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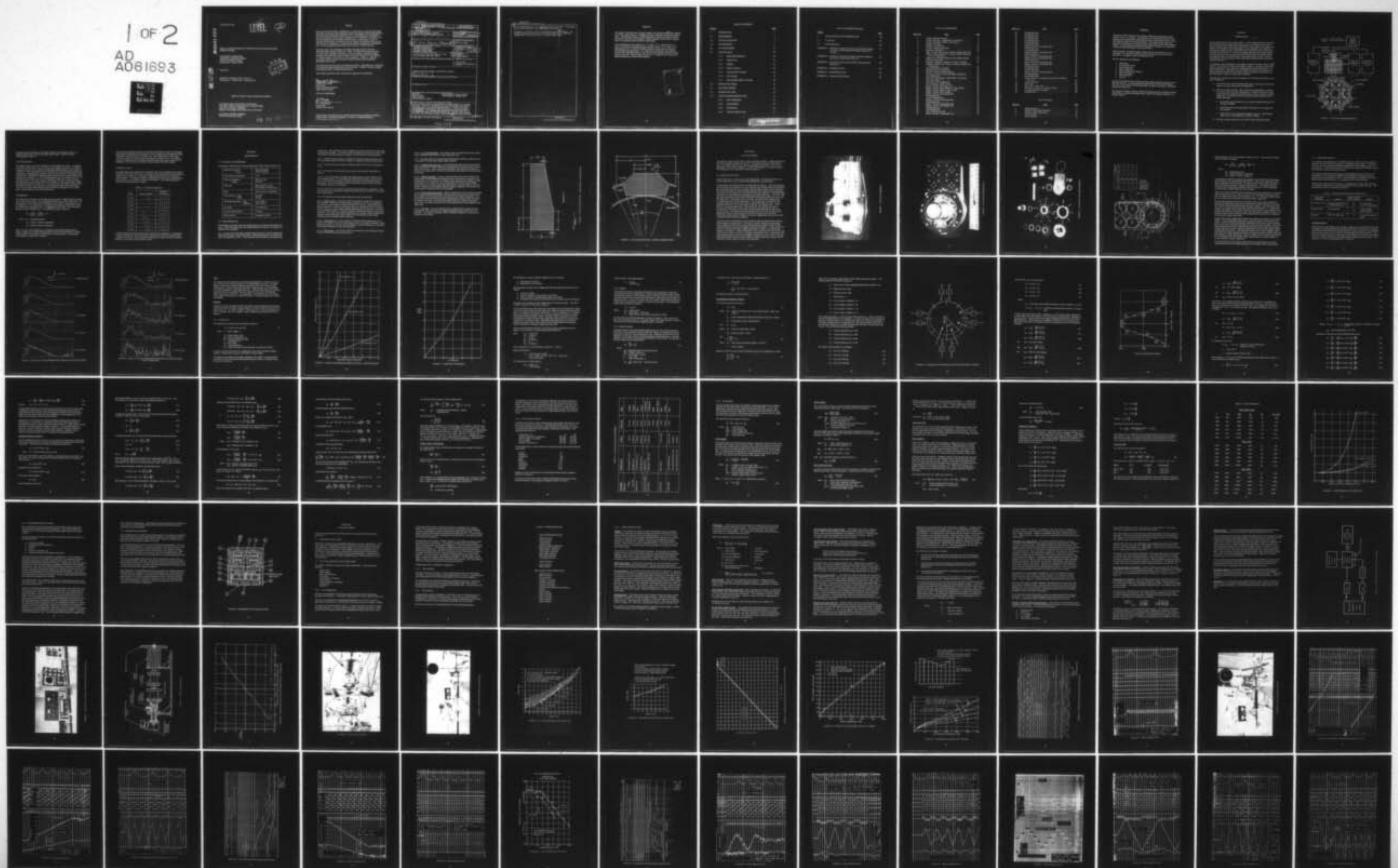

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DIGITAL ELECTROHYDRAULIC STEPPER ACTUATOR FOR ADVANCED MISSILE SYSTEMS

THE BENDIX CORPORATION
AEROSPACE SYSTEMS DIVISION
400 SOUTH BEIGER STREET
MISHAWAKA, INDIANA 46544

JUNE 1978

TECHNICAL REPORT AFAPL-TR-78-42
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This final report was submitted by the Bendix Aerospace Systems Division - Mishawaka under Contract F33615-74-C-2052. The effort was sponsored by the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright-Patterson AFB, Ohio under Project 3145, Task 30 and Work Unit 17 with Kenneth E. Binns and Major Pat Condon as Project Engineer. Eugene A. Sherrill and Jack M. Silvius of Bendix Aerospace Systems Division were technically responsible for the work.

This report has been reviewed by the Information Office, (ASD/OIP) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

This technical report has been reviewed and is approved for publication.

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A high performance digital electrohydraulic stepper actuator was designed, fabricated, and tested. Performance and space requirements were derived from design studies for the Multipurpose Missile. The design provides digital interface compatibility while achieving the required performance characteristics. The actuator performed well at the rated conditions of 140 degrees per second and 1333 inch pounds load. No load speed achieved during test was over twice as great as the 250 degrees per second required. over

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Stall torque exceeded the 2000 inch pounds design requirement. The actuator has yet to be evaluated at the 600°F design environment.

The design is a digital version of the Bendix Dynavector® actuator. The actuator combines a unique high speed arbitrary motor with a high-ratio transmission to provide high torque, low speed rotary power.

PREFACE

The Bendix Corporation has developed a unique line of Dynavector® high response, low inertia analog actuators, including electrical, pneumatic and hydraulic applications. This program explores a digital Dynavector concept developed by Bendix, and includes fabrication and testing of a digital hydraulic control surface actuator based on preliminary ASALM missile requirements.

The contributions to this program by L. F. Mayer, E. A. Sherrill and O. E. Carter of the Bendix Aerospace Systems Division, and by J. H. Tarter, W. D. MacLennan and R. G. Read of the Bendix Research Laboratories are hereby acknowledged with appreciation. Mr. Sherrill was technically responsible for the work and contributed heavily to the success of the program until his untimely death in June 1977. Special thanks also go to K. E. Binns for his interest and inputs throughout the course of the program.

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SUMMARY

The purpose of this program was to develop a digital electrohydraulic stepper actuator for use in a missile. The design was to provide digital interface compatibility while achieving the required performance characteristics in the volume and weight permitted in an airborne missile. The actuator performance and space requirements have been derived from design studies for the Multi-Purpose Missile. The technology developed in this program is intended to be applicable to all future high performance missiles and RPV's.

In this program, one digital stepper actuator and one set of spare parts were fabricated. The actuator received break-in and checkout tests and was then subjected to a complete series of performance tests.

The test consisted of the following:

- o Stall torque
- o No load motor speed
- o Back driving test
- o Static leakage test
- o Pull in and pull out evaluation
- o Dynamic response
- o Flow evaluation
- o Life test

The actuator performed well, meeting all of the primary objectives except for the fifty hour life test. A reaction pin spacer failed after 24 hours of life testing. The cause of the failure has been determined, the spacer redesigned, and actuator rebuilt and checked out.

The Dynavector Stepper Actuator satisfies the design objectives of digital interface compatibility, excellent performance with a volume and weight permitted by an airborne vehicle.

SECTION I

INTRODUCTION

The Work Statement for this contract states: "In future high performance missiles which contain primarily digital signal processing, it is desirable to use control surface actuators which can be commanded directly with a digital error signal. The purpose of this advanced technology program is to investigate a new technique in achieving this digital interface compatibility while still achieving the required performance characteristics in a volume and weight permitted in an airborne missile. The requirements for this actuator program have been taken from design studies conducted by Martin, Orlando Division, on the multi-purpose missile. However, the technology from this program will be applicable to all future high performance missiles and RPV's."

The technique under investigation is the digital version of the Bendix Dynavector® actuator. This actuator, shown schematically in Figure 1, combines a unique high speed orbiting motor with a high-ratio transmission to provide high-torque, low-speed rotary power. Controlled by the electrohydraulic valves, it performs as an open loop digital control surface actuation system, moving the control surface in discrete steps in response to digital input commands.

The Dynavector actuator has several advantages over conventional actuators in this type of application:

1) The transmission reduces the high-speed input to a low-speed, high torque output in one step, using only two moving gears.

2)) There is no physical motor, only a virtual motor consisting of a rotating force vector (hence the name "Dynavector"). Rotation of the force vector causes the input member of the transmission to orbit, driving the rotating output shaft. The orbiting motion of the input member produces the following advantages:

   a. Gear-tooth contact velocities are very small, producing long gear life and high reliability.

   b. Reflected inertia at the output shaft is extremely low, providing very fast response.

   c. Fluid volume in the displacement chamber is small, minimizing the effect of fluid compressibility on actuator stiffness.

3) The only bearings required are the control surface support bearings.

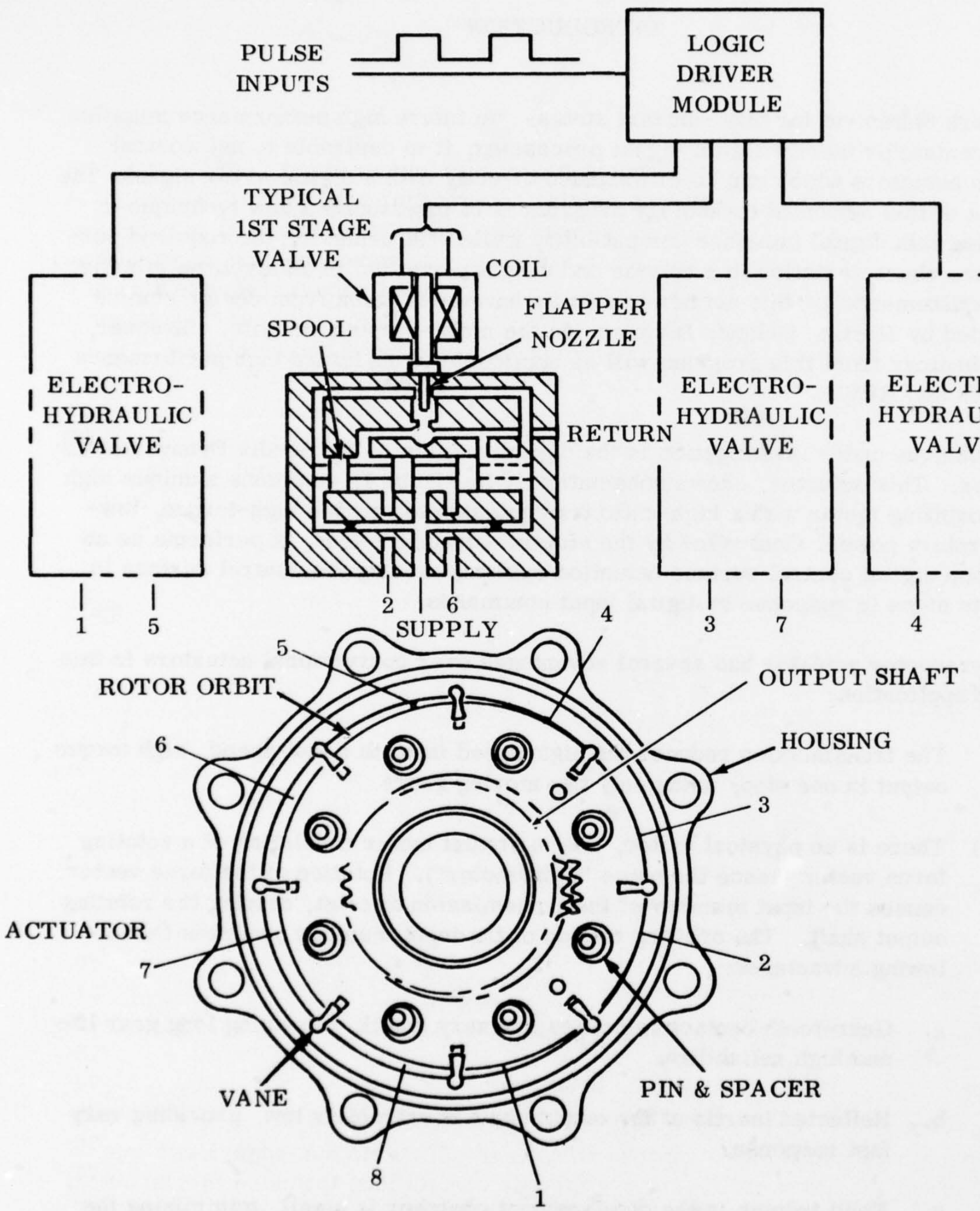


FIGURE 1 - ACTUATOR SYSTEM SCHEMATIC

The three major components of the actuator system are the actuator motor, an integral transmission, and the first stage control valves. These are shown schematically in Figure 1.

ACTUATOR MOTOR

The actuator motor is the power element or second stage of the system. It consists of a positive displacement, very low inertia, non-rotating vane motor. Its output is a radial force which can be rotated at commanded stepping speeds in either direction of rotation. The displacement chambers formed by the vanes and housing expand and collapse at the same speed as the force vector, but do not rotate. The direction of the force vector is established by applying supply pressure to four adjacent displacement chambers (for example, 1, 2, 3, 4) while venting the other four chambers (5, 6, 7, 8) to drain pressure. The force vector is rotated one "step" (or 45 degrees) by then pressurizing the proper vented chamber (for example, 5) while concurrently venting the opposing pressurized chamber (1). The actuator may be rotated through a single step while operating in the open loop mode by applying a single digital input pulse; or it may be rapidly rotated through a series of steps by applying a chain of digital pulses, and will stop at the pre-selected position.

TRANSMISSION

The transmission consists of an internal spur gear which is integral with the orbiting rotor of the actuator motor, and a mating external spur gear on the output shaft. The driving gear does not rotate, but orbits about a small radius of eccentricity to drive the output gear. The eccentricity is controlled by the clearance between the reaction pin and the holes through the rotor. As suggested by their name, the reaction pins provide the rotor reaction force. The transmission ratio is given as:

$$R_t = \frac{N_o}{N_o - N_i} = \frac{135}{138-135} = 45$$

where: R_t = transmission ratio

R_o = number of teeth on output gear

N_i = number of teeth on input gear

Thus, one step of the orbiting rotor (45 degrees) will rotate the output shaft one degree. Analysis of the multi-purpose missile control loop indicated that an output shaft resolution of one degree is satisfactory for missile control, so the actuator was designed to provide this resolution.

This transmission design provides an input gear pitch diameter which is only slightly larger than the output gear pitch diameter. Thus, a slight gear tooth deflection under load allows many gear teeth to share the load. This same feature provides high resistance to shock overload and minimizes dynamic loading forces. The transmission has excellent torque transmitting capability because the dynamic tooth loads are negligible so that the dynamic strength is nearly equal to the static strength.

CONTROL VALVES

The eight displacement chambers of the actuator motor are controlled by four electro-hydraulic servo valves. Each valve is connected to two diametrically opposed chambers, so that when one chamber is connected to supply pressure the other is connected to drain pressure. The stepper controller is designed to step the valves sequentially as shown in Table 1, for clockwise rotation of the actuator. The stepping sequence is reversed for counterclockwise rotation.

TABLE 1 - STEPPING SEQUENCE

Step	Valves Energized	Chambers Pressurized
0 CW	3, 4	7, 8, 1, 2
1 CW	4	8, 1, 2, 3
2 CW		1, 2, 3, 4
3 CW	1	2, 3, 4, 5
4 CW	1, 2	3, 4, 5, 6
5 CW	1, 2, 3	4, 5, 6, 7
6 CW	1, 2, 3, 4	5, 6, 7, 8
7 CW	2, 3, 4	6, 7, 8, 1
8 CW	3, 4	7, 8, 1, 2

A modified Moog Type 30 servo valve was selected for this application. The design of a unique first stage was reserved for later consideration in order to concentrate the available contract funds on proving that the Dynavector actuator concept is a practical approach to providing a digital actuation system.

SECTION II

REQUIREMENTS

2.1 TECHNICAL REQUIREMENTS

The technical requirements for the electrohydraulic digital stepper actuator are:

Hinge moment (stall) (rated)	2000 inch-pounds 1333 inch-pounds
Vane deflection (maximum)	$\pm 30^{\circ}$
Vane rate (unloaded) (rated)	250°/sec (max) 140°/sec
Panel load	3000 pounds @ 4.0 inch from actuator outside surface
Fluid	Chevron M-2V or equivalent
Fluid pressure - inlet - outlet	3400 psia 400 psia
Operating temperature - fluid - ambient	-65 to +600° F -65 to +550° F
Fin inertia	0.75 in-lb-sec^2
Air vane shaft diameter	1.25 inch
Space envelope	per Figures 2 and 3

2.2 TASK DESCRIPTION

The following paragraphs define the specific tasks to be performed under this program. Where the original task was modified during the program, the changes are included in this definition.

2.2.1 Design an electrohydraulic digital stepper actuator to meet the design goals stated under technical requirements above. Mechanical stops are not required to limit vane deflection to $\pm 30^{\circ}$. A zero position lock with hydraulic retraction shall

be provided. The minimum actuator resolution at the output shaft will be determined during the design phase. The actuator will be designed for open loop operation, with the method of specifying dynamic response to be determined during this program.

2.2.2 Conduct design analyses to establish the required design parameters and to show analytically that the concept is capable of meeting the design goal parameters.

2.2.3 The contractor shall conduct a detailed design of the actuator established in 2.2.1.

2.2.4 The hardware for test and delivery shall be fabricated and assembled as follows.

2.2.4.1 One (1) prototype electrohydraulic digital stepper actuator shall be fabricated and assembled. The unit shall contain sufficient test points, pressure ports, etc. to monitor the performance of both the first stage and the complete actuator during test. One motor controller shall be fabricated or procured under this task for checkout and test of the actuator.

2.2.4.2 One set of critical spare parts will be fabricated but not assembled. These parts will be used, if necessary, to repair the test unit in case of failure or excessive wear during testing.

2.2.5 The actuator assembly shall be subjected to the following tests.

2.2.5.1 Break-in Test - A one-hour break-in run shall be conducted on each actuator assembly. Shaft torque loading shall be constant or shall vary sinusoidally so as to impose a peak actuator pressure differential of 1500 psi. Output shaft speed may be constant at a minimum of 60 rpm or may vary sinusoidally from 0 to 60 rpm. After the break-in run the actuator shall be disassembled and examined. If all parts are in acceptable condition, the actuator shall be reassembled and the pressure test conducted. If working parts require replacement, the actuator shall be reassembled using the replacement parts and the break-in run and subsequent disassembly, examination and reassembly shall be repeated.

2.2.5.2 Pressure Test - A proof pressure of 5100 psi shall be applied twice for a period of two minutes, after which the actuator break-in run shall be repeated. There shall be no evidence of excessive external leakage, excessive distortion or permanent set during the application of the proof pressure.

2.2.5.3 Stall Torque - The actuator shall be operated with various supply pressures, with back torque increased until stall occurs.

2.2.5.4 No Load Motor Speed - The actuator shall be operated with no load, and the output shaft speed measured for various input pulse rates.

2.2.6 Test plans shall be prepared and the following tests shall be conducted on one (1) prototype electrohydraulic digital stepper actuator.

2.2.6.1 Backdriving Torque Test - Backdriving torque data shall be determined for the actuator with the actuator chambers pressurized at quiescent pressures of 1000, 2000, and 3000 psia. Under each pressure condition, the torque level required to backdrive the output shaft in both the clockwise and counterclockwise directions shall be recorded.

2.2.6.2 Dynamic Response - Dynamic response tests on the actuator shall be conducted under no load conditions and against a torque load having a spring rate load characteristic of 67 inch-pounds per-degree with a maximum load capability of 2000 inch-pounds at $\pm 30^{\circ}$ deflection, and an inertia load of 0.75 inch-pound-second^2. During all tests the actuator output shaft speed shall be velocity limited to 250° per second. Methods of presenting the dynamic response capability of the actuator will be developed in conjunction with the test program.

2.2.6.3 Pull-in and Pull-out Tests - Pull-in characteristics of the actuator assembly will be determined by measuring the maximum pulse rate at which the actuator can start, with given fixed torque loads on the output shaft, without losing steps. Pull-out characteristics will be determined by measuring the maximum pulse rate which the actuator can follow, with given fixed output torque load, without losing steps. Tests will be run with inertia loads of 0.75 inch-pound-second^2 superimposed on the output shaft.

2.2.6.4 Life Test - A 50-hour life test will be conducted on the actuator at room temperature. The actuator will be stepped repeatedly through a duty cycle to be specified. Performance parameters will be sampled periodically to check the performance of the actuator.

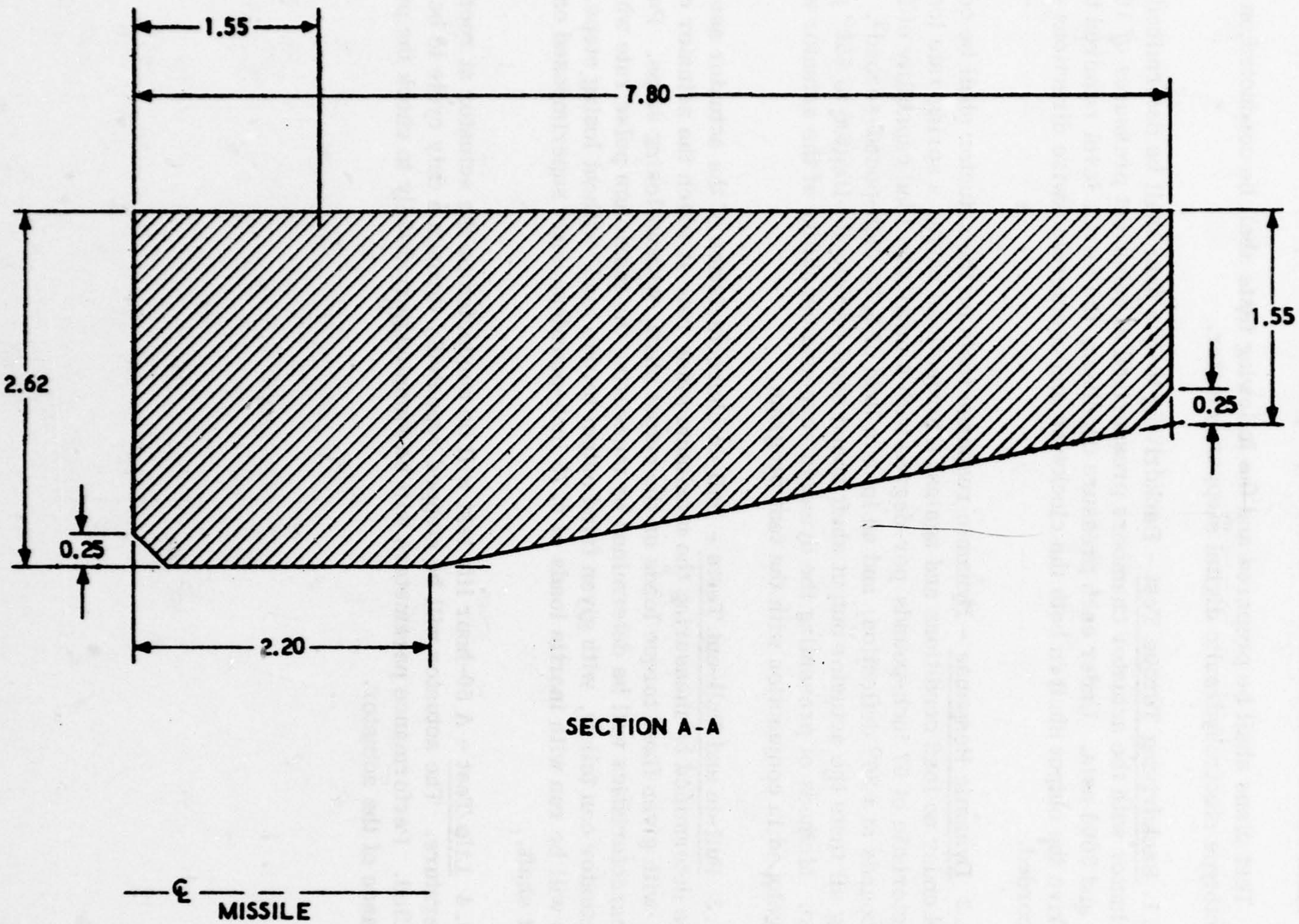


FIGURE 2 - ACTUATOR ENVELOPE, LONGITUDINAL CROSS SECTION

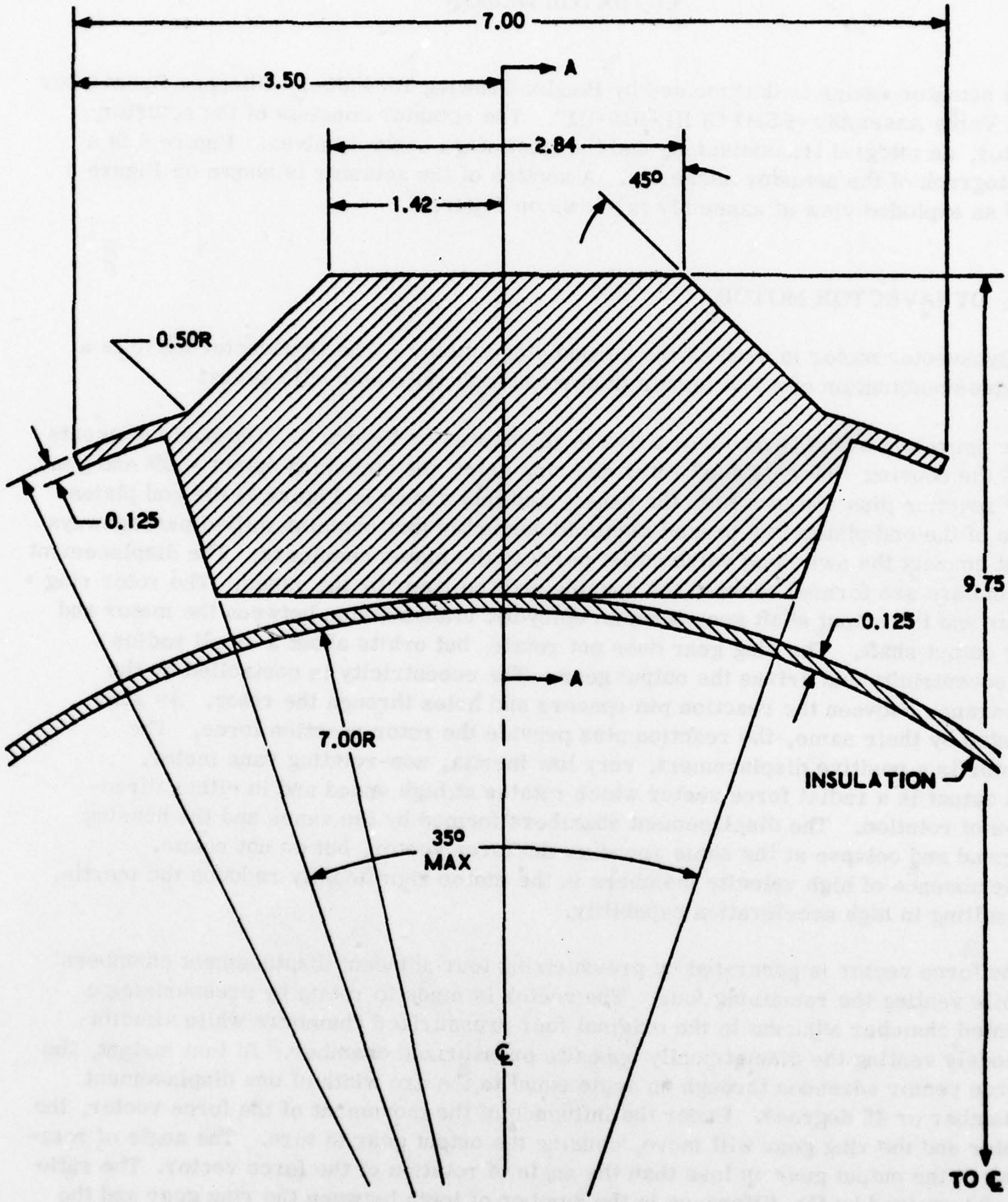


FIGURE 3 – ACTUATOR ENVELOPE, LATERAL CROSS SECTION

SECTION III

ACTUATOR DESIGN

The actuator design is documented by Bendix Drawing 1564330-1, "Stepper Dynavector and Valve Assembly (ESMFC) HL-045-U1". The actuator consists of the actuator motor, an integral transmission, and the first stage control valves. Figure 4 is a photograph of the actuator assembly. A section of the actuator is shown on Figure 5 and an exploded view of assembly is shown on Figure 6.

3.1 DYNAVECTOR MOTOR

A Dynavector motor is used as the second stage motor. The Dynavector drive is a unique combination of a low inertia motor and high ratio epicyclic gears.

The operation of the Dynavector drive is illustrated by Figure 7. The basic elements are the housing, the combined rotor and ring gear, the combined output shaft and gear, the reaction pins and spacers, the vanes, and (not shown in Figure 7) the end plates. One of the end plates is a brazed manifold assembly that contains milled passageways that connect the switching valve outlet ports to the motor chambers. The displacement chambers are formed between the housing and the rotor by the vanes. The rotor ring gear and the output shaft gear form an epicyclic transmission between the motor and the output shaft. The ring gear does not rotate, but orbits about a small radius of eccentricity and drives the output gear. The eccentricity is controlled by the clearance between the reaction pin spacers and holes through the rotor. As suggested by their name, the reaction pins provide the rotor reaction force. The motor is a positive displacement, very low inertia, non-rotating vane motor. Its output is a radial force vector which rotates at high speed and in either direction of rotation. The displacement chambers formed by the vanes and the housing expand and colapse at the same speed as the force vector, but do not rotate. The absence of high velocity members in the motor significantly reduces the inertia, resulting in high acceleration capability.

The force vector is generated by pressurizing four adjacent displacement chambers while venting the remaining four. The vector is made to rotate by pressurizing a vented chamber adjacent to the original four pressurized chambers while simultaneously venting the diametrically opposite pressurized chamber. At that instant, the force vector advances through an angle equal to the arc width of one displacement chamber or 45 degrees. Under the influence of the movement of the force vector, the rotor and the ring gear will move, causing the output gear to turn. The angle of rotation of the output gear is less than the angle of rotation of the force vector. The ratio is determined by the difference in the number of teeth between the ring gear and the output gear and the number of teeth on the output gear.

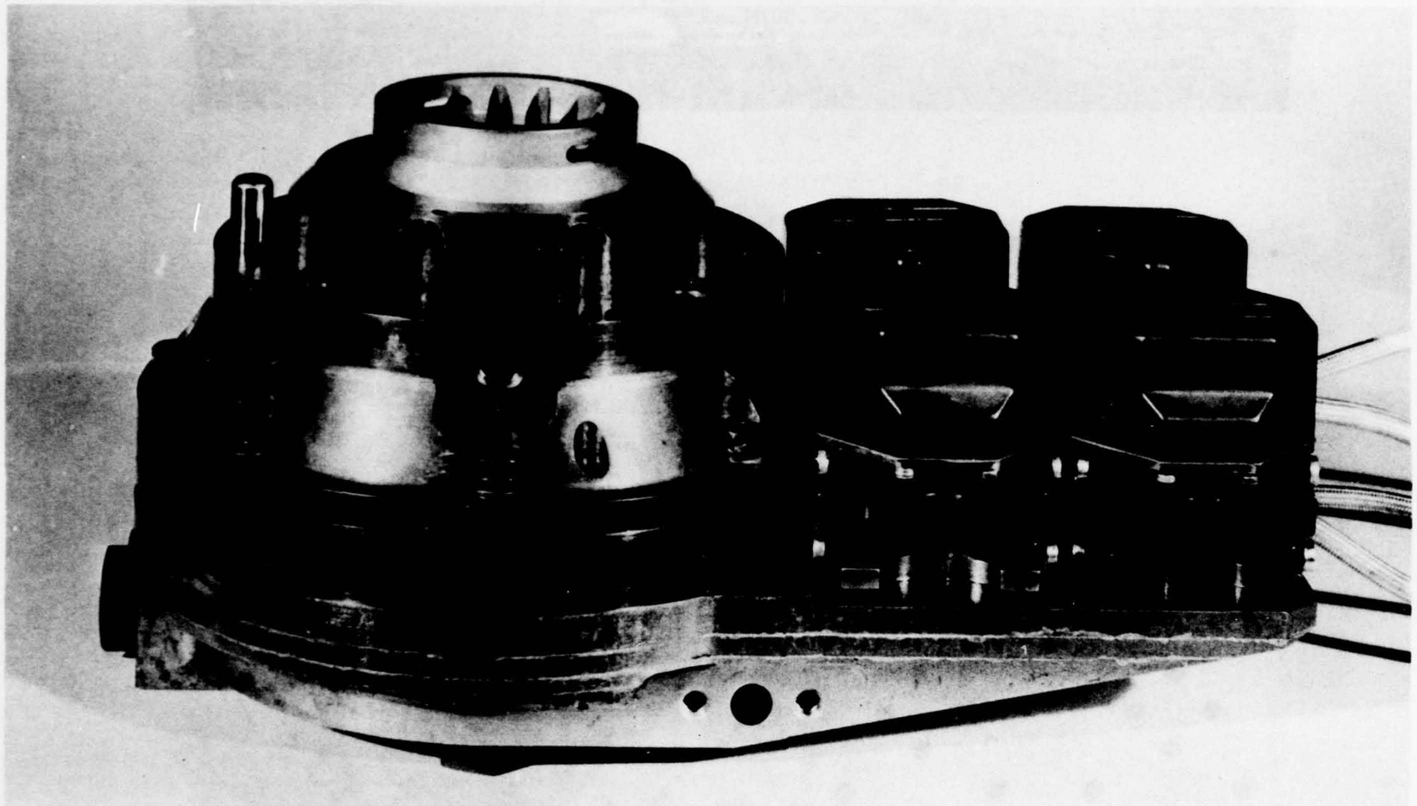


FIGURE 4 - ACTUATOR ASSEMBLY

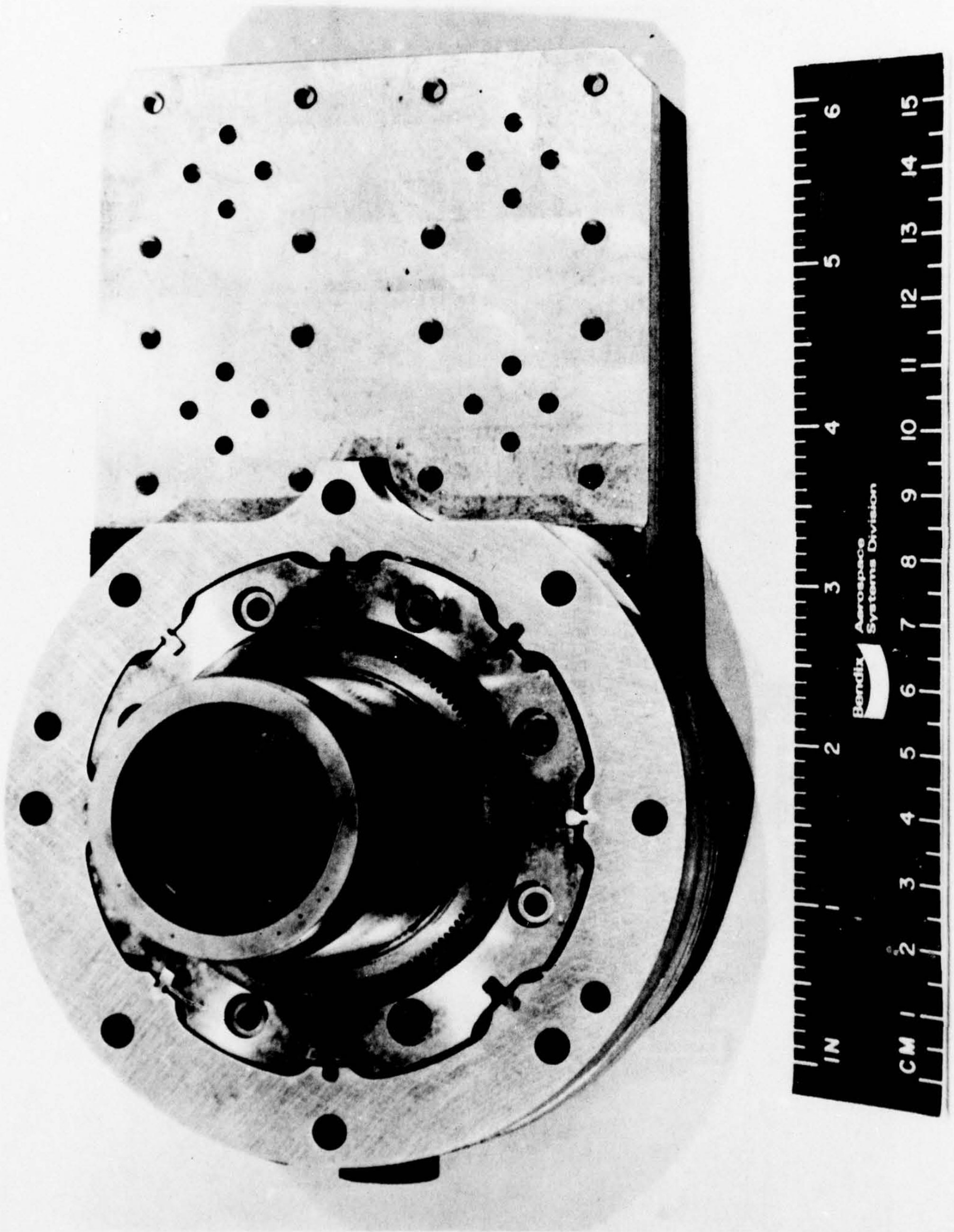


FIGURE 5 - ACTUATOR CROSS SECTION

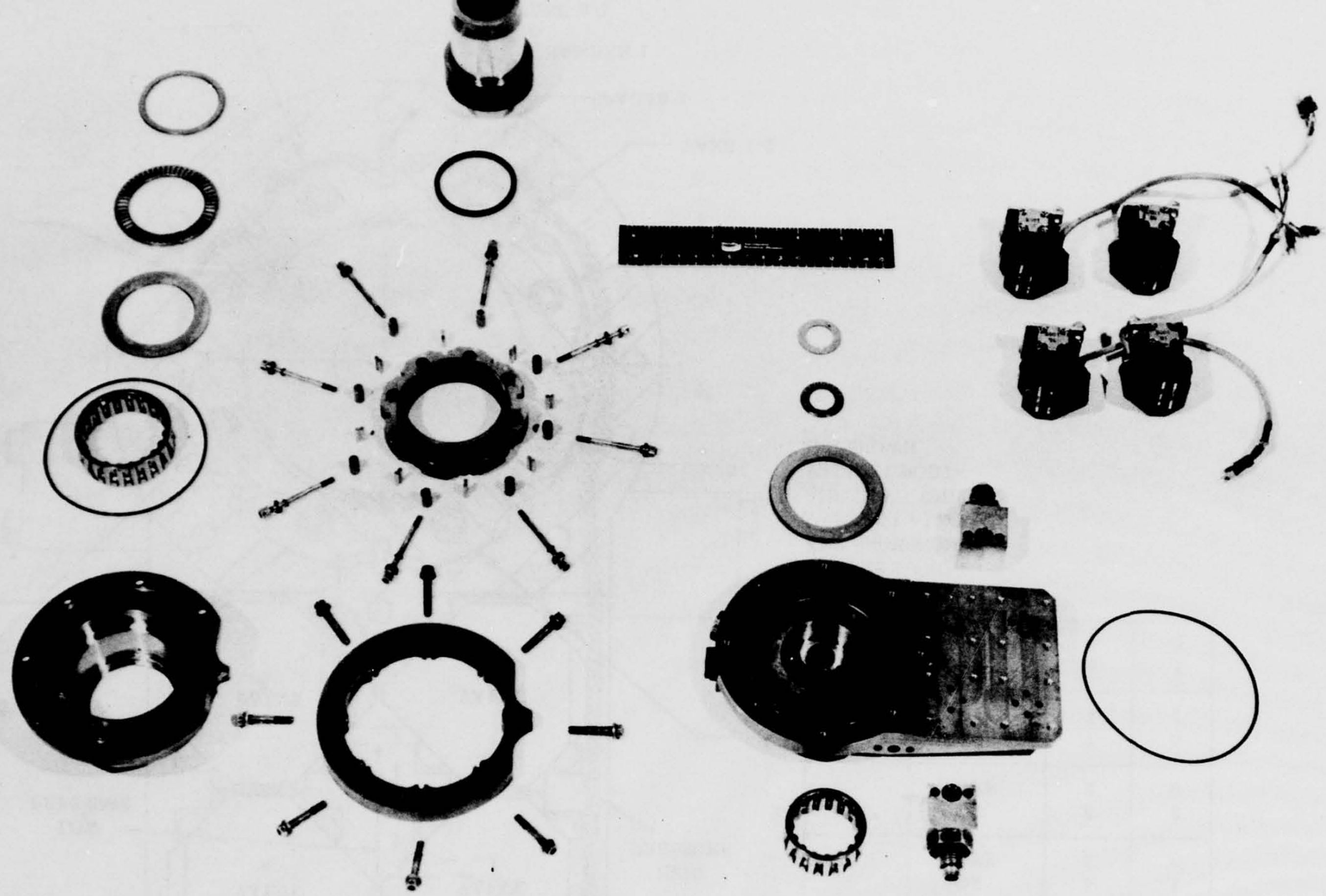
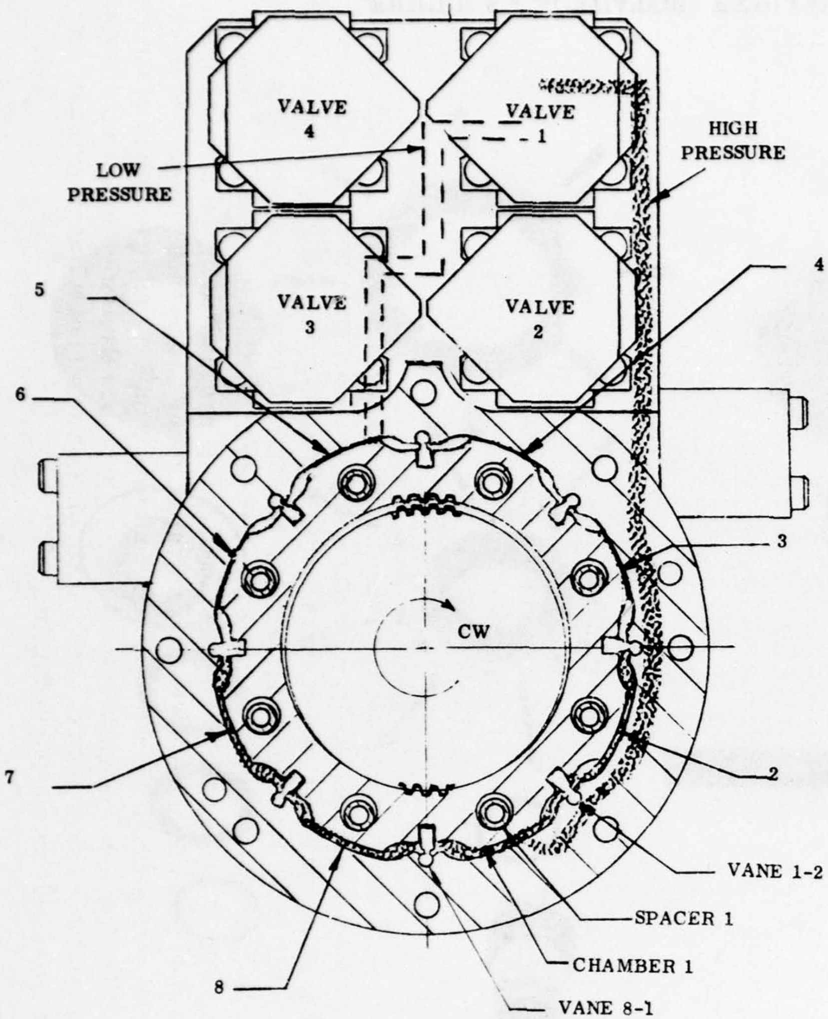


FIGURE 6 - ACTUATOR, EXPLODED ASSEMBLY



		CHAMBER	
VALVE	POSITION	HIGH	LOW
1	ON OFF	5 1	1 5
2	ON OFF	6 2	2 6
3	ON OFF	7 3	3 7
4	ON OFF	8 4	4 8

VALVES 3 AND 4 ARE SHOWN ON. VALVES 1 AND 2 ARE OFF. ONLY VALVE 1 PORTING SHOWN.

FIGURE 7 - DYNAVECTOR SCHEMATIC

The transmission ratio for the stepper actuator is 45 to 1. Each step of the output shaft is therefore one degree.

$$R_t = \frac{N_o}{N_o - N_r} = \frac{135}{138 - 135} = \frac{135}{3} = 45$$

where:

R_t = transmission ratio
N_o = number of teeth on output gear
N_r = number of teeth on ring gear

An advantage of having the ring gear pitch diameter nearly equal to the mating gear pitch diameter is the resulting high load capacity. Under load, deflections quickly allow many teeth to share the load. This same feature provides high resistance to shock overloads and minimizes dynamic loading forces. The transmission has excellent torque transmitting capability because the dynamic loads are negligible and the dynamic strength equals the static strength.

If the force vector is parallel to the eccentricity axis of the transmission, the actuator output torque will be zero. If the force vector is at right angles to the eccentricity axis, the output torque will be at its maximum value. For the eight-chamber motor, the zero torque point and the peak torque point are two steps apart.

Several limiting factors present in conventional rotary motors plus transmission systems are significantly improved by the Dynavector actuator design and operation. The relative velocities between dynamic and static members of the Dynavector actuator are very small because of the small amplitude orbital motion. In a Dynavector actuator, the relative velocity between the gears and housing is only a function of the eccentricity (which for the actuator is only .023 inch) times the angular velocity. The absence of high relative velocities produces high mechanical efficiency by reducing friction losses at high motor speed.

Another factor that is significantly reduced in the Dynavector actuator is the actuator inertia. In conventional high speed motors, the small volumes of fluid under compression tend to provide good response capabilities, but the motor inertia resulting from a rotor mass rotating at high angular velocities limits the response. Conversely, linear actuators have a lower reflected inertia because of the smaller mass moving at lower velocities, but their response capabilities are limited by the larger volumes of fluid under compression. The Dynavector actuator has no mass rotating at input speed and only a small reflected inertia due to the small eccentric rotation of the ring gear and the low speed output shaft. Thus, it combines the low volume characteristic of a conventional motor with the low inertia characteristic of a linear actuator, to provide excellent response capabilities.

A locking mechanism consisting of a hydraulically retracted plunger is provided. This prevents the fin from being displaced prior to initiation of the control system.

3.1.1 Output Shaft Resolution

In a missile control application, the digital dynavector actuator provides a quantized response of the control surface position to an autopilot control signal. Missile performance can vary considerably with the amplitude of the step change in control surface position. A study was conducted to determine the output shaft resolution required to provide the desired missile performance.

Since detailed aerodynamic performance of the multipurpose missile had not been established, a two-dimensional simulation of the ASMS (tail control) missile was used for closed loop simulation studies. The simulation was modified to reflect the digital actuator characteristics, i.e., quantization and velocity limiting.

Results of the study are shown in Table 2, indicating that an output shaft resolution of one degree is sufficient to meet the performance criteria used in the study. The performance criteria are discussed as follows:

TABLE 2 - REQUIRED OUTPUT SHAFT RESOLUTION

Performance Parameter	Criteria	Required Step Size, Degrees	Condition
Intercept Accuracy	Compare with accuracy of analog reference	3.0 1.0	No wing noise 0.5° rms Wing Noise
Range Penalty	Less than 10%	1.1 2.7	10K ft altitude 30K ft altitude
Response	90° max. phase lag	1.1	At 30 Hz oscillation rate

<u>Intercept Accuracy</u>

Noise free test results against a low altitude, incoming, non-maneuvering target show essentially no accuracy degradation until the actuator step size reaches 3 to 4 degrees. The effect of quantization level on angle of attack is shown in Figure 8 demonstrating that increases in step size will result in increased angle of attack oscillations. The same miss distance trends are noted when 0.5 rms degrees of wing noise is introduced. However, as shown by Figure 9, the angle of attack oscillations does increase. Performance is not seriously degraded with a 1° step size.

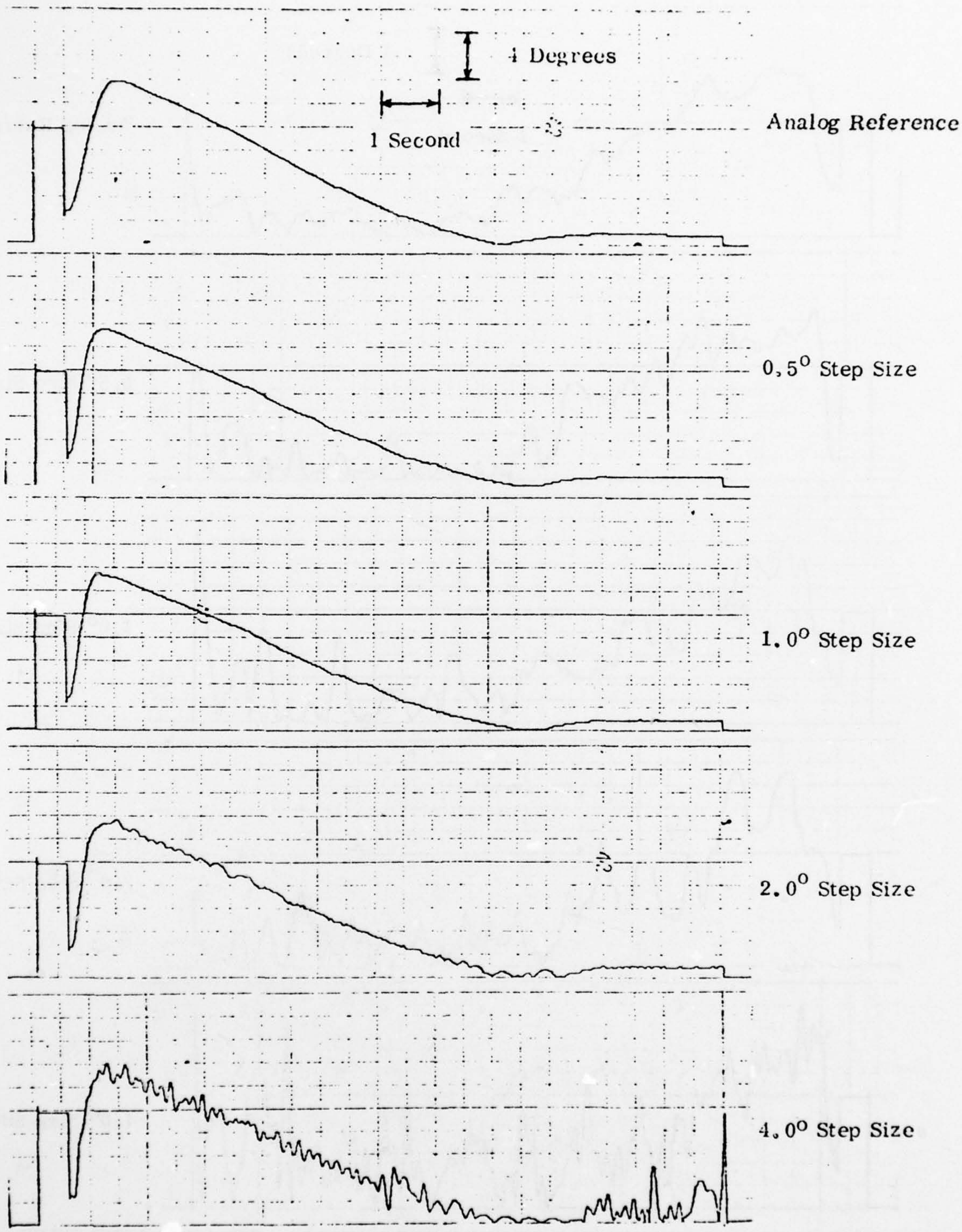


FIGURE 8 - ANGLE OF ATTACK HISTORIES FOR VARIOUS ACTUATOR STEP SIZES

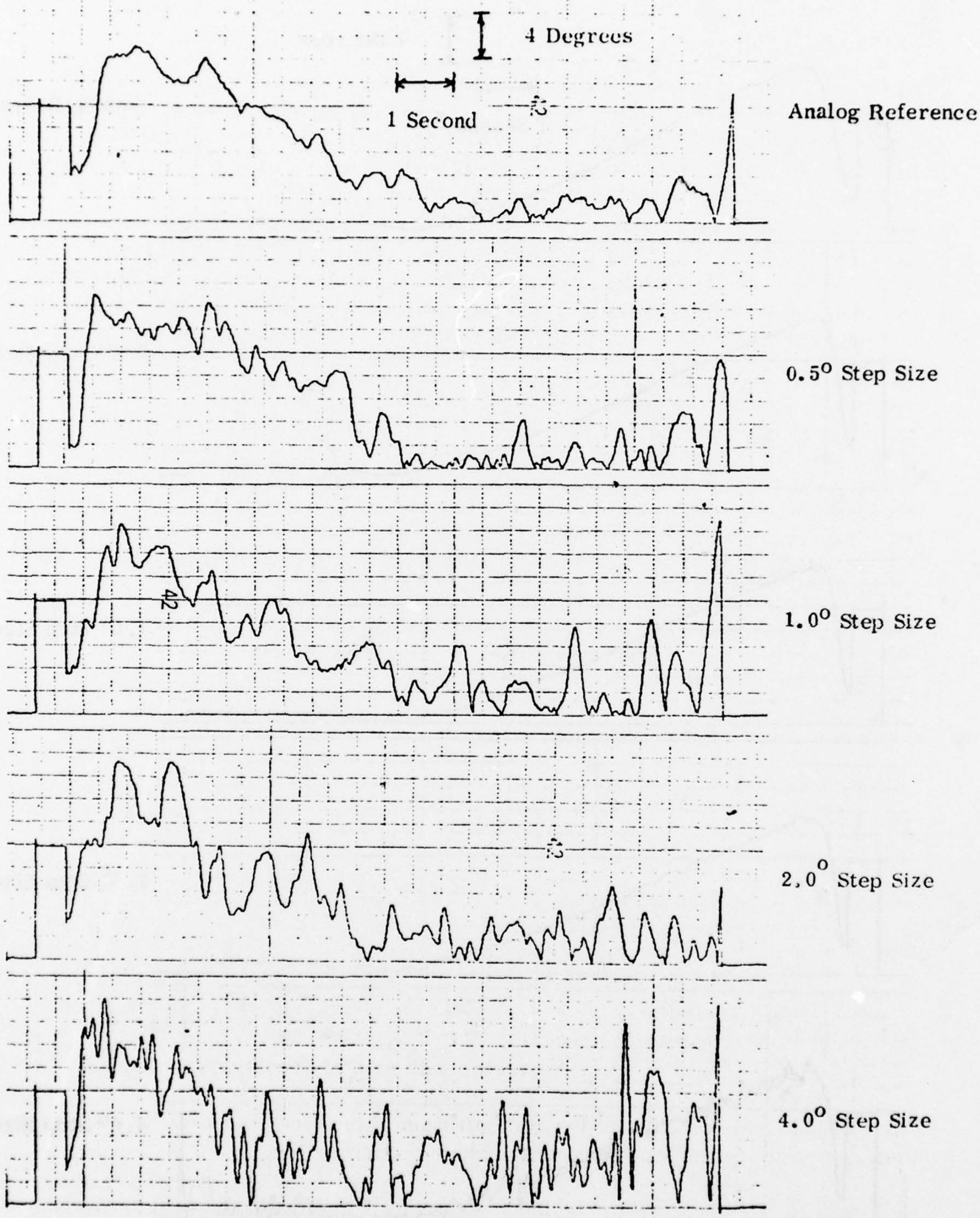


FIGURE 9 - ANGLE OF ATTACK HISTORIES FOR VARIOUS ACTUATOR STEP SIZES WITH 0.5° RMS NOISE

Drag

The simulation tests indicated no appreciable drag penalties for actuator step sizes up to 2 degrees for the short duration, 11-12 second flights examined. For longer flights, an empirical approach utilizing TALOS Data was used to estimate range loss penalties. Figure 10 shows the estimates of range loss for a 60 second flight at various altitudes for a given RMS wing error. Since the RMS wing error averages about 30 percent of the actuator step size, Figure 5 can be used to estimate the effect of step size on range loss. For example, a one degree step size represents an 0.3 degree RMS wing error, which will result in a 9 percent range loss at 10,000 feet altitude.

