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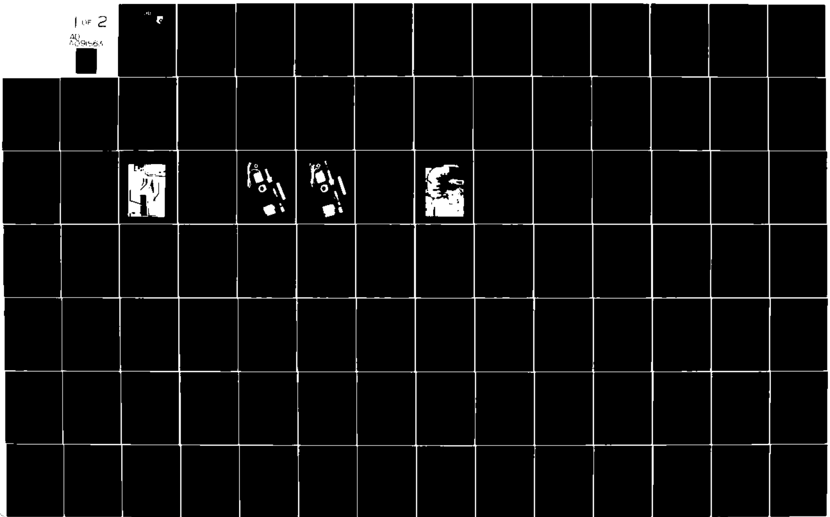

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AN INVESTIGATION OF A DIGITAL ELECTROHYDRAULIC SERVOVALVE

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This report describes the investigation of an electrohydraulic actuator which uses a digital servovalve for control. The digital servovalve uses poppet solenoid valves and fixed orifices to replace the flow control functions of the conventional electrohydraulic analog servovalves. The digital servovalve configuration allows direct digital control of the direction and rate of an actuator used with the digital servovalve.

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The report describes the hardware fabricated for the investigation, some theoretical limitations of the technique and the test results from performance measurements made on the mechanization.

The investigation was successful in demonstrating the validity of the concept and the performance characteristics of an example mechanization.

PREFACE

The effort described in this document was performed by Dynamic Controls, Inc., of Dayton, Ohio, under Air Force Contract F33615-79-C-3605. The contract was performed under Project Number 24030250. Work under the contract was carried out in the facilities of the Flight Dynamics Laboratory of the Air Force Wright Aeronautical Laboratories at Wright-Patterson Air Force Base. The work was administered by Gregory J. Cecere, AFWAL/FIGL Project Engineer.

This report covers work performed between April 1979 and April 1980. The technical report was submitted by the author in May 1980. The work was directed by the author, Dr. Gavin D. Jenney, President of Dynamic Controls, Inc.

The author wishes to express his appreciation to the Dynamic Controls, Inc. personnel, Harry W. Schreadley, William B. Talley and Heinrich J. Wieg for their contributions to the design, fabrication and testing associated with the effort.

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LIST OF ABBREVIATIONS AND SYMBOLS

A	Actuator Area
DC	Direct Current
Db	Decibel
div	Division (of the plotting paper used)
E_{in}	Input Voltage
f	Frequency in Hertz
GPM	Gallons Per Minute
H	Feedback Gain
Hz	Hertz
in	Inch
I	Electric Current
ϕ	Phase Angle in Degrees
K	Flow Gain
lbs	Pounds
n	Number of Solenoid Valves
O_i	Orifice (i = 1,2, ---7)
P	Supply Pressure
Psi	Pounds Per Square Inch
R	Return Pressure
S_p	Number of Flow Steps
sec	second
t	time
τ	Delay Time
τs	Laplace Operator
V	Volts
vs.	versus
X_{out}	Actuator Position

SECTION I

INTRODUCTION

The use of a digital control valve in place of the conventional analog electrohydraulic control valve of an electrohydraulic control system is attractive from several aspects. The first aspect is that the digital servovalve allows directly using digital control signals as an input to the servovalve of the control system. There is an increasing use of digital control elements and signals in control systems and the digital servovalve can interface with these elements without requiring (as does the conventional analog servovalve) a digital to analog converter. The other aspects that are attractive depend on the techniques used to mechanize the digital servovalve.

A digital control valve can be mechanized with solenoid operated two position poppet valves which exhibit both positive seal off and contamination insensitivity characteristics. With conventional control valves, a spool moves proportionally to the amplitude of the input signal. The spool valve is sensitive to hydraulic fluid contamination and has a leakage path between the spool and its sleeve. Reducing the leakage by using less clearance between the spool and sleeve increases the contamination sensitivity and the possibility of galling due to spool and sleeve thermal and/or structural distortions. In addition, the conventional servovalve requires a quiescent leakage flow through the valve for operation of the flapper nozzle or jet pipe first stage. Both the flapper-nozzle and jet pipe operation are based upon modulation of the quiescent flow for controlling the power (second stage) spool of the control valve.

Using poppet type solenoid valves for the digital servovalve mechanization eliminates the quiescent flow characteristic for the servovalve. Since a poppet type valve does not use a spool and sleeve configuration for flow control, the contamination sensitivity characteristics can be much better than that of the analog servovalve. Edge erosion associated with the wearout of conventional servovalves is also eliminated with the poppet solenoid valve approach.

The mechanization investigated used the poppet solenoid valves to replace the operation of the conventional servovalve both for the flow direct and flow rate modulation. As mechanized four poppet solenoid valves were used for the direction control and three solenoid valves were used for the modulating of the output flow. For the evaluation program, a set of driving electronics was constructed which allowed commanding the servoactuator with an analog input. To evaluate the servovalve, an actuator was constructed which mated with the digital servovalve so that the servovalve controlled the rate and direction of the actuator.

In testing the digital servovalve, a control system was mechanized as it would be for an analog system with an analog input and an analog feedback from the actuator. The digital servovalve and electronic driver were then used as a replacement for an analog servovalve and servoamplifier. The tests used to evaluate the digital servovalve mechanization are (for the most part) the same as those used to measure the performance characteristics of an analog electrohydraulic actuator.

The following sections of the report describe the mechanization concept, theoretical limitations, demonstration hardware and test results.

SECTION II

MECHANIZATION DESCRIPTION

1. Servovalve Description

Figure 1 is a schematic of the operational elements of the digital servovalve connected to an actuator. The servovalve uses 7 solenoid valves and 4 orifices. Four of the solenoids (numbers 1 through 4) are used for directional control. Solenoid valves 1 and 4 are connected from a cylinder port of the valve to hydraulic return. Solenoid valves 2 and 3 are connected between one cylinder port each and a gallery connected to the combined output flow from the flow modulation solenoid valves and orifices. As shown on Figure 1, four orifices (0_1, 0_2, 0_3 and 0_4) are used for flow modulation. Orifice 0_1 is connected directly to hydraulic supply while orifices 0_2, 0_3, and 0_4 are connected through solenoid valves 5, 6 and 7 respectively. Solenoid valves 5, 6 and 7 are used in combination with the non-switched orifice 0_1 to provide the flow to the directional solenoid valves.

Opening solenoid valves 2 and 4 causes the actuator to move to the right as shown on Figure 1. The rate at which the actuator moves is determined by the particular energizing of solenoid valves 5, 6 and 7.

Figure 2 illustrates the flow modulation capability of the four fixed orifices and three solenoid valve mechanizations of Figure 1. This figure shows the stepwise approximation of the flow characteristics of a conventional servovalve. Eight flow rate steps are available from the one fixed orifice and the three switched orifices. Table 1 lists the eight combinations determining the flow steps.

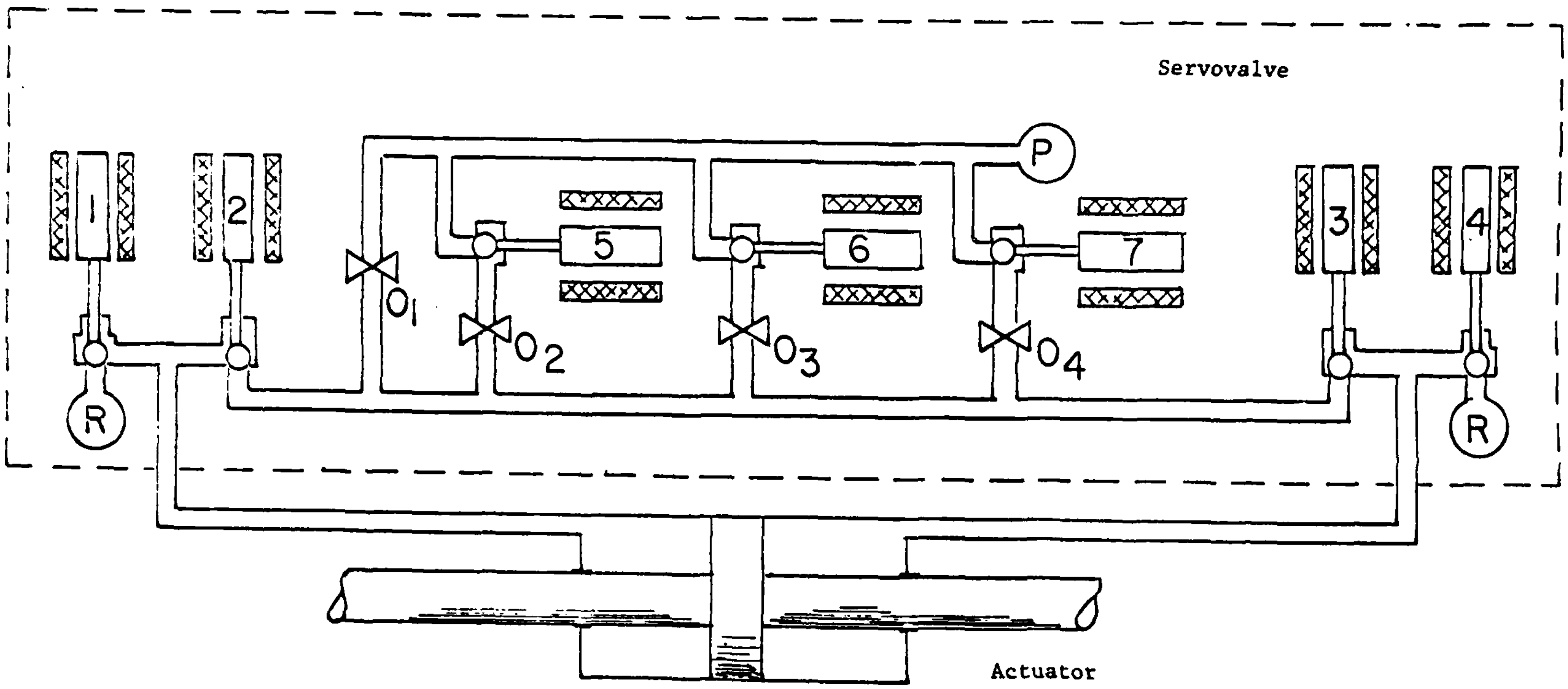


FIGURE 1 Digital Servovalve Schematic

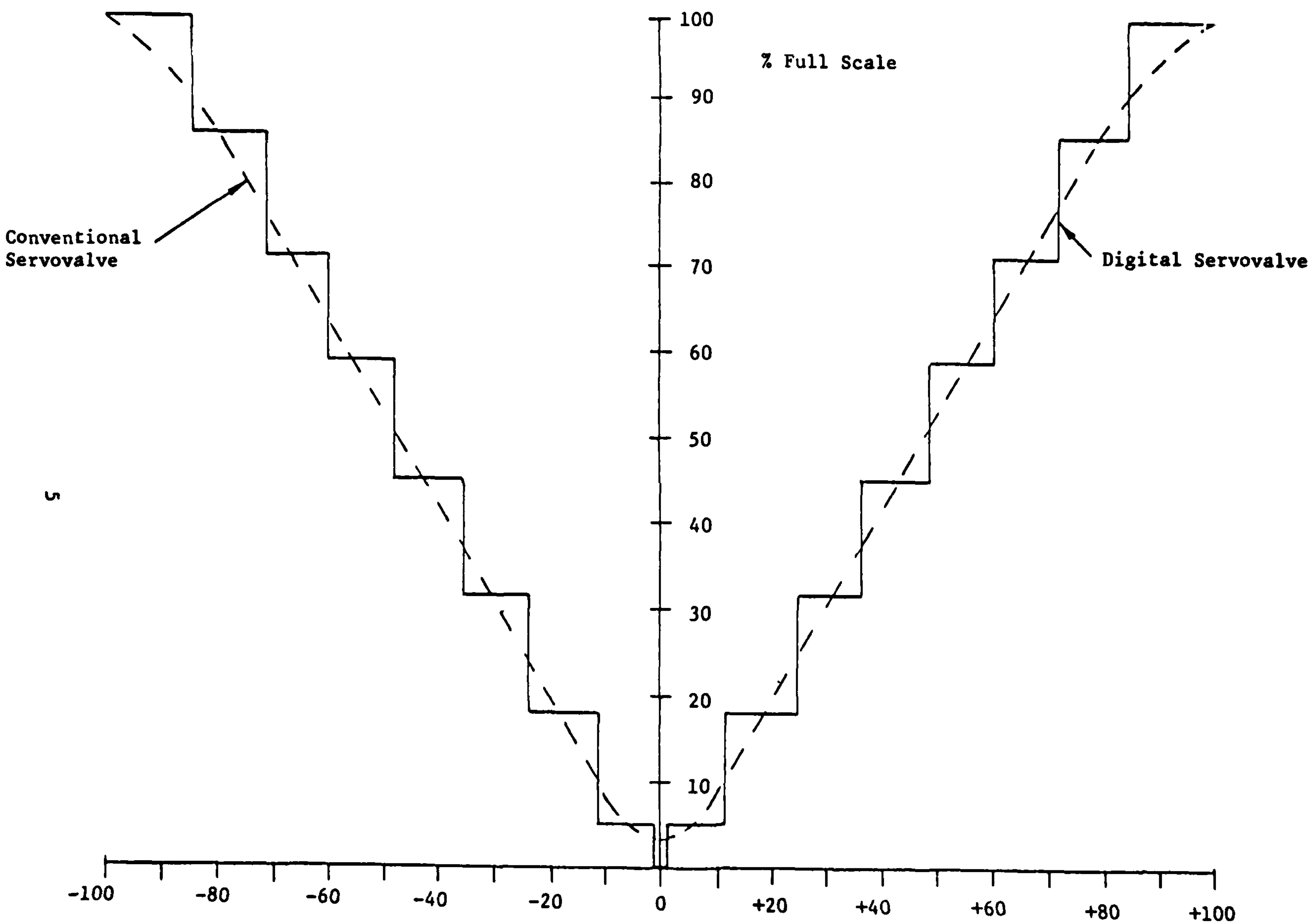


FIGURE 2 Flow Linearity of Digital Servovalve

TABLE 1

Flow Steps Tabulation

Flow Rate Orifice Combinations	Flow Rate Combination No.
0_1	1
$0_1 + 0_2$	2
$0_1 + 0_2 + 0_3$	3
$0_1 + 0_2 + 0_3 + 0_4$	4
$0_1 + 0_3$	5
$0_1 + 0_3 + 0_4$	6
$0_1 + 0_4$	7
$0_1 + 0_2 + 0_4$	8

Note that as shown on Figure 2, the flow at zero input is shown to be zero. This reflects the effect of the threshold built into the driving electronics for directional solenoids and that with the actuator stopped, no flow is required from the control valve to the actuator. In general, the number of flow modulation steps available from a particular configuration of a fixed orifice and a given number of solenoid valve switched orifices is:

$$S_p = 2^n$$

where S is the number of flow steps and n is the number of solenoid valves used for switching in the flow modulation orifices.

In order to achieve the best approximation of the linear flow modulation curve with the step-wise solenoid valve operation, the pressure drop across the directional solenoids at the maximum flow from the valve is much smaller than the pressure drop across the feed orifices used for the flow modulation. The flow modulation orifices used are sharp edged orifices in order to minimize the effect of fluid temperature upon the flow characteristics.

As shown on Figure 1, the solenoid valves are two way, normally closed, ball poppets. Flat disc and cone poppets are variations on the poppet design which offer similar characteristics in terms of seal-off and contamination insensitivity. The flow available through this type of valve at a given pressure drop is a function of the porting area. In order to open the valve against large differential pressures, the solenoid force (and size) increases with porting area (and available flow).

The direct operating poppet solenoids are limited in flow capacity unless large valves are used. For applications requiring flows above 2 GPM at pressure drops not exceeding 100 psi, pilot operated poppet solenoid valves can be used. With pilot operated solenoid valves, there is some increase in the response time of the valve and potentially some slight increase in contamination sensitivity as compared to the direct acting solenoid valves.

2. Driving Electronics

Figure 3 is a general schematic of the electronics used to drive the digital servovalve. The schematic shows an analog input and feedback signal being used as part of the electronics. The error (difference between the analog command and analog feedback) signal polarity and amplitude are converted to the command signals for the direction and flow modulation solenoids using two logic sections. The first logic section is a comparator section which

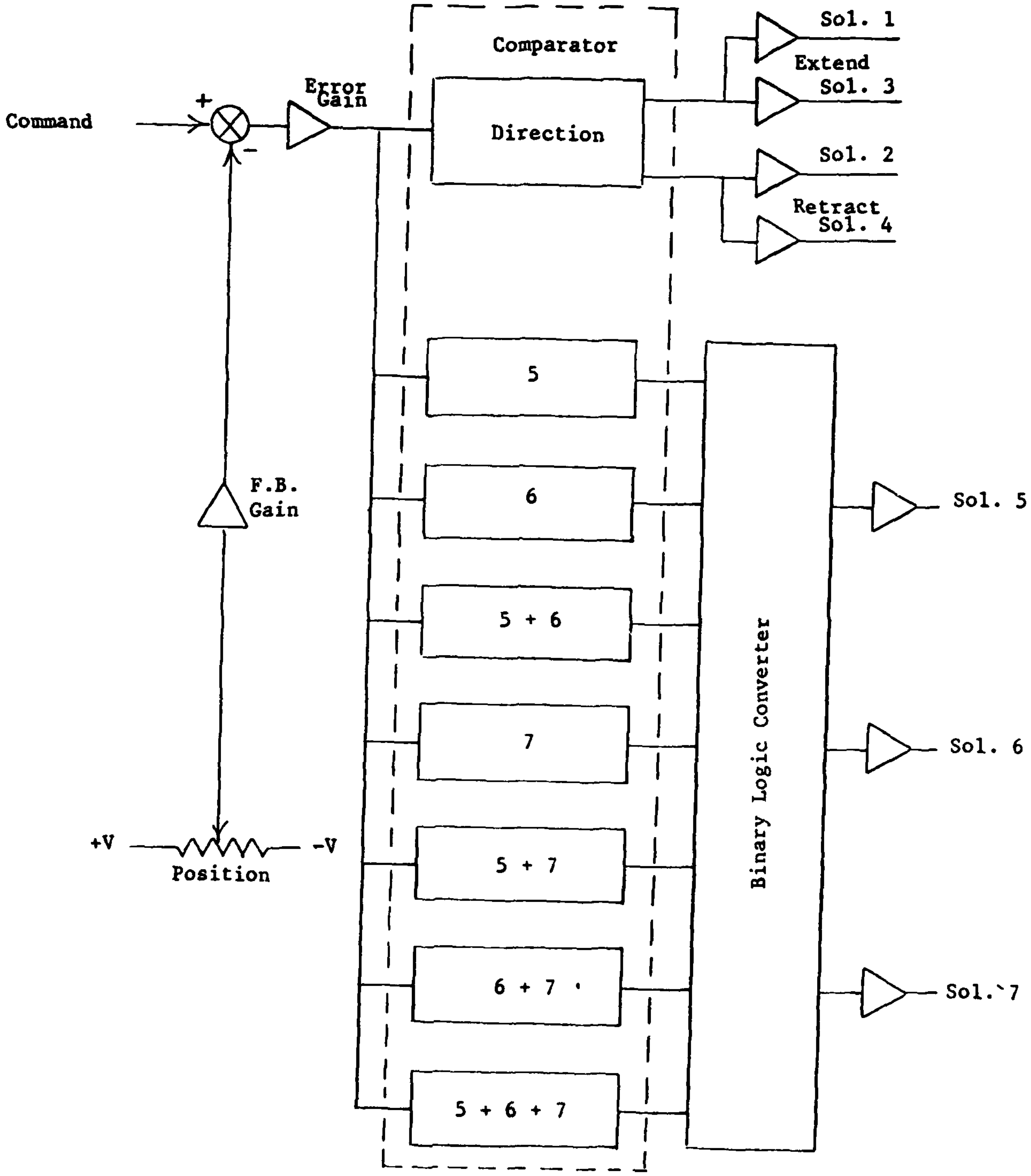


FIGURE 3 Electronic Schematic

determines the polarity of the error signal and drives the solid state relays for energizing appropriate directional solenoid valves when the error signal exceeds a predetermined level. The remaining portion of the comparator section converts the amplitude of the error signal into eight discrete signals, each of which carry a weight of the error amplitude. The output of this comparator section is connected to the binary logic converter section of the electronics. The binary logic converter section controls the energizing of the flow modulation solenoids. The comparator logic incorporates gates which prevent a solenoid combination determining the flow rate for one flow step from remaining engaged when a different flow step is commanded. The outputs of the binary logic section drive solid state relays which energize the flow modulation solenoids. The use of combinations of solenoids to generate the flow steps allows using 3 instead of 7 separate solenoids to generate the 8 flow rates.

The electronics as shown on Figure 3 may appear to be only a variation of an analog to digital converter. However, these electronics were designed to allow demonstration of the servovalve concept using analog feedback and input test signals. When used with a digital command system, the servovalve command signal of four bits (one hi-low bit for the directional solenoids and three hi-lo bits for the flow modulation solenoids) would be used to directly drive the solid state relays which energize the solenoid valves. This four bit word would be generated from a summation of a digitally encoded feedback signal and command signal. Any 8, 12 or 16 bit computer or microprocessor could be used to create the 4 bit word for the digital servovalve command.

Note that the command for the directional solenoids is necessarily a three state command and requires more than a simple single bit command connected directly to the directional solenoid relays. The three states are:

1. Both pairs directional solenoids off
2. Extend solenoid pair on and retract off
3. Retract solenoid pair on and extend off

State 1 is an additional requirement and can be provided by the technique of holding off the command from the directional solenoids until the error threshold requirement is met or by using a three state output device (a recent digital computer component development).[1] State 1 is provided in the present electronics by the threshold incorporated in the comparator logic.

SECTION III

APPLICATION LIMITATIONS

1. General

There are several characteristics unique to the digital servovalve approach that must be considered when applying the valve to closed loop control systems. These characteristics are the following:

1. The stepping operation of the flow modulation
2. The inherent threshold required for the operation of the valve
3. The inherent time delay in the response of the solenoid valves

These characteristics all affect the performance of the closed loop control system using the digital servovalve.

In addition to the above three characteristics which directly affect the control system performance, there is a power consumption, weight and volume associated with the digital servovalve which may limit its application. The following subsections discuss these aspects of the digital valve.

2. Flow Modulation Stepping Effect

The stepping flow modulation characteristic of the digital valve is not a problem from a position linearity aspect when the valve is used in a closed loop electrohydraulic actuation system. The steady state position is determined by the feedback transducer (analog or digital) used with the actuator controlled by the digital servovalve.

The stepping of the flow modulation will create output waveform distortion of the actuator motion with dynamic inputs. As previously shown on Figure 2, the deviation from a linear flow modulation curve is approximately 7% of the maximum flow when flow modulation steps are used. The stepping will create high frequency harmonic distortion of the dynamic input. The device controlled by the control actuator may be sensitive to the harmonic distortion components of the output waveforms in some cases. If lower distortion values for the dynamic output of the control system using a digital valve are required, then the number of modulation steps used may be increased easily. The dynamic waveform distortion associated with the discrete flow modulation steps is a function of the number of flow solenoid valves used and is reduced by using additional solenoid valves for the flow modulation function. One additional flow modulation solenoid applied to the mechanization shown in Figure 1 would increase the flow modulation steps from 8 to 16 and reduce the deviation of the flow modulation curve from a linear curve to below 3.5%.

3. Threshold Effect

The threshold necessary to ensure that the directional solenoid valve pairs (extend and retract) do not operate at the same time creates a potential for small amplitude limit cycling. The threshold of an analog servovalve has the same control implications and is normally reduced to a minimum by design. In the digital servovalve, it is necessary to design in a threshold level in order for the valve to operate properly. The effect of the threshold is to have the actuator cycle within a small band of output motion. Within this band, the actuator is uncontrolled in terms of responding to a system input. At the edges of the motion band, the error signal from the feedback transducer is large enough to activate the directional solenoid valves and stop the actuator from continued motion outside of the threshold band. The correcting control input into the actuator sends the actuator piston towards the opposite edge of the threshold band. If the actuator reaches the opposite edge of the threshold band without stopping, its motion is then again reversed by the directional solenoid valves. This phenomena then repeats itself and the actuator cycles between the limits of the threshold band without stopping, presenting a small amplitude limit cycle condition for the system output. This limit cycling can be unacceptable in some applications, requiring damping out in order for the operation of the system to be satisfactory.

4. Solenoid Valve Time Delay Effect

The time delays associated with the response time of the solenoid valves affect directly the frequency response that can be obtained from an actuation system which uses the digital valve. The frequency response of an analog electrohydraulic servovalve places a similar limitation on the control system it is used with.

The effect of the time delay is to cause a phase lag between the input to the digital servovalve and the output flow from the valve. The phase lag is directly proportional to the sinusoidal input frequency. The amount of phase angle contributed by the time delay is calculated from the following equation:

$$\Phi = -f\tau 360$$

Where: f is the input frequency in Hz

τ is the time delay in seconds

ϕ is the phase angle in degrees

This phase angle is added to the phase contribution of the other elements in the control loop the digital valve is used with.

For a simple electrohydraulic actuator with position feedback, the open loop phase angle of the actuator and digital valve is the -90 degrees contributed by the integration of the actuator plus the phase lag due to the time delay of the digital valve.

The frequency response (and stability) of an actuation system with the digital valve can easily be determined using the open loop gain response and a Nichol's chart. The frequency at which the time lag produces a -90 degrees phase angle for a simple actuator system is the frequency at which the open loop response has a phase angle of -180 degrees. This is the frequency at which the specification of the control loop gain margin is made. Figure 4 is a block diagram of the actuator and digital control valve in a typical control loop. By specifying the gain margin, the stability of the closed loop response is established. Note that in order to make this statement, the phase contributions for the open loop response are assumed limited to the actuator integration and the time lag. Gain margin is a necessary but not sufficient condition for control loop stability.

When additional frequency dependent elements are included in the loop, the stability of the loop must be re-examined. If a gain margin of 6 Db is used for the open loop gain, and the feedback gain set at unity, then the closed loop response of the system of Figure 4 in terms of the ratio of the input frequency to the frequency at which 180 degrees phase lag occurs is as listed in the following Table 2. Figure 5 shows the system response of the control loop as a function of the gain margin established.

TABLE 2

Closed Loop Response

Input Frequency / Frequency @ -180°	Amplitude Ratio (Db)	Phase Lag (Degrees)
.01	0	1
.02	0	2
.04	0	4
.06	.05	7
.08	.1	10
.1	.15	13
.2	.45	24
.4	1.5	48
.6	3.0	85
.8	2.0	135
1.0	0	180
1.2	-3.5	210
1.5	-7.5	242
2	-12.5	285

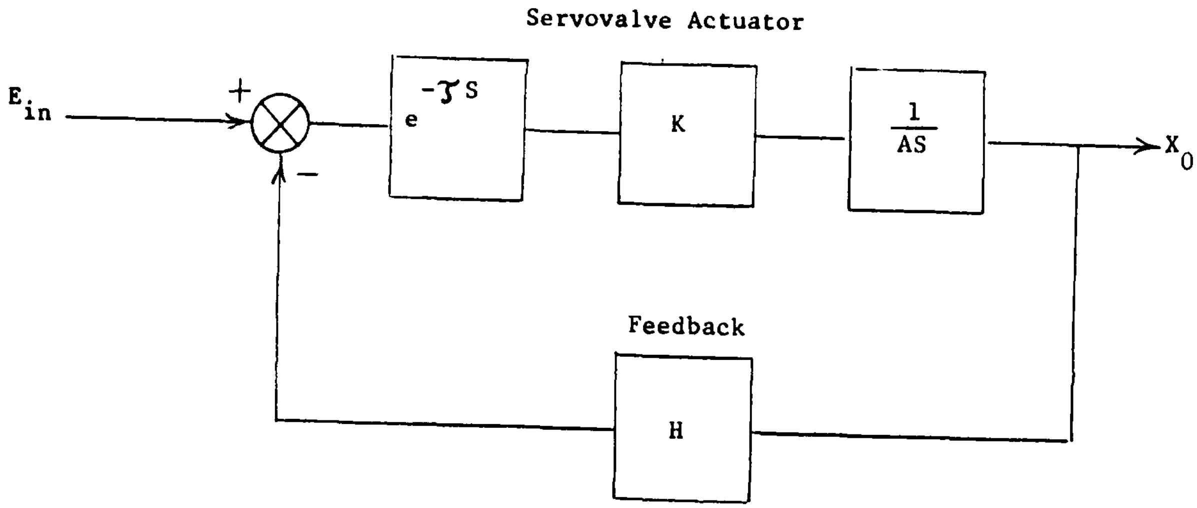


FIGURE 4 Control Loop

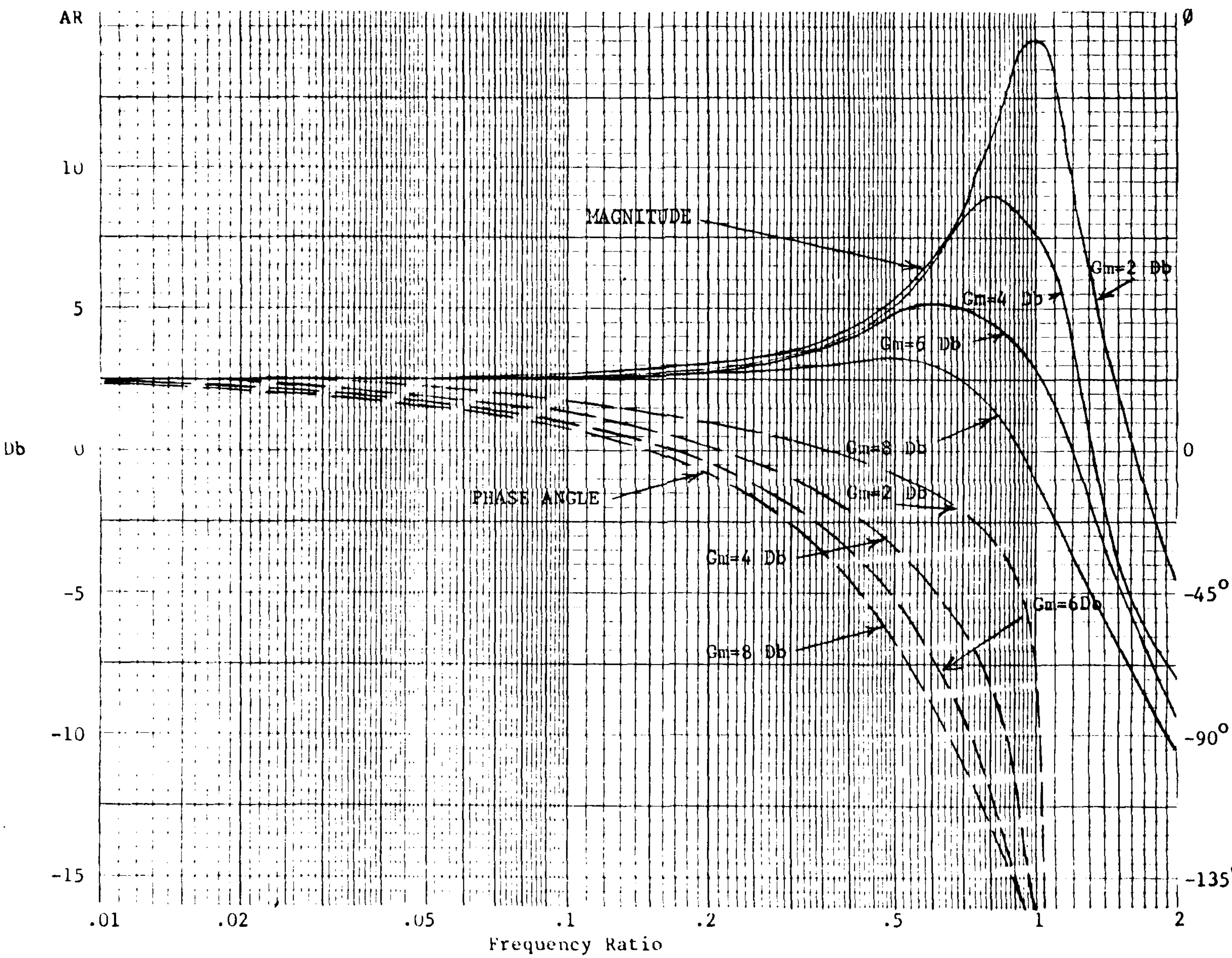


FIGURE 5 Control Loop Response VS. Gain Margin

From Table 2 and Figure 5, the closed loop response for an actuator control system having a gain margin of 6 DB peaks at a frequency ratio of .6. For a solenoid valve having a time delay of .015 seconds, the frequency at which the control loop of Figure 4 exhibits 180 degrees phase lag is 16.7 Hz. The frequency at which the control system would exhibit a + 3 DB response peak is 10 Hz. This illustrates that the response time of the solenoid valves used in the digital valve places a distinct upper limit on the frequency response of the control loop in which the digital valve is used.

