ABSTRACT

PROGRAMMABLE DIGITAL COMPENSATOR

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The theoretical response of a system may be formulated on the basis of known parameters. The actual performance, however, may vary from the theoretical because of either some unknown or "approximately formulated" factors.

Friction is one of the factors that appear in any mechanical system causing some variation between theoretical and actual performance. In the following chapters, nonlinearity of "M.S. 150" due to friction and saturation is discussed, and primarily, it is shown how a Microprocessor can be employed to compensate for nonlinearity versus the analog compensation.

In the process, all the hardware design, interfacing, flow charts and the software design are discussed.

ACKNOWLEDGEMENTS

I wish to acknowledge the invaluable assistance and the guidance of Professor Samuel J. Skarote. Furthermore, I appreciated the help and encouragement I received from my wife Jacqueline which made all this possible. Also, I would like to thank Anna Mae Serrecchio for typing the thesis.

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LIST OF SYMBOLS

$A_0, A_1, A_2, A_3, A_4, A_5, A_6, A_7$	Address bits
A/D	Analog to Digital Converter
$D_0, D_1, D_2, D_3, D_4, D_5, D_6, D_7$	Data Bits
D/A	Digital to Analog Converter
D.C.	Direct Current
F	Viscous Friction, Torque/Radian/Second
Hz	Hertz, Cycle/Second
I_a	Armature Current, Ampere
IC	Integrated Circuit
I/O	Input/Output
J_i	Inerta, Torque, Second/Radians
j	Complex Variable, $\sqrt{-1}$
K_b	Electro-motive Constant, Volts/Radian/Second
K_s	Velocity Constant, Speed/Volt
K_T	Torque Constant, Torque/Ampere
ma.	Milliampere, 10^{-3} ampere
micro -	10^{-6}
R_a	Armature Resistance, Ohms
S	Angular Speed, Radian/Seconds
T	Torque, Foot-pound
τ_m	Time Constant, Seconds
V_a	Armature Voltage, Volts
W	Radians/Second

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CHAPTER I

INTRODUCTION

In general, achievement of a predetermined output in a process is the objective of a feedback control system. In the past, conventional analog feedback loops have been employed, usually, in achieving the desired output in a system. However, due to the present advancements in digital technology, the availability and the economics of integrated circuits (I.C's) including microprocessors, have opened a new chapter in practical "REAL-TIME" feedback control engineering. With this new approach, analog feedback is combined or replaced with a digital feedback to produce extreme flexibility in the control process.

The purpose of this project is to demonstrate a digital approach to a typical feedback solution using an "8080" processor based micro-computer.

In the following chapters, two commonly used experiments namely, "BODE PLOT" and "SPEED CONTROL" experiments are investigated. In the Bode Plot experiment (See Chapter I and Appendix A) the necessity of a compensating network is shown. Once the need and the characteristics of the compensating network is determined, then in Chapter II, a digital compensator is introduced which is more flexible then the analog compensating network suggested by the manufacturer of the system.

In the Speed Control experiment, it is shown how a digital system can produce far superior regulation in comparison to the analog system.

In the experiments, the system under investigation is a universal teaching aid known as the "MS 150" modular servo system. The system includes an armature-controlled D.C. motor which is the main object to be controlled. Consequently, the theoretical characteristics and the actual performance of the D.C. motor is discussed which leads to the discrepancy between the ideal and actual performance of the motor due to friction that results in a nonlinear response.

In the digital section, Chapter II, all the necessary hardware and software are discussed including the design and implementation of a working prototype unit.

Theory on Armature Controlled D.C. Motors

In an armature controlled D.C. motor, the field current is held constant and the armature current is varied for control.

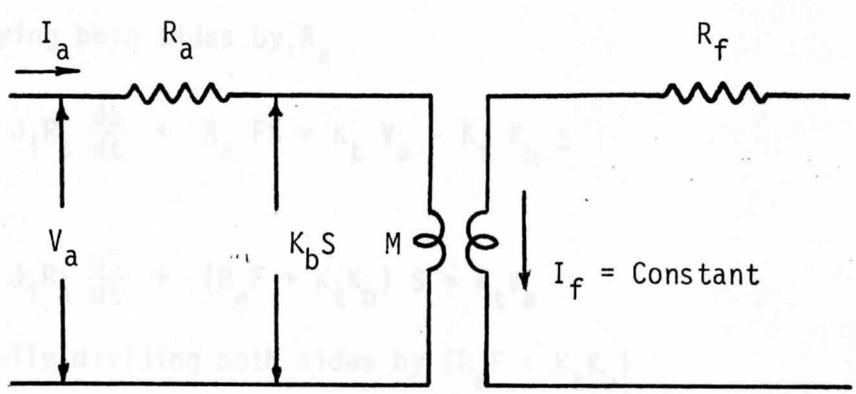


Figure 1. Representation of an Armature-Controlled D.C. Motor.

The relationship between the generated torque and the armature current is of the form:

$$T = K_t I_a \tag{1}$$

In this form, K_t is the torque constant, (torque/amp.) and T (foot-pound) is the torque. I_a (ampere) represents the armature current which depends on the armature resistance R_a.

$$I_a = \frac{V_a - K_b S}{R_a} \tag{2}$$

Since the generated torque is used up in accelerating the enertia J_i while opposing the friction, the governing equation is:

$$T = J_i \frac{dS}{dt} + FS \tag{3}$$

dS/dt represent the acceleration (radians/sec^2) while S represents the speed (radians/sec) and F is the viscous friction (Torque/radian/sec).

Substituting like values from Equations (2) and (3) into (1) we arrive at:

$$J_i \frac{dS}{dt} + FS = K_t \left(\frac{V_a - K_b S}{R_a}\right) \tag{4}$$

multiplying both sides by R_a

$$J_i R_a \frac{dS}{dt} + R_a FS = K_t V_a - K_t K_b S \tag{5}$$

or

$$J_i R_a \frac{dS}{dt} + (R_a F + K_t K_b) S = K_t V_a \tag{6}$$

and finally dividing both sides by $(R_a F + K_t K_b)$

$$\left(\frac{J_i R_a}{FR_a + K_b K_t}\right) \frac{dS}{dt} + S = \left(\frac{K_t}{FR_a + K_b K_t}\right) V_a \tag{7}$$

Equation (7) is a first order differential equation where the input is V_a, the applied armature voltage and the output is S the speed of the motor. Noting that the contents of the parenthesis in Equation (7) is a constant, Equation (7) then represents a system similar to a

RC circuit with an applied D.C. source.

In charging a capacitor through a resistance, the applied D.C. voltage charges up the capacitor to a maximum voltage. The process of charging takes place until the capacitor has reached its maximum charge. The charging time (τ) depends upon the capacitance of the capacitor and the series resistance of the circuit,

$$\tau = RC.$$

In the case of a D.C. armature controlled motor, the input voltage is applied to the armature and the output is the speed generated by the motor which reaches a maximum speed similar to the maximum voltage of the charging capacitor. There exists a time constant associated with the motor, τ_m, representing the time needed for the motor to reach its maximum speed. τ_m represents the first parenthesis is Equation (7) namely

$$\tau_m = \frac{J_i R_a}{FR_a + K_b K_t} \tag{8}$$

The second parenthesis is Equation (7) is also a constant which is a representation of the steady state speed for any applied D.C. input. If we name this parenthesis K_s, that is

$$K_s = \frac{K_t}{FR_a + K_b K_t} \tag{9}$$

Then we write

$$S = k_s V_a \quad \text{(steady state)} \tag{10}$$

Knowing K_s, the steady state speed S can be found for any D.C. input. Substituting τ_m and K_s, into Equation (7), we have

$$\tau_m \frac{dS}{dt} + S = K_s V_a \tag{11}$$

This equation can be represented in the frequency domain as

$$\frac{S}{V_a}(jW) = \frac{K_s}{(I + jW\,\tau_m)}, \qquad (12)$$

which is the transfer function of the D.C. armature controlled motor.

Effect of Friction on the Speed Vs. Input Voltage

Consider equation (10)

$$S = K_s V_a$$

In this equation S represents steady state speed, V_a is the armature input voltage, and K_s is the velocity constant. A plot of this equation is shown in Figure 2.

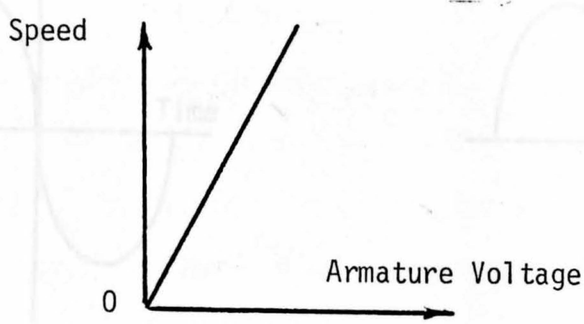


Figure 2. Ideal Response of An Armature-Controlled D.C. Motor Due to a Ramp Function.

In the laboratory, a variable input voltage was supplied to the motor through the servo amplifier unit, and the speed of the motor was recorded. The results are given in the following plot.

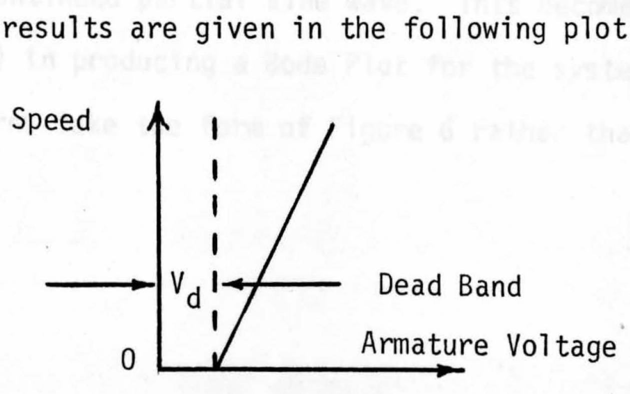


Figure 3. Actual Response of an Armature-Controlled D.C. Motor Due to a Ramp Function.

