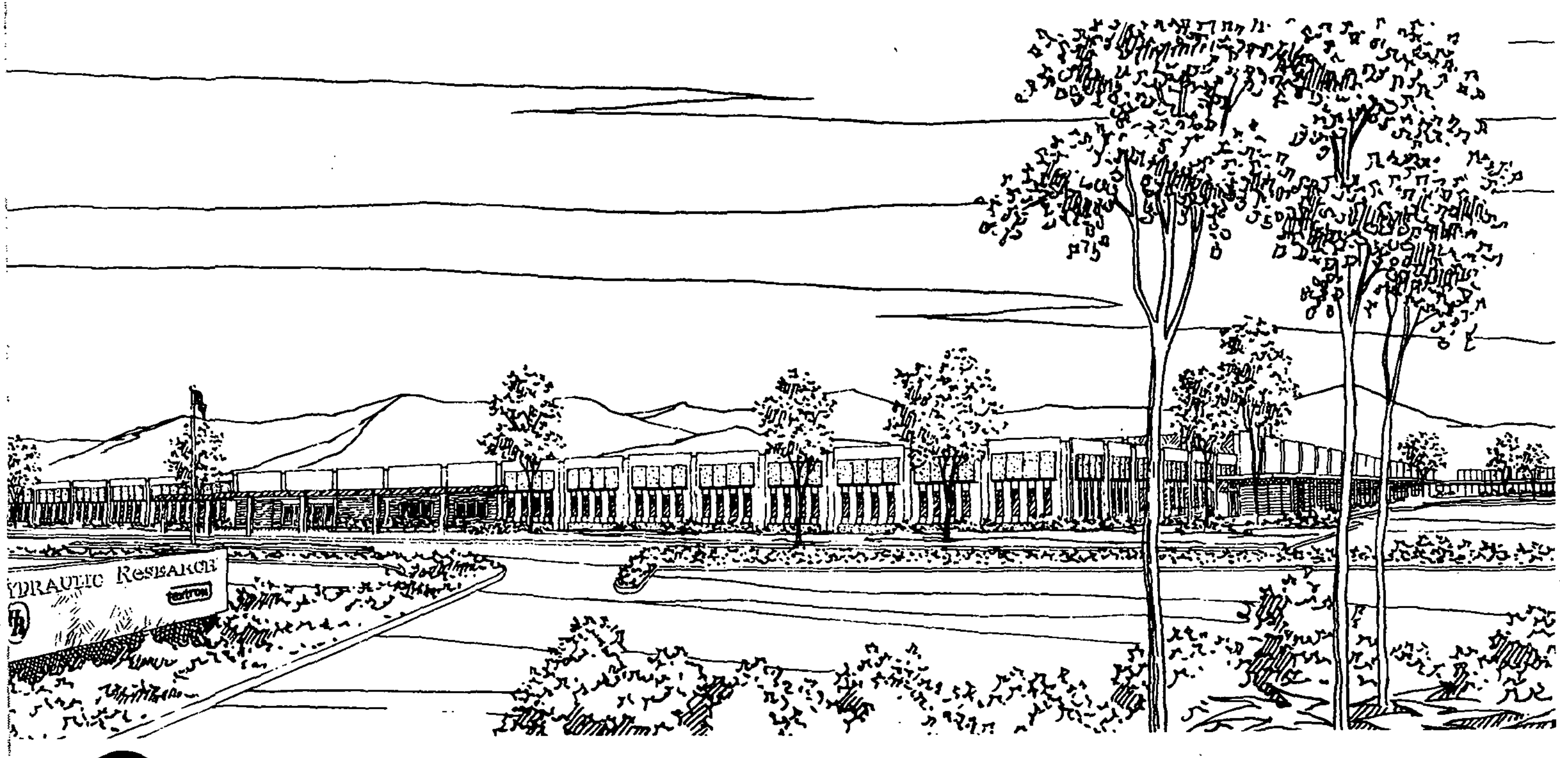
N73- 27418

ACTIVE-STANDBY SERVOVALVE/ACTUATOR DEVELOPMENT

FINAL REPORT



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ACTIVE-STANDBY SERVOVALVE/ACTUATOR DEVELOPMENT

FINAL REPORT

NASA CONTRACT NO. NAS 8-27838

PREPARED BY Richard K. Mason DATE May 15, 1973
CHECKED BY [illegible] DATE 5/21/73
APPROVED BY [illegible] DATE 5/28/73

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1.0 INTRODUCTION

1.1 General

An active-standby one-fail/operate servoactuator with electronic monitoring for failure detection and correction, along with the associated electronics, was fabricated and tested by HYDRAULIC RESEARCH for NASA/MSFC under Contract No. NAS 8-27838. The objective of the program was to demonstrate the feasibility of an electronic monitor for failure detection. The redundant concept used in this servovalve is essentially that to be used on the Space Shuttle Main Engine Hydraulic Actuation System (SSME-HAS).

This redundant concept features an electronic circuit as a model of the servovalve. An LVDT is used to monitor the second stage spool position of the servovalve. The signal generated by the electronic model is compared to the actual servovalve output as measured by the LVDT. This comparison is the failure detection mechanism. In order to obtain the fail/operate ability, two servovalves are provided, each having its own model and independent of the other.

During this program, it was necessary to develop a fast-acting electronic/hydraulic switch. A torque motor switch adapted from HYDRAULIC RESEARCH propellant valve technology was used. Propellant valves are used on small thrusters in space operation to control the fuel and/or oxidizer supply.

The electronics were designed and fabricated by HYDRAULIC RESEARCH for this program. A 110-V supply and the various recorders were the only accessories needed.

In the SSME-HAS system, the failure detection mechanism for the actuator feedback (LVDT) is independent of the failure detection system for the servoactuator. No detection system is included in this program for the actuator LVDT.

1.2 Objectives

The objective of this program was to prove the feasibility of having an electronic model of the servovalve as a failure detection mechanism. Secondary objectives of the program were to determine the operating characteristics of the system and to identify any problem areas.

1.3 Summary

All of the program objectives were accomplished. A redundant, fail/operate fail/fixed servoactuator was constructed and tested along with two electronic models of the servovalve. All the relative electronics and a load actuator were also constructed and used in the testing. This system did provide an effective failure monitoring technique.

A servovalve was modified by attaching a linear variable differential transducer (LVDT) to its second-stage spool. This LVDT provides an electrical signal proportional to spool position without having any detrimental effect on the performance of the servovalve.

An electronic model was made which duplicates the response characteristics of the servovalve. This model, though revised and expanded from its initial concept, is a relatively simple electronic device consisting of only four operation amplifiers. The servoactuator has a switching transient of 3.2% of full stroke with a step failure.

Additional testing is recommended to completely define the operation of the servoactuator and the detection system. These tests should also determine the sensitivity of the system to fabrication tolerances, environment variations, and changes in such various parameters as power supply (hydraulic and electrical), and carrier frequency. Failure mode analysis and testing should be conducted in order to reveal any hidden critical failure modes.

At the start of the program, a bifilar coil was required on the switching solenoid. In order to obtain the switching transients, the solenoid was required to de-energize very rapidly. These two requirements, the bifilar coil and the rapid switching, are not compatible.

It was therefore necessary to develop a fast-acting torque motor switch. The bifilar requirement was later dropped but the torque motor switch retained.

The results of this program were hampered by poor LVDT performance on the servovalve. The problem was relieved by increasing the carrier frequency to 4000 Hz. This allowed for more attenuation by the demodulator filter.

Additional design and development effort should be directed toward perfecting the model/delay. Modeling of the servovalve should not be necessary over the full servovalve operational range. As a minimum, the model must be able to respond to a failure within 2 ms or 80 Hz. An attenuator should be developed to block out higher frequencies but not effect the response below 80 Hz.

This unit was insensitive to nuisance-type disconnects. With a detection level as low as 25% (1.25% of actuator full stroke), the unit would not fail when subjected to various transients, hydraulic and electrical. The majority of the testing was conducted at 50% detection.

2.0 DISCUSSION

2.1 System Description

The premise on which this concept of electronic monitoring for failure detection was based is that failures can be detected electrically by using a simple electronic model of the servovalve. The second stage of the servovalve was chosen as the position for failure detection for various reasons, a few of which are listed below:

1. The position is readily available.
2. This position provides one of first state variables which results in small actuator transients when a failure occurs.
3. This position is not affected by actuator loading.
4. The servovalve second stage is insensitive to normal hydraulic pressure variations.

Figure 2-1 shows schematically the detection concept. The command and feedback signals are applied to the servoamplifier as well as to the model.

The servoamplifier sends a current $\underline{E}$ to the servovalve which is proportional to the difference between the command and feedback signals. This current is applied to the coils

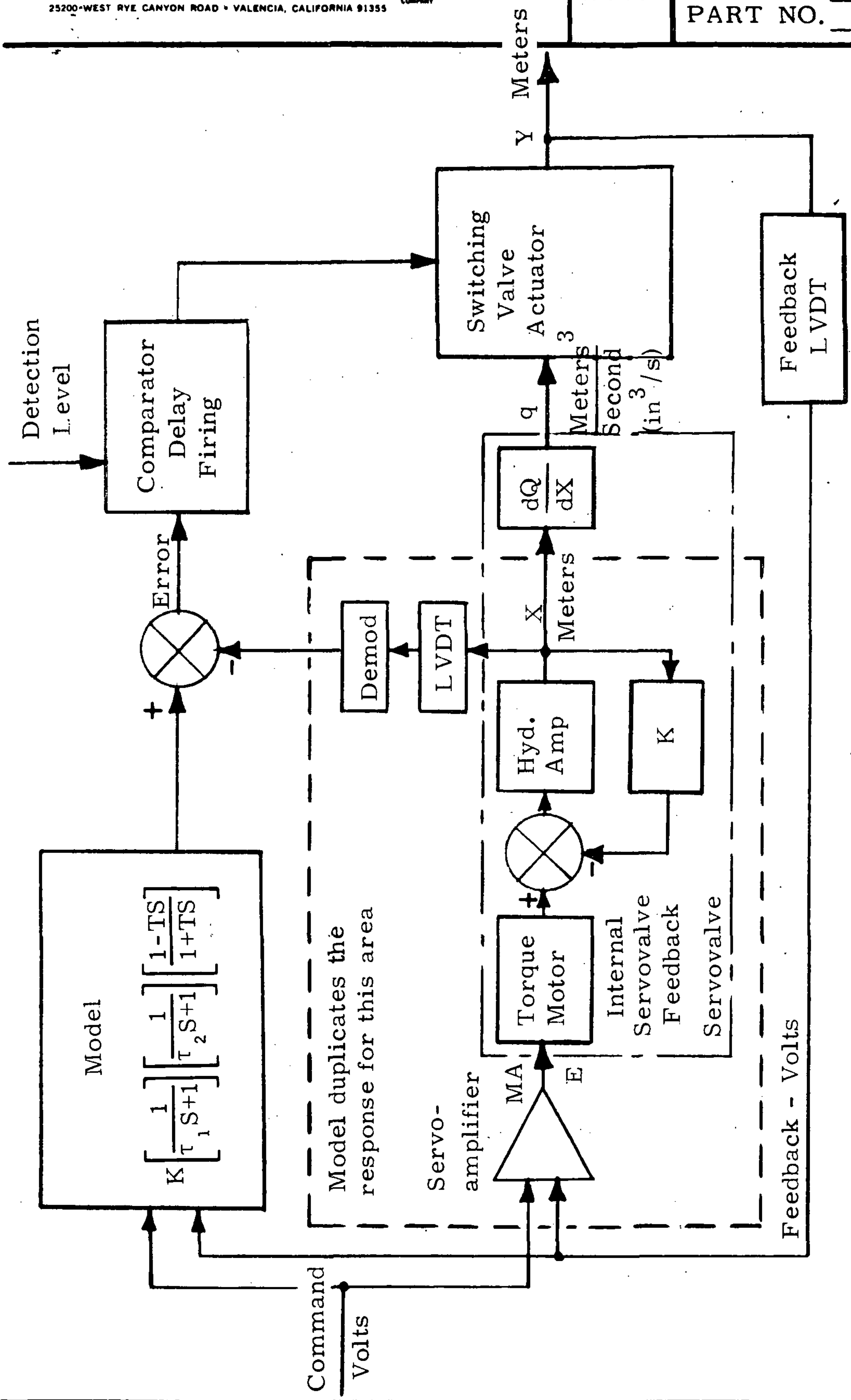

Figure 2-1. Detection Concept

in the servovalve torque motor creating a torque which, in turn, causes a displacement X of the second-stage spool. This displacement is fed back through the internal spring K, creating a counter torque and cancelling out the coil torque. A stroke or displacement of the second-stage spool is thus established which is directly proportional to current E. An LVDT is attached to the second-stage spool and converts the spool displacement X into a voltage. The command and feedback signals are also applied to the model. The model generates a voltage proportional to the difference between the command and feedback signal. For a perfect model, this signal would be identical to the LVDT signal. These signals are then compared, and if any difference exists an "ERROR" is created as shown in Figure 2-1. This "ERROR" will be created from any failure or drifts in the servovalve, servo-amplifier or model. The comparator simply compares the value of this "ERROR" to a predetermined detection level, a fixed voltage. When an "ERROR" exists which is as large as the detection voltage for a given time, a failure is computed.

Figure 2-2 is a System Block Schematic. This shows the two parallel channels required for one-fail/operate redundancy. A summer/limiter is shown in series and in front of the servoamplifier. This was necessary because the modification to the servovalve for attaching the LVDT inadvertently removed the stops from the spool. The limiter prevents over-stroking and possible damage to the

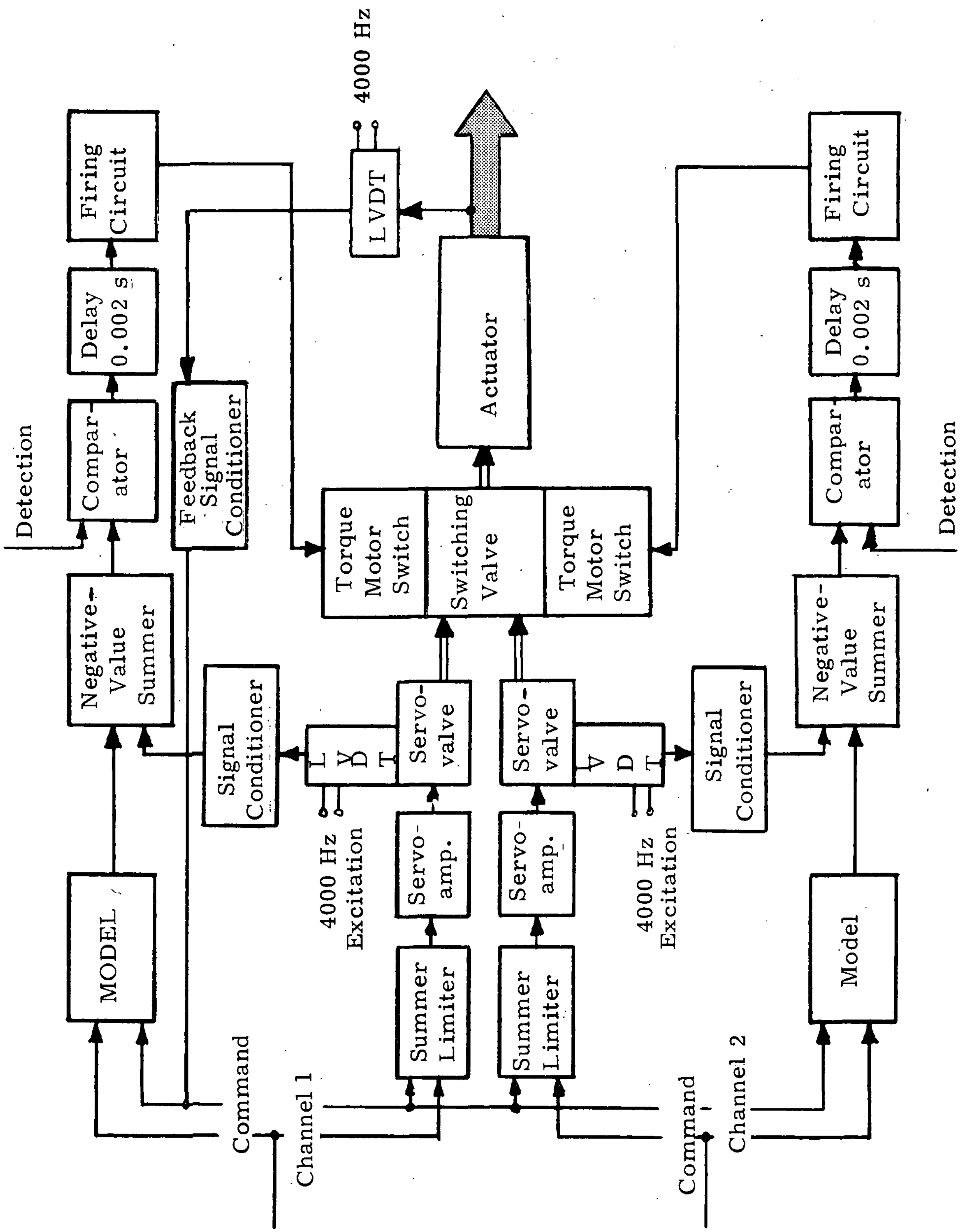

Figure 2-2. System Block Schematic

servovalve. The negative-value summer, which adds the servovalve/LVDT and model signals, will always have a negative output. This negative output simplifies the detector/comparator. The delay circuit will hold the failure for 0.002 seconds to assure that the failure is not a momentary transient. A transistor is used as a switch to drive the torque motor.

Figure 2-3 shows the five subassemblies which make up the total package; the servoactuator, electronic console, model/comparator, load actuator and the load control unit. The 110-V ac and function generators are the only required input.

2.2 Component Description

2.2.1 Servoactuator

The servoactuator is active-standby with one-fail/operate, fail/fixed capability. It consists of a single actuator (one hydraulic system) with two servovalves, one switching valve, and two torque motor switches. Figure 2-4 is a schematic of the system, Figure 2-5 is an actuator cross section, and Figure 2-6 is a photograph of the servoactuator.

For normal operation (no failures), the servoactuator will operate with servovalve #1 ported to the actuator and servovalve #2 blocked by the switching valve spool. The switching valve is controlled by the torque motor switch.

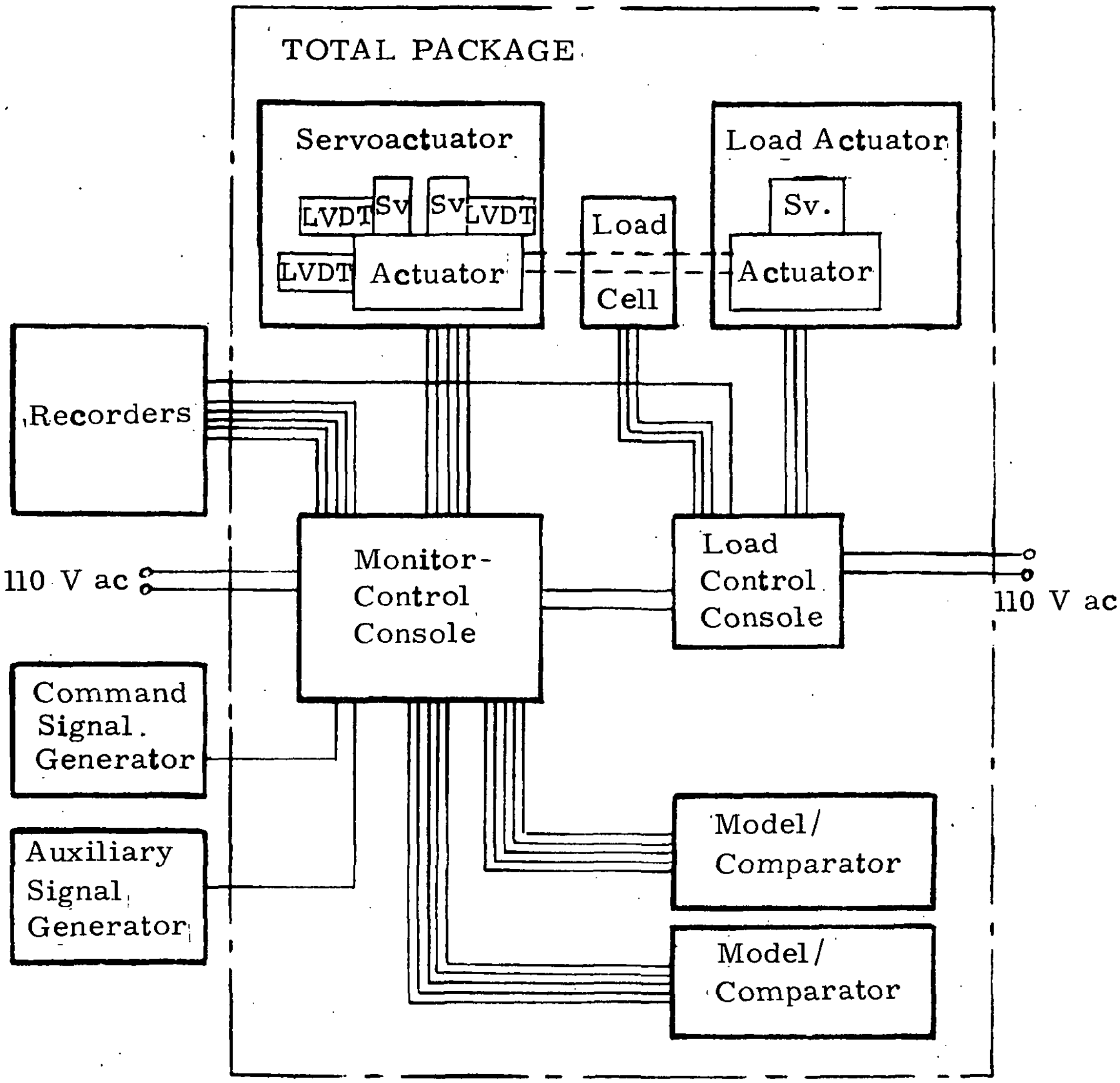

Figure 2-3. System Arrangement

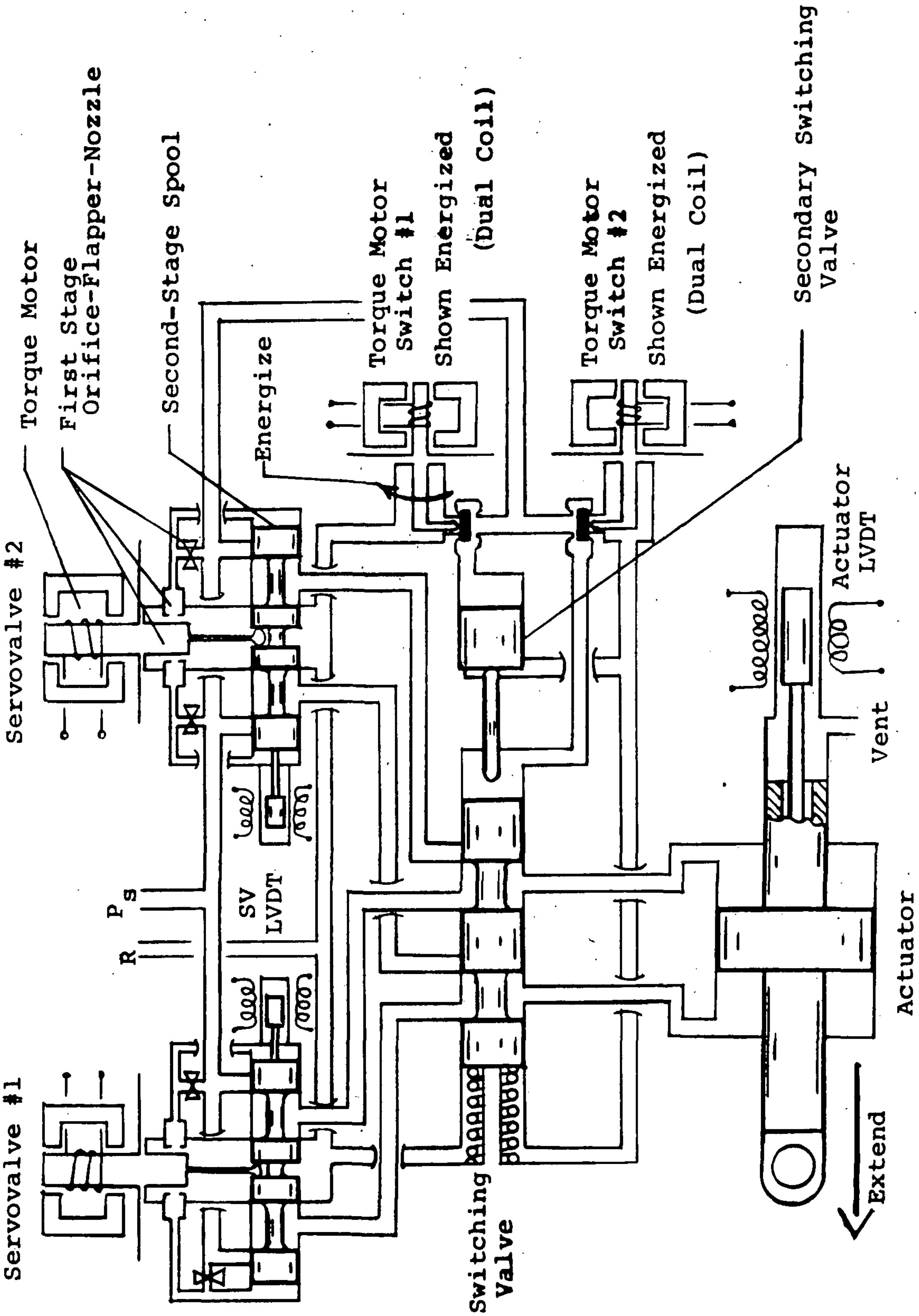

Figure 2-4. Servoactuator Schematic

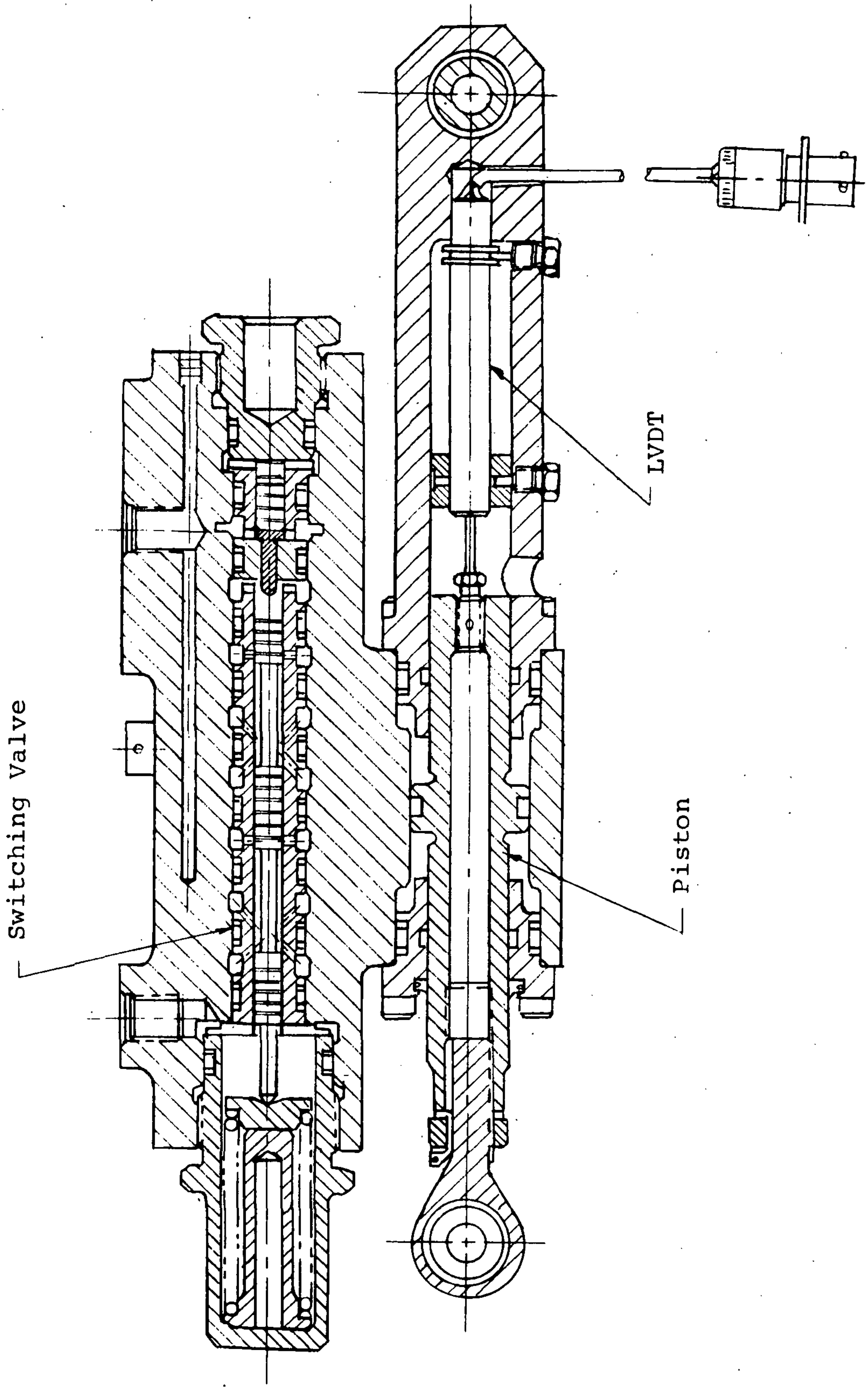

Figure 2-5. Servoactuator

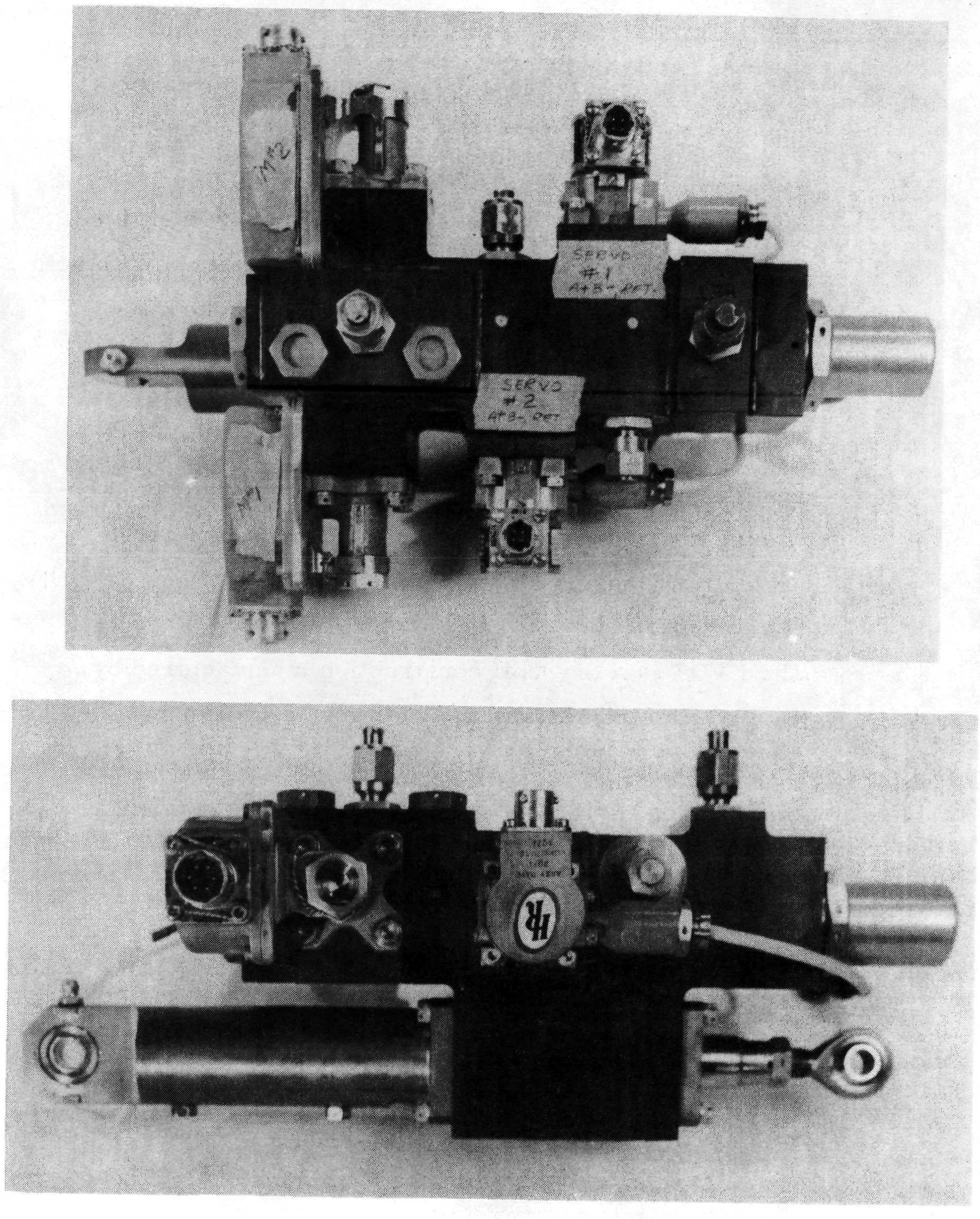

Figure 2-6. Servoactuator

This switching valve is a 3-position, spring-returned spool valve. With the #1 torque motor switch energized, flow will go from servovalve #1 to the actuator. With torque motor switch #1 de-energized, and #2 energized, flow will go from servovalve #2 to the actuator. With both de-energized, the cylinder ports will be blocked.

The servovalve is a standard HYDRAULIC RESEARCH Model 25A production valve (P/N 22252920-002), modified by adding the LVDT to the second stage and replacing the one end cap. Figure 2-7 shows the servovalve/LVDT assembly.

The LVDT is a dry-coil construction manufactured by Kavlico Electronics, Inc., Chatsworth, California.

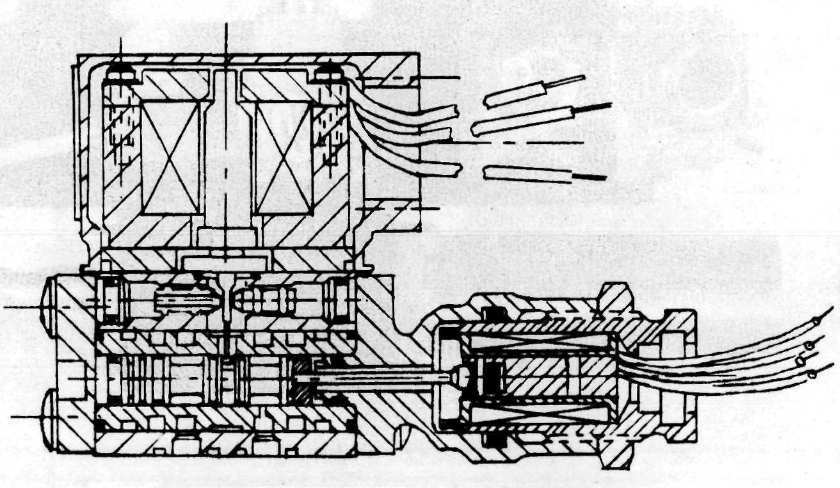

Figure 2-7. Servovalve/LVDT

The torque motor switch is a specially developed, fast-acting electric/hydraulic switch. Appendix I is a trade study on the torque motor and solenoid. Within 5 ms, the switch will cause the hydraulic pressure to start decreasing when the valve is de-energized. This switch was developed from a HYDRAULIC RESEARCH propellant valve. The initial requirement was for a bifilar coil for arc suppression, which consists of two coils simultaneously wound on one bobbin, and prevents arcing by slowing down the decay of the field when the coil is de-energized. This bifilar requirement has a significant effect on the switching time. Solenoid switching time was excessive but the torque motor was able to meet the switching time. The bifilar requirement was later removed. Figure 2-8 is a picture of the torque motor switch.

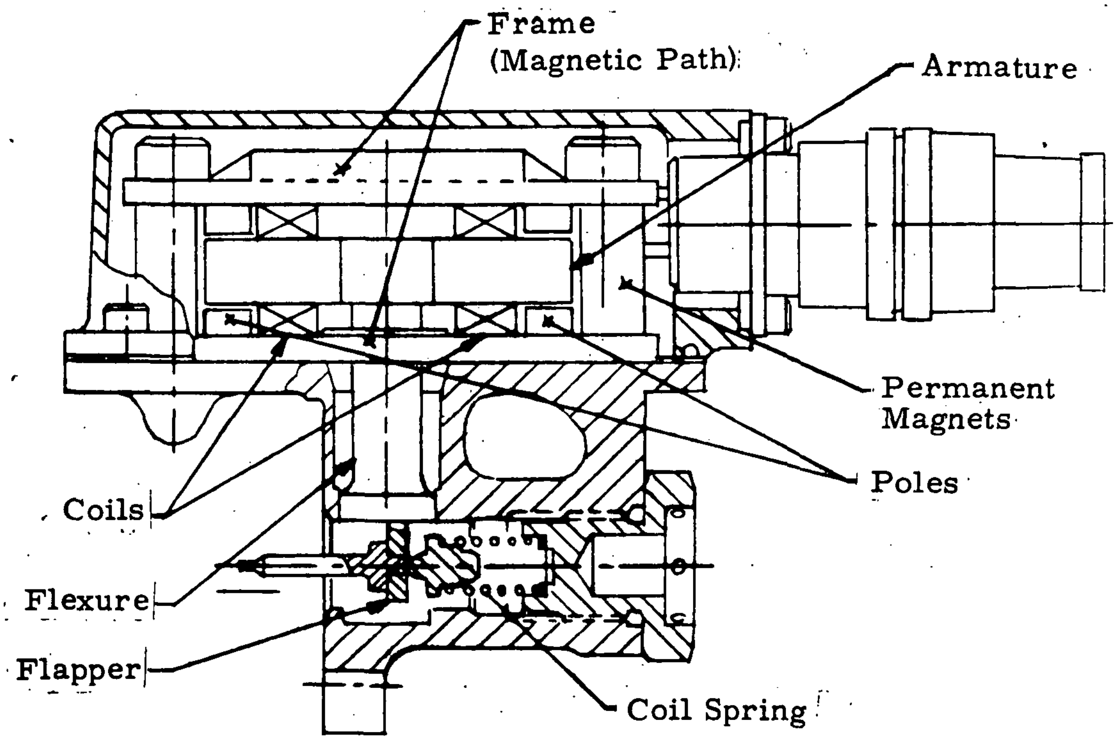

Figure 2-8. Torque Motor Switch

The theory and operation of this torque motor is the same as that of a servovalve torque motor, only the size is different. A torque motor for a servovalve will have an output in ounces, while this torque motor supplies approximately 8 lb.

Figure 2-9 is a schematic of the torque motor. The permanent magnet establishes the polarity of the poles. Energizing the coil will reverse the polarity of these poles and cause the armature to move. The flexure tube provides a spring rate as well as a positive seal. Since the closing response is important in this design, a coil spring was added on the flapper to provide more de-energizing force.

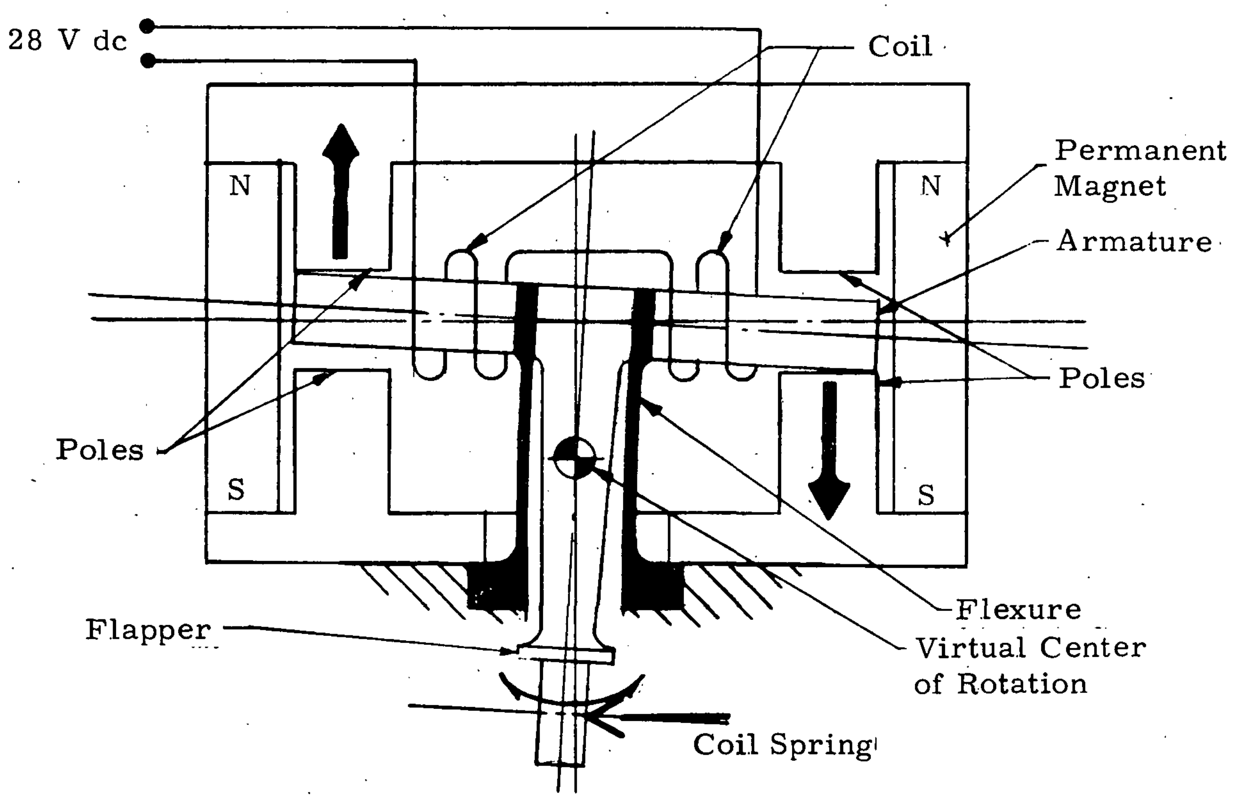

Figure 2-9. Torque Motor Schematic

2.2.2 Electronics

2.2.2.1 Model/Comparator

The model/comparator subassembly contains the model, the LVDT signal conditioner, the comparator and the circuit to energize and de-energize the torque motor (firing circuit). Figure 2-10 is a photograph of the model/comparator. There are two identical model/comparator circuit boards, both mounted on a roll-out shelf. The signal conditioner component for the servovalve LVDT is shown in detail in Figure 2-11.

Details of the model are shown in Figure 2-12. This model was made to match the frequency response of the servovalve. In order to match the step response of the model to that of the servovalve, it was necessary to match the frequency response up to where the amplitude ratio was less than -10 decibels (dB), about 400 Hz.

This model consists of three functions. The first function is of a first-order lag with a time constant of 500 Hz. The summing amplifier is in this function, which sums the command and feedback signals. A rate limit is also part of this function. This is a diode circuit around the summing amplifier which simulates the first-stage saturation exhibited by the servovalve.

