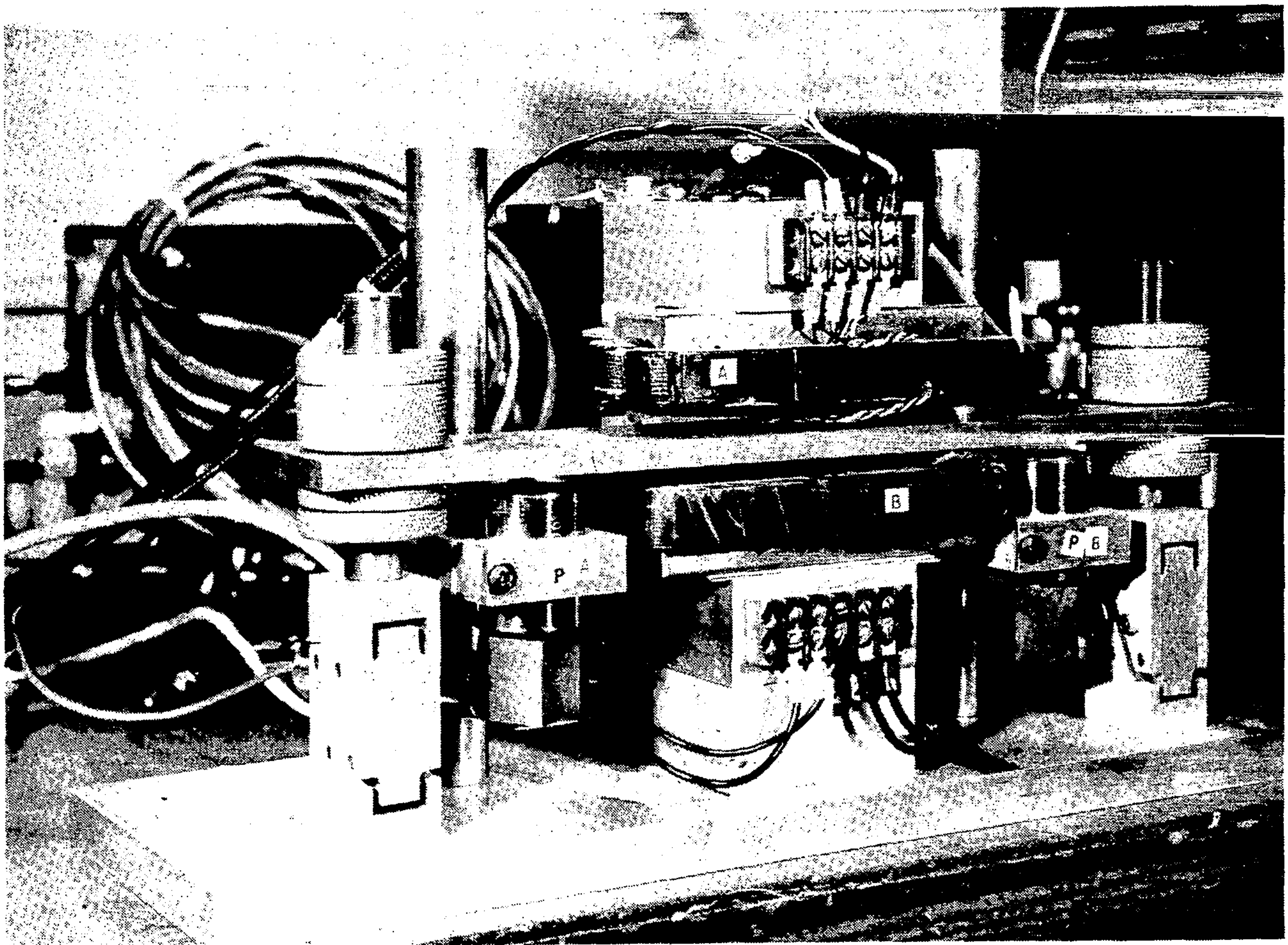

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Figure 5.- Magnetic bearing test fixture.

The load cells, shown in figure 5, are strain-gage bridge instrumented bending beams. The output of the bridge is a voltage which is directly proportional to the load applied to the beam. The cells were connected as shown in figure 6. They have a load range of ±44.48 N (±10 lb) and a nominal scale factor of ±0.045 mV/N-V (±0.2 mV/lb-V). Scale factor and offset differ from cell to cell and vary with changes in test fixture configuration, power supply voltage, and temperature; therefore, software was designed to provide for periodic system calibration.

Calibration was accomplished by applying a sequence of known loads to each cell and performing a first-order least-squares fit to the resulting data. Typical raw calibration data for one cell are given in figure 7.

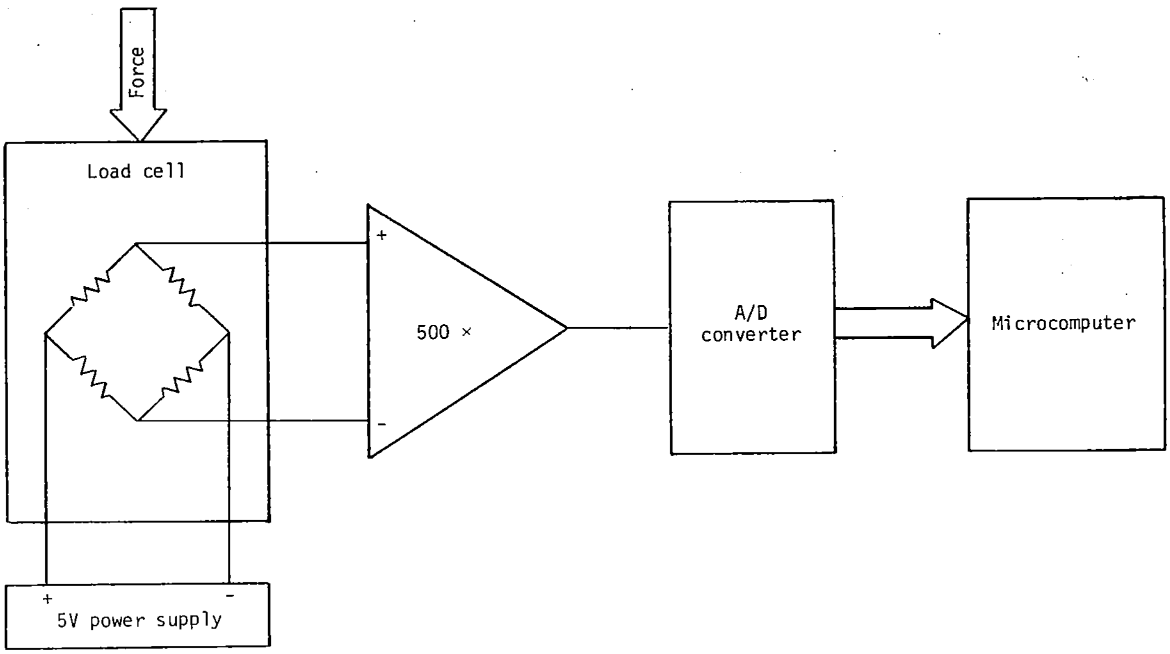

Figure 6.- Load cell connection diagram.