Response

A dynamic model of the digital actuator was used to determine the phase lag between control shaft output and input command signal for various oscillation rates with a one degree step size. As shown by Figure 11, the phase lag at ±1 degree amplitude for a 30 Hz oscillation rate is 83.7 degrees, which is within the required phase lag of 90 degrees.

3.1.2 Actuator Size

The output torque of the Dynavector hydraulic actuator is

$$T_o = b\, D_v\, \Delta P\, e\, R_t\, \eta_t \sin \phi_p \qquad (1)$$

where b = Motor length, in.

T_o = output torque, in-lb
D_v = Vane seal diameter, in.
ΔP = Pressure difference, psid
e = Eccentricity, in
R_t = Gear Ratio
η_t = Torque efficiency
ϕ_p = Angle of pressure vector with axis of eccentricity, degree

As part of the final selection of the configuration of the electro hydraulic stepper actuator, consideration was given to the choice of motor length.

A minimum motor length (rotor width) is possible if the length is sized to produce the required 2,000 inch-pound torque when the pressure vector is 90 degrees from the axis of eccentricity.

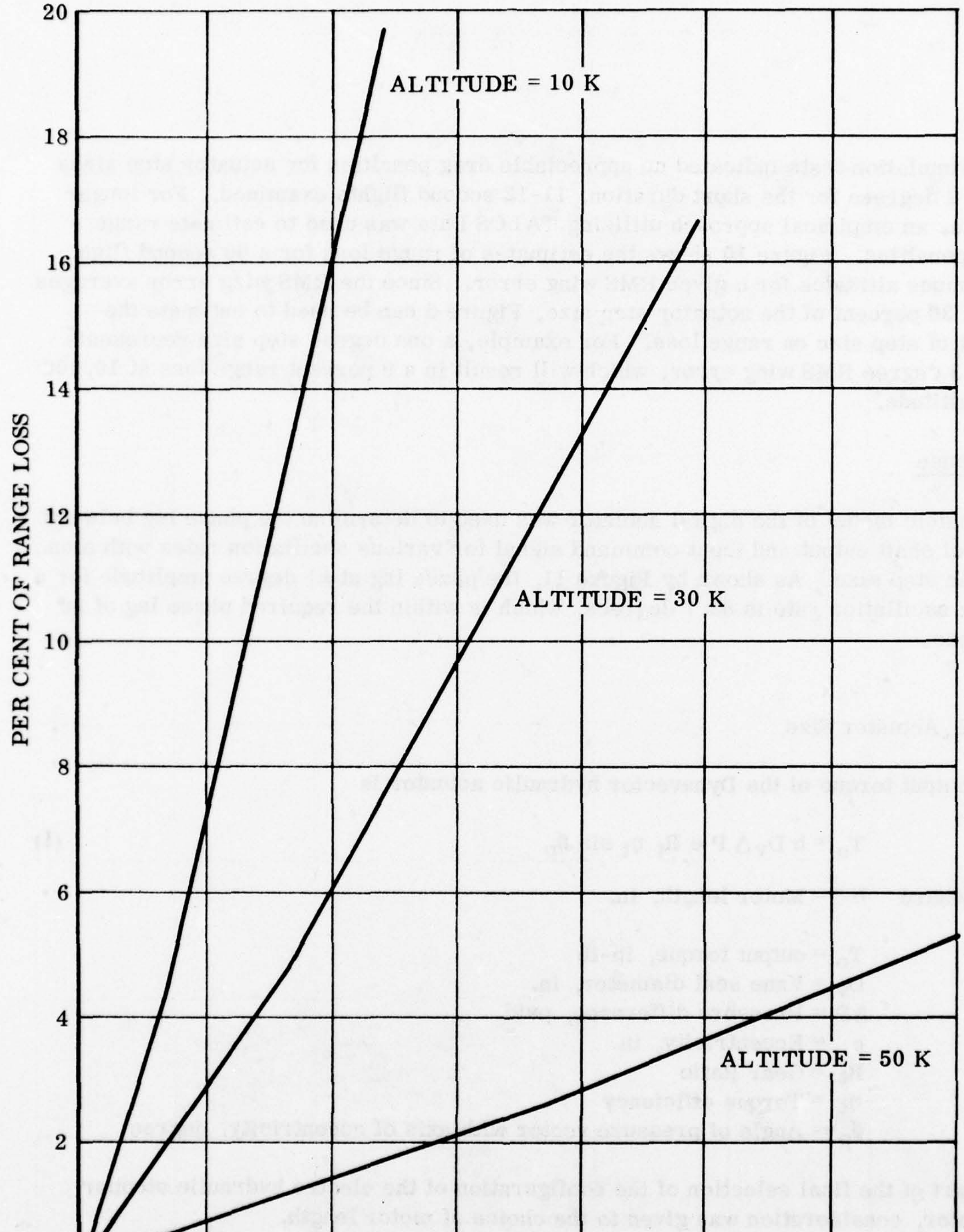


FIGURE 10 - RANGE LOSS ESTIMATES BASED ON 60 SEC. FLIGHT DURATION

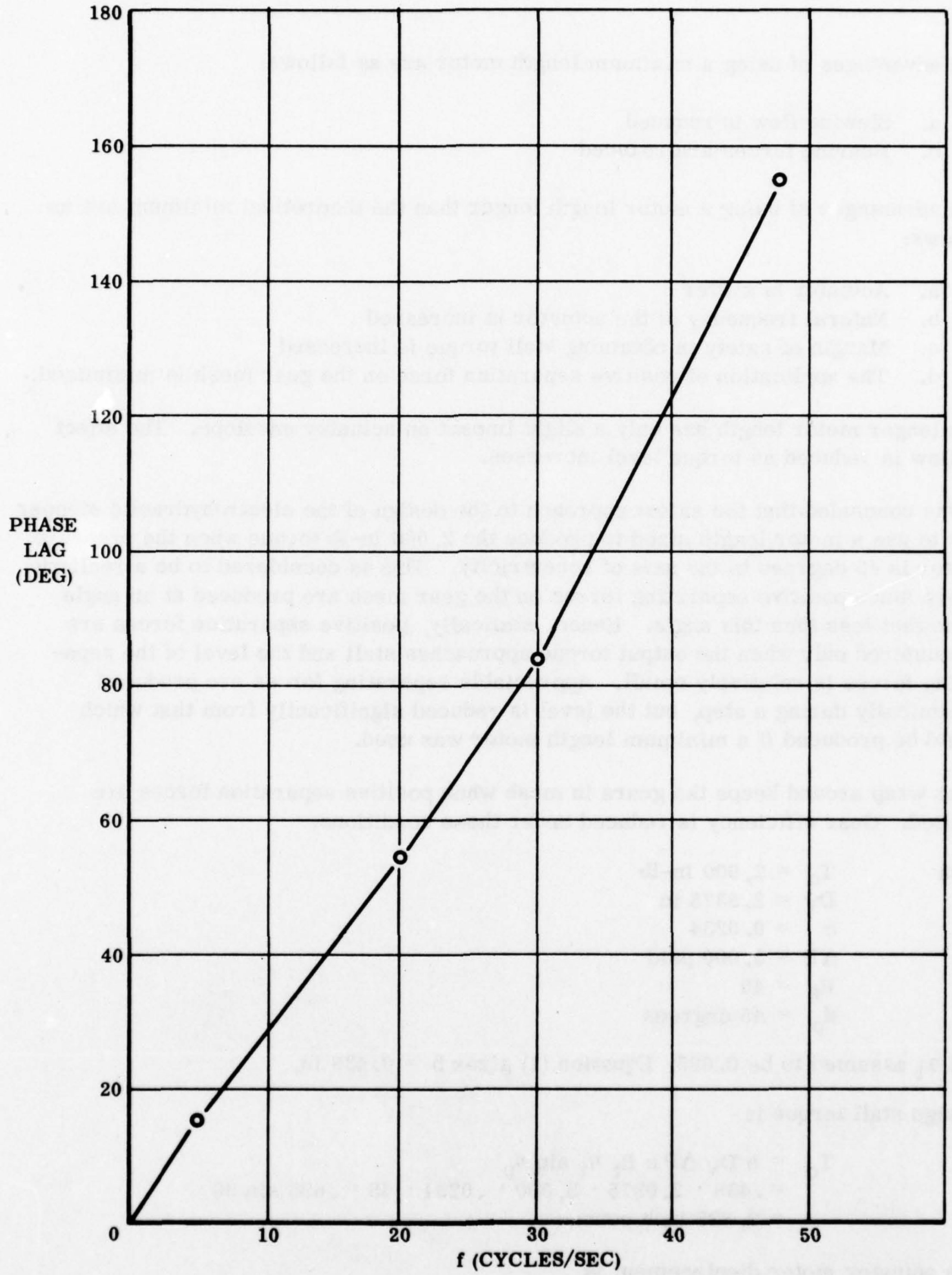


FIGURE 11 - COMPUTED PHASE SHIFT

The advantages of using a minimum length motor are as follows:

a. Slewing flow is reduced
b. Bearing forces are reduced

The advantages of using a motor length longer than the theoretical minimum are as follows:

a. Actuator is stiffer
b. Natural frequency of the actuator is increased
c. Margin of safety in obtaining stall torque is increased
d. The application of positive separation force on the gear mesh is minimized.

The longer motor length has only a slight impact on actuator envelope. The effect on flow is reduced as torque level increases.

It was concluded that the safest approach to the design of the electrohydraulic stepper was to use a motor length sized to produce the 2, 000 in-lb torque when the pressure vector is 45 degrees to the axis of eccentricity. This is considered to be a realistic figure since positive separating forces on the gear mesh are produced at an angle somewhat less than this angle. Hence, statically, positive separation forces are encountered only when the output torque approaches stall and the level of the separating forces is relatively small. Appreciable separating forces are produced dynamically during a step, but the level is reduced significantly from that which would be produced if a minimum length motor was used.

Gear wrap around keeps the gears in mesh when positive separation forces are applied. Gear efficiency is reduced under these conditions.

With

$$\begin{aligned} T_o &= 2,000 \text{ in-lb} \\ D_V &= 2.9375 \text{ in} \\ e &= 0.0234 \\ \Delta P &= 3,000 \text{ psid} \\ R_t &= 45 \\ \phi_p &= 45 \text{ degrees} \end{aligned}$$

and η_t assumed to be 0.695, Equation (1) gives $b = 0.438$ in.

Design stall torque is

$$\begin{aligned} T_o &= b\, D_V\, \Delta P\, e\, R_t\, \eta_t \sin \phi_p \\ &= .438 \cdot 2.9375 \cdot 3,000 \cdot .0234 \cdot 45 \cdot .695 \sin 90 \\ &= 2,825 \text{ inch pounds} \end{aligned}$$

The actuator motor displacement is

$$\begin{aligned} d_m &= 2\pi D_V\, e\, b \qquad (2) \\ &= .189 \text{ in}^3/\text{orbit} \end{aligned}$$

and the actuator total displacement is

$$d = d_m R_t = 8.51 \text{ in}^3/\text{rev} \tag{3}$$

3.1.3 Stiffness

The Dynavector produces maximum output torque when the pressure vector and eccentricity vector are at right angles. Under no load conditions the output will go to the position called for and the pressure and eccentricity vectors will be co-linear. Any load will back drive the Dynavector until there is sufficient torque developed to balance the load. For the 45 to 1 gear ratio, 90^o rotation of the pressure and eccentricity vectors is achieved by rotation of 2 degrees at the output. The relationship between the variables is as follows:

$$T_o = T_s \sin \theta \tag{4}$$

where: T_o = output torque
T_s = stall torque = 2825 in-lb
θ = angle between eccentricity and pressure vectors

For the rated load of 1333 inch pounds, θ must be 28 degrees. Thus, with a 45/1 gear ratio, this would result in a .62 degree change in the output position. Similarly, a load of 2000 inch pounds would change the output 1.0 degrees.

3.1.4 Dynamic Analysis

A dynamic analysis was made during the design phase for the actuator sized above from which it was concluded that the actuator was capable of accelerating to the 250 degree per second slew rate during the first step. Ramping to the slew rate is not required as is the case in many conventional stepper motor applications. The high response is the result of the extremely low Dynavector rotor inertia. The inertia of the rotor reflected at the output shaft is

$$J_R = \frac{W_R}{g} (e\ R)^2 \tag{5}$$

where

J_R = Reflected inertia of rotor lb-in-sec^2
W_R = Weight of rotor, lb
g = acceleration, in/sec^2
R = Gear ratio
e = Rotor eccentricity, in

$$J_R = \frac{.5}{386} (.0234 \times 45) = .0014 \text{ lb-in-sec}^2$$

A rotating motor of the same size would have a reflected inertia of

$$J_R = \frac{W_R (r\ R)^2}{g}$$

$$= \frac{.5}{386} (.813 \times 45)^2 = 1.73 \text{ lb-in-sec}^2$$

The dynamic analysis is presented below.

Non-Simplified Equations of Motion

For a stepper Dynavector actuator:

$$\theta_m = R_t \theta_o \qquad (6)$$

where θ_m = Angle traversed by axis of eccentricity during a single step, radians

θ_o = Angle traversed by output shaft during a single step, radians

R_t = Transmission ratio, dimensionless

also

$$T_o = R_t T_m \qquad (7)$$

where T_o = Torque on output shaft, in-lbs

T_m = Torque on rotor, in-lbs

and

$$J_T \frac{d^2\theta_o}{dt^2} = T_o \qquad (8)$$

where J_T = Total inertia reflected at output, in-lb-sec^2

t = Time, seconds

Equations (6) and (7) may be used to eliminate θ_o and T_o from Equation (8) to give:

$$\frac{J_T}{R_t^2} \frac{d^2\theta_m}{dt^2} = T_m \qquad (9)$$

Figure 12 is a schematic representation of the stepper Dynavector actuator. The following notation is defined for Figure 12.

A_v = Flow areas of valves supplying displacement chambers, in^2

P_s = Supply pressure, psig

P_r = Return pressure, psig

e = Eccentricity, in

F_2 = Force acting on chamber, 2 lb

F_3 = Force acting on chamber, 3 lb

F_4 = Force acting on chamber, 4 lb

F_5 = Force acting on chamber, 5 lb

In the following analysis, it will be assumed that chambers 3, 4 and 5 are always at the nominal high pressure, that chambers 1, 7, and 8 are always at the nominal low pressure, and that chamber 6 is switched from high to low pressure and chamber 2 from low to high pressure to initiate the step. The original position of the axis of eccentricity is along line 0A and the final position of the axis of eccentricity on the line 0B. We can define the following torques:

T_2 = Torque produced by F_2, in-lbs

T_3 = Torque produced by F_3, in-lbs

T_4 = Torque produced by F_4, in-lbs

T_5 = Torque produced by F_5, in-lbs

The values of these torques are as follows:

$$T_2 \doteq F_2 e \sin (1.963-\theta_m) \tag{10}$$

$$T_3 = F_3 e \sin (1.178-\theta_m) \tag{11}$$

$$T_4 = F_4 e \sin (0.393-\theta_m) \tag{12}$$

$$T_5 = F_5 e \sin (-0.393-\theta_m) \tag{13}$$

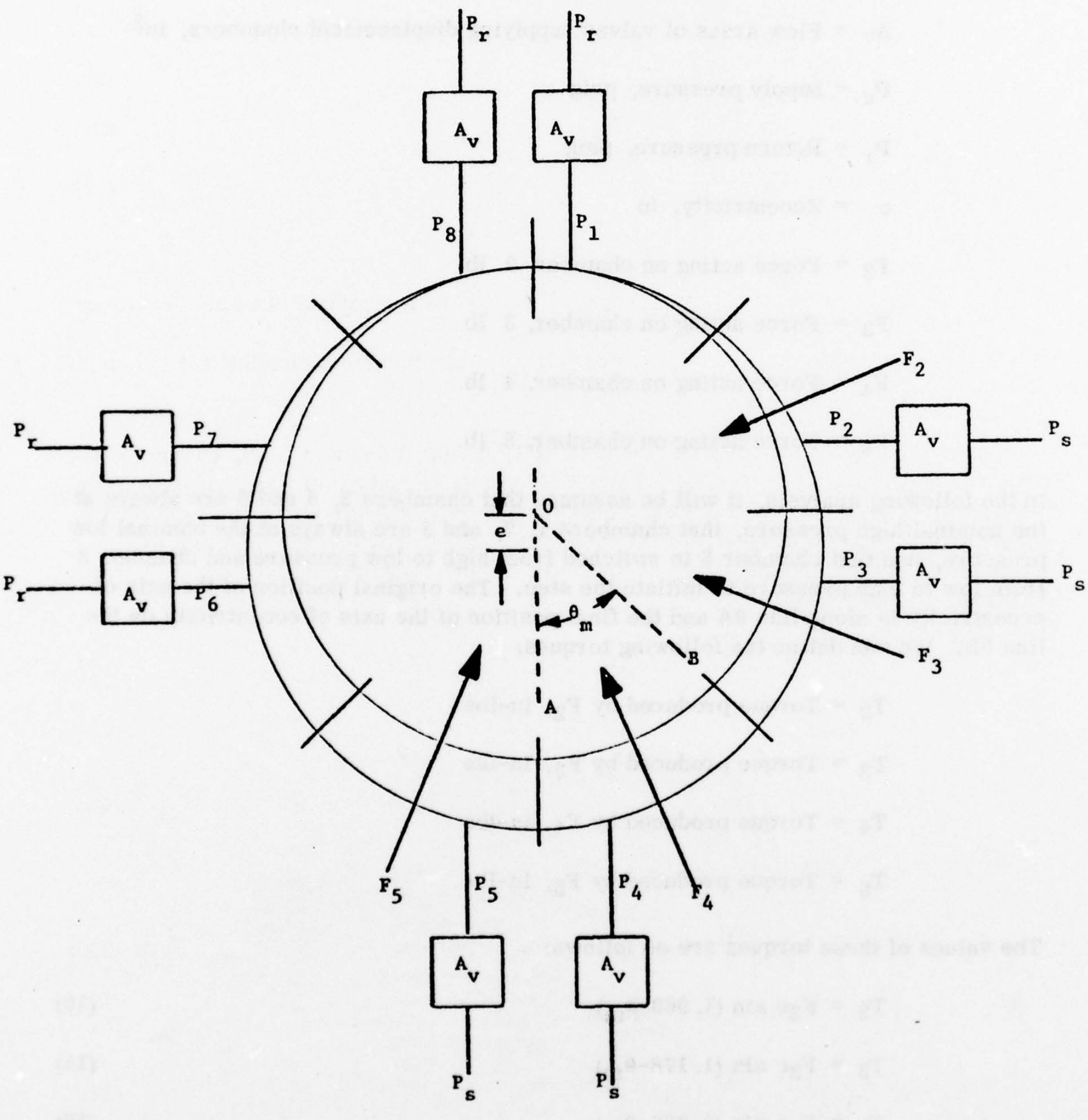


FIGURE 12 - SCHEMATIC OF STEPPER ACTUATOR FOR DYNAMIC ANALYSIS

The forces F_2, F_3, F_4, and F_5 are:

$$F_2 = A_c (P_2 - P_6) \tag{14}$$

$$F_3 = A_c (P_3 - P_7) \tag{15}$$

$$F_4 = A_c (P_4 - P_8) \tag{16}$$

$$F_5 = A_c (P_5 - P_1) \tag{17}$$

where

A_c = Area acted on by chamber pressure to produce chamber force, in^2

$P_1, P_2, \ldots\ldots P_7, P_8$ = Pressures in displacement chambers 1 through 8, psig

As the axis of eccentricity rotates, chambers 1, 2, and 3 draw in fluid, chambers 5, 6, and 7 expel fluid, and chambers 4 and 8 both draw in and expel fluid, depending on the value of θ_m. Figure 13 shows the change in displacement volume for each of the eight chambers. This drawing in and expelling of fluid provides the damping force. The effect of these flows on chamber pressure is as follows for the six non-actuated chambers:

$$q_1 = C_d A_v \sqrt{\frac{2g}{\gamma} (P_r - P_1)} \tag{18}$$

$$q_3 = C_d A_v \sqrt{\frac{2g}{\gamma} (P_s - P_3)} \tag{19}$$

$$q_4 = C_d A_v \sqrt{\frac{2g}{\gamma} (P_s - P_4)} \tag{20a}$$

for $\theta_m = 0$ to 0.393 radians

and $$q_4 = C_d A_v \sqrt{\frac{2g}{\gamma} (P_4 - P_s)} \tag{20b}$$

for $\theta_m = 0.393$ to 0.785 radians

$$q_5 = C_d A_v \sqrt{\frac{2g}{\gamma} (P_5 - P_s)} \tag{21}$$

$$q_7 = C_d A_v \sqrt{\frac{2g}{\gamma} (P_7 - P_r)} \tag{22}$$

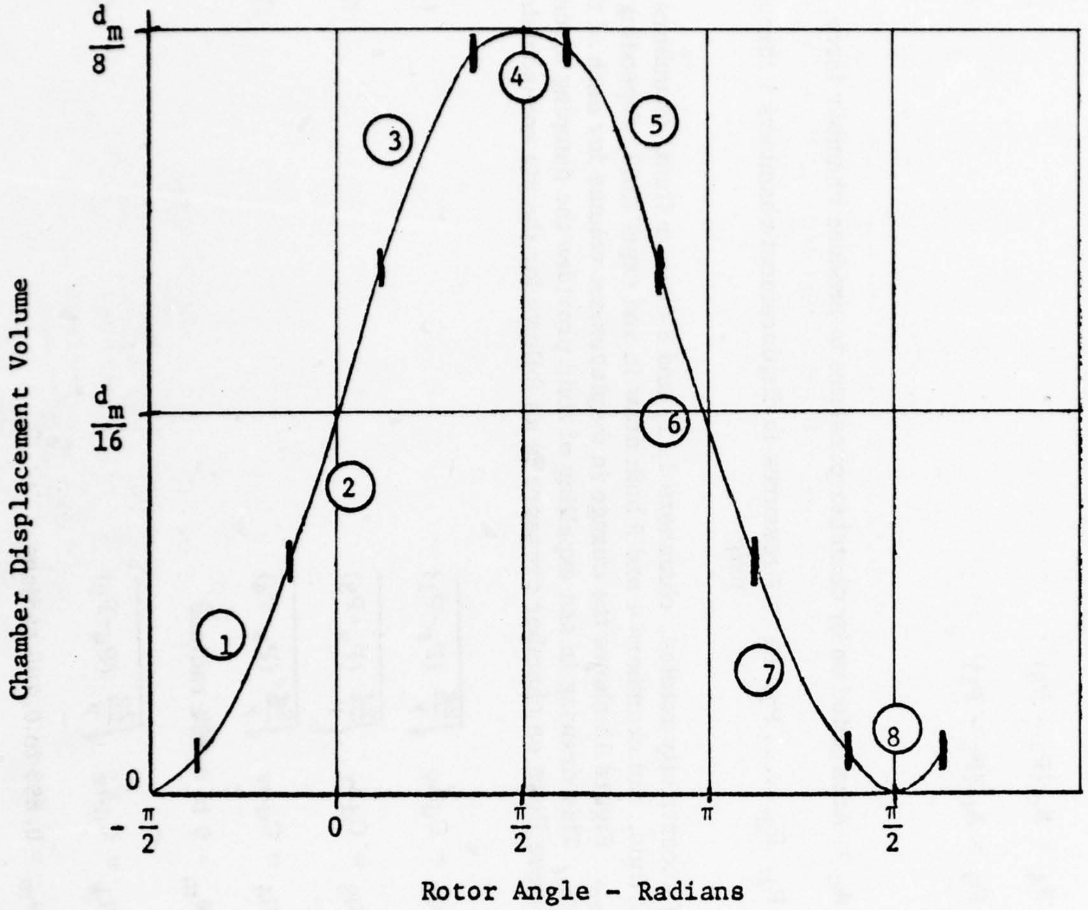


FIGURE 13 - CHANGE IN DISPLACEMENT VOLUME OF VARIOUS CHAMBERS FOR A SINGLE STEP

$$q_8 = C_d A_v \sqrt{\frac{2g}{\gamma}\ (P_8 - P_r} \tag{23a}$$

for $\theta_m = 0$ to 0.393 radians

and $$q_8 = C_d A_v \sqrt{\frac{2g}{\gamma}\ (P_r - P_8)} \tag{23b}$$

for $\theta_m = 0.393$ to 0.785 radians

In the case of the actuated chambers, the flow areas of the valves are functions of time, which can be symbolized by denoting these valve areas A_{vt}. Since both chambers are controlled by a two-position four-way valve, we can define the valve area as changing from $-A_v$ to $+A_v$ to initiate the step. The equations defining P_2 and P_6 are as follows:

$$P_2 = P_r \text{ for } A_{vt} = -A_v \text{ to } 0 \tag{24a}$$

$$q_2 = C_d A_v \sqrt{\frac{2g}{\gamma}\ (P_s - P_2)}$$

for $A_{vt} = 0$ to $+A_v$ (24b)

$$P6 = P_s \text{ for } A_{vt} = -A_v \text{ to } 0 \tag{25a}$$

$$q_6 = C_d A_v \sqrt{\frac{2g}{\gamma}\ (P_6 - P_r)}$$

for $A_{vt} = 0$ to $+A_v$ (25b)

For equations (18) to (25)

$q_1, q_2, \ldots\ldots q_7, q_8$ = Flows in or out of displacement chambers, in^3/sec

g = 386 in/sec^2

γ = Specific weight of fluid, lb/in^3

From Figure 13, we can write the following equations for the displacement volume of a given chamber as a function of θ_m:

$$v_1 = \frac{d_m}{16}\ [1 + \sin(-1.178 + \theta_m)] \tag{26}$$

$$v_2 = \frac{d_m}{16} [1 + \sin (1.178 + \theta_m)] \tag{27}$$

$$v_3 = \frac{d_m}{16} [1 + \sin (0.393 + \theta_m)] \tag{28}$$

$$v_4 = \frac{d_m}{16} [1 + \sin (1.178 + \theta_m)] \tag{29}$$

$$v_5 = \frac{d_m}{16} [1 + \sin (1.963 + \theta_m)] \tag{30}$$

$$v_6 = \frac{d_m}{16} [1 + \sin (2.749 + \theta_m)] \tag{31}$$

$$v_6 = \frac{d_m}{16} \; 1 + \sin (3.534 + \theta_m) \tag{32}$$

$$v_8 = \frac{d_m}{16} \; 1 + \sin (4.320 + \theta_m) \tag{33}$$

where, $v_1, v_2, \ldots\ldots v_7, v_8$ = Displacement volumes of Chambers 1 through 8, in^3

d_m = Motor displacement, in^3/orbit

Equations (26) through (33) may be differentiated to give:

$$q_1 = \frac{dv_1}{dt} = - \frac{d_m}{16} \cos (-1.178 + \theta_m) \frac{d\theta_m}{dt} \tag{34}$$

$$q_2 = \frac{dv_2}{dt} = - \frac{d_m}{16} \cos (-0.393 + \theta_m) \frac{d\theta_m}{dt} \tag{35}$$

$$q_3 = \frac{dv_3}{dt} = - \frac{d_m}{16} \cos (0.393 + \theta_m) \frac{d\theta_m}{dt} \tag{36}$$

$$q_4 = \frac{dv_4}{dt} = - \frac{d_m}{16} \cos (1.178 + \theta_m) \frac{d\theta_m}{dt} \tag{37}$$

$$q_5 = \frac{dv_5}{dt} = - \frac{d_m}{16} \cos (1.963 + \theta_m) \frac{d\theta_m}{dt} \tag{38}$$

$$q_6 = \frac{dv_6}{dt} = - \frac{d_m}{16} \cos (2.749 + \theta_m) \frac{d\theta_m}{dt} \tag{39}$$

$$q_7 = \frac{dv_7}{dt} = - \frac{d_m}{16} \cos (3.534 + \theta_m) \frac{d\theta_m}{dt} \tag{40}$$

$$q_8 = \frac{dv_8}{dt} = -\frac{d_m}{16} \cos (4.320 + \theta_m) \frac{d\theta_m}{dt} \tag{41}$$

Finally, $$T_m = T_2 + T_3 + T_4 + T_5 \tag{42}$$

In substituting equations (34) through (41) into equations (18) to (25) the minus signs resulting from differentiation or the evaluation of trigometric functions must be suppressed since the direction of flow has already been defined by the selection of signs for the pressures which have been assigned to avoid the appearance of the square roots of negative numbers in the equations.

Equations (9), (10) through (25), and (34) through (42) along with the definition of the function A_{vt} can in theory be combined to produce the differential equation describing the response of the stepper Dynavector actuator to a single input command. However, the equation would be complex, nonlinear, and contain discontinuous functions. An exact solution is practical only by means of machine computation. In order to obtain a reasonably accurate solution quickly, a simplified, linear analysis has been performed which is described in the following section.

Simplified Equations of Motion

For the simplified analysis, the forces F_3, F_4 and F_5 are replaced by a single fixed force acting colinearly with F_4 and not varying with time (damping effects are added separately). This fixed force is denoted F_p and from Equation (12):

$$T_p = F_p e \sin (0.393 - \theta_m) \tag{43}$$

where T_p = Torque produced by F_p, in-lbs

Since θ_m varies between 0 and 0.785 radians, we can approximate $\sin (0.393 - \theta_m)$ with $(0.393 - \theta_m)$ with a maximum error of approximately 2.5% so that Equation (43) becomes:

$$T_p = F_p e (0.393 - \theta_m) \tag{44}$$

Equation (10) is equivalent to:

$$T_2 = F_2 e \cos (0.393 - \theta_m) \tag{45}$$

This can be approximated by

$$T_2 = F_2 e \tag{46}$$

with a maximum error of 8%.

The damping effects on T_p are described by Equations (36), (37) and (38). Note that Equations (37) and (38) are more conveniently expressed as:

$$q_4 = + \frac{d_m}{16} \sin (0.393 - \theta_m) \frac{d\theta_m}{dt} \tag{47}$$

$$q_5 = - \frac{d_m}{16} \sin (0.393 + \theta_m) \frac{d\theta_m}{dt} \tag{48}$$

To linearize Equations (36), (47) and (48) we will assume that the trigomometric functions are always at their average values:

$$q_3 = \frac{\sqrt{2}}{32} d_m \frac{d\theta_m}{dt} \tag{49}$$

$$q_4 = 0 \tag{50}$$

$$q_5 = - \frac{\sqrt{2}}{32} d_m \frac{d\theta_m}{dt} \tag{51}$$

Combining Equations (49), (50) and (51) with Equations (19), (20) and (21) gives:

$$K_1 A_v \quad P_s - P_3 = \frac{\sqrt{2}}{32} d_m \frac{d\theta_m}{dt} \tag{52}$$

$$P_s = P_4 \tag{53}$$

$$K_1 A_v \quad P_5 - P_s = \frac{\sqrt{2}}{32} \quad \frac{d\theta_m}{dt} \tag{54}$$

where $\quad K_1 = C_d \sqrt{\frac{2g}{\gamma}}$

Equations (52) and (54) have been linearized by assuming that $\sqrt{P_s - P_3} = 0.25 = (P_s - P_3)$ and that $\sqrt{P_5 - P_s} = 0.25\ (P_5 - P_s)$. This is true only for $\Delta P = 16$ psid and gives too low a value at lower pressures and too high a value at higher pressures.

Based on this assumption, Equations (27) and (29) become:

$$0.25\ K_1 A_v\ (P_s - P_3) = \frac{\sqrt{2}}{32} d_m \frac{d\theta_m}{dt} \tag{55}$$

$$0.25\ K_1 A_v\ (P_5 - P_s) = \frac{\sqrt{2}}{32} d_m \frac{d\theta_m}{dt} \tag{56}$$

Since Chambers 1 and 7 operate similarly to Chambers 3 and 5, we can write:

$$0.25\ K_1 A_v\ (P_7 - P_r) = \frac{\sqrt{2}}{32} d_m \frac{d\theta_m}{dt} \tag{57}$$

$$0.25\ K_1A_v\ (P_r - P_1) = \frac{\sqrt{2}}{32}\ d_m \frac{d\theta_m}{dt} \tag{58}$$

Equations (55) through (58) can be combined to give:

$$0.25\ K_1A_v \quad (P_s - P_r) - (P_3 - P_7) \quad = \frac{\sqrt{2}}{16}\ d_m \frac{d\theta_m}{dt} \tag{59}$$

$$0.25\ K_1A_v \quad (P_5 - P_1) - (P_s - P_r) \quad = \frac{\sqrt{2}}{16}\ d_m \frac{d\theta_m}{dt} \tag{60}$$

or

$$P_3 - P_7 = P_s - P_r - \frac{\sqrt{2}}{4} \frac{d_m}{K_1A_v} \frac{d\theta_m}{dt} \tag{61}$$

$$P_5 - P_1 = P_s - P_r + \frac{\sqrt{2}}{4} \frac{d_m}{K_1A_v} \frac{d\theta_m}{dt} \tag{62}$$

Since forces F_3 and F_5 in the steady state are already included in the force F_p, we can define two damping forces acting on the Chambers 3 and 5

$$F_{d3} = - \frac{\sqrt{2}\ A_c d_m}{4K_1A_v} \frac{d\theta_m}{dt} \tag{63}$$

$$F_{d5} = \frac{\sqrt{2}\ A_c d_m}{4K_1A_v} \frac{d\theta_m}{dt} \tag{64}$$

where F_{d3} = Damping force on Chamber 3, lbs

F_{d5} = Damping force on Chamber 5, lbs

From Equations (11) and (13)

$$T_{d3} = - \frac{\sqrt{2}\ d_m A_c}{4\ K_1A_v} \frac{d\theta_m}{dt}\ e \sin (1.178 - \theta_m) \tag{65}$$

$$T_{d5} = - \frac{\sqrt{2}\ d_m A_c}{4\ K_1A_v} \frac{d\theta_m}{dt}\ e \sin (0.393 - \theta_m) \tag{66}$$

where T_{d3} = Chamber 3 damping torque in-lb
T_{d5} = Chamber 5 damping torque in-lb

The sum of $\sin (1.178 - \theta_m)$ and $\sin (0.393 + \theta_m)$ for θ_m of 0 to 0.785 rad is very close to a constant $\sqrt{2}$. Hence:

$$T_{d3} + T_{d5} = T_d = - \frac{2\ d_m A_c e}{4\ K_1A_v} \frac{d\theta_m}{dt} \tag{67}$$

The most convenient means of linearizing the valve dynamics is to assume that:

$$P_2 - P_6 = 2F(t)\ (P_s - P_r) - (P_s - P_r) \tag{68}$$

where F(t) describes the opening of the valve as a function of time.

From Equation (35) the average value of q_2 is

$$q_2 = \frac{d_m}{16} \frac{d\theta_m}{dt} \tag{69}$$

and the average value of q_6 from Equation (39) is:

$$q_6 = \frac{d_m}{16} \frac{d\theta_m}{dt} \tag{70}$$

Hence, the complete description for $P_2 - P_6$ is:

$$P_2 - P_6 = 2F(t)\ (P_s - P_r) - (P_s - P_r) - \frac{2\ d_m}{4\ K_1 A_v} \frac{d\theta_m}{dt} \tag{71}$$

From Equation (14):

$$F_2 = 2A_c F(t)\ (P_s - P_r) - A_c\ (P_s - P_r) - \frac{2A_c d_m}{4\ K_1 A_v} \frac{d\theta_m}{dt} \tag{72}$$

and from Equation (46):

$$T_2 = 2A_c e F(t)\ (P_s - P_r) - A_c e\ (P_s - P_r) - \frac{2A_c e d_m}{4\ K_1 A_v} \frac{d\theta_m}{dt} \tag{73}$$

Noting that for the assumed model:

$$T_m = T_p + T_2 + T_d \tag{74}$$

Equations (44), (67), (73) and (74) can be substituted into Equation (9) to give:

$$\frac{J_T}{R_t^2} \frac{d^2\theta_m}{dt^2} = F_p e\ (0.393 - \theta_m) + 2A_c e F(t)\ (P_s - P_r)\quad \frac{2A_c e d_m}{4\ K_1 A_v} \frac{d\theta_m}{dt}\quad \frac{2A_c e d_m}{4\ K_1 A_v} \frac{d\theta_m}{dt} \tag{75}$$

Prior to the initiation of the step $d^2\theta_m/dt^2$, θ_m, F(t), and $d\theta_m/dt$, all equal 0 and since the system must be in equilibrium,

$$0.393\ eF_p = A_c e\ (P_s - P_r) \tag{76}$$

and Equation (75) becomes:

$$\frac{J_t}{R_t^2} \frac{d^2\theta_m}{dt^2}\quad \frac{A_c e d_m}{K_1 A_v} \frac{d\theta_m}{dt} + F_p e \theta_m = 2A_c e F(t)\ (P_s - P_r) \tag{77}$$

Dividing both sides of Equation (77) by eF_p gives:

$$\frac{J_T}{R_t^2 F_p e} \frac{d^2\theta_m}{dt^2} + \frac{A_c d_m}{K_1 A_v F_p} \frac{d\theta_m}{dt} + \theta_m = \frac{2A_c}{F_p} (P_s - P_r)\ F(t) \tag{78}$$

The left side of this equation is of the standard form:

$$\frac{1}{\omega_n^2}\,\frac{d^2\theta_m}{} + \frac{2\delta}{\omega_n}\,\frac{d\theta_m}{dt} + \theta_m = \frac{2A_c}{F_p}\,(P_s - P_r)\,F(t) \tag{79}$$

where ω_n = Undamped natural frequency, rad/sec
δ = Damping factor

From (79) and (78)

$$\omega_n = \sqrt{\frac{R_t{}^2 F_p e}{J_T}} \tag{80}$$

The motor torque is 2000/45 = 44.44 in-lbs at $\theta_m = \pi/4$ radians. Then the motor force must be 44.44/e sin $(\pi/4)$ = 44.44/0.0234375 sin $(\pi/4)$ = 2681.5 lbs. This is provided by four forces acting at -1.178 radians, -0.393 radians, +0.393 radians, and +1.178 radians to the line of action. Hence, the force acting on an individual chamber is 2681.5/(2 cos 1.178 + 2 cos 0.393) = 1026.17 lb. The force F_p = F_c $1 \pm 2\cos(\pi/4)$ = 2477.4 lb. The value of R_t = 45, e = 0.0234375 in, and J_T = 0.75 lb-in-sec^2 for load, rotor and shaft inertia insignificant. Substitution of these values into Equation 75 gives ω_n = 396 rad/sec or 63.0 hz.

Ability to Slew at 250 Deg/Sec

If a constant output torque is delivered by the actuator, the equation of motion of the output shaft is

$$d\,\frac{d\theta_o}{dt} = \frac{T_o}{J_T}\,dt \tag{81}$$

Equation (81) may be integrated twice, assuming the initial values of θ_o and $d\theta_o/dt$ to be 0, to give

$$\frac{d\theta_o}{dt} = \frac{T_o}{J_T}\,t \tag{82}$$

$$\theta_o = \frac{T_o}{J_T}\,\frac{t^2}{2} \tag{83}$$

If we assume T_o is a constant 1000 in-lb (corresponding to θ_m = 0.42 rad or 24 deg) and t = 0.004 sec (corresponding to the length of the first pulse at a 250 pps rate) and, as before, J_T = .75 lb-in-sec^2, Equations (82) and (83) give:

$$\frac{d\theta_o}{dt} = 5.33 \text{ rad/sec or } 305 \text{ deg/sec}$$

$$\theta_o = 0.0107 \text{ rad or } 0.60 \text{ deg}$$

The significance of the above calculations is that they show that the actuator is capable of building up to the slew speed at a 250 pps rate during the first step. Since a fixed torque value is assumed while the actual torque is variable, these computations do not predict actual values of $d\theta_o/dt$ and θ_o, but only minimum values. The assurance that these are minimum values comes from the fact that the actual torque will always be greater or approximately equal to the assumed torque.

3.1.5 Load and Stress Analysis

Load and stress analyses were conducted on the components of the actuator, with the results summarized in Table 3. AMS-6488 high-standard steel (H-11 tool steel) is the material chosen for the critical fabrication components, because of its dimensional stability and high strength at temperatures up to 600°F. The significant properties are:

Temperature, °F	70	600
Tensile/compressive strength psi	260,000	220,000
Yield strength at .2% offset	205,000	178,000
Shear strength	155,000	138,000
Modulus of Elasticity, E	29×10^6	26×10^6

The mounting bolts were fabricated from a commercial material with the following composition:

Carbon	.50
Manganese	.07
Phosphorus	.004
Sulfur	.005
Silicon	.22
Chromium	4.62
Molybdenum	2.81
Vanadium	1.04
Tungsten	2.06

Sample lots of the mounting screws demonstrated ultimate tensile strength of 295,000 to 325,000 psi.

Comparison of the stress values in Table 3 with the physical properties of the materials indicates a safe margin of strength to stress in all cases.

TABLE 3 - ACTUATOR LOADS AND STRESSES

Component	Related Force	Loading	Stress, psi	Mode
Ring Gear				
Flange	Gear Separation Force	690 lbs	121,750	Bending
Vane Slot	Bending Force	2,053 lbs	21,950	Bending
Reaction Pin	Total Reaction Force	1,455 lbs	48,405	Shear
	Total Axial Force	13,039 lbs	160,579	Tension
Reaction Pin Spacer	Preload Force	1,630 lbs	71,370	Compression
Gear Teeth	Total Gear Tooth Load	2,017 lbs	89,550	Compression
			27,290	Shear
			112,990	Hertz Contact
Output Gear	Stall Torque	2,000 in-lbs	2,720	Shear
			26,575	Bending
Output Shaft	Panel Bending Load	12,000 in-lbs	5,210	Shear
	Front Bearing Normal Load	12,230 lbs		
	Rear Bearing Normal Load	4,000 lbs		

3.1.6 Flow Demand

The flow demand which must be provided by an external hydraulic power supply is influenced by the torque-speed requirements of the output shaft. For any given torque-speed relationship, the external flow demand can be determined. Since M2V hydraulic fluid is the design fluid, and MIL-H-5606 hydraulic fluid was used as the test fluid, examples of flow demand calculations are given for M2V at 100°F and 600°F bulk temperatures and MIL-H-5606 at 100°F.

The total actuator flow demand is given by:

$$Q_T = Q_{lv} + Q_{lR} + Q_v + Q_u \tag{84}$$

where Q_T = Total flow rate
Q_{lv} = Vane leakage rate
Q_{lR} = Rotor leakage rate
Q_v = Servo Valve tare flow rate
Q_u = Useful flow rate

Vane Leakage

The leakage path across both ends of the vanes is assumed to follow the orifice flow equation, as the leakage path is relatively short. Since four displacement chambers are operating at supply pressure and four at drain pressure during any given step, only two vanes have a pressure differential across them which will create leakage flow. For convenience in computation, it is assumed that the rotor and vanes are in contact with one end cap with all the available clearance appearing at the other end cap. The expression for this portion of the leakage is then:

$$Q_{lv} = \frac{2\, L_v\, h_v\, C_d}{3.85} \quad \frac{722\ \Delta P_s}{\gamma} \tag{85}$$

where Q_{lv} = Leakage across vane ends, GPM
L_v = Length of vane over which leakage occur, in.
h_v = Vane to end cap clearance, in.
C_d = Flow coefficient, dimensionless
ΔP_s = Pressure differential across vane, psid
γ = Specific weight of fluid, lb/in^3

with $L_v = 0.1$ inch, $C_d = 0.7$ and $P_s = 3000$ psid this reduces to:

$$Q_{lv} = 55.34\ \frac{h_v}{\sqrt{\gamma}} \tag{86}$$

Rotor Leakage

The rotor leakage is taken as laminar since the length of the flow path is much longer than the vane leakage path. The expression for this leakage is:

$$Q_{lR} = \frac{h_R^3 \; W \; \Delta P_R}{46.2 \; \mu L_R} \qquad (87)$$

where Q_{lR} = Leakage across rotor, GPM
h_R = Rotor to end cap clearance, in.
W = Leakage path width, in.
ΔP_R = Pressure differential across rotor face, psid
μ = Viscosity of fluid, lb-sec/in^2
L_R = Leakage path length, in.

The total leakage path width is equal to the mean circumference of the rotor. However, since only one-half of the displacement chambers are operating at supply pressure, the effective width is:

$$W = \frac{\pi}{4} (D_o + D_I) \qquad (88)$$

where D_o = Rotor outside diameter, in.
D_I = Rotor inside diameter, in.

and $W = \frac{\pi}{4} (3.250 + 2.375) = 4.418$

then $L_R = (3.250 - 2.375)/2 = 0.438.$

With P_R = 3000 psid, Equation (87) then reduces to:

$$Q_{lR} = 655 \frac{h_R^3}{\mu} \qquad (89)$$

Servo Valve Tare Flow

The servo valve tare flow for four valves was measured as 0.32 gpm, using MIL-H-5606 hydraulic fluid at 100°F temperature. Assuming orifice flow conditions:

$$Q_V = \frac{C_d A}{3.85} \sqrt{\frac{772 \; \Delta P_v}{\gamma}} \qquad (90)$$

where Q_V = Servo valve tare flow rate, gpm
C_d = Orifice flow coefficient, dimensionless
A = First stage orifice flow area, in^2
ΔP_v = Pressure differential across orifice, psid
γ = Fluid specific weight, lb/in^3

With an average pressure drop across the orifice of 1500 psid, $\gamma = .030$ for MIL-H-5606 fluid at 100°F, and $C_d = 0.7$, the total effective orifice area for the four valves is computed to be .00028 in^2. Using $= .028$ for M2V fluid at 600°F and $= .034$ for M2V fluid at 100°F, Equation (90) can be used to compute tare flow as:

$$Q_{VV} = \frac{.0548}{\sqrt{\gamma}}$$

which gives: $Q_V = 0.327$ for M2V fluid at 600°F.
$Q_V = 0.297$ for M2V fluid at 100°F

Useful Flow Rate

The useful flow is the flow of fluid through the motor displacement chambers which provides the required output torque and stepping rate. The pressure vector may be at any angle between 0 and 90 degrees, depending on the load torque. The zero degree angle represent a no-load (slew) condition and the 90 degree angle represents a maximum rate, zero rate (stall) condition.

Slew Conditions

Under slew conditions, where the load torque is assumed to be zero, the pressure vector is coincident with the axis of eccentricity. When the actuator is rotated continuously under these conditions, it can be demonstrated that half of the high pressure chambers are acting as pumps and half as motors. The same is true of the low pressure chambers. Hence, it would be theoretically possible to slew a frictionless, non-leaking actuator without needing any externally supplied flow.

In the case where the actuator is stepping (coming to rest between steps) and with the output loaded inertially only, the pressure vector will coincide with the eccentricity axis at the end of every step. Figure 12 shows that on the high pressure side, the displacement flow entering the Number 3 chamber is balanced by the flow being pumped out of the Number 5 chamber. The displacement volume of the Number 4 chamber is unchanged during the step. Hence, the only displacement flow on the high pressure side which needs to be supplied externally is that for Chamber 2.

This displacement flow for a single step is given by:

$$\Delta V_2 = \frac{d_m}{16}\left[\text{Sin}\,(-0.393 + 0.785) - \text{Sin}\,0.393\right] = \frac{0.765\,d_m}{16} \tag{91}$$

where ΔV_2 = Change in displacement volume, in^3
d_m = Motor displacement = .189 in^3/orbit

$$\Delta V_2 = .009 \text{ in}^3\text{/step}$$

The slew rate flow is given by

$$Q_u = \alpha V_2/3.85 \tag{92}$$

where Q_u = slew rate flow, gpm
α = output slew rate, steps/second

At the 250 deg/sec slew rate:

$$Q_u = \frac{250 \times .009}{3.85} = 0.58 \text{ gpm}$$

<u>Rated Load Conditions</u>

At the rated torque of 1333 in-lbs, the pressure vector will be at an angle of 28.12 degrees to the axis of eccentricity. When the actuator is stepped, the rotor force vector will traverse a 45 degree angle from 73.12 to 28.12 degrees. Referring to Figure 12, Chambers 2, 3, 4 and 5 will now be the high pressure chambers instead of Chambers 3, 4, 5 and 6. The original position of the axis of eccentricity is along line OA and the final position along line OB. The displacement volumes for these chambers are given by:

$$v_1 = \frac{d_m}{16}\left[1 + \sin(-0.883 + \theta_m)\right]$$

$$v_2 = \frac{d_m}{16}\left[1 + \sin(-0.098 + \theta_m)\right]$$

$$v_3 = \frac{d_m}{16}\left[1 + \sin(0.688 + \theta_m)\right]$$

$$v_4 = \frac{d_m}{16}\left[1 + \sin(1.473 + \theta_m)\right]$$

For a 0.785 radian (45 degree) step:

$$v_1 = \frac{d_m}{16}\left[\sin(-0.883 + 0.785) - \sin(-0.883)\right]$$

$$v_2 = \frac{d_m}{16}\left[\sin(-0.098 + 0.785) - \sin(0.098)\right]$$

$$v_3 = \frac{d_m}{16}\left[\sin(0.688 + 0.785) - \sin(0.688)\right]$$

$$v_4 = \frac{d_m}{16}\left[\sin(1.473 - 0.785) - \sin(1.473)\right]$$

from which

$$\Delta v_1 = 0.675 \frac{d_m}{16}$$

$$\Delta v_2 = 0.732 \frac{d_m}{16}$$

$$\Delta v_3 = 0.360 \frac{d_m}{16}$$

$$\Delta v_4 = 0.222 \frac{d_m}{16}$$

Total $\Delta v = 1.545 \frac{d_m}{16}$

Then from Equation (92) in the form

$$Q_u = \frac{\alpha \ \Delta v}{3.85} = \frac{140 \times 1.545 \times .188}{3.85 \times 16} = 0.66 \text{ gpm}$$

This compares to a useful flow rate of 0.58 gpm when the actuator is slewing at 250 steps per second. This demonstrates that the actual maximum external flow which must be supplied will depend on the shape of the required torque-speed curve, which has not been defined in detail in the specifications for this actuator.

Total Flow Rate

The total flow rate can be determined by

$$Q_T = Q_{LV} + Q_{LR} + Q_V + Q_u$$

$$Q_T = \frac{55.34 \text{ hv}}{\sqrt{\gamma}} + \frac{655 \text{ hr}^3}{\sqrt{\mu}} + \frac{.0548}{\sqrt{\gamma}} + Q_u \qquad (93)$$

The clearances h_V and h_R are considered to be equal. Values for and are:

Fluid	T, °F	γ, lb/in^3	μ, lb-sec/in^2
MIL-H-5606	100	.030	1.69×10^{-6}
M2V	100	.034	2.32×10^{-6}
M2V	600	.028	9.56×10^{-8}

The total flow for slew conditions are tabulated on Table 4 and plotted on Figure 14. The rotor clearance is of special importance when operating at higher temperature.

TABLE 4 - SLEW FLOW RATE

h	Q_{lv}	Q_{lR}	Q_v	Q_s	Q_T, GPM
			MIL-H-5606, 100°F		
.0001	.032	.0004	.3164	.58	.929
.0002	.064	.0031	.3164	.58	.954
.0005	.160	.0484	.3164	.58	1.095
.0010	.320	.3876	.3164	.58	1.594
.0015	.479	1.3081	.3164	.58	2.674
.0020	.639	3.1006	.3164	.58	4.626
			M2V, 100°F		
.0001	.0300	.0003	.2971	.58	.908
.0002	.0600	.0023	.2971	.58	.940
.0005	.1500	.0353	.2971	.58	1.063
.0010	.3001	.2823	.2971	.58	1.460
.0015	.4502	.9529	.2971	.58	2.280
.0020	.6002	2.2586	.2971	.58	3.736
			M2V, 600°F		
.0001	.0331	.0069	.3274	.58	.948
.0002	.0661	.0548	.3274	.58	1.028
.0005	.1654	.8564	.3274	.58	1.929
.0010	.3307	6.8514	.3274	.58	8.090
.0015	.4961	23.124	.3274	.58	24.53
.0020	.6614	54.81	.3274	.58	56.38

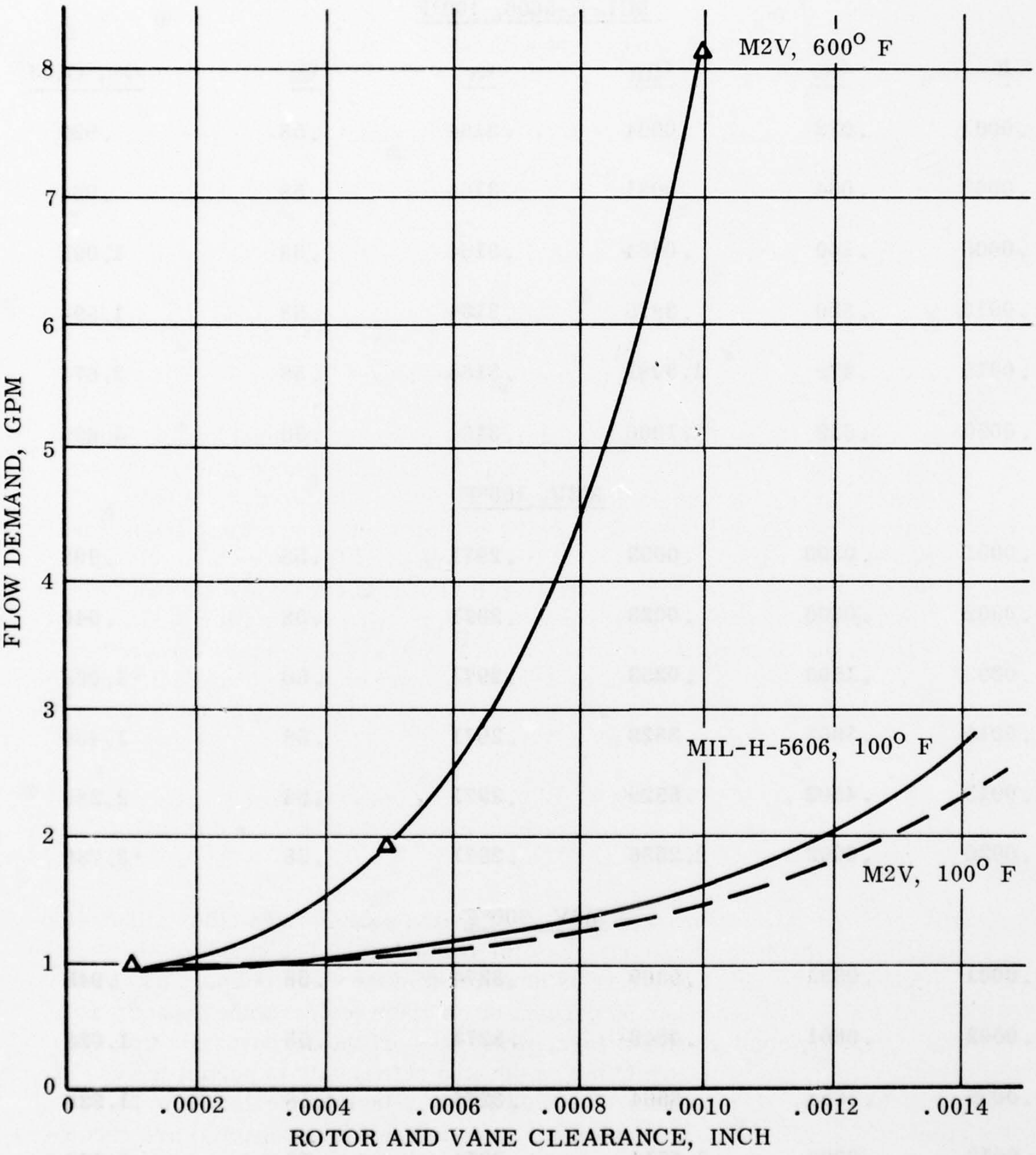


FIGURE 14 - FLOW DEMAND SLEW CONDITIONS

3.1.7 Environmental Effects on Design

The environmental parameter having the greatest impact on the design of the electrohydraulic stepper actuator is temperature. The prototype system was designed for use in a 550°F environment with 600°F fluid, and was to be tested at 450°F.