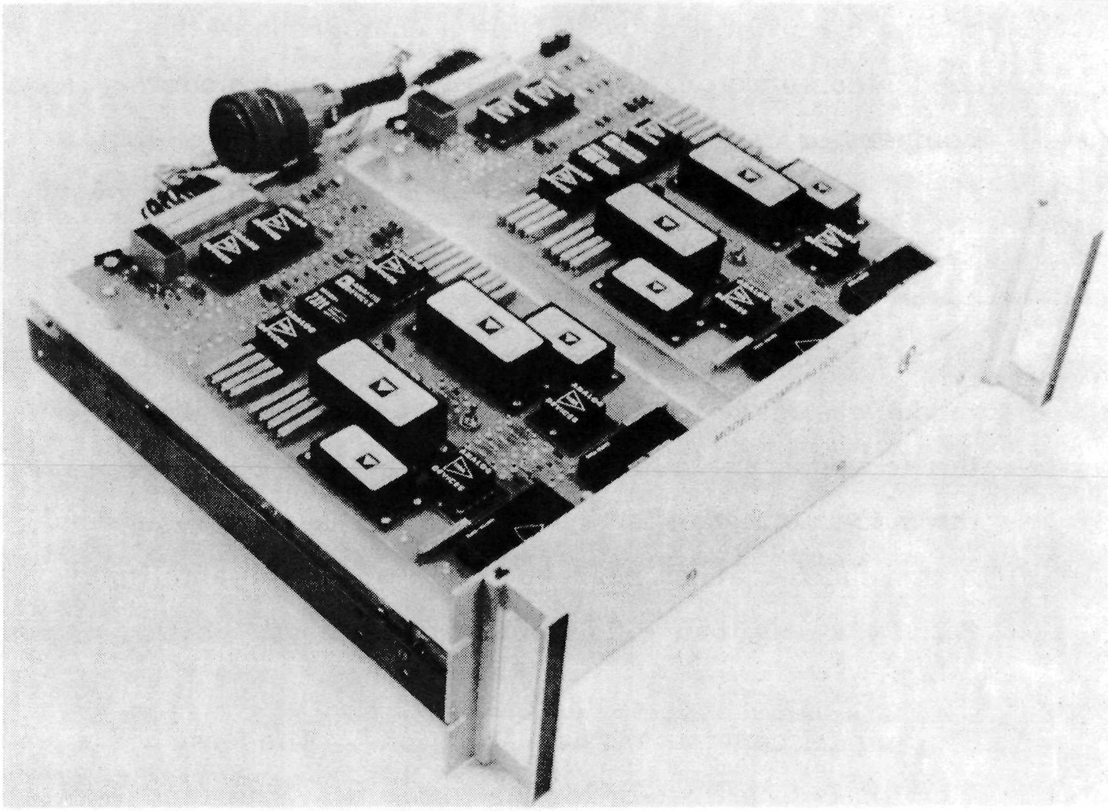

Figure 2-10. Model/Comparator Photograph

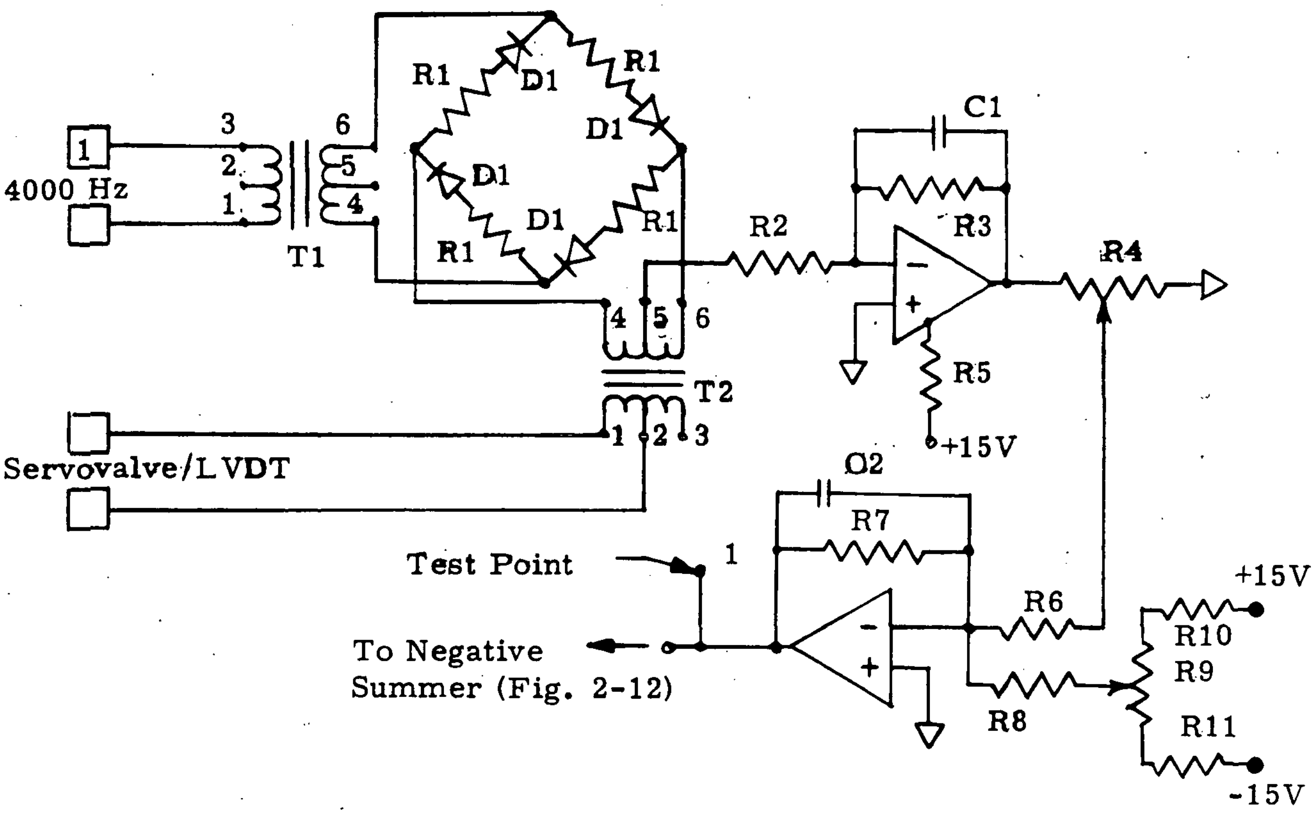

Figure 2-11. Signal Conditioner

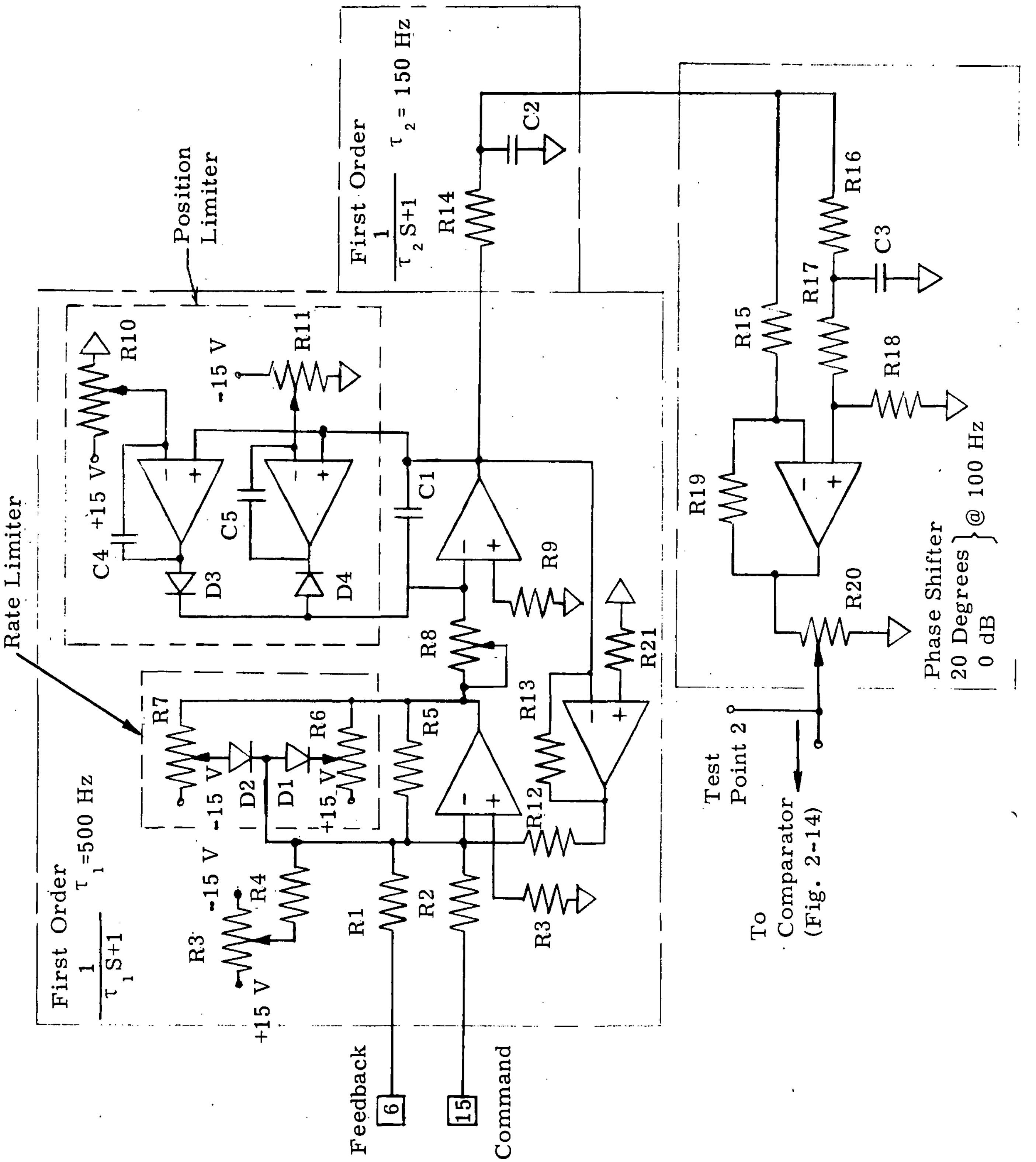

Figure 2-12. Model Schematic

A position limiter, consisting of a diode circuit around the integrating amplifier, is also included to simulate the function of the servovalve spool stops. An integrator is used with the diode to make a sharper cutoff. This function is an active circuit consisting of five operational amplifiers.

The second function in the model is that of a first-order lag with a time constant of 150 Hz. This is a passive circuit consisting of a resistance/capacitance (RC) circuit.

The third function in the model provides phase shift with no attenuation (20 degrees @ 100 Hz). This function was necessary to make the phase shift of the model match that of the servovalve to simulate a hydraulic delay. This function is part active and part passive. An active summer and an RC integrator are used.

The signals from the model and the servovalve/LVDT are compared (subtracted) at the negative-value summer. The servovalve/LVDT signal is inverted in the signal conditioner (Figure 2-11) and added to the model signal to provide the output as shown in Figure 2-13. Regardless of the sign of the sum of the signals, the output of the summer is always negative. The output of the negative-value summer is then compared to the detection level to determine if the mismatch is sufficient to be considered a failure. Figure 2-14 shows the details of this circuit.

The active comparator, used to compare the output of the summer to the detection level, is a standard comparator manufactured by Burr-Brown Research Corp., Tucson, Arizona. The detection level is applied as one input and is a positive fixed value. With no error signal, the output of the comparator will be +6 V. As a signal is applied to the second input from the negative summer, the output will remain constant at +6 V. When the negative summer signal becomes equal but opposite in sign to the detection level, the output will switch to -6 V ac. There is a small hysteresis band built into the comparator. If the negative summer signal drops below the detection level, the comparator output will change back to +6 V.

The delay and firing circuit is shown in Figure 2-15. It is a simple integrator with a limit on its output voltage, and has a 0.002-second delay which will assure that the failure actually exists. The firing circuit will cause the transistor (2N4347) to stop conducting when the voltage is +7 V. This signal will latch and require the manual reset circuit to re-energize the torque motor switch.

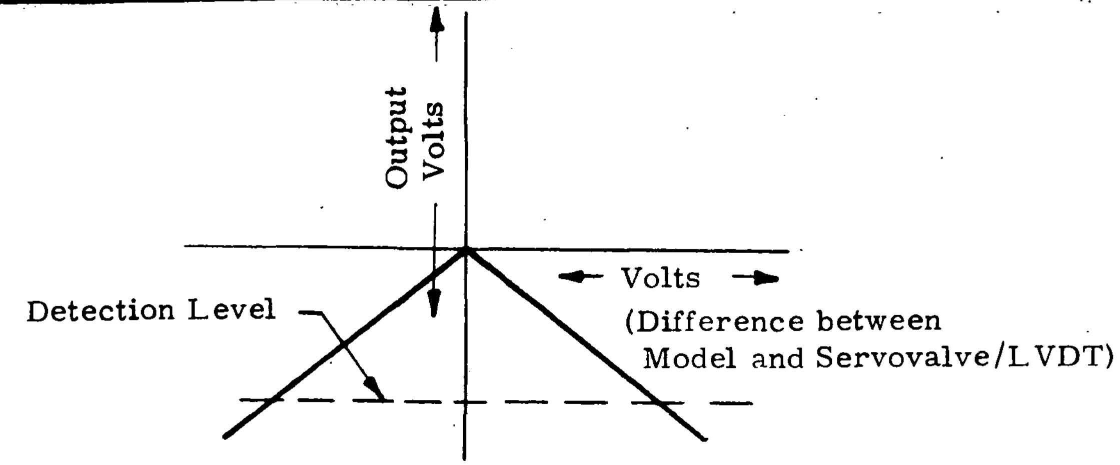

Figure 2-13. Negative Summer

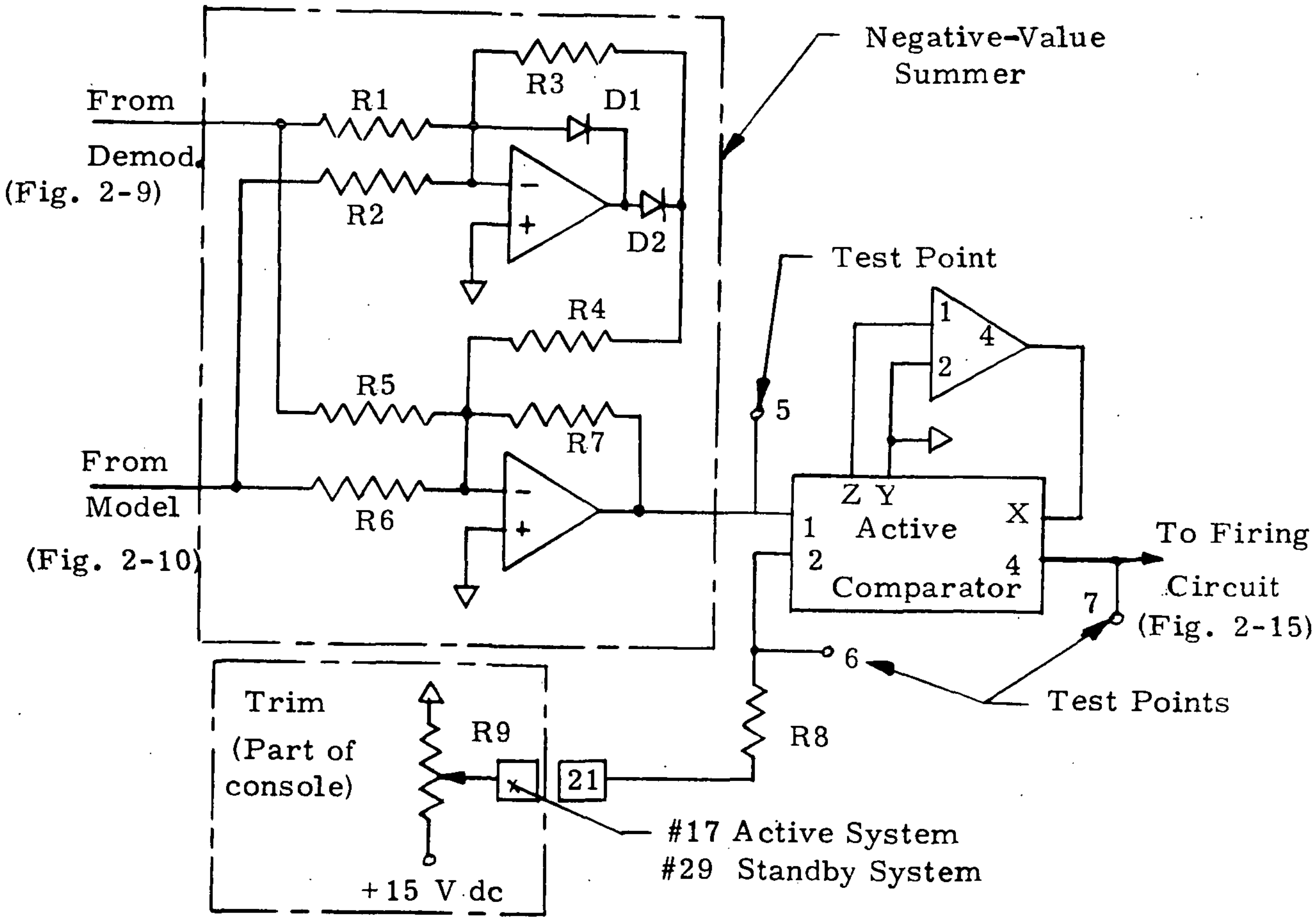

Figure 2-14. Comparator Schematic

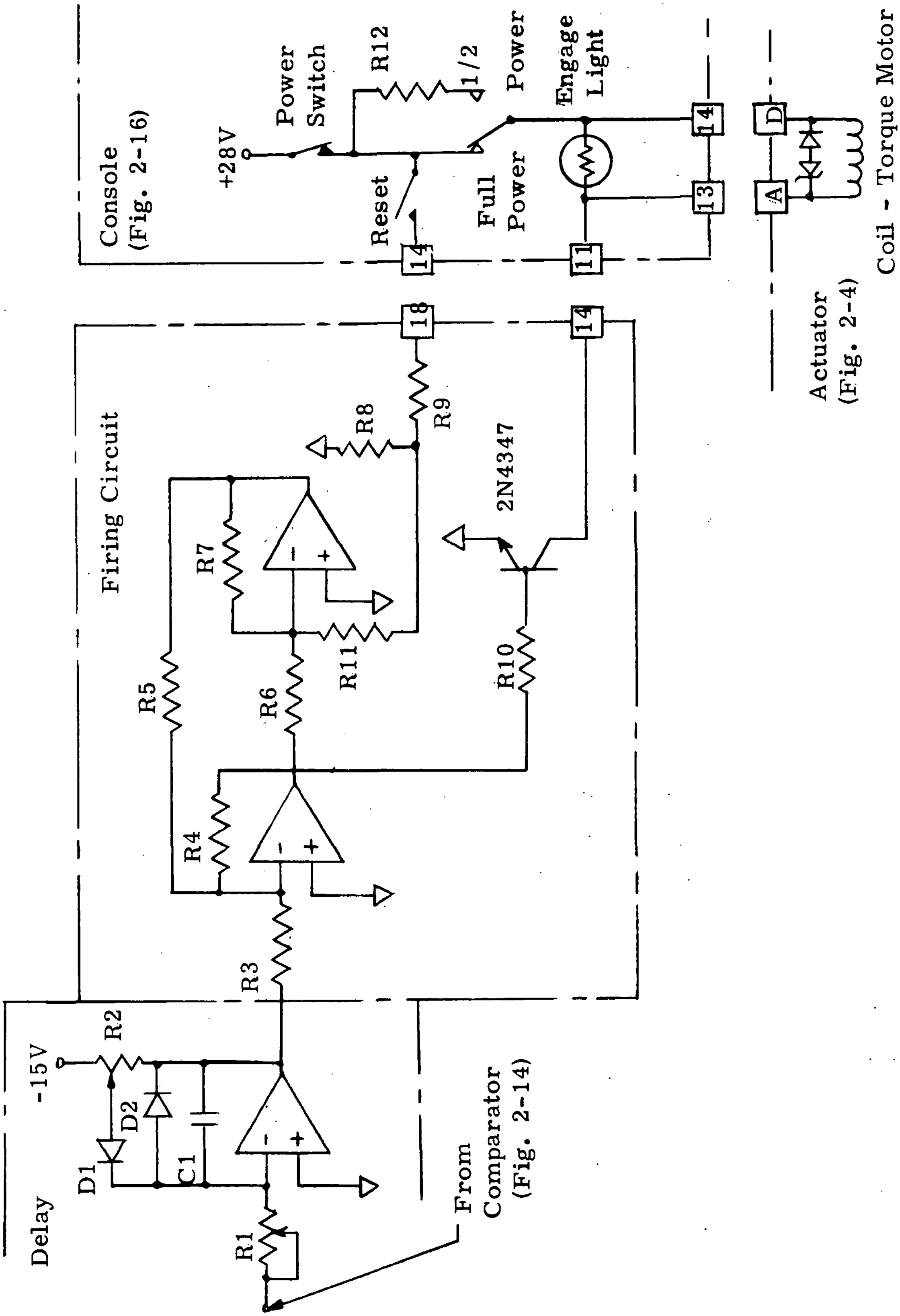

Figure 2-15. Delay/Firing Circuit Schematic

2.2.2.2 Electronic Console

A wiring diagram and photograph of the electronic console are shown in Figures 2-16 and 2-17. The summer limiter and servoamplifier are shown in Figure 2-18, and the frequency generator in Figure 2-19. Figure 2-20 shows the feedback demodulator. The 28-V power supply is a Model C214, obtained from Wanlass, Inc., Fort Washington, Pennsylvania, and the ±15-V power supply is a Model OA15DO.5 from ACDC Electronics, Inc., Oceanside, California. Figure 2-21 shows the wiring between the console, servoactuator and model/comparator.

2.2.3 Load Fixture

It was desirable to test the servoactuator under various loads, allowing the effect, if any, of loading on switching transients and detection level to be examined. Figure 2-22 is a schematic of the loading system.

The redundant actuator is mounted on a fixture and its output drives into a load cell. The load actuator supports the other end of the load cell and controls the load on the redundant actuator. The load cell provides a feedback signal which is the actual load, and the command signal (LVDT in the redundant actuator) provides the desired load. Figure 2-23 shows the load which is a function of the actuator position.

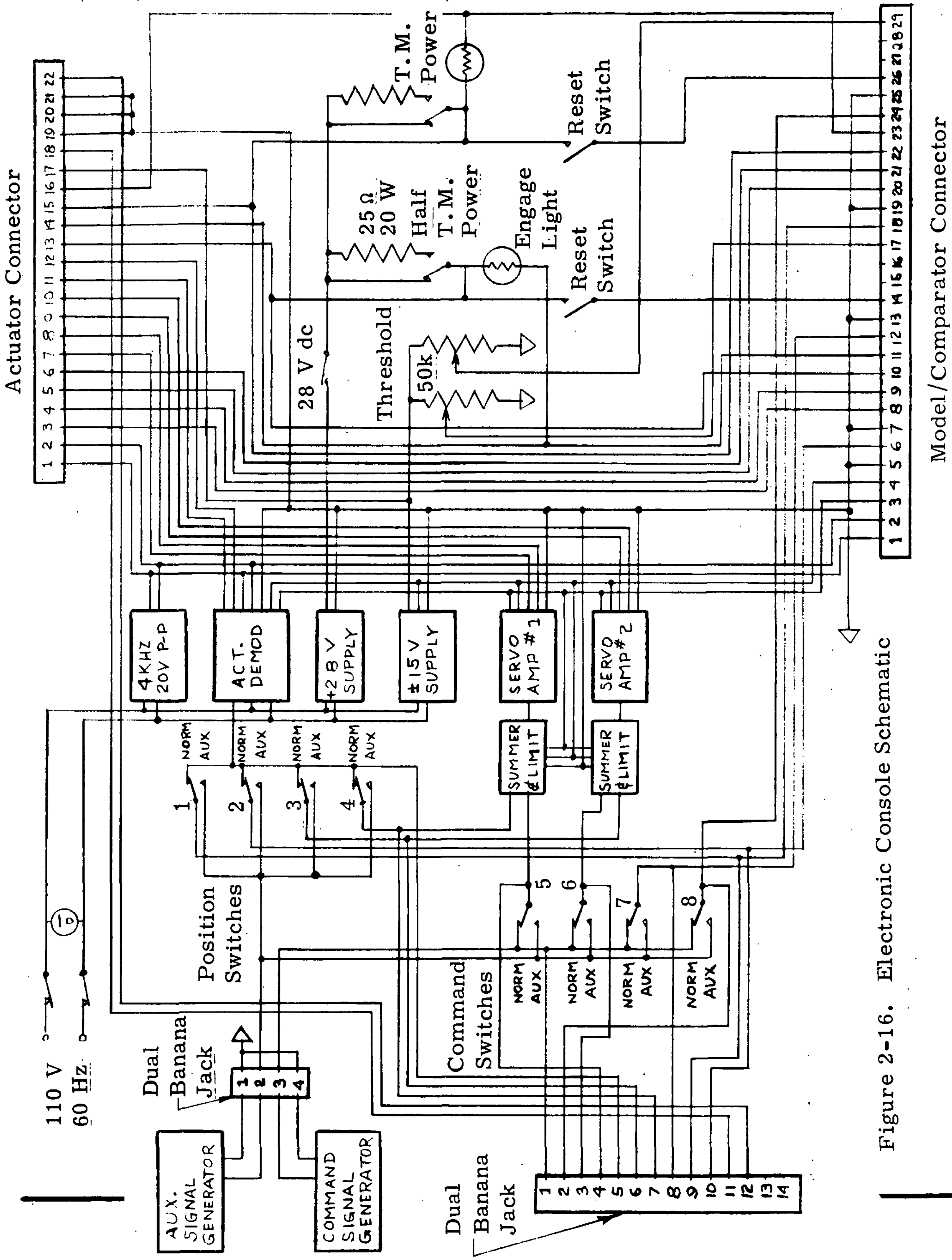

Figure 2-16. Electronic Console Schematic

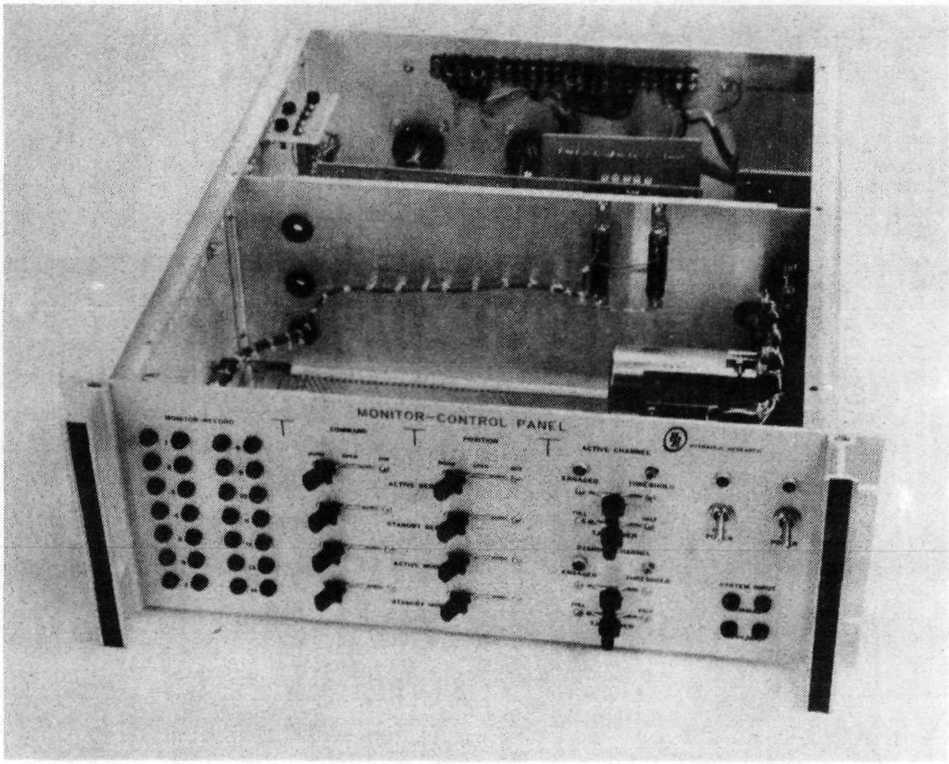

Figure 2-17. Electronic Console Photograph

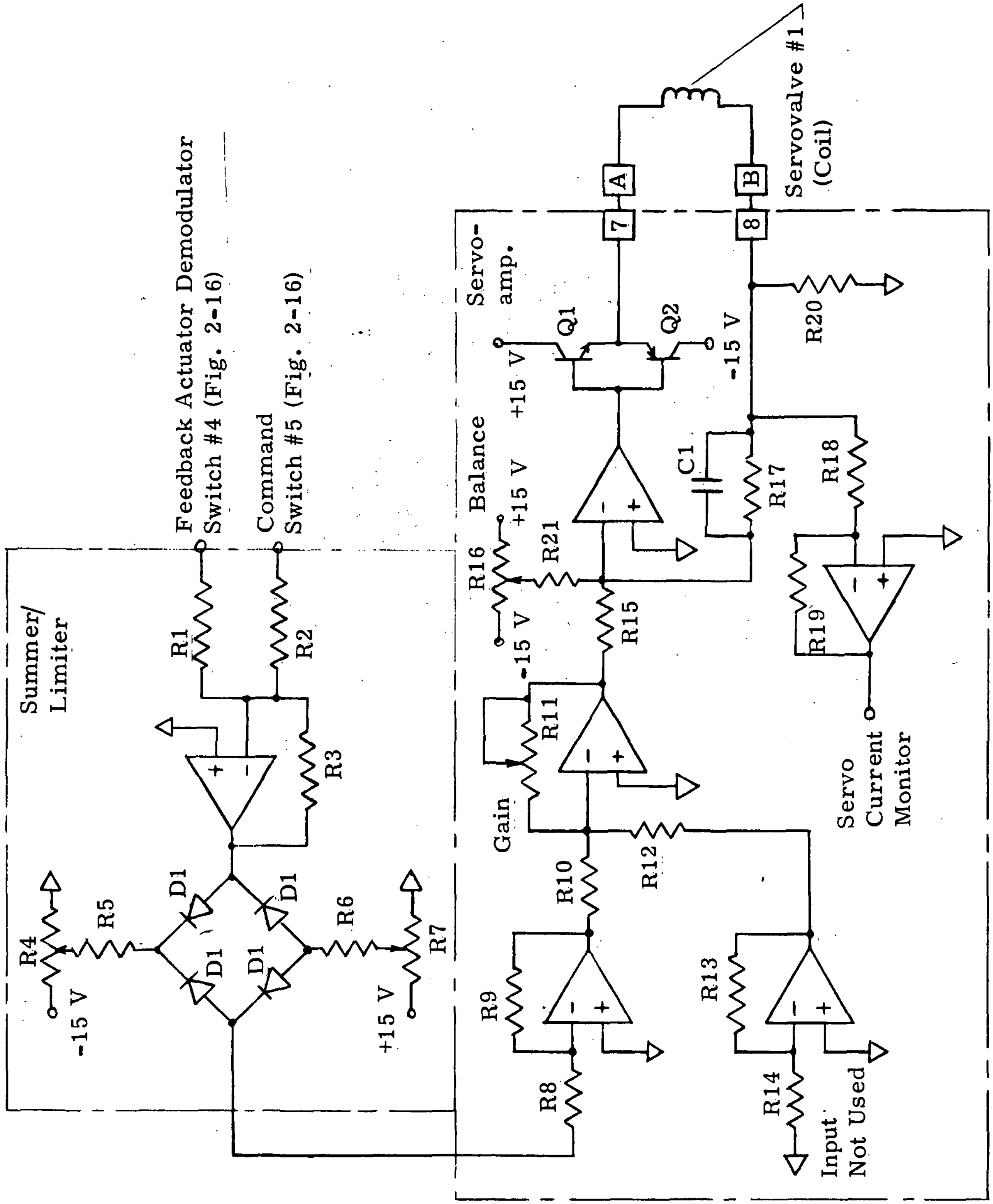

Figure 2-18. Summer/Limiter & Servoamplifier Schematic

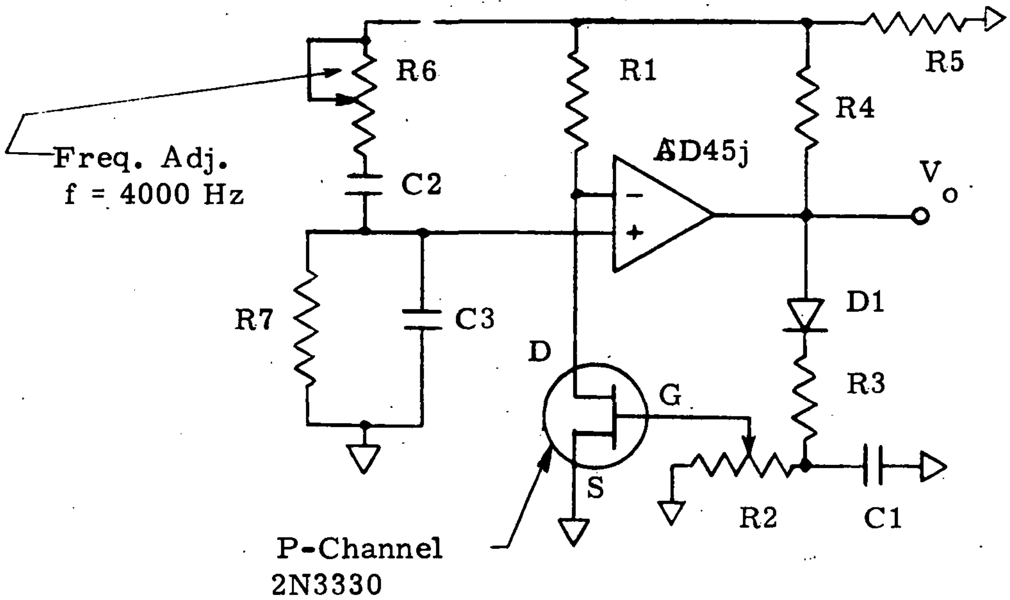

Figure 2-19. Frequency Generator Schematic

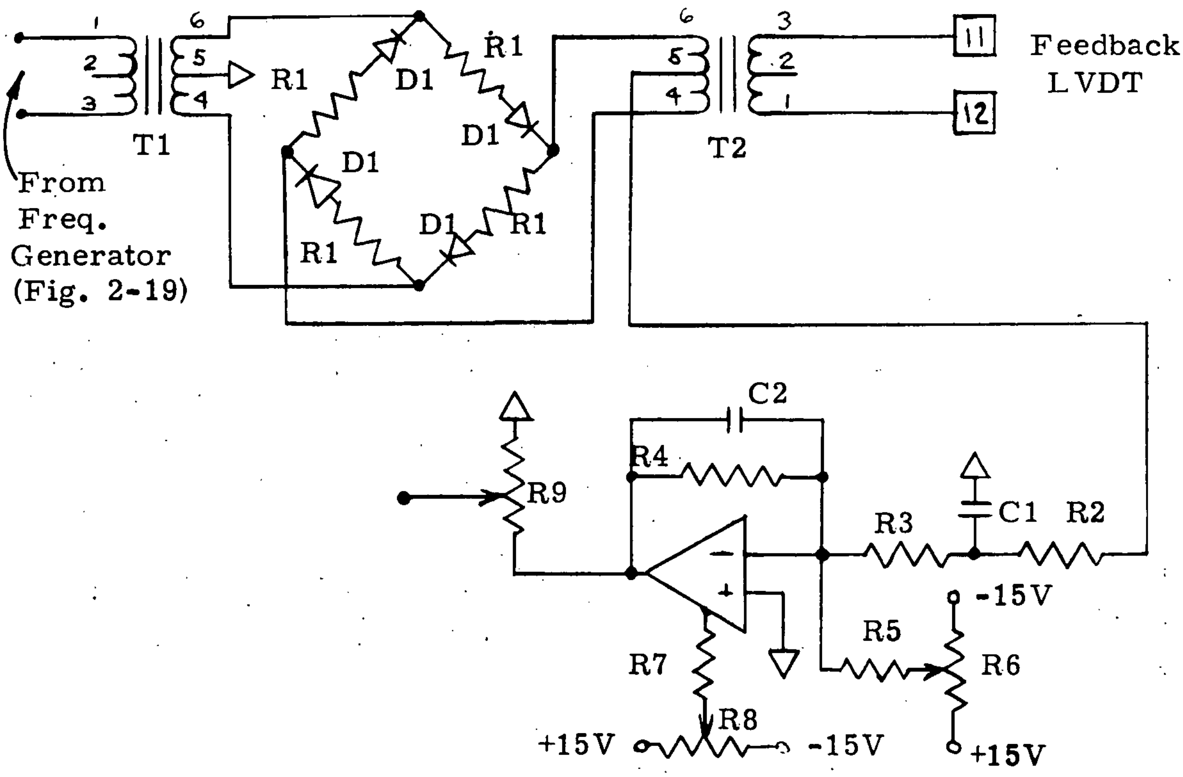

Figure 2-20. Feedback Demodulator

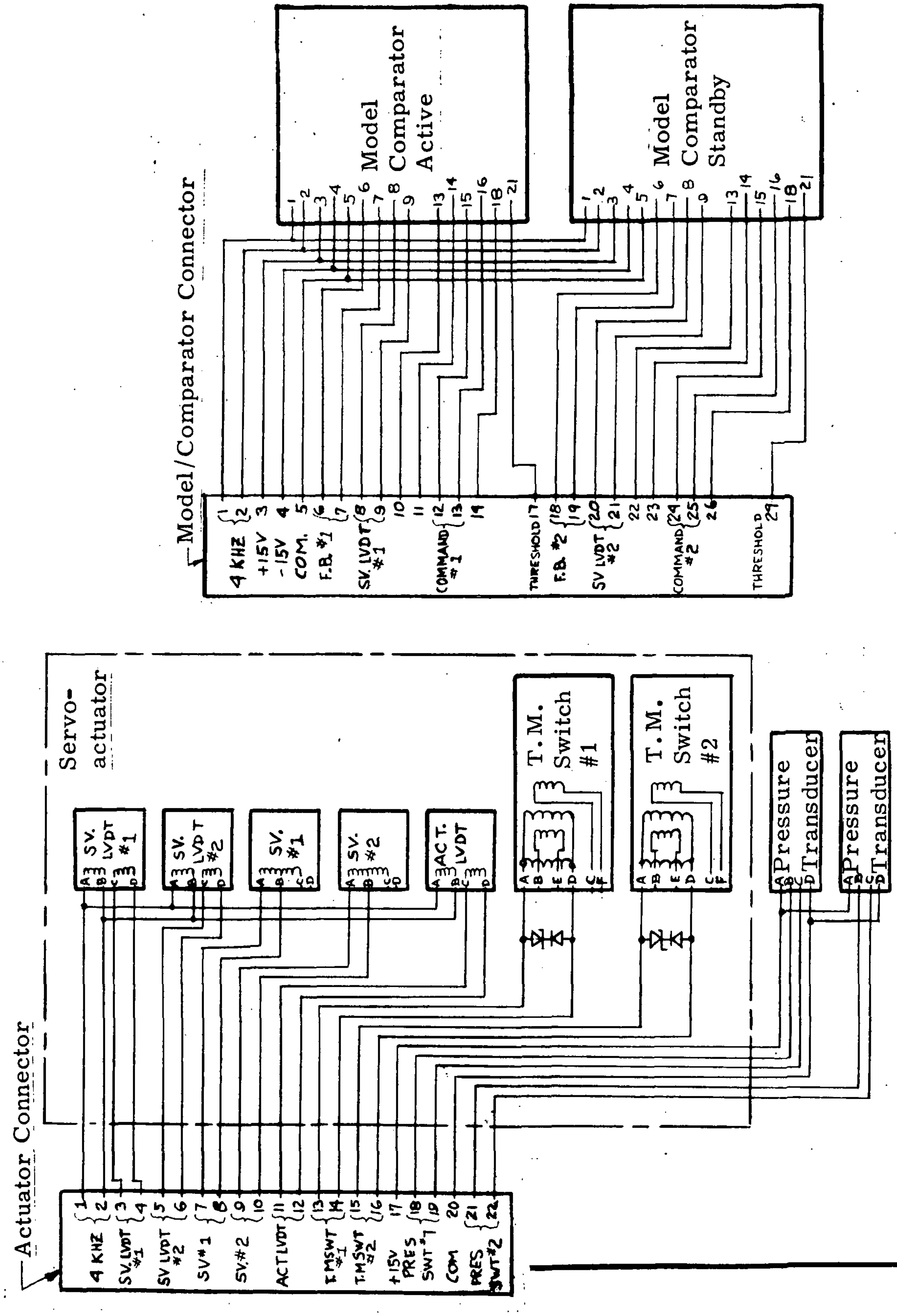

Figure 2-21. Actuator/Model Wiring

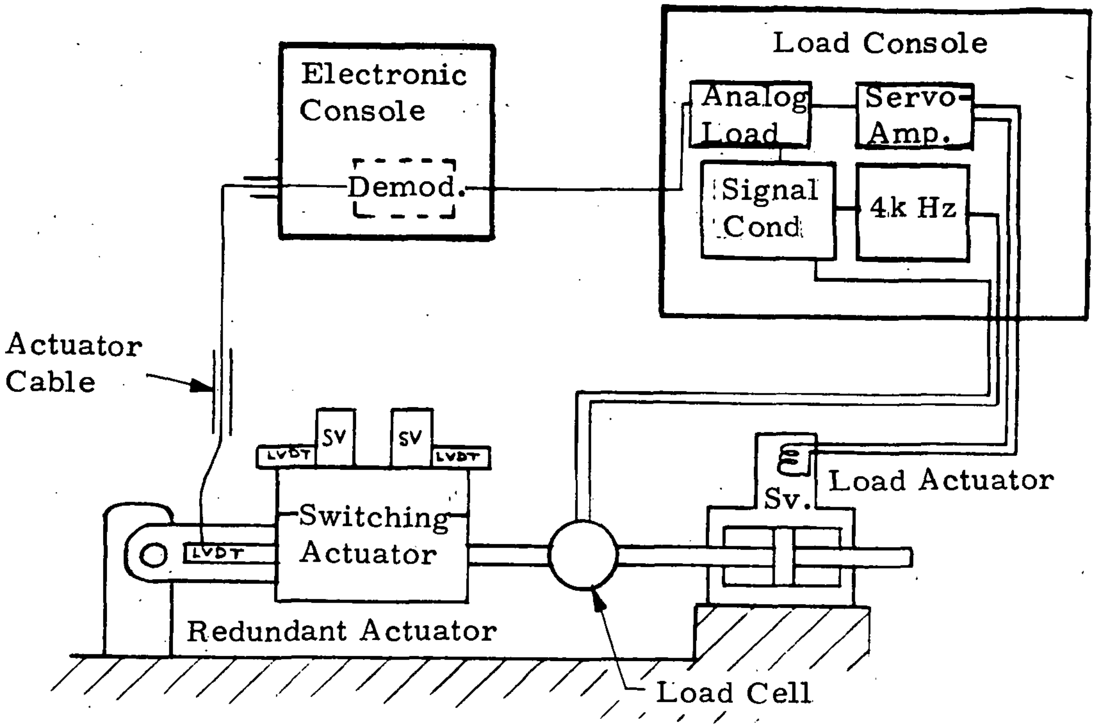

Figure 2-22. Loading System

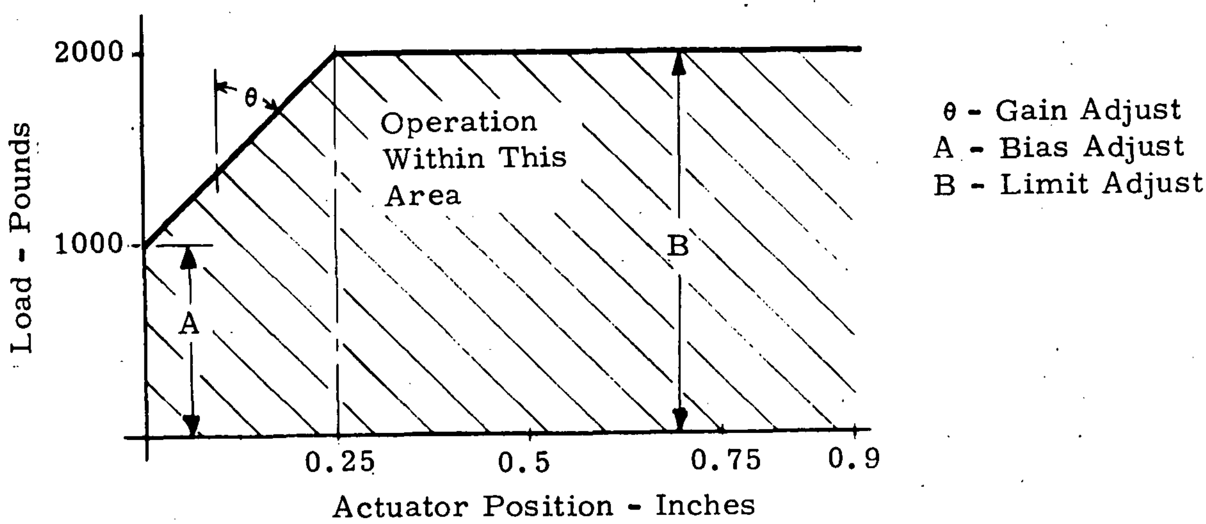

Figure 2-23. Load Characteristic

The load actuator is a 3.58-cm^2 (0.555-in^2) actuator with a stroke of 2.41 cm (0.95 in) total. A HYDRAULIC RESEARCH Model 25 servovalve (P/N 2225920-002) is used to control the actuator. The load cell is a ±2500-lb strain-type gage.

The load console, shown in Figure 2-22, contains the electronic control for the load fixture. This console takes its command from the electronic console and schedules a load as a function of the redundant actuator's position. The signal conditioner schematic is shown in Figure 2-24, the analog load curve schematic in Figure 2-25, and the servoamplifier in Figure 2-26. The frequency generator was shown in Figure 2-19.