SECTION IV

INVESTIGATION HARDWARE DESCRIPTION

1. General

In fabricating the hardware used for the experimental investigation of the digital servovalve technique, off-the-shelf hardware was used wherever possible. In particular, commercial solenoid valves were used (with some modification) due to the time and cost constraints on obtaining satisfactory aerospace type solenoid valves. The size of the manifold used to construct the digital servovalve was primarily determined by the mounting requirements of these commercial solenoids. An evaluation actuator was constructed to mate to the servovalve manifold. The actuator mounted an analog position transducer to measure the output position.

Driving electronics were constructed specifically to control the solenoid valves. The electronics incorporated techniques to reduce the opening response time of the solenoid valves below the normal response time of the solenoid valves.

The hardware was constructed strictly as demonstration hardware to allow evaluation of the digital servovalve technique. However, the operating pressures used with the servovalve demonstrator and the materials for the construction of the servovalve and actuator were consistent with aerospace application requirements. No attempt was made to minimize size or weight of the mechanization. Size and weight reductions would depend on the particular solenoid valves used, as well as the packaging effort applied to the associated hardware.

Figure 6 shows the hardware constructed for the evaluation as assembled for testing.

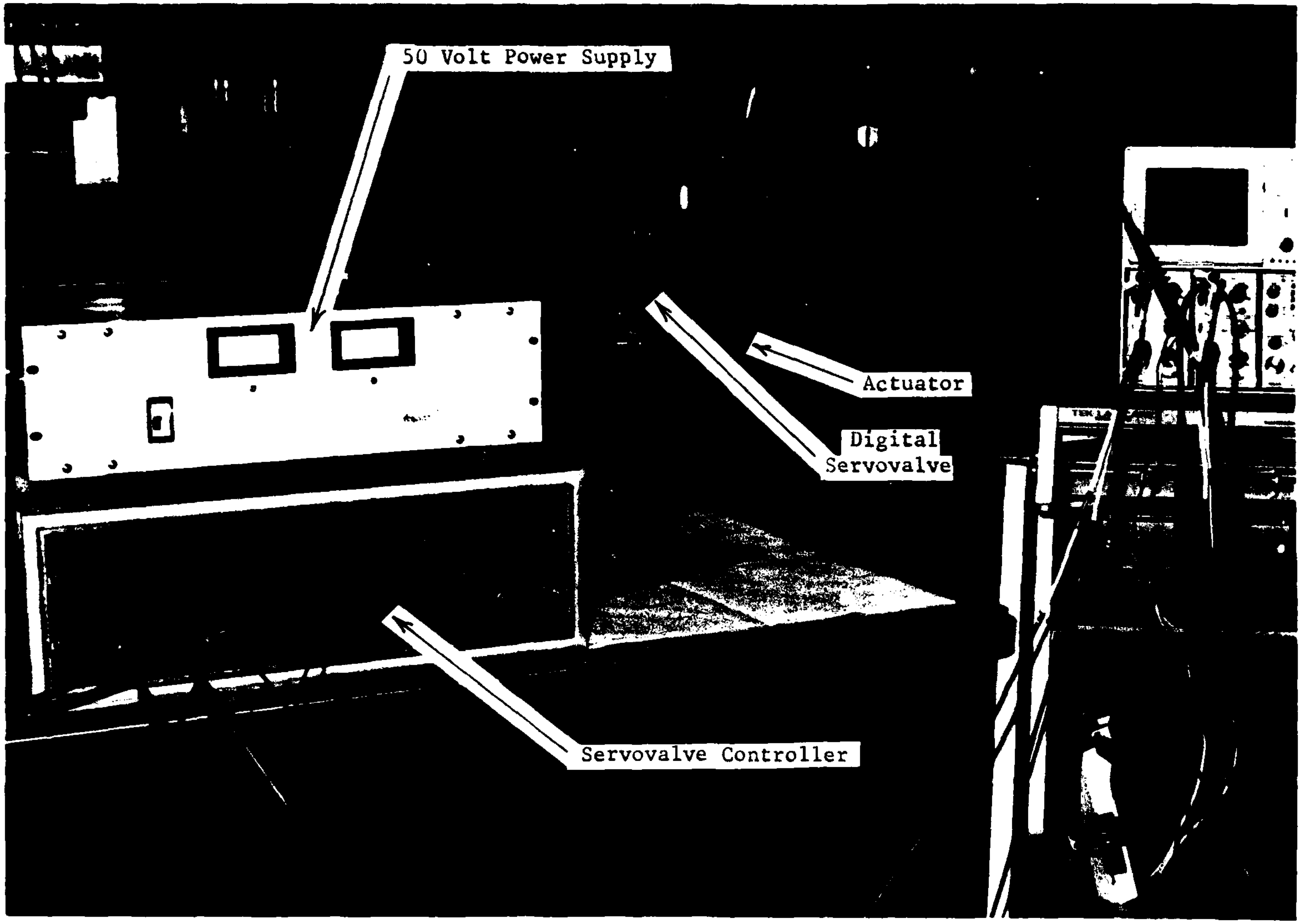


FIGURE 6 Laboratory Test Setup

2. Solenoid Valve Description

The solenoid valves used for the evaluation were valves manufactured by Modular Controls Corp. as part number SV1-10-C-012D and sold for commercial applications. The solenoid valves are pilot operated poppet valves with a flow rating of 10 GPM at a differential pressure drop across the valve of 50 psi. The solenoid valves require 1.5 amps current at 12 volts for operation. The valves were modified to reduce the closing response time from the original measured response of 65 milliseconds to close to an approximate response time of 15 milliseconds. Although direct operating (rather than pilot operated) solenoid valves were intended to be used for the demonstration unit, that type of valve was not available as an off-the-shelf item.

In order to reduce the closing response time, the flow rating of the solenoid valve was reduced to 1 GPM at 100 psi differential pressure drop by shortening the poppet travel. Figure 7 shows an unmodified solenoid valve disassembled. Note the pilot plunger and the poppet. A pilot operated solenoid valve uses system pressure to open and close the poppet. The solenoid core drives only the pilot plunger. Figure 8 shows a modified solenoid valve disassembled. The principal modifications involved the shortening of the poppet travel and the biasing of the solenoid plunger. These modifications reduced the response time to close from the original 65 milliseconds to approximately 15 milliseconds. The stop ring shown on Figure 8 was used to establish the open position of the poppet. The preload on the bias spring reduced the solenoid closing time by applying an initial closing force to the solenoid core. The coupler spacer shown on Figure 8 was used to eliminate play between the pilot plunger and the solenoid core.

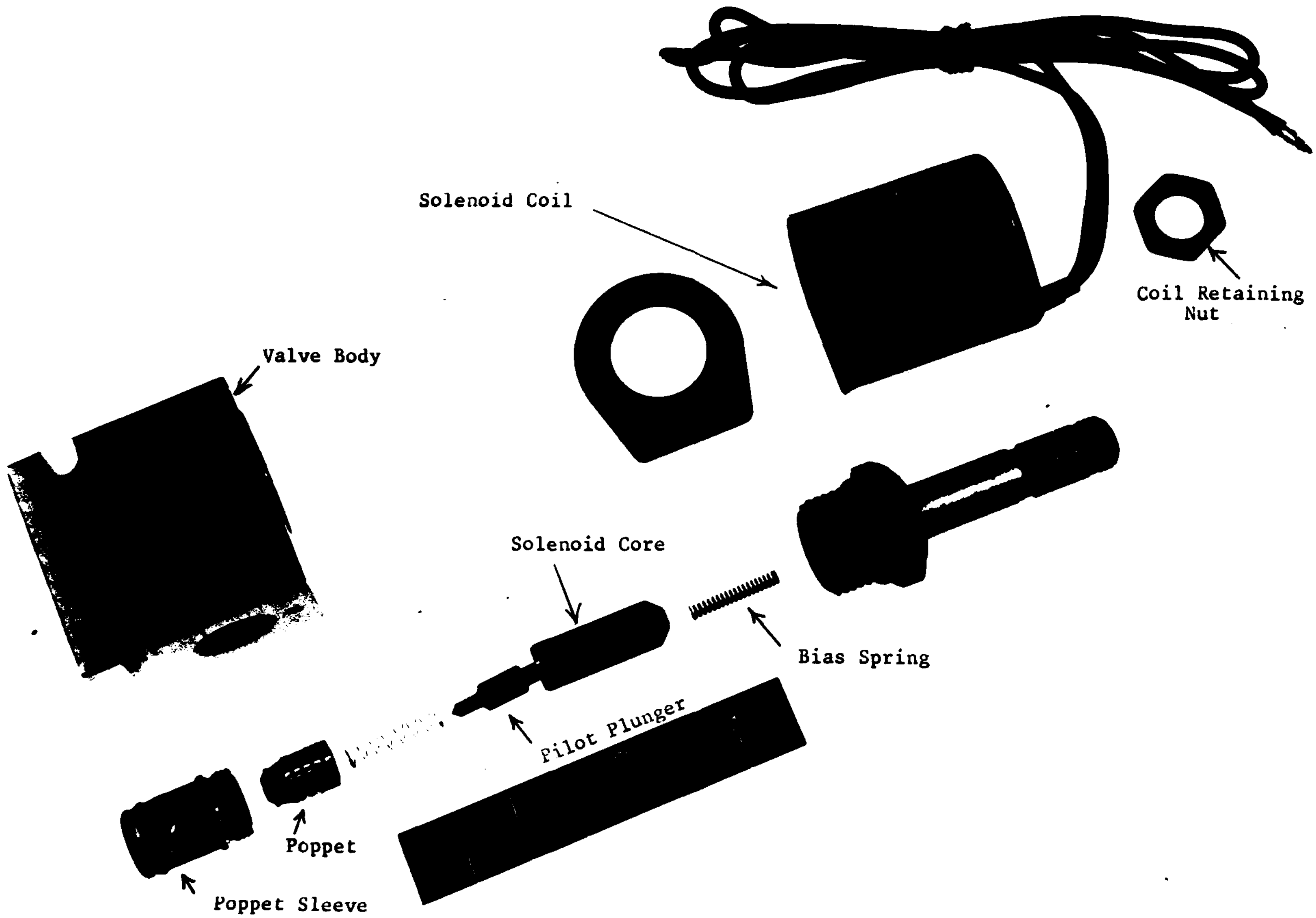


FIGURE 7 Unmodified Solenoid Valve

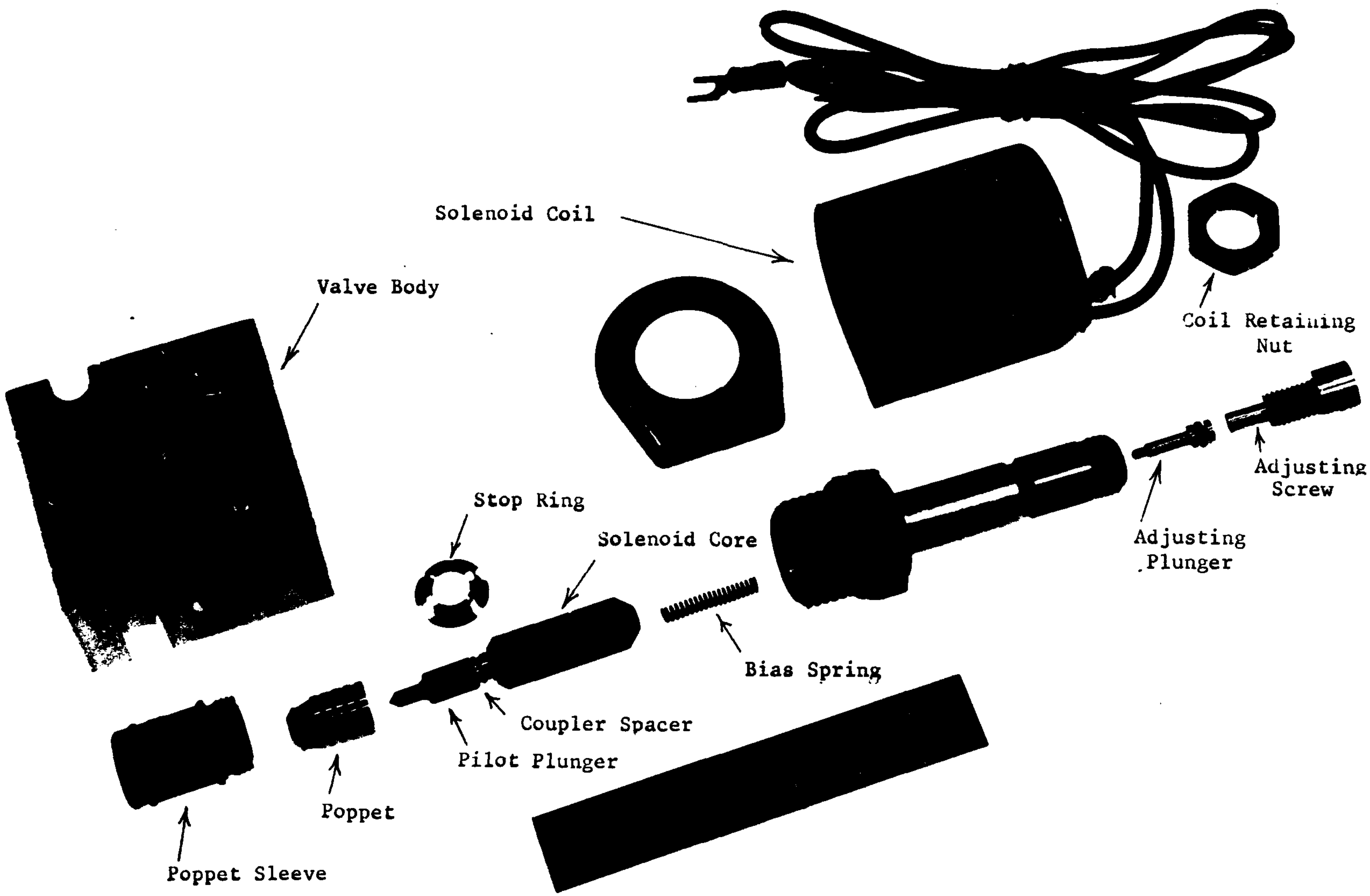


FIGURE 8 Modified Solenoid Valve

As received from the manufacturer, the solenoid valves had an opening time delay of approximately 35 milliseconds. This time delay was primarily associated with the response of the solenoid section of the solenoid valve. The opening time delay was reduced to approximately 15 milliseconds by the solenoid energizing technique used in the solenoid valve control electronics.

3. Digital Servovalve Description

Six solenoid valves as described in the previous section were used in making the digital servovalve. The digital servovalve assembly consisted of the six solenoid valves, four orifices and a manifold block providing the necessary interconnecting hydraulic passages (Reference Figure 1). The orifices were constructed as cartridges. Three of the orifices were installed in the manifold immediately below the three flow modulation solenoid valves and the fourth (the non-switched flow modulation orifice) was installed between supply pressure and the hydraulic passage feeding the directional solenoid valves. Figure 9 shows a closeup view of the digital servovalve and actuator body. As sized for the demonstration unit, the design flow rates through the flow modulation orifices at a differential pressure of 2500 psi were:

1. Non-Switched Orifice ---------- (5% of Max Flow)
2. First Switched Orifice -------- (13.5% of Max Flow)
3. Second Switched Orifice ------- (27% of Max Flow)
4. Third Switched Orifice -------- (54% of Max Flow)

Maximum flow for the test results presented in this report was .5 GPM. This maximum flow produced an actuator slew rate giving full actuator deflection from midstroke within 1 second.

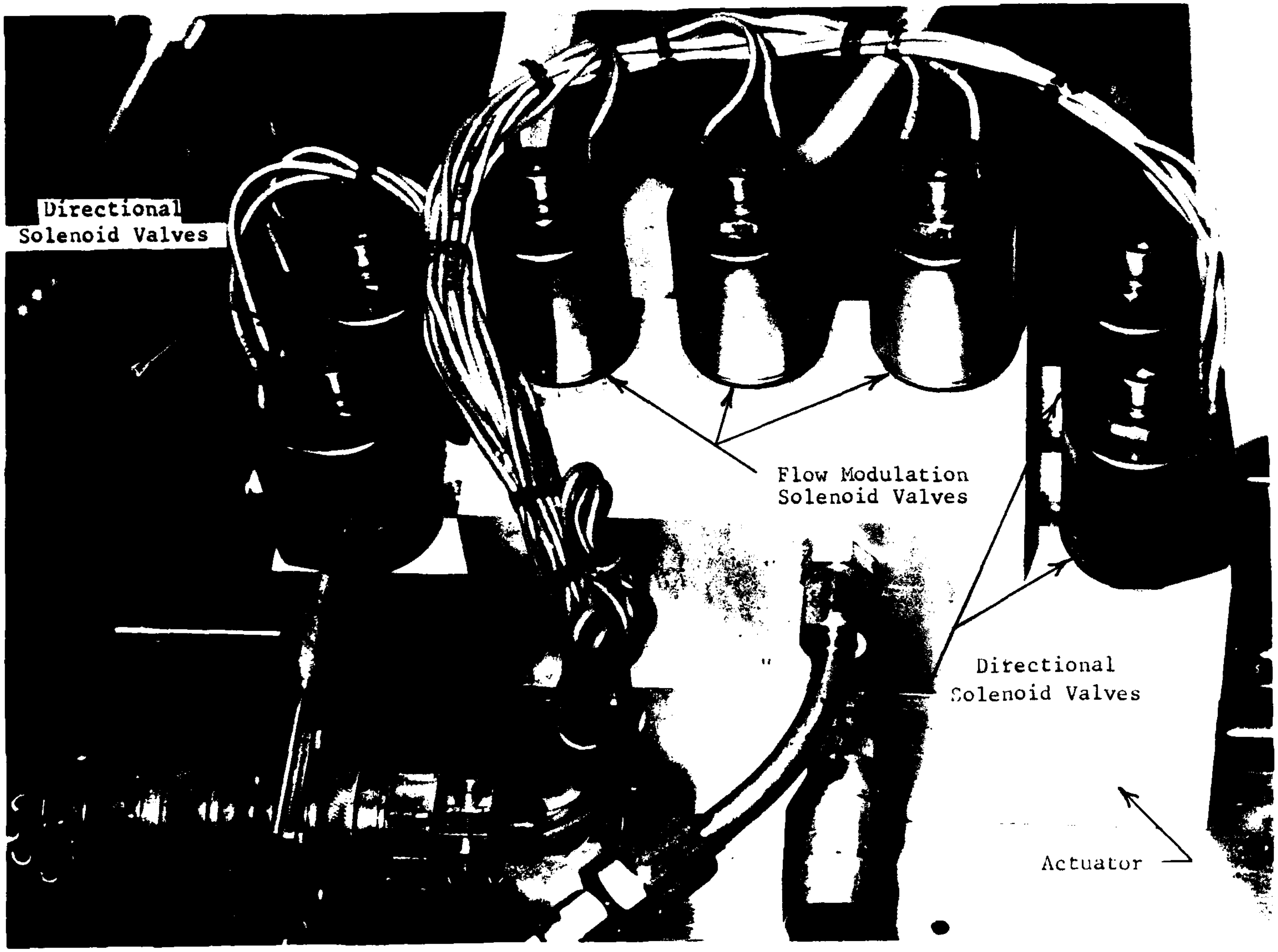


FIGURE 9 Digital Servovalve and Actuator Evaluation Hardware

Figure 10 is an assembly drawing of the servovalve manifold, solenoid valves and the flow modulation orifices making up the digital servovalve.

4. Test Actuator Description

Figure 11 is an assembly drawing of the actuator used with the digital servovalve. The actuator was designed with a total stroke of 4.75 inches and a drive area of .77 square inches. Shamban teflon Delta seals were used for both the actuator piston and cylinder rod seals. The actuator end caps were constructed of an aluminum bronze bearing material. The actuator piston section used two sets of delta seals, one set used for the hydraulic seal function and the other as a seal backup and a piston support. Type 304 stainless steel was used as the material for the actuator piston. The actuator body was constructed from 2024 T-351 aluminum. The position transducer used to measure the actuator output was a precision film potentiometer having a total stroke of 6 inches and a linearity of $\pm$.25% of the total stroke. The transducer was mounted in the actuator body parallel to the actuator piston motion axis and coupled to one end of the actuator piston with a combination clamp and anti-rotation arm.

5. Driving Electronics Hardware Description

The electronics used to control the digital servovalve consisted of a 50 volt power supply and the digital servovalve controller (Reference Figure 3). The controller allowed commanding the servo system with a DC potentiometer mounted on the front panel or commanding the digital servovalve system with an external input. Display lights showing the operation of the directional solenoids and the percent of maximum flow being applied to the control actuator were mounted on the front panel of the controller.

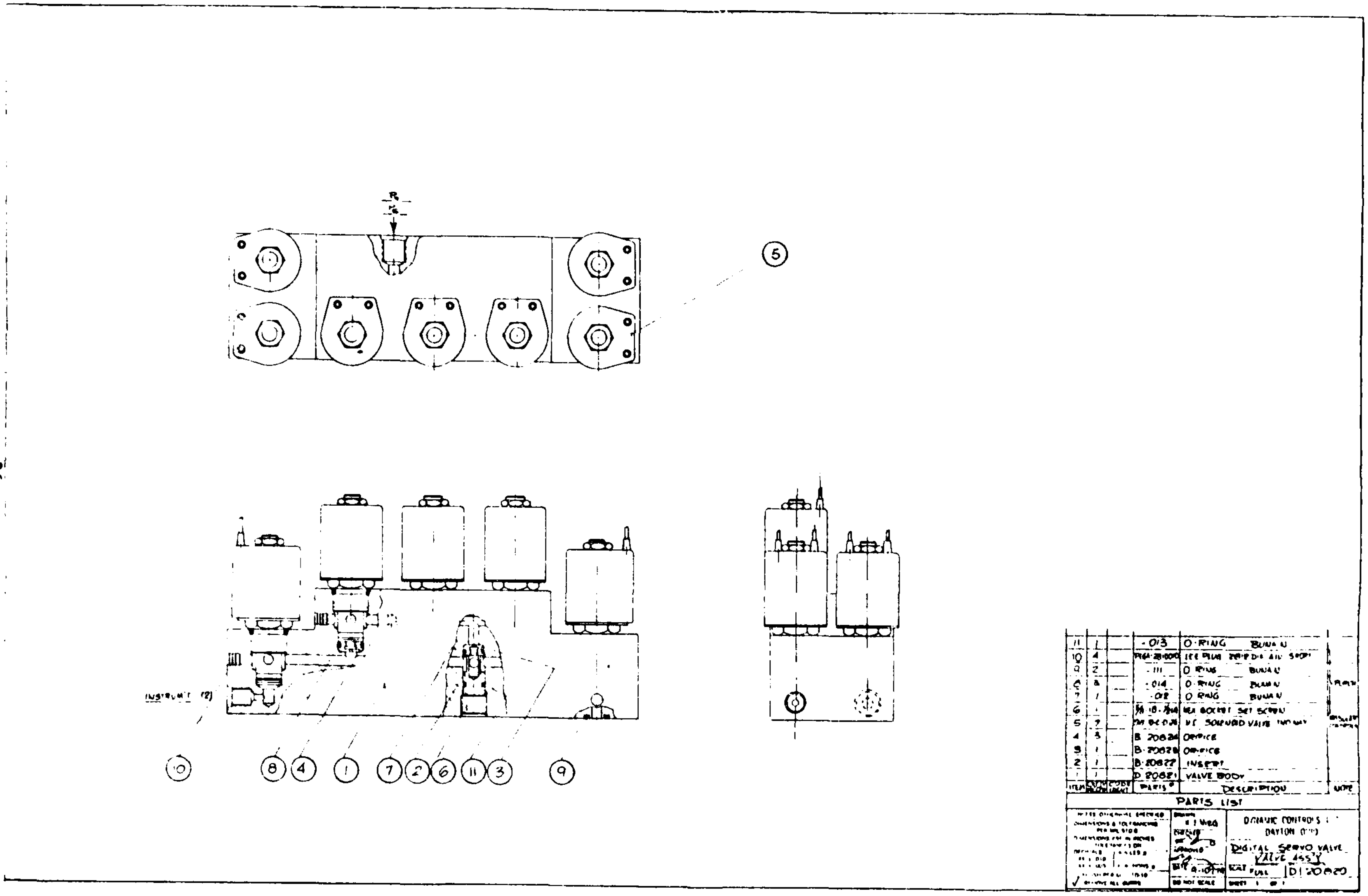


FIGURE 10 Digital Servo Valve Assembly

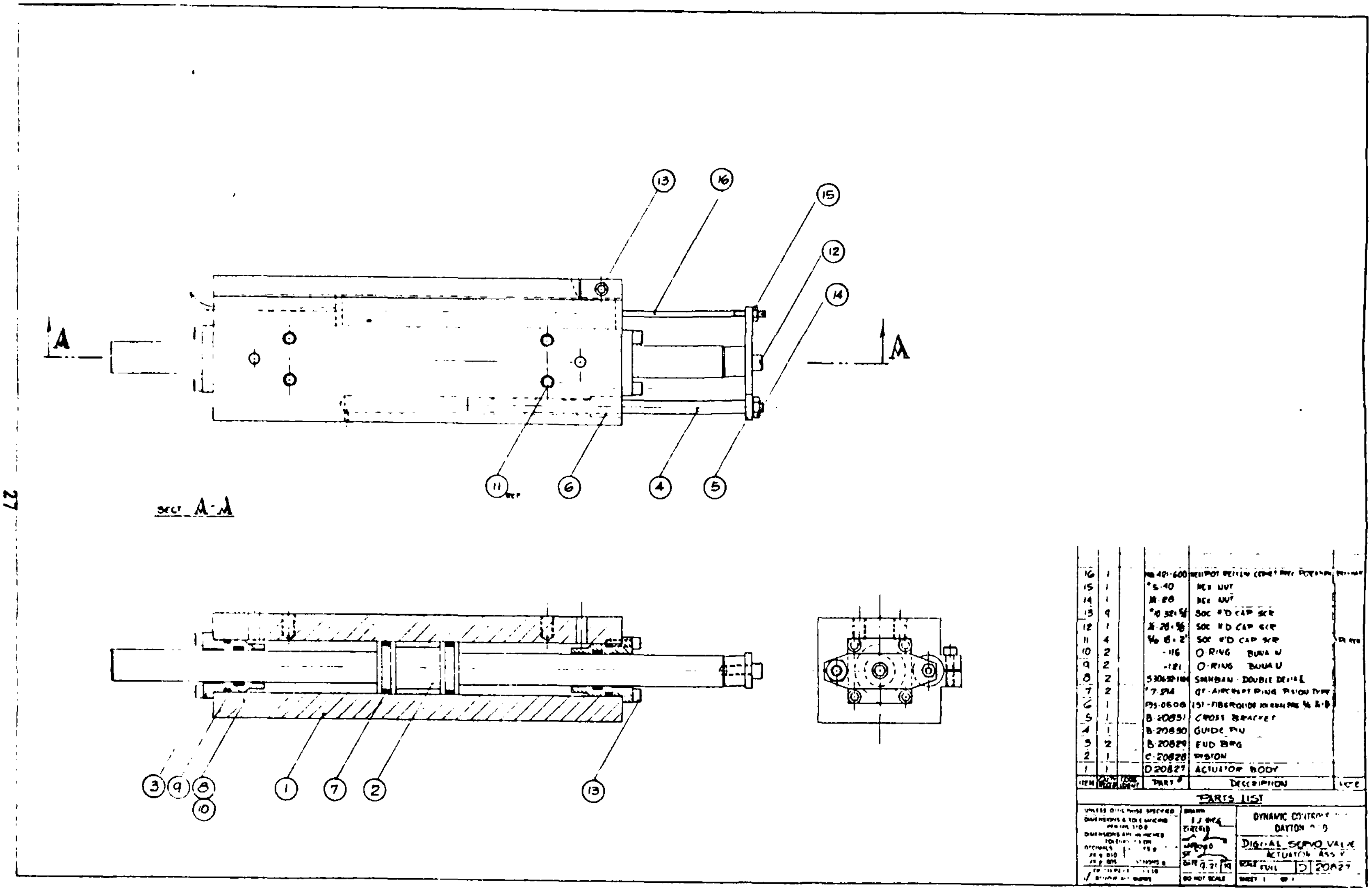


FIGURE 11 Digital Servo Valve Actuator Assembly

The controller included the necessary ± 15 volt and + 5 volt power supplies for the operation of the control electronics within its chassis. The 50 volt supply was used to directly drive the solenoid valves. This voltage was higher than the continuous operating maximum voltage rating of the solenoid valves. The application of the higher voltage reduced the time delay for operating the solenoid valves as shown on Figure 12. Figure 12 shows the "on" time response delay as a function of the driving voltage (as measured on one of the solenoid valves used in the demonstration valve). In order to prevent overheating the solenoid coils while maintaining the response time improvement, the driving voltage for the solenoids was applied on a time varying basis. Upon application, the 50 volts was initially maintained for 10 milliseconds. After the 10 millisecond application of the 50 volts (which caused the solenoid valve to open), the driving voltage was changed to a 50 volt pulse train. The frequency of the pulses was set to achieve solenoid hold-in with minimum power consumption. This technique provided both the desired reduction in the "on" time delay and the minimum of power consumed in the hold mode. A 50 volt pulse of .9 milliseconds width at a repetition of 300 hz/sec was sufficient to hold the solenoid valves in the "on" position.

