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A LINEAR-INDUCTION-MOTOR SLIDE DRIVE

W. E. Barkman

MASTER

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A LINEAR-INDUCTION-MOTOR SLIDE DRIVE

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ABSTRACT

A linear-induction-motor drive system has been developed on a test bed that utilizes an air-bearing slide, laser interferometer feedback, and a microprocessor-based servo system. Static and dynamic positioning accuracies of ± 16 nm (± 0.6 μ in) have been demonstrated.

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SUMMARY

A linear-induction-motor drive system has been developed which provides a slide motion that is smoother and more accurate than the conventional ball nut/lead screw drives. The system has been assembled on a test bed and utilizes an air-bearing slide, laser interferometer feedback, and a microprocessor-based servo system.

The system is programmed to accept 25.4-nm (1- μ in) commands and exhibits a static positioning ability of ± 16 nm (± 0.6 μ in). The dynamic positioning accuracy is also ± 16 nm (± 0.6 μ in) at feedrates between 0.01 and 0.1 ipm.

INTRODUCTION

The primary method used in the Oak Ridge Y-12 Plant^(a) to position machine tool slides utilizes a rotary prime mover coupled to a ball nut/lead screw. Linear slide motion is obtained by attaching the ball nut to the machine slide and driving the lead screw through a gear box. Slide-position information is obtained from a feedback device, such as a resolver or encoder, which is coupled to the lead screw. Unfortunately, vibration and positioning uncertainties are introduced due to the drive and feedback gearing that adversely affect the part quality. In addition, this gearing requires routine maintenance and may be damaged extensively if a machine slide forcefully contacts a stationary member, or "wrecks".

In order to obtain a smooth, accurate, low-maintenance slide motion, a linear-induction-motor drive system has been developed that utilizes an air-bearing slide, laser interferometer feedback, and a microprocessor-based servo system. The microprocessor has been programmed to accept position-command and position-feedback information and to generate the following error data. An analog servo system is used to generate the motor control signal.

(a) Operated by the Union Carbide Corporation's Nuclear Division for the US Energy Research and Development Administration.

SLIDE DRIVE

SYSTEM DESCRIPTION

The linear-induction-motor test bed, shown in Figure 1, consists of an air-bearing slide mounted on a steel-topped concrete table, a linear motor, a laser interferometer, and a microprocessor-based control system. Figure 2 is a block diagram of the system. A detailed description of each of the basic system components follows.

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Figure 1. LINEAR-INDUCTION-MOTOR TEST BED.

SYSTEM COMPONENTS

Linear Induction Motor

The motor cross section is shown in Figure 3. The stator is 305 mm (12 in) in diameter by 660 mm (26 in) long, and encloses a central pole piece. The exciting coil that generates the DC magnetic field for the stator is located near the forward end of the frame and is cooled by circulating water.

The motor moving member is attached to the air-bearing slide and undergoes an axial force that is a function of the electric current flowing through the control coil. The motor

Figure 2. SYSTEM COMPONENTS.

Figure 3. LINEAR INDUCTION MOTOR.

operation is analogous to a DC torque motor with the exception of the travel limit imposed by the moving member stroke. Figure 4 shows the slide in several positions.

The motor is designed to have a nominal force rating of 45 N (10 lb) with a maximum available force of 90 N (20 lbs). The maximum current required to develop the 90-N (20-lb) force occurs when the moving member (and its control coil) is extended all the way out of the motor. At this point, the force generated is approximately equal to 3.76 times the control coil current (in amperes). A plot of the control coil position versus the force coefficient for small currents is included in Appendix A. For large currents, a significant magnetizing or demagnetizing of the exciting coil is produced. The worst case is when the control coil is retracted all the way into the motor and the control current is flowing to yield a force to move the coil outward.

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Figure 4. LINEAR INDUCTION MOTOR IN SEVERAL POSITIONS.

Air-Bearing Slide

Figures 1 and 4 show the air-bearing slide which is guided by one Vee slideway and one flat slideway. After being bolted to the table top, these ways were scraped and honed to obtain a true slide motion. A 454-kg (1000-lb) slab of metal has been bolted to the top of the slide for simulation purposes.

Laser Interferometer

The system position feedback device is a Hewlett-Packard laser interferometer. The remote interferometer is bolted to the table top and may be seen in Figures 1 and 4. The remote reflector is attached to the slide. Position information is provided to the microprocessor from the up/down pulse output of the laser interferometer display. A 10X resolution extender is used to obtain a pulse resolution of approximately 16 nm ($0.6228 \mu\text{in}$) per pulse.