This plot shows a dead band on the input voltage from 0 to V_d where the output speed is zero. This dead band is due mainly to the friction of the brushes. This experiment was repeated for all the available motors in the laboratory; it was found to be approximately 3.6 to 4.2 volts for the motor investigated.

Necessity of a Compensating Network Due to Friction

As it was shown in Figure 3, friction nonlinearity creates a Dead Band in the input-output relationship of the motor. In the case of an ideal motor, a sinusoidal input should produce a sinusoidal speed (See Figure 4).

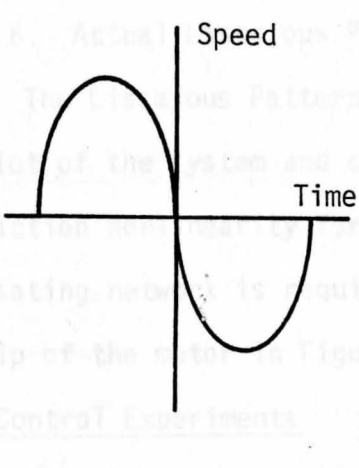


Figure 4. Ideal Output Speed Due to a Sinusoidal Input-No Dead Band.

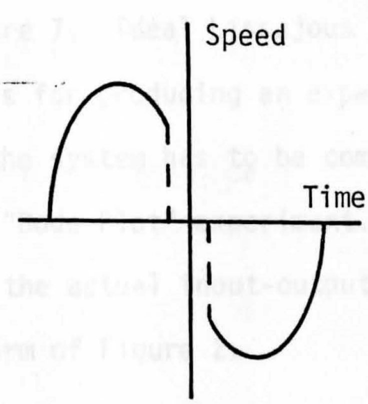
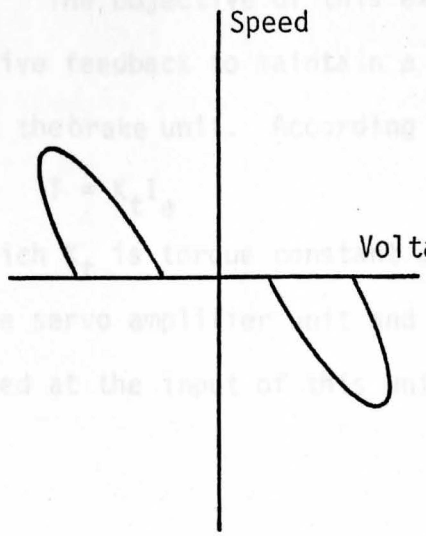


Figure 5. Actual Output Speed Due to a Sinusoidal Input-Dead Band.

But due to the friction the output speed behaves as in Figure 5 which produces a discontinued partial sine wave. This becomes a major problem (See Appendix A) in producing a Bode Plot for the system in which the Lissajous patterns take the form of Figure 6 rather than Figure 7.



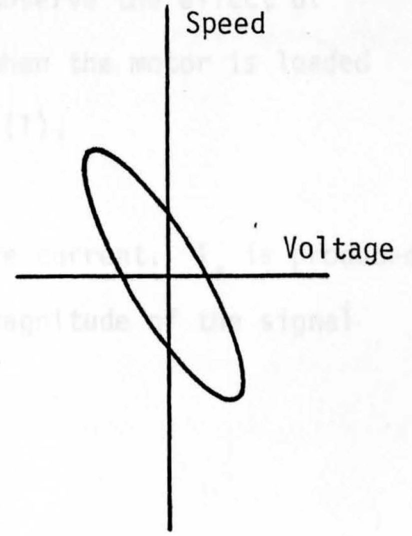


Figure 6. Actual Lissajous Pattern   Figure 7. Ideal Lissajous Pattern

The Lissajous Patterns are the basis for producing an experimental Bode Plot of the system and consequently, the system has to be compensated for friction nonlinearity for a successful "Bode Plot" experiment. The compensating network is required to change the actual input-output relationship of the motor in Figure 3 to the form of Figure 2.

Speed Control Experiments

In the experiment, the setup in Figure 8, is used.

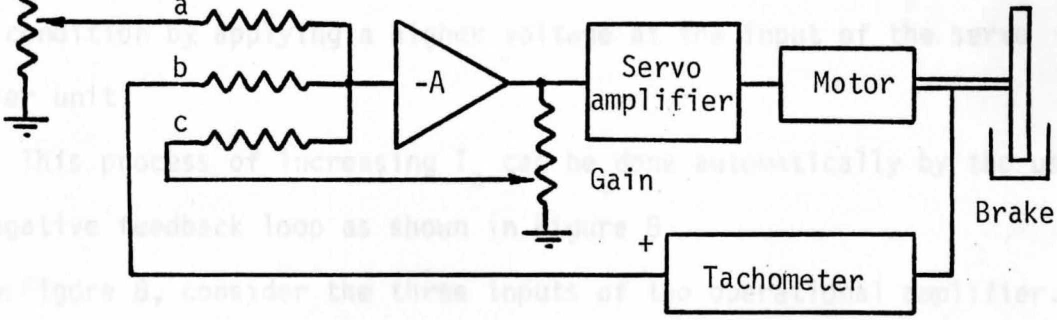


Figure 8. Experimental Setup for an Analog Feedback Speed Control.

The objective of this experiment is to observe the effect of negative feedback to maintain a constant speed when the motor is loaded using the brake unit. According to the equation (1),

$$T = K_t I_a$$

in which K_t is torque constant and I_a is armature current. I_a is produced by the servo amplifier unit and depends on the magnitude of the signal reached at the input of this unit.

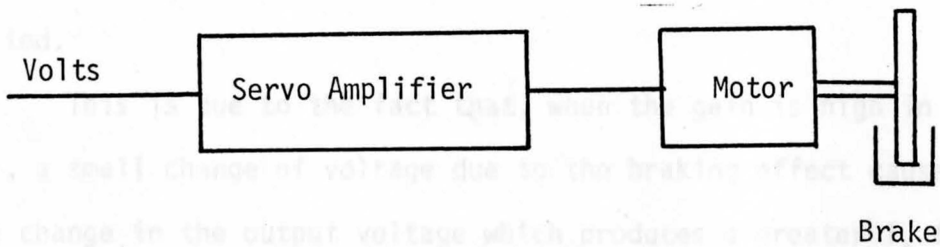


Figure 9. Loading Effect on Motor with no Feedback Loop.

If there is no feedback loop in the system, (See Figure 9), and the input voltage is held constant, the speed of the motor would slow down greatly when the brake is applied. However, if one wishes to produce a loaded speed equal to an unloaded one, one has to increase I_a for the loaded condition by applying a higher voltage at the input of the servo amplifier unit.

This process of increasing I_a can be done automatically by the use of a negative feedback loop as shown in Figure 8.

In Figure 8, consider the three inputs of the operational amplifier. Input "c" is used for the gain setting of the unit. Input "b" is used for the negative feedback from the tachometer (negative compared to the reference voltage). Finally, input letter "a" is the reference voltage.

In this setup, the voltage applied to the servo amplifier is the difference of the voltages at the terminals "a" and "b" multiplied by the gain of the operational amplifier.

$$V_0 = (-A)\ (-V_a + V_b) \qquad (13)$$

Consequently, if V_b decreases due to the loading effect $(-V_a + V_b)$ gives a higher negative voltage and V_0 increases to a higher positive voltage which in turn produces a greater value of I_a to maintain the speed constant for loaded condition. The amount of which one can control the speed depends on the forward gain set by the operational amplifier. High forward gain results in a smaller drop of the output speed when the brake is applied.

This is due to the fact that, when the gain is high in Equation (13), a small change of voltage due to the braking effect causes a rather high change in the output voltage which produces a greater I_a for the motor, and consequently, it will result in a better response of the system.

Figure 10 shows the results of the Speed Control Experiment in which curve A is produced with no feedback loop, and therefore, the sharp drop in output speed is justifiable. Curve (B), however, is produced with feedback loop at 100% gain setting. As curve (B) indicates, the speed stays rather constant only from (0) to (0.5) brake setting which is very poor compared to ideal results as shown in curve (C). Appendix (B) shows how to improve the results by the addition of an extra amplifier in the system. Finally, Chapter II covers a Digital Speed Control which approaches the ideal results within the limits of the unit.