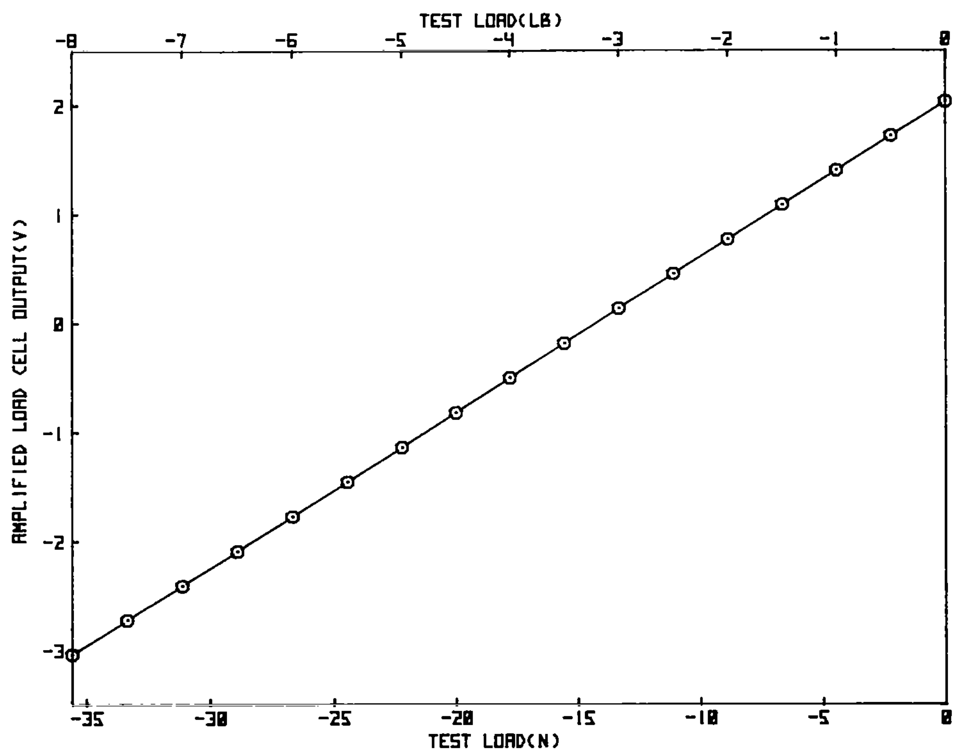

Figure 7.- Typical calibration data for a given load cell.

Microcomputer system.- The same microcomputer system was used for both characterization and performance tests. The major system components include (1) microcomputer and memory, (2) analog interface unit, (3) cartridge data recorder, and (4) portable data terminal (fig. 4).

The microcomputer is an Intel[1] 8080 microprocessor-based computer which includes serial and parallel ports, programmable hardware timers, and 2000 bytes of random access memory (RAM). This processor was selected for the initial phase of development because it is well supported in hardware and software. Available software includes FORTRAN as well as assembly language and the manufacturer's high-level language.

Most of the test programs were written in FORTRAN with assembly language hardware drivers. However, the table lookup routine was written in assembly language because of its time-critical nature. A listing of the table lookup routine is presented in appendix A. Memory expansion boards containing 24 000 bytes of RAM memory were added to permit run time storage of large FORTRAN programs and substantial test data.

The analog interface unit provides up to 32 multiplexed A/D input channels and two D/A output channels. The input channels provide the processor with position and force data from the test fixture position sensors and load cells and provide external command signals during those tests in which an analog force command is used. The two output channels are used to supply the current command to the bearing current driver. The analog interface unit was programmed to perform conversions in two modes. During characterization tests, conversions were initiated under program control, and a flag on the interface was set at end of conversion. During those portions of the performance test when the table lookup algorithm was running in a real-time environment, the interface was programmed to start a conversion sequence on the rising edge of a hardware timer and to interrupt the processor at the end of conversion. This technique provides a stable sampling rate and does not require software timing loops.

The data recorder was used for temporary storage and for transport of test programs and test results. This recorder permitted flexible use of the microcomputer system at a location which was remote from the microprocessor development system used for software generation.

The data terminal provided run time parameter selection, control, and monitoring of the system test programs.

Description of Tests

Characterization tests.- Characterization tests were required to establish the values of lookup table data. These data were collected by the microprocessor system and transferred to a programmable desk-top calculator for analysis

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[1]Use of names of manufacturers in this report does not constitute an official endorsement of such manufacturers, either expressed or implied, by the National Aeronautics and Space Administration.

and reduction. A FORTRAN test program applied a 2048-point sequence of equally spaced current drive signals to the magnetic bearing test fixture and measured the actual force registered by the test fixture load cells at a manually selected rim position. This process was repeated for a series of rim positions. These positions were varied from -0.127 cm (-0.050 in.) to 0.127 cm (0.050 in.) in increments of 0.0127 cm (0.005 in.). The resulting force vs current data were converted by linear interpolation to a 2048-point current vs force table with equal force steps. These data were systematically reduced to form an N-point minimum size lookup table ($N = 2^n$) capable of approximating the measured data to within ±1 percent. This tolerance is within the limits of the existing analog solution to the ideal force equation.

Performance tests.- Two tests were performed to evaluate the assembly language interpolation routine and the table lookup technique:

1. Linearity tests (static) - A sequence of force commands were applied to the test fixture through the linearization algorithm by a FORTRAN test program. The sequence of force commands was applied in the same direction and over the same range as in the characterization tests. The force produced on the rim was measured by the load cells and compared with the input command.

2. Frequency response tests (dynamic) - A sinusoidal force-command signal was applied to the test fixture through the linearization algorithm, and the output current response was observed. The response measurements were performed by a frequency response analyzer. The force-command signal was given a dc offset so that measurements could be performed independently on upper and lower bearing elements. For this portion of the test, the characterization data were replaced by a linear table to permit direct comparison of input force command with current output. This replacement was necessitated by a mechanical resonance of the test fixture which prevented use of load cells for frequency response measurements. The frequency was measured over a bandwidth slightly larger than half the sampling frequency of the algorithm.