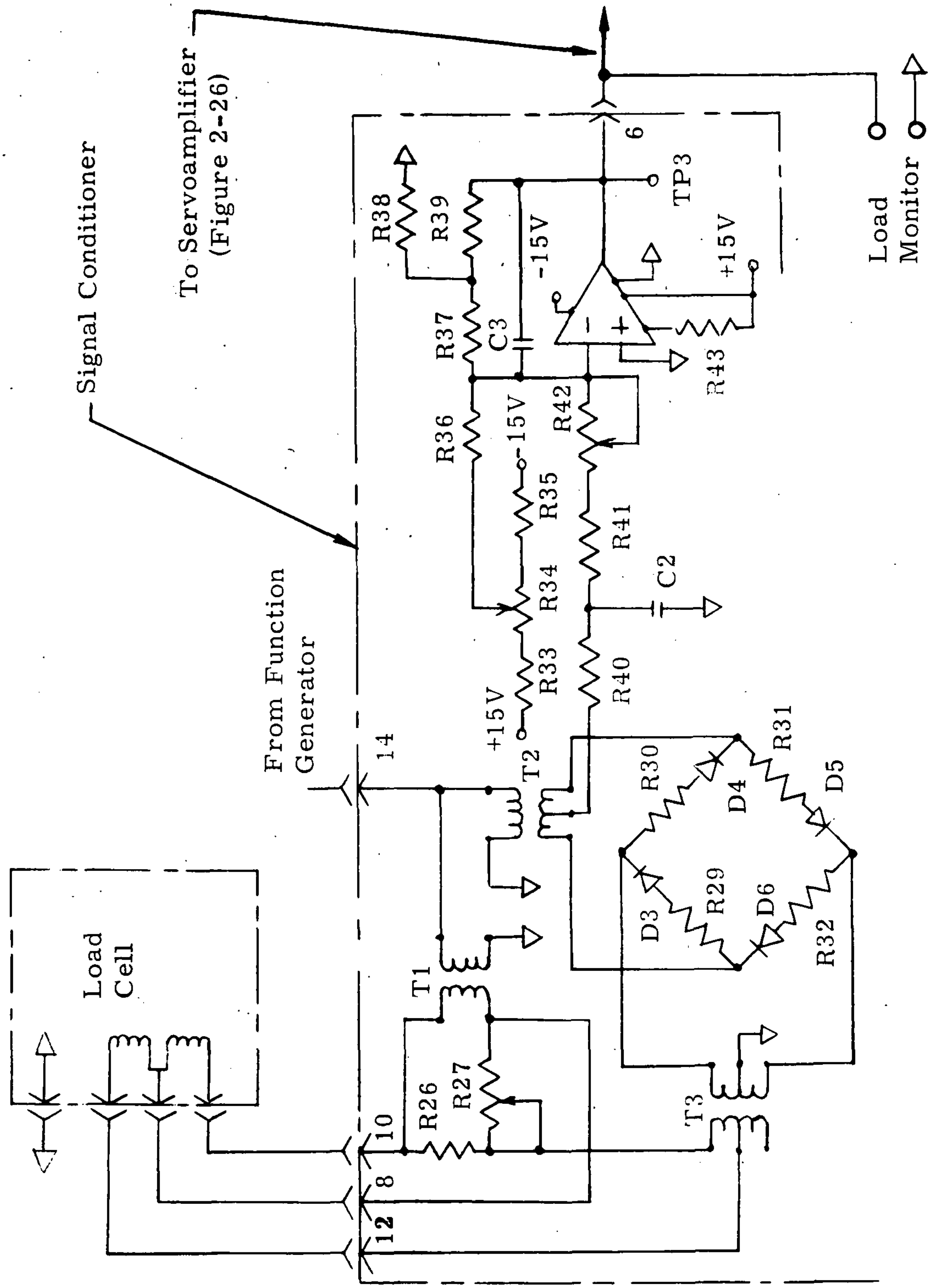

Figure 2-24. Signal Conditioner

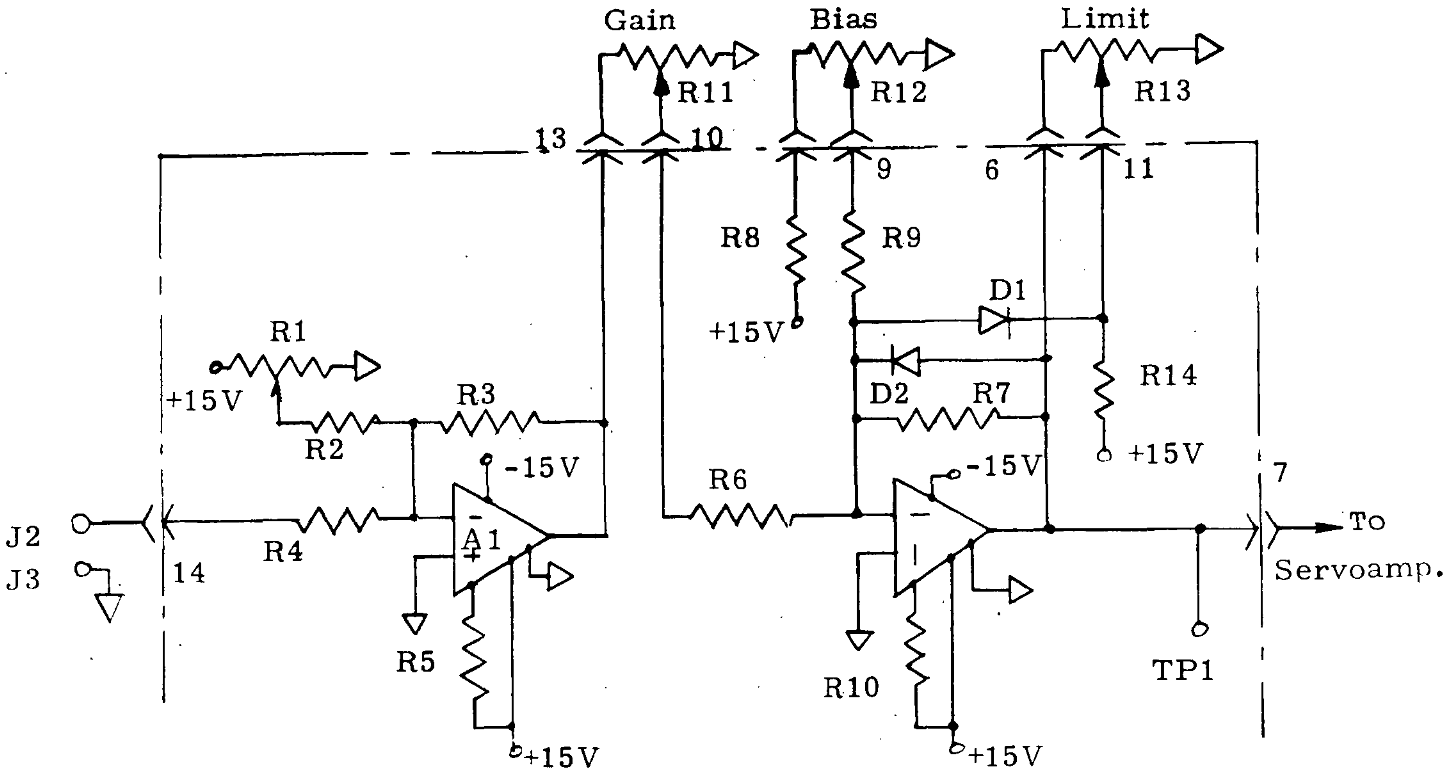

Figure 2-25. Analog Load Curve

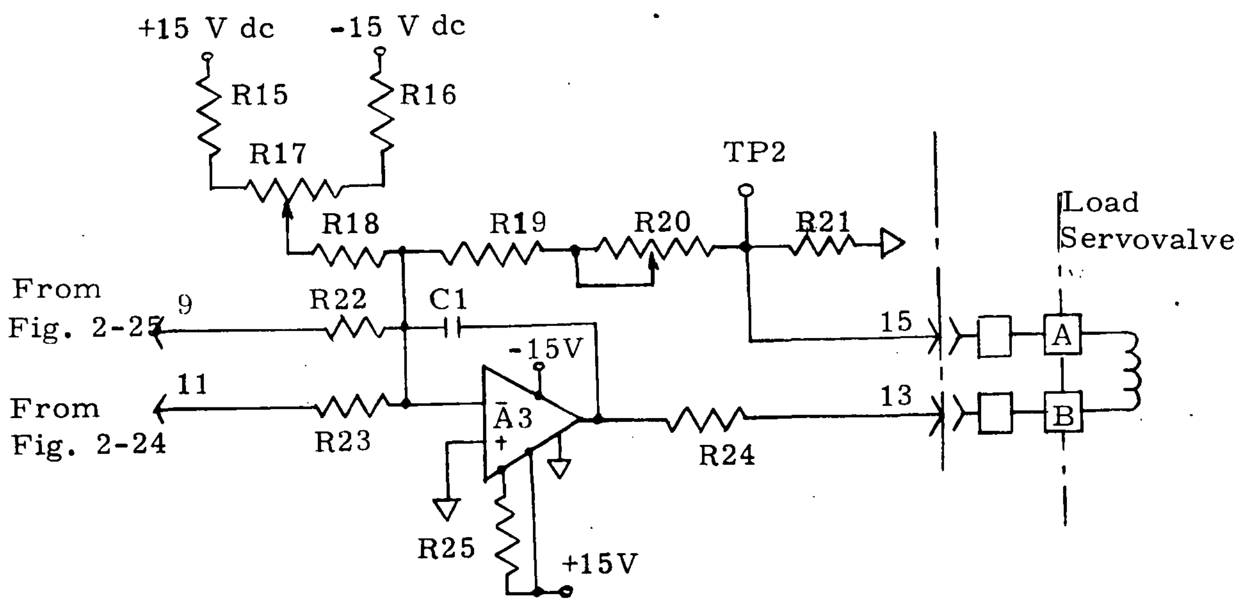

Figure 2-26. Servoamplifier

3.0 CALCULATIONS

3.1 Gain

Figure 3-1 (page 39) is a diagram of the servoactuator. The servovalve current input is 10 mA, the output stroke is ±0.25 cm, and maximum flowrate is 52.175 cm^3/s, resulting in the following:

$$K1 = 0.025 \text{ cm}/10 \text{ mA} = 0.00254 \text{ cm/mA}$$

$$K2 = \frac{52.175 \text{ cm}^3/\text{second}}{0.025 \text{ cm}} = 2050 \frac{\text{cm}^3/\text{second}}{\text{cm}}$$

Feedback gains, H1 and H2, are derived as follows:

Actuator stroke = ±1.142 cm
Output voltage = ±1.51 V

resulting in

$$H1 = 1.51 \text{ V}/1.142 \text{ cm} = 1.32 \text{ V/cm}$$

With a command voltage of ±5 V:

$$H2 = 5 \text{ V}/1.51 \text{ V} = 3.3 \text{ V/V}$$

The actuator area is:

$$A = 3.58 \text{ cm}^3$$
$$(0.555 \text{ in}^2)$$

The desired loop gain is 20 Hz, or 125.66 rad/s. System loop gain is the product of all of the gains around the loop, as follows:

$$\text{Loop gain} = K_{sv} \bullet K1 \bullet K2 \bullet H1 \bullet H2 \bullet 1/A$$

$$K_{sv} = \frac{(\text{Loop Gain})\ A}{K1 \bullet K2 \bullet H1 \bullet H2}$$

$$= \frac{125.66 \bullet 3.58}{0.00254 \bullet 2050 \bullet 3.31 \bullet 1.3} = 19.77$$

From this, let

$$K_{sv} = 20$$

Therefore

$$\text{Loop gain} = 20 \bullet 0.00254 \bullet 2050 \bullet 3.31 \bullet 1.3/3.58$$

$$= 127.097 \text{ rad/second}$$

3.2 LVDT

The small clearance around the moving slug may cause a reduction in the performance of the servovalve. The differential pressure (ΔP) required to force the oil by the slug at 70 Hz was calculated as follows:

Flowrate = Slug Area • Velocity

where

A_s = slug area = $11.977 \bullet 10^{6} m^{2}$

At a frequency of 70 Hz:

Maximum Velocity = 2π 70X

where

X = Maximum Stroke = 0.000254m (0.010 in)

resulting in

Maximum Velocity = $2\pi\ 70(0.000254)$

therefore

$$\text{Flow} = 11.977 \bullet 10^{6}(2\pi)\ 70(0.00025)$$
$$= 1.338 \bullet 10^{-6}\ m^{3}/\text{second}$$

To find the ΔP, the lap flow equation was used, in that

$$\Delta P = \frac{Q \bullet 12 \bullet \ell \bullet cP}{\pi \, (10^3) \, dB^3}$$

$$= 2.727 \bullet 10^5 \ N/m^2$$

$$(39.54 \ lb/in^2)$$

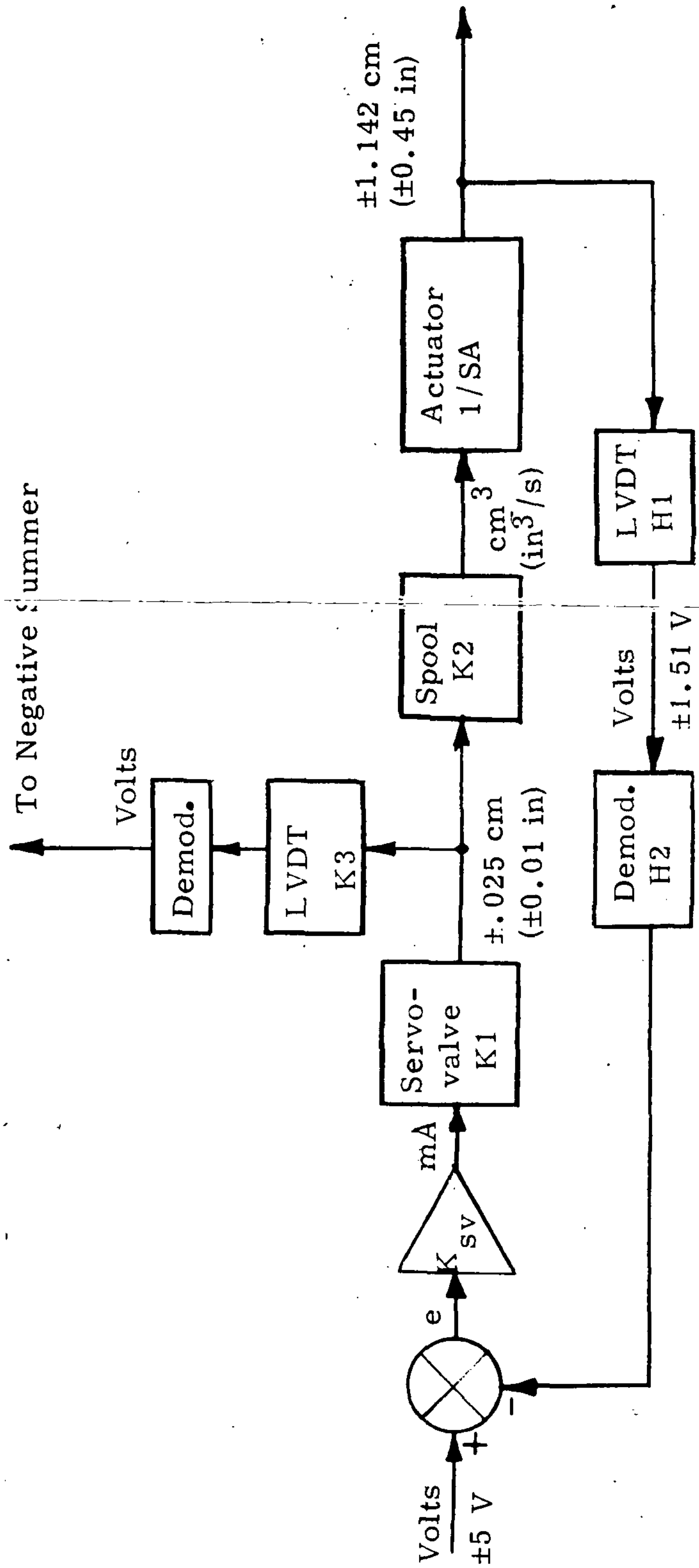

Figure 3-1. Servoactuator Block Diagram

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4.0 TEST RESULTS

4.1 Components

4.1.1 Torque Motor Switch

4.1.1.1 Torque Motor Switch Physical Constants

The requirements for the torque motor switch are:

1. De-energizing time: 0.007s @ 70°F and 20.68×10^{-6} N/m^2 (3000 lb/in^2; pressure change at the poppet).

2. Stroke at the poppet: 1.778×10^{-4} m (0.007 in)

3. Maximum current: 1.0 A @ 28 V dc

The measured physical constants for the torque motors are shown in Tables 4.1 and 4.2.

TABLE 4.1

Torque Motor # 1

P/N 48002010, Body No. 10

Final Assembly and Test Data:

Torque Motor Gaps After Plating:

Gap A = 3.05×10^{-4} m (0.012 in)

Gap B = 0.889×10^{-4} m (0.0035 in)

Gap C = 3.05×10^{-4} m (0.012 in)

Gap D = 0.889×10^{-4} m (0.0035 in)

Manifold pin length = 0.890×10^{-2} m (0.386 in)

Torque Motor:

1.	Flexure tube spring rate	= 36.9×10^{6} N/m (5357 lb/in)
2.	Flapper spring rate	= 24.6×10^{6} N/m (3570 lb/in)
3.	Armature breakaway force	= 111.2 N (25 lb)
4.	Flapper stroke	= 3.86×10^{-4} m (0.0152 in)
5.	Flapper breakaway force	= 114.6 N (32.5 lb)

Poppet and Seat Assembly:

1.	Poppet stroke	= 1.778×10^{-4} m (0.007 in)
2.	Poppet seat pre-load	= 161.7 N (24 lb)
	Flapper deflection	= 1.17×10^{-4} m (0.0046 in)
3.	Flapper spring load	= 33.4 N (7.5 lb)
4.	Flow at 3000 lb/in^2 gage press.	= 3.41×10^{-3} m^3/min (0.9 gal/min)

TABLE 4.1 (Continued)

Pull-in voltage:

@ 20.68×10^6 N/m^2 (3000 lb/in^2 gage press.);

inlet open = 11.5 V

Drop-out voltage:

@ 20.69×10^6 N/m^2 (3000 lb/in^2 gage press.);

inlet closed = 6.2 V

Response:

@ 1.0 A and 20.68×10^6 N/m^2 (3000 lb/in^2 gage press.);

inlet on = 10 ms

inlet off = 7 ms

Coil resistance = 27.7 Ω @ 70°F

Dielectric strength (600 V ac) 30 s

Insulation resistance (500 V dc) = 200k MΩ

Polarity: Pin A+, D-; valve shall open

TABLE 4-2

Torque Motor #2

P/N 480002010, Body No. 13

Final Assembly and Test Data

Torque Motor Gaps after Plating:

Gap A = 3.31×10^{-4} m (0.013 in)

Gap B = 0.762×10^{-4} m (0.003 in)

Gap C = 3.31×10^{-4} m (0.013 in)

Gap D = 0.762×10^{-4} m (0.003 in)

Manifold pin length = 0.970×10^{-2} m (0.382 in)

Torque Motor:

1.	Flexure tube spring rate	= 35.5×10^{6} N/m (5150 lb/in)
2.	Flapper spring rate	= 26.34×10^{6} N/m (3820 lb/in)
3.	Armature breakaway force	= 142.3 N (32.0 lb)
4.	Flapper stroke	= 4.06×10^{-4} m (0.016 in)
5.	Flapper breakaway force	= 153.5 N (34.5 lb)

Poppet and Seat Assembly:

1.	Poppet stroke	= 1.78×10^{-4} m (0.007 in)
2.	Poppet seat pre-load	= 106.3 N (23.9 lb)
	Flapper deflection	= 1.34×10^{-4} m (0.0053 in)
3.	Flapper spring load	= 15.56 N (3.5 lb)
4.	Flow at 3000 lb/in^2 gage press.	= 3.41×10^{-3} m^3/min (0.9 gal/min)

TABLE 4-2 (Continued)

Pull-in voltage:

@ 20.68×10^6 N/m^2 (3000 lb/in^2 gage press.);

inlet open = 12.0 V

Drop-out voltage:

@ 20.68×10^6 N/m^2 (3000 lb/in^2 gage press.);

inlet closed = 6.0 V

Response:

@ 1.0 A and 20.68×10^6 N/m^2 (3000 lb/in^2 gage press.);

inlet on = 11 ms

inlet off = 7 ms

Coil resistance = 27.9 Ω @ 70°F

Dielectric strength (600 V ac) 30 s

Insulation resistance (500 V dc) = 225k MΩ

Polarity: Pin A+, D-; valve shall open

4.1.1.2 Torque Motor Switching Transients-Fixture

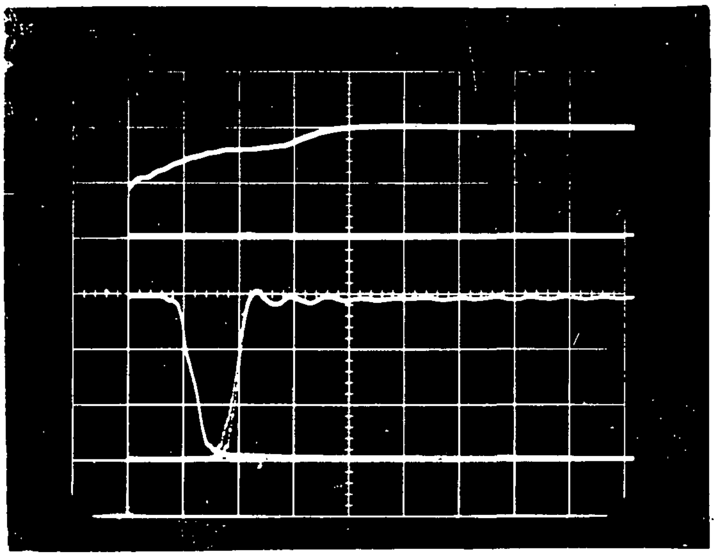
The torque motors were tested on a hydraulic fixture which contained the actual poppet hardware. Figures 4-1 and 4-2 are photographs of the oscilloscope tracing. The de-energizing time for torque motor #1 (Body #10) was 0.007 s with a suppressed back electromagnetic force (EMF) of 40 V. The de-energizing time for torque motor #2 is 0.007 s with a 40 V back EMF.

Date: 11-11-71

Torque Motor #1

Response:

Arc Suppression - Clipping Diodes
1 A Current
3000 lb/in^2 Inlet Pressure



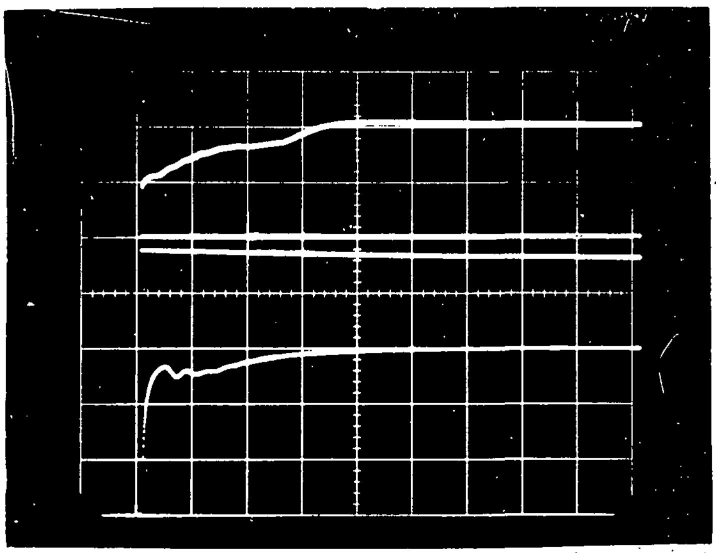
Scale:
Vert. = 0.5 A/cm
Hor. = 5 ms/cm

Current Tracing

Pressure Tracing

Scale:
Vert. = 1000 lb/in^2 per cm
Hor. = 5 ms/cm

Open = 11 ms
Close = 7 ms



Scale:
Same as above

Current Tracing

Back EMF Tracing

Scale:
Vert. = 20 V/cm
Hor. = 5 ms/cm

Suppressed Volts = 40 V

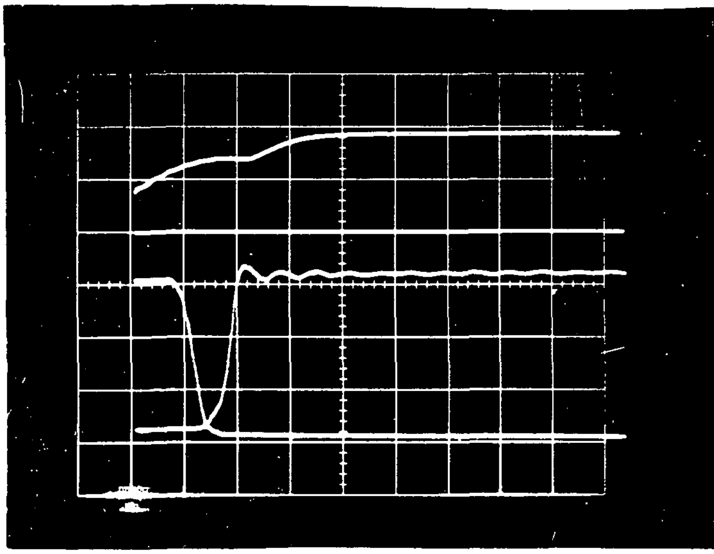
Figure 4-1. Oscilloscope Tracing

Date: 11-11-71

Torque Motor #2

Response:

Arc Suppression - Clipping Diodes
1 A Current
3000 lb/in^2 Inlet Pressure



Scale:

Vert. = 0.5 A/cm
Hor. = 5 ms/cm

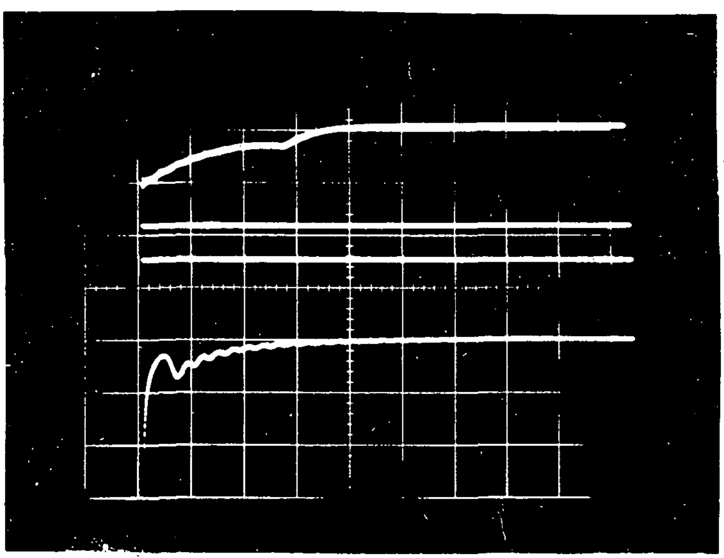
Current Tracing

Pressure Tracing

Scale:

Vert. = 1000 lb/in^2 per cm
Hor. = 5 ms/cm

Open = 11 ms
Close = 7 ms



Scale:

Same as above

Current Tracing

Back EMF Tracing

Scale:

Vert. = 20 V/cm
Hor. = 5 ms/cm

Suppressed Volts = 40 V

Figure 4-2. Oscilloscope Tracing

4.1.1.3 Torque Motor Switching Transient-Servoactuator

The torque motor was tested in the servoactuator. In order to determine the actual transient, the pressures in the cylinder were recorded. A hardover command was applied to each channel but in the opposite direction. The channel-1 servovalve was commanded hardover in the extend direction and the actuator was against the extend stop. With torque motor #1 energized, the pressure at C1 was 3000 lb/in^2 and the pressure in C2 was zero. On switching, both pressures went to 1500 lb/in^2 and the actuator moved towards retract. Figure 4-3 shows the oscilloscope tracing with torque motor #1 de-energized, giving a switching time of 6 ms with the "zener" clipping diode. This is shorter than the 0.007 s on Figures 4-1 and 4-2, but is not an inconsistency because:

1. Figure 4-1 pressure starts to fall at 0.003 s.

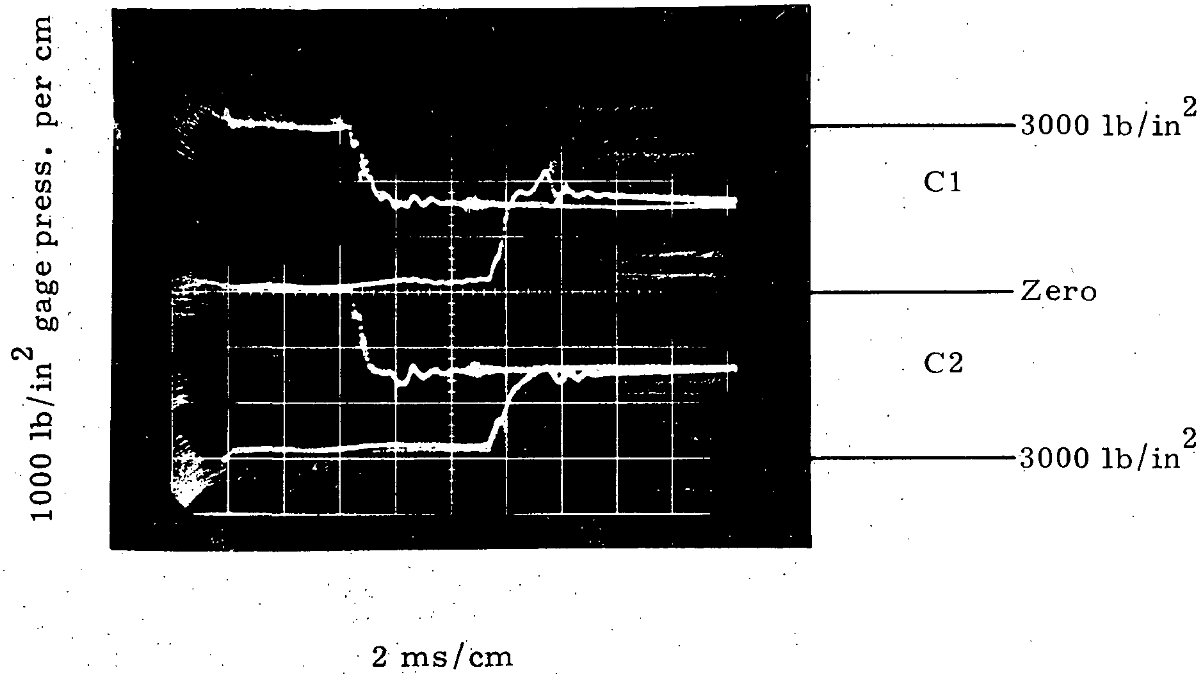
2. Switching valve will start moving at approximately 2000 lb/in^2.

3. Test fixture is different than actual servoactuator.

Torque Motor #2 Energized

Torque Motor #1 Energized then De-Energized

Arc Suppression - Clipping Diodes



Switching Time

ON $\left(\begin{array}{l}\text{C1 Zero to 1500 lb/in}^2\\ \text{C2 3000 to 1500 lb/in}^2\end{array}\right)$ 0.0105 s

OFF $\left(\begin{array}{l}\text{C1 3000 to 1500 lb/in}^2\\ \text{C2 Zero to 1500 lb/in}^2\end{array}\right)$ 0.006 s

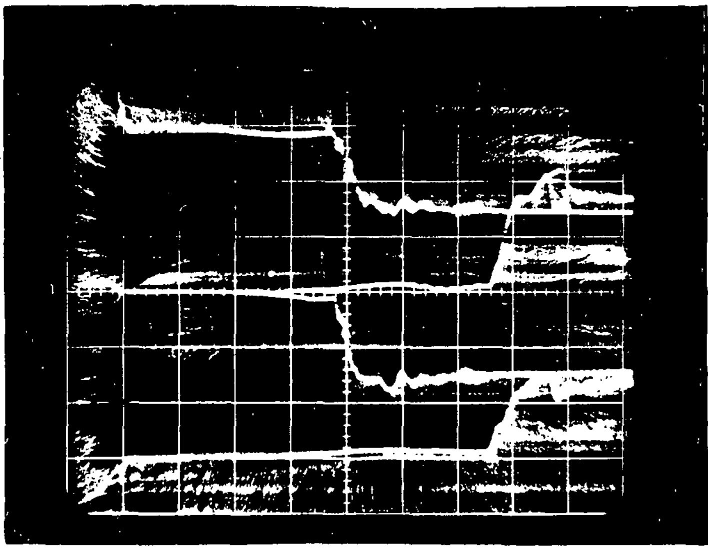
Figure 4-3. Actuator Switching

4.1.1.4 Bifilar Switching Transient-Servoactuator

The torque motor switch was constructed so that it could be used with various kinds of suppression. With the torque motor in its final developed configuration, the switching transient with the bifilar suppression was run. For this test, the switching time was determined by tracking the actuator cylinder pressure at the cylinder past the switching valve.

An extend hard-over command was applied to the channel-1 servovalve and a retract command applied to the channel-2 servovalve. The actuator was at its extend stop, and on switching, started moving in the retract direction, the pressure going from zero to 1500 lb/in^2 or 3000 lb/in^2 to 1500 lb/in^2. The switching time, as shown in Figure 4-4 was 0.009 s, the precise design goal.

Torque Motor #2 Energized
Torque Motor #1 Energized then De-Energized
Arc Suppression - Bifilar



2 ms/cm

Switching Time

ON $\left(\begin{array}{l}\text{C1 Zero to 1500 lb/in}^2\\ \text{C2 3000 to 1500 lb/in}^2\end{array}\right)$ 0.014 s

OFF $\left(\begin{array}{l}\text{C1 3000 to 1500 lb/in}^2\\ \text{C2 Zero to 1500 lb/in}^2\end{array}\right)$ 0.009 s

Figure 4-4. Bifilar Response

4.1.1.5 Torque Motor Suppression Investigation

Various methods for arc suppression were investigated. Since these tests were conducted early in the program, the switching time does not reflect the final values but shows the effect of the various suppression techniques. Figure 4-5 shows the torque motor with no suppression. The back EMF was 200 V and its de-energizing time was 0.015 s. Figure 4-6 is the torque motor with clipping diodes. The back EMF was clipped to 40 V and the de-energizing time was 0.016 s. Figure 4-7 is the torque motor with bifilar suppression. The back EMF was suppressed to 42 V and the de-energizing time was 0.035 s. The clipping-diodes condition was the final configuration and the torque motors were refined until the switching time was reduced to 0.007 s, as shown in Figures 4-1 and 4-2.

Date: 10-31-71

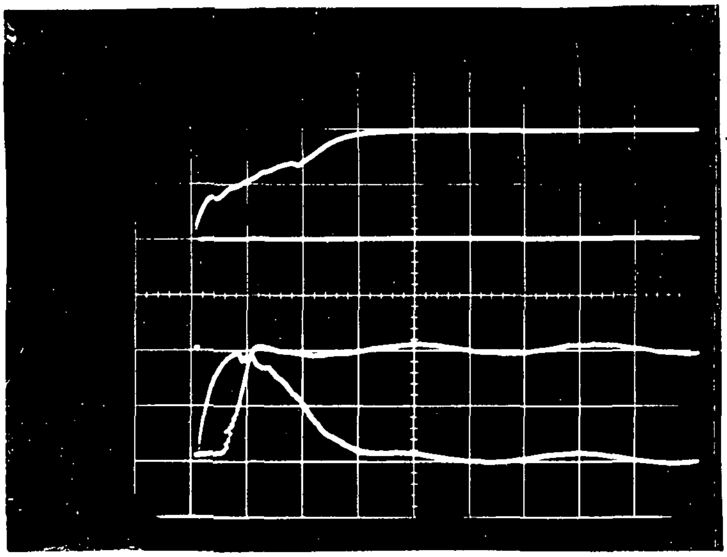
Response

Arc Suppression - None

1 A Current
3000 lb/in^2 Inlet Pressure

Scale:

Vert. = 0.5 A/cm
Hor. = 5 ms/cm



Current Tracing

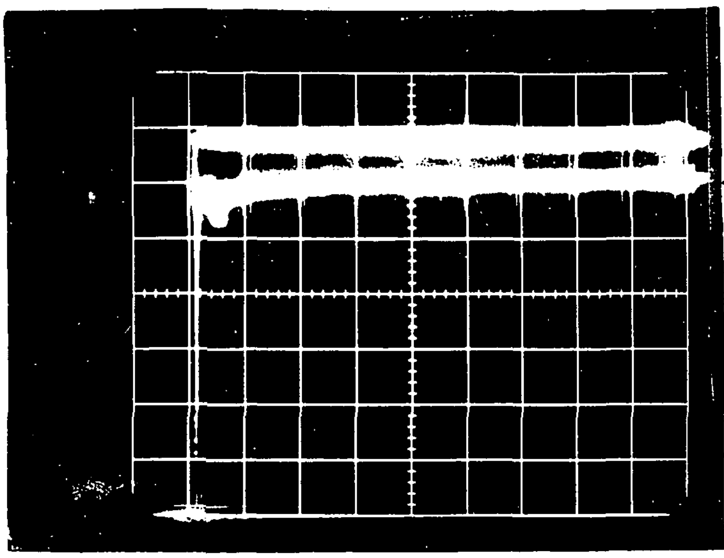
Pressure Tracing

Scale:

Vert. = 1500 lb/in^2 per cm
Hor. = 5 ms/cm

ON = 6 ms
OFF = 15 ms

Back EMF Tracing



Zero Volts

Vert. = 40 V/cm
Hor. = 10 ms/cm

200 V

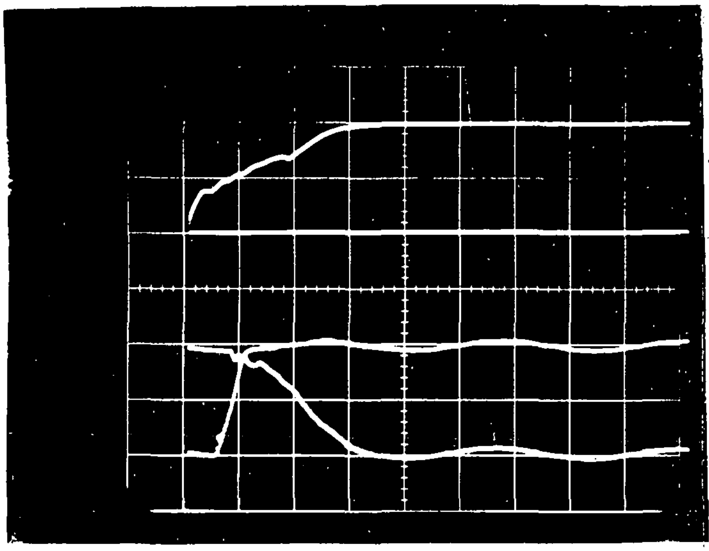
Figure 4-5. Torque Motor With No Suppression

Date: 10-31-71

Response:

Arc Suppression - Clipping Diodes

1 A Current
3000 lb/in^2 Pressure



Scale:

Vert. = 0.5 A/cm
Hor. - 5 ms/cm

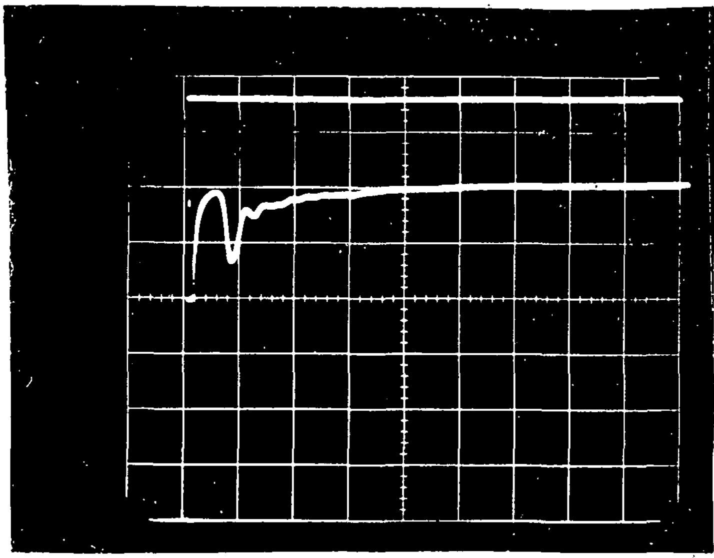
Current Tracing

Pressure Tracing

Scale:

Vert. = 1500 lb/in^2 per cm
Hor. = 5 ms/cm

ON = 6 ms
OFF = 16 ms



Back EMF Tracing

Zero Volts

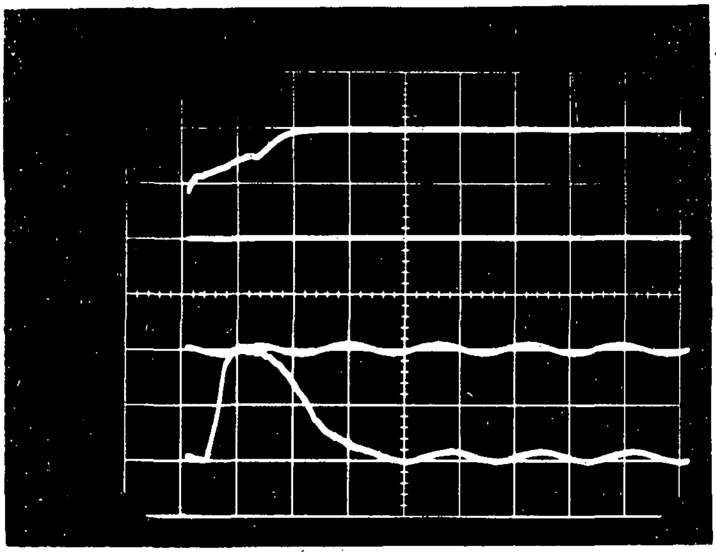
40 V

Vert. = 20 V/cm
Hor. = 5 ms/cm

Figure 4-6. Torque Motor With Coil Suppression

Response

Arc Suppression - Bifilar Coil
1 A Current
3000 lb/in^2 Pressure



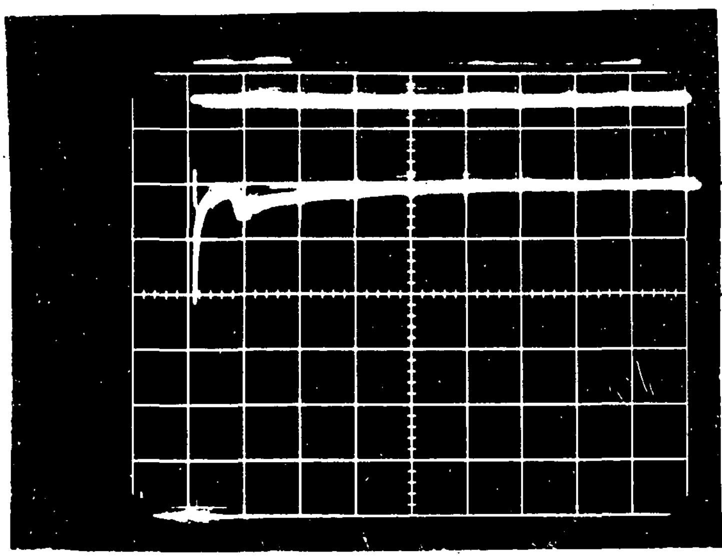


Figure 4-7. Motor With Bifilar Suppression

4.1.2 Servovalves

4.1.2.1 Servovalve Acceptance Test

The servovalves used were two HYDRAULIC RESEARCH Model 25A servovalves, modified by adding an LVDT to the second stage. The initial acceptance test data is shown in Figures 4-8 through 4-13. The valves have 45° phase shift at approximately 65 Hz and less than 2 dB down at 100 Hz. The flow plots were linear and the pressure gain good. The valves show typical Model 25A servovalve response. This frequency response is measured by using a low-friction actuator and a velocity transducer as per ARP 490B.

Part No. 22253370-001

Serial No. 001

Pressure 3000 psi

No load None

Oil Temp 100°F

Test Stand No. ________

Date 8-2-71

Operator J. Adams

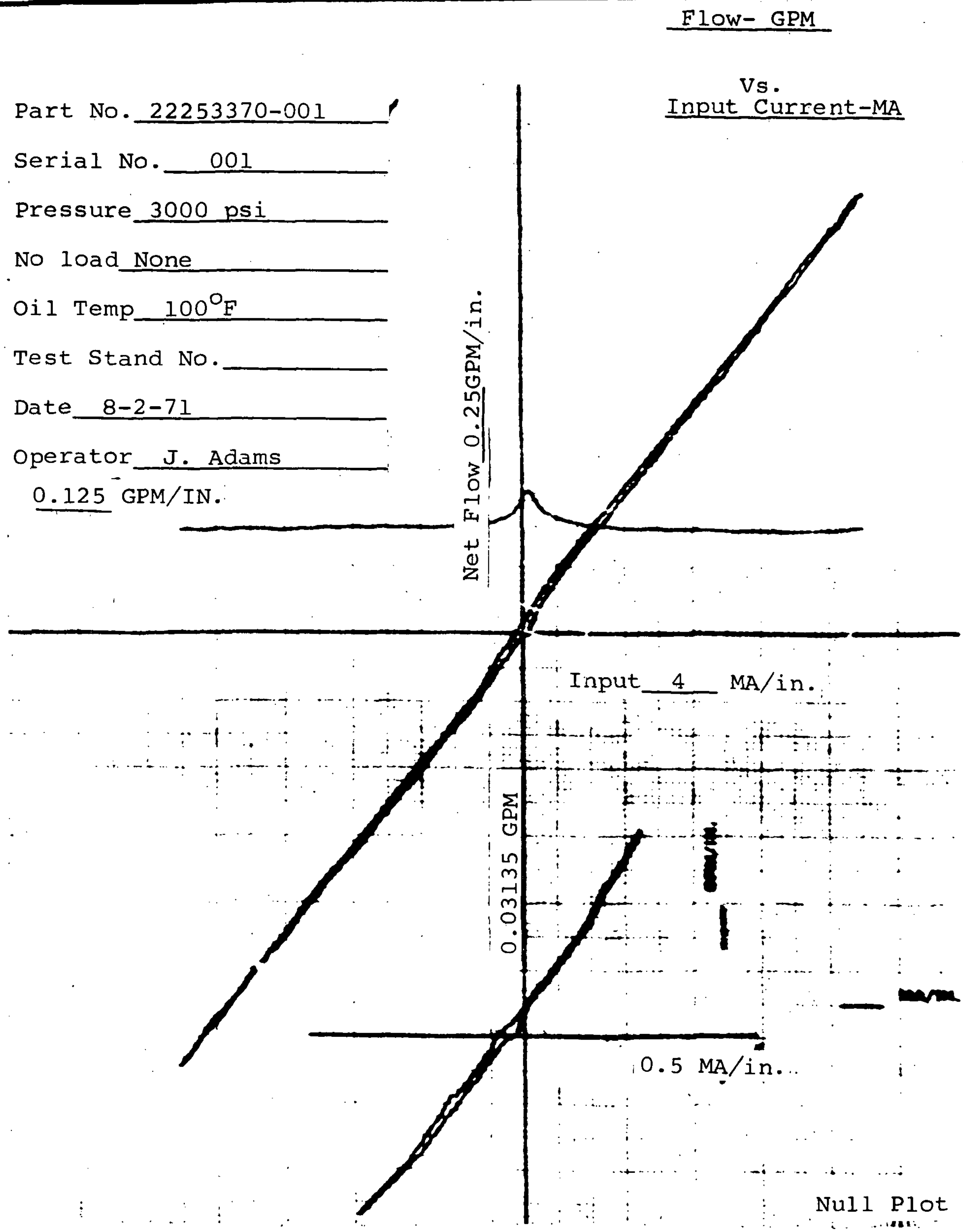


Figure 4-8. Servovalve Flow and Leakage

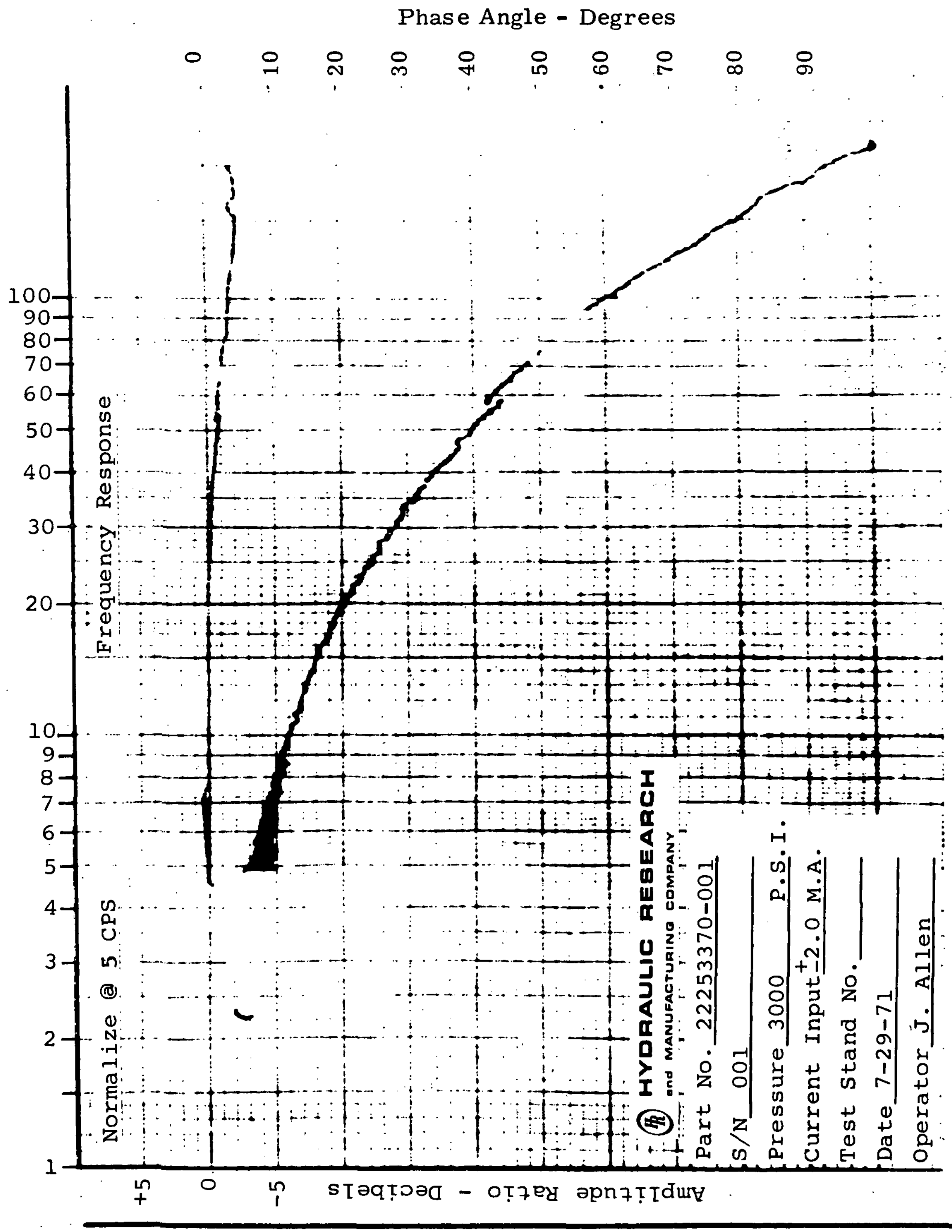


Figure 4-9. Servovalve Frequency Response

Part No. 22253370-001

Serial No. 001

Pressure 3000 psi

No load None

Oil Temp 100°F

Test Stand No. 90

Date 7/28/71

Operator J. Allen

LEAKAGE PLOT

_____ GPM/IN.

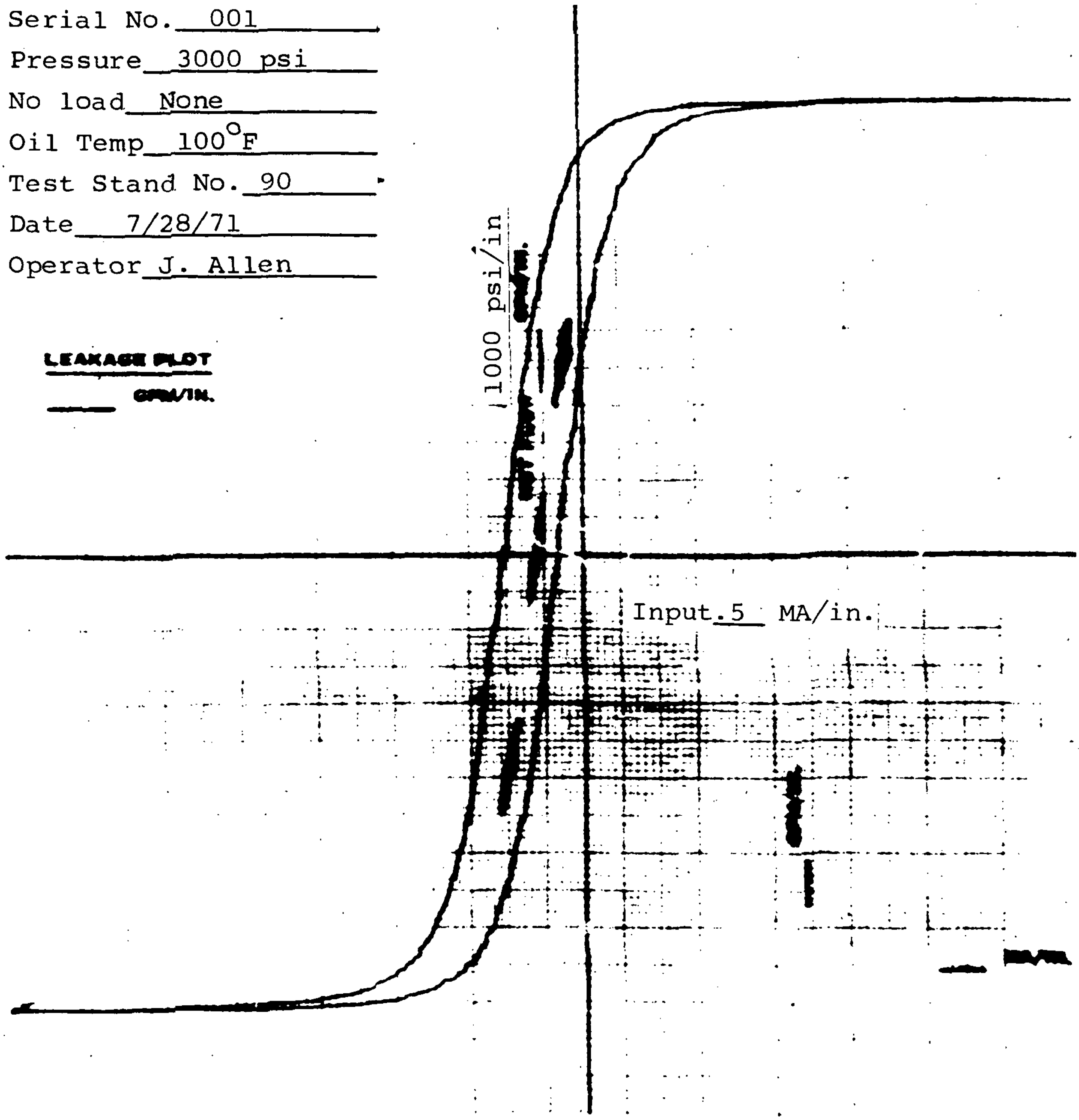


Figure 4-10. Servovalve Pressure Plot

Part No. 22253370-002
Serial No. 001
Pressure 3000 psi
No load None
Oil Temp $100^{o}F$
Test Stand No. ______
Date 8-2-71
Operator J. Adams