Figure 13 is the electronics circuit schematic for the digital valve controller. This corresponds to the block diagram schematic shown previously on Figure 3.

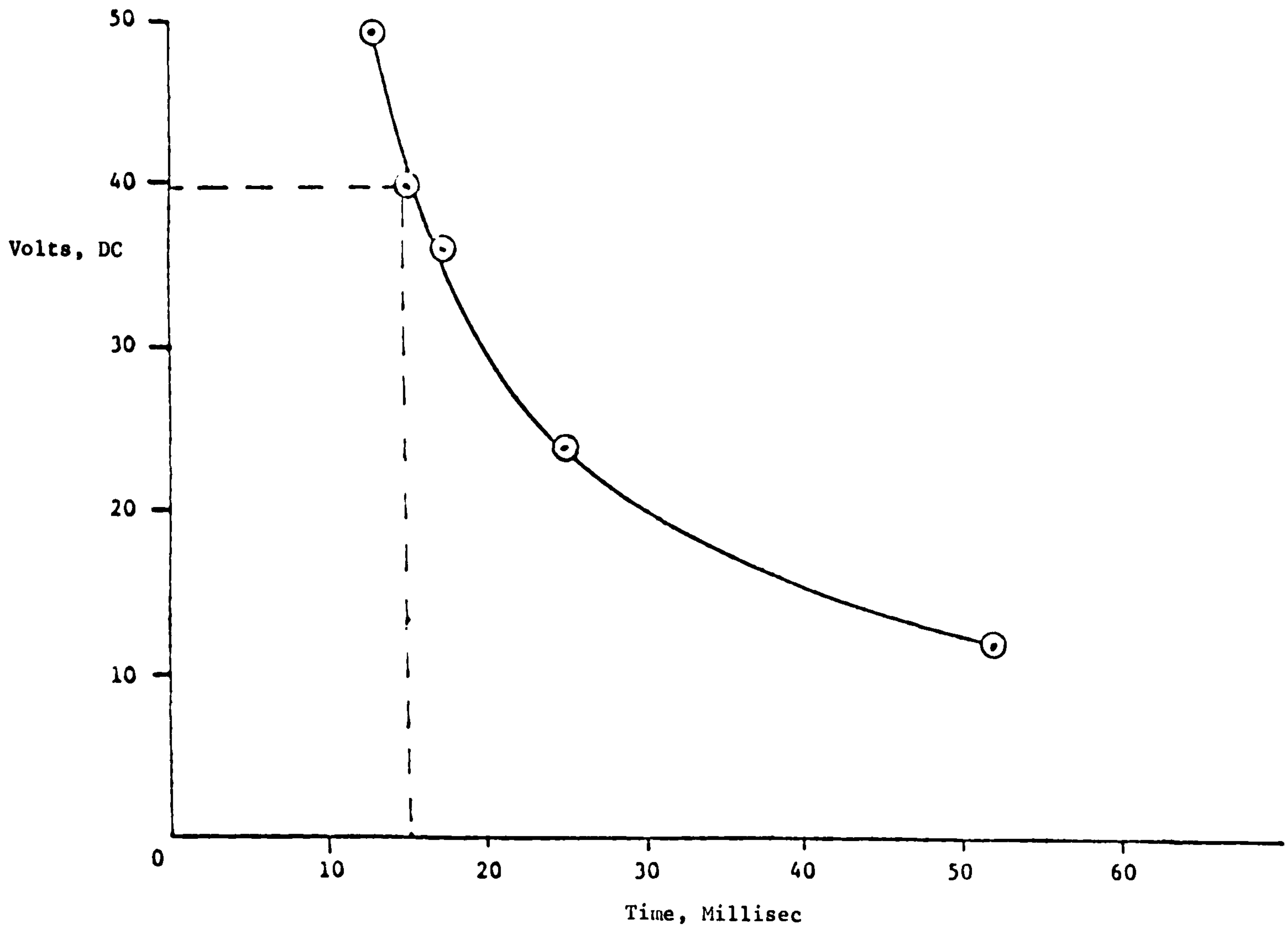


FIGURE 12 Solenoid Response Time Vs. Applied Voltage

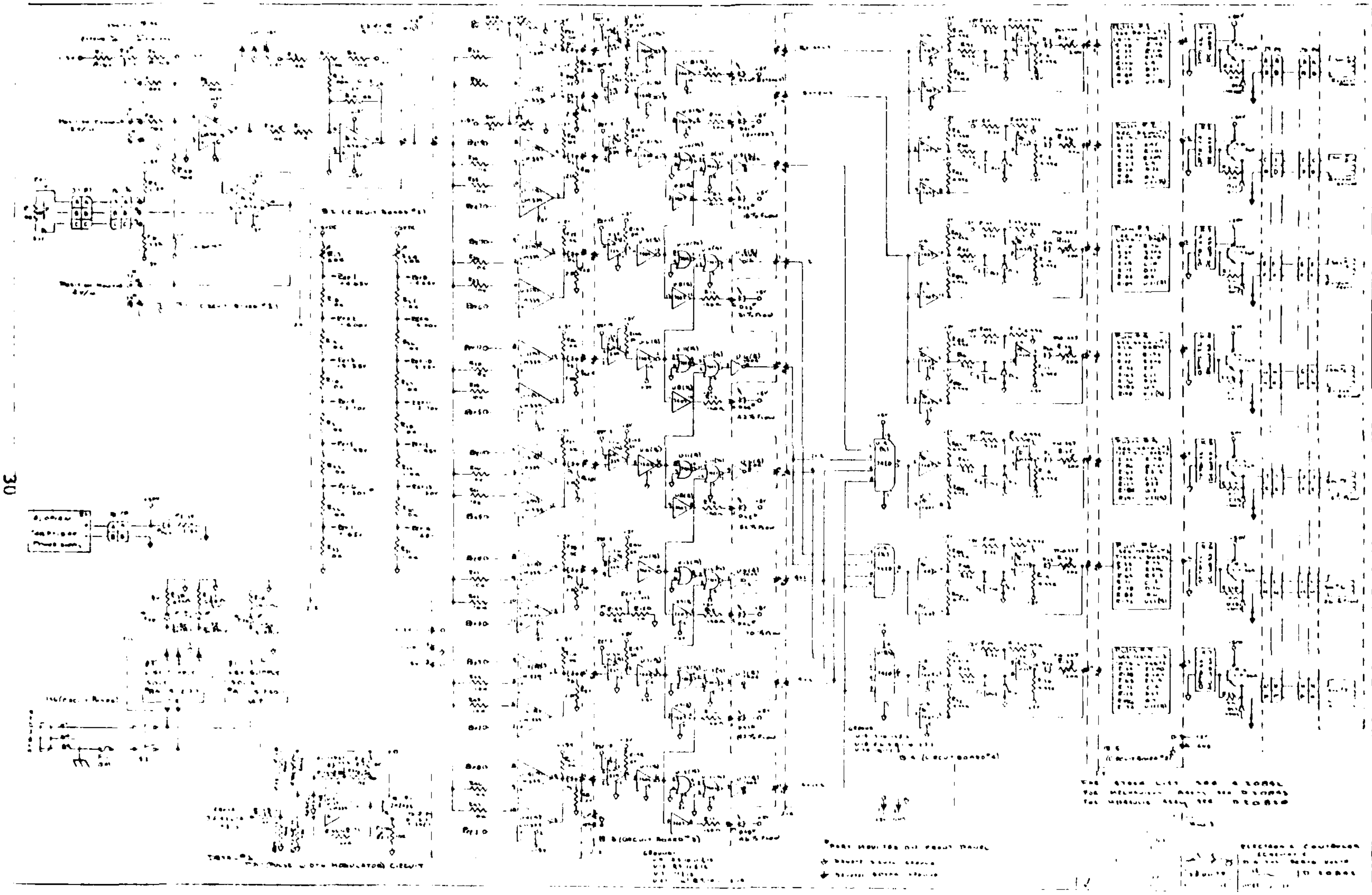


FIGURE 13 Electronic Controller Schematic

SECTION V

EVALUATION TESTING

1. General

The performance of the digital servovalve was evaluated indirectly by measuring the control characteristics of the control system in which the valve was used. The measurements performed on the control system were the same typically used for defining the control characteristics of any electrohydraulic position feedback control system in terms of the input-output performance. This evaluation approach was used because it allowed considering the digital valve in terms of its intended application and in terms of performance characteristics generally used to describe any electrohydraulic control system.

The evaluation tests performed on the evaluation hardware were the following:

1. Static Threshold
2. Dynamic Threshold
3. Linearity
4. Frequency Response
5. Waveform Characteristics
6. Step Response

For the evaluation, four slightly different setups of the test system were used. Configuration A is designated as the normal configuration. This configuration was with the control loop adjusted for a nominal frequency response of 3 Hz. Configuration A_1 was a modification of Configuration A with the loop gain doubled. Configuration B was a modification of Configuration A by the addition of a damping orifice across the actuator drive area to eliminate the small amplitude (less than 1% of the total actuator stroke) limit cycle existing with Configuration A. Configuration B_1 was a modification of Configuration B by the doubling of the loop gain.

The following subsections discuss the test procedure and the results obtained from the tests.

2. Static Threshold

Static threshold is defined as the minimum input change from a zero level which causes a measurable output change. The procedure used to measure static threshold is to apply a slowly increasing input until a measurable output change occurs. The threshold is indicated by the minimum input change which causes the measurable output change.

Figure 14 shows the data recorded in measuring the static threshold for Configuration A. The top data channel shows the input signal applied to the test system. Note that the amplitude of the .3 Hz triangular waveform input increases with increasing time. The bottom data channel of the figure shows the output motion of the test actuator. This channel shows the output limit cycle of the system. The limit cycle has a peak to peak amplitude of .016 inches (which is .34% of the total actuator stroke). The modulation of the limit cycle shows the system response to the test input. The control acuator responded to the test input at the lowest level of input available from the function generator. The lowest available level of input is .004 volts peak to peak (which is .023% of the input for the full actuator stroke). The actual threshold is therefore less than .023% of the maximum input for the control system. This threshold level is quite low. This is a direct result of the effect of the limit cycle on reducing the threshold of the system. The threshold level in terms of the control system input to generate maximum actuator rate is .83%. Relating the threshold to the maximum rate input does not use the actuator stroke to calculate the threshold level, providing an alternative and perhaps more objective indication of the threshold level.

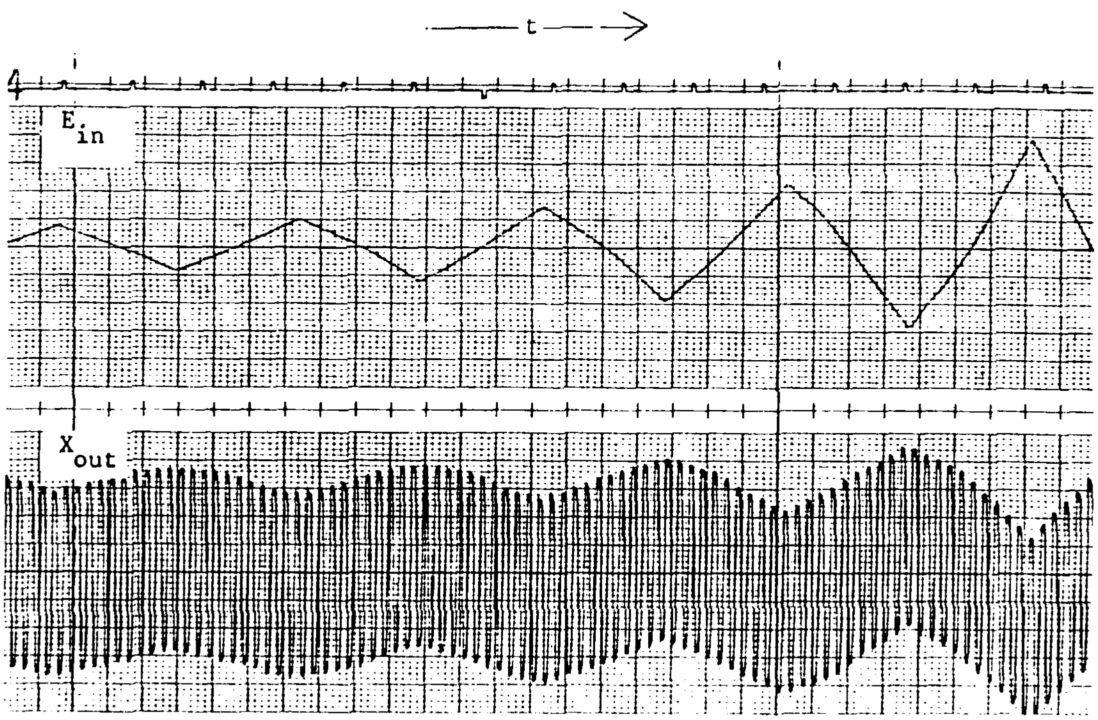
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/11/80

TEST - Static Threshold - Configuration A



Scale: E_{in} = 0.0005 v/div

X_{out} = 0.0005 in/div

t = 10 div/sec

FIGURE 14 Static Threshold - Configuration A

Figure 15 shows the data recorded in measuring the static threshold of Configuration B. Since the limit cycle has been eliminated by the addition of the damping orifice, the output of the actuator is stationary until the actuator responds to the increasing amplitude of the test input. As shown on Figure 15, the actuator starts moving at an input amplitude of .010 volts peak to peak. This corresponds to an input level of .116% of the maximum input to the control system ($\pm$4.3 volts) and 2.083% of the input necessary to generate full rate of the actuator ($\pm$ .24 volts). The threshold of 2.083% of the input to generate maximum actuator rate (and maximum flow from the control valve) is higher than the threshold found on an analog electrohydraulic servovalve. Typical analog electrohydraulic servovalves exhibit a threshold of .5% of the maximum rated current (equivalent to the percentage rating in terms of the maximum rate input voltage for maximum actuator rate). Although the threshold of the digital valve was created in the control electronics and could be reduced, the 2% level is considered representative of the digital servovalve setup in order to prevent both the directional solenoid valve pairs from operating at the same time with zero input level.

3. Dynamic Threshold

The dynamic threshold is defined as the input level required (at a particular frequency) to cause a measurable output level. The procedure used to measure the dynamic threshold is to apply an increasing amplitude sinusoidal input at a frequency of 50% of the bandpass of the actuator. The amplitude of input required to create the measurable output indicates the dynamic threshold. The bandpass of the actuator is defined as the frequency at which the - 3 Db amplitude or 90^{o} phase shift occurs, whichever is lower.

Figure 16 shows the test data recorded in measuring the dynamic threshold of Configuration A. The test frequency is 1.43 Hz. The modulation of the limit cycle envelope is the response of the actuator to the test input. Note that at the lowest amplitude available from

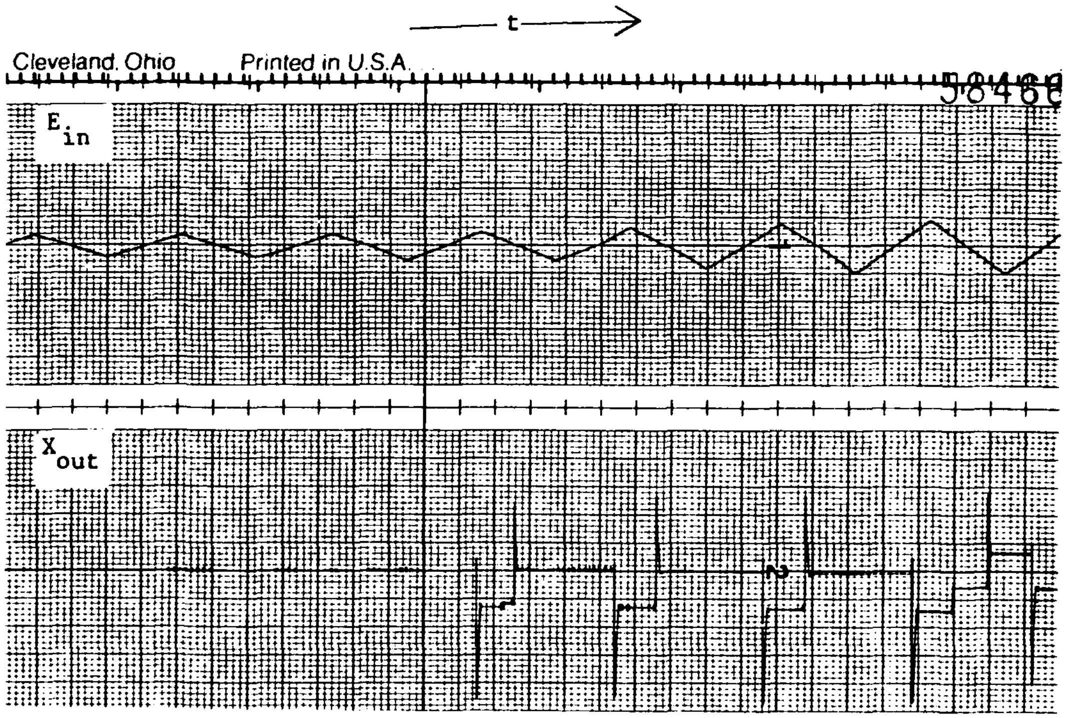
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/10/80

TEST - Static Threshold - Configuration B



Scale: E_{in} = .002 v/div

X_{out} = 0.001 in/div

t = 2 div/sec

FIGURE 15 Static Threshold - Configuration B

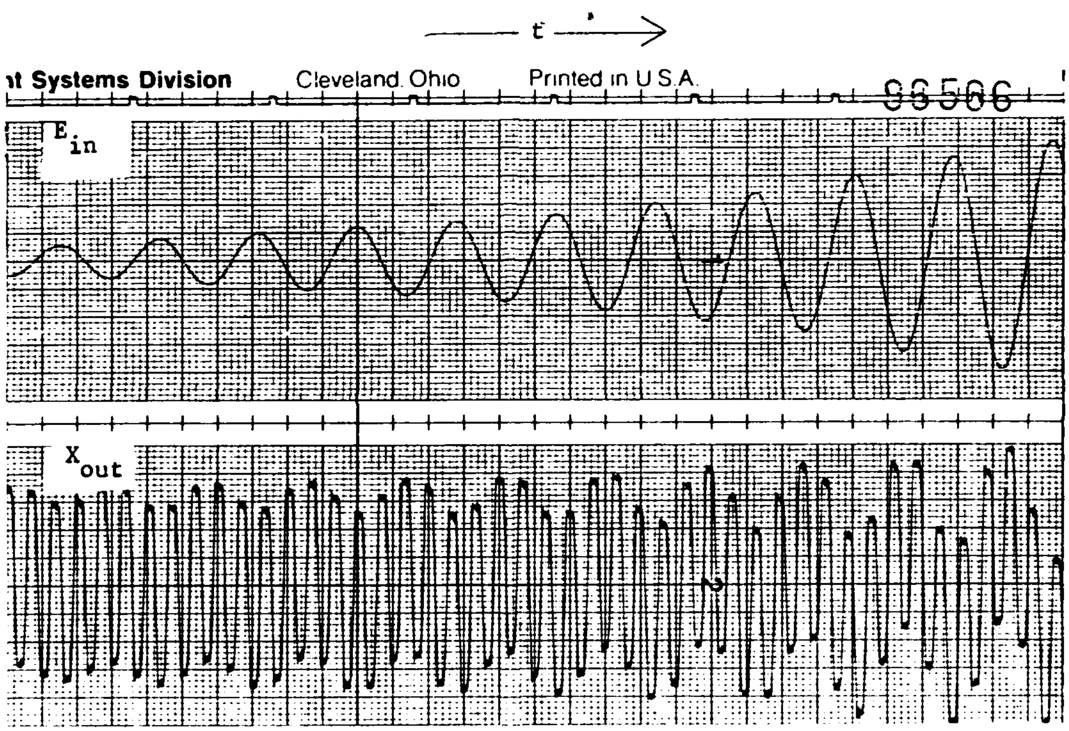
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/11/80

TEST - Dynamic Threshold - Configuration A



Scale: E_{in} = 0.0005 v/div

X_{out} = 0.0005 in/div

t = 20 div/sec

FIGURE 16 Dynamic Threshold - Configuration A the function generator, the actuator output responds to the test input. This is due to the limit cycle effectively reducing the normal threshold characteristic of the control system. For this operating condition, the dynamic threshold is less than .035% of the maximum input level for the system and less than .625% of the input corresponding to maximum rate of the control actuator. Both of these measured values are low and are directly attributed to the effect of the limit cycle on reducing the threshold.

Figure 17 shows the test data recorded in measuring the dynamic threshold of Configuration B. The test frequency is 1.43 Hz and the amplitude of the input is gradually increased with increasing time. Note that the output limit cycle has been damped out and the actuator is initially at rest. The level of input required to cause an output movement is .015 volts peak to peak. This corresponds to .174% of the maximum command input and to 3.125% of the input required to produce the maximum actuator rate. The actuator waveform in response to the low level input reflects the "on - off" characteristic of the solenoid valves as the threshold input level is reached. The initial motion appears one-sided, indicating that only one directional pair of solenoid valves is operating. As the input level continues to increase, the motion of the actuator assumes a more symmetrical character. The actuator motion as presented on Figure 17 reaches a maximum of ± .022 inches or .512% of the maximum actuator stroke.

4. Linearity

The linearity of the control system is defined as the deviation of the output versus the input from a straight line relationship. The procedure used to measure the linearity is to apply an input which is varied from the most negative value to the most positive and back while recording the output position. The linearity is indicated by the maximum deviation of the plotted output vs. the input from a straight line drawn between zero and a point which minimizes the maximum deviation of the plotted curve from the straight line.

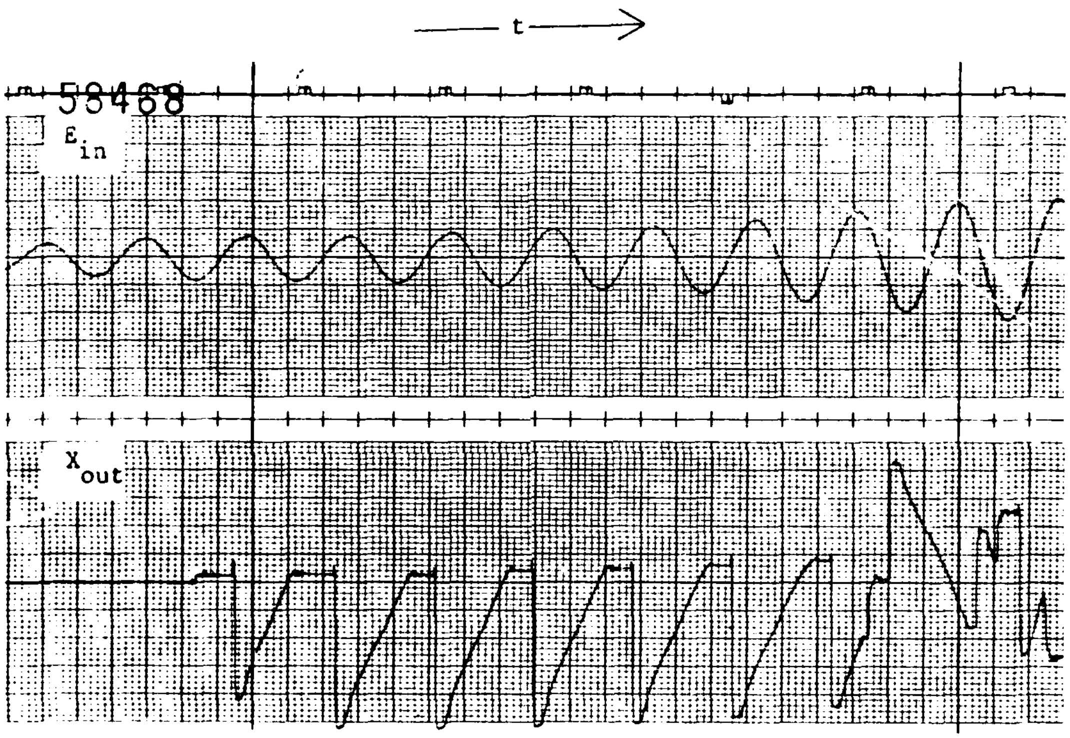
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/10/80

TEST - Dynamic Threshold - Configuration B



Scale: E_{in} = 0.002 v/div

X_{out} = 0.001 in/div

t = 20 div/sec

FIGURE 17 Dynamic Threshold - Configuration B

Figure 18 shows a plot of the linearity curve recorded for Configuration A over the full input level. As shown on Figure 18, the linearity is better than 1% of full scale. Figure 19 shows a plot of the linearity over a range of 10% of full scale. Note the effect of the limit cycle on the width of the output motion trace. The amplitude of the limit cycle shown is .20% of the maximum actuator stroke. Over the 10% of full scale range shown on Figure 19, the linearity deviation from a straight line is less than the amplitude of the limit cycle.

Figure 20 shows a plot of the linearity curve recorded for Configuration B over the full input range. Compared to Figure 18 for Configuration A, the plot of the linearity with the limit cycle damped out shows some hysteresis. The overall linearity is quite similar to that of Configuration A. Figure 21 shows a plot of the linearity curve recorded for Configuration B over a range of 10% of full scale. The amplitude deviation from a straight line shows a repetitive transient motion of the actuator amounting to .046% of the maximum actuator stroke. This is due to the "on-off" operation of the directional solenoids as the error voltage reaches the threshold value as the input changes. The linearity shown on Figure 21 for Configuration B is comparable to that shown on Figure 19 for Configuration A at the same percent range of full scale.