The fluid temperature range of -65 to 600°F made special attention necessary in the following areas:

- selection of metals,
- differential thermal expansion,
- bearings,
- seals,
- electrical insulation, and
- changes in electrical and magnetic properties.

The first two items required simultaneous consideration. To avoid changes in operating clearances or the binding of moving parts as the temperature changes, all parts were made from the same material or else made from materials having compatible thermal expansion coefficients. Strength and wear requirements dictate that certain Dynavector actuator components must possess high strength and hardness. Since problems with differential thermal expansion are most easily avoided by using the same alloy throughout, the selection of the alloy for the most severely stressed parts defined the material for most other parts. The need to fabricate the manifold plates in two pieces which must be bonded together imposed certain restrictions on materials selection. The gears and housing were fabricated from AMS-6488 (modified H-11 tool steel).

The manifold plates were AMS-6488, gold brazed. Reaction spacers were made from M2 tool steel. Vanes were also made from M-2 tool steel and thrust washers from 440C stainless steel.

Selection of materials for bearings was a separate problem from other alloy selections because of the specialized nature of the technology. The standard bearing steel is SAE 52100. This alloy retains 85 percent of its room temperature load capacity at 450°F, but less than 50 percent of its room temperature capacity at 600°F. The main output shaft bearings, which support the aerodynamic fin, are heavily loaded and therefore could not be derated sufficiently to permit the use of SAE 52100 bearings at temperatures of 600°F. Bearings fabricated from M-50 tool steel (which retains 95 percent of its room temperature capacity) are recommended for this type of application. However, such bearings must be purchased on special order, and for the program would have required 6 to 8 months for delivery at an excessively high cost. Such costs were not justified for an advanced development item which will not be tested to temperatures of +600°F. Therefore, SAE 52100 bearings are used. These bearings should withstand the applied loads at the +450°F test temperature. The technical risk in this approach was considered to be very low, and the M-50 bearings can be substituted at any time when the additional cost can be justified.

3.2 SWITCHING VALVE DESIGN

Four switching valves are used to control the pressure of the eight motor chambers. Each valve controls two diametrically opposed chambers. One chamber will be at the supply pressure (3000 psi rated) and the other chamber at return pressure. When a valve is switched the porting is reversed.

A modified Moog Type 30 servo valve was selected for this application. The Type 30 is a small (approximately 1.5 inch cube) two stage, four way flow control valve that is used extensively in the aerospace applications. The feedback wire that normally connects the flapper to the second stage spool was removed, see Figure 14, because proportionality is not required. The valves, modified with a high temperature coil, are rated at -65°F to +300°F with a 15 minute capability to 600°F.

The valves were supplied with three sets of spool end plates so that the effect of valve capacity could be evaluated. The end plates limit the spool travel and therefore the maximum flow rate. With the 100 percent stops the maximum flow rate is 8 cubic inches per second. The other stops limit the flow rate to 75 percent (6 in^3/second) 50 percent (4 in^3/second) of maximum.

Other approaches of controlling the Dynavector Actuator were initially considered. One approach was a single rotary valve with eight output ports, each connected to a Dynavector motor chamber. The rotary valve would be driven by an electrical stepper motor or an electrical stepper Dynavector motor. The Moog switching valve approach was selected because it involves less risk (a proven design) and could be packaged better. Results of a quantitative comparison of the two basic approaches is documented in Appendix A.

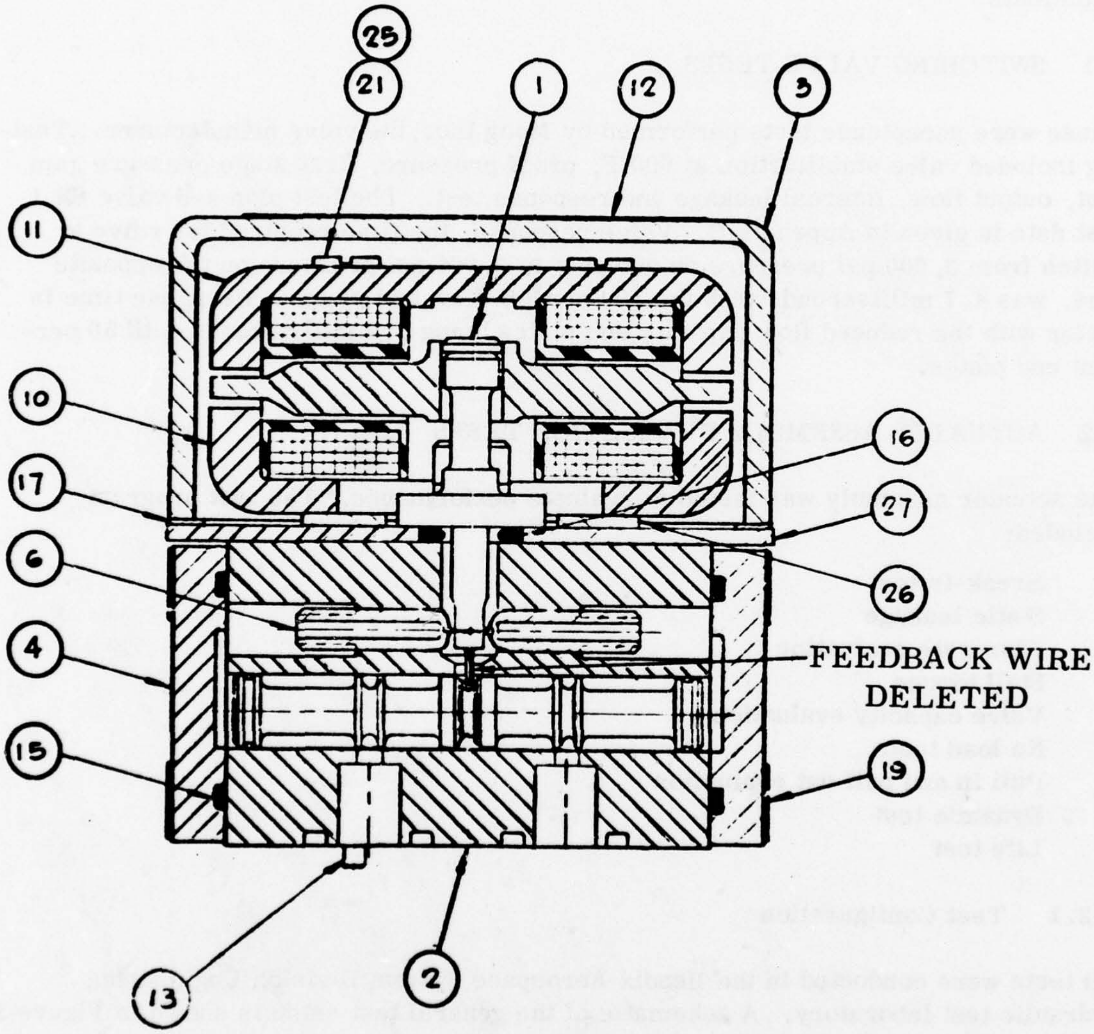


FIGURE 15 - SWITCHING VALVE CROSS SECTION

SECTION IV

ACTUATOR TESTING

Actuator testing consisted of switching valve tests and actuator assembly evaluation tests.

4.1 SWITCHING VALVE TESTS

These were acceptance tests performed by Moog Inc., the valve manufacturer. Testing included valve stabilization at 600°F, proof pressure, first stage pressure gain plot, output flow, internal leakage and response test. The test plan and valve SN 1 test data is given in Appendix B. Valve response, the time required for valve to switch from 3,000 psi pressure on one port to 2,000 psi pressure on the opposite port, was 4.7 milliseconds with the 100 percent flow end plates. Response time is faster with the reduced flow capacity end plates being 3.8 milliseconds with 50 percent end plates.

4.2 ACTUATOR ASSEMBLY EVALUATION TESTS

The actuator assembly was tested to evaluate performance. The test program included:

- Break-in test
- Static leakage
- Flow rate evaluation
- Stall torque
- Valve capacity evaluation
- No load tests
- Pull in and pull out evaluation
- Dynamic test
- Life test

4.2.1 Test Configuration

All tests were conducted in the Bendix Aerospace System Division Engineering hydraulic test laboratory. A schematic of the general test setup is shown in Figure 16.

Two pieces of equipment were designed specifically for use in the test program; a Dynavector Control Chassis, TED-E-8634, and the Dynavector Test Adapter, 1564345.

The Dynavector Control Chassis, Figure 17, provides the electrical pulses to control the stepper actuator. It has two modes of operation: Automatic and manual. In the manual mode the stepper actuator can be commanded to advance one step at a time by pressing a STEP button. Direction of rotation is controlled with a rotation switch. In the automatic mode the actuator can be commanded to run continuously or it can be commanded to cycle between selected output shaft positions. For this mode an external function generator provides the clock pulse rate. A digital readout on the control panel provides commanded position information. Operational instructions are given in Appendix C.

The Dynavector Test Adapter, 1564345, Figure 18, was designed to transmit torque and inertia loads to the actuator. The torque is developed with a torsion spring rated at 2000 inch pounds at 30 degrees deflection. A static calibration of the spring is given in Figure 19. The adapter is equipped with visual and electrical position indicators (see Figure 20). The adapter utilizes a Lebow Model 1204-200 torque sensor between the actuator and load. Inertia plates can be installed on the adapter to evaluate the effects of inertia. Inertia of the basic fixture is .11 inch pounds second^2. Two inertia plates, each having .32 inch pounds second^2 inertia, can be added. Inertia of the adapter with both plates installed is .75 inch pounds second^2. Figure 21 shows the 1564345 adapter with the actuator installed. The visual indicator reads 155.5 degrees at the neutral load (wing zero) position.

Configuration codes are identified in Appendix D.

4.2.2 Instrumentation

Data were taken by three means: visual, oscilloscope pictures, and oscillograph recordings. A list of the functions instrumented is given in Table 5. Instrumentation codes that identify the data taken during specific tests are given in Appendix E.

The oscillograph was calibrated periodically throughout the program. A calibration was usually made before each series of runs from which a final, static actuator position could be determined as a function of commanded input. This was very useful in analyzing the dynamic performance.

4.2.3 Run Summary

A run summary is given in Appendix F. The first 77 runs are invalid because of a problem with the Dynavector Control Chassis. There was an .008 second lag in switching valve current off. The control circuits were modified prior to Run 78 and the chassis provided virtually instantaneous switching currents thereafter.

The tests are covered in a chronological order in the following paragraphs.

TABLE 5 - INSTRUMENTATION

VISUAL INSTRUMENTATION

Supply pressure
Return pressure
Case pressure
Hydraulic flow
Hydraulic supply temperature
Shaft position, mechanical
Shaft position, electrical
Load torque, electrical
Input signal frequency
Input signal direction
Commanded position

OSCILLOSCOPE

Input Command
Shaft Position

OSCILLOGRAPH INSTRUMENTATION

Supply pressure
Return pressure
Case pressure
Chamber 1 pressure
Chamber 2 pressure
Chamber 5 pressure
Chamber 6 pressure
Hydraulic flow (Flowmeter frequency)
Torque
Shaft position
Valve 1 current
Valve 2 current
Valve 3 current
Valve 4 current
Input command

4.2.4 Actuator Break-in Tests

General - The actuator was broken in over a broad range of no load conditions. With 500 psi supply pressure and zero return pressure the actuator was run for approximately one minute at each of the following rates: 0, 1, 10, 25, 50, and 100 pps. The rate was then gradually increased until the maximum rate at which the actuator could follow was reached. The process was repeated for supply pressures of 1,000 psi and 1,500 psi for both clockwise and counterclockwise rotation. Stall torques were then measured for 500 psi, 1,000 and 1,500 psi and the actuator then run with light loads (±500 inch pounds) for 30 minutes over the entire speed range.

The actuator was then disassembled and inspected. The assembly was doweled together and run at successively higher pressures and loads until design operating conditions were reached. The actuator performed well at the design conditions although the flow rate was higher than predicted. Approximately five hours of running time were accumulated during the break-in tests. Details are given below.

Break-out Pressure - No load break-out pressure at 1 pps was initially 18 psi for both clockwise and counterclockwise inputs. Break-out pressure increased to 26 psi when measured midway through the testing just after the dowels were installed.

No Load Break-In - No load flow rate vs input rate is given on Figure 22. The rated no load speed of 250 pps was achieved for pressures above 1500 psi. The ability of the actuator to start and stop without losing steps was checked by switching the driver on momentarily with the Automatic Mode Switch and comparing the input counts registered on the driver display with the change in degrees of the test adapter position indicator. The actuator can start and stop at 250 pps without losing steps for supply pressures above 1500 psi. The no load flow at 250 degrees/second was 2.0 gpm. A flow rate of 1.0 gpm had been predicted. Part of the difference is due to a higher leakage rate than estimated. The rest is apparently due to a larger effective motor displacement than that assumed. Effective displacement is a function of pressure vector angle.

Loaded Break-In - The actuator was cycled ± 8 degrees (± 650 inch pounds) against the 1564345 load adapter with 1500 psi supply pressure. After the dowels were installed the actuator was cycled ±20 degrees (± 1650 inch-pounds) with 3000 psi supply pressure. Rated wing rate of 140 pps was achieved. Flow rate vs input rate is given on Figure 23. Flow rate is essentially the same as the no load flow rate.

The actuator was manually stepped against the spring load until it stalled. Position vs step number data is given on Figure 24 for 3000 psi.

Stall Torque - Stall torque was measured directly by stepping the actuator against a restrained 300 foot pound torque wrench. These data are presented in Figure 25. Stall torque with 3000 psi supply pressure was 2500 inch pounds. The minimum requirement is 2000 inch pounds. Test results were substantiated during the pull in and pull out tests, Reference Runs 234 and 247.

Stall torque efficiency may be calculated from:

$$\eta_t = \frac{T}{b\ D_v\ \Delta P\ e\ R_t\ \sin \phi_P}$$

where b,	motor length	=	.439 inch
T,	output torque	=	2500 inch pounds
D_v,	vane seal diameter	=	2.9375 inch
ΔP,	pressure difference	=	3000 psi
e,	eccentricity	=	.0234 inch
R_t,	gear ratio	=	45
ϕ_P,	angle of pressure vector with axis of eccentricity	=	90 degrees

$$\eta_t = \frac{2500}{.439 \times 2.9375 \times 3000 \times .0234 \times 45 \sin 90} = 61.3 \text{ percent}$$

Static Leakage - Static actuator leakage data were taken as a function of supply pressure and step number. Results are given on Figure 26. A reduction in spacer length of .0005 inches should virtually eliminate all ambient temperature oil leakage past the rotor.

Valve Capacity Evaluation, Runs 80-189 - Servo switching valve capacity was evaluated during Runs 80-189. Valves fitted with end caps that provide 50 percent flow capacity were the fastest and provided best performance. The evaluation was made by cycling the actuator against the load adapter. Figures 27 and 28 show the oscillograph data recorded during Runs 165 and 174.

Beginning with 190, all testing was made with the optimum valve configuration (50 percent end stops).

No Load Tests, Runs 191-198 - The spring fixture and inertial plates were removed for this test and the actuator run continuously in the clockwise direction. The test configuration is shown on Figure 29. The input command was slowly increased and data recorded at 250, 300, 400, 500, 600, 650, and 670 pps. Run 198, 670 pps oscillograph data, are shown on Figure 30. The actuator was still in sync and did not lose any steps. Higher input frequencies were not tried.

No Load Dynamic Tests, Runs 215-230 - The actuator was cycled ± 4 degrees and ± 8 degrees with no torque or inertia loads at pulse rates up to 750 pulses/second. Data are given in Appendix F run summary. For the ± 8 degrees cycles, the actuator followed command at 500 pps but lost sync at 600 pps. For the ± 4 degree cycles, the actuator was in sync at 700 pps.

Pull Out Tests, Runs 232-258 - Pull out characteristics were determined in Runs 232-258. Pull out rate is the maximum rate which the actuator can follow without losing steps. The procedure followed to obtain this information was as follows.

Position actuator 30 degrees from wing zero
Apply input command to drive actuator toward wing zero
Record data to show where actuator stalls

Tests were run for both clockwise and counterclockwise rotation.

Oscillograph data are presented in Figures 31-35. Reduced data are plotted on Figure 36. The actuator can follow with no external torque loads at 600 pps. This is considerably above the 250 pps requirement. The basic capability is increased with aiding loads and decreased with opposing loads. The maximum rate with aiding load was 800 pps. Pull out at rated (1330 inch pound) opposing load was 390 pps.

Pull In Tests, Runs 261-271 - An attempt was made to determine pull in characteristics during Runs 261-271. Pull in rate is the maximum rate which the actuator can start, stop, or reverse directions against combined torque and inertia loads. The actuator was positioned at 20 degrees from the neutral position where torque load was 1440 inch pounds. Commands were given to drive the actuator against increasing loads. Oscillograph data are given in Figures 37-40 for frequencies of 250, 300, 350, and 400 pps. There is no doubt that the actuator pulls in against the 1440 inch pound for frequencies up to 300 pps. At frequencies above 300 pps, this capability is less clear. The actuator starts to move but quickly stalls out when the pull out torque is reached. It was concluded that pull in performance could best be measured during dynamic cycling tests. Results from these tests are summarized on Figure 36. Pull in performance was considerably better than that required being 480 pps at zero load and 300 pps at rated load.

Dynamic Tests, Runs 274-404 - Dynamic response tests were conducted with the actuator driving the spring and inertia loads. The test consisted of cycling the actuator at wing rates, up to the limit which the actuator follows without losing step. Amplitude excursions of 1 degree, ±1°, ±2°, ±4°, ±8°, and ±20° were examined. Runs were made with initial positions of 0, 10, 20, and 30 degrees. Data were recorded on the oscillograph. The position trace was calibrated at a slow frequency prior to each series of runs. Figure 41, the calibration data taken during Run 171, is a typical calibration run.

Individual run results are given in the run summary, Appendix F. Examples of the oscillograph data are given on Figures 42-62. It was readily apparent from the oscillograph records when the actuator lost step. Figures 44, 46, 51, and 55 are good examples. As an added check, after the actuator was stopped, the final position was compared to the commanded position. This was done two ways. First, the position shown on the Dynavector Control Chassis panel was compared to the position of the Dynavector test adapter position indicator. Secondly, final actuator position and valve combination from the oscillograph recording was compared to the data obtained in the calibration run. Figure 50 shows an entire run. The run ended with Valves 1 and 2 off and Valves 3 and 4 on. The recorded position for this valve combination was the same as it was in Calibration Run 370.

The following observations were made:

1. The time lag (the time required for the actuator to reach its commanded position) was 6-7 milliseconds when operating within the pull in boundaries of Figure 36.

2. The spring mass system the actuator was driving sometimes produced different torque levels than was anticipated from the slow speed calibration runs.

3. The actuator worked satisfactorily at frequencies and loads much more severe than those required.

Figure 58 demonstrates how the time lag was determined. Commanded positions are superimposed on the record. Average time lag was .007 seconds.

The actuator design was based on the requirements developed by Martin-Orlando for a proportional (analog) fin control system in the multipurpose missile. The closed loop servo requirements for the analog fin control system were 30 Hz minimum at 90 degree phase lag. The specified damping ratio was 0.5 minimum. These requirements were not translated to define the requirements of the open loop Dynavector digital servo system. The method of specifying dynamic reponse for an open loop digital stepper device, and the dynamic response characteristics of the 1564330-1 actuator were to be defined during this program. A way of defining phase lag is illustrated by Figure 63. The phase lag is then:

$$\Delta\theta = \delta f \, 360$$

where:

$\Delta\theta$ = phase lag, degrees

δ = time lag, seconds

f = cyclic frequency Hz

The phase lag for 30 Hz with a .007 time lag is $.007 \times 30 \times 360 = 75.6$ degrees. The step rate for a 30 Hz frequency is 60 pps for one degree amplitude and 120 pps for ± 1 degree amplitude. Figures 42 and 48 show data taken at rated torque and 30 Hz. Figure 53 shows ± 1 degree data with no torque load (cycled about the neutral wing position).

First Life Test - Runs 405-459 - The lift test consisted of cycling the actuator ± 20 degrees about wing zero at the rated (140 degree/second) wing rate. Maximum load was ± 1350 inch pounds. Oscillograph records were taken periodically. The magnetic plug installed in the return line was inspected after runs for metal particles. Early in the test, Run 408, the actuator lost steps and started to cycle about the -10 degree position. Cause of the shift is not known. The actuator was repositioned and the test resumed. The stairstep like position trace on Run 414 was not as consistent as those taken at start of test. This was the result of the inertia plates keys wearing in the keyways. Performance changed abruptly during Run 453. Total motion was only ± 10 degrees. The life test was stopped and the actuator manually stepped ± 30 degrees. The life test was resumed. Performance was normal for a few seconds, but then deteriorated. The test was stopped and the plug inspected. It was covered with many particles. The life test was stopped. Atotal of 23.7 hours and 11,962,000 steps had been accumulated during the life test. Totals including break-in and performance testing were 44.2 hours and 18,027,000 steps.

The actuator was disassembled and inspected. Two of the reaction pin spacers, Numbers 3 and 4, were missing. Another, Number 8, was crushed to powder, most of which was still in the annular space between the bolt and the hole in the rotor. A fourth, Number 2, reaction pin spacer was fractured into three pieces.

The vanes were still in excellent condition. Gears looked normal except for metal from spacers imbedded in them. The rotor was badly scored in spacer holes and adjacent area. The face of the front and rear covers were scored near the spacers. Bearings and seals appeared normal. Documented condition of parts with Bendix photographs 8804-13 and 8804-16 through 25.

It was concluded that the fatigue failure was due to decarburization of the reaction pin spacers. The spacers apparently had not been machined after heat treatment to remove a decarburized surface condition formed during heat treatment.

Rework, Assembly, Break In and Inspection - New spacers were fabricated in strict accordance with JS 2102. The heat treat people were asked to take special precautions to prevent decarburization. Processing was as follows.

1. Rough machine
2. Heat treat
3. O. D. ground
4. I. D. honed
5. Ends ground and lapped

Final surface finish was 16 MU or less all over. Final length was .4416 inches. Ends were perpendicular to the bore within .0002 inches.

The mating surfaces of the front and rear covers were ground .001 inch to remove high spots. The bores that provide clearance with the rotor were also cleaned up. The actuator was reassembled using new seals, bearings, screws, rotor and shaft. The original vanes and servo valves were used.

Break in tests were run. The performance was essentially the same as the original actuator. Break out pressure was slightly higher, being 100 psi versus 26 psi on first actuator. Static leakage was .1 gpm higher. About five hours and 600,000 steps were accumulated during the break in tests.

The actuator was disassembled and inspected. The general appearance was excellent. The spacers still had a polished appearance. There was some evidence of rubbing between the rotor outside diameter and the housing inside diameter. It was decided to remove an additional .010 off both surfaces. After machining the rotor measured 3.2302 inches. The housing inside diameter was 3.1401 inches. Photographs 8804-26 through 34 document the appearance of the actuator hardware prior to the life test.

<u>Back Driving Torque Test Run 461</u> - Actuator position was measured for increasing loads imposed with a 300 foot pound torque wrench. The test configuration is illustrated by Figure 64. The test was performed on the rebuilt actuator prior to life test. Rated torque (1333 inch pound) deflects the actuator 0.35 degrees. Results are plotted on Figure 65.

<u>Second Life Test, Run 462</u> - The second life test procedure was similar to the first. The actuator was cycled ± 20 degrees at 140 degrees/second. Stepping pattern was observed on the oscilloscope. Oscillograph data was not taken. Visual data was taken every ten minutes. The magnetic plug was inspected hourly. Oil samples were taken every ten hours.

The life test was stopped after 34 hours when a large ($\approx$ .06 x .09 x .0025 inch) chip was found in the case return line. The actuator was disassembled after the chip material was identified as M2 tool steel. No deterioration in performance had been detected. Total time on the actuator was as follows:

Break In		5.2 hours	625,000 steps
Life Test		34.0 hours	17,136,000 steps
	Total	39.2 hours	17,761,000 steps

The Number 4 spacer was fractured into several pieces. See Figure 66 photograph. A small longitudinal crack was observed under magnification on Number 3 spacer. The rotor had a large burr on the Number 4 spacer hold (Figure 67). The rest of the actuator appears to be in good condition. It is suspected that the Number 4 spacer started to fail much earlier. A similar chip was found in the case drain line after the 20th hour of the life test.

Failure Analysis - The reaction pin spacers were thoroughly examined and results published in Bendix Research Laboratories Technical Memorandum 77-8514.

The most probable cause for spacer failure was attributed to abusive grinding (or honing) of bore during the final machining operation. This was evident from the severe scoring and heat discoloration of bore and the presence of a "dark etching" layer, about 0.0015" deep, along the inner diameter--on all the spacers examined including the one which was never used. The dark etching zone was found to consist of a thin white layer (untempered martensite), depleted of carbides, which was followed by a layer of overtempered martensite. This zone was somewhat harder, 64-65 Rc, compared to the bulk, 60-62 Rc. Numerous microcracks and nicks were found along the inner edge. Cracking initiated at several points along the inner edge, progressed by fatigue to a critical size and then fragmented by brittle fracture. Spalling of the surface, along the crack path, followed fracture.

It was recommended that final machining (honing) be done non-abusively and the edges of the spacer chamfered, if possible. Also, it was suggested that consideration be given to replacing the M2 tool steel with an alternate material that would be more tolerant to defects (tougher) and also satisfy the design requirements.

New Spacer Material - The reaction pin spacer material has been changed from M2 tool steel to Vasco Wear Tool steel. Vasco Wear tool steel has nearly equivalent compressive strength and wear characteristics and is appreciably tougher. The spacer corners specified on the drawing has been changed from .002 R maximum to .002 to .005 R.

Reassembly - The actuator has been rebuilt with Vasco Wear tool steel reaction pin spacers. The assembly has been checked out and will be delivered to the Air Force Aero Propulsion Laboratory, Air Force Systems Command, Wright Patterson AFB, Ohio.

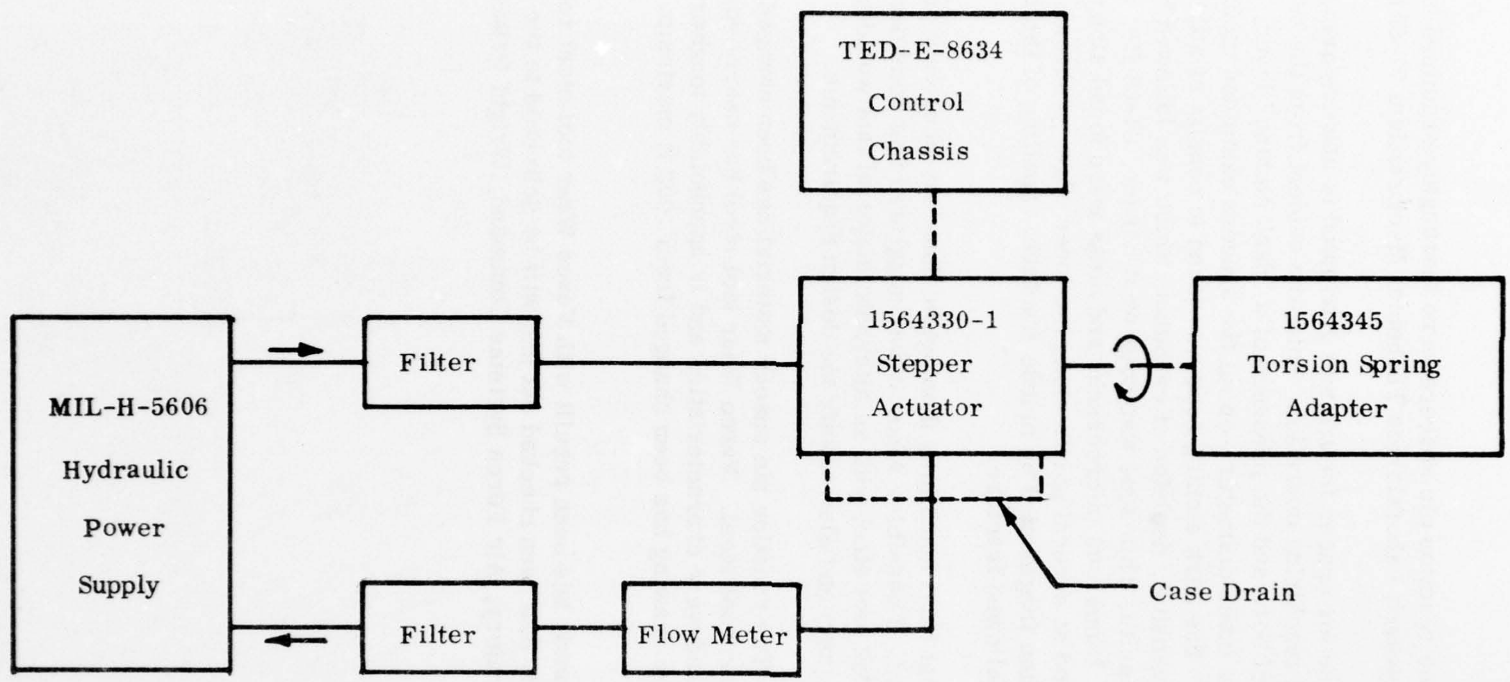


FIGURE 16 - GENERAL TEST SETUP BLOCK DIAGRAM

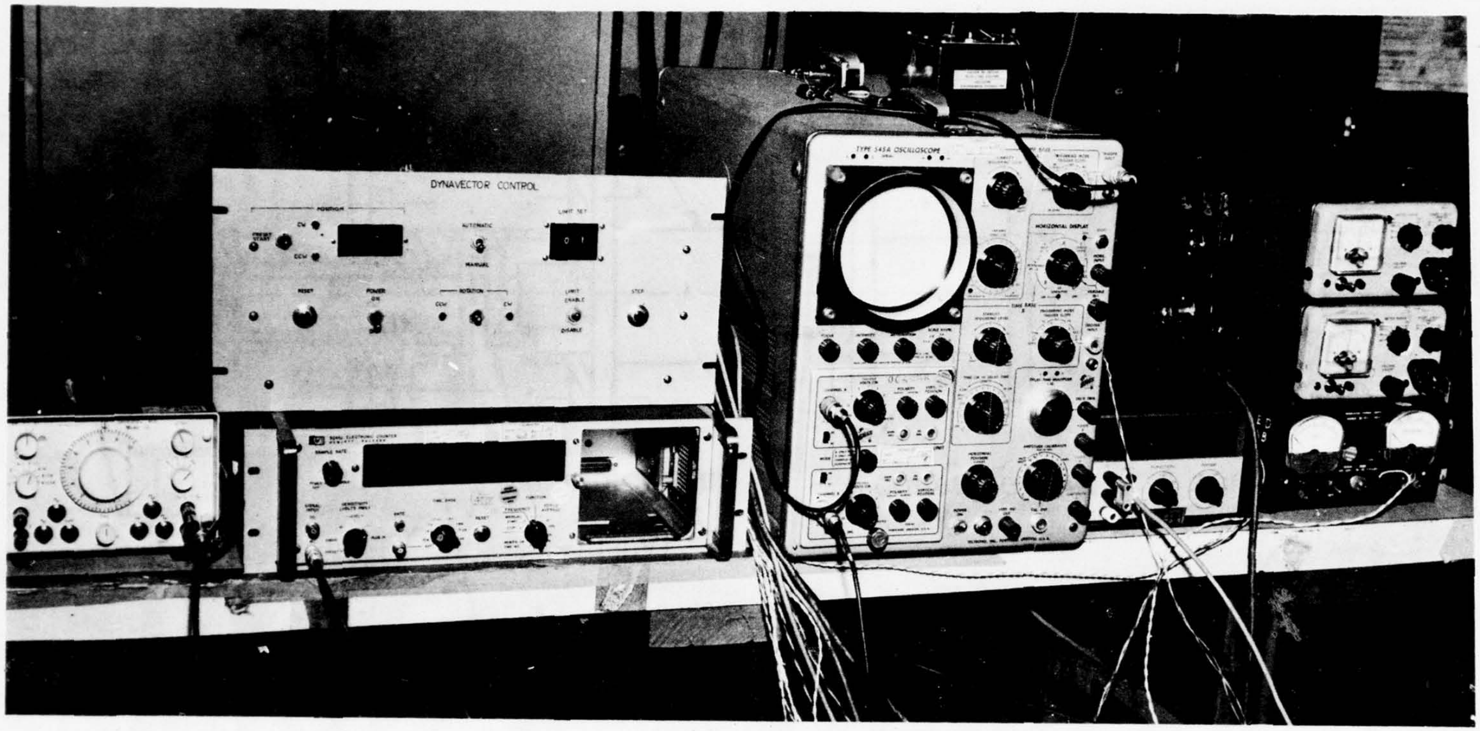


FIGURE 17 - DYNAVECTOR CONTROL CHASSIS AND SUPPORT EQUIPMENT

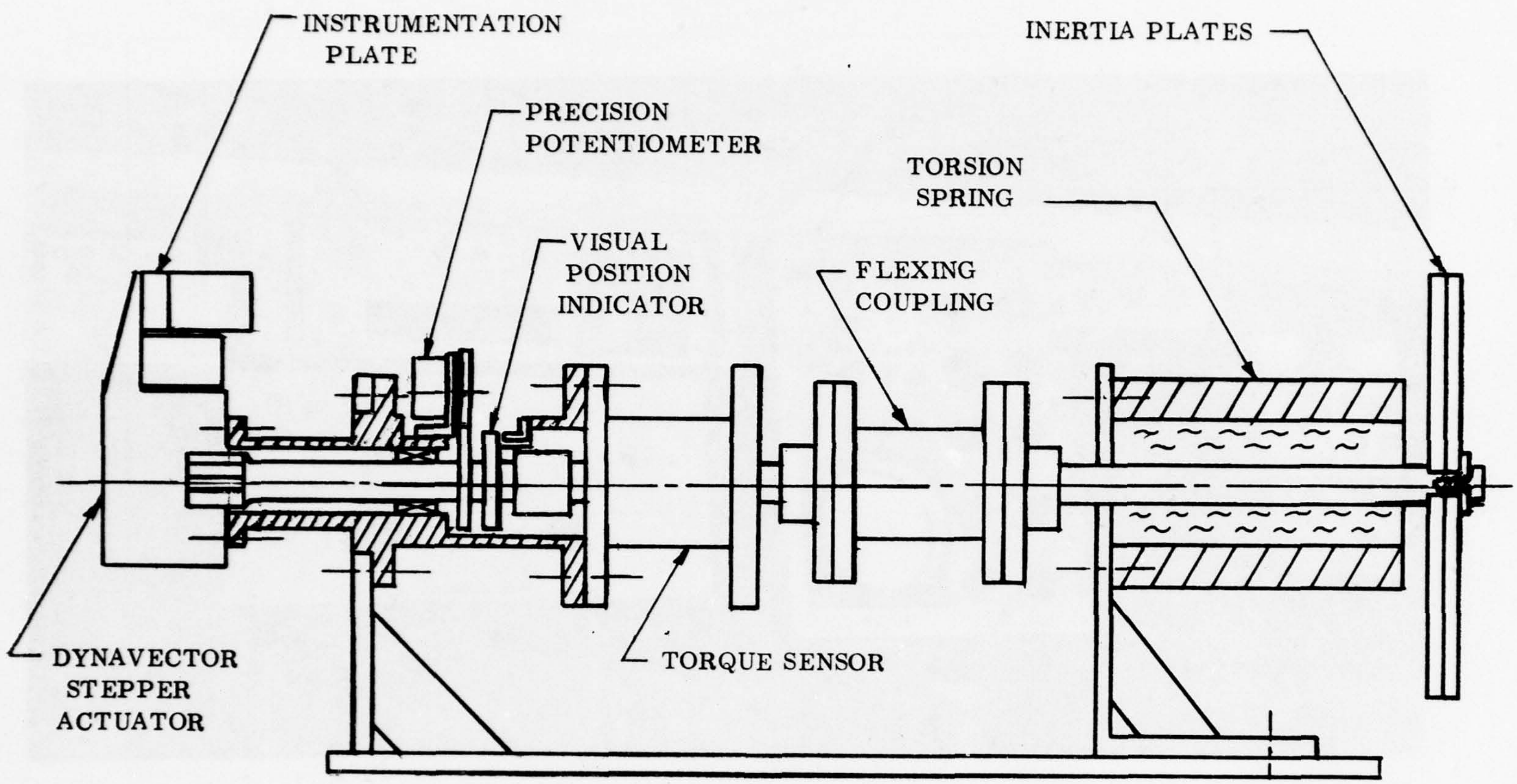


FIGURE 18 - TEST CONFIGURATION

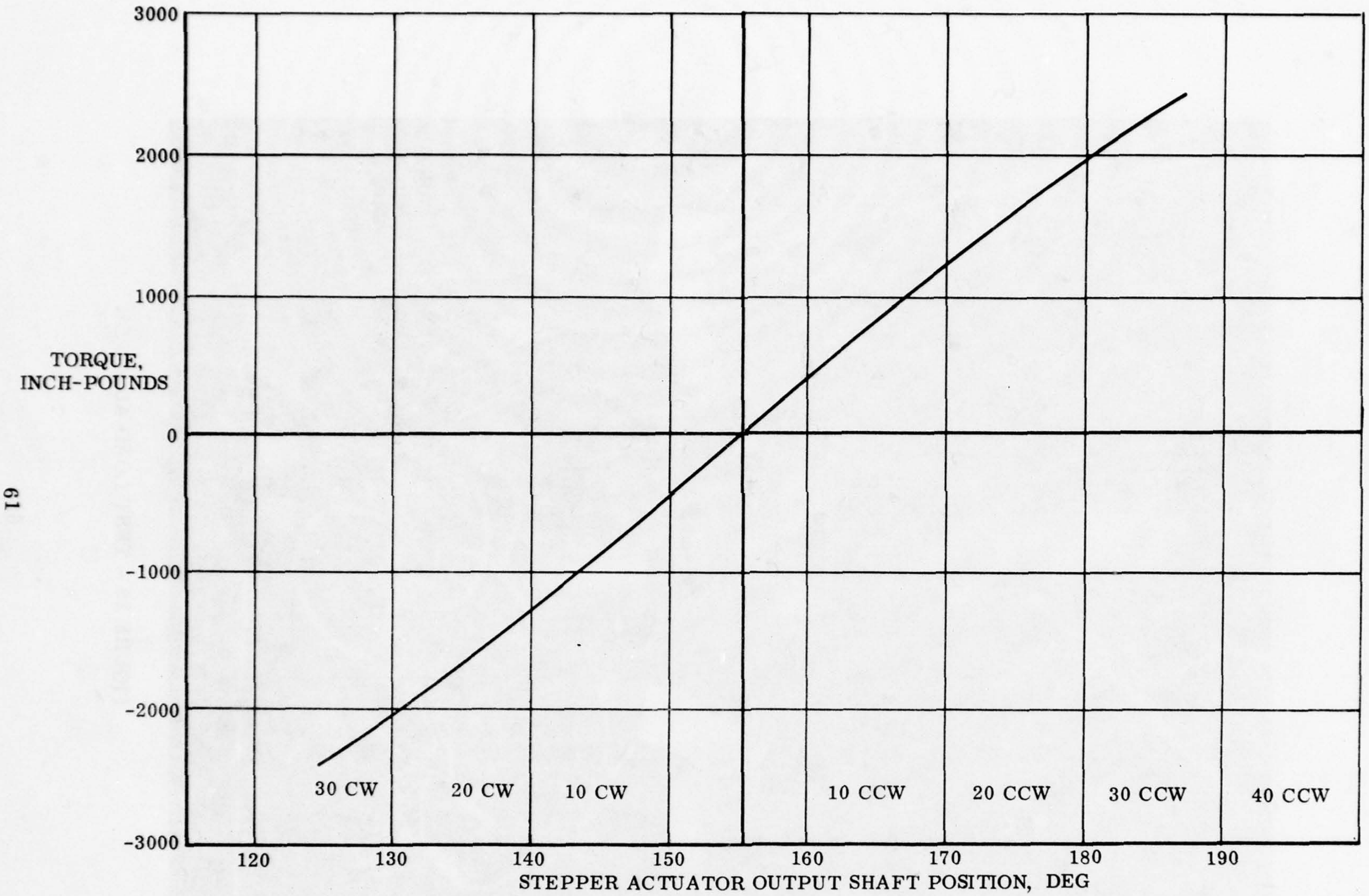


FIGURE 19 - DYNAVECTOR TEST ADAPTER 1564345 STATIC CALIBRATION

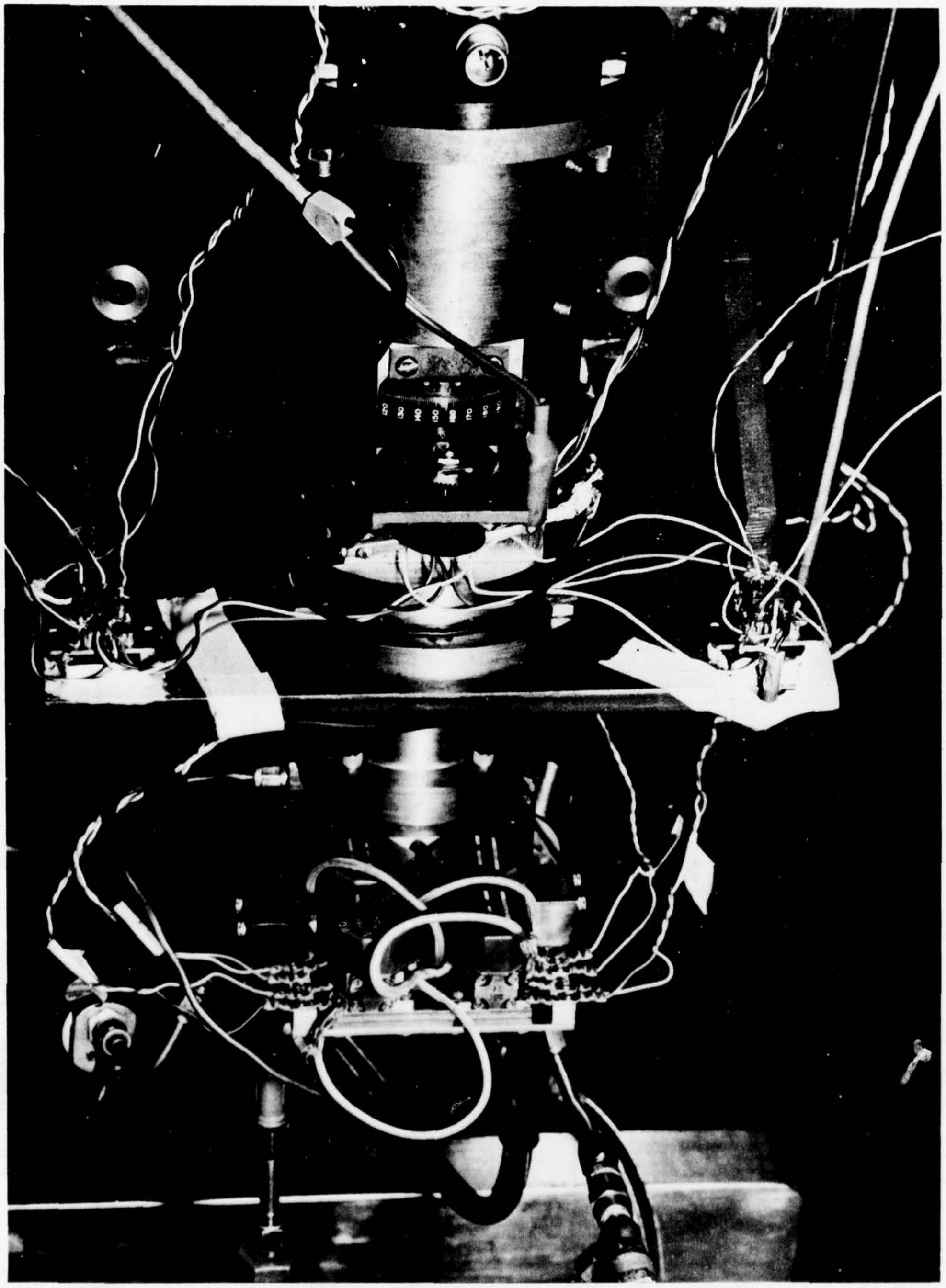


FIGURE 20 - TEST LOAD ADAPTER

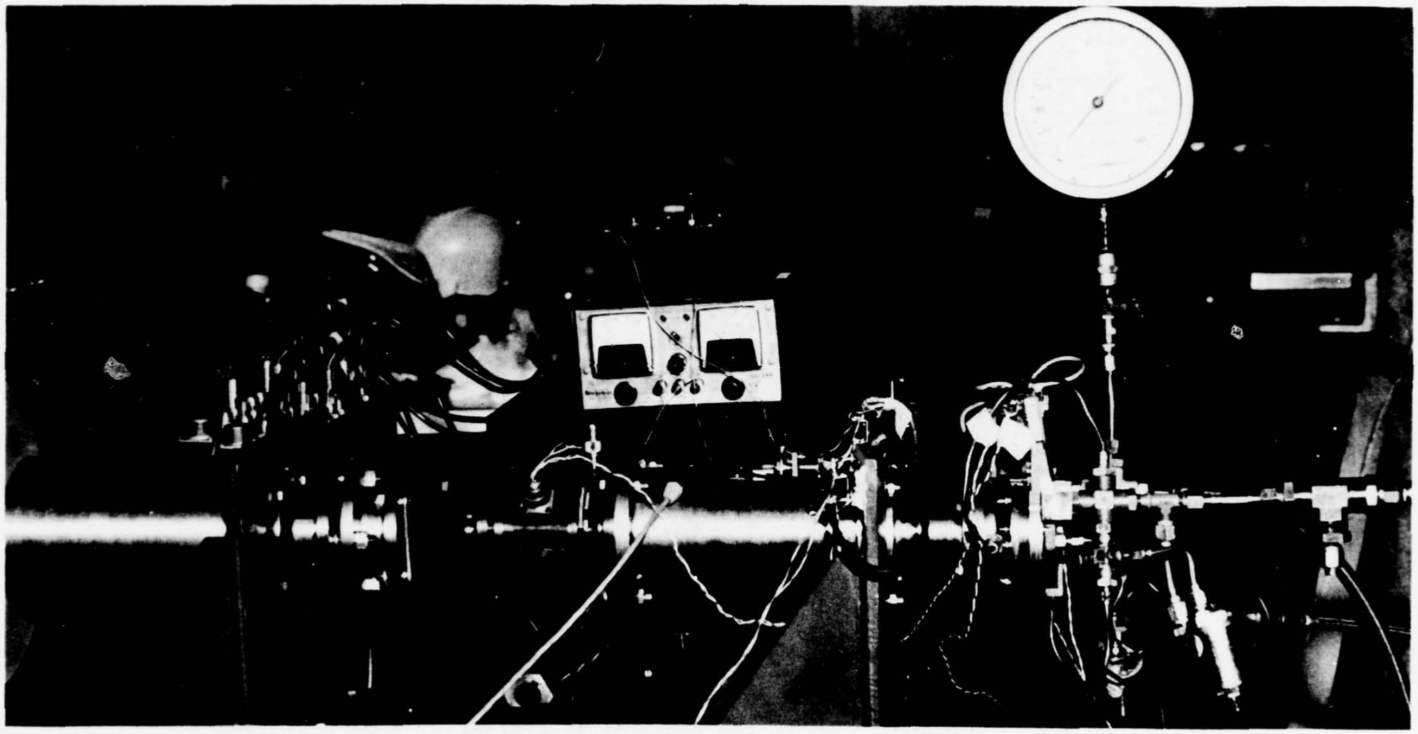


FIGURE 21 - DYNAVECTOR TEST CONFIGURATION

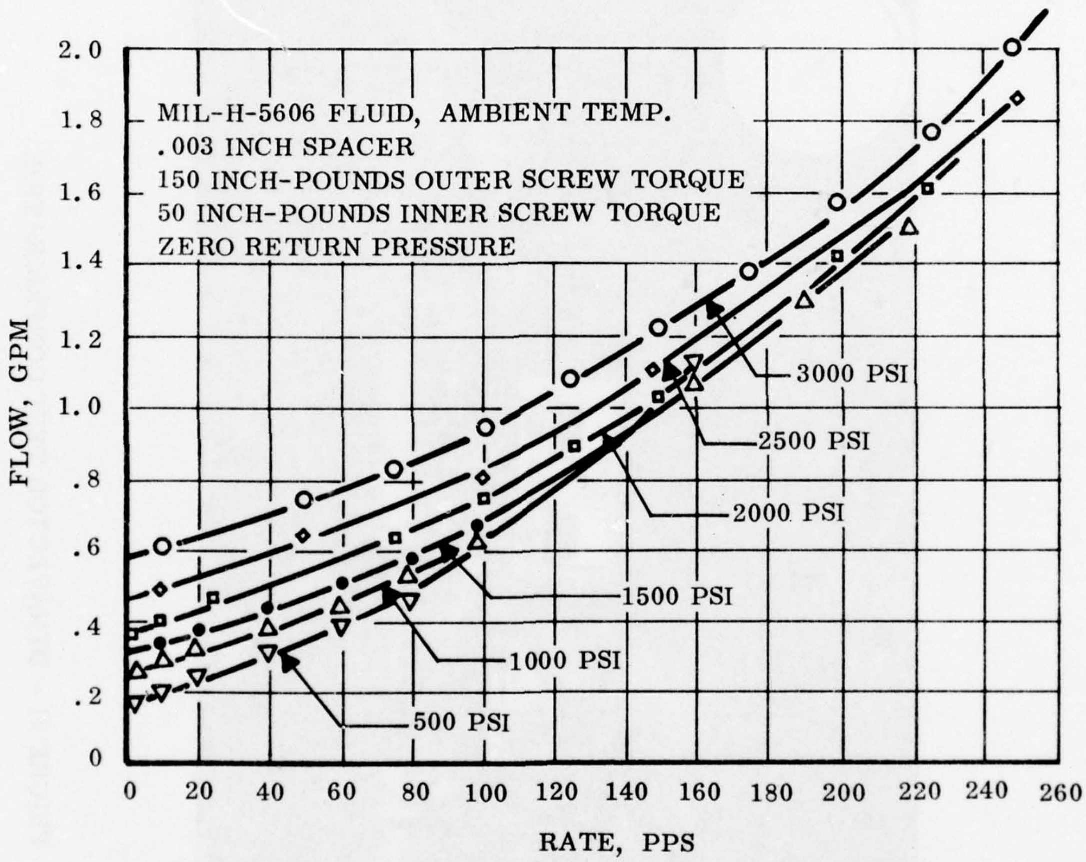


FIGURE 22 - NO LOAD STEPPER ACTUATOR FLOW

MIL-H-5606 HYDRAULIC FLUID, AMBIENT TEMP.
.003 SPACER
150 INCH-POUND OUTER SCREW TORQUE
50 INCH-POUND INNER SCREW TORQUE
3000 PSI SUPPLY, ZERO PSI RETURN

