AD-A047 283 DYNAMIC CONTROLS INC DAYTON OHIO F/G 1/4
RESEARCH AND DEVELOPMENT OF AIRCRAFT CONTROL ACTUATION SYSTEMS.--ETC(U)
SEP 77 G D JENNEY F33615-75-C-3068

UNCLASSIFIED AFFDL-TR-77-91 NL

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RESEARCH AND DEVELOPMENT OF AIRCRAFT CONTROL ACTUATION SYSTEMS.

The Development of a Direct Drive Fly-By-Wire Flight Control System and Evaluation of a Force Sharing Fly-By-Wire Actuator.

DYNAMIC CONTROLS, INC.
DAYTON, OHIO 45404

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SEPT[redacted] 1977

216p.

F33615-75-C-3068

TECHNICAL REPORT AFFDL-TR-77-91
Final Report, [redacted] Febr[redacted] 1975 – June 1977

1987
2049

Approved for public release; distribution unlimited.

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: AFFDL-TR-77-91 — 2. GOVT ACCESSION NO.: NA	3. RECIPIENT'S CATALOG NUMBER: NA
4. TITLE (and Subtitle): Research and Development of Aircraft Control Actuation Systems	5. TYPE OF REPORT & PERIOD COVERED: FINAL Jan 1975 - Jan 1977
	6. PERFORMING ORG. REPORT NUMBER: NA
7. AUTHOR(s): Gavin D. Jenney	8. CONTRACT OR GRANT NUMBER(s): F33615-75-C-3068
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Dynamic Controls, Inc. P. O. Box 281, North Dayton Station Dayton, Ohio 45404	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: Project No. 1987
11. CONTROLLING OFFICE NAME AND ADDRESS: Air Force Flight Dynamics Laboratory AFFDL/FGL, Flight Controls Division Wright-Patterson AFB, Ohio 45433	12. REPORT DATE: September 1977
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)	15. SECURITY CLASS. (of this report): Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

62201F

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

None

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Redundant Systems
Fly-By-Wire
Direct Drive
Force Motors

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

This report describes the design and test evaluation of a direct drive fly-by-wire redundant control system. Also included in the report is the evaluation testing of a fly-by-wire tandem actuator mechanization developed by Parker-Hannifin Aerospace Hydraulics Division, Irvine California.

The direct drive system is based on using moving coil force →

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(20. Abstract, Cont'd.) motors to position a hydraulic control valve without hydraulic amplification. The system is designed as a single fail operate system which will accept one input or component failure and continue to operate with acceptable performance. The test results verified that the failure modes and performance met the design goals. The system incorporates component dispersion techniques to allow single hit survivability. The direct drive mechanization offers adequate performance with minimum complexity as a fly-by-wire control system.

The Parker-Hannifin actuator mechanization is a two fail operate configuration using an integrated secondary actuator with both force and position summing. The test results document the operational characteristics of the design.

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FOREWORD

The effort described in this document was performed by the Dynamic Controls, Inc., of Dayton, Ohio, under Air Force Contract F33615-75-C-3068. The contract was performed under Project Number 1987 and 2049 entitled "Flight Control Actuation Systems Development". Work under the contract was carried out in the Air Force Flight Dynamics Laboratory (AFFDL), Flight Control Division at Wright-Patterson Air Force Base utilizing United States Air Force facilities. The work was administered by Bruce H. Earley and Greg Cecere AFFDL/FGL Project Engineers.

This report covers work performed between January 1975 and 31 May 1977. The technical report was submitted by the author in July 1977.

The author wishes to express his appreciation to the Dynamic Controls, Inc., personnel Carl N. Allbright, Heinrich J. Wieg, William G. Talley, and Harry Schreadley for their contributions in the areas of analysis, design, fabrication, and testing associated with the effort.

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LIST OF ABBREVIATIONS AND SYMBOLS

ABBREVIATIONS

ac	Alternating Current
C	Centigrade
db	Decibel
dc	Direct Current
div	Division (of the plotting paper used)
F	Fahrenheit
FBW	Fly By Wire
GPM	Gallons per Minute
Hz	Hertz (cycles per second)
in	Inch
lbs	Pounds
LED	Light Emitting Diode
LVDT	Linear Variable Differential Transformer
ma	Milliampheres
max	Maximum
mm	Millimeter
mv	Megavolt
psi	Pounds Per Square Inch
RC	Resistor/Capacitor
sec	Second
v	Volt
vs.	Versus

LIST OF ABBREVIATIONS AND SYMBOLS (Cont'd.)

SYMBOLS

C_1	Comparator 1
$D_{1,2,3}$	Zener Diodes 1, 2 and 3
E_{in}	Input Voltage
F_1	First Failure
F_2	Second Failure
P_1	Supply Pressure One
P_2	Supply Pressure Two
R_1-R_{21}	Resistors 1 - 21
t	Time
$X_{actuator}$	Actuator Output Displacement
X_{out}	Output Displacement
X_v X_{valve}	Control Valve Displacement

SECTION I

DIRECT DRIVE FBW DEVELOPMENT

1.0 INTRODUCTION

The use of electronic primary flight control (FBW) for aircraft has brought with it the advantages of precise control and flexibility associated with electronic technology. However, the requirement for preservation of control with component failures has led to the use of parallel redundancy levels which are considerably greater than the conventional hydromechanical controls. Present FBW mechanizations for primary flight controls use up to four parallel channels of signal transmission in addition to three to four electrohydraulic channels in converting electronic commands to a hydromechanical output. The majority of the systems developed to date incorporate the parallel redundancy for the electrohydraulics in a secondary actuator, since the size and power requirements of the power actuator (primary actuator) makes incorporating 4 channel parallel redundancy at that level impractical.

Reducing the redundancy level of a FBW system to the two parallel channel, single fail-operate level of conventional controls while meeting aircraft reliability requirements is practical with state-of-the-art technology. If the number of components of the FBW system can be reduced and those retained developed for maximum reliability, the reliability requirements for a single fail-operate FBW mechanization can be met. One approach to this type of mechanization is the direct drive FBW system designed and developed by Dynamic Controls, Inc.

A direct drive valve is used to accomplish the simplification of the FBW system for a single fail-operate mechanization. For this type of valve, no hydraulic amplification stage is used. The electromechanical force generator is connected directly to the spool valve controlling the hydraulic flow to the power actuator. This type of mechanization eliminates the secondary actuator from a FBW mechanization. This type of valve configuration has also been investigated by North American Rockwell, Columbus Division (under Navy Contract N62269-72-C-0108) and General Electric, Johnson City (under Air Force

Contract F33615-76-C-3037). The design objectives in terms of input power and force output have been similar for all three developments. The type of force generator selected for development by each company has been different. North American Rockwell investigated a torque motor configuration. General Electric is developing a "linear motion bi-directional force motor". The configuration developed by Dynamic Controls, Inc. is a moving coil force motor. Although the direct drive valve is a key element to the control system approach, the other elements of the control system are equally important to the success of the FBW mechanization.

2.0 SYSTEM DESCRIPTION

2.1 General

The performance characteristics of any redundant control system, hydromechanical or FBW, are defined by the following:

1. Nominal Performance
2. Failure Modes
3. Reliability
4. Performance in Failure Modes
5. Failure Removal

All of these characteristics except reliability can be established during a development program with simple tests. The long term reliability can only be established by extensive testing or "in service" use. The intent of the direct drive FBW system design was to meet or exceed the general performance requirements for a dual hydromechanical flight control system.

The design objectives for the system are the following:

1. The system shall operate with two separate hydraulic systems while maintaining hydraulic system isolation.
2. The system shall have a minimum frequency response capability of 5 Hz @ -3Db amplitude ratio with no more than 90^{o} phase shift at that frequency.

3. The system threshold and hysteresis characteristics shall be consistent with conventional servovalve controlled single channel actuator systems.
4. The valve direct drive shall have a minimum force capability of 80 lb. for the power spool of the actuator at the spool null.
5. The system shall fail operational for any probable failure of a single component or input (power or control) to the system. All failures shall be detectable during preflight checkout.
6. The performance degradation of the system between the operate and fail operate modes shall be acceptable in terms of typical aircraft control requirements.
7. System output deviations during failure removal shall be of low amplitude and short duration consistent with aircraft control requirements.
8. Components incorporated in the system shall be operated conservatively and be of state of the art quality in terms of reliability.

Design objectives 6 and 7 are general, since the required characteristics vary from aircraft to aircraft and control axis to control axis. However, the general objective is to prevent any significant change from the normal operational mode of the control system output both during the failure removal action and while in the fail operate mode. Design objective 4 specifying the minimum driving force for the valve drivers is based on the force determined by North American Rockwell as adequate for overcoming silting and particle contamination. This figure was used by North American Rockwell and General Electric in their direct drive investigations.

In addition to the preceding requirements, the requirement for survivability with one hit by a 12.7 mm projectile was used in the packaging of the direct drive system. This requirement primarily dictated the dispersion approach used in the construction of the system.

2.2 Specific

Figure 1 shows the direct drive control system in block diagram form. The control system is a fail-operate configuration where a first failure (hydraulic or electric) still allows the control system to operate with a satisfactory level of performance. The system is based on using two self-monitored control channels and a two section electrohydraulic control actuator. The control actuator uses two high force capability servo valve drivers directly connected to a tandem power spool. In the normal operational mode, both self-monitored control channels operate, commanding the two direct drive valve drivers. The direct drive valve drivers are a moving coil design. Either control channel with its moving coil driver has sufficient force capability to drive the tandem power spool to maximum stroke. Note that the two self-monitored control channels are completely independent and are brought together only at the tandem power spool. This was done to eliminate the possibility of common mode failures in the electronics.

For the FBW mechanization to meet the "fail-operate" criteria, hardover failures in either control channel must be eliminated. Hardover failures in the command and feedback paths of each control channel are detected and removed. This is accomplished using monitor feedback and command elements and comparing the outputs of the control channel with the monitor elements. For example, on Figure 1, command input 2 and feedback 2 are used as the monitor for command input 1 and feedback 1. The comparison is made after the summing junction at the control loop error point. Disagreement between the command and monitor portions of each control channel cause the command portion to be disconnected from control. The effect of hardover failures of the servo amplifiers driving the force motor are eliminated by using two amplifiers and two separate coils in the direct drive valve driver. The servo amplifiers are cross-strapped in their feedback paths so that failures of one amplifier-coil section are offset by the output of the other section.

For the system shown on Figure 1 to withstand single electrical or hydraulic failures, four independent electrical supplies and two hydraulic supplies are required. Typically,

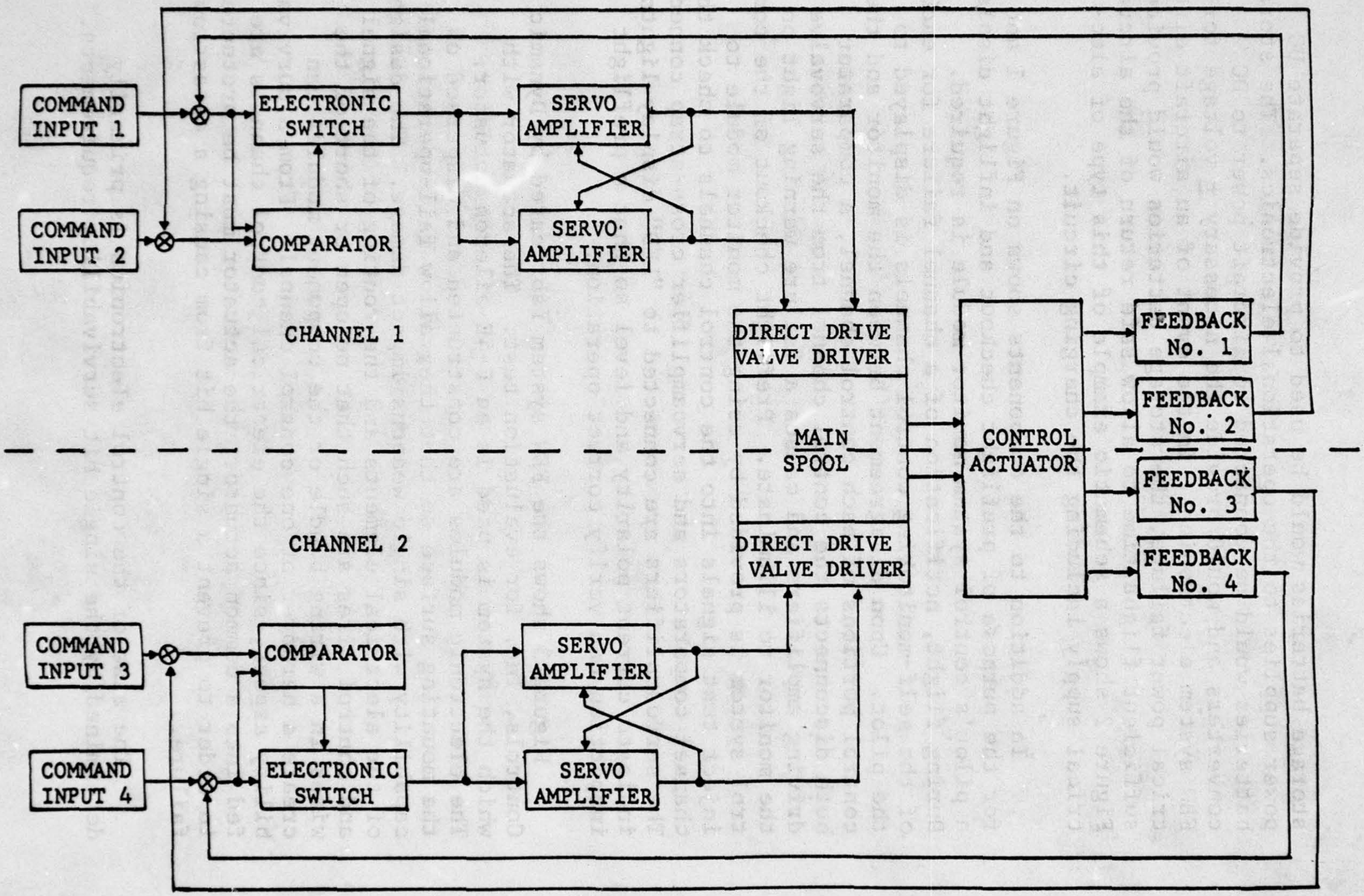


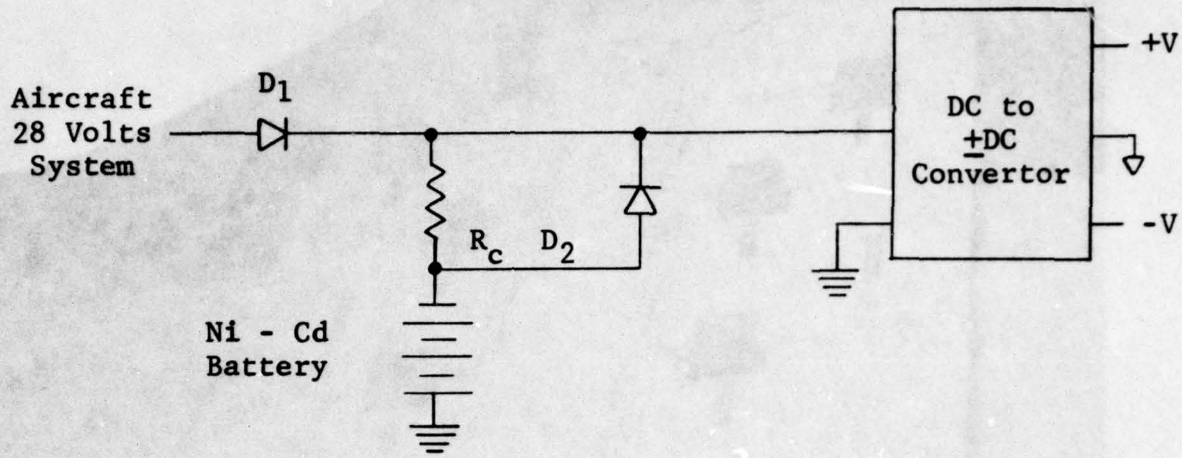
FIGURE 1 DIRECT DRIVE "FAIL-OPERATE" CONTROL SYSTEM

storage batteries would be used to provide separate DC power supplies to the operational electronics. The storage batteries would be connected to aircraft power to DC converters and would provide the necessary ± voltage for the FBW system electronics. In the event of an aircraft electrical power failure, the storage batteries would provide sufficient flight time to allow safe return of the aircraft. Figure 2 shows a schematic example of this type of electrical supply including the charging circuit.

In addition to the components shown on Figure 1 and for the purpose of preflight checkout and inflight display, a pilot's control system monitor module is required. During flight, notification of a channel failure for each of the self-monitoring control channels is displayed to the pilot. Upon disagreement between the monitor and the control portions of each control channel, a comparator both disconnects the control channel from the servovalve driving amplifiers and causes a failure warning light on the monitor to illuminate. Preflight checkout of the control system is provided by using the monitor module to inject test signals into the control channels to check the channel comparators and servoamplifier cross-strap connection. The servoamplifiers are connected to "LED" display lights to indicate current polarity and level so that a preflight inspection can verify correct operation.

Figure 3 shows the FBW system fabricated by Dynamic Controls, Inc. for evaluation test. The actuator with which the system is used is an F-4E aileron actuator. The electronic modules are constructed and dispersed on the mounting surface so that they allow fail-operational capability with single weapons impact damage. The design of the electrical elements and the routing of the signal and control wires are such that no open or short of the wires in a wiring bundle or the component modules can create a hardover of one control channel. From a survivability aspect, since the electrical control channels are fed into a common actuator, the actuator must be protected in order to prevent a single hit from causing a catastrophic failure.

The size of the control electronics is primarily determined by the single hit survivability requirements.



Where:

R_c = Charging current limiter

$\pm V$ = Supply voltage for direct drive

D_1, D_2 = Coupling diodes

FIGURE 2 TYPICAL ELECTRICAL SUPPLY FOR DIRECT DRIVE ELECTRONICS

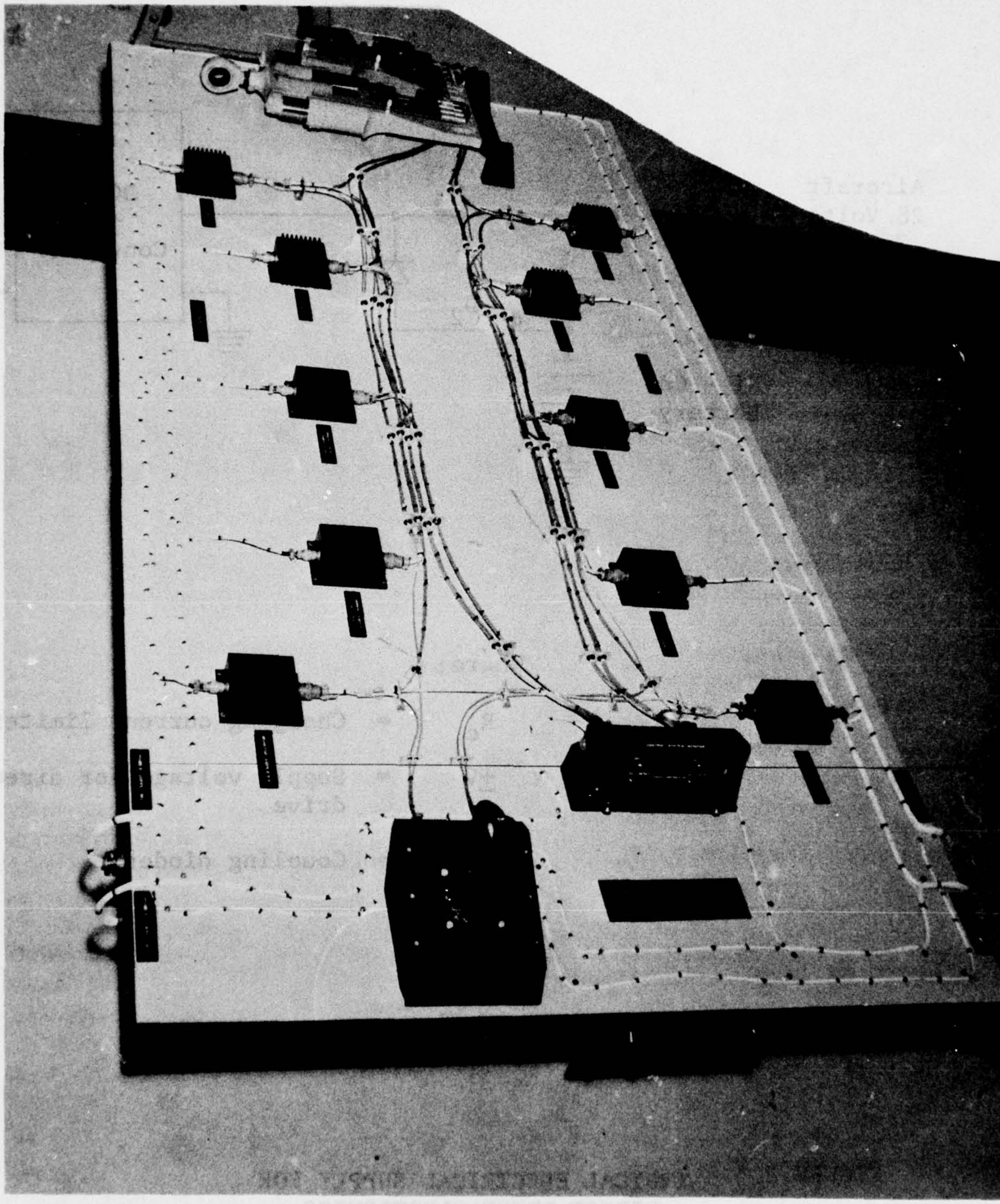


FIGURE 3 Direct Drive FBW

Each control channel uses only 10 operational amplifiers for its entire function, including the self-monitoring and failure removal. Without a single hit survivability requirement, the size of the electronics could be reduced to that of the four servo amplifier modules.

2.3 Electronics Description

2.3.1 General

All the electronics used in the direct drive FBW system are powered by four ± 15 volt DC supplies (Ref. Figure 2). All the modules are hermetically sealed, using "O" ring seals on the covers and Bendix hermetic MS connectors. The electronics are designed for Mil-E-5400 Class I operation. The servo amplifiers are presently provided with a 3°C/watt heat sink. For aircraft operation, these would be mounted on a thermally conductive surface to give a net effective thermal resistance of 1°C/watt in order to meet the Class I operating temperatures.

2.3.2 Specific

2.3.2.1 Command Amplifier and Disconnect

Figure 4 shows the internal construction of a command channel summing amplifier. Included in the amplifier is the reed relay used to disconnect the command signal in response to the comparator detecting a failure.

Figure 5 shows the electronic circuit for the command amplifier and disconnect module. As shown on the schematic, this module contains a single operational amplifier and a relay. The operational amplifier is used as a summing amplifier to add the command and feedback signals connected to R_1 and R_2 respectively. Three inputs to the summing amplifier are shown. R_3 is used to connect the summing amplifier to an alternate control signal as required. The

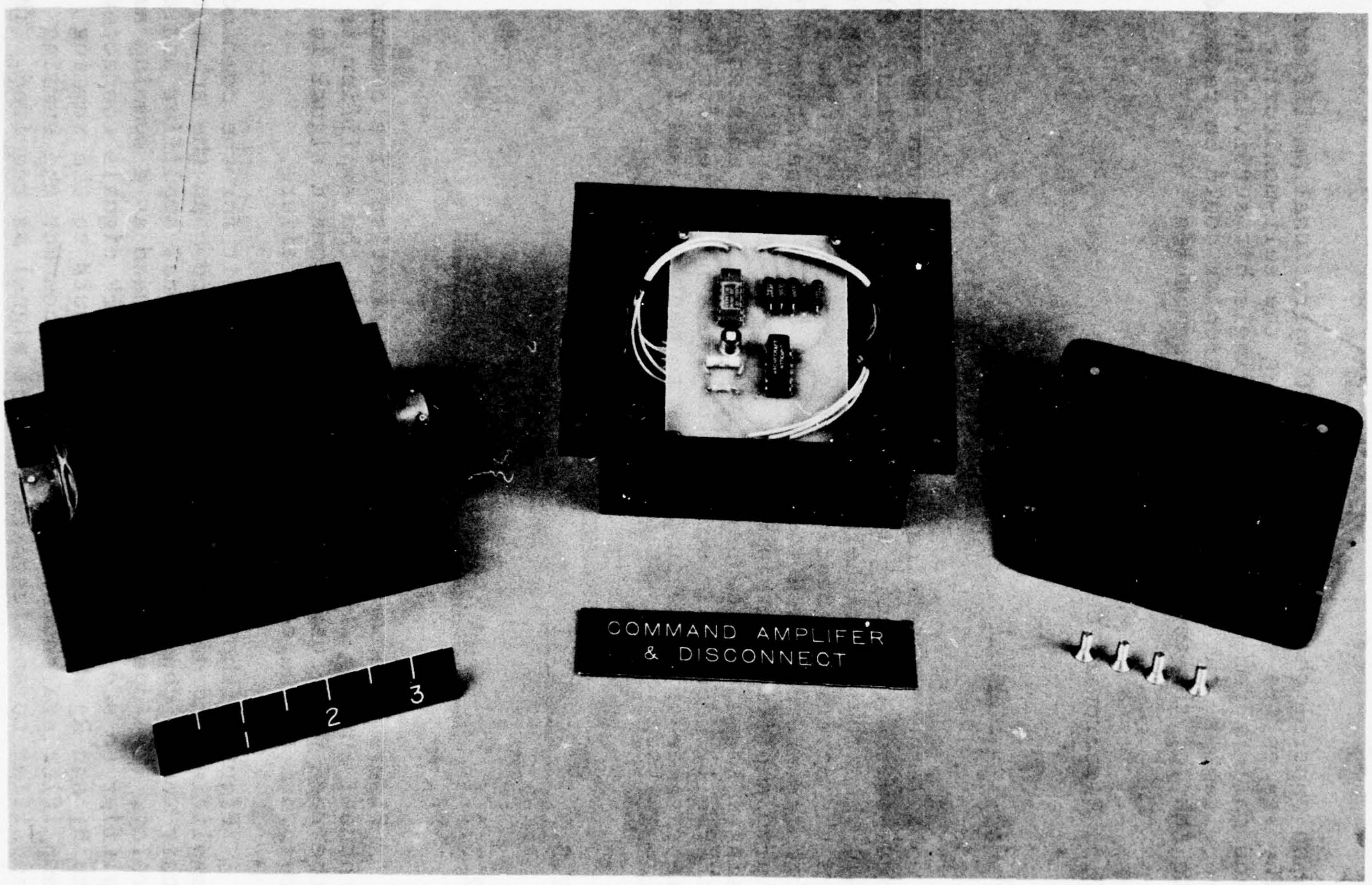


FIGURE 4 Command Amplifier and Disconnect

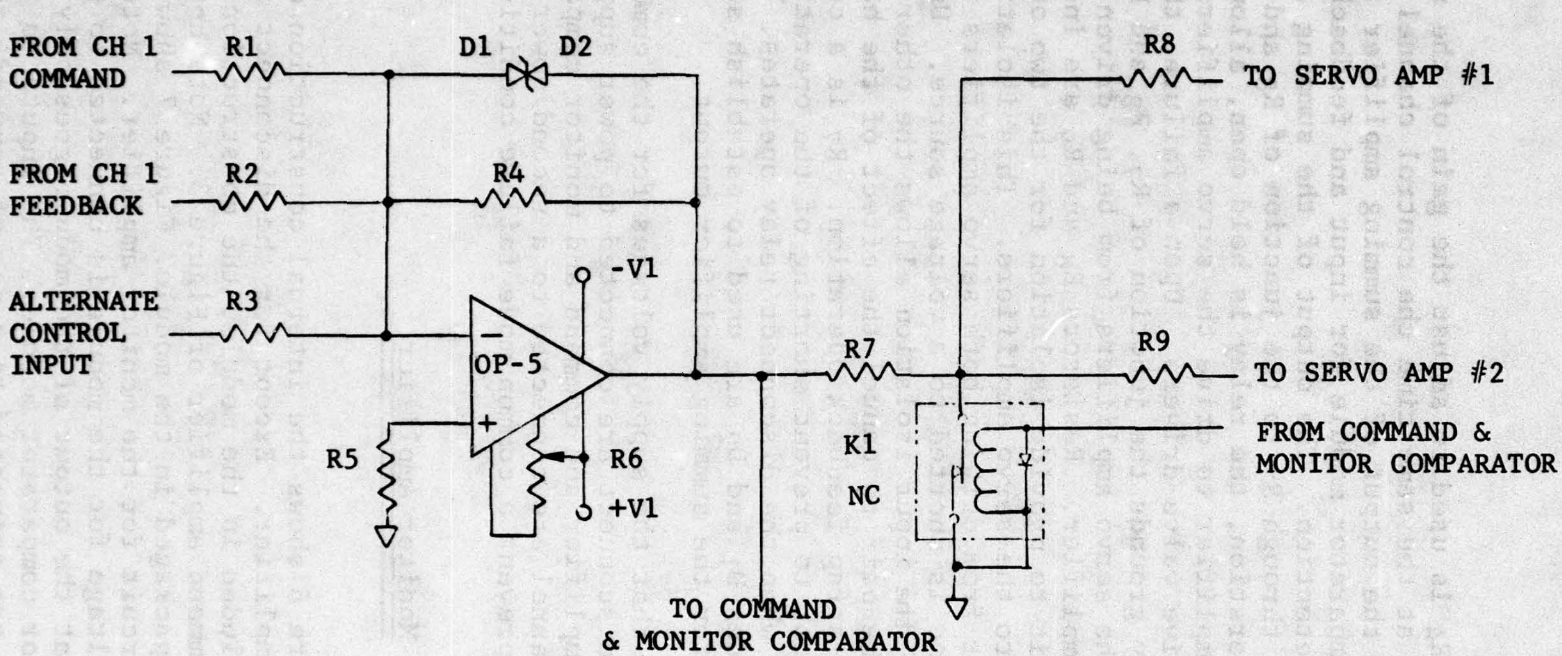


FIGURE 5 COMMAND AMPLIFIER & DISCONNECT

value of R_4 is used to adjust the gain of the summing amplifier (and at the same time the control channel loop gain). Note that the output of the summing amplifier is connected to the comparator module for input and feedback signal failure detection. The output of the summing amplifier is connected through R_7 to the junction of R_8 and R_9. For normal operation, the relay is held open, allowing the command amplifier to drive the servo amplifiers for the direct drive valve drivers. Upon a failure, the disconnect relay grounds the junction of R_7, R_8 and R_9, preventing the servo amplifiers from being driven by the command amplifier. Resistors R_8 and R_9 are included in the circuit to provide isolation for the two output connections to the servo amplifiers. This isolation prevents a hardover from driving both servo amplifiers if an input line to one is shorted to a voltage source. Under that condition, the input isolation allows the other servo amplifier of the pair to cancel the effect of the hardover through the cross-strap feedback operation. R_7 is a current limiting resistor to prevent shorting of the operational amplifier to ground when the disconnect relay operates. Back-to-back zener diodes D_1 and D_2 are used to establish saturation voltages for the summing amplifier output.

Note that the supply voltages for the command amplifier and disconnect are connected to power supply #1. The monitor amplifier and command and monitor comparator module of the channel are connected to a second power supply in order to prevent a common mode failure condition.

2.3.2.2 Monitor Amplifier

Figure 6 shows the internal construction of the monitor summing amplifier. Except for the disconnect relay not being included in the module, the construction is identical to the command amplifier of Figure 3. Note how few components are packaged in the module. Figure 7 shows the electrical circuit for the monitor amplifier. Note that the supply voltage for the module is connected to power supply #2 and that the output of the module goes only to the command and monitor comparator module. The inputs to the summing amplifier are connected to a set of command, feedback,

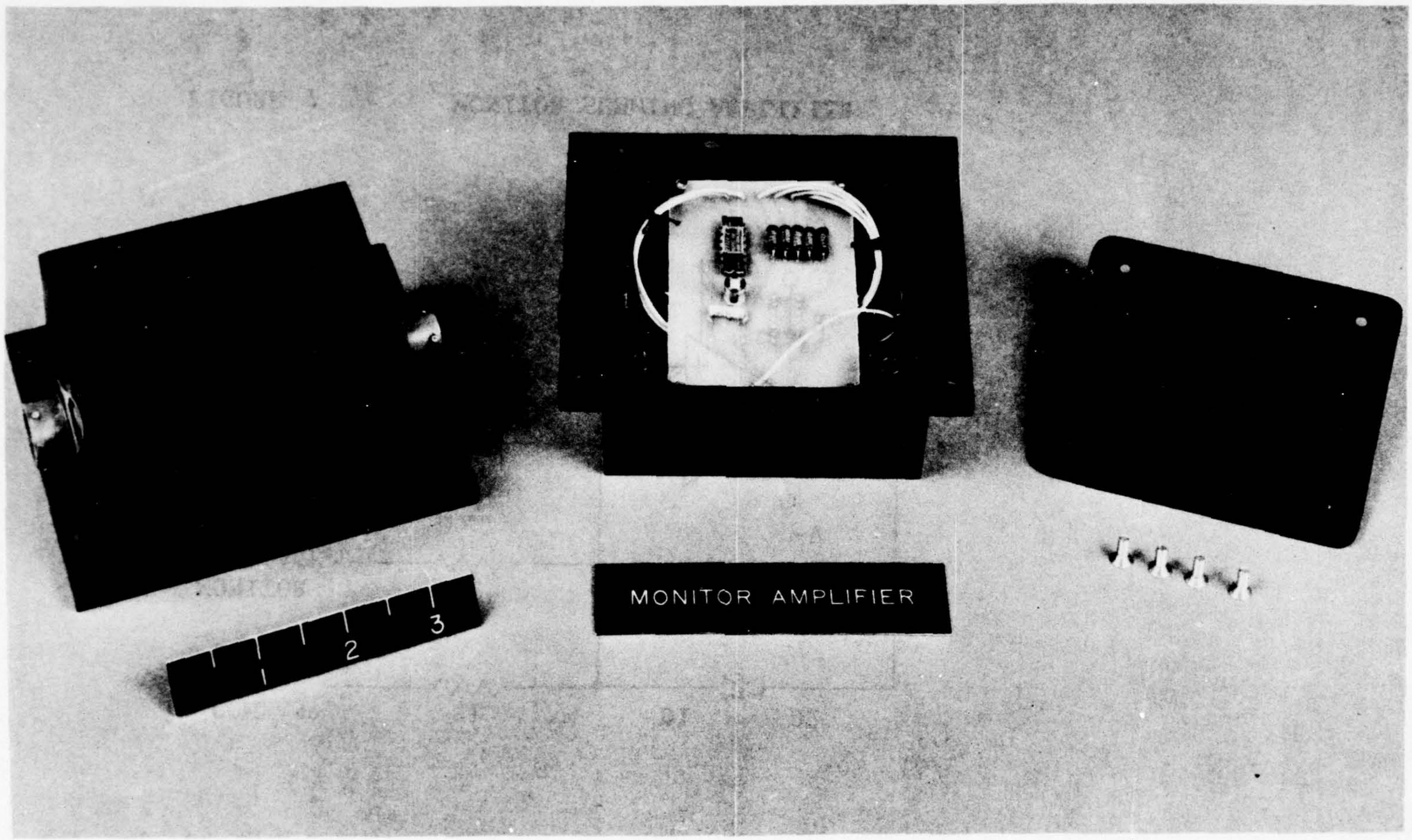


FIGURE 6 Monitor Summing Amplifier

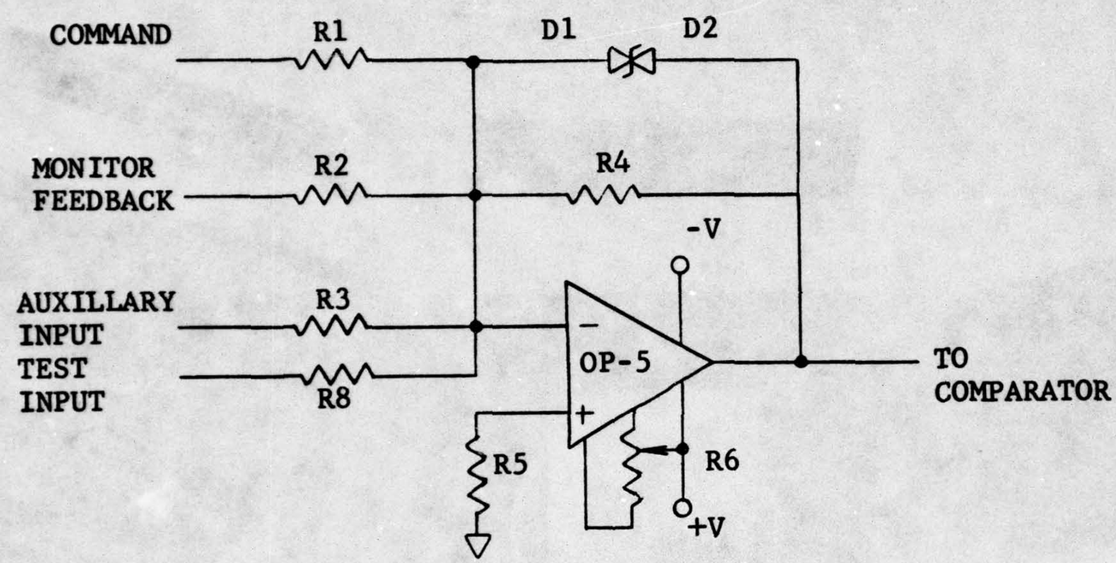


FIGURE 7 MONITOR SUMMING AMPLIFIER

auxiliary signal and operational test inputs. The operational test input is used to inject a voltage into the monitor amplifier to check operation of the failure detection logic.

2.3.2.3 Command and Monitor Comparator

Figure 8 shows the internal construction of the command and monitor comparator. This module incorporates a differential operational amplifier, 2 comparator operational amplifiers and a latching operational amplifier for driving the disconnect relay and failure warning relay. Figure 9 shows the command and monitor comparator circuit. All the electronics are powered by power supply #2. The output of the command and disconnect module is connected to the differential amplifier through R_1. The output of the monitor amplifier is connected to the differential amplifier through R_3. The output of the differential amplifier is connected to the two AD-351S comparators. Detection thresholds are set by potentiometers R_8 and R_{16}. These potentiometers are used to adjust the comparator detection levels for the evaluation unit. For a specific application, R_8 and R_{16} would be eliminated and a fixed detection level established by the values of R_7, R_9 and R_{15}, R_{17}. The relay driver operates as a latch when driven by the comparator output. The time delay for failure detection is determined by the RC filter made up of R_{18} and C_1. Diode D_1 across R_{18} is used to discharge C_1 when the comparator outputs are in a "no failure" state. This prevents C_1 from being "pumped up" and causing a disconnect by noise triggering the comparator circuits. Latching of the relay driver is accomplished with the diode D_3. Resetting of the logic is accomplished using the input into the feedback junction of R_{21} and D_3. Grounding of this junction eliminates the latched output feedback voltage, allowing the latching operational amplifier to return to normal output.

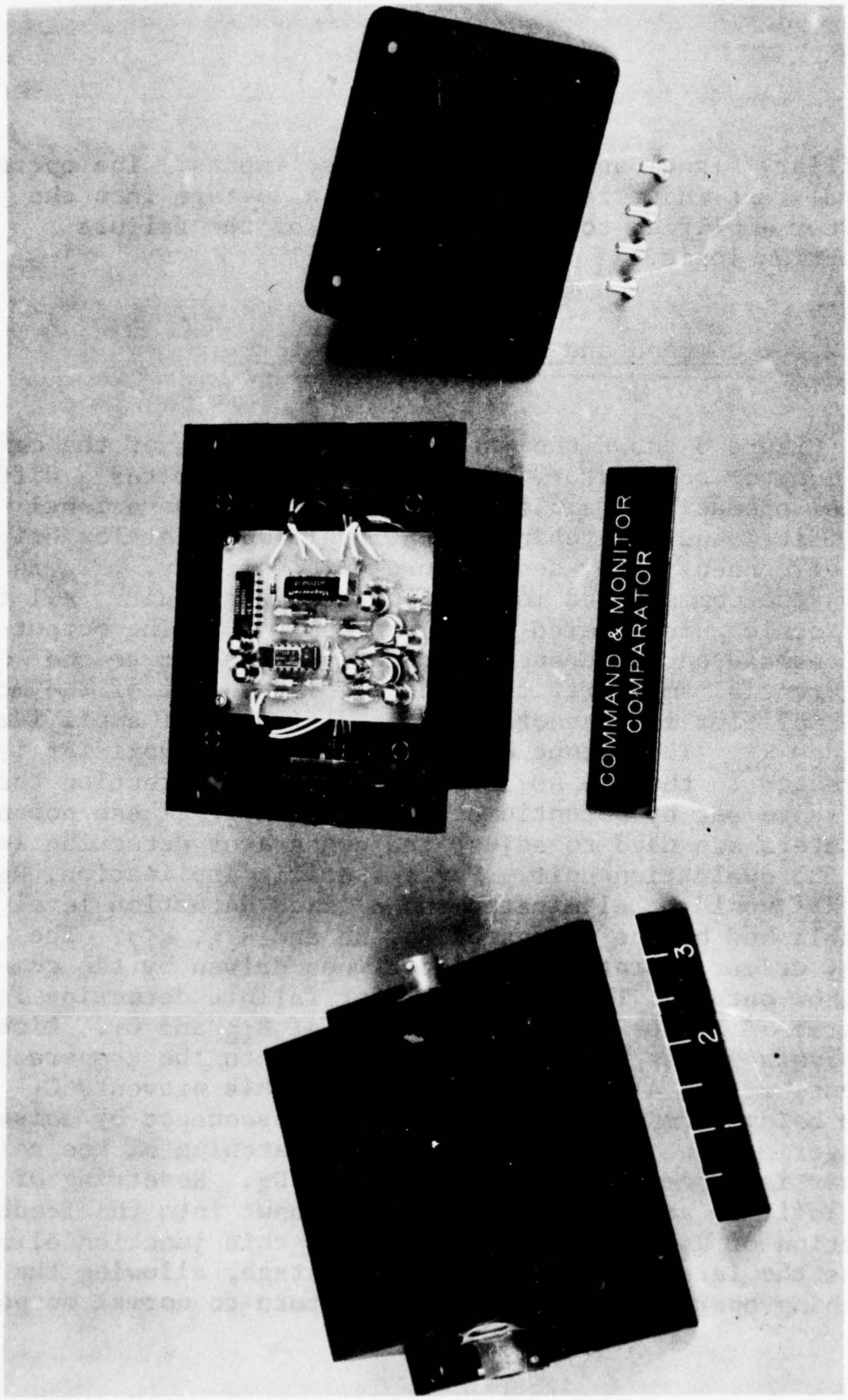


FIGURE 8 Command and Monitor Comparator

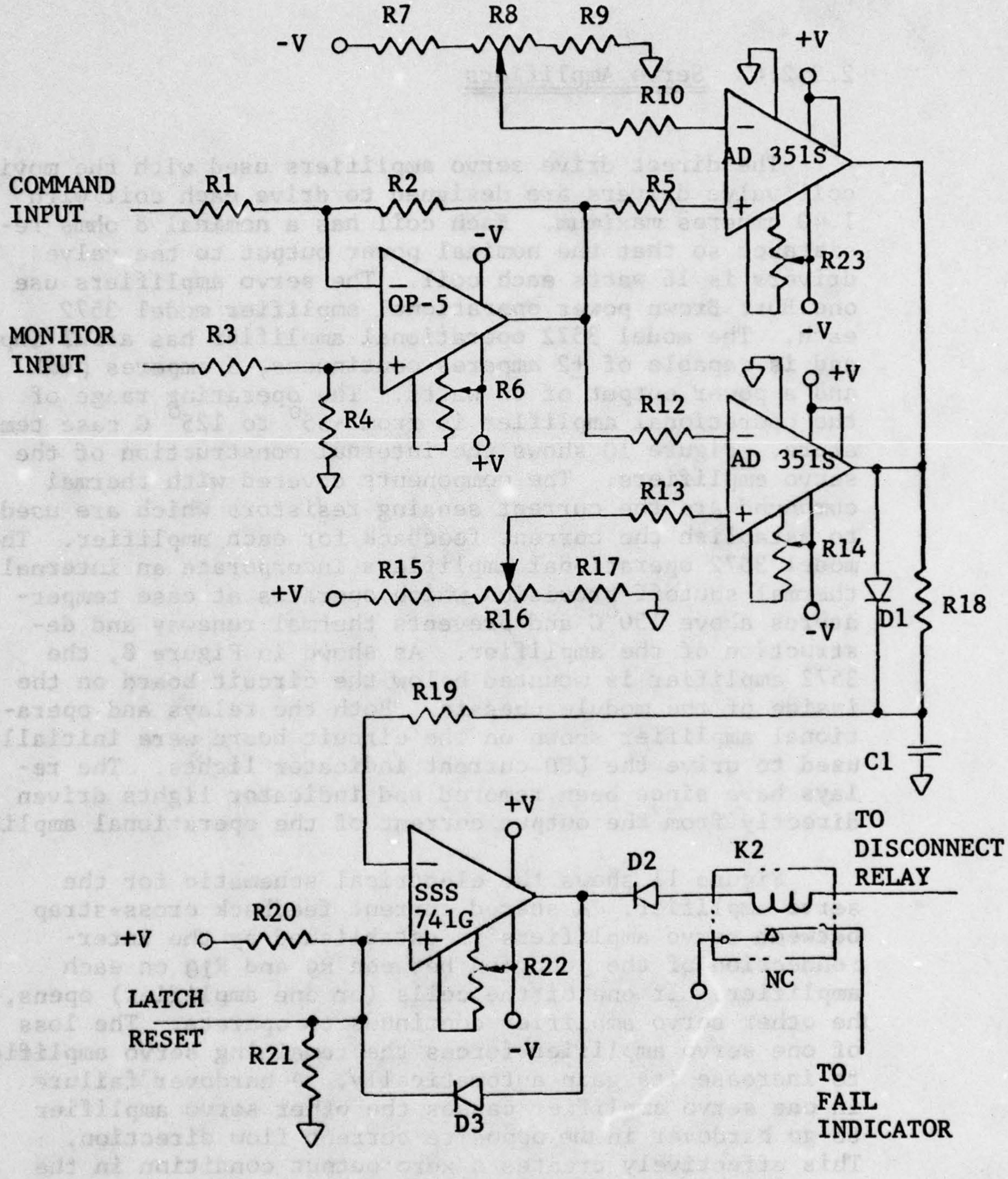


FIGURE 9 COMMAND & MONITOR COMPARATOR

2.3.2.4 Servo Amplifiers

The direct drive servo amplifiers used with the moving coil valve drivers are designed to drive each coil with 1.40 amperes maximum. Each coil has a nominal 8 ohms resistance so that the nominal power output to the valve drivers is 16 watts each coil. The servo amplifiers use one Burr Brown power operational amplifier model 3572 each. The model 3572 operational amplifier has a FET input and is capable of ± 2 amperes continuous, 5 amperes peak and a power output of 60 watts. The operating range of the operational amplifier is from -55° to 125° C case temperature. Figure 10 shows the internal construction of the servo amplifiers. The components covered with thermal compound are the current sensing resistors which are used to establish the current feedback for each amplifier. The model 3572 operational amplifiers incorporate an internal thermal shutoff provision which operates at case temperatures above 150°C and prevents thermal runaway and destruction of the amplifier. As shown in Figure 8, the 3572 amplifier is mounted below the circuit board on the inside of the module chassis. Both the relays and operational amplifier shown on the circuit board were initially used to drive the LED current indicator lights. The relays have since been removed and indicator lights driven directly from the output current of the operational amplifier.

Figure 11 shows the electrical schematic for the servo amplifier. A shared current feedback cross-strap between servo amplifiers is established by the interconnection of the junction between R_9 and R_{10} on each amplifier. If one of the coils (or one amplifier) opens, the other servo amplifier continues to operate. The loss of one servo amplifier forces the remaining servo amplifier to increase its gain automatically. A hardover failure in one servo amplifier causes the other servo amplifier to go hardover in the opposite current flow direction. This effectively creates a zero output condition in the valve driver for that channel. If the cross-strap opens, the amplifiers continue to function with no apparent change. A short of the cross-strap causes the gain of both amplifiers to increase (by a factor of 7). As shown on the Figure 9 schematic, the 3572 operational amplifiers

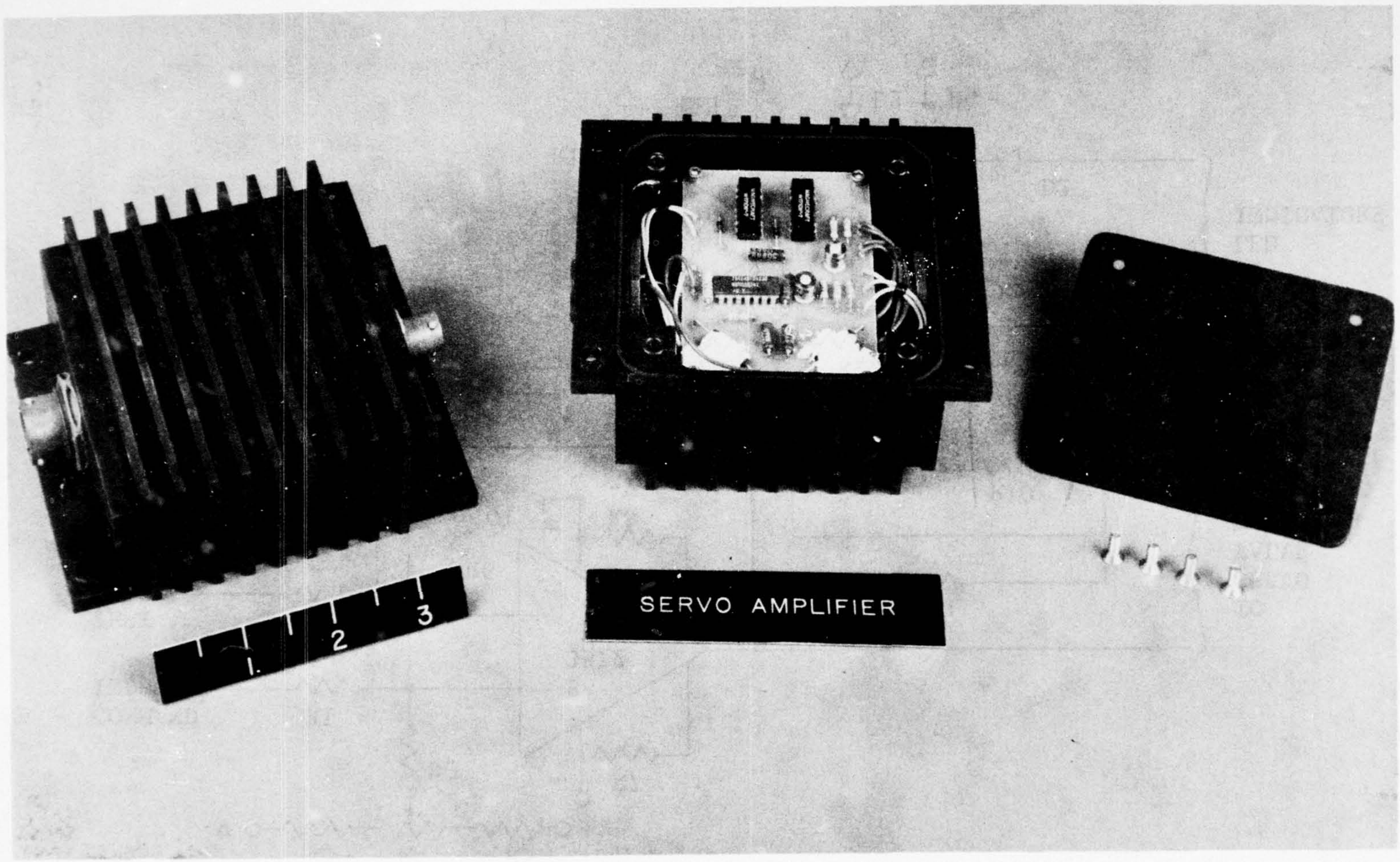


FIGURE 10 Servo Amplifier

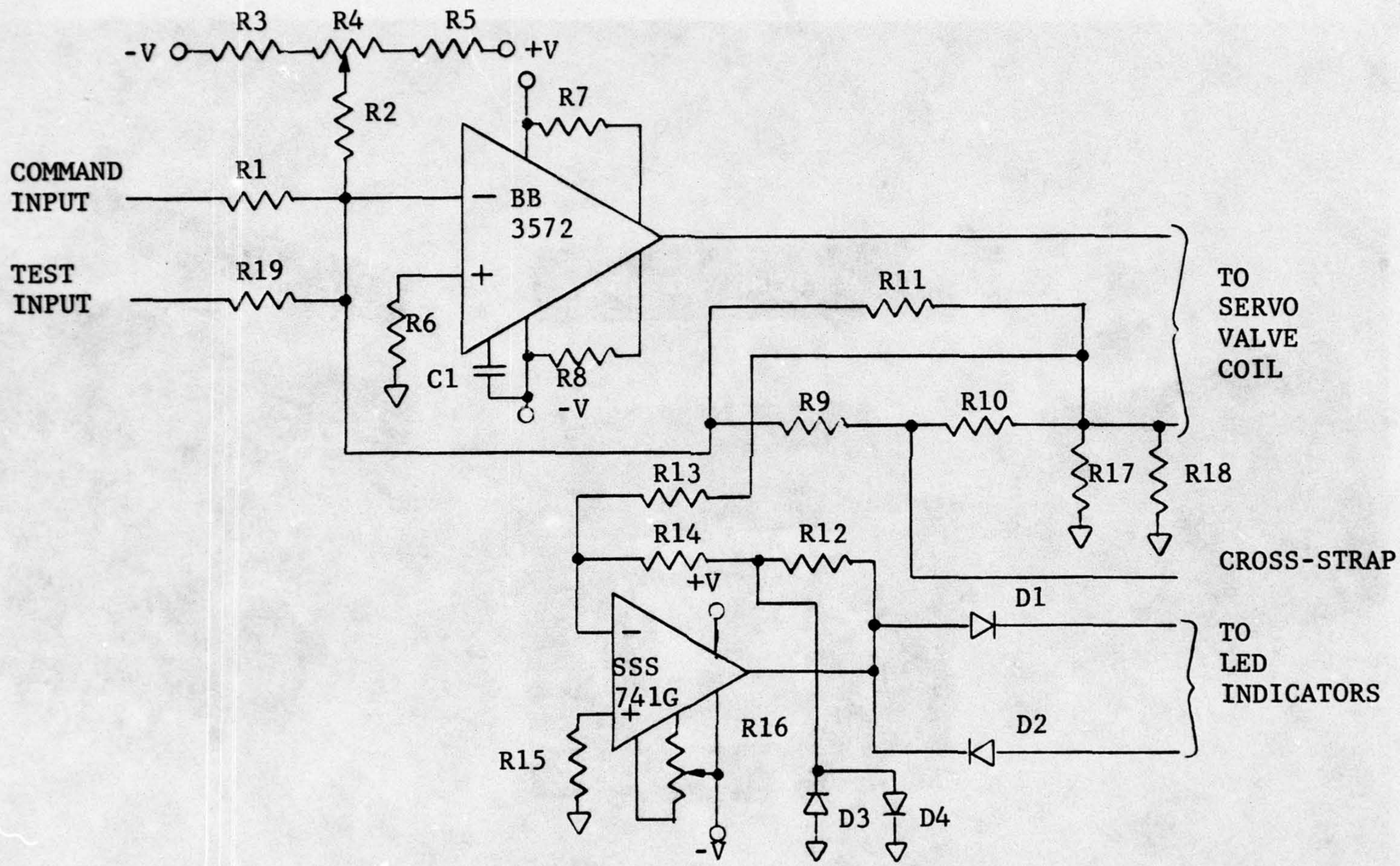


FIGURE 11 SERVO AMPLIFIER

are connected in a current amplifier configuration, with R_{17} and R_{18} establishing the feedback voltage proportional to coil current. The 741 operational amplifier (connected through R_{13} to the current feedback voltage) is used to drive the LEDs which indicate current polarity and relative amplitude. Diodes D_1 and D_2 (connected in series with the output voltages to the LEDs) are used to increase the peak inverse voltage tolerance of the LEDs. Diodes D_3 and D_4 are used to increase the gain of the 741 operational amplifier at a particular input voltage level. This causes the LEDs to turn on "hard" once the input voltage proportional to coil current has reached the selected level. Each servo amplifier is connected to a different electrical power supply, corresponding to the different supplies used with the particular control channel.