TEST RESULTS AND DISCUSSION

Characterization Tests

The force, current, and gap relationships obtained from the data collected during characterization tests are similar to those obtained from the ideal electromagnet force equations (eqs. (3) and (4)). However, measured data deviated from ideal relationships near the zero force points, and differences between constants for upper and lower bearing elements were observed. Figure 8 is a plot of the actual force data resulting from the application of a sequence of equally spaced current drive signals. Each curve represents 2048 data points

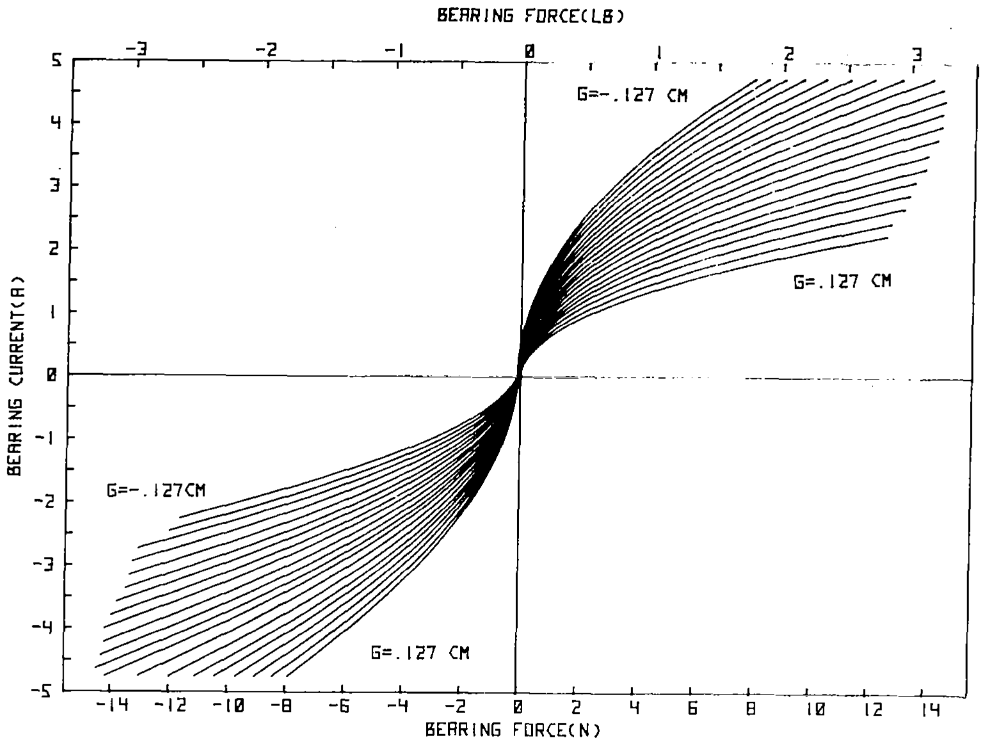


Figure 8.- Force-current data taken from magnetic bearing test fixture.

taken at a given gap setting. The force vs current data with equal current steps were converted by linear interpolation to current vs force data with equal force steps. Analysis of the resulting data indicated that the relationship between current and gap for a given force was sufficiently linear to permit gap compensation to be accomplished by multiplying the output current by the gap (as in eqs. (5) and (6)). Systematic reduction of the data for $G = 0$ resulted in a 128-point table that was capable of reproducing the original data to within 0.5 percent, as illustrated in figure 9. System memory requirements for this size table are quite reasonable.

Performance Tests

Linearity.- The main results of the table lookup algorithm linearity tests are shown in figures 10 and 11. Figure 10 shows the relation between force command input and the measured force output of the system. This particular plot is for $G = 0$, but the same result was obtained for other values of G. The actual percentage force error can be seen in figure 11. These results, although still within acceptable limits (less than ±1 percent error), do not agree completely with the errors predicted during data reduction (shown in fig. 9).

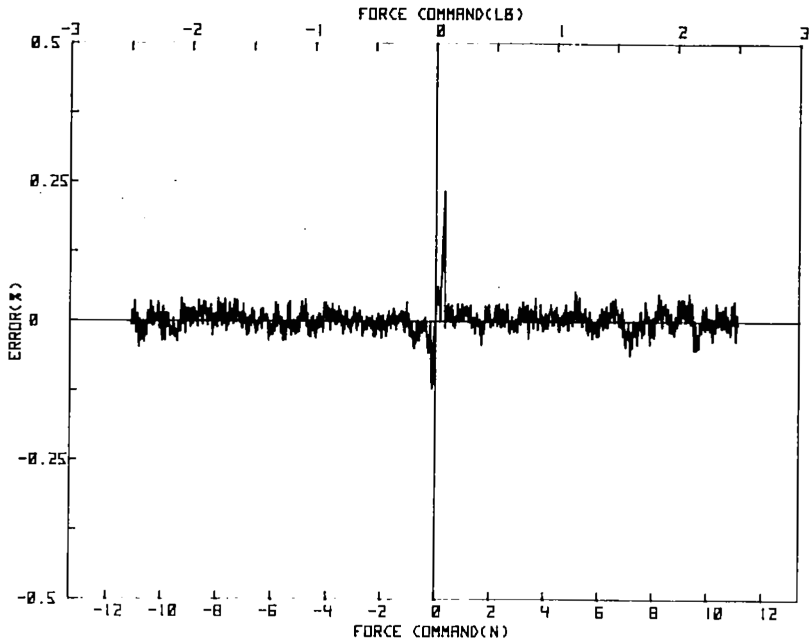


Figure 9.- Error associated with reduction of original data (for G = 0) to a 128-point table.

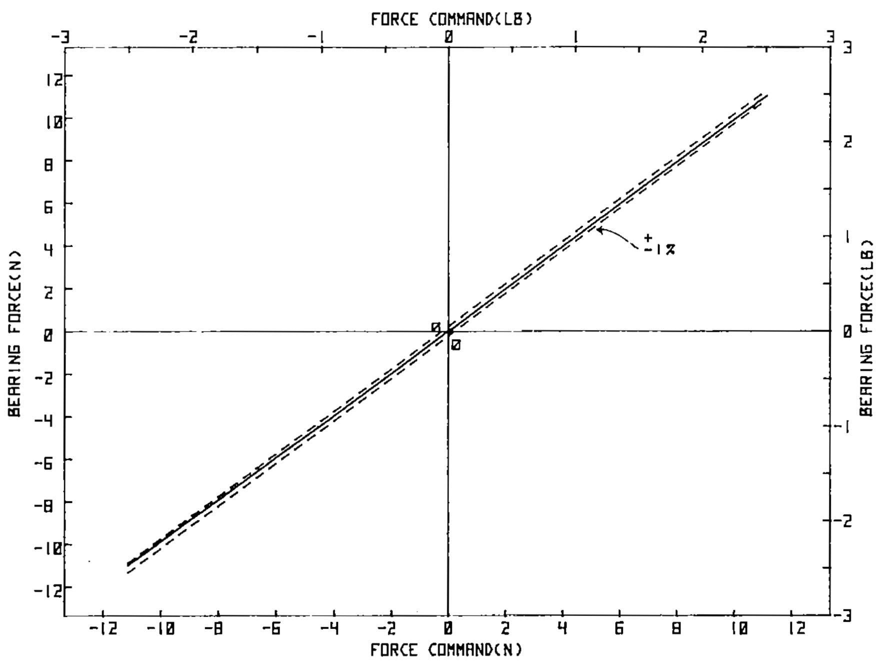


Figure 10.- Static output/input characteristics of table lookup algorithm.