1564345 LOAD ADAPTER, .75 INCH-POUND SEC^2
CYCLE BETWEEN $+20^o$ AND -20^o
(± 1650 INCH-POUND LOAD)

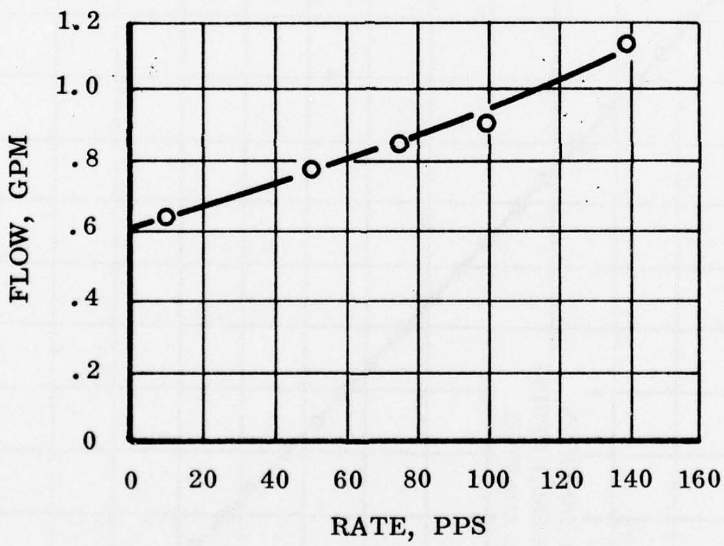


FIGURE 23 - STEPPER ACTUATOR FLOW UNDER LOAD

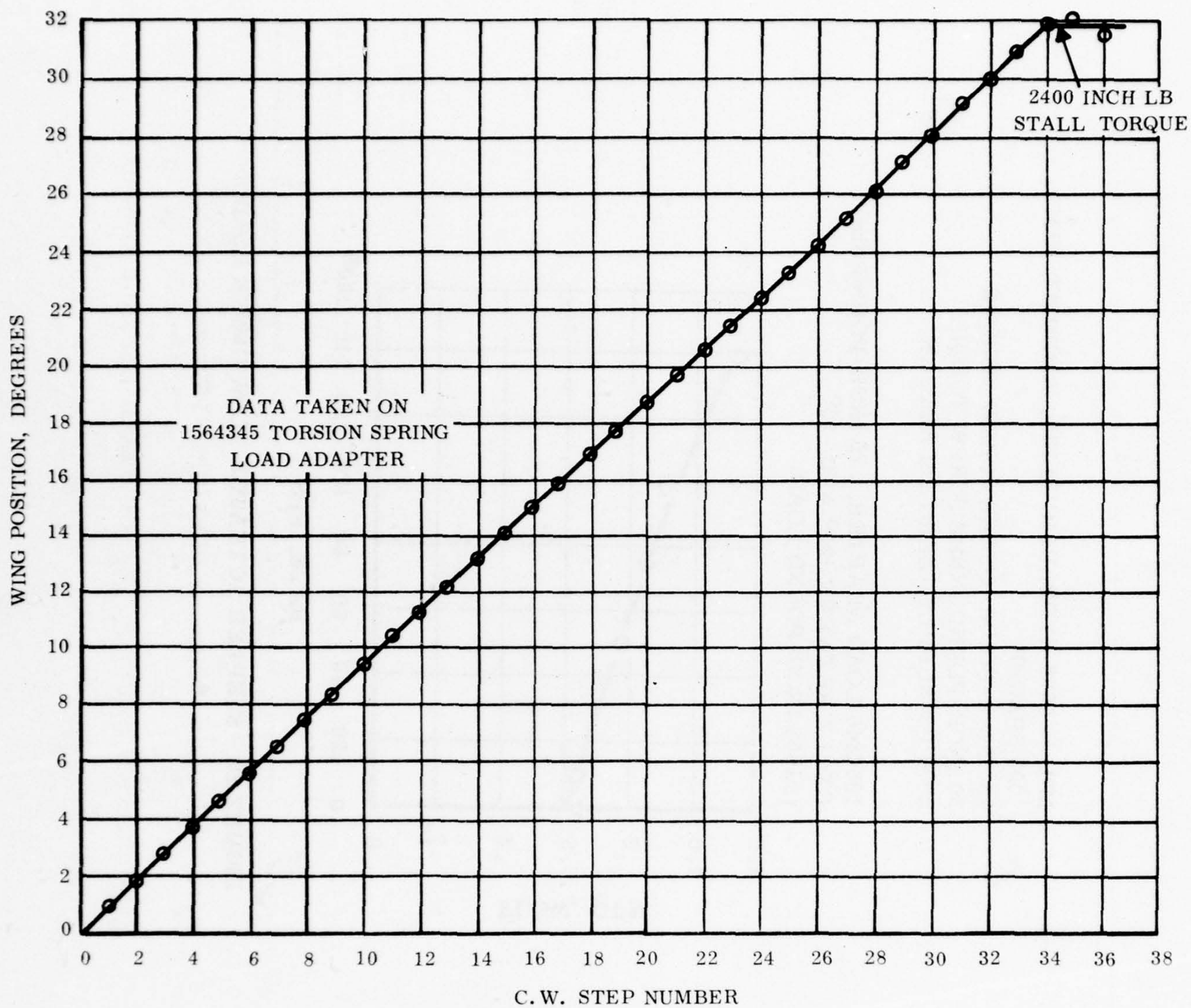


FIGURE 24 - STEPPER ACTUATOR WING POSITION VS STEP NUMBER

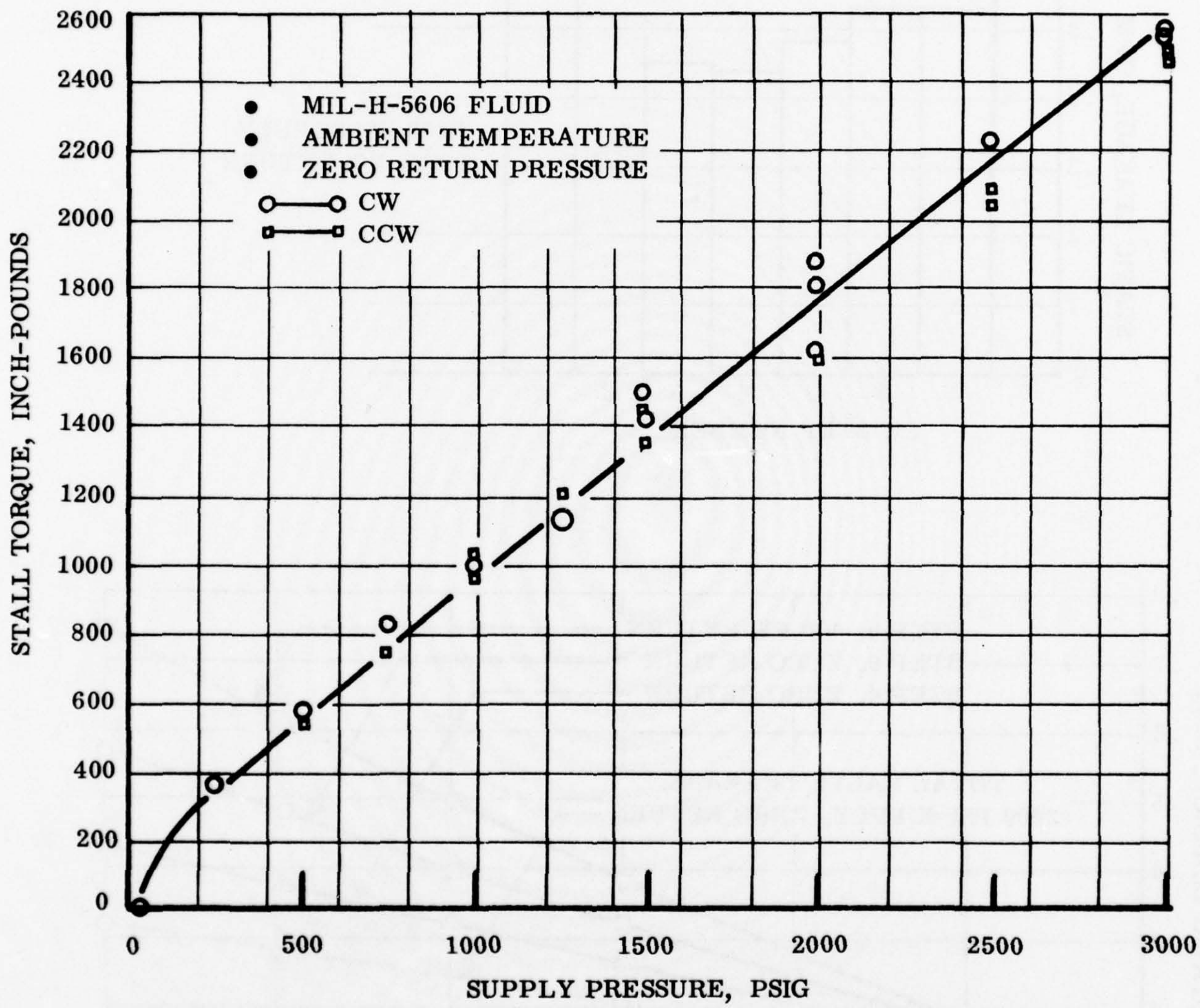
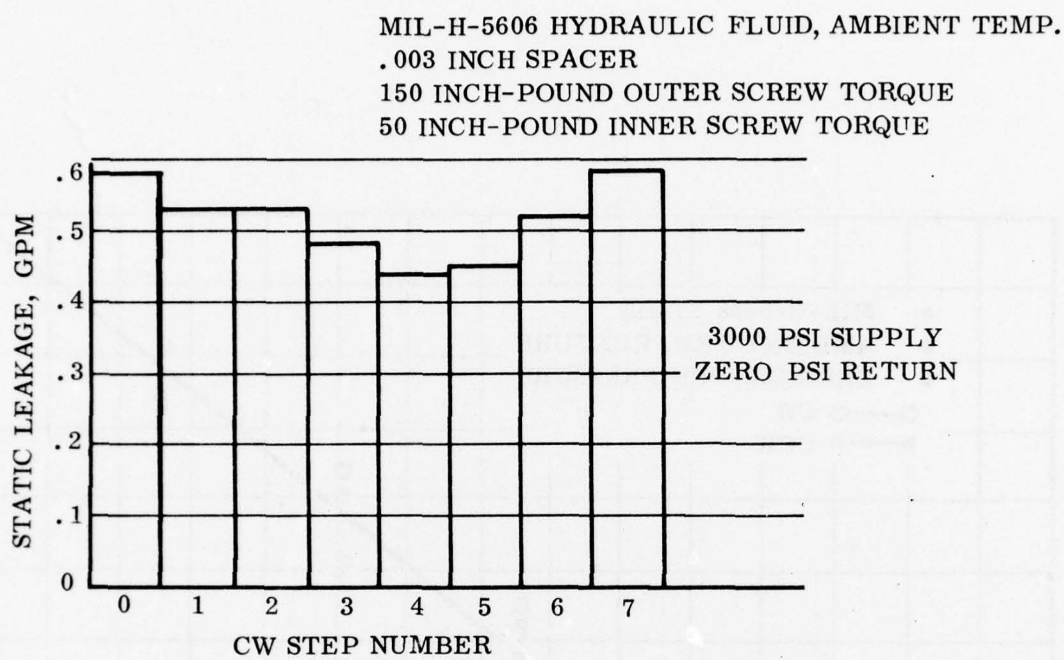


FIGURE 25 - STEPPER ACTUATOR BREAK-IN STALL TORQUE



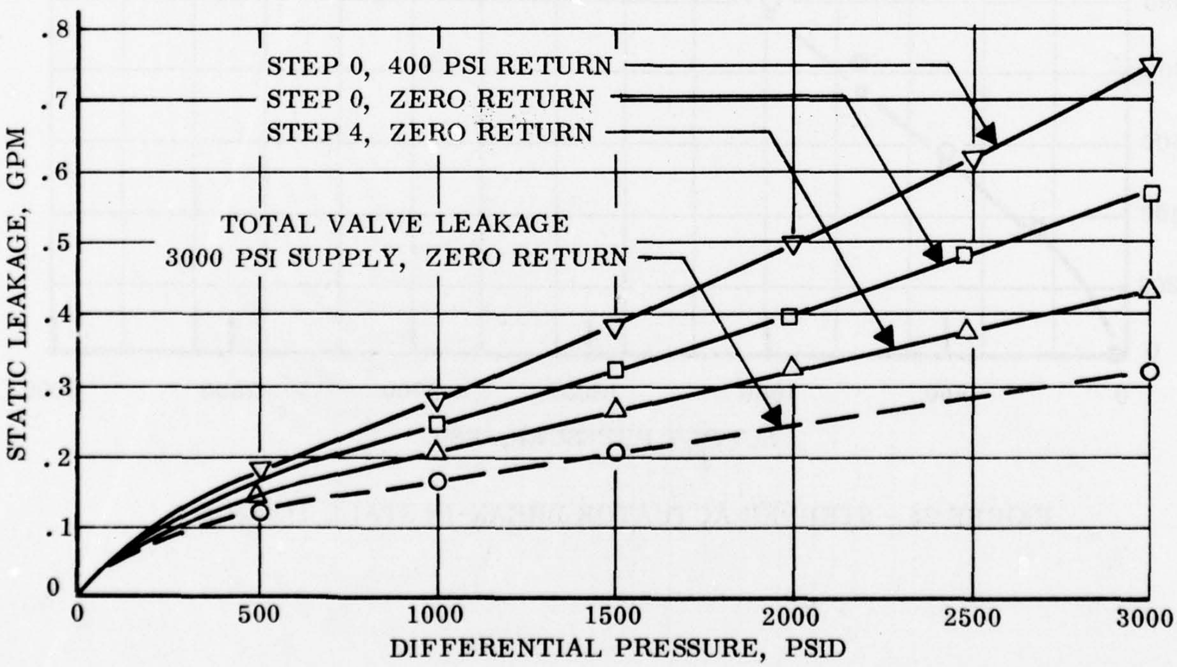
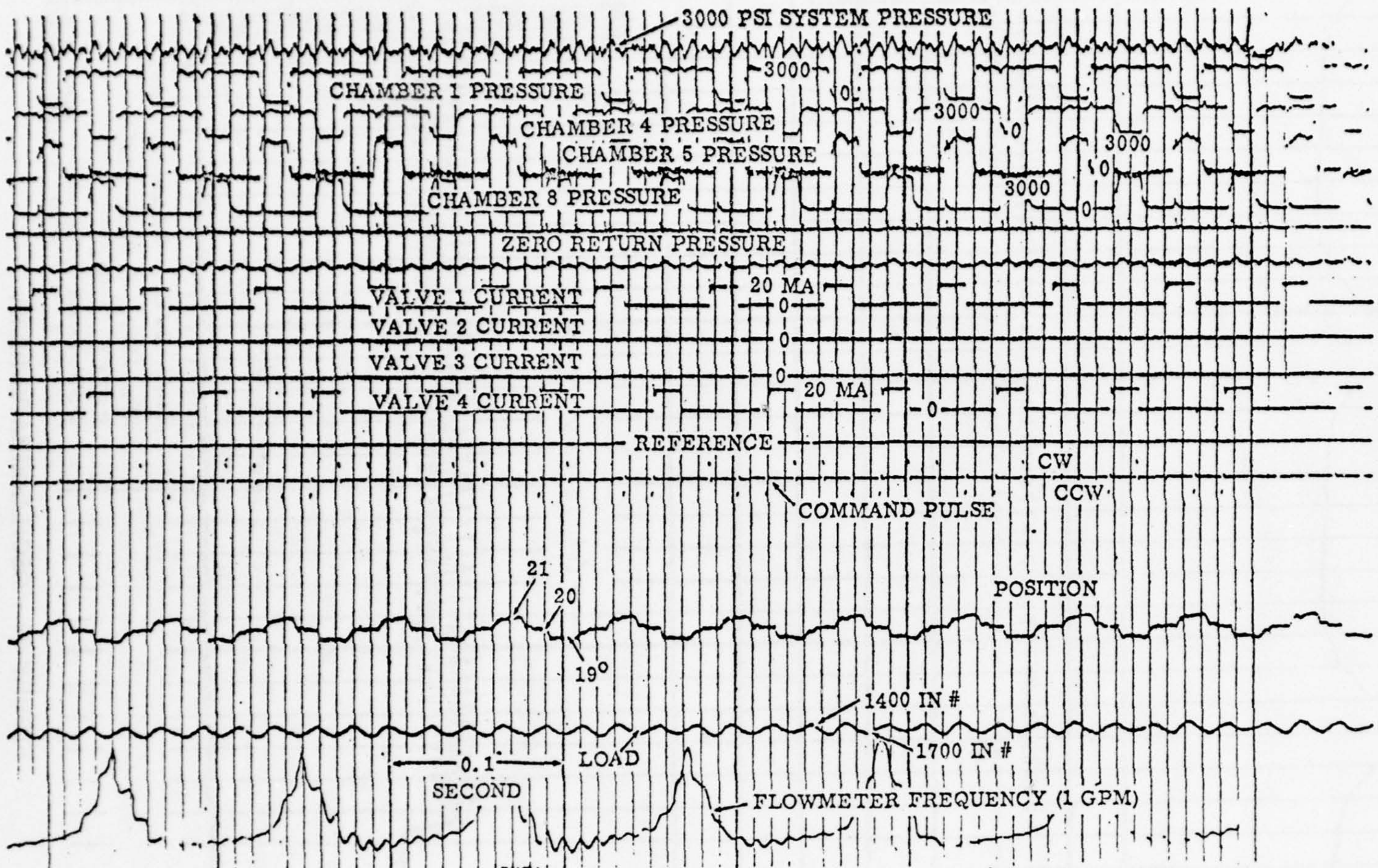