5. Frequency Response

The frequency response of the control system is defined as the amplitude ratio and phase shift of the output relative to the input as a function of frequency. The procedure used to measure the frequency response is to apply a sinusoidal input and record the output of the system in response to the sinusoidal input. The input amplitude used is large enough to minimize the non-linearity distortions of threshold and hysteresis on the output and small enough to avoid saturation of the control system elements within the frequency range of interest. The

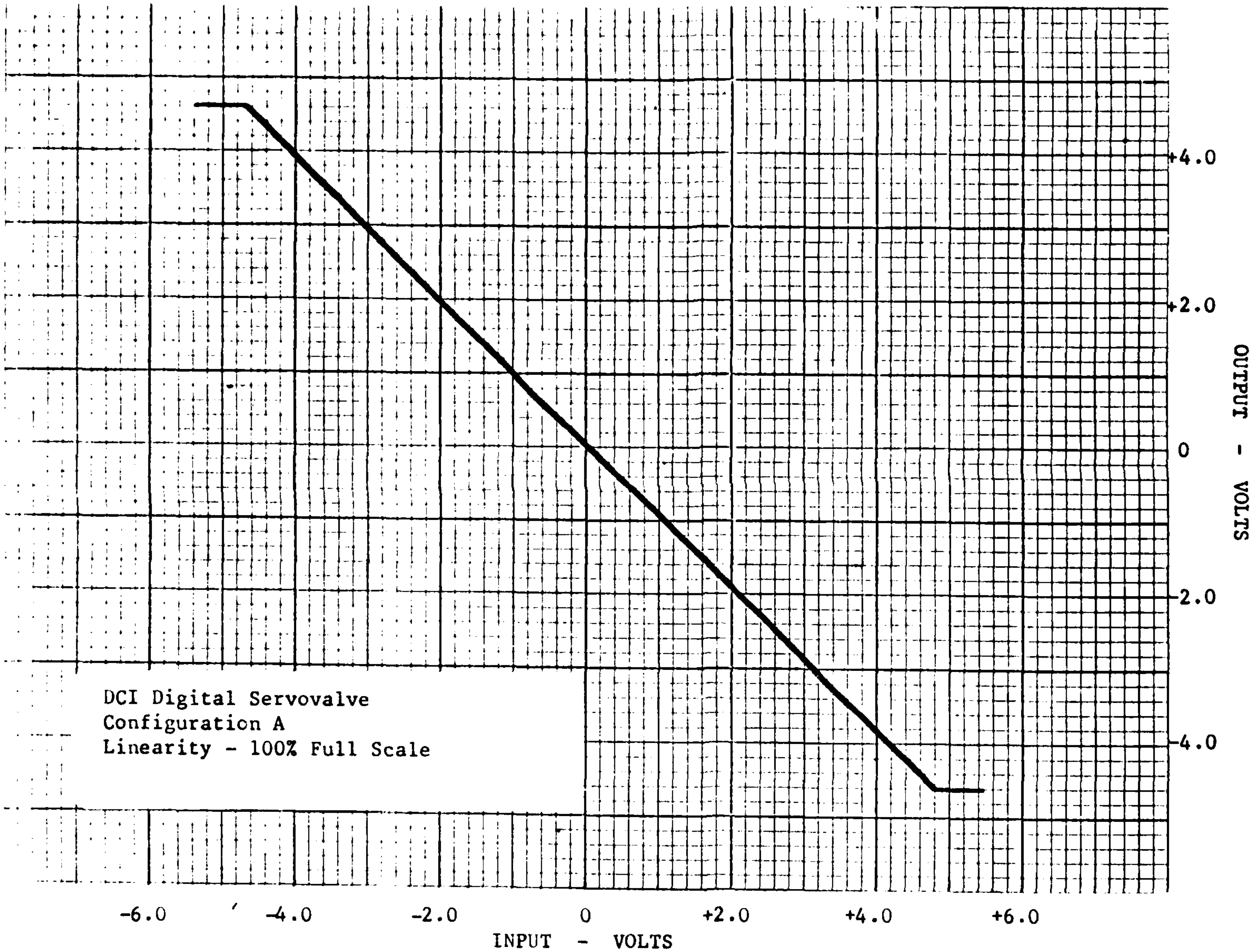


FIGURE 18 Linearity - Configuration A

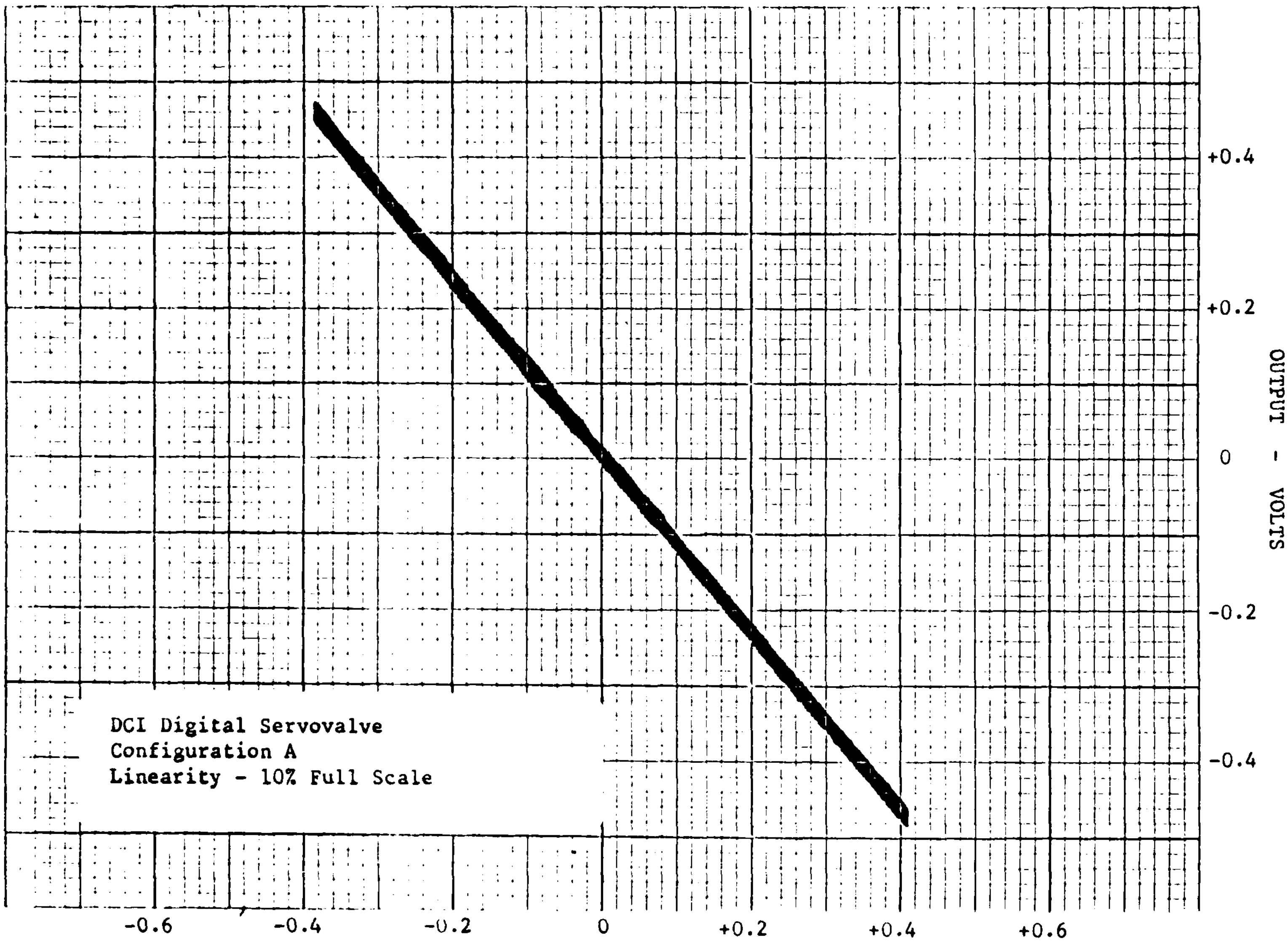


FIGURE 19 Linearity - Configuration A

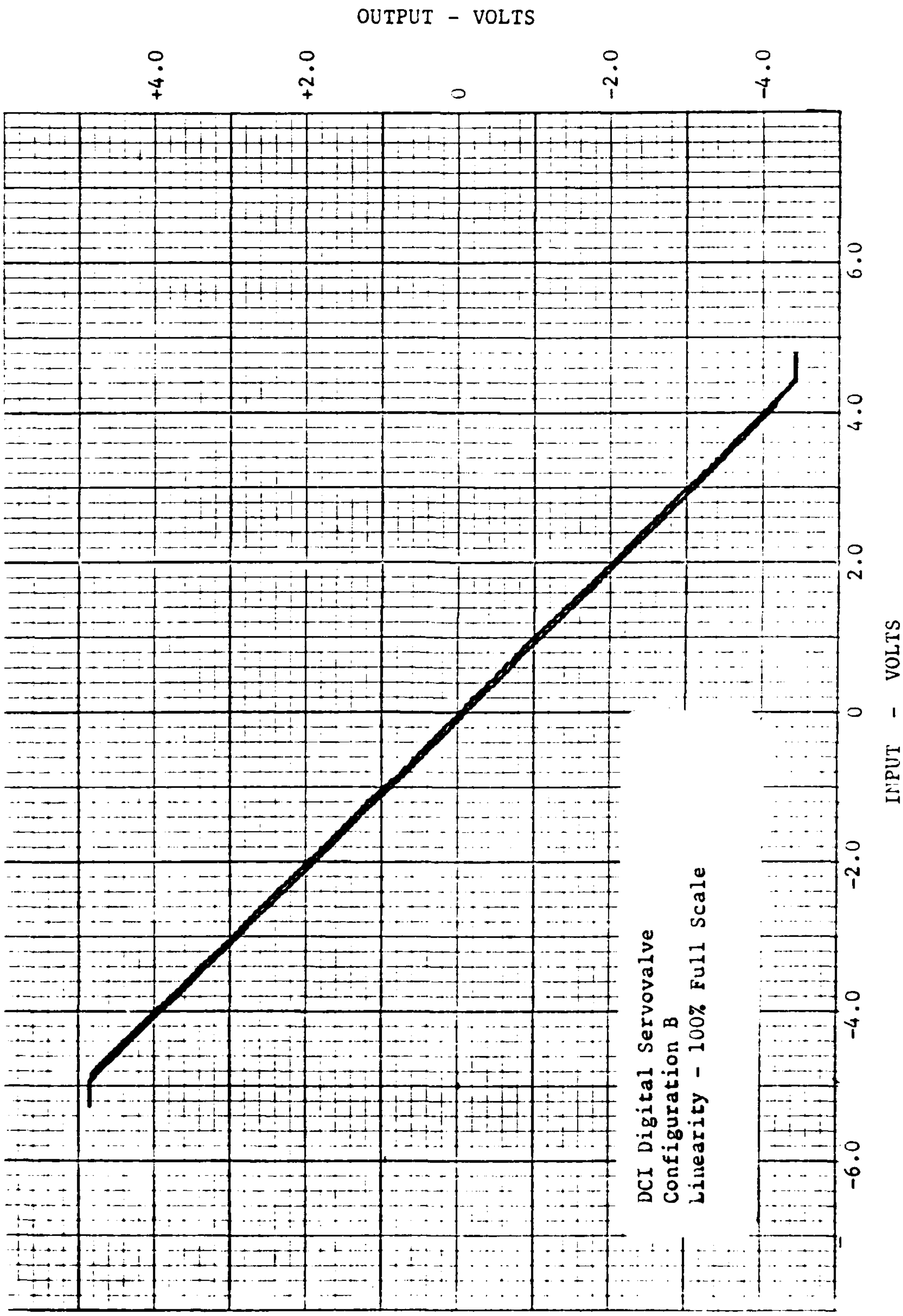


FIGURE 20 Linearity - Configuration B

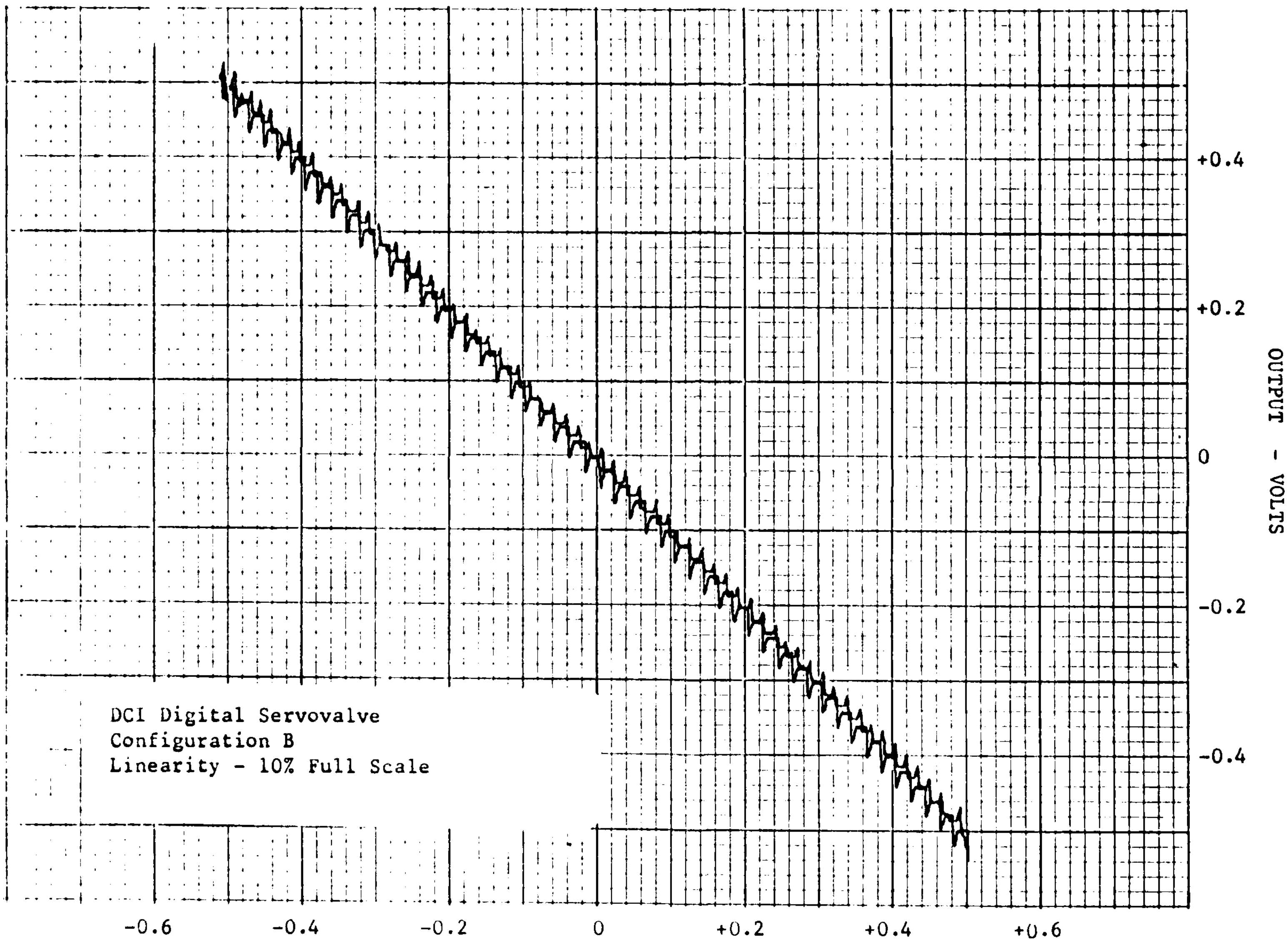


FIGURE 21 Linearity - Configuration B

ratio of the output amplitude to the input amplitude and the output phase angle relative to the input is then plotted as a function of the input frequency.

For the evaluation testing, a Bafco Servo Analyzer and an XYY' Plotter were used to generate the curves for the frequency response. The Bafco Servo Analyzer computes a Fourier Transform for the input and output time response from samples of the response of the system to a sinusoidal input. The analyzer then determines the ratio of the magnitude and relative phase angle of the fundamental frequency of the input and output for each sample of the time response. By varying the input frequency slowly and producing output voltages proportional to the magnitude and phase angle measured for each sample taken, the analyzer automatically generates the desired frequency response plot. Note that sampling characteristics of the analyzer can generate small steps in the plotted response when the sweep rate of the input frequency is not maintained at a very low rate.

Figure 22 is a frequency response plot for Configuration A with an input command of ± 10% of the full scale input. This response plot does theoretically involve rate saturation at frequencies greater than 3 Hz. The response shows a phase lag of 90 degrees at 2.8 Hz and an amplitude response which is 3 Db down at 3.2 Hz. The irregularities in the amplitude and phase plots are due to the combination of the sampling effect of the analyzer (for the small steps) and the waveform distortion of the test system at specific frequencies. No peaking of the amplitude response is evident.

The frequency response of the test system (as shown in Figure 22), is set lower than that allowed by the measured .015 second time delay of the solenoid valves. This is a result of the installed response time of the solenoid valves differing from that measured on each solenoid valve installed in a test circuit for evaluation.

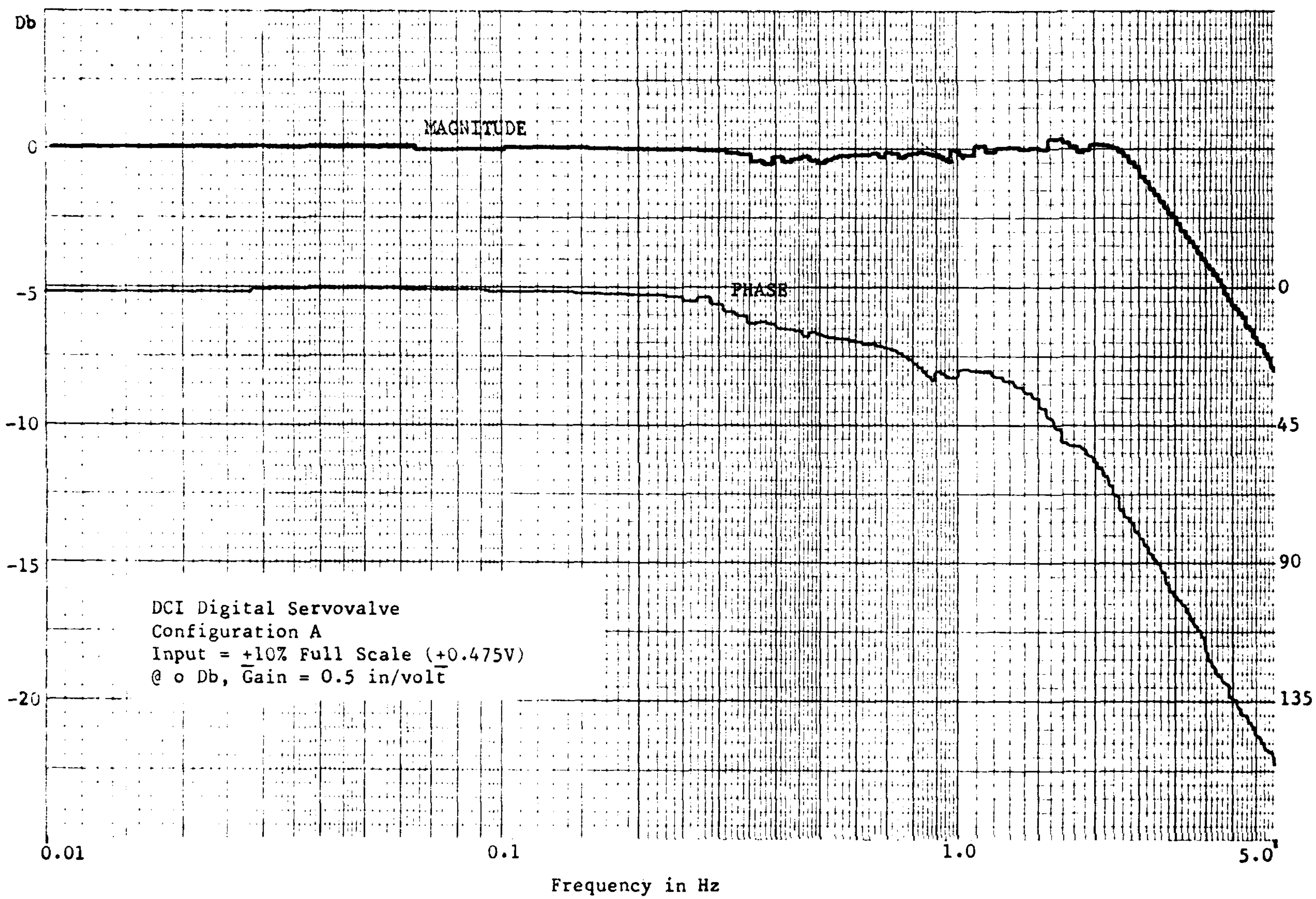


FIGURE 22 Frequency Response - Configuration A

As measured when installed in the test actuator, the solenoid valve time delay (from application of a step input to start of the motion of the actuator) was on the order of .050 seconds. This increase in the time delay for the solenoid valves (from .015 seconds) is attributed to the "pilot operated" characteristics of the solenoid valves. When originally tested, the solenoid valves were evaluated with a differential pressure of 3000 psi and a flow restricting orifice downstream of the solenoid valve (to limit the flow through the solenoid valve to the design flow of the digital valve). As installed in the test actuator, the solenoid valves are operated with differential pressures as low as 500 psi (cylinder port to return) and the flow restricting orifices are positioned upstream of the directional solenoid valves. This difference in operating conditions is considered to be the reason for the measured difference in time delay values. It is expected that the use of direct operating (rather than pilot operated) solenoid valves and/or downstream (rather than upstream) flow modulation orifices would produce shorter operational time delay values.

Figure 23 shows the frequency response of Configuration B with an input of ± 10% of the full scale. The response of the system with the orifice added to damp the limit cycle is similar to the response of Configuration A with the same test input. The 90 degree phase angle occurs at 2.6 Hz and the -3 Db response frequency occurs at 3.4 Hz. A slight amplitude peaking occurs with Configuration B. A comparison of Figure 22 and 23 indicates that the orifice used to damp the limit cycle has a negligible effect on the large input amplitude frequency response.

Figure 24 shows the frequency response of Configuration A with a ± 5% full scale input. The amplitude is low enough that rate saturation of the output motion does not effect the response curves. Note that the amplitude curve exhibits a 1½ Db peak at 3.2 Hz and a corresponding 90 degree phase lag at that frequency. This frequency response is consistent with the effect

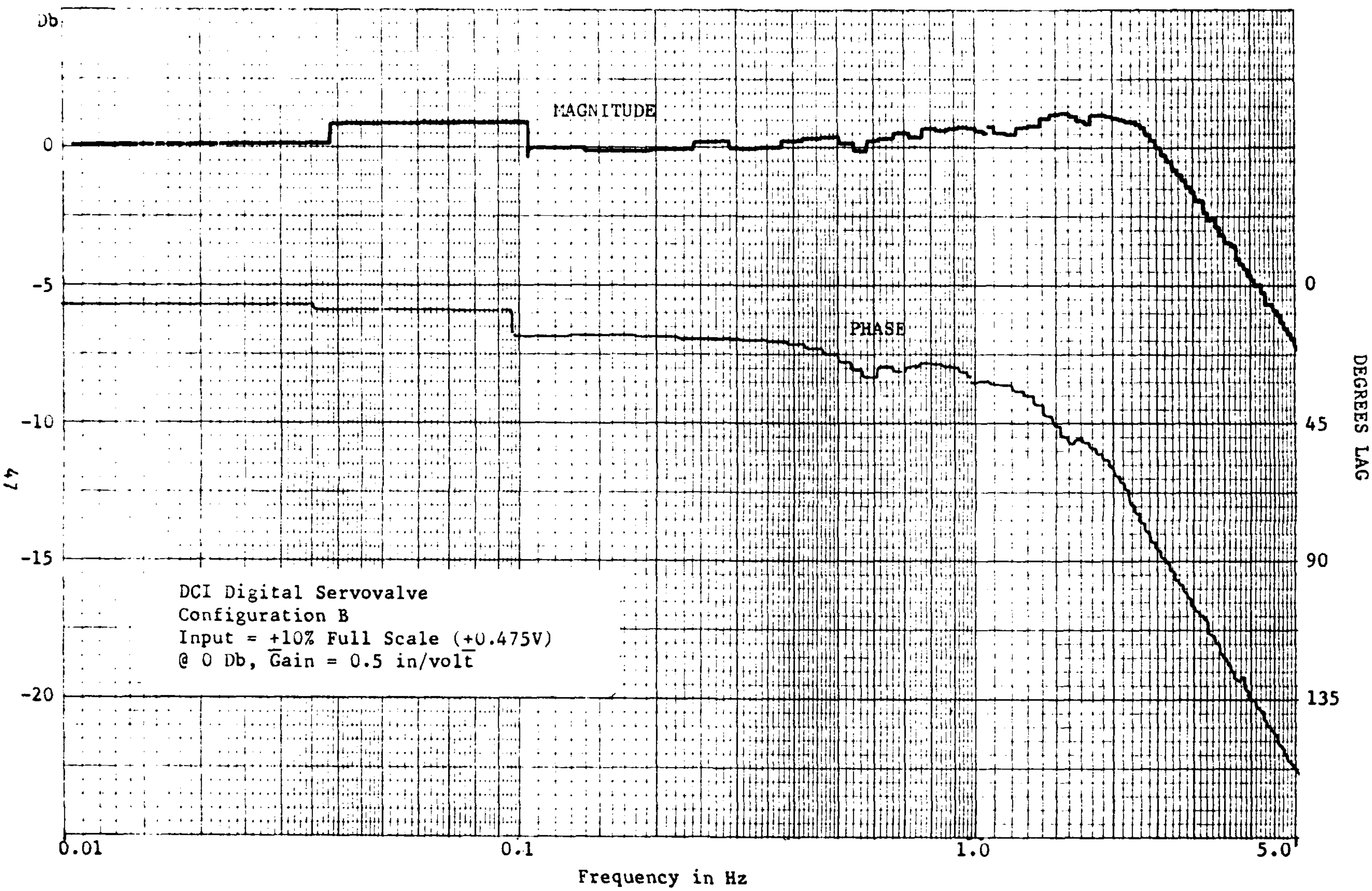


FIGURE 23 Frequency Response - Configuration B

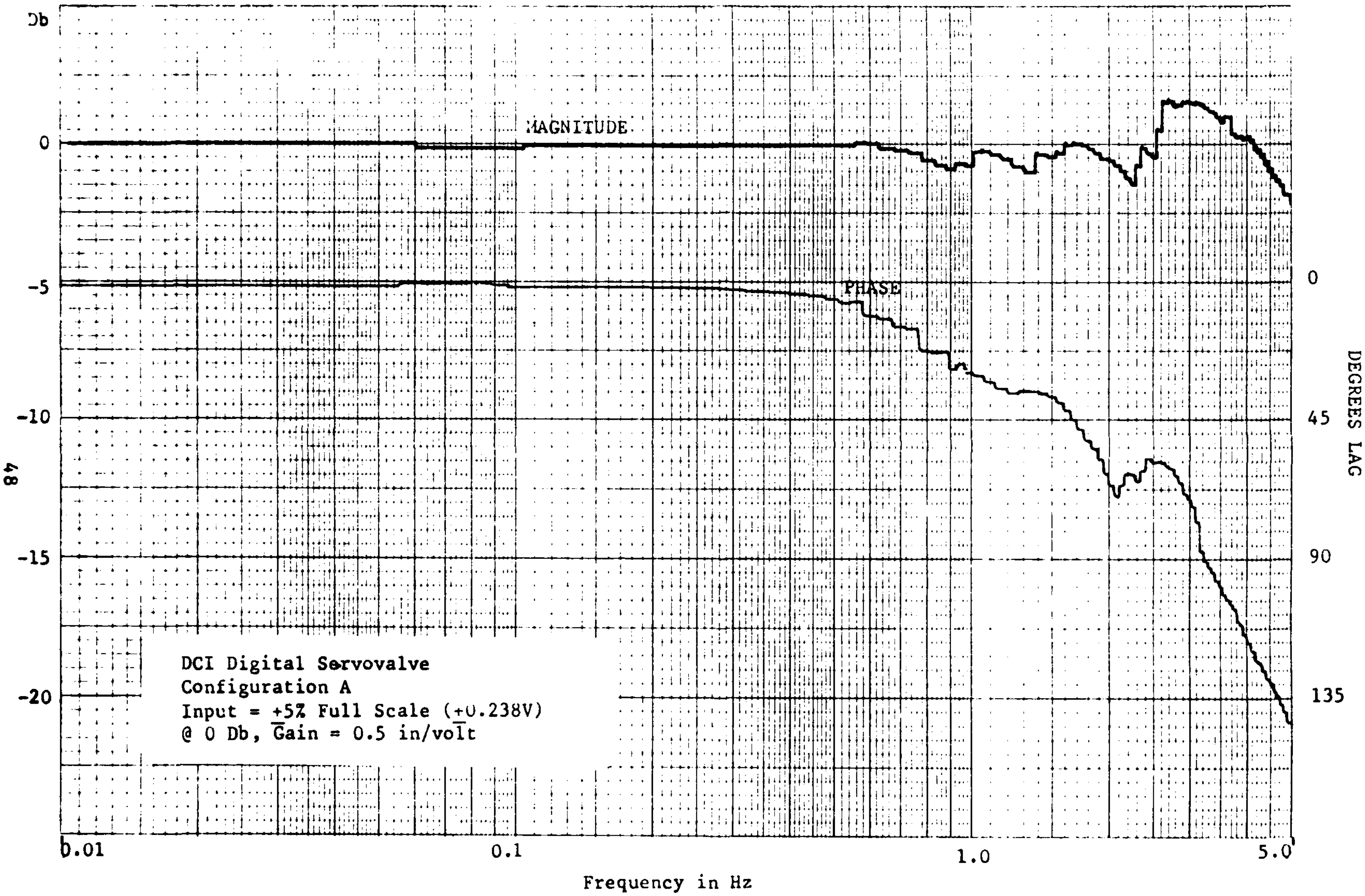


FIGURE 24 Frequency Response - Configuration A

of the time lag as discussed previously in Section III. The 3.2 Hz peak frequency corresponds to a time delay of .047 seconds.

Figure 25 shows the frequency response of Configuration B with a ± 5% full scale input. The response exhibits an amplitude peak of 1 Db at 2.2 Hz and a 90 degree phase lag at 3.1 Hz. The response curves exhibit some irregularities, particularly at 2 Hz. This probably is due to the waveform distortion of the output signal at that particular frequency. The response curves of Figure 25 in general resemble the response curves of Configuration A for the same test condition. The amplitude of peaking is somewhat lower as is the frequency at which the amplitude peak occurs. The slight difference in the response characteristics between Configuration A and Configuration B are attributed to the effect of the damping orifice on the flow (from the servovalve) available to move the actuator.

For both Figures 24 and 25, the flow saturation limit for the digital servovalve does not enter into the frequency response. At a ± 5% peak output displacement, the available flow from the servovalve will allow unsaturated operation up to 6 Hz.

Since the response of the control system attenuates at the same rate as the attenuation that would be caused by rate saturation (20 Db/decade) and the attenuation starts at a frequency below 6 Hz, no rate saturation effect on the response is possible.