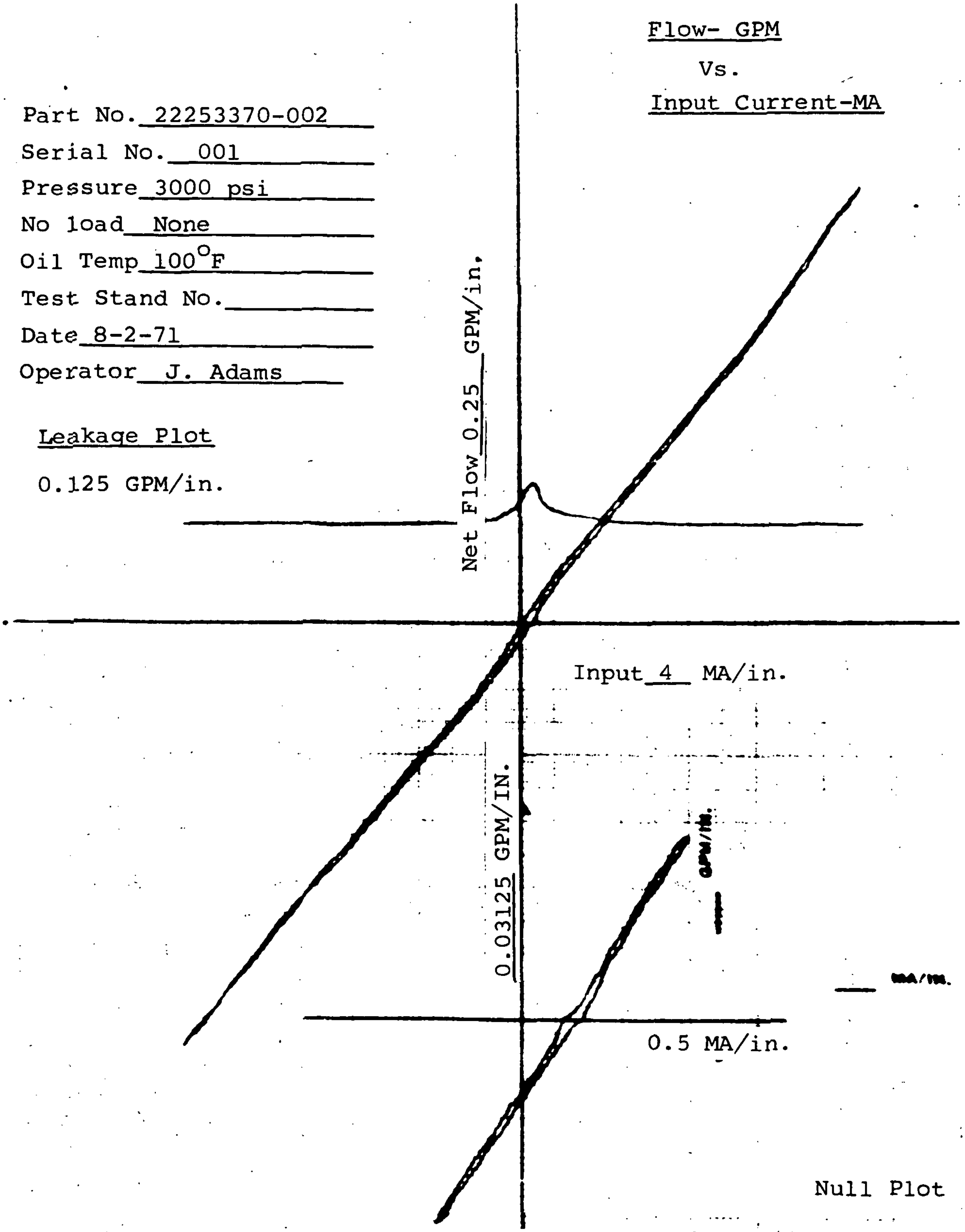


Figure 4-11. Servovalve Flow and Leakage

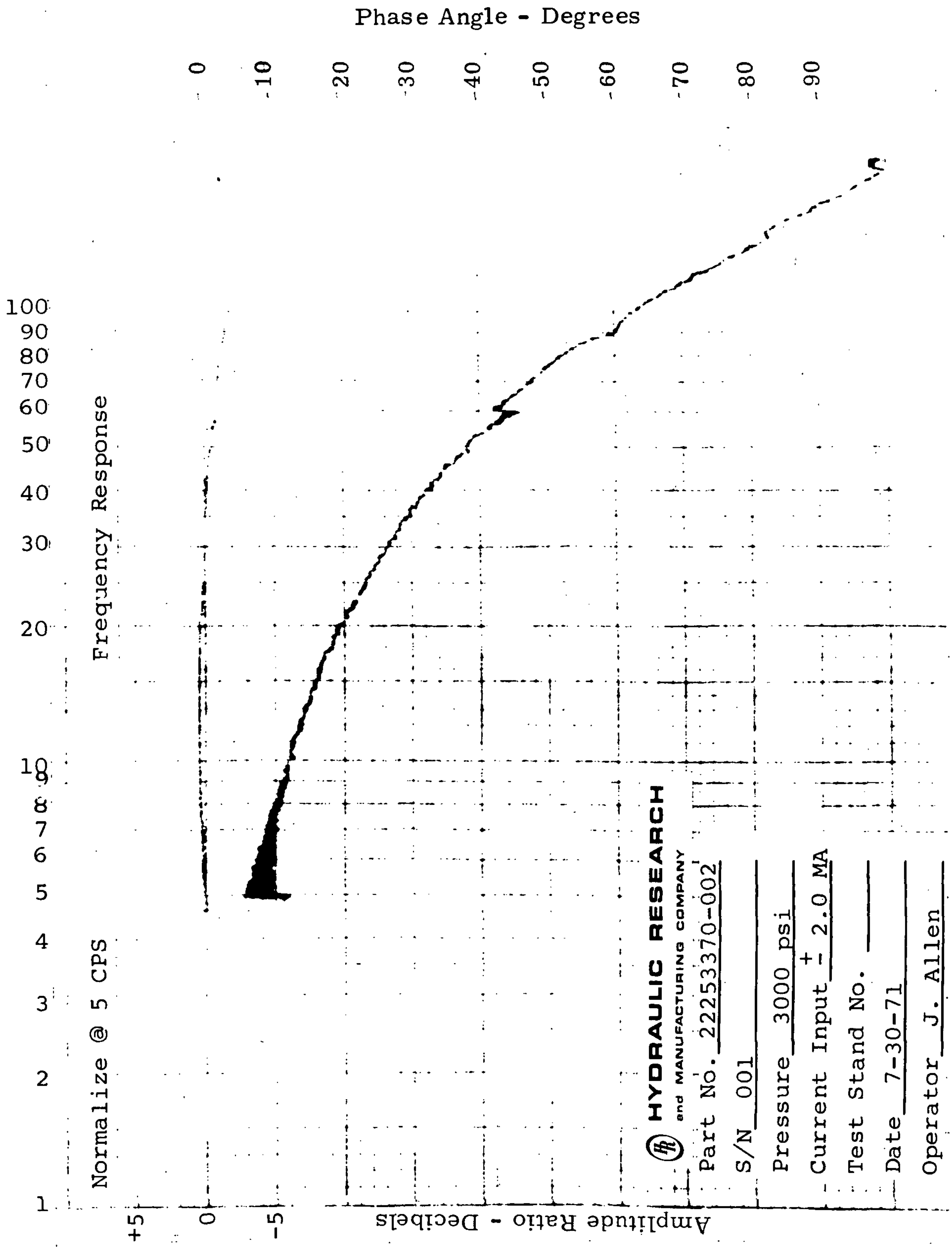


Figure 4-12. Servovalve Frequency Response

Part No. 22253370-002
Serial No. 001
Pressure 3000 psi
No Load ----
Oil Temp 100 °F
Test Stand No. ______
Date 7-29-71
Operator J. Allen

LEAKAGE PLOT
______ GPM/IN.

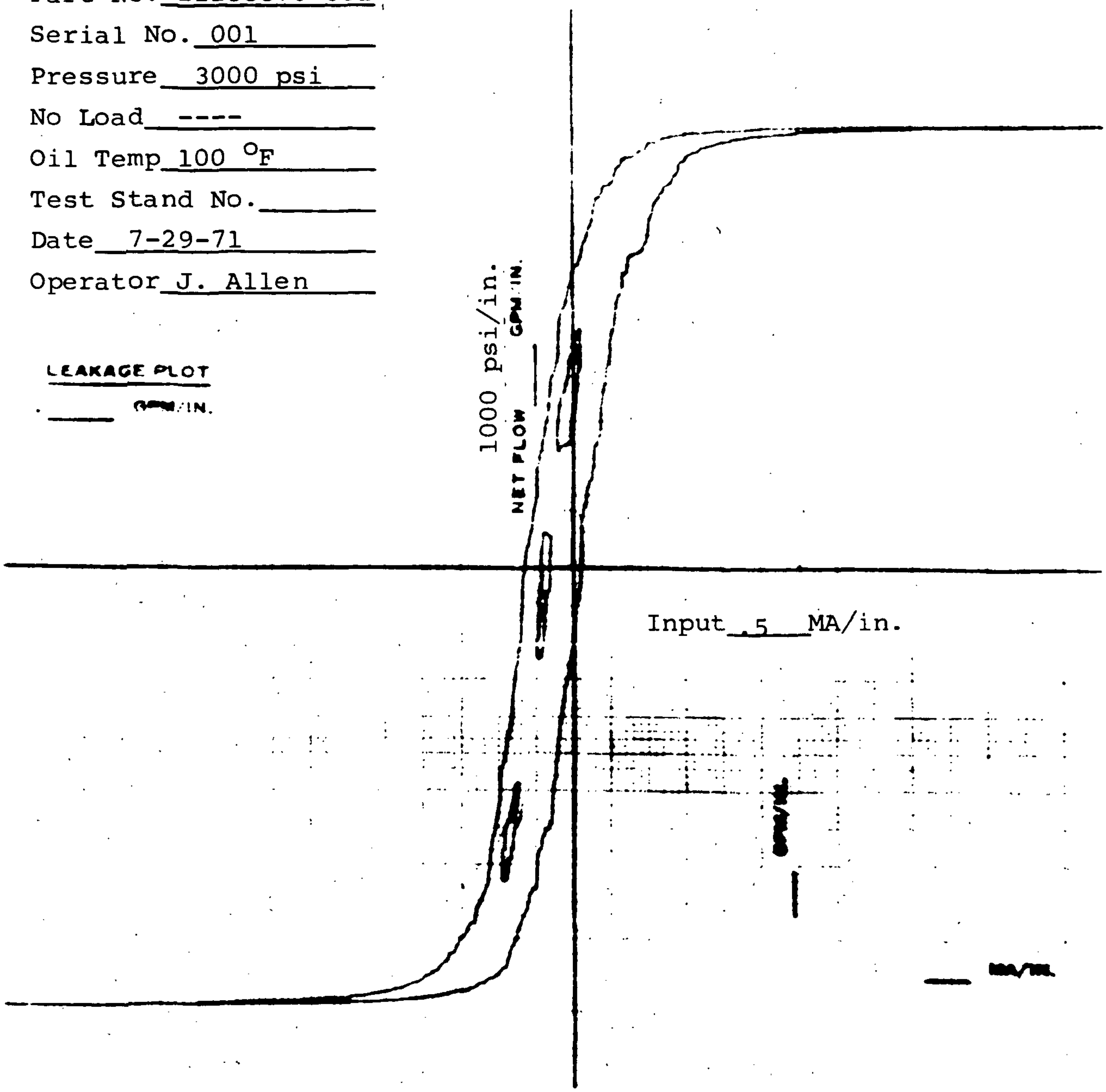


Figure 4-13. Servovalve Pressure Plot

4.1.2.2 Servovalve/LVDT Response

In order to obtain data to design the models, the frequency response of the servovalve was obtained using the LVDT as the output. The summer/limiter, servoamplifier, demodulator, filter, and frequency generator in the console were used. One plot was made for each valve. Each plot includes five different runs made at various command-signal levels. Figure 4-14 is the plot for the channel-#1 servovalve and Figure 4-15 for the channel-#2 servovalve.

The two frequency response plots show the effect of first stage saturation. The amplitude ratio and phase angle at 100 Hz and greater depend on the magnitude of the command signal. With a low-magnitude command (±0.1 V), the amplitude ratio reacts as a first-order system up to about 300 Hz when it is decreasing at 40 dB/decade. For a larger-magnitude command (±0.5 V), the amplitude ratio starts deviating from the first order at 70 Hz and is decreasing at 40 dB/decade at 100 Hz. The intermediate amplitude curves break off at various points depending on the magnitude of the command. This deviation from a first-order response is caused by the first-stage saturation.

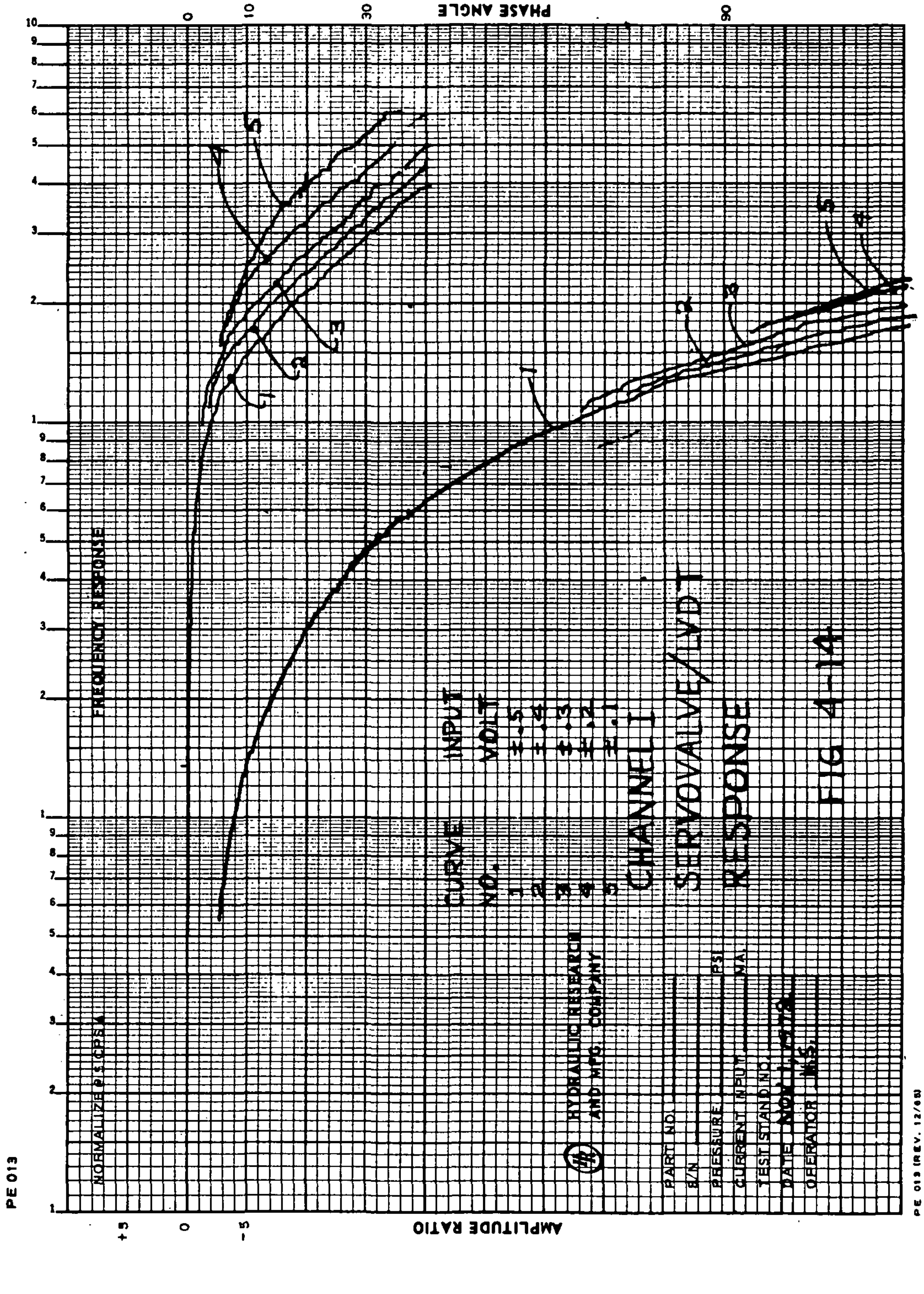


Figure 4-14. Channel 1 Servovalve/L VDT Response

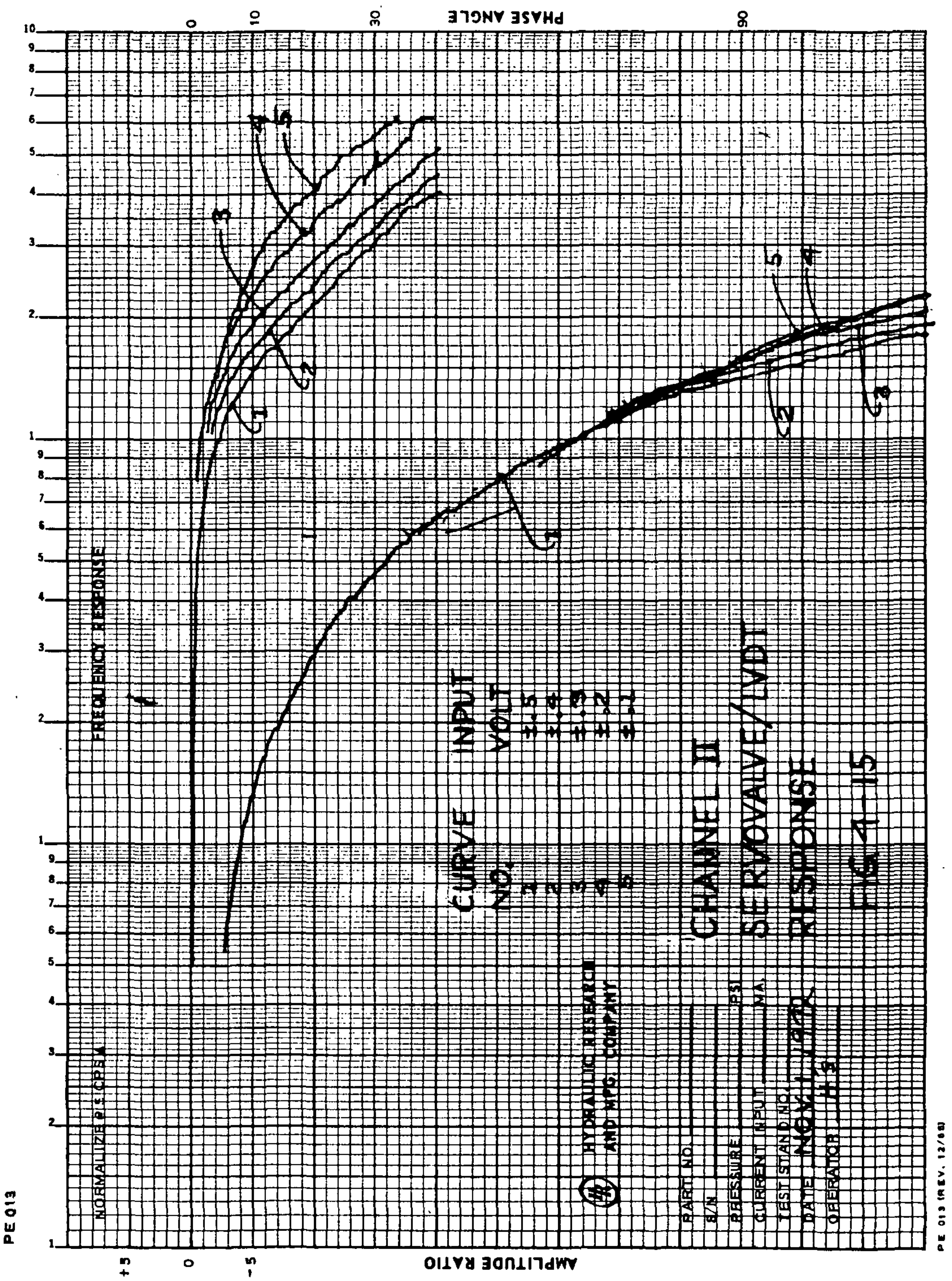


Figure 4-15. Channel 2 Servovalve/LVDT Response

The low-amplitude command signal shows the nonsaturated response. There is a first-order break at 150 Hz followed by a second-order break at 400 Hz and 0.5 damping ratio. The phase shift does not agree with the amplitude ratio. There is additional phase shift estimated to be 20° at 100 Hz. This phase shift is accountable to a hydraulic decay in the first stage.

4.1.3 Model

The initial model was a first-order lag with a time constant at 110 Hz. The response of this model along with the low-magnitude command response of the servovalve is shown in Figure 4-16. This model was acceptable with the filter in the model and servovalve/LVDT circuit. When these filters were removed as noted in paragraph 4.2.1 "Switching Transients-Filter," the model was no longer satisfactory. Any command above 70 Hz, or any step would fail the system.

A second model was made which consists of two first-order integrators with a time constant both at 150 Hz. Figure 4-17 is a composite plot of the model and servovalve response. The large and small signal response of the servovalve are both included on the plot. The response of the model was made to match the servovalve response up to 100 Hz. Above 100 Hz, the amplitude ratio was made to be between the large and small signal servovalve response. This model was

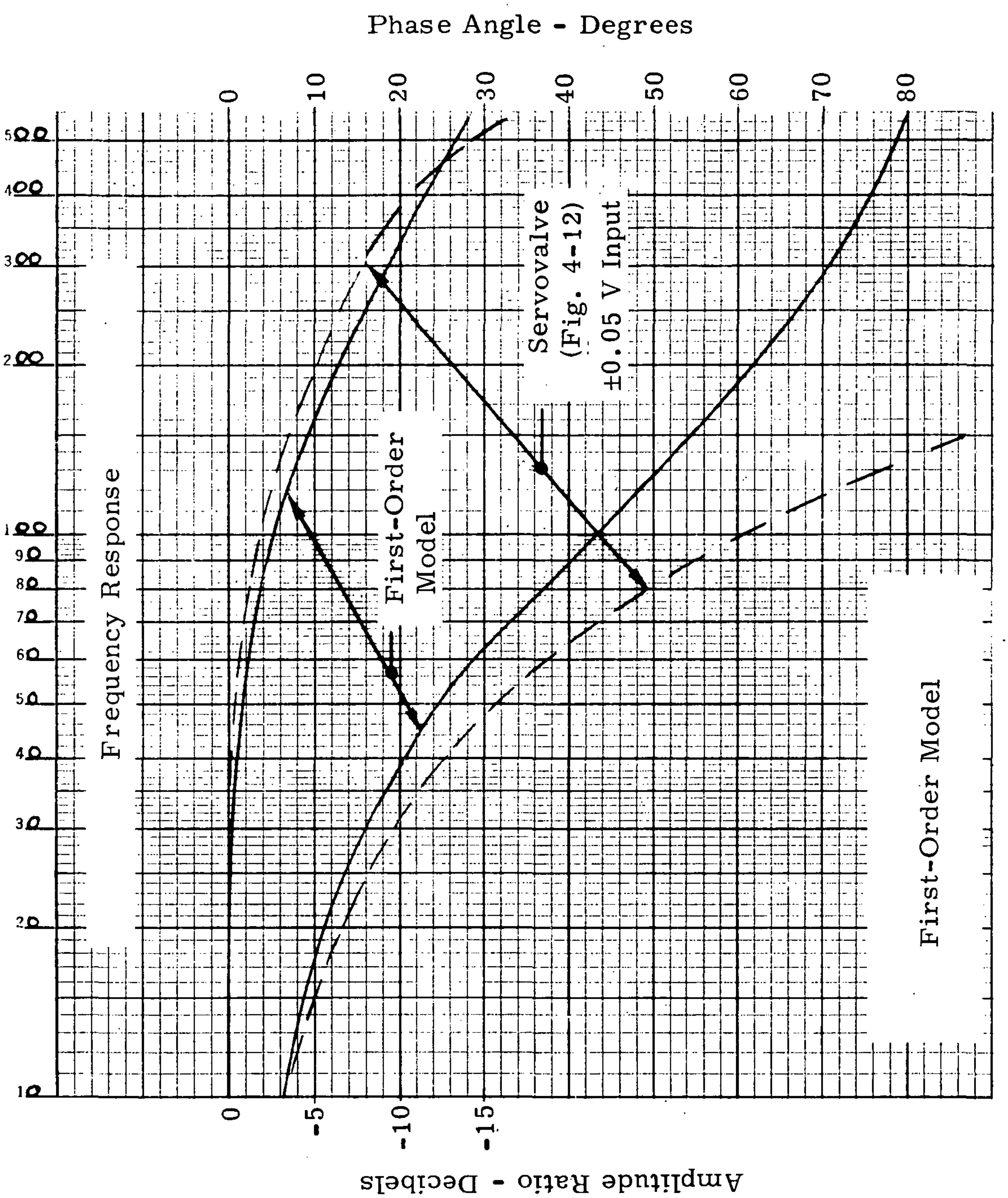


Figure 4-16. First-Order Model Frequency Response

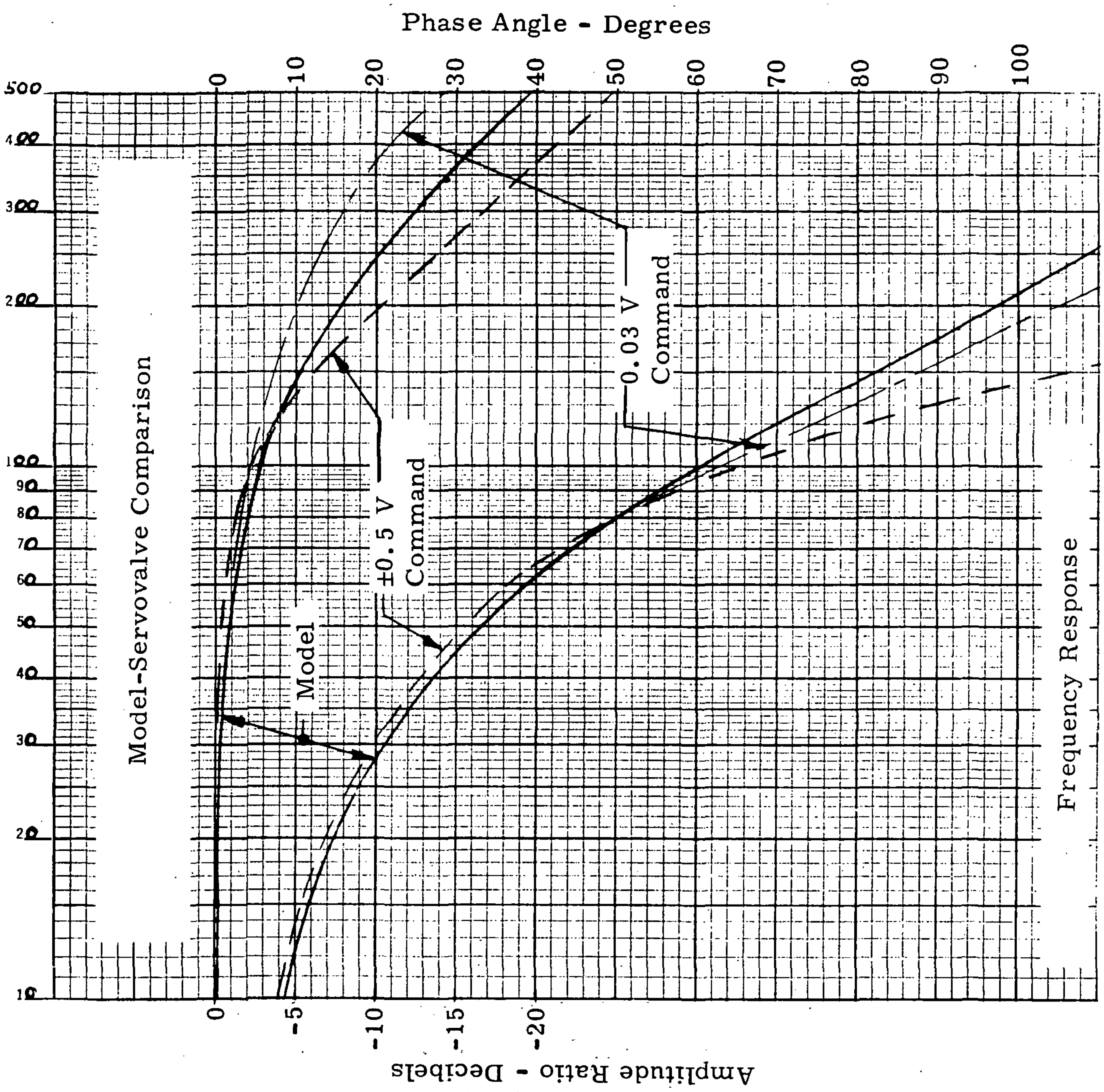


Figure 4-17. Frequency Response - Two First-Order Models

unsatisfactory in that it could not handle large-magnitude step commands.

A third model was made which consisted of:

1. A first order with $\tau_1 = 150$ Hz
2. A first order with $\tau_2 = 500$ Hz
3. Rate saturation (limiting)
4. Additional phase shift

The third model was simulated on the analog computer (Electronic Associates, Inc., "Pace" TR-48). The circuit diagram is shown in Figure 4-18, and the frequency response of this simulation is shown in Figure 4-19. As seen on that plot, the simulation does provide the flow saturation effect on the amplitude ratio and the phase shift.

A breadboard of the third model was made as shown in Figure 2-12. Some of the operational amplifiers were removed and passive RC circuits used in their place. Also, the position limiter and summer (command and feedback) were incorporated. The frequency response of this model, shown in Figure 4-20, is very similar to that of the servovalve and differs only where the attenuation is -10 dB or greater. This magnitude is well below any planned detection level.

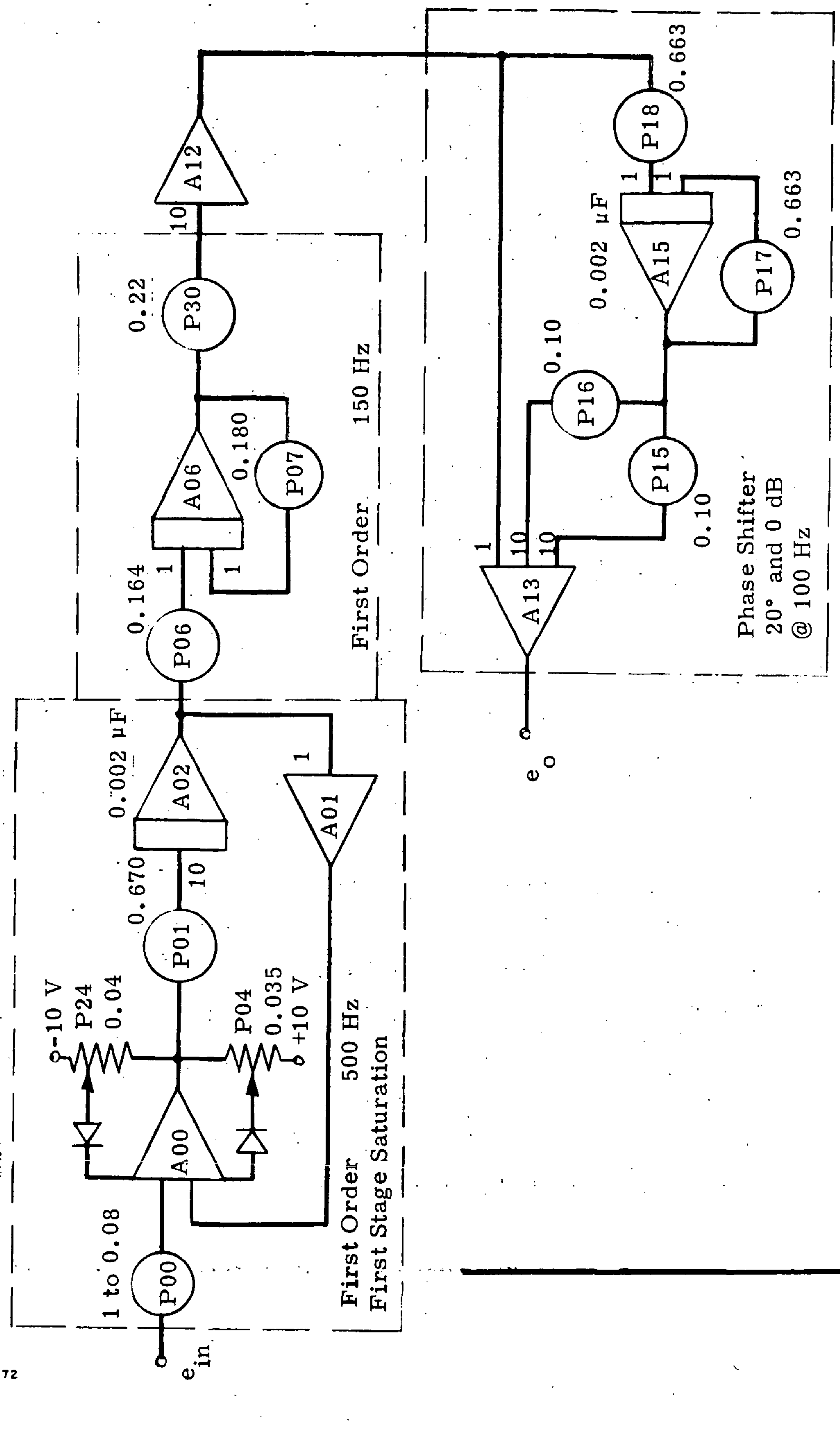


Figure 4-18. Analog Computer Model

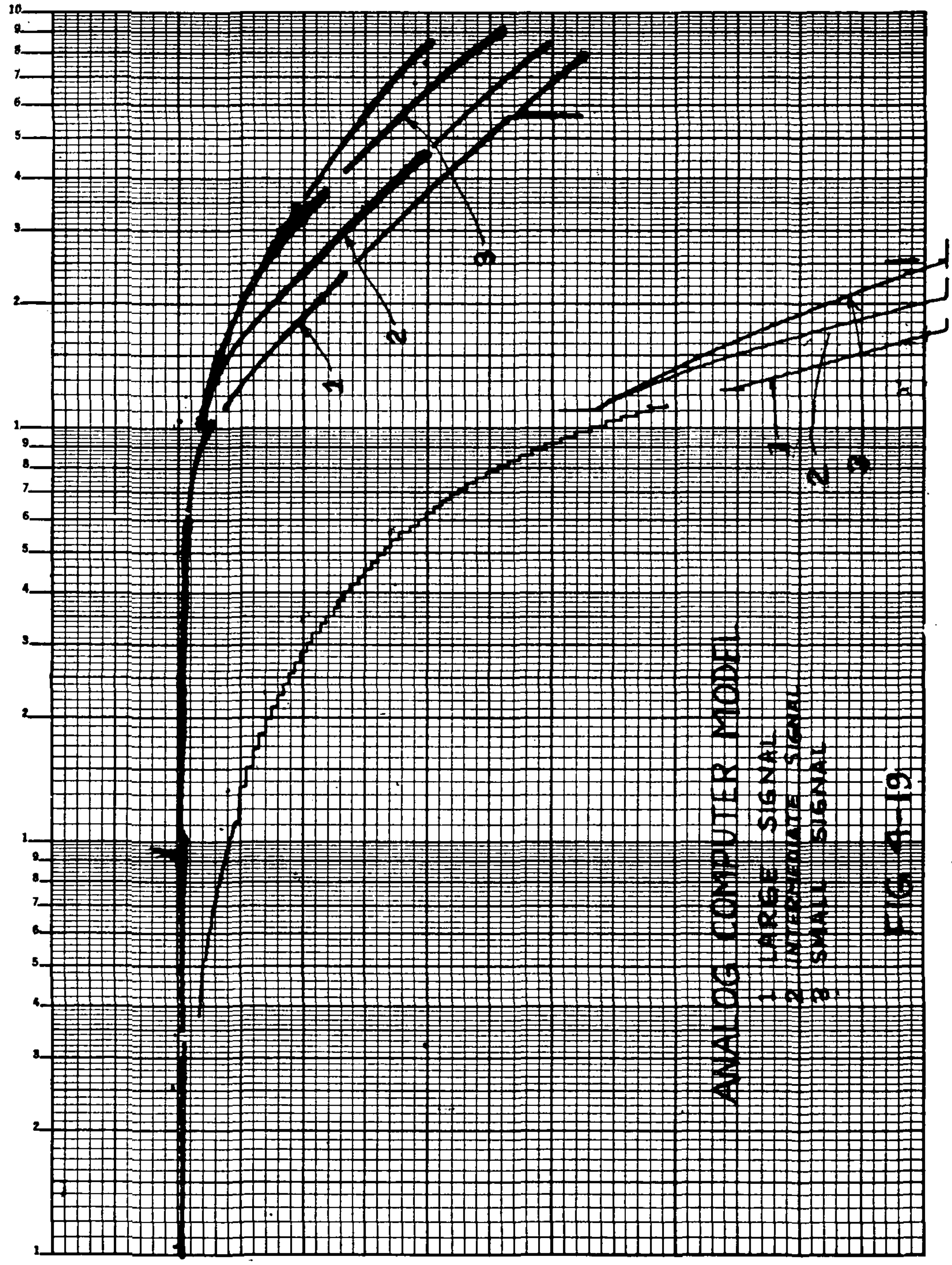


Figure 4-19. Analog Computer Model

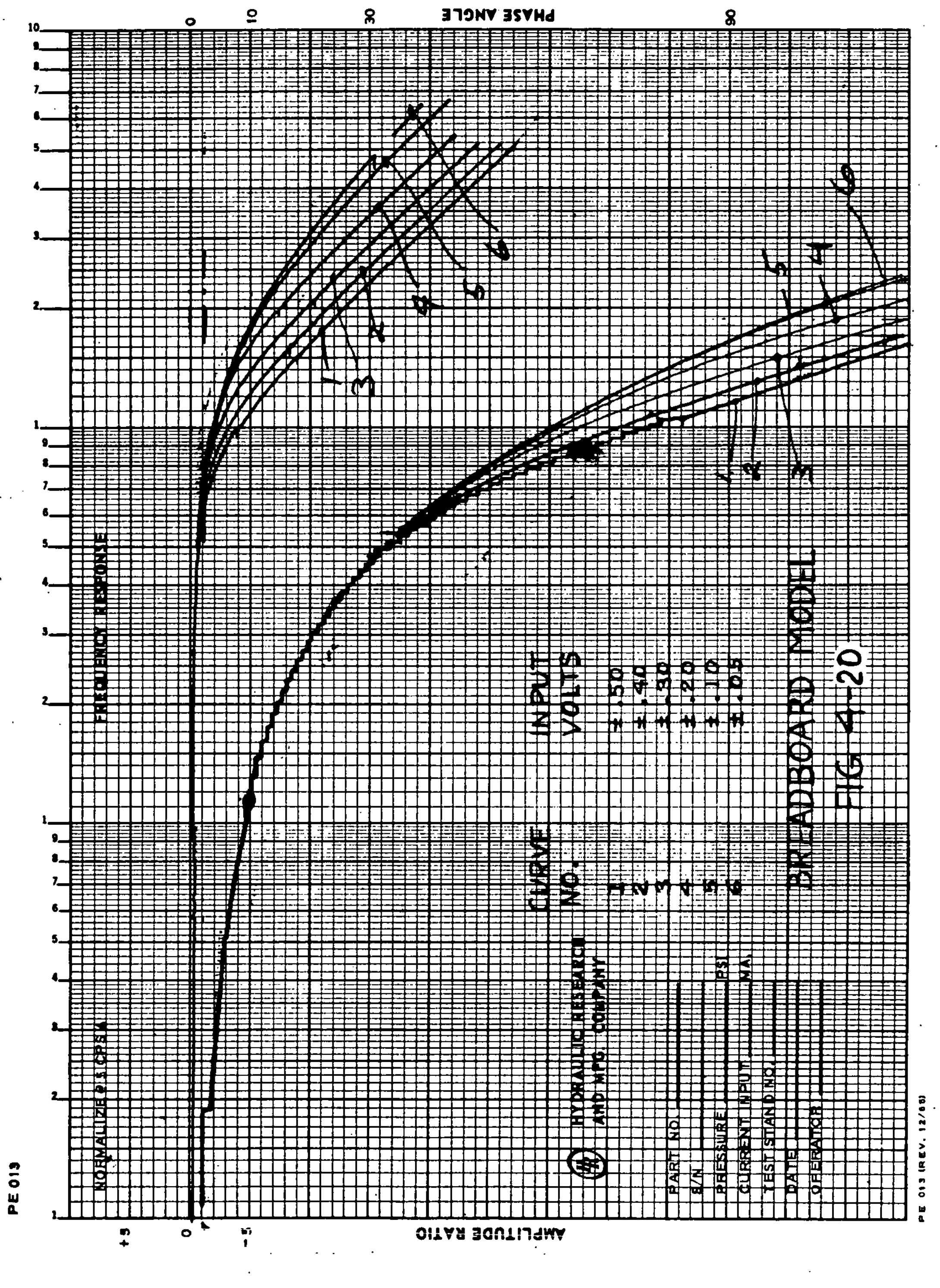


Figure 4-20. Breadboard Model

The final models were constructed on the model/comparator circuit board (Figure 2-10). These models have the same design circuitry as the breadboard, Figure 2-12. The frequency response for the channel-1 model is shown in Figure 4-21, and the channel-2 model response is in Figure 4-22.

4.1.4 Demodulators

The demodulator was specified to have a frequency response with no phase shift or attenuation below 80 Hz, at 2000 Hz carrier. This would assure that the demodulator would not effect the servovalve characteristics. The initial demodulator had a break at 30 Hz as well as unsymmetrical attenuation. Figure 4-23 shows the frequency response of the servovalve. The solid line is the servovalve response using the LVDT and demodulator while the dashed line is the servovalve response using flow (velocity of a low-friction actuator) as the output. Examination of the demodulator circuit, Figure 4-24, showed two problems; that the filter on the output stage was sized for a break frequency of approximately 25 Hz and the demodulator circuit board was in error.

The carrier frequency was increased to 4000 Hz because of LVDT problems. A ring demodulator was designed and used as shown in Figure 2-20.