The laser transducer has an accuracy of ± 0.5 part per million and a maximum velocity of 72 inches per minute in the 10X mode. Thumbwheel switches on the laser display and microprocessor interface are provided for the correction of errors due to ambient temperature, pressure, and humidity.

Microprocessor Hardware and Software

The slide control system is based on an Intel 8080 microprocessor. Figure 1 shows an Intellec 8 (which contains the 8080) mounted in the rack below the laser display. The Intellec 8 is being used for system development and will be replaced by a dedicated control processor when the system configuration is finalized.

The microprocessor reads the command and feedback information from two 8-bit up/down counters and converts this information into the system following error, as indicated in Figure 5. In addition, the processor reads a laser wavelength compensation value from a set of thumbwheel switches and uses these data to adjust the calculated following error for environmental changes. The value of a command pulse is 25.4 nm (1 μ in) while the resolution of the 1/4-wavelength feedback pulse is approximately 16 nm (0.6228 μ in).^(b) The schematic for the laser interface and the system control software is contained in Appendix B.

Figure 5. FUNCTIONS OF THE MICROPROCESSOR.

In order to generate the slide-drive signal, the microprocessor forms a 32-bit following error word. This step is accomplished by reading the number of counts accumulated in the up/down command and feedback counters during the last cycle. These data are converted into two 32-bit words that have least-significant-bit values of 25.4 fm (1 pin). The two words are then subtracted and the upper 16 bits of the result are output to the digital-to-analog converter. The remaining 16 bits are saved for use in the next following error calculation.

The control software performs the following error calculation on a continuous basis, and the overall program cycle time is dependent on the number of counts being processed in any

(b) The exact value depends on ambient temperature, pressure, and humidity.

given time period. However, the basic cycle time required to update the following error word is approximately 1.5 ms; and, as a result, only a few feedback and command counts need to be processed in each cycle at feedrates below 0.1 ipm. In addition, the interface counters have sufficient capacity to accommodate sudden disturbances to the system.

Servo System

The servo system, which is based on the Inland EM-1804 100-watt transistorized servo drive, is diagramed in Figure 6. The system utilizes lag compensation and acceleration feedback to provide stability along with a high-position loop gain. Velocity feedback was initially tried; however, it had a destabilizing effect, and acceleration feedback was found to be much more suitable.

Figure 6. COMPONENTS OF THE SERVO SYSTEM.

Because the linear motor has no rotating components, it is not feasible to use a tachometer to provide an accurate rate signal. Instead, the laser up/down pulses are coupled to individual frequency-to-voltage (F/V) converters to generate an analog signal. The output of the F/Vs is then summed to provide an analog velocity signal, as shown in Appendix C. The negative acceleration feedback signal is simulated by coupling the rate signal to the servo amplifier through a series capacitor.

Results

Initially, the servo system was configured for a position-and-velocity loop. However, it was found that, except for the case of a very low system gain, a stability problem existed due to the large slide mass and very low system friction. Lag compensation provided some increase in stability, but not enough to provide suitable operation.

Conversion of the velocity loop to an acceleration loop resulted in greatly increased stability; and, when combined with lag compensation, yielded a position loop gain of approximately 100 ipm/mil of following error. Figure 7 shows the system following error response to an analog step input at the servo system.

Figure 8 shows the system following error for three different feed-rate commands that were generated by presenting pulse trains to the microprocessor command input interface. Over the feed-rate range of 0.001 to 0.1 ipm, the positioning uncertainty of the system varied from about 150 to 200 nm (6 - 8 μin), with a fundamental frequency of about 60 Hz. Figure 9 shows the system following error at slide standstill under three conditions: View a, with the control power on; View b, with the control power off, and View c, with the air to the slide off and the control power off. A comparison of the vibration levels observed with the control power on and off indicated that the oscillation was not originating within the servo system. View c of Figure 8 indicates that the table top itself was behaving as a relatively rigid body. This and other supplemental data indicated that the positioning uncertainty was caused primarily by building structural vibration that was easily transmitted through the air bearing and appeared as an axial disturbance of 100 to 150 nm (4 - 6 μin).

Figure 7. SYSTEM-FOLLOWING-ERROR RESPONSE TO STEP INPUT AT THE SERVO AMPLIFIER.