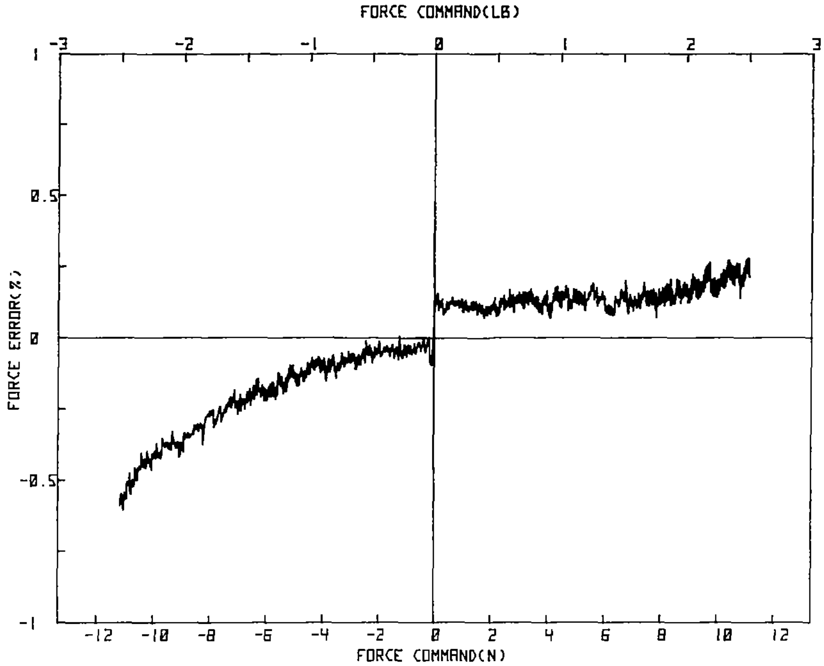
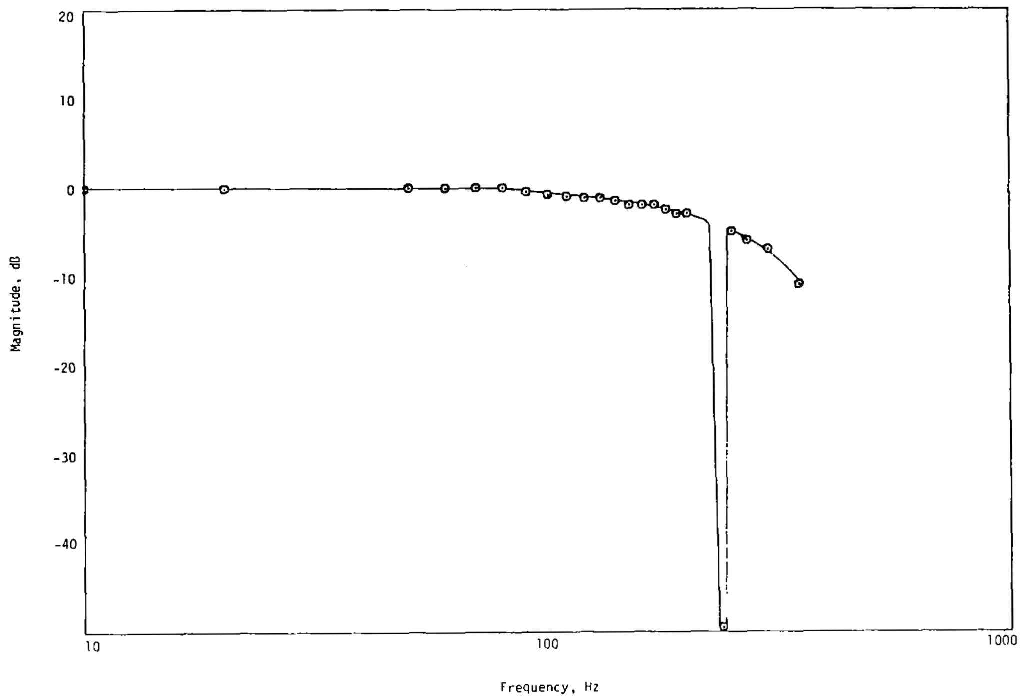


Figure 11.- Percentage force error of table lookup algorithm.

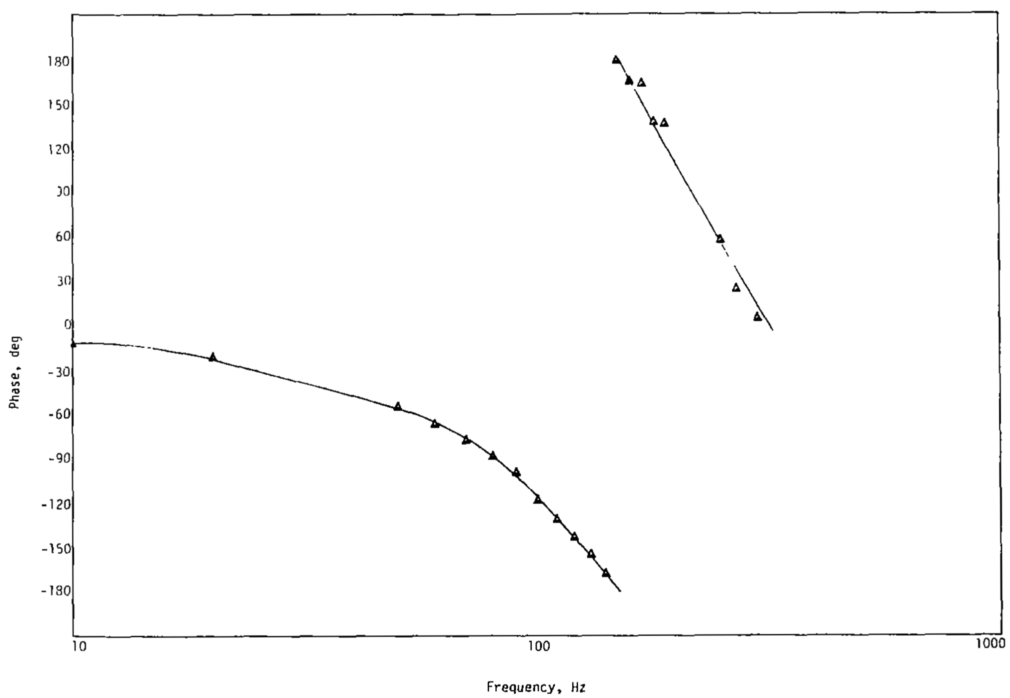
In particular, relatively large errors occur at the maximum positive and negative excursions of the force command. Since no attempt was made to minimize the effects of hysteresis in the test fixture, considerable residual magnetic flux can exist in the electromagnet cores and in the equivalent "suspended" element. Variations in the magnetic history of the test fixture are the probable cause of these errors. One possible way to reduce the effects of hysteresis on accuracy would be to use flux feedback in the power driver loop instead of current feedback. Another more obvious approach would be to use low-hysteresis material in both the electromagnet core and the suspended element magnetic circuit material.