An additional input to one servo amplifier of each control channel is used for preflight checkout. This input (through R_{19}) is connected to a test voltage to establish a hardover input into one servo amplifier. The test voltage allows checking the integrity of the cross-strap connection by observing the current direction and amplitudes of the monitoring LEDs for the amplifiers.

2.3.2.5 Control System Monitor

Figure 12 shows the pilot's control system monitor module. The module is constructed with the electronics for channel 1 and 2 physically isolated. On the top of the module are the failure warning lights which are controlled by the channel comparators. Immediately below the warning lights are reset toggle switches which allow resetting of the failure disconnect circuits for each channel and reconnection of the command to the servo amplifiers. Below the reset switches and shown uncovered by the drop down door are the LED current direction and amplitude indicating lights. In the center of the lights are momentary toggle switches which are used to inject failures to the control system in order to check the operation of the failure detection comparator and cross-strap integrity during preflight checkout.

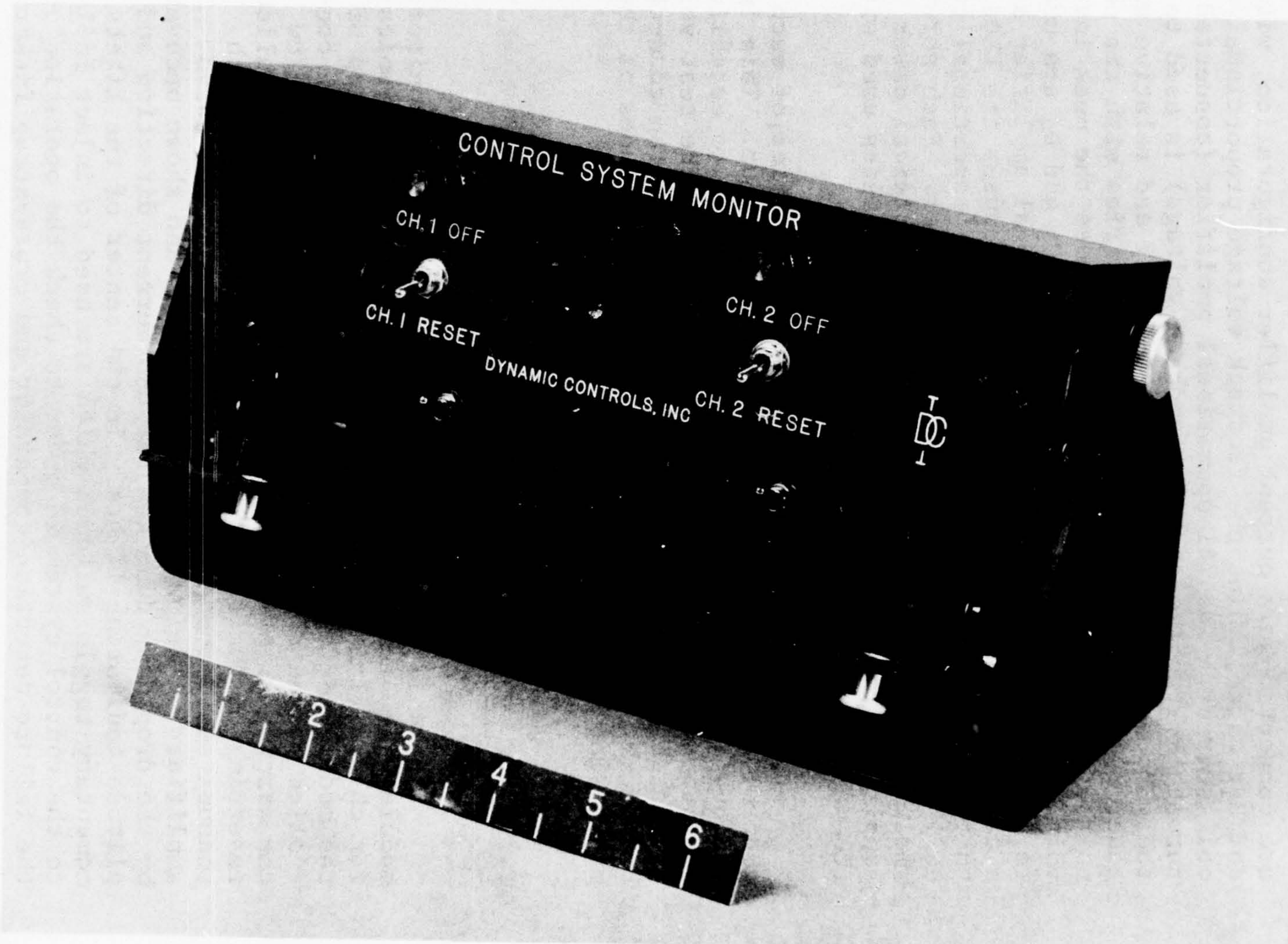


FIGURE 12 Pilot's Control System Monitor Module

Figure 13 shows the schematic for the electronics in the pilot's control system monitor module. Two circuits as shown on Figure 13 are used in the monitor module, one for each of the control channels. The failure test switch is connected to the same supply voltage used for the monitor and comparator modules. Since the failure test voltages are connected to modules which are powered by the same power supply as the test voltage, electrical power supply separation is maintained for the modules.

Although the LEDs mounted in the pilot's module provide satisfactory operation, an alternate technique for current monitoring display is attractive. This technique is to mount the LEDs in the servo amplifiers across the coil driving terminals. The light outputs of the LEDs are then coupled to the pilot's monitor using fiber optic cables. This alternate technique provides a greater degree of electrical isolation than the present method. Connector hardware and cabling, although presently not available as off-the-shelf hardware, has been developed to a degree that makes this technique quite practical.

2.4 Moving Coil Force Motor Description

2.4.1 <u>General</u>

Two moving coil force motors are used with the direct drive system, one mounted on each end of the control valve. The design requirement for each force motor was that it generate 40 pounds of force at valve null. For the valve designed for use with the F-4E aileron actuator, the maximum stroke required from the force motor was $\pm.014$ inches. The objective for input power to the force motor (for the 40 pound force) was to not exceed 32 watts each force motor, (16 watts each coil). The motor as designed consists of the following three principal parts:

1. Magnetic Structure
2. Coil
3. Suspension

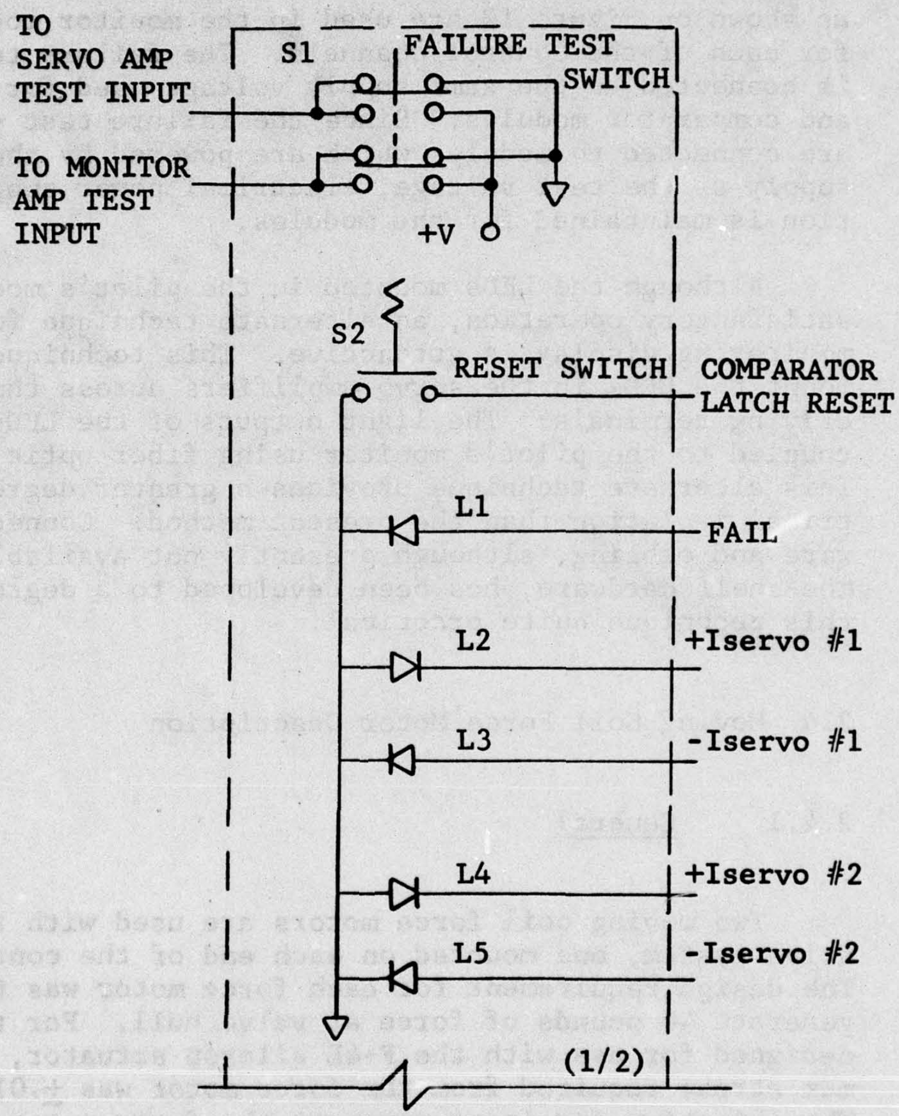


FIGURE 13 PILOT'S CONTROL SYSTEM MONITOR

The weight of each force motor as fabricated is 5.32 pounds. This weight is made up of 4.11 pounds magnetic structure and 1.21 pounds of coil, suspension and housing.

2.4.2 Specific

2.4.2.1 Magnetic Structure

The magnetic structure used for each force motor is based on a slug design and consists of three parts; the cup, pole piece and permanent magnet disc. Approximately 9 cubic inches of permanent magnet material are used in each magnetic structure. The magnetic material selected for the drivers is samarium cobalt. This material was selected on the basis of its high energy product (which is approximately three times that of Alnico 5). Ingot iron (which is very low in carbon) is used for the cup and pole piece.

The three parts of the magnetic structure are bonded together with a high strength thermal setting epoxy adhesive. Figure 14 shows the magnetic structure with the coil and suspension assembly. In designing the magnetic structure, leakage factors and reluctance factors were used which were empirically established for similar design magnetic circuits incorporating Alnico 5 magnets. The values used proved to be conservative when the actual flux levels in the gap of the magnetic structure were measured. The lower leakage and reluctance factors experienced are directly attributable to the characteristics of samarium cobalt, which exhibits lower flux leakage and higher permeability than Alnico 5.

2.4.2.2 Coil

The coil is constructed of four layers of #30 AWG wire which has an insulation rated for 392°F operating temperature. The coil diameter is approximately 2.75 inches. The coil is self supporting and does not use

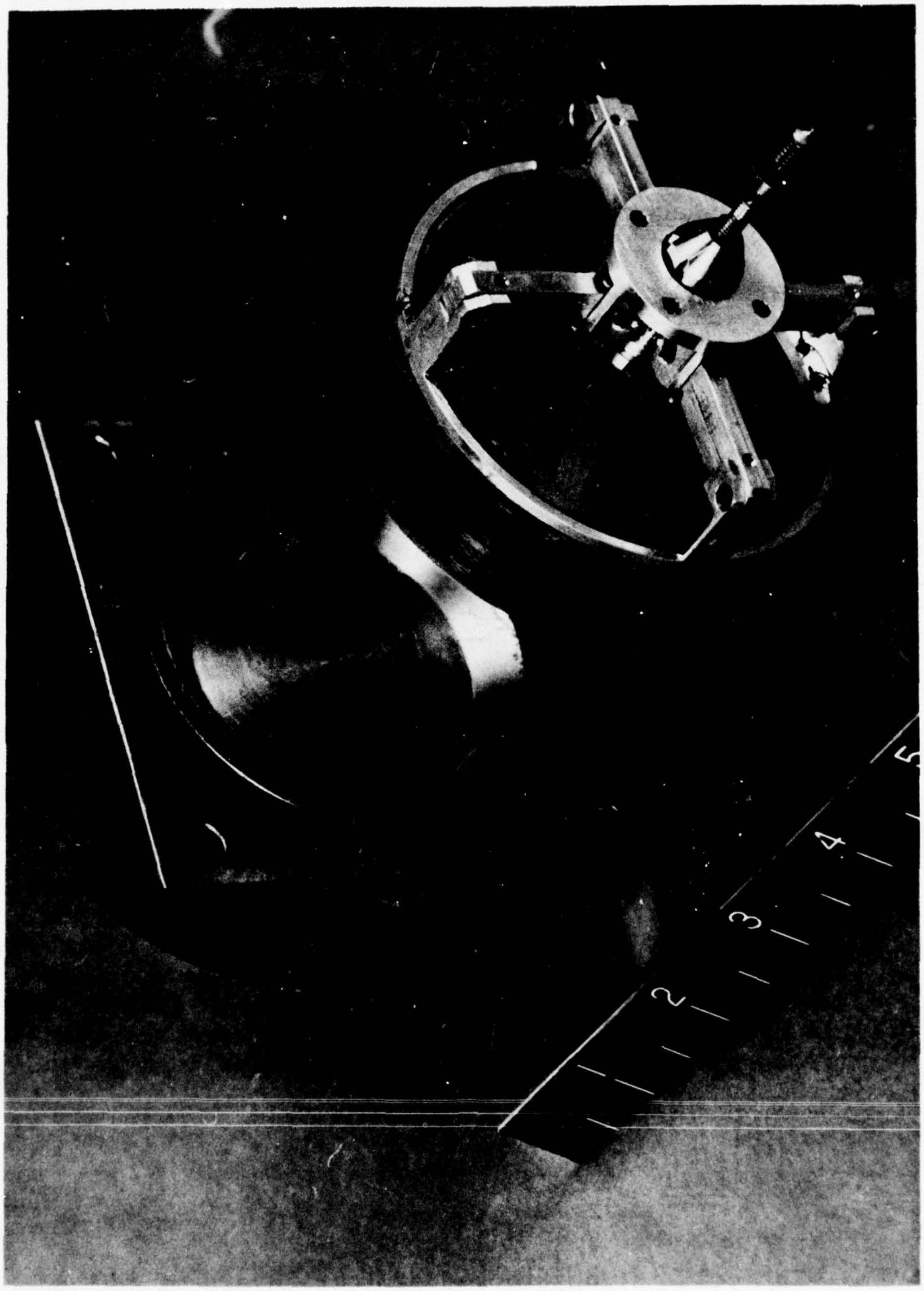


FIGURE 14 Magnetic Structure with Coil and Suspension Assembly

a support form. The wires are bonded to each other with a thermal setting epoxy adhesive which is rated for operating temperatures of 300°F without any strength degradation. The four layers are divided into two electrically and physically isolated two layer coils of 8 ohms resistance. One coil is used for each servo amplifier of the control channel connected to the particular force motor. The coil is attached to the suspension mounting ring with the same epoxy adhesive used to make the coil. The coil wires are soldered to terminal posts mounted in the suspension mounting ring. Soft copper braided wire is used to connect the terminals on the mounting ring to the electrical connectors in the suspension housing.

2.4.2.3 Suspension

The suspension used in the force motor couples the coil motion to the valve spool and provides the spring rate for centering the control valve. The coil suspension is a folded suspension which allows maintaining the overall diameter of the force motor within the dimension established by the sizing of the magnetic structure. Figure 15 shows an exploded view of the coil, suspension components and the suspension housing. The principal spring rate is produced in the center member of the suspension by the bending force and moment applied to the four cantilever sections of that member.

The folded suspension also provides a force multiplication ratio. The ratio is easily changed by varying the distance from the coil axis to the pivots in the mounting ring which attaches the suspension to its housing. The pivots used in the suspension are flexure pivots manufactured by Bendix (Electric & Fluid Power Division). Eight flexure pivots are used in each suspension. As shown in Figure 14, a short wire is used to couple each force motor to the control valve. Since the wire is short, the wire diameter required to prevent buckling is small and the wire has a low value of lateral stiffness. This allows axial misalignment of the driver and valve spool without sideloading the spool and makes the driver to valve alignment

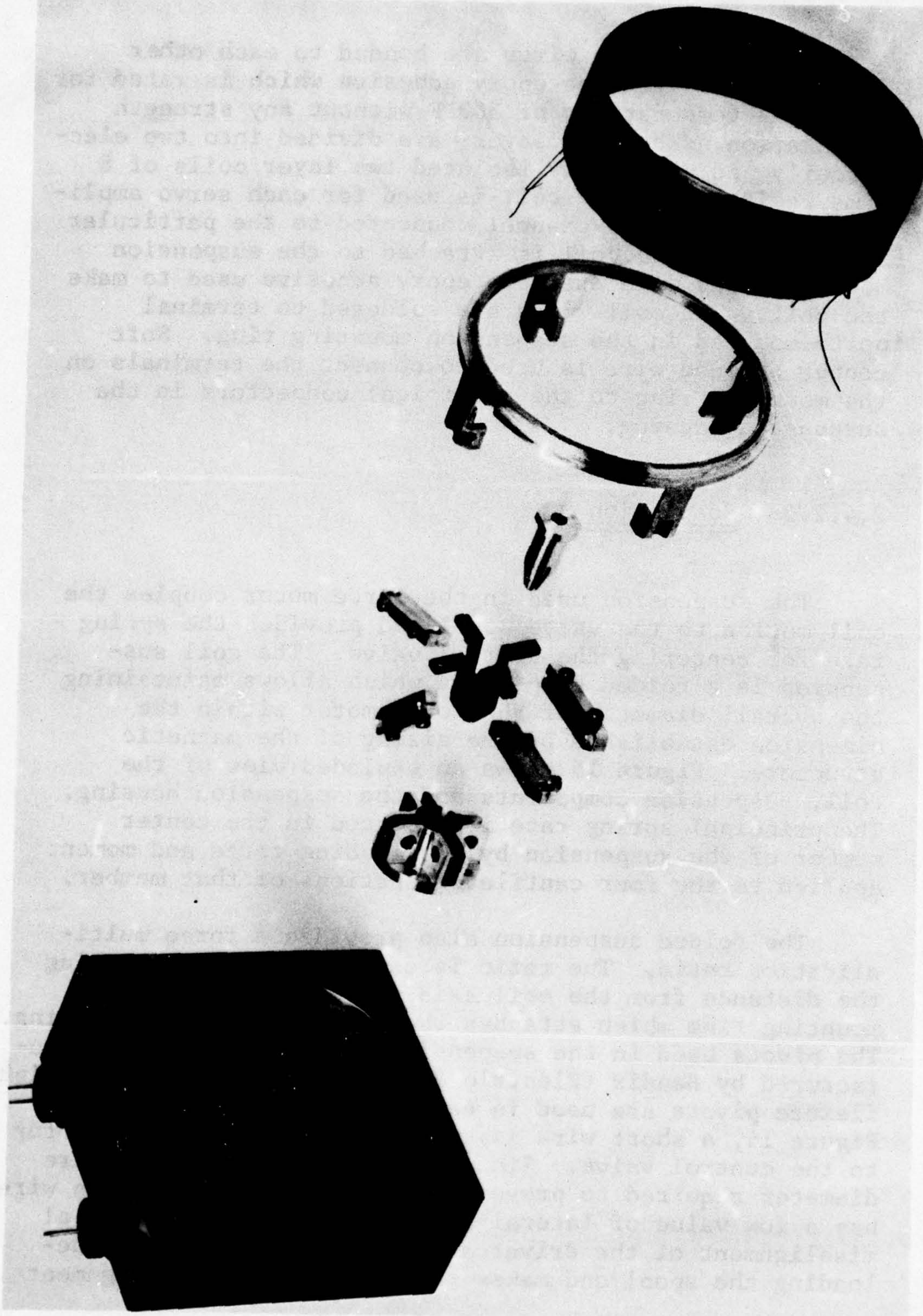


FIGURE 15 Exploded View of Coil, Suspension and Suspension Housing

non-critical. The coupling design provides for adjusting the position of the control valve with one force motor coupling and then attaching the second force motor without disturbing the initial adjustment. The materials used in constructing the suspension are magnesium for the coil mounting ring, aluminum for the suspension arms and mounting ring and spring steel for the center member.

2.4.2.4 Characteristics

As used in an electrohydraulic control system, the force motor has several inherent characteristics which are worth noting. The coil is operated in oil so that heat transfer from the coil is excellent. (A coil of similar design and wire size has been operated in the laboratory with 360 watts input without the coil exceeding a temperature of 200°F.) The cooling of the coil allows increasing the force output of the existing force motor by simply increasing the input power. Since the moving coil force motor does not operate by inducing a flux change in a magnetic member, there is no magnetic saturation characteristic of the driver to limit the force output with increasing input power.

Although "wet" magnetic structures can act as magnetic particle filters, the design of the moving coil force motor prevents system flow from passing through the structure. The housing of the force motors are oil flooded by connecting the housing to hydraulic system return. A 2 micron absolute filter disc is inserted in the connection between the housing and return to minimize particles entering the housing. The oil contained within the housing is essentially a non-circulating volume of oil and therefore does not carry in magnetic particles to the magnetic structure.

2.5 Control Valve and Actuator Description

To demonstrate operation of the direct drive mechanization, the system was applied to the aileron control of one wing of an F-4E aircraft. The control actuator used in the F-4E aircraft for normal aileron control is a dual tandem moving body actuator with a mechanical control input. For application of the direct drive system, a complete valve and driver package was designed to replace the normal manual input control valve. The normal manual control valve is a long stroke valve with multiple hole type porting for flow force compensation. Since with the FBW mechanization, flow forces are not reflected to the pilot, flow force compensation was not used in the design of the direct drive spool valve. The spool valve is a conventional tandem spool valve consisting of two 3 land, 4 way valve sections. The stroke of the valve for the required actuator flow is $\pm .014$ inches. This corresponds to a nominal flow of 14 GPM from each hydraulic system at 3000 psi differential pressure across the valve. Isolation of the two hydraulic systems used with the actuator is accomplished at the center of the spool by lap fit clearance between system returns.

Figure 16 shows the valve and driver package mounted on the F-4E aileron actuator. The hydraulic connection ports are located as on the normal manual control valve. As shown in Figure 16, four position transducers are mounted to the actuator to provide the necessary electrical position feedback to the actuator. The feedback signals and the control valve input wiring is enclosed in tubing for protection. A connector box is attached to the actuator to mount the interface electrical connectors. Four connectors are used, corresponding to the command and monitor channels. Figure 17 shows the actuator as mounted in the evaluation test setup.

The direct drive configuration mechanized and shown in Figure 2 uses DC position potentiometers for both actuator feedback position sensing and control stick motion sensing. The reliability of these potentiometers for control motions should be satisfactory. However, if necessary from a life standpoint, LVDTs could be used by incorporating oscillators and demodulators into each of the control channels. This would increase slightly the cost and parts count for the FBW system. No increase in size would occur, since the summing amplifier modules have adequate room for the components.

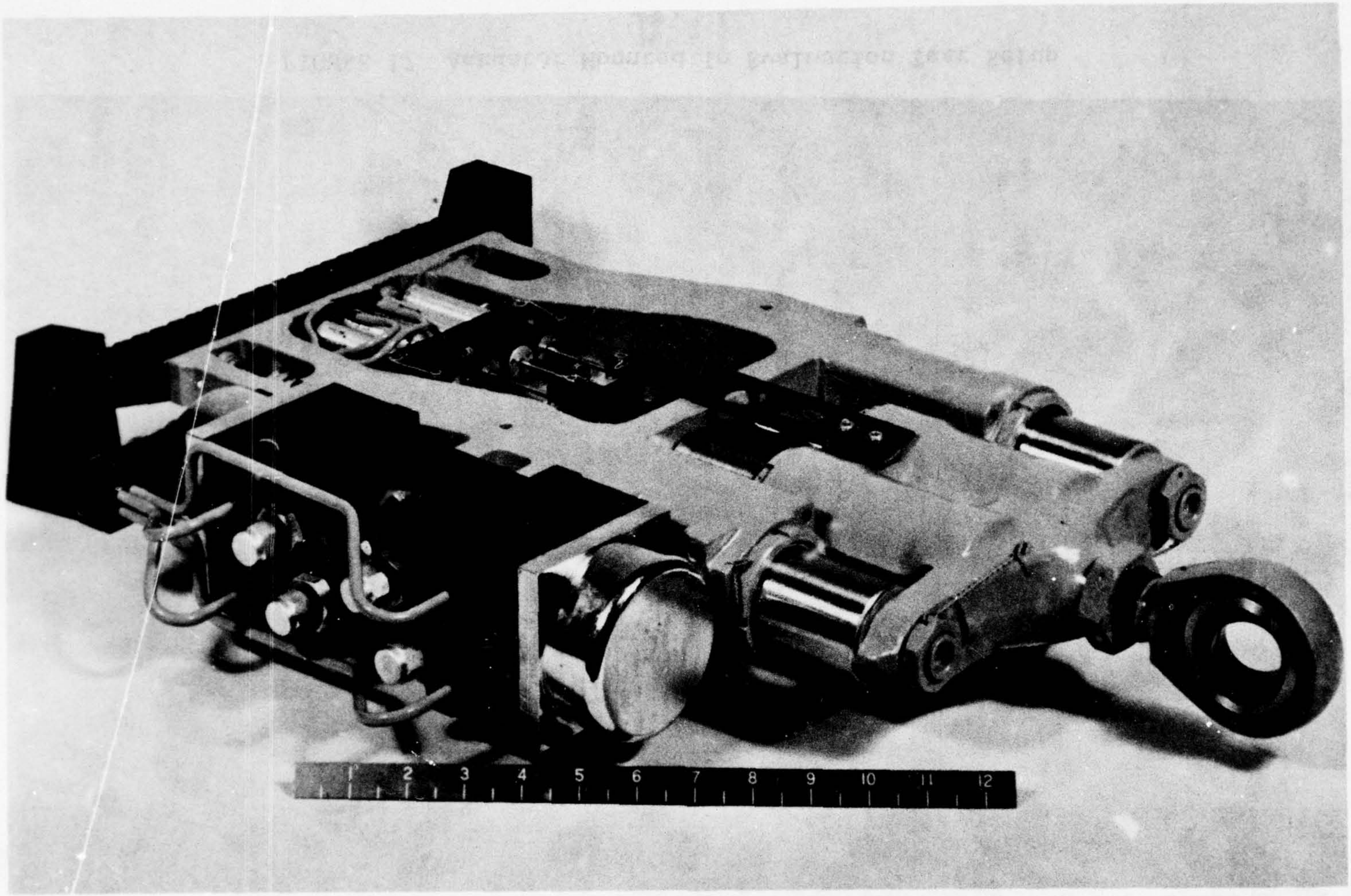


FIGURE 16 Valve and Driver Mounted on F-4E Actuator

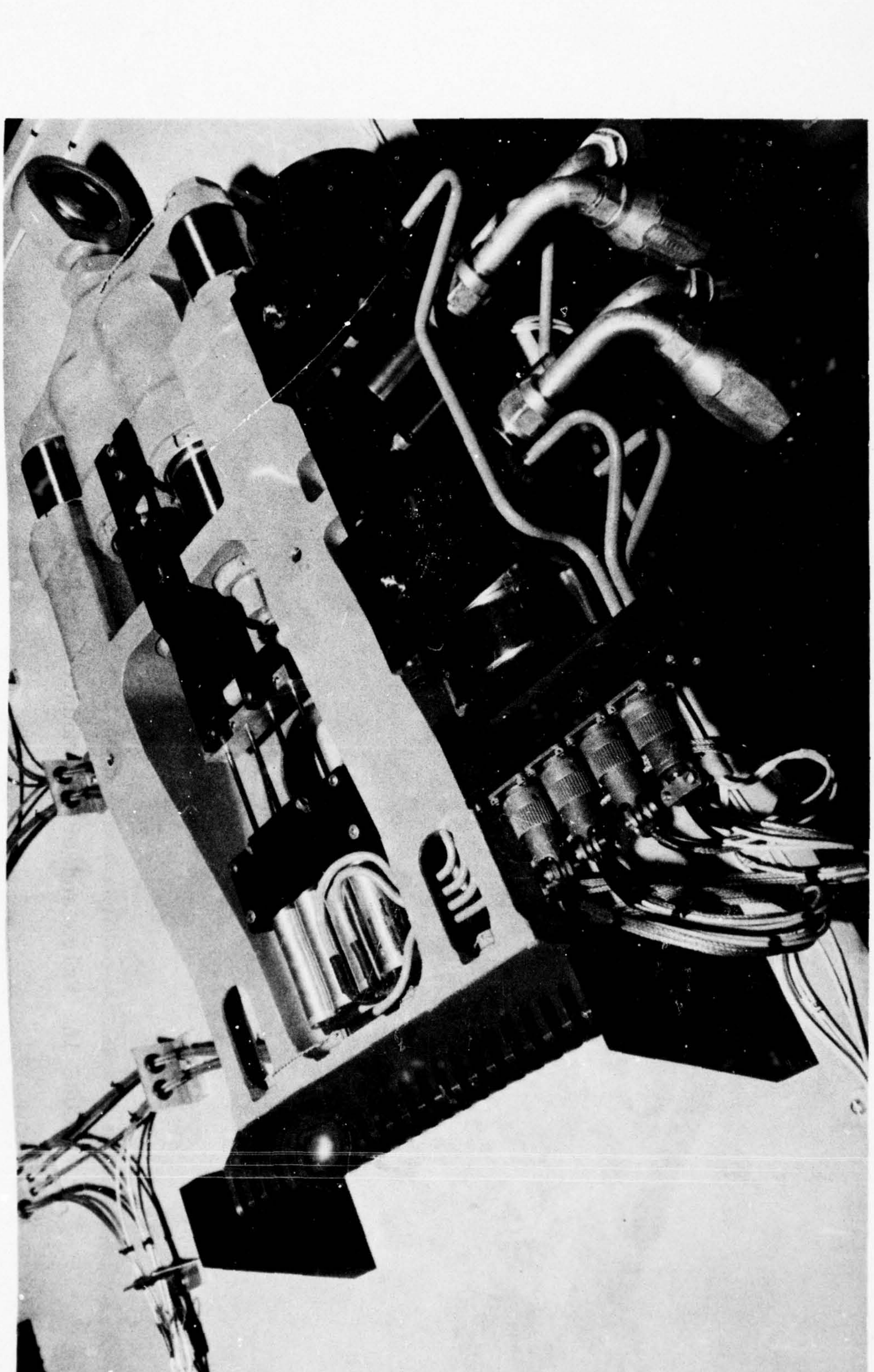


FIGURE 17 Actuator Mounted In Evaluation Test Setup

2.6 Preflight Checkout Procedure

Preflight checkout of the FBW system is accomplished with the control system monitor module. With the hydraulic supplies off, the control stick is moved and the pairs of LED lights indicating current polarity and amplitude are observed. If the lights do not light together and the same polarity lights illuminate, a problem with the servoamplifiers is indicated. Checkout of the comparator and the disconnect circuits is accomplished by injecting a failure with the failure inject toggle switches and observing the failure indicating lights. The failure indicating lights for each channel should light and the control stick should not affect the current indication for the servoamplifiers. Checkout of the crossstrap operation is also made at the same time with the failure inject toggle switch which applies a hardover input into one servoamplifier of a command channel. For this test condition, the servoamplifier indicating lights should show opposite current polarity directions for correct crossstrap operation. After the preflight checkout procedure is completed, the channel failure logic is reset and the drop down door closed.

3.0 EVALUATION TESTS

3.1 General

The evaluation testing of the direct drive FBW system was conducted in two parts. The first part involved establishing the characteristics of the direct drive force motor. The second part of the testing involved measuring the characteristics of the direct drive FBW system.

Evaluation of the direct drive moving coil force motor included measurement of the suspension stiffness, the output deflection vs. input current relationship and the force motor frequency response.

Evaluation of the direct drive FBW system included measuring the general performance characteristics (both in the normal and fail-operate conditions) and failure removal transients. Also included in the evaluation was failure mode verification testing and a verification test for the crossstrap operation. For the system evaluation, the direct drive FBW system parameters were set to the following values:

1.	Nominal loop gain each command channel	31.5 radians/sec.
2.	Failure detection level as a % of maximum error	6.3%
	as a % of actuator command input	.97%
3.	Failure detection time delay	10 millisecs.
4.	Servo amplifier maximum current	1.4 amperes
5.	Input command for full actuator stroke	+2.85 volts -2.3 volts

The loop gain was set at 31.5 radians/sec. to provide for the expected 50% reduction of the system frequency response when one control channel is failed. (The normal F-4 aileron actuator has a loop gain of approximately 14 radians/sec.) The failure detection was set to 6.3% of maximum error voltage. This level is low compared to the 30 to 50% generally used for a FBW system. The low setting without occurring nuisance disconnects is practical with the direct drive FBW system since the failure logic monitors only 2 voltages (rather than comparing 3 or more). The monitored voltages (feedback and command difference voltages) do not have dynamic response differences and are well matched statically with the position transducers used (.1% full scale).

The time delay in the disconnect circuitry was set at 10 milliseconds. This is shorter than the 100 milliseconds typically used for a disconnect delay with a force sharing system. The short time delay without incurring nuisance disconnect problems is practical since batteries used with the aircraft power to DC converters prevent aircraft power transients from affecting the electrical power for the FBW system.

The command voltage level was arbitrarily set at the +2.85, -2.3 volt level by the output voltage generated by the command position transducers used in the control stick of the system. Different potentiometers, supply voltages or motion gearing could have been used to change the maximum position command voltage.

3.2 Test Procedure - Force Motor

3.2.1 Suspension Stiffness

To measure the stiffness characteristics presented to the power spool by the folded moving coil suspension, a force gauge and dial indicator were used. Each suspension was assembled in its housing and clamped to a test support. The force gauge was attached to the suspension output coupling and the dial indicator positioned to read the deflection of the output coupling. The deflection as a function of force was recorded for both directions of force application up to a force reading of 40 pounds.

3.2.2 Output Deflection vs. Input Current

In measuring the output deflection of each moving coil force motor, a completely assembled force motor was attached to a test support. A dial indicator was positioned to read the deflection of the output coupling. Two variable DC power supplies were used to drive the force motor coils. The deflection vs. input current was recorded for selected input current settings.

3.2.3 Frequency Response

To measure the frequency response of the force motor, the motors were mounted on the valve body and connected to the control valve. Since a coil moving in a magnetic field is a velocity transducer, one force motor was used to drive the control valve and the other force motor was used to measure the output velocity as a function of input frequency. A Bafco Response Analyzer and an Esterline Angus xyy' plotter were used to generate the control signal and record the frequency response. The frequency response obtained was the response of the force motors and control valve combination and is easily interpreted in terms of position output frequency response. The input level used for the response measurements was .8 amperes peak through each coil.

3.3 Test Results - Force Motor

Figure 18 shows the stiffness characteristic of the force motor suspension. Note that the stiffness increases with increasing deflection, particularly above the design deflection of .014 inches. This is predictable from the design equations for the suspension and is due to the stiffness contribution of the coil coupling to the suspension arms. For the design stroke of ±.014 inches, 22 pounds of force is required. This gives a spring rate of 1571 pounds/inch around the .014 deflection point. Forty pounds of force corresponds to a deflection of .0175 inches and is the minimum design force point for the force motor. Figure 19 shows the motion linearity and hysteresis for one valve driver output over the input current range of ±1.5 amperes. Note that a deflection of .0175 inches is generated by 1.0 ampere through both coils of the force motor. Since each coil is nominal 8 ohms in resistance, the power required for forty pounds output force is 8 watts each coil or 16 watts each driver. This power requirement is lower than that expected for the design. The reduction in power from the design value is primarily due to lower flux leakage in the magnetic structure than predicted.

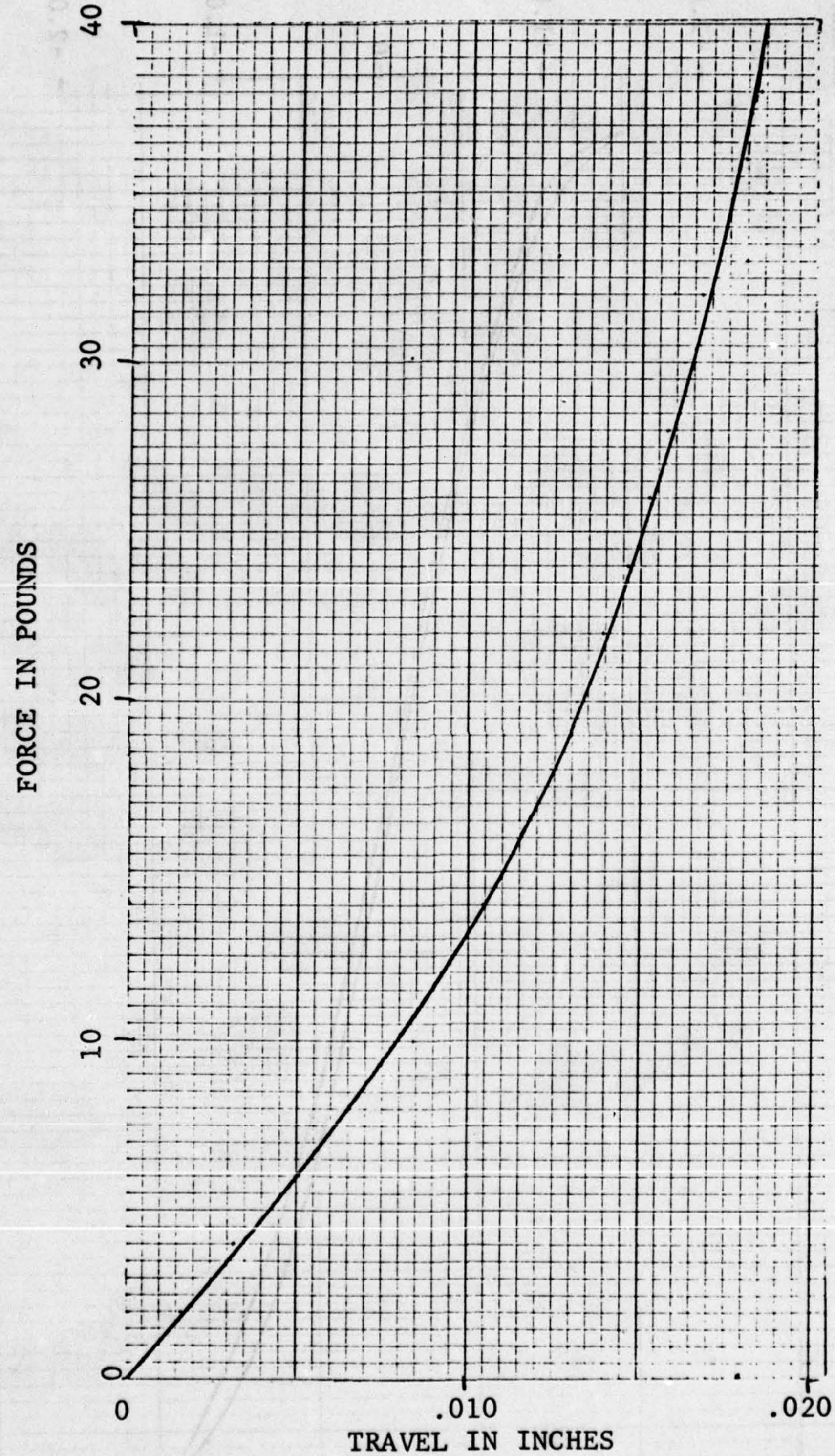


FIGURE 18 Force Motor Suspension Stiffness Characteristics

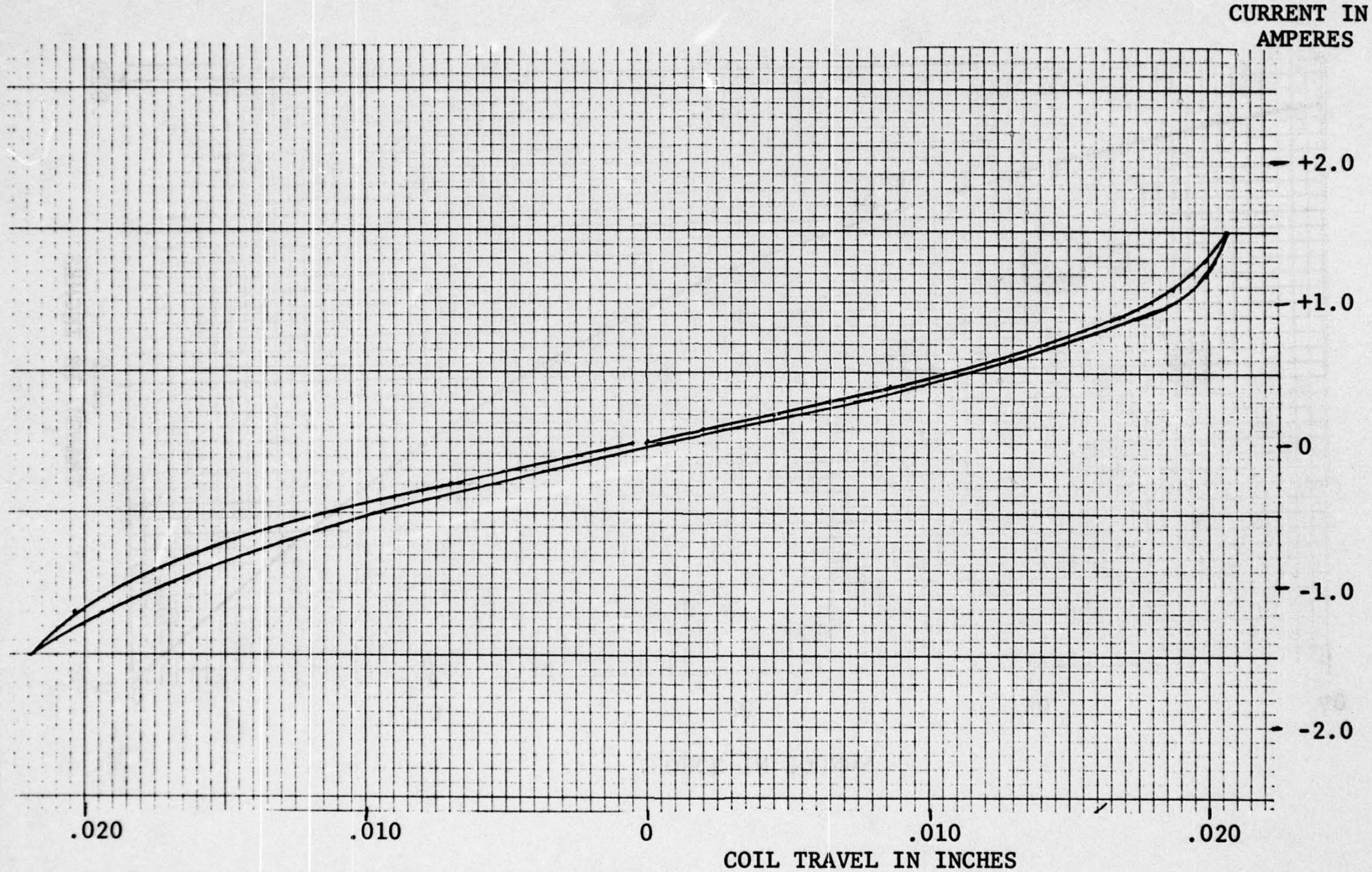


FIGURE 19 Force Motor Linearity & Hysteresis

Over the stroke range of $\pm.014$ inches, the hysteresis is 3.3% or less. The linearity over the same stroke range is $\pm3\%$. These figures are similar to those obtained from measurements of two stage electrohydraulic servovalves. The non-linearity is directly attributable to the suspension stiffness characteristics. The hysteresis must also be attributed to the suspension, since a moving coil force motor has no inherent electrical hysteresis.

Figure 20 shows the frequency response of the force motor as measured with the control valve attached. The response is a velocity response taken by using one moving coil force motor as a driver and the other as a velocity transducer. A velocity response corresponding to a constant position amplitude response exhibits a 6 Db/octave amplitude rise with increasing frequency and a $+90^{\circ}$ phase angle. On Figure 20, the 90° phase lag frequency (relative to the 1 Hz phase angle) occurs at 60 Hz. The indicated amplitude response remains flat to this same frequency and shows no sign of peaking. Since the force motor frequency response is more than 10 times higher than the response requirements for the F-4 aileron actuator and well damped, the force motor dynamics do not cause a stability problem with the actuator control loop.

3.4 Test Procedure - System Performance

3.4.1 General

The following general test procedure was used for the measurements of the direct drive system. This test procedure was established as a general procedure for any FBW primary flight control system evaluation and has been applied to other system mechanizations. The test procedure as listed defines the measured parameter and states the procedure used in obtaining the measurement. The procedure is divided into the following sections:

1. Performance measurements

2. Failure Effect of Performance Measurements

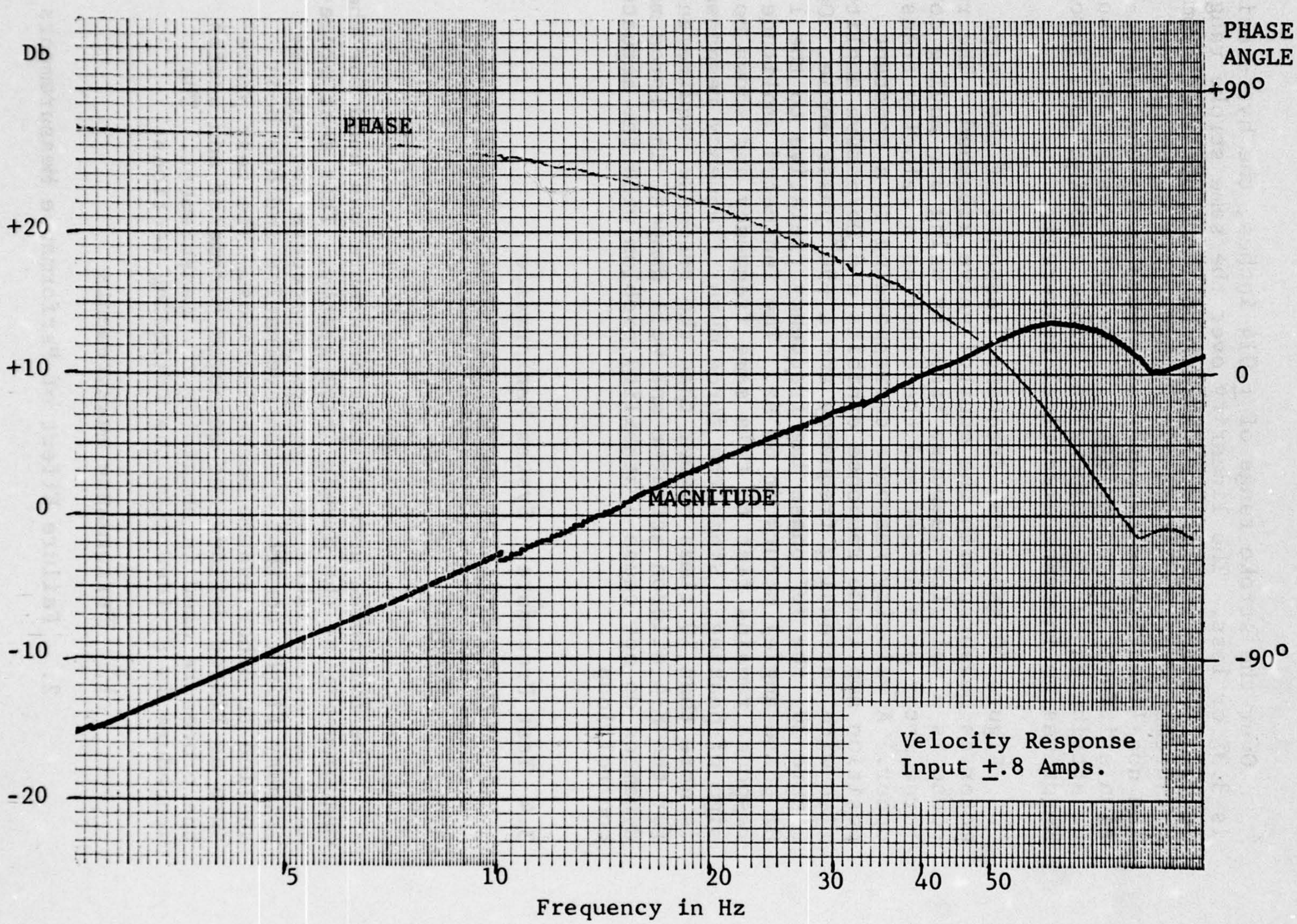


FIGURE 20 Force Motor Frequency Response

3. Input Deviation Effect Measurements

4. Failure Removal Transient Measurements

3.4.2 Performance Measurements

3.4.2.1 Threshold

Static Threshold - "The minimum input change from zero level which causes a measurable output change."

Procedure - Apply a slowly increasing + input until a measurable output change occurs. Repeat for - input. Threshold is indicated by the minimum input change for a measurable output change.

Dynamic Threshold - "The input level (at a particular frequency) required to cause a measurable output level."

Procedure - A sinusoidal input at a selected frequency of 50% of the bandpass of the actuator is applied to the actuator. The amplitude of input to create a measurable output indicates the dynamic threshold. The bandpass of actuator is defined as the frequency at which -3db amplitude or 90° phase shift occurs (whichever is lower in frequency).

3.4.2.2 Frequency Response

"With a sinusoidal actuator input, the frequency response of the actuator is the curves of the amplitude ratio and phase shift as a function of frequency."

Procedure - A sinusoidal input of an amplitude which is

a. large enough to minimize the nonlinearity distortions of threshold and hysteresis

b. small enough to avoid velocity saturation in the frequency range of interest

is applied to the actuator input. The ratio of output amplitude to input amplitude and output phase relative to input is recorded.

The curves of the amplitude ratio and phase indicate the frequency response.

3.4.2.3 Distortion

"The amount of deviation of the the actuator output from the input waveform."

Procedure - The harmonic distortion, at the input level used to measure the frequency response, is recorded at sinusoidal input frequencies of 10%, 50% and 100% of the bandwidth.

3.4.2.4 **Linearity**

"The deviation of output vs. input from a straight line relationship."

Procedure - Apply an input from - max to + max input while recording the corresponding output position. Linearity is indicated by max deviation of the plotted output vs. input from a straight line drawn between zero and a point which minimizes the maximum deviation of the plotted curve from the straight line. Repeat for + input to - input.

3.4.2.5 **Hysteresis**

"The non-coincidence of loading and unloading curves."

Procedure - Apply a slowly varying input to the actuator at 10% and 1% of max input in the following sequence while recording the actuator output position:

0 to + direction input

+ input to - direction input

- input to + input

From the plot of output vs. input, the hysteresis is indicated by the difference between + direction actuator output position and - direction output position for the same input level.

3.4.2.6 Time Response

Saturation Velocity - "The maximum velocity at which the actuator is capable of moving in each direction."

Procedure - With the actuator at zero position, a maximum amplitude input is applied to the actuator while the actuator motion vs. time is recorded. The test is conducted for both directions of actuator motion. The slope of the position vs. time record indicates the saturation velocity.

Transient Response - "The time response of the actuator output to an applied step input."

Procedure - Apply a step input to the actuator and record the corresponding actuator motion. The amplitude of the step should be

a. large enough to minimize the nonlinearity distortion of threshold and hysteresis

b. small enough to avoid velocity saturation.

The plot of actuator output motion vs. time indicates the transient response.

3.4.3 Failure Effect On Performance

3.4.3.1 Failure Effect

"The change on the performance of a redundant actuator due to input failures or internal failures of actuator components."