A pneumatic vibration isolation system was used to reduce the level of external disturbance. Figure 10 shows the variation in the present system following error at standstill and at feedrates between 0.001 and 0.1 ipm. The static positioning uncertainty is seen to be ± 1 feedback count, or ± 16 nm ($\pm 0.6 \mu\text{in}$), at standstill. At a feedrate of 0.001 ipm, the positioning uncertainty increases to approximately 53 nm (2.1 μin); while, at the higher feedrates of 0.01 and 0.1 ipm, the positioning uncertainty decreases back to the ± 1 feedback count level.

Figure 8. SYSTEM FOLLOWING ERROR FOR A CONSTANT FEEDRATE COMMAND. [Each Horizontal Division Equals 20 ms/div; Each Vertical Division Equals 100 nm/div (4 μ in/div)]

Figure 9. SYSTEM FOLLOWING ERROR AT STANDSTILL. [Each Horizontal Division Equals 20 ms/div; Each Vertical Division Equals 100 nm/div (4 μ in/div)]

Figure 10. SYSTEM FOLLOWING ERROR WITH THE ISOLATION SYSTEM INSTALLED. [Each Vertical Division Equals 5 nm/div (0.2 μ in/div); Chart Speed, 5 mm/s]

CONCLUSIONS

Because of the successful results obtained with the 510 mm (20 in) linear motor, plans have been made to investigate a longer travel motor for use with a large diamond turning machine. The new motor will also be capable of exerting an axial force of 90 N (20 lb), and will have a travel of 854 mm (34 in). The associated control system will have a command resolution of 25.4 nm (1 μ in).

The original control system was initially configured for a 254-nm (10- μ in) command resolution, and it will be necessary to expand the microprocessor interface to provide a suitable 25.4-nm (1- μ in) operation.

Altering the system resolution to the 25.4-nm (1- μ in) and lower levels does not require increased word length in the processor calculations as long as the servo loop is sufficiently tight and/or the processor speed is adequate, but it does require an increased interface capacity since the command and feedback pulses are now accumulated much faster for a given feedrate command.

Following the expansion of the processor interface, the feedback pulse resolution limit will be investigated using an additional laser interferometer resolution extender and, possibly, more involved compensation networks. In addition, the processor capability for multiaxis control and other data-handling tasks will be evaluated. Finally, incorporation of the linear-induction-motor drive system into a machine tool will be investigated; however, this effort will require special consideration of the unique features of this drive system.

One of the unusual features of this drive system is the strong, local magnetic field associated with the motor stator. Care must be taken during the design phase of the basic machine tool to ensure that this does not interfere with the system operation. Another unique system constraint and advantage is the lack of a lead screw. This arrangement permits a smooth drive motion, but also provides no stopping mechanism in the event of an emergency stop condition such as slide runaway due to loss of feedback signal. A positive braking technique will be needed with the slide system to provide a definite stopping action whenever needed.

APPENDIX A

FORCE CHARACTERISTIC

Figure A-1. APPROXIMATE FORCE RATIO AS A FUNCTION OF THE POSITION FOR A SMALL CURRENT (< 0.1 A).

APPENDIX B

SOFTWARE DOCUMENTATION

The slide control software consists of the following subroutines which are described in detail in the subtopics to follow.

Subroutine

1	Laser Compensation
2	Initialization
3	Read Feedback (FB) Counts (CTS)
4	FB CTS Conversion
5	Negative FB Value Conversion
6	FB Value Storage
7	Read Command (CMD) CTS
8	CMD CTS Conversion
9	Positive CMD Value Conversion
10	Following Error (FE) Calculation
11	FE Output
12	Algorithm Logic

A BCD Laser Compensation Constant is read from a thumb wheel switch and converted to its binary equivalent. The FB and CMD constants are then stored in memory for use during the FB and CMD value conversions. The software converts the FB and CMD input counts into a 32-bit binary word where the least significant bit (LSB) represents 1×10^{-12} inches. The most significant bit (MSB) is Bit 31; Bit 32 is a sign bit. Following the FB and CMD to microinches conversion, the following error is calculated and output to the D/A converter. The software calculates $-FE$.

Laser Compensation (Subroutine 1)

The three-digit binary coded decimal (BCD) laser compensation value ($1/4 \lambda$) is input via Port 15 and the upper four bits of Port 14. The least significant digit (LSD) is loaded into the E register while the other two digits are left in the A register.