Frequency response.- The table lookup algorithm required approximately a 10-percent greater execution time than the 1.85-ms worst-case value predicted by evaluating the microprocessor instruction execution times. This loss of time occurred during the test because the table lookup algorithm instructions and data were stored in RAM memory on a memory expansion board. The increased execution time limited the system sample rate f_s to a maximum of approximately 490 Hz rather than the 540 Hz which was predicted.

Results of the frequency response test are summarized in figure 12. The bandwidth exceeds 100 Hz, which was considered adequate for this portion of the bearing system. The magnitude is flat from dc to approximately $f_s/4$ and then rolls off gradually to approximately $f_s/2$, which is the theoretical frequency limit for a sampled data system. Since this algorithm retains no history of the signals and has an almost fixed execution time, the phase response varies linearly with frequency to approximately $f_s/2$.



(a) Magnitude.



(b) Phase.

Figure 12.- Frequency response (magnitude and phase) of table lookup algorithm at 490-Hz repetition rate.

CONCLUDING REMARKS

A microprocessor based table lookup approach for magnetic bearing linearization without flux biasing has been presented, and an experimental test setup used to demonstrate the feasibility of the concept has been described. Results obtained with the experimental test setup generally showed very close agreement with theoretical predictions. Using a 128-point table, the table lookup algorithm produced a linear transfer characteristic between force command and force output of the test fixture magnetic bearing actuator to within ±1-percent error. The frequency response of the algorithm was greater than 100 Hz, which should be adequate for this portion of the bearing system.

This approach when used as an inner loop for the actuators could form the basis for an all-digital magnetic suspension control system. One application would be the laboratory model annular momentum control device (AMCD). An all-digital system would allow control-system parameter changes to be made in software without requiring the circuit component changes and circuit rewiring which are necessary with existing analog systems. Also, advanced controller design approaches could be more easily implemented.

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Hampton, VA 23665
March 19, 1981

APPENDIX A

TABLE LOOKUP ALGORITHM

Algorithm Description

This appendix presents a listing, in assembly language, of the table lookup algorithm used to drive the magnetic bearing test fixture. The algorithm performs a nonlinear transformation of an input force command F_C and a measured rim displacement G into current commands I_C to either the top or bottom bearing element. The transformation approximates the solutions of equations (5) and (6) in the main text. The lookup table contains 128 four-byte data groups. Each of the groups consists of a 16-bit value of SLOPE(m) and a 16-bit value of current $I_C(m)$ obtained from measurement of the actual bearing force-current characteristic with the rim centered (i.e., $G_T = G_B = G_O$).

The routine is interrupt driven and is called upon completion of the force command A/D conversion which is initiated by a hardware real-time clock. After reading the force command, the processor sets up the analog interface and initiates conversion of the rim displacement. Because of the configuration of the analog interface, the force command F_C and rim displacement G are 12-bit two's complement numbers which are sign extended to 16 bits.

The least significant 5 bits of F_C are removed and stored, since they contain the value δF_C. The remaining 7 bits identify the 128 data groups. These bits are appropriately shifted, converted to offset binary, and added to the lookup-table base address to produce a memory pointer. The stored slope value is loaded using this memory pointer, and the pointer is incremented. The slope value is then multiplied by δF_C (an 8-bit by 16-bit multiplication routine is used to conserve time). This result is added to the stored value of $I_C(m)$, which is now addressed by the memory pointer. The result, $I_C(F_C,G_O)$, is the current command required to produce a desired force by either bearing element when the rim is centered $(G_T = G_B = G_O)$. Since the required current is directly proportional to the bearing gap, the current command for any rim displacement is given by the following relationships:

$$I_T = |I_C|\left(\frac{G_T}{G_O}\right) \qquad (I_C \geq 0)$$

$$I_B = |I_C|\left(\frac{G_B}{G_O}\right) \qquad (I_C < 0)$$

where $I_C = f(F_C,G_O)$. After substitution of the table lookup algorithm for I_C and the expressions for G_T and G_B from equations (1) and (2) in the main text, these equations become

APPENDIX A

$$I_T = \left(I_c(m) + SLOPE(m)\ \delta F_c\right)\left(\frac{G_o - G}{G_o}\right)$$

$$I_B = \left(I_c(m) + SLOPE(m)\ \delta F_c\right)\left(\frac{G_o + G}{G_o}\right)$$

Since G_o is a constant, these equations can be rewritten as

$$I_T = \left[\left(\frac{I_c(m)}{G_o}\right) + \left(\frac{SLOPE(m)}{G_o}\right)\delta F_c\right](G_o - G)$$

$$I_B = \left[\left(\frac{I_c(m)}{G_o}\right) + \left(\frac{SLOPE(m)}{G_o}\right)\delta F_c\right](G_o + G)$$

The lookup table slope and current entries are predivided by G_o to eliminate a real-time multiplication by $1/G_o$.

Because of the scaling of inputs and outputs (see table A1) and the need to perform all calculations on 16-bit or less integer numbers, the stored look-up table values are scaled as shown in table A2.

TABLE A1.- SCALING OF INPUTS AND OUTPUTS

Variable	Range	Analog scale factor	Analog range	Digital scale factor	Digital range	Total scale factor
F_c	±11.12 N ±2.5 lb	0.9 V/N 4 V/lb	±10 V	204.8	±2047	184.2 819.2
I_c	±5 A	1 V/A	±5 V	409.6	±2047	409.6
G	±0.127 cm ±0.05 in.	[a]78.7 V/cm 200 V/in.	±10 V	[b]409.6	±4096	32.2×10^3 5×2^{14}

[a]These values include the sum of both position sensors.
[b]This value includes a software multiplication by 2 (line 95).

TABLE A2.- SCALING OF TABLE VALUE

Variable	Units	Scaling factors[a,b,c]
SLOPE(m)	A/N	$\frac{(0.5)(2^8)(2^{16})}{(G_o)(32.2)(10^3)}$
	A/lb	$\frac{(0.5)(2^8)(2^{16})}{(G_o)(5)(2^{14})}$
$I_c(m)$	A	$\frac{(2^{16})}{(G_o)(32.2)(2^{14})}$
	A	$\frac{(2^{16})}{(G_o)(5)(2^{14})}$

[a]The (0.5) factor accounts for the difference between the total scale factors for F_c and I_c.

[b]The (2^8) and (2^{16}) factors are employed to maximize the number of significant bits while maintaining intermediate and final results within a 16-bit integer format. These factors are removed by implied shifts during the two multiplications.

[c]Factors $(G_o)(32.2)(10^3)$ and $(G_o)(5)(2^{14})$ are for G_o in SI (cm) and U.S. Customary Units, respectively.