FIGURE 26 - STAPPER ACTUATOR STATIC LEAKAGE



RUN 165
RECORD 4
60 PPS
±1° AT RATED LOAD

FIGURE 27 - STEPPER ACTUATOR OSCILLOGRAPH DATA

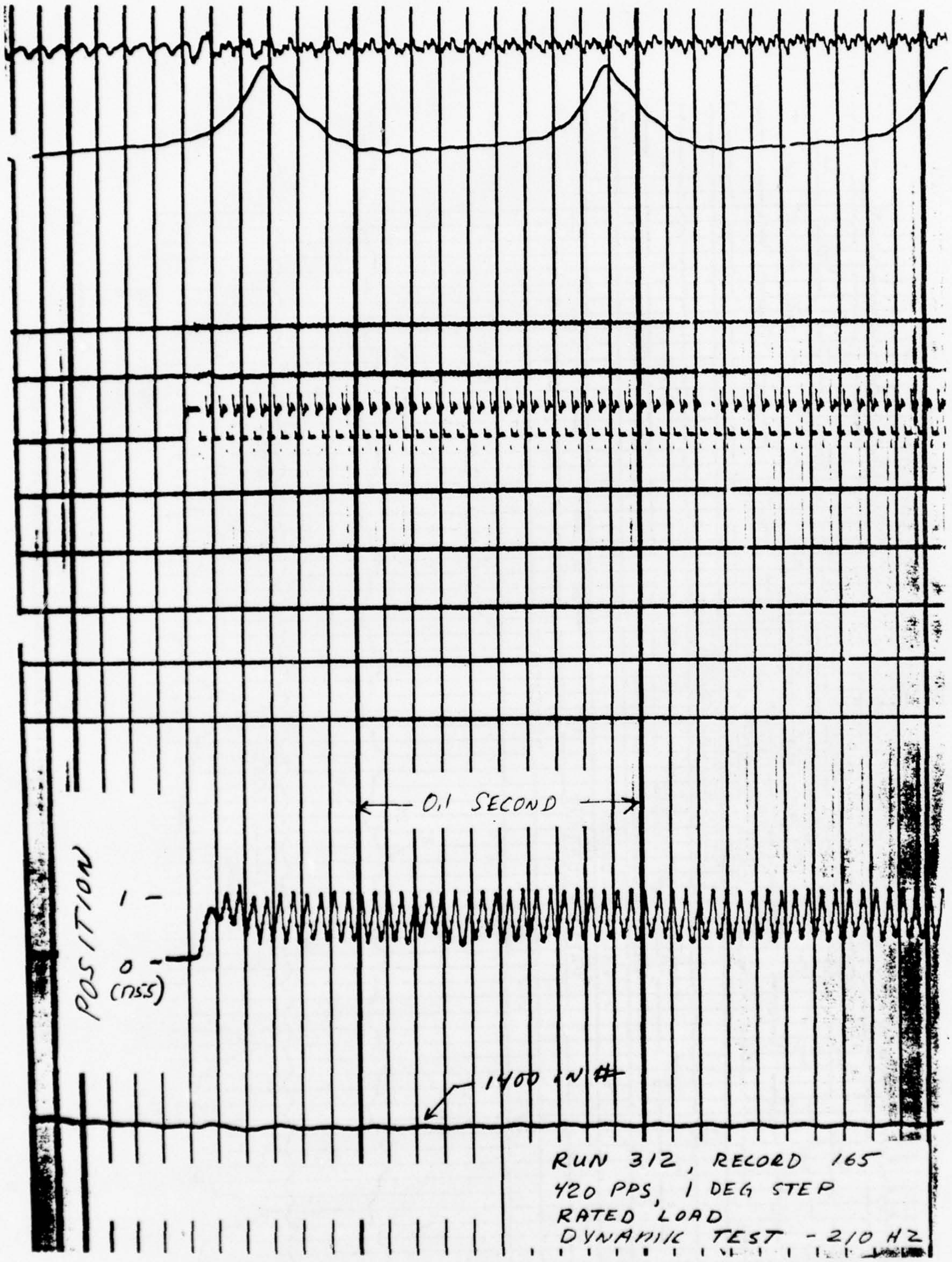


FIGURE 28 - OSCILLOGRAPH DATA

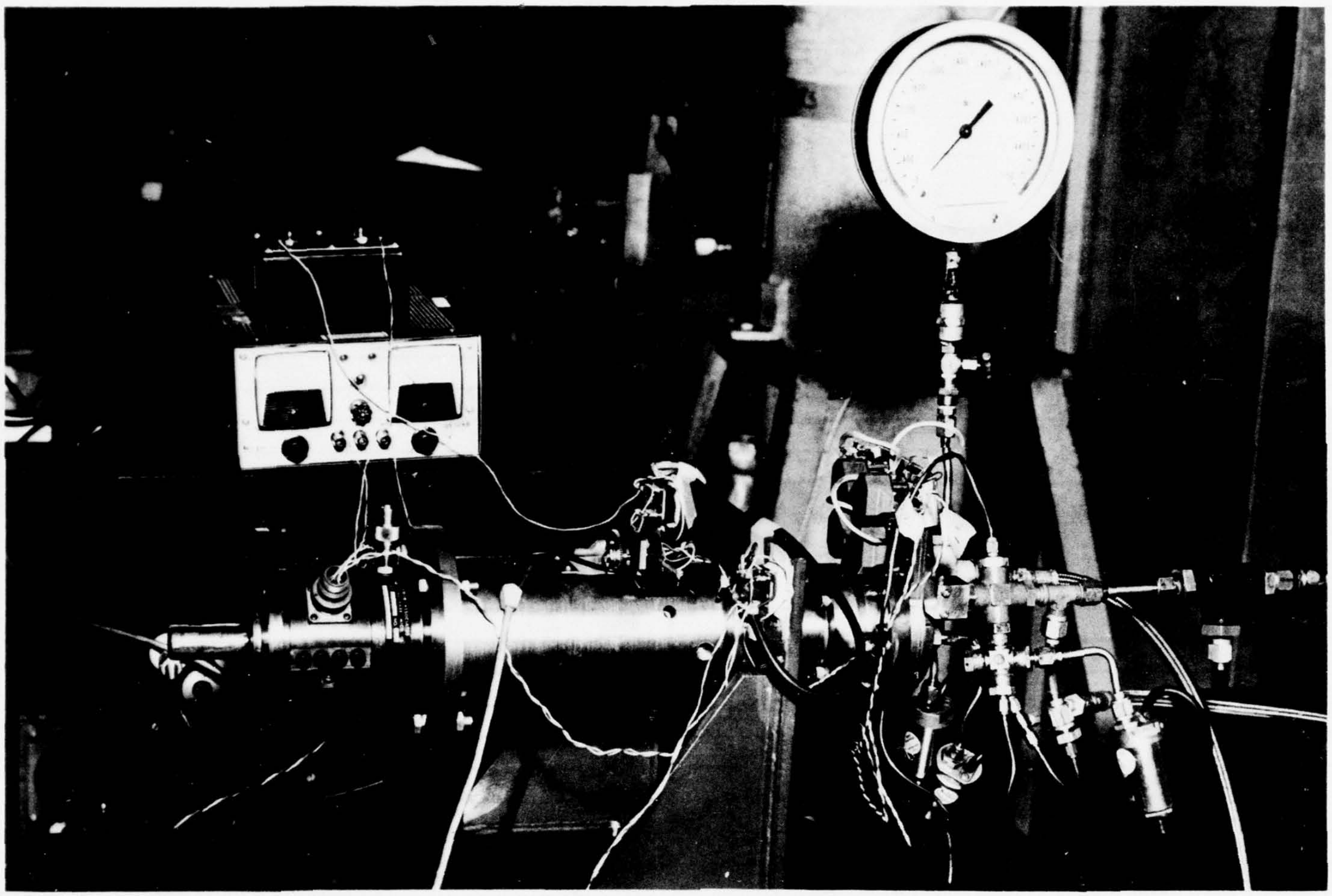


FIGURE 29 - NO LOAD CONFIGURATION

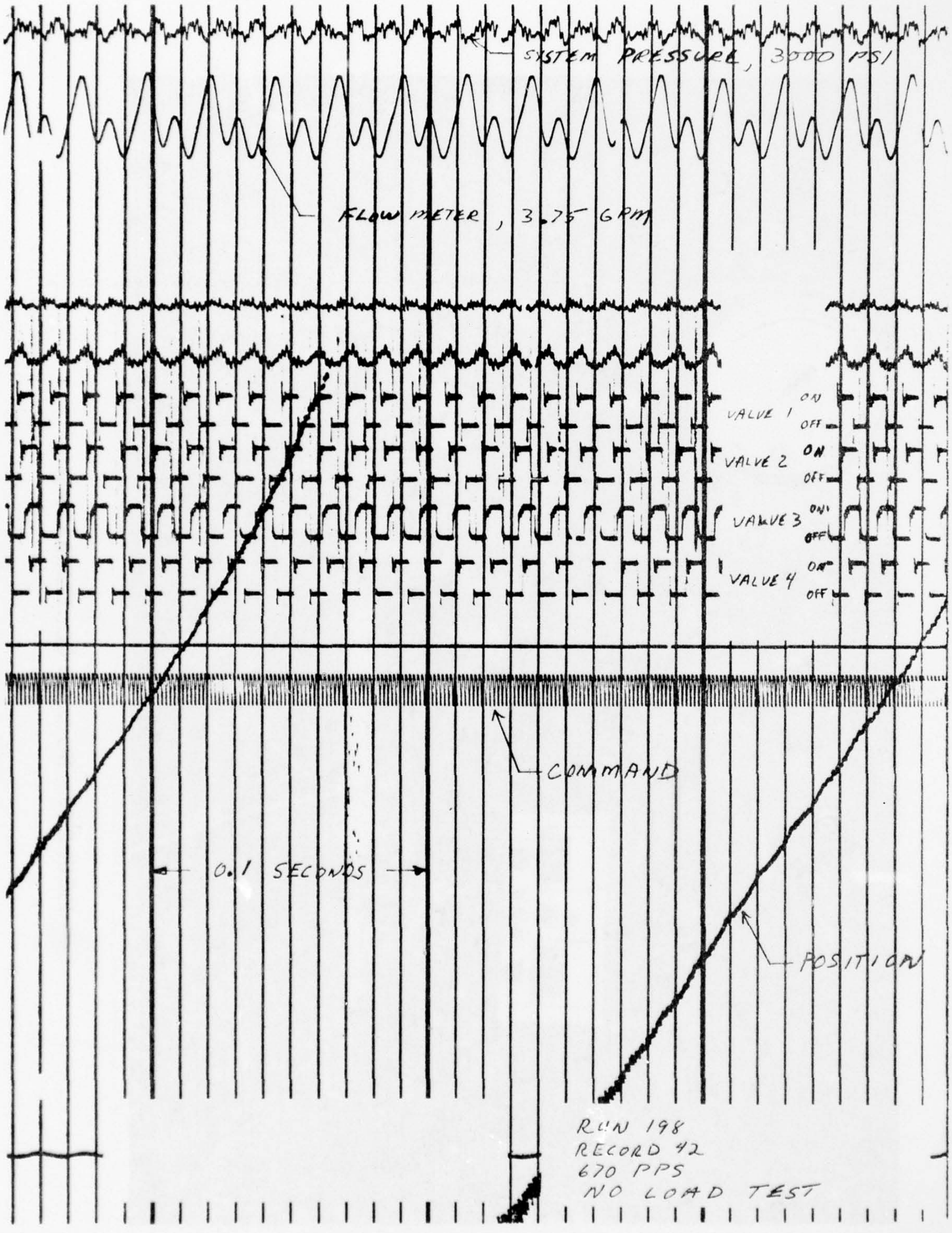


FIGURE 30 - STEPPER ACTUATOR OSCILLOGRAPH DATA

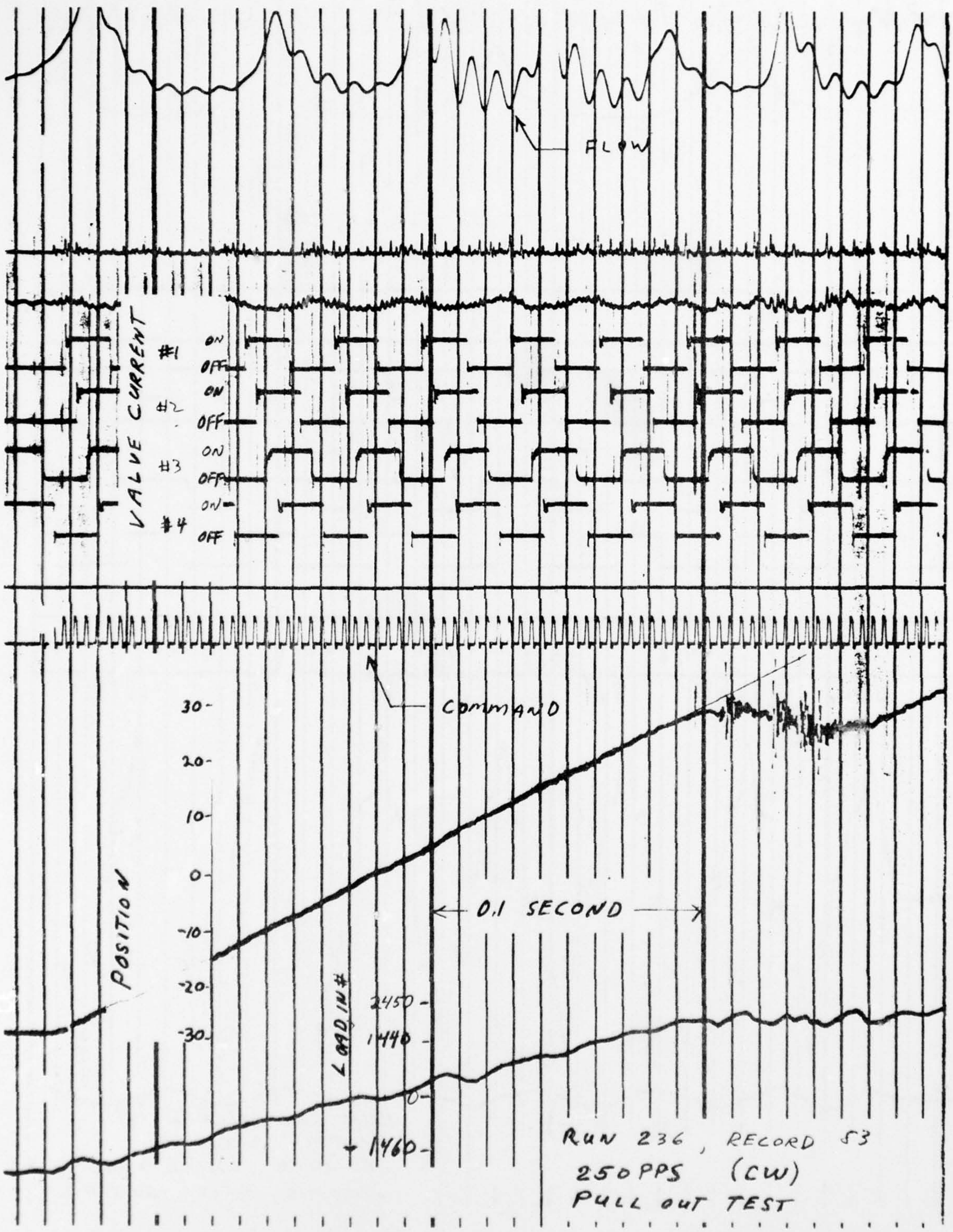


FIGURE 31 - OSCILLOGRAPH DATA

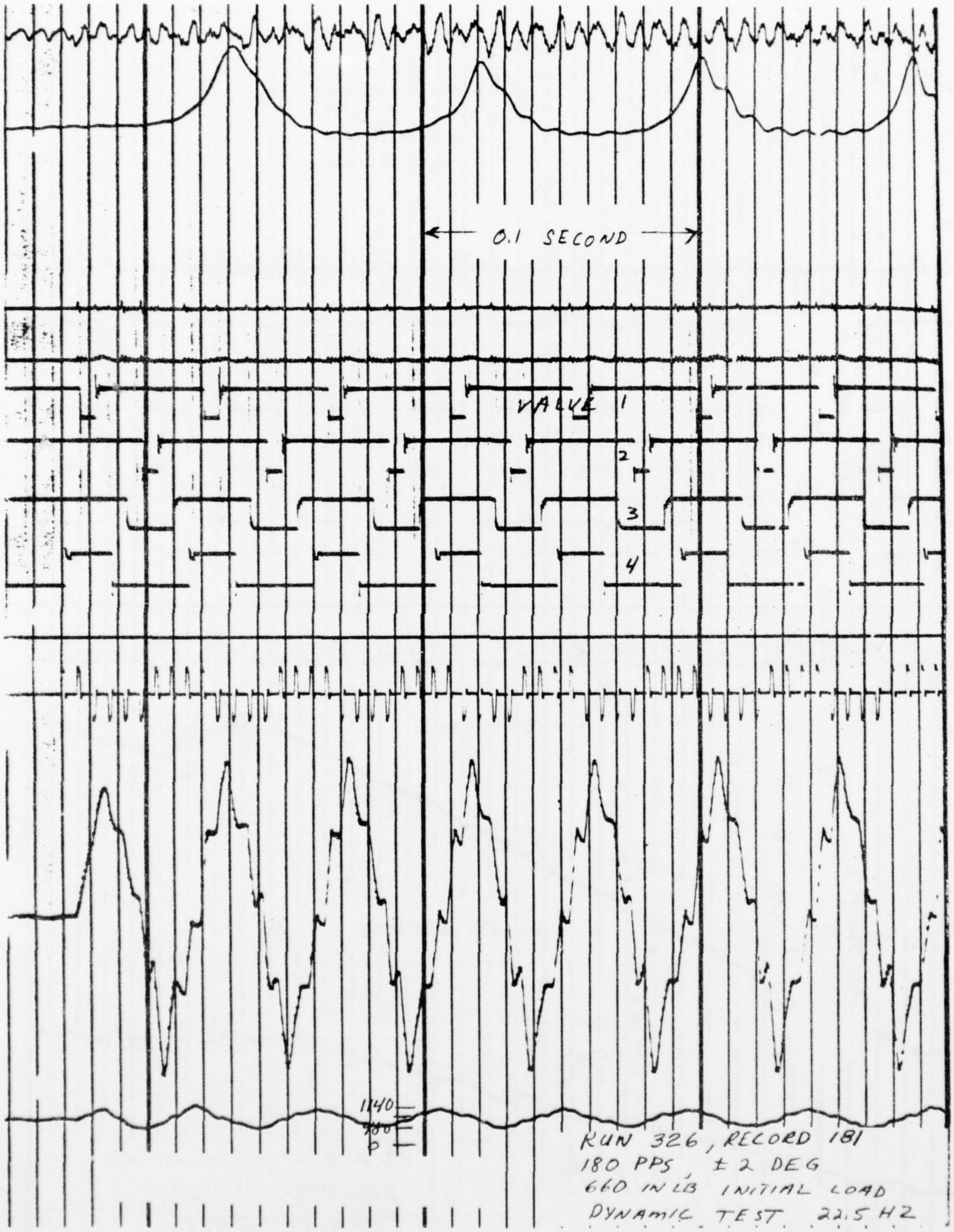


FIGURE 32 - STEPPER ACTUATOR OSCILLOGRAPH DATA

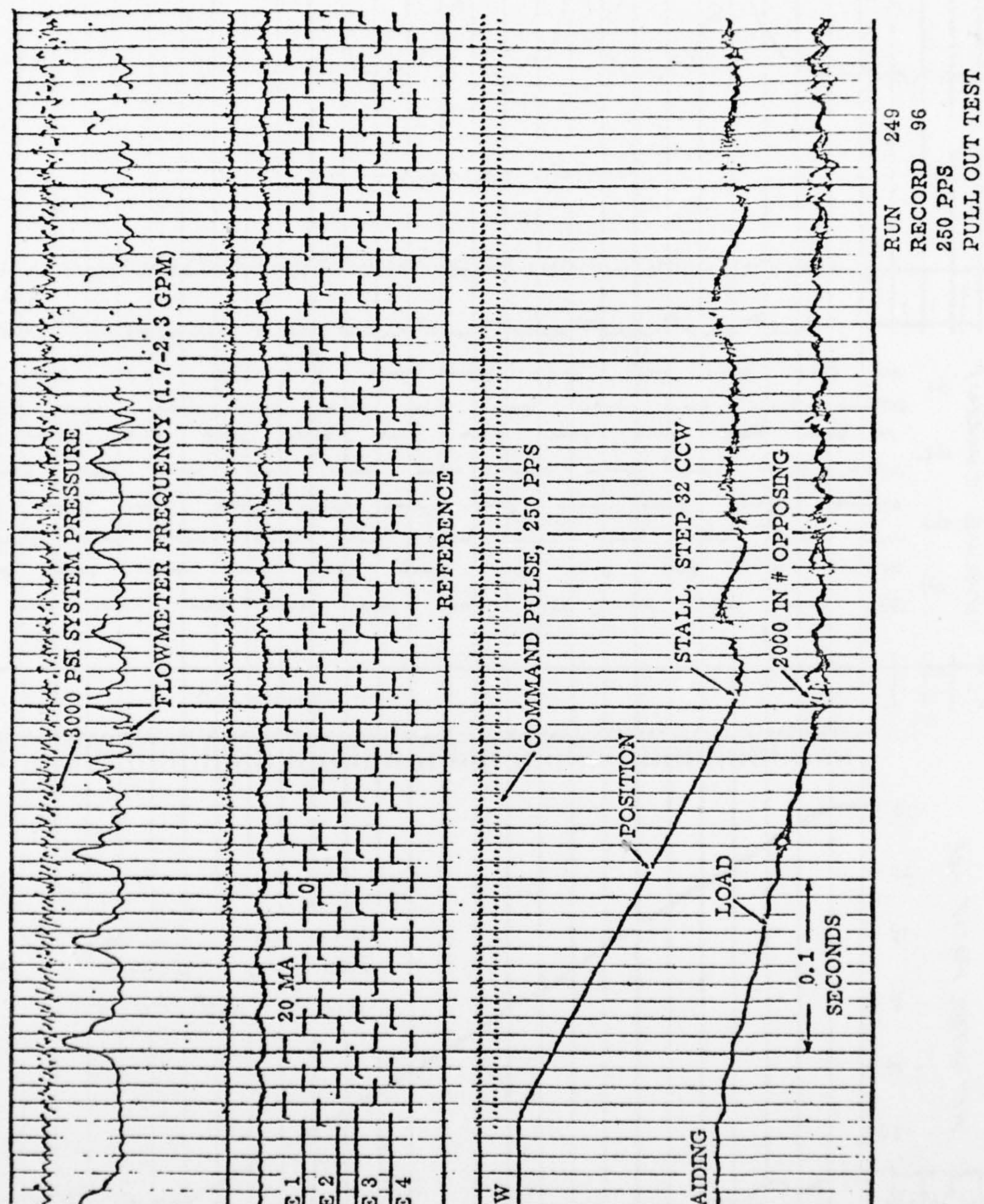


FIGURE 33 - STEPPER ACTUATOR OSCILLOGRAPH DATA

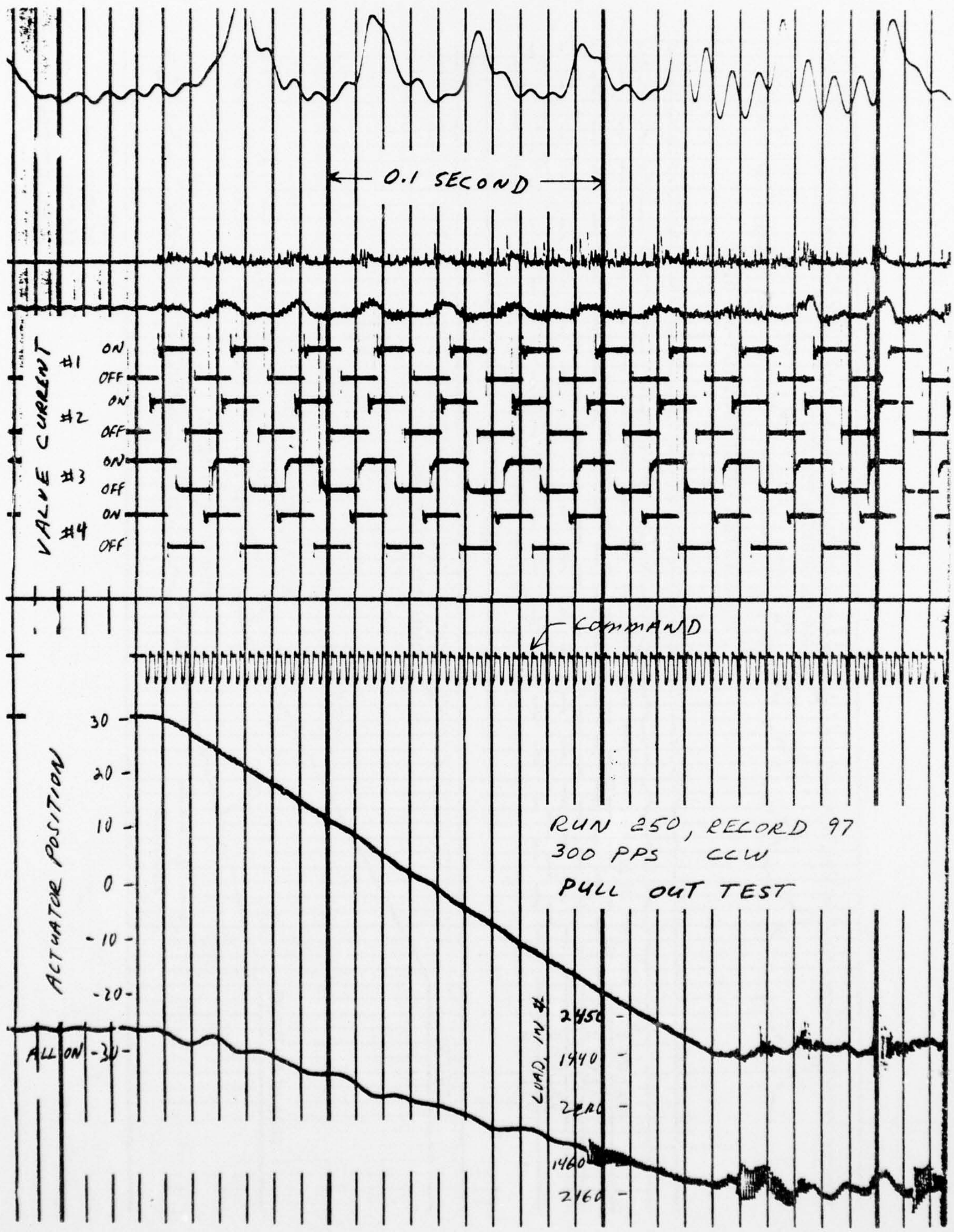


FIGURE 34 - OSCILLOGRAPH DATA

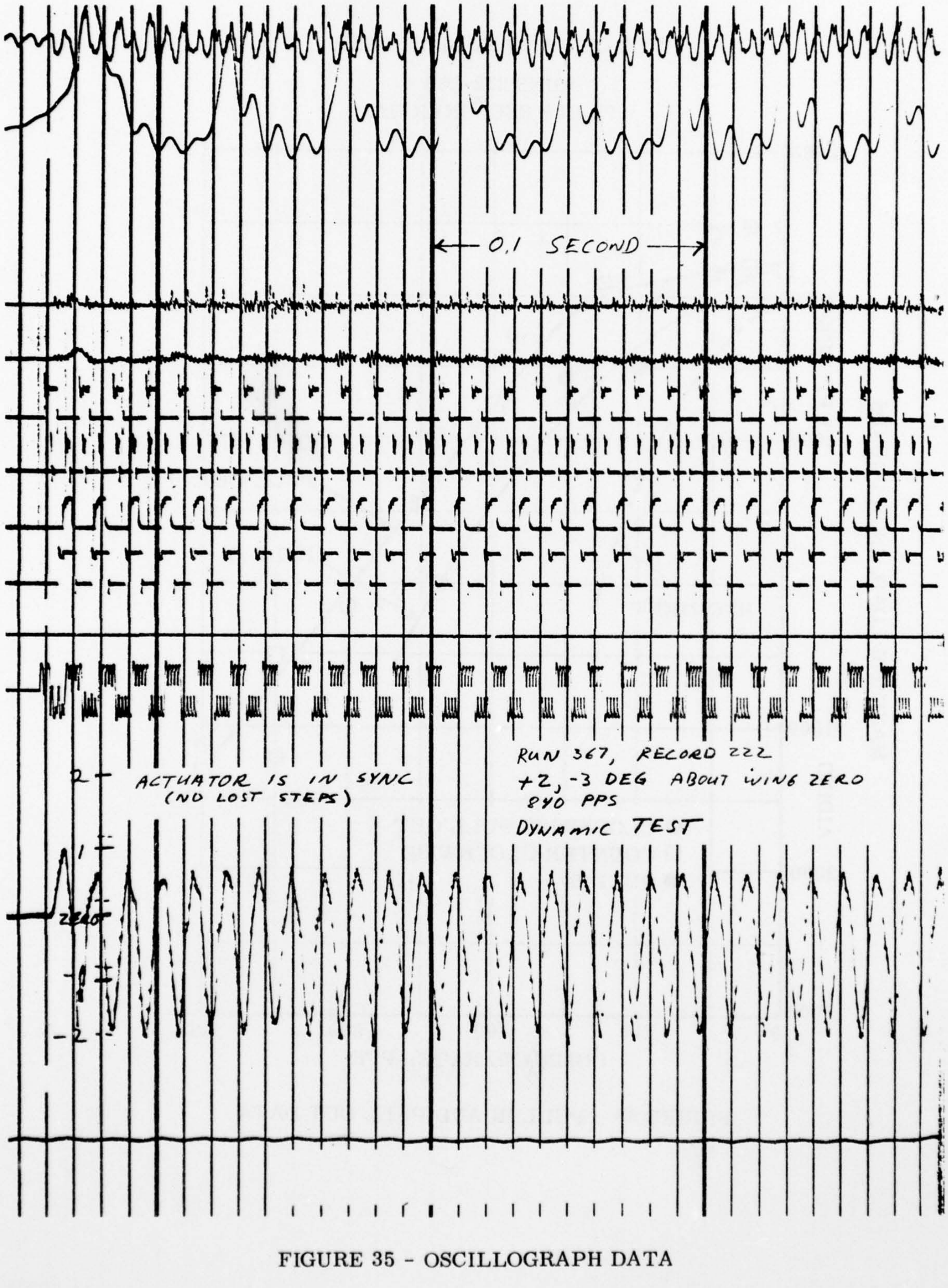


FIGURE 35 - OSCILLOGRAPH DATA

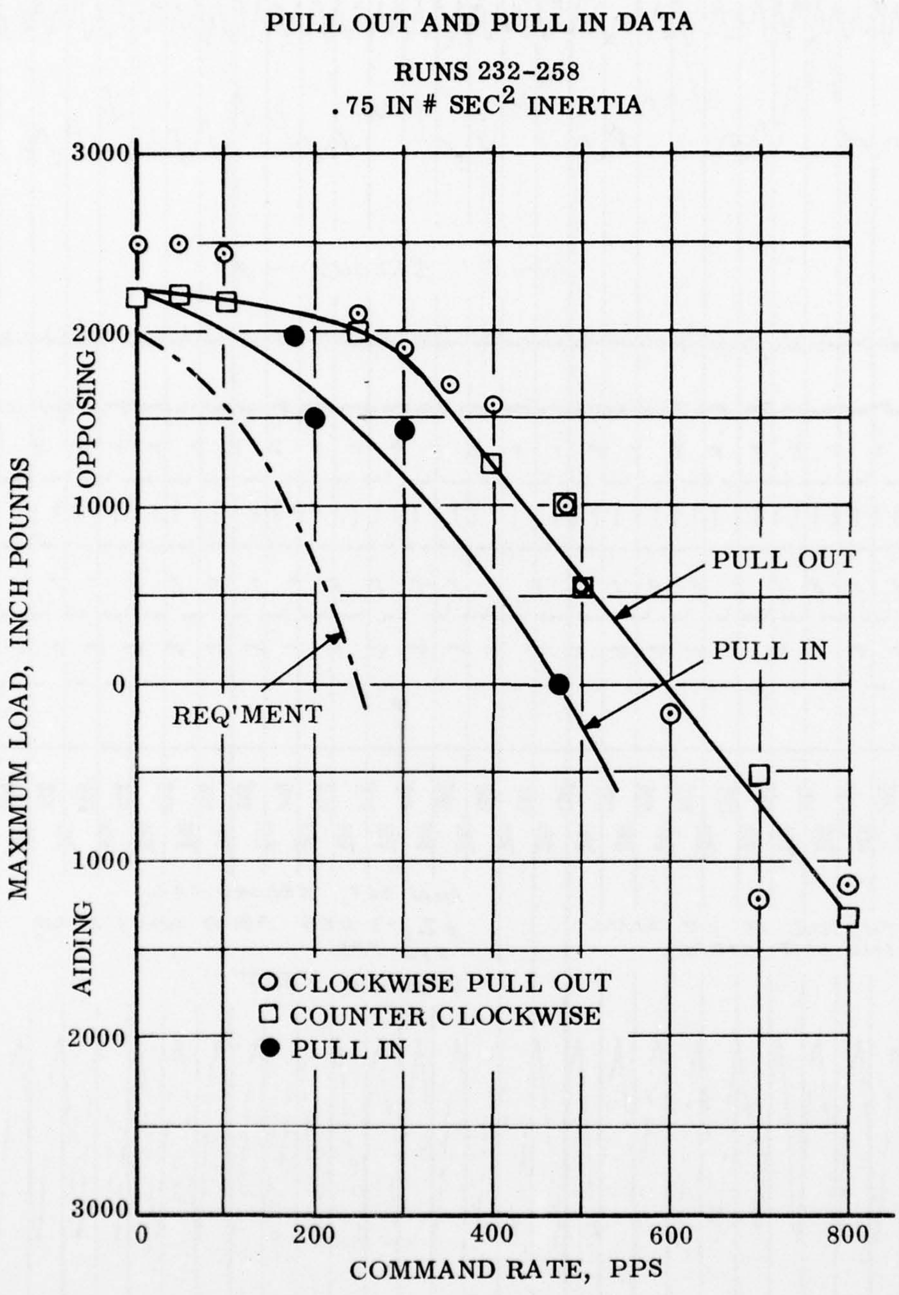


FIGURE 36 - PULL IN AND PULL OUT DATA

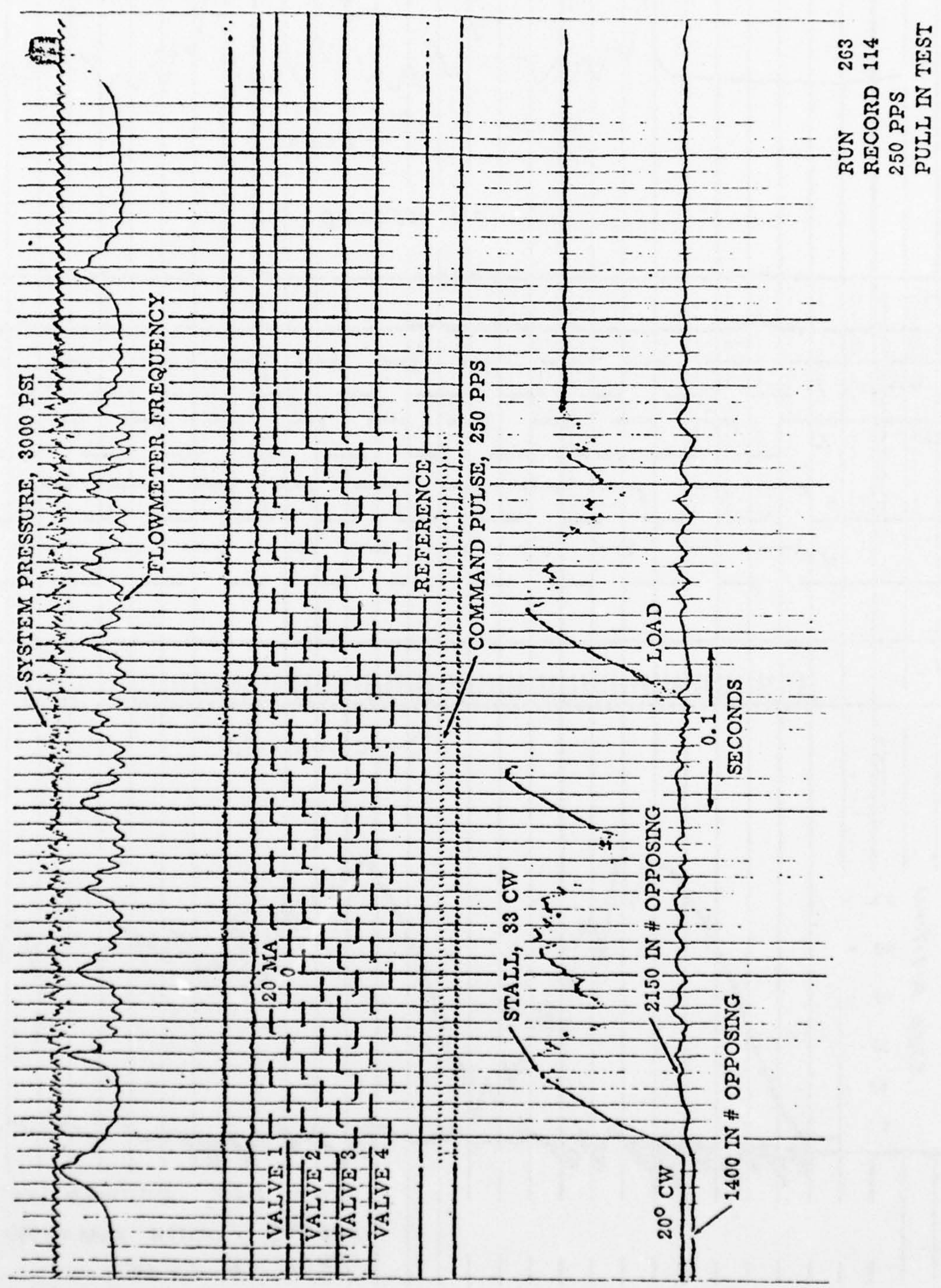


FIGURE 37 - STEPPER ACTUATOR OSCILLOGRAPH DATA

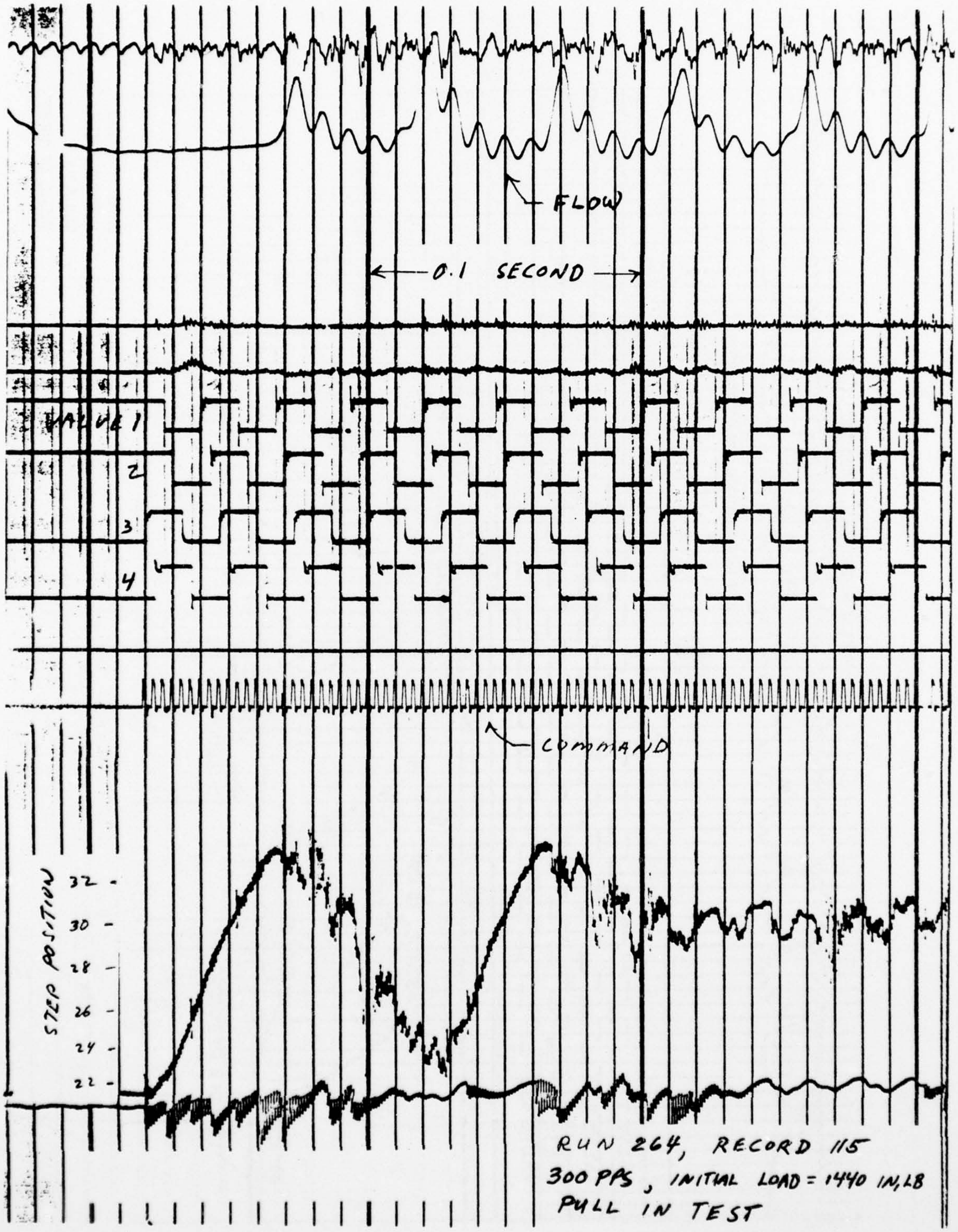


FIGURE 38 - OSCILLOGRAPH DATA

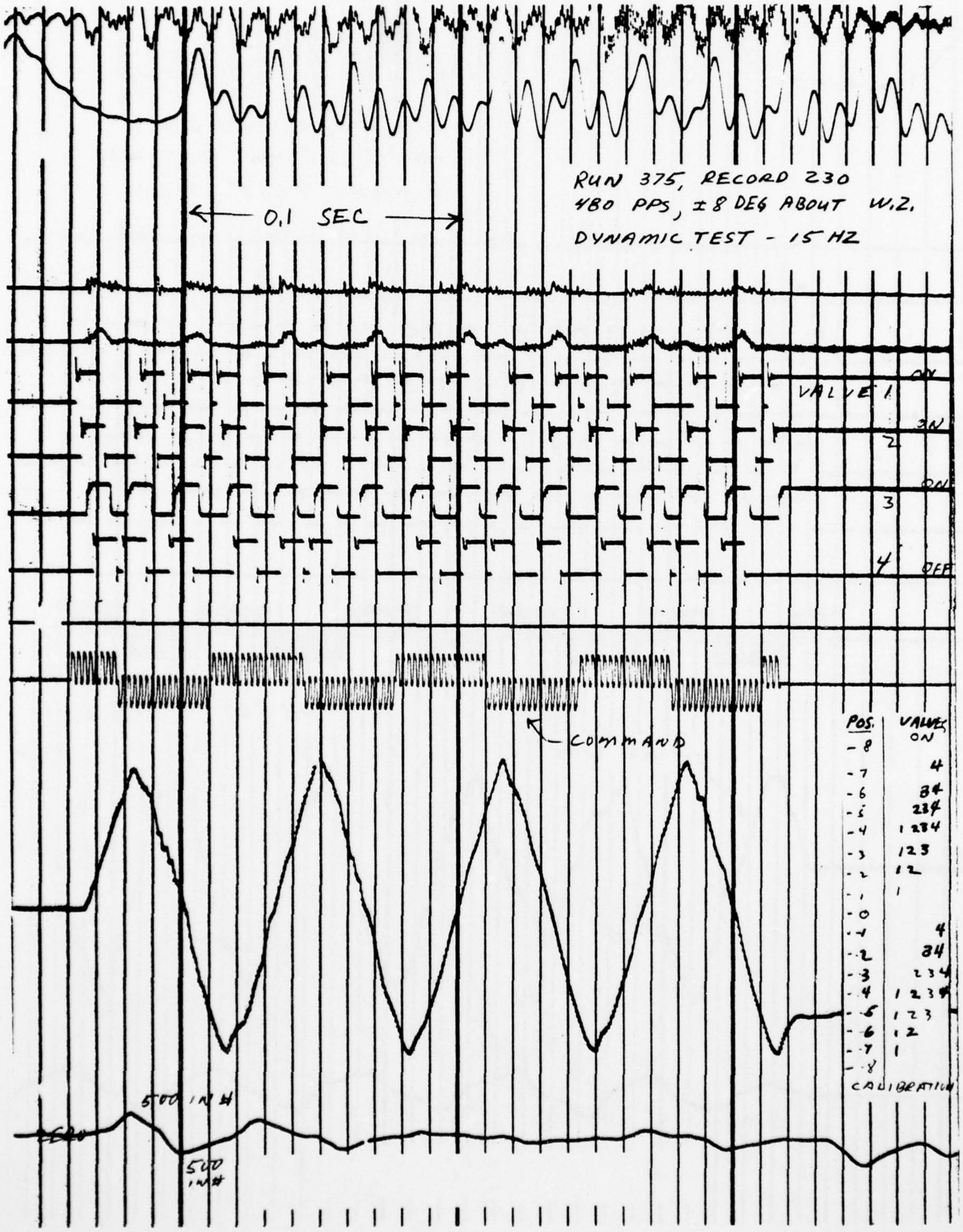


FIGURE 39 - OSCILLOGRAPH DATA

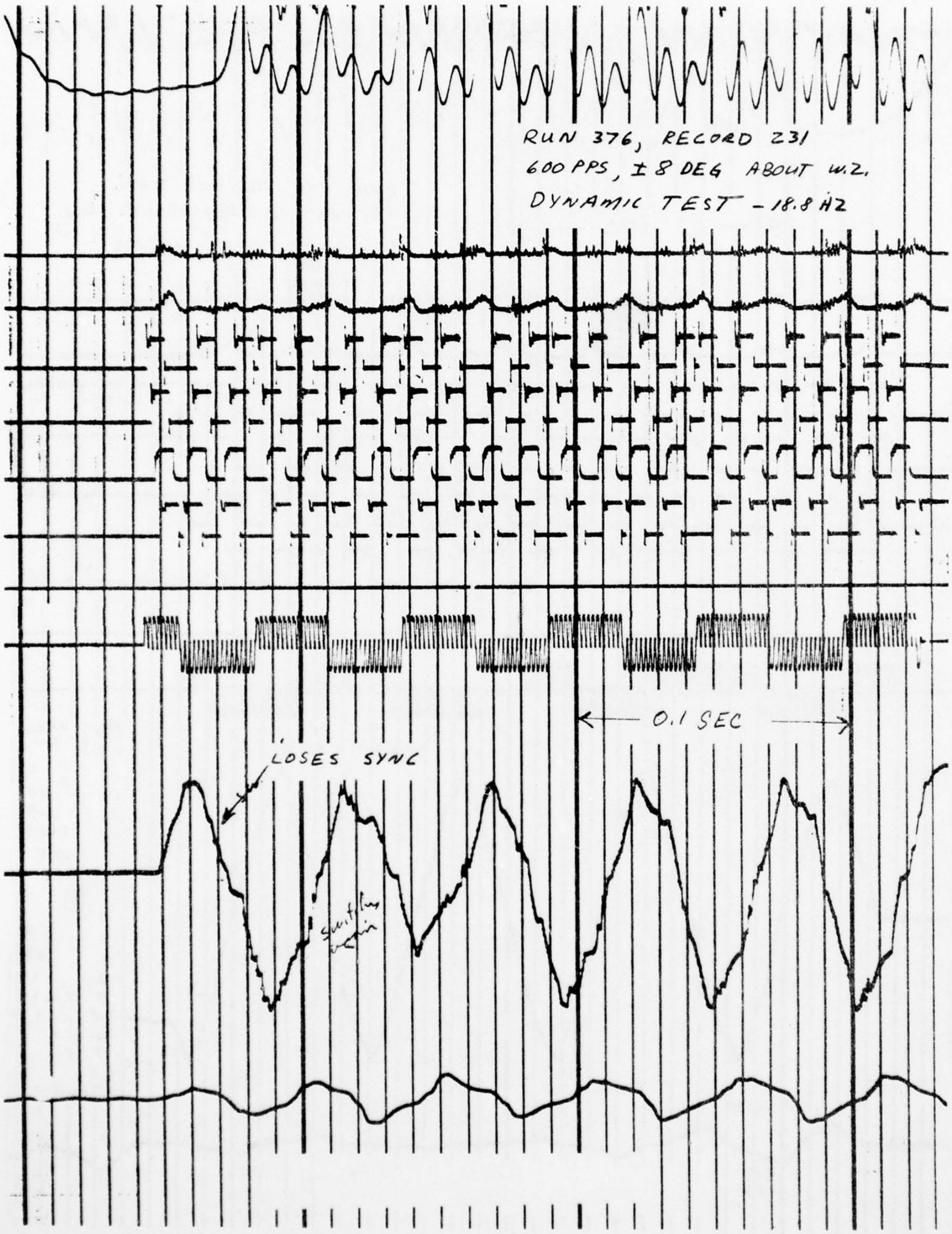


FIGURE 40 - OSCILLOGRAPH DATA

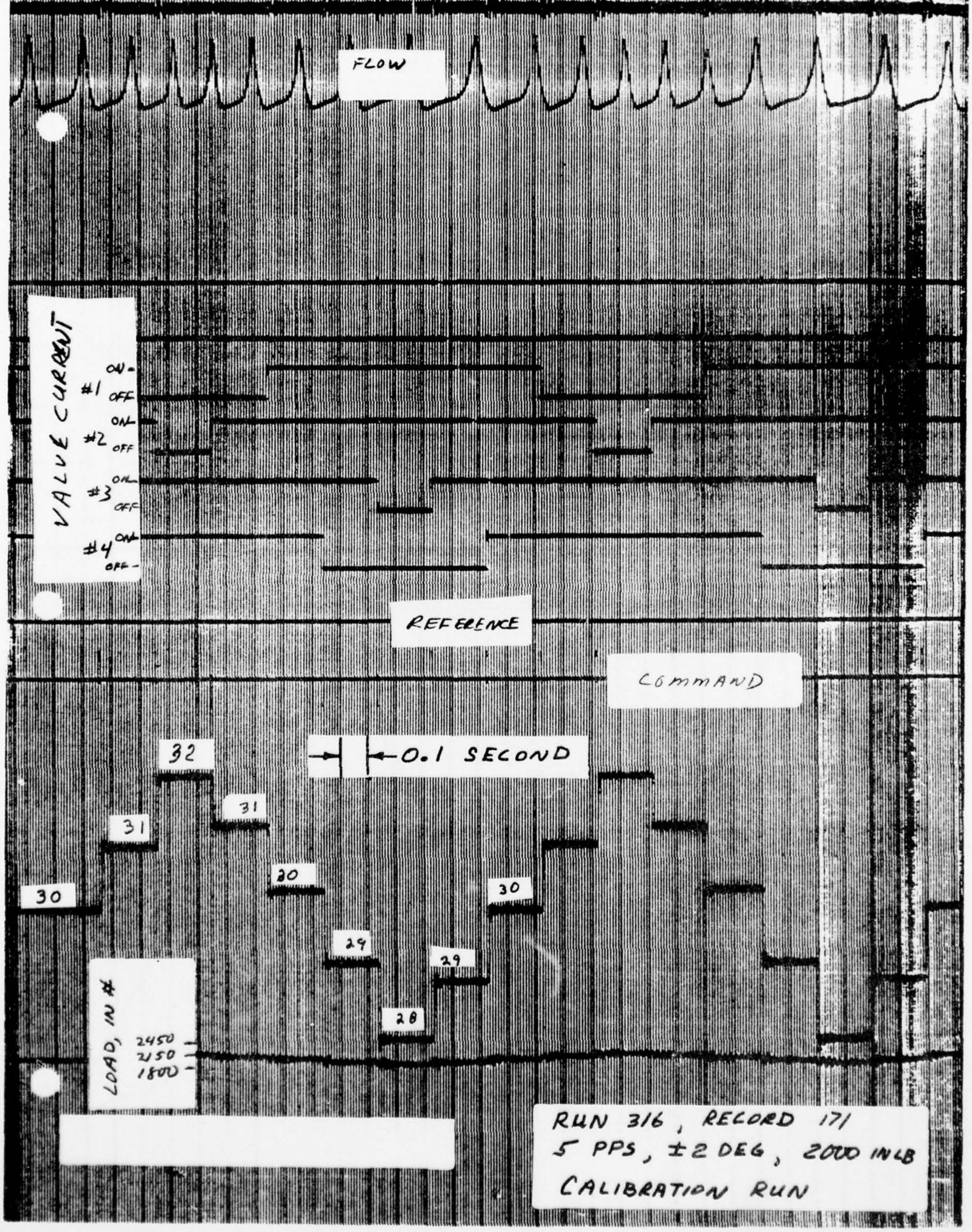


FIGURE 41 - OSCILLOGRAPH DATA

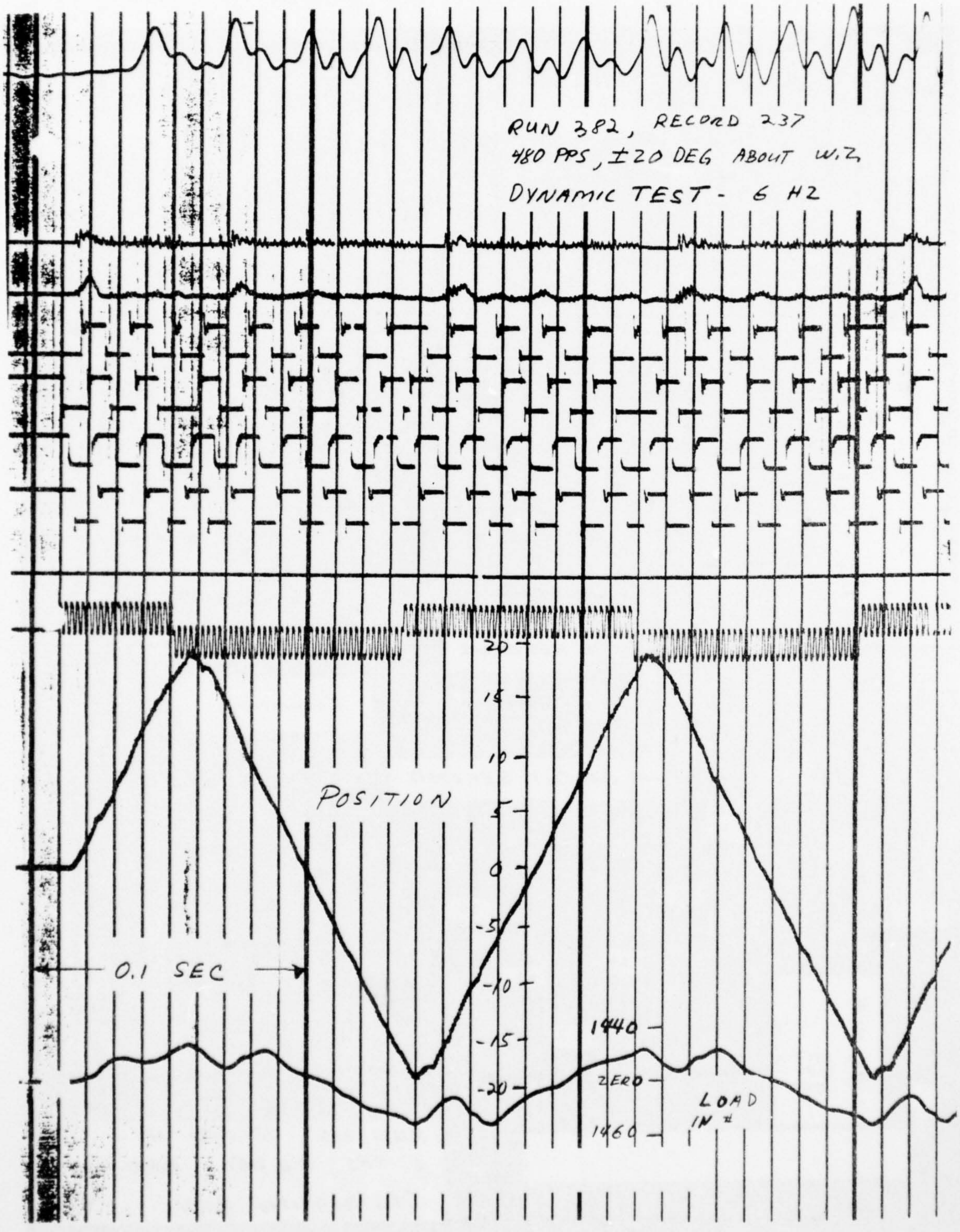


FIGURE 42 - OSCILLOGRAPH DATA

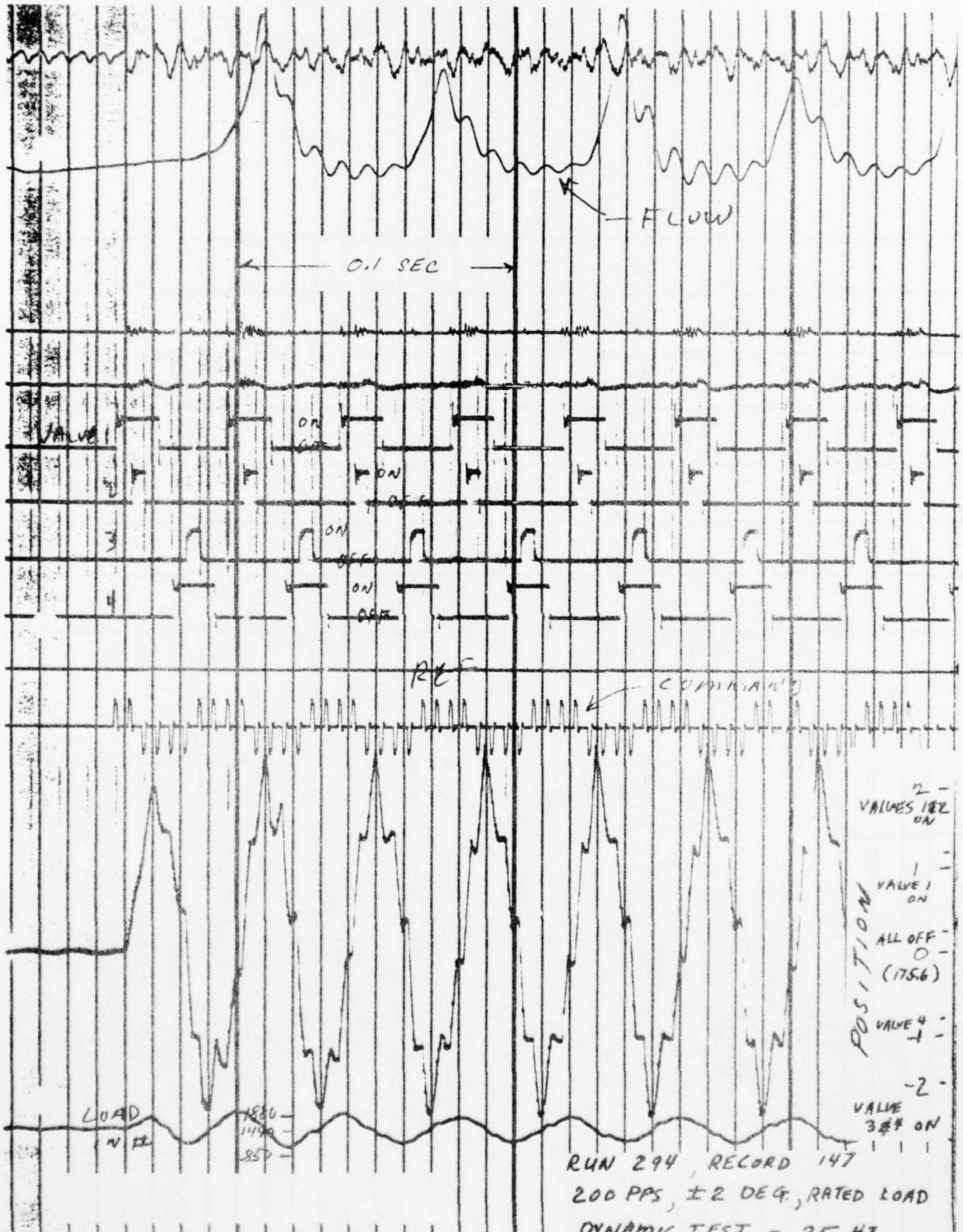


FIGURE 43 - OSCILLOGRAPH DATA

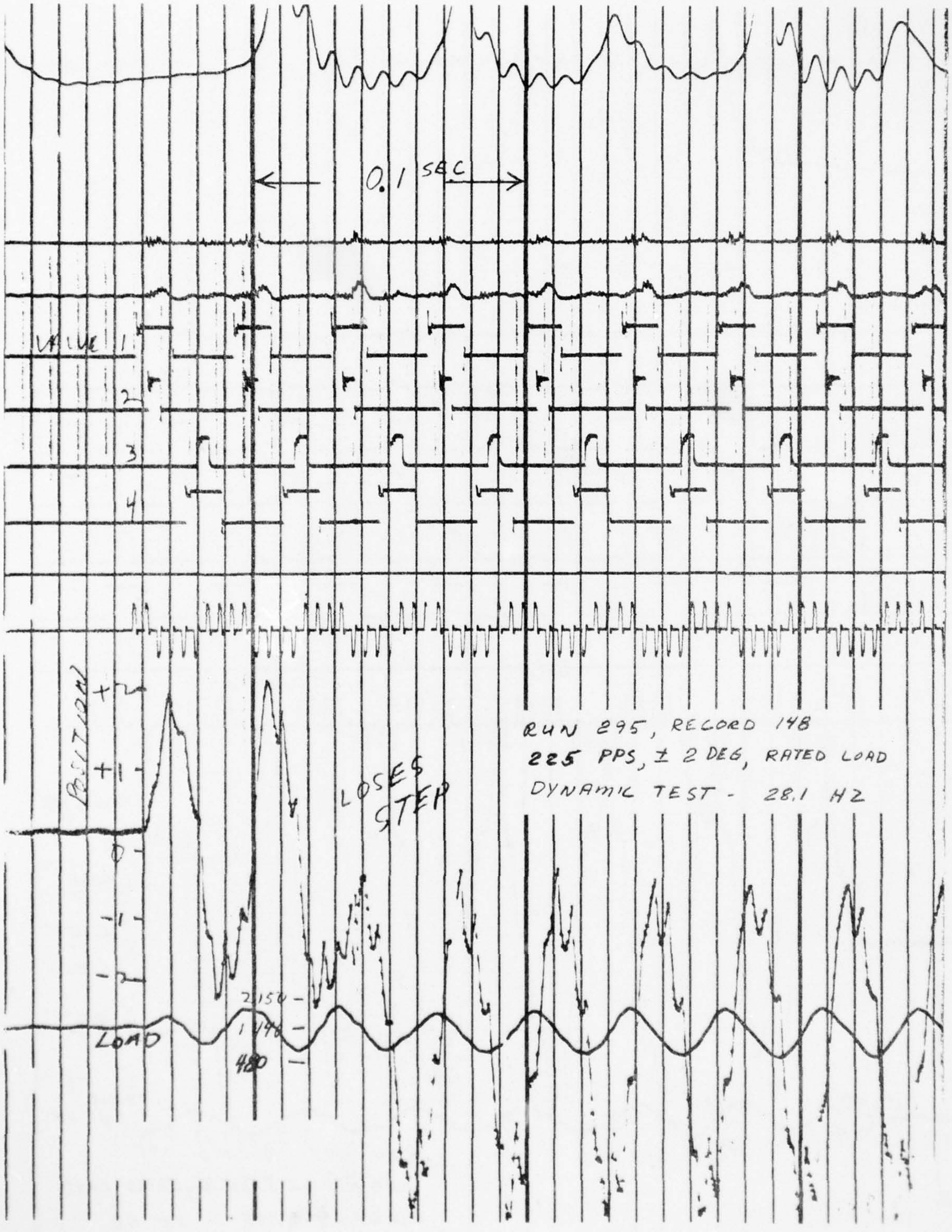
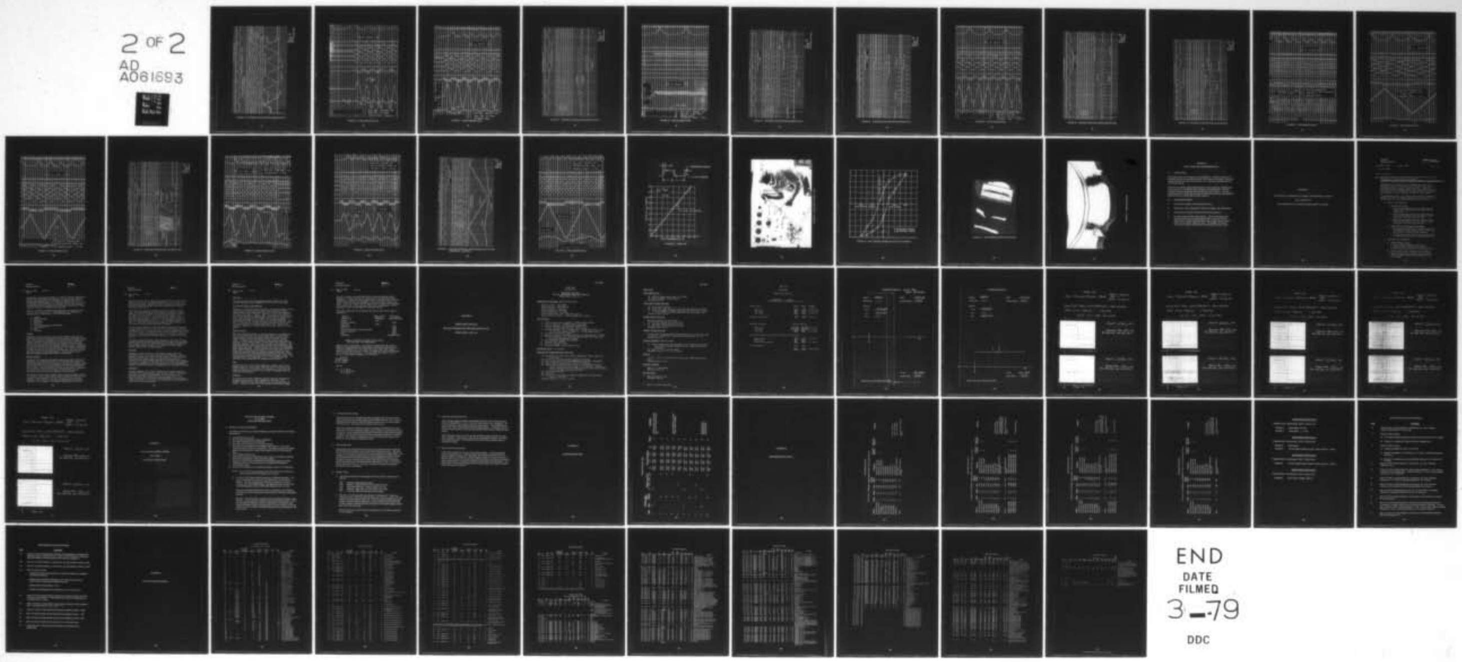


FIGURE 44 - OSCILLOGRAPH DATA

AD-A061 693 BENDIX AEROSPACE SYSTEMS DIV MISHAWAKA IND MISHAWAK--ETC F/G 9/5
DIGITAL ELECTROHYDRAULIC STEPPER ACTUATOR FOR ADVANCED MISSILE --ETC(U)
JUN 78 J M SILVIUS, E A SHERRILL F33615-74-C-2052
UNCLASSIFIED AFAPL-TR-78-42 NL

2 OF 2
AD
A061693



END
DATE
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3-79
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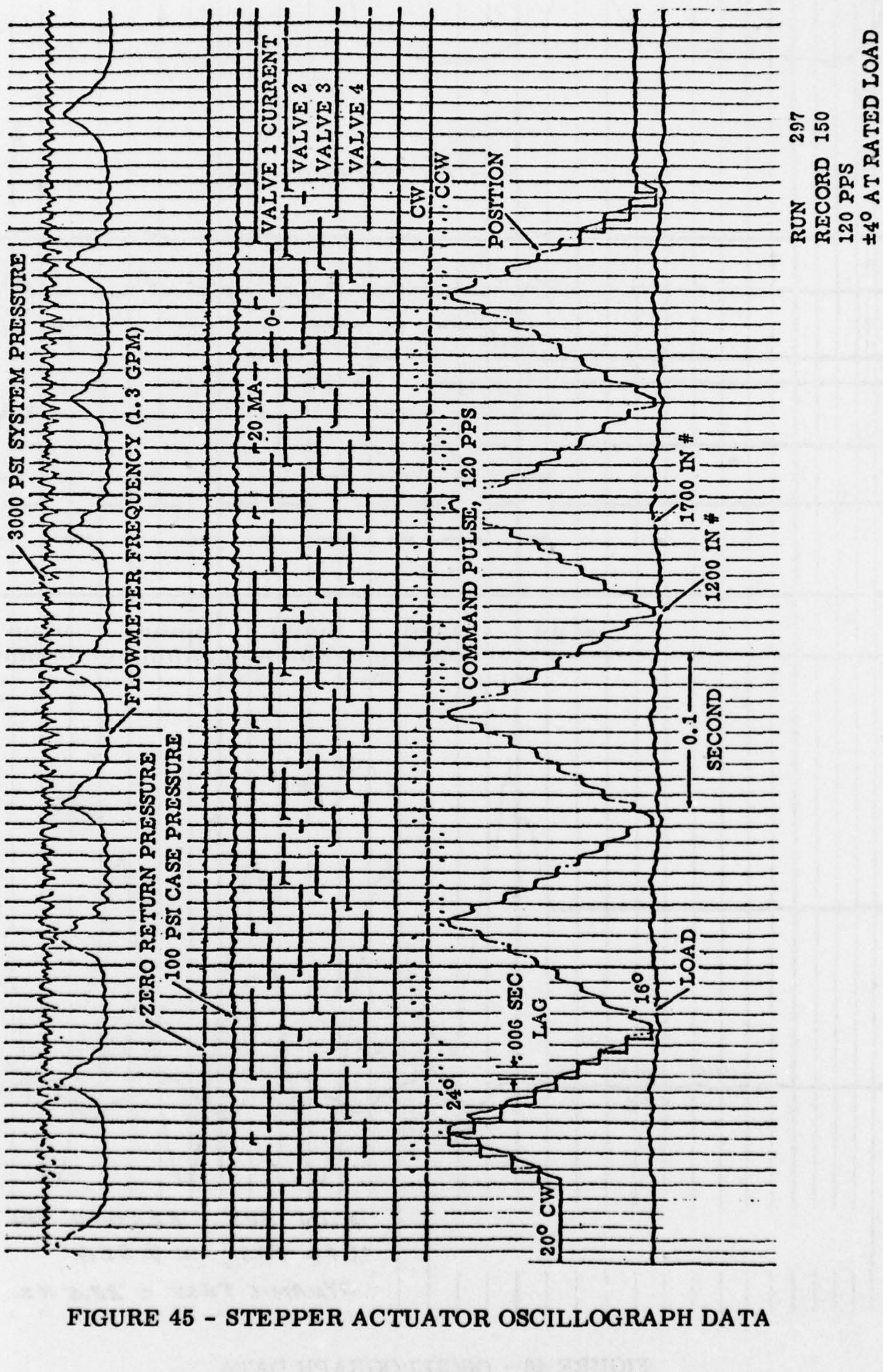