The A-register word is then shifted left and a carryout check is made. If the carryout occurs, the binary equivalent of the weight of the particular bit is loaded into the HL register pair and added to the contents of the DE register pair. The process is continued until each bit of the BCD laser compensation word has been tested and the binary equivalent of the BCD value has been formed in the DE register pair.

Initialization (Subroutine 2)

The two 16-bit following error words are initially set to zero. FEMIL is the upper 16-bit word and FESUB is the lower 16-bit word. (Only FEMIL is output to the D/A.)

Table B-1
SOFTWARE FOR SUBROUTINE 1

0000		OGR	0000H	001E 19	DAD D	
0056	MAIN	EQU	0056H	001F EB	XCHG	
2020	FEMIL	EQU	2020H	0020 17	TWOH: RAL	
2022	FESUB	EQU	2022H	0021 D22900	JNC ONEH	
2024	FATEM	EQU	2024H	0024 21C800	LXI H,200	
2026	FBCTS	EQU	2026H	0027 19	DAD D	
2030	CATEM	EQU	2030H	0028 EB	XCHG	
2032	CMDCT	EQU	2032H	0029 17	ONEH: RAL	
2040	LFBV	EQU	2040H	002A D23200	JNC ATEEE	
2042	HFBV	EQU	2042H	002D 216400	LXI H,100	
2050	FBLOC	EQU	2050H	0030 19	DAD D	
2070	CLOC	EQU	2070H	0031 EB	XCHG	
				0032 17	ATEEE: RAL	
				0033 D23B00	JNC FORTY	
				0036 215000	LXI H,80	
				0039 19	DAD D	
				003A EB	XCHG	
				003B 17	FORTY: RAL	
				003C D24400	JNC TWENT	
				003F 212800	LXI H,40	
				0042 19	DAD D	
				0043 EB	XCHG	
				0044 17	TWENT: RAL	
				0045 D24D00	JNC TEN	
				0048 211400	LXI H,20	
				004B 19	DAD D	
				004C EB	XCHG	
				004D 17	TEN: RAL	
				004E D25600	JNC MAIN	
				0051 210A00	LXI H,10	
				0054 19	DAD D	
				0055 EB	XCHG	

;2050 THRU 206B
 ;2070 THRU 208B
 ;LASER COMPENSATION
 ;BCD INPUT CONVERTED
 ;TO BINARY VALUE (PICOINCHES)
 ;LOAD 1'S VALUE (UPPER 4 BITS)
 ;LOAD 100'S & 10'S VALUES
 ;RESULT IN DE
 ;LASER COMP. IN DE

Figure B-1. LASER COMPENSATION FLOW CHART.

Table B-2
SOFTWARE FOR SUBROUTINE 2

INITIALIZATION				JNZ FCLOP				;CMD CONSTANT INITIALIZATION	
0056	210000	MAIN:	LXI H,0	0094	C27900				
0059	222020		SHLD FEMIL ;ZERO CURRENT FOLLOWING ERROR	0097	217020		LXI H,CLOC		
005C	222220		SHLD FESUB ;ZERO CURRENT FOLLOWING ERROR	009A	1E80		MVI E,80H		
005F	212008		LXI H,0820H	009C	73		MOV M,E		
0062	19		DAD D ;FORM FB CONVERSION CONSTANT	009D	23		INX H		
0063	EB		XCHG	009E	1696		MVI D,96H		
0064	215020		LXI H,FBLOC	00A0	72		MOV M,D		
0067	73		MOV M,E	00A1	23		INX H		
0068	23		INX H	00A2	0E98		MVI C98H		
0069	72		MOV M,D	00A4	71		MOV M,C		
006A	23		INX H	00A5	23		INX H		
006B	365F		MVI M,5FH ;FB BASE CONSTANT	00A6	7B		MOV A,E		
006D	23		INX H	00A7	42		MOV B,D		
006E	3600		MVI M,0 ;BASIC FB CONSTANT IS STORED	00A8	1600		MVI D,0		
0070	23		INX H	00AA	3600		MVI M,0		
0071	7B		MOV A,E	00AC	23		INX H		
0072	42		MOV B,D	00AD	1E06		MVI E,6		
0073	1600		MVI D,0	00AF	00		NOP		
0075	0E5F		MVI C,5FH	00B0	37	CCLOP:	STC		
0077	1E06		MVI E,6 ;DCBA	00B1	3F		CMC		
0079	37	FCLOP:	STC ;SHIFTED CONSTANTS ARE FORMED	00B2	17		RAL		
007A	3F		CMC	00B3	323020		STA CATEM		
007B	17		RAL	00B6	77		MOV M,A		
007C	322420		STA FATEM	00B7	78		MOV A,B		
007F	77		MOV M,A	00B8	23		INX H		
0080	78		MOV A,B	00B9	17		RAL		
0081	23		INX H	00BA	77		MOV M,A		
0082	17		RAL	00BB	47		MOV B,A		
0083	77		MOV M,A	00BC	23		INX H		
0084	47		MOV B,A	00BD	79		MOV A,C		
0085	23		INX H	00BE	17		RAL		
0086	79		MOV A,C	00BF	77		MOV M,A		
0087	17		RAL	00C0	23		INX H		
0088	77		MOV M,A	00C1	4F		MOV C,A		
0089	23		INX H	00C2	7A		MOV A,D		
008A	4F		MOV C,A	00C3	17		RAL		
008B	7A		MOV A,D	00C4	77		MOV M,A		
008C	17		RAL	00C5	23		INX H		
008D	77		MOV M,A	00C6	57		MOV D,A		
008E	23		INX H	00C7	3A3020		LDA CATEM ;DCBA		
008F	57		MOV D,A	00CA	1D		DCR E		
0090	3A2420		LDA FATEM ;DCBA AND MEMORY	00CB	C2B000		JNZ CCLOP		
0093	1D		DCR E						