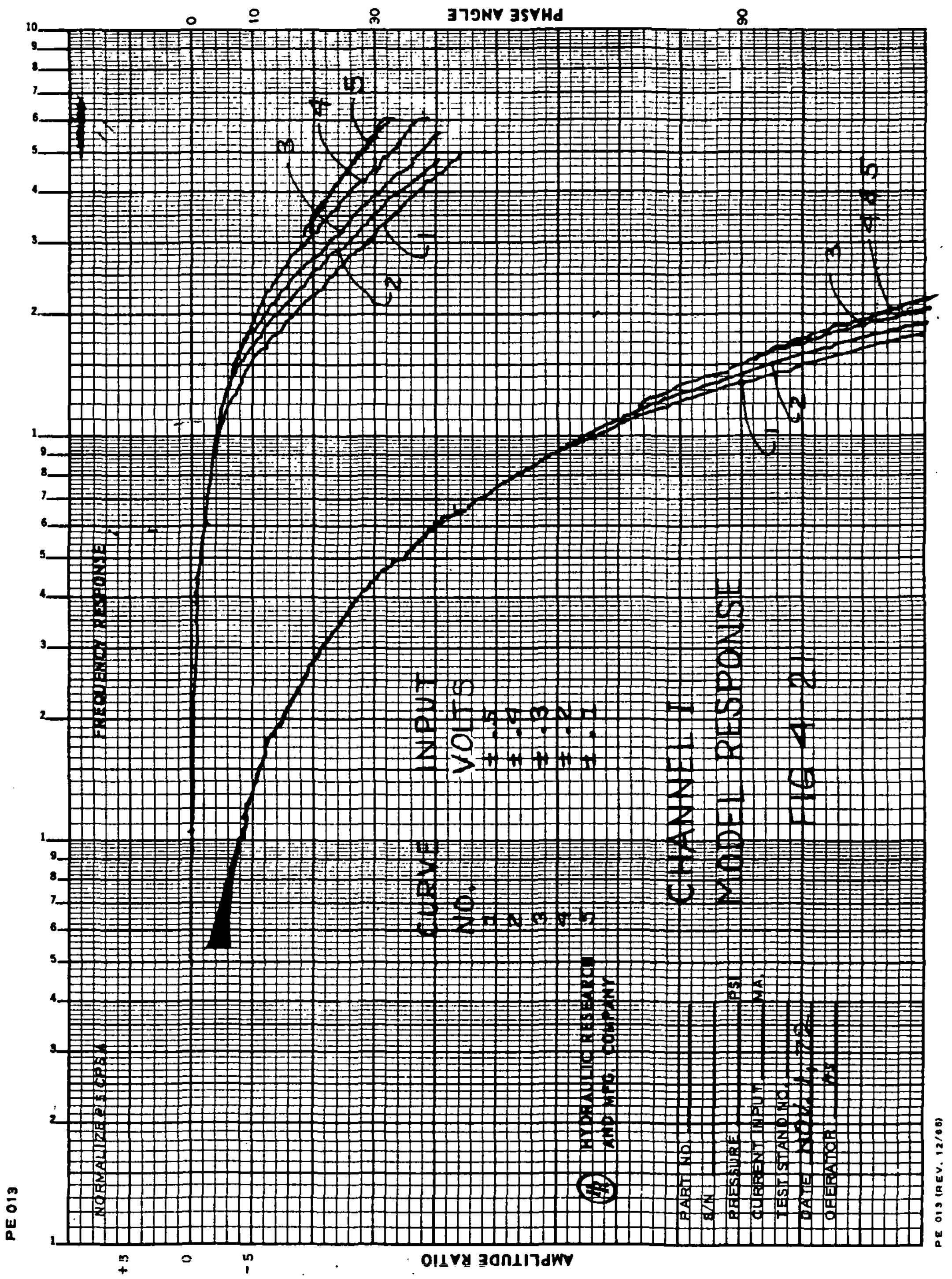


Figure 4-21. Channel 1 Model Response

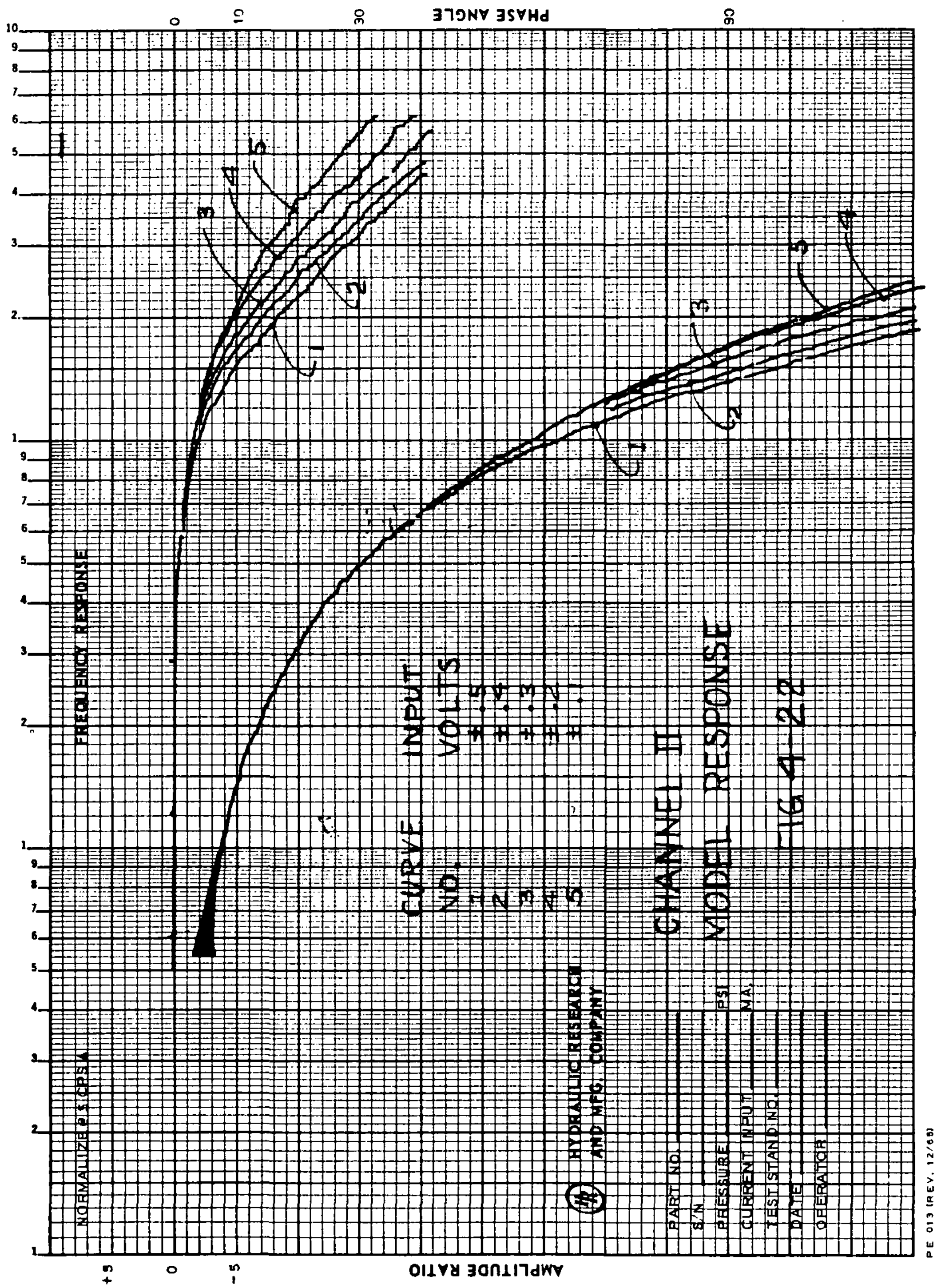


Figure 4-22. Channel 2 Model Response

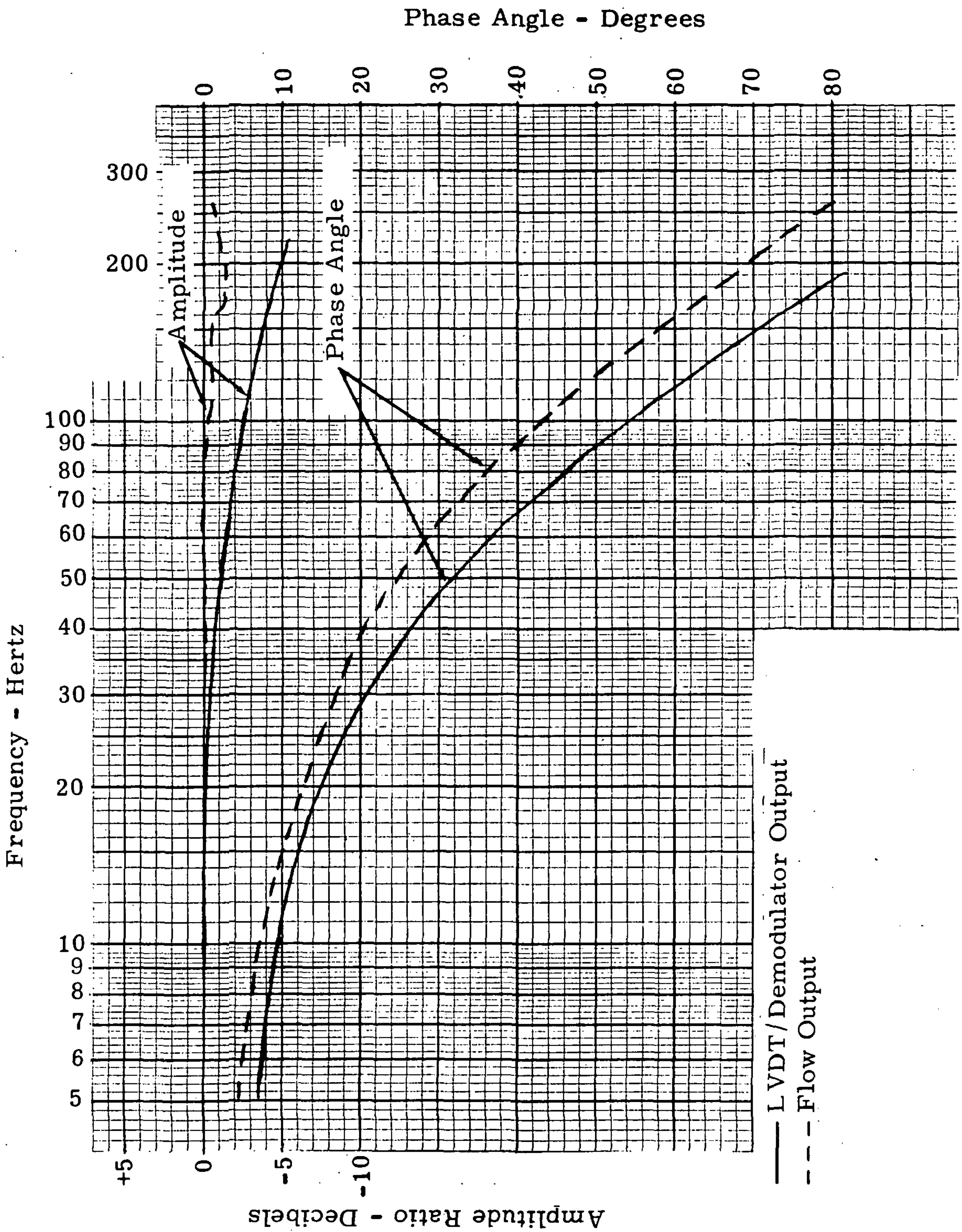


Figure 4-23. Servovalve/Demodulator Lag

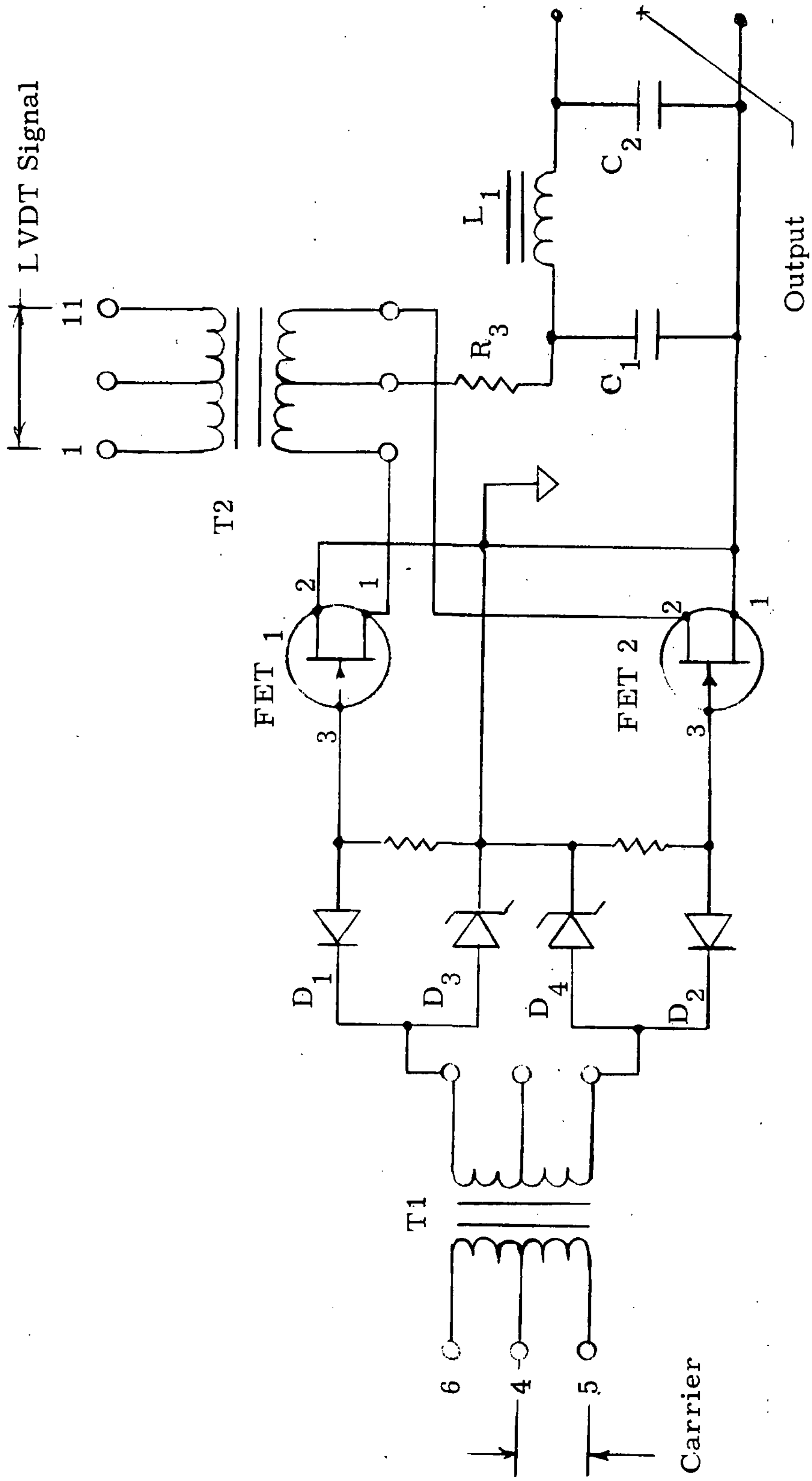


Figure 4-24. Demodulator

4.1.5 LVDT

The performance of the LVDT/demodulator was not satisfactory. The response of the servovalve with the ring demodulator did not exactly match that of the response using the flow as an output. Also, the response would change with the magnitude of the command signal.

A detailed study of the system was made with the following results:

1. Summer/limiter response flat to 500 Hz
2. Servoamplifier modified to give a response flat to 300 Hz with 5° phase
3. Servovalve response same as initially measured; -3 dB with 50° phase
4. LVDT showed linearity problems; a large quadrature voltage and excessive null voltage

The LVDT was tested by observing the output on a scope. A dual-beam scope was used to observe the excitation and output voltage. The command to the servovalve was varied for +10 to -10 mA. Figure 4-25 shows an ideal curve while Figures 4-26 and 4-27 show the actual performance. These two are the best of the four available transducers.

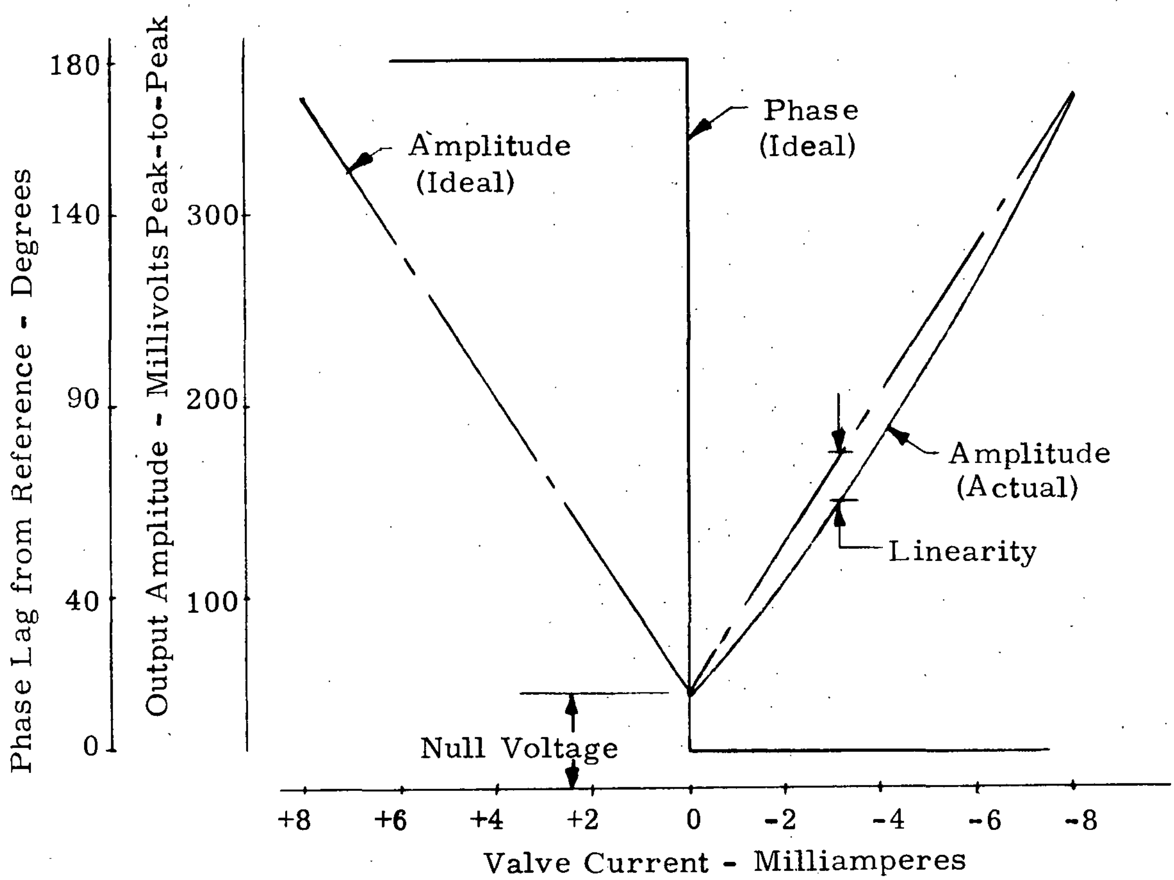


Figure 4-25. LVDT Characteristics

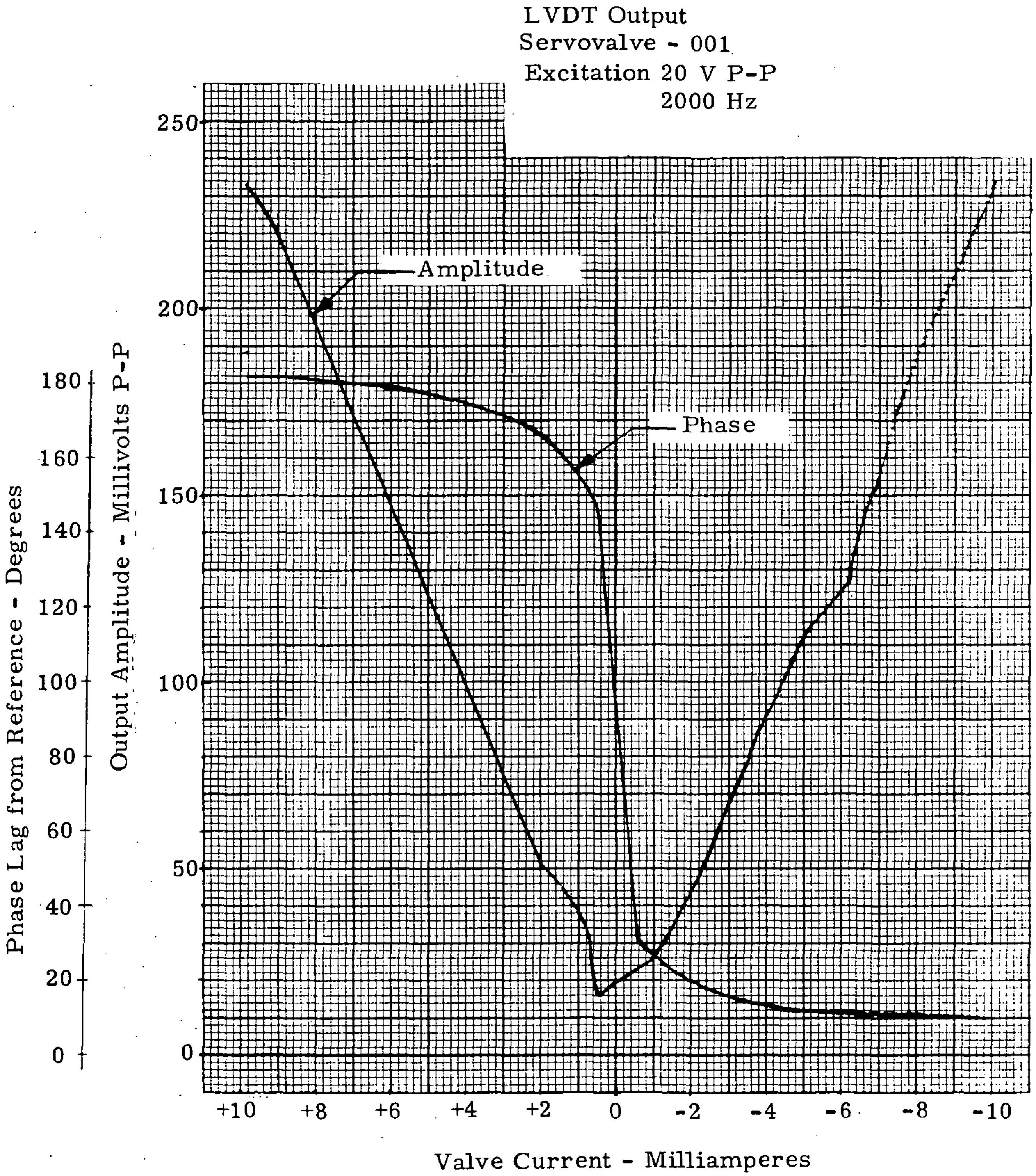


Figure 4-26. LVDT Performance

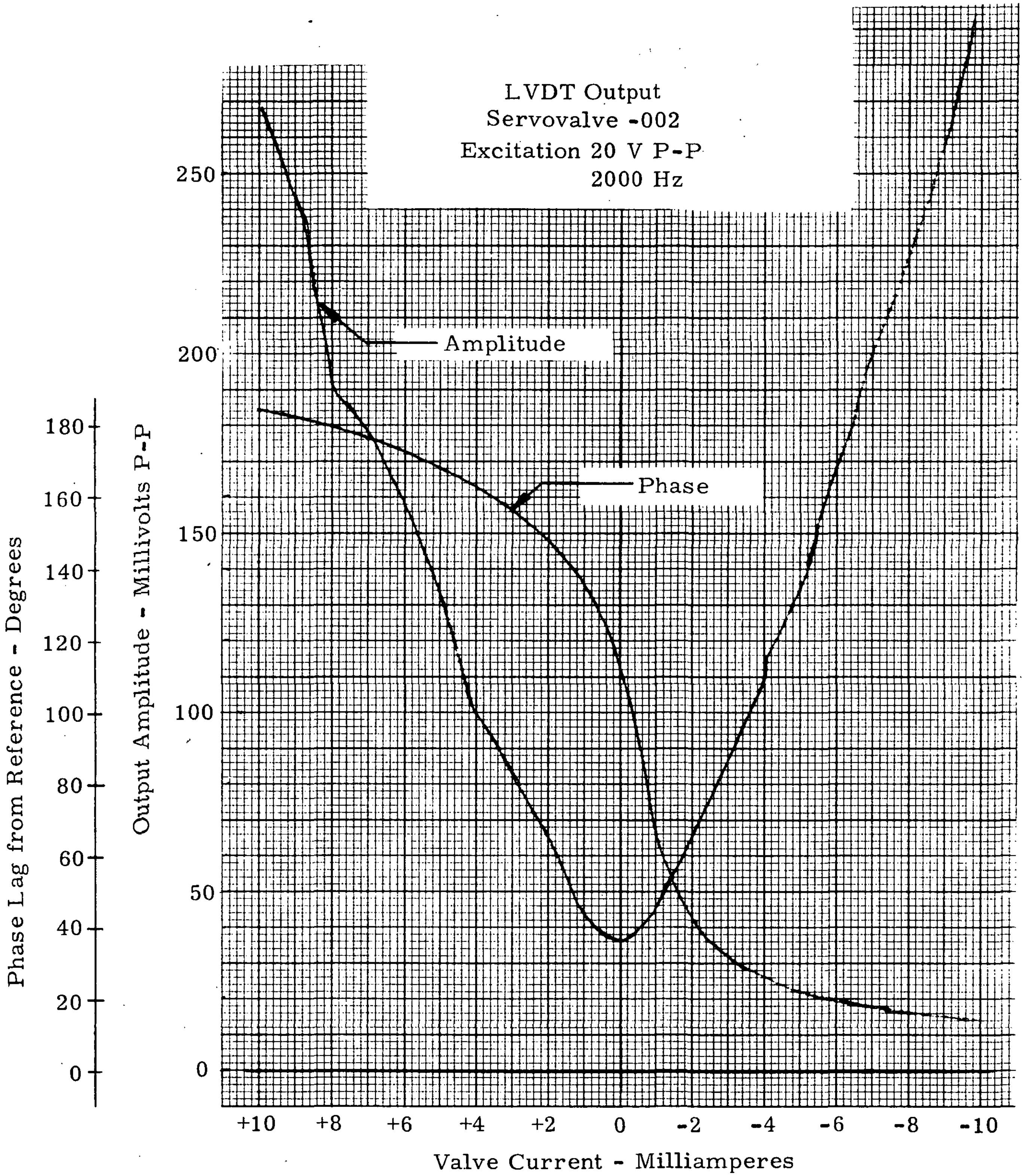


Figure 4-27. LVDT Performance

4.1.6 Load System

The load system was calibrated and tested by driving into a fixed block as shown in Figure 4-28.

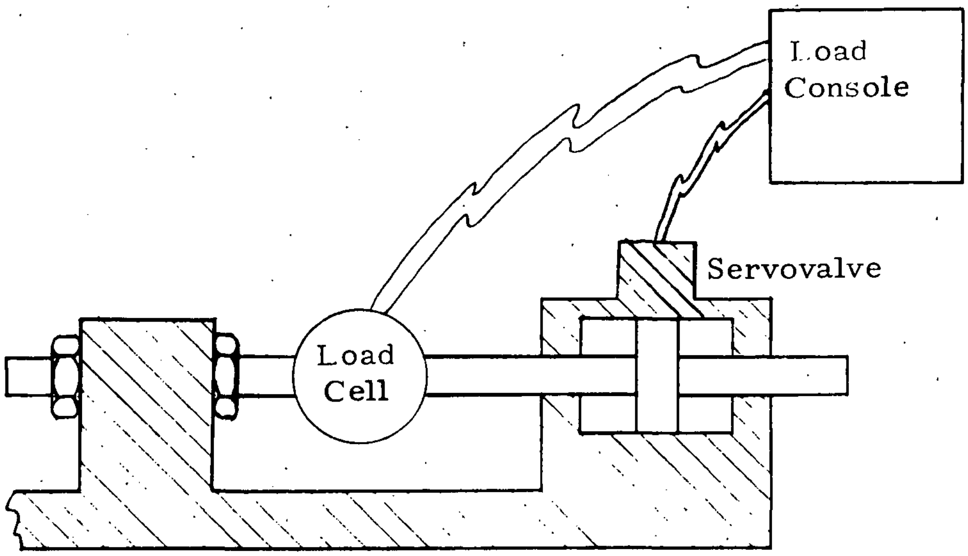
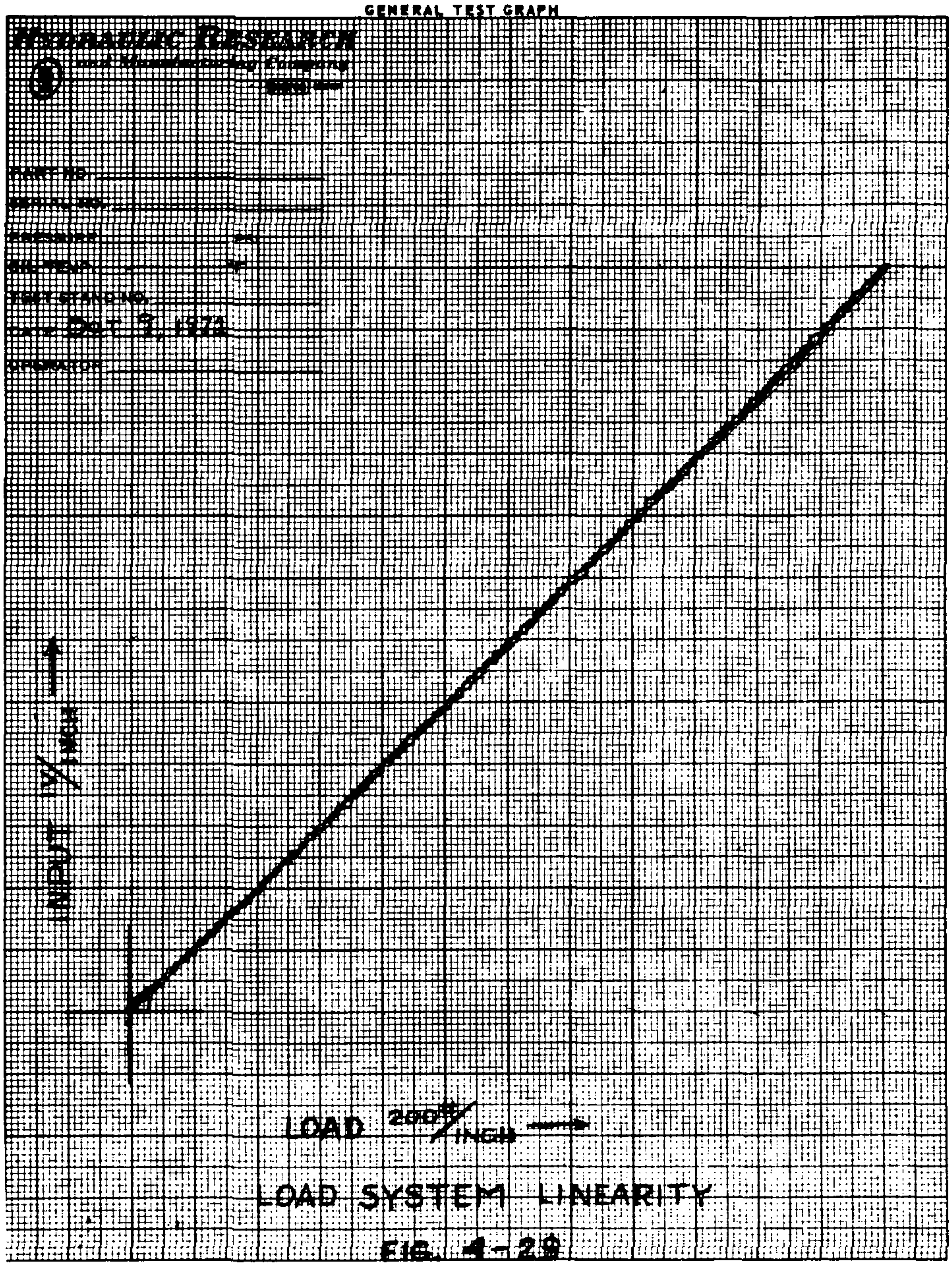


Figure 4-28. Load Test System

Figure 4-29 is the linearity and hysteresis plot. The system averaged approximately 12 lb hysteresis with a linearity or deviation from the best straight line of 30 lb maximum.

The frequency response of the load system is shown in Figure 4-30. This test was also conducted using the fixture shown in Figure 4-28. The phase shift is very nearly the same as for the test actuator. The amplitude ratio peaks at one dB at 25 Hz; the test actuator is down 3 dB at 25 Hz.



EL 009

Figure 4-29. Load System Linearity

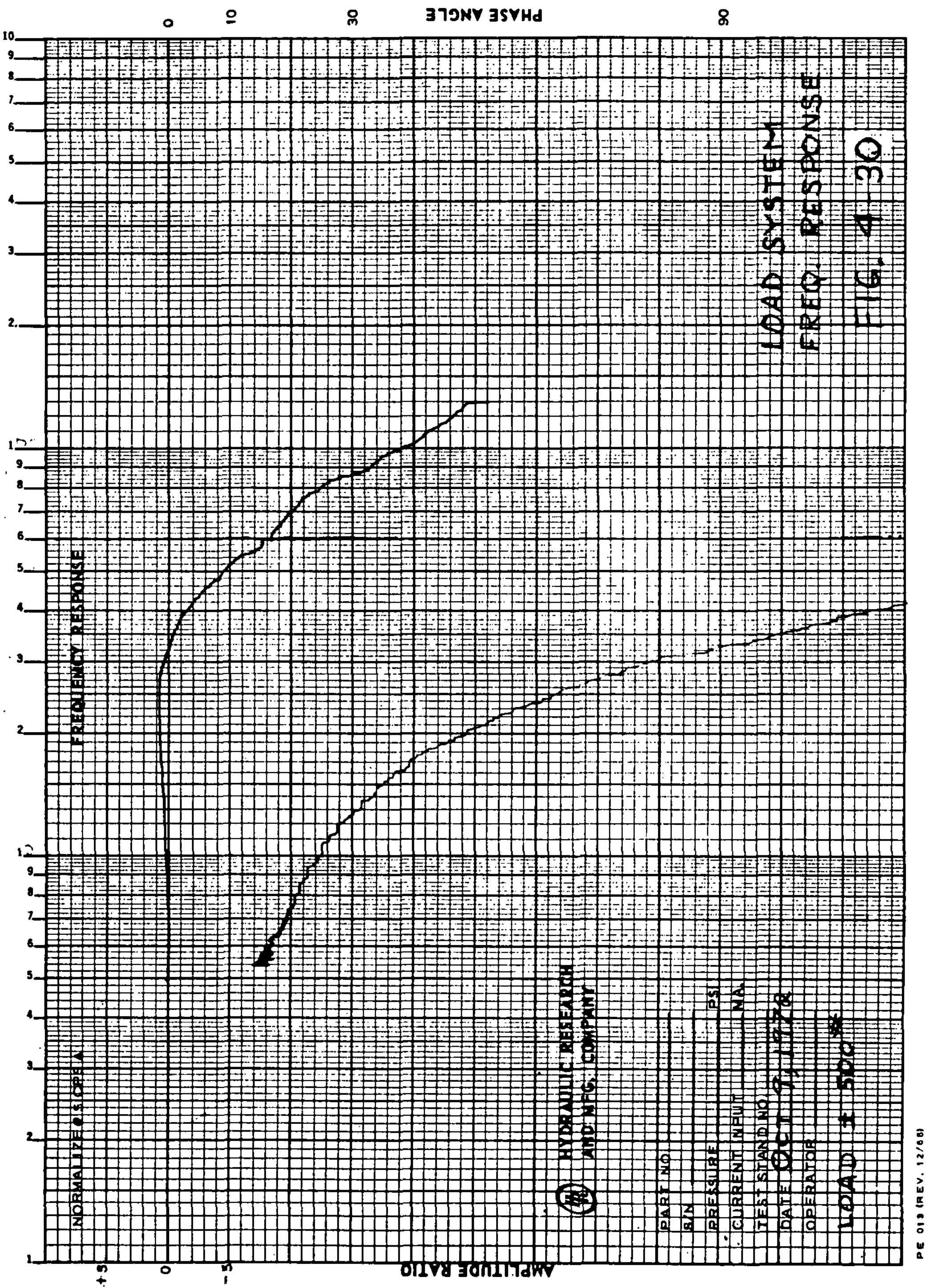


Figure 4-30. Load System Frequency Response

4.2 Preliminary Servoactuator Test

The servoactuator, model/comparator, and console were assembled and initially checked out.

4.2.1 Switching Transient

4.2.1.1 Filter Transients

The model/comparator circuit board was initially assembled with a Butterworth filter in the model and serovalve/LVDT circuit positioned before the negative summer, shown in Figure 4-31 (Reference Figure 2-2). A step change was applied to the model and a null signal applied to the servoamplifier/servovalve. Figure 4-32 shows the oscilloscope data, and the large letters in Figure 4-31 show the location at where the signals were obtained. Figure 4-33 is a photograph of the oscilloscope screen. The filter curve "B" in Figure 4-32 is the output of the filter, which is a lag response and shows the delay. This delay is unacceptable, so the filters were omitted from the circuit.

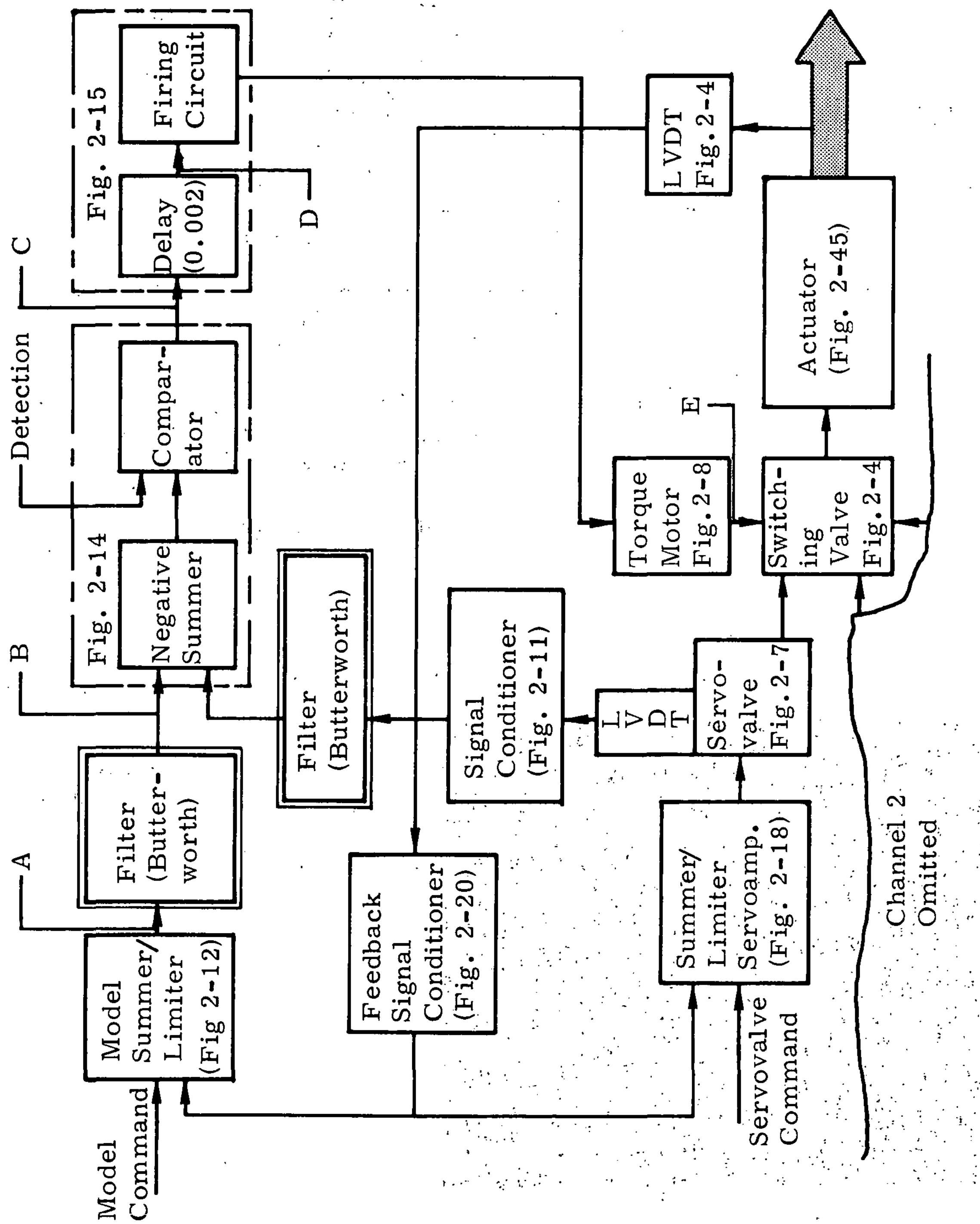


Figure 4-31. Block Schematic - Filter

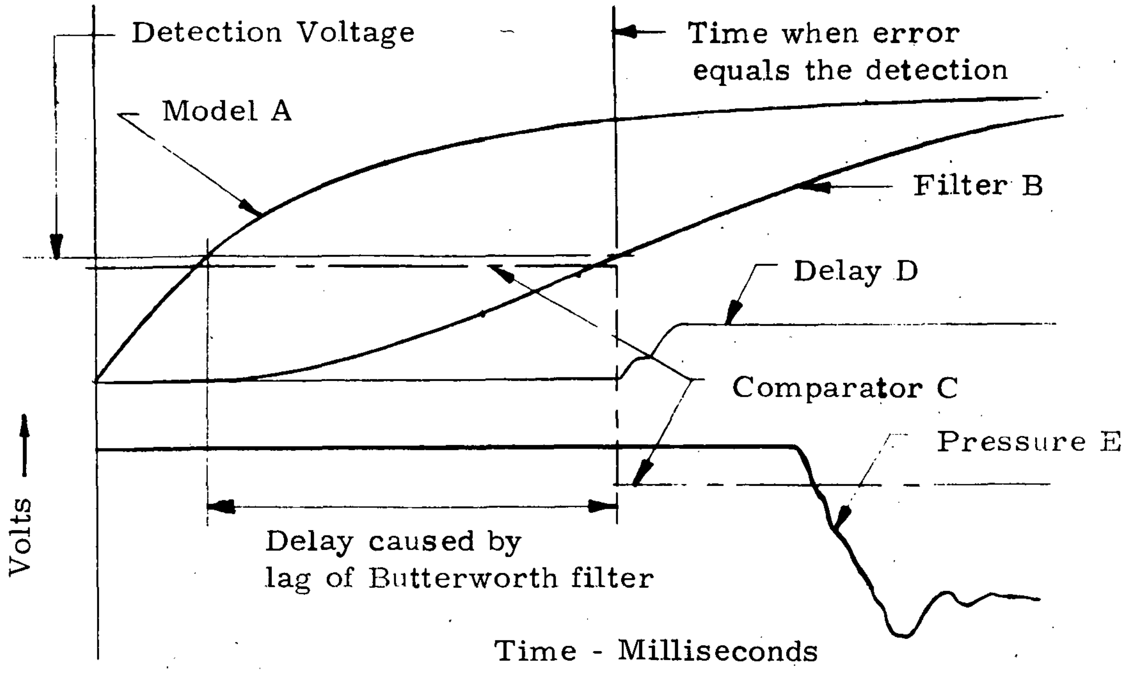
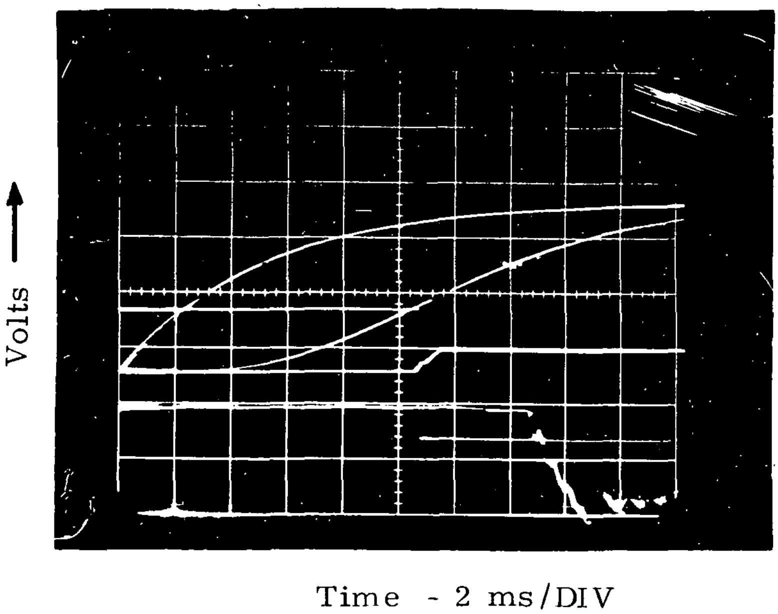


Figure 4-32. Oscilloscope Data



25% Detection
Butterworth Filter

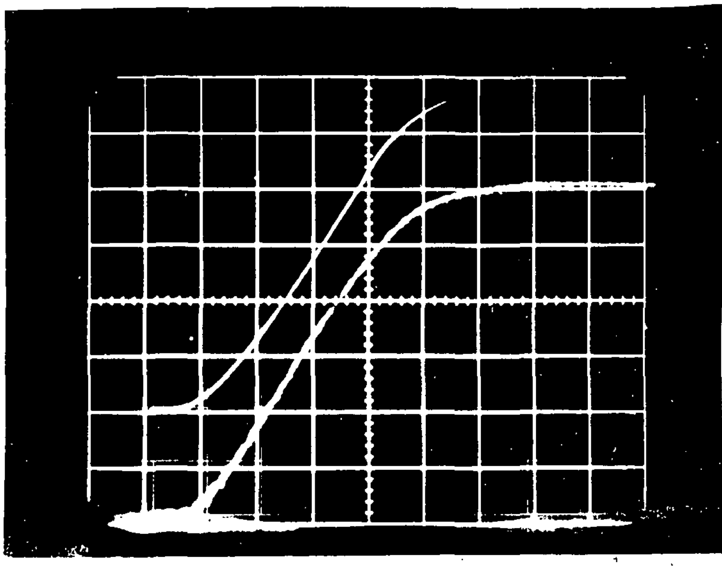
Figure 4-33. Oscilloscope Photograph

4.2.1.2 Final Transients

The servoactuator was run open-loop with a ±1-V square-wave command signal. This magnitude of command is above the saturation (position limit) of the model and servovalve. A signal of ±0.5 V will drive the servovalve hard-over open-loop. Exploratory testing had shown this condition (±1-V command) to give the largest error. The response was recorded using a dual-beam oscilloscope and photographing the screen. For the model, the signal was obtained at test point 2, Figure 2-12. For the servovalve/LVDT, the signal was obtained after the demodulator filter at test point 1, Figure 2-11. The transients were obtained on both sides of the square wave. The step voltage going from negative to positive (-1 to +1 V) was termed a positive step, and the step voltage going from positive to negative (+1 to -1 V) was termed a negative step. The step response and the error (instantaneous difference) are shown in Figures 4-34 through 4-37. Step response of the model and servovalve/LVDT is shown on the top photograph of each figure, the model being the upper beam on the upper photograph. The model signal is inverted for clarity, and zero voltages are displaced in order to separate the tracing.