APPENDIX A

Program Listing

```
ASM80 :F1:LOOKUP.ASM PRINT(:F1:LOOKUP.LST) OBJECT(:F1:LOOKUP.OBJ)PAGEWIDTH(80)
                     EJECT


ISIS-II 8080/8085 MACRO ASSEMBLER, V3.0        MODULE   PAGE    1


 LOC  OBJ         LINE        SOURCE STATEMENT

                        ;
                        ;           LOOKUP.ASM
                        ;
                        ;
                                EXTRN CURPOS,CURNEG,ADCIN,TABLE,CONV,MUXADR,STAT
                        US

                        ;     SAVE MAIN PROGRAM REGISTERS
 0000 F5                INTRU:  PUSH PSW        ;SAVE A & PSW
 0001 C5                        PUSH B          ;SAVE BC
 0002 D5                        PUSH D          ;SAVE DE
 0003 E5                        PUSH H          ;SAVE HL

                        ;     LOAD FORCE COMMAND AND
                        ;     SETUP FOR GAP MEASUREMENT
 0004 2A0000    E               LHLD ADCIN      ;LOAD FORCE(N)
 0007 3E06                      MVI A,6H        ;LOAD GAP CHANNEL
 0009 320000    E               STA MUXADR      ;SELECT GAP CHANNEL
 000C 320000    E               STA CONV        ;START GAP CONVERSION

                        ;     GENERATE DELTA FORCE COMMAND
                        ;     AND TABLE ADDRESS OFFSET
 000F 0600                      MVI B,00H       ;CLEAR B
 0011 7C                        MOV A,H         ;HIGH FORCE DATA > A
 0012 E60F                      ANI 0FH         ;MASK OUT HIGH 4 BITS
 0014 67                        MOV H,A         ;STORE DB11 THRU DB8 > H
 0015 7D                        MOV A,L         ;LOW FORCE DATA > A
 0016 E61F                      ANI 1FH         ;MASK OUT HIGH 3 BITS
 0018 4F                        MOV C,A         ;DELTA FORCE > C
 0019 AD                        XRA L           ;MOVE LOW DATA > A (LOW 5 BITS M
                        ASKED)
 001A 84                        ADD H           ;COMBINE DB11 THRU DB8 WITH DB7
                        THRU DB5
 001B 07                        RLC             ;
 001C 07                        RLC             ;REARRANGE BYTE
 001D 07                        RLC             ;   TO FORM
 001E 07                        RLC             ;    DB10,DB9,DB8,DB7,DB6,DB5,0,
                        0
 001F 17                        RAL             ;
 0020 6F                        MOV L,A         ;CONVERT TO
 0021 3F                        CMC             ; OFFSET
 0022 17                        RAL             ;  BINARY
 0023 E601                      ANI 01H         ;   FORM
 0025 67                        MOV H,A         ;

                        ;     COMPUTE ADDRESS OF SLOPE(N)
 0026 110000    E               LXI D,TABLE     ;LOAD TABLE START ADDRESS
 0029 23                        INX H           ;ADJUST "TABLE" ADDRESS VALUE
 002A 23                        INX H           ;
 002B 19                        DAD D           ;ADD TABLE START TO OFFSET


                        ;     LOAD SLOPE(N)
```

```
ISIS-II 8080/8085 MACRO ASSEMBLER, V3.0        MODULE   PAGE    2

 LOC  OBJ        LINE        SOURCE STATEMENT

 002C 5E           50          MOV E,M          ;LOAD LOW BYTE SLOPE(N)
 002D 23           51          INX H            ;INCREMENT POINTER FOR HIGH BYTE
 002E 56           52          MOV D,M          ;LOAD HIGH BYTE SLOPE(N)
 002F 23           53          INX H            ;INCREMENT POINTER FOR CURRENT A
                      DDRESS
                   54
                                          55 ;    MULTIPLY SLOPE(N) BY DELTA FORCE
                                          56 ;    (SPECIAL 8BIT X 16BIT MULT. )
 0030 E5           57          PUSH H           ;SAVE ADDRESS
 0031 EB           58          XCHG             ;SWAP MULTIPLICAN(SLOPE) TO HL
 0032 22D000       59          SHLD TEMP        ;SAVE MULTIPLICAN IN TEMP
 0035 21CE00       60          LXI H,BNUM       ;LOAD CYCLE COUNTER ADDRESS
 0038 3609         61          MVI M,09H        ;LOAD CYCLE COUNTER
 003A 110000       62          LXI D,0H         ;CLEAR TEMPORARY RESULT
 003D 79           63 LOOP:    MOV A,C          ;
 003E 1F           64          RAR              ;ROTATE MULTIPLIER(DELTAF)
 003F 4F           65          MOV C,A          ;
 0040 35           66          DCR M            ;DECREMENT CYCLE COUNTER
 0041 CA5800       67          JZ FINI          ;TEST FOR MULTIPLY COMPLETE
 0044 D24F00       68          JNC SKIP         ;JUMP IF MULTIPLIER BIT 0
 0047 2AD000       69          LHLD TEMP        ;GET MULTIPLICAN
 004A 19           70          DAD D            ; AND ADD
 004B EB           71          XCHG             ;SAVE PARTIAL PRODUCT
 004C 21CE00       72          LXI H,BNUM       ;RELOAD BNUM ADDRESS
 004F 7A           73 SKIP:    MOV A,D          ;
 0050 1F           74          RAR              ;ROTATE
 0051 57           75          MOV D,A          ;
 0052 7B           76          MOV A,E          ;  TEMPORARY
 0053 1F           77          RAR              ;
 0054 5F           78          MOV E,A          ;   RESULT
 0055 C33D00       79          JMP LOOP         ;LOOP
 0058 E1           80 FINI:    POP H            ;RESTORE ADDRESS
                   81
                                          82 ;    COMPUTE CURRENT COMMAND FROM
                                          83 ;    BASEI(N) AND DELTA I
 0059 4E           84          MOV C,M          ;LOAD LOW BYTE BASEI(N)
 005A 23           85          INX H            ;
 005B 46           86          MOV B,M          ;LOAD HIGH BYTE BASEI(N)
 005C EB           87          XCHG             ;SWAP DELTAI TO HL
 005D 09           88          DAD B            ;ADD BASEI(N) TO DELTAI
 005E 44           89          MOV B,H          ;MOVE CURRENT COMMAND
 005F 4D           90          MOV C,L          ;  TO BC
                   91
                                          92 ;    CORRECT FOR BEARING GAP VARIATION
 0060 3A0000   E   93          LDA STATUS       ;CLEAR RTI1200 EOC FLAG
 0063 2A0000   E   94          LHLD ADCIN       ;LOAD GAP
 0066 29           95          DAD H            ,DOUBLE GAP
 0067 3E05         96          MVI A,5H         ;LOAD FORCE COMMAND CHANNEL
 0069 320000   E   97          STA MUXADR       ;SELECT FORCE COMMAND CHANNEL
 006C 111621       98          LXI D,GAP        ;LOAD NOMINAL GAP VALUE
 006F B0           99          ORA B            ;TEST FOR SIGN OF CURRENT COMMAN
                      D
 0070 F5          100          PUSH PSW                ;SAVE SIGN FLAG
 0071 F27F00      101          JP UPPER         ;JUMP TO UPPER BEARING COIL
                  102
```

```
ISIS-II 8080/8085 MACRO ASSEMBLER, V3.0        MODULE   PAGE    3

  LOC  OBJ         LINE       SOURCE STATEMENT

                                       ;     COMPUTE LOWER BEARING COIL GAP
  0074 19               LOWER:  DAD D           ;ADD GAP(T) TO NOMINAL GAP
  0075 0B                       DCX B           ;
  0076 79                       MOV A,C         ;TAKE
  0077 2F                       CMA             ;  ABSOLUTE
  0078 4F                       MOV C,A         ;
  0079 78                       MOV A,B         ;   VALUE
  007A 2F                       CMA             ;    OF
  007B 47                       MOV B,A         ;   CURRENT
  007C C38500                   JMP FINAL       ;JUMP TO FINAL CURRENT COMMAND C
                        OMPUTATION

                                       ;     COMPUTE UPPER BEARING COIL GAP
  007F 7B               UPPER:  MOV A,E         ;SUBTRACT
  0080 95                       SUB L           ;  GAP(T)
  0081 6F                       MOV L,A         ;  FROM
  0082 7A                       MOV A,D         ;  NOMINAL
  0083 9C                       SBB H           ;  GAP AT
  0084 67                       MOV H,A         ;  CENTER

                                       ;     MULTIPLY GAP BY CURRENT COMMAND
  0085 220000           FINAL:  SHLD TEMP       ;STORE MULTIPLICAN IN TEMP
  0088 21CE00                   LXI H,BNUM      ;STORE
  008B 3611                     MVI M,11H;      ; BIT COUNT
  008D 110000                   LXI D,00H       ;INITALIZE RESULT
  0090 78               LOOP1:  MOV A,B         ;ROTATE
  0091 1F                       RAR             ;
  0092 47                       MOV B,A         ;MULTIPLIER
  0093 79                       MOV A,C         ;
  0094 1F                       RAR             ;RIGHT
  0095 4F                       MOV C,A         ;
  0096 35                       DCR M           ;DECREMENT BIT COUNT
  0097 CAAE00                   JZ FINI1        ;DONE? THEN OUTPUT
  009A D2A500                   JNC SKIP1       ;JUMP IF NO CARRY FROM ROTATE
  009D 2A0000                   LHLD TEMP       ; OTHERWISE
  00A0 19                       DAD D           ; ADD MULTIPLICAN
  00A1 EB                       XCHG            ;SAVE RESULT
  00A2 21CE00                   LXI H,BNUM      ;RESTORE BIT COUNT POINTER
  00A5 7A               SKIP1:  MOV A,D         ;ROTATE
  00A6 1F                       RAR             ; TEMP
  00A7 57                       MOV D,A         ; RESULT
  00A8 7B                       MOV A,E         ; RIGHT
  00A9 1F                       RAR             ;
  00AA 5F                       MOV E,A         ;
  00AB C39000                   JMP LOOP1       ;REPEAT LOOP

                                       ;     CHECK FOR OVERCURRENT VALUE
                                       ;     AND OUTPUT RESULT TO CORRECT PORT
  00AE EB               FINI1:  XCHG            ;SWAP CURRENT TO HL
  00AF 7C                       MOV A,H         ;LOAD CURRENT
  00B0 FE08                     CPI 08H         ;TEST CURRENT VALUE
  00B2 DAB800                   JC OK           ;JUMP IF OK
  00B5 21FF07                   LXI H,07FFH     ;CURRENT=MAXIMUM CURRENT
  00B8 F1               OK:     POP PSW         ;RESTORE CURRENT SIGN
```