Prior to the calculation of the 32-bit following error word (LSB = 1 pin), the contents of the FB and CMD counters are converted into 32-bit words through a process of shifting the FB and CMD words and adding when a carryout occurs.

The constants used in the summation process are stored in memory by the initialization part of the control program. The first memory location used to store the low order part of the constant is FBLOC (FB) and CLOC (CMD).

The constant which corresponds to the binary equivalent of the LSB of the FB or CMD counter is stored in memory and also shifted to form the other constants which correspond to the other bits in the FB or CMD counter words.

The memory storage locations used for the constants are controlled by the HL register pair. This register pair is initialized to FBLOC for the FB counts and CLOC for the CMD counts. The HL pair is then incremented following each shift operation to define a new memory location.

The value of the FB constant is modified by the laser compensation value prior to the shifting process.

Read Feedback Counts (Subroutine 3)

The feedback counts (FB CTS) are transferred from the up/down counters of the buffer register by outputting a RESET and LOAD pulse to the counter interface. The reset pulse is coded as a 40H output word to Port 14, while the load pulse is coded as an 80H output word to Port 14. The FB counts are then read from Port 12. If the FB counts are negative, the A register is complemented and incremented and the MSB of the B register is set equal to one.

Feedback Counts Conversion (Subroutine 4)

The feedback counts in the A register are converted (FBCC) to the 32-bit binary picoinch (pin) word by forming a sum which is based on the bits present in the A register. The constants formed earlier in the initialization section are utilized to perform the conversion through a process of shifting the A register, checking for a carry, and forming the approximate summation.

The HL register pair is again used to hold the memory location of the appropriate constant (beginning at FBLOC). Double-word additions using the SP register are done to check for a carryout.

Following the conversion, the sign of the B register is checked. If a positive result is obtained the program jumps to the storage of the result. If a negative result is obtained the 2s complement is formed and stored.

Figure B-2. INITIALIZATION FLOW CHART.

Negative Feedback Value Conversion (Subroutine 5)

A negative result is 2s complemented because the conversion process does not consider the sign of the FB counts, it just performs a strict bit-for-bit conversion.

Feedback Value Storage (Subroutine 6)

The 32-bit converter feedback value is stored using the FSTOR routine. Two 16-bit words are used—LFBV and HFBV, where HFBV is the high-order 16 bits.

Read Command Counts (Subroutine 7)

This section is similar to the Read FB Counts section. Since the CMD up/down counter has already been loaded into buffer storage by the RESET and LOAD pulses generated in the Read FB counts section, it is only necessary to input the CMD CTS via Port 13.

Since $FB - CMD = -FE$ is accomplished through addition, positive CMD CTS are 2s complemented and the MSB of the B register is set equal to one.

Command Counts Conversion (Subroutine 8)

This section is similar to the FB CTS conversion software. However, since subtraction is being implemented via 2s complement arithmetic, the resulting sign check causes different things to occur. Here, if the result of the sign is positive, the result is 2s complemented.