Top Tracing
Model

0.5 V/DIV



Zero (Model)

Zero (Servovalve)

Bottom Tracing
Servovalve

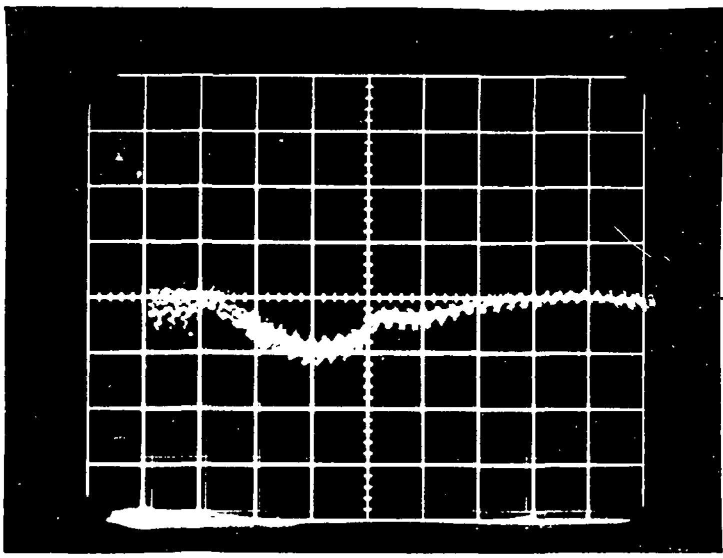
Step Response

Trigger

1 ms/DIV

±1 V Square-Wave
10 Hz Command

0.1 V/DIV



Zero

Error Signal
(Negative Summer)

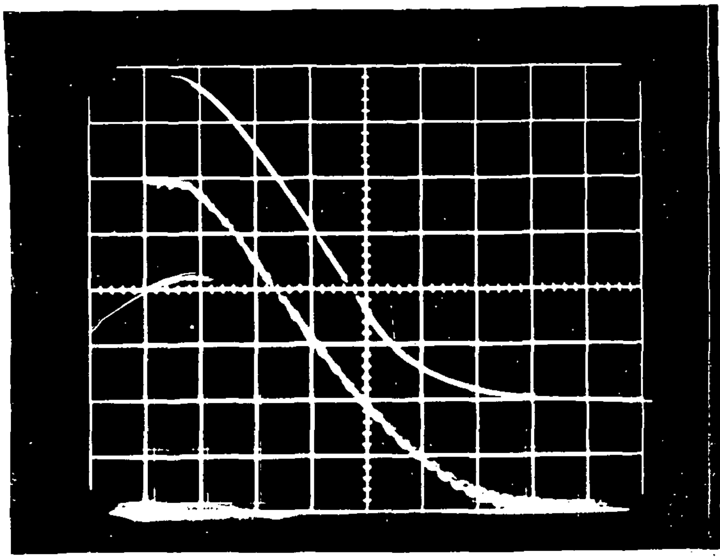
Trigger

1 ms/DIV

Figure 4-34. Channel 1 Positive Step

Top Tracing
Model

0.5 V/DIV



Zero (Model)

Zero (Servovalve)

Bottom Tracing
Servovalve

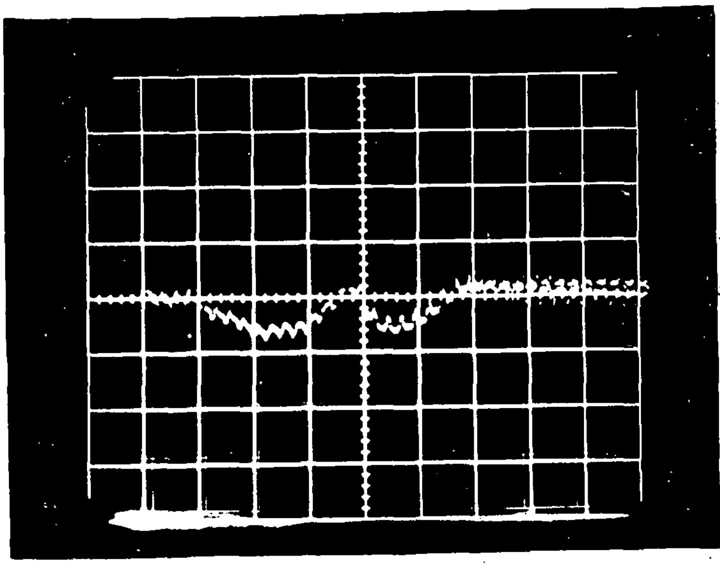
Trigger →

1 ms/DIV

Step Response

±1 V Square-Wave
10 Hz Command

0.1 V/DIV

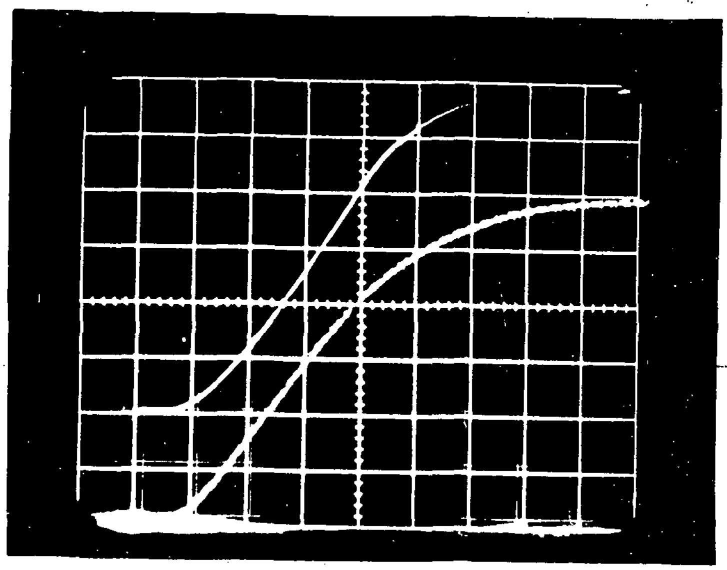


Zero

Trigger →

1 ms/DIV

Figure 4-35. Channel 1 Negative Step



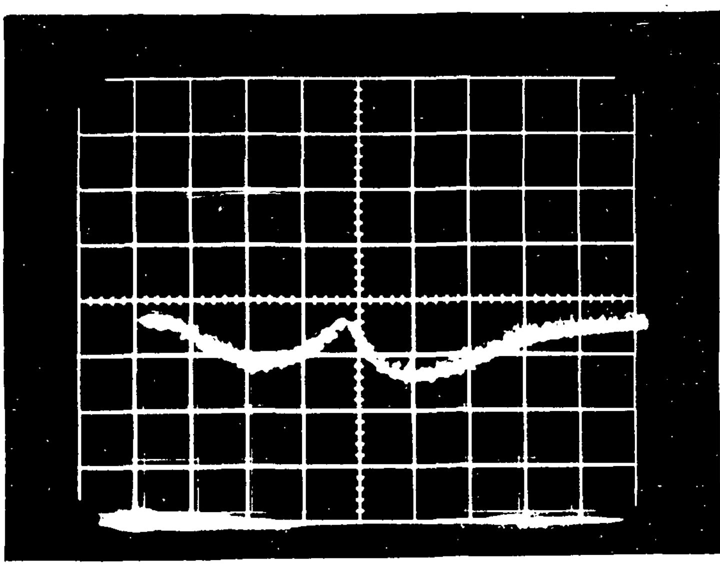
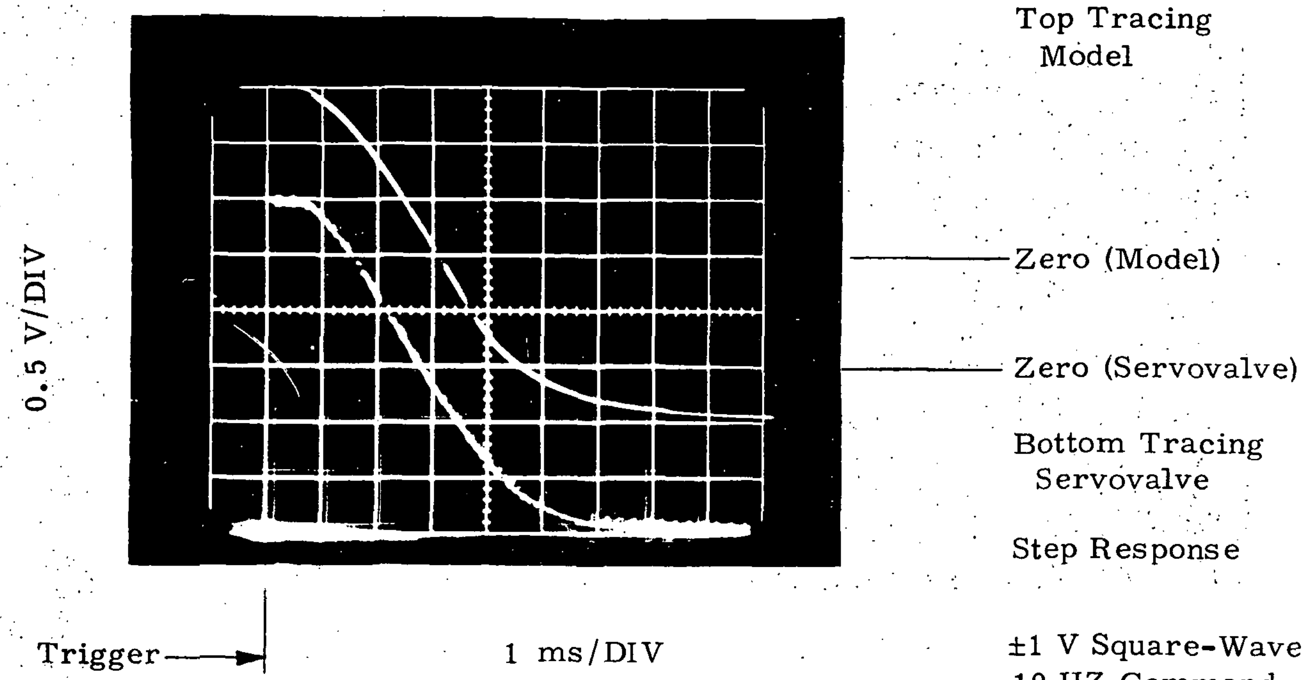


Figure 4-36. Channel 2 Positive Step



±1 V Square-Wave
10 HZ Command

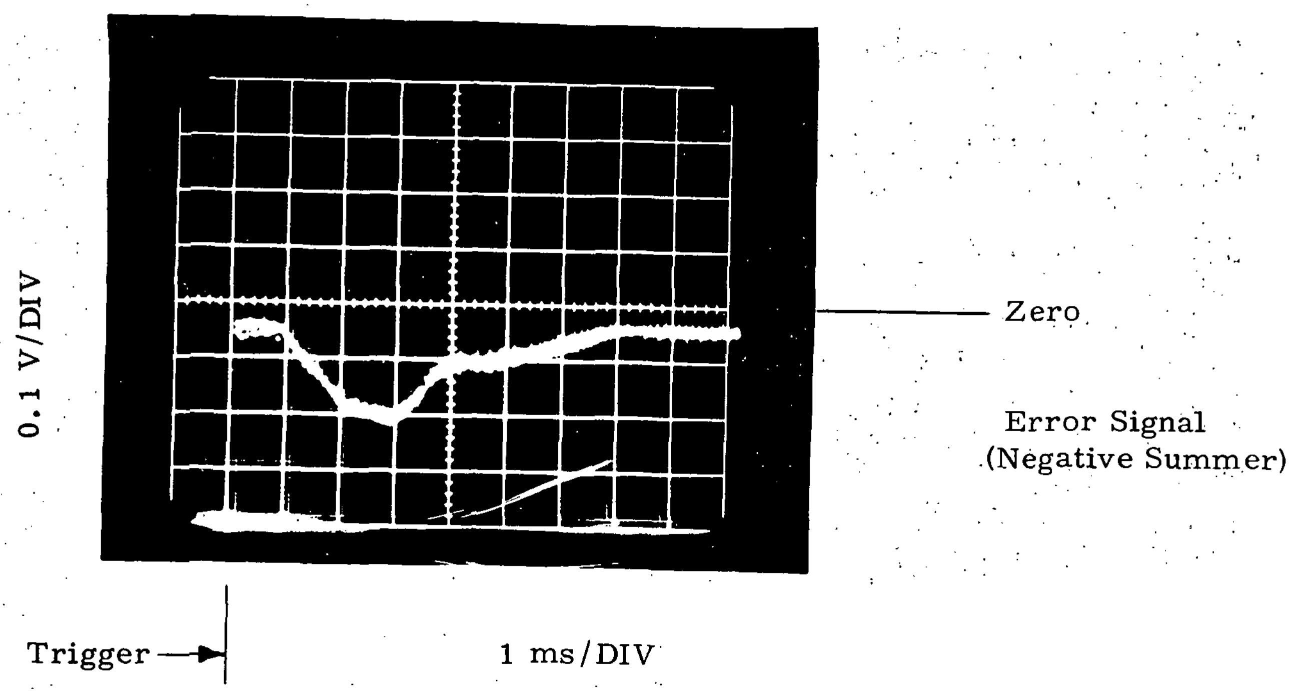


Figure 4-37. Channel 2 Negative Step

The error or instantaneous differences shown in the bottom photograph of Figures 4-34 through 4-37 is the negative summer output obtained at test point 7, Figure 2-14. This summation actually provides a difference between the two signals since the model signal is opposite in sign to the signal from the servo-valve/LVDT. Because of the design of the negative-value summer, the "difference" will always have a negative value. The photographs show the magnitude of any difference in the model/servovalve response. The time base of these photographs is the same as for the corresponding step tracing shown on the upper photograph. The magnitude (vertical axis) is five times greater. The time of triggering is shown and the input step is used as the trigger.

A sketch of the output of the negative summer is shown in Figure 4-38. This sketch illustrates the effect of the delay and detection level. As noted before, in order for a failure to be computed, the error must exist at or above the detection level for 0.002 s, shown in Figure 4-38 as a cross-hatched area. Of the four steps shown, Figure 4-37 has the largest error in terms of both time and magnitude. Holding the 2 ms fixed, the detection level could be reduced to 0.15 V (15%) before a failure should be computed. The servo-actuator was tested with a 25% detection level with no undesired failures. The majority of the testing was performed with 50% detection. This 50% of the

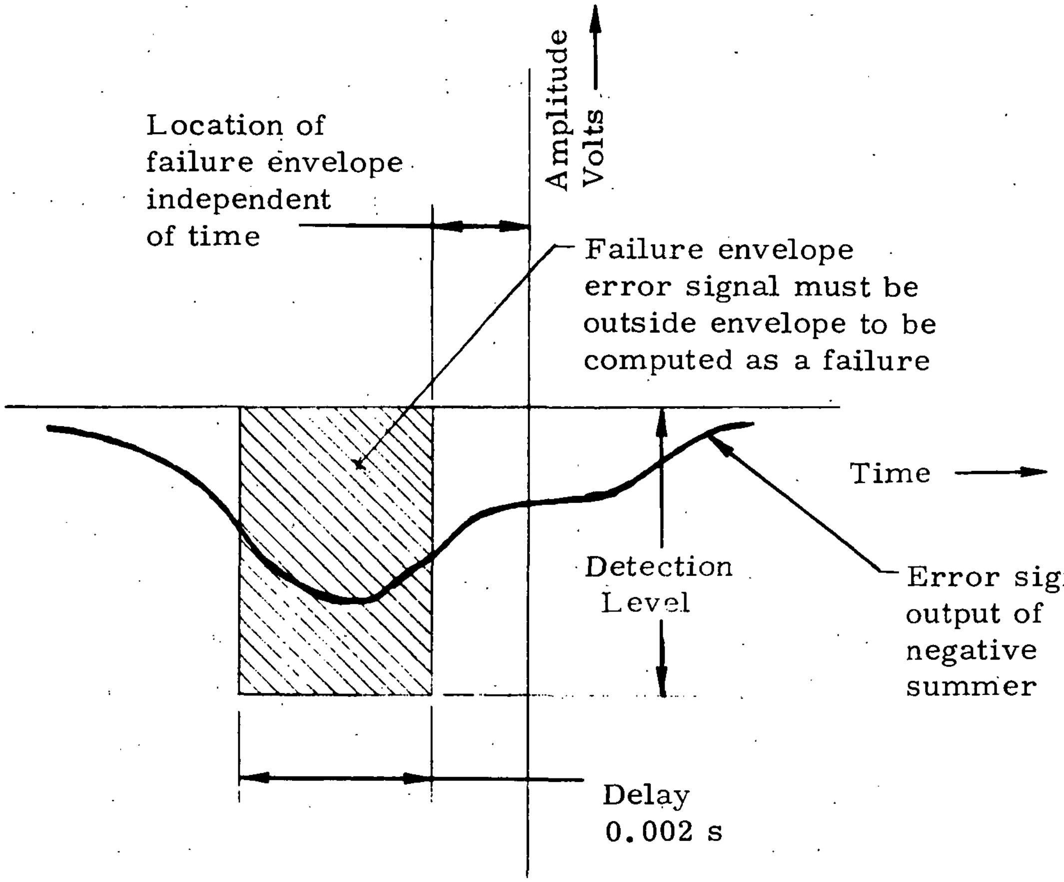


Figure 4-38. Error Signal Sketch

servovalve maximum signal is equal to 5% actuator motion for a loop gain of 30 per second. The relation between actuator error and detection level depends on the loop gain.

Any increase in command above the position limit (±0.5 V) did not result in any change in the output of the servovalve/LVDT but the output of the model would change. The magnitude (±1.5 V) would not change but the wave shape and rate would. Examination of the model showed this to be a combination of factors. First is the location of the position limiter. For the servovalve the position limiter is located before the valve and assures that the servovalve will not receive a signal larger than that for which the limiter is set. The model has this position limiter located after the rate limiter. As a consequence, additional command will result in more rate limiter output. The rate limiter is not a hard limiter; therefore, additional command will cause additional rate command and result in the model response changing. No change in the model was made. Normally the position limiter is accomplished by the stops on the servovalve spool which are after the rate limiter. The valve would then more closely match the model.

4.2.2 Switching Valve, Blocked Port Position

With the switching valve (Figure 2-4) in the blocked-port position, excessive spool leakage was noted. This leakage directly affects the blocked or fixed mode of the actuator. With two failures, the actuator is unable to hold a fixed position. Since the blocked-port requirement is not essential for this program, no additional effort was expended in this direction.

4.3 Servoactuator Testing

The servoactuator was tested per HR 73700060. This procedure and the resulting data is included as Appendix II. Figure 4-39 is a photograph of the test setup. The following referenced paragraph numbers in the brackets refer to HR 73700060.

4.3.1 Actuator Phasing (1.0)

The servoactuator and its components were checked for the proper phasing. All parts respond in the proper direction.

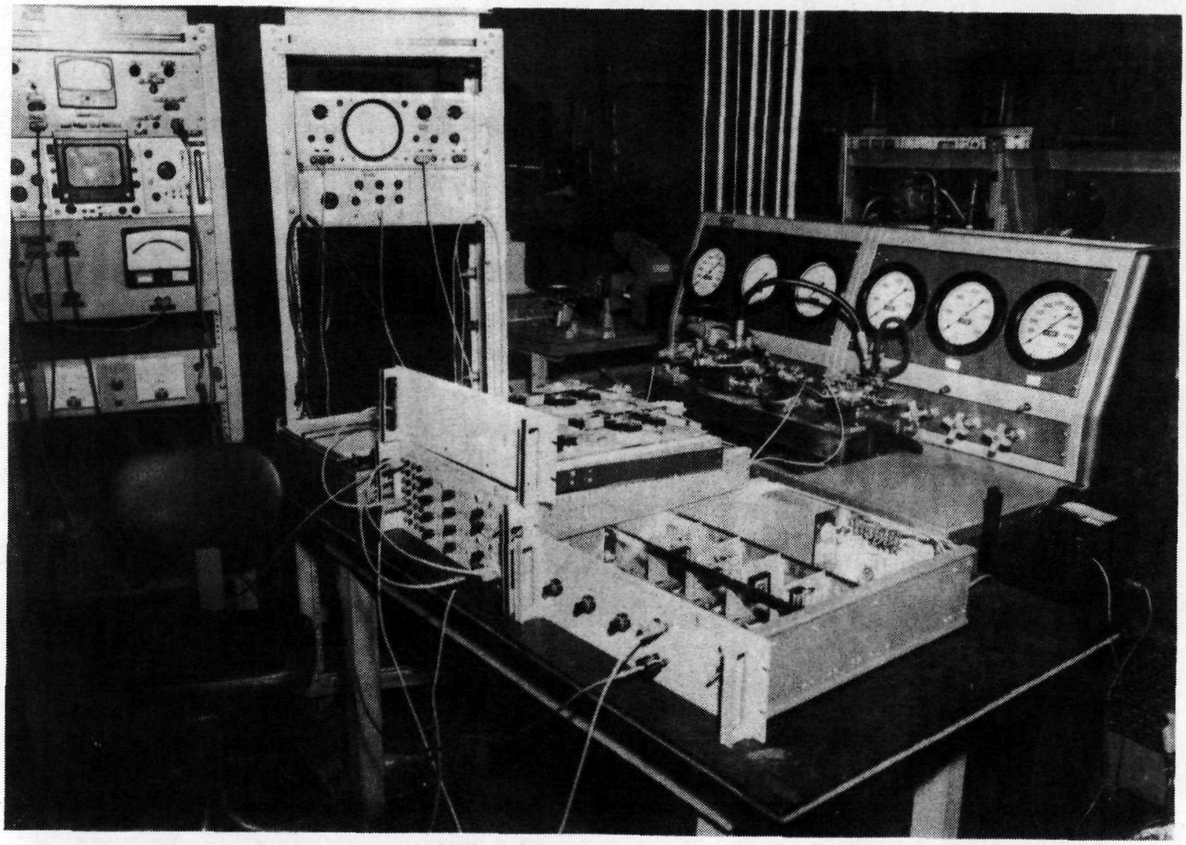


Figure 4-39. Test Setup Photograph

4.3.2 Actuator Characteristics (2.0)

The null position and stroke of the actuator were checked in paragraph 2.2 and are per design. The fail-fixed position was checked in paragraph 2.3. The actuator does stop, but will not hold its position due to leakage in the switching valve.

4.3.3 Frequency Response (2.4)

The frequency response of the servoactuator shows a second-order response with the break at 32 Hz. The response is probably the result of two first-order breaks. The actuator break is estimated at 28 Hz, whereas the design objective was a first-order break at 20 Hz. The second first-order break is believed to be the filter in the demodulator. No additional investigation was made into this response.

4.3.4 Failure Response (3.0)

A dual-beam oscilloscope was used to record the data for this test. The photographs of the oscilloscope data appear in Figure 8 of Appendix II, with an index of the photographs included as Table II.

4.3.4.1 No-Failure Response (3.2)

The command signal and error current for the test in paragraphs 3.2.1 and 3.2.2 of HR 73700060 are recorded in Photographs 1 through 10. The tests were conducted for channels 1 and 2. Five different frequencies were recorded (1, 10, 25, 50 and 100 Hz). The maximum error current in these tests was 0.215 V or 21.5% but this error was not of sufficient duration (0.002 s) to pass the delay. The largest error that would have passed the delay was approximately 0.13 V, or 13%. This means that a detection level of just over 13% would have been sufficient for this test. The wide line of the error signal was due to the poor performance of the LVDT on the servovalve. It was impossible to better filter this signal.

The step responses are shown in Photographs 11 and 12. The maximum error was a spike of approximately 0.25 V. This spike was of insufficient time to fail the unit.

4.3.4.2 Step Failures (3.3)

The step failures are recorded in Photographs 13 through 17. A ±1-V step was applied as indicated in the specification. The servovalve saturation is ±0.5 V, so this will cause full servovalve flowrate. Photograph 13 is the active channel failure and the time sequence can be seen. The detection is ±0.5 V which was reached at 0.003 s, then the 0.002 s delay. At that time (0.005 s), the signal went to the torque motor switch, and at an additional 0.006 s, the actuator position trace started decreasing rate indicating that the standby system was in command. It appears that the trigger for the scope occurred at 0.0015 s. This would make the initial timing 0.0015 s instead of 0.003 s for the error to reach the -0.5 V, which is more consistent with the predicted servovalve response. The maximum servoactuator position error was 0.3 V, or a 3% error, reaching this position in approximately 0.010 s from the time the failure was applied.

Photograph 14 is channel 2 failing and the unit going to the fixed position. Again, the actuator is displaced by approximately 3 V, or 3%.

Photographs 15, 16 and 17 show failure of the standby system and models. These failures did not affect the actuator position.

4.3.4.3 Ramp Failures (3.4)

The response to a ramp-type failure is shown in Photographs 18 through 23. Photographs 18 and 19 are both for the active channel-1 failure. Photograph 18 is the actuator position, and Photograph 19 the error current. From the error current, the failure occurs when the command is down 0.22 V. This corresponds to an actuator displacement of 0.2 V, or a 2% position error. The channel-2 failure shows a position change of 0.26 V, or 26%. Again, failure of the standby channel and the models did not affect the actuator position.

4.3.4.4 Actuator Load (5.0)

The preceding tests were all repeated with a loaded actuator.

4.3.4.4.1 No Failure Response (5.0 - 3.2)

The frequency response was repeated (Photographs 24 through 33). Three tracings are shown on these photographs. The maximum error is approximately 0.14 V (sufficient time for failure). This is approximately equal to the no-load condition.

The step response is shown in Photographs 34 and 35. The maximum error is approximately 0.1 V (1%).

4.3.4.4.2 Step Failure (5.0 - 3.0)

The loaded step failure response is shown in Photographs 36 through 40. The actuator displacement is less than it was for the no-load condition as shown in Photograph 13. This is because the failure was in the direction to oppose the load and the load decreased the motion.

Failure of channel 2 also shows a smaller transient than it did for the no-load condition. Failure of the standby channel and the models had no affect on the actuator position.

4.3.4.4.3 Ramp Failure (5.0 - 3.4)

The loaded ramp failure response is shown in Photographs 41 through 47. Photographs 41, 42 and 43 are all for channel 1 failure, recording the actuator position, error and load all with the command.

4.3.5 Pressure Variation (4.0)

The actuator showed no effect from variation in the supply and return pressure as defined in the test procedure.

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GLOSSARY OF TERMS

Amplitude Ratio - The ratio of the control-flow amplitude to the input-current amplitude at a particular frequency divided by the same ratio at the same input-current amplitude at a specified low frequency (usually 5 or 10 Hz). Amplitude ratio (AR) may be expressed in decibels where $dB = 20 \log_{10} AR$.

Coil Resistance - The dc resistance of each torque motor coil, expressed in ohms.

Flow Curve - The graphical representation of control flow versus input current. This is usually a continuous plot of a complete cycle between plus and minus rated current values.

Flow Saturation Region - The region where flow gain decreases with increasing input current.

Frequency Response - The complex ratio of flow-control flow to input current as the current is varied sinusoidally over a range of frequencies. Frequency response is normally measured with constant input current amplitude and zero load pressure drop, expressed as amplitude ratio, and phase angle. Valve frequency response may vary with the input-current amplitude, temperature, supply pressure, and other operating conditions.

Hydraulic Amplifier - A fluid valving device which acts as a power amplifier, such as a sliding spool, or a nozzle flapper, or a jet pipe with receivers.

Input Current - The current to the valve, expressed in mA, which commands control flow.

Internal Leakage - The total internal valve flow from pressure to return with zero control flow (usually measured with control ports blocked), expressed in in^3/s or gal/min. Leakage flow will vary with input current, generally being a maximum at the valve null (null leakage).

Linearity - The degree to which the normal flow curve conforms to the normal flow gain line with other operational variables held constant. Linearity is measured as the maximum deviation of the normal flow curve from the normal flow gain line, expressed as percent of rated current.

GLOSSARY OF TERMS (Continued)

Null - The condition where the valve supplies zero control flow at zero load-pressure drop.

Phase Lag - The instantaneous time separation between the input current and the corresponding control-flow variation, measured at a specified frequency and expressed in degrees (time separation in seconds x frequency in Hz x 360° per cycle).

Polarity - The relationship between the direction of control flow and the direction of input current.

Port - A fluid connection to the servovalve, e.g., supply port, return port, control port.

Pressure Gain - The rate of change of load pressure drop with input current at zero control flow (control ports blocked), expressed in lb/in^2 per mA. Pressure gain is usually specified as the average slope of the curve of load pressure drop versus current between ±40% of maximum load-pressure drop.

Servovalve, Electrohydraulic Flow-Control - An electrical input, flow-control valve, which is capable of continuous control.

Stage - A hydraulic amplifier used in a servovalve. Servovalves may be single-stage, two-stage, three-stage, etc.

Torque Motor - The electromechanical transducer commonly used in the input stages of servovalves.

APPENDIX I

TRADE STUDY

ELECTRIC/HYDRAULIC SWITCH

(HR 73500006)

HYDRAULIC RESEARCH
and MANUFACTURING COMPANY
A textron COMPANY
25200 WEST RYE CANYON ROAD • VALENCIA, CALIFORNIA 91355
(805) 259-4030 TWX 910-336-1438
CODE IDENT 81873

REPORT NO. HR 73500006
HR&M JOB NO.
CONTRACT NAS 8-27838
NO. PAGES 9
DATE September 1, 1971
REV. B

TRADE STUDY

ELECTRICAL/HYDRAULIC SWITCH

PREPARED BY	Richard K. Mason RM	DATE	August 31, 1971
CHECKED BY	[signature]	DATE	9/2/71
APPROVED BY	[signature]	DATE	9/3/71

REVISION PAGE

REVISION LETTER	DATE OF REVISION	REVISED PAGES	REVISIONS
A	9-15-72	All	Major Revision - Text Rewritten
B	4-9-73	All	Text rewritten without technical change

SCOPE

This trade study presents an evaluation of the electrical/hydraulic switch for the "Active-Standby Servovalve/Actuator Development" contract based on the requirements for the Space Shuttle Main Engine Hydraulic Actuation System (SSME-HAS).

SUMMARY

The three designs which were considered are:

1. Solenoid, concentric coil
2. Solenoid, end-to-end coil
3. Torque motor switch

The comparison matrix, Table I, shows that the torque motor switch was the only satisfactory design for SSME application, switching time being the predominant reason for that selection.

FUNCTIONAL AND TECHNICAL REQUIREMENTS

For this contract, a servovalve failure was computed electrically. An electric signal activates an electrical/hydraulic (EH) switch which causes a spool valve to change channels. The EH switch had to be a fast-acting device, since its actuation time directly contributes to the time required to change channels. The effect of this delay in changing channels for the SSME is shown in Figures 1, 2, and 3, plots taken from

COMPARISON MATRIX

TABLE I

Criteria	Solenoid Concentric	Solenoid End-to-End	Torque Motor Switch
Switching Time(Seconds) 1			
Energize	0.016 2 3	0.012 2 3	0.006 4
De-energize	0.020+ 2 3	0.020+ 2 3	0.006 4
Stroke (In)	0.0105 3	0.0105 3	0.020+
Output Force(Pounds) 5	9	9	17
Armature	Wet	Wet	Dry
Development % Redesign (Estimate)	85	95	10
Coil Separation	Poor 6	Good	Excellent
Weight Factor	1	1	1.5
Cost Factor (Estimate)	1	1	3

NOTES:

1. Time from electric signal to the EH switch to hydraulic pressure change
2. Unsatisfactory
3. Based on solenoid manufacturing estimates
4. Based on HYDRAULIC RESEARCH production experience
5. Available force at maximum stroke
6. Does not meet Rocketdyne design requirements

OPERATING CONDITIONS			
CURVE SYMBOL	FAILURE RATE, %/SEC	RECOVERY RATE, %/SEC	ACTUAL LOAD CONDITIONS
———	190	190	MINIMAL LOAD
—·—·—	250	150	LOAD ASSISTING FAILURE
— — —	150	250	LOAD RESISTING FAILURE

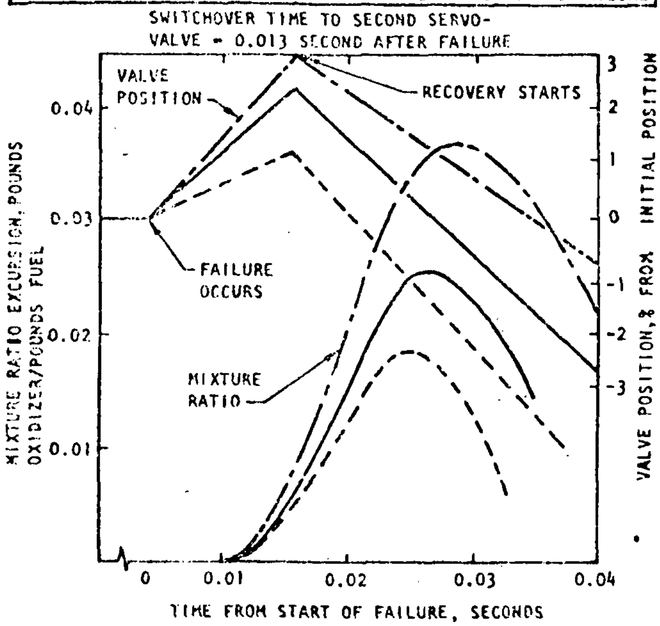

Figure 1 Transient Mixture Ratio Response to Fuel Preburner Servovalve Step Failure at NPL

OPERATING CONDITIONS				
CURVE SYMBOL	FAILURE RATE, %/SEC	RECOVERY RATE %/SEC	MAX THRUST CHANGE RATE, LB/10 MS	ACTUAL LOAD CONDITIONS
———	190	190	4222	MINIMAL LOAD
—·—·—	250	150	5776	LOAD ASSISTING FAILURE
— — —	150	250	3215	LOAD RESISTING FAILURE

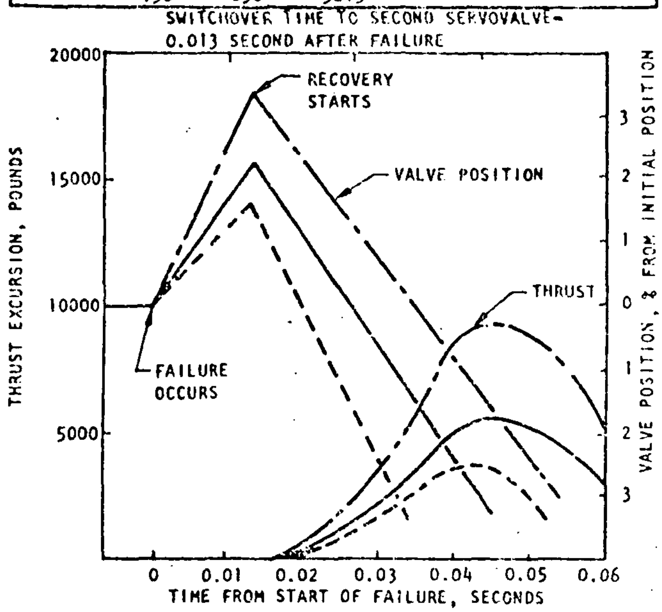

Figure 2 Transient Thrust Response to Oxidizer Preburner Servovalve Step Failure at NPL

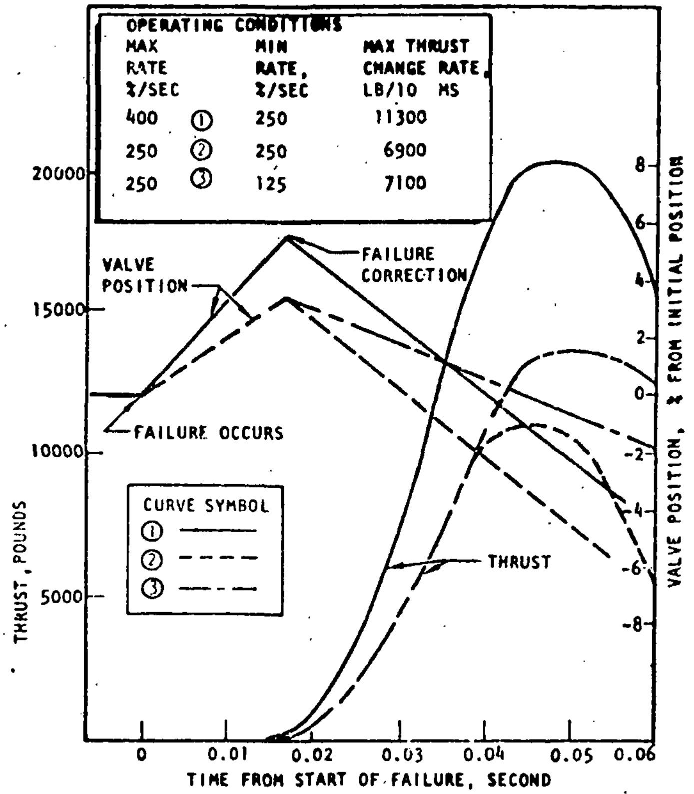

Figure 3 Transient Thrust Response at Various Slew Rates

As noted on these plots, a switching time of 0.013 s was assigned the servoactuator. This 0.013-s time will be distributed as follows:

	0.002 s	comparator delay
	0.001 s	servovalve slew rate
	0.002 s	spool valve motion
	0.008 s	EH switch
Total	0.013 s	

the Rocketdyne SSME Phase II Study (RSS-8502-5, pages 6-13 and 6-14). The torque motor switch must have dual-redundant coils which are separately wound and insulated. The dual-redundant coils are required for the electrical fail/operate requirement for SSME. This allows either electrical system to energize the EH switch. Each coil must have a bifilar-wound coil for arc suppression. The EH switch shall be energized with 0.9 A and held with 0.5 A.

Because of Rocketdyne experience, the following special requirements were imposed on solenoids:

> Solenoid structure consists of CRES 430F end plates, silver brazed to CRES 303 bobbin. Coils are wound on insulating bobbins (Hysol #4278) and vacuum-impregnated with Dow Corning 997 varnish. Coils consist of two magnetically identical force coils which are bifilar-wound to provide transient suppression. Lead wires and coils are potted using Stycast 2850 GT epoxy. The outer shell (430F CRES) is silver-soldered in place.

The valve used for this study was a modified HYDRAULIC RESEARCH bipropellant valve, qualified for space environment application.

The hydraulic poppet valve is shown in Figure 4.

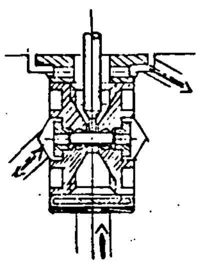

Figure 4. Hydraulic Poppet Valve

The valve was identical for all three designs, being an existing flat-lapped design used on many HYDRAULIC RESEARCH products.

The design shown in Figure 5 uses two coils wound on the same centerline but at different diameters. In order to keep the coil resistance the same for the two coils, the outer coil uses a larger-diameter wire. A groove is cut in the armature to allow hydraulic oil to circulate around the armature, and an electric-resistant material is placed between the coils. This coil arrangement does not offer good protection against a coil failure on one coil in turn burning out the other.

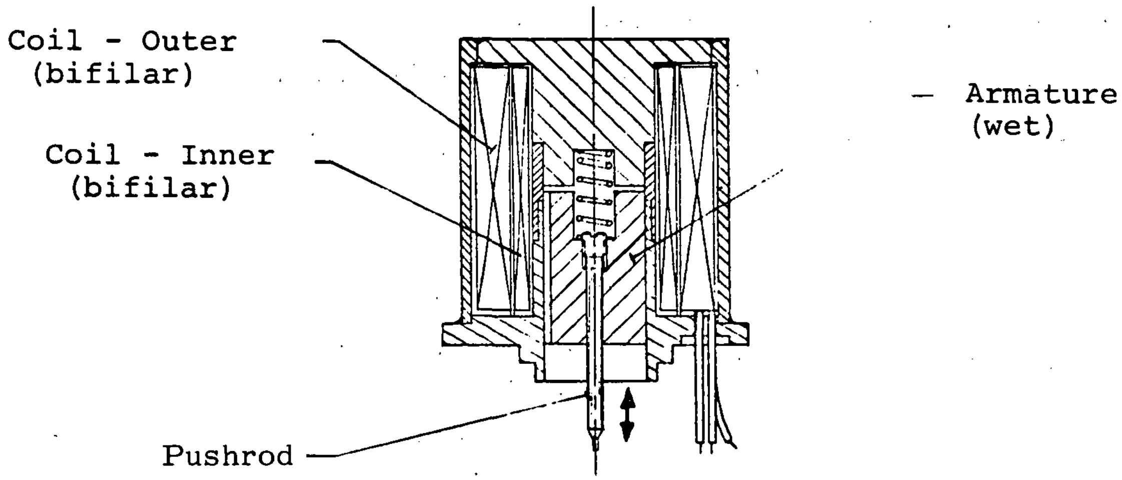

Figure 5. Concentric-Coil Solenoid

The design shown in Figure 6 uses two coils placed end-to-end. The top coil is somewhat shorter and wider than the bottom to allow bringing the leads past the bottom coil. The coils are separated by insulating material as well as a non-magnetic steel shoulder, allowing good separation of the coils. Again, the armature is wet with provisions for oil circulation (coils are dry).

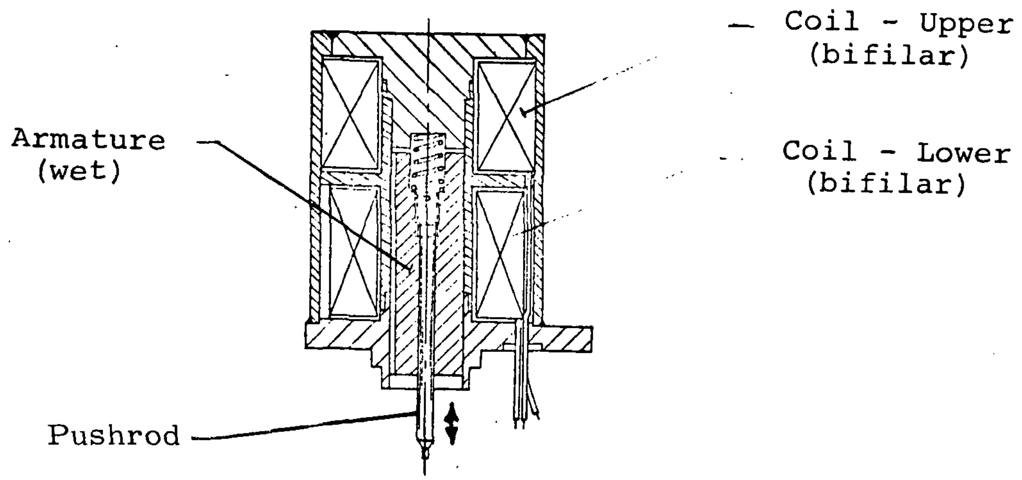

Figure 6. End-To-End Coils Solenoid

The design illustrated in Figure 7 uses an existing torque motor to drive the pushrod. Essentially, the torque motor is modified only to add the pushrod, and is from a bipropellant valve for a 25 lb thruster. Approximately 40 of these torque motor valves have been manufactured for customers such as Rocket Research, JPL, Sundstrand and TRW. Individual valves have been cycled up to 4.5×10^6 times with no failures.

This design features a dry armature driven by one of two coils and two permanent magnets, with a flexure tube used as seal, pivot and spring. The valve has the capacity for approximately 40 lb force at the poppet, though only 17 lb is specified.

The torque motor design would be modified for the SSME-HAS to reduce both cost and weight, and the connector will be replaced by pigtails.

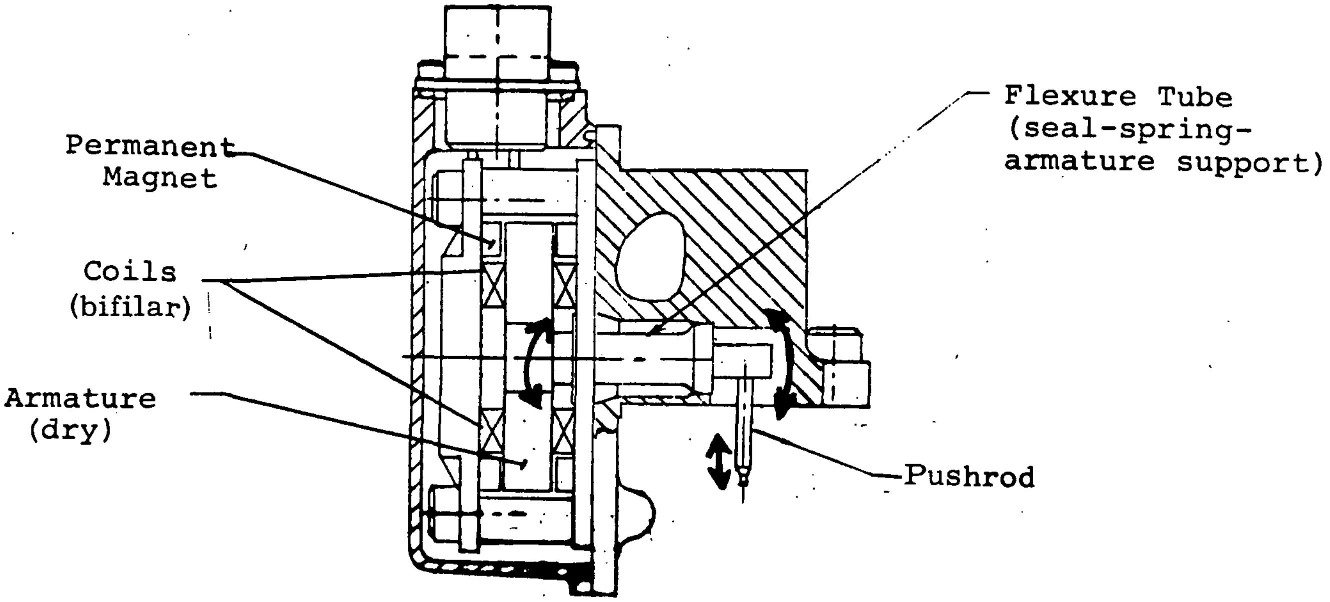

Figure 7. Torque Motor Switch

CONCLUSION

Table I shows that the only acceptable design is the torque motor switch. The two solenoid designs have actuation times in excess of the 0.008 s required. For this contract, the cost of the torque motor switch is three times that of the solenoid valves, but the development costs are very low. Redesign for the SSME will allow this cost to be reduced, while the solenoid valves are now at their minimum cost. The weight of the torque motor switch is 1.5 times the solenoid valves. Again, redesign for SSME application will remove much of this weight.

One factor not considered in Table I is reliability. Since the torque motor does not have hydraulic fluid around the sliding parts, it should have improved reliability over the solenoids.

It is noted that the overriding requirement of actuation time essentially rules out the solenoids considered here.

APPENDIX II

TEST PROCEDURE

ACTIVE-STANDBY, SERVOVALVE/ACTUATOR

(HR 73700060)

HYDRAULIC RESEARCH
and MANUFACTURING COMPANY
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HR&M JOB NO.
CONTRACT NAS 8-27838
NO. PAGES 38
DATE November 1, 1971
REV. B

TEST PROCEDURE

ACTIVE-STANDBY, SERVOVALVE/ACTUATOR

PREPARED BY Richard K. Mann DATE Oct 12, 1971
CHECKED BY [illegible signature] DATE 10/20/71
APPROVED BY [illegible signature] DATE 10/27/71

REVISION PAGE

REVISION LETTER	DATE OF REVISION	REVISED PAGES	REVISIONS
A	9-7-72	All	Major Revision - Text Rewritten
B	4-9-73	All	Text rewritten without technical change

1.0 PHASING

1.1 Setup - Attach the pressure transducers at torque motors (TM) #1 and #2 on the actuator assembly. Connect servovalve to a current driver and apply 3000 lb/in^2 supply, 50 lb/in^2 return.

1.2 TM Switches Phasing

1.2.1 TM Switch #1

1.2.1.1 Attach recorder to pressure transducer #1. The recorder shall indicate return pressure at TM #1 (50 lb/in^2)

50 lb/in^2

1.2.1.2 Apply 28 V dc to TM switch #1. The recorder shall indicate 2800 lb/in^2 minimum at TM #1.

3000 lb/in^2

1.2.2 TM Switch #2

1.2.2.1 Attach the recorder to pressure transducer #2. The recorder shall indicate return pressure (50 lb/in^2) at TM #2.

50 lb/in^2

1.2.2.2 Apply 28 V dc to TM Switch #2. The recorder shall indicate 2800 lb/in^2 minimum at TM #1.

3000 lb/in^2

1.3 Servovalve Phasing

1.3.1 Servovalve #1

1.3.1.1 Apply 28 V dc to TM Switch #1.

1.3.1.2 Apply +2.5 mA to servovalve #1. The actuator shall retract. OK

1.3.1.3 Apply -2.5 mA to servovalve #1. The actuator shall extend. OK

1.3.2 Servovalve #2

1.3.2.1 De-energize TM switch #1. Apply 28 V dc to TM switch #2.

1.3.2.2 Apply +2.5 mA to servovalve #2. The actuator shall retract. OK

1.3.2.3 Apply -2.5 mA to servovalve #2. The actuator shall extend. OK

1.4 Actuator LVDT Phasing

1.4.1 Connect the actuator to the monitor-control console. Close the dc and the 28 V dc power switches. Put all the command switches at NORMAL. Set the position switches at OPEN. Activate the active reset switch.