FIGURE 45 – STEPPER ACTUATOR OSCILLOGRAPH DATA

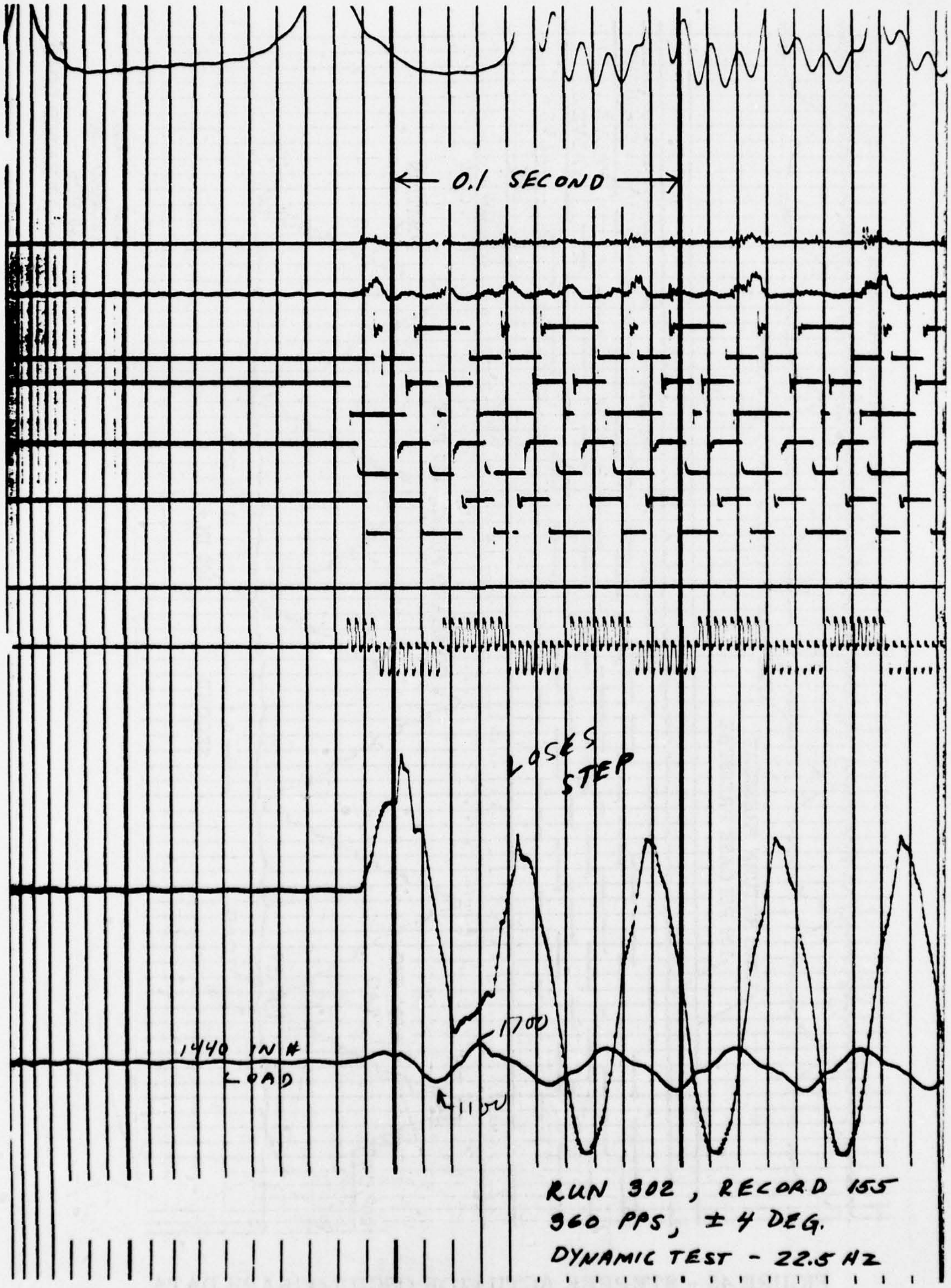

FIGURE 46 - OSCILLOGRAPH DATA

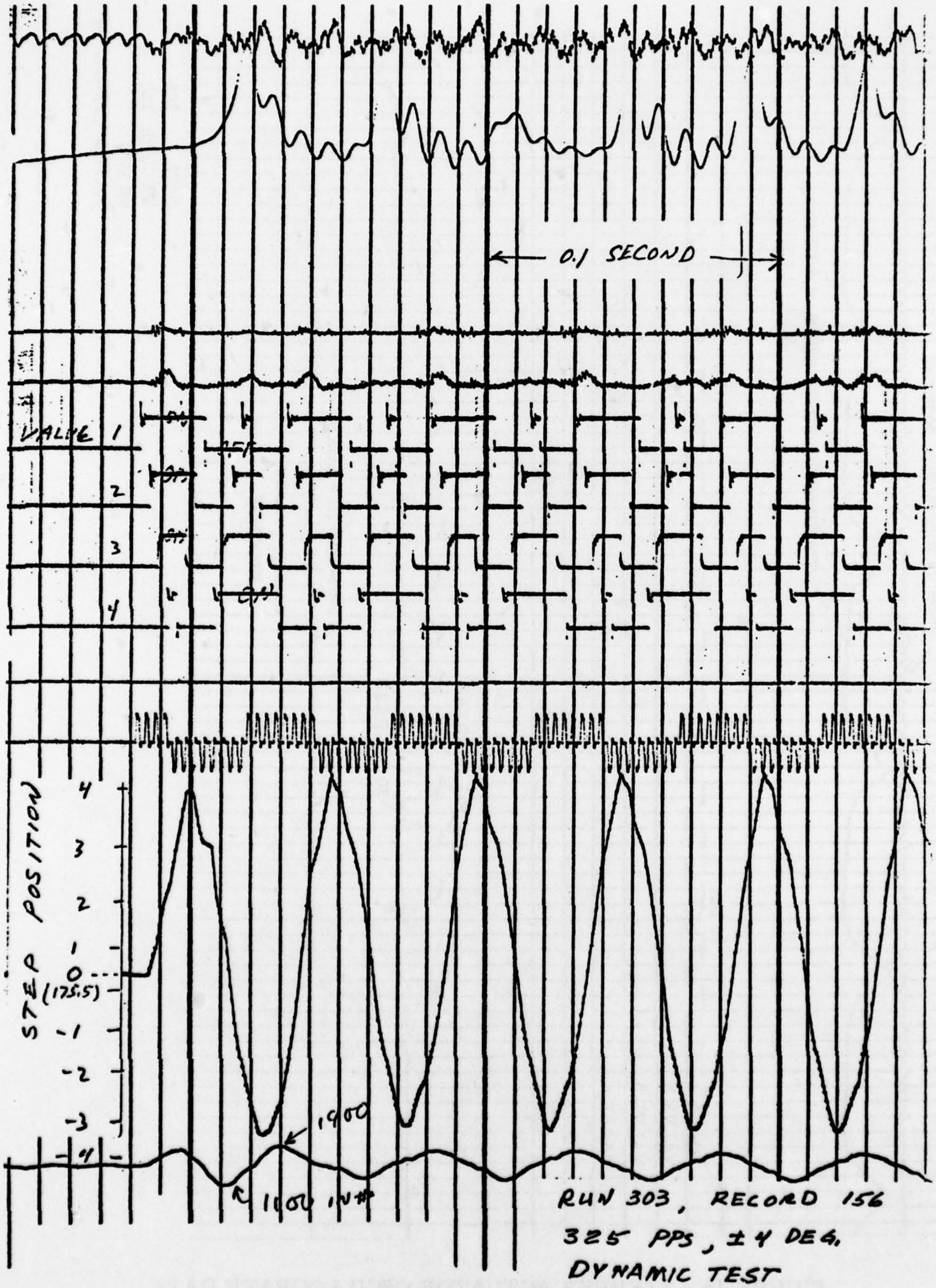

FIGURE 47 - OSCILLOGRAPH DATA

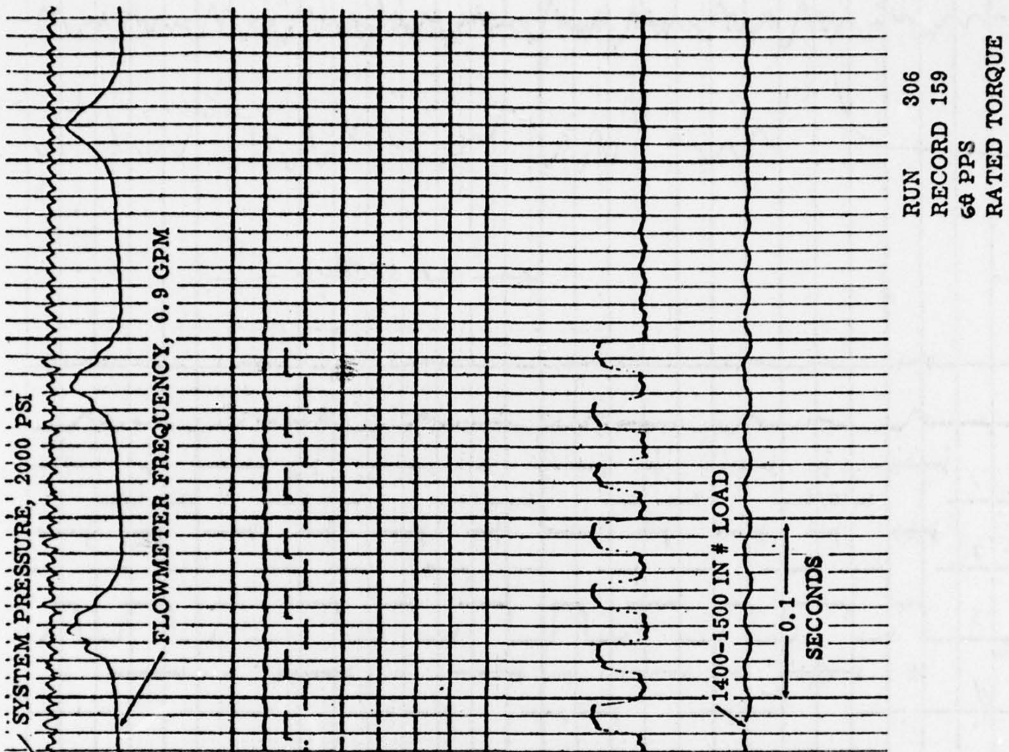

FIGURE 48 - STEPPER ACTUATOR OSCILLOGRAPH DATA

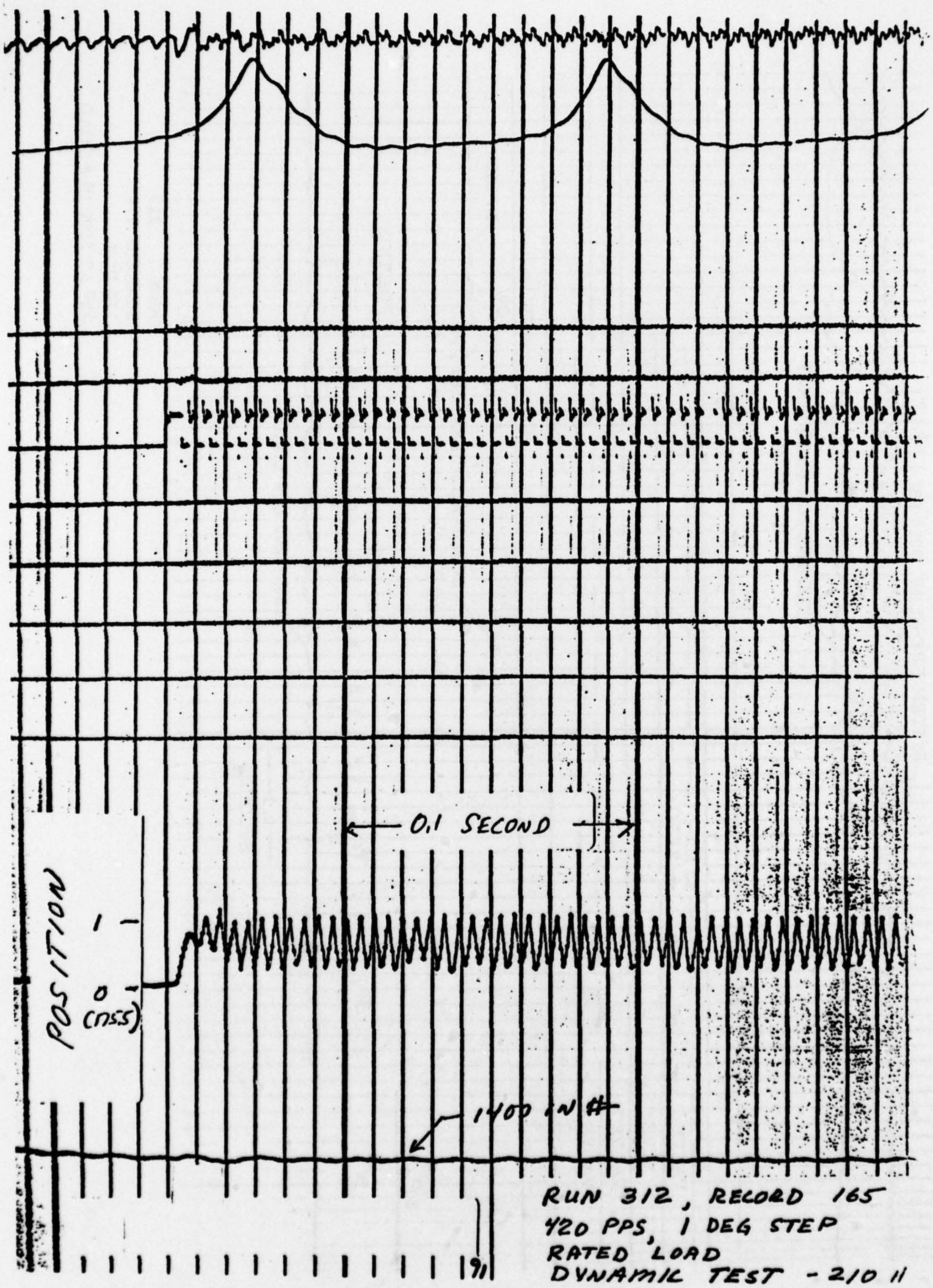

FIGURE 49 - OSCILLOGRAPH DATA

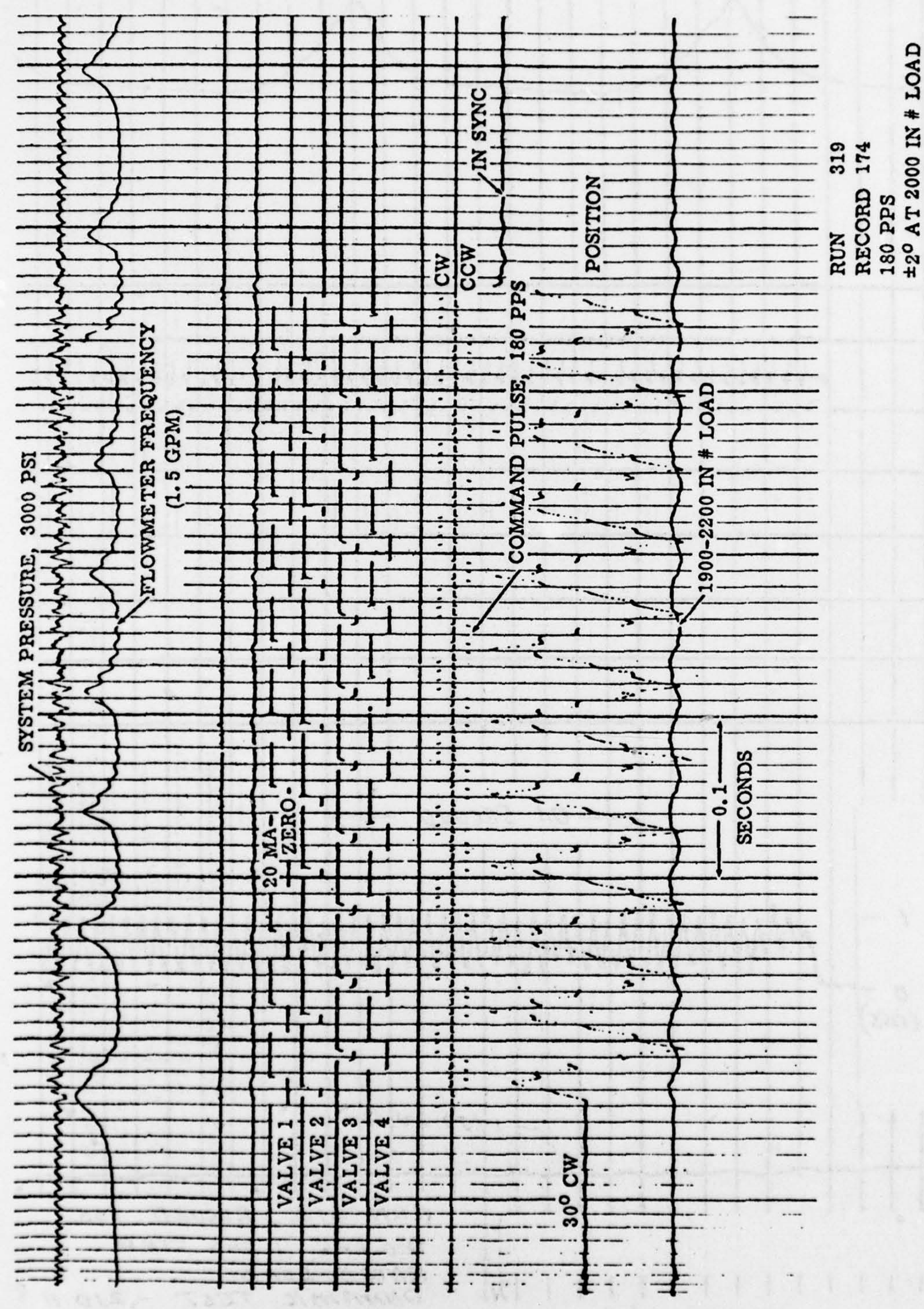

FIGURE 50 - STEPPER ACTUATOR OSCILLOGRAPH DATA

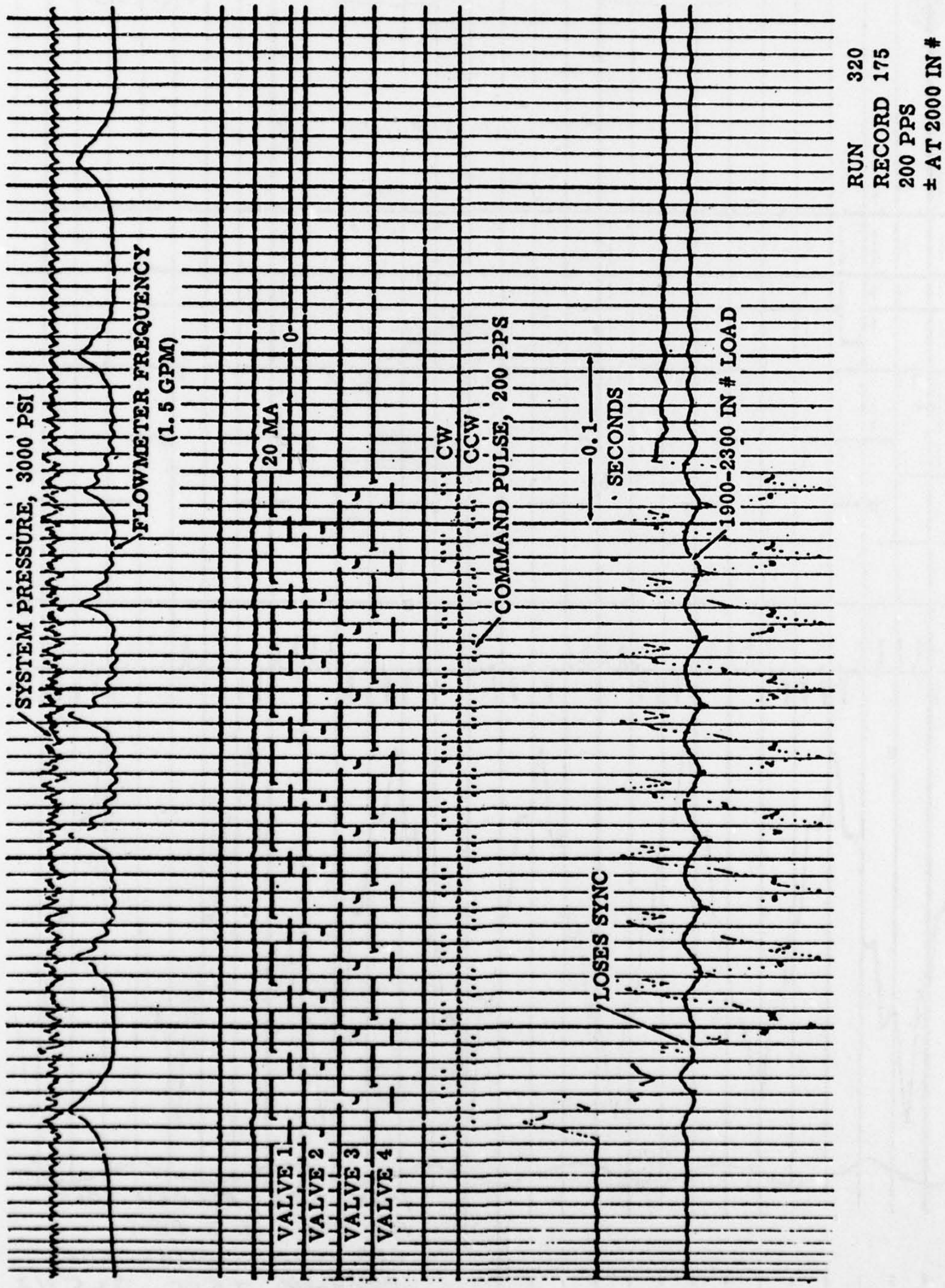

FIGURE 51 - STEPPER ACTUATOR OSCILLOGRAPH DATA

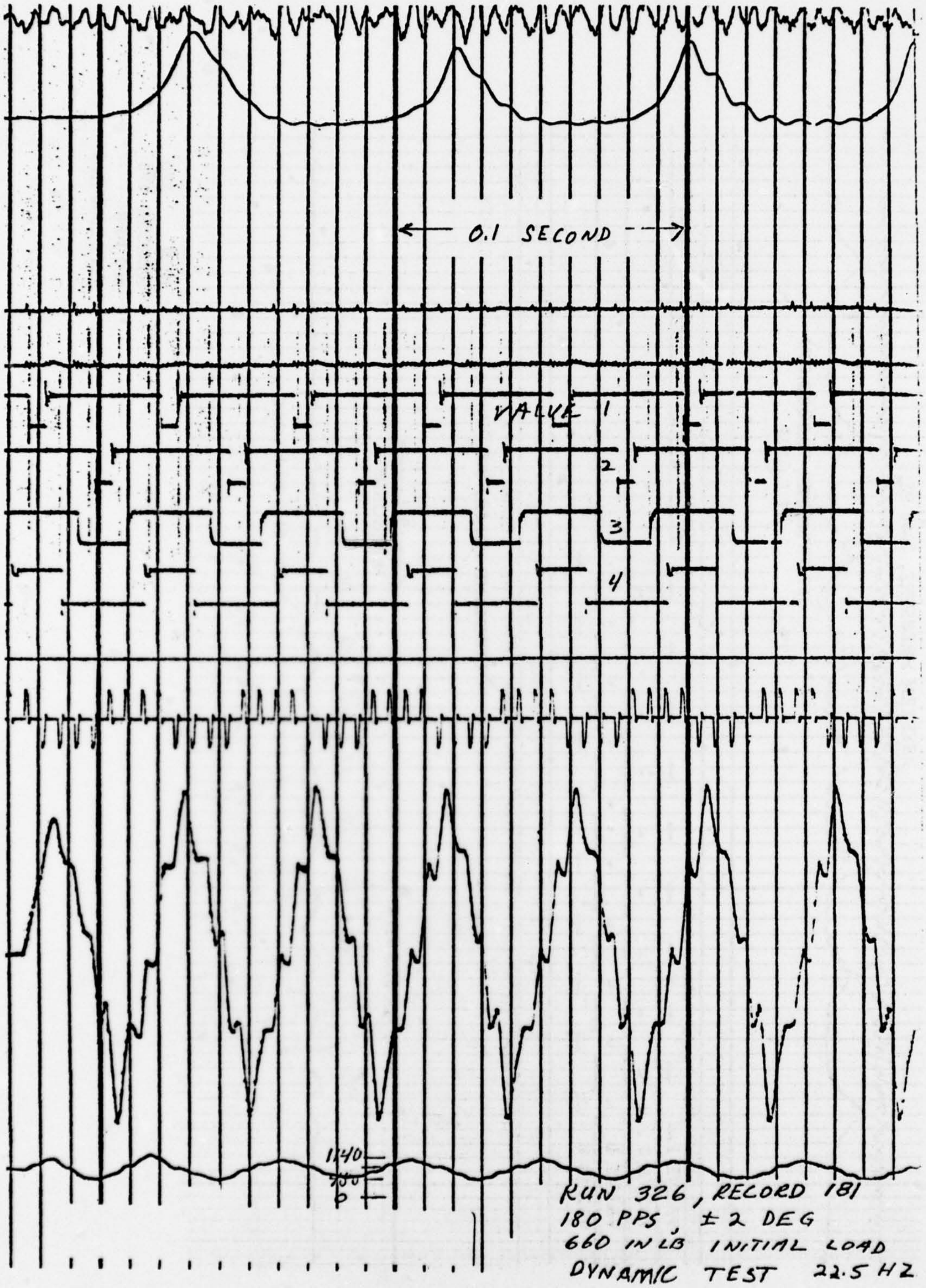

FIGURE 52 - OSCILLOGRAPH DATA

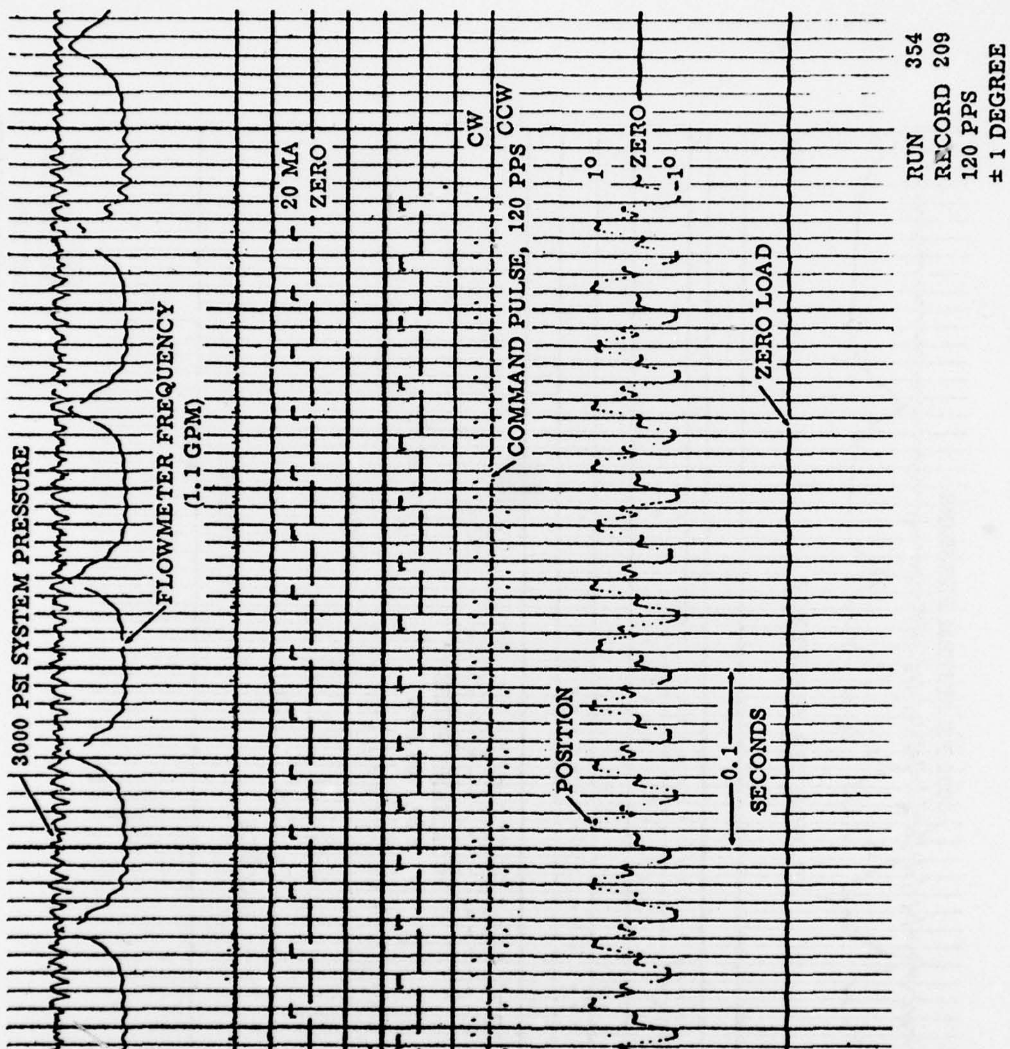

FIGURE 53 - STEPPER ACTUATOR OSCILLOGRAPH DATA

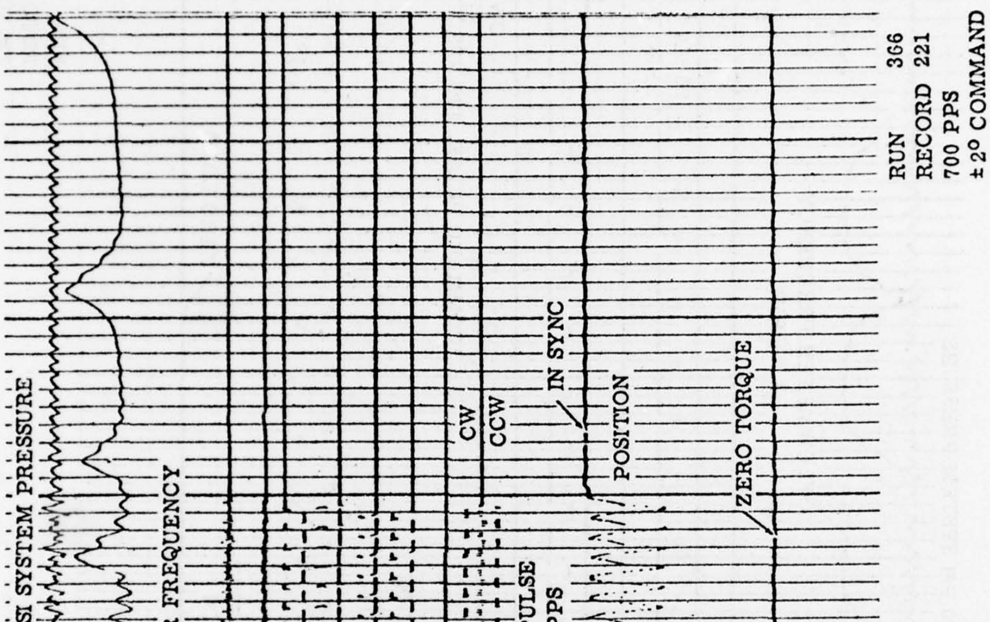

FIGURE 54 - STEPPER ACTUATOR OSCILLOGRAPH DATA

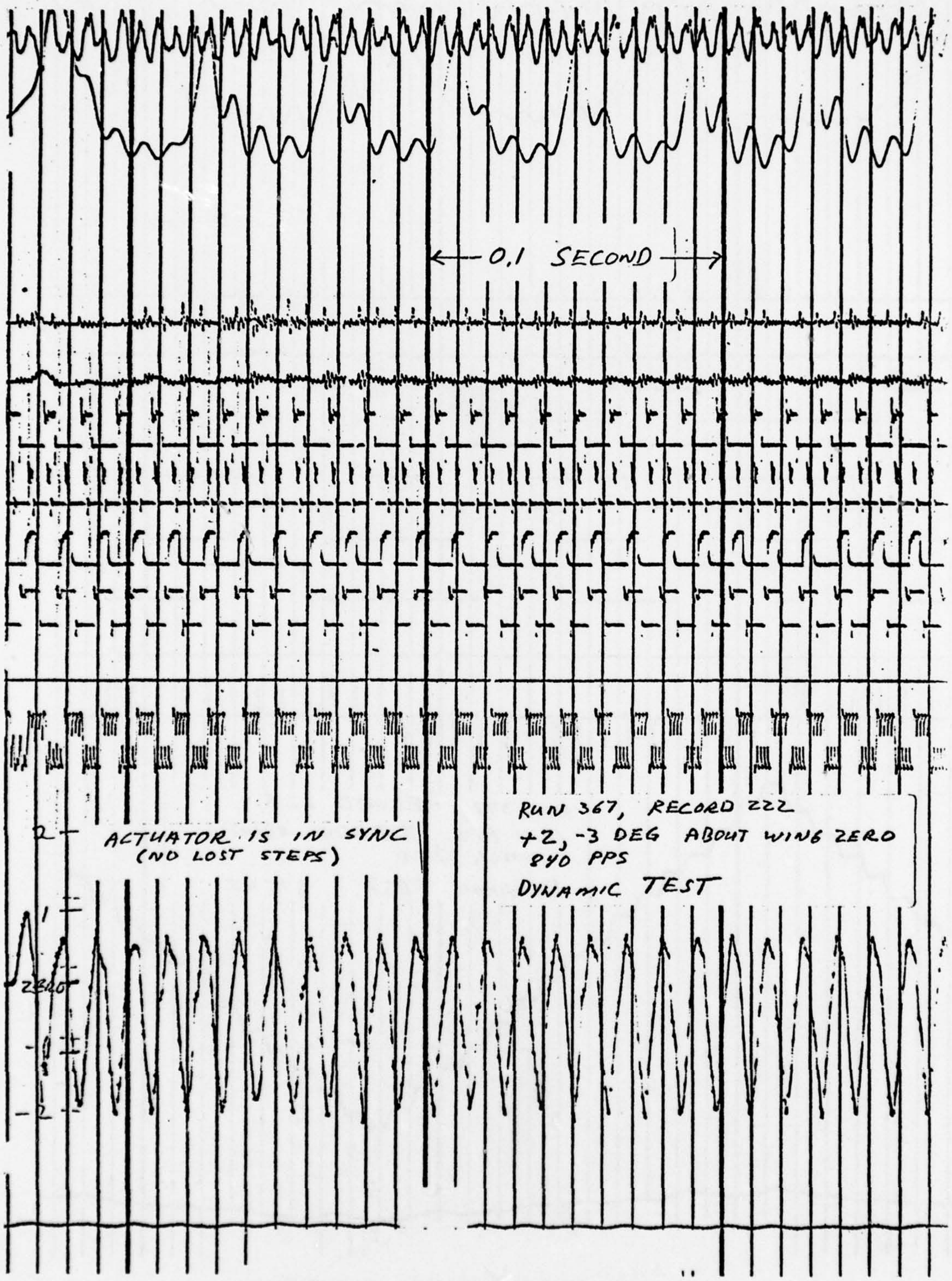

FIGURE 55 - OSCILLOGRAPH DATA

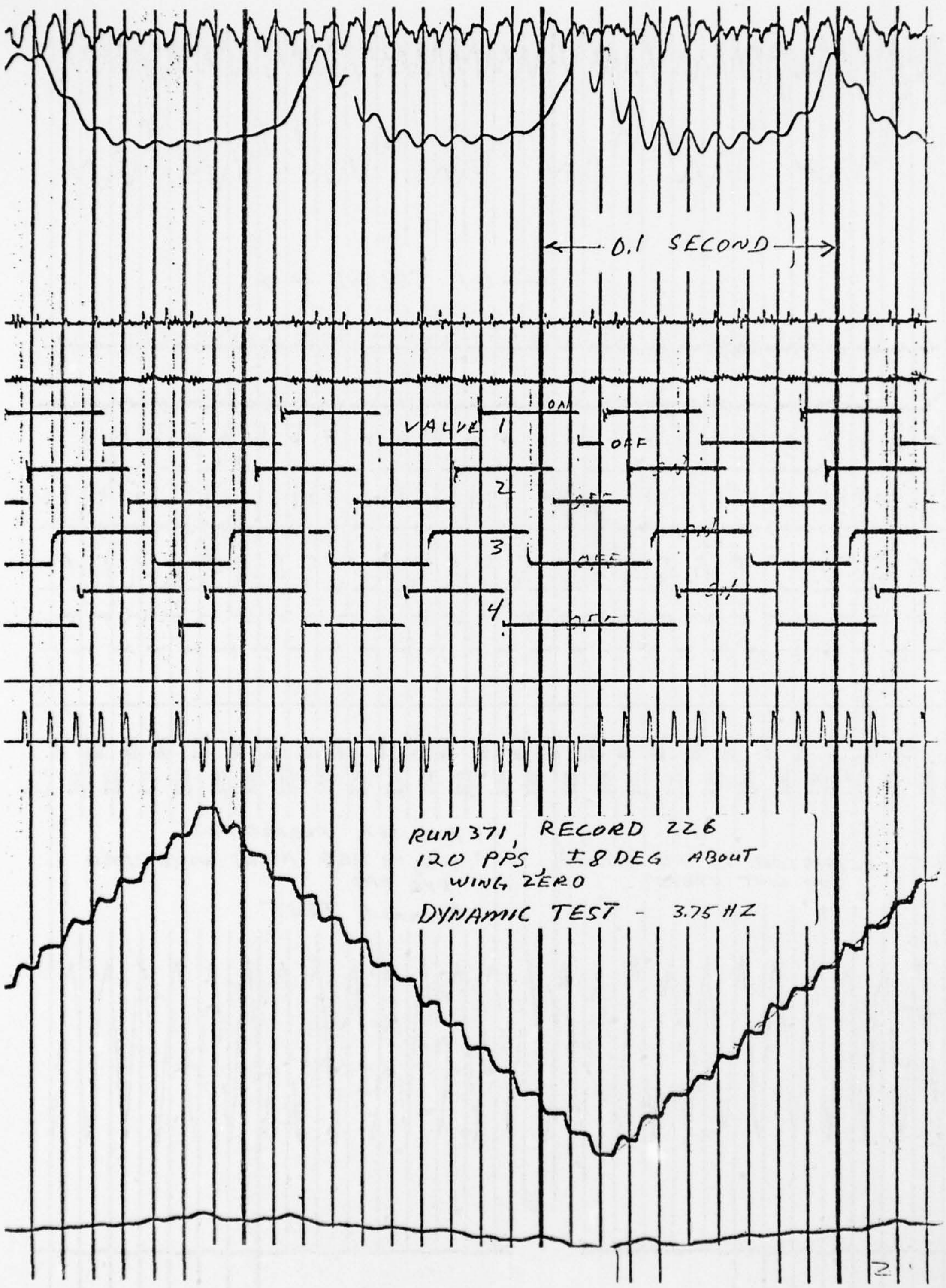

FIGURE 56 - OSCILLOGRAPH DATA

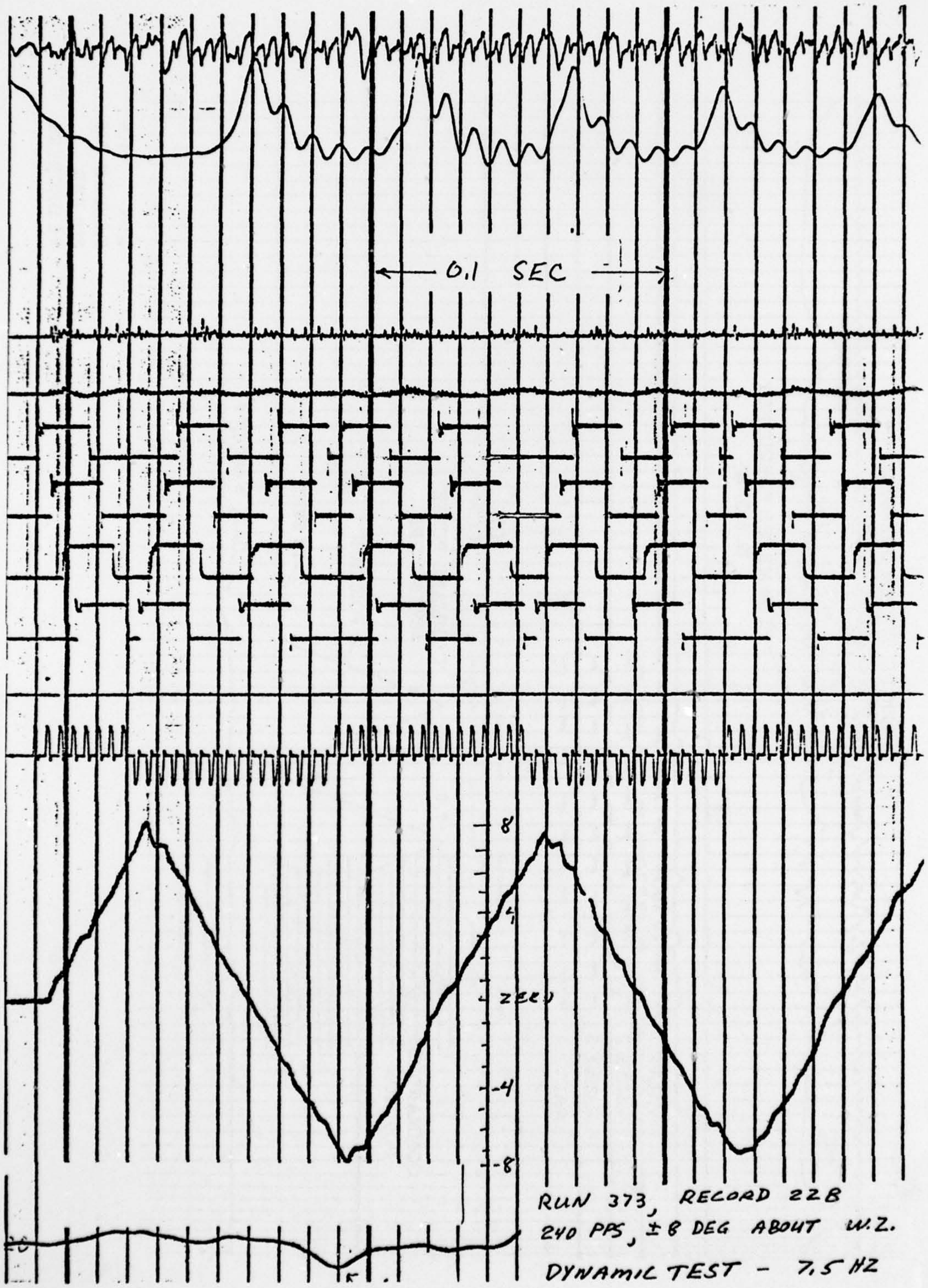

FIGURE 57 - OSCILLOGRAPH DATA

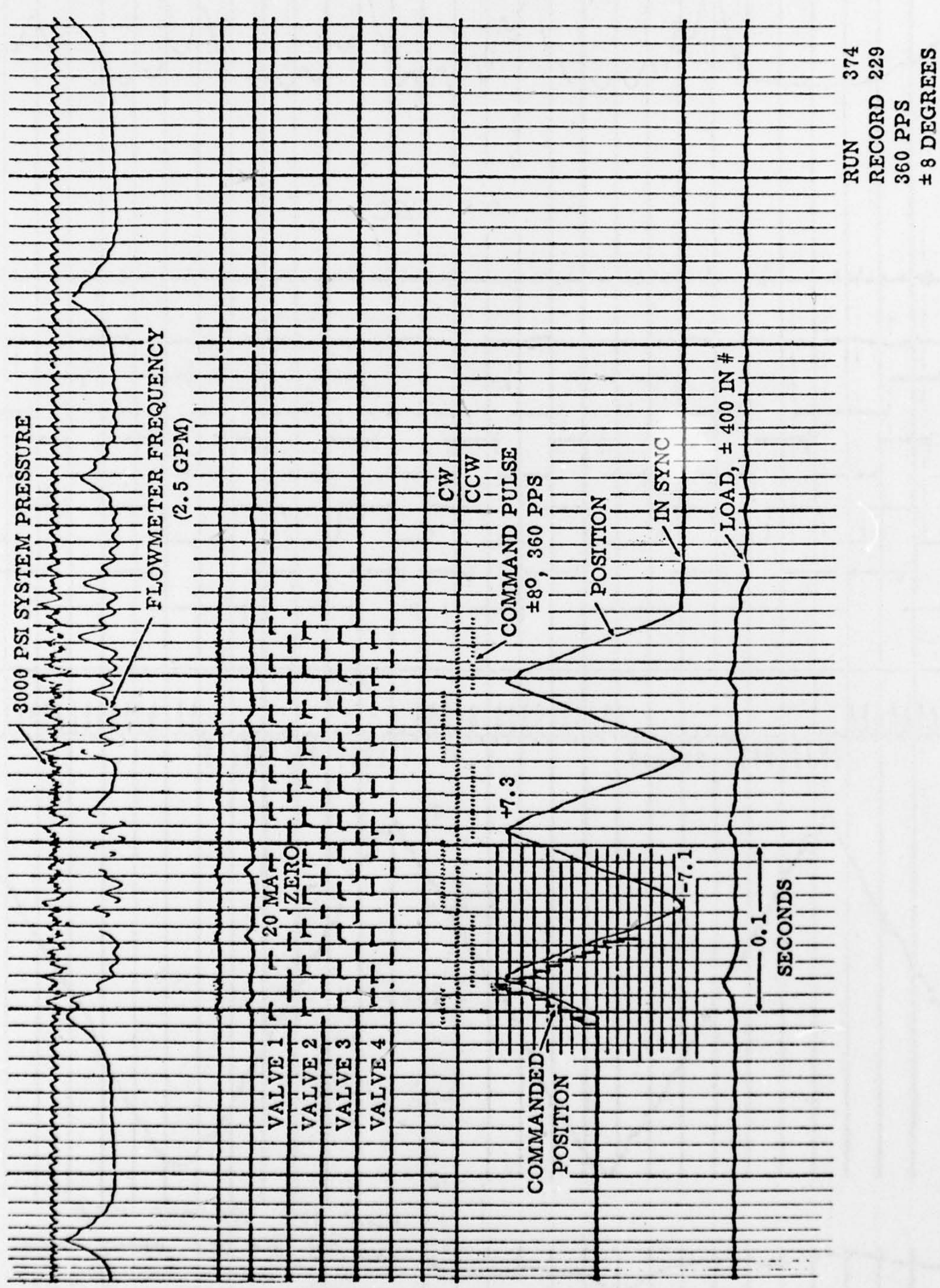

FIGURE 58 - STEPPER ACTUATOR OSCILLOGRAPH DATA

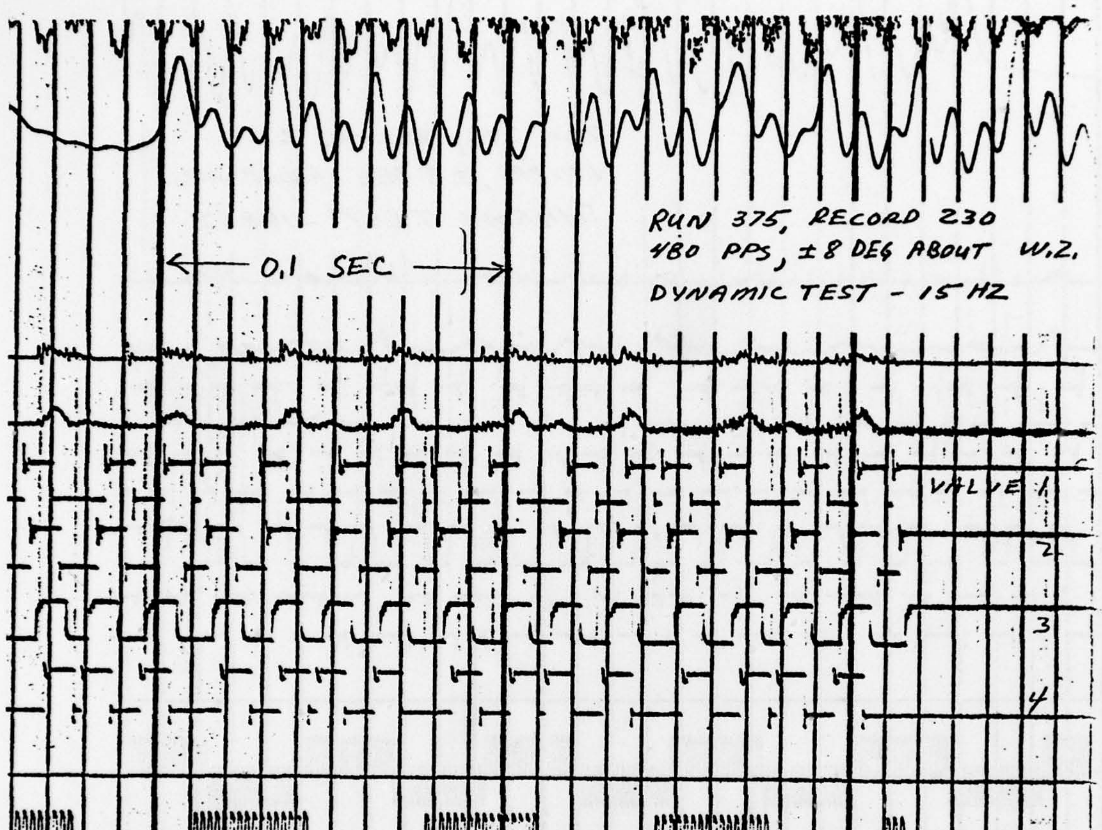

FIGURE 59 - OSCILLOGRAPH DATA

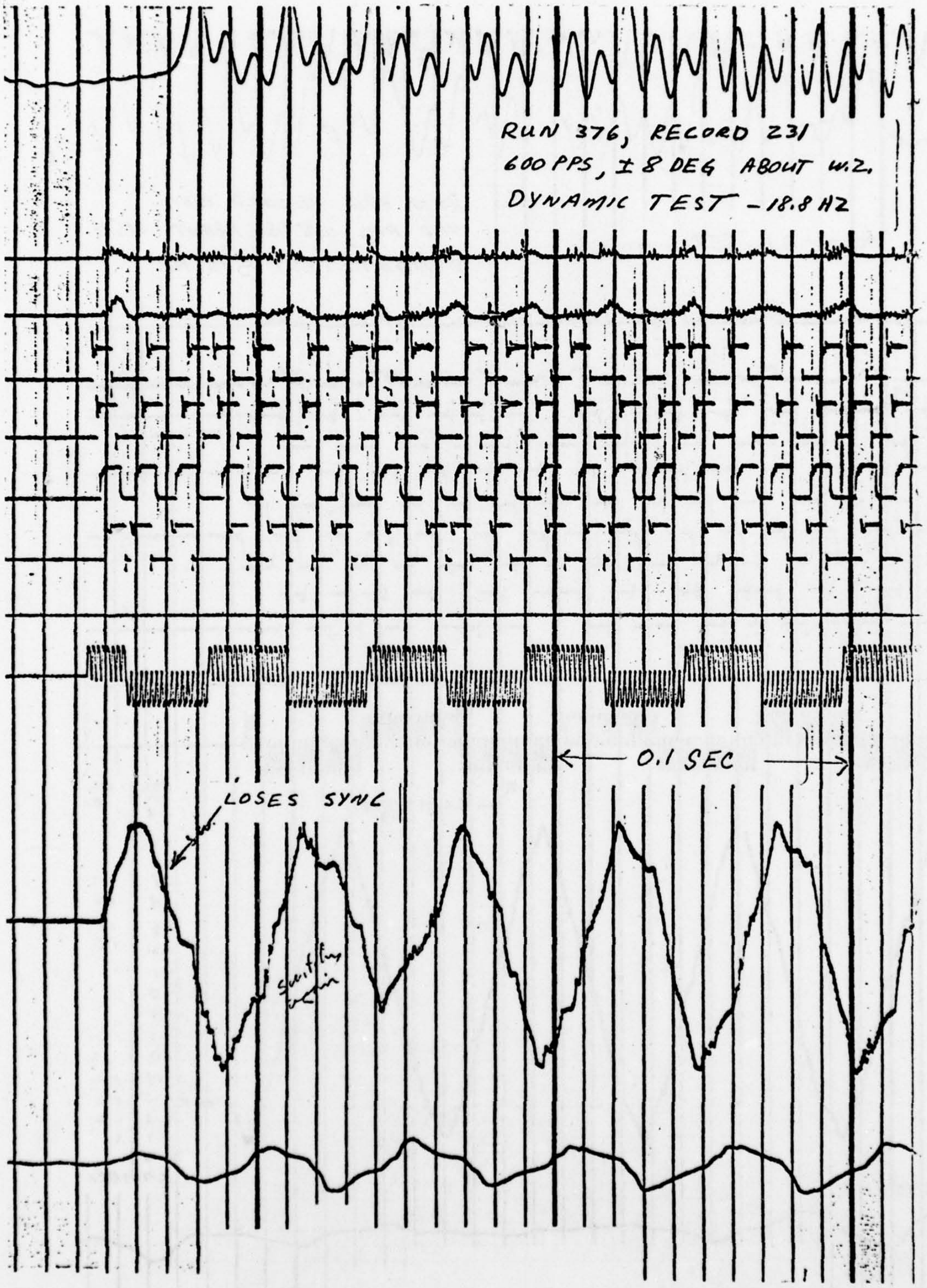

FIGURE 60 - OSCILLOGRAPH DATA

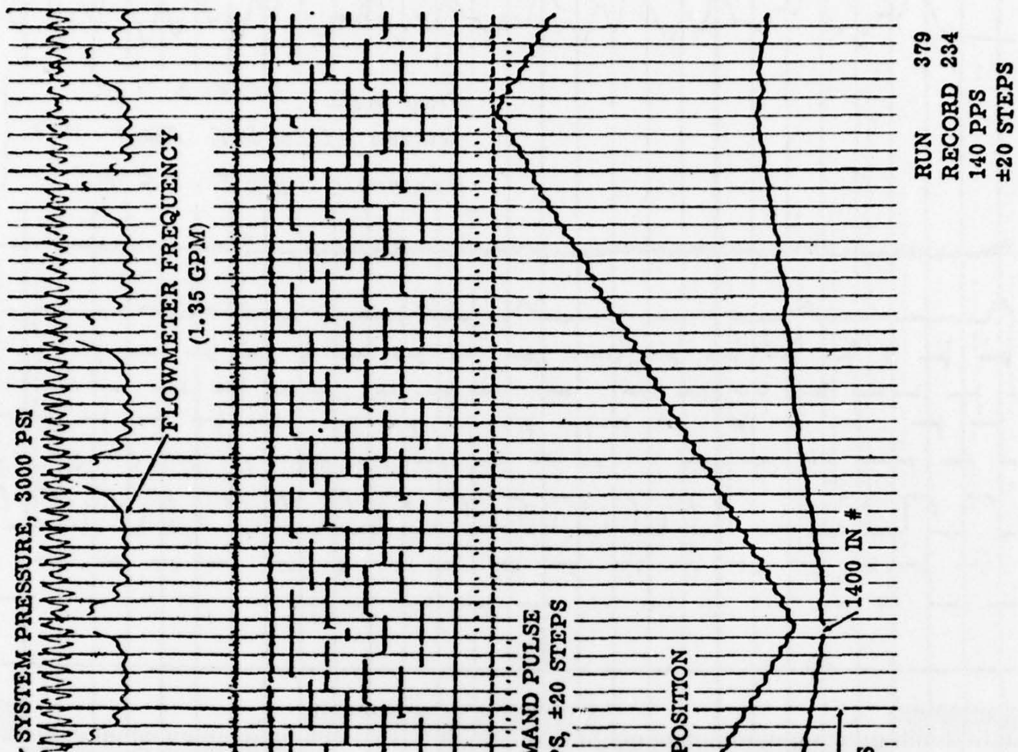

FIGURE 61 - STEPPER ACTUATOR, OSCILLOGRAPH DATA RATED CONDITIONS, LIFE TEST

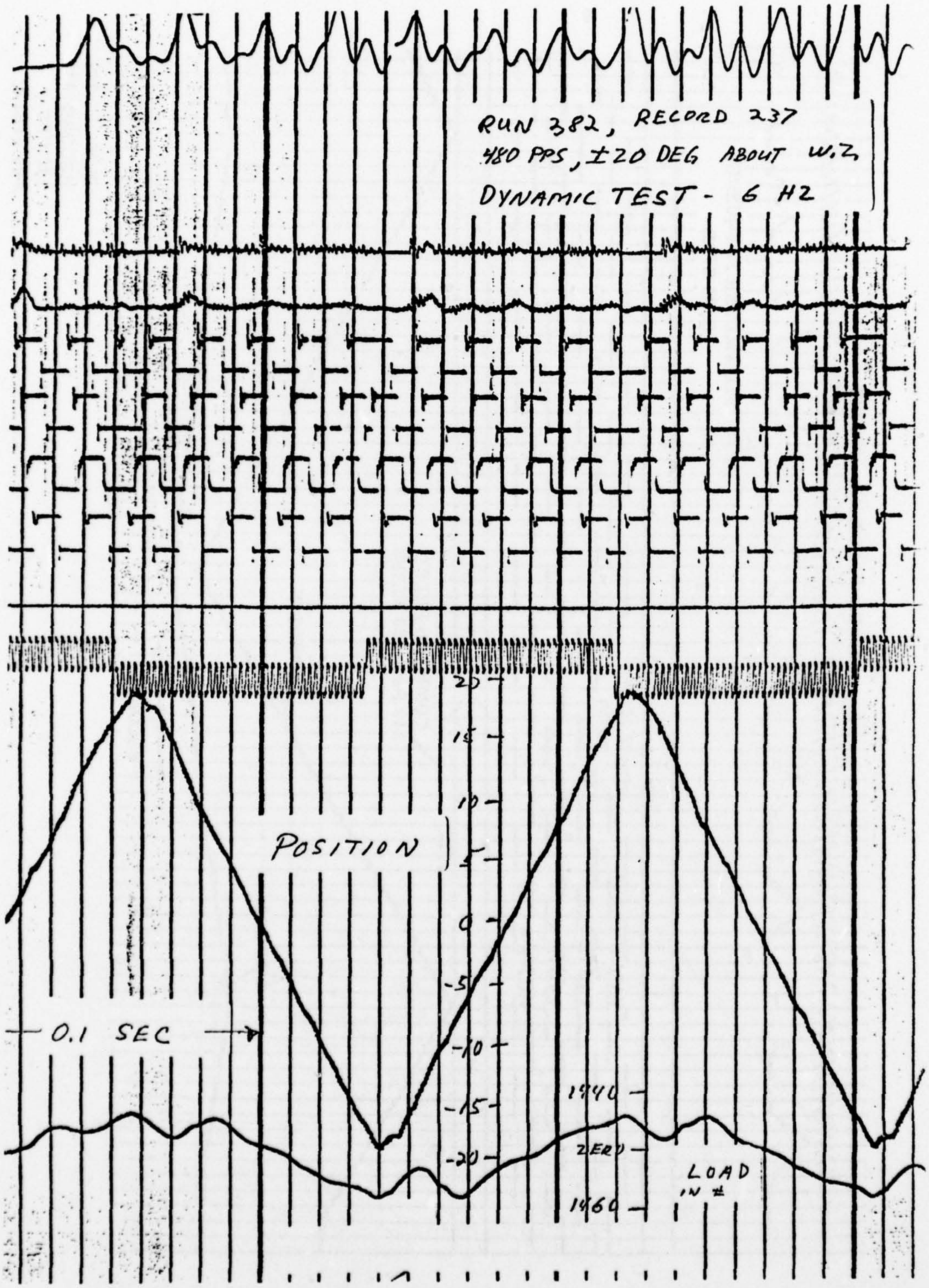

FIGURE 62 - OSCILLOGRAPH DATA

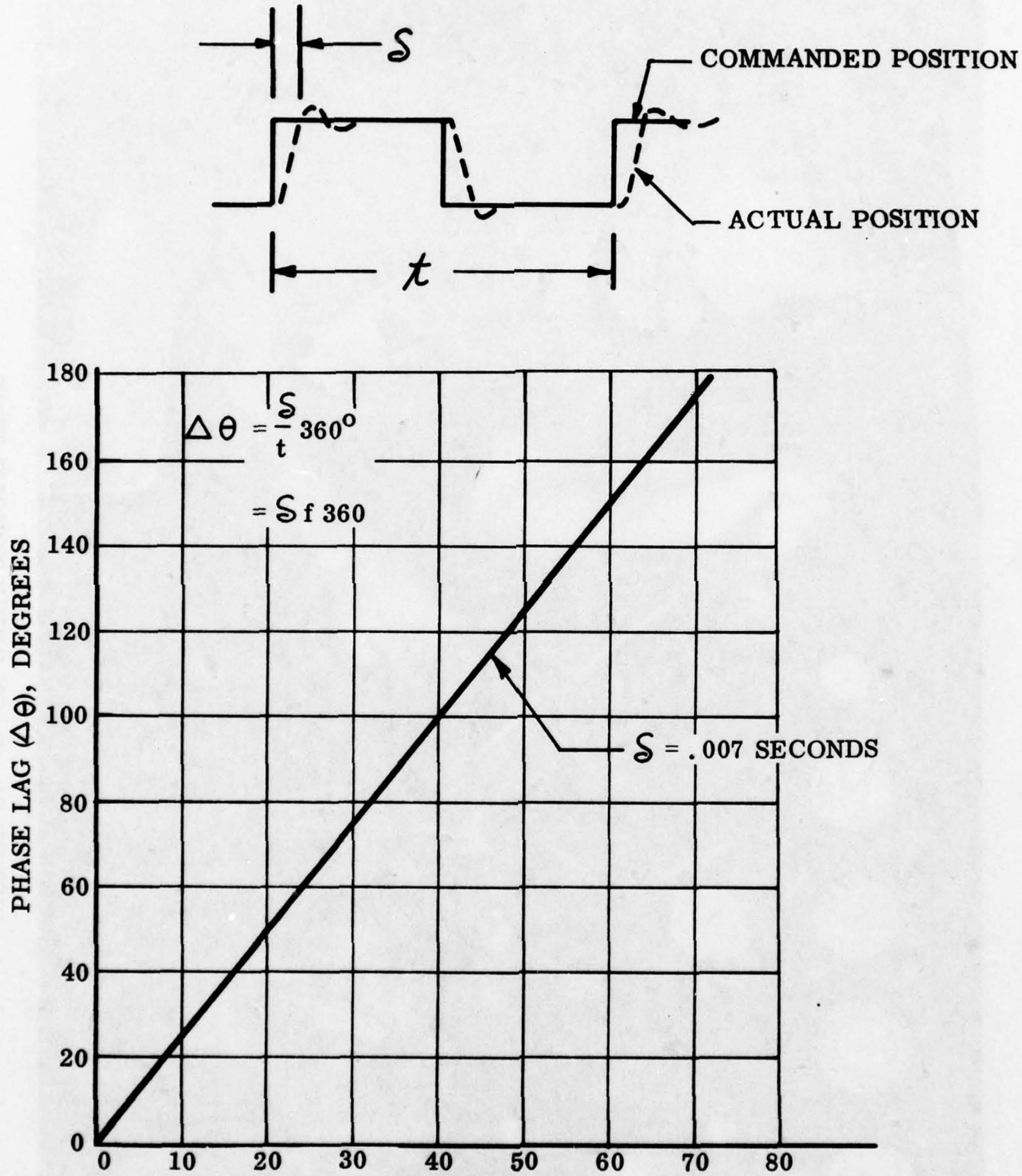

FIGURE 63 - PHASE LAG

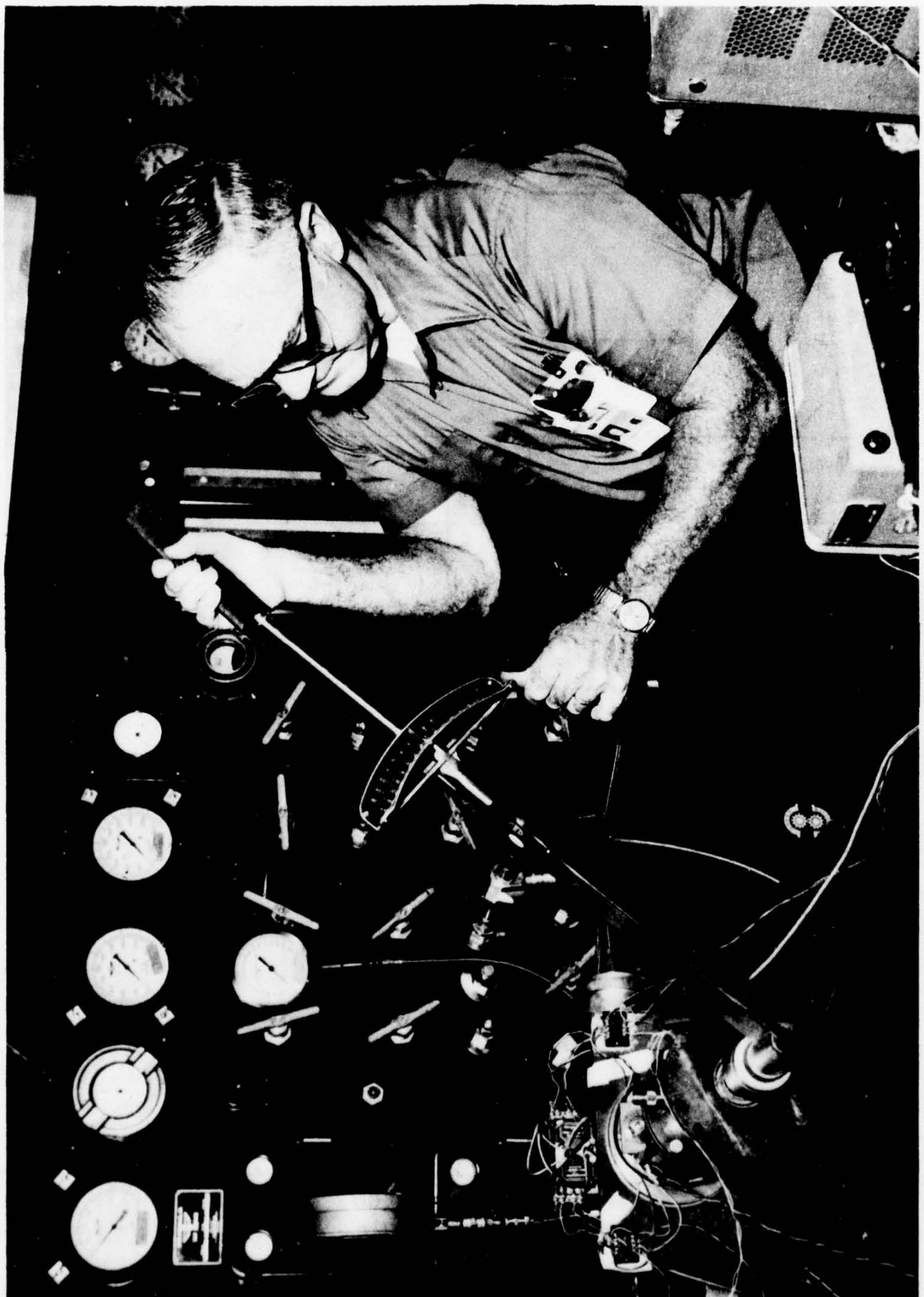

FIGURE 64 - BACK DRIVE TORQUE TEST

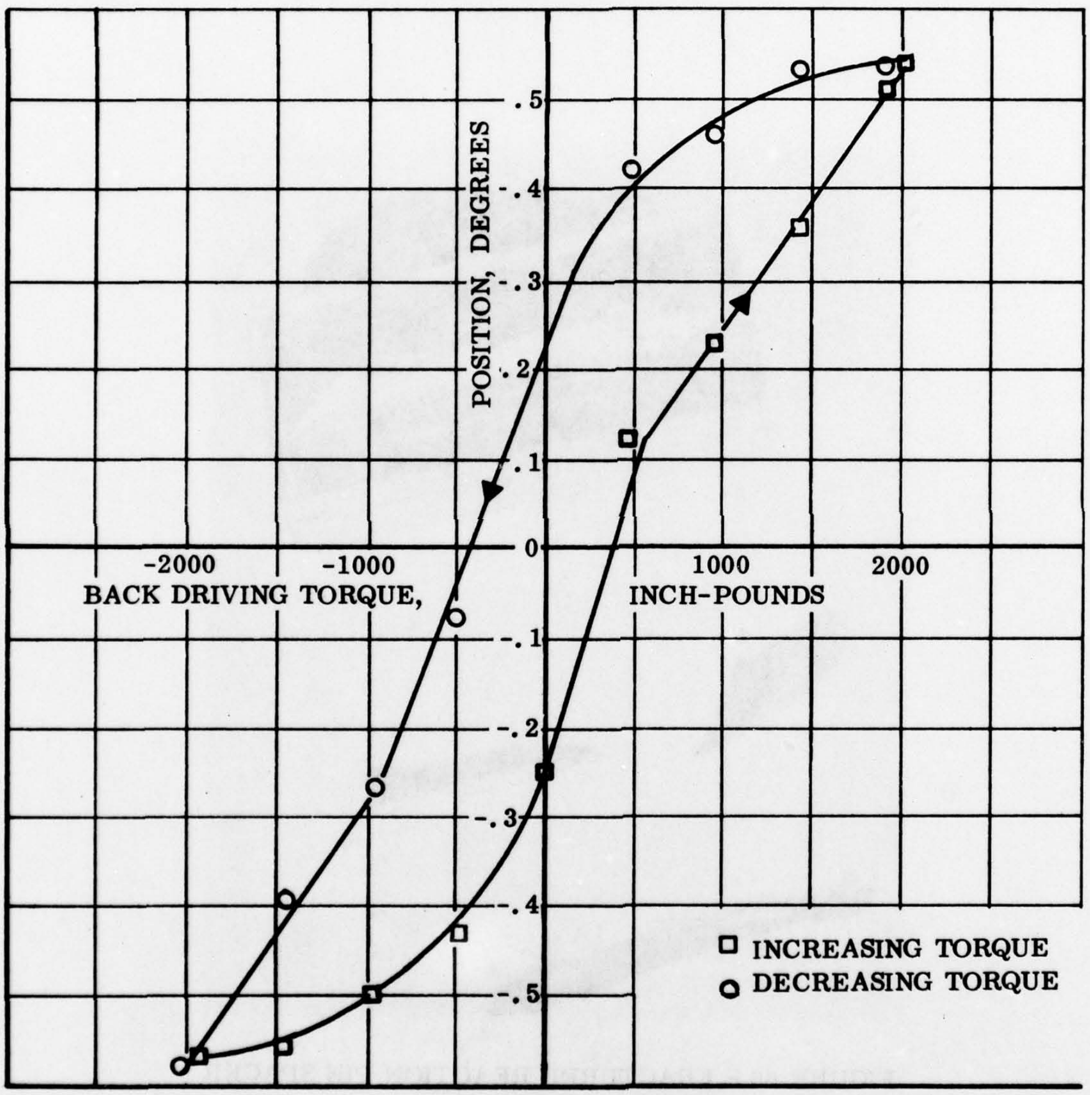

FIGURE 65 - BACK DRIVING TORQUE VS ACTUATOR POSITION

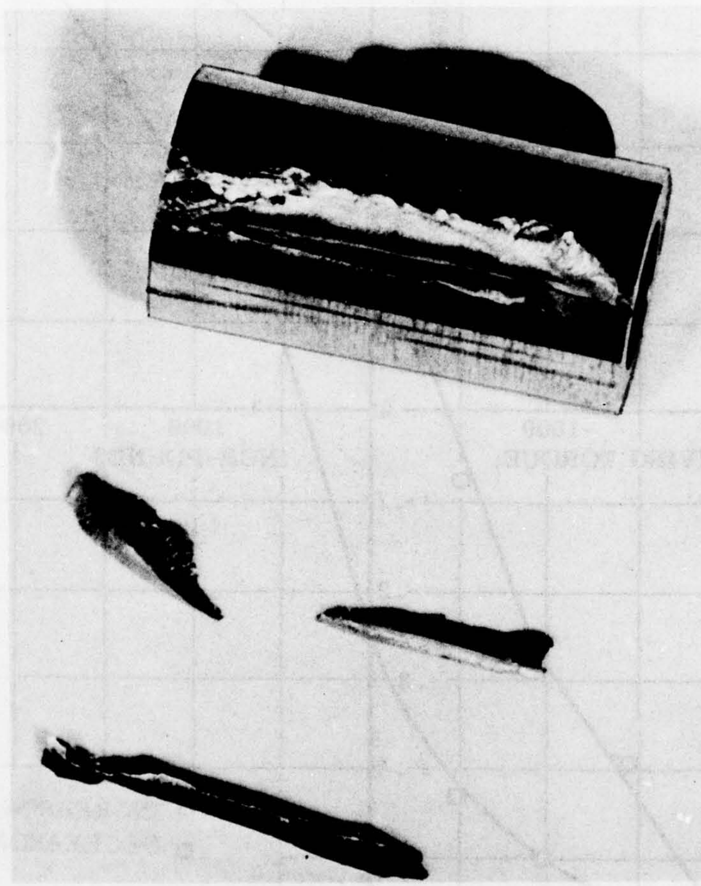

FIGURE 66 - FRACTURED REACTION PIN SPACER

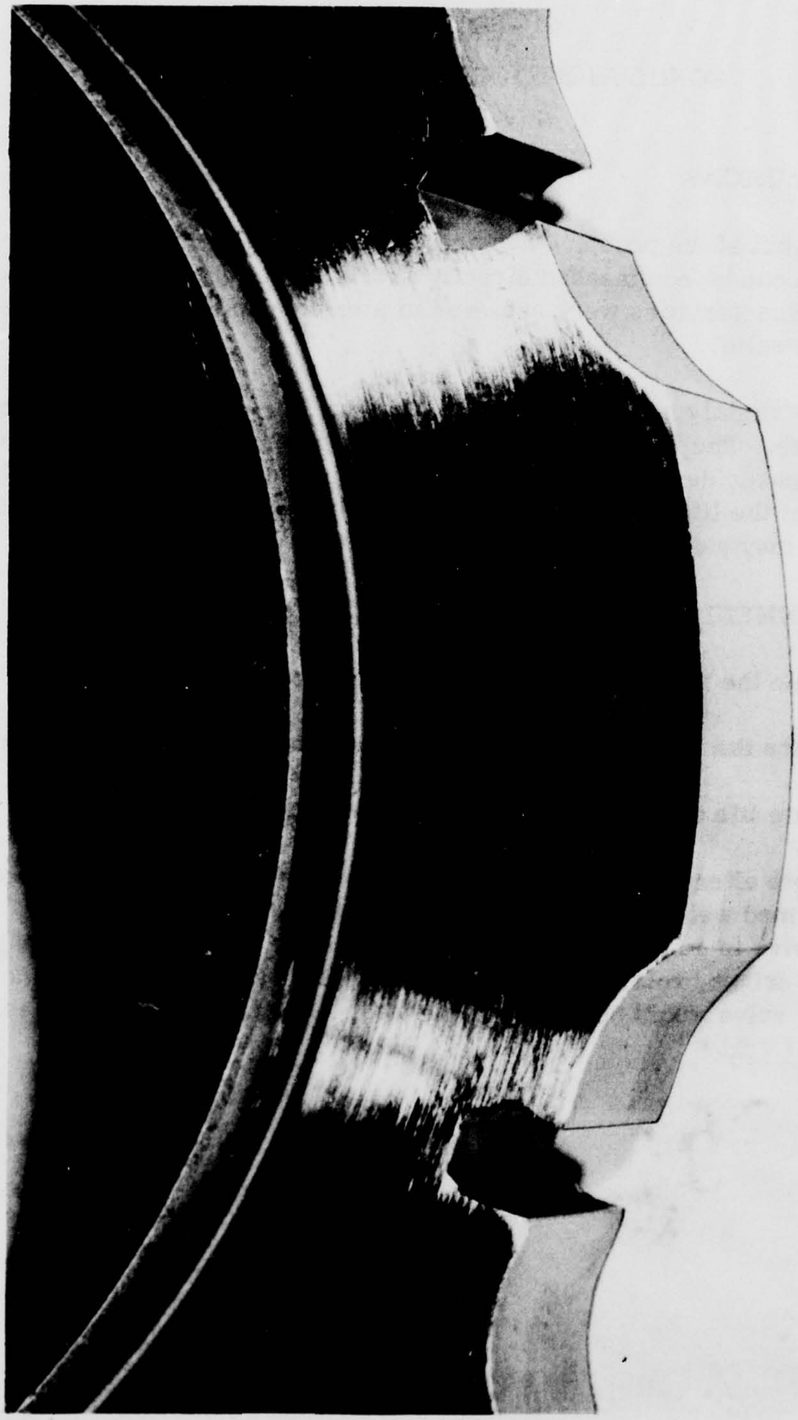

FIGURE 67 - DAMAGED ROTOR

SECTION V

CONCLUSIONS AND RECOMMENDATIONS

5.1 CONCLUSIONS

The primary goal of the probject was accomplished. A hydraulic actuator was developed that can be commanded directly with a digital error signal. Required speed/load characteristics were achieved in a volume and weight permitted by an airborne missile.