Positive Command Value Conversion (Subroutine 9)

The positive conversion (PCVC) result is changed to the 2s complement form as was done in the Negative feedback Value Conversion section (Subroutine 5).

Following Error Calculation (Subroutine 10)

The result from the CMD counts conversion is placed in registers DESP. The low-order 16 bits from the FB counts conversion, LFRV, are placed in HL and added to the contents of SP. If a carry occurs, the register pair DE is incremented. The 16 high-order bits, HFRV, are then used to complete the calculation. This step calculates the difference between the FB and CMD CTS for the current sample increment.

The true following error (FE) is then calculated (FECAL) by adding the results of the present calculation to the results of the previous calculations. The result is stored in FEMIL (high-order 16 bits) and FESUB (low-order 16 bits). Only FEMIL is output to the D/A.

Following Error Output (Subroutine 11)

The upper 16 bits of the 32-bit following error word (FEMIL) are output via Ports 12 and 13. The MSB of FEMIL is complemented in software to accommodate the offset binary format of the 16-bit D/A converter.

Table B-3
SOFTWARE FOR SUBROUTINES 3 - 6

				;READ FB COUNTS			
00CE 0600	RFBC:	MVI	B,0				
00D0 48		MOV	C,B				
00D1 3E40		MVI	A,40H				
00D3 D30E		OUT	14				
00D5 3E00		MVI	A,00H				
00D7 D30E		OUT	14				
00D9 3E80		MVI	A,80H	;RESET FLIP FLOP			
00DB D30E		OUT	14	;LOAD INPUT BUFFERS			
00DD 3E00		MVI	A,0				
00DF D30E		OUT	14				
00E1 DB0C		IN	12	;LOAD FB CTS			
00E3 3C		INR	A				
00E4 3D		DCR	A				
00E5 F2EC00		JP	FBCC				
00E8 2F		CMA					
00E9 3C		INR	A				
00EA 0680		MVI	B,80H				
				;FB CTS CONVERSION			
00EC 215020	FBCC:	LXI	H,FBLOC				
00EF 310000		LXI	SP,0	;BCSP=0			
00F2 3C		INR	A				
00F3 3D		DCR	A				
00F4 CA3E01		JZ	FSTOR				
00F7 37	FOTER:	STC					
00F8 3F		CMC					
00F9 1F	FINER:	RAR					
00FA DA0401		JC	FGO				
00FD 23		INX	H				
00FE 23		INX	H				
00FF 23		INX	H				
0100 23		INX	H				
0101 C3F900		JMP	FINER				
0104 5E	FGO:	MOV	E,M				
0105 23		INX	H				
0106 56		MOV	D,M	;CONSTANT IN DE			
0107 23		INX	H				
0108 EB		XCHG		;BCSP, ADDRESS IN DE			
0109 39		DAD	SP				
010A D20E01		JNC	FONE				
010D 03		INX	B	;BCHL			
010E F9	FONE:	SPHL		;BCSP			
010F EB		XCHG		;BCDE, ADDRESS IN HL			
0110 5E		MOV	E,M				
0111 23		INX	H				
0112 56		MOV	D,M	;CONSTANT IN DE			
0113 23		INX	H				
0114 EB		XCHG		;BCSP, ADDRESS IN HL			
0115 09		DAD	B	;HLSP			
0116 44		MOV	B,H				
0117 4D		MOV	C,L				
0118 EB		XCHG		;BCSP, ADDRESS IN HL			
0119 3C		INR	A				
011A 3D		DCR	A				
011B C2F700		JNZ	FOTER				
011E 04	BFCHK:	INR	B	;SIGN CHECK			
011F 05		DCR	B				
0120 F23E01		JP	FSTOR	;BCSP			
				;NEGATIVE FB VALUE CONVERSION			
0123 210000		LXI	H,0				
0126 39		DAD	SP	;BCHL			
0127 78		MOV	A,B	;ACHL			
0128 17		RAL					
0129 2F		CMA					
012A 1F		RAR					
012B 47		MOV	B,A				
012C 79		MOV	A,C				
012D 2F		CMA					
012E 4F		MOV	C,A				
012F 7C		MOV	A,H				
0130 2F		CMA					
0131 67		MOV	H,A				
0132 7D		MOV	A,L				
0133 2F		CMA					
0134 6F		MOV	L,A	;BCHL			
0135 310100		LXI	SP,1				
0138 39		DAD	SP				
0139 D23D01		JNC	FONMO				
013C 03		INX	B				
013D F9	FONMO:	SPHL		;BCSP IN 2'S COMPLEMENT FORM			
				;FB VALUE STORAGE			
013E 210000	FSTOR:	LXI	H,0				
0141 39		DAD	SP				
0142 224020		SHLD	LFBV	;BCHL			
0145 60		MOV	H,B				
0146 69		MOV	L,C				
0147 224220		SHLD	HFBV

Figure B-3. READ FEEDBACK COUNTS FLOW CHART.