Figure 26 shows the frequency response of Configuration A at an input level of ± 2% full scale. This is a low input amplitude and is indicative of the systems small signal response capability. The response as shown on Figure 20 shows smooth amplitude and phase response to 3 Hz. At this frequency, the amplitude and phase curves exhibit a jump characteristic, probably associated with the waveform characteristics of the system output at 3 Hz. This irregularity appears to some extent in the larger signal response measurement

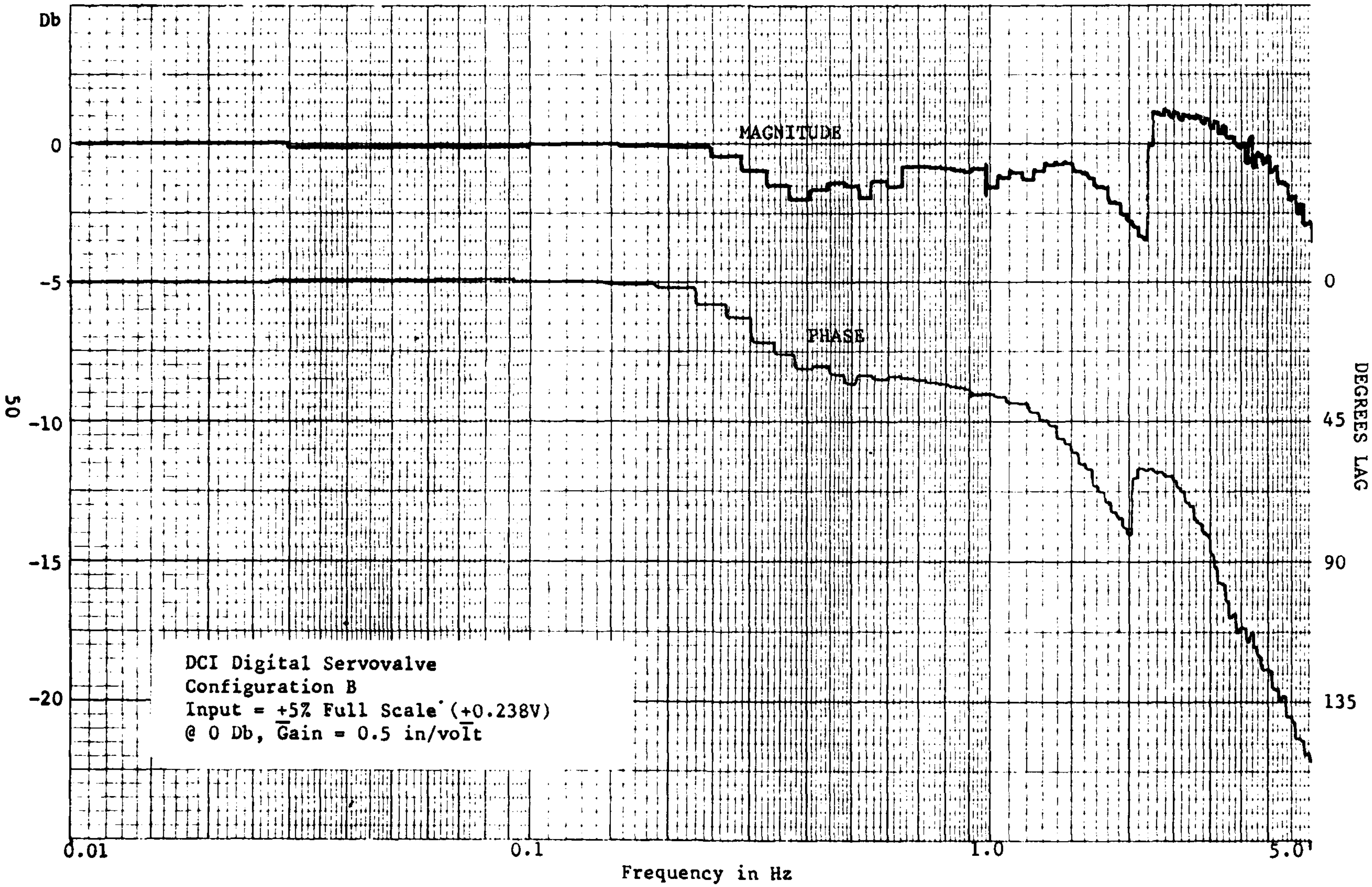


FIGURE 25 Frequency Response - Configuration B

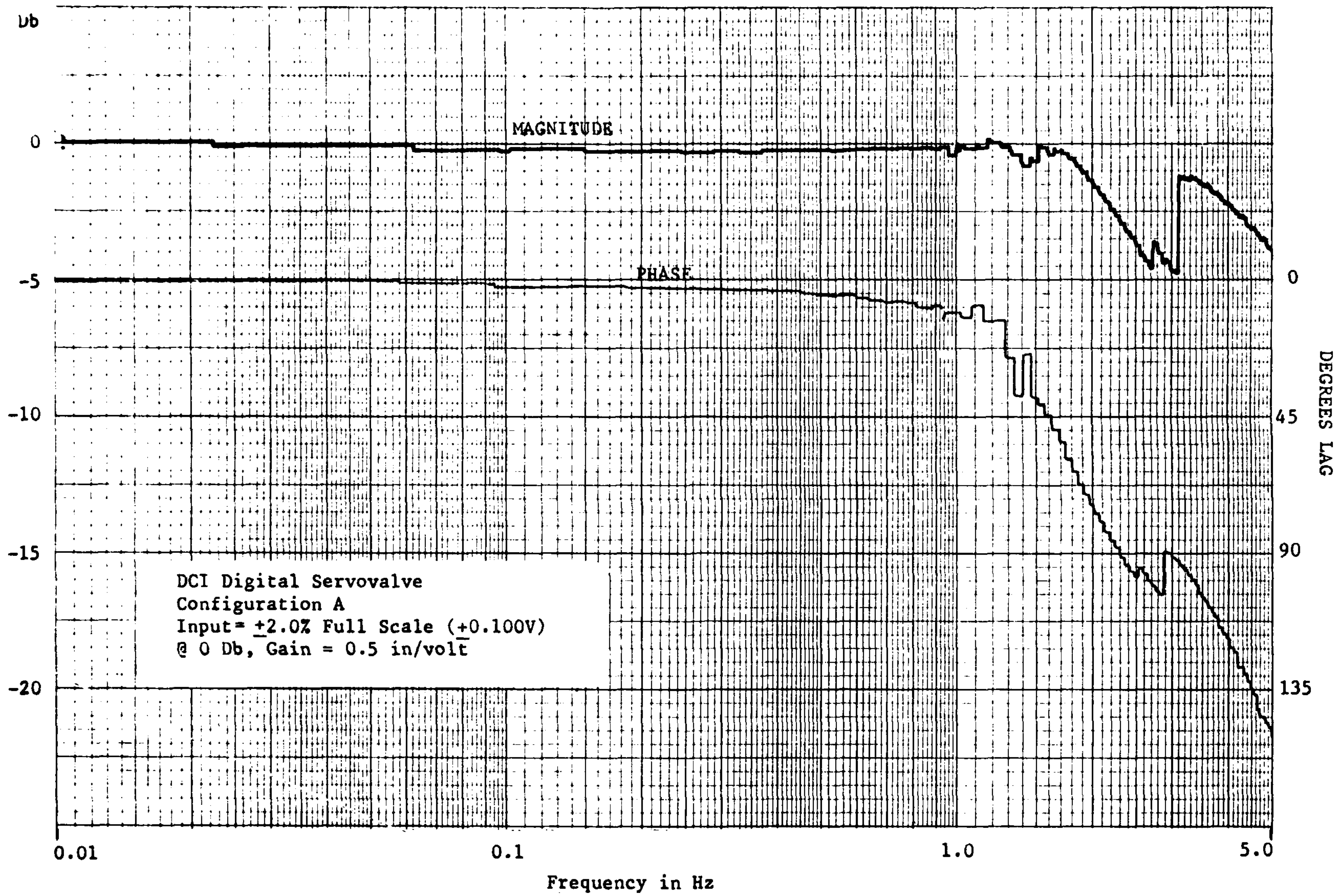


FIGURE 26 Frequency Response - Configuration A

shown previously on Figure 24, although at a slightly lower frequency (2.1 vs 3 Hz). The response is -3 Db at both 2.2 Hz and 4.5 Hz on Figure 26. The phase angle passes through -90 degrees both at 2.3 Hz and 3 Hz.

Figure 27 shows the frequency response of Configuration A with the forward loop gain doubled, changing the Configuration A to Configuration A1. The frequency response exhibits a 6 Db peak at 4.3 Hz and a 90 degree phase lag at the same frequency. The peak resembles that associated with the 4 Db gain margin for a simple actuator and digital servovalve, as described in Section III. This is probably the upper limit on the loop gain setting for the particular test hardware.

Figure 28 shows the frequency response of Configuration B with the damping orifice installed across the actuator drive area. The response curves are fairly smooth, showing only a little irregularity compared to the Configuration A response. The response does attenuate starting at a lower frequency than that of Configuration A. This is caused by the reduction of the effective flow gain of the valve due to the orifice installed across the actuator drive area.

Figure 29 shows the frequency response of Configuration B with the forward loop gain doubled. This particular configuration is designated as B1. The input level is maintained at $\pm$ 2% of the full scale input. The response curves are somewhat irregular, indicating some output distortion at specific frequencies. The amplitude curve peaks at 4.2 Hz. The phase curve reaches -90 degrees at the same frequency. The damping used with the configuration appears to have little effect on the response at high frequencies. The Configuration A1 response above .5 Hz is quite similar (Reference Figure 27) to that of Figure 29. The irregularities in the response of Configuration B1 that occur below .5 Hz can be attributed to the damping orifice. The orifice affects the available flow from the digital valve at small flow demand conditions and causes waveform distortion.

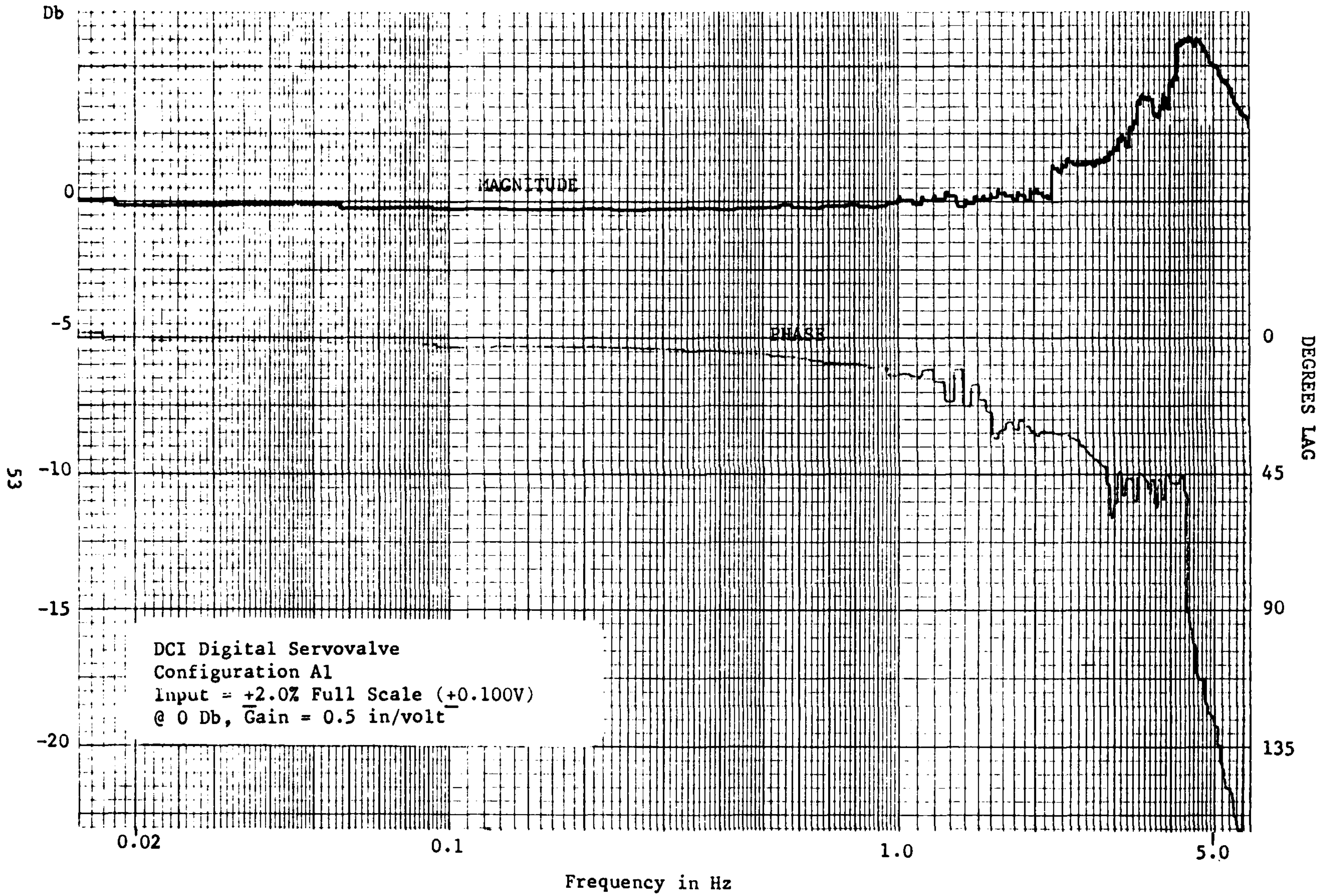


FIGURE 27 Frequency Response - Configuration A1

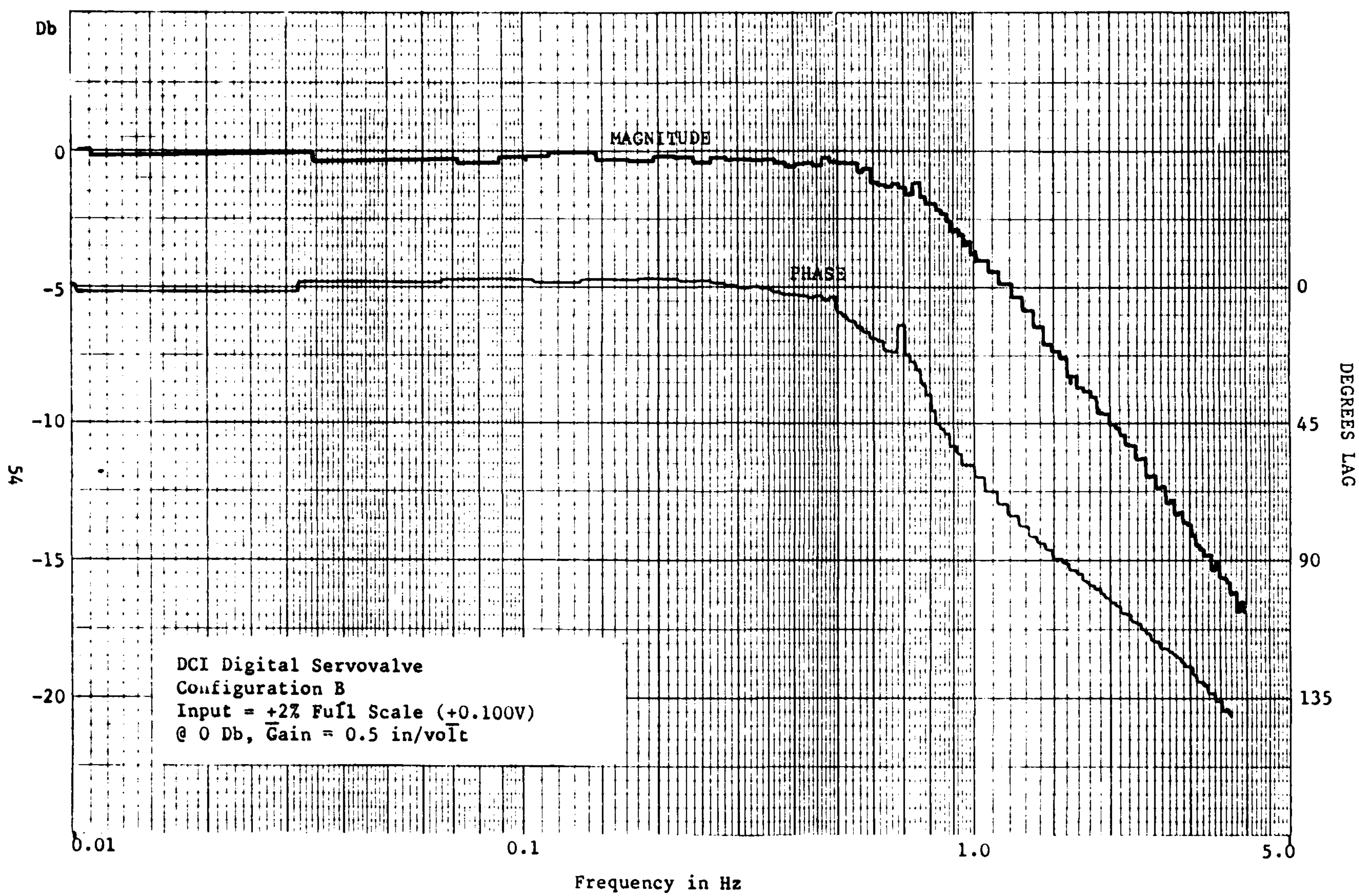


FIGURE 28 Frequency Response - Configuration B

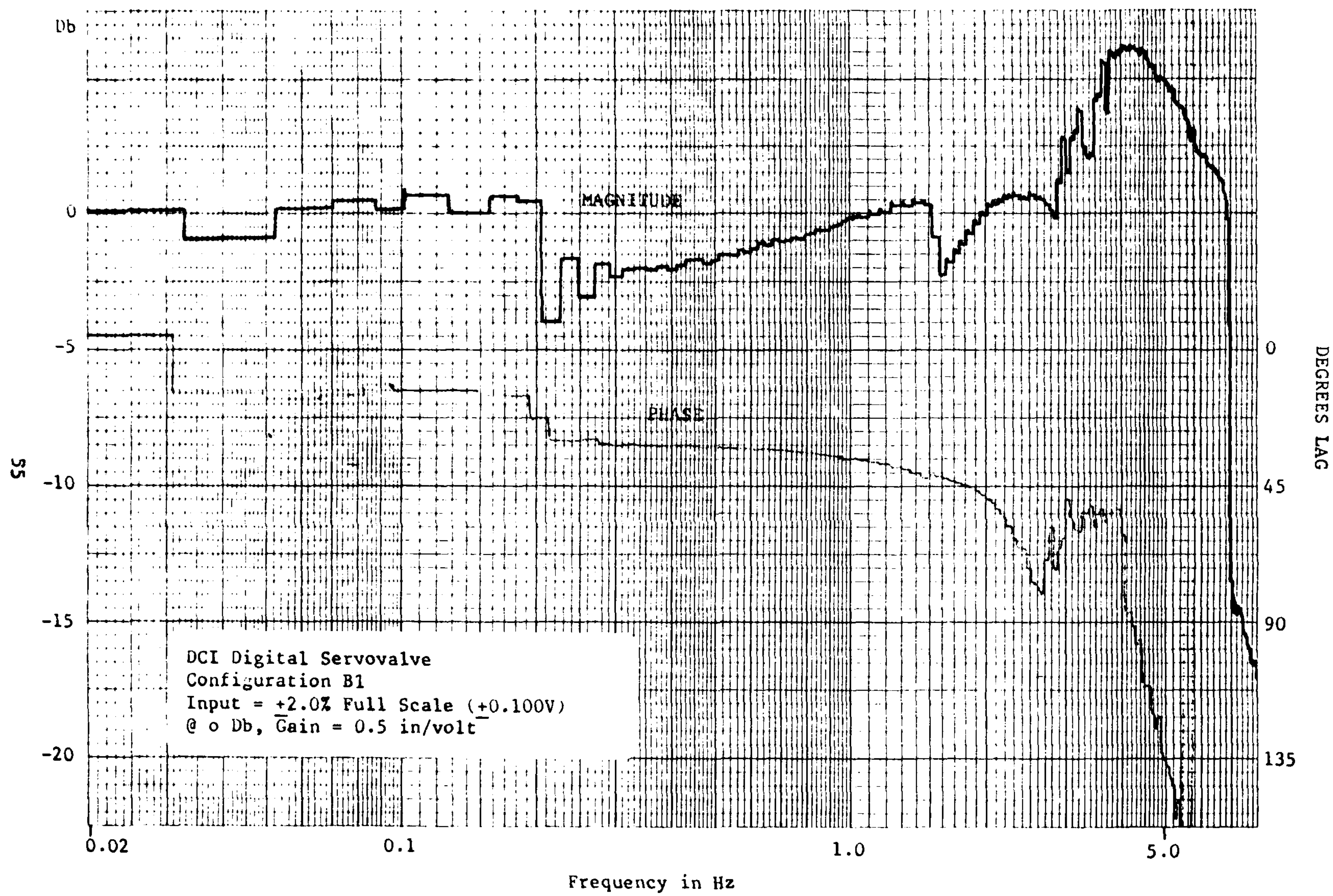


FIGURE 29 Frequency Response - Configuration B1

6. Waveform Characteristics

To indicate the distortion characteristics of the control system output in response to a sinusoidal input, chart recordings at .3 Hz, 1.5 Hz and 3.0 Hz were recorded. These frequencies correspond to 10%, 50% and 100% of the configuration bandpass, respectively. At each frequency three different input levels of ± 2%, ± 5% and ± 10% were used. Both Configuration A and B waveform characteristics were recorded. In addition, in order to demonstrate the amplitude effect on the output waveform of the system at a specific frequency, Configuration A and B's output with an increasing amplitude 1 Hz sinusoidal input was recorded.

Figure 30 shows the output waveform of Configuration A with a ± 10% of full stroke input at a frequency of .3 Hz. The output waveform shows little distortion. Note that the input and output are 180 degrees out of phase as recorded at this frequency. This corresponds to a control system phase lag of zero degrees. A small amount of limit cycle motion at the peaks of the sine wave appears on the recorded waveform. Figure 31 shows the output waveform of Configuration A at an input of ± 10% of full stroke input at a frequency of 1.5 Hz. The waveform resembles the input with some minor distortion. Note that some phase shift between the input and output at this frequency is apparent from Figure 31. This is a reflection of the phase angle characteristics of the frequency response of the control system. No limit cycle at the peaks of the sinusoid is evident at this input frequency. Figure 32 shows the output waveform of Configuration A with an input of ± 10% of full stroke input at a frequency of 3 Hz. This particular frequency is the bandpass limit frequency at which the output of the system lags the input by 90 degrees. Figure 32 shows the 90 degrees control system phase shift (from the original 180 degrees out-of-phase relationship between the input and output signals).

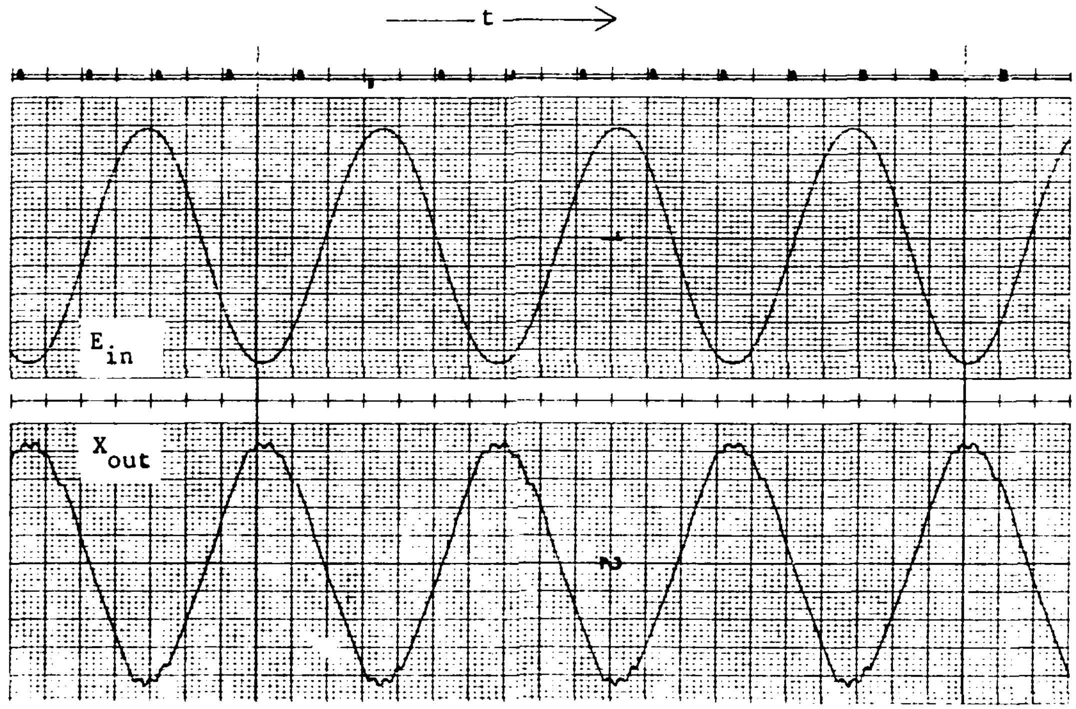
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/8/80

TEST - Input-Output Waveform - Configuration A
(@ 0.3 Hz, $\pm$10.0% Full Stroke $\pm$0.475V)



Scale: E_{in} = 0.020 v/div
X_{out} = 0.010 in/div
t = 10 div/sec

FIGURE 30 Input-Output Waveform - Configuration A
(@ 0.3 Hz, $\pm$10.0% F.S.)

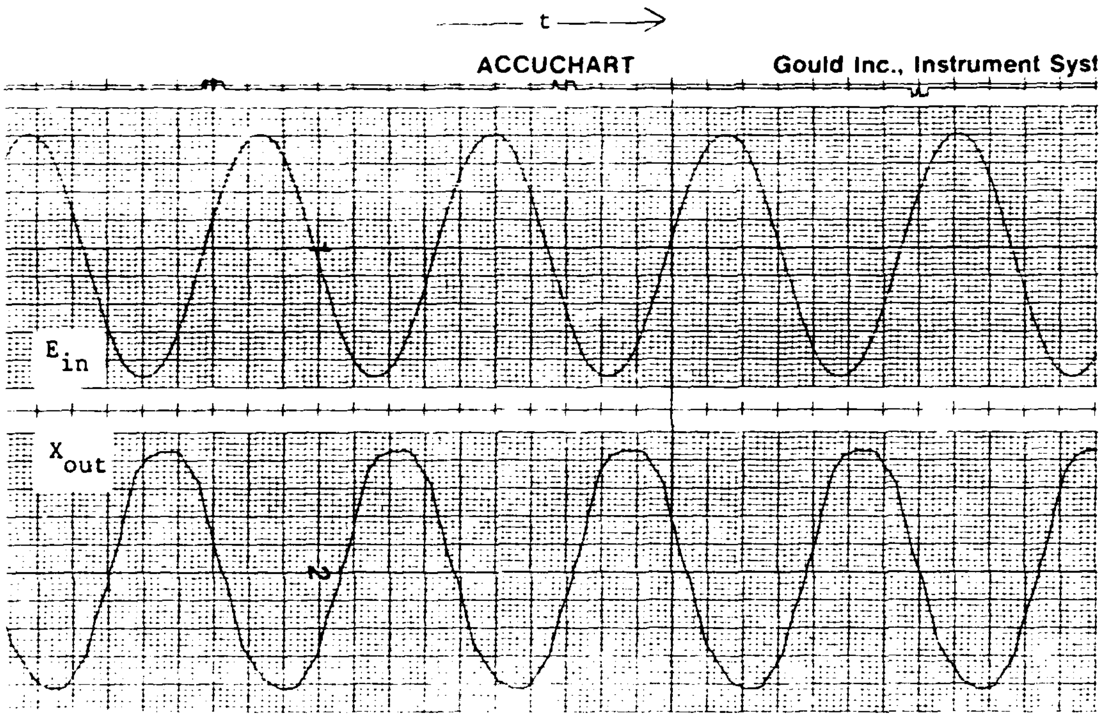
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/8/80

TEST - Input-Output Waveform - Configuration A (@ 1.5 Hz, ±10.0% Full Stroke ±0.475V)



Scale: E_{in} = 0.020 v/div

X_{out} = 0.010 in/div

t = 50 div/sec

FIGURE 31 Input-Output Waveform - Configuration A (@ 1.5 Hz, ±10.0% F.S.)

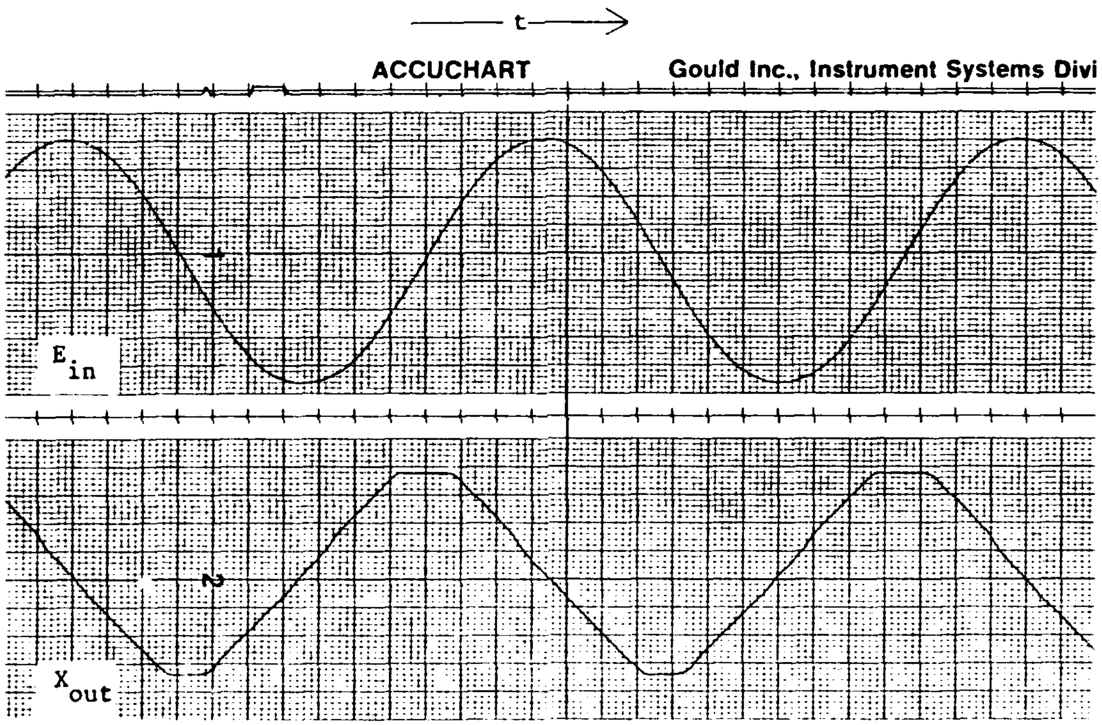
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/8/80

TEST - Input-Output Waveform - Configuration A (@ 3.0 Hz, ±10.0% Full Scale ±0.475V)



Scale: E_{in} = 0.020 v/div

X_{out} = 0.010 in/div

t = 200 div/sec

FIGURE 32 Input-Output Waveform - Configuration A (@ 3.0 Hz, ±10.0% F.S.)

At this input level of ± 10% of the maximum input, the highest frequency at which the servovalve flow can maintain the commanded output motion is 3 Hz. Above this frequency, the output amplitude attenuates because of the flow limit of the servovalve. Figure 32 shows the onset of rate saturation on the output motion of the control system, as indicated by the output motion waveform changing from a sinusoidal motion to a triangular motion.

Figure 33 shows the output waveform of Configuration A with an input of ± 5% of full stroke input at a frequency of .3 Hz. The output closely resembles the input waveform with the addition of some low amplitude modulation due to the Configuration's limit cycle. Note that the output is exactly 180 degrees out of phase with the input. Figure 34 shows the system output waveform with a ± 5% of full scale input at a frequency of 1.5 Hz. The output waveform shows little distortion. Note that the output is lagging the initial 180 degree out of phase relationship.

Figure 35 shows the output waveform of the control system with a ± 5% of full stroke input at a frequency of 3 Hz. Some distortion of the output at the waveform peaks is evident. This frequency is well below the frequency at which rate saturation affects the output motion of the system at the ± 5% full scale output amplitude. The phase relationship between the output and the input waveform shows a 90 degree phase shift at this frequency. This is consistent with the bandpass characteristics of the control system and the phase shift previously measured for the ± 10% of full scale input.