Procedure - Inject hydraulic or electrical input failures into the actuator under test to cause it to operate in its "failure operational" modes. For each mode, measure the performance by repeating the Performance Measurement Tests. The input levels should be maintained at those used for the "no failure" performance tests unless the performance changes dictate different levels in order to obtain reasonable test data.

3.4.4 Input Deviations Effect

3.4.4.1 Electrical Deviations

"The change of electronic inputs, both power and control, with respect to the normal values and/or each other."

Procedure - Adjust the electrical inputs one at a time until either the maximum expected deviation of the input is reached or the failure trip level is reached. Section 3.4.2 will be measured with each electrical input deviation adjusted one at a time to the maximum deviation expected or a value of 90% of that which will cause a failure trip.

3.4.4.2 Hydraulic Deviations

"The change of hydraulic pressure inputs with respect to the normal values."

Procedure - Adjust the hydraulic inputs one at a time until the maximum expected deviation or a failure trip level is reached. The performance parameters of Section 3.4.2 will be measured with each hydraulic input adjusted one at a time to the maximum deviation expected or a deviation value of 90% of that which will cause a failure trip.

3.4.5 Failure Removal Transients

3.4.5.1 Electrical Failure Transients

"The change in actuator output during failure corrective action due to electronic input failures causing transfer from one operational mode to another."

Procedure - Apply a slowly changing input into one control channel of the actuator. Record the actuator output change during the corrective action of actuator. Repeat the test for each control channel input and failure mode condition. Repeat for a hardover step input.

Apply a sinusoidal input to all channels. Open each input while recording actuator output.

3.4.5.2 Hydraulic Failure Transients

"The change in actuator output during failure removal corrective action due to hydraulic input failures causing transfer from one operational mode to another."

Procedure - Apply a slowly decreasing hydraulic input into one control channel of the actuator output change during the corrective action of the actuator. Repeat the test for all hydraulic inputs.

Repeat the preceding test with a rapid decrease of hydraulic input pressure.

3.4.6 Test Procedure Application

The general test procedure was applied to the direct drive FBW system measurements as stated with the following exceptions:

a. The electrical deviation tests as listed in 3.4.4.1 were not performed. This is because preliminary testing verified that the failure detection level allowed only input deviations which have no significant effect on the system output. (A command input deviation of 90% of the system detection level produces only a .44% shift of the actuator output position.) The system performance is essentially unchanged from the normal operation test results, in terms of recorded performance. System performance for input deviations allowed with a higher detection level (say 50% of error current) would be measurable, although the force sharing characteristics of the mechanization would have the effect of reducing the input deviation effect to ½ in terms of the system output change.

b. The hydraulic deviation tests listed in 3.4.4.2 were not performed since the mechanization does not detect hydraulic failures (hydraulic power is not used in the direct drive spool positioning).

c. The hydraulic failure transient tests listed in 3.4.5.2 were not performed since the unit does not transfer control as a result of hydraulic failures.

Figure 21 is a block diagram schematic of the instrumentation, command and power connections used during the evaluation of the direct drive FBW system. As shown on the schematic, a Bafco servoanalyzer was used with an Esterline Angus XYY' plotter for frequency response measurements. The Hewlett Packard Model 333A distortion analyzer was used for the input and output signal distortion measurements. The Wavetec Model 144 sweep generator and the XYY' plotter were used for the hysteresis and linearity measurements. Failure removal transients were recorded on the Brush 200 recorder. The 100 V ac 60 Hz power connection was used to power ±15 volt dc power supplies. As shown on the schematic, the 4 input commands were run through a general purpose switch and potentiometer panel. This panel allowed individual variation of the 4 inputs separately and the injection of hardover input commands. Hydraulic power was obtained from the 30 GPM, 3000 psi laboratory pumping system. Supply pressure for each actuator half was connected through a pressure shutoff valve.

3.4.7 Test Conditions

The following three test conditions for the operational modes of the system were used in the evaluation:

Condition 1 - Normal operation with no failures

Condition 2 - Fail operate with one channel failed electrically

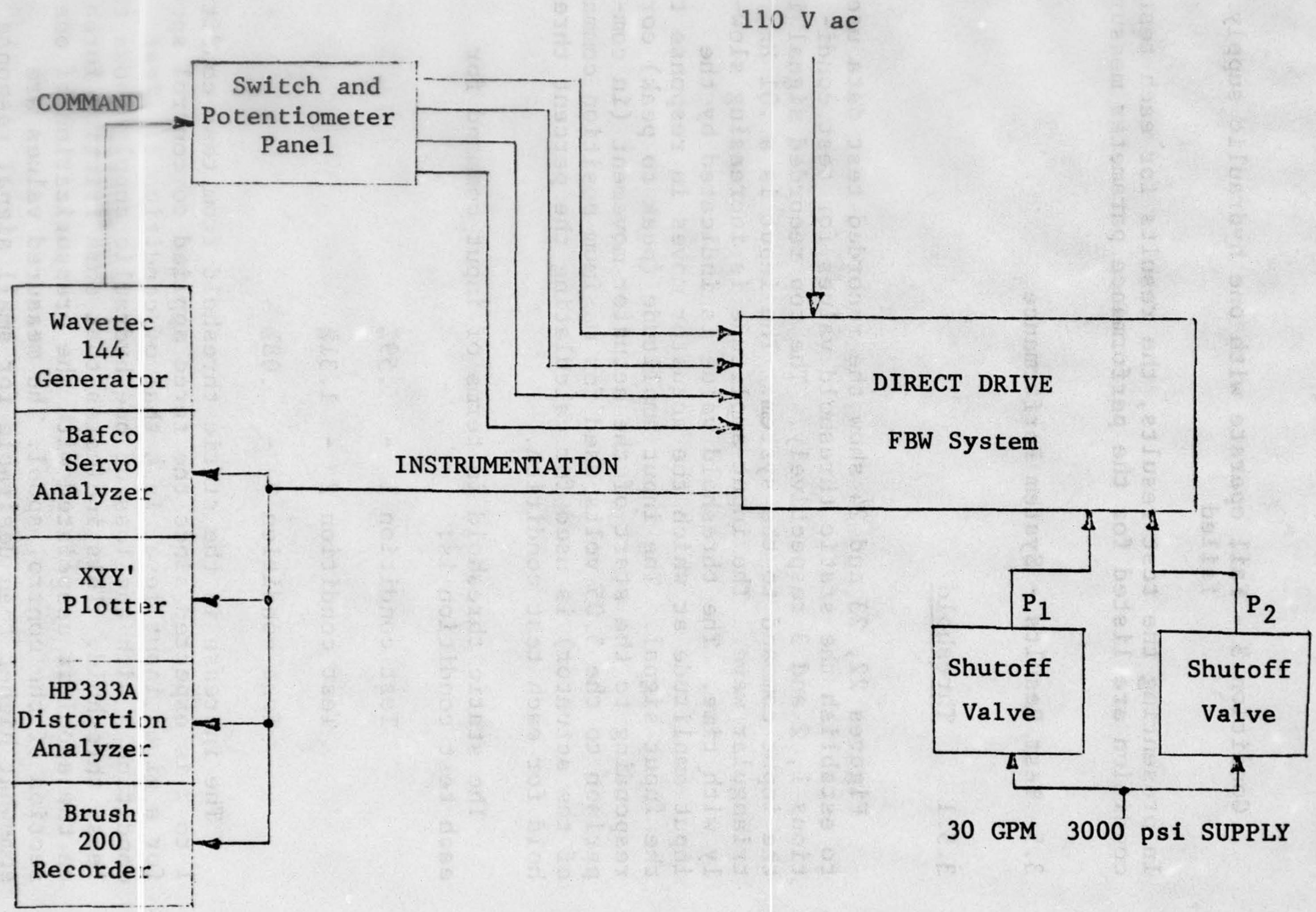


FIGURE 21 Test Schematic

Condition 3 - Fail operate with one hydraulic supply failed

In presenting the test results, the results for each test condition are listed for the performance parameter measured.

3.5 Test Results - System Performance

3.5.1 Threshold

Figures 22, 23 and 24 show the recorded test data used to establish the static threshold values for test conditions 1, 2 and 3 respectively. The top recorded signal is the input command to the system. The input is a .01 Hz triangular wave. The input amplitude is increasing slowly with time. The threshold value is indicated by the input amplitude at which the actuator moves in response to the input signal. The input amplitude (peak to peak) corresponding to the start of the actuator movement (in comparison to the 5.05 volts used for maximum position command of the actuator) is used for calculating the percent threshold for each test condition.

The static threshold in terms of input command for each test condition is:

Test condition 1 - .59%

Test condition 2 - 1.31%

Test condition 3 - .08%

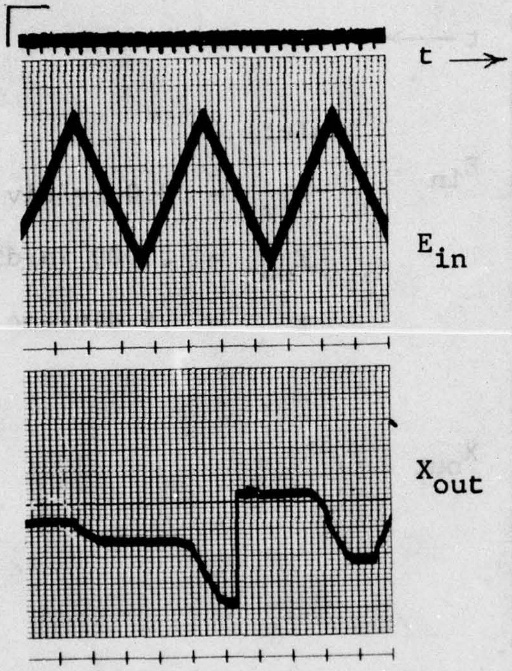
The increase in the static threshold from test condition 1 to 2 is expected since the force applied to control spool for a given input level is ½ that of condition 1. Test condition 3 with the loss of one hydraulic supply shows the least threshold. This indicates that some friction force on the spool is associated with the pressurization of one section of the control spool. The measured values are somewhat higher than desirable for small signal response

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire

Date Prepared: 3/30/77

TEST - Static Threshold - Condition 1



Scale:

E_{in} = 1 mv/div

X_{out} = .0009 in/div

t = .2 div/sec

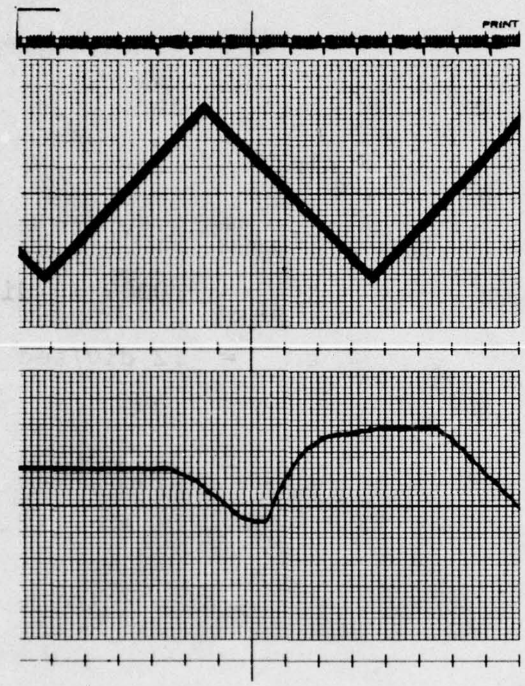
FIGURE 22 Static Threshold Results - Condition 1

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire

Date Prepared: 3/30/77

TEST - Static Threshold - Condition 2



Scale:

E_{in} = 2.0 mv/div

X_{out} = .0009 in/div

t = .5 div/sec

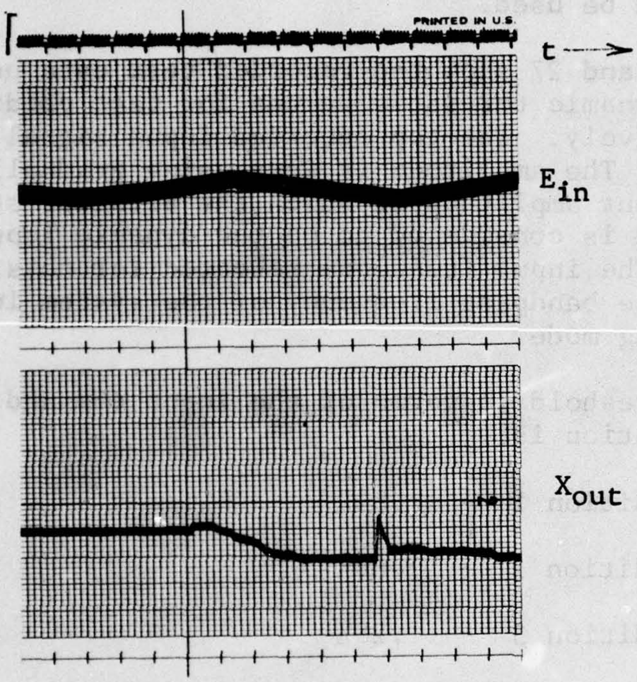
FIGURE 23 Static Threshold Results - Condition 2

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire

Date Prepared: 3/30/77

TEST - Static Threshold - Condition 3



Scale:

E_{in} = 1 mv/div

X_{out} = .0009 in/div

t = .5 div/sec

FIGURE 24 Static Threshold Results - Condition 3 and are directly related to the characteristic of low force gain (in comparison to a two stage servovalve driving the control spool) inherent with any direct drive force motor using a spring to determine position with force. To obtain lower threshold figures, the application of a low amplitude dither signal could be used.

Figures 25, 26 and 27 show the recorded test data used to establish the dynamic threshold values for test conditions 1, 2 and 3 respectively. The top recorded input signal is a 2.4 Hz sinusoid. The amplitude is increasing gradually with time. The input amplitude at which the actuator starts to follow the input is considered to be the dynamic input threshold level. The input frequency selected for this test is one half the bandpass frequency of the system in the normal operating mode.

The dynamic threshold in terms of the input command for each test condition is:

Test condition 1 - .84%

Test condition 2 - 1.66%

Test condition 3 - .28%

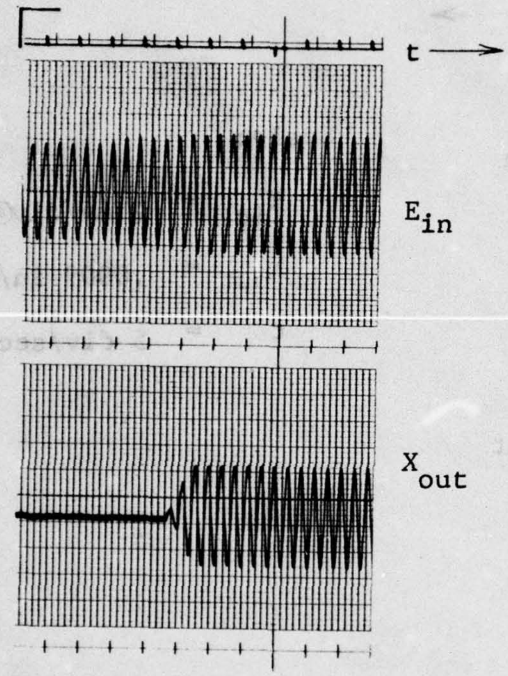
The increase in the dynamic threshold is as expected from the decreased force gain of condition 2 and agrees with the static threshold results in terms of the amount of increase. Again, test condition 3 has the lowest threshold and indicates the potential for lower thresholds with lower levels of friction for the control spool. The values of the dynamic threshold agree in magnitude with the static threshold test results. A high frequency dither signal could be used to decrease the measured threshold levels if desired.

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire

Date Prepared: 3/30/77

TEST - Dynamic Threshold - Condition 1



Scale:

E_{in} = 2 mv/div@2.4Hz

X_{out} = .0009 in/div

t = 5 div/sec

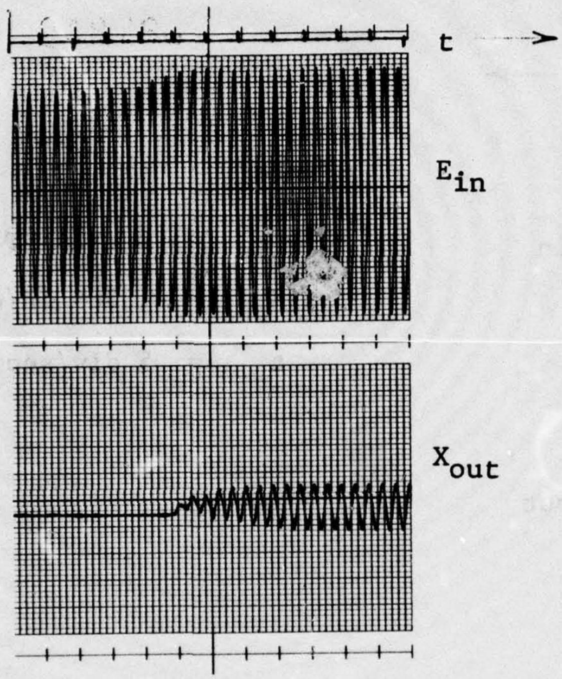
FIGURE 25 Dynamic Threshold - Condition 1

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire

Date Prepared: 3/30/77

TEST - Dynamic Threshold - Condition 2



Scale:

E_{in} = 2 mv/div@2.4Hz

X_{out} = .0009 in/div

t = 5 div/sec

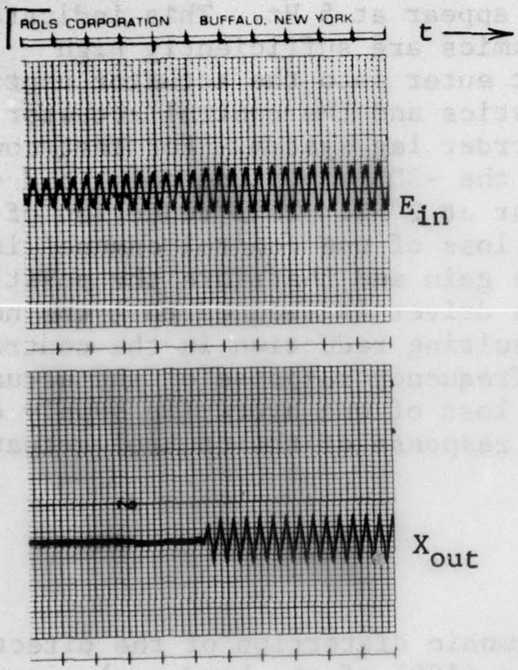
FIGURE 26 Dynamic Threshold - Condition 2

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire

Date Prepared: 3/30/77

TEST - Dynamic Threshold - Condition 3



Scale:

E_{in} = 2 mv/div @ 2.4 Hz

X_{out} = .0009 in/div

t = 5 div/sec

FIGURE 27 Dynamic Threshold - Condition 3

3.5.2 Frequency Response

Figures 28, 29 and 30 show the frequency response test results for test conditions 1, 2 and 3 respectively. For the test condition 1, the -3Db amplitude point and 45° phase lag frequency both appear at 5 Hz. This indicates that the force motor dynamics are sufficiently high response that they do not enter into the actuator control loop response characteristics and the control actuator appears as a pure first order lag system. For test condition 2 as shown in Figure 29, the -3Db amplitude point and 45° phase lag frequency appear at 2 Hz. This reduction of frequency response for a loss of one control channel is expected, since the force gain and therefore the position gain of the control valve driver is reduced to ½ the normal value. This causes a resulting reduction in the control loop gain and hence the frequency response of the actuator. Figure 30 shows that the loss of one hydraulic supply does not affect the frequency response of the control actuator.

3.5.3 Distortion

In measuring the harmonic distortion of the direct drive system, only one frequency (100% of the bandpass) was used. This was a test frequency of 5 Hz and was used because the distortion analyzer does not allow measurement below that frequency. The distortion figures were measured with an input level of 10% of the maximum command voltage. The harmonic distortion of the input, output and the net contribution of the FBW system at 5 Hz are as follows:

	Distortion		
	Input	Output	Net
Test Condition 1	1.3%	6.2%	4.9%
Test Condition 2	1.3%	8.8%	7.5%
Test Condition 3	1.3%	5.2%	3.9%

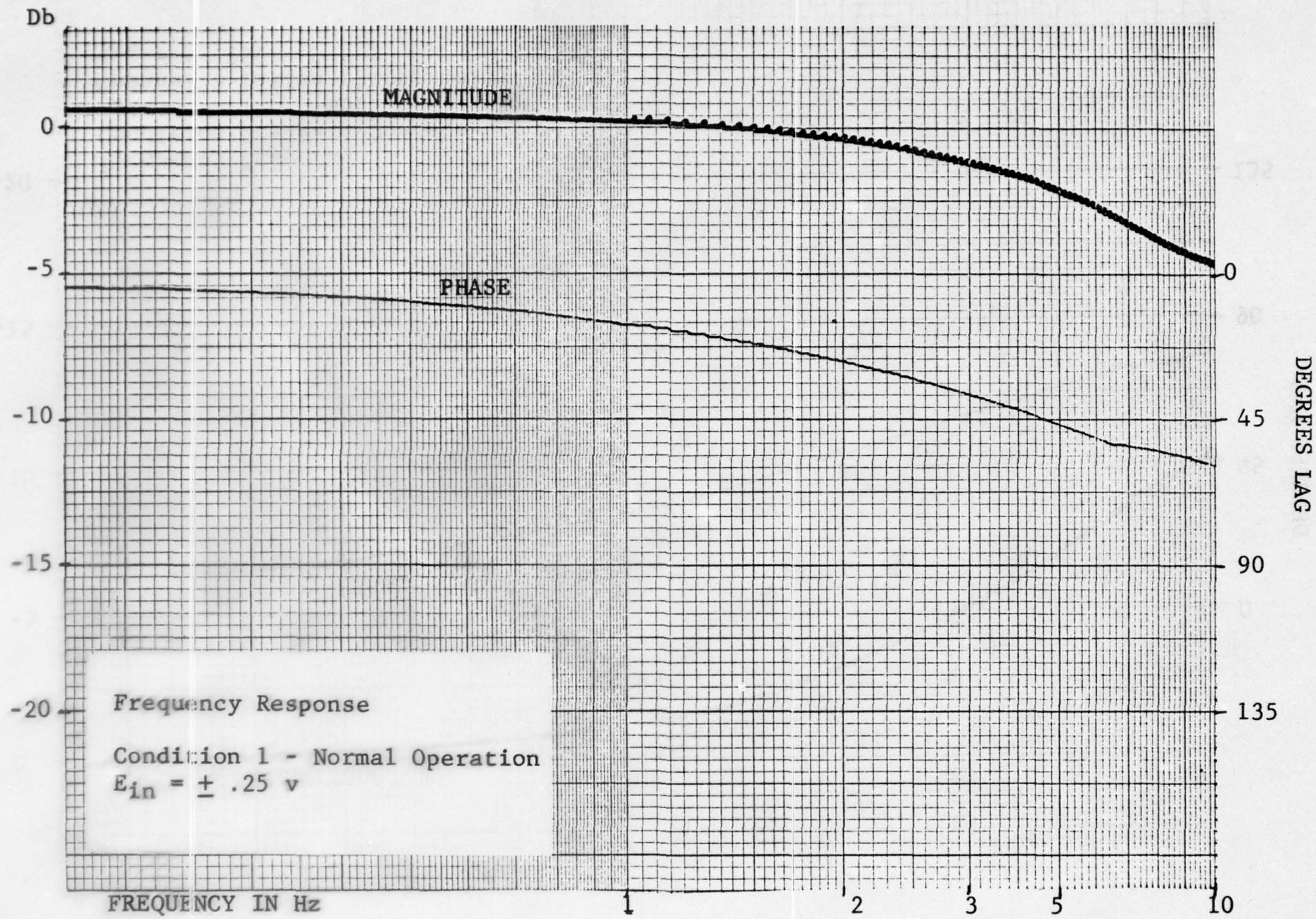


FIGURE 28 Frequency Response - Condition 1

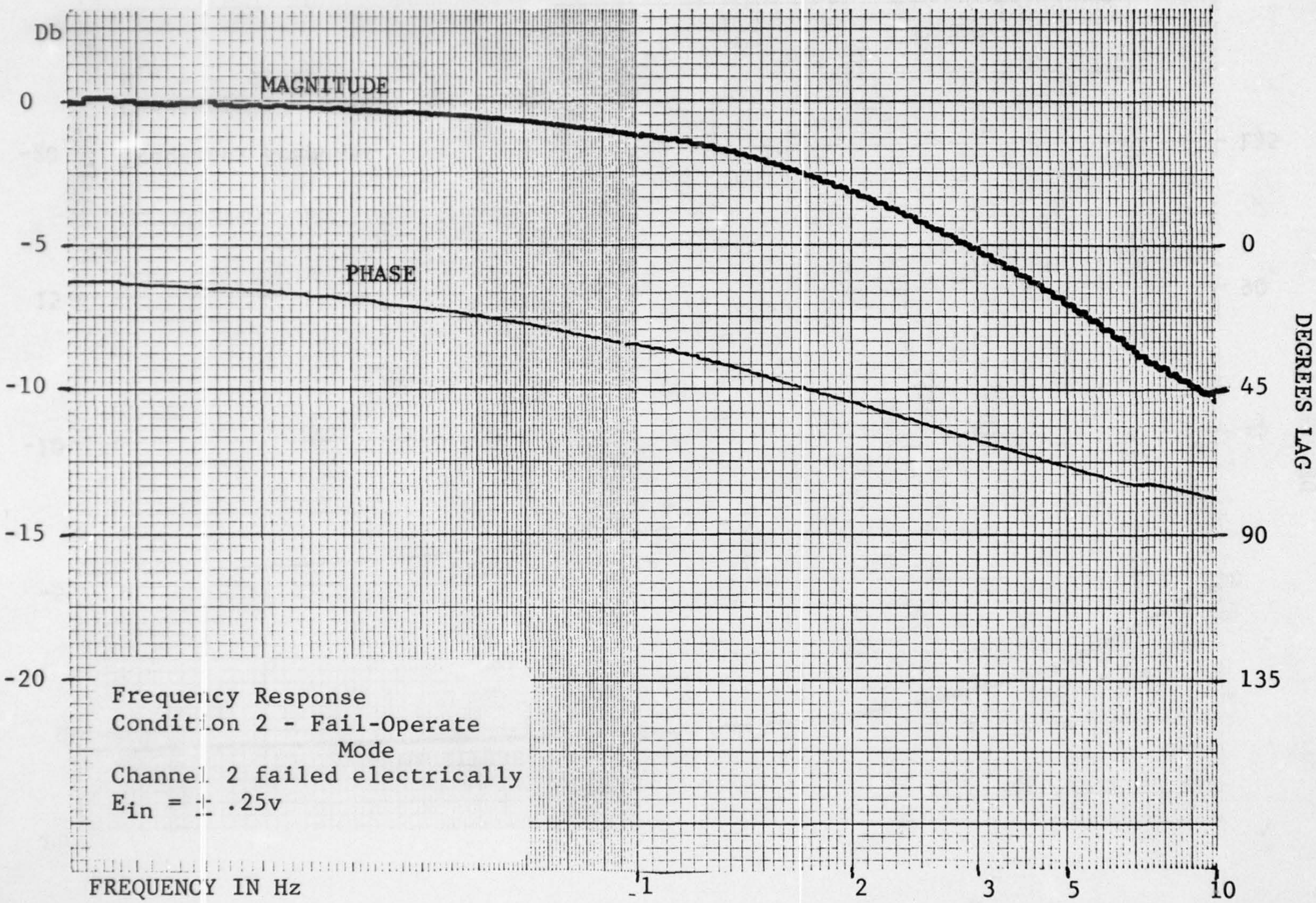


FIGURE 29 Frequency Response - Condition 2

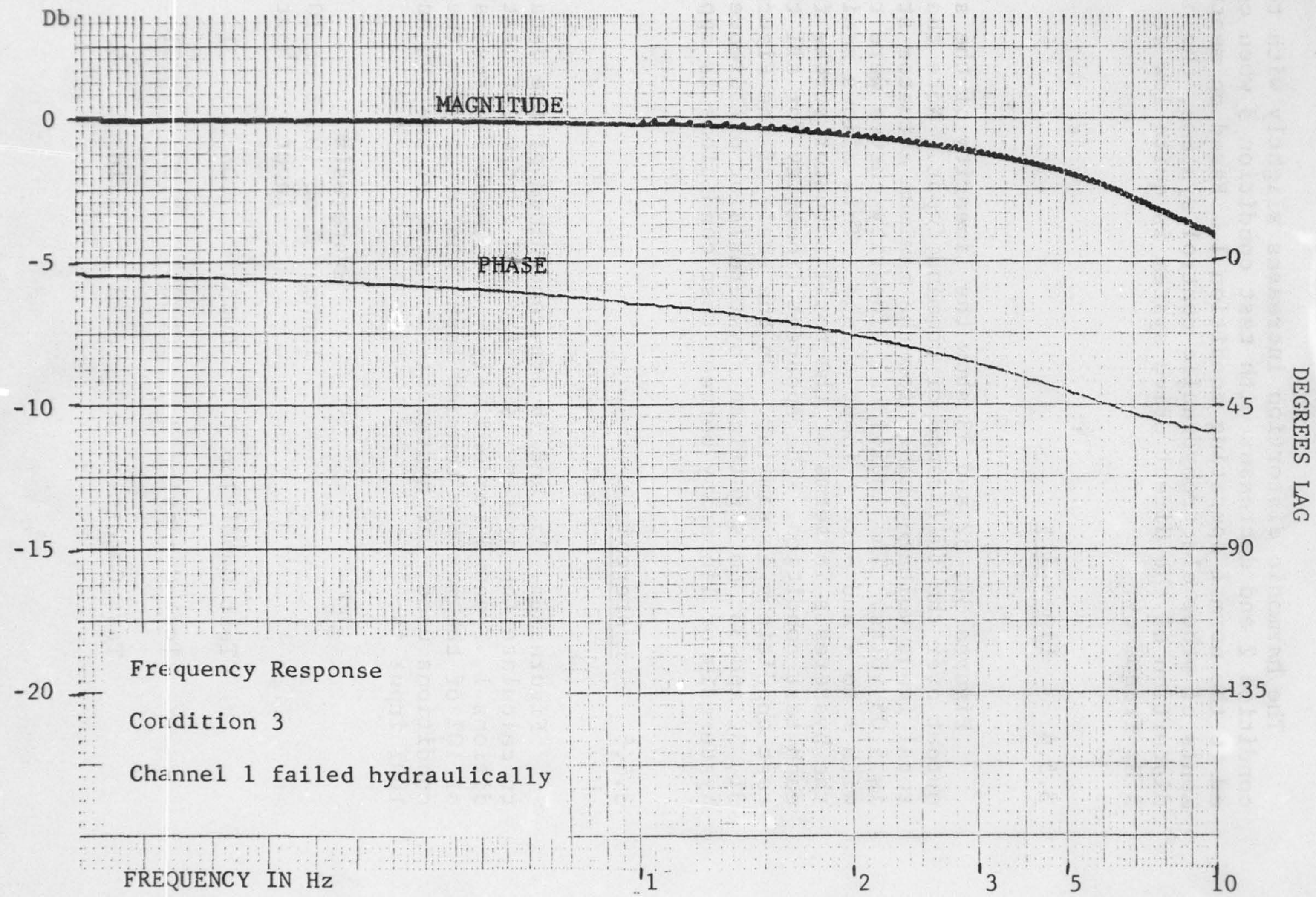


FIGURE 30 Frequency Response - Condition 3

The harmonic distortion increases slightly with test condition 2 and decreases with test condition 3 when compared to the normal operating condition 1. Based on measurements of other electrohydraulic control systems, the harmonic distortion of the direct drive system is quite low at the 5 Hz frequency.

3.5.4 Linearity

Figures 31, 32 and 33 show the linearity of the system output over the full range of command input. Note that the total input voltage change for the maximum actuator stroke is 5.05 volts. The individual linearity curves were run with + to - and - to + input change. This allows seeing the hysteresis in terms of the total actuator stroke for each test condition. The apparent linearity for all three test conditions is similar. On the scale of the Figures 31, 32 and 33, no significant hysteresis or difference in hysteresis or linearity between test conditions is apparent.

3.5.5 Hysteresis

Figures 34, 35, and 36 are recordings of the data used to calculate the hysteresis of the FBW system for test conditions 1, 2 and 3 respectively. For these figures, an input of 10% of the maximum command input was used. For the test conditions used, the hysteresis in terms of the 10% and the 100% input is:

	Hysteresis Inches	% of 10% Input	% of 100% Input
Test Condition 1	.0045	2.06	.21
Test Condition 2	.0068	3.09	.31
Test Condition 3	.0113	5.16	.52

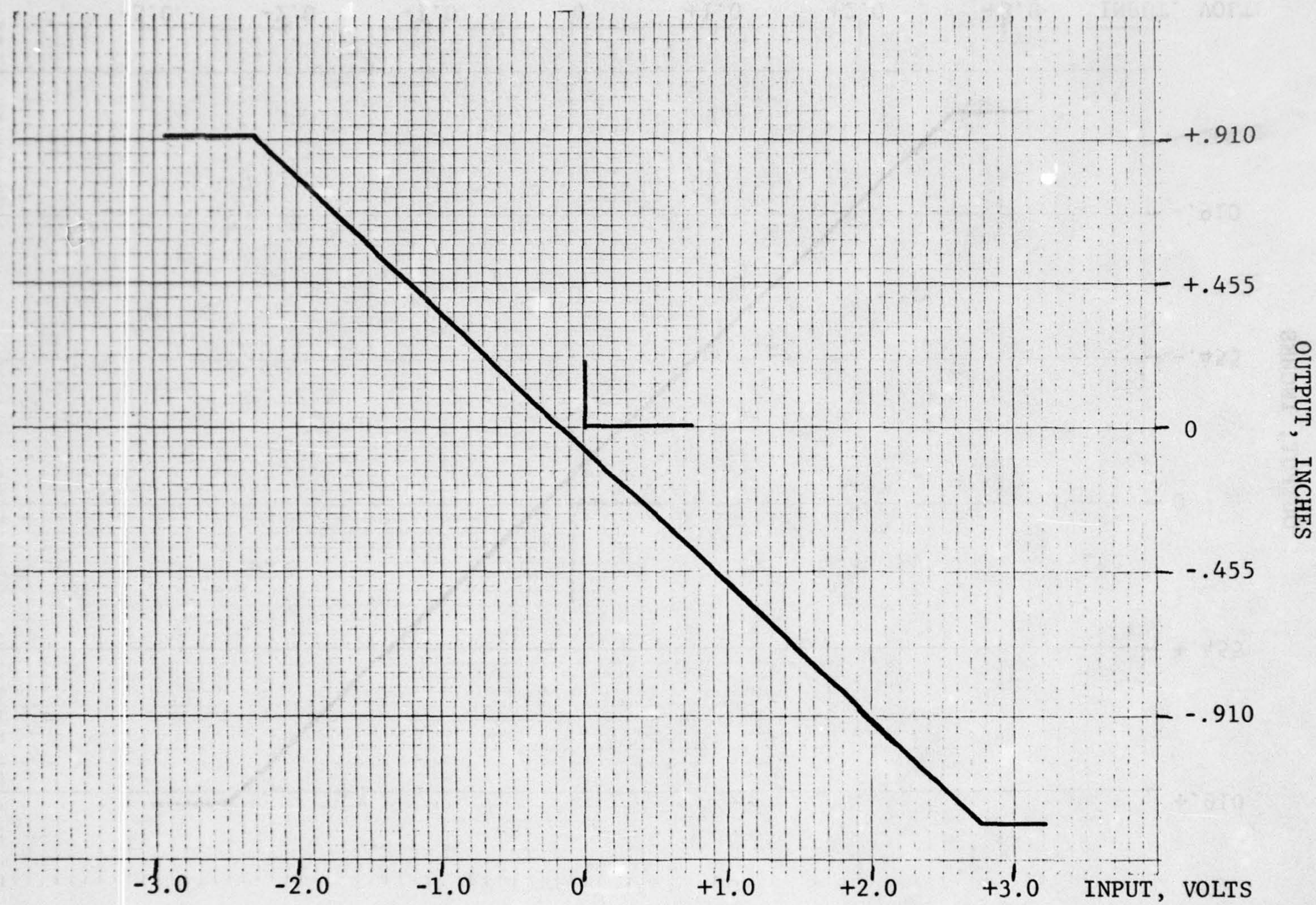


FIGURE 31 Linearity - Condition 1

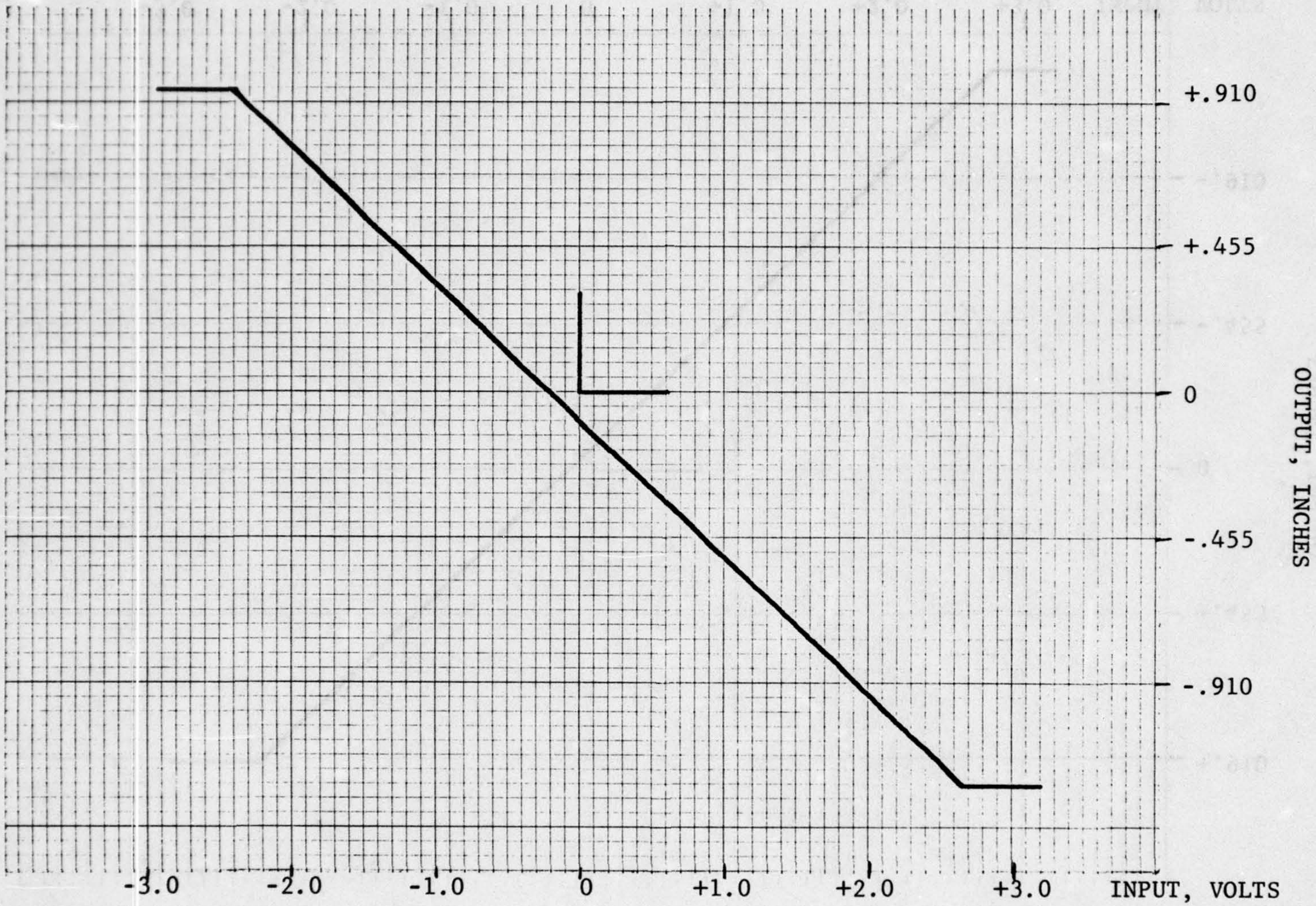


FIGURE 32 Linearity - Condition 2

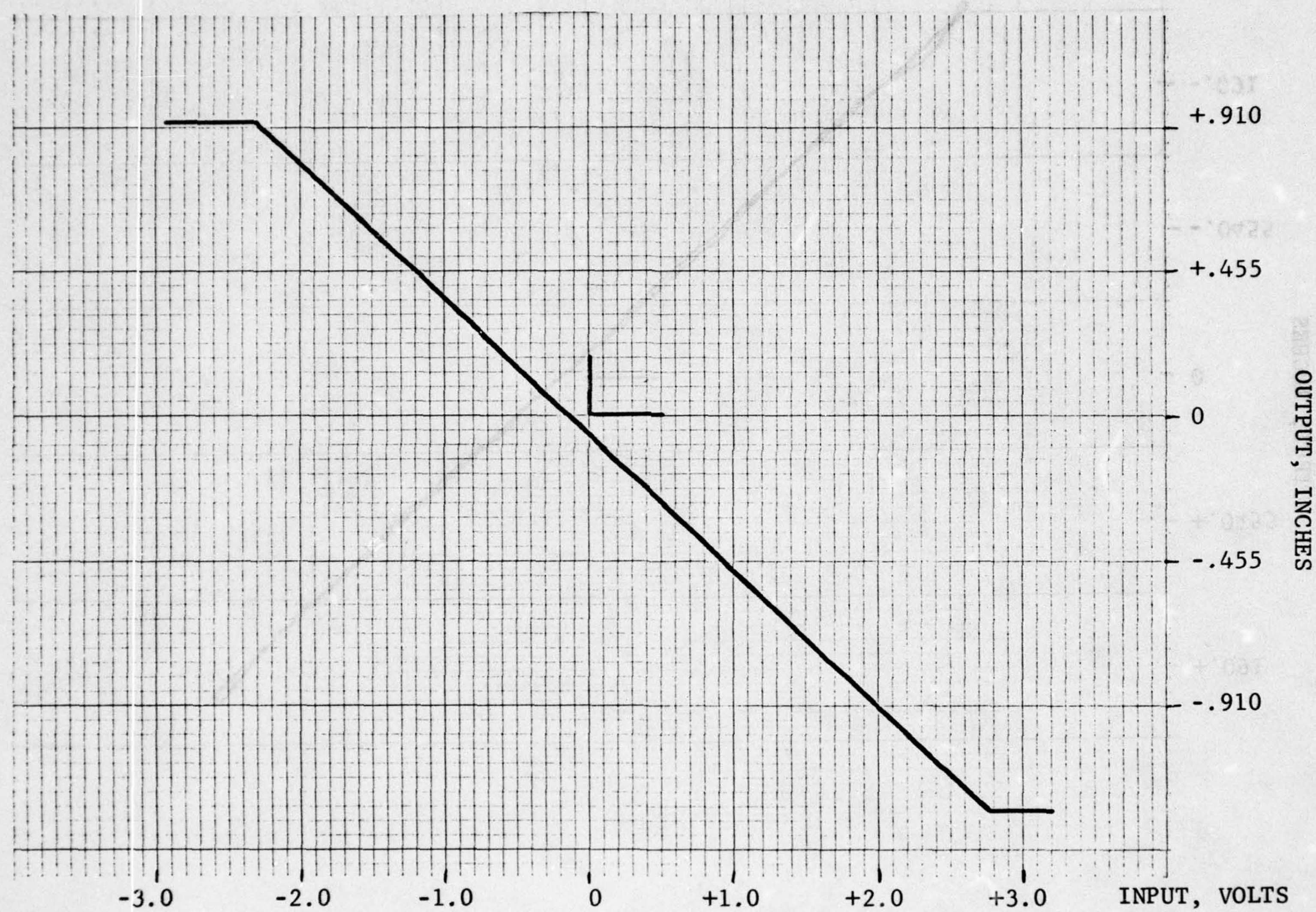


FIGURE 33 Linearity - Condition 3

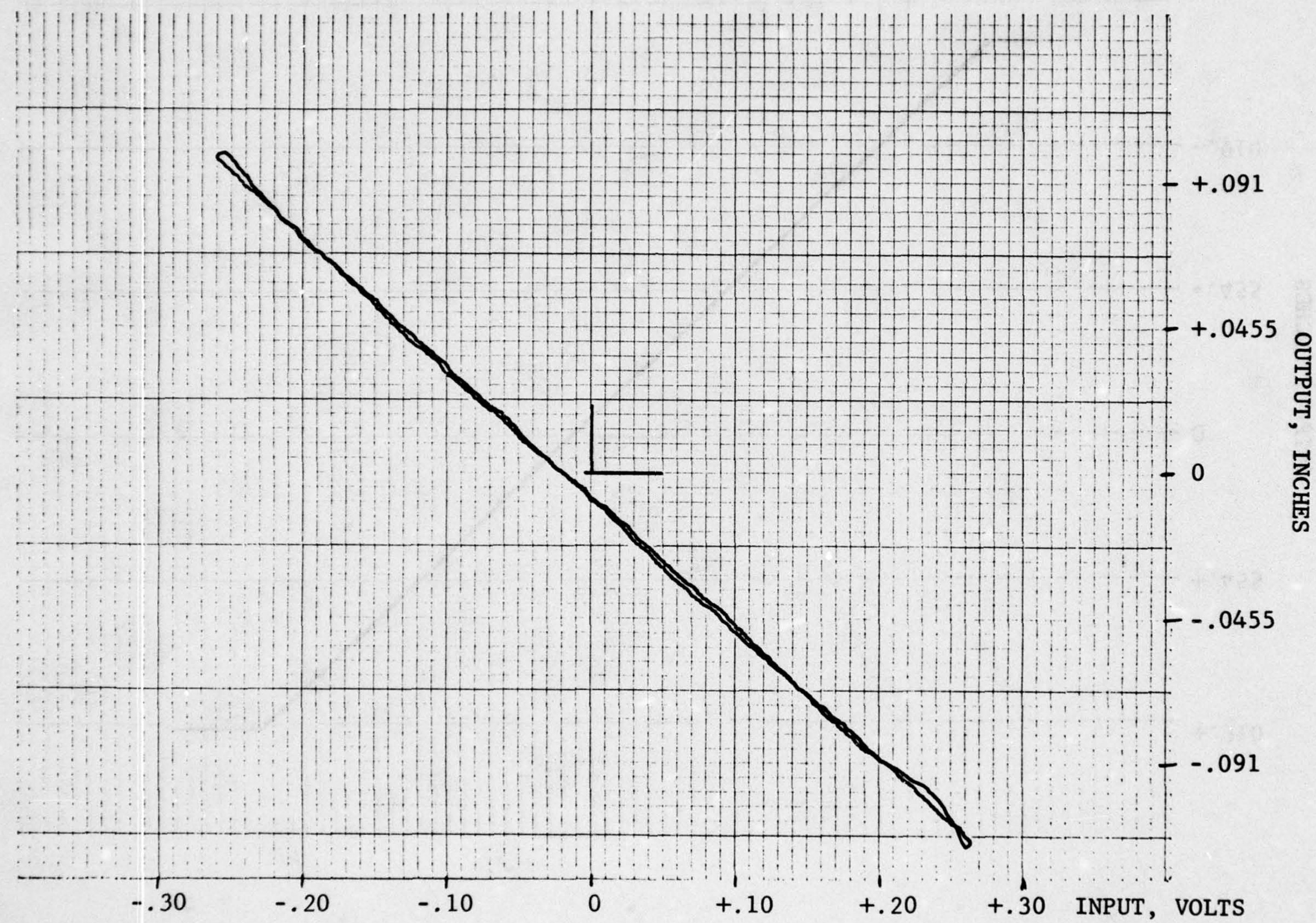


FIGURE 34 Hysteresis - Condition 1 - 10% input

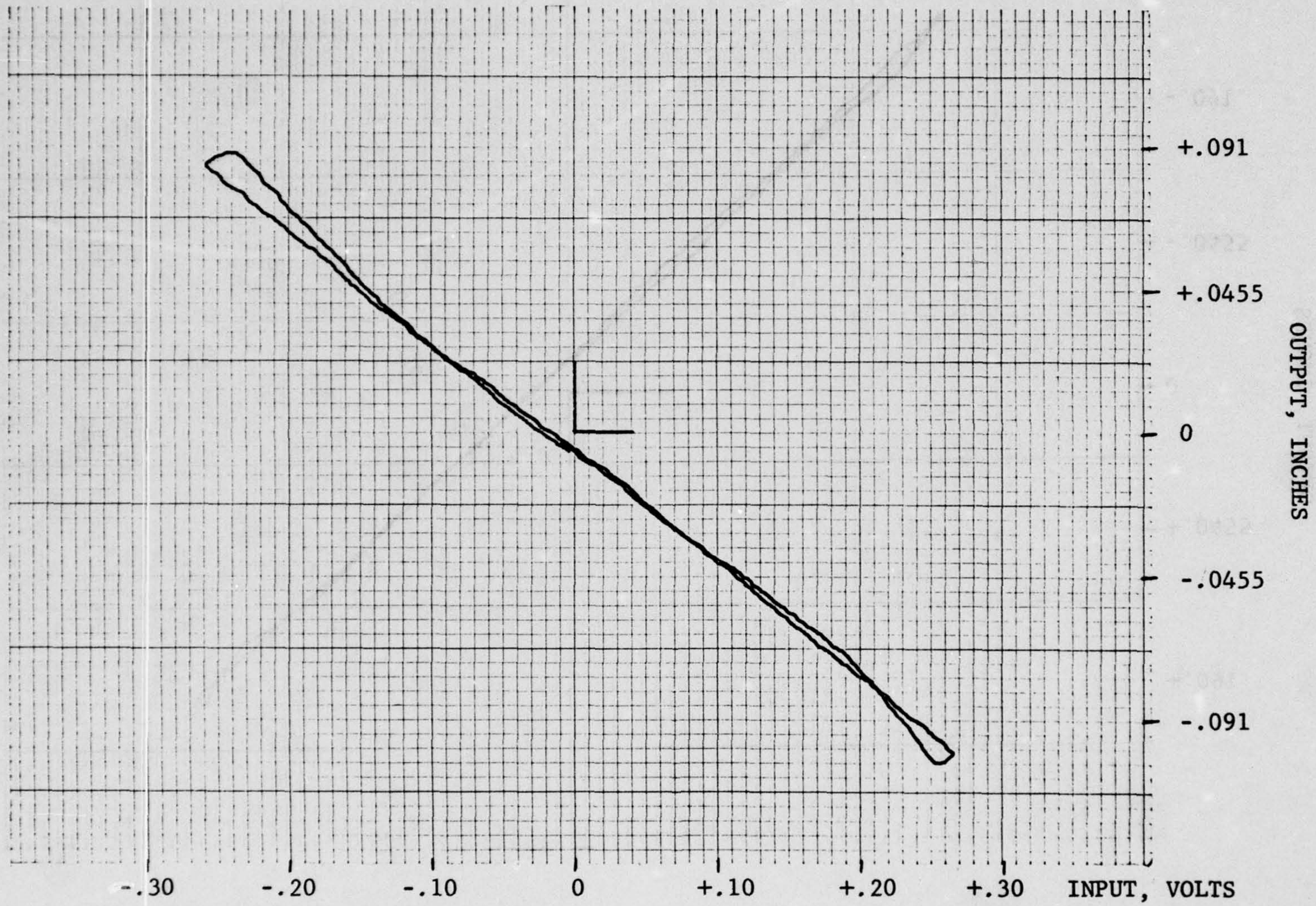


FIGURE 35 Hysteresis - Condition 2 - 10% Input

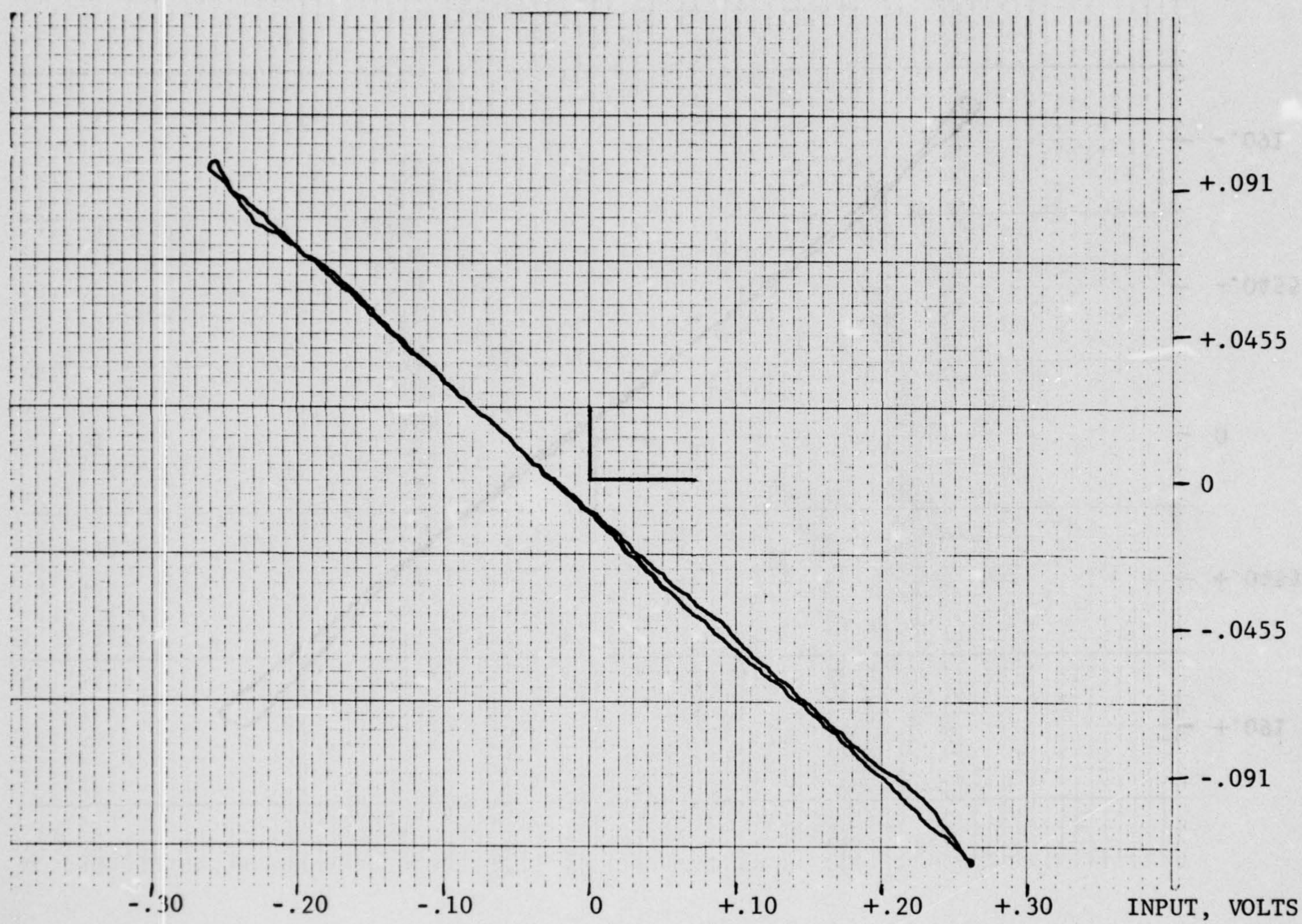


FIGURE 36 Hysteresis - Condition 3 - 10% Input

Figures 37, 38 and 39 show the hysteresis measurement recordings for an input of 1% of the maximum command input. For the test conditions used, the hysteresis in terms of the 1% and the 100% input is:

	Hysteresis		
	Inches	Input % of 1%	Input % of 100%
Test Condition 1	.008	30.2	.30
Test Condition 2	.015	54.7	.55
Test Condition 3	.0085	32.1	.33

Note that the general magnitude of the hysteresis in terms of maximum command input is similar for both the 10% and 1% input. This hysteresis is associated with the friction levels of the suspension and spool and could be reduced (if desired) with the application of a small amplitude dither signal to the system.