Table B-4
SOFTWARE FOR SUBROUTINES 7 - 10

				;READ CMD COUNTS			
014A 0600		MVI	B,0				
014C 48		MOV	C,B				
014D DB0D		IN	13	;LOAD CMD CTS			
014F 3C		INR	A				
0150 3D		DCR	A				
0151 F25801		JP	CMDCC				
0154 2F		CMA					
0155 3C		INR	A				
0156 0680		MVI	B,80H				
				;CMD CTS CONVERSION			
0158 217020	CMDCC:	LXI	H,CLOC				
015B 310000		LXI	SP,0				
015E 3C		INR	A				
015F 3D		DCR	A				
0160 CA9701		JZ	PCVC				
0163 37	COTER:	STC					
0164 3F		CMC					
0165 1F	CINER:	RAR					
0166 DA7001		JC	CGO				
0169 23		INX	H				
016A 23		INX	H				
016B 23		INX	H				
016C 23		INX	H				
016D C36501		JMP	CINER				
0170 5E	CGO:	MOV	E,M				
0171 23		INX	H				
0172 56		MOV	D,M	;BCSP, CONSTANT IN DE			
0173 23		INX	H				
0174 EB		XCHG		;ADDRESS IN DE			
0175 39		DAD	SP				
0176 D27A01		JNC	CONE				
0179 03		INX	B				
017A F9	CONE:	SPHL		;BCSP			
017B EB		XCHG		;ADDRESS IN HL			
017C 5E		MOV	F,M				
				;CONSTANT IN DE			
017D 23		INX	H				
017E 56		MOV	D,M				
017F 23		INX	H				
0180 EB		XCHG		;ADDRESS IN DE			
0181 09		DAD	B	;HLSP			
0182 44		MOV	D,H	;BLSP			
0183 4D		MOV	C,L	;BCSP			
0184 EB		XCHG		;ADDRESS IN HL			
0185 3C		INR	A				
0186 3D		DCR	A				
0187 C26301		JNZ	COTER				
018A 04	BCCHK:	INR	B				
018B 05		DCR	B				
018C F29701		JP	PCVP				
018F 78		MOV	A,B	;ACSP			
0190 17		RAL					
0191 3F		CMC					
0192 1F		RAR					
0193 47		MKV	B,A	;BCSP			
0194 C3B001		JMP	FECAL				
				;POSITIVE CMD VALUE CONVERSION			
0197 210000	PCVP:	LXI	H,0				
019A 39		DAD	SP				
019B 78		MOV	A,B	;ACHL			
019C 2F		CMA					
019D 47		MOV	B,A				
019E 79		MOV	A,C				
019F 2F		CMA					
01A0 4F		MOV	C,A				
01A1 7C		MOV	A,H				
01A2 2F		CMA					
01A3 67		MOV	H,A				
01A4 7D		MOV	A,L				
01A5 2F		CMA					
01A6 6F		MOV	L,A	;BCHL			
01A7 310100		LXI	SP,1				
				;BCSP			
01AA 39		DAD	SP				
01AB D2AF01		JNC	CONMO				
01AE 03		INX	B				
01AF F9	CONMO:	SPHL		;BCSP			
				;FE CALCULATION			
01B0 50	FECAL:	MOV	D,B				
01B1 59		MOV	E,C	;DESP			
01B2 2A4020		LHLD	LFBV				
01B5 39		DAD	SP	;DEHL			
01B6 D2BA01		JNC	TWO				
01B9 13		INX	D				
01BA EB	TWO:	XCHG		;HLDE			
01BB F9		SPHL		;SPDE			
01BC 2A4220		LHLD	HFBV	;HIGH FEEDBACK VALUE			
01BF 39		DAD	SP	;HLDE			
01C0 EB		XCHG		;DEHL			
01C1 F9		SPHL		;DESP			
01C2 2A2220		LHLD	FESUB				
01C5 39		DAD	SP				
01C6 D2CA01		JNC	TWOMO				
01C9 13		INX	D				
01CA EB	TWOMO:	XCHG		;HLDE			
01CB F9		SPHL		;SPDE			
01CC 2A2020		LHLD	FEMIL				
01CF 39		DAD	SP	;HLDE			
01D0 222000		SHLD	FEMIL				
01D3 EB		XCHG		;DEHL			
01D4 222220		SHLD	FESUB	;FE OUTPUT			
01D7 7A		MOV	A,D				
01D8 17		RAL					
01D9 3F		CMC					
01DA 1F		RAR		;OFFSET BINARY FORMAT			
01DB D30D		OUT	13				
01DD 7B		MOV	A,E				
01DE D30C		OUT	12				
01E0 C3CE00		JMP	RFBC	;CONTINUE