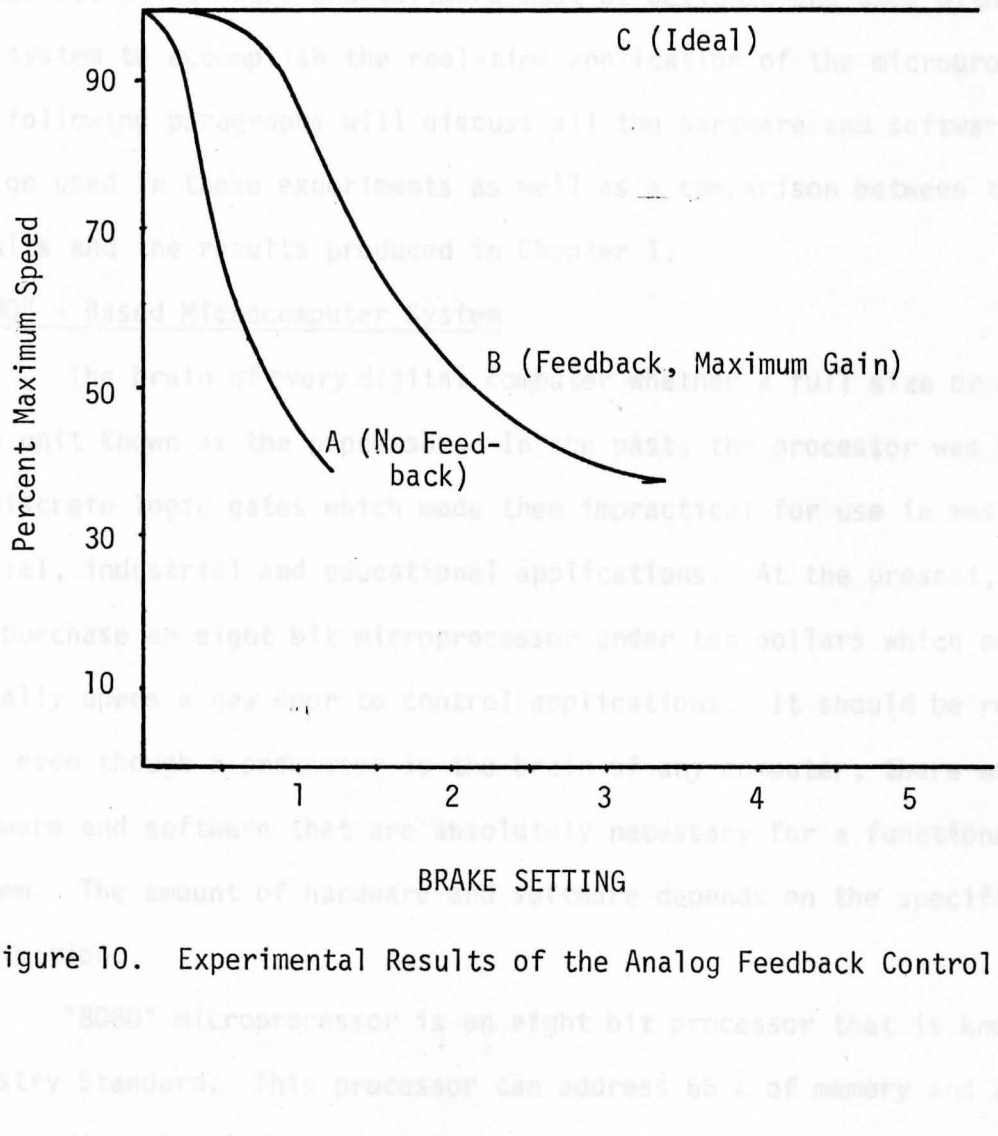


Figure 10. Experimental Results of the Analog Feedback Control System.

CHAPTER II
MICROPROCESSOR-BASED CONTROL SYSTEM

In this chapter, it is demonstrated how a Microprocessor-based system can be used to compensate for nonlinearity due to friction in the Bode Plot Experiment as well as its advantages in the Speed Control Experiment.

In the process, an E&L Microcomputer will be used. However, a proper set of hardware and software must be designed and used with the E&L system to accomplish the real-time application of the microprocessor. The following paragraphs will discuss all the hardware and software design used in these experiments as well as a comparison between the new results and the results produced in Chapter I.

"8080" - Based Microcomputer System

The brain of every digital computer whether a full size or a micro, is a unit known as the processor. In the past, the processor was composed of discrete logic gates which made them impractical for use in most commercial, industrial and educational applications. At the present, one may purchase an eight bit microprocessor under ten dollars which economically opens a new door to control applications. It should be remembered that even though a processor is the brain of any computer, there are other hardware and software that are absolutely necessary for a functional system. The amount of hardware and software depends on the specific application.

"8080" microprocessor is an eight bit processor that is known as Industry Standard. This processor can address 65 K of memory and 256 I/O devices directly with a powerful set of instructions. As it was mentioned previously, a microprocessor has to be used in conjuction with other components, such as, memory, timing circuits, encoders, decoders, keyboard, and finally a program. One may purchase a prepackaged unit which may contain some or all of the above mentioned components. In the following experiments, an E&L microcomputer is used which contains some of the hardware and software necessary for the experiments. In the next section, details of the hardware and software requirements will be covered.

Hardware and Software Requirements

For the Nonlinearity Compensation and/or Speed Control Experiment via a programmable digital system, the following items are needed:

(1) A microprocessor-based system which should contain some means of data entry to the processor such as a keyboard, tape interface or any other means. An E&L microcomputer was used in the experiments.

(2) An Analog-to-digital converter to convert analog input signals, such as speed, to a digital signal suitable for the processor. An Analogic A/D converter model #MPS28082D2C was used.

(3) A digital-to-analog converter to convert digital commands of the processor to an analog output for the devices, such as, the servo amplifier. For this, an Analogic D/A converter model #MP1808A was used.

(4) An interfacing and timing circuitry to establish and synchronize communications between the components. An especially designed and wire wrapped circuit to be used in conjuction with items 1, 2, and 3 was made for these experiments.

Details of each item will be discussed in the following sections.

E&L Microcomputer

The E&L Microcomputer is an educational and engineering microcomputer using an 8080 type microprocessor chip. It features direct keyboard entry of data and instructions. Also, it has status and data indicators via light emitting diodes. All the buses can be accessed by means of a 28 pin flat cable connector. The basic unit contains 512 words of RAM and provisions for 256 words of ROM which is adequate for the experiments.

The Analog-to-Digital Converter

Analogic model #MPS28082D2C is an eight bit analog to digital converter which requires a maximum of 80 microseconds conversion time. It has a full scale input range of ±10 volts. The unit provides serial and parallel outputs. Brief characteristics of the unit are as follows:

Power Requirements	+15 ± 0.5 volts D.C. at 45 ma
	-15 ± 0.5 volts D.C. at 30 ma
	+ 5 ± 0.25 volts D.C. at 300 ma
Accuracy	0.1%
Recalibration	6 months
Trigger	Edge trigger from positive to negative
Word Length	Selectable 2 to 8 bits

The unit is an offset binary which means it has an analog-to-digital relationship of:

11 111 111 = 9.92 volts

10 000 000 = 0.00 volts

00 000 000 - 10.00 volts

To use the unit, first the power requirements should be met. Then, the analog input ±10 volts should be applied to pin 28, while pins number 2 and 29 are grounded. At this time the A/D unit will update the conversion for every trigger pulse applied to pin 21. The conversion time depends on the internal clock and the value of the input voltage with the maximum delay time of 80 microseconds. Once the conversion is completed, the data will latch in at pin 11, 10, 9, 8, 7, 6, 5, and 4 corresponding to data bits D0 to D7 respectively.

Digital-to-Analog Converter

The D/A conversion is accomplished by the Analogic model number MP1808A. The unit is an eight-bit D/A converter which requires only 4 microseconds conversion time. The unit does not have an input latch to capture the data issued by the microcomputer. Consequently, an external latch must be used whenever the unit is used in conjunction with a microcomputer. Brief characteristics of the unit are as follows:

Power Requirements.....	+15 ± 3%	At 22 ma plus external load.
	-15 ± 3%	At 8 ma plus external load.
	+ 5 ± 5%	At 45 ma
Analog Output.........	11 111 111 = 9.92 volts	
	10 000 000 = 0.00 volts	
	00 000 000 = -10 volts	
Accuracy..............	.05%	

The input digital data is applied to pin numbers 14, 16, 17, 19, 21, 23, 25, and 27 corresponding to D0 to D7 data bits. Pin 28 is the output pin which can supply ± 10 volts analog output.

Interfacing Circuitry

The communication between the microcomputer, A/D converter, and the D/A converter must be established in a synchronized and orderly manner. To accomplish this, a total of seven gates, inverters and latches are used, see Figure 11.

In any computer system, all the input and output devices require a code number in order to be addressed individually. In an 8080-based system, this code number could be any number between (000_8) and (377_8) octal if the number is an unused code number. In the E&L system, device numbers (000_8), (001_8) and (002_8) are used by the microcomputer. Except for these numbers, any number can be used to address the A/D and D/A converters. In these experiments, code numbers (377_8) and (376_8) are assigned to D/A and A/D converters respectively. In Figure (11), socket number 1 is a terminating socket which connects the E&L unit to the rest of the hardware, (A/D, D/A and interfacing circuitry) by means of a double ended transition cable. Data lines D0 to D7 are connected to pins 16 to 23, address lines A0 to A7 are connected to pins 13 to 6, $\overline{\text{in}}$ signal to pin 26 and $\overline{\text{out}}$ signal to pin number 25.

In an 8080-Based microcomputer, such as the E&L, the data transfer between the I/O devices and the processor occurs as follows:

For the access and transmission of data, the processor sends an 8 bit data on the data bus and an 8 bit address on the address bus. After these two signals are settled, the microcomputer decodes and transmits an $\overline{\text{in}}$ and $\overline{\text{out}}$ signal. The interfacing circuitry has to decode the address and notify the proper I/O device of a data transmission between the device and the processor. At this time, the device either captures or transmits the data depending on whether an $\overline{\text{out}}$ or an $\overline{\text{in}}$ signal was transmitted by the processor.

Referring to Figure 11, IC number 4 associated with the D/A converter is an output device with a code number (377_8). IC 4 (Intel 8212) is a general purpose integrated circuit that is designed to be used as either a latch or a tri-state (solid state switch) buffer, depending on the mode of pin number 2. The decoding circuitry for IC 4 consists of an eight input nand-gate and an inverter. IC 2 and IC 3-1 combined will produce a positive pulse when the address bus contains all "ones" (377_8). This positive pulse in combination with an $\overline{\text{out}}$ signal enables IC 4 to capture the data from the data bus. Once the data is captured by IC 4, it will be used by the D/A unit for the conversion process. This means, to access the D/A unit one must program "out (377_8)" with the proper data.