1.4.2 Extend the actuator by applying +1 V dc to servovalve #1 (normal input jacks). The output of the actuator demodulator shall be -5 V at jack #5.

-5 V

1.4.3 Retract the actuator by applying -1 V dc to servovalve #1 (normal input jack). The output of the actuator demodulator shall be +5 V at jack #5.

+5 V

1.5 Servovalve/LVDT Phasing

1.5.1 Servovalve #1 LVDT

1.5.1.1 Connect model/comparator #1 to the console.

1.5.1.2 With the switches set per paragraph 1.4.1, apply a command of -10 V dc to servovalve #1 (normal input jack). The output of the servovalve #1 LVDT demodulator shall be +1.5 V dc at test point (TP) 1 (Test point #1 on the model/comparator #1, Figure 1).

+1.5 V dc

1.5.1.3 Apply a command of +10 V dc to servovalve #1 (normal input jacks). The output, TP 1, shall be -1.5 V dc.

-1.5 V dc

1.5.2 Servovalve #2 LVDT

1.5.2.1 Connect the model/comparator #2 to the console.

1.5.2.2 With the switches set per paragraph 1.4.1, apply a command of -10 V dc to servovalve #2 (normal input jack). The output of the servovalve #2 LVDT demodulator shall be +1.5 V dc at TP 1 on the model/comparator #2.

+1.5 V dc

1.5.2.3 Apply a command of +10 V dc to servovalve #2 (normal input jack). The output at TP #1 shall be -1.5 V dc.

-1.5 V dc

2.0 ACTUATOR CHARACTERISTICS

2.1 With the actuator connected to the console, apply 3000 lb/in^2 gage supply and 50 lb/in^2 gage return. Put the four active and standby servo switches in the NORMAL position and the four model switches in the OPEN position. Actuate the active channel reset switch and the standby channel reset switch. The two lights should stay lit. OK

2.2 Actuator Stroke

2.2.1 Null Position - Apply a command signal of zero volts (normal input). The actuator piston should be at approximately midposition. OK

2.2.2 Extend Position - Apply a command signal of +5 V. The actuator shall extend 0.45 in from the midposition.

0.45" Actuator Position

2.2.3 Retracted Position - Apply a command signal of -5 V. The actuator shall retract 0.45 in from the midposition.

0.45" Actuator Position

2.2.4 Stroke - Record the actuator position, jack 5 and command jack 4. Cycle the actuator with a command of +5 V to -5 V. Plot actuator position versus command and attach to end of procedure.

2.3 Stop Actuator

2.3.1 Energize TM switch #1 and TM switch #2. Close the 28-V power switch and the two reset switches. Apply a 0.1-Hz ±4-V command (normal input jack). When the actuator is near null, de-energize both TM switches by the 28-V power switch. The actuator shall come to a stop.

Actuator Stopped (Yes/No) YES

2.4 Frequency Response

2.4.1 Frequency Response Channel 1.

2.4.1.1 Connect the command signal, jack 4, and the feedback signal, jack 5, to the frequency analyzer. All switches in the NORMAL position. Assure TM switch #1 and #2 are energized.

2.4.1.2 Apply a sinusoidal ±0.5-V command signal. Record phase and attenuation to 60 Hz normalized at 0.5 Hz, and attach frequency versus phase and amplitude ratio plot at end of procedure.

2.4.2 Frequency Response Channel 2.

2.4.2.1 Connect the command signal, jack 3, and the feedback signal, jack 5, to the frequency analyzer. Open and then close the 28-V power switch. Energize the standby channel switch.

2.4.2.2 Apply a sinusoidal ±0.5-V command signal. Record phase and attenuation to 60 Hz normalized at 0.5 Hz, and attach frequency versus phase and amplitude ratio plot at end of procedure.

3.0 FAILURE RESPONSE

3.1 Setup

3.1.1 Hydraulic - Apply 3000 lb/in^2 gage supply and 50 lb/in^2 gage return.

3.1.2 Electrical - Set command and position switches to the NORMAL position. Energize TM switches #1 and #2 with the reset switches. Set detection level at 50% by adjusting the threshold for 0.5 V at the monitor control panel, and read at TP 6 (Figure 1).

3.1.3 Record - Record command signal jack 4, actuator position jack 5, error level at TP 5 and the signal as noted for each test. Attach plot of command signal, actuator position and error level to end of procedure.

3.2 No-Failure Response

3.2.1 Frequency Response - Apply a sine wave command signal of ±1 V, 0.5 to 100 Hz. Record per paragraph 3.1.3.

3.2.2 Step Response - Apply a ±0.1-V square wave at 5 Hz. Record per paragraph 3.1.3

3.3 Step Failures

3.3.1 Servovalve #1 Step Failure

3.3.1.1 Assure that TM switches #1 and #2 are energized. Put all switches in the NORMAL position. Set auxiliary signal at +1.0 V.

3.3.1.2 Apply a step of +1.0 V to servovalve #1 by moving the command active servo switch to the AUXILIARY position. Record per paragraph 3.1.3 and command signal on jack 4.

3.3.2 Servovalve #2 Step Failure (One Failure)

3.3.2.1 Maintain TM switches #1 and #2 as resulted from paragraph 3.3.1.2. Return all other switches to the NORMAL position.

3.3.2.2 Apply a step of ±1 V to servovalve #2 by moving the command standby servo switch to the AUXILIARY position. Record per paragraph 3.1.3 and command signal on jack 3.

3.3.3 Servovalve #2 Step Failure (No Failure)

3.3.3.1 Energize TM switches #1 and #2. Return all switches to the NORMAL position.

3.3.3.2 Apply a step of +1 V to servovalve #2 by moving the command standby servo switch to the AUXILIARY position. Record per paragraph 3.1.3 and command to servovalve #2 on jack 3.

3.3.4 Model #1 Step Failure

3.3.4.1 Energize both TM switches #1 and #2. Return all switches to the NORMAL position.

3.3.4.2 Apply a step of +1 V to the active model by moving the command active model switch to the AUXILIARY position. Record per paragraph 3.1.3 and command to the active model on jack 8.

3.3.5 Model #2 Step Failure (Channel 1 Failed)

3.3.5.1 Maintain TM switches #1 and #2 as resulted from paragraph 3.3.4.2. Return all switches to the NORMAL position.

3.3.5.2 Apply a step of +1 V to the standby model by moving the command standby model switch to the AUXILIARY position. Record per paragraph 3.1.3 and command to the standby on jack 2.

3.4 Ramp Failures

3.4.1 Servovalve #1 Ramp Failures

3.4.1.1 Setup - Apply a null command signal. Reset TM switches #1 and #2. All switches in the NORMAL position.

3.4.1.2 Apply a triangular wave on the AUXILIARY signal generator at 0.1 Hz, ±1.0 V. Move the command active servo switch to the AUXILIARY position as triangular wave goes from (-) to (+) at null. Record per paragraph 3.1.3 and command signal on jack 3.

3.4.2 Servovalve #2 Ramp Failure (One Failure)

3.4.2.1 Maintain torque motor switches as resulting from paragraph 3.4.1.2. Return all switches to NORMAL position per paragraph 3.1.2.

3.4.2.2 Apply a triangular wave on the AUXILIARY signal generator at 0.1 Hz, ±1.0 V. Move the command standby servo switch to the AUXILIARY position as the triangular wave goes from (-) to (+) at null. Record per paragraph 3.1.3 and command signal on jack 3.

3.4.3 Servovalve #2 Ramp Failure (No Failure)

3.4.3.1 Reset both torque motor switches. Return all switches to NORMAL position.

3.4.3.2 Apply a triangular wave on the AUXILIARY signal generator at 0.1 Hz, ±1.0 V. Move the command standby servo switch to AUXILIARY position as the triangular wave goes from (-) to (+) at null. Record per paragraph 3.1.3 and command to servovalve #2 on jack 3.

3.4.4 Ramp Failure Active Model Comparator

3.4.4.1 Reset both torque motor switches. Return all switches to NORMAL position.

3.4.4.2 Apply a triangular wave on the AUXILIARY signal generator at 0.1 Hz, ±1.0 V. Move the command active model switch to the AUXILIARY position as the triangular wave goes from (-) to (+) at null. Record for paragraph 3.1.3 and command to the active model on jack 8.

3.4.5 Model #2 Ramp Failure (Channel 1 Failed)

3.4.5.1 Maintain torque motor switches as resulted from paragraph 3.4.4.2. Return all switches to NORMAL position.

3.4.5.2 Apply a triangular wave on the AUXILIARY signal generator at 0.1 Hz, ±1.0 V. Move command standby model switch to the AUXILIARY position as the triangular wave goes from (-) to (+) at null. Record per paragraph 3.1.3 and the command to model #2 on jack 2.

4.0 PRESSURE VARIATIONS

4.1 Apply 3000 lb/in^2 supply and 50 lb/in^2 return. Put all switches in NORMAL position and reset TM switches #1 and #2.

4.2 Variation at Null

4.2.1 Apply a null command, then vary supply pressure to 2500 and 3500 lb/in^2. Record pressure, error level, TP 7, and actuator position jack 5. The unit shall not switch. NO CHANGE IN ERROR CURRENT OR ACT. POSITION.

4.2.2 Apply a null command, then vary return pressure 10 to 275 lb/in^2. Record pressure, error level TP 5, and actuator position jack 5. NO CHANGE IN ERROR CURRENT OR ACT. POSITION.

5.0 LOAD FIXTURE

5.1 Setup - Assemble the actuator on the load fixture and connect the load actuator to the load control unit. Energize power switch, connect the feedback (jack 5) from the monitor-control console to the command jacks on the load control unit.

5.1.1 Set the gain at 0.5 on dial, Figure 2. Set the limit at 1500 lb, Figure 2 (0.75 on dial). Set the bias at 700 lb, Figure 2 (0.7 on dial).

5.2 Frequency Response

5.2.1 Repeat the frequency response test, paragraph 2.4 through 2.4.2.2, recording the data as required.

5.3 Failure Response

5.3.1 Repeat test in Section 3, recording the data as required, in addition to the load.

TABLE I

LIST OF MONITOR-RECORD JACKS

1. Command Signal Generator
2. Command to Standby Model
3. Command to Standby Servovalve
4. Command to Active Servovalve
5. Feedback Signal from Demodulator
6. Feedback to Standby Servovalve
7. Feedback to Active Servovalve
8. Command to Active Model
9. Feedback to Active Model
10. Feedback to Standby Model
11. Pressure Transducer
12. Pressure Transducer
13. Open
14. Open
15. Open
16. Open
17. Open
18. Open

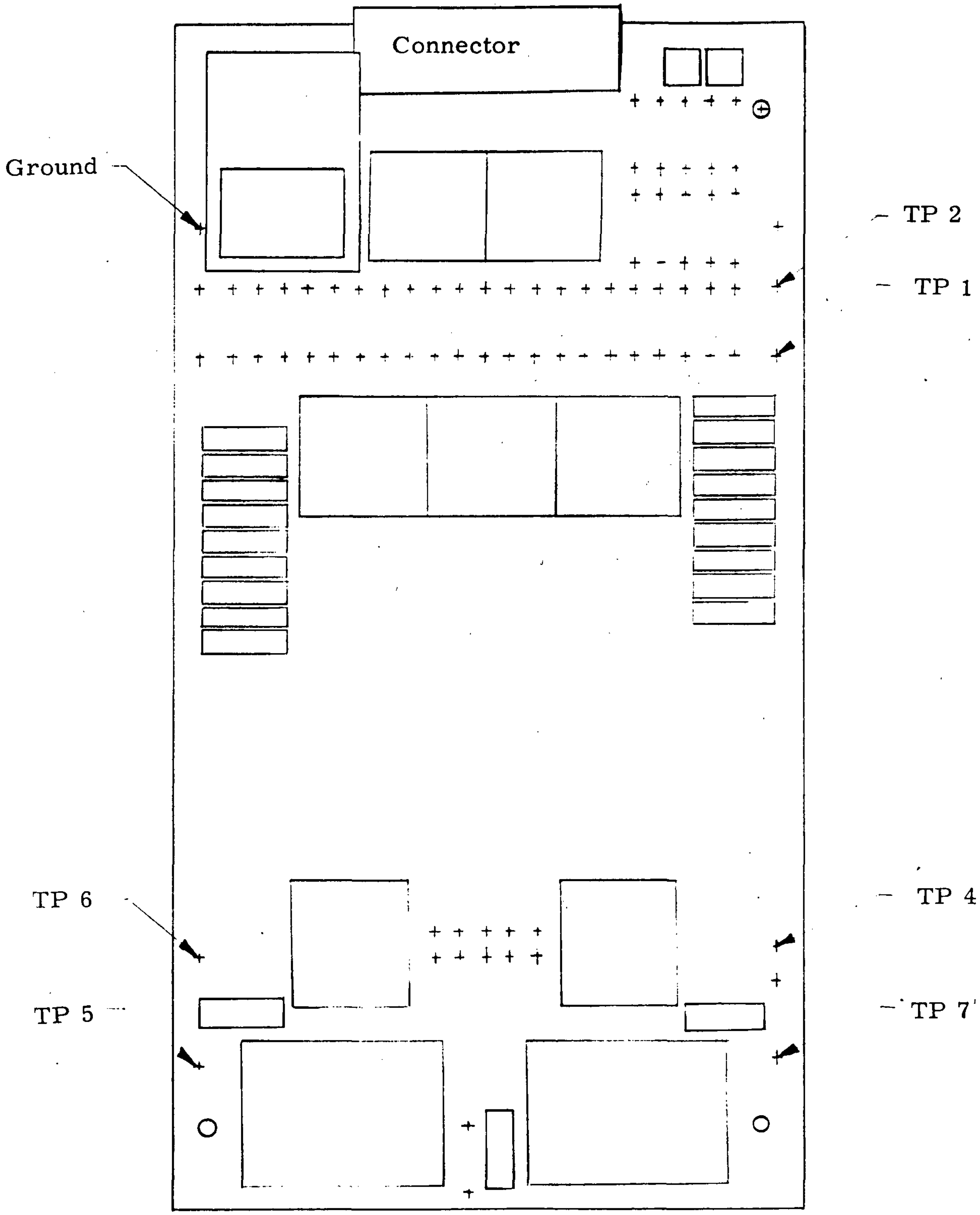
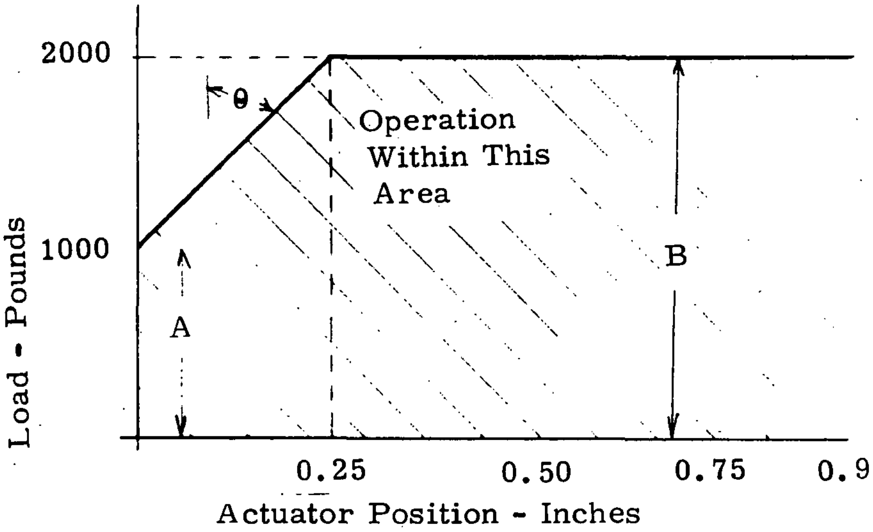


Figure 1. Model/Comparator-Test Positions Locations



θ - Gain

A - Bias

B - Limit

Figure 2. Load Characteristics

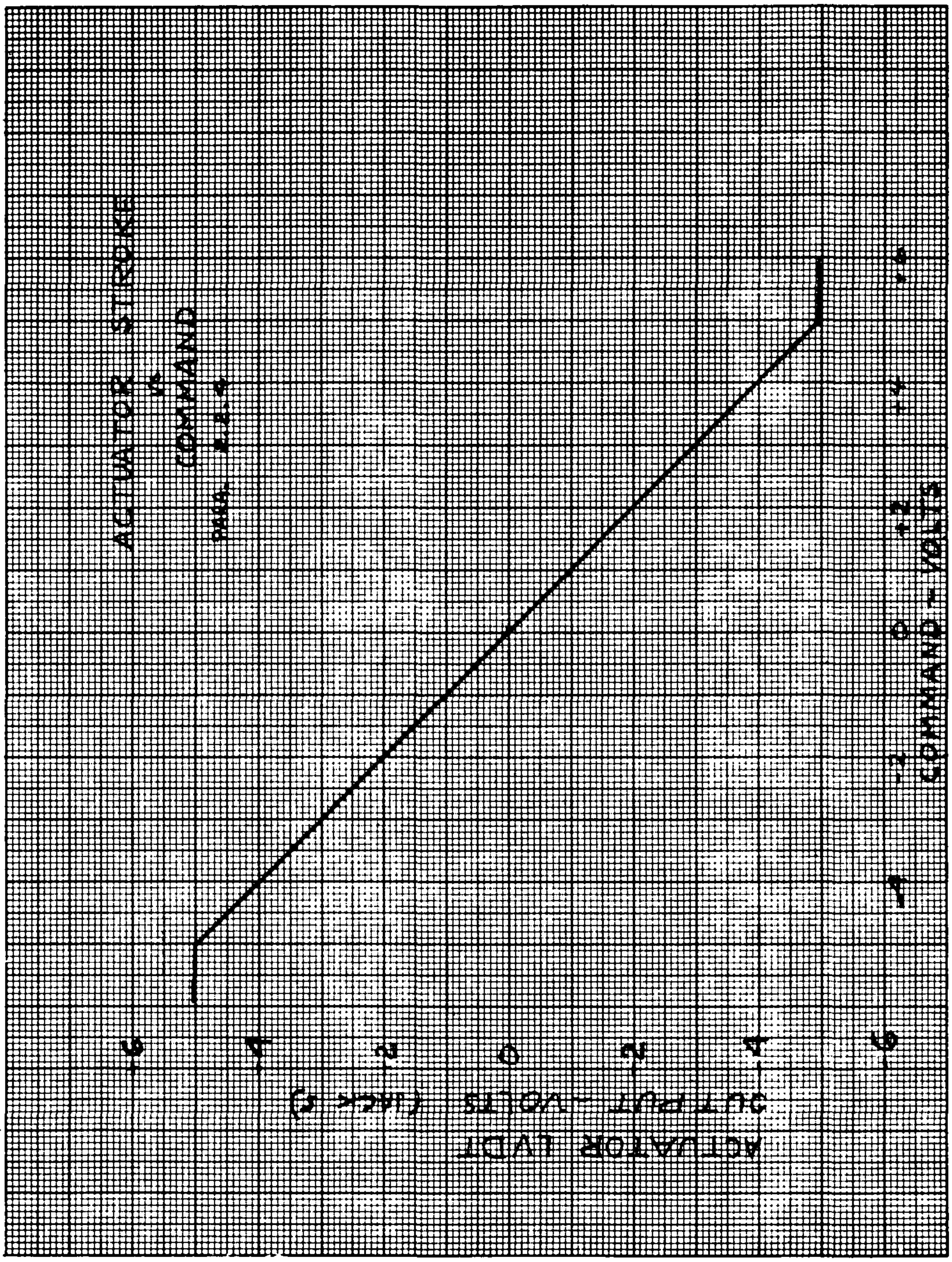


Figure 3. Actuator Stroke Versus Command

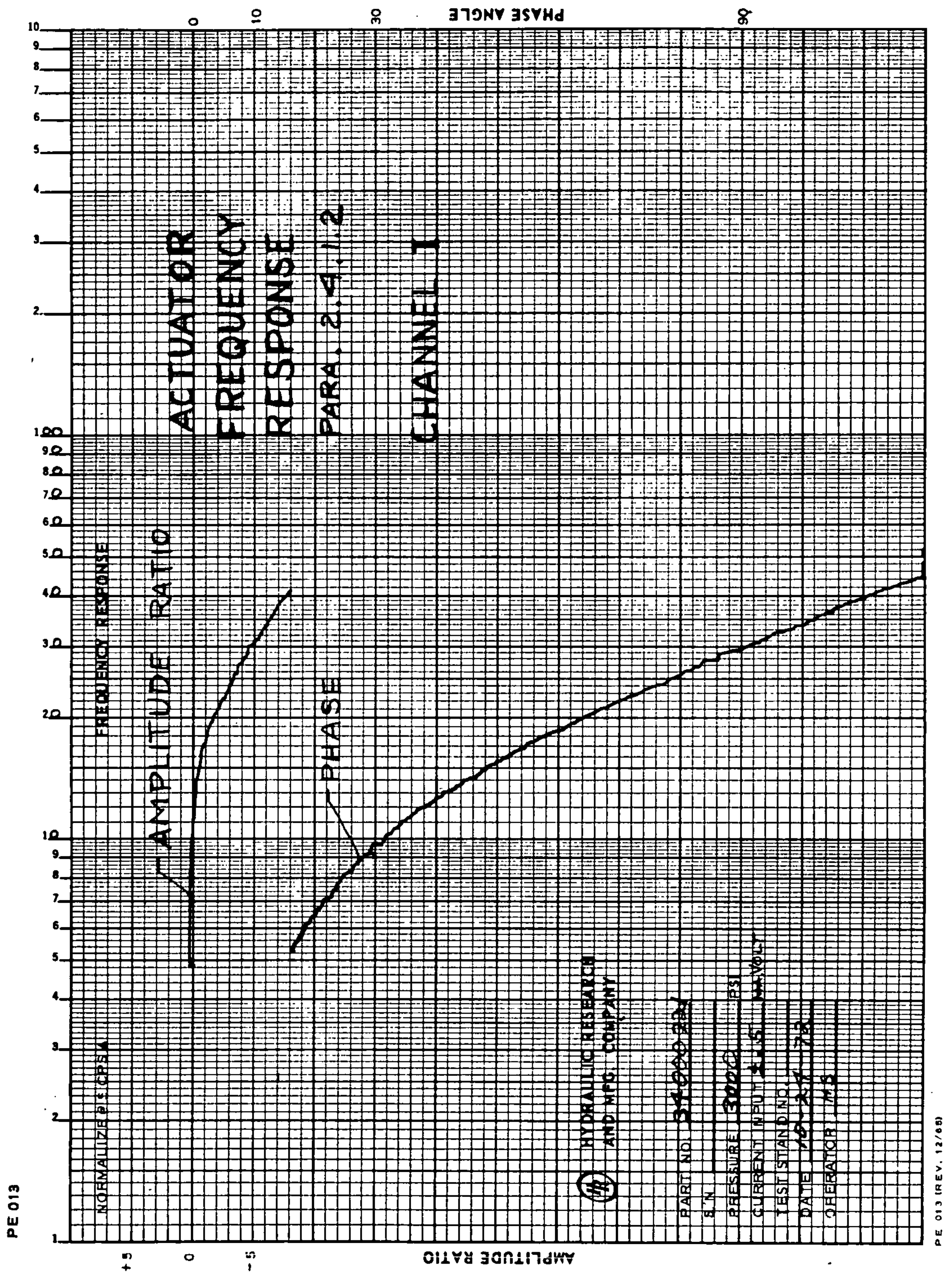


Figure 4. Actuator Frequency Response
Channel 1

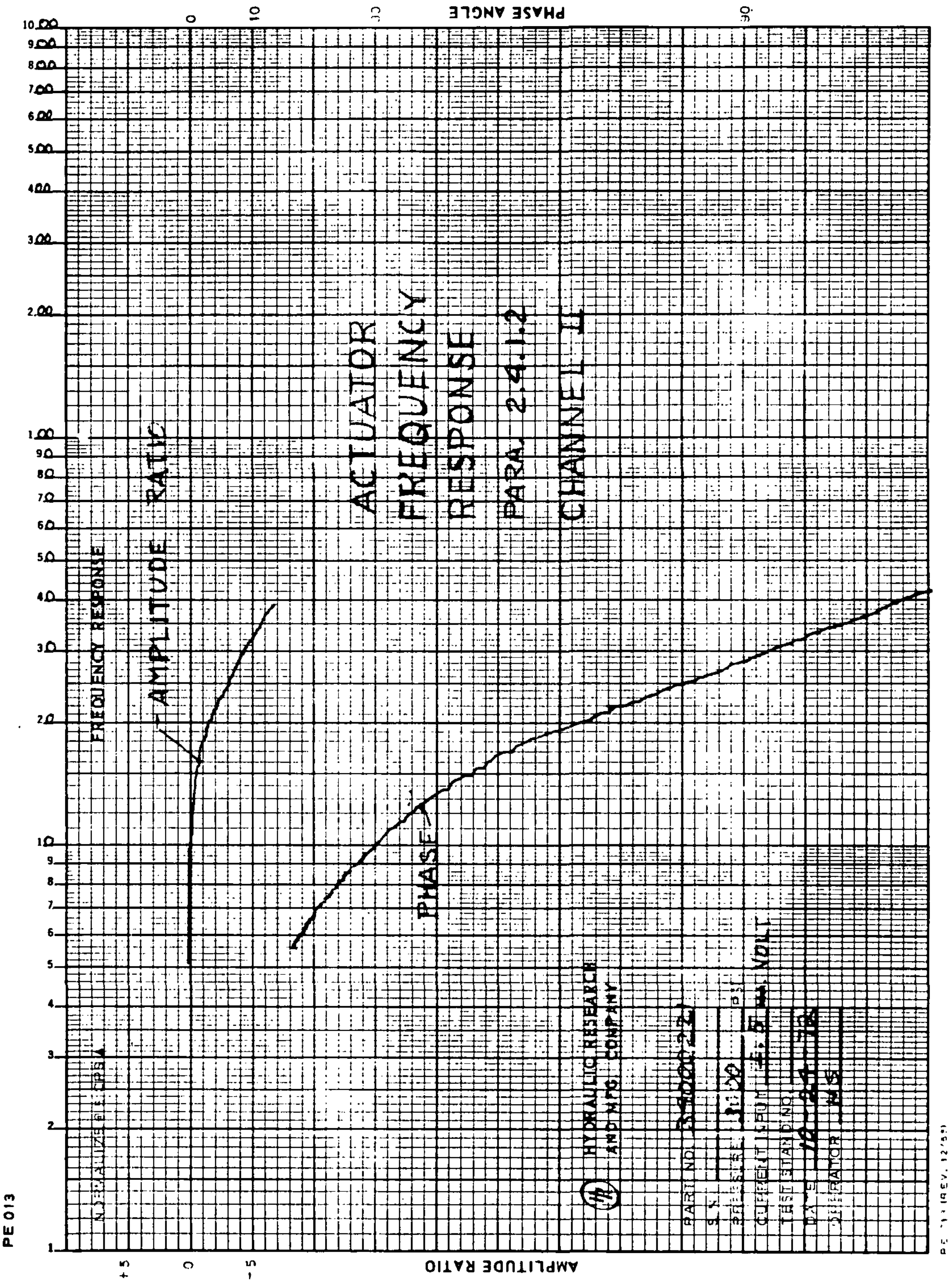


Figure 5. Actuator Frequency Response
Channel 2

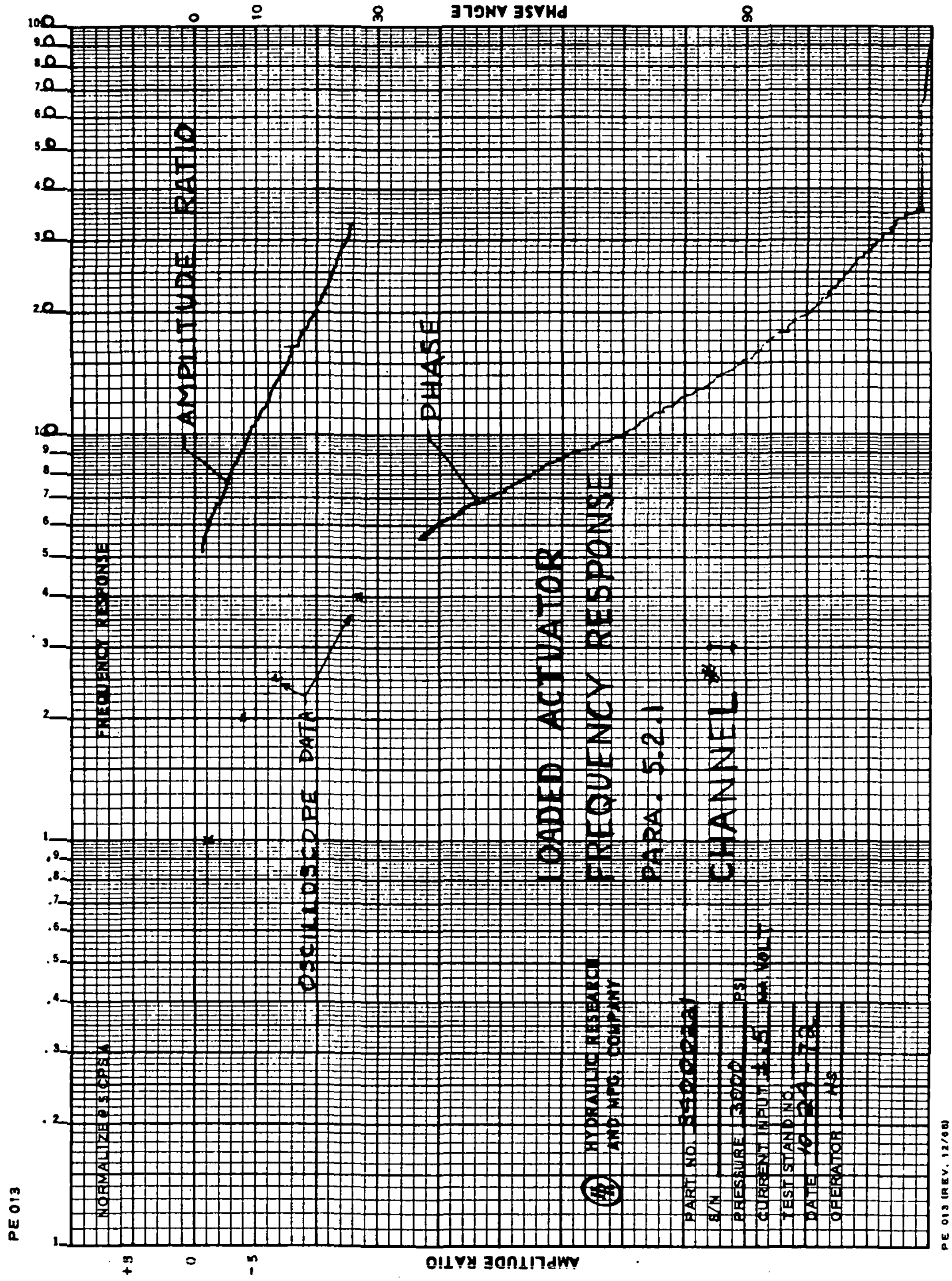


Figure 6. Loaded Actuator Frequency Response
Channel 1

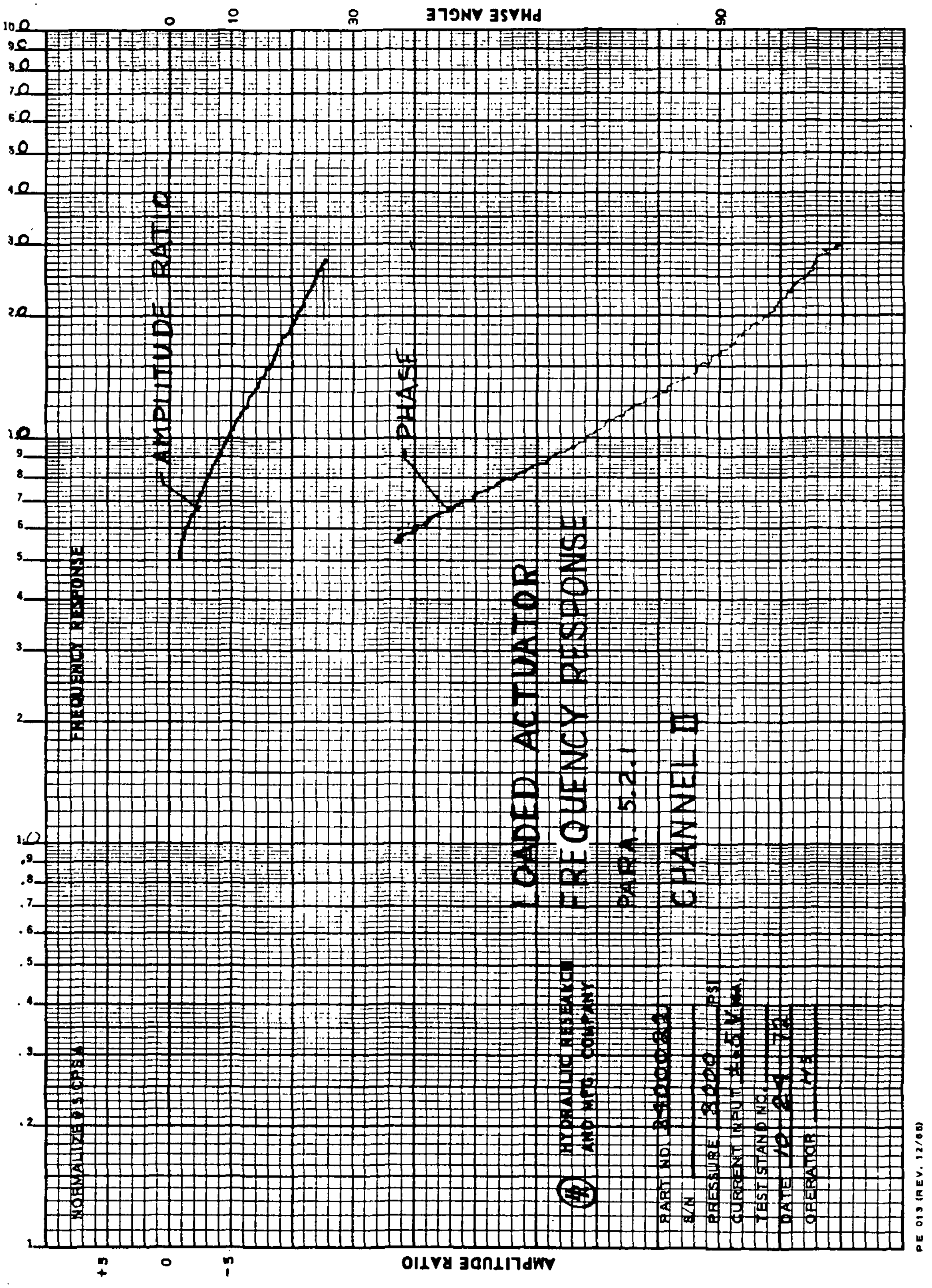


Figure 7. Loaded Actuator Frequency Response
Channel 2

Table II. Oscilloscope Photograph Index

PHOTO NO.	SHEET NO.	PARA. NO.	COMMENTS	TOP TRACING	VERTICAL AMP VOLTS/DIV.	ZERO-DIVISIONS FROM CENTER	MIDDLE TRACING	VERTICAL AMP VOLTS/DIV.	ZERO-DIVISIONS FROM CENTER	BOTTOM TRACING	VERTICAL AMP VOLTS/DIV.	ZERO-DIVISIONS FROM CENTER	SWEEP RATE SEC./DIV.
1	27	3.2.1	±1 Hz Channel 1	Error Current	0.05	2 UP	-	-	-	Command Signal	0.5	2 Down	0.1
2	27	3.2.1	±10 Hz Channel 1	Error Current	0.05	2 UP	-	-	-	Command Signal	0.5	2 Down	0.02
3	27	3.2.1	±25 Hz Channel 1	Error Current	0.05	2 UP	-	-	-	Command Signal	0.5	2 Down	0.005
4	27	3.2.1	±50 Hz Channel 1	Error Current	0.05	2 UP	-	-	-	Command Signal	0.5	2 Down	0.002
5	28	3.2.1	±100 Hz Channel 1	Error Current	0.05	2 UP	-	-	-	Command Signal	0.5	2 Down	0.001
6	28	3.2.1	±1 Hz Channel 2	Error Current	0.05	2 UP	-	-	-	Command Signal	0.5	2 Down	0.1
7	28	3.2.1	±10 Hz Channel 2	Error Current	0.05	2 UP	-	-	-	Command Signal	0.5	2 Down	0.02
8	28	3.2.1	±25 Hz Channel 2	Error Current	0.05	2 UP	-	-	-	Command Signal	0.5	2 Down	0.005
9	29	3.2.1	±50 Hz Channel 2	Error Current	0.05	2 UP	-	-	-	Command Signal	0.5	2 Down	0.002
10	29	3.2.1	±100 Hz Channel 2	Error Current	0.05	2 UP	-	-	-	Command Signal	0.5	2 Down	0.001

Table II. Oscilloscope Photograph Index (Continued)

PHOTO NO.	SHEET NO.	PARA. NO.	COMMENTS	TOP TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	MIDDLE TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	BOTTOM TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	SWEEP RATE SEC/DIV.
11	29	3.2.2	Step Channel 2	Error Current	0.05	2 UP	-	-	-	Command	0.5	2 Down	0.02
12	29	3.2.2	Step Channel 1	Error Current	0.05	2 UP	-	-	-	Command	0.5	2 Down	0.02
13	30	3.3.1.2	Step S.V. 1	Error Current	0.5	2 UP	-	-	-	Actuator Position	0.2	1 Down	0.005
14	30	3.3.2.2	Step S.V. 2 Failed	Error Current	0.5	2 UP	-	-	-	Actuator Position	0.2	1 Down	0.005
15	30	3.3.3.2	Step S.V. 2 No Fail	Error Current	0.5	2 UP	-	-	-	Actuator Position	0.2	1 Down	0.005
16	30	3.3.4.2	Step Model 1	Error Current	0.5	2 UP	-	-	-	Actuator Position	0.2	1 Down	0.005
17	31	3.3.5.2	Step Model 2 1 Failed	Error Current	0.5	2 UP	-	-	-	Actuator Position	0.2	1 Down	0.005
18	31	3.4.1.2	Ramp S.V. 1	Command Signal	0.2	2 UP	-	-	-	Actuator Position	0.2	1 Down	0.1
19	31	3.4.1.2	Ramp S.V. 1	Command Signal	0.2	2 UP	-	-	-	Position Error Current	0.5	1 Down	0.1
20	31	3.4.2.2	Ramp S.V. 2 1 Failed	Command Signal	0.2	2 UP	-	-	-	Actuator Position	0.2	1 Down	0.1

Table II. Oscilloscope Photograph Index (Continued)

PHOTO NO.	SHEET NO.	PARA. NO. HS 73700060	COMMENTS	TOP TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	MIDDLE TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	BOTTOM TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	SWEEP RATE SEC/DIV
21	32	3.4.3.2	Ramp S.V. 2 No Fail	Command Signal	0.2	2 UP	-	-	-	Actuator Position	0.2	1 Down	0.10
22	32	3.4.4.2	Ramp Model 1	Command Signal	0.2	2 UP	-	-	-	Actuator Position	0.2	1 Down	0.10
23	32	3.4.5.2	Ramp Model 2	Command Signal	0.2	2 UP	-	-	-	Actuator Position	0.2	1 Down	0.10
24	32	5.2.1 (3.2.1)	Loaded ±1 Hz Channel 1	Load Signal	5	0	Error Current	.05	0	Command Signal	0.5	2 Down	0.10
25	33	5.2.1 (3.2.1)	Loaded ±25 Hz Channel 1	Load Signal	5	0	Error Current	.05	0	Command Signal	0.5	2 Down	0.005
26	33	5.2.1 (3.2.1)	Loaded ±25 Hz Channel 1	Load Signal	5	0	Error Current	.05	0	Command Signal	0.5	2 Down	0.005
27	33	5.2.1 (3.2.1)	Loaded ±50 Hz Channel 1	Load Signal	5	0	Error Current	.05	0	Command Signal	0.5	2 Down	0.002
28	33	5.2.1 (3.2.1)	Loaded ±100 Hz Channel 1	Load Signal	5	0	Error Current	.05	0	Command Signal	0.5	2 Down	0.001
29	34	5.2.1 (3.2.1)	Loaded ±1 Hz Channel 2	Load Signal	5	0	Error Current	.05	0	Command Signal	0.5	2 Down	0.1

Table II. Oscilloscope Photograph Index (Continued)

PHOTO NO.	SHEET NO.	PARA. NO.	COMMENTS	TOP TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	MIDDLE TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	BOTTOM TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	SWEEP RATE SEC/DIV.
30	34	5.2.1 (3.2.1)	Loaded 10 Hz Channel 2	Load Signal	5	0	Error Current	0.05	0	Command Signal	0.5	2 Down	0.02
31	34	5.2.1 (3.2.1)	Loaded 25 Hz Channel 2	Load Signal	5	0	Error Current	0.05	0	Command Signal	0.5	2 Down	0.005
32	34	5.2.1 (3.2.1)	Loaded 50 Hz Channel 2	Load Signal	5	0	Error Current	0.05	0	Command Signal	0.5	2 Down	0.002
33	35	5.2.1 (3.2.1)	Loaded 100 Hz Channel 2	Load Signal	5	0	Error Current.	0.05	0	Command Signal	0.5	2 Down	0.001
34	35	5.2.1 (3.2.2)	Loaded Step Channel 2	Load Signal	5	0	Error Current	0.05	0	Command Signal	0.5	2 Down	0.02
35	35	5.2.1 (3.2.2	Loaded Step Channel 2	Load Signal	5	0	Error Current	0.05	0	Command Signal	0.5	2 Down	0.02
36	35	5.2.1 (3.3.1.2)	Loaded Step S.V. 1	Load Signal	5	0	Error Current	0.05	0	Actuator Position	0.2	2 Down	0.005
37	36	5.2.1 (3.3.2.2)	Loaded Step S.V. 1	Load Signal	5	0	Error Current	0.5	0	Actuator Position	0.2	2 Down	0.005
38	36	5.2.1 (3.3.3.2)	Loaded Step S.V. 2	Load Signal	5	0	Error Current	0.5	0	Actuator Position	0.2	2 Down	0.005

Table II. Oscilloscope Photograph Index (Continued)

PHOTO NO.	SHEET NO.	PARA. NO.	COMMENTS	TOP TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	MIDDLE TRACING	VERTICAL AMP VOLTS/DIV.	ZERO-DIVISIONS FROM CENTER	BOTTOM TRACING	VERTICAL AMP VOLTS/DIV	ZERO-DIVISIONS FROM CENTER	SWEEP RATE SEC/DIV
39	36	5.2.1 (3.3.4.2)	Loaded Step Model 1	Load Signal	5	0	Error Current	0 .5	0	Actuator Position	0.2	2 Down	0.002
40	36	5.2.1 (3.3.4.2)	Loaded Step Model 2	Load Signal	5	0	Error Current			Actuator Position	0.2	2 Down	0.002
41	37	5.2.1 (3.4.1.2)	Loaded Ramp S.V. 1	Command Signal	0 .2	2 UP	-	-	-	Actuator Position	0.2	2 Down	0.1
42	37	5.2.1 (3.4.1.2)	Loaded Ramp S.V. 1	Command Signal	0 .2	2 UP	-	-	-	Error Signal	0.5	2 Down	0.1
43	37	5.2.1 (3.4.1.2)	Loaded Ramp S.V. 1	Command Signal	0 .2	2 UP	-	-	-	Load Signal	5	2 Down	.01
44	37	5.2.1 (3.4.2.2)	Loaded Ramp S.V. 2	Command Signal	0 .2	2 UP	-	-	-	Actuator Position	0.2	2 Down	.01
45	38	5.2.1 (3.4.3.2)	Loaded Ramp S.V. 2	Command Signal	0 .2	2 UP	-	-	-	Actuator Position	0.2	2 Down	.01
46	38	5.2.1 (3.4.4.2)	Loaded Ramp Model 1	Command Signal	0 .2	2 UP	-	-	-	Actuator Position	0.2	2 Down	.01
47	38	5.2.1 (3.4.4.2)	Loaded Ramp Model 2	Command Signal	0 .2	2 UP	-	-	-	Actuator Position	0.2	2 Down	.01