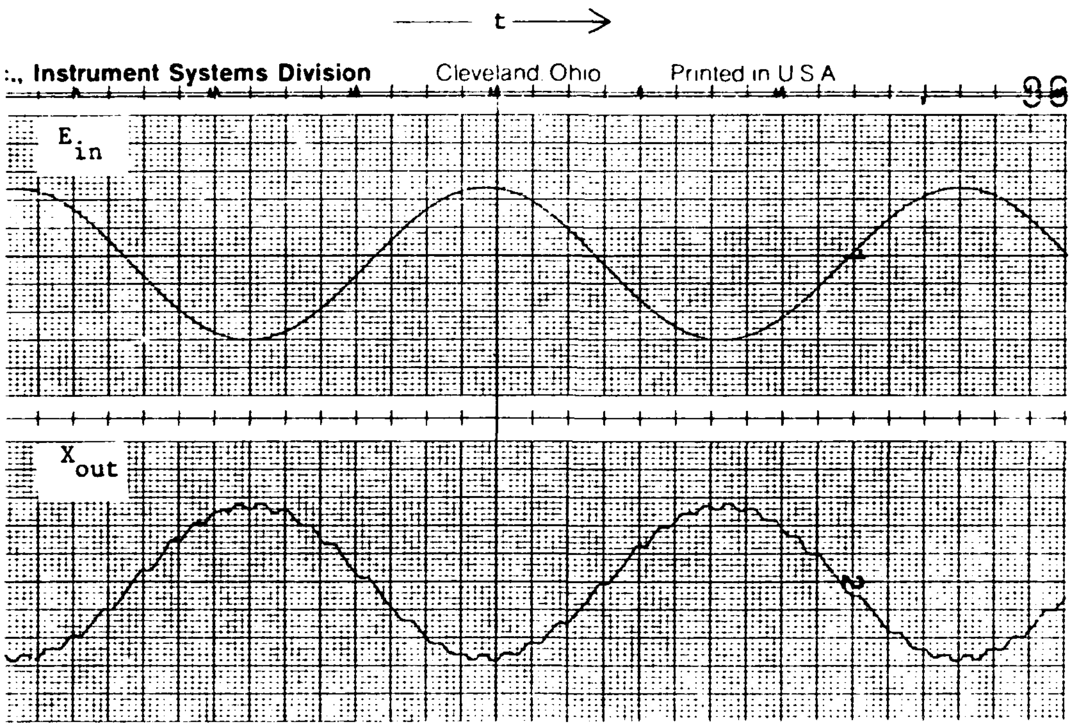
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/7/80

TEST - Input-Output Waveform - Configuration A (@ 0.3 Hz, ±5.0% Full Stroke ±0.238V)



Scale: E_{in} = 0.020 v/div
X_{out} = 0.010 in/div
t = 20 div/sec

FIGURE 33 Input-Output Waveform - Configuration A (@ 0.3 Hz, ±5.0% F.S.)

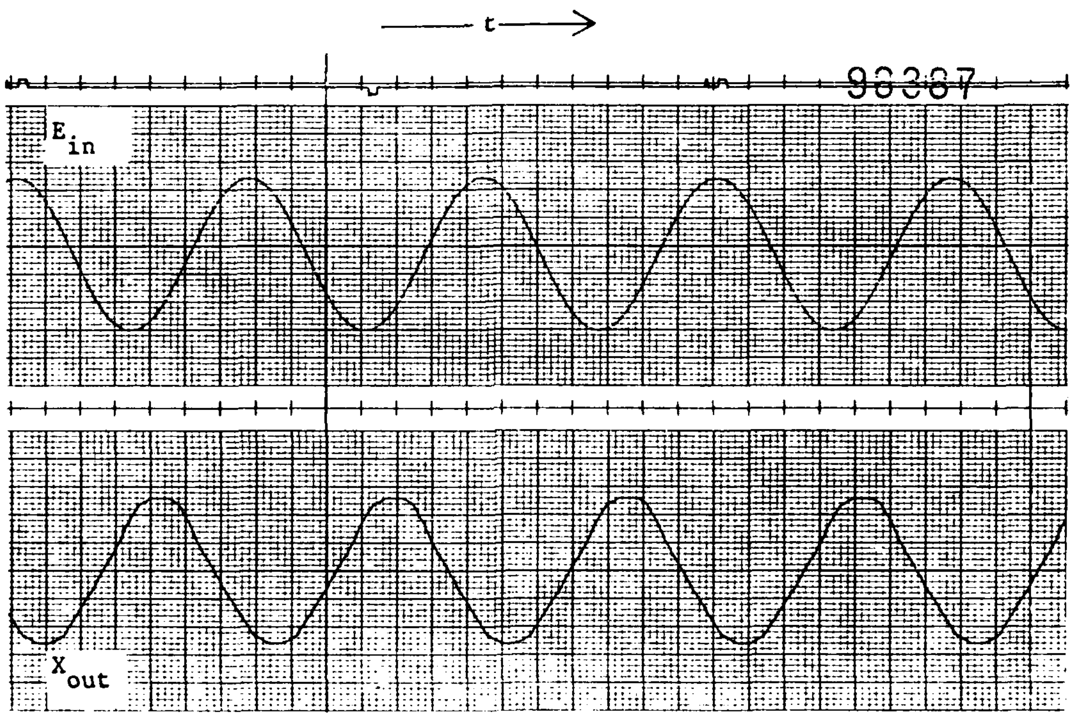
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/7/80

TEST - Input-Output Waveform - Configuration A (@ 1.5 Hz, ±5.0% Full Stroke ±0.238V)



Scale: E_{in} = 0.020 v/div

X_{out} = 0.010 in/div

t = 50 div/sec

FIGURE 34 Input-Output Waveform - Configuration A (@ 1.5 Hz, ±5.0% F.S.)

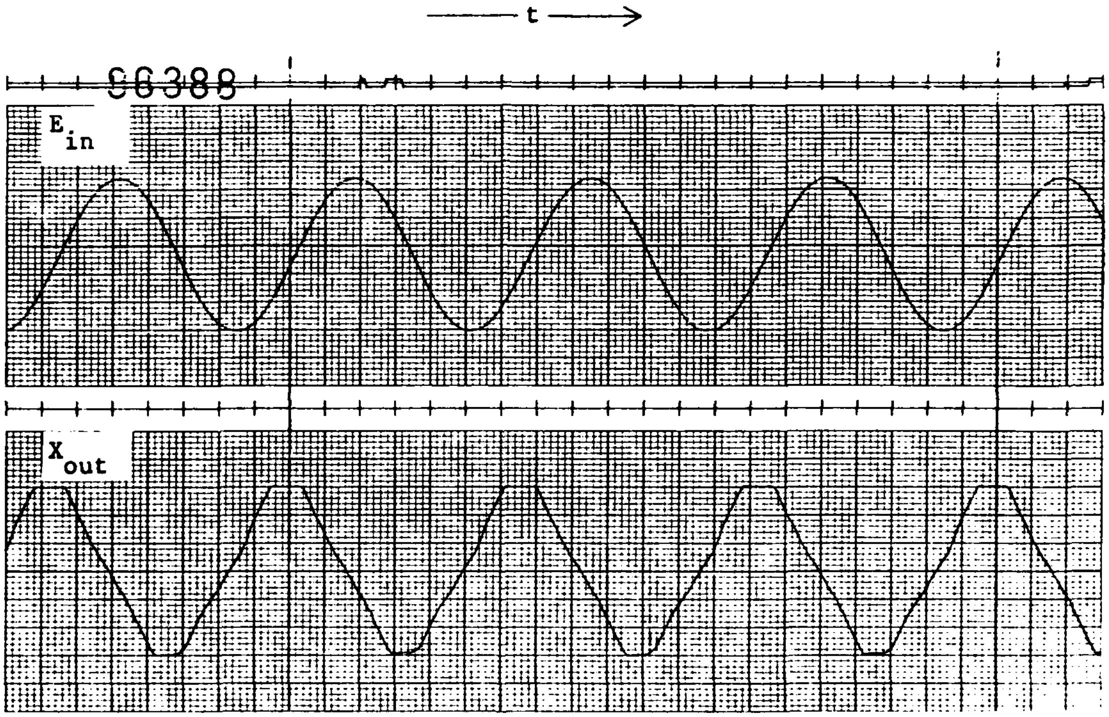
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/7/80

TEST - Input-Output Waveform - Configuration A (@ 3.0 Hz, ±5.0% Full Stroke ±0.238V)



Scale: E_{in} = 0.020 v/div

X_{out} = 0.010 in/div

t = 100 div/sec

FIGURE 35 Input-Output Waveform - Configuration A (@ 3.0 Hz, ±5.0% F.S.)

Figure 36 shows the output waveform of Configuration A with a ± 2% of full stroke input at a frequency of .3 Hz. The output motion resembles the input waveform with the addition of the low amplitude limit cycle motion at a frequency of 3 Hz. The input and output motion are 180 degrees out of phase (corresponding to a control system phase lag of zero degrees).

Figure 37 shows the output waveform at a 2% of full stroke input and 1.5 Hz. The output waveform shows some distortion at the peaks of the sinusoidal motion. As with the 10 and 5 percent input levels, the output motion signal exhibits a phase shift of the output relative to the normal 180 degree out of phase relationship. Figure 38 shows the output waveform of Configuration A with ± 2% of full stroke input at a frequency of 3 Hz. The output motion is delayed 90 degrees relative to the normal 180 degree relationship between input and output. The output waveform exhibits some distortion in terms of the rounding of the peaks of the sinusoidal output motion.

Figure 39 illustrates the amplitude dependency of the output waveform distortion at an input frequency of 1 Hz. The amplitude of input is varied from 3 to 30% of the maximum input level. Note that the output waveform shows a rate limit characteristic at the maximum input amplitude. This figure illustrates the type of output distortion encountered with the digital valve flow characteristics from a low level to a high level input signal.

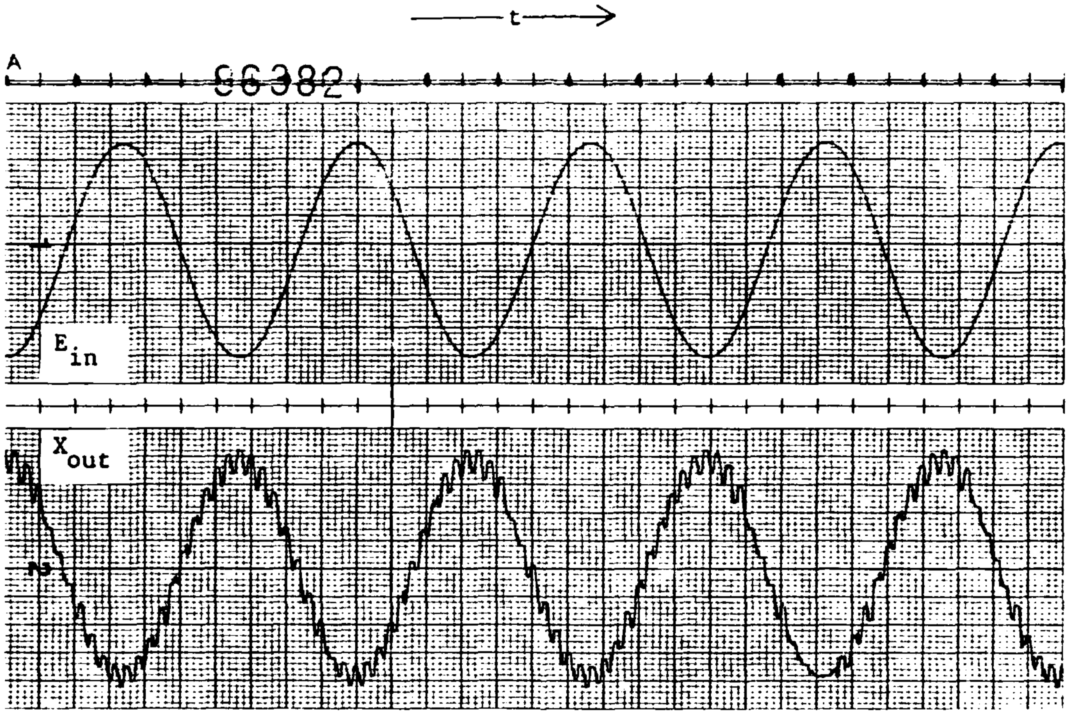
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/7/80

TEST - Input-Output Waveform - Configuration A (@ 0.3 Hz, ±2.0% Full Stroke ±0.100V)



Scale: E_{in} = 0.005 v/div

X_{out} = 0.0025 in/div

t = 10 div/sec

FIGURE 36 Input-Output Waveform - Configuration A (@ 0.3 Hz, ±2.0% F.S.)

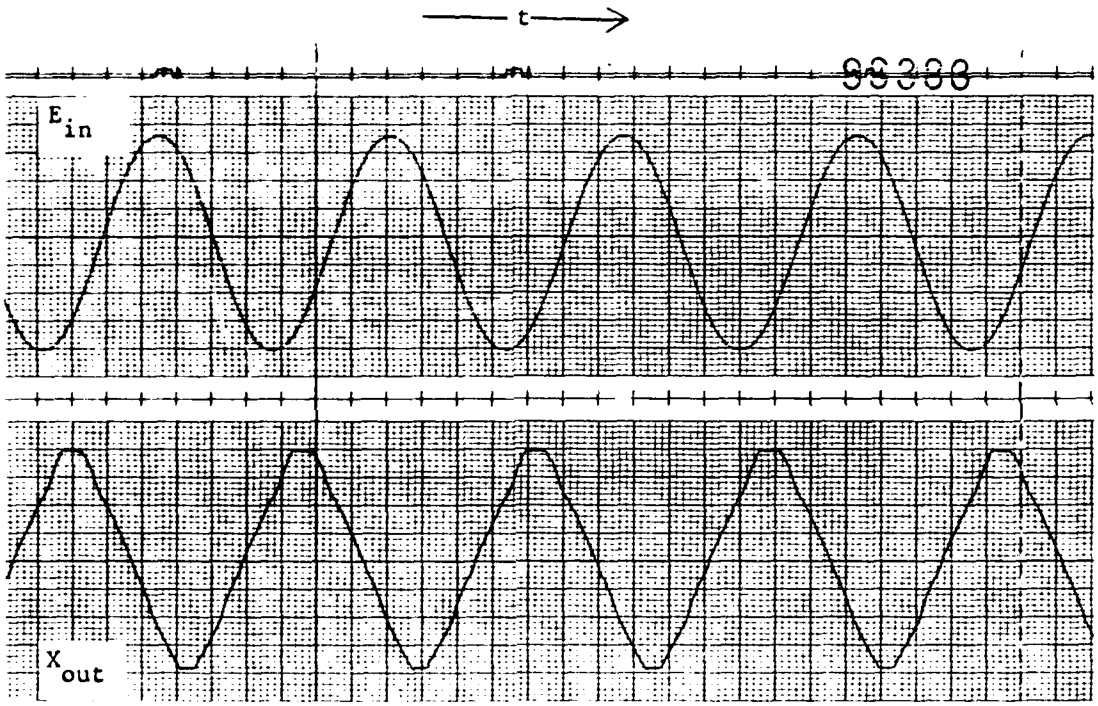
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/7/80

TEST - Input-Output Waveform - Configuration A (@ 1.5 Hz, ±2.0% Full Stroke ±0.100 V)



Scale: E_{in} = 0.005 v/div

X_{out} = 0.0025 in/div

t = 50 div/sec

FIGURE 37 Input-Output Waveform - Configuration A (@ 1.5 Hz, ±2.0% F.S.)

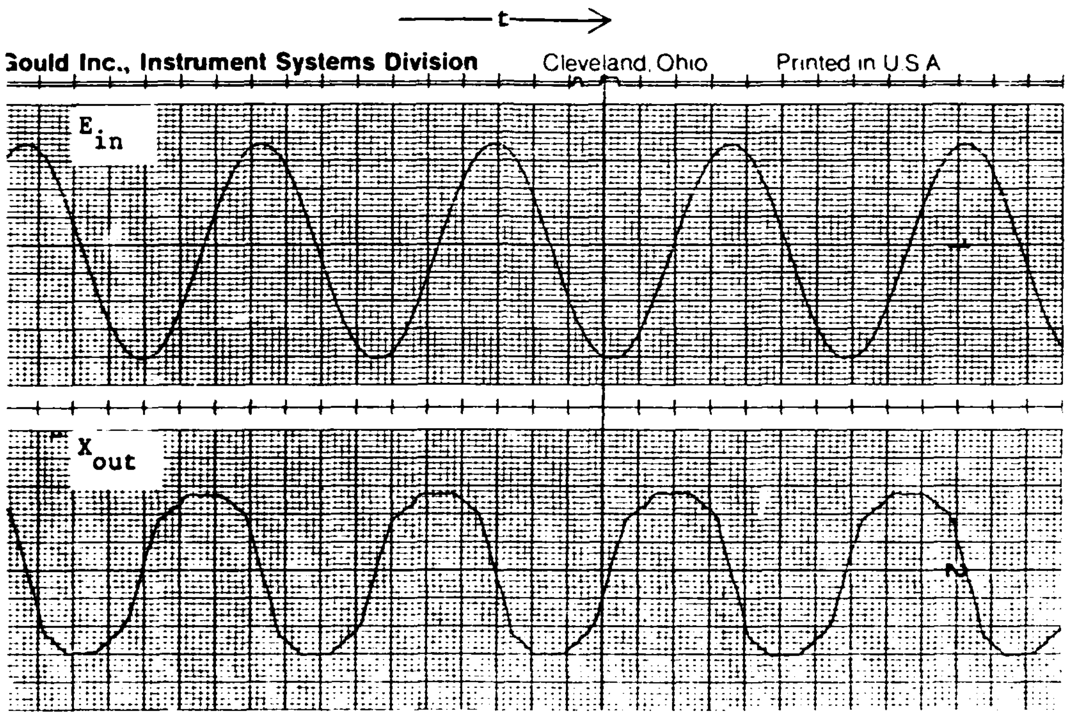
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/7/80

TEST - Input-Output Waveform - Configuration A
(@ 3.0 Hz, ±2.0% Full Stroke ±0.100V)



Scale: E_{in} = 0.005
X_{out} = 0.0025
t = 100 div/sec

FIGURE 38 Input-Output Waveform - Configuration A
(@ 3.0 Hz, ±2.0% F.S.)

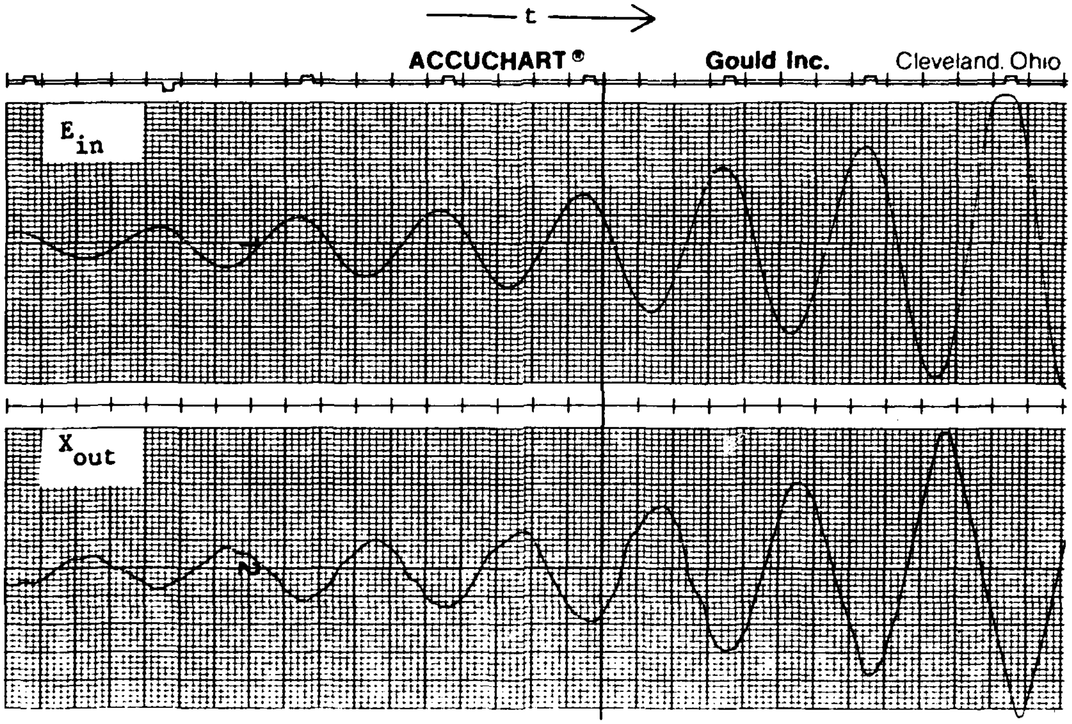
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 5/26/80

TEST - Input - Output Waveform - Configuration A (@ 1.0 Hz, Increasing Amplitude)



Scale: E_{in} = 0.050 v/div
X_{out} = 0.025 in/div
t = 20 div/sec

FIGURE 39 Input Output Waveform - Configuration A
(@ 1.0 Hz, Increasing Amplitude)

Figure 40 illustrates the input-output waveform relationship for Configuration B at an input level of ± 10% of the full scale input and a frequency of .3 Hz. The effect of the limit cycle damping orifice appears in the shape of the output waveform. The peaks of the output motion are significantly flattened, showing that the orifice across the actuator piston degrades the apparent low flow output characteristics of the digital servovalve. As with Configuration A, the phase relationship between the input and output is 180 degrees at this frequency. Figure 41 illustrates the input-output waveform relationship for Configuration B at an input level of ± 10% of the full scale input and a frequency of 1.5 Hz. The output waveform resembles the input with minor distortion. The effect of the damping orifice on the output waveform is not as apparent as at the .3 Hz input frequency, although "flat-topping" of the output motion is still evident on Figure 41.

Figure 42 illustrates the input-output waveform relationship for Configuration B at an input level of ± 10% of the full scale and a frequency of 3 Hz. The output waveform has a triangular, rather than a sinusoidal shape. The output waveform exhibits flat-topping, indicating that the apparent low flow characteristics of the digital servovalve are degraded by the damping orifice. The triangular waveform is a reflection of the onset of rate saturation of the digital servovalve at this combination of frequency and output amplitude. This onset is consistent with the flow capability of the digital servovalve and the flow demand of the actuator motion at the 3 Hz frequency.

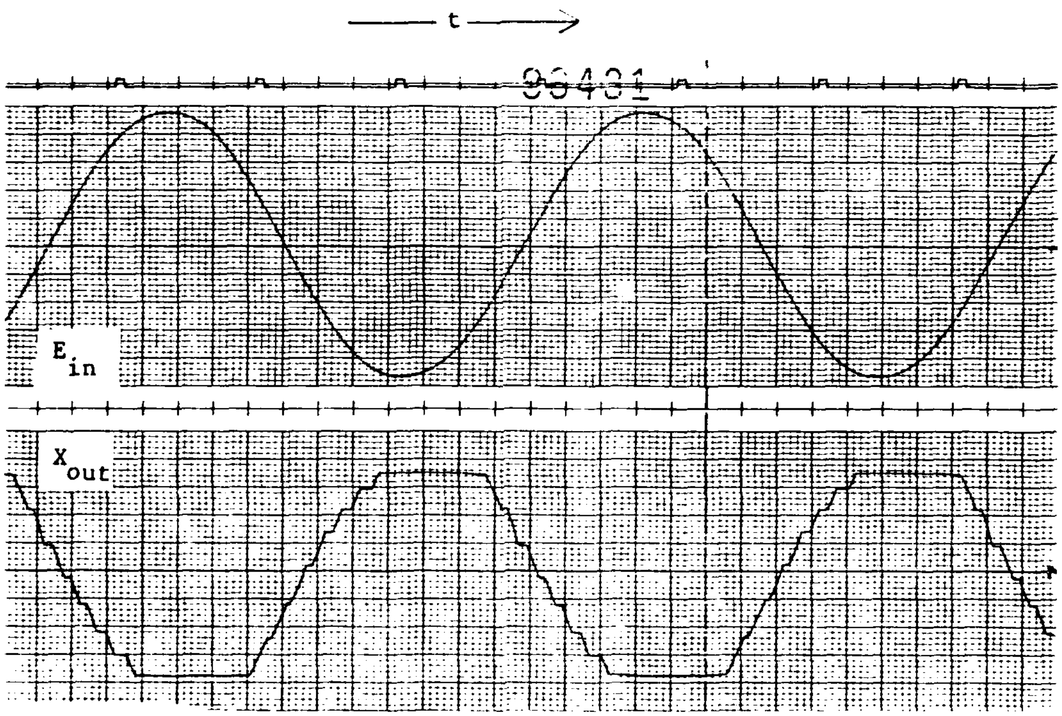
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/8/80

TEST - Input-Output Waveform - Configuration B
(@ 0.3 Hz, ±10.0% Full Stroke ±0.475V)



Scale: E_{in} = 0.020 v/div
X_{out} = 0.010 in/div
t = 20 div/sec

FIGURE 40 Input-Output Waveform - Configuration B
(@ 0.3 Hz, ±10.0% F.S.)

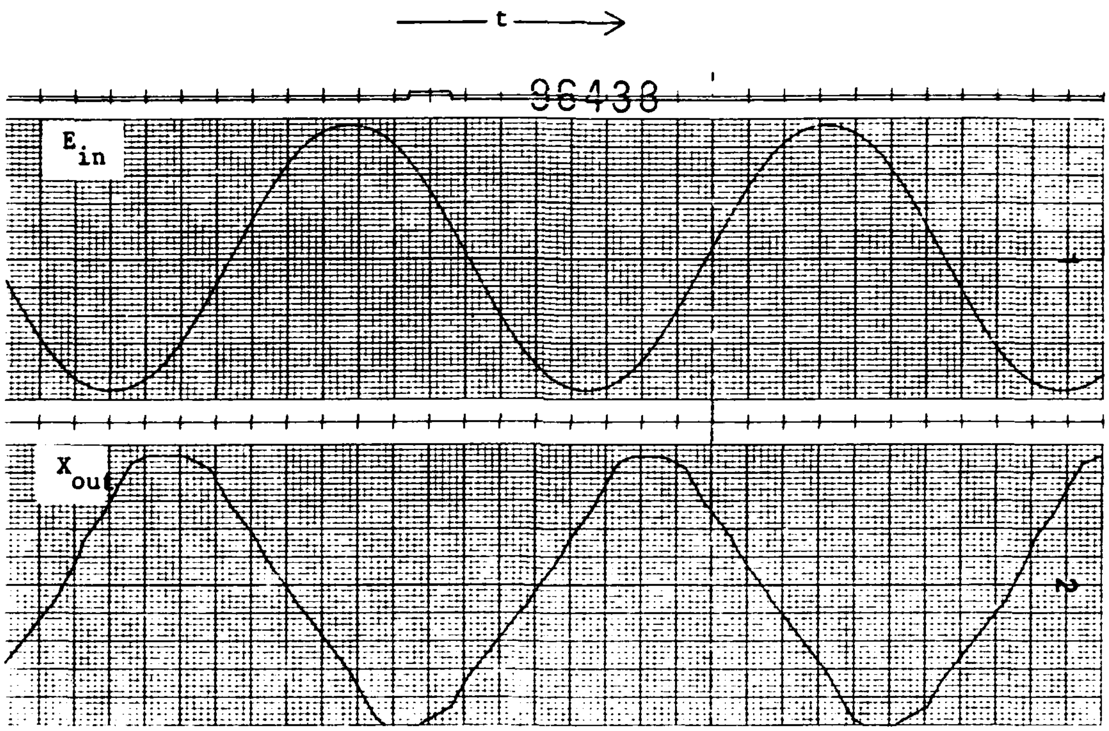
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/8/80

TEST - Input-Output Waveform - Configuration B (@ 1.5 Hz, ±10.0% Full Stroke ±0.475V)



Scale: E_{in} = 0.020 v/div

X_{out} = 0.010 in/div

t = 100 div/sec

FIGURE 41 Input-Output Waveform - Configuration B (@ 1.5 Hz, ±10.0% F.S.)

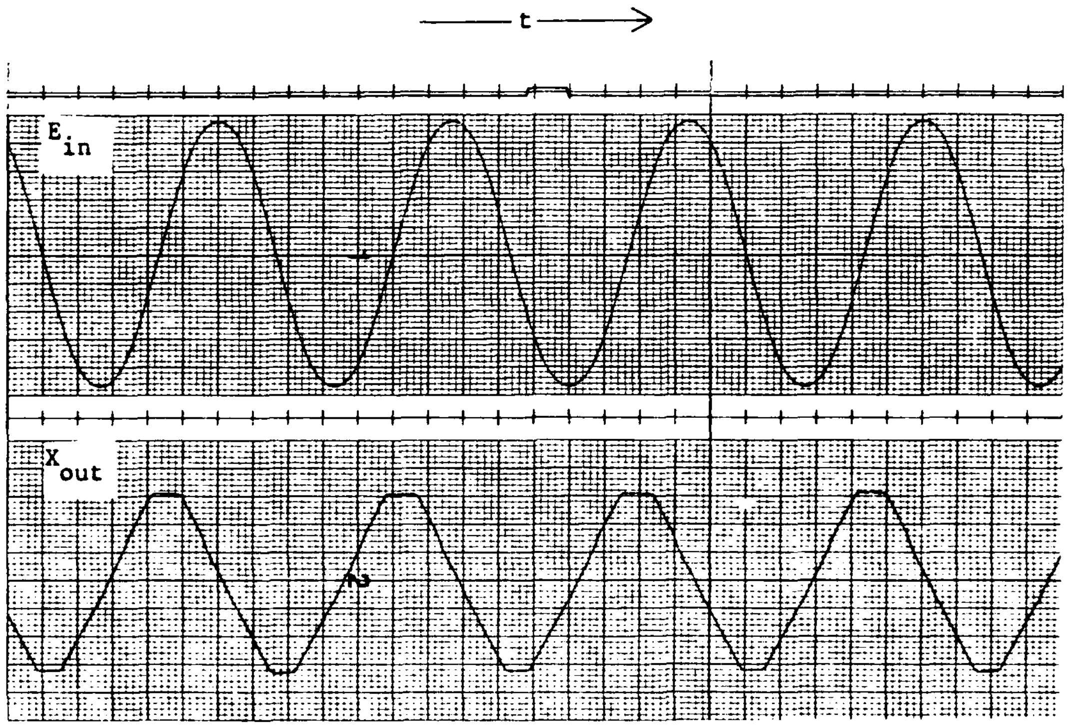
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/8/80

TEST - Input-Output Waveform - Configuration B (@ 3.0 Hz, ±10.0% Full Stroke ±0.475V)



Scale: E_{in} = 0.020 v/div

X_{out} = 0.010 in/div

t = 100 div/sec

FIGURE 42 Input-Output Waveform - Configuration B (@ 3.0 Hz, ±10.0% F.S.)