3.5.6 Time Response

Figure 40 illustrates the test data recorded for measuring the extend and retract maximum rates for the control actuator. The data shown is for test condition 1 extend motion. The data recorded for the retract motion and the other test conditions resembles the Figure 40 data with only the elapsed time varying. The extend and retract times measured for each test condition are the following:

	Extend Time in Seconds	Retract Time in Seconds
Test Condition 1	.28	.43
Test Condition 2	.38	.43
Test Condition 3	.24	.41

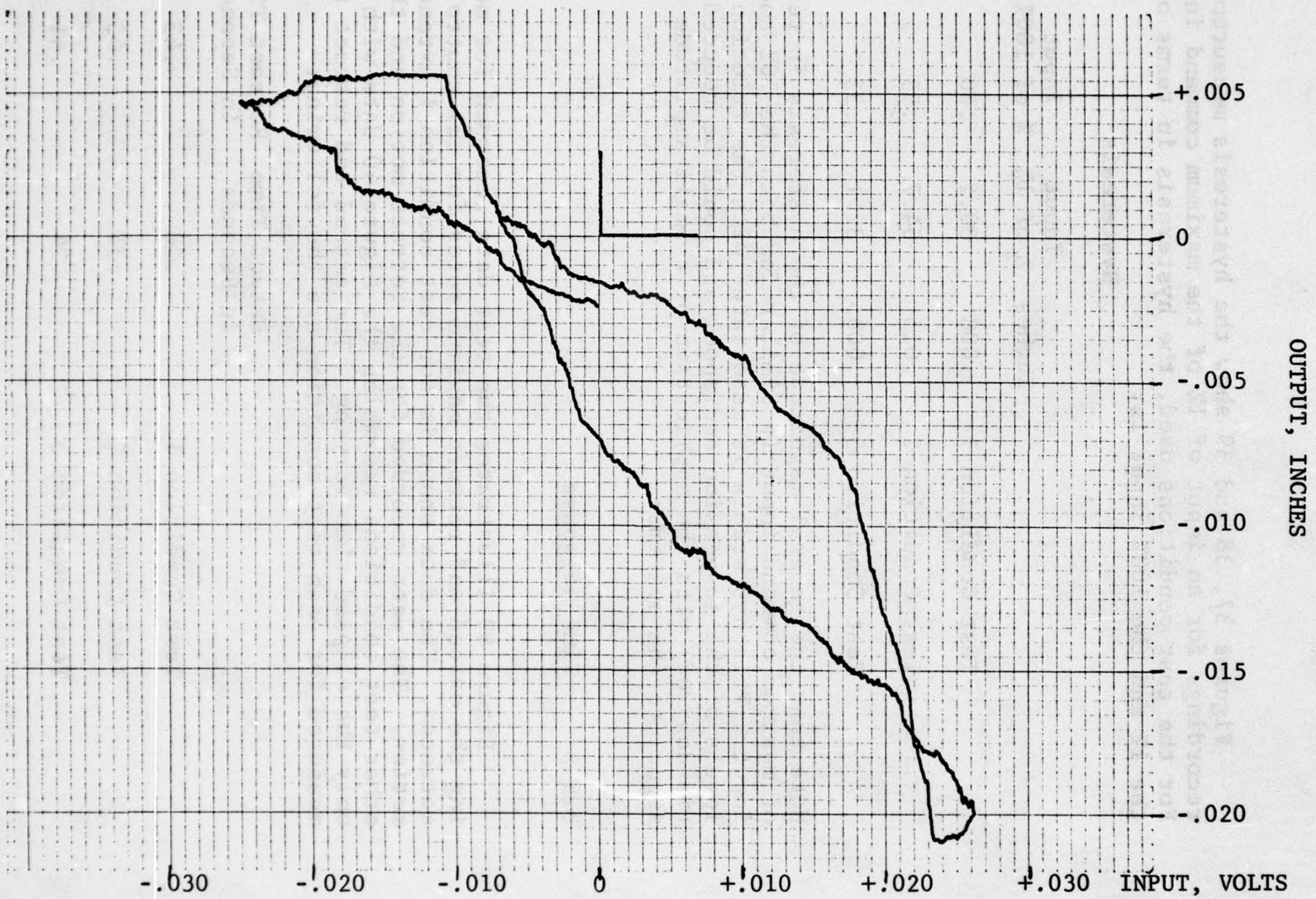


FIGURE 37 Hysteresis - Condition 1 - 1% Input

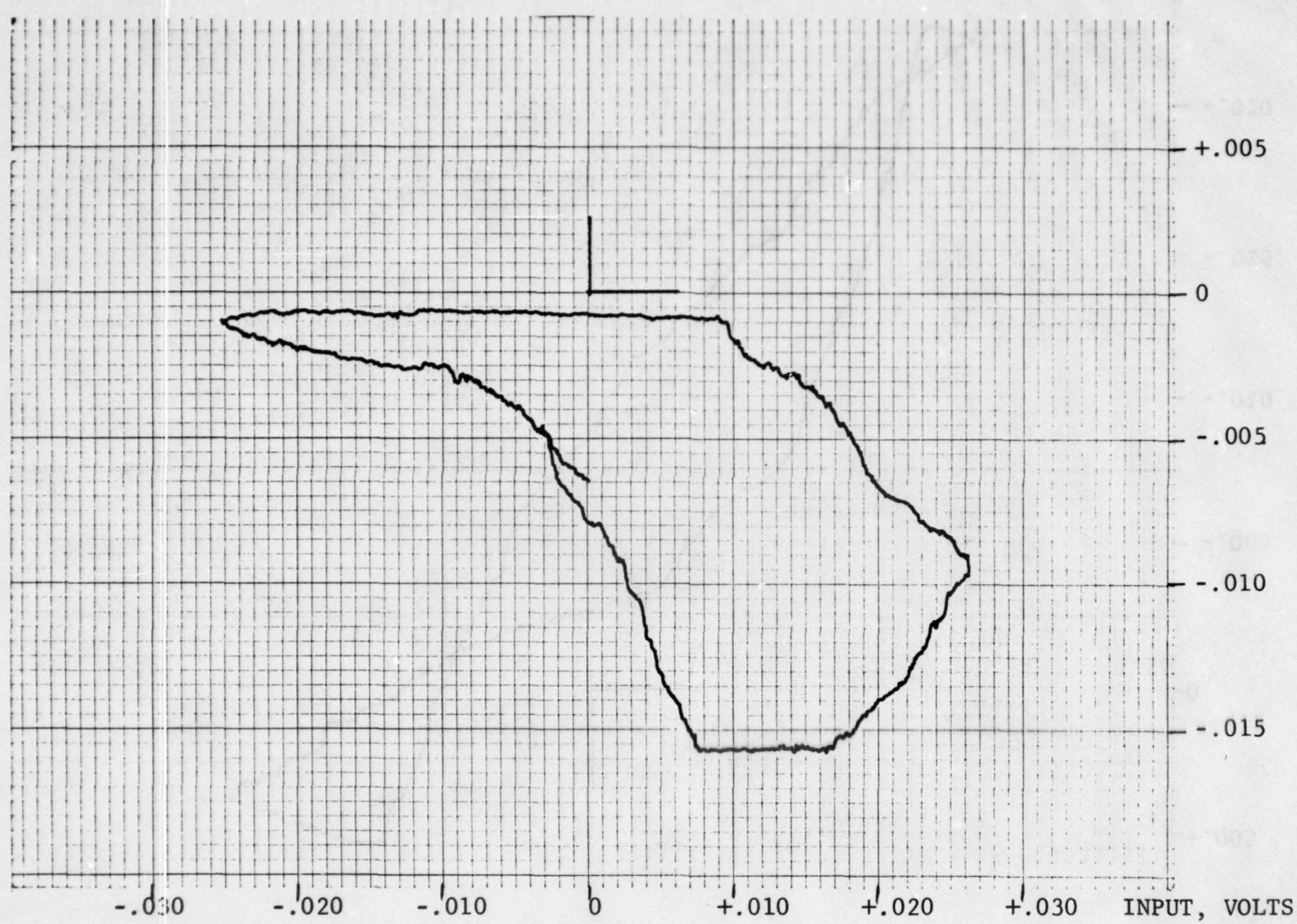


FIGURE 38 Hysteresis - Condition 2 - 1% Input

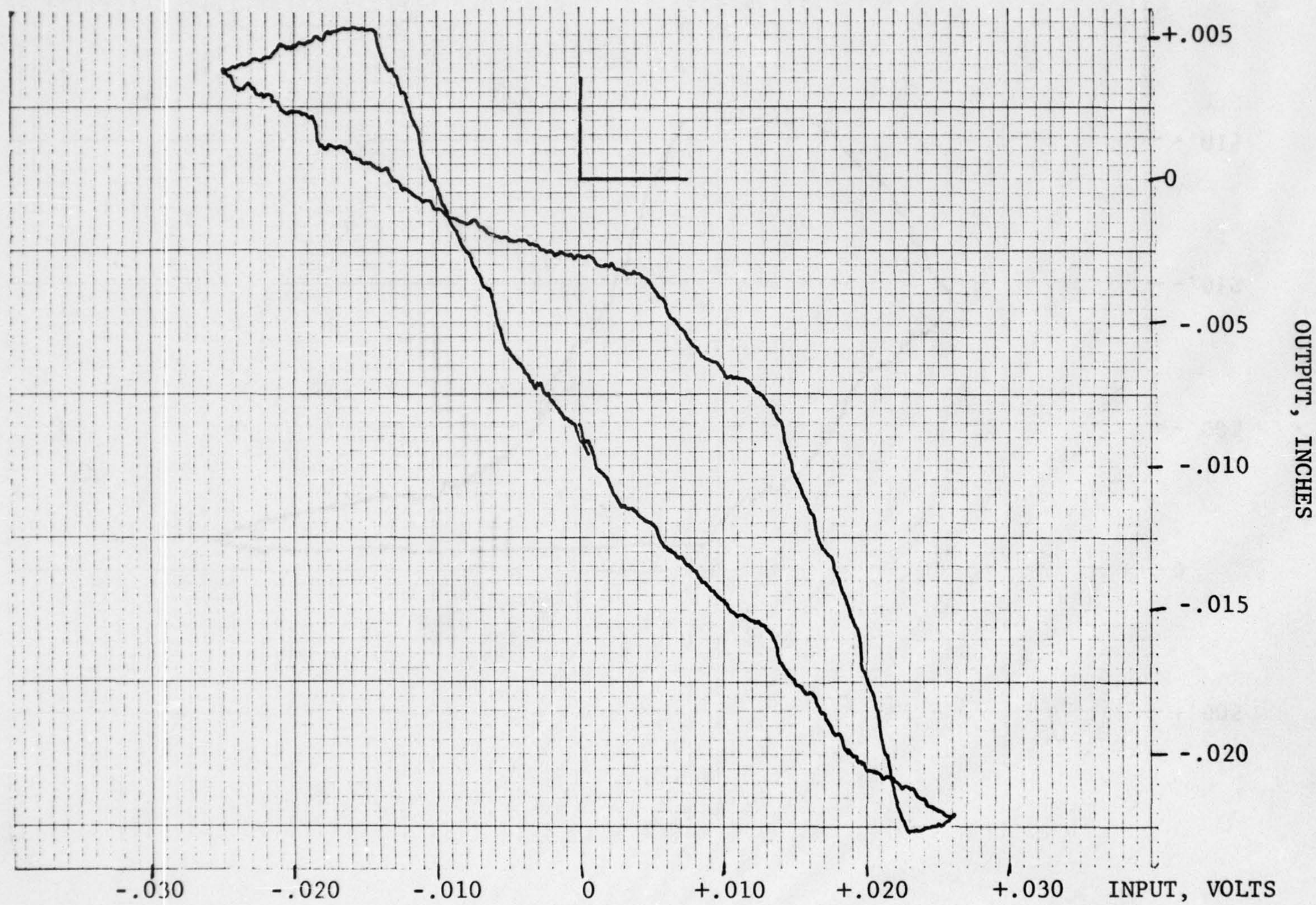
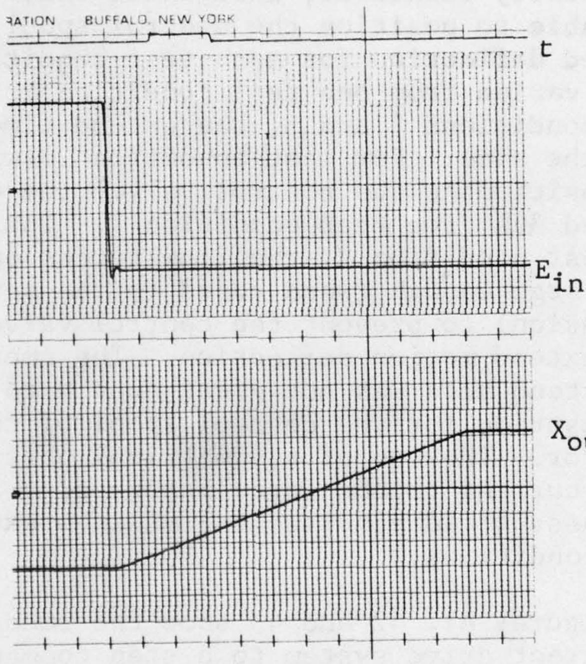


FIGURE 39 Hysteresis - Condition 3 - 1% Input

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire　　Date Prepared: 3/30/77

TEST - Saturation Velocity - Condition 1 - Extend Motion



Scale:

E_{in} = 200 mv/div

X_{out} = .091 in/div

t = 200 div/sec

FIGURE 40 Actuator Saturation Velocity - Condition 1

For the demonstration system, the valve sleeve was constructed with symmetrical porting (i.e. the open porting area for the valve was the same for all cylinder ports). The normal F-4E actuator control valve is asymmetrical with unequal area porting corresponding to the actuator unequal drive areas. The asymmetrical porting gives more equal extend and retract maximum rates.

The retract rate for all three test conditions was essentially identical, indicating that the force motors were able to position the control spool at its maximum stopped deflection for each test condition. The extend times varied from one test condition to another. For test conditions 1 and 3, the extend times were essentially the same. For test condition 2 (with one force motor positioning the control valve) the extend time increased 36% from test condition 1. This indicates that for test condition 2, the flow forces on the control valve were large enough (when added to the spring force of the suspension) to prevent the control valve from reaching the full extend motion deflection. The amount of change of the extend rate was not great enough to use flow force compensation for the control spool of the demonstration actuator. The use of asymmetrical porting, increasing drive current to the force motors or a lower suspension stiffness would equalize the maximum extend rate for the test conditions.

Figures 41, 42 and 43 show the recorded response of the direct drive system to a step command input. The step response for all test conditions is exponential and does not exhibit any overshoot or ringing. This step response of the system is consistent with the frequency response measurements. For all the test conditions a .5 volt amplitude step was used as the input. This is approximately an input command of 10% of the full actuator position command. The response times to reach 63% of the final value for each test condition (as taken from Figures 41, 42 and 43) is the following:

AD-A047 283 DYNAMIC CONTROLS INC DAYTON OHIO F/G 1/4
RESEARCH AND DEVELOPMENT OF AIRCRAFT CONTROL ACTUATION SYSTEMS.--ETC(U)
SEP 77 G D JENNEY F33615-75-C-3068

UNCLASSIFIED AFFDL-TR-77-91 NL

2 OF 3

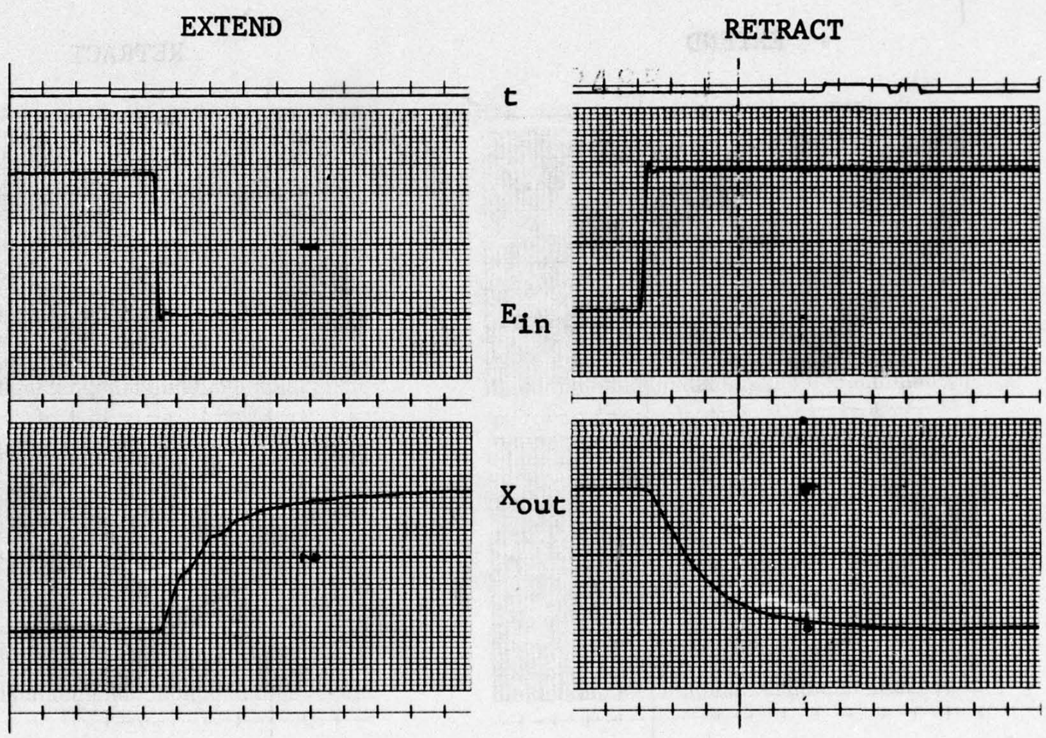
AD
A047 283

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire

Date Prepared: 3/30/77

TEST - Transient Response - Condition 1



Scale:

E_{in} = 20 mv/div

X_{out} = .009 in/div

t = 200 div/sec

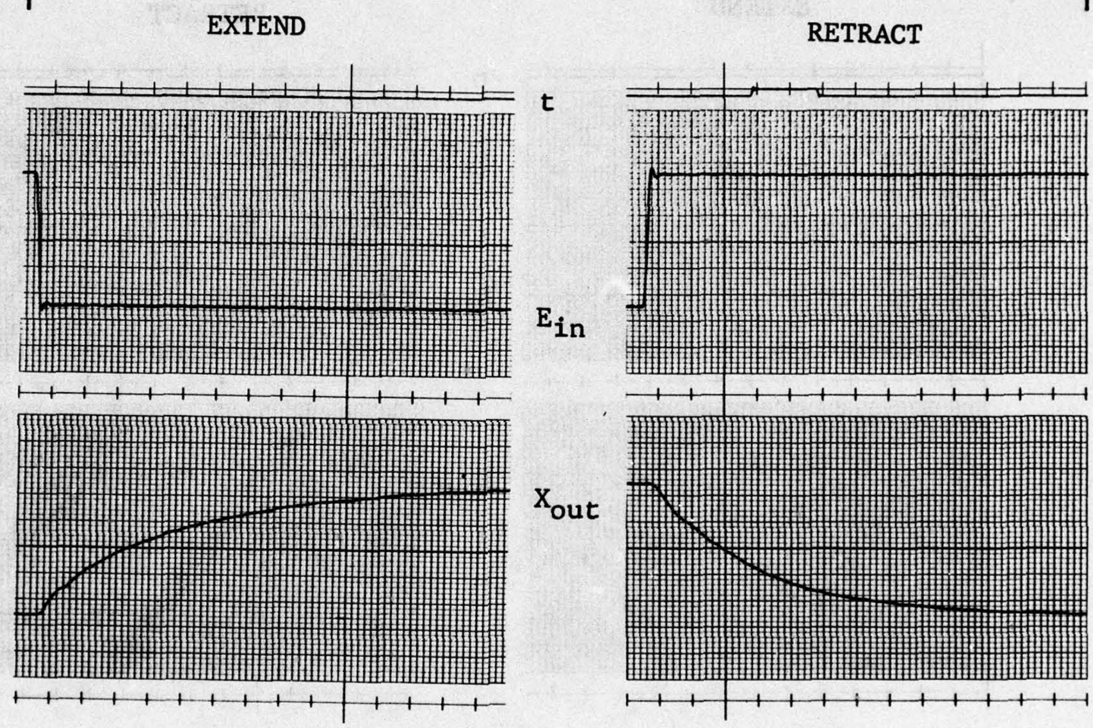
FIGURE 41 Step Response - Condition 1

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire

Date Prepared: 3/30/77

TEST - Transient Response - Condition 2



Scale:

E_{in} = 20 mv/div

X_{out} = .009 in/div

t = 200 div/sec

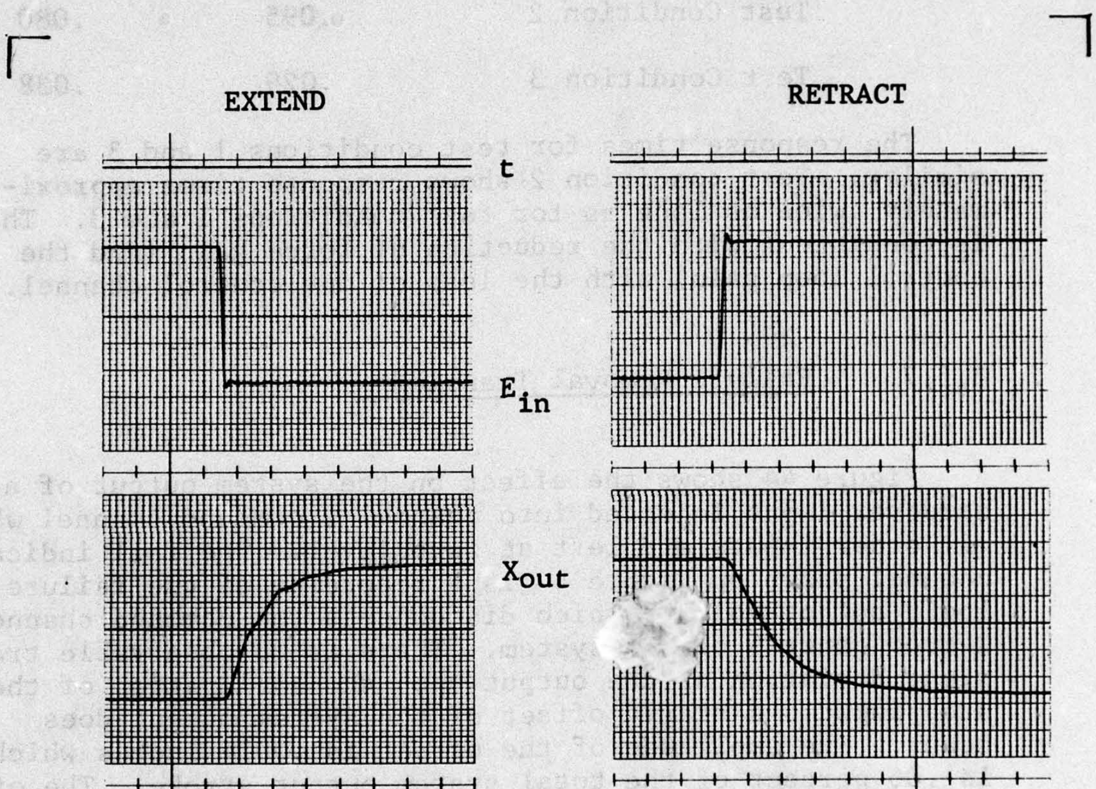
FIGURE 42 Step Response - Condition 2

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire

Date Prepared: 3/30/77

TEST - Transient Response - Condition 3



Scale:

E_{in} = 20 mv/div

X_{out} = .009 in/div

t = 200 div/sec

FIGURE 43 Step Response - Condition 3

	Response Time in Seconds	
	Extend	Retract
Test Condition 1	.038	.045
Test Condition 2	.095	.080
Test Condition 3	.029	.038

The response times for test conditions 1 and 3 are similar. Test condition 2 shows response times approximately twice as long as for test conditions 1 and 3. This is consistent with the reduction of force gain (and the control loop gain) with the loss of one control channel.

3.5.7 Failure Removal Transients

Figure 44 shows the effect on the system output of a hardover input injected into channel 2 command channel while all other inputs are left at zero level. The fail indicate channel shown on Figure 44 is a recording of the failure logic output voltage which disconnects the command channel 2 from control of the system. There is no observable transient deviation of the output upon the application of the step input. A static offset of the system output does occur. The amplitude of the offset is .0014 inches which is .06 percent of the total system output stroke. The offset reflects the small null offset between the two command channels of the system and a corresponding output change when one channel is disconnected.

Figure 45 shows the effect on the system output of a hardover input injected into channel 2 command while all inputs are being commanded by a .8 Hz signal. Transient deviation of the actuator output is .010 inches or .46 percent of the total actuator stroke.

Figure 46 shows the effect on the system output of a slowover input applied to channel 2 command with channel 1 and channel 2 monitor input grounded. The maximum actuator position deviation is .018 inches or .82 percent of the total actuator stroke.

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire   Date Prepared: 4-26-77

TEST - Static Condition, Hardover Into Channel 2 Command Input

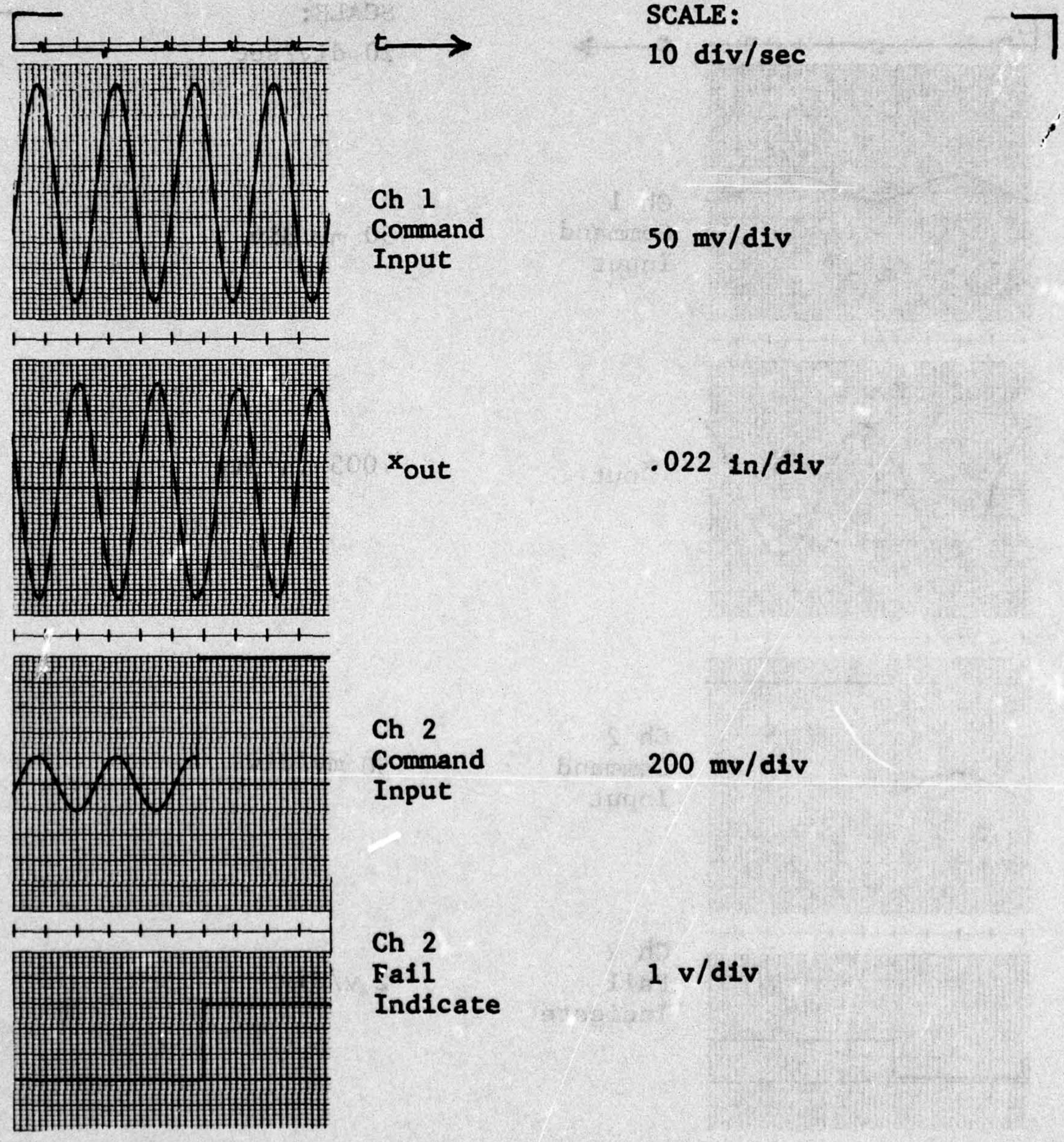


FIGURE 44 Hardover Failure - Static Initial Condition

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire

Date Prepared: 4-26-77

TEST - Dynamic Failure - Hardover Into Channel 2 Command Input

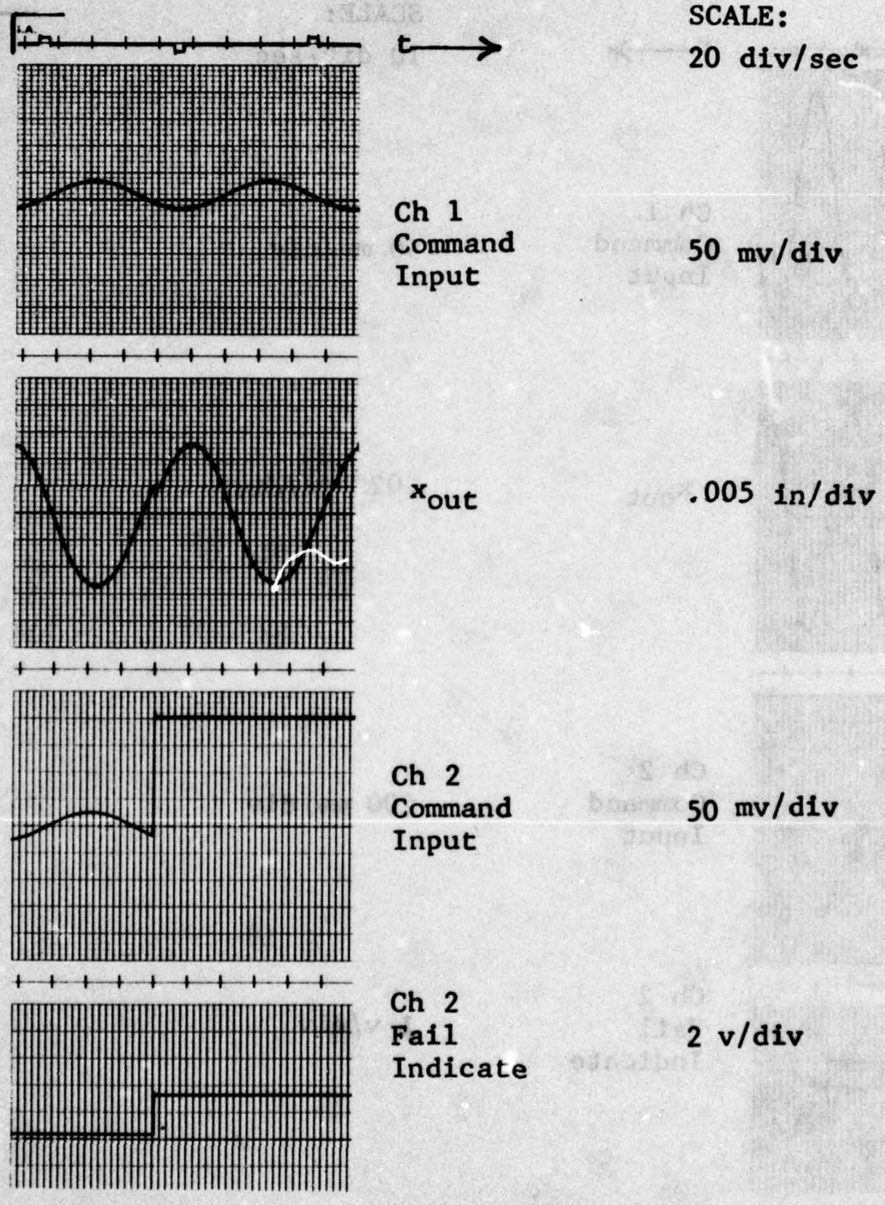


FIGURE 45 Hardover Failure - Dynamic Initial Condition

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Direct Drive Fly-By-Wire   Date Prepared: 4-26-77

TEST - Slowover Failure - 3 Inputs Grounded

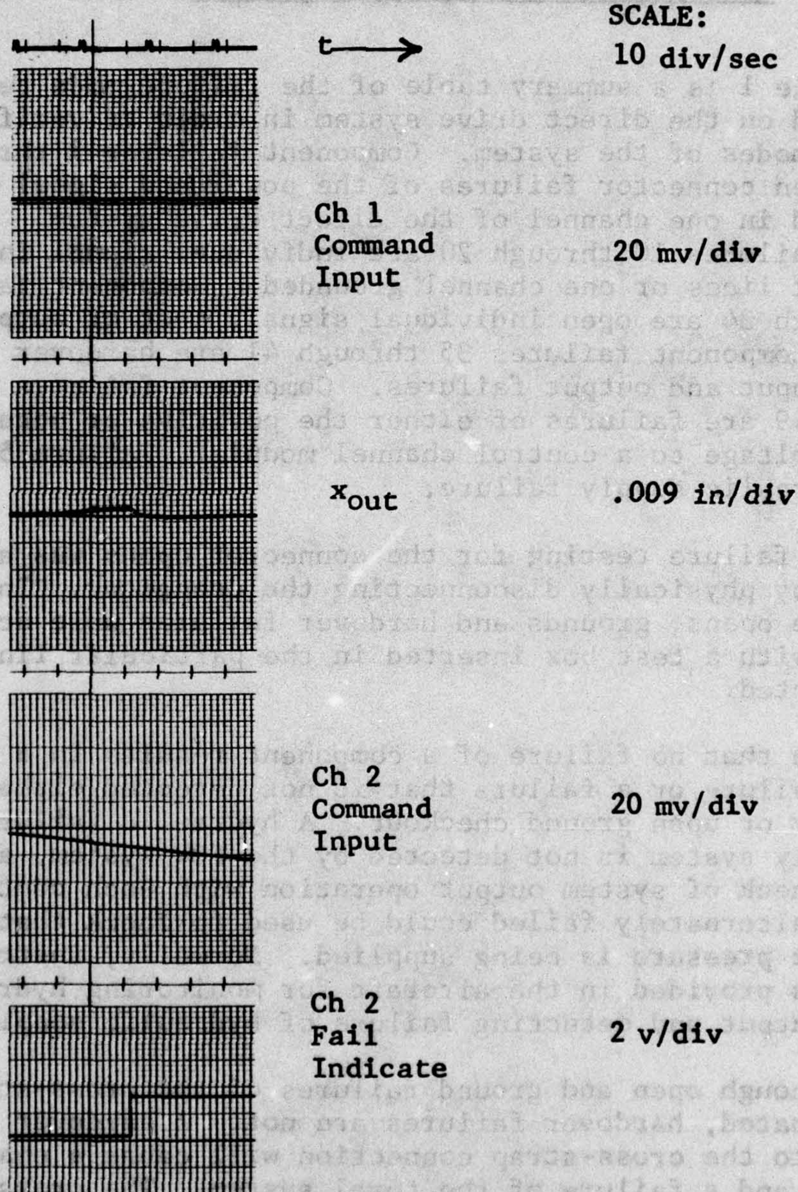


FIGURE 46 Slowover Failure - Static Initial Condition

The small output deviation with injected failures is a direct result of the detection level and logic time delay settings usable with the direct drive system mechanization.

3.5.8 Failure Mode Verification Testing

Table 1 is a summary table of the failure mode tests performed on the direct drive system in order to verify the failure modes of the system. Component failures 1 through 9 are open connector failures of the power and signal connectors used in one channel of the direct drive system. Component failures 10 through 20 are individual signal input or output lines or one channel grounded. Component failures 21 through 34 are open individual signal, test or output lines. Component failures 35 through 41 are hardover individual input and output failures. Component failures 42 through 49 are failures of either the positive or negative supply voltage to a control channel module. Failure 50 is a hydraulic supply failure.

The failure testing for the connector opens was accomplished by physically disconnecting the connector. Individual line opens, grounds and hardover failures were accomplished with a test box inserted in the particular line being tested.

Note that no failure of a component results in a total system failure or a failure that is not detected either immediately or upon ground checkout. A hydraulic failure of one supply system is not detected by the FBW system, although ground check of system output operation with each control channel alternately failed could be used to check that hydraulic pressure is being supplied. Normally, instrumentation is provided in the aircraft for monitoring hydraulic system output and detecting failure of hydraulic supply.

Although open and ground failures of the cross-strap are evaluated, hardover failures are not. A hardover voltage applied to the cross-strap connection will cause a channel hardover and a failure of the total system. The cross-strap wiring is therefore routed separately and not in

TABLE 1

FAILURE MODE TEST RESULTS

	COMPONENT FAILURE	FAILURE INDICATION	FAILURE EFFECT
1.	Monitor Amp Input Connector Open	Channel Failure Light	Channel Failed soft, System Operable
2.	Command Amp Input Connector Open	Channel Failure Light	Channel Failed Soft, System Operable
3.	Comparator Input Connector Open	Current Lights For Channel	Channel Failed Soft, System Operable. Failure Detected on Ground Check
4.	Servo Amp Input Connector Open	Current Lights For Amp	Channel Failed Soft, System Operable. Failure Detected on Ground Check
5.	Stick Output Connector Open	Channel Failure Light	Channel Failed Soft, System Operable.
6.	Monitor Amp Power Connector Open	Channel Failure Light	Channel Failed Soft, System Operable.
7.	Command Amp Power Connector Open	Channel Failure Light	Channel Failed Soft, System Operable.
8.	Comparator Power Connector Open	Current Lights For Channel	Channel Failed Soft, System Operable. Failure Detected on Ground Check
9.	Servo Amp Power Connector Open	Current Lights For Amp	Channel Failed Soft, System Operable. Failure Detected on Ground Check

TABLE 1 (Cont'd.)

FAILURE MODE TEST RESULTS

	COMPONENT FAILURE	FAILURE INDICATION	FAILURE EFFECT
10.	Monitor Amp Command Input Grounded	Channel Failure Light	Channel Failed Soft, System Operable
11.	Monitor Amp Feedback Input Grounded	Channel Failure Light	Channel Failed Soft, System Operable
12.	Monitor Amp Output Grounded	Channel Failure Light	Channel Failed Soft, System Operable
13.	Command Amp Command Input Grounded	Channel Failure Light	Channel Failed Soft, System Operable
14.	Command Amp Feedback Input Grounded	Channel Failure Light	Channel Failed Soft, System Operable
15.	Command Amp Output to Comparator Grounded	Channel Failure Light	Channel Failed Soft, System Operable
16.	Comparator Output Grounded	Current Lights For Channel	Channel Failed Soft, System Operable. Failure Detected on Ground Check
17.	Servo Amp #1 Input Grounded	Current Lights For Amp	Channel Failed Soft, System Operable. Failure Detected on Ground Check
18.	Servo Amp #2 Input Grounded	Current Lights For Amp	Channel Failed Soft, System Operable. Failure Detected on Ground Check

TABLE 1 (Cont'd.)

FAILURE MODE TEST RESULTS

	COMPONENT FAILURE	FAILURE INDICATION	FAILURE EFFECT
19.	Servo Amp Output Grounded	Current Lights For Amp	Channel Failed Soft, System Operable. Failure Detected on Ground Check
20.	Servo Amp Cross-strap Grounded	Current Lights For Channel	System Operates Normally, Failure Detected on Ground Check
21.	Monitor Amp Command Input Open	Channel Failure Light	Channel Failed Soft, System Operable
22.	Monitor Amp Feed-back Input Open	Channel Failure Light	Channel Failed Soft, System Operable
23.	Monitor Amp Output Open	Channel Failure Light	Channel Failed Soft, System Operable
24.	Monitor Amp Test Input Open	No Failure Transfer During Logic Test	System Operates Normally, Failure Detected on Ground Check
25.	Command Amp Command Input Open	Channel Failure Light	Channel Failed Soft, System Operable
26.	Command Amp Position Input Open	Channel Failure Light	Channel Failed Soft, System Operable
27.	Command Amp Relay Input Open	Channel Failure Light	Channel Failed Soft, System Operable

TABLE 1 (Cont'd.)

FAILURE MODE TEST RESULTS

	COMPONENT FAILURE	FAILURE INDICATION	FAILURE EFFECT
28.	Command Amp Output to Monitor Open	Channel Failure Light	Channel Failed Soft, System Operable
29.	Command Amp Output to One Servo Amp Open	Current Lights For Amp	Channel Failed Soft, System Operable. Failure Detected on Ground Check
30.	Command Amp Output to Both Servo Amps Open	Current Lights For Channel	Channel Failed Soft, System Operable. Failure Detected on Ground Check
31.	Comparator Reset Input Open	No Failure During Reset Logic Test	System Operates Normally, Failure Detected on Ground Check
32.	Servo Amp Output Open	Current Lights For Amp	Channel Failed Soft, System Operable. Failure Detected on Ground Check
33.	Servo Amp Cross-strap Open	Current Lights For Channel	System Operates Normally, Failure Detected on Ground Check
34.	Monitor Amp Command Input Hardover	Channel Failure Light	Channel Failed Soft, System Operable
35.	Monitor Amp Feedback Input Hardover	Channel Failure Light	Channel Failed Soft, System Operable

TABLE 1 (Cont'd.)

FAILURE MODE TEST RESULTS

	COMPONENT FAILURE	FAILURE INDICATION	FAILURE EFFECT
36.	Command Amp Command Input Hardover	Channel Failure Light	Channel Failed Soft, System Operable
37.	Command Amp Feedback Input Hardover	Channel Failure Light	Channel Failed Soft, System Operable
38.	Command Amp Output to Comparator Hardover	Channel Failure Light	Channel Failed Soft, System Operable
39.	Comparator Output Hardover	No Failure During Logic Test	Channel Failed Soft, System Operable. Failure Detected on Ground Check
40.	Servo Amp Input Hardover	Current Lights For Channel	Channel Failed Soft, System Operable. Failure Detected on Ground Check
41.	Servo Amp Output Hardover	Current Lights For Channel	Channel Failed Soft, System Operable. Failure Detected on Ground Check
42.	Command Amp + Supply Voltage	Channel Failure Light	Channel Failed Soft, System Operable
43.	Command Amp - Supply Voltage	Channel Failure Light	Channel Failed Soft, System Operable
44.	Monitor Amp + Supply Voltage	Channel Failure Light	Channel Failed Soft, System Operable

TABLE 1 (Cont'd.)

FAILURE MODE TEST RESULTS

	COMPONENT FAILURE	FAILURE INDICATION	FAILURE EFFECT
45.	Monitor Amp - Supply Voltage	Channel Failure Light	Channel Failed Soft, System Operable
46.	Comparator + Supply Voltage	No Failure During Logic Test	Channel Failed Soft, System Operable. Failure Detected on Ground Check
47.	Comparator - Supply Voltage	Channel Failure Light	Channel Failed Soft, System Operable
48.	Servo Amp + Supply Voltage	Current Lights For Amp	Channel Failed Soft, System Operable. Failure Detected on Ground Check
49.	Servo Amp - Supply Voltage	Current Lights For Amp	Channel Failed Soft, System Operable. Failure Detected on Ground Check
50.	Hydraulic Supply	None	Channel Fails Soft, Failure Detected with Normal Aircraft Instrumentation For The Hydraulics

proximity to any line carrying a voltage. This is a constraint on using the system and was applied in the design of the evaluation system.

3.5.9 Cross-strap Operation

The use of the cross-strap for a common feedback signal for each servo amp prevents a single amplifier hardover failure from causing an actuator output change. Without the cross-strap, an amplifier going hardover would be offset by the resulting actuator motion causing the other servoamplifiers to offset the failed servo amp. With the cross-strap feedback, the other amplifier of a channel with a hardover servo amp offsets the hardover failure before the actuator moves in response to the hardover failure. The following test results (with a hardover input applied to one servo amp) illustrate the operational characteristics.

Mode	Servo Amp #1 Current In Amperes	Servo Amp #2 Current In Amperes
With Cross-strap	-.903	1.156
Without Cross-strap	.061	1.163

Note that without the cross-strap, the output of the amplifier goes hardover. With the cross-strap, the hardover is almost completely offset by the opposite current generated in the other servoamplifier.

4.0 RESULTS SUMMARY AND CONCLUSIONS

In terms of both component and system performance, the direct drive FBW mechanization meets or exceeds the design objectives.

In terms of nominal control system performance parameters, the system mechanization provides excellent frequency response. The moving coil force motor has a sufficiently high frequency response that the control system response of 5 Hz at no more than 90° phase shift is easily obtained. The force motor 90° phase shift when driving the control valve spool occurs above 50 Hz. The force motor amplitude is well damped and shows no peaking. These characteristics allow using a control system gain setting which would give actuator flat response out to 20 Hz with no peaking.

The system exhibits satisfactory threshold, hysteresis and linearity characteristics both in the normal and the fail operational mode. The degradation of threshold and hysteresis measurements from the normal to the fail operate mode corresponds to the reduction in force gain with the loss of one force motor. Maximum threshold measured was 1.66% of maximum command input while in the fail operational mode. Maximum hysteresis was .55% of maximum command input while in the fail operate mode. These numerical values are without any dither signal and are halved in the normal operating mode.

The full actuator rates were identical in the fail operate and normal operating modes. The extend rate degraded slightly from the normal to the fail operate mode, due to the flow forces on the control spool. The frequency response in the fail operate mode degraded from the normal mode by about 50% as expected. This characteristic is inherent in a force sharing system configuration like the direct drive FBW system and requires that the normal operating response be set high enough to allow degradation in the fail operate mode with one control channel failed.

The failure transients measured on the direct drive system were all below 1% of the maximum actuator motion. The largest transient experienced was with a slowover input failure into one channel which resulted in a .82% transient deviation of the maximum actuator motion. The transients are directly determined by the failure logic settings which for the direct drive system can be set quite low without encountering nuisance disconnects.

The failure mode testing revealed no single failures which would fail the entire system. All failures were indicated either immediately or upon ground checkout.

In terms of a direct drive force motor, the moving coil force motor generates 40 pounds of output force for 16 watts each driver. The force motor is not limited by magnetic saturation characteristics to the 40 pounds force and the force output can be increased with increased input current. The frequency response characteristics are consistent with FBW electrohydraulic response requirements for a direct drive force motor.

From the test results on the system, it is concluded that the mechanization is a viable candidate for a single fail operate FBW system. The system is simple in execution and has sufficiently low parts count to allow practical development of the components for maximum system reliability.

SECTION II

PARKER-HANNIFIN REDUNDANT ACTUATOR EVALUATION

1.0 INTRODUCTION

1.1 Test Approach - General

This section of the report describes the test of a Fly-By-Wire tandem actuator mechanization developed by Parker-Hannifin Aerospace Hydraulics Division, Irvine, California and submitted to the Air Force Flight Dynamics Laboratory at Wright-Patterson AFB for evaluation. The purpose of the test sequence used for the actuator evaluation was to obtain input-output performance data in order to document the characteristics of the mechanization in terms of control and redundancy parameters. No attempt was made as part of the investigation to estimate and establish reliability of the unit.

1.2 Description of Unit

The mechanization submitted by Parker-Hannifin consisted of two interdependent units, the actuator and the control console. According to the manufacturer, the actuator is representative of flight type hardware. The control console, on which the mechanization depended for many of its operating characteristics, was constructed as a laboratory demonstration item and was not representative of flight hardware.

The actuator evaluated was designed to operate with two independent hydraulic supplies, four electrical input signals and incorporated a mechanical input reversion capability. FIGURE 47 is a Parker-Hannifin schematic of the actuator. The actuator is constructed with a manifold using ripstop construction for the mounting of all valves and linkages. FIGURE 48 shows the actuator in hardware form.