In the case of A/D converter, the data should be transferred from the A/D converter to the processor. The A/D converter does not update the analog information continously. For every trigger pulse applied to pin 21 of this unit, a new conversion takes place; the updated results are fed to a tri-state buffer, (IC 6), to be used by the processor. The decoding in this section is done by 4 gates. The device code (376_8) is assigned to the A/D converter which is decoded by IC 3-2 and IC 6. This combination produces a negative pulse when the address bus contains the address (376_8). This code is used to trigger the A/D converter as well as, to input data from the A/D unit to the processor. To trigger the unit, the negative pulse (377_8) is combined with the $\overline{\text{out}}$ signal by means of IC 7, which is a nor-gate. The result is a positive pulse which is produced if and only if the instruction "out(376_8)" is executed by the processor. To input updated data to the processor, IC 6 must be activated. To do so, the in signal from the processor is inverted by IC 3-4 and fed to the pin numbers 13 of IC 6 while the negative "device code" pulse is applied directly to the pin 1 of IC 6. Now IC 6 will be activated simply by executing the instruction "in (376_8)".

Application Instructions of the Prototyped Interfacing Hardware

A prototype of this unit has been wire-wrapped and presented to the Electrical Engineering Department of the Youngstown State University. This unit must be used in conjunction with an E&L microcomputer as well as a regulated ± 15 volts power supply.

The unit connects to the microcomputer via a 28 double-ended transition cable. Two banana plugs marked, "in", "out", provide analog connections to the unit. These analog signals can vary in magnitude between ± 10 volts.

To input an analog signal, the A/D converter sould be updated. To do so, one must program "out (376_8)" this command triggers the A/D converter. Once the command is executed by the processor, the A/D unit starts the conversion. The programmer needs to allow approximately 80 microseconds delay for the conversion time. After the delay, the updated results can enter the processor if the processor executes the instruction "in(376_8)".

To output a digital data to the D/A converter, one must simply program "out (377_8)" at this time the content of the accumulator is routed to, and captured by the D/A converter. The conversion time for this unit is only 4 microseconds.

Digital Compensator in the Friction Nonlinearity

As it was discussed in Chapter I, the input-output relationship of an ideal armature-controlled D.C. motor should be a straight line (see Figure 12), but the actual performance demonstrates a dead band (see Figure 13) indicating a nonlinear relationship. The objective of the digital compensator is to alleviate the dead band and consequently create a linear input-output relationship for the whole system.

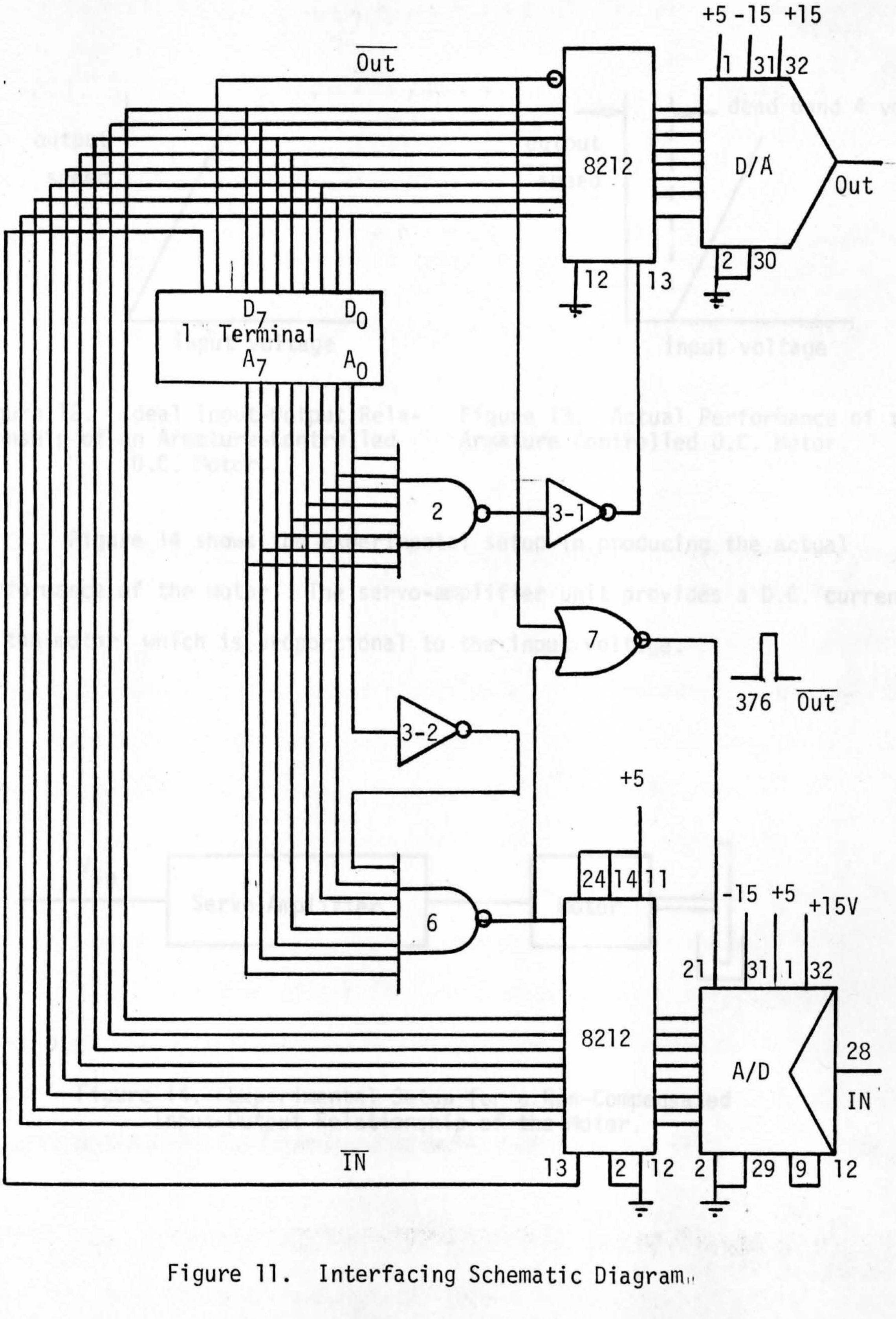


Figure 11. Interfacing Schematic Diagram.

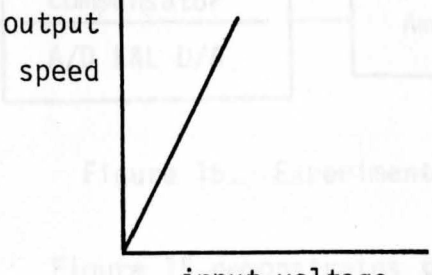


Figure 12. Ideal Input-Output Relationship of an Armature-Controlled D.C. Motor.

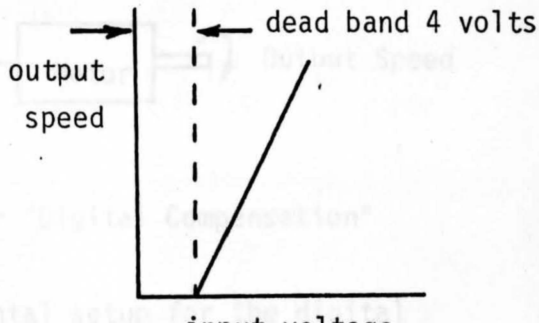


Figure 13. Actual Performance of the Armature Controlled D.C. Motor.

Figure 14 shows the experimental setup in producing the actual performance of the motor. The servo-amplifier unit provides a D.C. current to the motor, which is proportional to the input voltage.

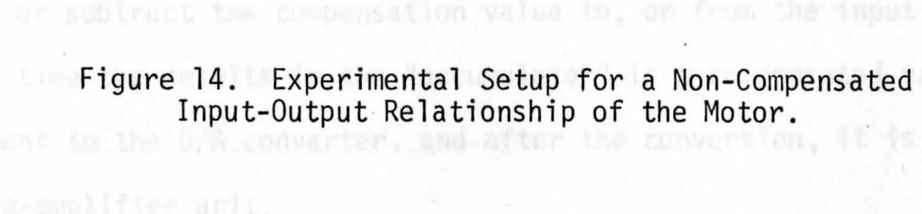


Figure 14. Experimental Setup for a Non-Compensated Input-Output Relationship of the Motor.

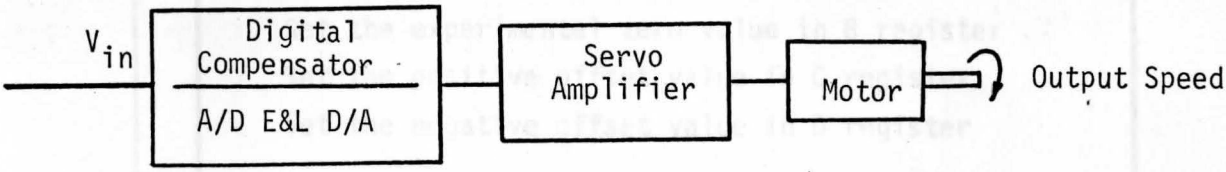


Figure 15. Experimental Setup for "Digital Compensation"

Figure 15 demonstrates the experimental setup for the digital compensation. This compensator must receive the analog input voltage and compensate for the nonlinearity by shifting the input voltage equal to the value of the dead band. This value is digitally programmable which is the biggest advantage of the digital compensator.

Referring to Figure 16, the compensation values are stored in registers C and D where register C contains the positive offset value and register D contains the negative offset value. The computer tests the input voltage by triggering the A/D converter and inputting the results after a conversion delay. Once the data has entered the computer in digital form, the computer tests for the polarity of the input signal, this is necessary to determine whether a positive or negative compensation must be used. Once the polarity has been determined, the computer recalls the proper offset value from either the C or D register, and correspondingly adds or subtract the compensation value to, or from the input voltage. At this time the results in the "accumulator" is a compensated value, which is sent to the D/A converter, and after the conversion, it is used by the servo-amplifier unit.