Flow rate was slightly higher that desired but can be reduced by optimizing the rotor clearance. The fifty hour life remains to be demonstrated. The new reaction pin spacer design will increase the life of the actuator. It should be pointed out that the life testing was done at rated loads and the 24 hour endurance demonstrated may satisfy some missile programs.

5.2 RECOMMENDATIONS

1. Evaluate the actuator at elevated temperatures.

2. Optimize the rotor clearance for minimum leakage, high performance.

3. Evaluate life of actuator with the new reaction pin spacer.

4. Evaluate alternative first stage designs. The four switching valves performed well, have a proven high reliability, but may be more expensive in a high production program than a single electric stepper motor driven, rotary, hydraulic valve. Oil leakage rate across a rotary valve would be less than the total leakage of the four valves.

APPENDIX A

QUALITATIVE COMPARISON OF ROTARY AND INDIVIDUAL VALVES

FOR CONTROL OF

ELECTROHYDRAULIC STEPPER DYNAVECTOR^R ACTUATOR

Internal
Memorandum

Bendix Research Laboratories

Date May 13, 1974   Letter No. 3662   Southfield, Michigan

To A. A. Seleno

From J. H. Tarter

Subject Qualitative Comparison of Rotary and Individual Valves for Control of Electrohydraulic Stepper Dynavector[R] Actuator

The purpose of this memorandum is to document the results of a qualitative comparison of the two basic approaches to controlling the electrohydraulic stepper Dynavector actuator. These are a single rotary valve with eight output ports, each output connecting to a Dynavector motor chamber; and individual linear solenoid valves, each connected to a motor chamber, or a pair of motor chambers.

As a preliminary step, a list of the various alternative methods of controlling a hydraulic stepper Dynavector actuator with an electric input was made up. The following approaches were identified:

1. Rotary Valve Approaches

   a. Direct Electric Drive

      i Rotary valve separating vent and supply pressures into two 180° segments driven by conventional dc stepper motor.

      ii Rotary valve separating vent and supply pressures into two 180° segments driven by electric stepper Dynavector motor with one-to-one ratio.

      iii Rotary valve separating vent and supply pressures into four 90° segments driven by electric stepper Dynavector motor with two-to-one ratio.

   b. Electrically piloted hydraulic approaches

      i All approaches listed under "a" above porting flow to a hydraulic stepper motor driving a rotary valve which ports flow to main stepper actuator.

      ii All approaches listed under "a" above porting flow to individual hydraulically actuated linear valves.

2. Individual Valve Approaches

   a. Eight three-way valves

      i Direct solenoid actuated, spring return
      ii Direct solenoid actuated, solenoid return
      iii Solenoid pilot, hydraulically actuated and return

   b. Four four-way valves, variations as in "a" above.

   c. Four four-way or eight three-way pilot valves controlling a hydraulically driven rotary valve as in "1.b.i" above.

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For purposes of the present program, all electric piloted, hydraulically actuated valve approaches were rejected. The basis of this rejection was the undue complexity, which was deemed to be undesirable for a preliminary design prototype. It is believed however, that as step size is decreased, causing pulse rate to increase, the use of an electric-piloted hydraulically actuated valve of one type or another will become necessary to obtain the required valve response.

Based on the above, the comparison described here was limited to "1.a.i", "1.a.ii", 2.a.i", and "2.b.i". These approaches were compared with regard to their characteristics in the following areas.

a. Leakage
b. Dynamic response
c. Slew rate
d. Complexity
e. Coil size
f. Friction and bearing considerations
g. Growth potential
h. Risk
i. Packaging

Leakage

Although the rotary valve must have a larger diameter spool than the individual valves and because of pressure balancing considerations, must have a fairly complex land geometry; the fact that only a single spool is required instead of four or eight as is the case with the individual valves, leads to the conclusion that the leakage of the rotary valve will be less than that of the equivalent individual valves. Preliminary calculations indicate that the individual valves will have a leakage two to three times that of the individual valves. This indicates that great care must be taken in the design of the individual valves since the oil gets quite thin at elevated temperatures. Spool clearance must be kept to a minimum (no more than 0.0004 in the diameter).

Dynamic Response

For purposes of comparing the dynamic response associated with the two approaches, an estimate of the mass of an individual valve spool and of the mass moment of inertia of two rotary valve spools was made. These were assumed to be part of a spring-mass system and the spring constant either linear of rotary, required to obtain a given natural frequency was completed. This multiplied by the required deflection of the valve for a step gives a value of coil force or torque which gives an indication of the difficulty of obtaining a given response.

The linear valve spool was assumed to consist of two cylinders, one 0.25 in diameter x 1.00 in long, the other 0.50 in diameter by 0.50 in long. The mass of such a spool is 1.14×10^{-4} lb-sec^2/in. For a natural frequency of 30 hz (which is obviously the very minimum for a system requiring a 30 hz bandpass), the required spring rate is 4.07 lb/in.

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For 0.016 in spool travel, the required solenoid force is 0.065 lb; for 0.032 in spool travel, the required solenoid force is 0.130 lb. If a more realistic natural frequency of 90 hz is assumed, the spring rate is 36.6 lb/in and the required forces for 0.016 or 0.032 in travel become 0.58 and 1.2 lbs.

The rotary valve spool was assumed to be 0.50 in diameter x 1.00 in long. The rotor of the dc motor was assumed to be a 0.375 in thick semicircle of 0.875 in radius. This gives a mass moment of inertia of 1.389×10^{-4} in-lb-sec^2. For a 30 hz natural frequency, the required spring constant is 4.94 in-lb/rad. Each step is /4 rad so that the required torque is 3.87 in-lb. If the natural frequency is 90 hz, the required torque 34.9 in-lb. Since the moment arm is less than 1 in, coil forces are obviously larger than those required for a linear valve having an equivalent natural frequency.

For the electric Dynavector driver (as shown in the proposal drawing) the mass moment of inertia is 5.09×10^{-6} lb-in-sec^2 and for a natural frequency of 30 hz, the spring constant is 0.181 in-lb/rad giving a torque of 0.142 in-lb for a /4 step;for a 90 hz natural frequency, the spring constant is 1/628 in-lb/rad and the torque is 1.279 in-lb. With the 0.0375 in eccentricity these torques require coil forces of 3.8 lb and 34.1 lb.

It may be concluded from these rough calculations that the coil forces required for either of the direct electric drive rotary valve approaches will be greater than those required to obtain equivalent response with the individual valves. Hence, it will be easier to obtain higher dynamic response with the latter approach.

Slew Rate

Although the rotary valve has a lower dynamic response than the individual valves, it will have a better slewing capability. This is because the rotary valve will rotate continuously or semi-continuously while driving the output stage in a single direction, while the individual valves must reverse direction for every pulse while slewing. In this case, assuming that the step size is not smaller than one degree, the dynamic requirements on the individual valves to meet the dynamic response requirements and the slew requirements are not greatly different.

Complexity

Although judgements in the area of complexity are somewhat subjective, the rotary valve approach appears to be the most complex. The land configuration required to pressure balance the rotary valve spool is definitely more complex than that of the individual valves. The rotary valve requires a shaft seal and bearings and has a more complicated coil geometry; considerations of rotor geometry and electromagnetic design are also more complicated.

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Coil Size

The fact that the rotary valve approach requires higher coil forces than the individual valves suggests that coil sizes will be larger.

Friction and Bearing Considerations

Although it is possible on paper to derive a rotary valve geometry that is statistically pressure balanced, uncertainties regarding flow and dynamic effects would suggest that there will be some side loading on the rotary valve spool. Moreover, there will be side loads imposed on the rotor by the electric stepper stage. A 250 deg-sec slew rate with a 48 to 1 gear ratio on the main actuator require that the rotary valve have a 2000 rpm speed. At this speed, with side load, materials considerations between the spool and the sleeve become important. Moreover, if materials are selected for bearing consideration, difficulties in thermal expansion as operating temperatures rise. Design of the shaft seal required on the rotary valve also becomes critical at these speeds.

Growth Potential

The present prototype design will give approximately a one degree step. This is considered larger than would be desirable in a final design. Obtaining smaller step sizes requires higher pulse rates which will almost certainly require electrically piloted, hydraulic actuated valves. It appears that the individual valves are much more readily adaptable to this approach than any of the rotary valve approaches that have been suggested. Small pilot on-off solenoid valves capable of much higher pulse rates than are being considered for the present application have already been built. Based on what has been said in this memorandum under "Dynamic Response", a rotary electric pilot stage (which could not be much smaller than the direct electric driver rotary valve investigated here) would have definite frequency response limitations. Hence, a high response rotary valve would have to be hydraulically driven with the electric pilot stage consisting of individual solenoid valves. This approach appears quite cumbersome. Thus, it is concluded that the individual valve approach has the greatest growth potential.

Risk

Evaluation of risk is also rather subjective. However, based on the greater complexity, the fact that side loads will be difficult to completely eliminate, and the fact that less experience is available, the rotary valve approach is deemed to be a higher risk approach than the individual valve approach.

Packaging

It is difficult to draw a completely general conclusion regarding the packaging characteristics of one approach over the other, since envelope requirements may change dramatically from one application to another. However, for the case of the envelope that has been assumed for this project, the individual valves certainly package better. Moreover, it would seem that an approach that involves four volume components is inherently more flexible than an approach which has the volume concentrated in one component, even if the total volumes are equal. Since the volumes are not equal, and the rotary valve approach will require more volume because of coil force requirements, it will probably be easier to package the individual valves.

The table summarizes the conclusions derived in the various areas of comparison.

Area of Comparison	Rotary Valve Approach	Individual Valve Appraoch
Leakage	Best	
Dynamic Response		Best
Slew Rate	Best	
Complexity		Best
Coil Size		Best
Friction and Bearing Considerations		Best
Growth Potential		Best
Risk		Best
Packaging		Probably Best

Summary of Comparison Between Rotary Valve
and Individual Valve Approaches

Based on these comparisons, it has been concluded that the electro-hydraulic stepper should be controlled by individual solenoid valves. Since an arrangement has been shown that gives equal path lengths when four four-way valves are used, this approach will be used instead of the eight three-way valves. This minimizes the number of coils, which are the largest components in the valves.

J H Tarter

J. H. Tarter

JHT:vh

cc: C. R. Kelso
W. D. MacLennan
R. G. Read

APPENDIX B

PRODUCTION TEST PLAN

FOR HIGH TEMPERATURE SWITCHING SERVOVALVE,

MODEL 18E112, S/N's 1-6

(CSM #668)

MOOG INC.
May 26, 1975

PRODUCTION TEST PLAN
FOR HIGH TEMPERATURE SWITCHING SERVOVALVE,
MODEL 18E112, S/N's 1-6

STANDARD TEST CONDITIONS (Moog Prototype Lab.)

Hydraulic Fluid: MIL-H-5606
Supply Pressure: 3000 ±50 psig
Return Pressure: 0-50 psig
Fluid Temperature: 100 ±20°F
Ambient Temperature: 80 ±20°F
Fluid Contamination Limit: NAS 1638, Class 3
Normal Operating Current: 0-20 ma, square wave, 0-60 Hz

TEST EQUIPMENT

1. Function Plotter Test Equipment: T-4858 & Model 40-107C
2. Function Generator: HP Model 202A or equivalent
3. Frequency Response Test Amplifier, Model 43-153
4. DC Bias, Auxillary Input to above: battery & pot.
5. Response Manifold, .15 in^3 volume/side: T-17378 with Detail 3 plus .10 in^3 slugs inboard of Detail 3. T-17380 adapter plate.
6. Dual Beam Oscilloscope & Camera
7. Special end caps to instrument 30 Series 1st stage pressure: T-20574
8. Pressure Transducers (2): Standard Controls Model 100-3 (with Moog excitation and summing circuitry).
9. High Temperature Chamber (80 to 600°F)
10. Pyrometer (80 to 600°F)
11. Static Test Stand: T-5147
12. Resistance Bridge & Hi-pot Tester, 60 Hz

PRELIMINARY TESTS - as required

STABILIZE AND TEMPERATURE NULL SHIFT TEST

(a) Disassemble end caps, inlet orifice assemblies, filter, spool, and all O-rings.
(b) Flush out the nozzles and body passages with freon.
(c) Heat in oven until valve body temperature stabilizes at 600-625°F.
(d) Apply 0-20-0 ma square wave at 60 Hz for 15 minutes.
(e) Apply 0-20-0 ma triangle wave at 1 Hz, and photograph the oscilloscope lissajous of coil voltage vs. coil current. Ascertain, from the voltage transients shown on the photo, the current levels at which switching initiates, each way.
(f) Cool down to 80-150°F
(g) Repeat (e)
(h) Ascertain the null shift at 600°F by comparison of (e) data with respect to (g) data.

(Equipment Items 2, 3, 4, 6, 8, and 9)

(CSM #668)

FINAL TESTS

PROOF PRESSURE TEST

(a) 5100 psi supply, return open. 0 and 20 ma
(b) 3400 psi supply, return blocked
(Equipment Item 11)

FIRST STAGE PRESSURE GAIN PLOT

(a) Verify nozzle sealing
* (b) Verify that output saturation occurs each way between 4 and 16 ma
* (c) Verify that output saturation will occur each way between 2 and 18 ma at +600^{o}F by applying temperature null shift data to (b).
(Equipment Items 1 and 7)

MAXIMUM OUTPUT FLOW TESTS

Measure no load flow at 0 and 20 ma:
* (a) 50% rated flow end caps (4.0-5.0 cis)
* (b) 75% rated flow end caps (6.2-7.4 cis)
* (c) 100% rated flow end caps (8.1-9.9 cis)
(Equipment Item 1 or 11)

INTERNAL LEAKAGE FLOW PLOT

* Automatic plot of (blocked load) return line flow vs. current, full loop, 0 to 20-0 ma. Maximum flow, excepting switching spikes: $\leq$ .32 cis
(Equipment Item 1)

TRANSIENT RESPONSE (100% flow stops)

* (a) Measure elapsed time from initiation of 0 to 20 ma step input until load pressure switches through zero ΔP to 2000 psid in other direction.
* (b) Repeat for 20 to 0 ma step input.
(Equipment Items 2, 3, 4, 5, 6, 7, and 8)

POLARITY

A & C (+), B & D (-), Flow out port 2 (left side, facing pressure port side).
(Equipment Item 1 or 11)

DIELECTRIC STRENGTH

1000 vac ($\geq$ 100 megohms)
(Equipment Item 12)

COIL RESISTANCE

* (800-1100 ohms per coil)
(Equipment Item 12)

* Report on customer Data Sheet

MOOG INC.

DATA SHEET

MODEL 18E112 S/N 1

Date 5/28/75 By RLB

Maximum Flow:	0 ma	20 ma	Limits
100% stops	8.6	9.0	8.1-9.9 cis
75% stops	6.6	6.5	6.1-7.4 cis
50% stops	4.2	4.6	4.0-5.0 cis
Internal Leakage Flow:	.29	.30	≤.32 cis

Transient Response:	0→20 ma	20→0 ma	
100% stops	4.7, 4.6	4.7, 4.3	(≤ 5.0 ms)
75% stops	4.1, 3.8	3.8, 3.4	(≤ 4.5 ms)
50% stops	3.4	3.5	(≤ 4.0 ms)

First Stage Blocked Load Output Saturation Current (ma):

normal temp.	9.5	7.5	4 - 16 ma
600^{o}F shift	-1.0	+1.0	
at 600^{o}F (calculated)	8.5	8.5	2 - 18 ma

Coil Resistance:	AB	CD	
	800	800	(800-1100 Ω)

AUTOMATIC FLOW PLOT 100% Flow
Stops Installed

MODEL: 18E112 DATE: 5-28-75

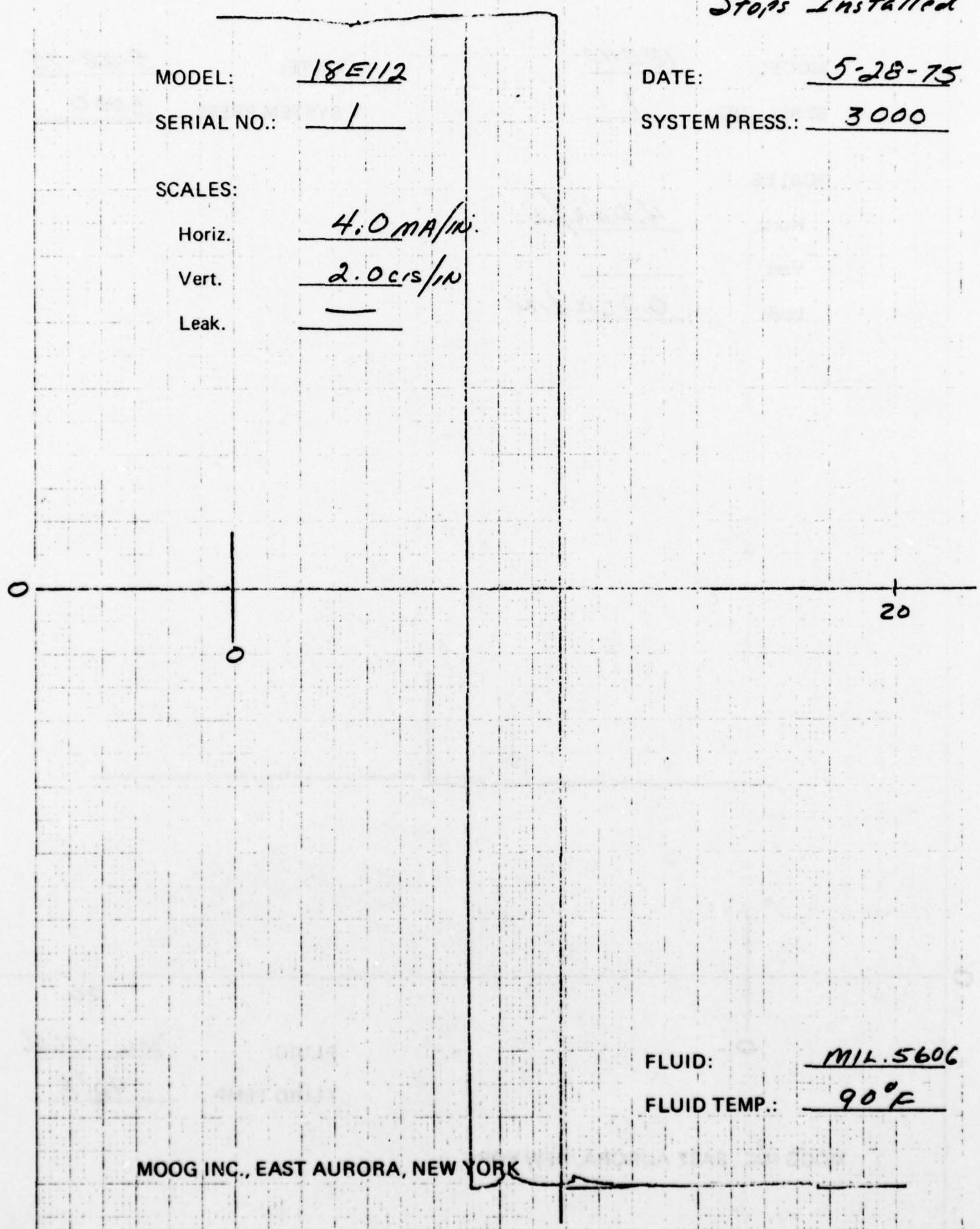
SERIAL NO.: 1 SYSTEM PRESS.: 3000

SCALES:

Horiz. 4.0 MA/IN.

Vert. 2.0 CIS/IN

Leak. —



FLUID: MIL.5606

FLUID TEMP.: 90°F

MOOG INC., EAST AURORA, NEW YORK

AUTOMATIC FLOW PLOT

MODEL: 18E112

DATE: 5-28-75

SERIAL NO.: 1

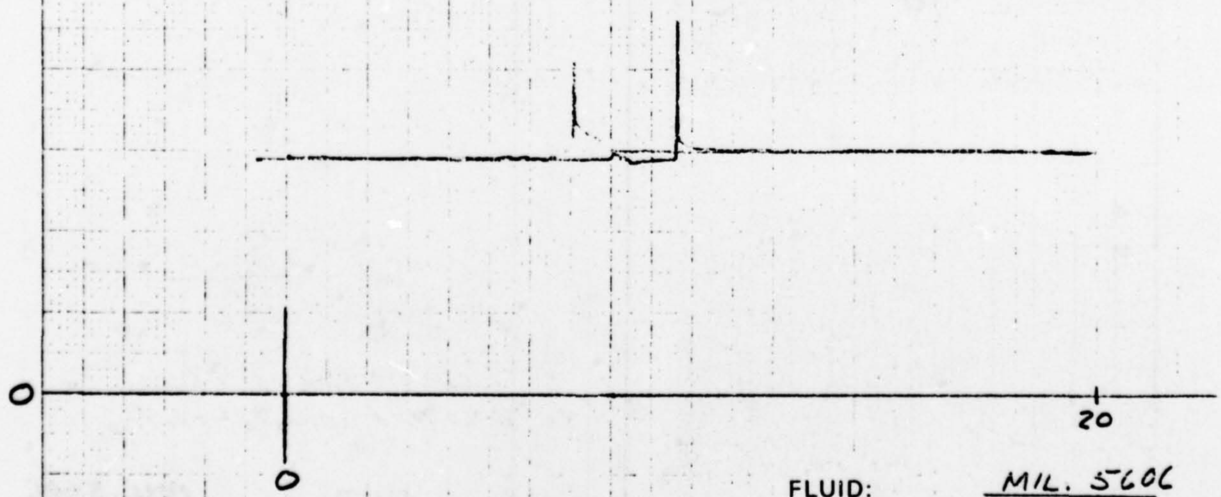
SYSTEM PRESS.: 3000

SCALES:

Horiz. 4.0 MA./IN.

Vert. –

Leak. 0.2 CIS./IN.



FLUID: MIL. 5606

FLUID TEMP.: 90°F

MOOG INC., EAST AURORA, NEW YORK

MOOG INC.

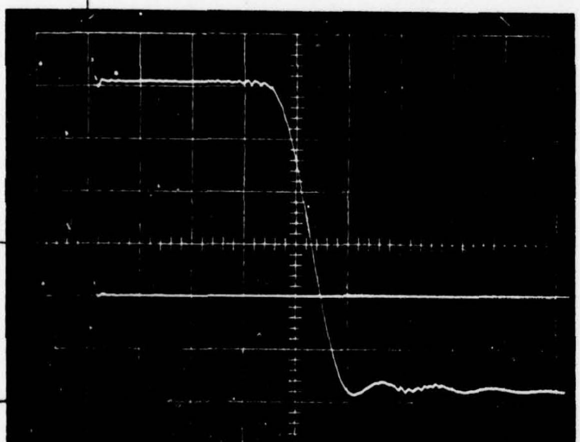
Final Transient Response Photos

Model 18E112
S/N 1
Date: 5-27-75

Load Diff. Press. Scale (Vertical): 500 psid/cm

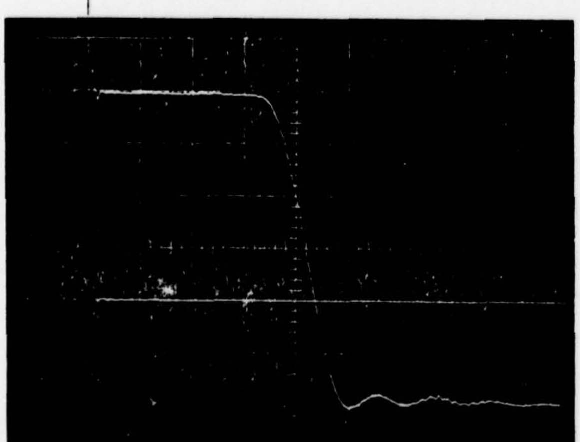
Time scale (Horiz.): 1 ms/cm

100% Flow Stops Installed



Input: 0→20 ma

Response Time 4.7 ms
(to 2000 psid, opp. direction)



Input: 0→20 ma

Response time 4.6 ms
(to 2000 psid, opp. direction)

0 Time →

MOOG INC.

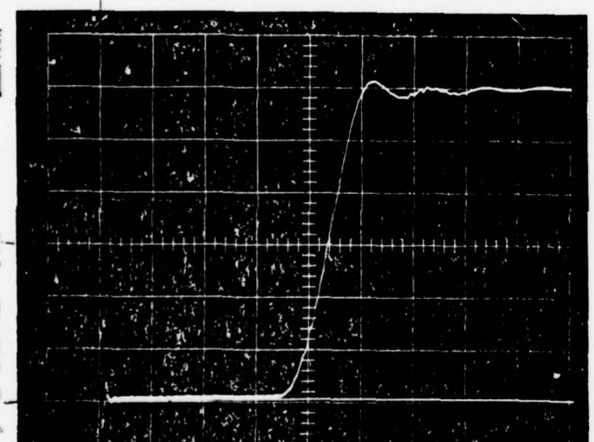
Final Transient Response Photos

Model 18E112
S/N 1
Date: 5-27-75

Load Diff. Press. scale (vertical): 500 psid/cm

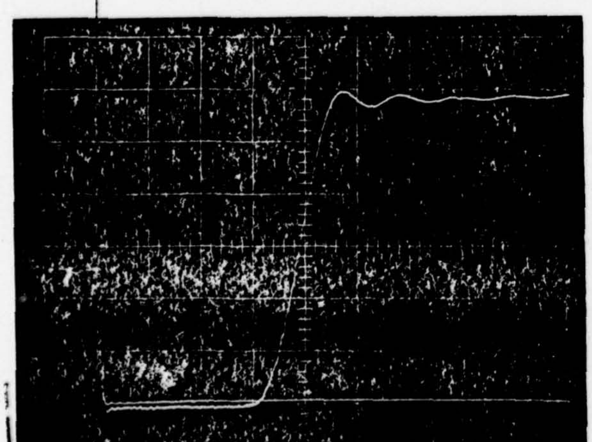
Time scale (Horiz.): 1 ms/cm

100 % Flow Stops Installed



Input: 20 → 0 ma

Response Time 4.7 ms
(to 2000 psid, opp. direction)



Input: 20 → 0 ma

Response time 4.3 ms
(to 2000 psid, opp. direction)

0 Time →

MOOG Inc.

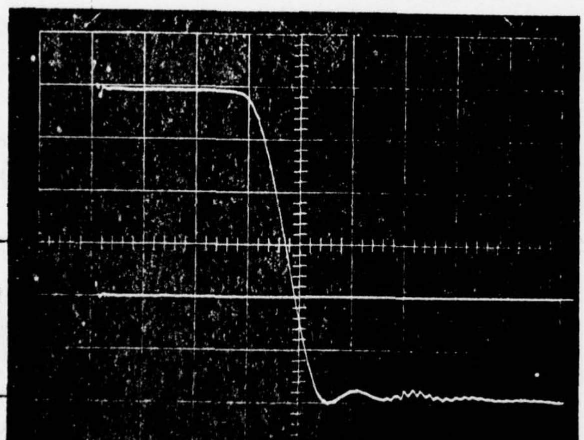
Final Transient Response Photos

Model 18E112
S/N 1
Date: 5-27-75

Load Diff. Press. Scale (Vertical) : 500 psid/cm

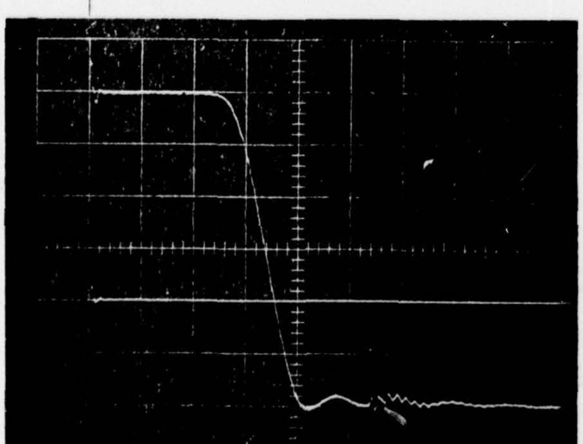
Time scale (Horiz.) : 1 ms/cm

75 % Flow Stops Installed



Input: 0 → 20 ma

Response Time 4.1 ms
(to 2000 psid, opp. direction)



Input: 0 → 20 ma

Response time 3.8 ms
(to 2000 psid, opp. direction)

0 Time →

MOOG Inc.

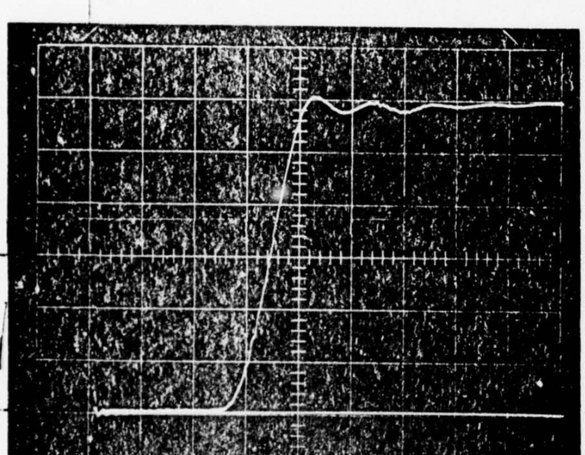
Final Transient Response Photos

Model 18E112
S/N 1
Date: 5-27-75

Load Diff. Press. scale (vertical): 500 psid/cm

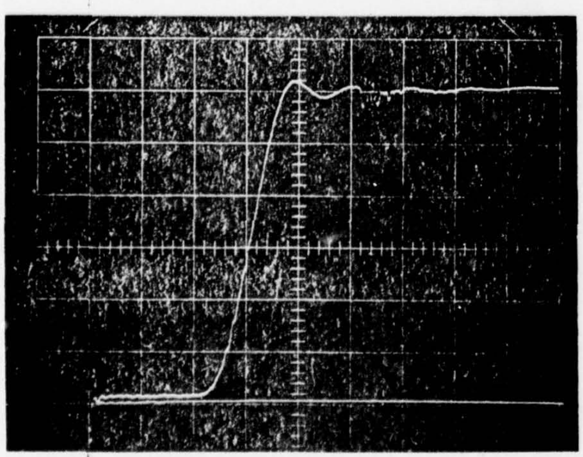
Time scale (Horiz.): 1 ms/cm

75% Flow Stops Installed



Input: 20 → 0 ma

Response Time 3.8 ms
(to 2000 psid, opp. direction)



Input: 20 → 0 ma

Response time 3.4 ms
(to 2000 psid, opp. direction)

0 Time →

MOOG IN:

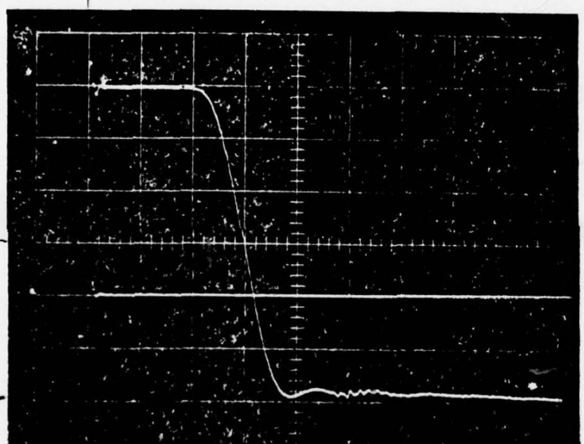
Final Transient Response Photos

Model 18E112
S/N 1
Date: 5-27-75

Load Diff. Press. scale (vertical) : 500 psid/cm

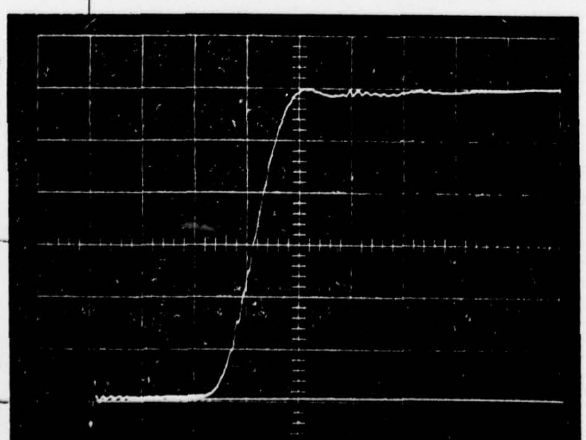
Time scale (Horiz.) : 1 ms/cm

50 % Flow Stops Installed



Input: 0→20 ma

Response Time 3.4 ms
(to 2000 psid, opp. direction)



Input: 0-20 ma

Response time 3.5 ms
(to 2000 psid, opp. direction)

0 Time →

APPENDIX C

DYNAVECTOR CONTROL CHASSIS

TED-E-8634

OPERATING INSTRUCTIONS

DYNAVECTOR CONTROL CHASSIS
TED-E-8634
OPERATING INSTRUCTIONS

A. Automatic Cycling Test Sequence

To conduct an automatic cycling Test Sequence, place the switches in the following positions:

1. Set POWER switch to OFF.
2. Set AUTOMATIC/MANUAL switch to MANUAL.
3. Set LIMIT DISABLE switch to ENABLE.
4. Set LIMIT SET switches to cycle limits required.
5. Set external signal generator for stepping rate required. TP1 can be monitored with a counter or oscilloscope. For proper operation the signal generator should provide a square wave signal of 12 to 15 volts peak-to-peak.
6. Turn POWER switch to ON.
7. Select desired direction of Rotation (CW or CCW) by momentarily pushing ROTATION toggleswitch toward associated callout.
8. Preset the Position start condition by momentarily pushing the START PRESET switch to the same direction as the ROTATION indication.
9. Push RESET button.
10. Start test by switching the AUTOMATIC/MANUAL switch to AUTOMATIC.

NOTE: If it is desired to cycle about a point other than zero, perform the following steps before starting test as in step 10.

a. Press the STEP button and note readouts of POSITION indicator. The system will advance one step (1^{o}) for each time the STEP button is pushed. When the desired point about which cycling is to occur is reached, press the RESET button. The Dynavector will remain at the commanded position, but the POSITION indication will read zero.

When the AUTOMATIC/MANUAL switch is positioned to AUTOMATIC the Dynavector will cycle plus and minus about the manually commanded position.

Example: The STEP button is pushed until the POSITION indicator reads 022 CW. Assume that 06 is selected on the LIMIT SET switches. When the AUTOMATIC MANUAL switch is positioned to AUTOMATIC after pushing the RESET button, the Dynavector will cycle between 16 CW and 28 CW (22 CW ± 6), but the POSITION indicator will cycle between 06 CW and 06 CCW.

B. Automatic Run No Cycling

The procedure for the automatic run with no cycling is the same as the automatic cycling sequence except that the Limit Disable switch of step 3 is in the DISABLE position and the Limit set switches of step 4 are set at any number other than zero. (Direction will be random if set on zero.)

After the AUTOMATIC/MANUAL switch is switched to AUTOMATIC the Dynavector will run in the selected direction (CW or CCW) at the external clock rate. In order to reverse rotation the AUTOMATIC/MANUAL switch should be placed in MANUAL and then the ROTATION switch momentarily toggled to the desired direction. The automatic sequence can then be resumed by selecting AUTOMATIC on the AUTOMATIC/MANUAL switch.

C. Manual Step Tests

The procedure for manual tests is the same as for automatic tests except that the AUTOMATIC/MANUAL switch is left in the MANUAL position. The Dynavector can be advanced one step (1°) at a time by pressing the STEP button. The rotation can be changed between CW and CCW by using the ROTATION switch. The ROTATION CW and CCW indicators and the POSITION readouts are in operation during the manual mode, but the LIMIT SET switches are disabled. (Push reset switch after rotation direction and position are set.) The limit set switch must not be on zero. If on zero, direction is random even though a direction has been commanded.

D. Monitor Points

1. The chassis test points TP1 through TP5 can be used for monitoring as follows:

TP1	External signal generator input.
TP2	Rotation. High level for CW, low level for CCW.
TP3	Gated Internal Clock. Positive pulse 1 to 2 ms.
TP4	Position. High level for CW, low level for CCW.
TP5	Combined input and rotation direction signal.

2. The valve current test points are labeled ±V1 through ±V4. These test points provide a means of measuring each valve current by placing a 27 ohm resistor in series with the valve coil. The current monitoring instrument must be isolated from the Dynavector control chassis ground because the 27 ohm resistor is between the plus side of the 76 volt power supply and the plus side of the valve coil.

   The nominal 20 mA valve current is indicated by a 54 mV drop across the 27 ohm resistor.

E. Automatic One Step Operation

Four miniature toggle switches are mounted at the rear of the control chassis. They are identified as V1, V2, V3 and V4, and control valves 1 through 4. For normal operation, keep switches in up (normal) position. To automatically one step a valve, place that switch in down (one step) position. CAUTION: If more then one switch is placed in the one step position, false actuator indications may result.

After selecting any one valve for one step operation, follow sequence for automatic operation. Selected valve will step in commanded direction; then return to its original position. This sequence will continue until automatic mode is switched to manual.

F. Remote Automatic Operation

A jack (J5) is located at the rear of the control chassis. A cable is provided with a mating plug for J5. Insert the plug; then switch the MANUAL/AUTOMATIC switch to AUTOMATIC. With the plug inserted in the jack, the control chassis will remain in the manual mode until the switch on the cable is depressed. Follow instructions for automatic operation to obtain desired performance. The cable switch is momentary contact and the control chassis will return to manual mode when switch is released.

APPENDIX D

CONFIGURATION CODE

CONFIGURATION CODE

	Torsion Load		Inertia, in # sec^2				Valve and Capacity					
Code	None	Spring Fixture	0	.11	.43	.75	1	2	3	4	Driver	Comments
1	X		X				S/N 4 100%	S/N 5 100%	S/N 2 100%	S/N 1 100%	A	Driver caused .008 second lag when switching current off
2		X				X	S/N 4 100%	S/N 5 100%	S/N 2 100%	S/N 1 100%	A	
3		X				X	S/N 4 100%	S/N 5 100%	S/N 2 100%	S/N 1 50%	A	
4		X				X	S/N 4 100%	S/N 5 100%	S/N 2 100%	S/N 1 50%	B	Driver modified to provide proper (fast) switching.
5		X		X			S/N 4 100%	S/N 5 100%	S/N 2 100%	S/N 1 50%	B	
6	X		X				S/N 4 50%	S/N 5 50%	S/N 2 50%	S/N 1 50%	B	
7		X				X	S/N 4 50%	S/N 5 50%	S/N 2 50%	S/N 1 50%	B	
8		X		X			S/N 4 50%	S/N 5 50%	S/N 2 50%	S/N 1 50%	B	
9	X		X				S/N 4 50%	S/N 5 50%	S/N 2 50%	S/N 1 50%	B	Rebuilt actuator, replumbed main case drain line.
10		X				X	S/N 4 50%	S/N 5 50%	S/N 2 50%	S/N 1 50%	B	

APPENDIX E

INSTRUMENTATION CODE 1

INSTRUMENTATION CODE 1

CEE Type 5-119 Oscillograph - Datarite Magazine 5-036B, Kodak Linagraph 1884 Paper

Function	Channel	Postion	Galvo	External Damping ohms	Transducer	Demodulator Channel	Demodulator Attenuation	Comments
System High Pressure	1	9.5	7-320	85	Wiancko P1702, S/N 21388	1	4	
System Low Pressure	4	9.0	7-320	85	Wiancko P1701, S/N 14084	4	0	
Case Pressure	5	8.5	7-320	85	Wiancko P1701, S/N 24141	5	0	
Valve 1 Current	6	8.0	7-317	None	27 ohm resistor			
Valve 2 Current	8	7.5	7-317	None	27 ohm resistor			
Valve 3 Current	10	7.0	7-317	None	27 ohm resistor			
Valve 4 Current	12	6.5	7-317	None	27 ohm resistor			
Flow Frequency	26	2.5	7-312	None	JX-114-281, S/N 3			200 mA bulb current
Input (combined)	19	5.5	7-323	1000	Driver Op. Amp.			5 K op. amp. feedback
Position pot.	21	4.5	7-363	130	Pot. (New England 156-PS-219) with op. amp.			10 K op. amp. feedback
Torque	28	1.5	7-323	1000	Lebow Model 1204-200 with Op. Amp.			900 K ohm op. amp. feedback resistor

INSTRUMENTATION CODE 16

CEE Type 5-119 Oscillograph - Datarite Magazine 5-036B, Kodak Linapgraph 1884 Paper

Function	Channel	Postion	Galvo	External Damping ohms	Transducer	Demodulator Channel	Demodulator Attenuation	Comments
System High Pressure	1	9.5	7-320	85	Wiancko P1702, S/N 21388	1	4	
System Low Pressure	4	9.0	7-320	85	Wiancko P1701, S/N 14084	4	0	
Case Pressure	5	8.5	7-320	85	Wiancko P1701, S/N 24141	5	0	
Valve 1 Current	6	8.0	7-317	None	27 ohm resistor			
Valve 2 Current	8	7.5	7-317	None	27 ohm resistor			
Valve 3 Current	10	7.0	7-317	None	27 ohm resistor			
Valve 4 Current	12	6.5	7-317	None	27 ohm resistor			
Flow Frequency	15	10.5	7-312	None	JX-114-281, S/N 3			200 mA bulb current
Input (combined)	19	5.5	7-323	1000	Driver Op. Amp.			2.2K Op Amp. feedback
Position pot.	21	3.5	7-363	200	Pot. (New England 156-PS-219) with op. amp.			70 K op. amp. feedback. The 3.5 inch position is the initial position, not necessarily zero.
Torque	28	1.5	7-323	1000	Lebow Model 1204-200 with Op Amp			900 K Ohm Op Amp feedback resistor
Chamber 1 pressure	7	10.7	7-220A	85	Wiancko P1902 S/N 45170 (±3500)	7	16	
Chamber 4 pressure	9	10.2	7-220A	85	Wiancko P1902 S/N 45168 (±5000)	9	10	
Chamber 5 pressure	11	9.7	7-220A	85	Wiancko P1902 S/N 45169 (±5000)	11	12	
Chamber 8 pressure	13	9.2	7-220A	85	Wiancko P1902 S/N 14087 (±3500)	12	20	not functioning properly

INSTRUMENTATION CODE 18

CEE Type 5-119 Oscillograph - Record Magazine 5-006 Ser. 9239, Kodak Linagraph 1884 Paper

Function	Channel	Postion	Galvo	External Damping ohms	Transducer	Demodulator Channel	Demodulator Attenuation	Comments
System High Pressure	1	9.5	7-320	85	Wiancko P1702, S/N 21388	1	4	
System Low Pressure	4	9.0	7-320	85	Wiancko P1701, S/N 14084	4	0	
Case Pressure	5	8.5	7-320	85	Wiancko P1701, S/N 24141	5	0	
Valve 1 Current	6	8.0	7-317	None	27 ohm resistor			
Valve 2 Current	8	7.5	7-317	None	27 ohm resistor			
Valve 3 Current	10	7.0	7-317	None	27 ohm resistor			
Valve 4 Current	12	6.5	7-317	None	27 ohm resistor			
Flow Frequency	33	0.7	7-312	None	JX-114-281, S/N 3			200 mA bulb current
Input (combined)	19	5.5	7-323	1000	Driver Op. Amp.			2.2K Op Amp. feedback
Position pot.	21	3.5	7-363	200	Pot. (New England 156-PS-219) with op. amp.			70 K op. amp. feedback. The 3.5 inch position is the initial position, not necessarily zero.
Torque	28	1.5	7-323	1000	Lebow Model 1204-200 with Op Amp			900 K Ohm Op Amp feedback resistor
Chamber 1 pressure	7	10.7	7-220A	85	Wiancko P1902 S/N 45170 (±3500)	7	16	
Chamber 4 pressure	9	10.2	7-220A	85	Wiancko P1902 S/N 45168 (±5000)	9	10	
Chamber 5 pressure	11	9.7	7-220A	85	Wiancko P1902 S/N 45169 (±5000)	11	12	not functioning properly
Chamber 8 pressure	13	9.2	7-220A	85	Wiancko P1902 S/N 14087 (±3500)	12	20	

INSTRUMENTATION CODE 28

CEE Type 5-119 Oscillograph - Record Magazine 5-006A Ser. 5031, Dupont Linowrit #2 Paper

Function	Channel	Postion	Galvo	External Damping ohms	Transducer	Demodulator Channel	Demodulator Attenuation	Comments
System High Pressure	1	9.5	7-320	85	Wiancko P1702, S/N 21388	1	4	
System Low Pressure	4	9.0	7-320	85	Wiancko P1701, S/N 14084	4	0	
Case Pressure	5	8.5	7-320	85	Wiancko P1701, S/N 24141	5	0	
Valve 1 Current	6	8.0	7-317	None	27 ohm resistor			
Valve 2 Current	8	7.5	7-317	None	27 ohm resistor			
Valve 3 Current	10	7.0	7-317	None	27 ohm resistor			
Valve 4 Current	12	6.5	7-317	None	27 ohm resistor			
Flow Frequency	15	10.5	7-312	None	JX-114-281, S/N 3			200 mA bulb current
Input (combined)	19	5.5	7-323	1000	Driver Op. Amp.			2.2K Op Amp. feedback
Position pot.	22	3.5	7-363	200	Pot. (New England 156-PS-219) with op. amp.			40 K op. amp. feedback. The 3.5 inch position is the initial position, not necessarily zero.
Torque	28	1.5	7-323	1000	Lebow Model 1204-200 with Op Amp			900 K Ohm Op Amp feedback resistor

INSTRUMENTATION CODE 6

Tektronix 545A Oscilloscope, 53/54 C Plug-in Unit

Channel A	Input signal, 20 V/cm
Channel B	Position pot., .1 V/cm

INSTRUMENTATION CODE 7

Tektronix 545A Oscilloscope, 53/54 C Plug-in Unit

Channel A	Input signal
Channel B	Current signal (voltage across 27 ohm resistor), .2V/cm

INSTRUMENTATION CODE 8

Tektronix 545A Oscilloscope, 53/54 C Plug-in Unit

Channel B	Current signal (voltage across 27 ohm resistor), .2V/cm

INSTRUMENTATION CODE 9

Tektronix 545A Oscilloscope, 53/54 C Plug-in Unit

Channel B	Driver Pin 7 voltage, 50V/cm

INSTRUMENTATION CODE REVISIONS

Code	Comments
2	Same as Code 1 except channel 21, position pot. op. amp. feedback resistor changed to 5K to reduce gain.
3	Same as Code 2 except: a) Flowmeter frequency changed to channel 15 and positioned at 10.5 inches. b) Channel 21, position pot feedback resistor changed to 2K.
4	Same as Code 3 except: a) Polarity of channel 19, input, is reversed b) Polarity of channel 21, position pot, is reversed. (Clockwise direction is now up.) c) Channel 21, position pot, op amp feedback resistor is 4 K, wing zero at 3.5 inch.
5	Same as Code 4 except channel 21, position pot. op. amp. feedback resistor is 10 K.
10	Same as Code 5 except channel 19, input signal (combined) op. amp. design modified to yield smaller gain. Feedback resistor is 2.2 K. Galvo deflection is down for C.W. command.
11	Same as Code 10 except channel 21, position pot. op. amp. feedback resistor is 8 K. Trace for the initial position is at 1.8 inches.
12	Same as Code 11 except channel 21, position pot. op. amp. feedback resistor is 10 K and trace for the initial position is at 2 inches.
13	Same as code 10 except polarity of channel 19, input signal (combined), reversed so that galvo deflection is up for CW command.
14	Same as code 13 except channel 21, position pot trace positioned at 2 inches for initial position.
15	Same as code 14 except channel 21, position pot instrumentation,revised in an attempt to improve linearity and to increase deflection capability. OP amp input resistor = 100K, feedback resistor = 70 K. Galvo series external damping resistance = 200 Ω. Trace positioned at 3.5" for initial conditions.
17	Same as Code 16 except Chamber 8 pressure now on Demodulator Channel 8 with an attenuation of 16.

INSTRUMENTATION CODE REVISIONS

Code	Comments
19	Same as Code 18 except chamber pressure instrumentation removed and flow frequency moved to Channel 15 at 10.5 inches. Also Channel 21, position pot, OP Amp feedback resistor changed to 20K to decrease amplitude.
20	Same as 19 except Channel 21, position pot, Op Amp feedback resistor is 90K.
21	Same as 19 except Channel 21, position pot, Op Amp feedback resistor is 170K.
22	Same as Code 19 except: . Position pot moved from Channel 21 to Channel 22 (Channel 21 developed a bad galvo connector). . Position pot reoriented to obtain zero volts at the initial position in order to allow a larger galvo deflection per step. . Position pot Op Amp feedback = 70K. . Position pot oscillograph trace positioned at 2.2" at start of run.
23	Same as Code 22,except Channel 22 position pot feedback resistor now 270K to produce approximately .7 inch deflection per step and oscillograph trace is internally at 3.5 inches.
24	Same as Code 23, except Channel 22 positionpot feedback resistor changed to give .4 inch deflection per step. (160 K ?)
25	Same as Code 23 except Channel 22 position pot feedback resistor = 260K.
26	Same as Code 23 except Channel 22 position pot feedback resistor = 70K.
27	Same as Code 23 except Channel 22 position pot feedback resistor = 40K.
28	Same as Code 27 except for type paper used - see Inst code sheet.
29	Visual data only. Position observed directly on test fixture and on oscilloscope.