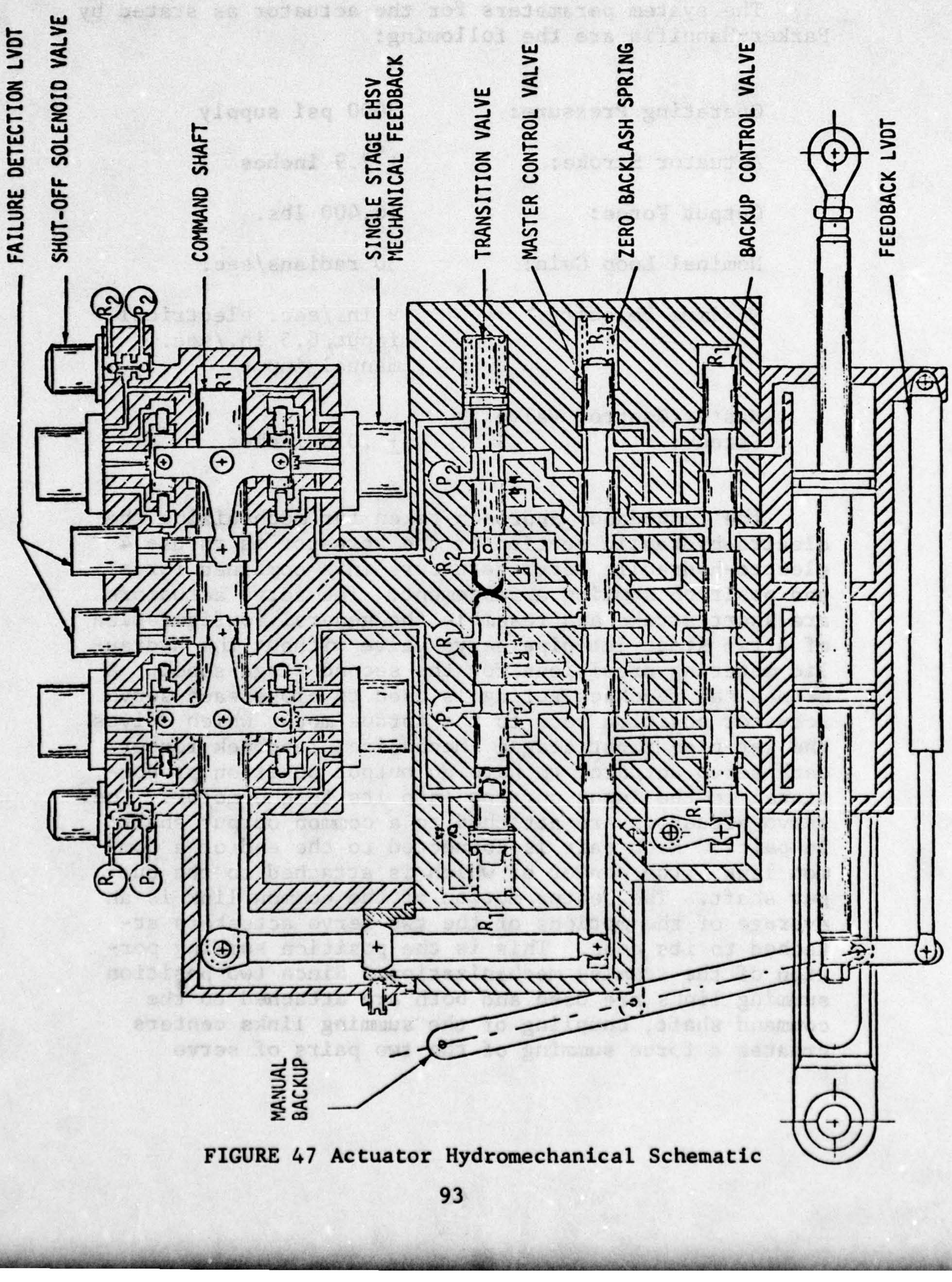


FIGURE 47 Actuator Hydromechanical Schematic

The system parameters for the actuator as stated by Parker-Hannifin are the following:

Operating Pressure:	3000 psi supply
Actuator Stroke:	± 2.9 inches
Output Force:	16,400 lbs.
Nominal Loop Gain:	30 radians/sec.
Maximum Velocity:	9 in./sec. electrical input, 6.5 in./sec. manual input
Master Control Valve Stroke:	± .070 inches

The redundancy approach taken for mechanizing the electro-hydraulic section of the actuator is to use 4 electro-hydraulic servo actuators in a combined force and position summing arrangement. The servo actuators are short stroke and resemble the general configuration of a two stage jet-pipe servo valve without the hydraulic metering provisions for the second stage spool. A mechanical feedback spring is used to close each servo actuator position back to the torque motor which drives the jet-pipe first stage. Mechanical feedback forces each servo actuator to have an output position proportional to the input current into its torque motor. The servo actuators are attached to a common output shaft in pairs. Each pair is connected to the end of a common link, the center of which is attached to the output shaft. The center motion of the common link is an average of the motions of the two servo actuators attached to its ends. This is the position summing portion of the summing mechanization. Since two position summing links are used and both are attached to the command shaft, coupling of the summing links centers creates a force summing of the two pairs of servo

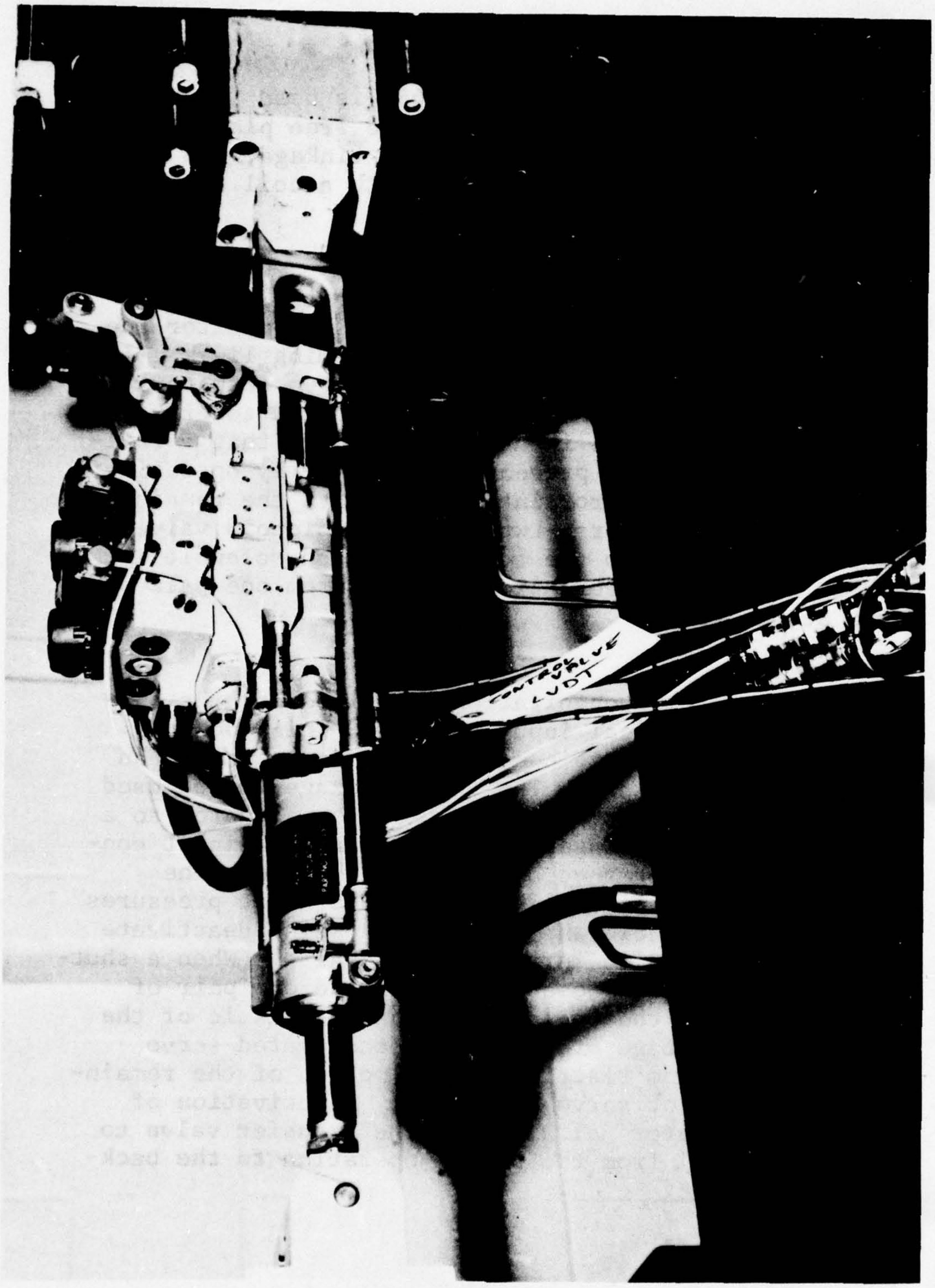


FIGURE 48 Parker-Hannifin Fly By Wire Actuator

actuators. The command shaft output is used to drive a tandem control valve. To eliminate free play in the summing and control valve connection linkage, the end of the control valve is preloaded with a coil spring operating in compression.

For servo valve failure detection, the mechanization uses two LVDT position transducers to monitor the differential motion of the position summing links. If the position outputs of each pair of servo actuators fails to track each other within a selected tolerance, the LVDT output change is used to indicate that a failure has occurred. To prevent an incorrectly operating servo actuator pair from interfering with the remaining pair of servo actuators, two shut-off solenoid valves are incorporated into the actuator. Each solenoid is used to disconnect hydraulic pressure from one pair of servo actuators.

The actuator mechanization also incorporates provisions for mechanical input control. This mode of control uses a separate control valve connected to an external input linkage. The input linkage can be used for manual input control or to power the actuator to a selected position. Engagement of the manual input control valve is determined by a transfer valve. The transfer valve is controlled by the hydraulic pressures from the two solenoid shut-off valves which deactivate the electro-hydraulic servo actuator pairs. When a shut-off solenoid valve is used to deactivate one pair of servo actuators, the open center characteristic of the jet-pipe first stage prevents the deactivated servo actuator pair from restricting the motion of the remaining active pair of servo actuators. Deactivation of both servo actuator pairs causes the transfer valve to transfer control from the normal operation to the back-up control valve.

The torque motor coils of each servo valve are made up of 4 separate sections. Each coil section of the torque motors is connected in series with a corresponding section of the other three torque motors. Four separate amplifiers are used to drive the servo actuators. A servo amplifier is connected to each of the four series connected coil sections. The net torque motor output and the servo actuator position for each servo actuator is therefore proportional to the sum of the coil currents from all four servo amplifiers. Since the output current of each servo amplifier is connected to all four servo actuator torque motors, current differences between servo amplifiers cannot cause output position differences between the individual servo actuators.

The control console, as shown in FIGURE 49 was provided by Parker-Hannifin for use with the actuator. This console contains the failure detection logic, gain changing, servo amplifiers, and status display indicators for operating the actuator. To provide for failure detection of both servo actuator failures and servo amplifier output disagreements, the control console uses two failure logic sections.

One section is used to monitor the failure detection LVDT outputs. The other section is used to monitor the servo amplifier output currents. Since the servo actuator torque motor coils share the current outputs of all four servo amplifiers, the servo actuator LVDT failure logic cannot detect any failure other than the failure of servo actuator hydro-mechanical components. Therefore, the second section of the failure logic is required to monitor the servo amplifier currents. Since servo amplifier currents reflect the difference between electrical command and electrical feedback voltages, failures of both input and feedback voltages are detected along with failures of the servo amplifiers.

The logic used in the control console for hydromechanical failures monitored the output of each failure LVDT. Above a set output amplitude, the logic activates the shutoff solenoid for the corresponding servo actuator pair. To demonstrate operation of the failure logic, the control console incorporates bias potentiometers and failure switches in order to simulate a position disparity of the servo actuators.

The control console logic used for detecting the servo amplifier failures is designed to represent the general characteristics of a current comparison and majority vote failure detection technique. The servo amplifiers used to drive the servo actuators are a current amplifier design. The voter design is based on comparing the current of channels 1, 2 and 3 servo amplifier against channel 4's servo amplifier current. This voting is not a majority voting technique (since 3 channels are compared only to one reference channel). However, for selected failures, the failure detection characteristics are the same as if an actual majority voter were used. Disagreement of channel's 1, 2 and 3 servo amplifier current with channel 4's current caused a comparator to disconnect the output of the disagreeing servo amplifier. To reduce the occurrence of nuisance disconnects caused by transients, the input to each comparator is filtered with a low pass RC filter.

The logic also incorporates a gain network which increased the gain of the remaining servo amplifiers when any servo amplifier is disconnected. Without the gain changer, the actuator frequency response would degrade with each servo amplifier disconnected. This degradation is inherent with the mechanization, since control valve position is proportional to the sum of the servo amplifier current. A reduction of control valve position for a given input error voltage appears as a flow gain reduction of the control valve (and hence a frequency response reduction for the actuator).

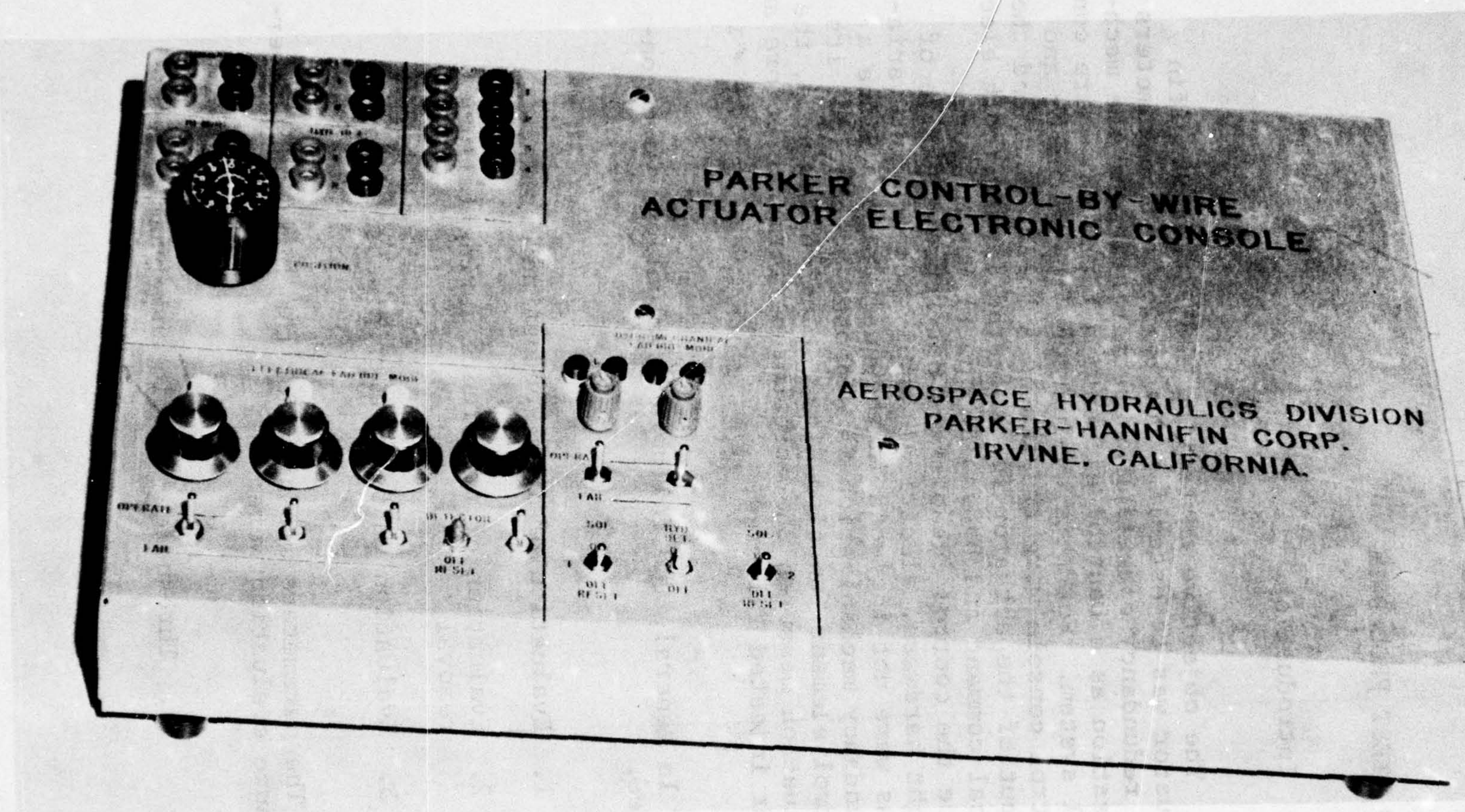


FIGURE 49 Parker-Hannifin Control Console

2.0 TEST PROCEDURE

2.1 Introduction

The objective in testing the Parker-Hannifin actuator was to establish the performance parameters and redundancy operating characteristics of the mechanization as a control element in the Fly-By-Wire control system. For this evaluation, the actuator and control console were treated as a "black box" and the output of the actuator for selected inputs (both electrical command and hydraulic power) was measured. Since the control console was not representative of flight hardware, electrical supply power input variations were not included in the evaluation. Since a redundancy mechanization is supposed to continue its control element function after selected failures, the evaluation measured the actuator performance before and after injected failures.

In general, the following evaluations were conducted.

1. Evaluation of input-output performance
2. Evaluation of transients during failure removal
3. Evaluation of failure trip sensitivity

The parameters measured for the input-output performance evaluation were:

a. Threshold - static and dynamic

b. Frequency response and distortion - small and large signal

c. Linearity and Hysteresis

d. Time response - large and small step input

These performance parameters were measured under the conditions of no failures, after selected failures, and with input deviations near the failure trip level for the particular input. The failure transient evaluation documented the actuator output change during the failure correction action due to hydraulic or electical failures. The failure trip sensitivity testing documented the variation of electrical or hydraulic inputs which caused the actuator to indicate a failure. In order to apply separate electrical command inputs to the four electrical channels of the actuator control console, it was necessary to modify the electrical input circuitry of the console slightly. This was done with Parker-Hannifin's approval.

For all testing performed on the actuator and console, the actuator was mounted in the General Purpose Actuator Test Rig (GPATR) in Bldg. 145 at Wright-Patterson AFB, Ohio. FIGURE 50 shows the actuator and console as mounted during testing. The patch box to the left of the control console box in FIGURE 50 is an interface box used to connect the laboratory instrumentation to the control console. For hydraulic power, the actuator was connected to a 30 GPM supply through pressure reducing valves with allowed variation of the hydraulic supply pressure. FIGURE 51 shows the actuator mounted in the GPATR frame and the hydraulic connections to the actuator.

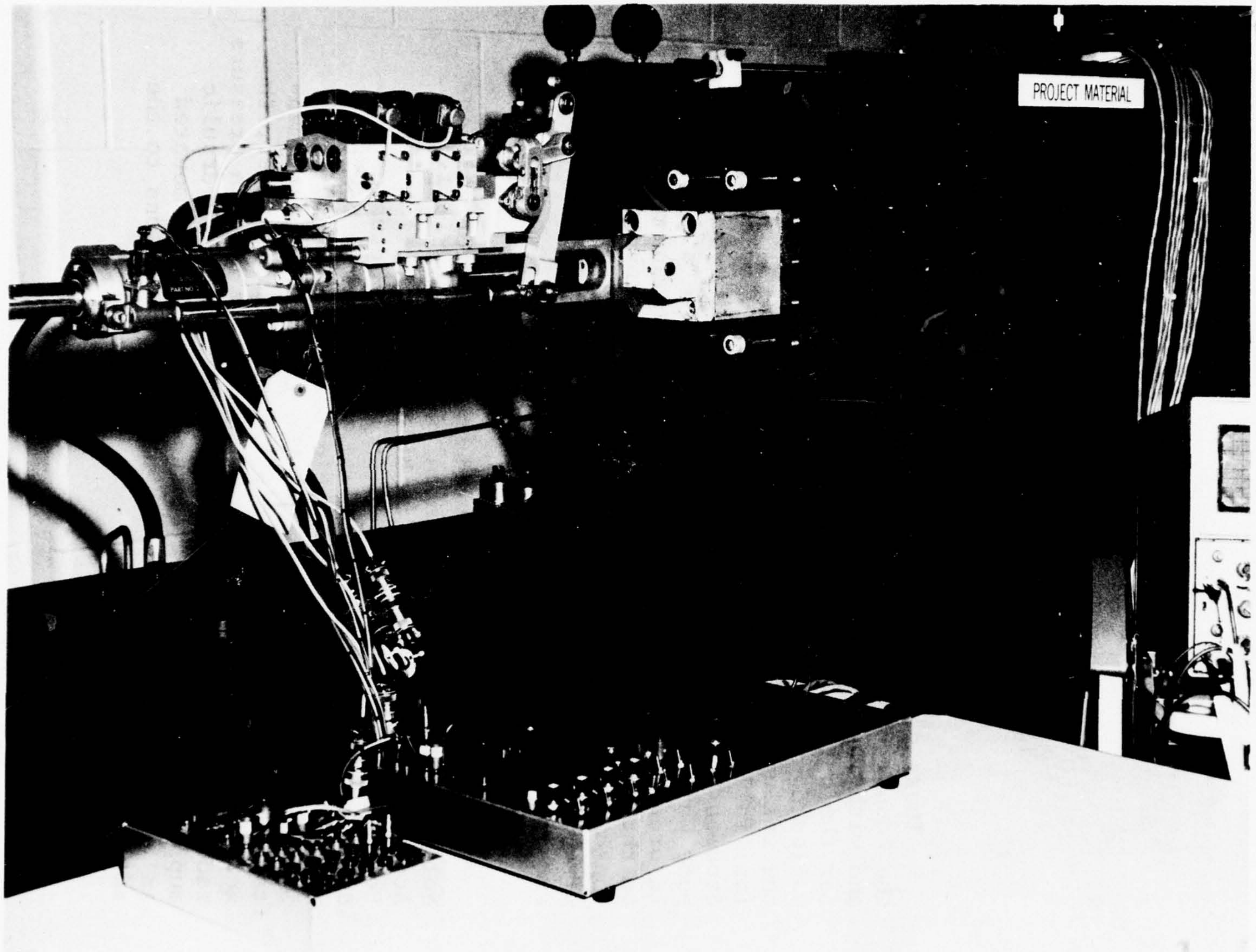


FIGURE 50 Test Actuator and Control Console During Testing

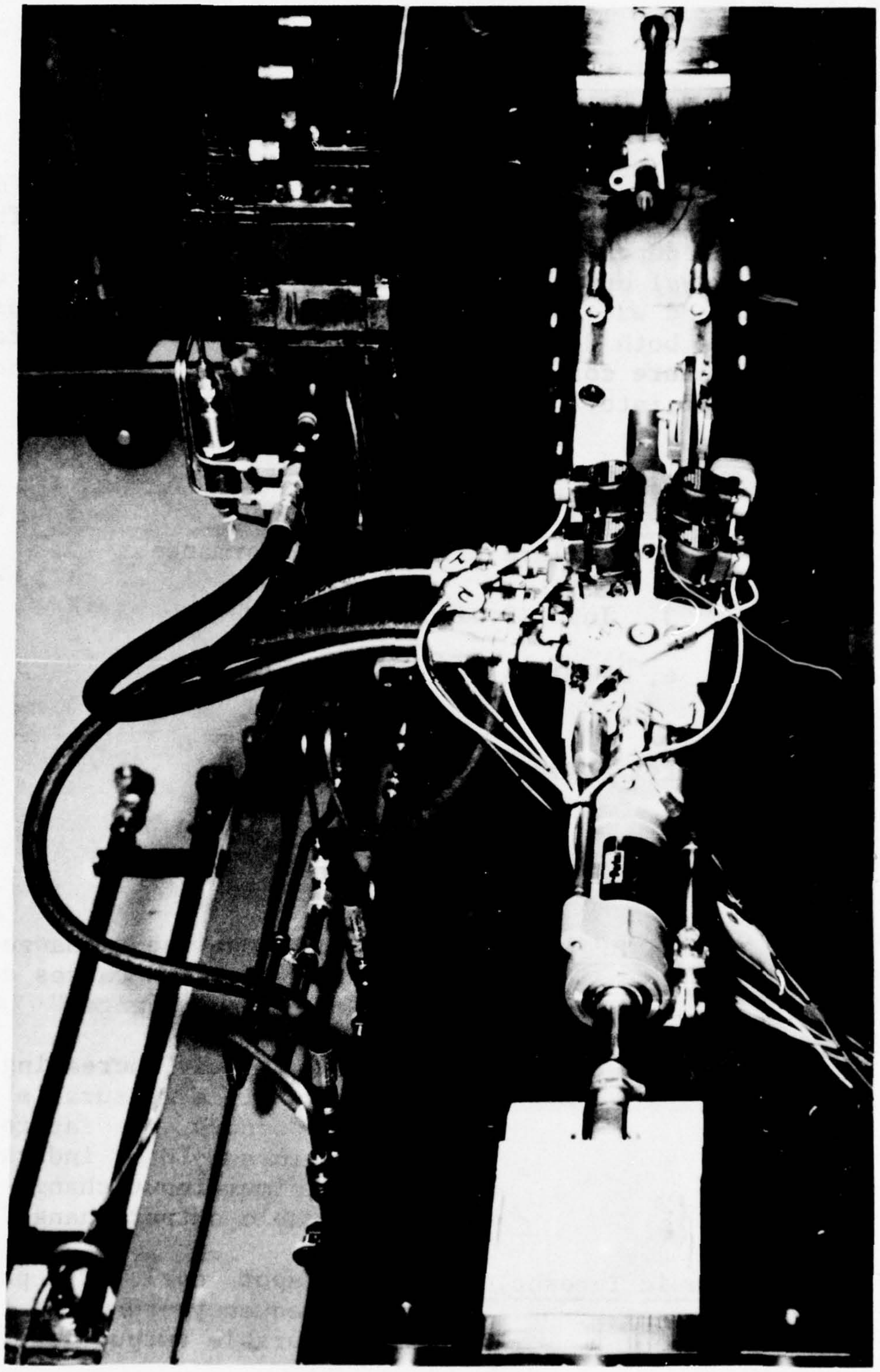


FIGURE 51 Test Actuator Mounting and Hydraulic Connections

2.2 General Test Procedure

The following general test procedure was used for the measurements on the Parker-Hannifin actuator. This test procedure was established by Dynamic Controls, Inc. as a general procedure for any Fly-By-Wire actuator evaluation, and was reviewed by Parker-Hannifin. The test procedure both defines the measured parameter and states the procedure for making the measurement. The procedure is divided into the following sections:

1. Performance Measurements
2. Failure Effect On Performance
3. Input Deviations Effect
4. Failure Removal Transients

2.2.1 Performance Measurements

2.2.1.1 Threshold

Static Threshold - "The minimum input change from zero level which causes a measurable output change."

Procedure - Apply a slowly increasing + input until a measurable output change occurs. Repeat for - input. Threshold is indicated by the minimum input change for a measurable output change.

Dynamic Threshold - "The input level (at a particular frequency) required to cause a measurable output level."

Procedure A sinusoidal input at a selected frequency of 50% of the bandpass of the actuator is applied to the actuator. The amplitude of input to create a measurable output indicates the dynamic threshold. The bandpass of actuator is defined as the frequency at which - 3db amplitude or 90° phase shift occurs (whichever is lower in frequency).

2.2.1.2 Frequency Response

"With a sinusoidal actuator input, the frequency response of the actuator is the curves of the amplitude ratio and phase shift as a function of frequency."

Procedure A sinusoidal input of an amplitude which is

a. large enough to minimize the nonlinearity distortions of threshold and hysteresis

b. small enough to avoid velocity saturation in the frequency range of interest

is applied to the actuator input. The ratio of output amplitude to input amplitude and output phase relative to input is recorded.

The curves of the amplitude ratio and phase indicate the frequency response.

2.2.1.3 Distortion

"The amount of deviation of the actuator output from the input waveform."

Procedure

The harmonic distortion, at the input level used to measure the frequency response, is recorded at sinusoidal input frequencies of 10%, 50% and 100% of the bandwidth.

2.2.1.4 Linearity

"The deviation of output vs. input from a straight line relationship."

Procedure

Apply an input from - max to + max input while recording the corresponding output position. Linearity is indicated by max deviation of the plotted output vs. input from a straight line drawn between zero and a point which minimizes the maximum deviation of the plotted curve from the straight line. Repeat for + input to - input.

2.2.1.5 Hysteresis

"The non-coincidence of loading and unloading curves."

Procedure Apply a slowly varying input to the actuator at 10% and 1% of max input in the following sequence while recording the actuator output position:

0 to + direction input

+ input to - direction input

- input to + input

From the plot of output vs. input, the hysteresis is indicated by the difference between + direction actuator output position and - direction output position for the same input level.

2.2.1.6 Time Response

Saturation Velocity "The maximum velocity at which the actuator is capable of movin each direction."

Procedure With the actuator at zero position, a maximum amplitude input is applied to the actuator while the actuator motion vs. time is recorded. The test is conducted for both directions of actuator

	motion. The slope of the position vs. time record indicates the saturation velocity.
<u>Transient Response</u>	"The time response of the actuator output to an applied step input."
Procedure	Apply a step input to the actuator and record the corresponding actuator motion. The amplitude of the step should be a. large enough to minimize the nonlinearity distortion of threshold and hysteresis b. small enough to avoid velocity saturation. The plot of actuator output motion vs. time indicates the transient response.

2.2.2 <u>Failure Effect On Performance</u>

2.2.2.1 <u>Failure Effect</u>

	"The change on the performance of a redundant actuator due to input failures or internal failures of actuator components."
Procedure	Inject hydraulic or electrical input failures into the actuator

under test to cause it to operate in its "failure operational" modes. For each mode, measure the performance by repeating the Performance Measurement Tests. The input levels should be maintained at those used for the "no failure" performance tests unless the performance changes dictate different levels in order to obtain reasonable test data.

2.2.3 Input Deviations Effect

2.2.3.1 Electrical Deviations

"The change of electronic inputs, both power and control, with respect to the normal values and/or each other."

Procedure

Adjust the electrical inputs one at a time until either the maximum expected deviation of the input is reached or the failure trip level is reached. Section 2.2.1 will be measured with each electrical input deviation adjusted one at a time to the maximum deviation expected or a value of 90% of that which will cause a failure trip.

2.2.3.2 Hydraulic Deviations

"The change of hydraulic pressure inputs with respect to the normal values."

Procedure

Adjust the hydraulic inputs one at a time until the maximum expected deviation or a failure trip level is reached. The performance parameters of Section 2.2.1 will be measured with each hydraulic input adjusted one at a time to the maximum deviation expected or a deviation value of 90% of that which will cause a failure trip.

2.2.4 Failure Removal Transients

2.2.4.1 Electrical Failure Transients

"The change in actuator output during failure corrective action due to electronic input failures causing transfer from one operational mode to another."

Procedure

Apply a slowly changing input into one control channel of the actuator. Record the actuator output change during the corrective action of actuator. Repeat the test for each contron channel input and failure mode condition. Repeat for a hardover step input.

Apply a sinusoidal input to all channels. Open each input while recording actuator output.

2.2.4.2 Hydraulic Failure Transients

"The change in actuator output during failure removal corrective action due to hydraulic input failures causing transfer from one operational mode to another."

Procedure

Apply a slowly decreasing hydraulic input into one control channel of the actuator output change during the corrective action of the actuator. Repeat the test for all hydraulic inputs.

Repeat the preceding test with a rapid decrease of hydraulic input pressure.

2.2.5 Test Configuration

FIGURE 52 is a block diagram schematic of the instrumentation, command and power connections used during the evaluation of the Parker-Hannifin actuator. As shown on the schematic, a Bafco servo analyzer was used with an Esterline Angus XYY' plotter for frequency response measurements. The Hewlett Packard Model 333A distortion analyzer was used for the input and output signal distortion measurements. The Wavetec Model 144

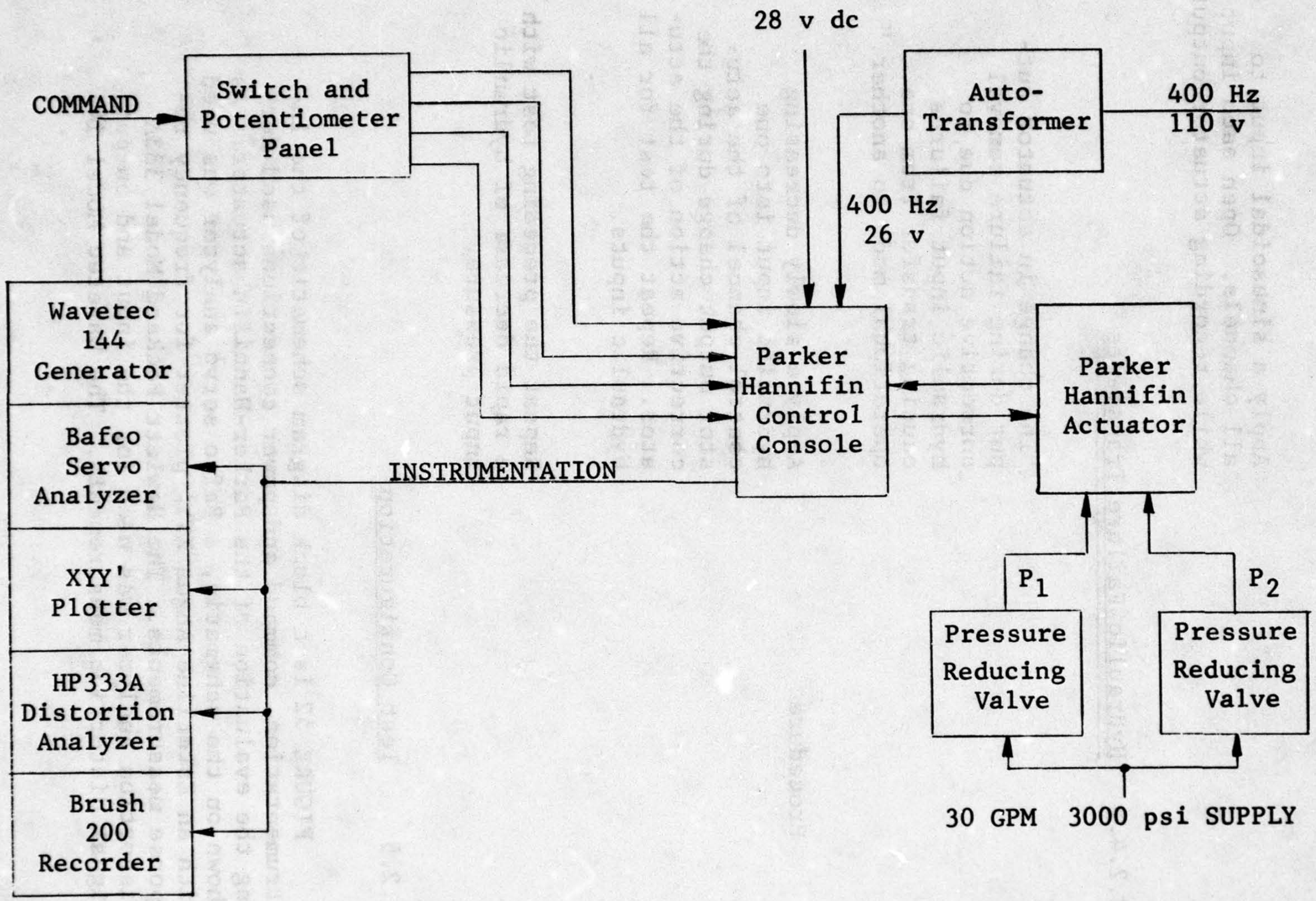


FIGURE 52 Schematic of the Instrumentation, Command and Power Connections During Evaluation

sweep generator and the XYY' plotter were used for the hysteresis and linearity measurements. Failure removal transients were recorded on the Brush 200 recorder. The 400 Hz exitation power required for the control console was connected to laboratory 400 Hz power. As shown on the schematic, the 4 separate input commands were run through a general purpose switch and potentiometer panel. This panel allowed individual variation of the 4 inputs separately and injection of hardover input commands. Hydraulic power was obtained from the 30 GPM, 3000 psi laboratory pumping system. Supply pressure for each actuator half was connected through a pressure reducing valve.

2.3 Specific Test Procedure

TABLE 2 lists the 31 different test conditions and values used for evaluating the Parker-Hannifin actuator. Test conditions 1-19 and 13-24 refer to the actuator testing on the total actuator package. Tests 10-12 and 25-31 refer to the tests of the control valve (secondary ram) motion with the control of the main ram locked out. The purpose of testing the secondary ram without the main ram operating was to allow establishing the basic characteristics of the secondary ram mechanization without masking by the particular actuator main ram it is used to drive.

Test conditions 1 through 12 are the various operational modes of the actuator and secondary ram. For each of these operational modes, the performance measurement methods described in Sections 2.2.1 were used to document the performance characteristics. Note that the test conditions 1 and 10 are the baseline test conditions for the overall actuator and control valve, respectively. These two test conditions were with all inputs (power and control) at their nominal values and with no failure injected into the mechanization. The

TABLE 2

TEST CONDITIONS

Test Condition Number	Test Condition Description
1	Main Ram Baseline (all channels nulled, pressurized and operating correctly)
2	Main Ram Electrical Channel Deviation - +4 ma. bias for channel 1 servo valve current (50% of maximum valve coil current = 4 ma.)
3	Main Ram Electrical Channel Deviation - +4 ma. Deviation to channels 1 and 3 servo valves
4	Main Ram Electrical Channel Deviation - -2 ma. bias to channel 1 and +2 ma. bias to channel 3 servo valves
5	Main Ram Hydraulic deviation - P_1 @ 1500 psi with P_2 @ 3000 psi
6	Main Ram Electrical Failure - channel 1 failed (using control box fail switch)
7	Main Ram Electrical Failure - channel 1 and 2 failed (using control box fail switches)

TABLE 2

TEST CONDITIONS (Cont'd)

Test Condition Number	Test Condition Description
8	Main Ram Hydraulic Failure - P_1 @ 0 psi and P_2 @ 3000 psi
9	Main Ram Hydromechanical Failure - Mode 2 failed via control box failure switch
10	Secondary Ram Baseline (all channels nulled, pressurized and operating correctly)
11	Secondary Ram Electrical Failure - channel 1 and 2 failed (using pulled relay)
12	Secondary Ram Hydraulic Failure - P_2 @ 0 psi with P_1 @ 3000 psi
13	Main Ram Failure Transient - Electrical Input Loss - 1.0 Hz sine wave input initially driving all channels to 3% output amplitude, channel 1 and then 2 input grounded
14	Main Ram Failure Transient - Electrical Input Loss - 1.0 Hz sine wave input initially driving channels 3 and 4 to 3% output amplitude. Channel 1 and 2 inputs grounded. Channels 3 and then 4 inputs grounded

TABLE 2

TEST CONDITIONS (Cont'd.)

Test Conditions Number	Test Condition Description
15	Main Ram Failure Transient - Electrical Input Loss - 1.0 Hz sine wave input initially driving all channels to 3% output amplitude. Channel 1 and 2 grounded simultaneously
16	Main Ram Failure Transient - Electrical Hardover Input - All channels initially grounded, Channel 1 driven hardover with a +10.0 volt input
17	Main Ram Failure Transient - Electrical Hardover Input - with a +10.0 volt hardover input in channel 1, channels 3 and 4 grounded, channel 2 is driven hardover with a +10.0 volt input
18	Main Ram Failure Transient - Electrical Hardover Input - with a +10.0 volt input in channels 1 and 2 and channel 4 input grounded, channel 3 is driven hardover with a +10.0 volt input
19	Main Ram Failure Transient - Electrical Hardover Input - with all channels grounded initially, channels 1 and 2 driven hardover simultaneously with a +10.0 volt input

TABLE 2

TEST CONDITIONS (Cont'd.)

Test Condition Number	Test Condition Description
20	Main Ram Failure Transient - Extend Motion - Slowover input into channel 1 input, channel 2, 3 and 4 inputs grounded
21	Main Ram Failure Transient - Retract Motion - Slowover input into channel 1 input, channel 2, 3 and 4 inputs grounded
22	Main Ram Failure Transient - Hydraulic Failure - with all channels grounded input, hydraulic pressure P_1 shut off.
23	Main Ram Failure Transient - Hydraulic Failure - with a 5 Hz electrical input driving all channels at a 3% output amplitude, P_1 was failed
24	Main Ram Failure Transient - Hydraulic Failure - with a 5 Hz input driving all channels at 3% output amplitude and P_2 at 0 psi, P_1 was failed
25	Secondary Ram Failure Transient - with a 0.5 Hz sine wave driving all channels at 50% output, initially channel 1 was grounded then with channel 1 failed, channel 2 was grounded

TABLE 2

TEST CONDITIONS (Cont'd.)

Test Condition Number	Test Condition Description
26	Secondary Ram Failure Transient - with a 0.5 Hz sine wave driving channel 3 and 4 initially and channel 1 and 2 failed. The input to channel 3 was grounded
27	Secondary Ram Failure Transient - with a 0.5 Hz sine wave driving all channels initially the inputs to channel 1 and 2 were grounded simultaneously
28	Secondary Ram Failure Transient - Electrical Hardover Input - all channels initially grounded, channel 1 driven hardover with a -10.0 volt input
29	Secondary Ram Failure Transient - Electrical Hardover Input - with channel 1 failed and a -10.0 volt input in channel 1, channels 3 and 4 grounded, channel 2 is driven hardover with a -10.0 volt input
30	Secondary Ram Failure Transient - Electrical Hardover Input - with channels 1 and 2 failed and a -10.0 volt input in channels 1 and 2, channel 4 grounded, channel 3 is driven hardover with a -10.0 volt input

TABLE 2

TEST CONDITIONS (Cont'd.)

Test Condition Number	Test Condition Description
31	Secondary Ram Failure Transient - Electrical Hardover Input - with all channels grounded initially, channels 1 and 2 driven hardover simultaneously with a -10.0 volt input

other test conditions correspond to the "Failure Effect On Performance" measurements described in Section 2.2.2 and "Input Deviations Effect" measurements described in Section 2.2.3.

Test conditions 13 through 31 are all failure transient measurement test conditions and correspond to the "Failure Removal Transients" measurements described in Section 2.2.4. The test conditions 13 through 31 state both the initial conditions and the test used for creating the transient condition.

As originally received, the failure detection logic in the electronic console was not operating properly. For the input deviation effect tests, therefore, the electrical inputs were offset by an amount which generated a 50% mismatch of maximum servo valve coil current. This is a representative value for electro-hydraulic redundancy mechanizations which used the loop error signal for failure monitoring. Subsequent tests of the failure logic detection characteristics were run after the console logic had been corrected by Parker-Hannifin and it was determined that the control logic detection level closely approximated the 50% mismatch level used for the deviation tests. The failure logic detection characteristic tests are not listed in the test condition table. These tests were performed by applying a test input voltage into each channel's input until the failure logic tripped and indicated a failure. This input voltage was applied at selected frequencies from 0 to 8 Hz in order to establish the dependency of the detection level on signal frequency.

3.0 TEST RESULTS

3.1 General

In order to reduce the volume of test data presented in this section, the majority of the performance measurement data has been reduced to tabulated form. Since time response characteristics are not well defined by listing only one or two characteristic values, the step response measurements and the failure transient measurements are presented as recorded. The following results are presented in tabulated form for conditions 1 through 12:

1. Static Threshold
2. Dynamic Threshold
3. Frequency Response
4. Distortion
5. Hysteresis
6. Saturation Velocity

For the test results reduced to table form, a sample of the actual recorded data is included as recorded for conditions 1 and 10. Also included in recorded form are the linearity measurements for conditions 1 through 12.

In presenting the measurements of threshold and hysteresis, the results are given both in percent of the input for full actuator stroke and the input for full valve stroke. In terms of the percent of full actuator stroke, the percentage value for a given amount of hysteresis reduces as the maximum stroke of the actuator increases. Presenting the percentage in terms of the input for maximum control valve stroke shows the threshold and hysteresis characteristics better in terms comparing different control valve driving mechanizations independent of the power actuator sizing.

In performing tests with test condition 9 (where one pair of servo actuators are depressurized using the failure switch provided on the control console), it was impossible to apply large inputs to the actuator without the remaining servo actuator pair shutting down. Since it was possible to run and test the actuator with only one hydraulic system operating (which duplicated the depressurization of one servo actuator pair), the problem was apparently associated with the hydro-mechanical failure logic in the control console and was not investigated any further. Because of this logic problem, test data for condition 9 was not obtained for all performance measurements.

3.2 Specific

The specific test results are presented in this section in the following order:

1. Performance measurements for conditions 1 through 12
2. Failure transients for conditions 13 through 31
3. Failure logic detection characteristics

3.2.1 Static Threshold

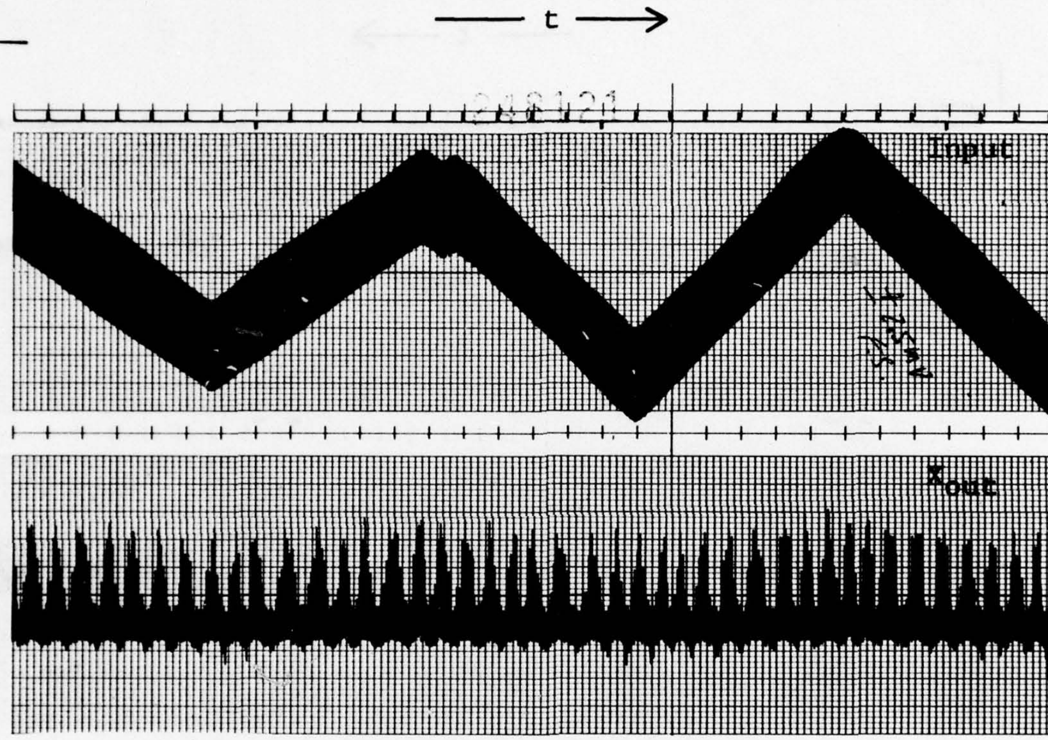
FIGURE 53 shows the data recorded in establishing the static threshold for condition 1. FIGURE 54 shows the data recorded in establishing the threshold for condition 10. Note that the .1 Hz ramp input is slowly increasing with increasing time. The threshold value is determined by the first input amplitude where the actuator or secondary ram output starts to respond to the control input. Note that the high frequency noise content of the output signals is

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Static Threshold - Condition 1



0.1 Hz Ramp Input

Scale: Input $= .0001$ v/div
X_{out} $= .00008$ in/div
t $= 5$ div/sec

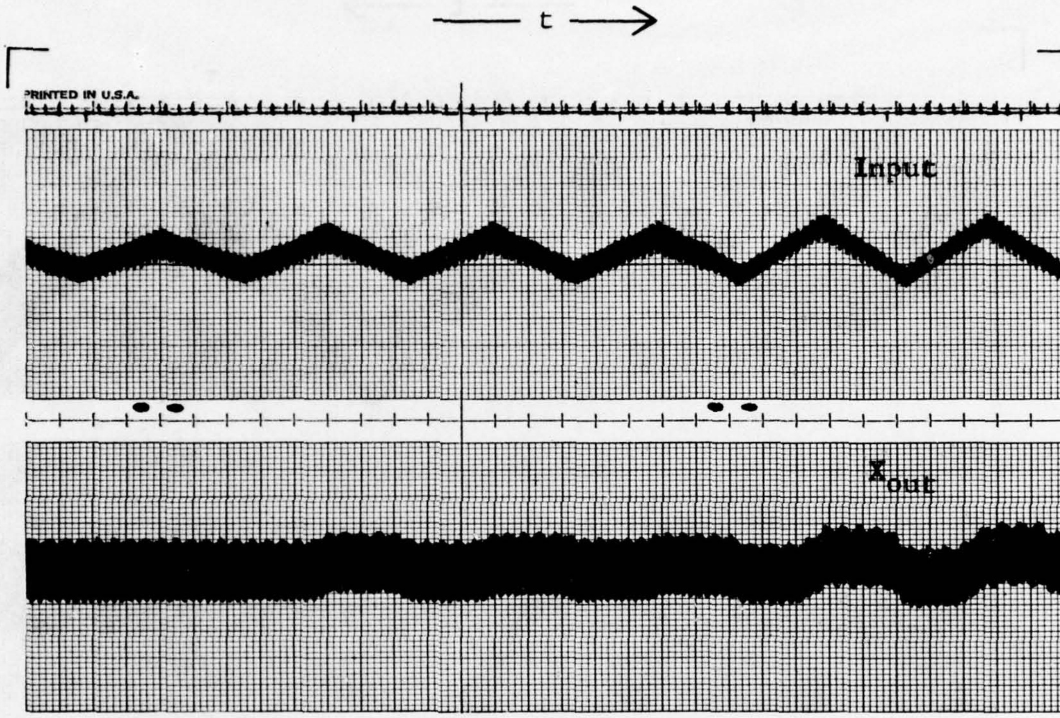
FIGURE 53 Static Threshold - Condition 1

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire
Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Static Threshold - Condition 10



0.1 Hz Ramp Input

Scale: Input = .0005 v/div
X_{out} = .000034 in/div
t = 50 div/sec

FIGURE 54 Static Threshold - Condition 10 due to the characteristics of the output position LVDT and the demodulation circuit used in the control console. This noise is primarily made up of a 400 Hz frequency component, obtained from the demodulation of the 400 Hz LVDT excitation signal. The upper edge of the noise shows the actuator or secondary ram responding to the .1 Hz input ramp. TABLE 3 shows the static threshold measured for test conditions 1 through 12.

As shown in TABLE 3, the static threshold value does vary for the different test conditions. In terms of the maximum input command of 8.18 volts peak, the worst threshold is .17 percent. In comparing conditions 2, 3 and 4 with the baseline condition 1, it is apparent that bias off-sets of the servo amplifiers increase the threshold by approximately a factor of two for these conditions. For condition 5, with P_1 reduced to 1500 psi, the threshold reduced slightly from the baseline value (perhaps indicating a decreasing driving force to friction ratio with increasing pressure for the servo actuator pair pressurized by system 1).

The test conditions 6 and 7 (with channel 1 and 1 + 2 failed respectively), show an increase in threshold over the baseline value. This was not expected, since the gain changing of the control console was expected to keep the driving force to error signal constant by increasing the servo amplifier gains of the remaining servo amplifiers after failure detection. However, the threshold did not increase as much as for condition 8 where P_1 was adjusted to 0 psi (indicating that the gain change was somewhat effective). Since there was no automatic gain changing for condition 8, the servo actuator driving force for a given error voltage was reduced to half of the baseline value. Condition 8 gave the largest threshold value of 2.5% of maximum spool stroke input voltage or .17% of maximum input voltage.

TABLE 3

Static Threshold

DYNAMIC CONTROLS, INC.
Test Data

Date Prepared: 12/6/76

TEST ITEM - Parker-Hannifin Fly-By-Wire
Four Channel Tandem Actuator

TEST - STATIC THRESHOLD

Test Condition	Static Threshold Input Volts	% of max Input	% of X_v max
1	0.0036	0.022	.33
2	0.0074	0.046	.67
3	0.0050	0.031	.46
4	0.0070	0.043	.64
5	0.0022	0.014	.20
6	0.0145	0.090	1.32
7	0.0080	0.049	.73
8	0.0275	0.170	2.50
9	-----	-----	---
10	0.0035	-----	.32
11	0.0095	-----	.86
12	0.0050	-----	.46

For the secondary ram threshold measurements of conditions 10, 11 and 12, only presenting the measurements in terms of maximum spool stroke input voltage is applicable. The base line measurement of condition 10 agrees with the baseline measurements of condition 1 in terms of the threshold. This implies that the static threshold characteristics of the main ram when driven by the secondary ram (control valve) were negligible. With channel 1 and 2 failed (for condition 11), the threshold increased, due to the reduction in servo actuator gain. (Note that condition 11 failed electrical channels 1 and 2 so that the automatic gain changing was prevented.) For P_2 failed (condition 12), the threshold increased over the baseline, although not as much as with condition 11.

With the exception of conditions 6 and 8, all the threshold values remained under 1% in terms of the maximum spool stroke input. Typical electro-hydraulic servo valves exhibit threshold of .5% of maximum rate current (equivalent to the percent rating in terms of the maximum spool stroke input voltage). From the measured static threshold values on the Parker-Hannifin mechanization in terms of spool stroke, the Parker-Hannifin control valve mechanization is quite comparable to a good electro-hydraulic valve.

3.2.2 Dynamic Threshold

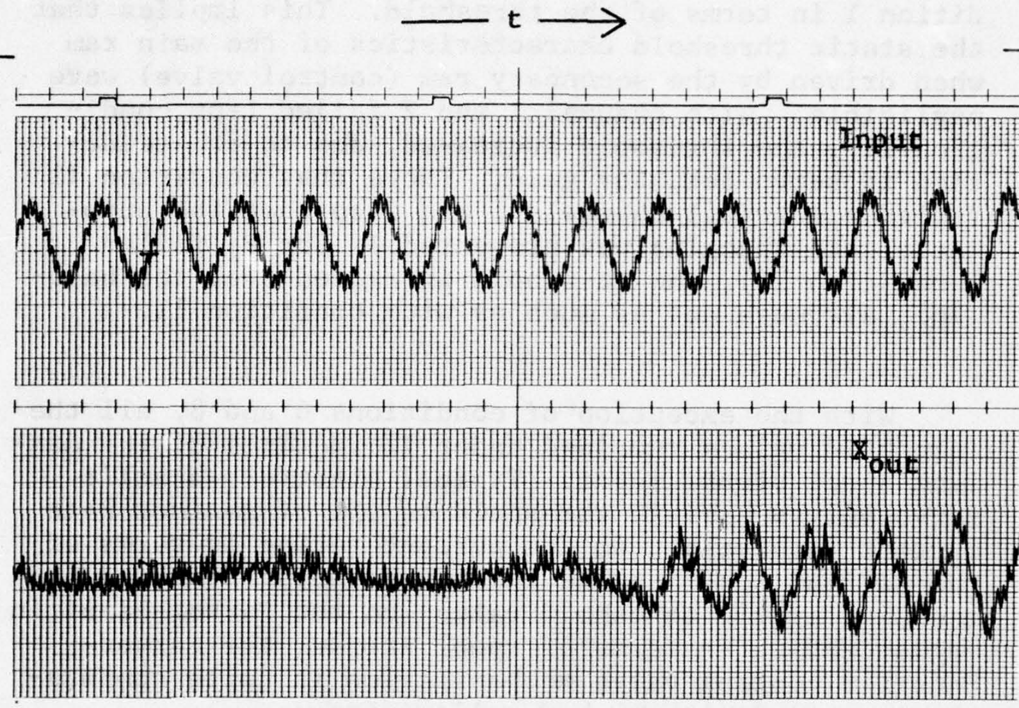
FIGURE 55 shows the data recorded in establishing the dynamic threshold for condition 1. A 5 Hz sine wave input was used to drive the actuator. This frequency was .5 of the bandpass frequency of the actuator. Note on FIGURE 55 that with increasing time, the input amplitude of the driving frequency was gradually increased. On the lower trace, the start of the actuator response to the input signal is quite apparent. Note the low frequency, low amplitude, hunting of the actuator output when not responding to the input signal. This characteristic was observed throughout the testing.

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Dynamic Threshold - Condition 1



5.0 Hz Sine Wave Input

Scale: Input = .0005 v/div
X_{out} = .0004 in/div
t = 50 div/sec

FIGURE 55 Dynamic Threshold - Condition 1

According to Parker-Hannifin personnel, the hunting is due to the coupling linkage compliance between the output of the servo actuator pairs and the normal control spool and can be eliminated by increasing the stiffness of the linkage. In any case, the hunting was of the order of .003 inches peak to peak and not a large amplitude compared to the total actuator stroke. FIGURE 56 shows the data recorded in establishing the dynamic threshold for condition 10.

TABLE 4 shows the dynamic threshold measurements for conditions 1 through 12. In comparison to the static threshold, the dynamic threshold measured somewhat greater, a result which would normally not be anticipated. For the baseline (condition 1), the threshold increased by a factor of two when compared to the static threshold. One possible reason for the threshold increase is that the flow from the jet pipes required to drive the servo actuator pairs' oil volume compliance at the 5 Hz input signal degraded the dynamic pressure gain of the jet pipe slightly. Since the baseline threshold of the overall actuator (condition 1) and the secondary ram (condition 10) were identical, the threshold appeared entirely determined by the secondary ram mechanization.