In reality, the computer converts any input signal such as the one shown in Figure 17 to a signal of the form in Figure 18. It should be noted

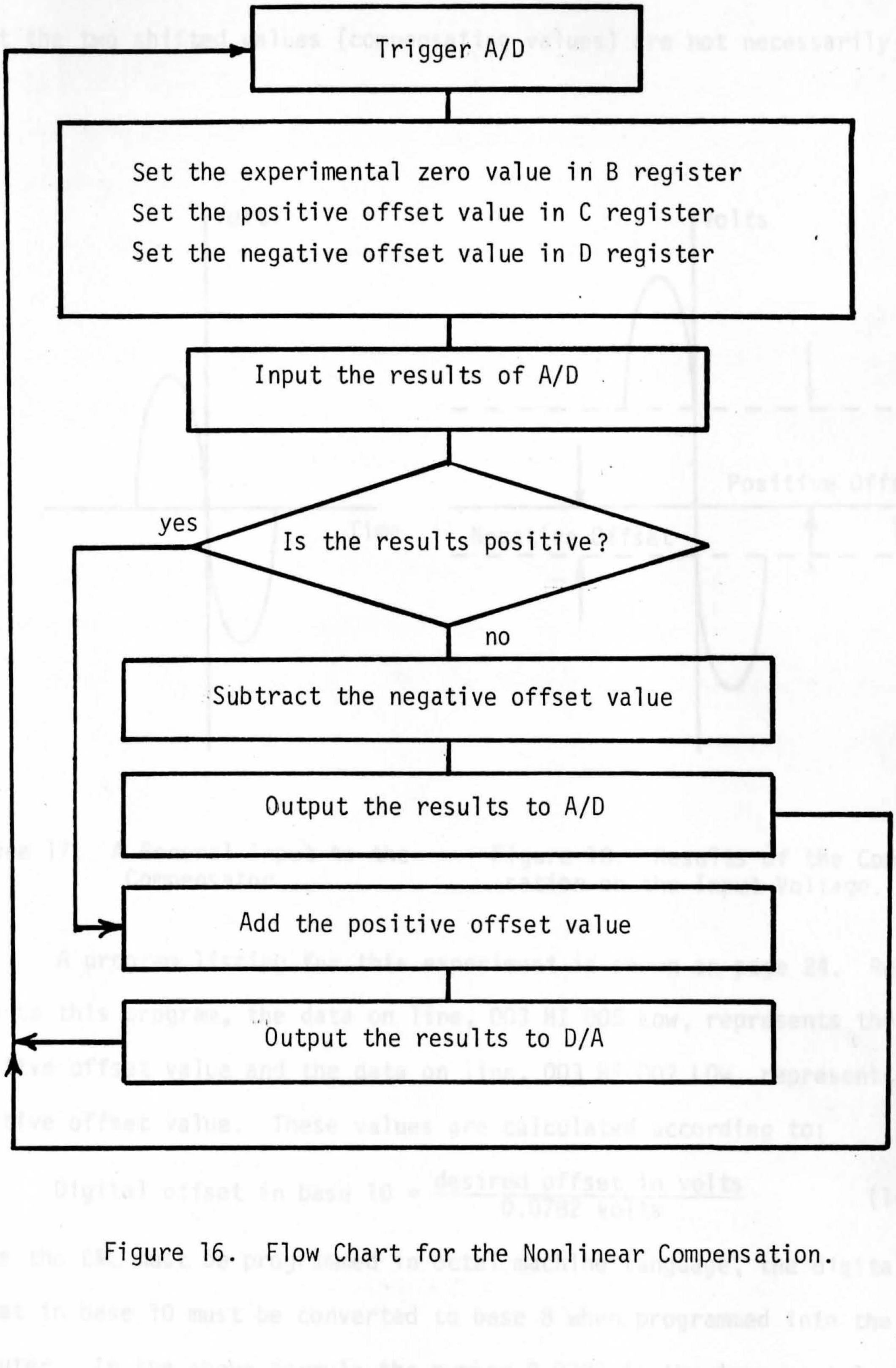
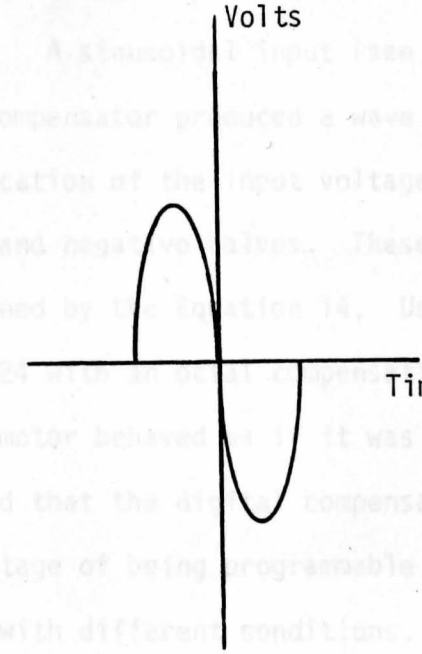


Figure 16. Flow Chart for the Nonlinear Compensation.

that the two shifted values (compensating values) are not necessarily equal.



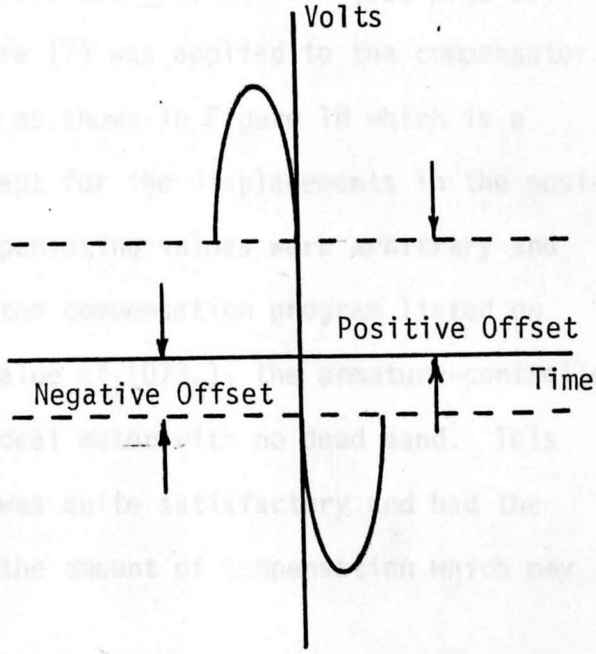


Figure 17. A General Input to the Compensator.

Figure 18. Results of the Compensation on the Input Voltage.

A program listing for this experiment is shown on page 24. Referring to this program, the data on line, 003 HI 005 Low, represents the positive offset value and the data on line, 003 HI 007 LOW, represents the negative offset value. These values are calculated according to:

$$\text{Digital offset in base 10} = \frac{\text{desired offset in volts}}{0.0782 \text{ volts}} \qquad (14)$$

Since the E&L must be programmed in octal machine language, the digital offset in base 10 must be converted to base 8 when programmed into the E&L computer. In the above formula the number 0.0782 is the incremental voltage change for the D/A unit. It should be remembered that the output of

D/A converter is limited to ± 10 volts. This means, the offset voltage plus the input voltage should not exceed ± 10 volts. In the speed control experiment, it is shown how the computer can be programmed to exhibit a warning signal if the output requirement exceeds the ± 10 volts. (See page 25).

A sinusoidal input (see Figure 17) was applied to the compensator. The compensator produced a wave form as shown in Figure 18 which is a duplication of the input voltage except for the displacements in the positive and negative halves. These compensating values were arbitrary and governed by the Equation 14. Using the compensation program listed on page 24 with an octal compensation value of (073_8), the armature-controlled D.C. motor behaved as if it was an ideal motor with no dead band. This proved that the digital compensator was quite satisfactory and had the advantage of being programmable for the amount of compensation which may vary with different conditions.

PROGRAM LISTING FOR THE DIGITAL COMPENSATOR

Hi	Low			
003	000	323	out	Trigger A/D converter
003	001	376	376	at 376
003	002	006	MVI B	Set the experimental zero value
003	003	167	167	equal to 167
003	004	016	MVI C	Set the positive offset value
003	005	074	074	equal to 74
003	006	026	MVI D	Set the negative offset value
003	007	073	073	equal to 73
003	010	333	IN	Input the results of the
003	011	376	376	A/D converter at 376
003	012	270	CMP B	Compare the results with B register
003	013	322	JNC	Jump if no carry, offset the
003	014	024	024	positive value
003	015	003	003	
003	016	222	SUB D	Offset the negative or zero value
003	017	323	OUT	Output the results to the D/A
003	020	377	377	at 377
003	021	303	JMP	recyle
003	022	000	000	
003	023	003	003	
003	024	201	ADD C	Offset the positive value
003	025	323	OUT	Output the results to D/A
003	026	377	377	at 377
003	027	303	JMP	Recycle
003	030	000	000	
003	031	003	003	

Digital Speed Control Experiment

In this experiment, the microcomputer controls the output speed of the amature-controlled D.C. motor under different loads. The desired output speed will be programmed into the computer, and upon the "GO" command the computer will maintain a constant speed under different load settings. The experimental setup for this experiment is shown in Figure 19.

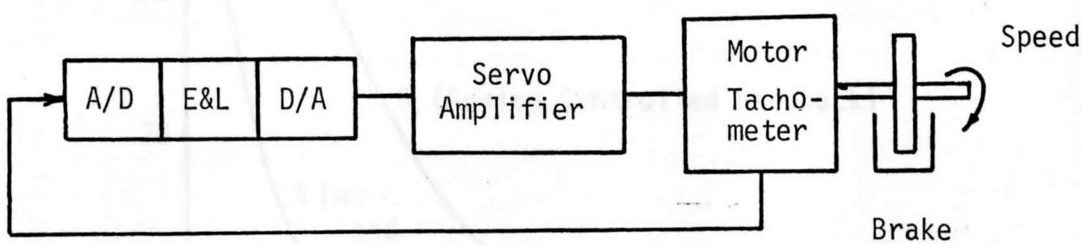


Figure 19. Experimental Setup for the Speed-Control Experiment.