APPENDIX A

```
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 LOC  OBJ         LINE        SOURCE STATEMENT

 00B9 F2C200       157         JP OUTPOS       ;JUMP IF POSITIVE
 00BC 220000   E   158         SHLD CURNEG     ;OUTPUT RESULT TO LOWER BEARING
                       D/A
 00BF C3C500       159         JMP RETURN      ;RETURN
 00C2 220000   E   160 OUTPOS: SHLD CURPOS     ;OUTPUT RESULT TO UPPER BEARING
                       D/A
 00C5 E1           161 RETURN: POP H           ;RESTORE HL
 00C6 D1           162         POP D           ;RESTORE DE
 00C7 C1           163         POP B           ;RESTORE BC
 00C8 3E20         164         MVI A,20H       ;LOAD END OF INTERUPT
 00CA D3DA         165         OUT 0DAH        ;OUTPUT EOIC
 00CC F1           166         POP PSW         ;POP A & PSW
 00CD C9           167         RET             ;RETURN
                   168
                   169
                   170
                   171
 00CE 0000         172 BNUM:   DW      0
 00D0 0000         173 TEMP:   DW      0
 2116              174 GAP     EQU     8470
                   175         END

PUBLIC SYMBOLS


EXTERNAL SYMBOLS
ADCIN  E 0000    CONV   E 0000    CURNEG E 0000    CURPOS E 0000
MUXADR E 0000    STATUS E 0000    TABLE  E 0000

USER SYMBOLS
ADCIN  E 0000    BNUM   A 00CE    CONV   E 0000    CURNEG E 0000
CURPOS E 0000    FINAL  A 0085    FINI   A 0058    FINI1  A 00AE
GAP    A 2116    INTRU  A 0000    LOOP   A 003D    LOOP1  A 0090
LOWER  A 0074    MUXADR E 0000    OK     A 00B8    OUTPOS A 00C2
RETURN A 00C5    SKIP   A 004F    SKIP1  A 00A5    STATUS E 0000
TABLE  E 0000    TEMP   A 00D0    UPPER  A 007F

ASSEMBLY COMPLETE,    NO ERRORS
```

APPENDIX B

MAGNETIC BEARING CURRENT DRIVER

A schematic diagram of the current driver used in the magnetic bearing test system is shown in figure B1. The driver is capable of supplying up to