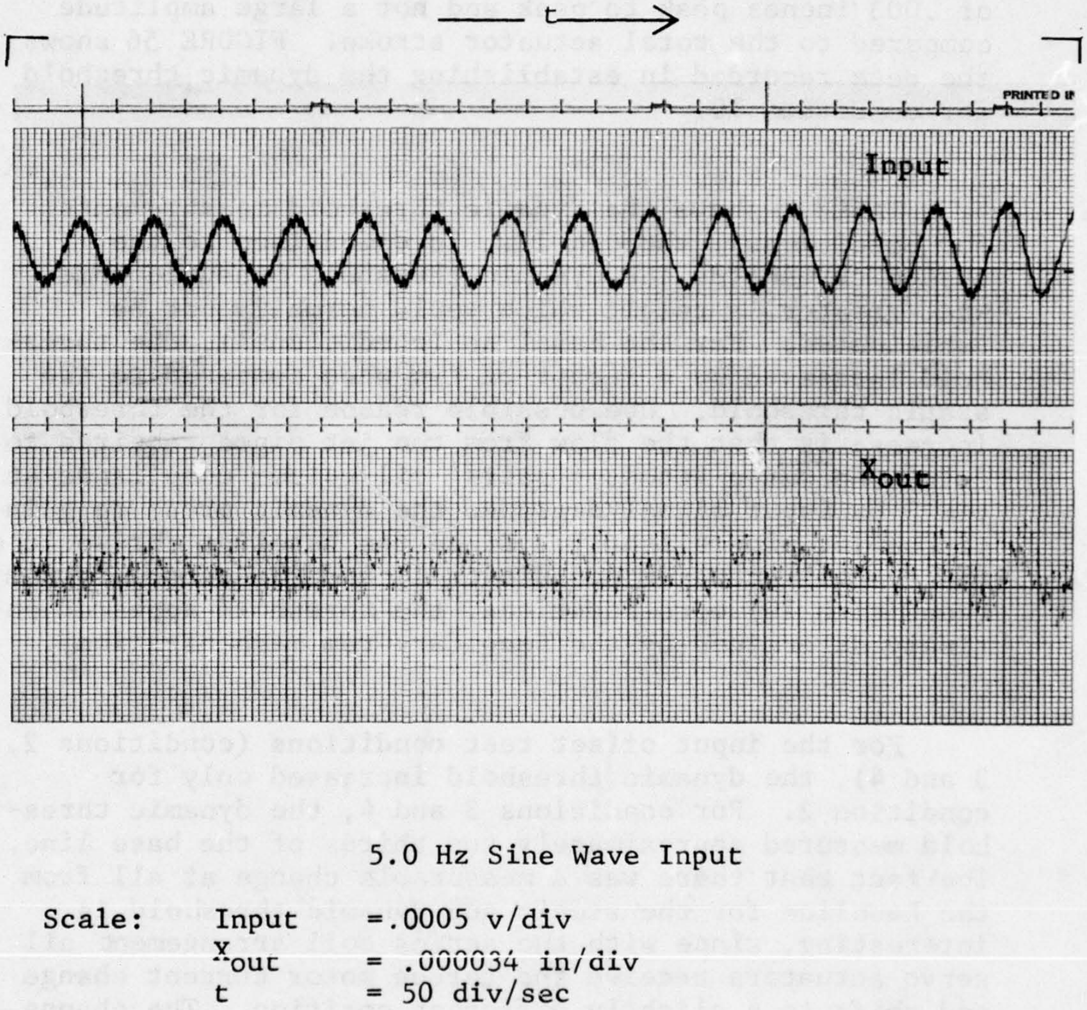
For the input offset test conditions (conditions 2, 3 and 4), the dynamic threshold increased only for condition 2. For conditions 3 and 4, the dynamic threshold measured approximately two thirds of the base line. The fact that there was a measurable change at all from the baseline for the static and dynamic threshold is interesting, since with the series coil arrangement all servo actuators receive the torque motor current change and shift to a slightly different position. The change of threshold may indicate that the servo actuators have running positions where the friction levels are slightly lower than at other positions. For condition 5 with P_1 reduced to 1500 psi, the dynamic threshold increased over the baseline value by about 50% (as contrasted to the decrease in static threshold when compared to its

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Dynamic Threshold - Condition 10



5.0 Hz Sine Wave Input

Scale: Input = .0005 v/div
X_{out} = .000034 in/div
t = 50 div/sec

FIGURE 56 Dynamic Threshold - Condition 10

TABLE 4

Dynamic Threshold

DYNAMIC CONTROLS, INC.
Test Data

Date Prepared: 12/6/76

TEST ITEM - Parker Hannifin Fly-By-Wire
Four Channel Tandem Actuator

TEST - DYNAMIC THRESHOLD

Test Condition	Dynamic Threshold		
	Input Volts	% of max Input	% of X_v max
1	0.0075	0.046	.68
2	0.0090	0.056	.82
3	0.0055	0.034	.50
4	0.0045	0.028	.41
5	0.0110	0.068	1.00
6	0.0045	0.028	.41
7	0.0260	0.160	2.36
8	0.0135	0.083	1.23
9	------	-----	----
10	0.0075	-----	.68
11	0.0130	-----	1.18
12	0.0100	-----	.91

baseline value). This increase is consistent with the reduction in pressure gain for the servo actuator pair connected to P_1. For the condition of electrical channels 1 and 1 + 2 failed (conditions 6 and 7), the threshold increased over the baseline value despite the automatic gain changing associated with the particular failure condition. For condition 8 (with P_1 reduced to 0 psi), the threshold increased 81% over the baseline value, probably due to the reduced driving force from the P_1 failure.

For the secondary ram dynamic threshold measurements of conditions 10, 11 and 12, the failure conditions increase the threshold over the baseline measurements. The threshold worst case measurement of 1.18% for channels 1 and 2 electrically failed is an increase of 74% over the baseline value. This increase is consistent with the loss of channels 1 and 2 with the automatic gain change prevented. However, in terms of the normal electro-hydraulic servo value threshold of .5%, the dynamic thresholds for the mechanization are comparable, both for the baseline and for failure test conditions.

3.2.3 Frequency Response

FIGURE 57 for condition 1 shows the test data recorded for the condition 1 frequency response measurements. FIGURE 58 shows the frequency response data recorded for the baseline secondary actuator response of condition 10. These response measurements are representative in terms of lack of peaking and the roll-off slopes for all test conditions 1 through 12. Zero db on FIGURE 57 corresponds to an output amplitude of 3% of the maximum actuator stroke. Zero db on FIGURE 58 corresponds to a 50% output stroke of the secondary ram driving the control valve. These input test amplitudes met the criteria of not creating output waveform distortion over the recorded frequency range due to threshold or saturation effects.

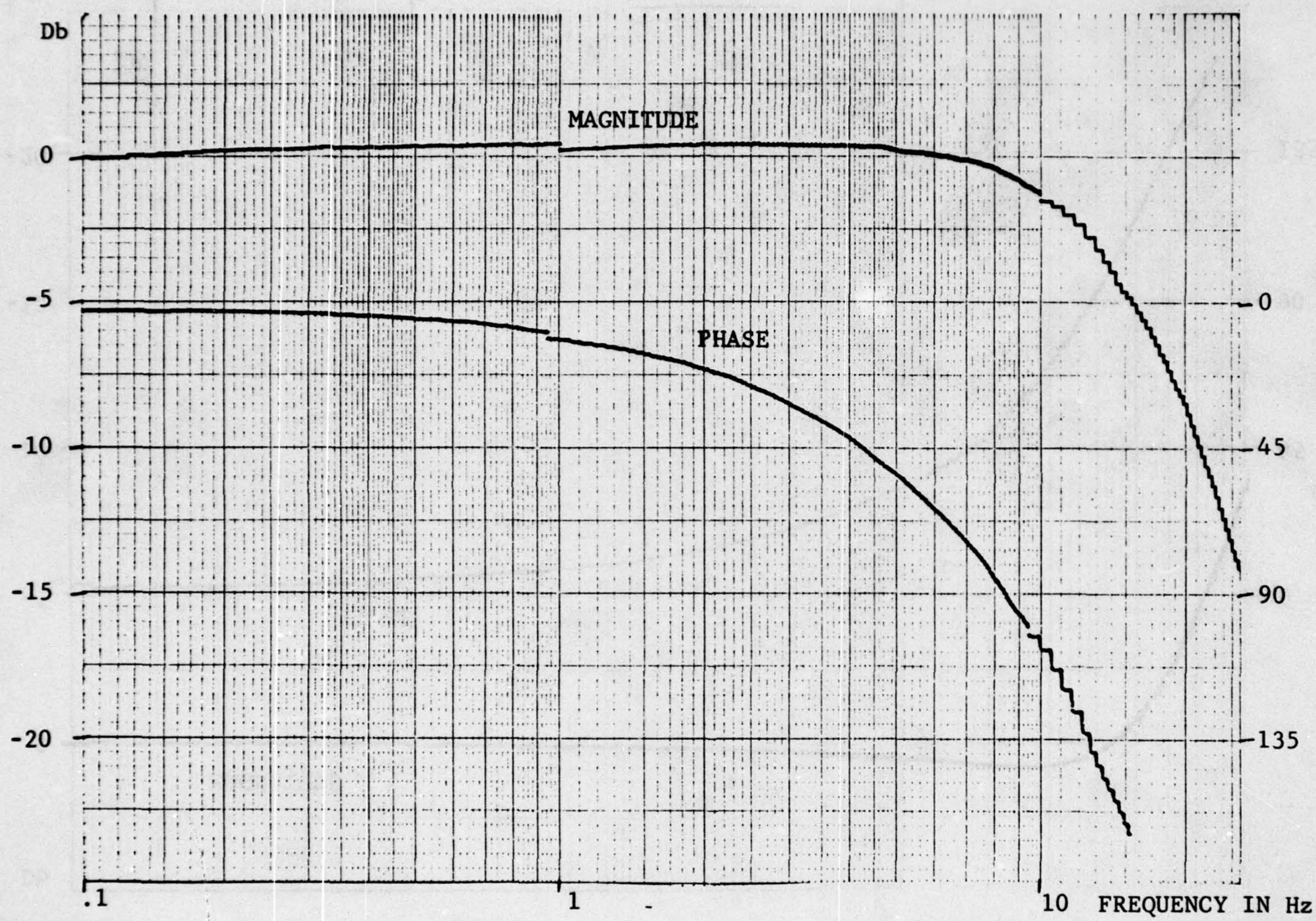


FIGURE 57 Frequency Response - Condition 1

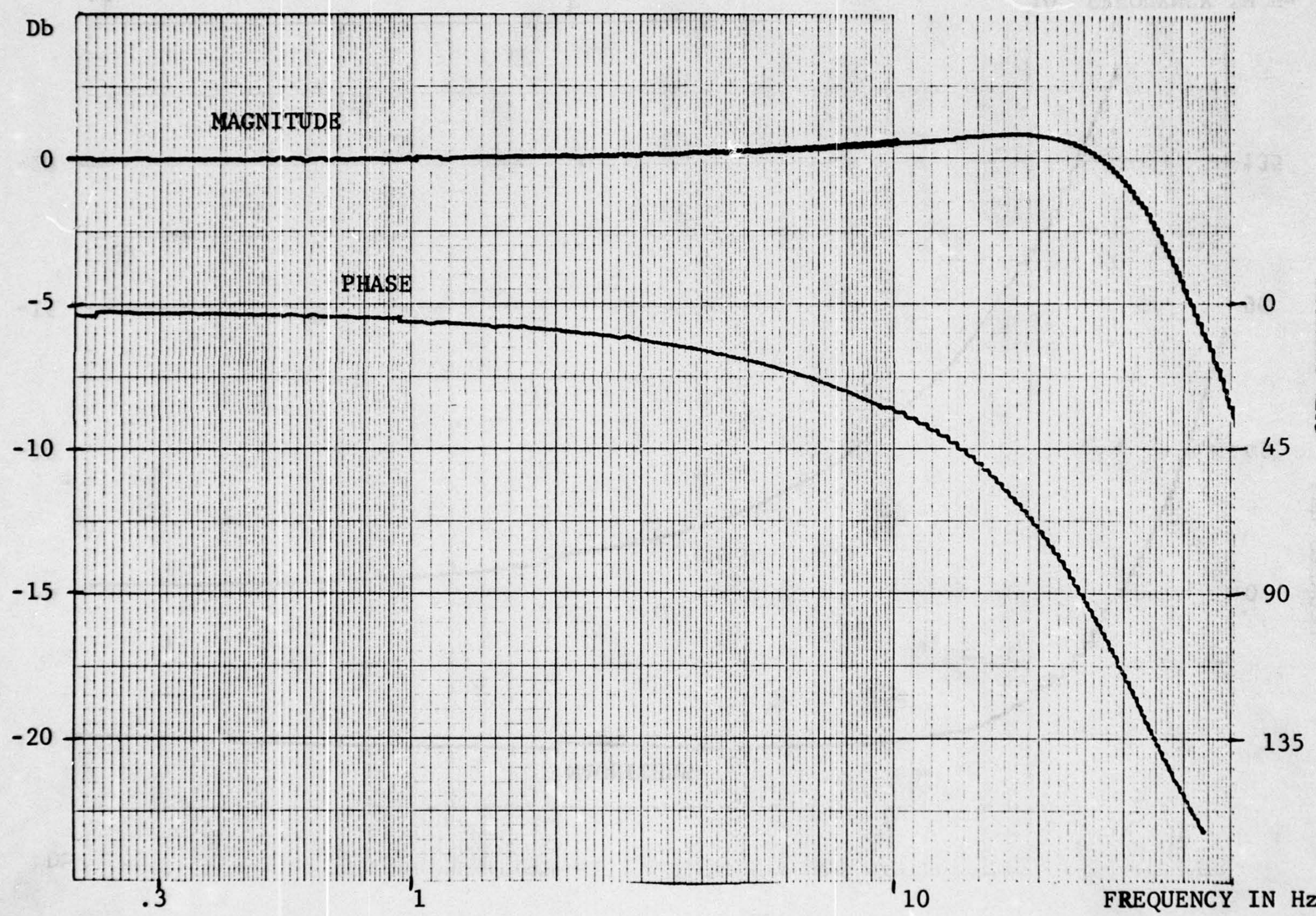


FIGURE 58 Frequency Response - Condition 10

TABLE 5 lists the frequency response for conditions 1 through 12 in terms of the frequencies at which the -90° phase angle and -3db amplitude ratio point occurred for each test condition. Note that for conditions 1 through 9, the actuator response remained quite constant, with the -90° phase lag frequency varying from only 8.4 to 10.4 Hz. Conditions 6 and 7 showed the greatest change in the -90° phase angle frequency. This was probably due to the automatic gain changing over-compensating the loop gain in response to the electrical failures injected for these test conditions.

For the secondary ram frequency response measurements, (conditions 10, 11 and 12) the response increased slightly with condition 11. No frequency response degradation from the baseline occurred with condition 12 (P_2 failed), indicating that the inertia loading of the servo actuators by the summing linkages was not great enough to effect the frequency responses.

3.2.4 Distortion

For test conditions 1 through 9 for the actuator, the distortion measurement figures were quite large (on the order of 30%), largely due to the 400 Hz noise included in the demodulated output of the position LVDT. Since the output amplitude was run at 3% full scale (the same as used for the frequency response measurements) the noise did affect the distortion readings significantly. For the secondary ram distortion measurements, the output amplitude was run at 50% full scale and the distortion components of the output waveform due to LVDT noise were smaller. Due to the noise, the absolute value of the distortion readings was not considered valid as an indicator of the input-output performance and the change in distortion from the baseline measurements was used as the measurement criteria. (Since the input amplitude was not changed during the test conditions and the test frequencies were within the bandpass of the actuator, the output waveform amplitude was

TABLE 5

Frequency Response

DYNAMIC CONTROLS, INC.
Test Data

Date Prepared: 12/6/76

TEST ITEM - Parker-Hannifin Fly-By-Wire
Four Channel Tandem Actuator

TEST - FREQUENCY RESPONSE

Test Condition	Output 3% Full Scale *	
	- 3 db Hz	- 90° Hz
1	12.9	8.4
2	17.9	9.4
3	17.2	9.5
4	17.2	9.6
5	13.6	8.7
6	17.0	11.1
7	12.7	10.4
8	14.8	9.6
9	16.8	9.2
10	36.5	24.4
11	43.5	29.8
12	38.0	24.7

* Conditions 10, 11 and 12 @ 50% full scale.

approximately the same for all test conditions 1 through 9. Because the relative amount of 400 Hz noise on the output waveform did not change for the different test conditions as long as the amplitude remained the same, the change in the percent distortion figures did reflect changes in the basic waveform of the output at the test frequencies). TABLE 6 lists the distortion measurement results for test conditions 1 through 12.

For the main ram test conditions 1 through 9, all failure conditions reduced the output distortion. The greatest reduction in the percent distortion was 11.4 percent for condition 5. This indicates that the baseline actuator configuration had at least 11.4 percent harmonic distortion at 5 Hz. Note that the distortion at 10 Hz was not reduced as much as at 5 Hz for the test conditions 1 through 9.

For the test conditions 10, 11 and 12, the output distortion both increased and decreased from the baseline value of 3.2% at both the 5 and 10 Hz frequencies. The largest increase occurred with condition 11 and was an increase of 1.3% distortion. These distortion values are quite low both for the baseline and for the two failure conditions (Note that it is difficult to detect visually a harmonic distortion of less than 5% on a sinusoidal signal). The difference between the main ram and secondary ram distortions indicates that the most of the distortion measured on the output of the main ram was associated with the main ram components, and not the secondary ram (control valve) motion.

3.2.5 Hysteresis

FIGURE 59 shows the data recorded for measuring the hysteresis for the baseline actuator (condition 1). FIGURE 60 shows the data recorded in measuring the hysteresis for the secondary ram baseline (condition 10).

TABLE 6

Distortion

DYNAMIC CONTROLS, INC.
Test Data

Date Prepared: 12/6/76

TEST ITEM - Parker-Hannifin Fly-By-Wire
Four Channel Tandem Actuator

TEST - DISTORTION

Test Condition	Change of % distortion from baseline value	
	% @ 5 Hz	% @ 10 Hz
1	Baseline Value*	Baseline Value**
2	- 5.0	- 3.5
3	- 4.1	- 3.9
4	- 5.0	- 4.5
5	-11.4	- 8.4
6	- 9.0	- 6.9
7	- 8.0	- 3.1
8	- 9.0	- 6.8
9	- 2.0	- 0.5
10	Baseline Value***	Baseline Value****
11	+ 0.8	+ 1.3
12	- 1.0	+ 0.1

* 30.8%, ** 30.3%, *** 3.2%, **** 3.2%

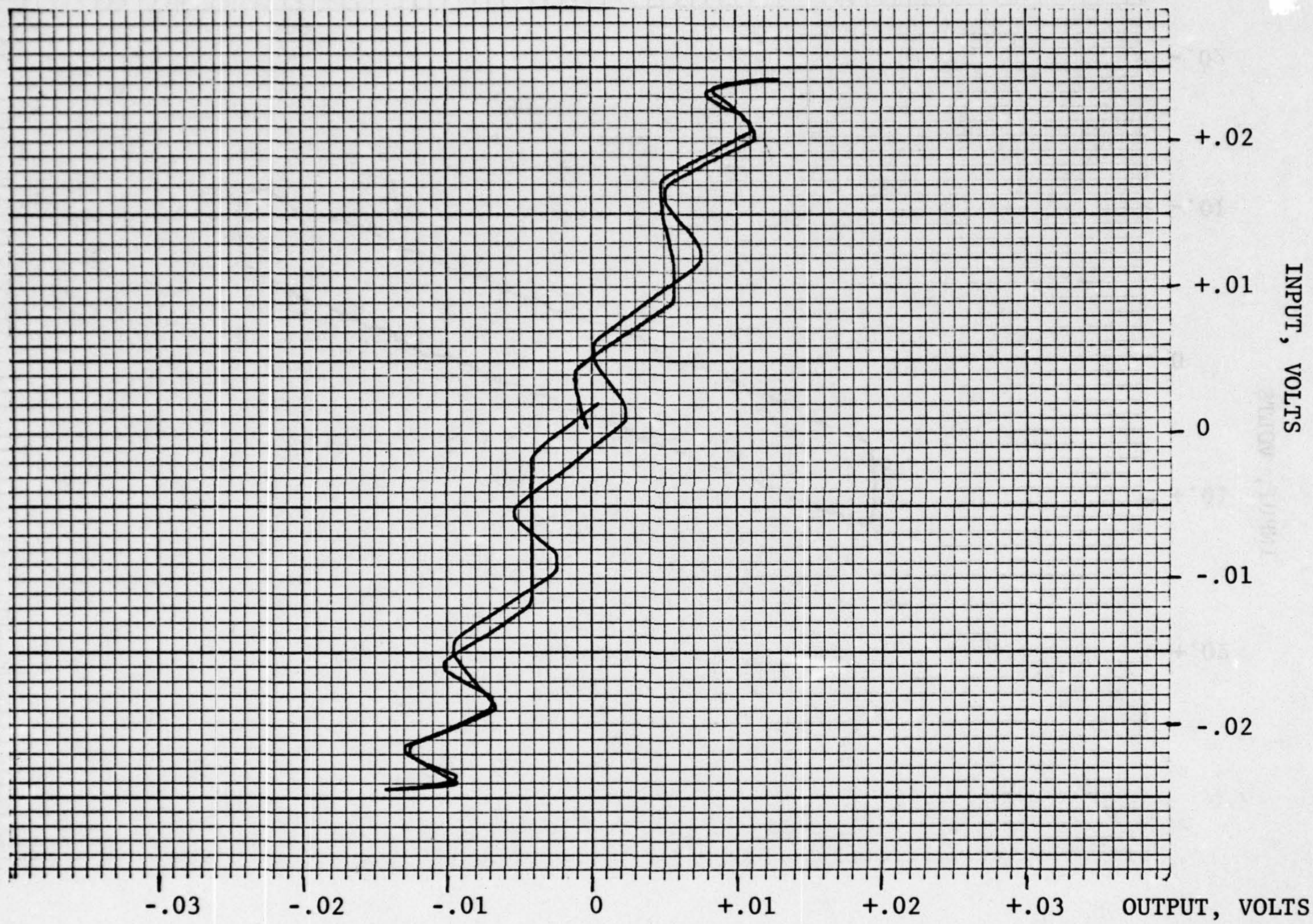


FIGURE 59 Hysteresis - Condition 1

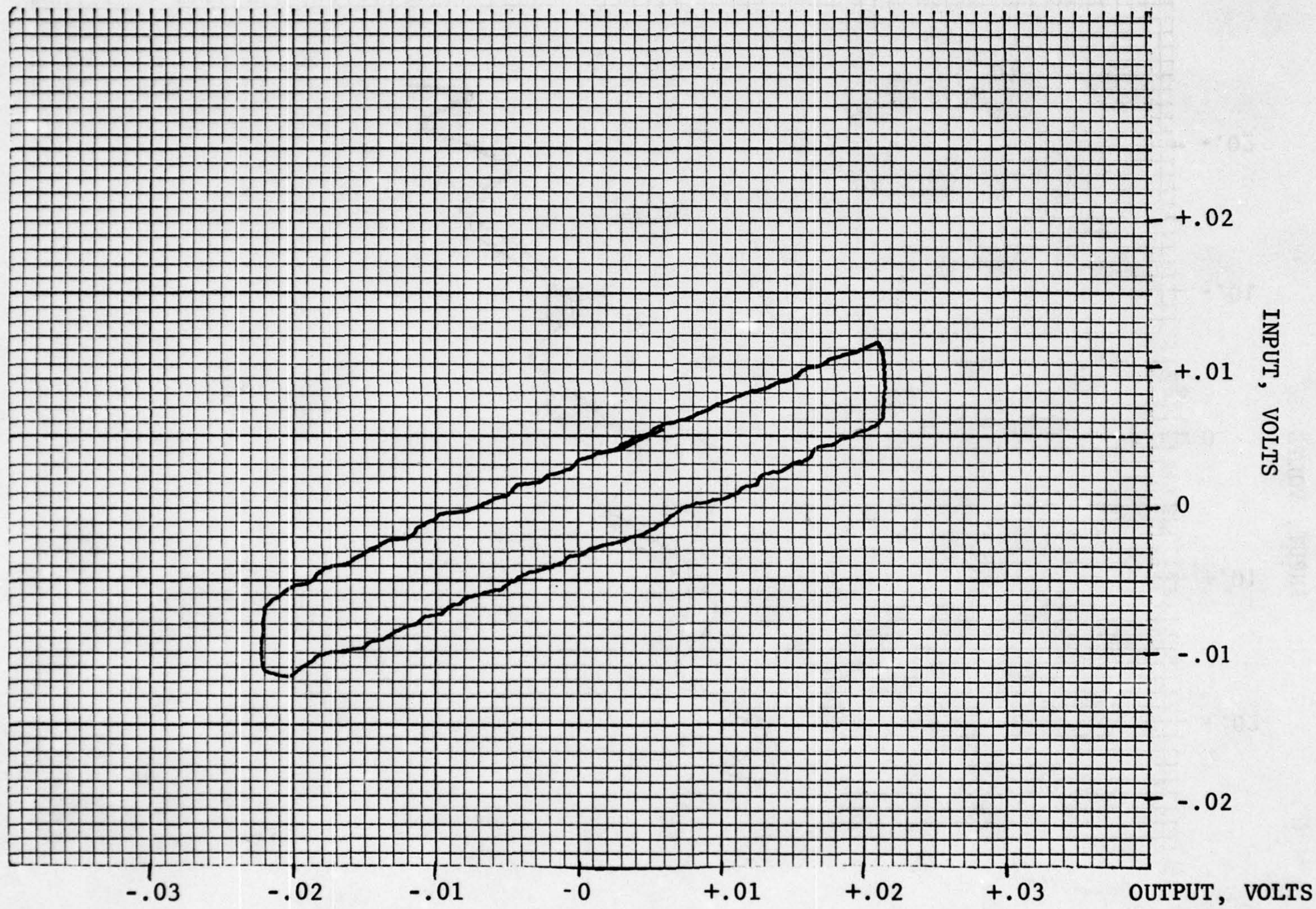


FIGURE 60 Hysteresis - Condition 10

These plots are representative of the main ram and secondary hysteresis plots respectively. On FIGURE 59 note that actuator output motion with a gradually increasing and decreasing input signal does not describe the conventional hysteresis loop. The increasing and decreasing direction motions actually cross each other. This apparently was due to the random hunting of the actuator output motion (previously mentioned in Section 3.2.2) acting effectively as a dither input to reduce the hysteresis.

As shown in TABLE 7 , this hunting made the apparent hysteresis of the actuator very low. The hysteresis for the secondary ram as shown in FIGURE 60 was of a conventional appearance. In terms of maximum control valve stroke, the secondary ram hysteresis was a maximum of 10%. This is approximately 3 times the hysteresis of a typical electro-hydraulic servo valve. If the main ram had not exhibited the hunting characteristics, it is expected that the hysteresis of the total actuator in terms of the maximum spool stroke would be only slightly greater than the secondary ram measurement. In terms of the long stroke of the power actuator, the percent hysteresis with or without hunting would be less than 1%.

3.2.6 Saturation Velocity

FIGURE 61 shows the actual data recorded in determining the extend saturated rate for test condition 1 (main ram baseline). FIGURE 62 shows the data recorded in determining the extend and retract saturated rate for test condition 10. TABLE 8 lists the extend and retract saturated velocities for test conditions 1 through 12. The baseline main ram rates met the nominal 9 inches per second specified by Parker-Hannifin for the actuator. With the exception of test conditions 5 and 7, the main ram maintained the baseline extend and retract rates for test conditions 2 through 8. Test condition 5

TABLE 7

Hysteresis

DYNAMIC CONTROLS, INC.
Test Data

Date Prepared: 12/6/76

TEST ITEM - Parker Hannifin Fly-By-Wire
Four Channel Tandem Actuator

TEST - HYSTERESIS

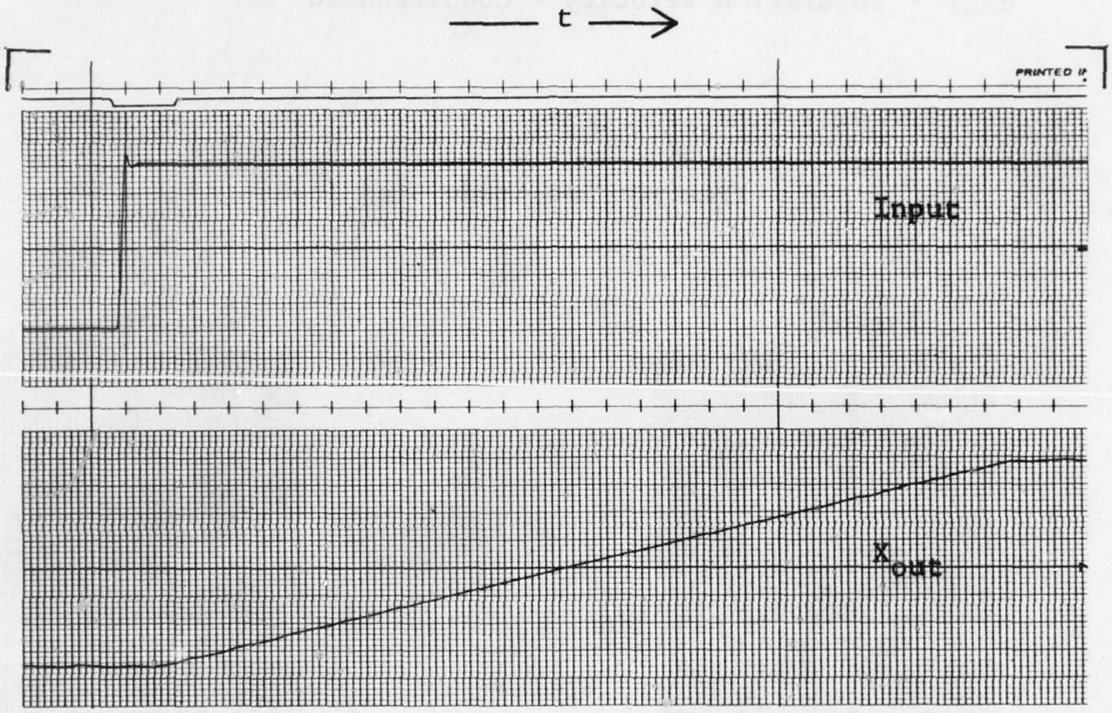
Test Condition	% Full Scale	% of X_v max
1	0.047	.71
2	0.065	.68
3	0.054	.62
4	0.065	.74
5	0.065	.74
6	0.043	.49
7	0.016	.18
8	0.081	.92
9	-----	---
10	-----	6.67
11	-----	10.00
12	-----	8.57

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Saturation Velocity - Condition 1



Maximum Amplitude Step Input

Scale: Input = 1.0 v/div
X_{out} = .157 in/div
t = 200 div/sec

FIGURE 61 Saturation Velocity - Condition 1

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Saturation Velocity - Condition 10

Maximum Amplitude Step Input

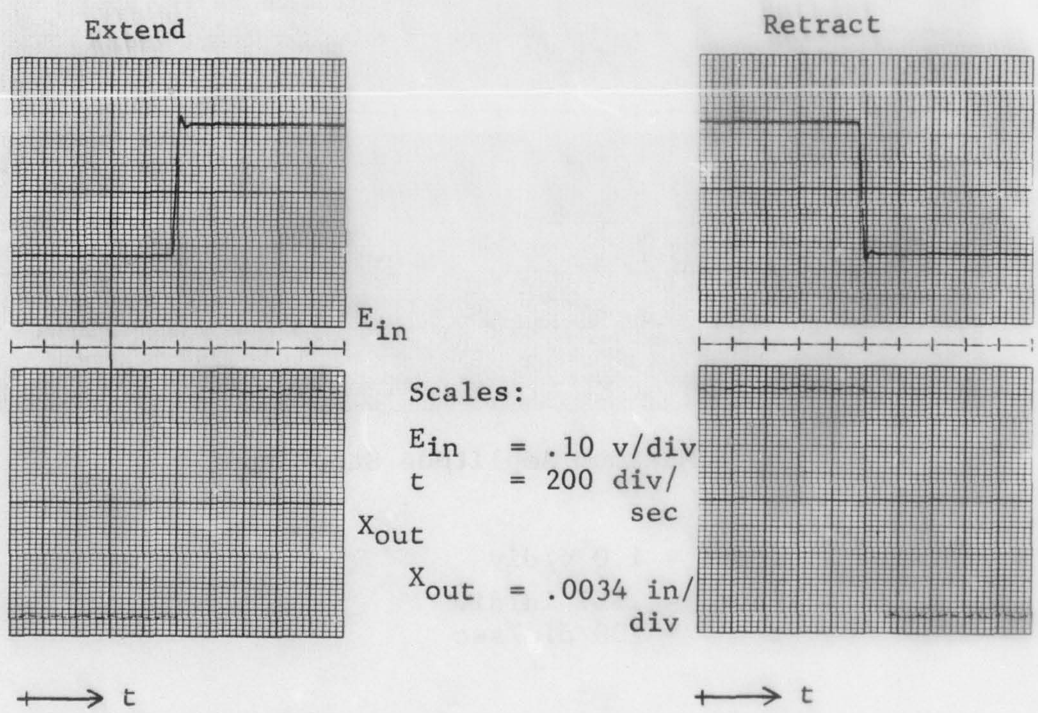


FIGURE 62 Saturation Velocity - Condition 10

TABLE 8

Saturation Velocity

DYNAMIC CONTROLS, INC.
Test Data

Date Prepared: 12/6/76

TEST ITEM - Parker-Hannifin Fly-By-Wire
Four Channel Tandem Actuator

TEST - SATURATION VELOCITY

Test Condition	Extend - in./sec.	Retract - in./sec.
1	9.45	9.13
2	9.01	9.64
3	9.26	9.45
4	9.13	9.45
5	7.87	8.19
6	9.10	9.45
7	8.00	9.13
8	8.82	9.16
9	Failed when step was applied	
10	12.19	11.49
11	11.49	10.10
12	11.40	11.84

shows a reduction of approximately 1 inch/second for both the extend and retract motions. This reduction may be associated with that half of the actuator ram connected to P_2 loading the other half of the actuator during maximum rate motions. Condition 7 shows a reduction in the extend rate. This probably was due to servo amplifier saturation not driving the control valve to the same maximum position as with the baseline test condition 1. (Condition 7 causes the two servo amplifiers that are operational to provide all the current to the four torque motors).

For test conditions 11 and 12, the secondary ram extend and retract rates did not change significantly from the baseline condition 10. The retract motion saturated velocity for condition 11 was reduced slightly from the baseline test condition 10, perhaps due to the servo amplifier or jet pipe servo valve saturation characteristic.

3.2.7 Linearity

FIGURE 63 shows the actuator output linearity measured for conditions 1 through 9. The data shown was recorded for condition 1. The recorded results for conditions 2 through 9 were essentially identical to the condition 1 results and in order to avoid repetition, are not shown separately. Notice that there is no apparent hysteresis shown on the linearity plot. As previously mentioned, the very low amplitude hunting of the actuator effectively eliminates the apparent hysteresis in the main ram motion. The lack of linearity change with the different conditions is expected, since the position linearity of the actuator depended only on the feedback transducer used with the actuator. FIGURE 64 shows the secondary ram baseline linearity (Condition 10). A very slight deviation from a straight line exists between 0 and .2 volts input (0 and .6 volts output). This is no greater than expected with a normal servovalve. Note the

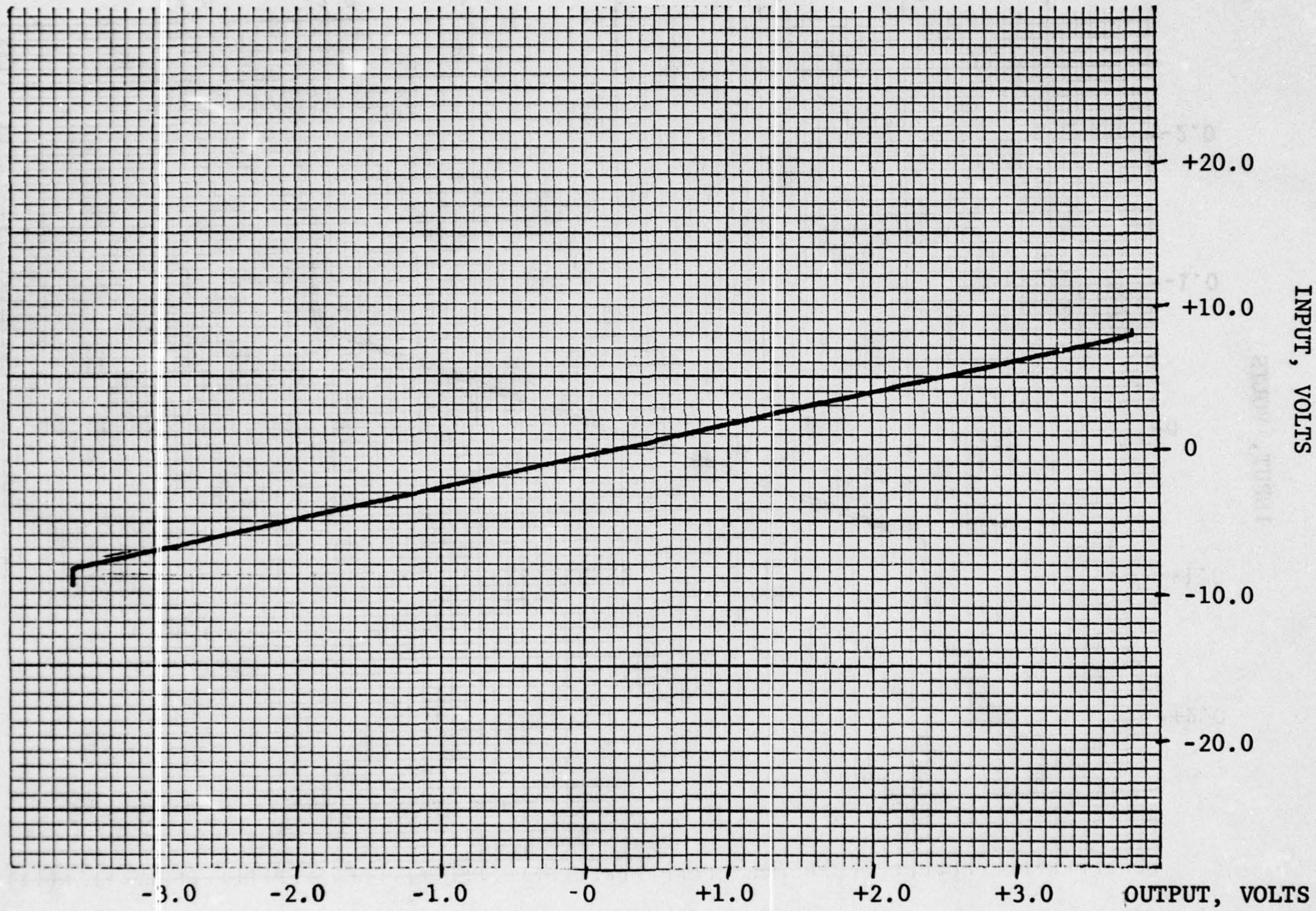


FIGURE 63 Linearity - Conditions 1 through 9

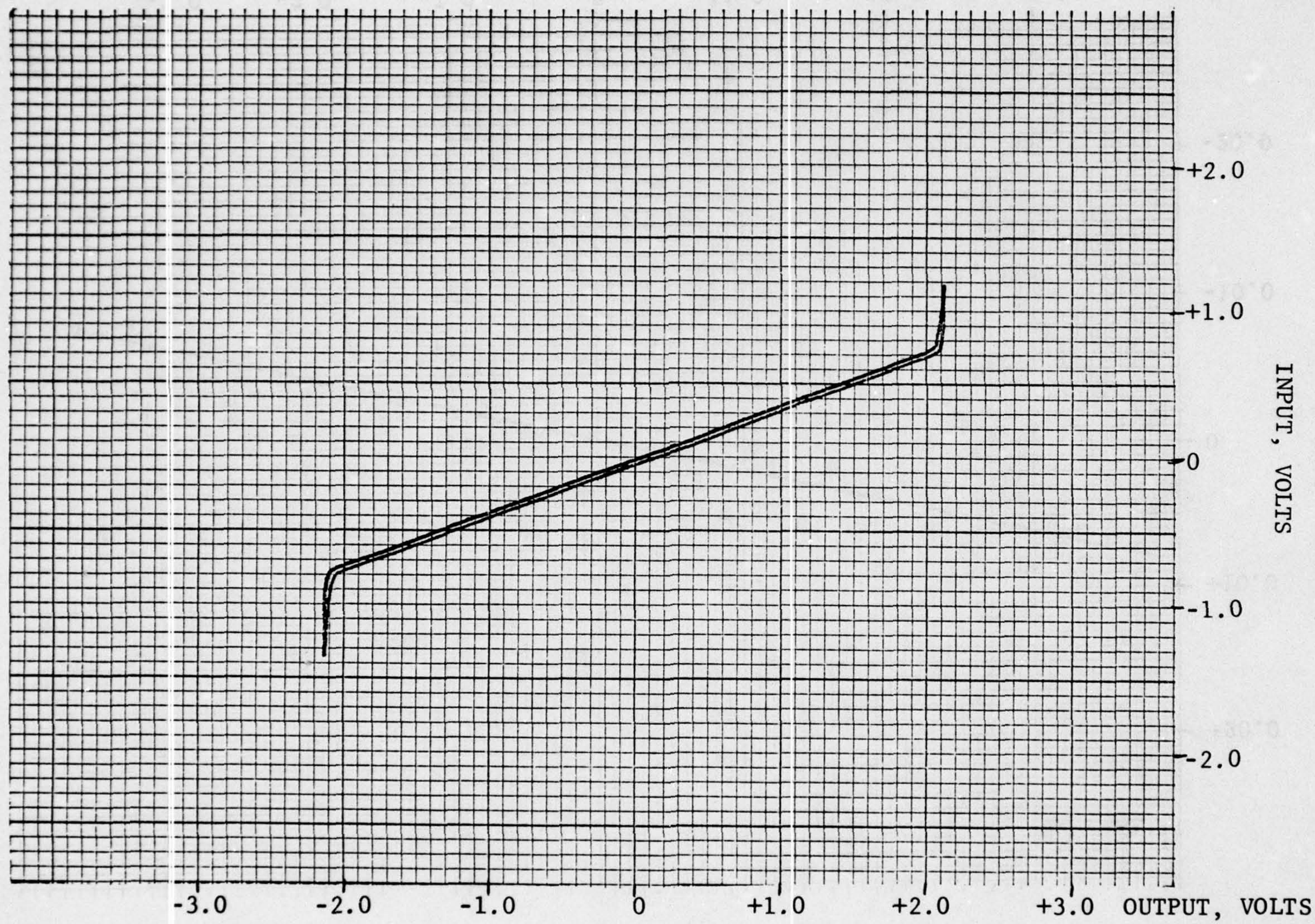


FIGURE 64 Linearity - Condition 10

hysteresis loop which agrees with the results of the hysteresis testing. Condition 11 (FIGURE 65) with channels 1 and 2 failed by pulling a relay, shows a gain change from the base condition 10. This gain change is to be expected, since the method of failing channels 1 and 2 eliminated the automatic gain changing circuitry of the control console. Condition 12 (FIGURE 66), with P_2 failed, shows the same linearity and hysteresis as condition 10. Since the linearity of the secondary ram is determined by the mechanical feedback from the servo-actuator pistons to their respective torque motors, little change with failure conditions would be expected. This result is confirmed by the recorded data.

3.2.8 Step Response

FIGURE 67 shows the step response data for test conditions 1 through 4. The data shown was recorded for condition 1. Conditions 2, 3 and 4 gave identical step response measurements. Two levels of step inputs were used to measure the main ram response, corresponding to 1% and 3% of full output. FIGURE 67 shows both the input step and the actuator response. The slight slope of the leading edge of the step input trace is due to the response characteristics of the Brush recorder. Note that the step response to the 1% and 3% input both exhibit the same 12.5 millisecond time delay and a 30 millisecond total response time to reach 2/3 of the final value. The time delay is due to the actuator dynamics being a higher order than a second order system. The response of the main ram after the time delay resembles a second order system step response with a damping ratio of .5. As shown on FIGURE 67, the extend and retract direction responses are identical. Note that the 1% full scale output step response shows the low amplitude actuator hunting characteristics previously observed.

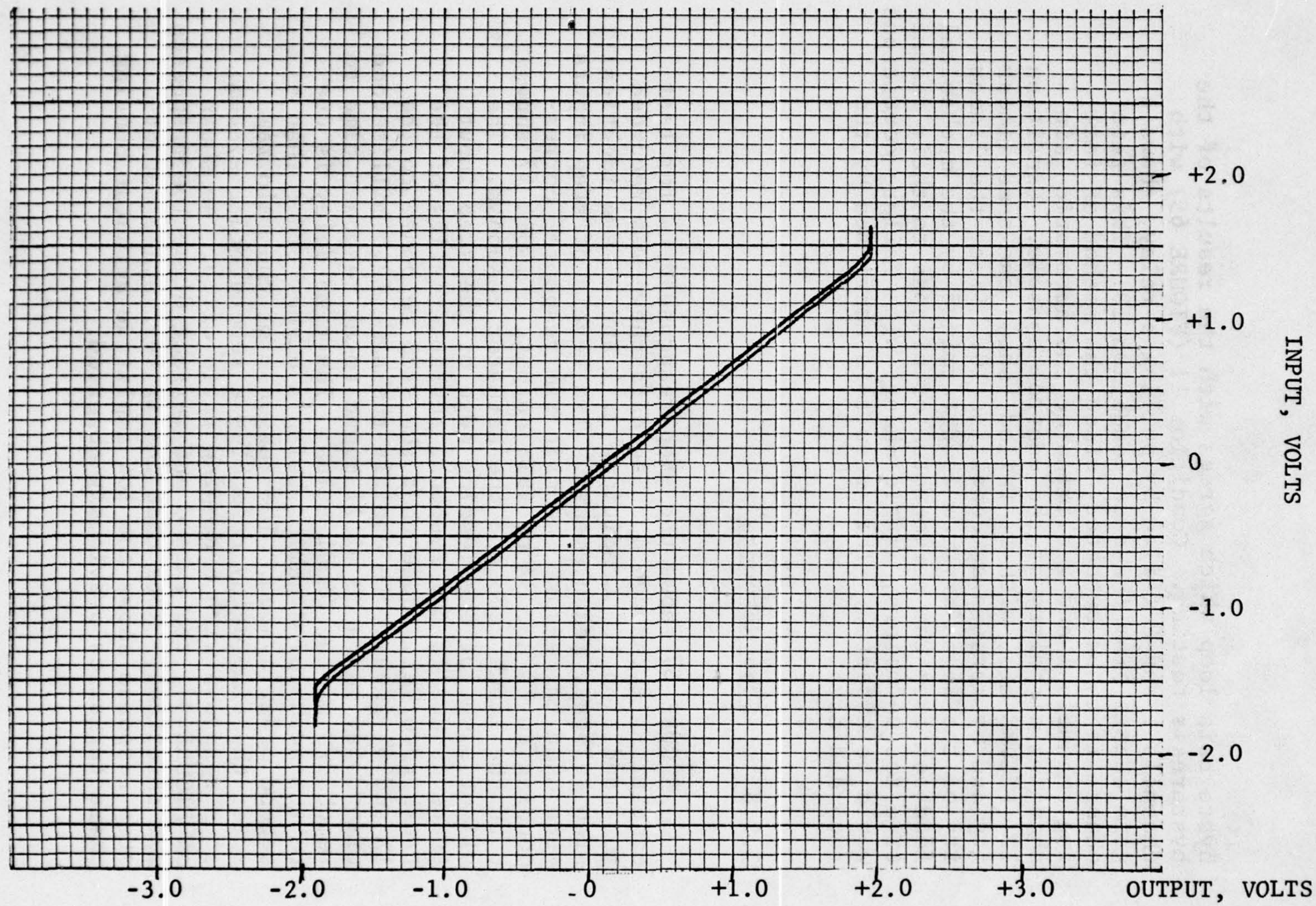


FIGURE 65 Linearity - Condition 11

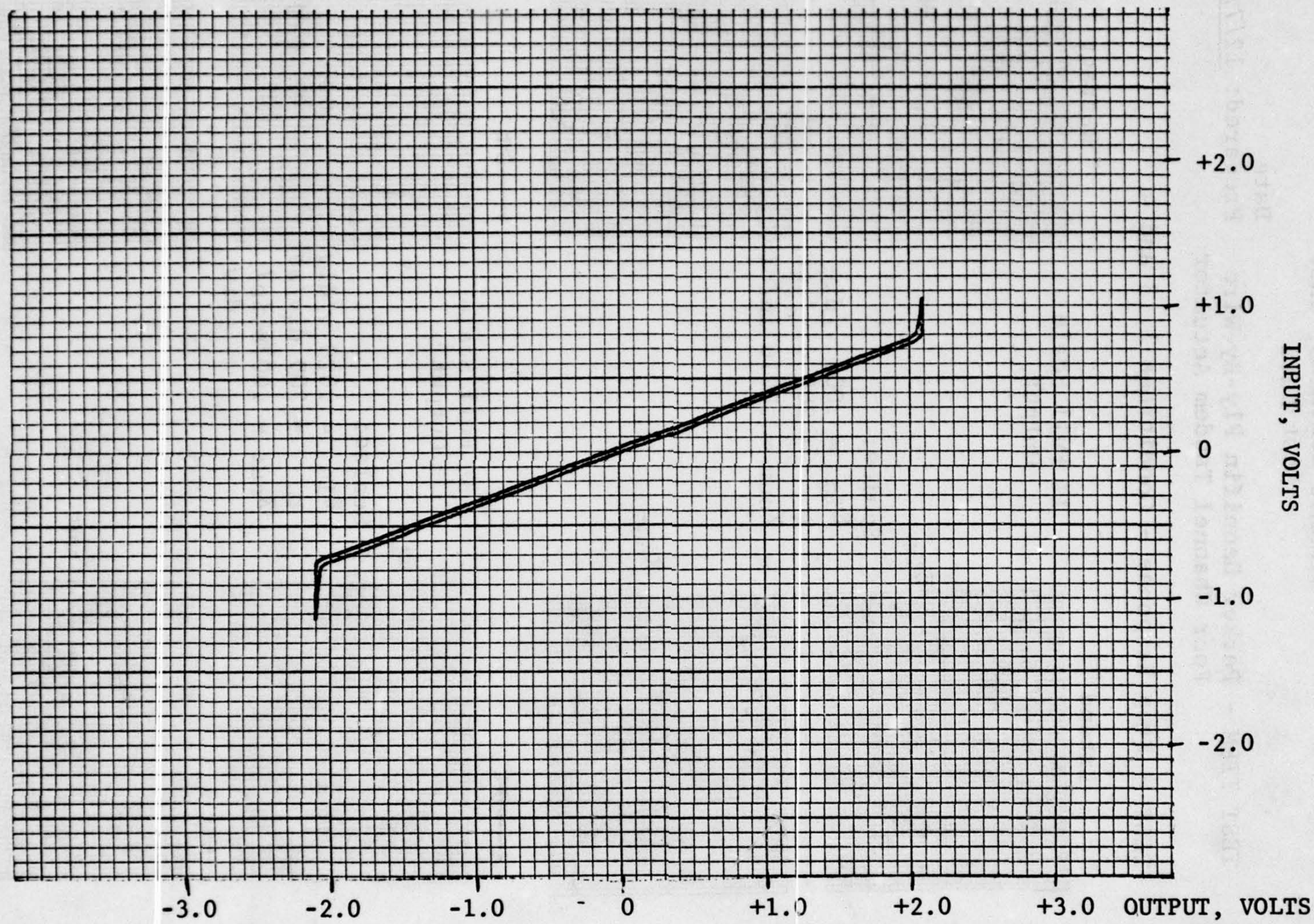


FIGURE 66 Linearity - Condition 12

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Step Response - Conditions 1, 3 and 4

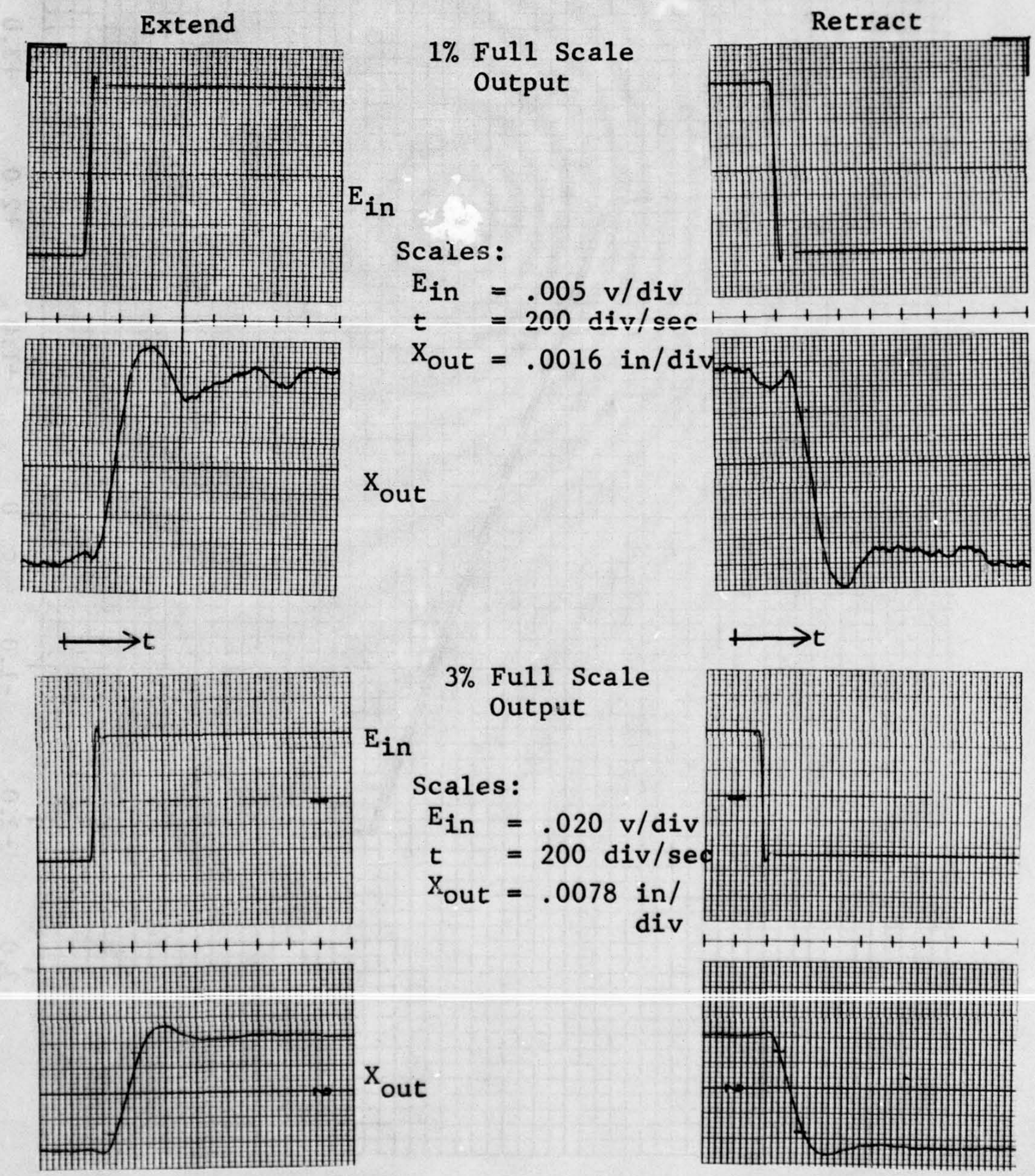


FIGURE 67 Step Response - Conditions 1, 3 and 4

Conditions 2, 3 and 4 did not exhibit any change from the baseline response. The offset currents for these test conditions did not cause amplifier saturation for the size of input used for the step response measurements and all servo actuator torque motors receive the same offset current. No change in the dynamic response would be expected for these test conditions.