APPENDIX F

DYNAVECTOR RUN SUMMARY

DYNAVECTOR RUN SUMMARY

NOTE: Neutral position is at 155.5 degrees

Run Number	Date	Type Test	Initial Position, Steps From Zero Reset	Direction	Pulse Rate, pps	Pressure psi	Config. Code	Inst. Code	Comments
1	7-13-76	Dynamic	+7	± 1°	120	3000	1	1	Favors CCW position
2	"	"	0	"	"	"	"	"	Favors CCW position
3	"	"	+1	"	"	"	"	"	Favors CCW position
4	"	"	+2	"	"	"	"	"	Full ±1 degree amplitude
5	"	"	+3	"	"	"	"	"	Favors CW position
6	"	"	+3	"	"	"	"	"	Favors CW position
7	"	"	+4	"	"	"	"	"	Favors CW position
8	"	"	+5	"	"	"	"	"	Favors CW position
9	"	"	+6	"	"	"	"	"	Grossly reduced amplitude
10	"	"	+7	∓ 1°	"	"	"	"	Same result as Run 1
11	"	"	+7	± 4°	50	"	"	"	Follows OK. Ran continuous CW at end of run.
12	"	"	+7	"	100	"	"	"	Follows OK, ± 4 degrees
13	"	"	+7	"	150	"	"	"	Amplitude = +4, -3 degrees
14	"	"	+7	"	200	"	"	"	Amplitude = +4, -3 degrees
15	"	"	+7	"	250	"	"	"	Amplitude = +4, -3 degrees
16	"	"	+7	"	275	"	"	"	Amplitude = +4, -3 degrees
17	"	"	+7	"	300	"	"	"	Amplitude = ±3 degrees
18	"	"	+7	CW	100	"	"	"	Position rate = 100 deg/sec.
19	"	"	+2	± 8°	200	"	"	2	Amplitude = ±7 degrees
20	"	"	+2	"	250	"	"	"	Amplitude = ± 7 degrees
21	"	"	+2	"	300	"	"	"	Amplitude = +6, -7 degrees
22	"	"	+7	"	350	"	"	"	Loses track, runs away
23	"	"	+7	CW	350	"	"	"	Loses steps, rate = 100 deg/sec.
24	"	"	+2	±8°	200	2000	"	"	Amplitude = ±7 degrees
25	"	"	--	"	250	"	"	"	Amplitude = ±7 degrees
26	7-13-76	Dynamic	+2	± 8	300	2000	1	2	Loses track, runs away
27	"	"	+7	± 8	200	1000	"	2	Amplitude = ± 7°
28	"	"	+7	± 8	250	1000	"	2	Loses track, runs away
29	"	--	--	--	---	3000	"	-	Oscillograph calibrationn
30	"	--	--	--	---	3000	"	2	Oscillograph calibration
31	7-14-76	--	--	--	---	---	2	3	Oscillograph calibration
32	"	*Dynamic*	+4	±30	10	3000	"	3	Preliminary run
33	"	--	--	--	---	---	"	4	Oscillograph calibration
34	"	Dynamic	+2	±30	10	3000	"	4	Used to calibrate position
35	"	Pull out	--	CW	10	3000	"	4	2450 in # stall
36	"	--	--	--	---	---	"	4	Oscillograph calibration
37	"	Pull out	--	CW	50	3000	"	4	2450 in # stall
38	"	Pull out	--	CW	100	3000	"	4	2150 in # stall
39	"	Pull out	--	CW	140	3000	"	4	Follows to 1800 in # opposing
40	"	Pull out	--	CW	200	3000	"	4	Follows to 1300 in # opposing
41	"	--	--	--	---	---	"	4	Oscillograph calibration
42	"	Pull out	--	CW	250	3000	"	4	Follows to 700 in # opposing
43	"	Pull out	--	CW	300	3000	"	4	Follows to 200 in # opposing
44	"	Pull out	--	CW	350	3000	"	4	Can't follow
45	"	Pull out	--	CW	400	3000	"	4	Can't follow
46	"	Pull out	--	CCW	400	3000	"	4	Can't follow
47	"	Pull out	--	CCW	350	3000	"	4	Follows with aiding load
48	"	Pull out	--	CCW	300	3000	"	4	Follows to 500 in # opposing
49	"	Pull out	--	CCW	250	3000	"	4	Follows to 1100 in # opposing
50	"	Pull out	--	CCW	200	3000	"	4	Follows to 1500 in # opposing
51	7-14-76	Pull out	--	CCW	140	3000	2	4	Follows to 2000 in # opposing
52	"	Pull out	--	CCW	100	3000	"	4	Follows to 2100 in # opposing
53	"	Pull out	--	CCW	50	3000	"	4	Follows to 2300 in #
54	"	Pull out	--	CCW	10	3000	"	4	Follows to 2300 in #
55	"	Pull out	--	CCW	5	3000	"	4	Follows to 2300 in #
56	"	Dynamic	+4	0° ± 20	140	3000	"	4	+19° to -20°, 1300-1400 in # maximum
57	"	--	--	---	---	None	"	4	Oscillograph calibration
58	7-15-76	--	--	---	---	None	"	5	Oscillograph calibration
59	"	Dynamic	+4	0° ± 1	5	3000	"	5	Position calibration
60	"	Dynamic	+4	0° ± 1	25	3000	"	5 & 6	Switching time data
61	"	"	+4	0° ± 1	75	3000	"	5 & 6	Favors CW position
62	"	"	+4	0° ± 1	120	3000	"	5 & 6	Favors CW position
63	"	"	0	-4° ± 1	120	3000	"	5	Favors CCW position
64	"	"	+1	-3 ± 1	120	3000	"	5	Favors CCW position
65	"	"	+2	-2 ± 1	120	3000	"	5	Full ± 1 degree amplitude
66	"	"	+2	-2 ± 1	140	3000	"	5	Full ± 1 degree amplitude
67A	"	"	+2	-2 ± 1	25	3000	"	5	Full ± 1 degree amplitude
68A	"	"	"	"	75	3000	"	6	Full ± 1 degree amplitude
69A	"	"	"	"	120	3000	"	6	Full ± 1 degree amplitude
70A	"	"	"	"	140	3000	"	6	Full ± 1 degree amplitude
71A	"	"	"	"	200	3000	"	6	Full ± 1 degree amplitude
72A	"	"	"	"	250	3000	"	6	Full ± 1 degree amplitude
73A	"	"	"	"	300	3000	"	6	Full ± 1 degree amplitude
74A	7-19-76	Current	--	±1	120	None	"	7	Valve current data (false information)
75A	"	"	--	"	120	3000	"	7	Valve current data (false information)
76A	"	"	--	"	120	300	"	7	Valve current data (false information)

DYNAVECTOR RUN SUMMARY

Run Number	Date	Type Test	Zero Reset	Initial Position, Steps From Zero Reset	Direction	Pulse Rate, pps	Pressure psi	Config. Code	Inst. Code	Comments
77A	7-26-76	Current	- - -	- - -	±1	120	3000	3	8	Valve 3 current data
78A	7-26-76	Current	- - -	- - -	±1	120	3000	4	8	Valve 3 current data
79A	7-26-76	Voltage	- - -	- - -	±1	120	3000	4	9	Valve 3 driver voltage data
80	7-27-76	- - -	- - -	- - -	--	---	----	4	5	Oscillograph zero
81	7-27-76	Dynamic	151.4	+4	±8	25	3000	4	10	Valve response and position calibration. 5-7 ms to reach commanded position.
82	7-27-76	Dynamic	151.4	+5	±8	120	3000	4	10	±8 degree amplitude. All valves have about same response.
83	7-27-76	Dynamic	151.4	+5	±8	250	3000	4	10	±8 degree amplitude
84	7-27-76	Dynamic	151.4	+5	±8	300	3000	4	10	+8, -6 degrees amplitude
85	7-27-76	Dynamic	151.4	+5	±8	350	3000	4	10	±7 degree amplitude
86	7-27-76	Dynamic	151.4	+2	±1	120	3000	4	10	5 ms lag (54°) Valve 4 7 ms lag (75°) Valve 1 Some ringing with Valve 1
87	7-27-76	Dynamic	151.4	+4	±1	120	3000	4	10	±1 degree amplitude 7 ms lag (75°) Valve 2 7 ms lag (75°) Valve 3 Some position ringing
88	7-27-76	Dynamic	151.4	+6	±1	120	3000	4	10	±1° amplitude 5 ms lag (54°) Valve 4 7 ms lag (75°) Valve 1 Some ringing both valves
89	7-27-76	Pull in	151.4	+25	CW	25	3000	4	11	Preliminary data
90	7-27-76	Pull in	155.0	+20	CW	5	3000	4	11	Preliminary data
91	7-27-76	Pull in	151.3	+25	CW	5	3000	4	12	Used to calibrate position Initial position = 174.9
92	7-27-76	Pull in	153.8	+22	CW	2	3000	4	12	Used to calibrate position Initial = 174.8 Final = 188.4. Rings at 45 Hz.
93	7-27-76	Pull in	148.4	+28	CW	140	3000	4	12	OK (1340 In #)
94	7-27-76	Pull in	151.3	+25	CW	140	3000	4	12	OK (127°/sec x 32/30 = 136° steps/sec) Pull in at 1340 in # Pull out at 2200 in #
95	7-27-76	Pull in	148.0	+28	CW	200	3000	4	12	Inconclusive
96	7-27-76	Pull in	153.7	+22	CW	250	3000	4	12	OK 1340 in # Pull out = 1700 in #
97	8-2-76	---	---	--	--	--	zero	5	13	Oscillograph zero burst
98	8-2-76	Dynamic	155.8	+5	±8	120	3000	5	13	Not significantly different from run 82
99	8-2-76	Dynamic	155.9	+4	±8	120	3000	5	13	Not significantly different from run 81, 145 Hz ringing
100	8-2-76	Dynamic	155.9	+2	±1	120	3000	5	13	Not significantly different from run 86
101	8-2-76	Dynamic	155.8	+4	±1	120	3000	5	13	Not significantly different from run 87
102	8-2-76	Dynamic	155.9	+6	±1	120	3000	5	13	Not significantly different from run 88
103	8-2-76	Pull in	150.9	+22	CW	2	3000	5	14	Similar to run 92 except rings at 145 Hz
104	8-2-76	Pull in	150.9	+22	CCW	2	3000	5	14	Similar to run 92 except rings at 145 Hz
105	8-2-76	Pull in	150.9	+22	CW	2	3000	5	14	Similar to run 92 except rings at 145 Hz
106	8-2-76	Pull in	150.8	+22	CW	2	3000	5	14	Similar to run 92 except rings at 145 Hz
107	8-3-76	---	---	---	---	---	zero	4	--	Zero burst prior to changing pos op amp inst.
108	8-3-76	Dynamic	153.9	+18	-1, 0	1	3000	4	15	Position calibration (1100 in #)
109	8-3-76	Dynamic	153.9	+18	-1, 0	60	3000	4	15	5ms (54°) lag; 100% amplitude
110	8-3-76	Dynamic	153.9	+18	-1, 0	120	3000	4	15	5ms (108°) lag; 75% amplitude
111	8-3-76	Dynamic	153.9	+18	-1, 0	180	3000	4	15	5ms (162°) lag; 90% amplitude
112	8-3-76	Dynamic	153.9	+18	-1, 0	240	3000	4	15	5ms (216°) lag; 100% amplitude
113	8-3-76	Dynamic	153.9	+18	-1, 0	300	3000	4	15	5ms (270°) lag; 100% amplitude

DYNAVECTOR RUN SUMMARY

Run Number	Date	Type Test	Zero Reset	Initial Position, Steps From Zero Reset	Direction	Pulse Rate, pps	Pressure psi	Config. Code	Inst. Code	Comments
114	8-3-76	Dynamic	153.9	+18	-1, 0	400	3000	4	15	5 ms(360°) lag; 100% amplitude
115	8-3-76	Dynamic	153.9	+18	-1, 0	500	3000	4	15	Doesn't follow; const. +18° position
116	8-3-76	Dynamic	153.9	+18	-1, 0	450	3000	4	15	5 ms(405°) lag; 70% amplitude

Note: Runs 108 - 116 were evaluation runs made by operating valve 4 which had 50% flow capacity spool end caps. Valve 1 (100% flow capacity end caps) is operated in runs 118-124.

Run Number	Date	Type Test	Zero Reset	Initial Position, Steps From Zero Reset	Direction	Pulse Rate, pps	Pressure psi	Config. Code	Inst. Code	Comments
117	8-4-76	---	---	---	---	---	zero	4	15	Zero burst
118	8-4-76	Dynamic	153.5	+18	+1, 0	1	3000	4	15	Position calibration (1140 in #)
119	8-4-76	Dynamic	153.5	+18	+1, 0	60	3000	4	15	7 ms(75°) lag; 100% amplitude
120	8-4-76	Dynamic	153.5	+18	+1, 0	120	3000	4	15	7 ms(150°) lag; 75% amplitude
121	8-4-76	Dynamic	153.5	+18	+1, 0	180	3000	4	15	7 ms(225°) lag; 80% amplitude
122	8-4-76	Dynamic	153.5	+18	+1, 0	240	3000	4	15	7 ms(300°) lag; 15% amplitude
123	8-4-76	Dynamic	153.5	+18	+1, 0	300	3000	4	15	Doesn't follow; const. +18° position
124	8-4-76	Dynamic	153.5	+18	+1, 0	260	3000	4	15	7 ms(325°) lag; 20% amplitude
125	8-4-76	Dynamic	153.5	+22	-1, 0	1	3000	4	15	Position calibration (1333 in #)
126	8-4-76	Dynamic	153.5	+22	+1, 0	1	3000	4	15	Position calibration (1333 in #)
127	8-4-76	Dynamic	153.5	+22	-1, 0	60	3000	4	15	5 ms(54°) lag; 100% amplitude
128	8-4-76	Dynamic	153.5	+22	+1, 0	60	3000	4	15	7 ms(75°) lag; 100% amplitude
129	8-4-76	Dynamic	153.5	+22	-1, 0	109	3000	4	15	5-12 ms lag; 40% amplitude, amplitude is at a minimum at 109 pps
130	8-4-76	Dynamic	153.5	+22	-1, 0	150	3000	4	15	5 ms(135°) lag; 95% amplitude
131	8-4-76	Dynamic	153.5	+22	-1, 0	300	3000	4	15	5 ms(270°) lag; 100% amplitude
132	8-4-76	Dynamic	153.5	+22	-1, 0	400	3000	4	15	5 ms(360°) lag; 100% amplitude
133	8-4-76	Dynamic	153.5	+22	-1, 0	450 453	3000	4	15	5 ms(405°) lag; 100% amplitude No longer follows at 453 pps
134	8-4-76	Dynamic	150.9	+22	+1, 0	1	3000	4	15	Position calibration (1200 in #)
135	8-4-76	Dynamic	150.9	+22	+1, 0	60	3000	4	15	7 ms(75°) lag; 100% amplitude
136	8-4-76	Dynamic	150.9	+22	+1, 0	109	3000	4	15	7 ms lag; 60% amplitude (amplitude is at minimum at 109°)
137	8-4-76	Dynamic	150.9	+22	+1, 0	250	3000	4	15	6 ms(270°) lag; 50% amplitude Maximum frequency that actuator can respond is 254 pps
138	8-4-76	Dynamic	150.9	+2	-1,0	1	3000	4	15	Position calibration (-100 in #)
139	8-4-76	Dynamic	150.9	+2	+1, 0	1	3000	4	15	Position calibration (-100 in #)
140	8-4-76	Dynamic	150.9	+2	-1, 0	440	3000	4	15	5 ms(395°) lag; 50-100% amplitude Maximum pulse rate that actuation can respond is 445 pps.
141	8-4-76	Dynamic	150.9	+2	+1, 0	250	3000	4	15	5 ms lag (valve 1); near zero amplitude. 255 is maximum pulse rate

It is concluded from runs 107-141 that the performance of valve 4 (50% flow capacity spool end stops) is much superior to that of valve 1 (100% flow capacity spool end stops). Also, performance at rated torque is not significantly different than the performance at near zero torque.

Run Number	Date	Type Test	Zero Reset	Initial Position, Steps From Zero Reset	Direction	Pulse Rate, pps	Pressure psi	Config. Code	Inst. Code	Comments
142	8-6-76	--	--	--	--	--	--	4	16	Zero burst
143	8-6-76	Dynamic	150.9	+22	±1	1	3000	4	16	Position calibration
144	8-9-76	--	--	--	--	--	--	4	16	Zero burst
145	8-9-76	Dynamic	150.9	+22	±1	1	3000	4	16	Position calibration, 1200 in #
146	8-9-76	Dynamic	150.9	+22	±1	60	3000	4	16	Chamber pressure data
147	8-9-76	Dynamic	150.9	+22	±1	120	3000	4	16	5-7 ms lag valve 4 7-8 ms lag valve 1
148	8-9-76	Dynamic	150.9	+22	±1	450	3000	4	16	10% amplitude ccw (valve 4) only No motion at 455 pps

DYNAVECTOR RUN SUMMARY

Run Number	Date	Type Test	Zero Reset	Initial Position, Steps From Zero Reset	Direction	Pulse Rate, pps	Pressure psi	Config. Code	Inst. Code	Comments
149	8-9-76	Dynamic	150.9	+22	0, -1	1	3000	4	16	Position calibration
150	8-9-76	Dynamic	150.9	+22	0, -1	60	3000	4	16	5-6 ms lag (valve 4) not significantly different from Run 127
151	8-9-76	Dynamic	150.9	+22	0, -1	120	3000	4	16	30% amplitude
152	8-9-76	Dynamic	150.9	+22	0, -1	415	3000	4	16	50% amplitude; actuation doesn't respond above 417 pps
153	8-9-76	Dynamic	150.9	+22	0, +1	1	3000	4	16	Position calibration
154	8-9-76	Dynamic	150.9	+22	0, +1	60	3000	4	16	100% amplitude; 7 ms lag same as Run 135
155	8-9-76	Dynamic	150.9	+22	0, +1	120	3000	4	16	100% amplitude, 7 ms lag
156	8-9-76	Dynamic	150.9	+22	0, +1	250	3000	4	16	30% amplitude, 7 ms lag Doesn't respond above 255 pps
157	8-9-76	- - -	- -	- -	- -	- -	- -	4	16	Zero burst
158	8-9-76	- - -	- -	- -	- -	- -	0	4	17	Chamber 8 calibration
159	8-9-76	- - -	- -	- -	- -	- -	1500	4	17	Chamber 8 calibration
160	8-9-76	- - -	- -	- -	- -	- -	3000	4	17	Chamber 8 calibration
161	8-9-76	- - -	- -	+22	±1	1	3000	4	17	Chamber 8 calibration

The chamber pressure instrumentation used for Runs 142-161 does not significantly affect performance.

DYNAVECTOR RUN SUMMARY

NOTE: Neutral actuator position is at 155.5 degrees

Run Number	Date	Record No.	Type Test	Zero Reset	Initial Position	Direction	Pulse Rate pps	Cyclic Rate Hz	Pressure psi	Flow gpm	Config. Code	Inst. Code	Comments
162	8-10-76	1	---------	-----	-----	---	-----	--	---		4	18	Zero burst
163	8-10-76	2	Dynamic	150.9	175.6	± 1	1	.25	3000		4	18	N.G.
164	8-10-76	3	Dynamic	150.9	175.6	± 1	1	.25	3000	.9	4	18	Position calibration at 1450 in #
165	8-10-76	4	Dynamic	150.9	175.6	± 1	60	15	3000	1.0	4	18	Valve 4: 2-3 ms before pressure starts to change (50%) 5 ms for pressure to reach final value 4 ms for initial movement 6 ms to reach final position Valve 1: 3.5-4 ms before pressure starts to change (100%) 5-6 ms for pressure to reach final value 5-6 ms for initial movement 7-8 ms to reach final position NOTE: 175.6 is Z.R. + 26 steps. Load is 1440 in #.
166	8-10-76	5	Dynamic	150.9	175.6	± 1	120	30	3000	1.2	4	18	100% amplitude
167	8-10-76	6	Dynamic	150.9	175.6	± 1	300	75	3000	1.2	4	18	Responds only to valve 4 commands (80% amplitude)
168	8-10-76	7											N. G.
169	8-10-76	8											N. G.
170	8-10-76	9											N. G.
171	8-10-76	10											N. G.
172	8-10-76	11	Dynamic	150.9	175.6	± 1	1	.25	3000	0.9	4	18	Same as run 164
173	8-10-76	12	Dynamic	150.9	175.6	± 1	60	15	3000	1.0	4	18	Same as run 165
174	8-10-76	13	Dynamic	150.9	175.6	± 1	120	30	3000	1.2	4	18	Same as run 166
175	8-10-76	14	Dynamic	150.9	175.6	± 1	200	50	3000	1.3	4	18	Position responds to .5, -.75
176	8-10-76	15	Dynamic	150.9	175.6	± 1	300	75	3000	1.2	4	18	Position responds + 0, -.8
177	8-10-76	16	Dynamic	150.9	175.6	± 1	360	90	3000	1.1	4	18	Position responds +0, -.5
178	8-10-76	18	Dynamic	150.9	175.6	0, -1	1	.5	3000	0.9	4	18	Position calibration (1450 in #)
179	8-10-76	19	Dynamic	150.9	175.6	0, -1	60	30	3000	1.0	4	18	Position responds +0, -1.2 (valve 4)
180	8-10-76	20	Dynamic	150.9	175.6	0, -1	120	60	3000	1.1	4	18	Position responds -0.1, -0.9
181	8-10-76	21	Dynamic	150.9	175.6	0, -1	200	100	3000	1.2	4	18	Position responds -0.3, -1.0
182	8-10-76	22	Dynamic	150.9	175.6	0, -1	300	150	3000	1.4	4	18	Position responds 0, -1
183	8-10-76	25	Dynamic	150.9	175.6	0, -1	430	215	3000	1.1	4	18	Position responds -.3, -.4. Doesn't respond above 434 pps.
184	8-10-76	26	Dynamic	150.9	175.6	0, +1	1	0.5	3000	0.7	4	18	Position calibration (1450 in #)
185	8-10-76	27	Dynamic	150.9	175.6	0, +1	60	15	3000	0.95	4	18	Position responds -0.2, +1.0 (valve 1)
186	8-10-76	28	Dynamic	150.9	175.6	0, +1	120	60	3000	1.05	4	18	Position responds 0, +0.8
187	8-10-76	29	Dynamic	150.9	175.6	0, +1	200	100	3000	1.2	4	18	Position responds 0, +0.9
188	8-10-76	30	Dynamic	150.9	175.6	0, +1	248	128	3000	1.1	4	18	Position responds +0.5, +1. Maximum frequency is 250 pp
189	8-10-76	31	---------	-----	-----	-----	---	---	----	---	4	18	Zero burst
190	8-12-76	34	---------	-----	-----	-----	---	---	----	---	6	19	Zero burst

DYNAVECTOR RUN SUMMARY

Run Number	Date	Record No.	Type Test	Zero Reset	Initial Position	Direction	Pulse Rate pps	Cyclic Rate Hz	Pressure psi	Flow gpm	Config. Code	Inst. Code	Comments
191	8-12-76	35	No load	-----	-----	±40	5	---	3000	.7-.9	6	19	Position calibration
192	8-12-76	36	No load	-----	-----	CW	250	---	3000	2.02	6	19	Wing rate measures 360°/1.444 = 249.3°/sec.
193	8-12-76	37	No load	-----	-----	CW	300	---	3000	2.48	6	19	Wing rate measures 360°/1.200 = 300°/sec.
194	8-12-76	38	No load	-----	-----	CW	400	---	3000	3.34	6	19	Wing rate measures120°/1.800 = 400°/sec.
195	8-12-76	39	No load	-----	-----	CW	500	---	3000	4.08	6	19	Wing rate measures 720°/1.440 = 500°/sec.
196	8-12-76	40	No load	-----	-----	CW	600	---	3000	3.95	6	19	Wing rate measures 720°/1.201 = 599.5°/sec.
197	8-12-76	41	No load	-----	-----	CW	650	---	3000	3.9	6	19	Wing rate measures 720°/1.010 = 648.6°/sec.
198	8-12-76	42	No load	-----	-----	CW	670	---	3000	3.75	6	19	Wing rate measures 720°/1.070 = 672.9°/sec. Conclude that actuator under zero load can follow CW commands to at least 670°/sec.
199-204	8-12	43-48	No load	-----	-----	±8	1-600	---	3000	---	6	20	No good
205-214	8-12	49-58	No load	-----	-----	±4	1-650	---	3000	---	6	21	No good
215	8-13-76	59	------	-----	-----	----	---	---	----	---	6	20	Zero burst
216	8-13-76	60	No load	150.8	155.5	±8	6.5	---	3000	.6-.7	6	20	Position calibration
217	8-13-76	61	No load	150.8	155.5	±8	250	7.8	3000	2.0	6	20	Position responds +7.8, -7.9; stops in sync.
218	8-13-76	62	No load	150.8	155.5	±8	300	9.4	3000	2.3	6	20	Position responds +7.5, -7.6; stops in sync.
219	8-13-76	63	No load	150.8	155.5	±8	400	12.5	3000	3.0	6	20	Position responds +7.1, -7.1; stops in sync.
220	8-13-76	--	No load	150.8	155.5	±8	500	15.6	3000	3.5	6	20	Position responds +7.0, -6.9; stops in sync.
221	8-13-76	--	No load	150.8	155.5	±8	600	18.7	3000	3.6	6	20	Position responds +6, -8; loses sync.
222	8-13-76	--	No load	150.8	155.5	±4	5	---	3000	0.7-0.9	6	21	Position calibration
223	8-13-76	---	No load	150.8	155.5	±4	250	15.6	3000	1.95	6	21	Position responds +3.8, -4; stops in sync.
224	8-13-76	---	No load	150.8	155.5	±4	300	18.7	3000	2.2	6	21	Position responds +3.6, -3.8; stops in sync.
225	8-13-76	---	No load	150.8	155.5	±4	400	25	3000	2.55	6	21	Position responds +3.1, -3.0; stops in sync.
226	8-13-76	---	No load	150.8	155.5	±4	500	31	3000	2.9	6	21	Position responds +3.1, -3.0; stops in sync.
227	8-13-76	---	No load	150.8	155.5	±4	600	37	3000	3.05	6	21	Position responds +2.75, -3.0; stops in sync.
228	8-13-76	---	No load	150.8	155.5	±4	650	40	3000	3.1	6	21	Position responds +2.8 -3; stops in sync.
229	8-13-76	---	No load	150.8	155.5	±4	700	43	3000	2.1	6	21	Position responds +2.5; -2.8; Records end before actuator is stopped. Conclude from visual oscilloscope data that actuator stays in sync to 700-750 pps.
230	8-13-76	---	No load	150.8	155.4	±4	750	46	3000		6	21	Record no good
231	8-13-76	---	------	-----	-----	---	---	--	----	---	6	21	Zero burst record no good
232	8-13-76	79	------	-----	-----	---	---	--	----	---	7	19	Zero burst
233	8-13-76	80	Cal	-----	-----	±30	5.5	--	3000	.6-.85	7	19	Position calibration
234	8-13-76	81	Pull out	-----	WZ-30	CW	50	--	3000	.8-1.1	7	19	Follows at 50 steps/sec. to step + 34 (2500 in #)
235	8-10-76	82	Pull out	-----	WZ-30	CW	100	--	3000	.9-1.2	7	19	Follows at 100 steps/sec to step 33 (2450 in #)
236	8-13-76	83	Pull out	-----	WZ-30	CW	250	--	3000	1.3-2.35	7	19	Follows at 250 steps/sec to step + 30 (2100 in #)
237	8-13-76	84	Pull out	-----	WZ-30	CW	300	--	3000	1.4-2.6	7	19	Follows at 300 steps/sec to step 28 (1900 in #)
238	8-13-76	85	Pull out	-----	WZ-30	CW	400	--	3000	2.8-3.1	7	19	Follows at 400 steps/sec to step 23 (1600 in #)
239	8-13-76	86	Pull out	-----	WZ-30	CW	500	--	3000	3.2-3.8	7	19	Follows at 500 steps/sec to step +3 (zero in #)
240	8-13-76	87	Pull out	-----	WZ-30	CW	600	--	3000	3.3-3.8	7	19	Follows at 600 steps/sec to step +4 (150 in # aiding)
241	8-13-76	88	Pull out	-----	WZ-30	CW	700	--	3000	3.8	7	19	Loses step at -25° (1200 in # aiding) but starts following again at 700 steps per second until -0.5° (200 in # aiding)
242	8-13-76	89	Pull out	-----	WZ-30	CW	800	--	3000	3.5	7	19	Loses step at -25° (1100 in aiding) but starts following again at 800 steps/second until -5° (600 in # aiding)
243	8-13-76	90	Pull out	-----	WZ-30	CW	450	--	3000	3.4	7	19	Tried to run at 900 pps which driver could not handle. Driver output was 450 pps. Actuator follows at 450 steps/sec to +17° (1000 in #)
244	8-13-76	91	Pull out	-----	WZ-30	CW	500	--	3000	--	7	19	Tried to run at 1000 pps but driver limited to 500 pps. Record no good.
245	8-13-76	92	Cal	-----	Wing zero	CCW	5	---	3000	.6-.9	7	19	Position calibration.
246	8-13-76	93	Cal	-----	Wing zero	±30	5	---	3000	.6-.9	7	19	Position calibration.
247	8-13-76	94	Pull out	-----	183.4	CCW	50	---	3000	.9-1.0	7	19	Follows at 50 steps/sec to Step-34 (2200 in #)
248	8-13-76	95	Pull out	-----	183.4	CCW	100	---	3000	1.1-1.3	7	19	Follows at 100 steps/sec to Step-33 (2150 in #)
249	8-13-76	96	Pull out	-----	183.4	CCW	250	---	3000	1.7-2.3	7	19	Follows at 250 steps/sec to Step-32 (2000 in #)
250	8-13-76	97	Pull out	-----	183.4	CCW	300	---	3000	2.0-2.5	7	19	Follows at 300 steps/sec to Step-30 (1900 in #)
251	8-13-76	98	Pull out	-----	183.4	CCW	400	---	3000	2.5-3.0	7	19	Follows at 400 steps/sec to Step-22 (1250 in #)
252	8-13-76	100	Pull out	-----	183.4	CCW	500	---	3000	3.5	7	19	Follows at 500 steps/sec to Step-10 (515 in #)
253	8-13-76	101	Pull out	-----	183.4	CCW	600	---	3000	3.0	7	19	No good.
254	8-13-76	102	Pull out	-----	183.4	CCW	700	---	3000	3.2	7	19	Follows at 700 steps/sec to Step +4 (500 in # aiding)
255	8-13-76	103	Pull out	-----	183.4	CCW	800	---	3000	----	7	19	Follows at 800 steps/sec to Step +25 (1300 in # aiding)
256	8-13-76	104	Pull out	-----	183.4	CCW	450	---	3000	3.3	7	19	900 pps to driver but driver output only 450 pps. Follows to Step -18 (1030 in #)
257	8-13-76	105	Pull out	-----	183.4	CCW	500	---	3000	3.6-3.8	7	19	Follows at 500 steps/sec to Step -13 (800 in #)
258	8-13-76	106	------	-----	----	----	---	---	----	----	7	19	Zero burst.
259	8-17-76	110	------	-----	----	----	---	---	----	----	7	22	Zero burst (before repositioning position trace)
260	8-17-76	111	Pull in	153.4	175.3 (1440 in #)	CW	5	---	3000	.6-.9	7	22	Position calibration (Step -40, 2600 in # stall)
261	8-17-76	112	Pull in	155.9	175.3	CW	5	---	3000	.6-.9	7	22	Position calibration (Step 27, 2450 in # stall)
262	8-17-76	113	Pull in	153.4	175.3	CW	140	---	3000	1.5	7	22	Pull in OK; Pull out step 36 (2450 in #)
263	8-17-76	114	Pull in	153.4	175.3	CW	250	---	3000	----	7	22	Pull in OK; Pull out step 33.5 (2150)
264	8-17-76	115	Pull in	155.9	175.1	CW	300	---	3000	----	7	22	Pull in OK; Pull out step 34 (torque erratic)
265	8-17-76	116	Pull in	155.9	175.1	CW	350	---	3000	----	7	22	Pull in OK; Pull out step 26.5 (1800 in #)
266	8-17-76	117	Pull in	150.9	175.7	CW	5	---	3000	----	7	22	Position calibration (2500 in # stall)
267	8-17-76	118	Pull in	153.4	175.4	CW	400	---	3000	----	7	22	Pull in OK; Pull out step 23.5 (1600 in #)
268	8-17-76	119	Pull in	155.9	175.1	CW	450	---	3000	----	7	22	Pull in OK; Pull out step 23.5 (1600 in #)
269	8-17-76	120	Pull in	155.9	175.1	CW	500	---	3000	----	7	22	Pull in OK; Pull out step 23.0 (1600 in #)
270	8-17-76	121	Pull in	153.4	175.3	CW	550	---	3000	----	7	22	Pull in OK; Pull out step 23.0 (1600 in #)
271	8-17-76	122	Pull in	153.4	175.3	CW	200	---	3000	----	7	22	Pull in OK; Pull out step 38 (2500 in #)
272	8-17-76	123	------	-----	----	----	---	---	3000	----	7	22	Zero burst
273	8-17-76	126	------	-----	175.6 (1440 in #)	----	---	---	----	----	7	23	Zero burst

DYNAVECTOR RUN SUMMARY

Run Number	Date	Record No	Type Test	Zero Reset	Initial Position	Direction	Pulse Rate pps	Cyclic Rate Hz	Pressure psi	Flow gpm	Config. Code	Inst. Code	Comments
274	8-17-76	127	-	150.9	175.6 (1440 in #)	-	3.5	-	3000	-	7	23	Position calibration
275	8-17-76	128	Dynamic	150.9	175.7	±1	30	7.5	3000	.9	7	23	7 ms (.007 x 7.5 x 360 = 19°) lag;amplitude = + 1, -1
276	8-17-76	129	Dynamic	150.9	175.7	±1	3	.75	3000	-	7	23	No test
277	8-17-76	130	Dynamic	150.9	175.7	±1	60	15	3000	1.0	7	23	7 ms (.007 x 15 x 360 = 38°) lag;amplitude = +1, -1
278	8-17-76	131	Dynamic	150.9	175.7	±1	120	30	3000	1.1	7	23	7 ms (.007 x 30 x 360 = 76°) lag;amplitude = +1.1, -1.1
279	8-17-76	132	Dynamic	150.9	175.8	±1	180	45	3000	1.3	7	23	6 ms (.006 x 45 x 360 = 97°) lag;amplitude = +1, -1
280	8-17-76	133	Dynamic	150.9	175.7	±1	240	60	3000	1.3	7	23	6 ms (.006 x 60 x 360 = 130°) lag;amplitude = +1, -1
281	8-17-76	134	Dynamic	150.9	175.6	±1	285	71.2	3000	1.3	7	23	7 ms (.007 x 71 x 60 = 180°) lag;amplitude =+.6, -.6
282	8-17-76	135	Dynamic	150.9	175.6	±1	300	75	3000	1.3	7	23	7 ms (.007 x 75 x 360 = 189°) lag;amplitude = +.6, -.6
283	8-17-76	136	Dynamic	150.9	175.6	±1	325	81	3000	1.3	7	23	7 ms (.007 x 81 x 360 = 204°) lag;amplitude = +.6, -.6
284	8-17-76	137	Dynamic	150.9	175.6	±1	350	87.5	3000	1.3	7	23	7 ms (.007 x 87.5 x 360 = 220°) lag;amplitude = +.6, -.5
285	8-17-76	138	Dynamic	150.9	175.6	±1	375	94	3000	1.3	7	23	7 ms (.007 x 94 x 360 = 236) lag;amplitude = +.5, -.4
286	8-17-76	139	Dynamic	150.9	175.6	±1	400	100	3000	1.2	7	23	No motion
287	8-17-76	140	Dynamic	150.9	175.6	±1	425	106	3000	1.1	7	23	No motion
288	8-17-76	141	Dynamic	150.9	175.6	±1	450	112	3000	1.1	7	23	No motion
289	8-17-76	142	Dynamic	150.9	175.6	±1	500	125	3000	.9	7	23	No motion
290	8-17-76	143	-	-	-	-	-	-	-	-	7	23	Zero burst
291	8-17-76	144	Dynamic	150.9	175.6 (1450 in #)	±2	5		3000	.6-.9	7	23	Position calibration
292	8-17-76	145	Dynamic	150.9	175.8	±2	120	15	3000	1.2	7	23	7 ms (.007x 15 x 360 = 38°) lag
293	8-17-76	146	Dynamic	150.9	175.8	±2	240	30	3000	1.5	7	23	Loses track after 7 steps. Dynamic torque reached 2000 in #
294	8-17-76	147	Dynamic	150.9	175.8	±2	200	25	3000	1.6	7	23	7 ms (.007 x 25 x 360 = 63°) lag. Peak amplitude = + 2.5, -2.5 Dynamic torque reaches 2000 in #
295	8-17-76	148	Dynamic	150.9	175.8	±2	225	28.1	3000	1.6	7	23	7 ms (.007 x 28 x 360 = 71°) lag;amplitude = +2.1, -2.1 Follows for 15 steps then loses track at dynamic load of 2100 in #
296	8-17-76	149	Dynamic	153.4	175.3	±4	5	-	3000	.6-.9	7	24	Position calibration
297	8-17-76	150	Dynamic	153.4	175.3	±4	120	7.5	3000	1.3	7	24	6-7 ms lag; +4, -4
298	8-17-76	151	Dynamic	153.4	175.3	±4	180	11.2	3000	1.5	7	24	7 ms lag; +4.1, -4.1
299	8-17-76	152	Dynamic	153.4	175.3	±4	240	15	3000	1.8	7	24	7 ms lag; +4, -4
300	8-17-76	153	Dynamic	153.4	175.3	±4	240	15	3000	1.8	7	24	7 ms lag; +4, -4
301	8-17-76	154	Dynamic	153.4	175.3	±4	300	18.7	3000	2.3	7	24	7 ms lag; +3.9, -3.6
302	8-17-76	155	Dynamic	153.4	175.3	±4	360	22.5	3000	2.6	7	24	Loses track during 1st cycle; dynamic torque = 1800 in #
303	8-17-76	155	Dynamic	150.9	175.5	±4	325	20.3	3000	2.3	7	24	7 ms lag; +4.2, -3.2; OK
304	3-17-76	157	Dynamic	150.9	175.5 (1450 in #)	+1, 0	5	2.5	3000	.6-.9	7	25	Position calibration
305	3-17-76	158	Dynamic	150.9	175.5	+1, 0	30	15	3000	.9	7	25	7 ms (37°); +1, 0 (Valve 1)
306	3-17-76	159	Dynamic	150.9	175.5	+1, 0	60	30	3000	.9	7	25	6 & 7 ms (70°); +1.2, 0
307	3-17-76	160	Dynamic	150.9	175.5	+1,0	120	60	3000	1.0	7	25	6-7 ms (140°); +1.1, -1
308	3-17-76	161	Dynamic	150.9	175.5	+1, 0	180	90	3000	1.0	7	25	6 ms (194°); +1.0, -.8
309	3-17-76	162	Dynamic	150.9	175.5	+1, 0	240	120	3000	1.1	7	25	6 ms (259°); +1, -1
310	3-17-76	163	Dynamic	150.9	175.5	+1, 0	300	150	3000	1.1	7	25	6 ms (324°); +1.1, -1
311	3-17-76	164	Dynamic	150.9	175.5	+1, 0	360	180	3000	1.1	7	25	6 ms (388°); +1, -1
312	3-17-76	165	Dynamic	150.9	175.5	+1, 0	420	210	3000	1.0	7	25	5 ms (453°); +1, -0.6
313	3-17-76	166	Dynamic	150.9	175.5	+1, 0	430	215	3000		7	25	Moves to +0.9 & stays there until end of run. Stays in sync.
314	3-17-76	167	-	150.9	175.5	-	-	-	-	-	7	25	Zero burst
315	3-18-76	170	-	-	-	-	-	-	-	-	7	23	Zero burst
316	3-18-76	171	Dynamic	155.9	184.8	±2	5	.6	3000	.6-.9	7	23	Position calibration around W.Z.+ 30 steps (2040 in #)
317	3-18-76	172	Dynamic	155.9	184.8	±2	60	7.5	3000	1.0	7	23	7 ms lag; amplitude = +2, -2
318	3-18-76	173	Dynamic	155.9	184.8	±2	120	15	3000	1.1	7	23	7 ms lag; +2, -2
319	3-18-76	174	Dynamic	155.9	184.8	±2	180	22	3000	1.5	7	23	7 ms lag; +2.2, -2.3
320	3-18-76	175	Dynamic	155.9	184.9	±2	200	25	3000	1.5	7	23	Loses track during 1st cycle
321	3-18-76	176	Dynamic	153.4	184.8	±2	200	25	3000	1.8	7	23	No test, limit disabled
322	8-18-76	177	Dynamic	155.9	184.8	±2	200	25	3000	1.5	7	23	Loses track; 1st cycle
323	8-18-76	178	Dynamic	153.4	165.9	±2	5	.6	3000	.6-.9	7	23	Position calibration - load at the 165.9 initial position is 660 in #
324	8-18-76	179	Dynamic	153.4	165.9	±2	60	7.5	3000	.9	7	23	6-8 ms lag, amplitude = +2, -2
325	8-18-76	180	Dynamic	153.4	165.9	±2	120	15	3000	1.1	7	23	6-8 ms lag; amplitude = +2, -2
326	8-18-76	181	Dynamic	153.4	165.9	±2	180	22.5	3000	1.25	7	23	5-8 ms lag; amplitude = +2.2, -2.3
327	8-18-76	182	Dynamic	153.4	165.9	±2	200	25	3000	1.4	7	23	6-7 ms lag; amplitude +2.2, -2.3
328	8-18-76	183	Dynamic	153.4	165.9	±2	220	27.5	3000	1.5	7	23	5-13 ms lag; +2.0, -1.7; moved to -3.0 degrees when command was shut off but settled out at the correct -2.0 degree commanded position. Stayed in sync for entire run but had the appearance of being nearly out of step. Opposing loads, however, due to spring dynamics varied between 200 and 1800 in #.
329	8-18-76	184	Dynamic	153.4	165.9	±2	250	31.2	3000	1.4	7	23	5-11 ms lag; amplitude = 1.2, -1.2
330	8-18-76	185	Dynamic	153.4	165.9	±2	275	34.3	3000	1.5	7	23	Amplitude = +1.2, -1.2
331	8-18-76	186	Dynamic	153.4	165.9	±2	300	37.5	3000	1.6	7	23	Amplitude = +1.2, -1.2
332	8-18-76	187	Dynamic	153.4	165.9	±2	325	40.6	3000	1.7	7	23	Amplitude = +1.2, -1.0
333	8-18-76	188	Dynamic	153.4	165.9	±2	350	43.7	3000	1.5	7	23	Amplitude = +1.2, -.85
334	8-18-76	189	Dynamic	153.4	165.9	±2	375	46.8	3000	1.4	7	23	Amplitude = +1.0, -0.9 until commands were stopped and actuator moved to the correct -2.0 position
335	8-18-76	190	Dynamic	153.4	165.9	±2	400	50	3000	1.4	7	23	Amplitude = +1.15, -0.9
336	8-18-76	191	Dynamic	153.4	165.9	±2	450	56	3000	1.4	7	23	Amplitude = +1.2, -1.0
337	8-18-76	192	Dynamic	153.4	165.9	±2	500	62	3000	1.4	7	23	Amplitude = +1.0, -0.8
338	8-18-76	193	Dynamic	153.4	165.9	±2	550	69	3000	1.5	7	23	Amplitude = +1.0, -0.5
339	8-18-76	194	Dynamic	153.4	165.9	±2	600	75	3000	1.6	7	23	Amplitude = +1.0, -0.5
340	8-18-76	195	Dynamic	153.4	165.9	±2	650	81	3000	1.6	7	23	Amplitude = +1.0, -0.5
341	8-18-76	196	Dynamic	153.4	165.9	±2	700	87	3000	1.6	7	23	Amplitude = +0.9, -0.6
342	8-18-76	197	Dynamic	153.4	165.9	+2, -3	750	75	3000	2.0	7	23	Amplitude = +0.6, -1.3; although a ±2 command was dialed into the driver, the driver actually commanded the actuator to +2, -3. The actuator kept in sync. Did not lose track.

DYNAVECTOR RUN SUMMARY

Run Number	Date	Record No.	Type Test	Zero Reset	Initial Position	Direction	Pulse Rate pps	Cyclic Rate Hz	Pressure psi	Flow gpm	Config. Code	Inst. Code	Comments
343	8-18-76	198	Dynamic	153.4	165.9	+2, -3	800	80	3000	2.0	7	23	+0.6, -1.3; in sync. Did not lose track.
344	8-18-76	199	-	-	-	-	-	-	-	-	7	23	Zero burst
345	8-18-76	200	-	-	-	-	-	-	-	-	7	25	Zero burst
346	8-18-76	201	Dynamic	153.4	155.0	+1, 0	5	2.5	3000	0.7	7	25	Position calibration
347	8-18-76	202	Dynamic	153.4	155.0	+1, 0	60	30	3000	0.9	7	25	6 ms (65°) lag; +1, 0 amplitude
348	8-18-76	203	Dynamic	153.4	155.0	+1, 0	120	60	3000	1.0	7	25	6 ms (130°) lag; +1.3, -0.3
349	8-18-76	204	Dynamic	153.4	155.0	+1, 0	240	120	3000	1.2	7	25	6 ms (260°) lag; +1.2, -0.2
350	8-18-76	205	Dynamic	153.4	155.0	+1, 0	360	180	3000	1.1	7	25	6 ms (389°) lag; +1.1, -0.1
351	8-18-76	206	Dynamic	153.4	155.0	+1, 0	420	210	3000	1.0	7	25	No motion; positioned at +1°
352	8-18-76	207	Dynamic	153.4	155.0	+1, 0	380	190	3000	1.05	7	25	6 ms (410°) lag; +1.0, +0.1
353	8-18-76	208	Dynamic	153.4	155.1	±1	5	1.25	3000	.75	7	25	Position calibration
354	8-18-76	209	Dynamic	153.4	155.1	±1	120	30	3000	1.1	7	25	6 ms (65°) lag; ±1 amplitude
355	8-18-76	210	Dynamic	153.4	155.1	±1	240	60	3000	1.5	7	25	5-6 ms lag; +1.1, -1.2
356	8-18-76	211	Dynamic	153.4	155.1	±1	360	90	3000	1.2	7	25	+0.5; -0.3
357	8-18-76	212	Dynamic	153.4	155.1	±1	480	120	3000	0.9	7	25	No motion; positioned at zero. Stays in sync.
358	8-18-76	213	Dynamic	153.4	155.1	±1	420	105	3000	1.0	7	25	No motion; positioned at zero. Stays in sync.
359	8-18-76	214	Dynamic	153.4	155.1	±2	5	.62	3000	0.7	7	25	Position calibration.
360	8-18-76	215	Dynamic	153.4	155.1	±2	120	15	3000	1.2	7	25	5-6 ms lag; +2.0, -2.2
361	8-18-76	216	Dynamic	153.4	155.1	±2	120	15	3000	1.2	7	25	5-6 ms lag; +2.0, -2.2
362	8-18-76	217	Dynamic	153.4	155.1	±2	240	30	3000	1.6	7	25	5-6 ms (59.4°) lag; +2.0, +1.8
363	8-18-76	218	Dynamic	153.4	155.1	±2	360	45	3000	1.95	7	25	5-7 ms lag; +1.6, -1.6
364	8-18-76	219	Dynamic	153.4	155.1	±2	480	60	3000	1.95	7	25	5-6 ms lag; +1.0, -1.0
365	8-18-76	220	Dynamic	153.4	155.1	±2	600	75	3000	1.8	7	25	5 ms lag; +0.9, -0.9
366	8-18-76	221	Dynamic	153.4	155.1	±2	700	87.5	3000	1.8	7	25	5 ms lag; +0.8, -1.0
367	8-18-76	222	Dynamic	153.4	155.1	+2, -3	840	84	3000	2.35	7	25	±2 was set to driver, but driver actually commanded +2, -3. Actuator has 5 ms lag with +0.7, -2.0 amplitud Did not lose track.
368	8-18-76	223	Dynamic	153.4	155.1	+2, -3	780	78	3000	2.35	7	25	5 ms lag; +.7, -2
369	8-18-76	224	Dynamic	153.4	155.5	±8	5	.31	3000	.6-.8	7	26	No good.
370	8-18-76	225	Dynamic	153.4	155.1	±8	5	.31	3000	.6-.8	7	26	Position calibration (±480 in #)
371	8-18-76	226	Dynamic	153.4	155.1	±8	120	3.75	3000	1.2	7	26	5-6 ms lag; ±8
372	8-18-76	227	Dynamic	153.4	155.1	±8	240	7.5	3000	1.9	7	26	5-9 ms lag; ±7.5
373	8-18-76	228	Dynamic	153.4	155.1	±8	240	7.5	3000	1.9	7	26	5-9 ms lag; ±7.5
374	8-18-76	229	Dynamic	153.4	155.1	±8	360	11.25	3000	2.5	7	26	6-8 ms lag; +7.3, -7.0
375	8-18-76	230	Dynamic	153.4	155.1	±8	480	15	3000	3.4	7	26	7 ms lag; +7.3, -7.1; OK
376	8-18-76	231	Dynamic	153.4	155.1	±8	600	18.75	3000	3.2	7	26	+4.5, -7; loses sync.
377	8-18-76	232	Dynamic	150.9	155.5	±8	540	16.9	3000	3.1	7	26	+8, -7; loses sync.
378	8-18-76	233	Dynamic	156.0	154.9	±20	5	.06	3000	.6-.8	7	27	Position calibration.
379	8-18-76	234	Dynamic	156.0	154.9	±20	140	1.75	3000	1.35	7	27	5-7 ms lag; ±20 (±1350 in #)
380	8-18-76	235	Dynamic	156.0	154.9	±20	240	3.0	3000	2-2.1	7	27	7 ms lag; +19.5, -20
381	8-18-76	236	Dynamic	156.0	154.9	±20	360	4.5	3000	3.0	7	27	7 ms lag; ±19 steps
382	8-18-76	237	Dynamic	156.0	154.9	±20	480	6.0	3000	3.5	7	27	7 ms lag; ±18.8; OK
383	8-18-76	238	Dynamic	156.0	154.9	±20	600	7.5	3000	3.5	7	27	Loses sync, ±13
384	8-18-76	239	Dynamic	153.5	155.4	±20	540	6.75	3000	3.5	7	27	Loses sync, +16, -17
385	8-18-76	240	----	----	----	----	----	----	----	----	-	27	Zero burst
386	8-19-76	244	----	----	----	----	----	----	----	----	-	--	No Good
387	8-19-76	245	----	----	----	----	----	----	----	----	-	--	No Good
388	8-19-76	246	----	----	----	----	----	----	----	----	-	28	Torque sensor calibration -Zero in. #.
389	8-19-76	247	----	----	----	----	----	----	----	----	-	28	Torque sensor calibration 450 in. #
390	8-19-76	248										28	Torque sensor calibration 864 in. #
391	8-19-76	249										28	Torque sensor calibration 1464 in. #
392	8-19-76	250										28	Torque sensor calibration 1980 in. #
393	8-19-76	251										28	Torque sensor calibration 2160 in. #
394	8-19-76	252										28	Torque sensor calibration 2316 in. #
395	8-19-76	253										28	Torque sensor calibration 2316 in. #
396	8-19-76	254										28	Torque sensor calibration 2460 in. #
397	8-19-76	255										28	Torque sensor calibration 492 in. #
398	8-19-76	256										28	Torque sensor calibration Zero in. #
399	8-19-76	257										28	Torque sensor calibration 480 in. #
400	8-19-76	258										28	Torque sensor calibration 960 in. #
401	8-19-76	259										28	Torque sensor calibration 1440 in. #
402	8-19-76	260										28	Torque sensor calibration 1920 in. #
403	8-19-76	261										28	Torque sensor calibration 2400 in. #
404	8-19-76	262										28	Torque sensor calibration Zero in. #
													Data agrees with initial calibration.

DYNAVECTOR RUN SUMMARY

Run Number	Date	Record No.	Type Test	Zero Reset	Initial Position	Direction	Pulse Rate pps	Cyclic Rate Hz	Pressure psi	Flow gpm	Config. Code	Inst. Code	Life Test Elapsed Time Hrs	Comments
405	8-19-76	263	Life	153.5	----	----	----	----	----	----	7	28	0	Zero burst
406	8-19-76	264	Life	153.5	155.1	±20	10	.125	3000	.67	7	28	0	Position calibration, ±1450 in. #
407	8-19-76	265	Life	153.5	155.1	±20	140	1.75	3000	1.3	7	28	0	Start life test (±1350 in. #) 5-6 ms lag; ±20
408	8-19-76	266	Life	153.5	155.1	+ 10, -30	14	.175	3000	.85	7	28	0.7	At 40 min. into life test, it was noted that actuator was cycling about -10° rather than wing zero. The pulse rate was reduced to 14 pps and a recording made. Load was +800 to -2000 in.#. The cause for the shift is not known. The time cycling about -10° is not known. The actuator was not stalling at 14 pps and apparently was running all right at 140 pps also.
409	8-19-76	267	Life	153.5	155.1	±20	14	.175	3000	.8-1.0	7	28	0.7	Actuator was repositioned at W. Z and a ±20 calibration run made.
410	8-19-76	268	Life	153.5	155.1	±20	140	1.75	3000	1.3	7	28	0.7	Resumed life test. Data identical to run 407.
411	8-19-76	269	Life	153.5	155.1	±20	140	1.75	3000	1.3	7	28	1.0	
412	8-19-76	270	Life	153.5	155.1	±20	14	.175	3000	.7 - .9	7	28	1.5	Shut down just prior to this run. Very few chips on magnetic plug.
413	8-19-76	271	Life	153.5	155.1	±20	140	1.75	3000	1.3	7	28	1.5	Data identical to run 407.
414	8-19-76	272	Life	156.0	155.6	±20	14	1.75	3000	.7 - .9	7	28	2.5	Shut down just prior to this run to examine magnetic plug. Very few chips. Noticed that zero reset had changed. Ran at 14 pps to calibrate position trace.
415	8-19-76	273	Life	156.0	155.6	±20	140	1.75	3000	1.3	7	28	2.5	Steps are not as distinct as in earlier runs. Performance otherwise unchanged.
416	8-19-76	274	Life	156.0	155.6	±20	140	1.75	3000	1.3	7	28	3.5	Same as run 415. Shut down and examined plug prior to run 417. Few particles.
417	8-19-76	275	Life	153.5	155.1	±20	14	.175	3000	.7 - .9	7	28	4.5	Accidently ran into stall while setting up which resulted in a change of zero reset.
418	8-19-76	276	Life	153.4	155.1	±20	140	1.75	3000	1.3	7	28	4.5	Steps are not as distinct as run 407. Otherwise no change.
419	8-19-76	277	Life	153.4	155.1	±20	140	1.75	3000	1.3	7	28	5.5	Data is same as run 418.
420	8-19-76	278	Life	153.4	155.1	±20	140	1.75	3000	1.3	7	28	6.5	Data same as run 418.
421	8-19-76	279	Life	153.4	155.1	±20	140	1.75	3000	1.3	7	28	7.5	Data same as run 418.
422	8-19-76	280	Life	153.4	155.1	±20	140	1.75	3000	1.3	7	28	8.0	Data same as run 418.
423	8-19-76	281	------	-----	----	----	---	---	----	---	7	28	8.0	Zero burst.
	8-20-76													Inspected magnetic plug. Few particles.
424	8-20-76	284	------	-----	----	----	---	---	----	---	7	28	8.0	Zero burst.
425	8-20-76	285	Life	153.6	155.2	±20	14	.175	3000	.7-.9	7	28	8.0	Position calibration.
426	8-20-76	286	Life	153.6	155.2	±20	140	1.75	3000	1.3	7	28	8.0	Resumed life test. Data same as run 418.
427	8-20-76	287	Life	153.6	155.2	±20	140	1.79	3000	1.3	7	28	9.0	Data same as run 418.
													9.3	Hydraulic bench shut down from over heating. Resulted in changing zero reset of actuator. Inspected magnetic plug. Few particles.
428	8-20-76	288	------	-----	----	----	---	---	----	---	7	28	9.3	Zero burst.
429	8-20-76	289	Life	155.9	155.9	±20	14	.175	3000	.7-.9	7	28	9.3	Position calibration.
430	8-20-76	290	------	155.9	136.9	----	---	---	3000	---	7	28	9.3	Step -20 calibration.
431	8-20-76	291	------	155.9	155.9	----	---	---	3000	---	7	28	9.3	Zero calibration.
432	8-20-76	292	------	155.9	175.2	----	---	---	3000	---	7	28	9.3	Step + 20 calibration.
433	8-20-76	293	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	9.3	Resume life test. Data similar to run 415.
434	8-20-76	294	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	10.3	Data similar to run 415.
435	8-20-76	295	------	155.9	155.9	----	---	---	----	---	7	28	10.3	Zero burst.
436	8-20-76	296	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	10.3	OK, data similar to run 415.
437	8-20-76	297	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	11.3	OK, data similar to run 415.
438	8-20-76	298	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	12.3	OK, data similar to run 415.
439	8-20-76	299	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	13.3	OK, data similar to run 415.
440	8-20-76	300	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	14.3	OK, data similar to run 415.
441	8-20-76	301	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	15.3	OK, data similar to run 415.
442	8-20-76	302	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	16.3	OK, data similar to run 415.
443	8-20-76	303	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	17.3	OK, data similar to run 415.
444	8-20-76	304	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	18.3	OK, data similar to run 415.
445	8-20-76	305	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	19.3	OK, data similar to run 415.
446	8-20-76	306	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	20.3	OK, data similar to run 415.
447	8-20-76	307	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	21.3	OK, data similar to run 415.
448	8-20-76	308	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	21.5	OK, data similar to run 415.
449	8-20-76	309	Life	155.9	155.9	±20	140	1.75	3000	1.3	7	28	21.5	Zero burst.
-	8-23-76	-	-	-	-	-	-	-	-	-	7	28	21.5	Examined magnetic plug. Few particles
450	8-23-76	310	-	-	-	-	-	-	-	-	7	28	21.5	Zero burst.
451	8-23-76	311	Life	156.0	156.0	±20	140	1.75	3000	1.3	7	28	21.5	Resume life test. Data similar to run 415. Steps are not quite distinct.
452	8-23-76	312	Life	156.0	156.0	±20	140	1.75	3000	1.3	7	28	22.5	No change. Same as run 451.
453	8-23-76	313	Life	156.0	156.0	±20	140	1.75	3000	1.5	7	28	23.7	Actuator sound and performance changed abruptly. Position trace is erratic. Total motion only ±10 degrees.
454	8-23-76	-	-	155.9	155.9	-	-	-	3000	.5-.6	7	28	23.7	Actuator responds ±30 degrees to manual commands. Took visual, static calibration data

DYNAVECTOR RUN SUMMARY

Run Number	Date	Record No.	Type Test	Zero Reset	Initial Position	Direction	Pulse Rate pps	Cyclic Rate Hz	Pressure psi	Flow gpm	Config. Code	Inst. Code	Life Test Elapsed Time Hours	Comments
455	8-23-76	314	-	-	-	-	-	-	-	-	7	28	23.7	Zero burst spring fixture has a fair amount of oil in it, an indication of shift seal leakage.
	8-23-76													The inertia plate keyway has worn resulting in a very loose fit. Removed inertia plate.
456	8-23-76	315	-	-	-	-	-	-	-	-	8	28	23.7	Zero burst.
457	8-23-76	316	Life	150.6	155.7	± 20	14	1.75	3000	.7-.9	8	28	23.7	Position calibration normal performance
458	8-23-76	317	Life	150.6	155.7	± 20	140	1.75	3000	1.3	8	28	23.7	Momentarily performed normally. Actuator failed before data could be recorded. Recorded data while actuator performance was erratic. Actuator follows for up to 10 steps then stills and starts again. The actuator was shut down and the magnetic plug examined and found to be covered with many metallic particles.
459	8-23-76	318	-	-	-	-	-	-	-	-	8	28	23.7	Zero burst
460	6-13-77	-	Break in								9 & 10	29		Rebuilt actuator.
461	7-18-77	-	Checkout and back back driving torque								9 & 10	29		Actuator was disassembled, inspected and reassembled after run 460
462	7-19-77 through 8-3-77	-	Life Test	154.5	155.5	± 20	140	1.75	3,000	1.36	10	29	34	Fractured #4 reaction pin spacer after 34 hours

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