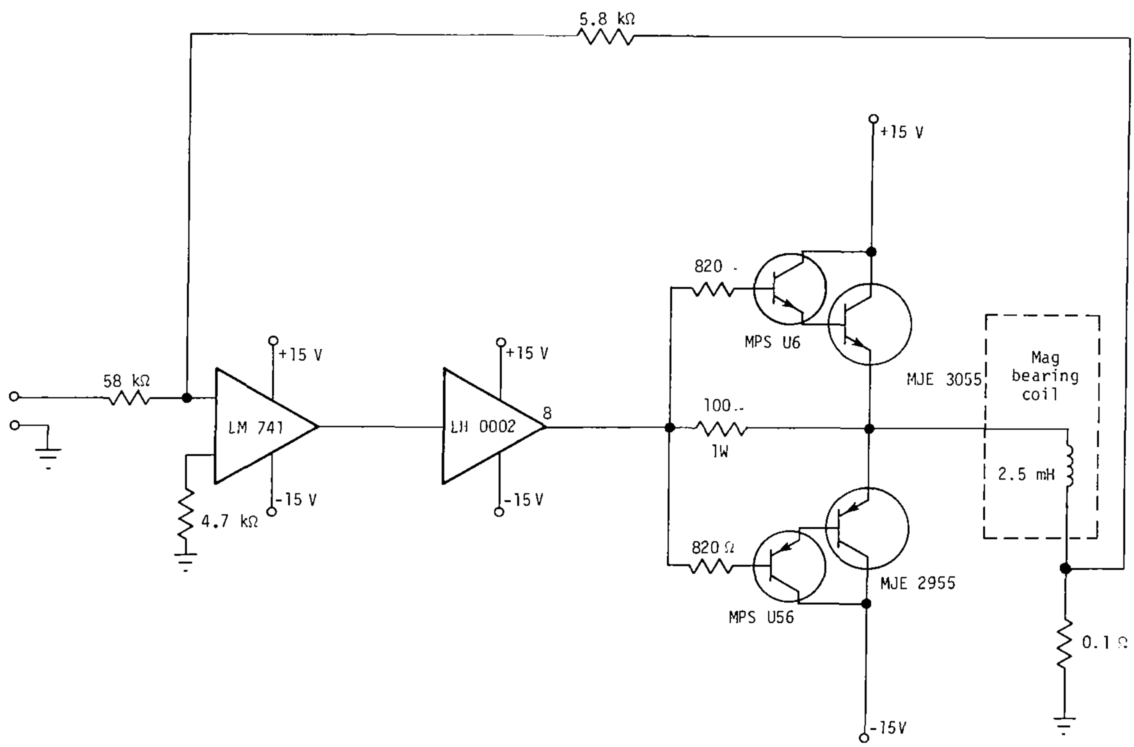
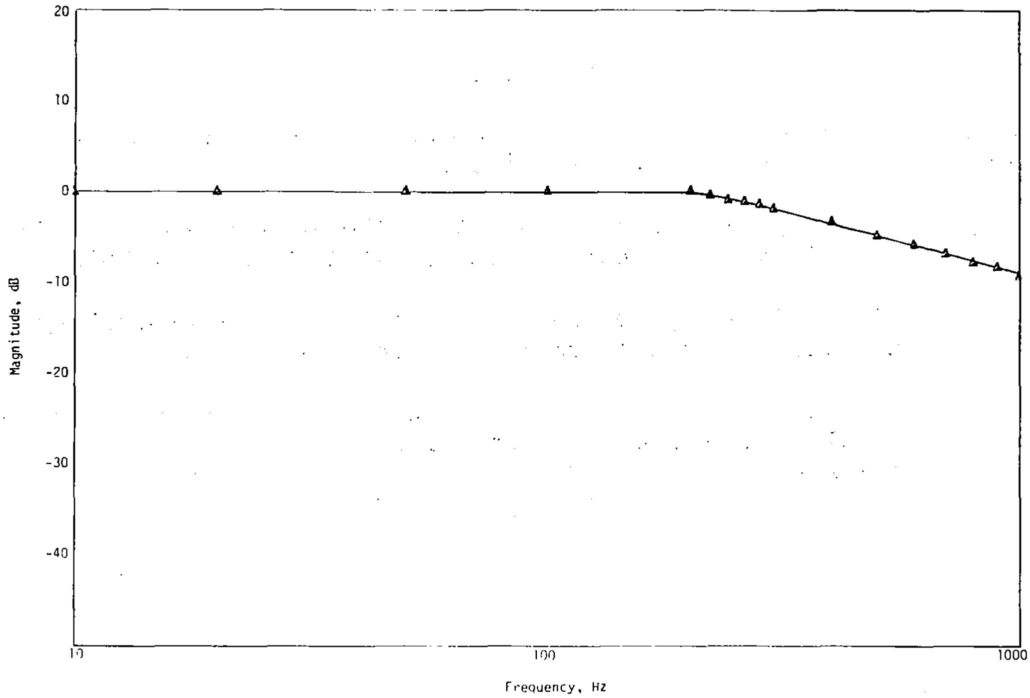


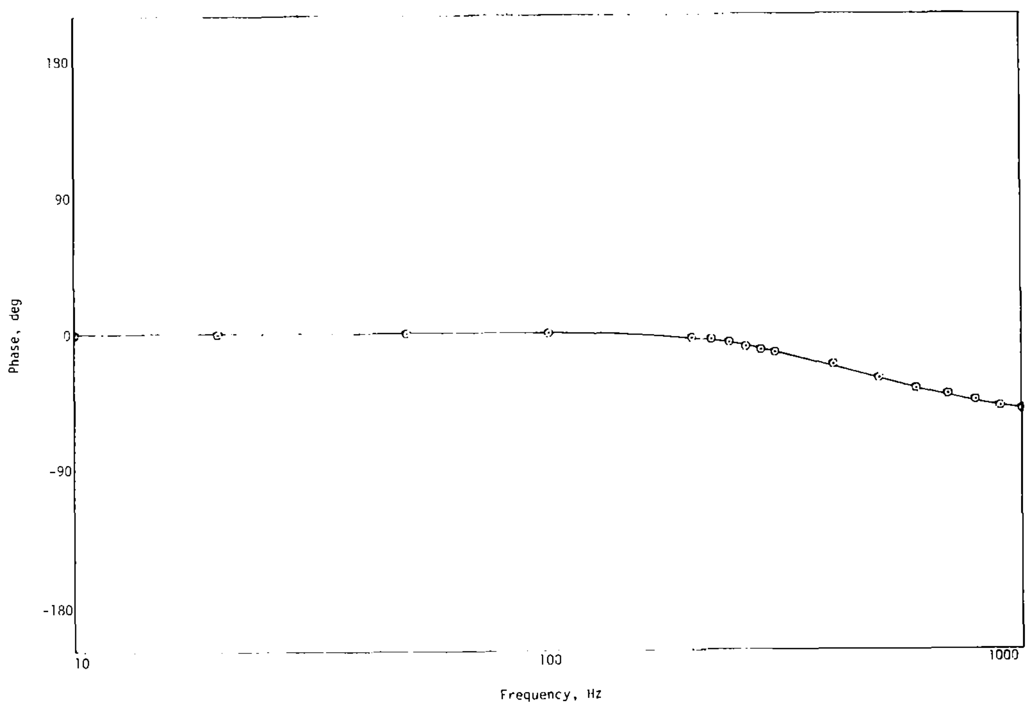
Figure B1.- Magnetic bearing current driver.

5 A to each bearing coil and has a gain of 1 A/V. Drive is provided by the LH 0002 current amplifier at low current levels (<100 mA) and by the complementary Darlington configuration at higher levels. The driver provides flat response over a bandwidth greater than 200 Hz (fig. B2). The frequency response is limited by the ability of the power supply voltage to overcome the back emf of the bearing coil, and the effect is observed as an apparent slew rate limitation. The 200-Hz bandwidth is sufficient to evaluate the table look-up algorithm.

APPENDIX B



(a) Magnitude.



(b) Phase.

Figure B2.- Frequency response (magnitude and phase) of magnetic bearing current driver.