The computer continuously monitors the output speed by the means of the tachometer unit. If the output speed differs from the programmed speed, then, the computer makes the proper adjustments on the output value of the D/A converter. It should be remember that, the output of the D/A converter is limited to ± 10 volts. However, these values are sufficient to produce the maximum rated current in the servo-amplifier unit. If the maximum values of the D/A unit are not sufficient to maintain the programmed speed, then the indicating lights on the E&L unit will flash.

Referring to Figure 21, the constant values are first determined and introduced to the proper registers; these constants are, reference speed, maximum positive output of the D/A converter and the minimum output of the D/A converter. The computer will continuously monitor the output speed and make proper adjustments in the output value of D/A unit.

To monitor the output speed, the computer issues an update command to the A/D unit. Then the computer waits for approximately 80 microseconds for conversion time, after which time the computer inputs the updated data (latest value of output speed), makes necessary adjustments, and issues an updated value to the D/A converter.

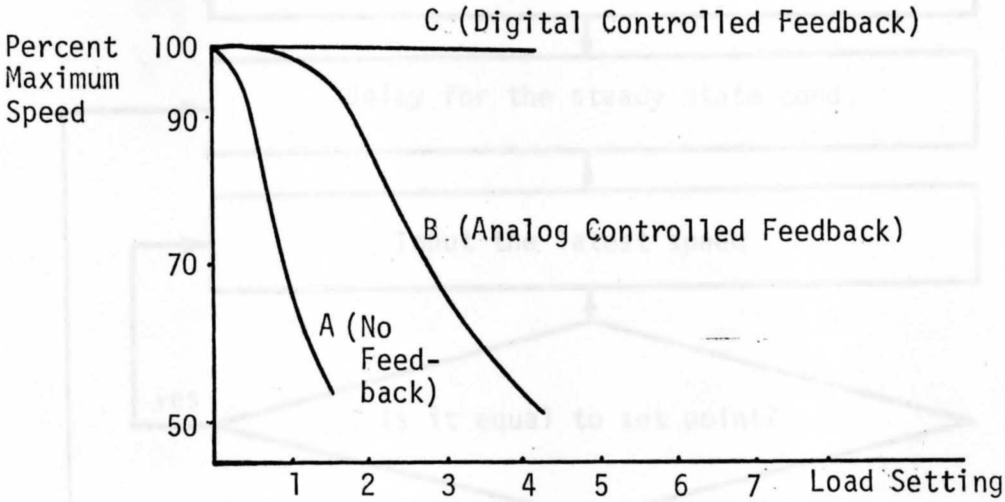


Figure 20. Experimental Results of the Digital Feedback Control System.

This experiment, requires a delay subroutine for the proper speed control operation. This delay is designed to guarantee a steady state condition of the motor speed before any readjustment in the output value of the D/A converter. The required time delay is estimated from the Bode Plot of the motor (Appendix A) to be approximately 0.3 seconds. The delay subroutine and its flow chart is (See Figure 27) covered in Appendix C.

Using the speed control program in conjunction with the time delay subroutine produced an excellent speed control of the motor which was far superior in comparison with the results of the analog speed control of Chapter I. Figure 20 indicates the results of this experiment.

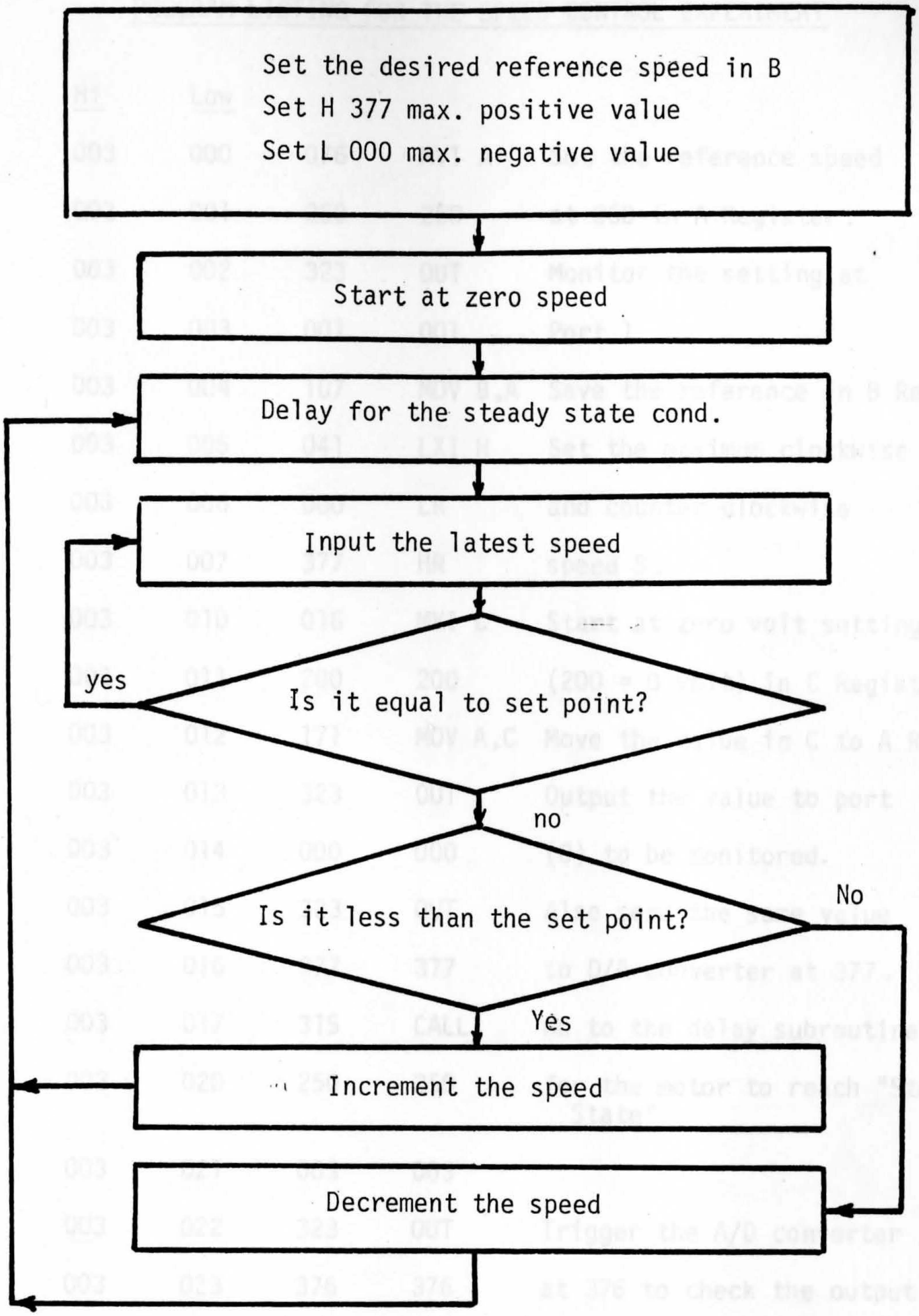


Figure 21. Flow Chart for Speed Control

PROGRAM LISTING FOR THE SPEED CONTROL EXPERIMENT

Hi	Low			
003	000	076	MVI A	Set the reference speed
003	001	250	250	at 250 in A Register.
003	002	323	OUT	Monitor the setting at
003	003	001	001	Port 1.
003	004	107	MOV B,A	Save the reference in B Register.
003	005	041	LXI H	Set the maximum clockwise
003	006	000	LR	and counter clockwise
003	007	377	HR	speed S.
003	010	016	MVI C	Start at zero volt setting
003	011	200	200	(200 = 0 volt) in C Register.
003	012	171	MOV A,C	Move the value in C to A Register.
003	013	323	OUT	Output the value to port
003	014	000	000	(0) to be monitored.
003	015	323	OUT	Also send the same value
003	016	377	377	to D/A converter at 377.
003	017	315	CALL	Go to the delay subroutine
003	020	250	250	for the motor to reach "Steady State"
003	021	003	003	
003	022	323	OUT	Trigger the A/D converter
003	023	376	376	at 376 to check the output speed.
003	024	000	NOP	
003	025	000	NOP	Delay few microseconds for
003	026	000	NOP	conversion time.
003	027	000	NOP	

Hi	Low			
003	030	000	NOP	
003	031	000	NOP	
003	032	000	NOP	
003	033	000	NOP	
003	034	333	IN	Check the latest output
003	035	376	376	speed at 376.
003	036	323	OUT	Display the binary equivalent
003	037	002	002	value of the speed to
003	040	270	CMP B	compare the output speed to the set point in Register B.
003	041	312	JZ	If AR-BR=0, it means that the
003	042	012	012	output speed is equal to setpoint.
003	043	003	003	Then, do not make any adjustments
003	044	322	JNC	if A-B=0, check if A-B had no
003	045	060	060	carry, if so then jump to
003	046	003	003	reduce the speed.
003	047	014	INR C	Increment the last speed value in C.
003	050	171	MOV A,C	Move the incremented C value to A.
003	051	274	CMP H	Check for the maximum positive value.
003	052	312	JZ	If the input to servo unit has reached
003	053	071	071	the maximum value 377, then go to
003	054	003	003	flashing subroutine
003	055	303	GO TO	if the speed has not reached
003	056	013	013	The maximum value, then go to 013
003	057	003	003	to update the speed.