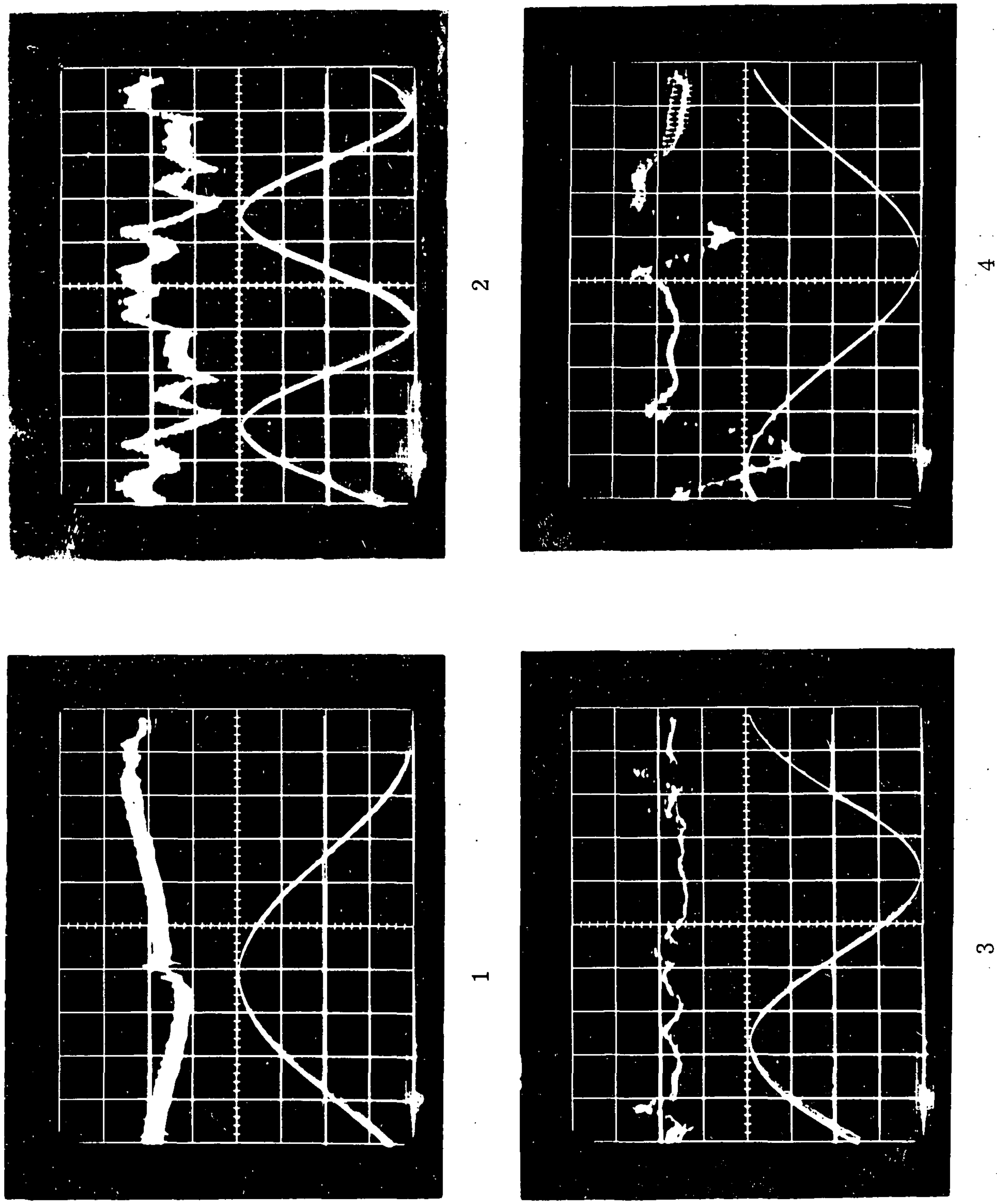


Figure 8. Oscilloscope Photographs

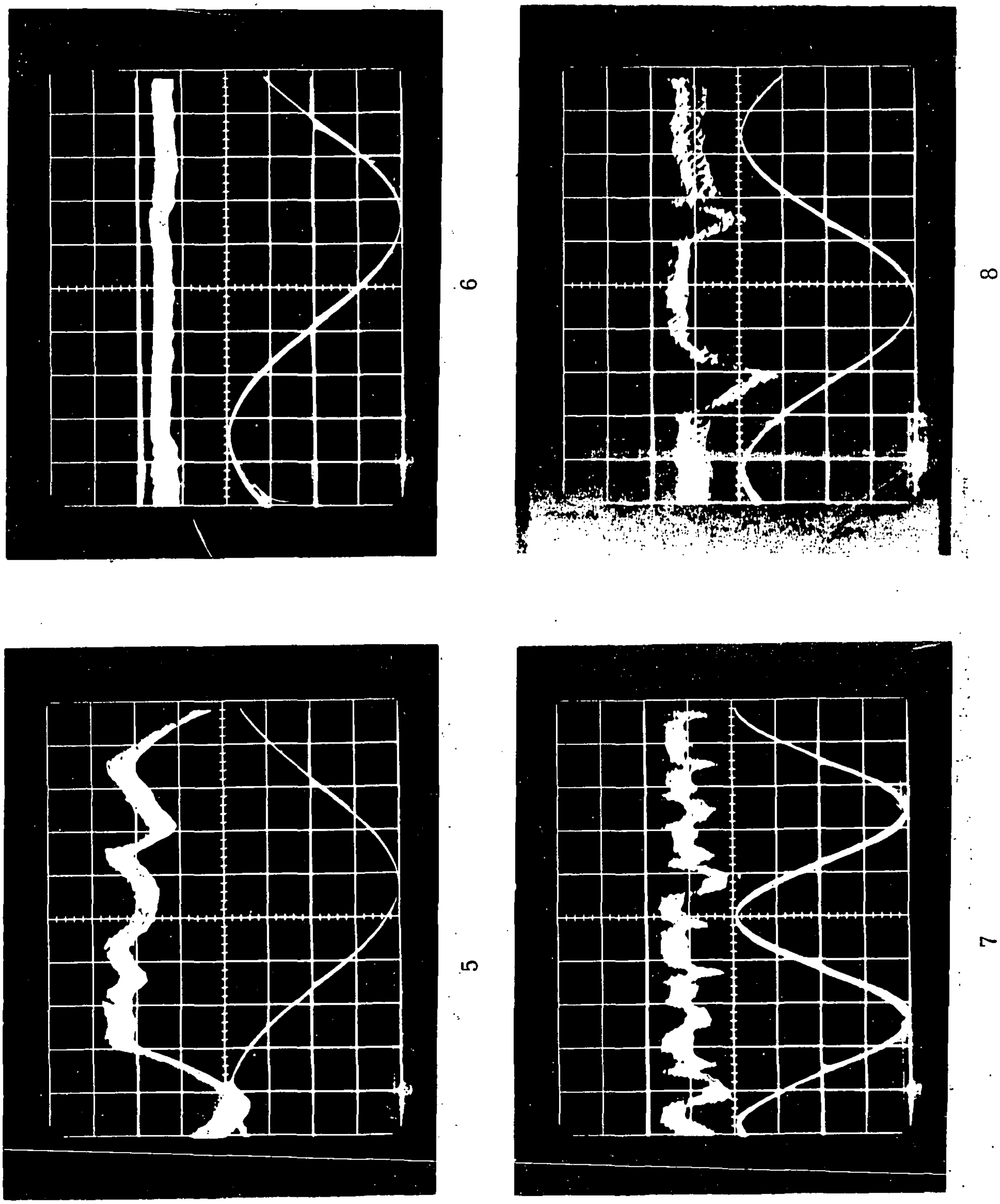
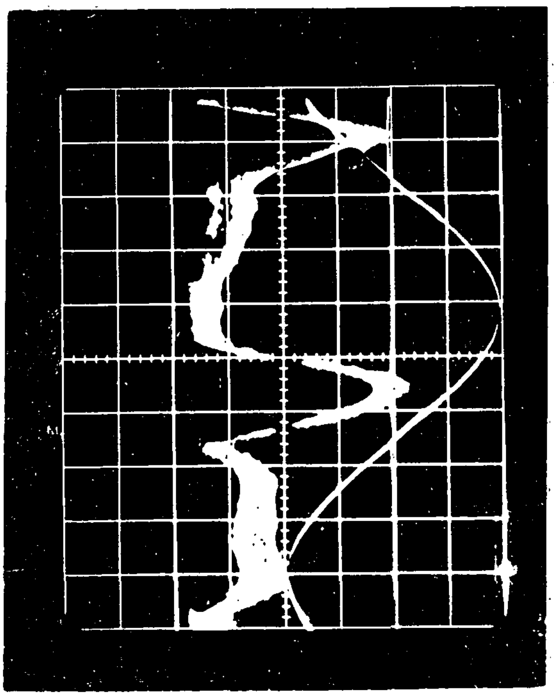


Figure 8. Oscilloscope Photographs



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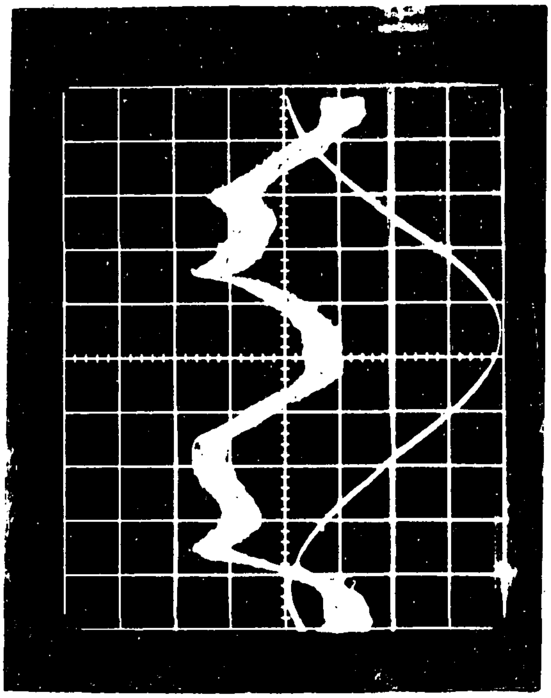

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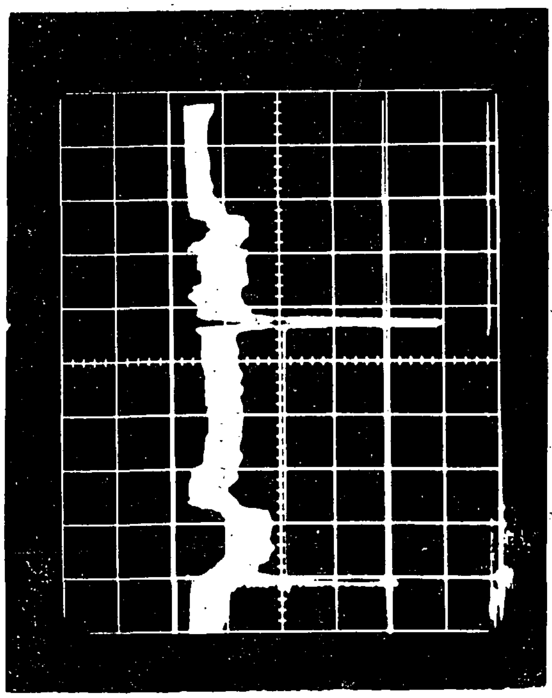

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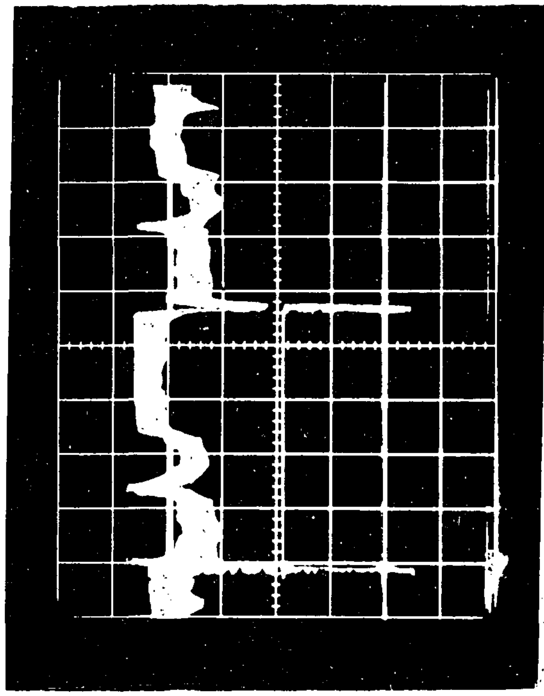

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Figure 8. Oscilloscope Photographs

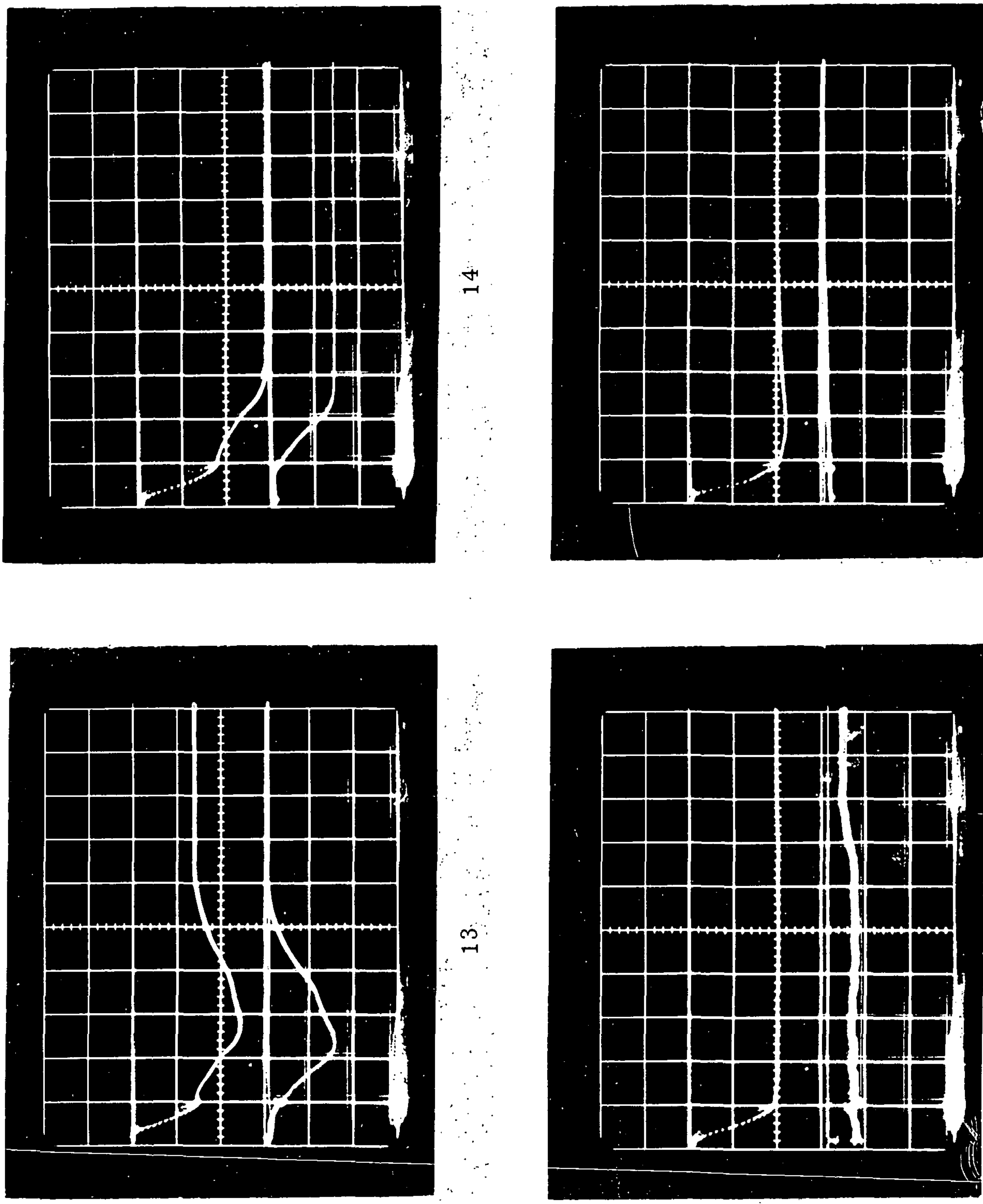


Figure 8. Oscilloscope Photographs

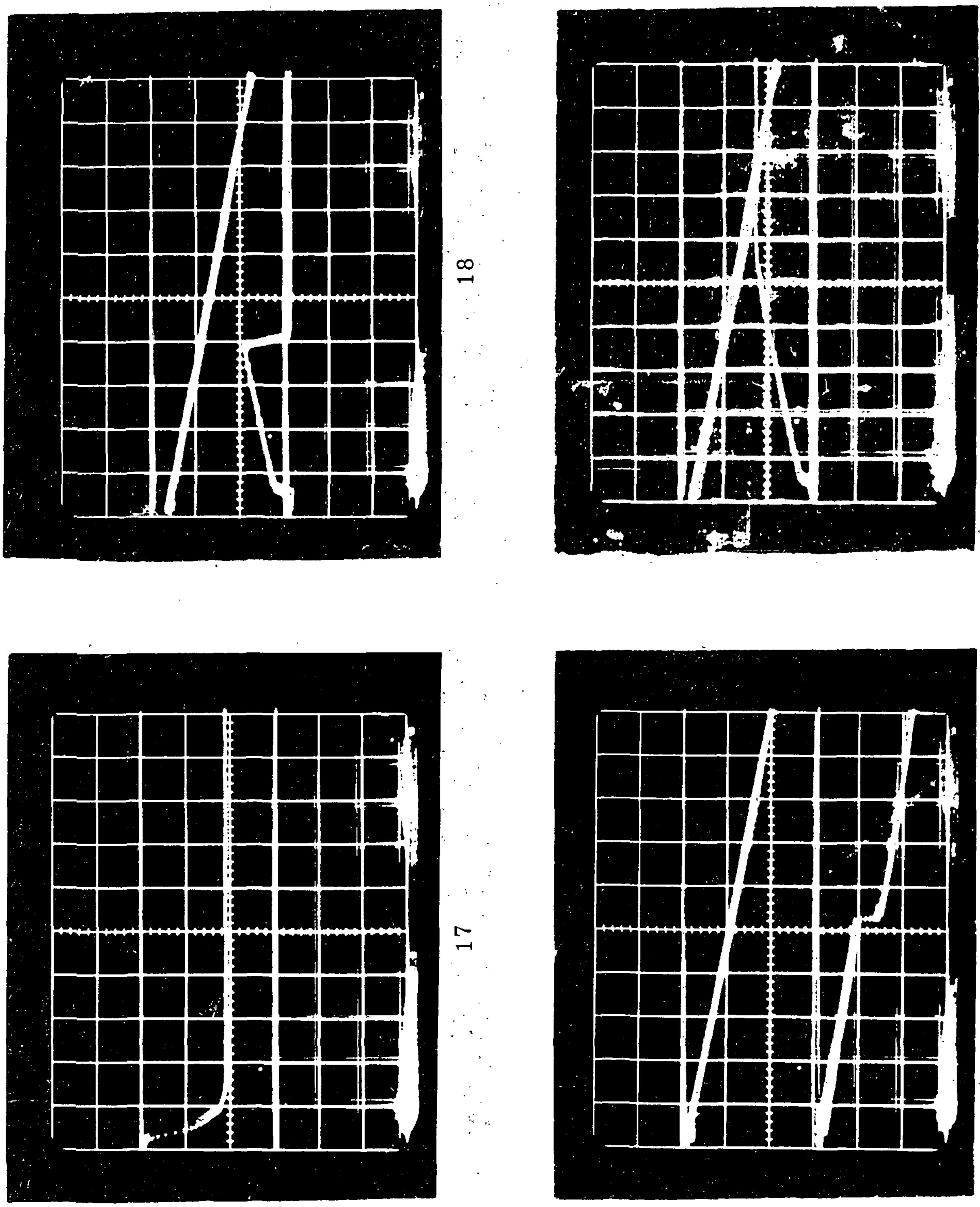


Figure 8. Oscilloscope Photographs

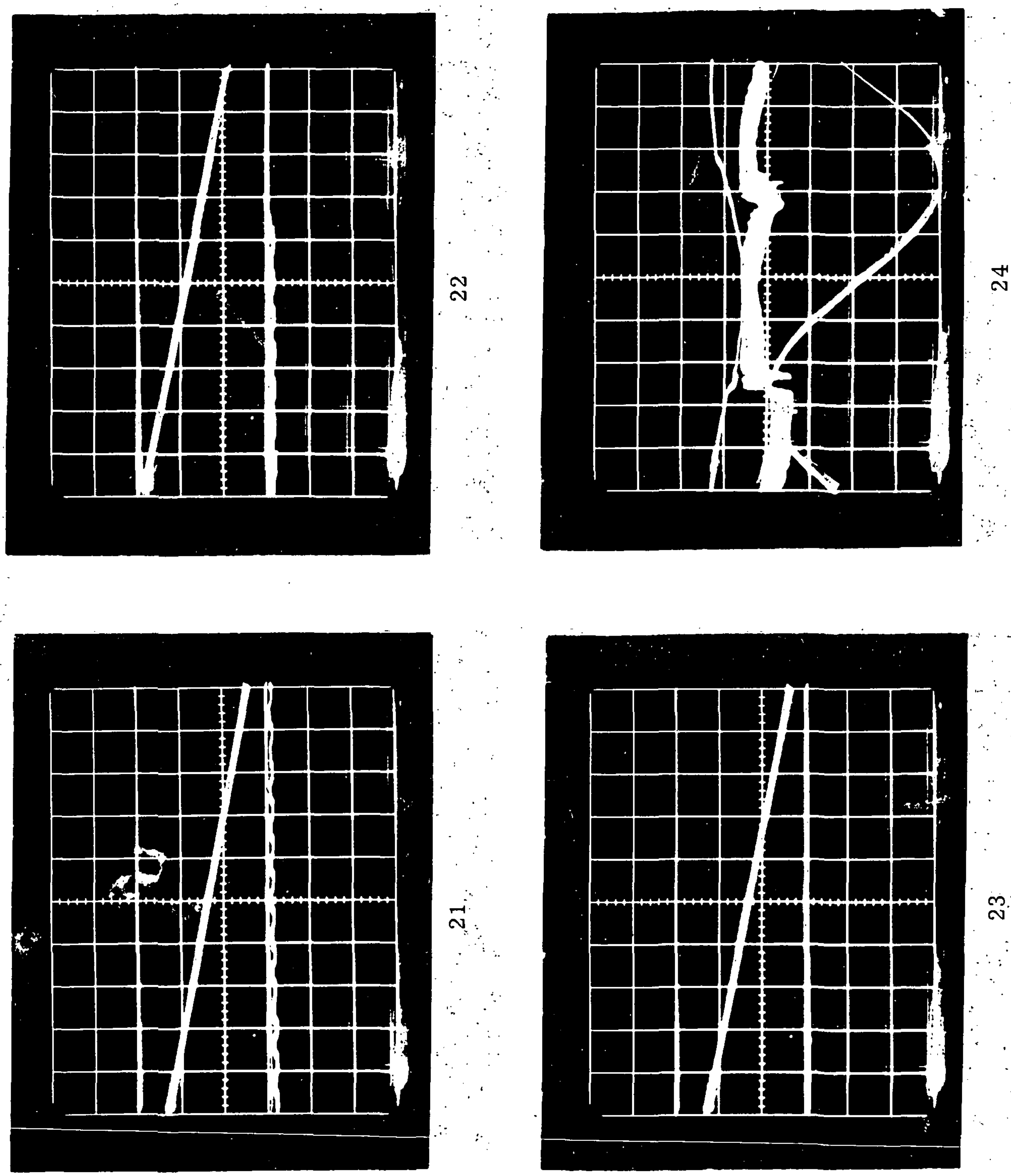
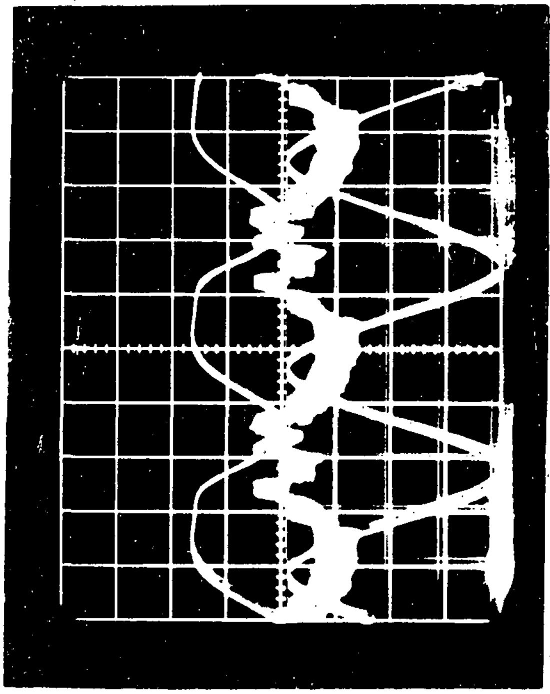


Figure 8. Oscilloscope Photographs



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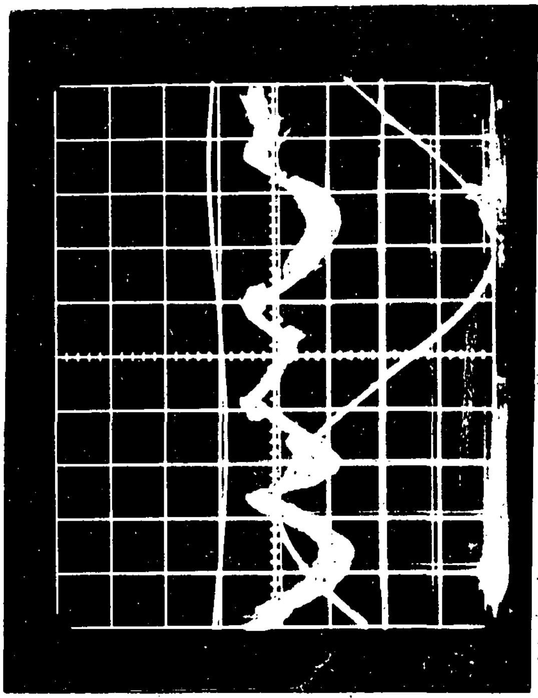

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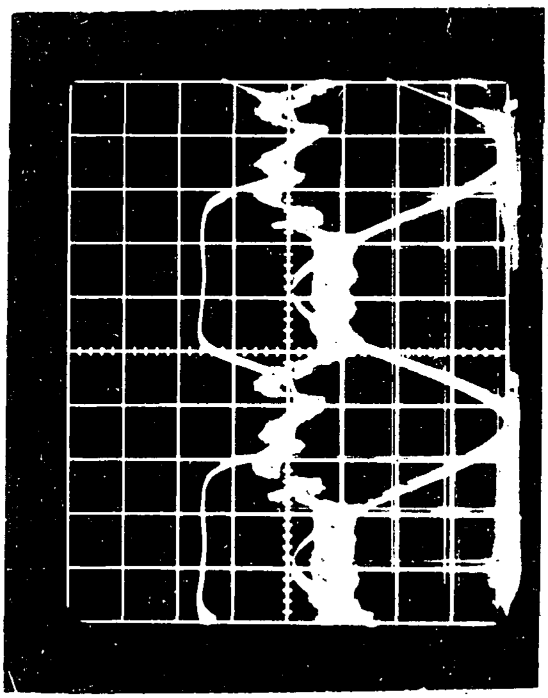

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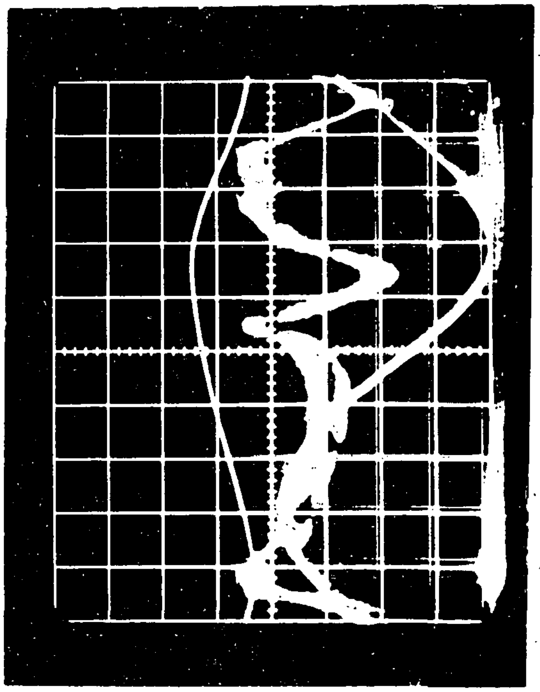

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Figure 8. Oscilloscope Photographs

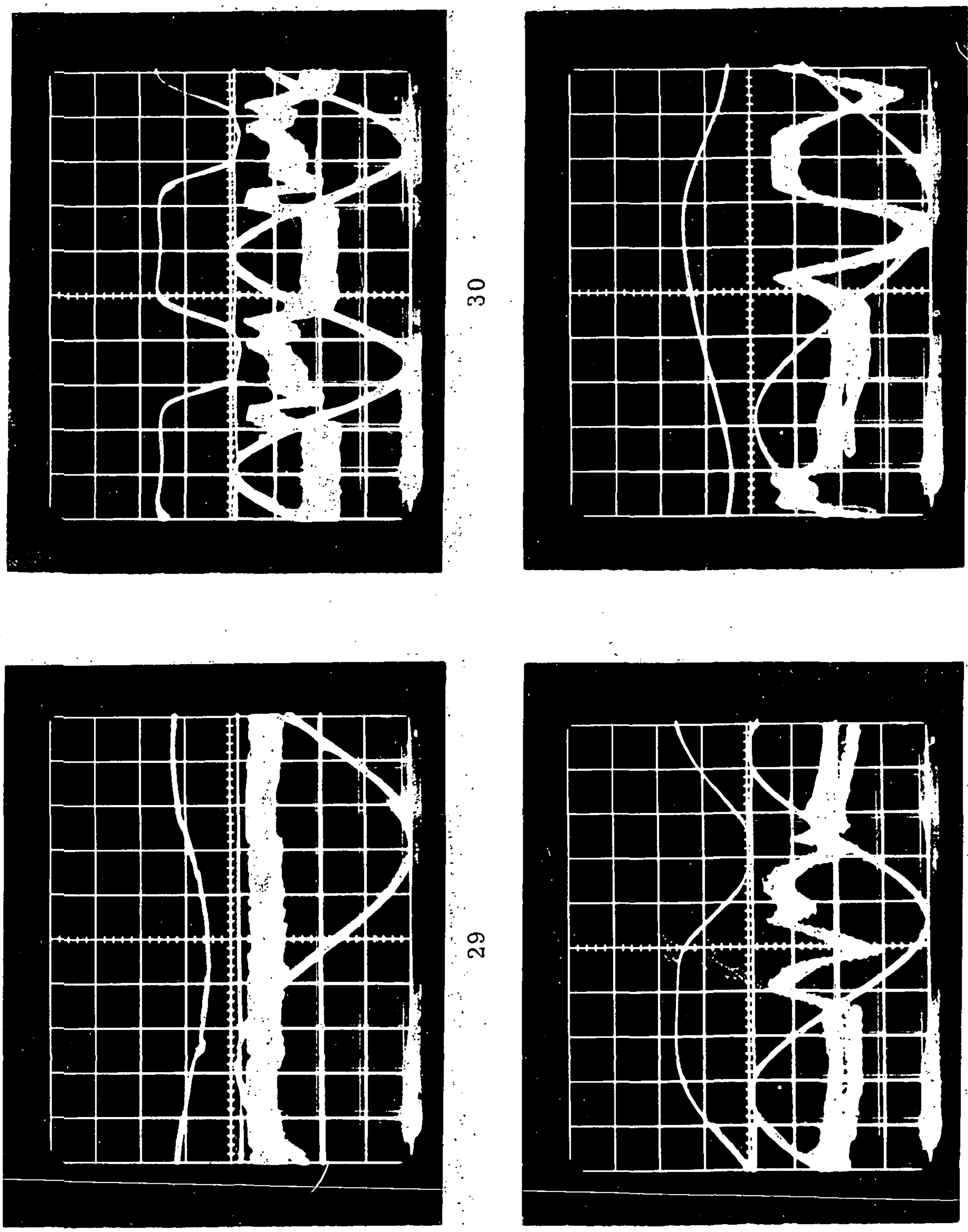

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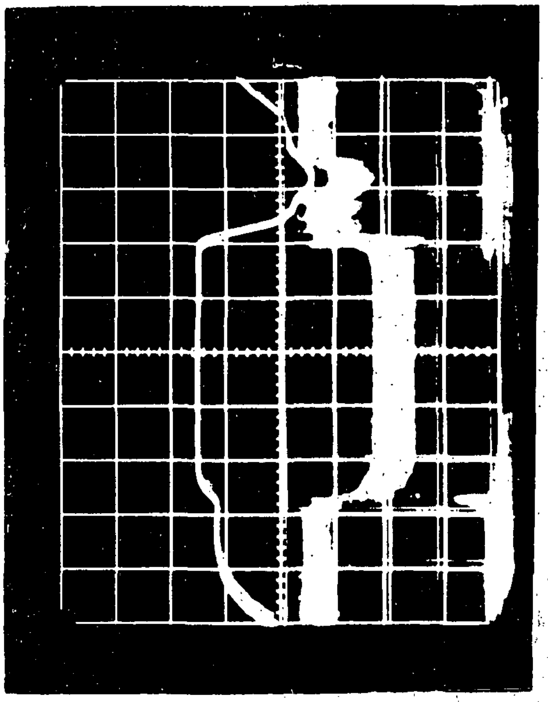
Figure 8. Oscilloscope Photographs



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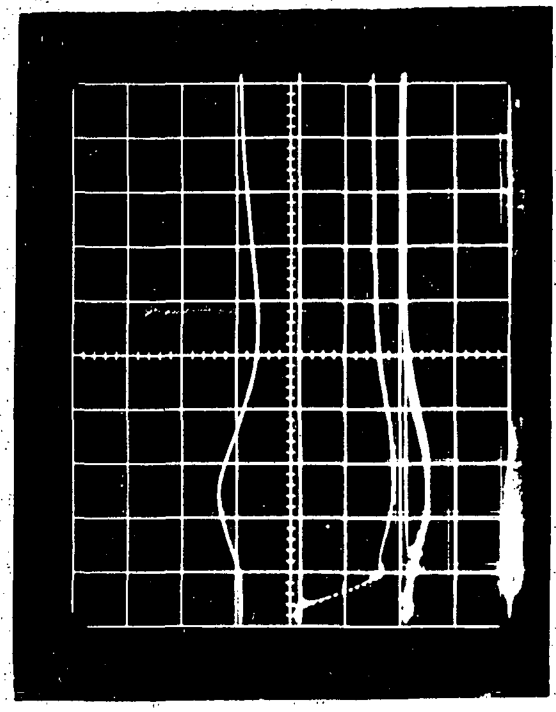

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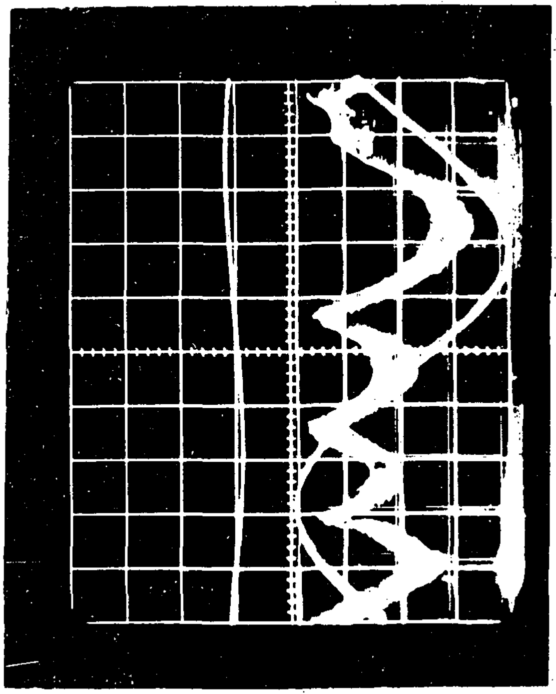

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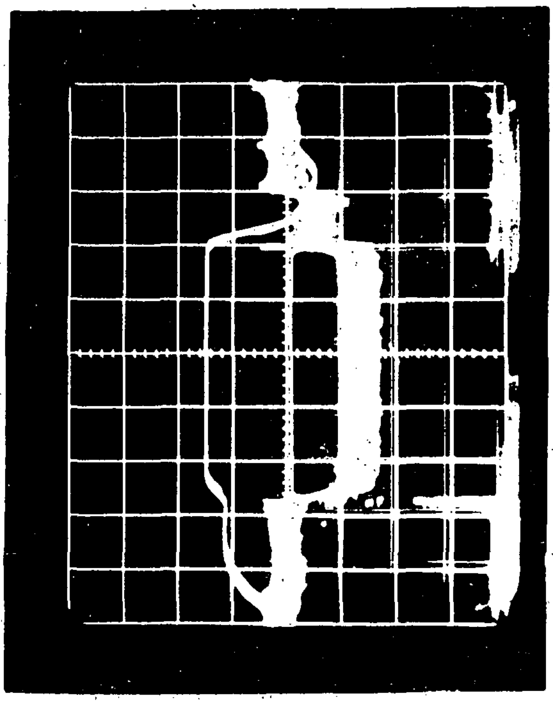

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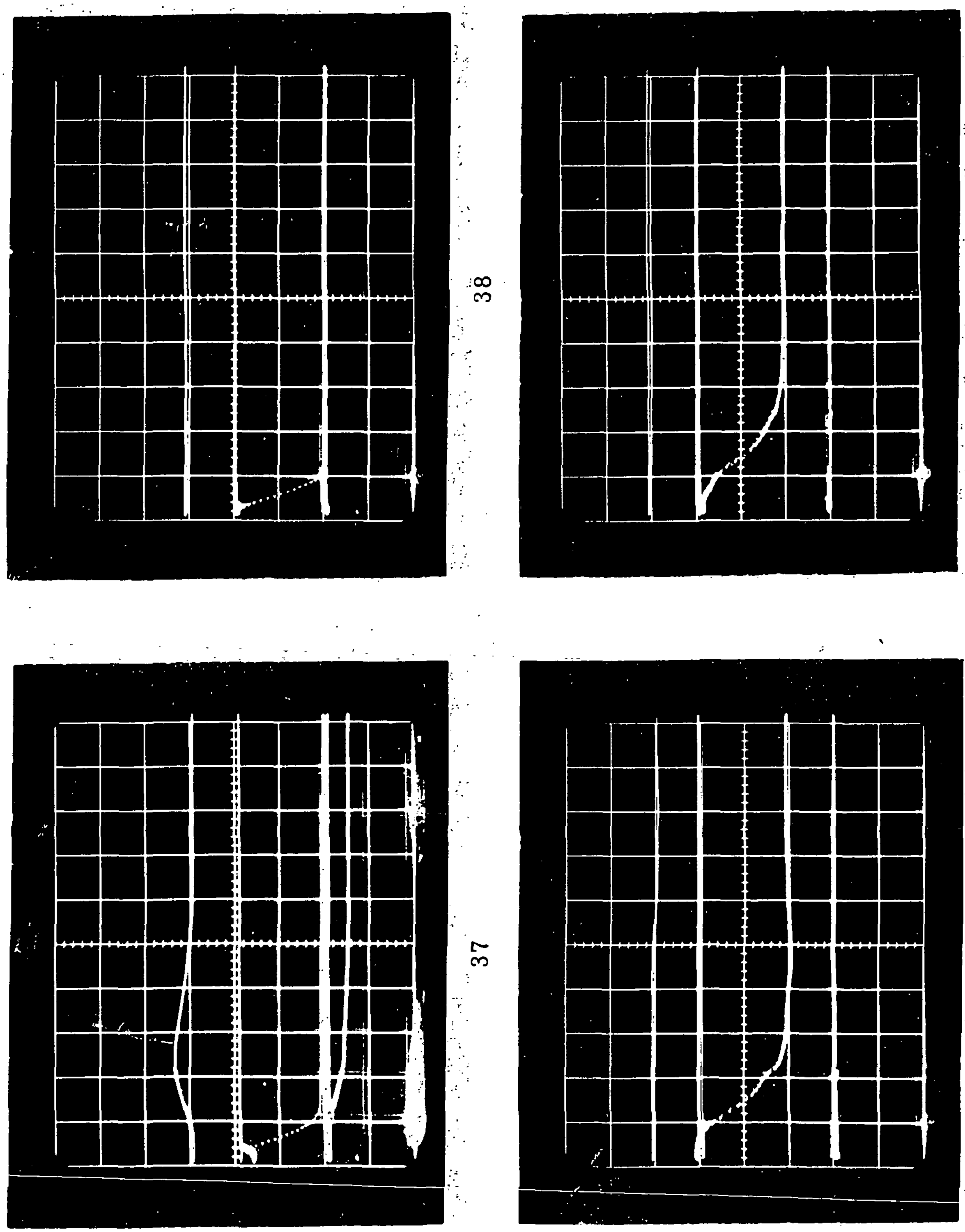

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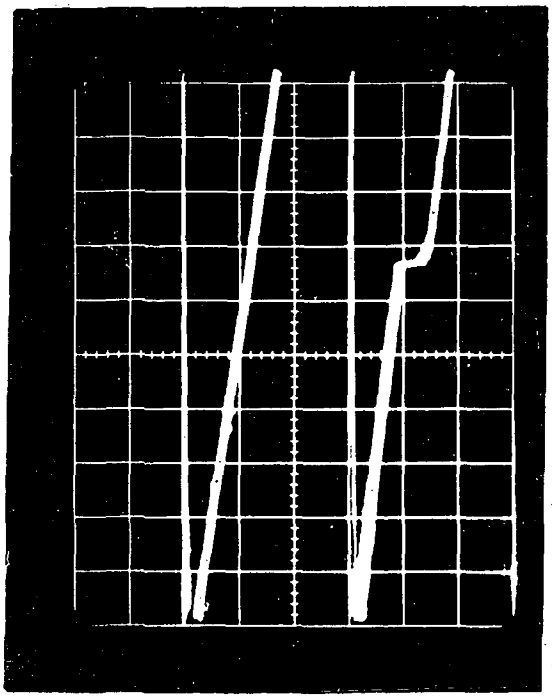
Figure 8. Oscilloscope Photographs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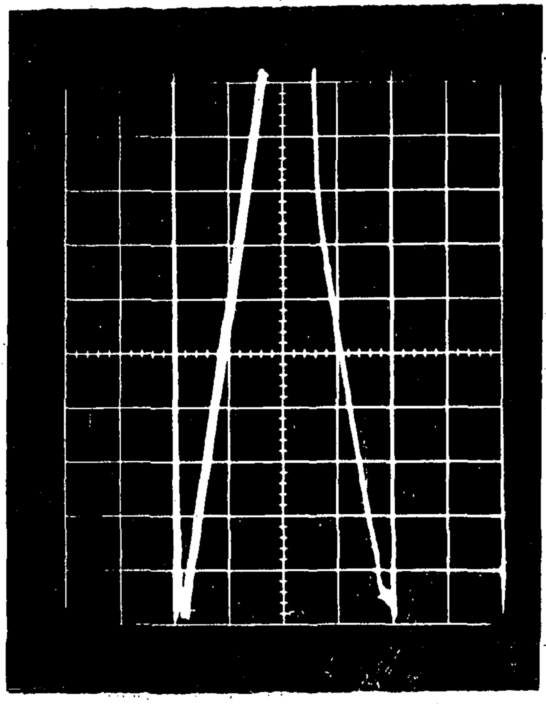
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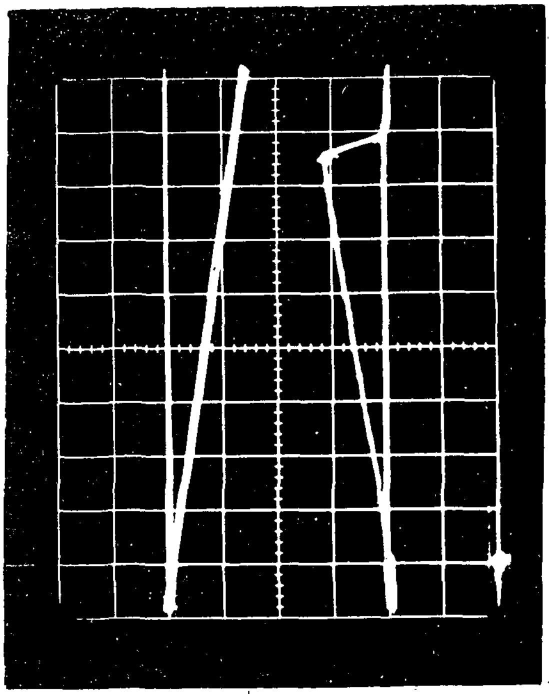
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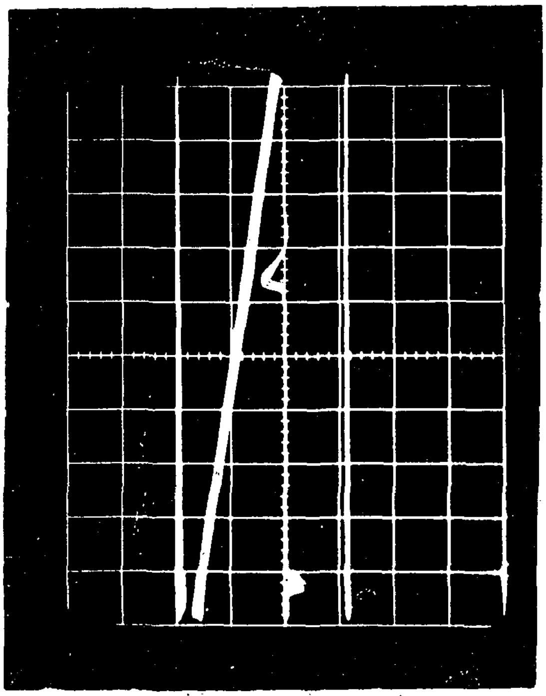
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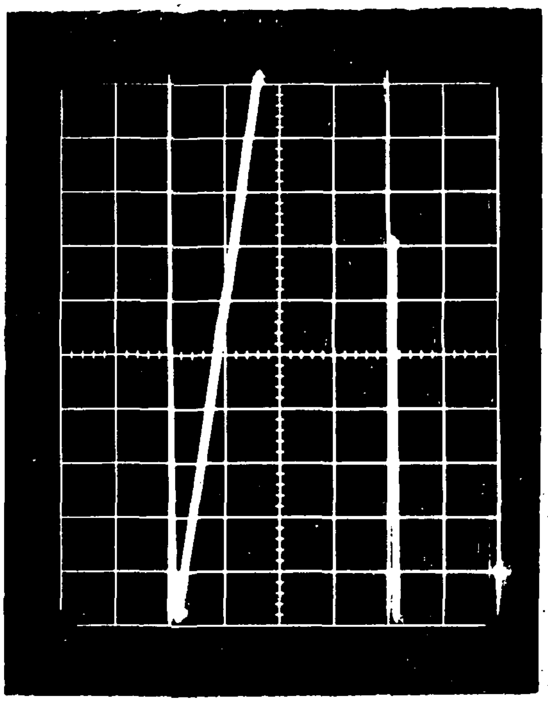
Figure 8. Oscilloscope Photographs



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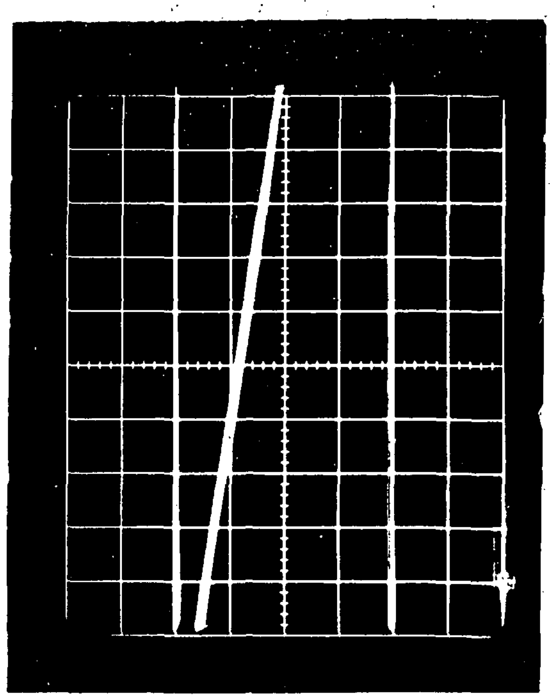

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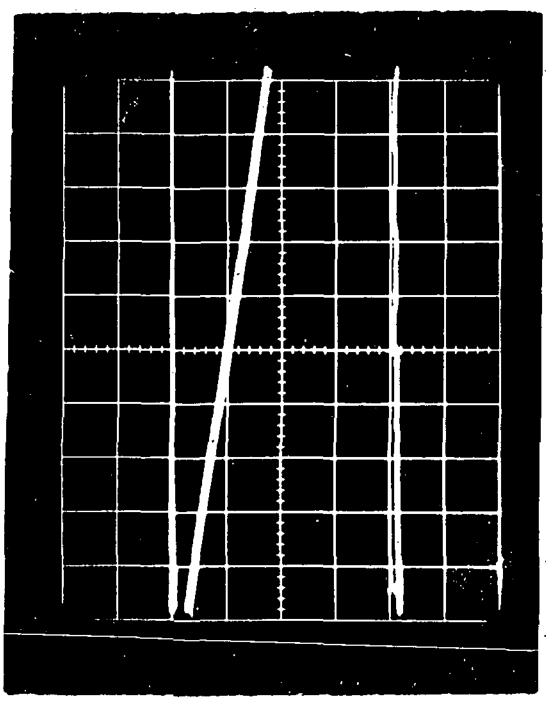

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Figure 8. Oscilloscope Photographs

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