Figure 43 illustrates the input-output waveform relationship of Configuration B at an input level of ± 5% of the full scale input and a frequency of .3 Hz. The output waveform shows significant flat-topping. This indicates that the limit cycle damping orifice reduces the lowest flow step of the digital valve much below the normal value, preventing the actuator from being driven for small flow commands to the digital servovalve. At the .3 Hz input frequency, the flow requirements from the valve are for relatively low flows. The damping orifice bypasses the actuator piston, reducing the flow from the valve available to drive the actuator. At higher flows from the digital servovalve, the damping orifice has a relative minor effect on the actuator motion.

Figure 44 shows the input-output waveform relationship of Configuration B at an input level of ± 5% of the full scale input and a frequency of 1.5 Hz. The output exhibits flat-topping of the waveform and a general waveform tending towards a triangular, rather than a sinusoidal shape.

Figure 45 shows the input-output waveform relationship for Configuration B at an input level of ± 5% of the full scale input and a frequency of 3.0 Hz. The output exhibits some flat-topping distortion and a phase shift from the normal 180 degrees out of phase relationship of approximately 82 degrees. Note that the output amplitude at the 3 Hz input frequency is greater than [illegible] recorded at 1.5 Hz. This is caused by the peaking of the [illegible] system at the 3 Hz frequency.

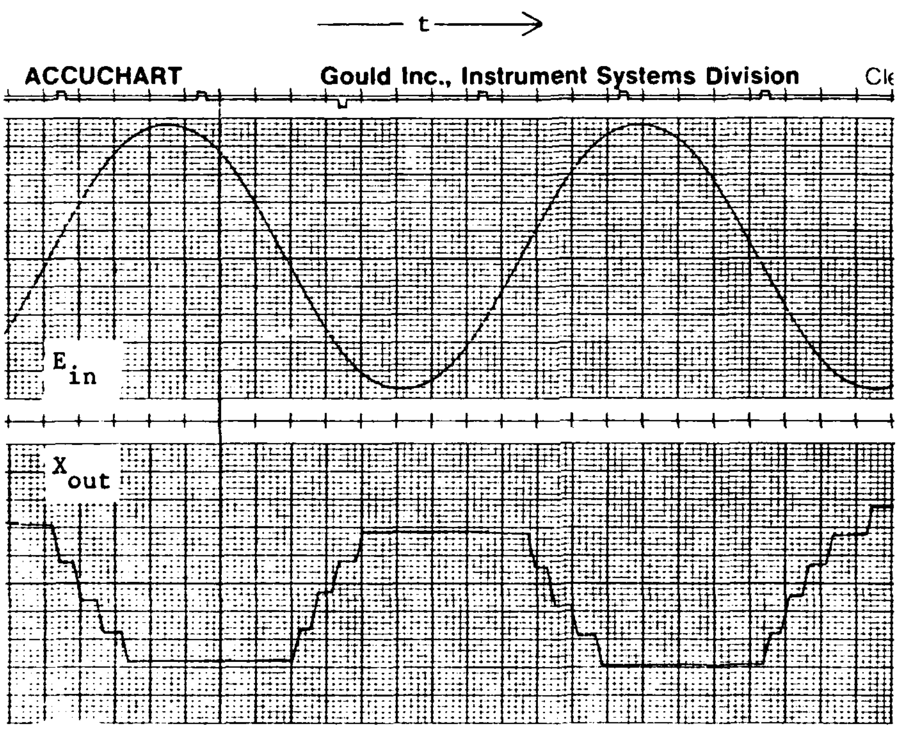
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/8/80

TEST - Input-Output Waveform - Configuration B (@ 0.3 Hz, ±5.0% Full Stroke ±0.238V)



Scale: E_{in} = 0.010 v/div

X_{out} = 0.005 in/div

t = 20 div/sec

FIGURE 43 Input-Output Waveform - Configuration B (@ 0.3 Hz, ±5.0% F.S.)

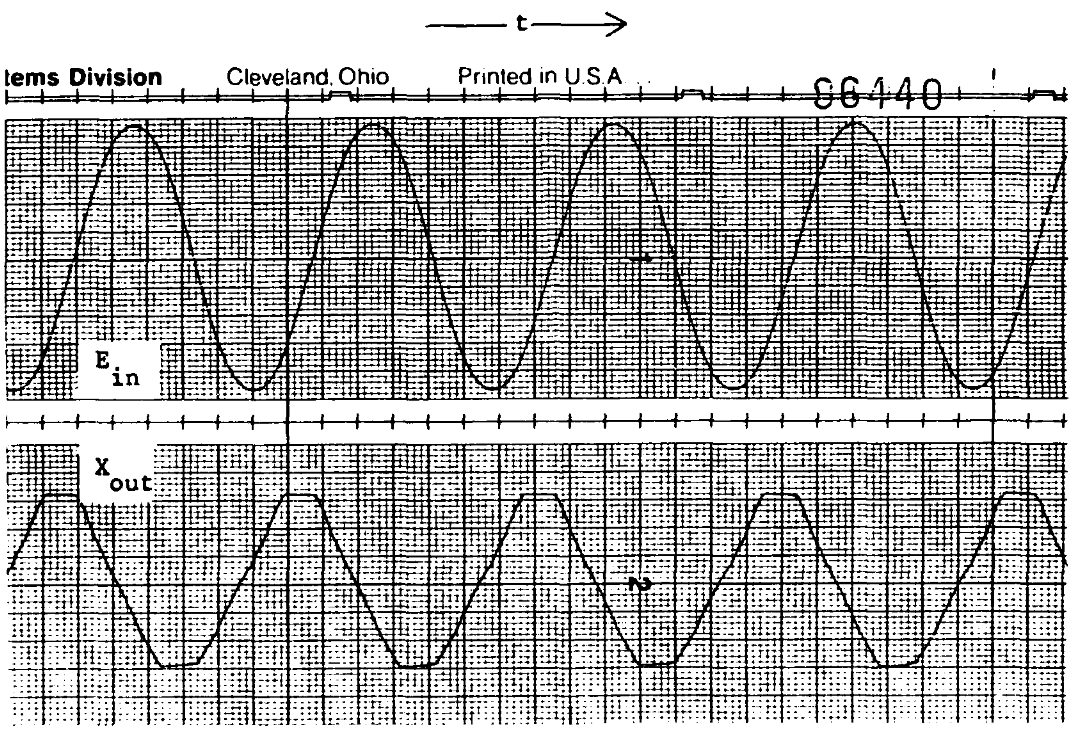
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/8/80

TEST - Input-Output Waveform - Configuration B (@ 1.5 Hz, ±5.0% Full Stroke ±0.238V)



Scale: E_{in} = 0.010 v/div

X_{out} = 0.005 in/div

t = 50 div/sec

FIGURE 44 Input-Output Waveform - Configuration B (@ 1.5 Hz, ±5.0% F.S.)

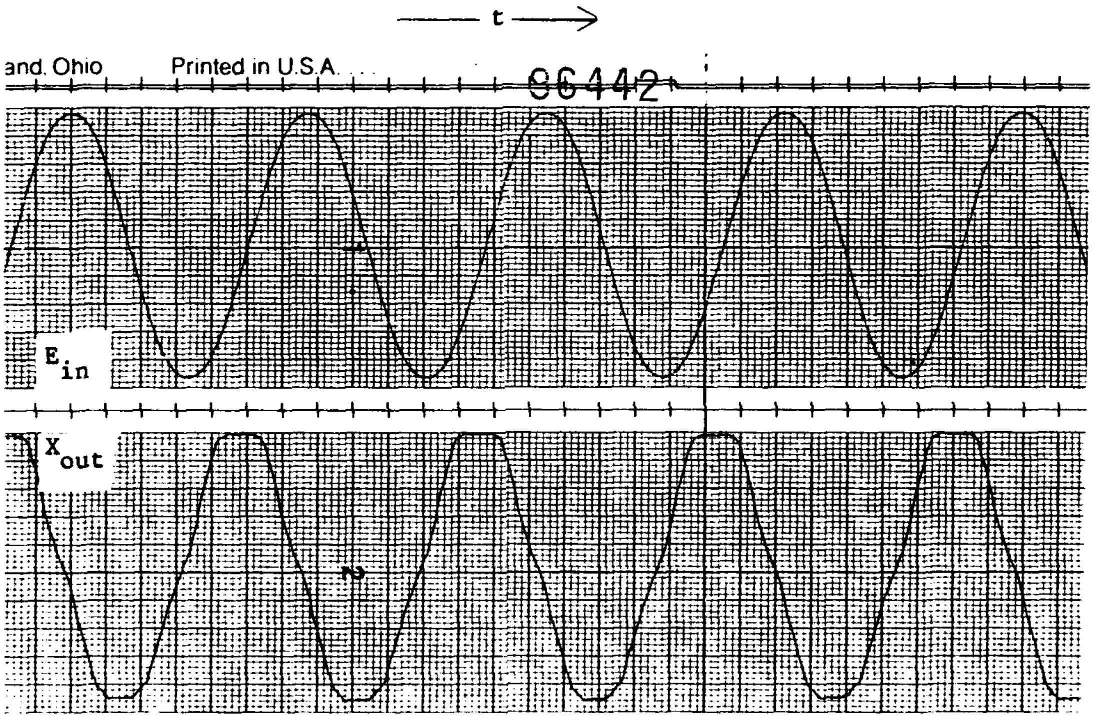
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/8/80

TEST - Input-Output Waveform - Configuration B (@ 3.0 Hz, ±5.0% Full Stroke ±0.238V)



Scale: E_{in} = 0.010 v/div
X_{out} = 0.005 in/div
t = 100 div/sec

FIGURE 45 Input-Output Waveform - Configuration B (@ 3.0 Hz, ±5.0% F.S.)

Figure 46 illustrates the input-output waveform relationship of Configuration B at an input level of ± 2% of the full scale input and a frequency of .3 Hz. The output waveform shows some threshold and overshoot modulation of the .3 Hz sinusoidal output motion.

Figure 47 illustrates the input-output waveform relationship of Configuration B at an input level of ± 2% of the full scale input and a frequency of 1.5 Hz. The output waveform is triangular with a phase lag between the output and input which approaches 80 degrees. The output distortion is similar to that encountered with Configuration A and the same test condition (Reference Figure 37).

Figure 48 shows the input-output waveforms at 3 Hz for an input of ± 2.0% of the full scale input. The output waveform phase angle lags the normal 180 degrees out of phase relationship by 90 degrees. The output waveform is sinusoidal, with the peaks of the sinusoid showing flat-topping. This flat-topping is associated with the damping orifice degrading the apparent flow from the digital servovalve at low input levels to the control system.

Figure 49 shows the amplitude dependency of the output waveform distortion at an input frequency of 1 Hz. The amplitude of the input is varied from 3 to 30% of the maximum input level. Note that the output waveform shows a rate limit characteristic at the maximum input amplitude used. This figure illustrates the type of output distortion resulting from the use of the digital valve with an input signal varied from a low to high level.

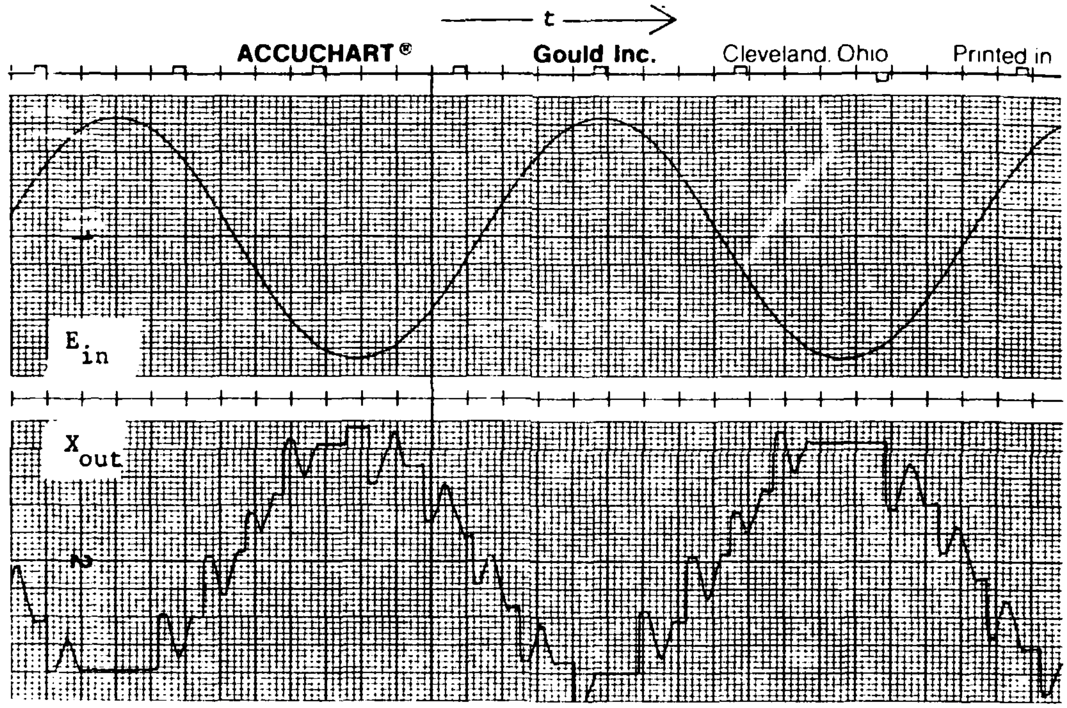
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/14/80

TEST - Input-Output Waveform - Configuration B (@ 0.3 Hz, $\pm$2.0% Full Stroke $\pm$0.100V)



Scale: E_{in} = 0.005 v/div

X_{out} = 0.0025 in/sec

t = 20 div/sec

FIGURE 46 Input - Output Waveform - Configuration B (@ 0.3 Hz, $\pm$2.0% F.S.)

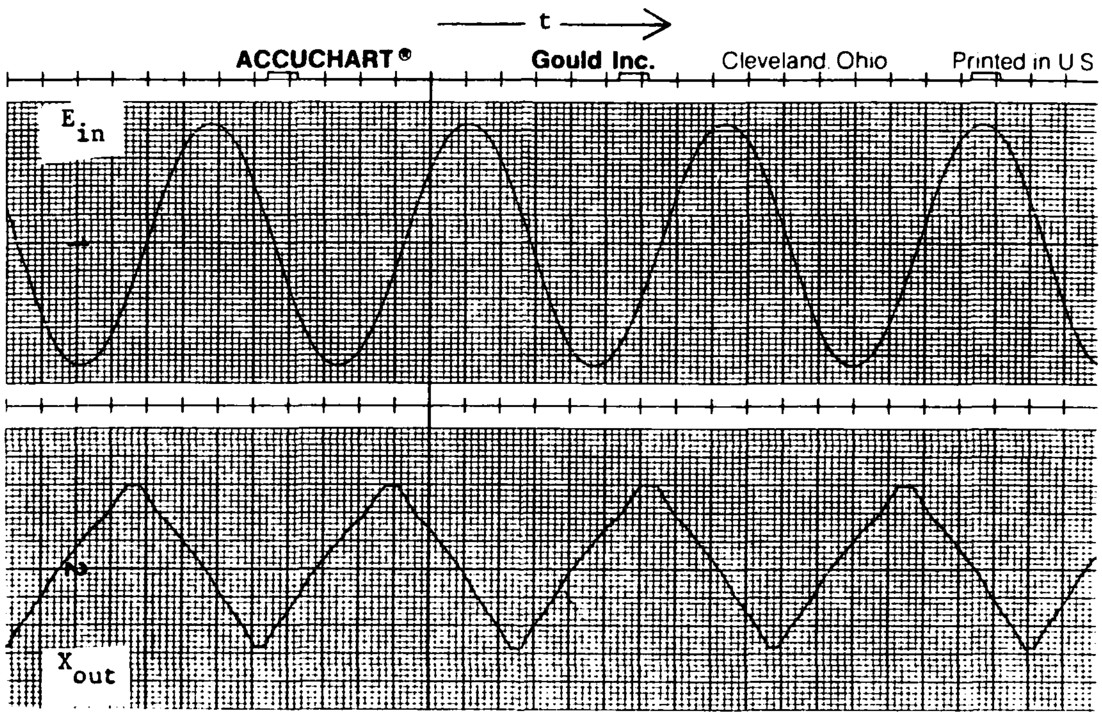
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/14/80

TEST - Input - Output Waveform - Configuration B (@ 1.5 Hz, ±2.0% Full Stroke ±0.100V)



Scale: E_{in} = 0.005 v/div

X_{out} = 0.0025 in/div

t = 50 div/sec

FIGURE 47 Input-Output Waveform - Configuration B (@ 1.5 Hz, ±2.0% F.S.)

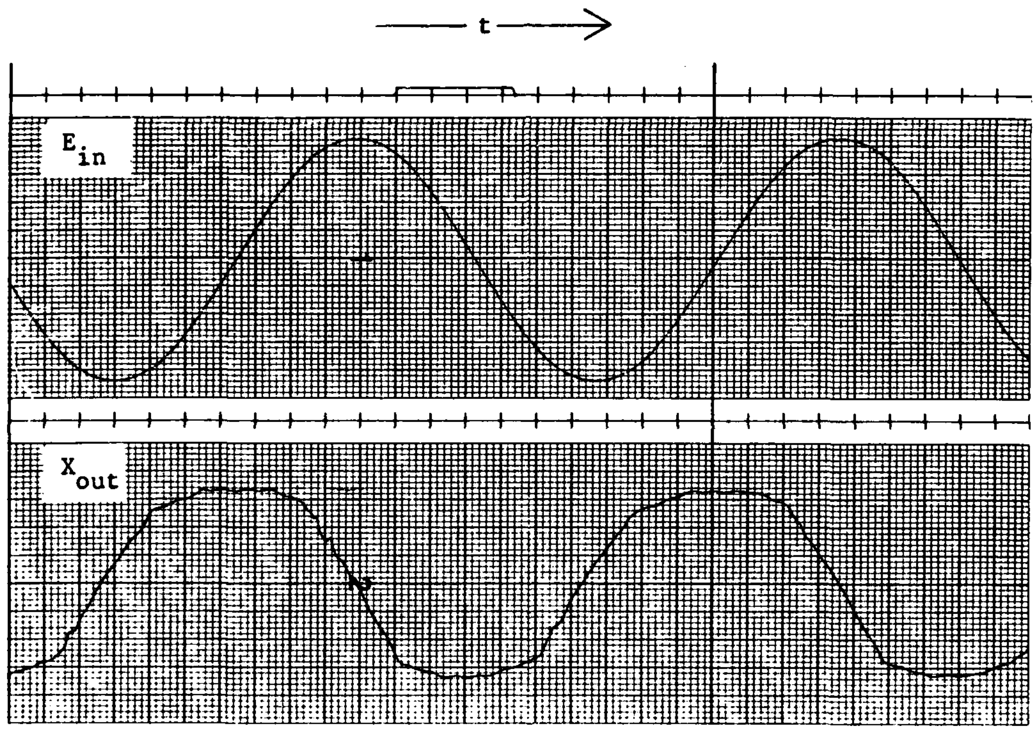
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/14/80

TEST - Input - Output Waveform - Configuration B
(@ 3.0 Hz, ±2.0% Full Stroke ±0.100V)



Scale: E_{in} = 0.005 v/div
X_{out} = 0.0025 in/div
t = 200 div/sec

FIGURE 48 Input-Output Waveform - Configuration B
(@ 3.0 Hz, ± 2.0% F.S.)

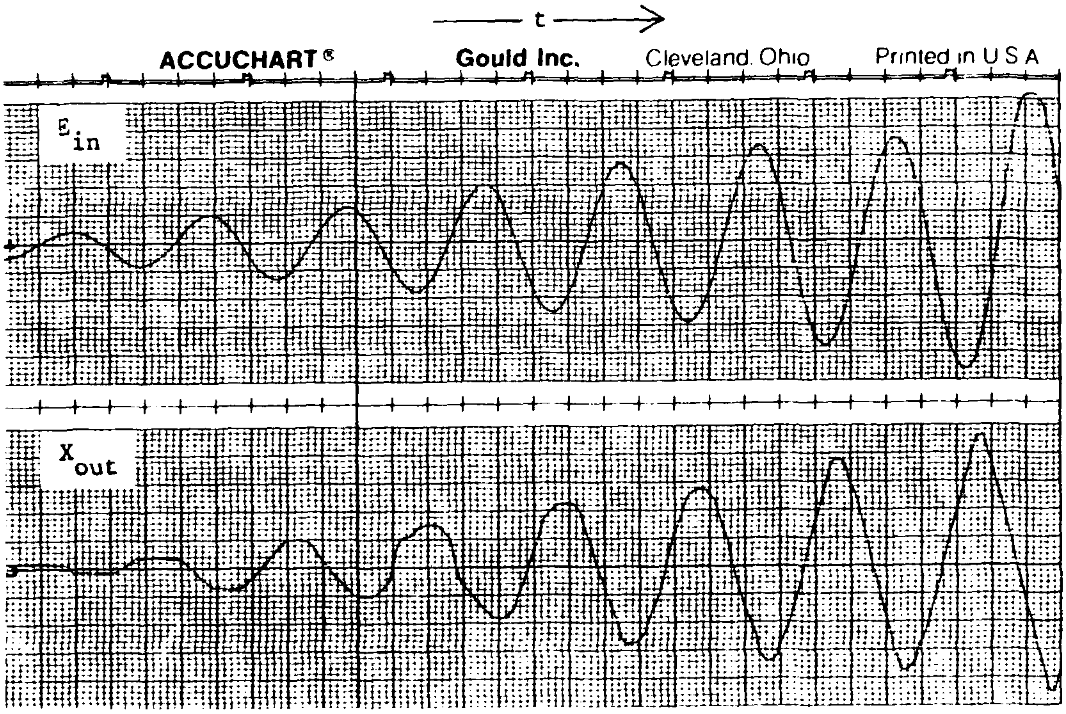
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 5/26/80

TEST - Input - Output Waveform - Configuration B (@ 1.0 Hz, Increasing Amplitude)



Scale: E_{in} = 0.050 v/div

X_{out} = 0.025 in/div

t = 20 div/sec

FIGURE 49 Input-Output Waveform - Configuration B (@ 1.0 Hz, Increasing Amplitude)

7. Step Response

Figures 50 and 51 illustrate the system response of Configuration A to a step input of .238 volts. Figure 50 shows the extend motion in response to a positive .238 volt step and Figure 51 shows the retract motion in response to a negative .238 volt step. This applied step input voltage level is the maximum voltage that can be used without exceeding the error voltage that commands maximum flow from the digital servovalve. As illustrated on both figures, the output motion response to the applied step occurs .05 seconds after the applied step has reached its maximum value. This is consistent with the frequency response limitations indicated by the frequency response measurements performed as part of the system evaluation. The movement of the actuator both before and after the step input response is the limit cycle motion of the system that exists with Configuration A. This limit cycle output motion as shown on Figures 50 and 51 has a peak to peak amplitude of .35% of the total actuator stroke. The step response (ignoring the limit cycle motion) exhibits no overshoot or ringing. This is consistent with the frequency response measured on the system.

Figures 52 and 53 illustrate the system response to a step input of .475 volts. This corresponds to an input amplitude of 5% of the full stroke command. This input voltage is greater than the error voltage required for maximum flow from the digital servovalve. Initially, the actuator moves at the rate corresponding to the maximum flow from the digital servovalve. After the feedback voltage reduces the error voltage to the servovalve below the maximum flow value, the system responds as it did for the .238 step input voltage of Figures 50 and 51.

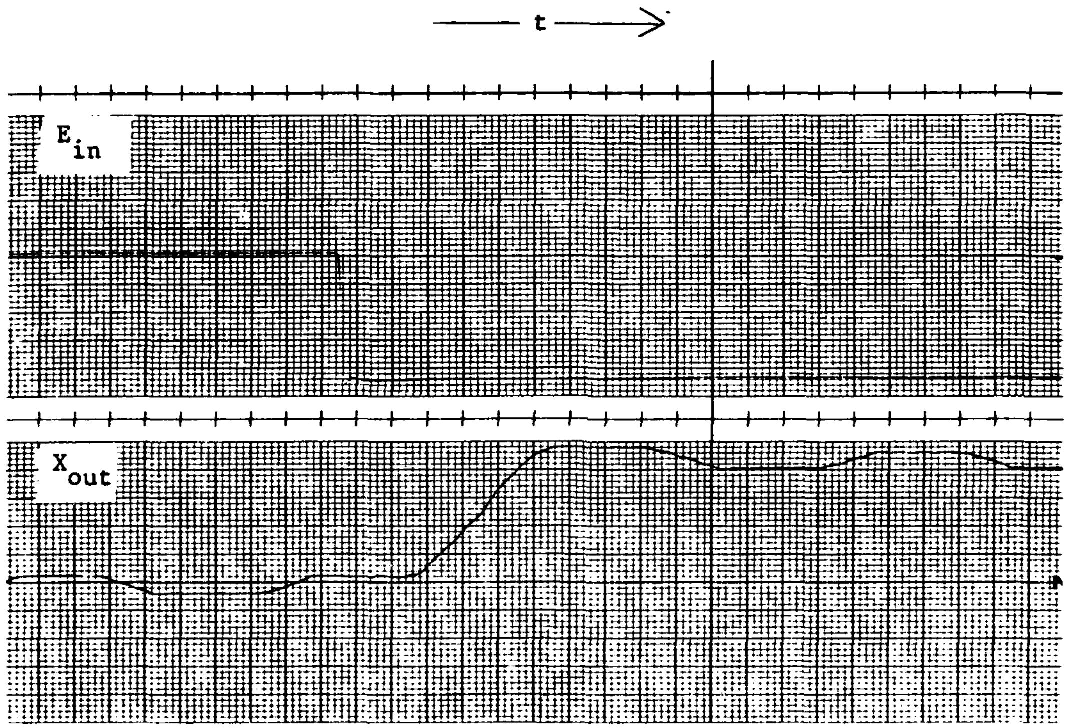
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/11/80

TEST - Step Response - Configuration A (Retract 2.5% Full Stroke - 0.238V)



Scale: E_{in} = 0.010 v/div

X_{out} = 0.005 in/div

t = 200 div/sec

FIGURE 50 Step Response - Configuration A (Retract 2.5% Full Stroke - 0.238V)

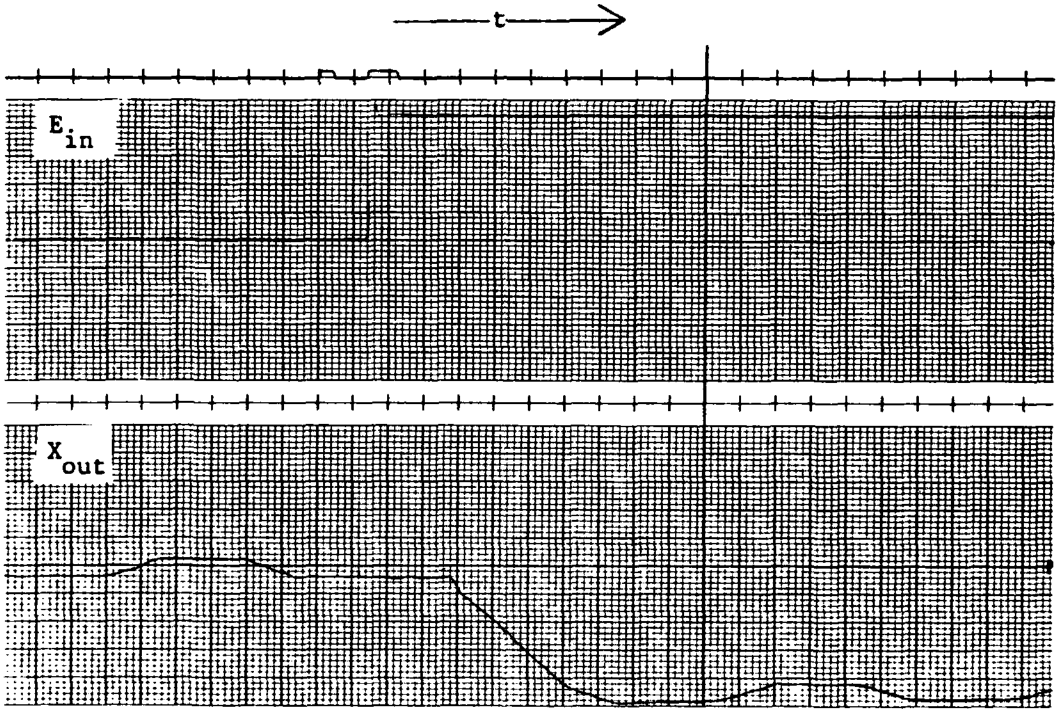
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/11/80

TEST - Step Response - Configuration A
(Extend 2.5% Full Stroke +0.238V)



Scale: E_{in} = 0.010 v/div
X_{out} = 0.005 in/div
t = 200 div/sec

FIGURE 51 Step Response - Configuration A
(Extend 2.5% Full Stroke +0.238V)