Hi	Low			
003	060	015	DCR C	Reduce last speed value in C.
003	061	171	MOV A,C	Move decremented C to A .
003	062	275	CMPL	Check the value for minimal setting.
003	063	312	JZ	Jump to minimum subroutine if
003	064	124	124	the new value of C has reached the
003	065	003	003	set point (000).
003	066	303	JMP	Recycle.
003	067	013	013	
003	070	003	003	
			Flashing Subroutine	
003	071	076	MVI A	
003	072	377	377	
003	073	323	OUT	
003	074	001	001	
003	075	323	OUT	
003	076	002	002	
003	077	076	MVI A	
003	100	000	000	
003	101	323	OUT	
003	102	000	000	
003	103	315	CALL	
003	104	250	250	
003	105	003	003	
003	106	076	MVI A	
003	107	000	000	
003	110	323	OUT	

Hi	Low		
003	111	001	001
003	112	323	OUT
001	113	002	002
003	114	315	CALL
003	115	250	250
003	116	003	003
003	117	015	DEC C
003	120	303	JMP
003	121	012	012
003	122	003	003

SUMMARY AND CONCLUSION

This text introduces a digital approach in solving two typical control processes, namely a "Compensation Process" and a "Speed Control Process" using an Armature-Controlled D.C. motor.

Chapter I covers the theoretical and actual properties of the armature controlled D.C. motor which leads into the necessity of a compensation network. Furthermore, the manufacturer's suggested analog speed control was investigated.

Chapter II introduces the use of a microcomputer in solving control problems such as the "Compensation Process" and the "Speed Control Process". The microcomputer used for the control was an "E&L" unit. Since a microcomputer, generally, does not contain all the necessary hardware for real-time applications, an interfacing circuitry was designed and implemented to be used with the "E&L", A/D and D/A units to perform the digital approach in solving the compensation and the speed control problems.

Based on the knowledge obtained from the previously mentioned experiments, the following conclusions can be drawn. Due to the friction, there exists a nonlinearity in the motor which can be observed either in Figure 3 as a dead band, or in Figure 6 as splits in the Lissajous Patterns. The compensating network suggested by the manufacturer, (Appendix A) as well as the digital compensator (Chapter II) produced satisfactory results, that is, deleted the dead band due to the friction in the system. The digital compensator was found to be more desirable for the fact that the compensation value could be tailored for the best results depending on the particular motor simply by changing a single value in the digital compensator program.

In the speed control experiment, the experimental set up suggested by the manufacturer of the system did not produce a well regulated speed under different load settings. The cause of this discrepancy was discovered and a remedy was suggested in Appendix B. Finally, a digital speed control was introduced in Chapter II which resulted in far better speed regulation than the analog feedback control.

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Dorf, R.C., Modern Control System, Addison-Wesley Publishing Co.

Manufacturer's Manual, Modular Servo Type MS150 Feedback, LTD England

The 8080A Bugbook, Microcomputer Interfacing and Progamming, Sams Publication

APPENDIX A

EXPERIMENTAL BODE PLOT OF THE SYSTEM

In the laboratory, the experimental Bode Plot is obtained by the use of the Lissajous Patterns from which one can obtain the magnitude and the phase angle of the transfer function.

In General, a sinusoidal input is applied to the system, and the output is measured. From the input-output relationship repeated for different frequencies, the Bode Plot of the system can be constructed Figure 22.

$$G(jw) = \frac{\overline{ab}}{\overline{ef}} = \frac{\overline{oa}}{\overline{of}} = |G(jW)|$$

$$\sin\phi = \frac{\overline{cd}}{\overline{ab}} = \frac{\overline{oc}}{\overline{oa}}$$

Where $\phi = \angle G(jW)$

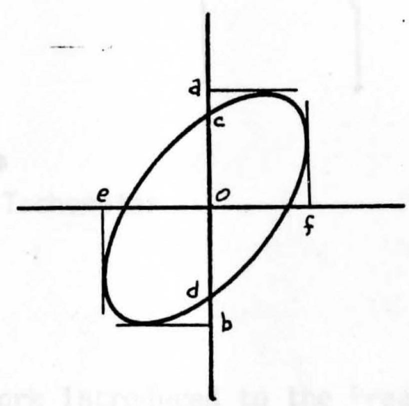

Figure 22. Necessary Measurements for the Construction of A Bode Plot Diagram

By changing the input frequency, different Lissajous Patterns can be obtained from which the Bode Plot can be constructed. As discussed in Chapter I, the motor exhibited a dead band during which the output remained equal to zero (see Figure 6). To obtain a simulated Bode Plot of the system, a compensating network is used (see Figure 23).

The pin numbers in Figure 23 refer to the Octal Socket on the preamplifier unit.

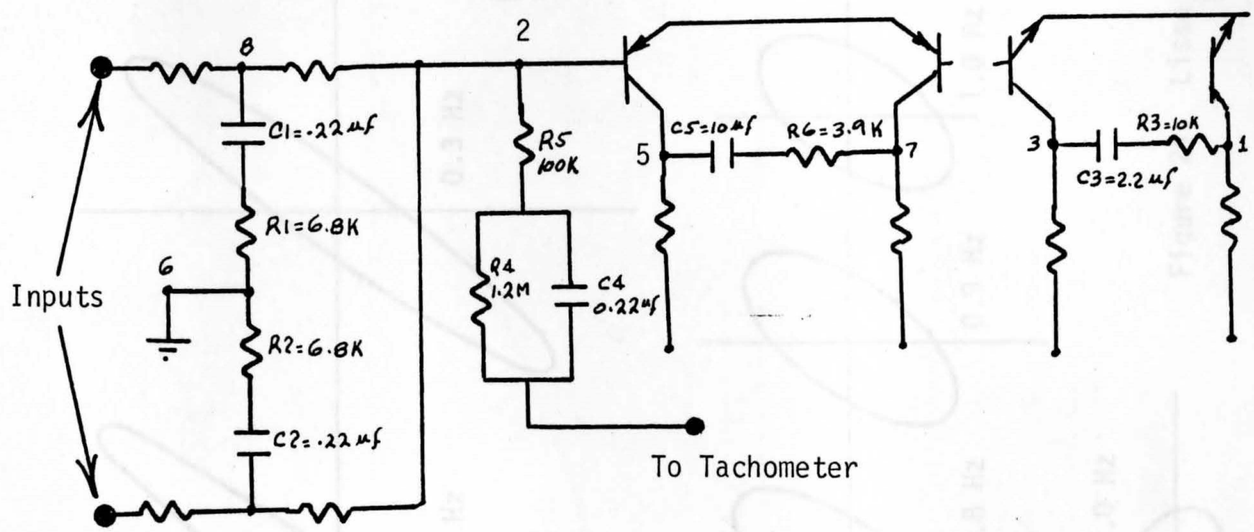

Figure 23. Analog Compensation Network Introduced to the Preamplifier.

This network was designed by the manufacturer and should be used in conjunction with the preamplifier unit. Using the above compensator, the system as a whole, behaves as an ideal motor for which the Bode Plot, in Figure 24 and 25 were produced.