The step response for condition 5 as shown in FIGURE 68, resembles the baseline response for condition 1. The response time (34 milliseconds) and damping ratio (.6) are slightly greater than the values for condition 1. This is probably caused by the half of the actuator connected to P_1 acting as slight load (proportional to rate) for the actuator half supplied by P_1.

For condition 6 (channel 1 failed electrically) the damping ratio increased over condition 1 to .6. The time delay and rise time were identical to the baseline condition 1 test results. FIGURE 69 illustrates the response results for this test condition. FIGURE 70 shows the test results for condition 7, with both channels 1 and 2 failed electrically. The damping ratio is the only apparent change from the baseline test results. For condition 8, the damping ratio is .8 as compared to .5 for the baseline condition 1. The change in the damping ratio for conditions 6 and 7 are probably due to the change in the amplifier gains due to the automatic gain changing incorporated into the control console. The response of condition 9 was similar to that of condition 1 with an apparent damping ratio increase to .7.

The step response for the secondary ram was measured at 50% full scale output for the secondary ram. As shown in FIGURE 71, the step response exhibited no time delay and appears as a true second order system. As shown in FIGURE 71, the response of the secondary ram for condition 10 (baseline) exhibited a rise time of

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Step Response - Condition 5

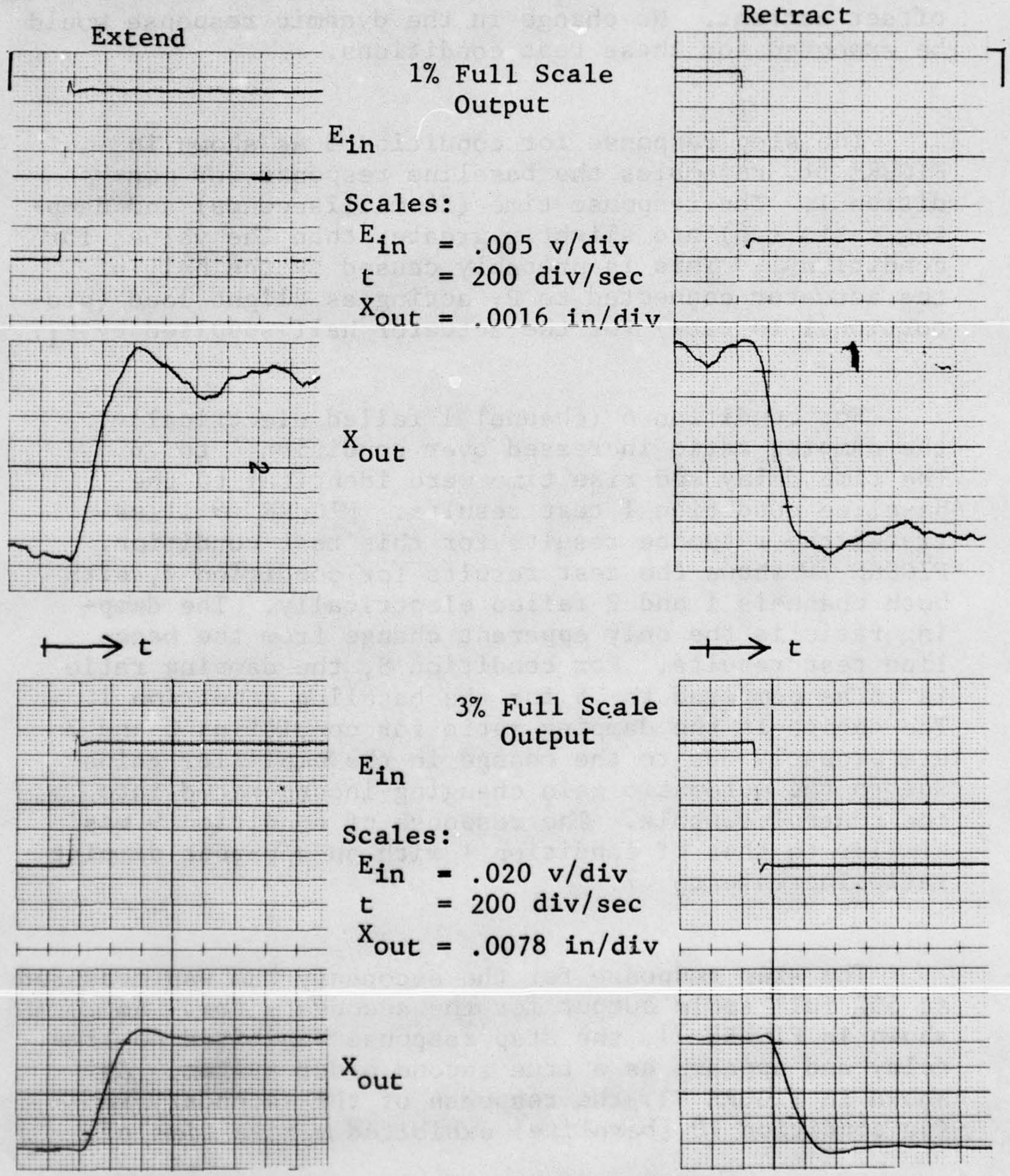


FIGURE 68 Step Response - Condition 5

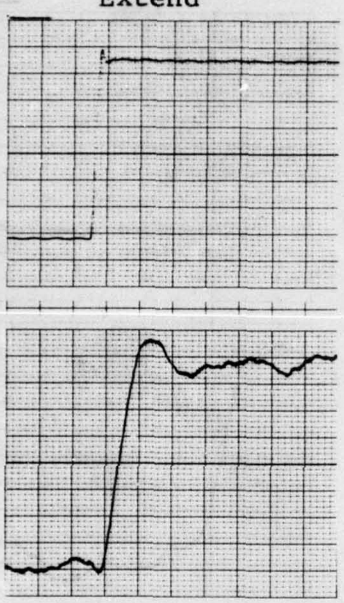
DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

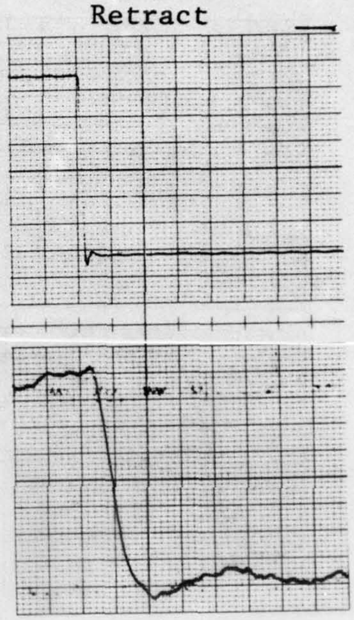
Date Prepared: 12/7/76

TEST - Step Response - Condition 6

Extend



Retract

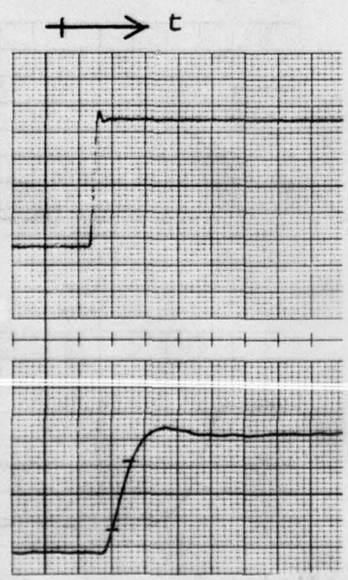


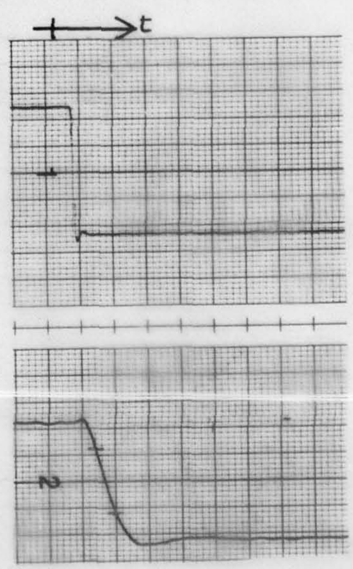
1% Full Scale Output

E_{in}

Scales:
E_{in} = .005 v/div
t = 200 div/sec
X_{out} = .0016 in/div

X_{out}





3% Full Scale Output

E_{in}

Scales:
E_{in} = .020 v/div
t = 200 div/sec
X_{out} = .0078 in/div

X_{out}

FIGURE 69 Step Response - Condition 6

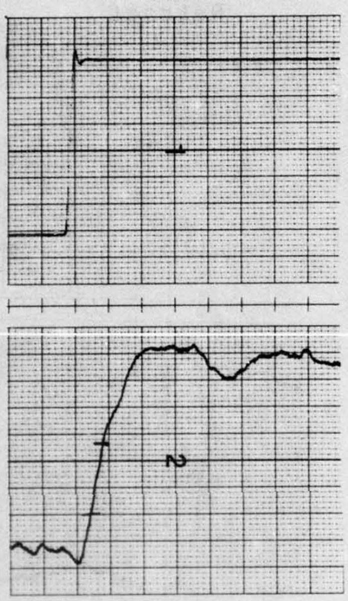
DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Step Response - Condition 7

Extend



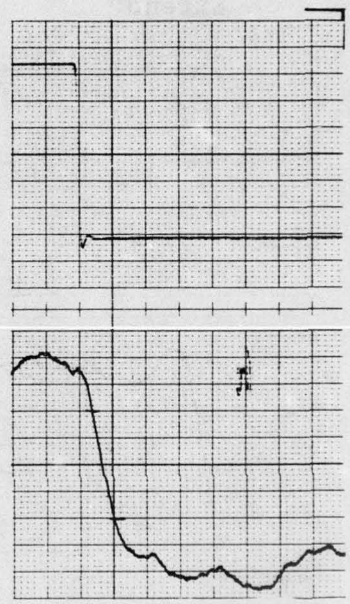
1% Full Scale Output

E_{in}

Scales:
E_{in} = .005 v/div
t = 200 div/sec
X_{out} = .0016 in/div

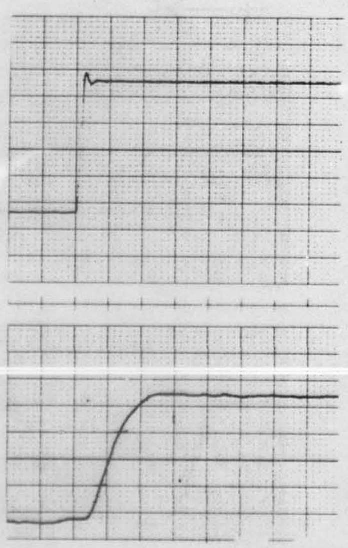
X_{out}

Retract



→ t

→ t



3% Full Scale Output

E_{in}

Scales:
E_{in} = .020 v/div
t = 200 div/sec
X_{out} = .0078 in/div

X_{out}

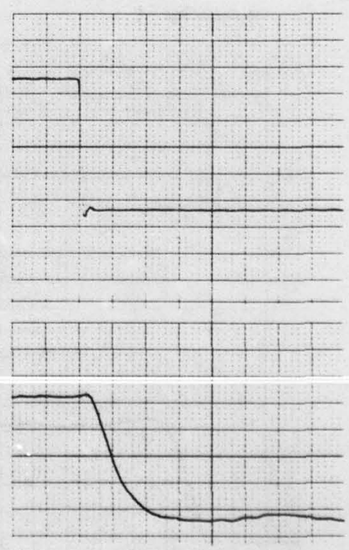


FIGURE 70 Step Response - Condition 7

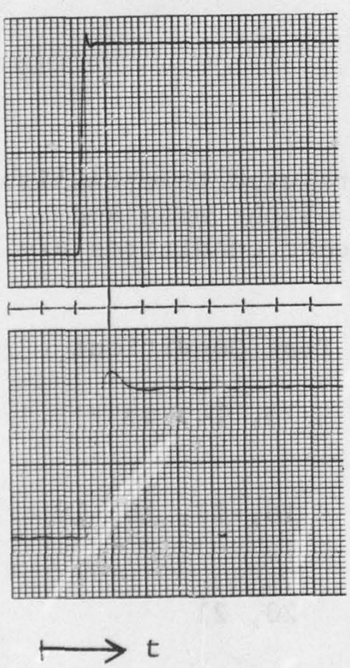
DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire
Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Step Response - Condition 10

Extend



50% Full Scale Output

E_{in}

Scales:

E_{in} = .020 v/div

t = 200 div/sec

X_{out} = .0034 in/div

Retract

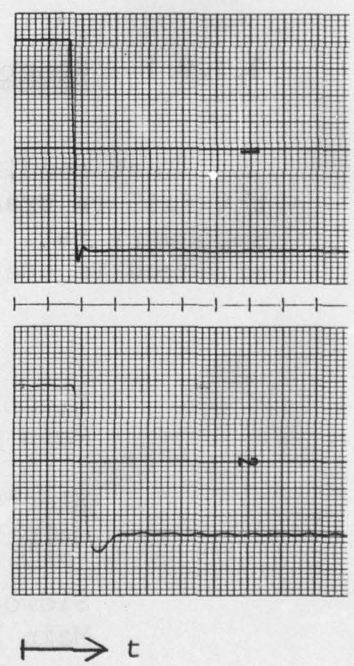


FIGURE 71 Step Response - Condition 10

15 milliseconds and a damping ratio of .6. The extend and retract responses are identical. Conditions 11 and 12 resembled the condition 10 response results and had the same damping ratio and rise time.

As with the frequency response measurements, little change in the dynamic response was apparent with the test condition changes. The damping ratios demonstrated by the step response measurements indicated that the response of the actuator was adjusted to have the characteristic of a minimum rise time with no ringing.

3.2.9 Failure Transients

3.2.9.1 General

Test conditions 13 through 31 were used to establish the failure transient characteristics of the main and secondary ram. The test results and test conditions are arranged in the following order:

Test	Test Conditions
Electrical Input Loss - Main Ram Transient	13, 14, 15
Electrical Hardover Input - Main Ram Transient	16, 17, 18, 19
Slowover Electrical Input - Main Ram Transient	20, 21
Hydraulic Failure - Main Ram Transient	22, 23, 24
Electrical Input Loss - Secondary Ram Transient	25, 26, 27

Test	Test Conditions
Electrical Hardover Input - Secondary Ram Transient	28, 29, 30, 31

The test results in the following sub-sections are presented as listed above.

3.2.9.2 Electrical Input Loss - Main Ram Transient

FIGURE 72 shows the effect of a sequential channel 1 and channel 2 input loss on the main ram motion. The input signal to the actuator is a 3% full scale input at approximately 1 Hz. Note that because of space limitations, on FIGURE only four channels of recorded information are presented. The top two channels of data are recordings of the inputs to channels 1 and 2 of the actuator. The third channel of recorded data is the actuator output. The fourth and bottom channel of recorded data is the output voltages used to drive the failure indicating lights. For this test condition, both channels 3 and 4 of the actuator continue to receive the 1 Hz input signal. For the failure of channel 1 input, there is a distinct time delay between the loss of channel 1 input and the detection of the failure (as indicated by the F_1 driving light voltage). For the particular input amplitude and frequency used, the time delay between the input loss and transfer out of the failed channel was .8 seconds. The waveform shows a transient upon the loss of input signal 1 and upon the failure transfer. Note that for the .8 seconds until failure transfer, the amplitude of the actuator motion is attenuated slightly. Upon failure transfer, the amplitude of output motion is increased to the "no failure" value.

For the second channel failure, the time delay for the failure transfer to occur is approximately .15 seconds. The time delay for both the first and second

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 13

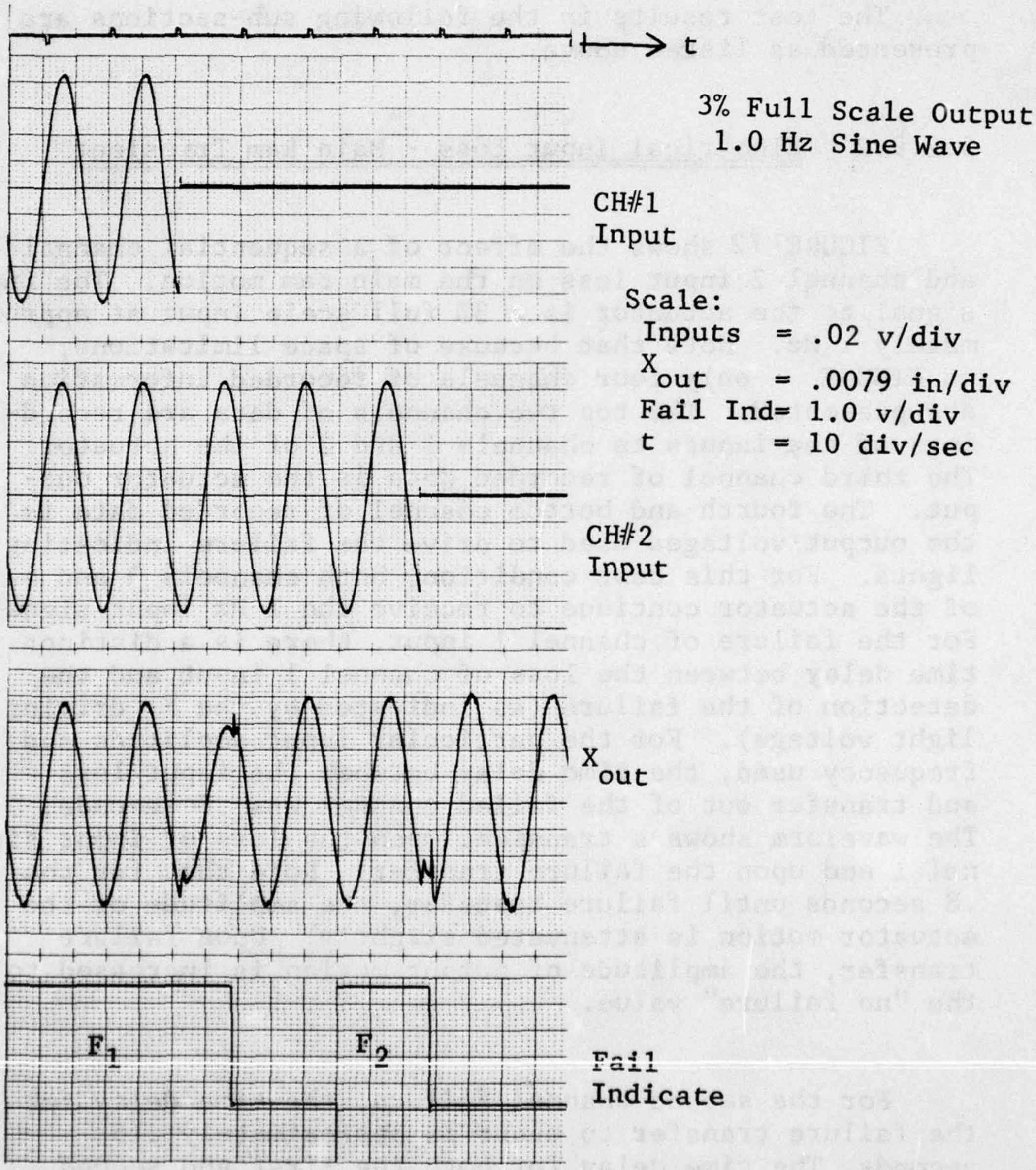


FIGURE 72 Failure Transients - Condition 13

failures is determined by the control console logic design. The main ram transient appears to be less than .039 inches for the first failure and less than .094 inches for the second failure. For both failures, the transient consists of a short duration loss of the correct output amplitude.

FIGURE 73 shows the effect of a sequential loss of channel 3 and 4 inputs on the main ram output motion. Inputs to channels 1 and 2 were already grounded for this test (test condition 14). As with test condition 13, the input to the actuator control channels is a 3% full scale input at approximately 1 Hz. The time delay between loss of channel 3 input and failure transfer was .25 seconds. The failure transient at the end of the .25 second delay appears as an apparent loss of output response to the input signal. The actuator centered after the third failure input loss (channel 3). The channel 4 input loss had no effect on the actuator output since the actuator had reverted to the manual input valve when the channel 3 input was grounded.

FIGURE 74 shows the failure transient results for test condition 15 with channel 1 and channel 2 inputs grounded simultaneously. The simultaneous input failures are detected correctly as failures. Since the control console logic compared all other channels' error voltages against channel 4's error voltage, whether channels 1 and 2 failed sequentially or simultaneously made no difference to the failure detection. If the control logic used a true inter-channel voting of error voltages for failure detection, the simultaneous failures of two inputs would not be detected as failures. The time delay between failure and failure transfer was approximately .4 seconds. The failure transient was due to the loss of output amplitude response to the input during the .4 second delay. The maximum amplitude loss was .071 inches. In terms of the maximum actuator stroke of ± 2.9 inches, the maximum actuator transient deviation for an input loss occurred with the second channel input failure. For this failure,

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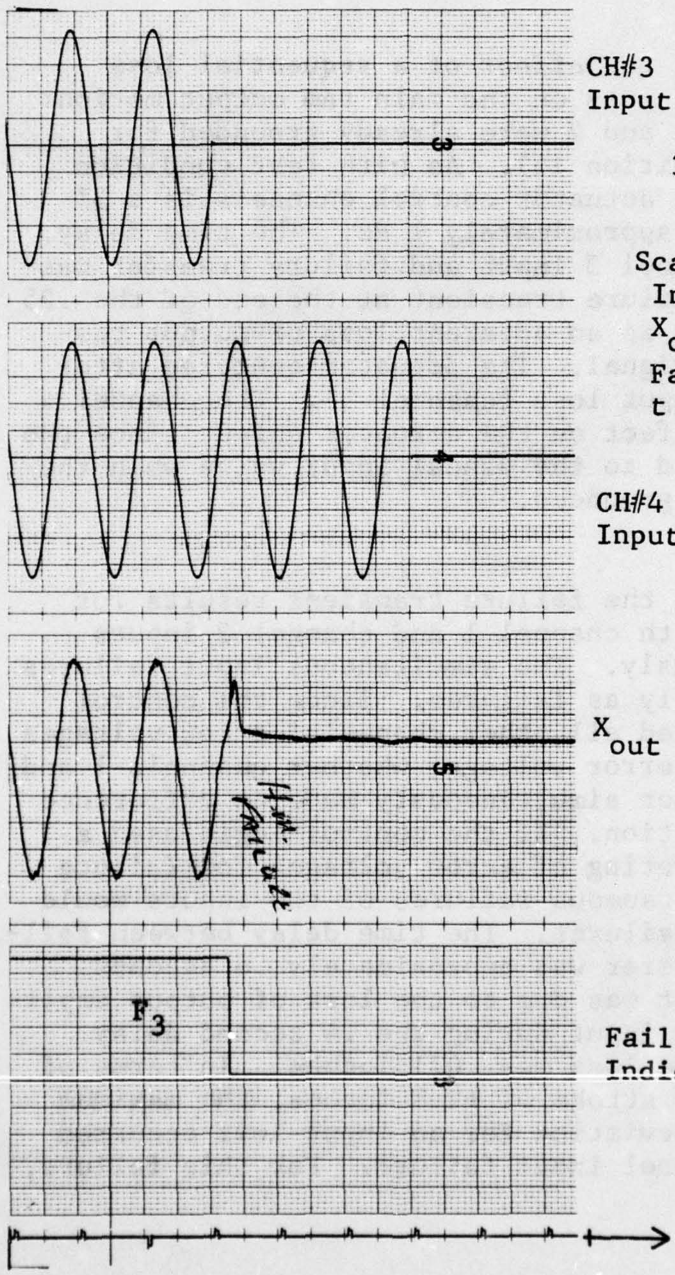
TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 14



3% Full Scale Output
1.0 Hz Sine Wave

Scale:
Inputs = .02 v/div
X_{out} = .0079 in/div
Fail Ind = 1.0 v/div
t = 10 div/sec

FIGURE 73
Failure Transients
Condition 14

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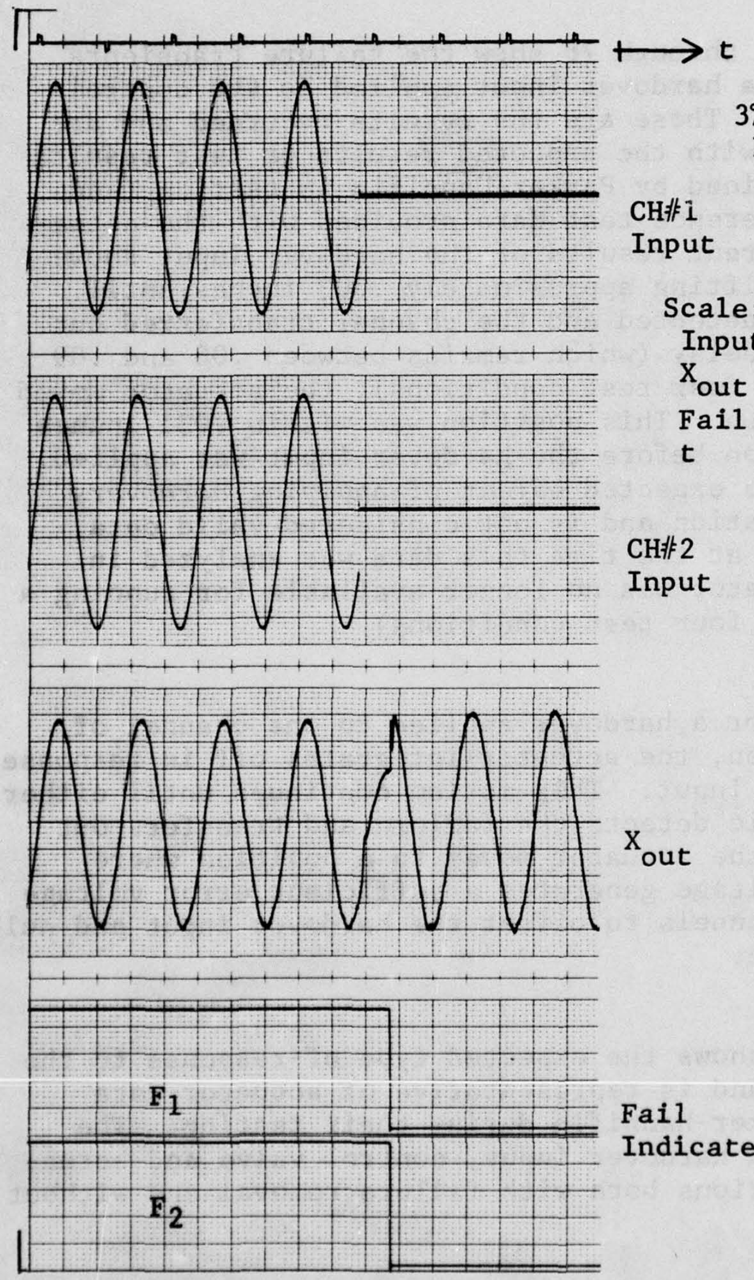
TEST - Failure Transients - Condition 15



3% Full Scale Output
1.0 Hz Sine Wave

Scale:
Inputs = .02 v/div
X_{out} = .0079 in/div
Fail Ind = 1.0 v/div
t = 10 div/sec

FIGURE 74
Failure Transients
Condition 15

the amplitude deviation was 1.62% of the 5.8 inch total stroke.

3.2.9.3 Electrical Hardover Input - Main Ram Transient

FIGURES 75 through 78 show the failure transients resulting from a hardover input applied to the control channel inputs. These are the results recorded and are not consistent with the expected results or test results previously obtained by Parker-Hannifin in testing (and provided in reference test data provided with the actuator). The apparent results of the hardover input shows the main ram shifting approximately .003 inches until the failure is detected and the channel transferred out. After the time delay (which remains between .06 and .09 seconds for all four test conditions), the actuator moved to a new position. This position was within .031 inches from the position before the hardover input was applied. This was not the expected effect of applying hardovers to the mechanization and is not considered valid data. (Unfortunately, at the time this data was analyzed in depth, the actuator was no longer available for running a retest of these four test conditions)

Normally for a hardover applied to one channel of the mechanization, the actuator integrates off in response to the hardover input. This motion continues until either the failure logic detects the failure and transfers out the channel or the actuator moves to a position where the feedback voltage generates a sufficient error voltage in the other channels to offset the hardover input and null the control valve.

FIGURE 79 shows the expected type of response to the hardover input and is representative of actuator data recorded by Parker-Hannifin during their testing. The figure shows the hardover input, control valve and actuator position motions both with failure removal and without

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Test Data

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Date Prepared: 12/7/76

TEST - Failure Transients - Condition 16

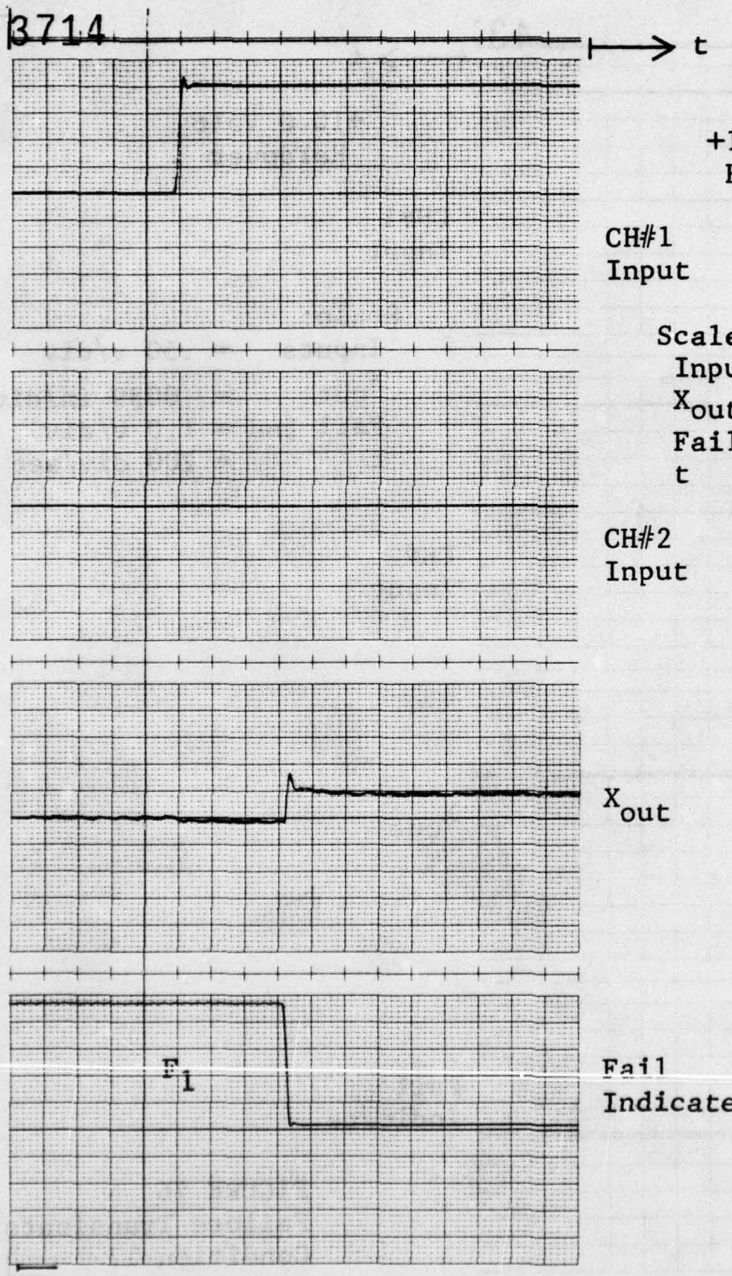


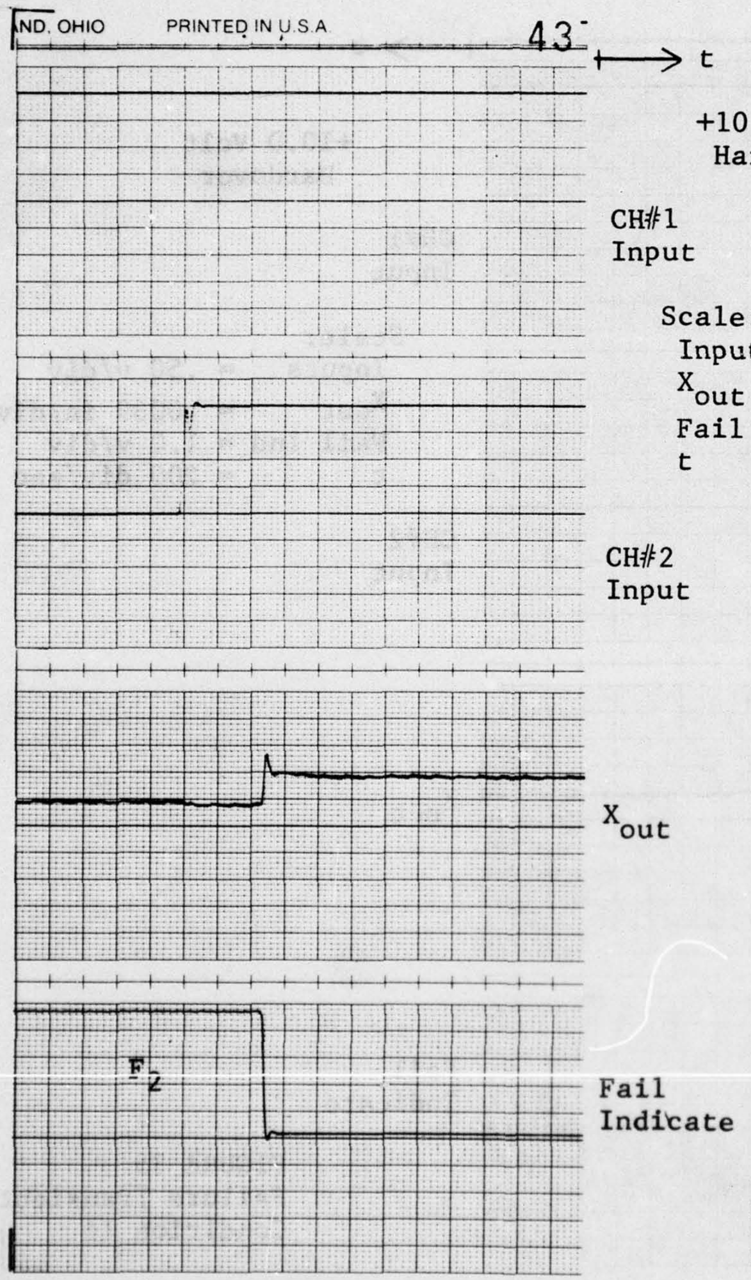
FIGURE 75
Failure Transients
Condition 16

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 17



Scale:
Inputs = .50 v/div
X_{out} = .0039 in/div
Fail Ind = 1.0 v/div
t = 200 div/sec

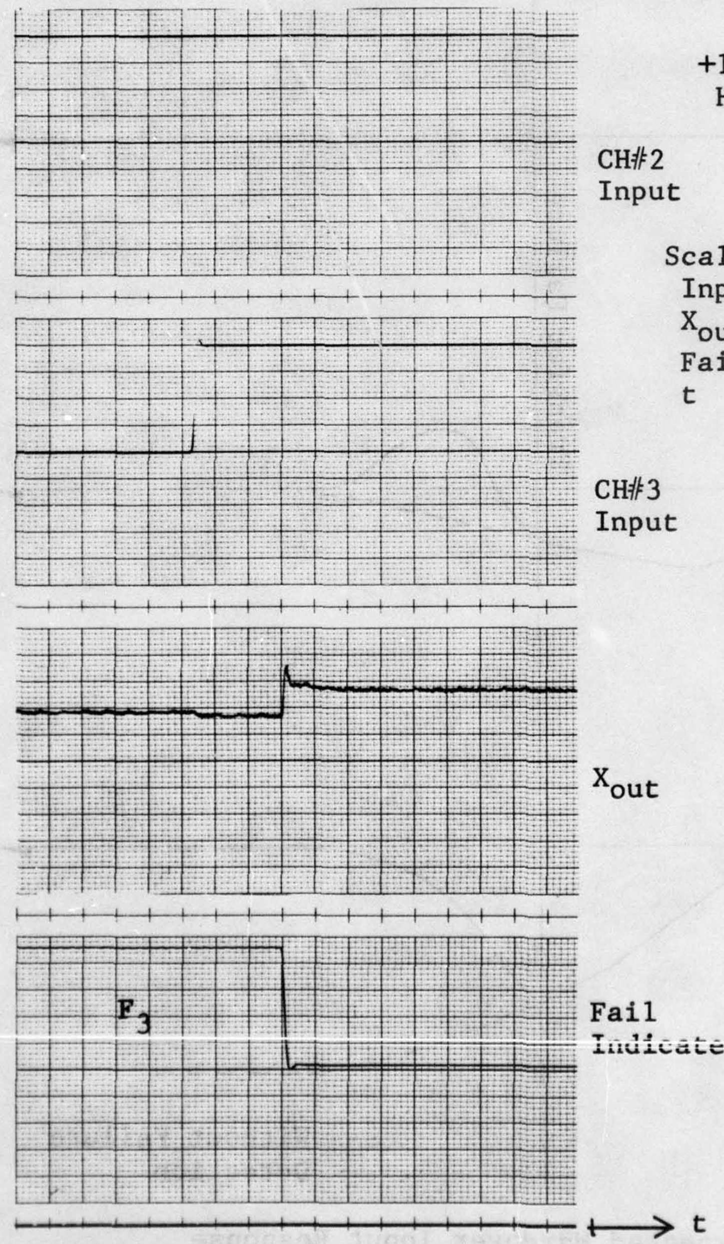
FIGURE 76
Failure Transients
Condition 17

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 18



Scale:

Inputs	=	.50 v/div
X_{out}	=	.0039 in/div
Fail Ind	=	1.0 v/div
t	=	200 div/sec

FIGURE 77
Failure Transients
Condition 18

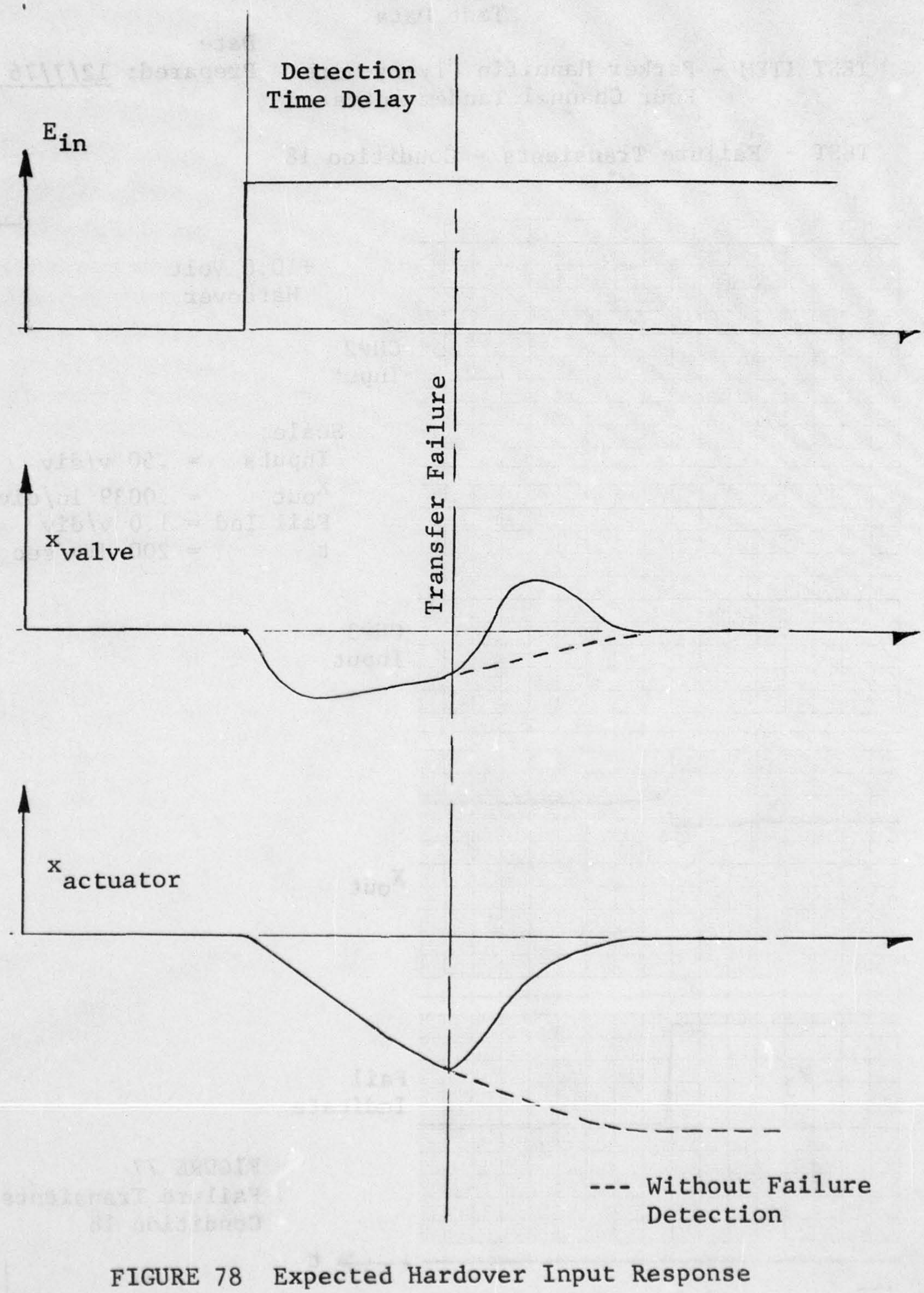


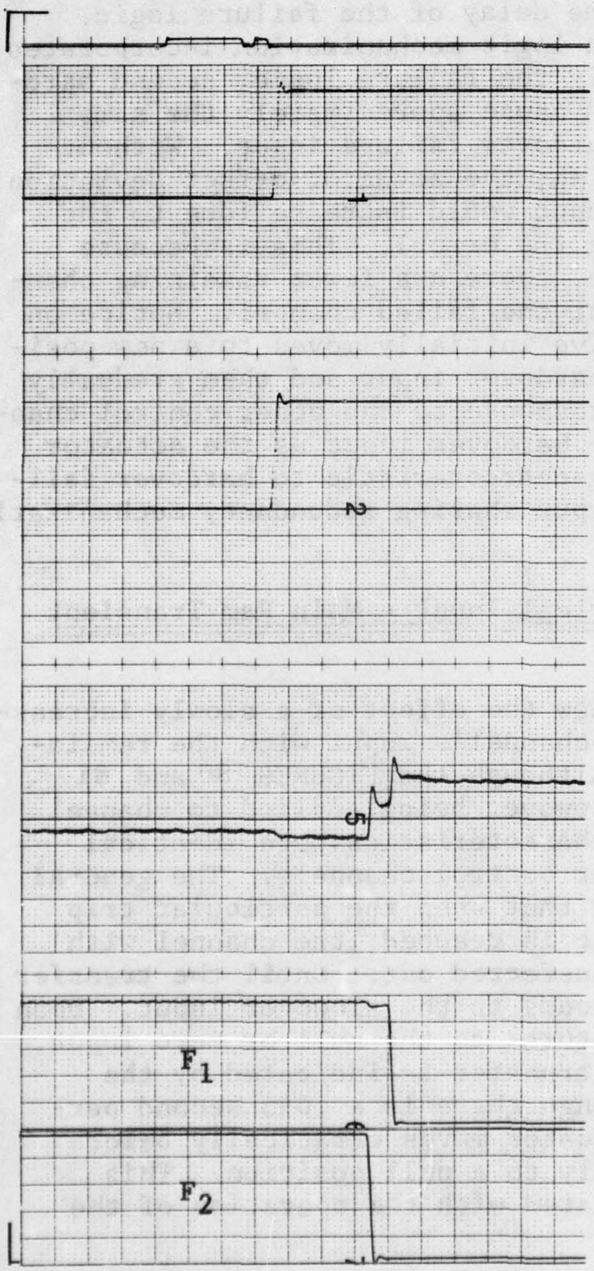
FIGURE 78 Expected Hardover Input Response

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire
Four Channel Tandem Actuator

Date
Prepared: 12/7/76

TEST - Failure Transients - Condition 19



t

+10.0 Volt
Hardover

CH#1
Input

Scale:
Inputs = 0.50 v/div
X_{out} = .0039 in/div
Fail Ind = 1.0 v/div
t = 200 div/sec

CH#2
Input

X_{out}

Fail
Indicate

FIGURE 79
Failure Transients
Condition 19

failure removal. For the distribution of loop gains and saturation levels provided in the Parker-Hannifin electronics, the maximum deviation due to the first failure hardover without failure detection would be approximately .200 inches. This displacement would be reduced by the transfer of control with the amount of reduction depending on the particular time delay of the failure logic. Since the Parker-Hannifin logic mechanization incorporates a gain changing circuit in the failure logic, second hardover failure inputs would cause approximately the same deviation as the first hardover failure input. Without the automatic gain changing, the actuator offset deviation to the second hardover input would increase (due to the feedback signal canceling the error). This is because with each channel failure, there are fewer remaining channels to collectively fight the failed channel. Notice on FIGURE the control valve initially moves to a new position in response to the hardover input and then gradually returns towards null in response to the other control channels trying to offset the hardover input as the actuator ram moves. This limiting characteristic to hardover failures is typical of an output sharing redundancy mechanization.

3.2.9.4 Slowover Electrical Input - Main Ram Transient

FIGURES 80 and 81 show the effect of a slowly increasing input applied to one channel's input with the remaining channels grounded. Although the FIGURES 80 and 81 show the effect of the slowover being applied to channel 1's input, the transfer characteristics were identical for ramp inputs into other control channels. The general effect of the slowover is that when the particular trip level of the failure logic is reached, the channel with the slowover input is transferred out. Until the transfer occurs, the actuator responds to the slowover input. Upon transfer, the actuator returns to the null or zero input position. After failure transfer is indicated by the fail indicate voltage change there is a .025 second period of time where the actuator moves erratically before starting to return smoothly to a null position. This motion is probably associated with the operation of the

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RESEARCH AND DEVELOPMENT OF AIRCRAFT CONTROL ACTUATION SYSTEMS.--ETC(U)
SEP 77 G D JENNEY F33615-75-C-3068
UNCLASSIFIED AFFDL-TR-77-91 NL

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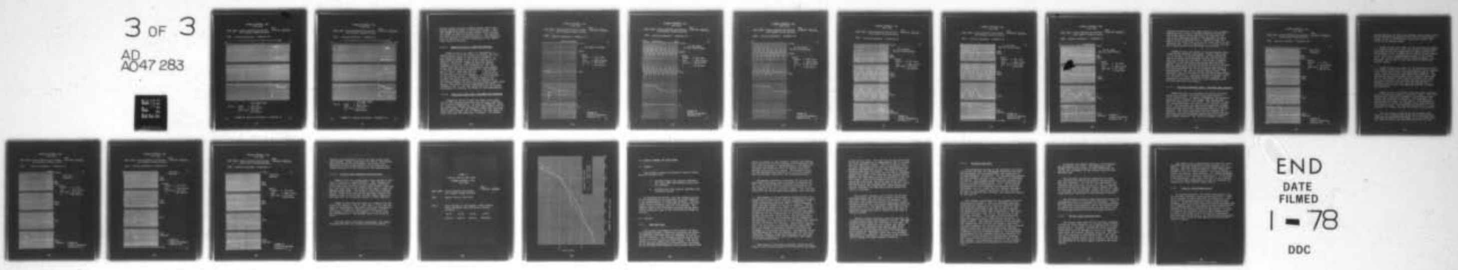


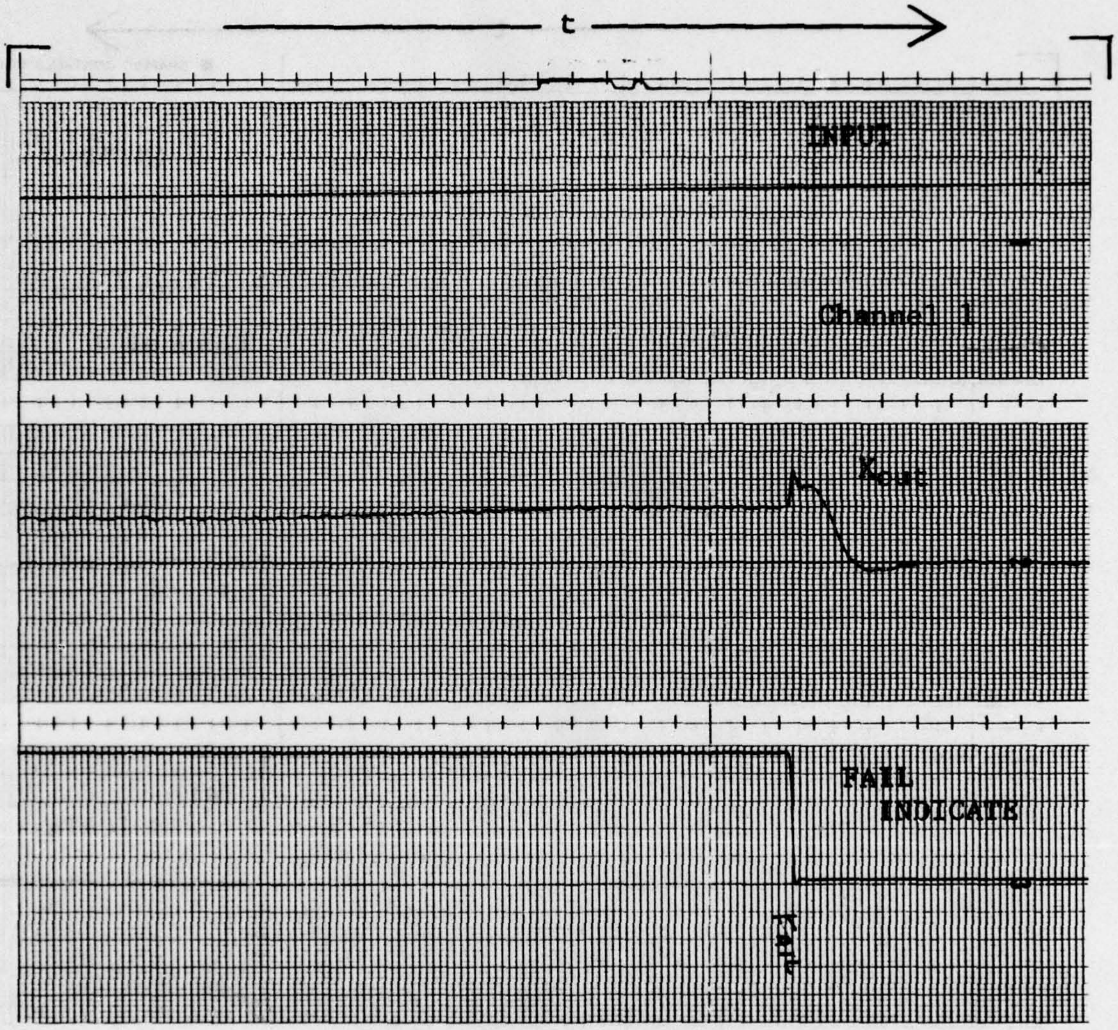
END
DATE
FILMED
1 - 78
DDC

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 20



SLOW RAMP INPUT

Scale:
Input = .05 v/div
X_{out} = .0039 in/div
Fail Ind = 1.0 v/div
t = 200 div/sec

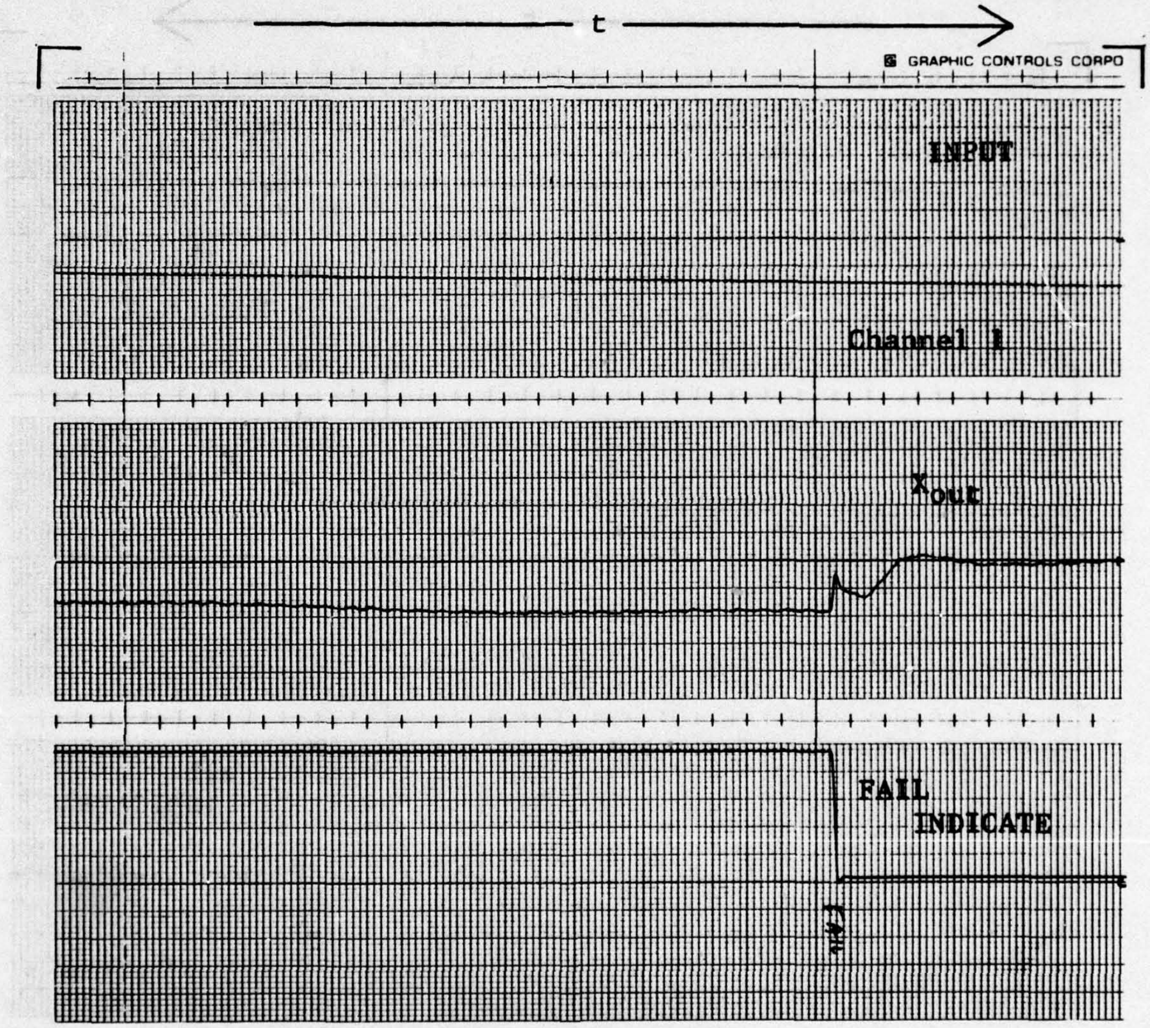
FIGURE 80 Failure Transients - Condition 20

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 21



SLOW RAMP INPUT

Scale: Input = .05 v/div
X_{out} = .0039 in/div
Fail Ind = 1.0 v/div
t = 200 div/sec

FIGURE 81 Failure Transients - Condition 21

failure removal and gain changing relays used in the failure detection logic of the control console. Note that FIGURE 80 shows the extend motion of the actuator and FIGURE 81 shows the retract motion. The transient for both motions is a simple return to a null condition with the deviation from null determined by the failure logic detection settings.