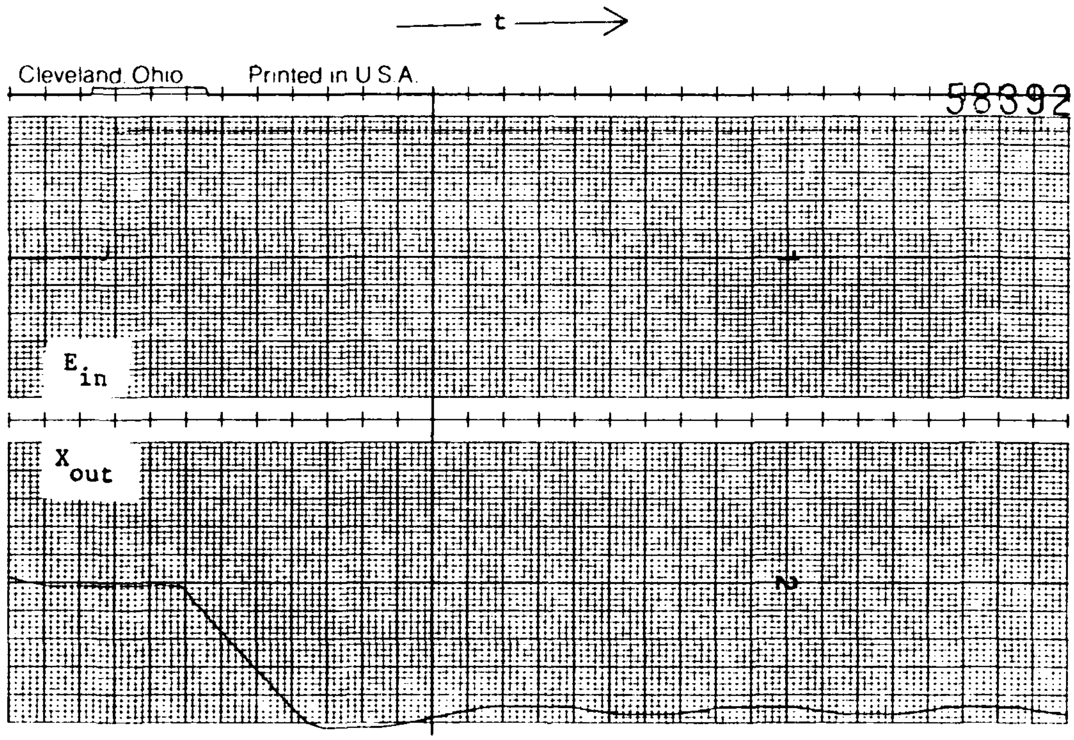
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/11/80

TEST - Step Response - Configuration A (Extend 5% Full Stroke +0.475V)



Scale: E_{in} = 0.020 v/div

X_{out} = 0.010 in/div

t = 200 div/sec

FIGURE 52 Step Response - Configuration A (Extend 5% Full Stroke +0.475V

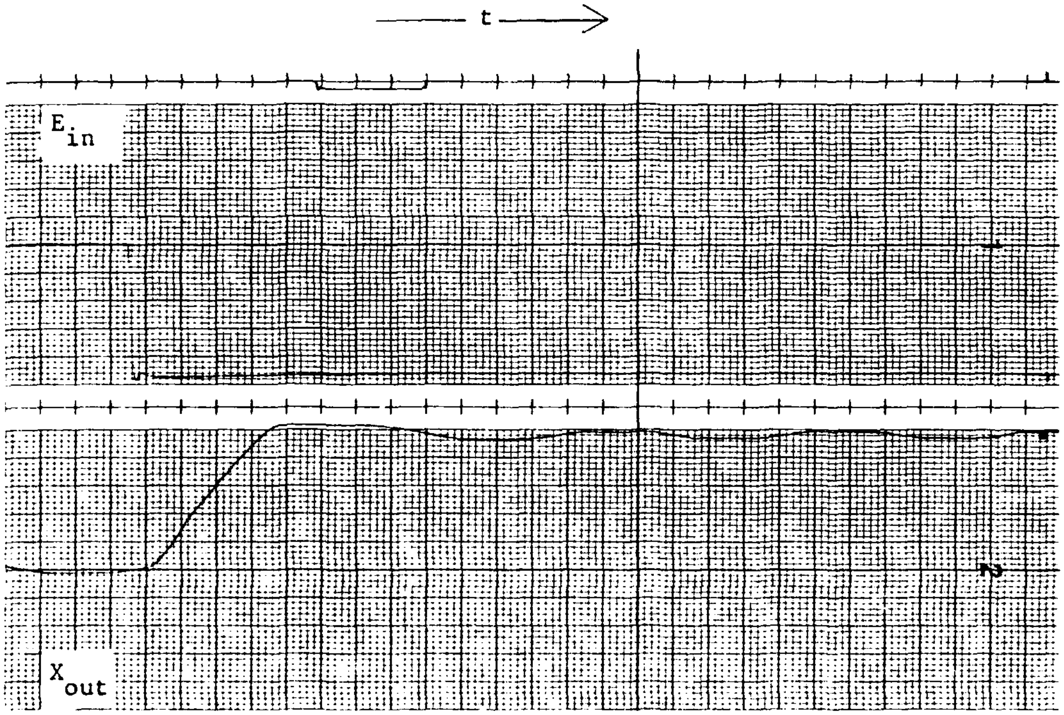
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/10/80

TEST - Step Response - Configuration A (Retract 5% Full Stroke -0.475V)



Scale: E_{in} = 0.020 v/div
X_{out} = 0.010 in/div
t = 200 div/sec

FIGURE 53 Step Response - Configuration A
(Retract 5% Full Stroke -0.475V)

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Figures 54 and 55 illustrate the system step response of the system in response to a step of an amplitude which commands full actuator movement from midposition, or 50% of the full stroke. Figure 54 shows the extend motion and Figure 55 shows the retract motion. The actuator moves at the maximum rate corresponding to the maximum flow from the digital servovalve. Note that the actuator reaches full stroke from mid-position within 1 second for both the extend and retract motions. As expected from considering the design, the maximum rate for both the extend and retract motions is the same at 2.05 inches per second.

On Figures 51 through 55 there is indicated a variation in the time delay between the application of the step to the control system input and the start of actuator movement. For the 2.5% step input of Figures 51 and 52, the time delay is approximately .060 seconds. For the 5% step input of Figures 52 and 53, the time delay is .050 seconds for the extend motion on Figure 52 and .010 seconds for the retract motion on Figure 53. For the 50% step input shown on Figures 54 and 55, the time delay is .01 seconds for the extend motion of Figure 54 and .06 seconds for the retract motion of Figure 55. This variation in the time response is attributed to the operational characteristics of the pilot operated solenoid valves. The particular solenoid valves determining the response time delay of the actuator to a step input are the directional solenoid valves. The long response time delay is attributed to having to build up cylinder pressure in the side of the actuator being connected to return before a differential pressure exists across the cylinder to return pilot operated solenoid valve. Since the solenoid valve is pilot operated, the opening of the valve poppet depends on the existence of a differential pressure across the valve.

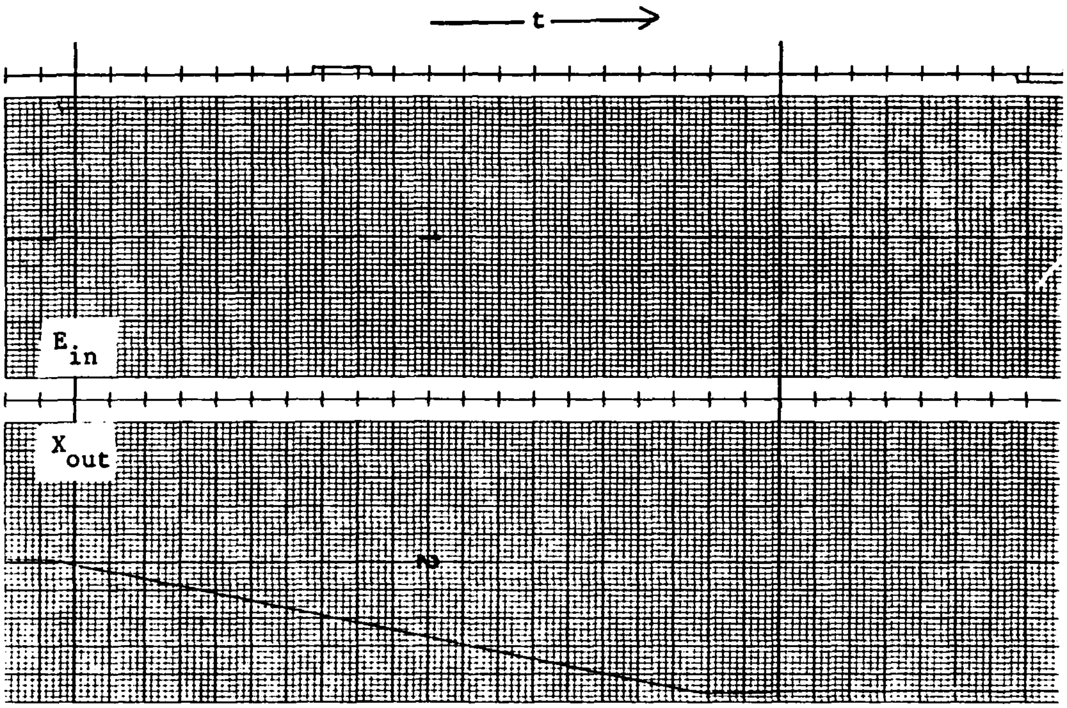
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/11/80

TEST - Maximum Step - Configuration A (Extend 50% Full Stroke +4.75V)



Scale: E_{in} = 0.200 v/div

X_{out} = 0.100 in/div

t = 100 div/sec

FIGURE 54 Maximum Step - Configuration A (Extend 50% Full Stroke +4.75V)

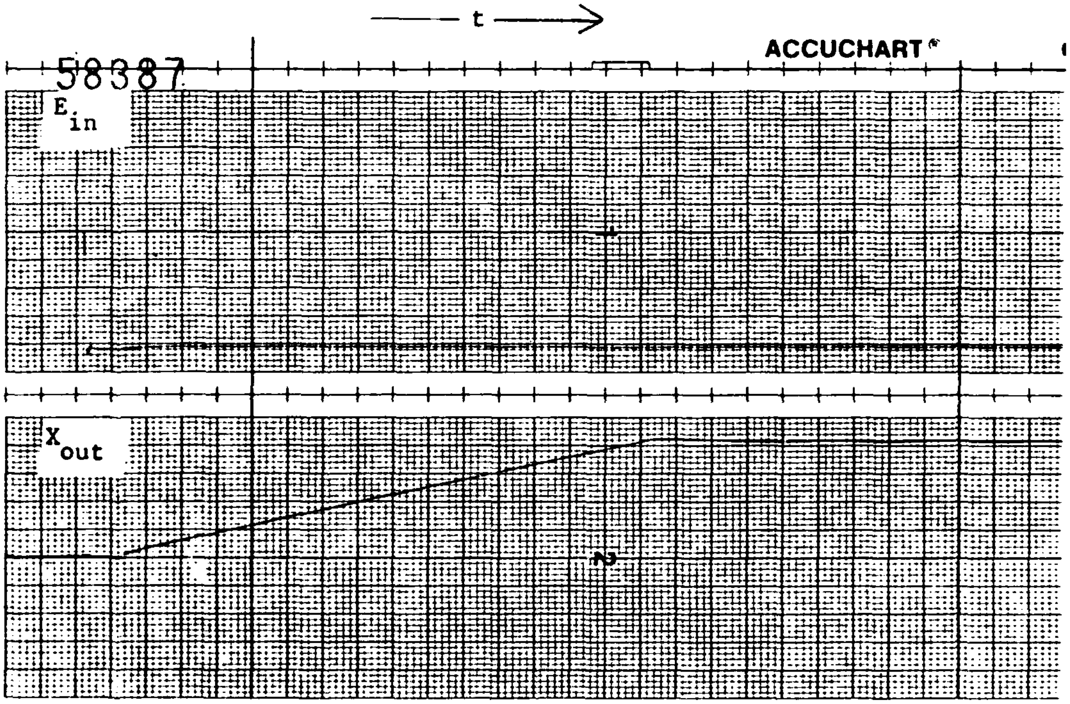
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/11/80

TEST - Maximum Step - Configuration A (Retract 50% Full Stroke +4.75V)



Scale: E_{in} = 0.200 v/div

X_{out} = 0.100 in/div

t = 100 div/sec

FIGURE 55 Maximum Step - Configuration A (Retract 50% Full Stroke +4.75V)

Figures 56 and 57 illustrate the system response of Configuration B to a step input of .238 volts, corresponding to an input amplitude of 2.5% of the full stroke input. Figure 56 shows the extend motion response for the 2.5% input. Note that the output motion shows movement at three distinct rates, corresponding to different flow rates from the digital servovalve. Note that the motion of the actuator for the .025 inches before stopping requires .23 seconds. This slow rate (as compared to the response of Configuration A for the same test condition) is due to the orifice across the actuator drive area using part of the flow from the digital servovalve provided by the non-switched flow control orifice. Figure 57 shows the retract motion response for the 2.5% input. The motion characteristics are similar to that of Figure 56. Note that for both Figures 56 and 57, the time delay between application of the step input and the beginning of the actuator motion is .010 seconds.

Figure 58 illustrates both the extend and retract system response for Configuration B to a .475 volt step input. This input corresponds to a step amplitude of 5% of the input for full actuator stroke. Note that the time to reach the 5% output change in response to the input step is 20% longer than that for Configuration A. Comparing the response characteristics (Reference Figures 52 and 53), the response time difference is due to the rate of motion in the last 10% of the actuator position change in response to the input step. This, again, is die to the damping orifice changing the available flow at the small input signal level to the control system.

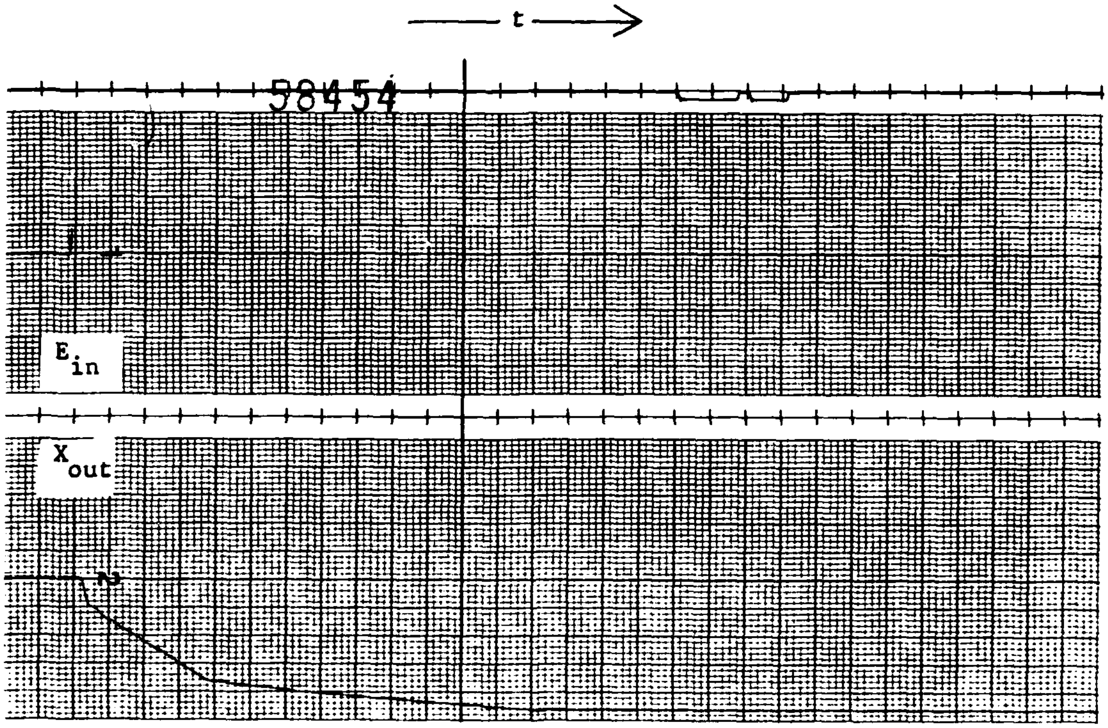
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/14/80

TEST - Step Response - Configuration B (Extend 2.5% Full Stroke +0.238V)



Scale: E_{in} = 0.010 v/div

X_{out} = 0.005 in/div

t = 200 div/sec

FIGURE 56 Step Response - Configuration B (Extend 2.5% Full Stroke +0.238V)

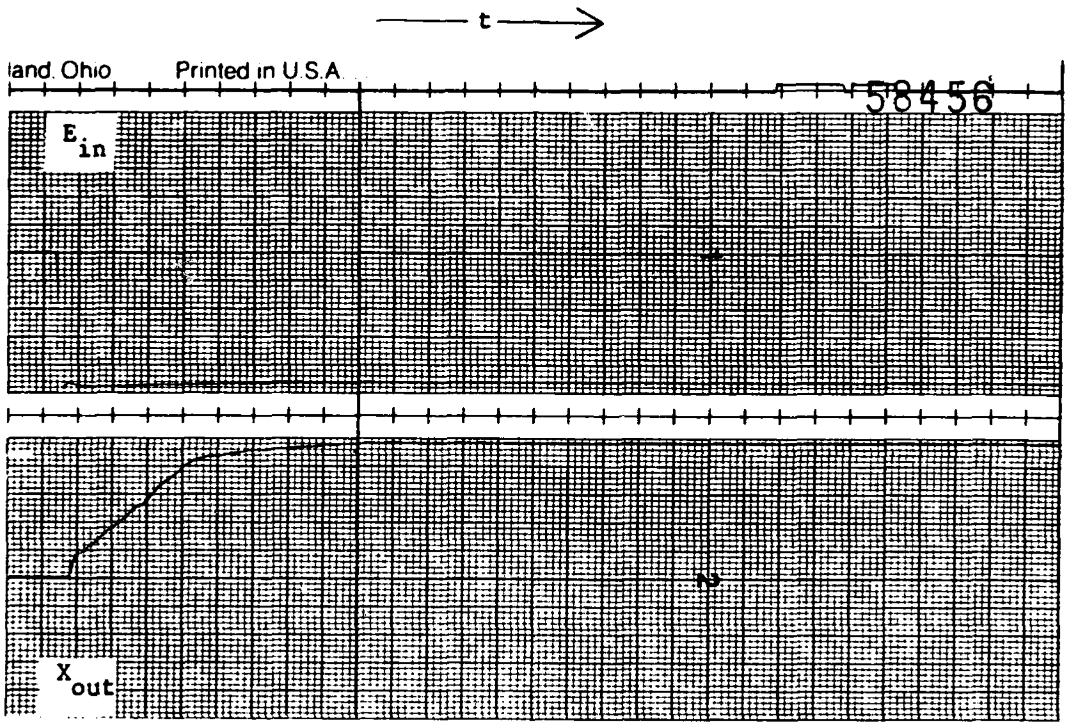
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared $?L$?*)

TEST - Step Response - Configuration B
(Retract 2.5% Full Scale -0.238V)



Scale: E_{in} = 0.010 v/div
X_{out} = 0.005 in/div
t = 200 div/sec

FIGURE 57 Step Response - Configuration B
(Retract 2.5% Full Scale -0.238V)

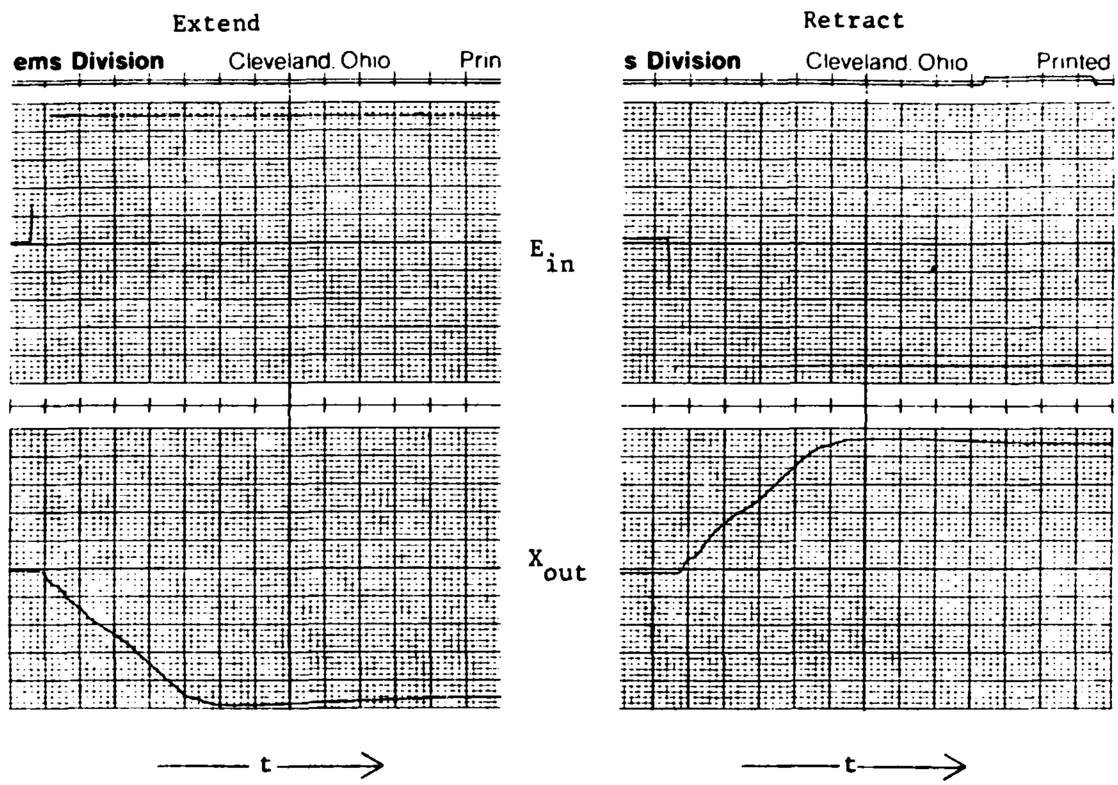
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/10/80

TEST - Step Response - Configuration B
($\pm$5% Full Stroke $\pm$0.475V)



Scale: E_{in} = 0.020 v/div

X_{out} = 0.010 in/div

t = 200 div/sec

FIGURE 58 Step Response - Configuration B
($\pm$5% Full Stroke $\pm$0.475V)

Figure 59 and 60 illustrate the Configuration B system response to a full deflection step input command from mid actuator position. The actuator moves at a rate corresponding to maximum effective flow from the digital servovalve. Note that the actuator moves at a rate of 2.42 inches per second for both the extend motion shown on Figure 59 and the retract motion shown on Figure 60. For both motions, the actuator starts moving approximately .010 seconds after the application of the step input.

The actuator slew rate is 8% slower than the Configuration A slew rate for the same test condition. This is probably due to the damping orifice effecting the flow available from the digital servovalve to drive the actuator.

The response time delay for all the Configuration B step input tests was on the order of .010 seconds. This is considerably faster than that measured for many of the Configuration A step response tests. The damping orifice apparently improves the pressure differential operating conditions for the cylinder to return solenoid valves, decreasing the response time. The response time variation as previously stated, is associated with the use of pilot operated solenoid valves and should be eliminated with the use of direct operating solenoid valves in the digital servovalve construction.

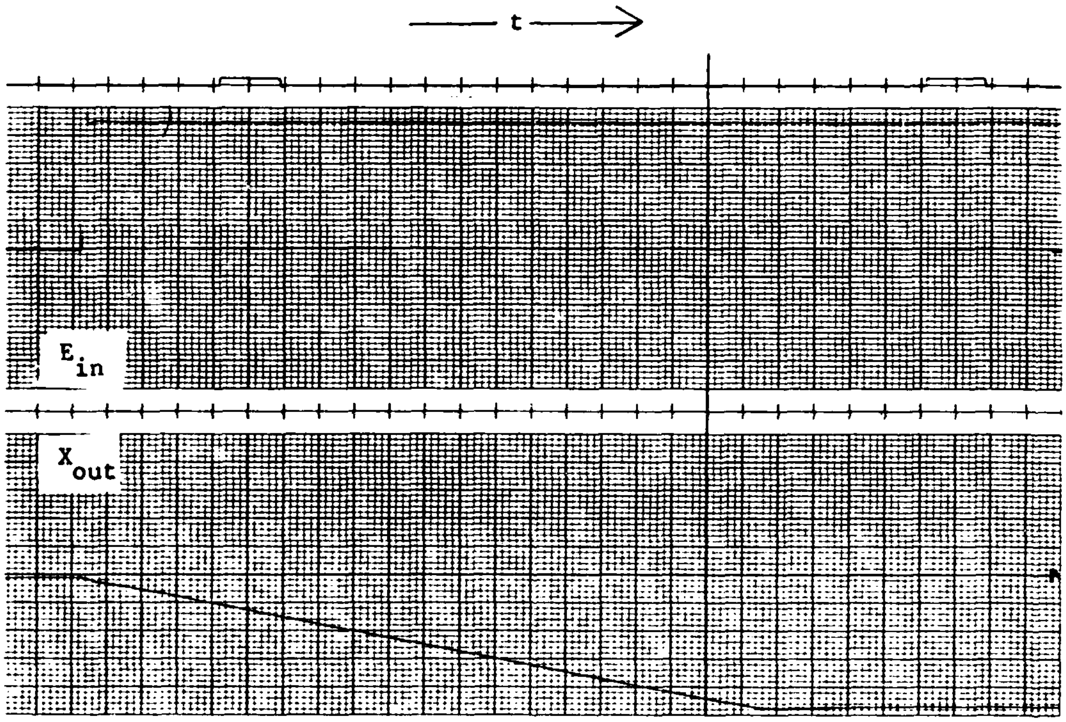
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date Prepared 4/1/80

TEST - Maximum Step - Configuration B (Extend 50% Full Stroke +4.75V)



Scale: E_{in} = 0.200 v/div
X_{out} = 0.100 in/div
t = 100 div/sec

FIGURE 59 Maximum Step - Configuration B (Extend 50% Full Stroke +4.75V)

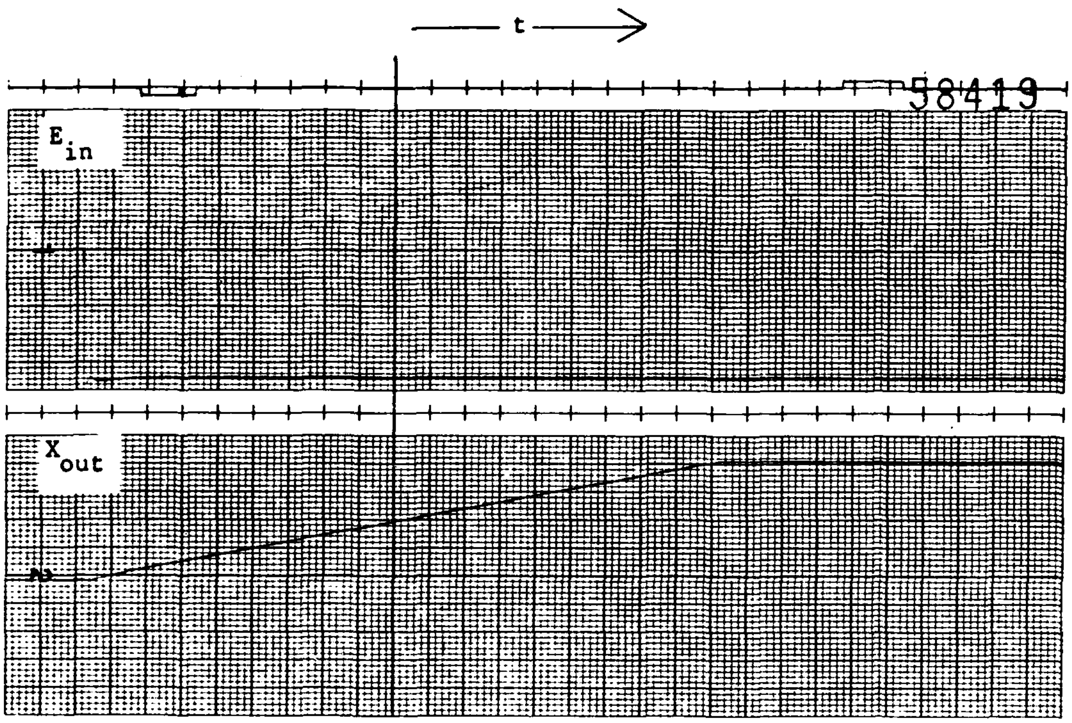
DYNAMIC CONTROLS, INC.

Test Data

TEST ITEM - DCI Digital Servovalve

Date
Prepared 4/14/80

TEST - Maximum Step - Configuration B
(Retract 50% Full Stroke -4.75V)



Scale: E_{in} = 0.200 v/div

X_{out} = 0.100 in/div

t = 100 div/sec

FIGURE 60 Maximum Step - Configuration B
(Retract 50% Full Stroke -4.75V)

SECTION VI

CONCLUSIONS AND RECOMMENDATIONS

From the test results obtained from the evaluation hardware, it is concluded that the digital valve operated essentially as intended by design and verified the mechanization concept. The performance of a closed loop actuator system with the digital servovalve is comparable to the performance of the system with a conventional analog servovalve.

The time delay associated with the operation of the solenoid valves used to mechanize the digital servovalve determines the frequency response of the control actuator system using the digital servovalve. Mechanizing an actuator control loop to have a frequency response on the order of 30 Hz would require constructing the digital servovalve with solenoid valves having an operating time on the order of 5 milliseconds. This is feasible with state of the art technology and hardware.

The maximum power consumption of the evaluation hardware under worst case dynamic operating conditions was 125 watts. The power consumption for zero input is less than 5 watts. Since a typical analog servovalve with a quiescent leakage of .25 cubic inches per second at 3000 psi consumes (continuously) hydraulic power of 84 watts, the digital servovalve (even in its present development state) is attractive from a power consumption aspect.

The step input time delays measured on the control system mechanized for evaluation varied from test to test. This is apparently due to the use of pilot operated, rather than direct operated, solenoid valves for constructing the test hardware. The use of direct operating solenoid valves should produce consistent step response time delay measurements.

From this research and development investigation it is concluded that the digital servovalve offers an electrohydraulic valve capable of operating satisfactorily with direct digital input signals. The valve also offers lower power consumption (quiescent) and potentially less contamination sensitivity than the conventional electrohydraulic servovalve. It is therefore recommended that the development of the digital valve be continued. It is recommended that the continued development be conducted in three separate phases, either in parallel or in series.

The first phase of the continued development would be a design integration of the hardware, particularly the solenoid valve. The solenoid valve size determines the digital servovalve size. Mechanizing the digital valve with an aerospace version of the poppet solenoid valve should significantly reduce the weight and volume of the digital valve, making it more compatible with aerospace applications. The solenoid valve should be a direct acting poppet valve designed for a time delay of not longer than 10 milliseconds.

The second phase of the continued development is the use of a micro-processor as the controller for the digital servovalve. This phase of the program would investigate the use of off-the-shelf digital components to command the digital servovalve.

The third phase of the continued development program is the incorporation of a digital feedback position measuring device for the control actuator. This phase of the program would investigate the use of digital feedback techniques to close the control loop using the digital valve, thereby making the command, feedback and hydraulic flow control entirely digital in operation.

The result of this continued development of the digital servovalve approach would be the availability of an electrohydraulic actuator for aerospace applications which is able to use directly digital inputs from the control sections of the flight control system and having lower power consumption and higher reliability than conventional actuation techniques.

*U.S.Government Printing Office: 1980 — 657-084/147