Figure B-4. FEEDBACK COUNTS CONVERSION FLOW CHART.

Algorithm Logic (subroutine 12)

This section is used to describe some of the logic behind the form of the final control algorithm.

The up/down counters used represented +1 as 0001 and -1 as 1111, so a direct conversion from counts to picoinches (via multiplication, addition, or whatever) was not easily done. It was decided to treat all counts in the positive form so that an absolute-value conversion could be formed. This action reduced the program complexity and storage required. Given this assumption, it is then necessary to keep track of the actual sign for later adjustment of the converted results. Addition of appropriate constants based on a carryout following a shifting operation was chosen over other multiplication techniques on the basis of speed.

Since 2s-complement arithmetic was used to form the quantity $-FE = FB\ CTS - CMD\ CTS$, it was necessary to modify the conversion results of the CMD CTS to obtain the desired subtraction. If the CMD counter contents were negative, then the contents were 2s complemented, converted, and added to the FB conversion results since the 2s-complement form was needed for the $-FE$ calculation. However, if the CMD counter contents were positive, then it was necessary to complement the results of the CMD CTS conversion.

Similar logic was followed following the FB CTS conversion. Here, of course, it was necessary to complement the conversion results when the FB counter contents were negative.

Table B-5
SOFTWARE DOCUMENTATION

Examples: $-FE = FB - CMD$, both conversion factors equal two.

a) For a positive number of FB counts

i) Positive CMD counts

FB = 3, CMD = 2.

$$3(2) - 2(2) = ?$$

$$6 - 4 = +2$$

CTS	0011	0010		0110
convert	0110	0100		1100
		1011	1's comp.	<u>0010</u> → +2
		1100	2's comp.	

ii) Negative CMD counts

FB = 2, CMD = - 1

$$2(2) - (-1)(2) = ?$$

$$4 - (-2) = 6$$

CTS	0010	1111		
convert	0100	0000	1's comp.	
		0001	2's comp.	0100
		1010	convert	0010
		0010	clear sign bit	<u>0110</u> → +6

Note that in this instance it is necessary to clear the sign bit before proceeding.

b) For a negative number of FB counts

i) Positive CMD counts

FB = - 1, CMD = +2

$$-1(2) - 2(2) = ?$$

$$-2 - 4 = -6$$

CTS	1111	0010		
2's comp.	0001	0100	convert	1100
convert	1010	1011	1's comp.	<u>1110</u>
clear sign	0010	1100	2's comp.	<u>1010</u> → - 6
2's comp.	1110			0101
				0110

ii) Negative CMD counts

FB = - 2, CMD = - 2

$$-2(2) - (-2)(2) = ?$$

$$-4 + 4 = 0$$

CTS	1110	1110		
2's comp.	0010	0010	2's comp.	1100
convert	1100	1100	convert	0100
clear sign	0100	0100	clear sign	<u>0000</u> → 0
2's comp.	1100			

APPENDIX C
INTERFACE SCHEMATICS

(a) Printed Circuit Card 5.

(b) Printed Circuit Card 6.

(c) Printed Circuit Card 6 (concluded).

Type	Function	Chip Number
SN7400N	NAND	A8-B6-B6
SN7404N	Inverter	A4
SN7406N	Inverter	A1-A2-A3-E1-E7
SN7407N	Inverter	A5-A6
SN7410N	NAND	E3-E9
SN7413N	S/T	A7-E2
SN7474N	D/F/F	E4-E20
SN74123N	O/S	A9-C11-E5-E8-E11
SN74193N	Counter	C1-C2-C3-C4-C7-C8-C9-C10

(d) Definitions for Printed Circuit Card 6.

Figure C-1. LINEAR INDUCTION MOTOR PRINTED CIRCUIT CARDS.

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