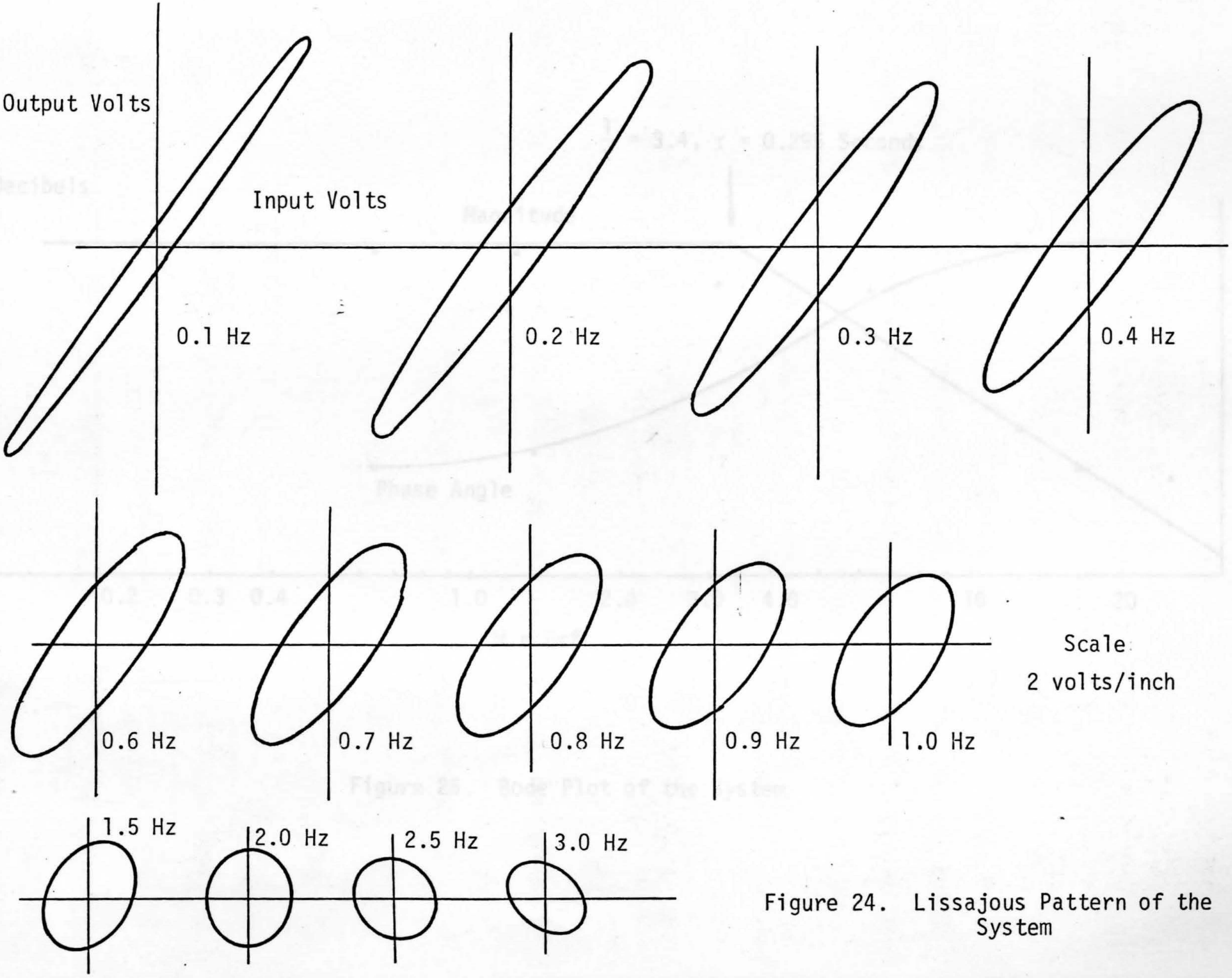

Figure 24. Lissajous Pattern of the System

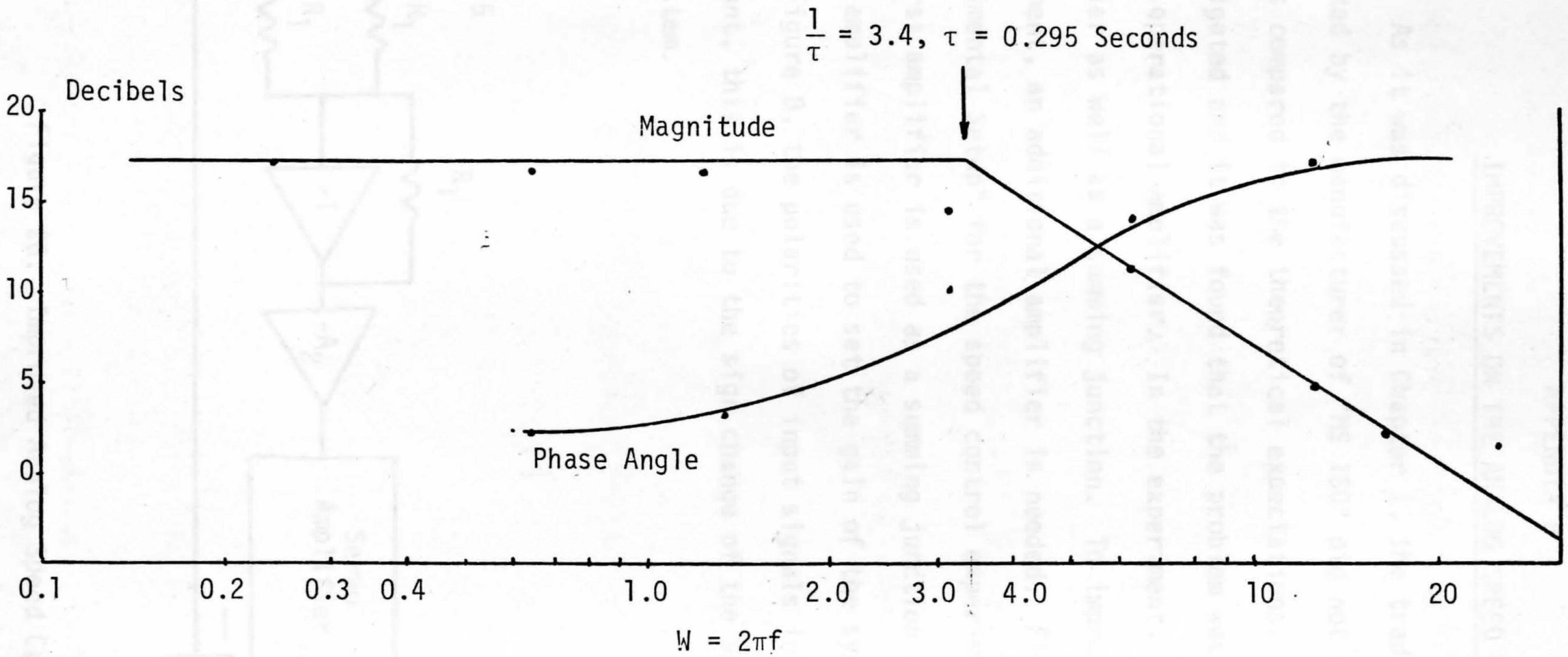

Figure 25. Bode Plot of the System

APPENDIX B

IMPROVEMENTS ON THE ANALOG SPEED CONTROL

As it was discussed in Chapter I, the traditional speed control suggested by the manufacturer of "MS 150" did not produce a satisfactory results compared to the theoretical expectations. This discrepency was investigated and it was found that the problem was due to the saturation of the operational amplifier. In the experiment, this unit is used as an amplifier as well as a summing junction. To improve the results of the experiment, an additional amplifier is needed. Figure 26 is an improved "Experimental Setup" for the speed control experiment. As it is shown, the first amplifier is used as a summing junction only, (gain of -1), the second amplifier is used to set the gain of the system. Comparing Figure 26 to Figure 8, the polarities of input signals in the two figures are different, this is due to the sign change of the additional amplifier in the system.

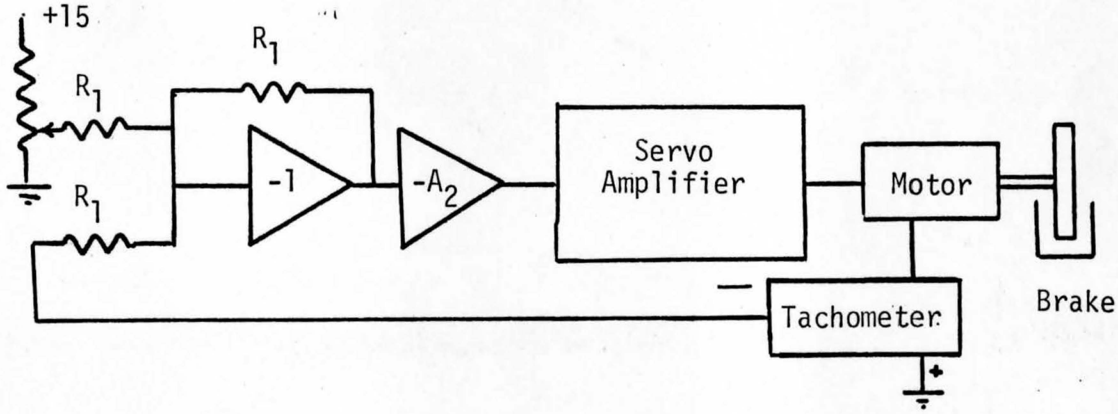

Figure 26. Improved Analog Speed Control

APPENDIX C

DELAY SUBROUTINE PROGRAM LISTING

Hi	Low		
003	250	046	MVI H
003	251	040	000
003	252	056	MVI L
003	253	000	000
003	254	055	DEC L
003	255	302	JNZ
003	256	254	254
003	267	003	003
003	260	045	DEC H
003	261	302	JNZ
003	262	252	252
003	263	003	003
003	264	311	RTN

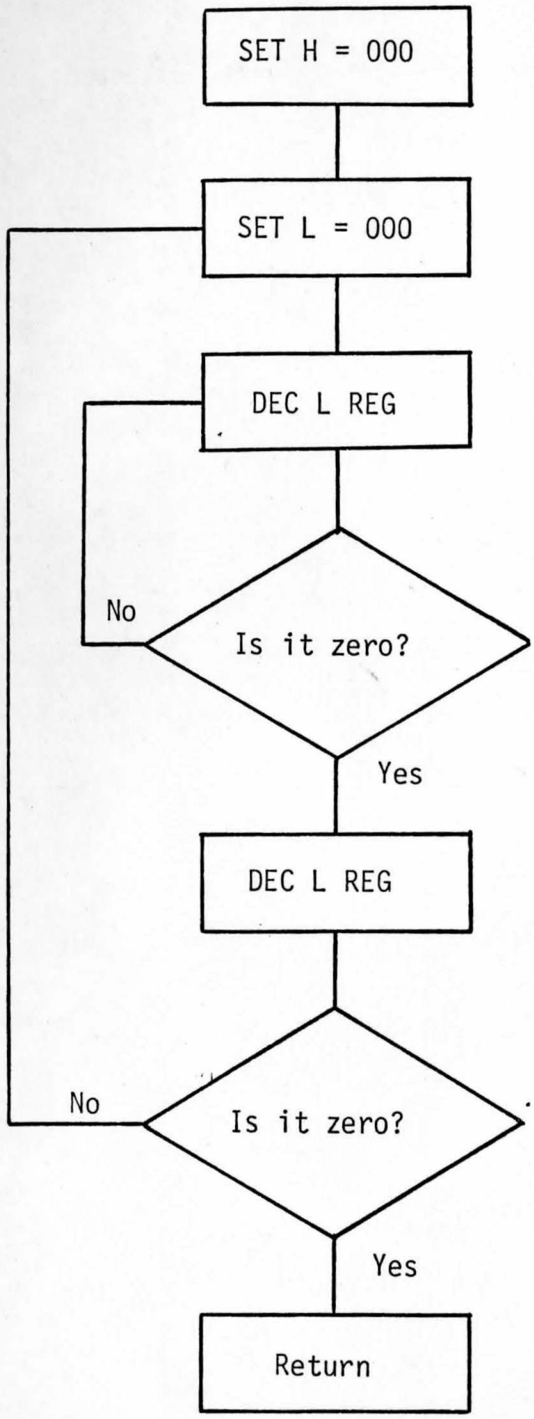

Figure 27. Flow Chart for Delay Subroutine