3.2.9.5 Hydraulic Failure - Main Ram Transient

FIGURE 82 shows the effect of a degradation of supply pressure P_1 on the output of the main ram, with all electrical inputs to the actuator grounded. A very slight deviation of the actuator output (on the order of .008 inches) occurs at the point where P_1 dropped to 1000 psi. FIGURE 83 shows the failure transient results for test condition 23. The test result shows that there is no apparent output change of the main ram while operating at the 5 Hz frequency when P_1 fails. Note that the traces for the P_1 and P_2 pressures reflect the line pressure variations due to the actuator cycling. FIGURE 84 for test condition 24 shows the effect on the actuator output of two failures of supply pressure. With the failure of P_1 (P_2 already failed) the output of the actuator simply stops moving. The failure effects demonstrated by these test conditions (22, 23, 24) were consistent with the results anticipated in reviewing the design of the mechanization.

3.2.9.6 Electrical Input Loss - Secondary Ram Transient

FIGURES 85, 86 and 87 show the effect of an input loss on the secondary ram motion for the test conditions 25, 26 and 27 respectively. As shown on FIGURE 85, there is a time delay between loss of each input channel and the failure transfer. For the channel 1 input loss, the time delay before transfer was 2.1 seconds. For the channel 2 input loss, the time delay was .8 seconds. The failure

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Test Data

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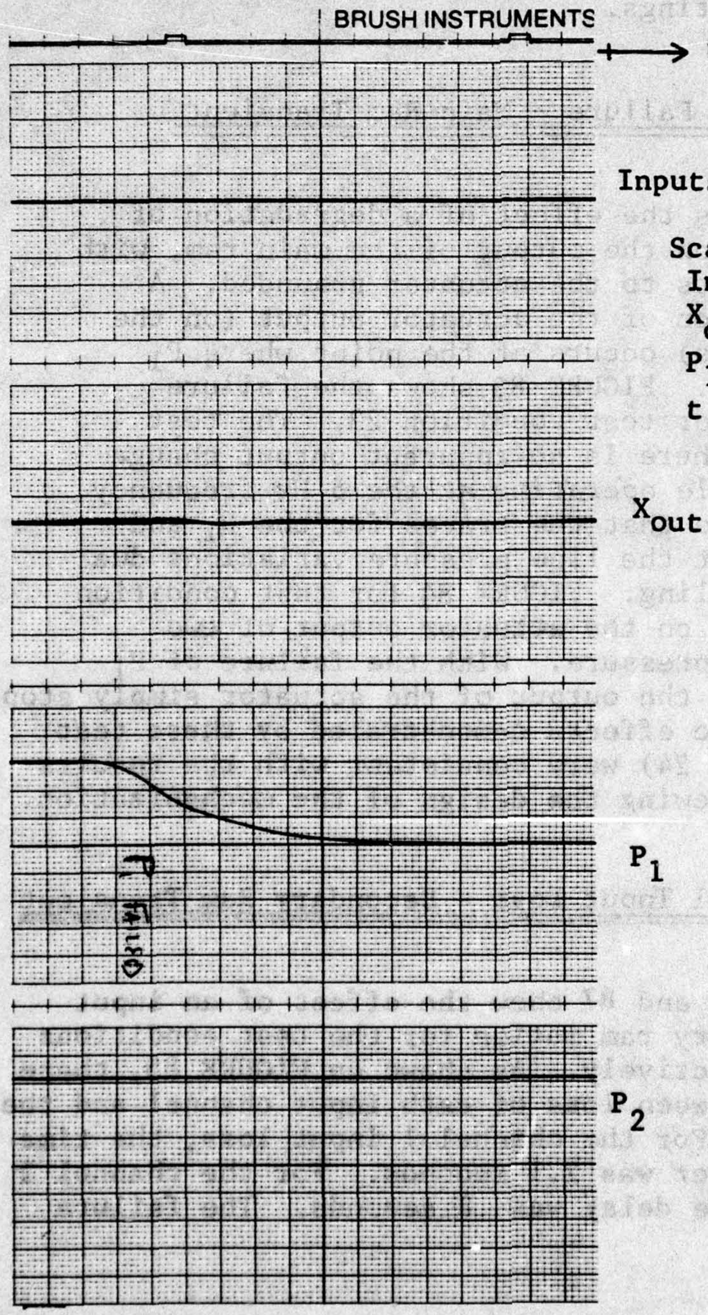
Date Prepared: 12/7/76

TEST - Failure Transients - Condition 22



Scale:
Inputs = 0.02 v/div
X_{out} = .0079 in/div
P_1 & P_2 = 200 psi/div
t = 50 div/sec

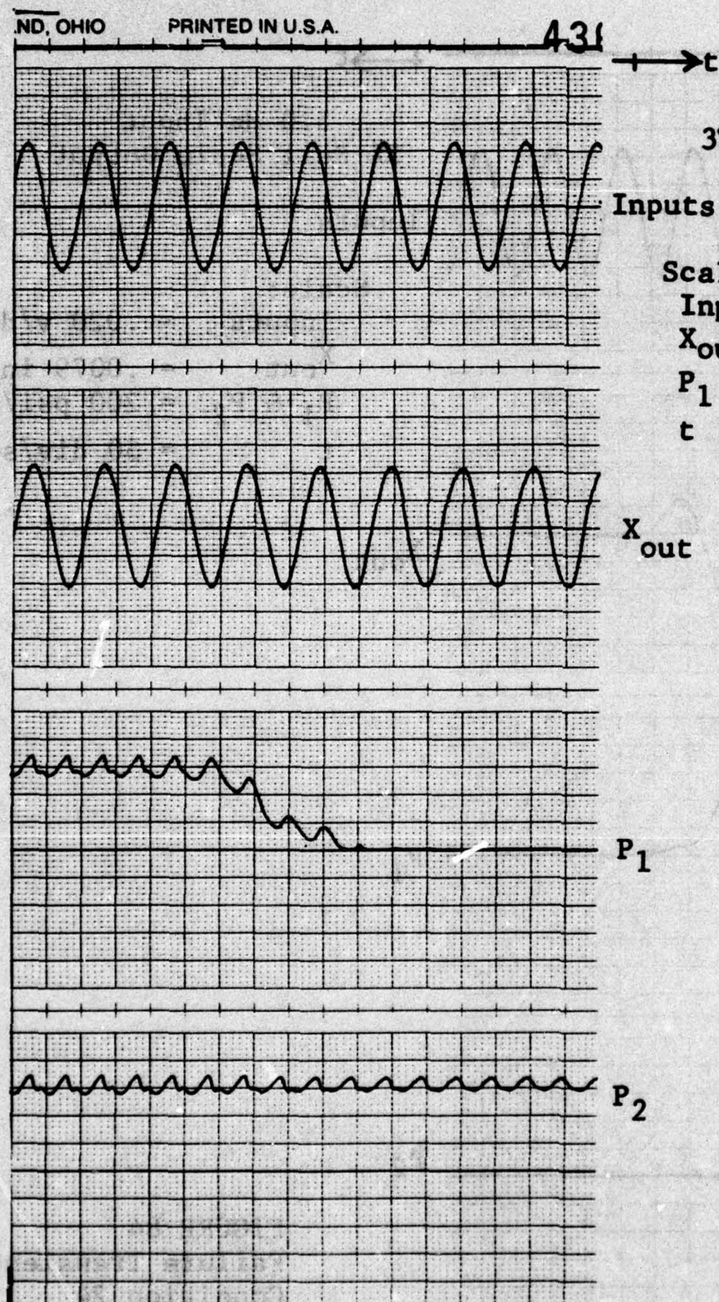
FIGURE 82
Failure Transients
Condition 22

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 23



5.0 Hz Input
3% Full Scale Output

Scale:

Inputs	= 0.02 v/div
X_{out}	= .0079 in/div
P_1 & P_2	= 200 psi/div
t	= 50 div/sec

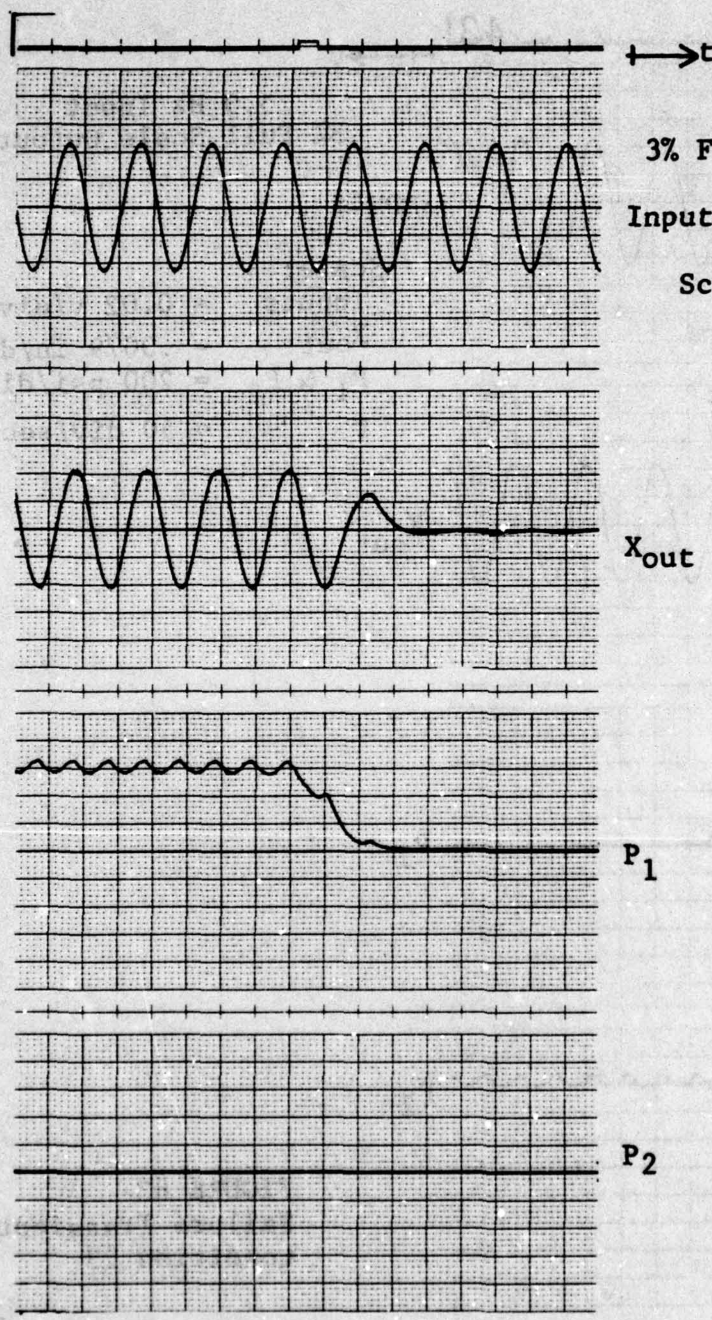
FIGURE 83
Failure Transients
Condition 23

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 24



5.0 Hz Input
3% Full Scale Output

Scale:
Inputs = .020 v/div
X_{out} = .0079 in/div
P_1 & P_2 = 200 psi/div
t = 50 div/sec

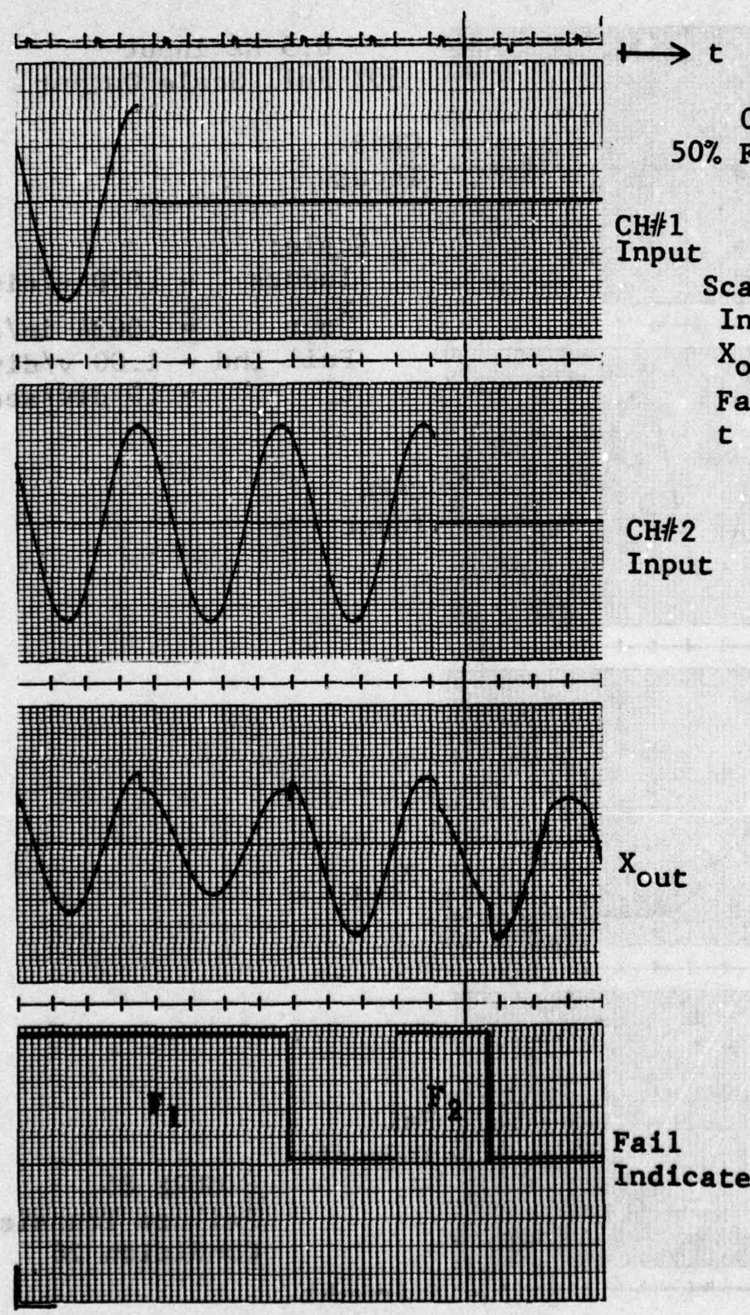
FIGURE 84
Failure Transients
Condition 24

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 25



0.5 Hz Input
50% Full Scale Output

Scale:
Inputs = 0.02 v/div
X_{out} = .0034 in/div
Fail Ind = 1.0 v/div
t = 10 div/sec

FIGURE 85
Failure Transients
Condition 25

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 26

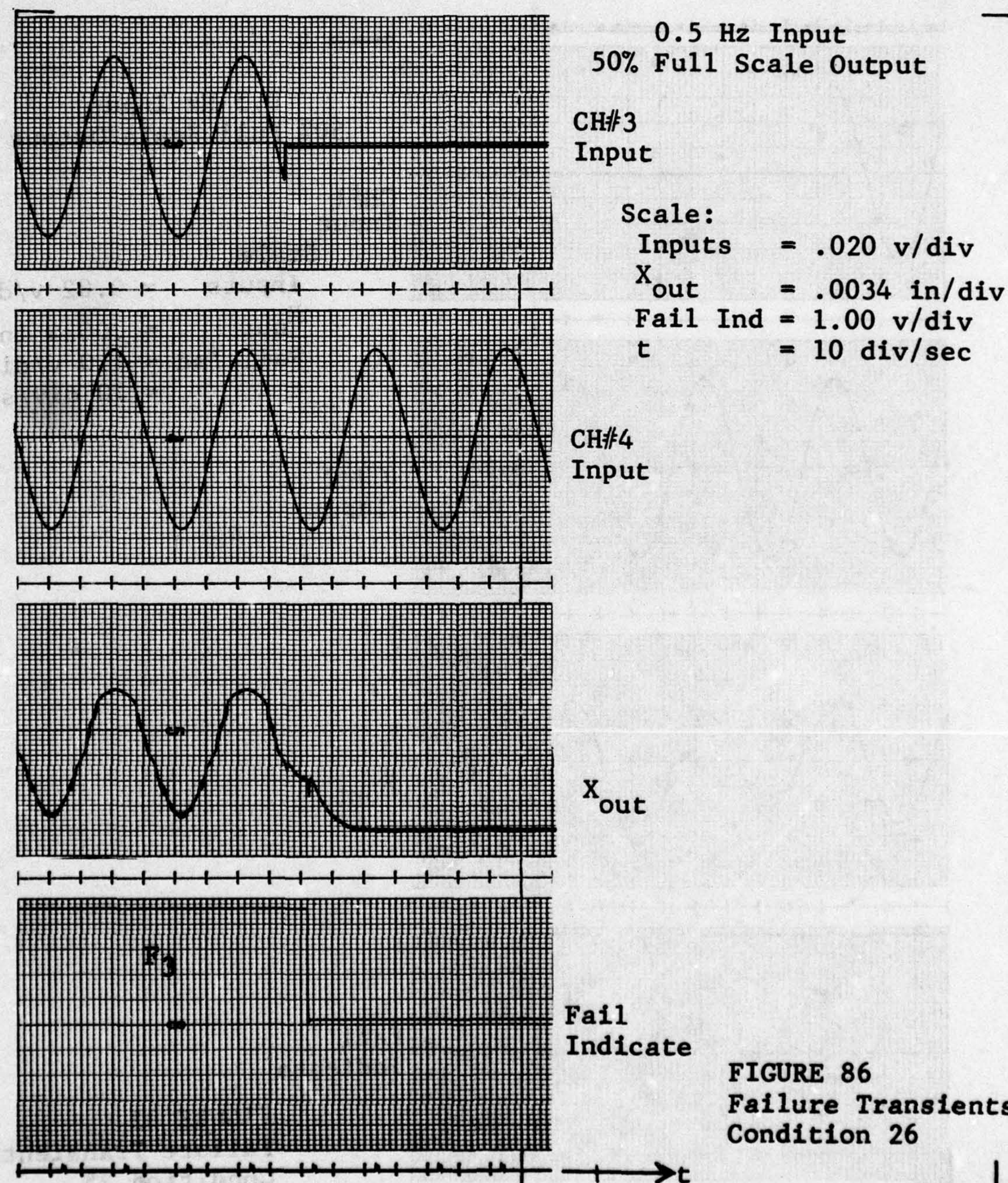


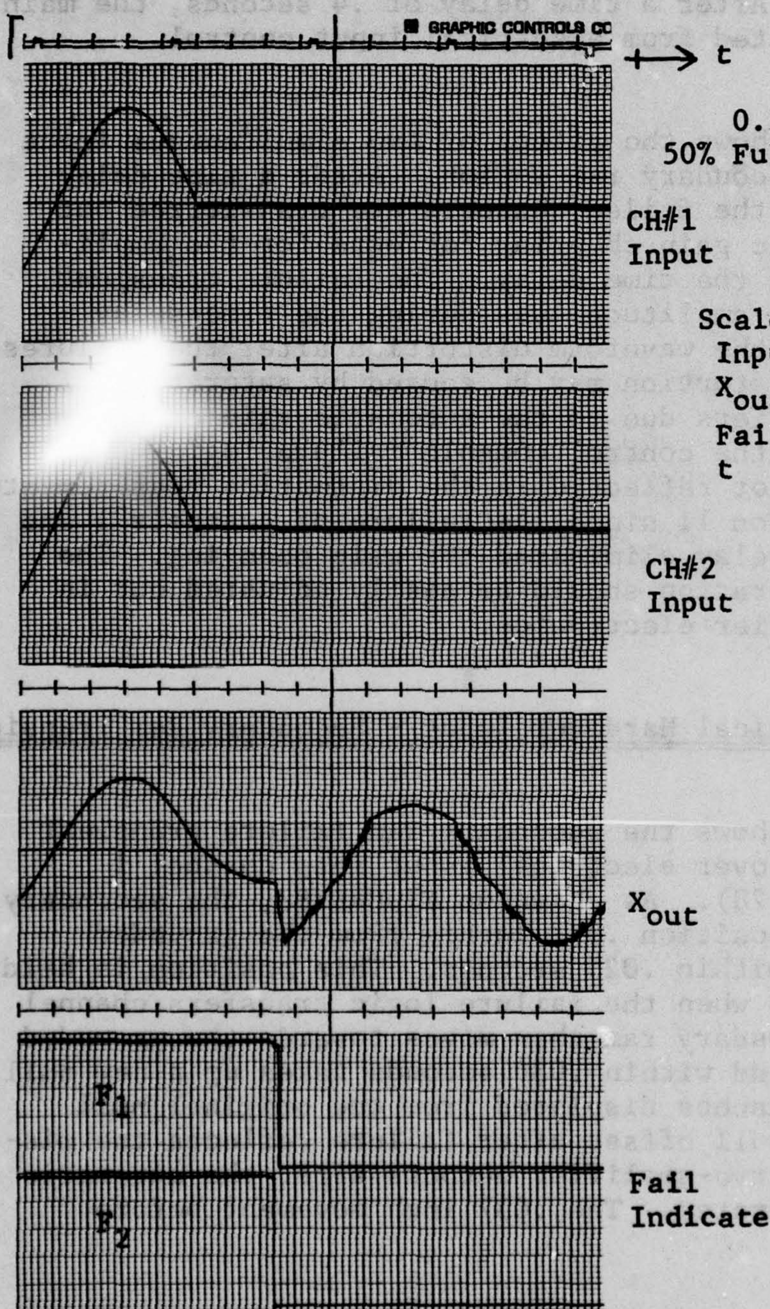
FIGURE 86
Failure Transients
Condition 26

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire
Four Channel Tandem Actuator

Date
Prepared: 12/7/76

TEST - Failure Transients - Condition 27



0.5 Hz Input
50% Full Scale Output

Scale:
Inputs = .02 v/div
X_{out} = .0034 in/div
Fail Ind = 1.0 v/div
t = 10 div/sec

FIGURE 87
Failure Transients
Condition 27

transient occurring on the output motion of the secondary ram was due to a loss of response amplitude during the time delay period. Note that after two failures, the top of the sinusoidal motion of the secondary ram shows some saturation characteristics. FIGURE 86 shows the effect of the third input loss on the output motion of the secondary ram. After a time delay of .4 seconds, the main ram is disconnected from electrical input control.

FIGURE 87 shows the effect of two simultaneous input losses on the secondary ram motion. After a time delay of 1.2 seconds, the failed channels are transferred out and the automatic gain changing corrects for the amplitude loss during the time delay. The failure transient amplitude is the amplitude loss during the time delay period. Notice the waveform distortion after the failures. This waveform distortion may be caused by saturation of the servo-amplifiers due to the automatic gain changing incorporated in the control console failure logic. The distortion was not reflected in the distortion measurements for test condition 11 since the failure of channels 1 and 2 by pulling a relay eliminated the gain changing. The asymetrical saturation should be easily adjusted out in the servo-amplifier electronics.

3.2.9.7 Electrical Hardover Input - Secondary Ram Transient

FIGURE 88 shows the secondary ram failure transient caused by a hardover electrical input into channel 1 (test condition 28). As shown on FIGURE 88, the secondary ram moves to a position .037 inches from the grounded input position within .025 seconds. This position is held for .040 seconds when the failure logic transfers channel 1 out. The secondary ram then moves towards the grounded input position and within .030 seconds takes up a new null position, .007 inches displaced from the original null position. The null offset after failure reflects the mismatch between servo-amplifier outputs after the automatic gain changer operates. The .037 inch movement before

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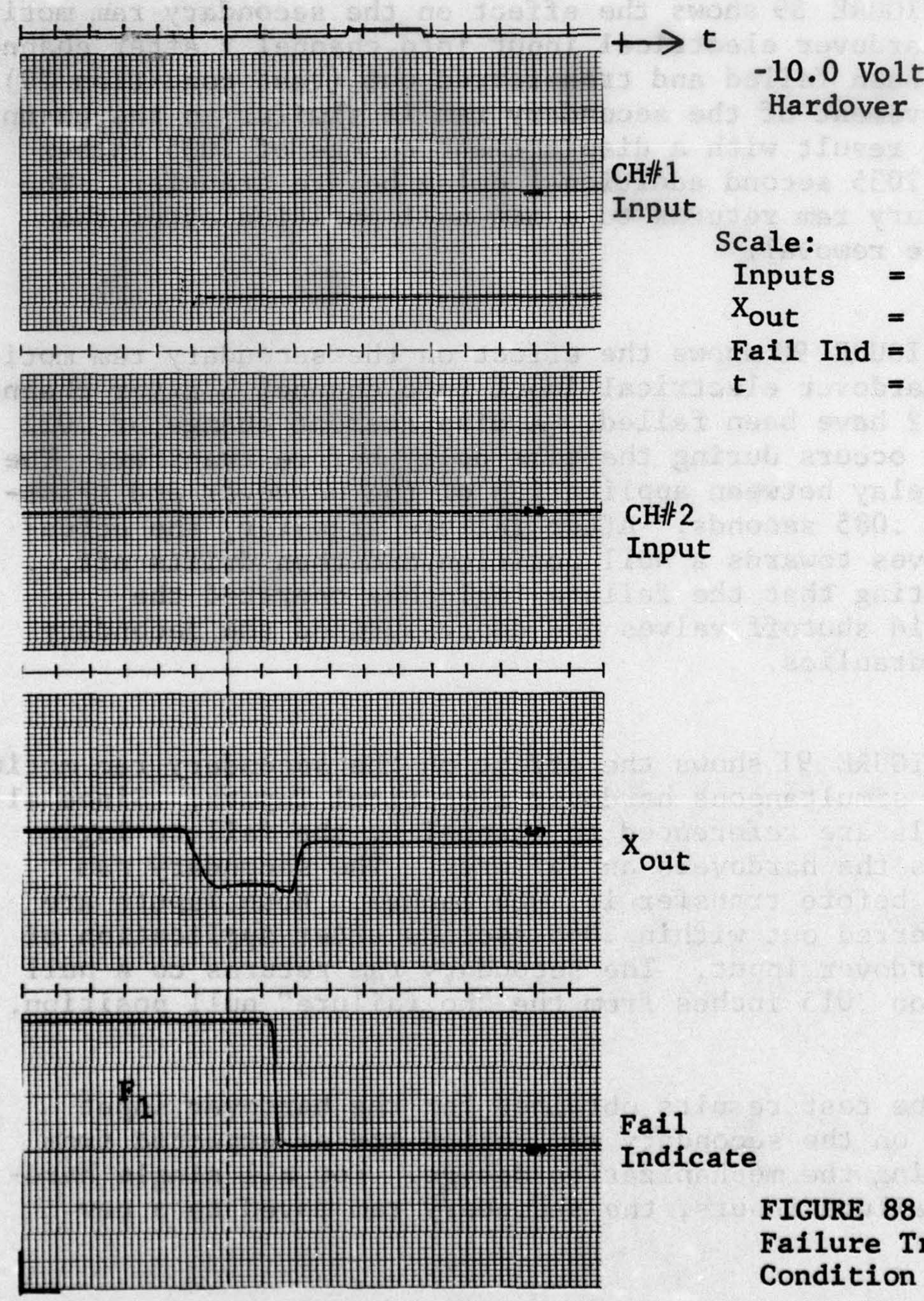
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 28



Scale:

Inputs	=	.5 v/div
X_{out}	=	.0035 in/div
Fail Ind	=	1.0 v/div
t	=	200 div/sec

FIGURE 88
Failure Transients
Condition 28

failure detection is 50% of the maximum control valve stroke in one direction and indicates that one servo-amplifier's output current is sufficient to stroke the control spool to 50% of its maximum stroke.

FIGURE 89 shows the effect on the secondary ram motion of a hardover electrical input into channel 2 after channel 1 has been failed and transferred out (test condition 29). The movement of the secondary ram is similar to the channel 1 test result with a displacement change of .035 inches and a .035 second additional delay before transfer. The secondary ram returns to a new null position after the failure removal.

FIGURE 90 shows the effect on the secondary ram motion of a hardover electrical input into channel 3 after channels 1 and 2 have been failed. A displacement change of .022 inches occurs during the time delay before transfer. The time delay between application of the hardover and transfer is .085 seconds. After failure transfer, the actuator moves towards a null position and then drifts off, indicating that the failure logic has operated the solenoid shutoff valves and depressurized the secondary ram hydraulics.

FIGURE 91 shows the effect on the secondary ram motion of two simultaneous hardover electrical inputs. Since all channels are referenced to channel 4, the failure logic detects the hardovers as failures. The secondary ram motion before transfer is .066 inches. Both inputs are transferred out within .065 seconds after application of the hardover input. The secondary ram returns to a null position .015 inches from the "no failure" null position.

The test results obtained for the hardover input effect on the secondary ram motion are as expected from reviewing the mechanization design. For all single hardover failure inputs, the secondary ram moved to a new

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Test Data

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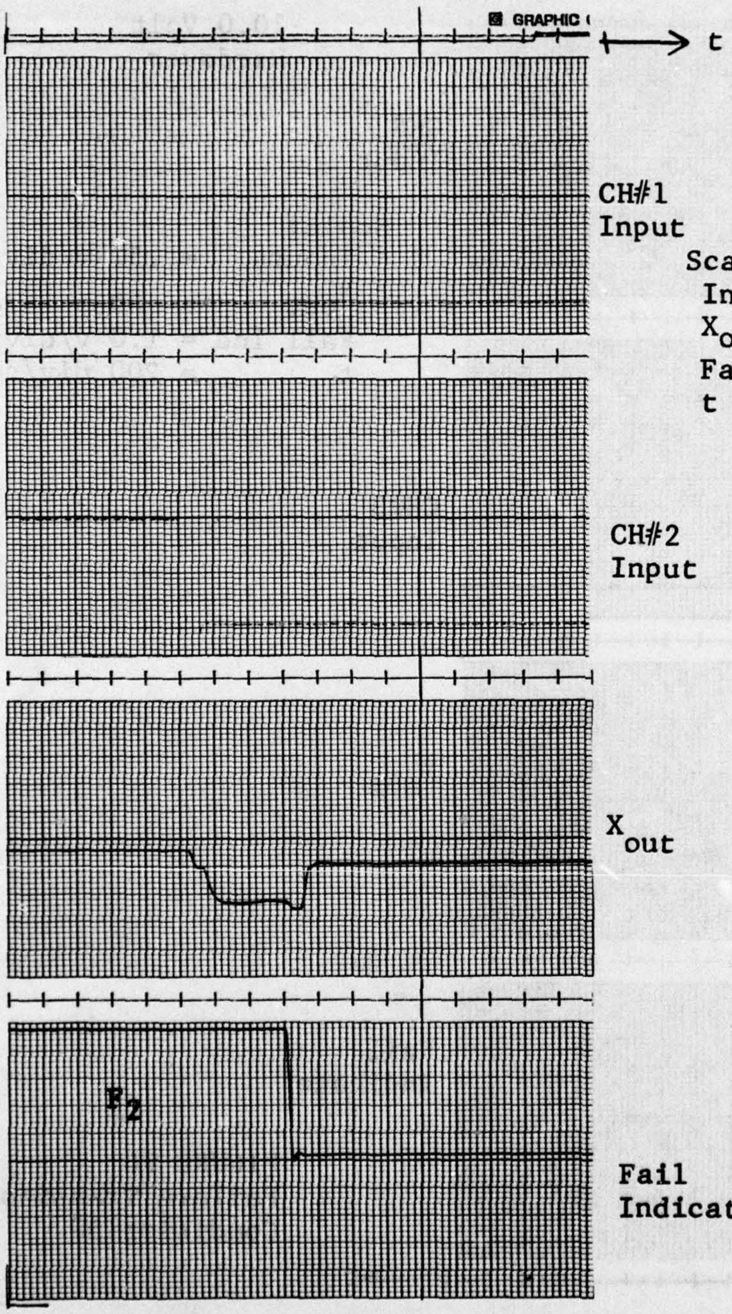
TEST - Failure Transients - Condition 29



Scale:
Inputs = .50 v/div
X_{out} = .0035 in/div
Fail Ind = 1.0 v/div
t = 200 div/sec

FIGURE 89
Failure Transients
Condition 29

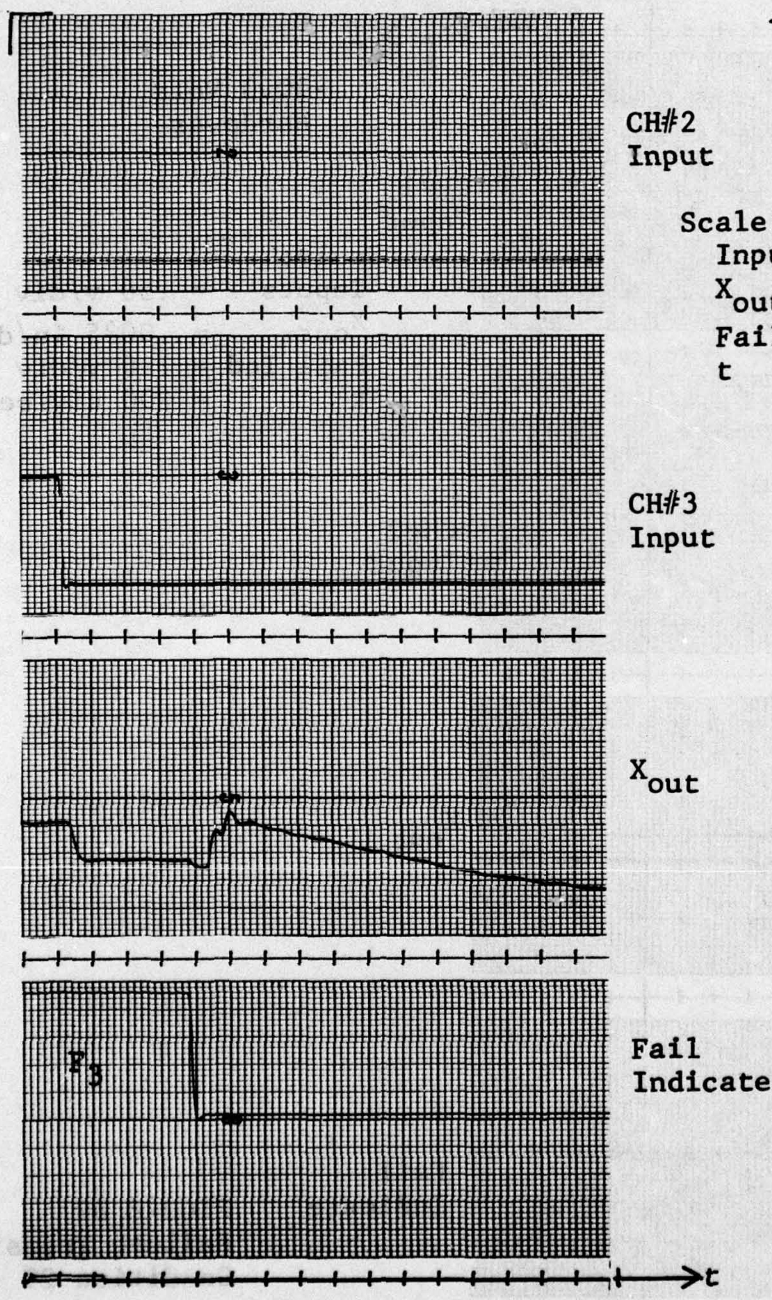
DYNAMIC CONTROLS, INC.
Test Data

Date Prepared: 12/7/76

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

TEST - Failure Transients - Condition 30

-10.0 Volt Hardover



Scale:

Inputs = .50 v/div
X_{out} = .0035 in/div
Fail Ind = 1.0 v/div
t = 200 div/sec

FIGURE 90
Failure Transients
Condition 30

DYNAMIC CONTROLS, INC.
Test Data

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

Date Prepared: 12/7/76

TEST - Failure Transients - Condition 31

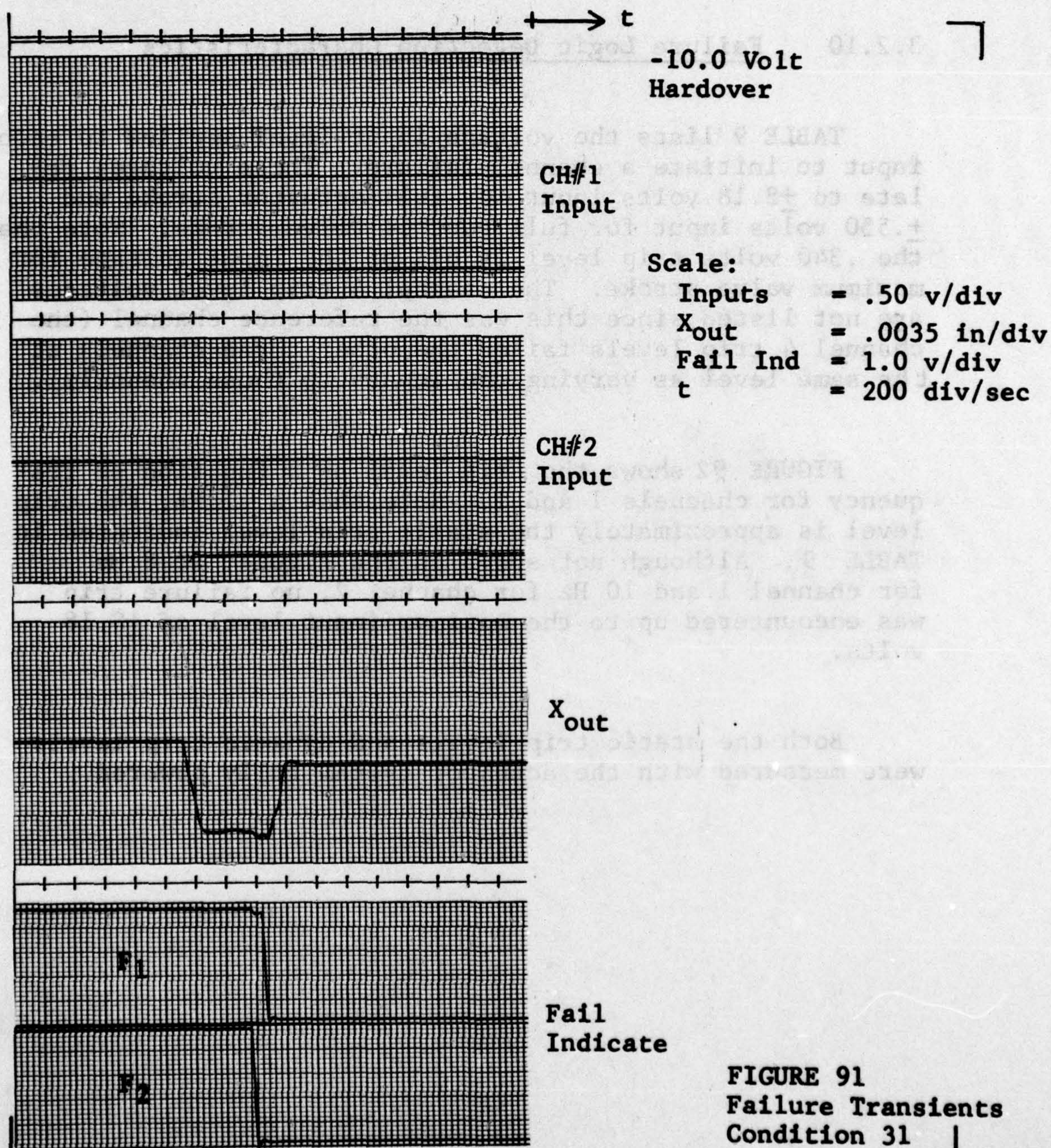


FIGURE 91
Failure Transients
Condition 31

position of approximately 50% of the peak stroke within .025 seconds. After a time delay of .065 to .085 seconds after application of the hardover, the failure logic transfers out the failed channel and the secondary ram either returned to a null position or was depressurized.

3.2.10 Failure Logic Detection Characteristics

TABLE 9 lists the voltage input level applied to each input to initiate a channel failure. These voltages relate to ±8.18 volts input for full actuator stroke and ±.550 volts input for full control valve stroke. Note that the .340 volts trip level is 61% of the input voltage for maximum valve stroke. The channel 4 trip level voltages are not listed since this was the reference channel (the channel 4 trip levels failed the other three channels at the same level as varying the inputs to those channels).

FIGURE 92 shows the trip level as a function of frequency for channels 1 and 2. Note that a .1 Hz, the trip level is approximately the static trip level indicated in TABLE 9. Although not shown on the figure, at 8 Hz for channel 1 and 10 Hz for channel 2, no failure trip was encountered up to the maximum input level of ±8.18 volts.

Both the static trip levels and dynamic trip levels were measured with the actuator system fully powered.

TABLE 9

Channel Failure Trip Level

DYNAMIC CONTROLS, INC.
Test Data

Date
Prepared: 12/6/76

TEST ITEM - Parker Hannifin Fly-By-Wire Four Channel Tandem Actuator

TEST - Channel Failure Trip Level

Test A - Input Voltage to each Channel (other channel inputs grounded) that initiates a failure detection

CH #1	CH #2	CH #3	CH #4
±340 mv	±350 mv	±320 mv	Reference

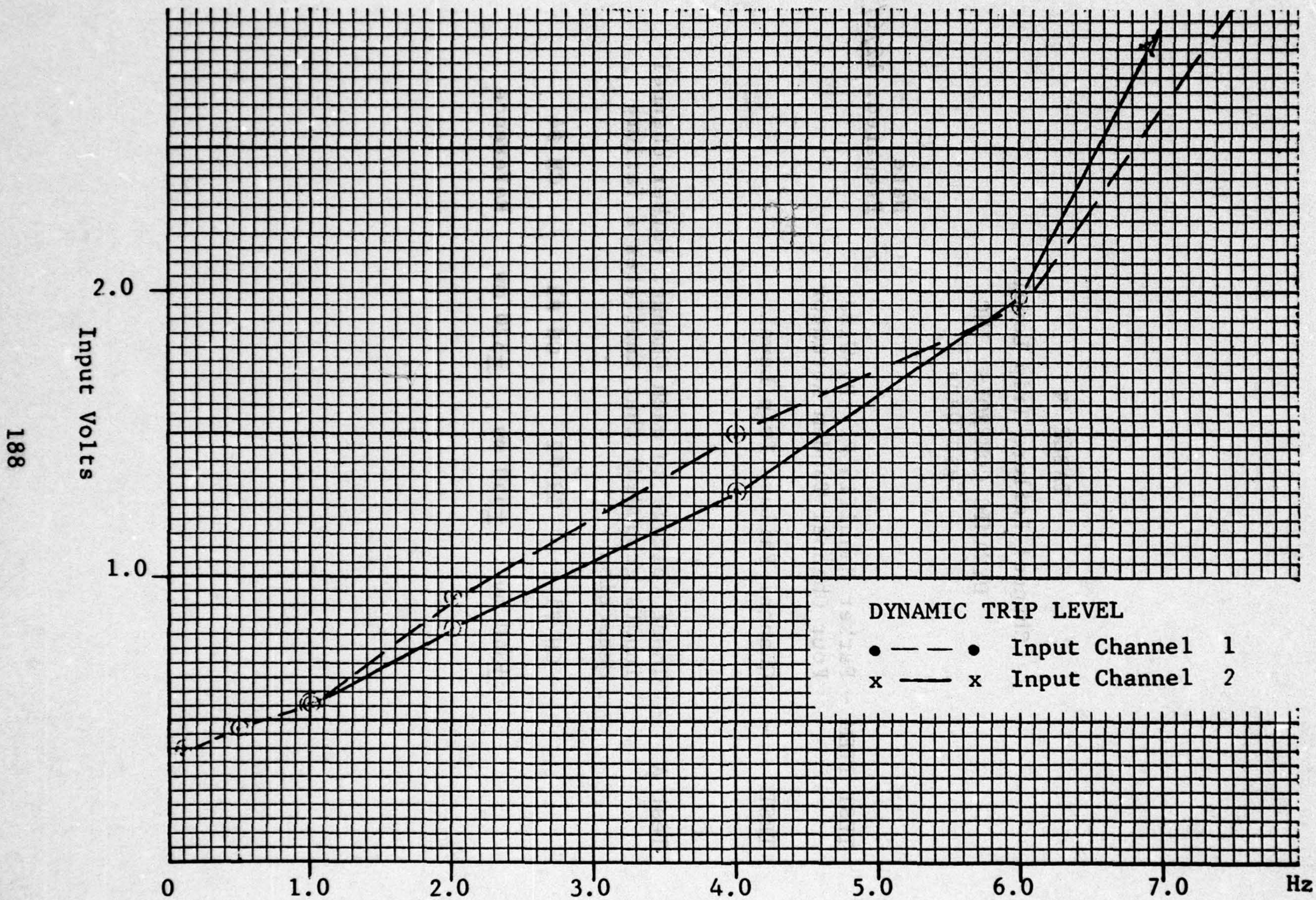


FIGURE 92 Dynamic Trip Level

4.0 RESULTS SUMMARY AND CONCLUSIONS

4.1 General

The actuator worked as intended in terms of redundancy in as much as it:

1. Provided single fail operate redundancy for servo valve and hydraulic power supply failures.

2. Provided dual fail operate redundancy for electrical inputs.

As described previously, only the actuator portion of the mechanization was considered by Parker-Hannifin to be representative of flight type hardware. The electronic logic provided to work with the actuator was designed to only indicate principle of operation. The comments made in the following subsection should therefore be viewed in light of the two different design objectives.

4.2 Specific

4.2.1 Main Ram Tests

The nominal performance of the actuator in terms of frequency response, threshold, hysteresis and linearity appeared consistent with non-redundant electrohydraulic actuators. The frequency response of the actuator was essentially flat to approximately 10 Hz and appeared as a well damped high order system. The values of the apparent hysteresis and threshold were decreased by the low amplitude hunting of the actuator output which acted as a dither to the actuator. Without the hunting, which apparently could be eliminated by stiffening a control link (according to Parker-Hannifin), the measured threshold and hysteresis would be greater than those recorded during this test series. The measured values for the hysteresis and threshold for the total actuator were attributable entirely to the secondary actuator.

The nominal saturation velocities for the main ram agreed with the design values provided by Parker-Hannifin. The absolute harmonic distortion measurements for the main ram motion were obscured by the amount of carrier signal in the main ram motion signal. Only relative values for the various operating conditions were recorded.

The changes in the performance characteristics with the different failure modes and test conditions were measurable, but in most cases, of minor significance. The static threshold varied from .022% to .170% of maximum input from the baseline to the worst condition. The dynamic threshold varied from .046% to .16% of maximum input from the baseline to the worst test condition. The frequency response did vary from the baseline measurement, in part due to over-compensation by the automatic gain changer incorporated in the control console electronics. The variation in the -3db frequency was 41% compared to the baseline. The variation in the -90° phase lag frequency was 32% compared to the baseline. The variation was essentially an increase in response, rather than a degradation. The distortion varied with the test conditions. The worst change in the output harmonic distortion was a change of 11.4 percent distortion. The apparent hysteresis increased 72% from the baseline value for the worst condition. However, since the hysteresis was less than .1% for full scale for all test conditions, the change is of minor significance.

The results of the output transient testing for the effect of the failure removal was influenced by the design of the control logic. The logic was set for input error detection corresponding to approximately 50% of the maximum servo amplifier current. This is a typical value for error detecting failure logic mechanizations and is probably representative of any logic mechanization that would be used with the actuator. In terms of failure transient for input loss while driving with a sinusoidal signal, the amount of the transient was directly determined by the time delay circuit incorporated in the control logic. Since an RC charging circuit was used to create the time delay, the delay time varied with the amplitude of the error signal applied to the RC circuit. For the various test conditions for establishing the failure transient, the time delay period varied from .06 to 2.1 seconds.

The slowover transient test results for the main ram demonstrated that the main ram moved .039 inches from null before the input failure was detected. Upon detection, the actuator returned to null with a minor deviation lasting for .025 seconds immediately after the failure detection. The amplitude of the failure transients due to a loss of input were simply the loss of amplitude between the time of failure and the time of failure transfer.

Hardover failure transient tests for the main ram yielded results which are considered invalid. The mechanization should limit the transient to less than .200 inches actuator deflection even without any failure detection. The transient with failure logic which transfers the failed input out with minimum delay would reduce the transient below the .200 inch amplitude deflection. Hydraulic supply failures produced essentially no transients. The output of the actuator did not change for single hydraulic failures.

4.2.2 Secondary Ram Tests

The performance testing of the secondary ram (control valve) with the main ram disengaged showed that the nominal performance of the mechanization was comparable to an electrohydraulic servovalve. The threshold measurements for the secondary ram gave values typical of an aerospace servovalve. The frequency response of the secondary ram was flat to approximately 38 Hz. The 90° phase lag frequency occurred at approximately 25 Hz. The hysteresis measurements for the secondary ram indicated that the hysteresis was 2 to 3 times that of a typical aerospace servovalve. The harmonic distortion for the 5 and 10 Hz input frequencies gave secondary ram distortion figures of less than 4%.

The change in performance of the secondary ram with failures was noticeable. The test procedure used for evaluating the effect of two electrical failures eliminated the gain changing of the failure logic, so that the failure effects were indicative of the secondary ram mechanization without gain compensation. The static threshold increased from .32% to .86% for loss of two electrical channels. The dynamic threshold increased from .68% to 1.18% for the same failure condition. A lesser threshold increase occurred with loss of one hydraulic supply. The frequency response of the secondary ram changed less than 22% for the failure conditions. With gain changing, the threshold would not have increased nearly as much with loss of two electrical channels. Harmonic distortion increased slightly with the failure conditions, but still remained below 4%. The hysteresis measurements for the secondary ram motion showed an increase to 10% for the loss of two electrical channels. This value would not have been effected by use of the gain changer. The saturation velocity of the secondary ram remained essentially unchanged with failure conditions.

In general, the failure effects on the secondary ram performance were minor. The magnitude of the changes that occurred would not have significant impact on the performance of the actuator used with the secondary ram.

The secondary ram failure transients for input loss reflected the results observed in measuring the main ram transients. As with the main ram motion, the transient that does occur is due to a loss of response amplitude during the time delay period between the loss of input and failure transfer. After loss of two inputs, the secondary ram showed some waveform distortion resembling amplitude saturation in one direction of motion.

The electrical hardover input transients caused the anticipated result in the secondary ram motion. Upon a hardover input into one channel, the secondary ram moved to a position corresponding to 50% of the stroke in one direction and stayed there during the time delay (.065 to .09 seconds) between failure and failure transfer.

4.2.3 Failure Logic Characteristics

The failure logic used with the actuator exhibited a detection level dependency on frequency which limited the ability of the logic to detect failures of an oscillatory nature. Normally, the rolloff of the detection sensitivity would be designed to occur at a frequency above where the actuator response rolls off. The static trip level measured at approximately 60% of the input voltage for maximum control valve stroke. The time delay characteristics before failure transfer varied with the amplitude of the error signal created by the input failure.

The failure logic voting method for input and servo-amplifier failures compared all other channels to one channel. This did allow detection of simultaneous input failures, but also allowed a failure of the reference channel to fail all other channels. The logic did demonstrate that nominal characteristics of a voting mechanization applied to the actuator mechanization. In an actual flight application, the logic would have to be converted to a true voting configuration in order to eliminate the single point total failure characteristic.

4.2.4 Comments and Recommendations

As stated previously, the nominal mechanization met the intended redundancy operating characteristics. There was no attempt in this evaluation to estimate the reliability of the mechanization or conduct a failure mode analysis. Since the electronics used with the actuator are an inseparable part of the overall actuation mechanization, the techniques used in mechanizing the electronics are critical to the overall success of the concept. In order to evaluate the potential of the overall mechanization in terms of providing a given reliability improvement, the electronics would have to be conceived and implemented with the same concern as that applied to the electrohydraulic actuator.

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