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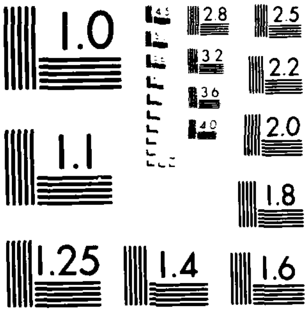

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A PARALLEL FLY-BY-WIRE HELICOPTER CONTROL SYSTEM

BELL HELICOPTER TEXTRON
P.O. Box 482
Fort Worth, Texas 76101

March, 1982

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Failure Tolerance Level (FTL)
Single Fail-Operate
Dual Fail-Operate
Redundancy Level
Quadruplex
Electronic Control Unit (ECU)
Electrohydraulic Servo Valve (EHSV)
Failure Management
Actuation System

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

The fly-by-wire actuation system uses quad-redundant electrical control paths to drive a dualized hydraulic actuator with mechanical reversion capability. The ECU provides self-contained characteristics in that it includes actuator drive circuitry, auto-track circuitry to keep the four EHSVs synchronized, and the failure management function. It can be interfaced for operation with other control media, e.g., digital/optics. The self-contained characteristics allow the actuation system to be used in a distributed type system as well as a centrally controlled-type system.

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FOREWORD

This report was prepared by Bell Helicopter Textron for the Aircraft and Crew Systems Technology Directorate, Naval Air Development Center, Warminster, Pennsylvania under Contract N62269-80-C-0128. Program direction was administered by Mr. Charles R. Abrams, Technical Manager of Navy Flight Control Research and Development at the Naval Air Development Center and M. R. Murphy, Senior Staff Engineer - Advanced Controls at Bell Helicopter Textron. Technical support was provided by Walter W. Kaniuka, Naval Air Development Center.

The author wishes to acknowledge the efforts of Frank DePauw, Senior Hydraulics Engineer, for providing support during the design, test, and evaluation of the FBW/Mechanical Control System for use in a potential test helicopter.

A

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LIST OF ACRONYMS AND ABBREVIATIONS

AFCS	Automatic Flight Control System
CKT	Circuit
CM	Control Motion
ECU	Electronic Control Unit
EHSV	Electrohydraulic Servo Valve
FB	Feedback
FBW	Fly-By-Wire
FM	Failure Management
FMEA	Failure Modes and Effects Analysis
4V-ACC	4-Valve Actuation Control Concept
FTL	Failure Tolerance Level
HYD	Hydraulic

TABLE OF CONTENTS (Concluded)

I/O	Input/Output
LVDT	Linear Voltage Displacement Transducer
OSC	Oscillator
Pos	Position
REG	Regulated
SOL	Solenoid
TP	Test Point
XDUCER	Transducer

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1. SUMMARY

This report describes a technology program for a candidate Fly-By-Wire (FBW) Control System with an auxiliary (back-up) mechanical control system for use in a potential test helicopter. In addition to covering the basic program, it includes an updated discussion on the 4-Valve Actuation Control Concept (V4-ACC), and a copy of the Integration Test Plan in the Appendices.

1.1 SCOPE

The program included the design, fabrication, test, and evaluation of a laboratory model of the candidate actuation system. The system basically consists of the V4-ACC module with a mechanical back-up control that can be used as a permanent function or to enhance safety during the initial phase of an anticipated development flight test program. The current program entailed developing electronic circuitry that subsequently can be used in a flight test model; modifying the existing V4-ACC module so that it would accept a mechanical control input as well as a quad electrical input; and conducting operational suitability and failure mode effect tests on the system depicted in block diagram form in Figure 1. The major equipments are shown in Figures 2, 3, and 4.

The concept of this control system can be applied to almost any helicopter, tilt rotor, or fixed wing control system.

1.2 OBJECTIVE

The objective of this program was to evaluate the V4-ACC mechanical system relative to its potential use in a potential test helicopter. The evaluation primarily related to operational characteristics, failure mode effects, and the automatic/manual reversion to the mechanical back-up control system. The objective was accomplished by developing a laboratory test model of the FCS, installing the model on a suitable test stand, and conducting laboratory tests in accordance with the Integration Test Plan (see Appendix B).

1.3 CONCLUSIONS

A laboratory model of the V4-ACC has been evaluated within the scope of this program and is recommended as a valid candidate for use in a potential test helicopter. Implementation of the

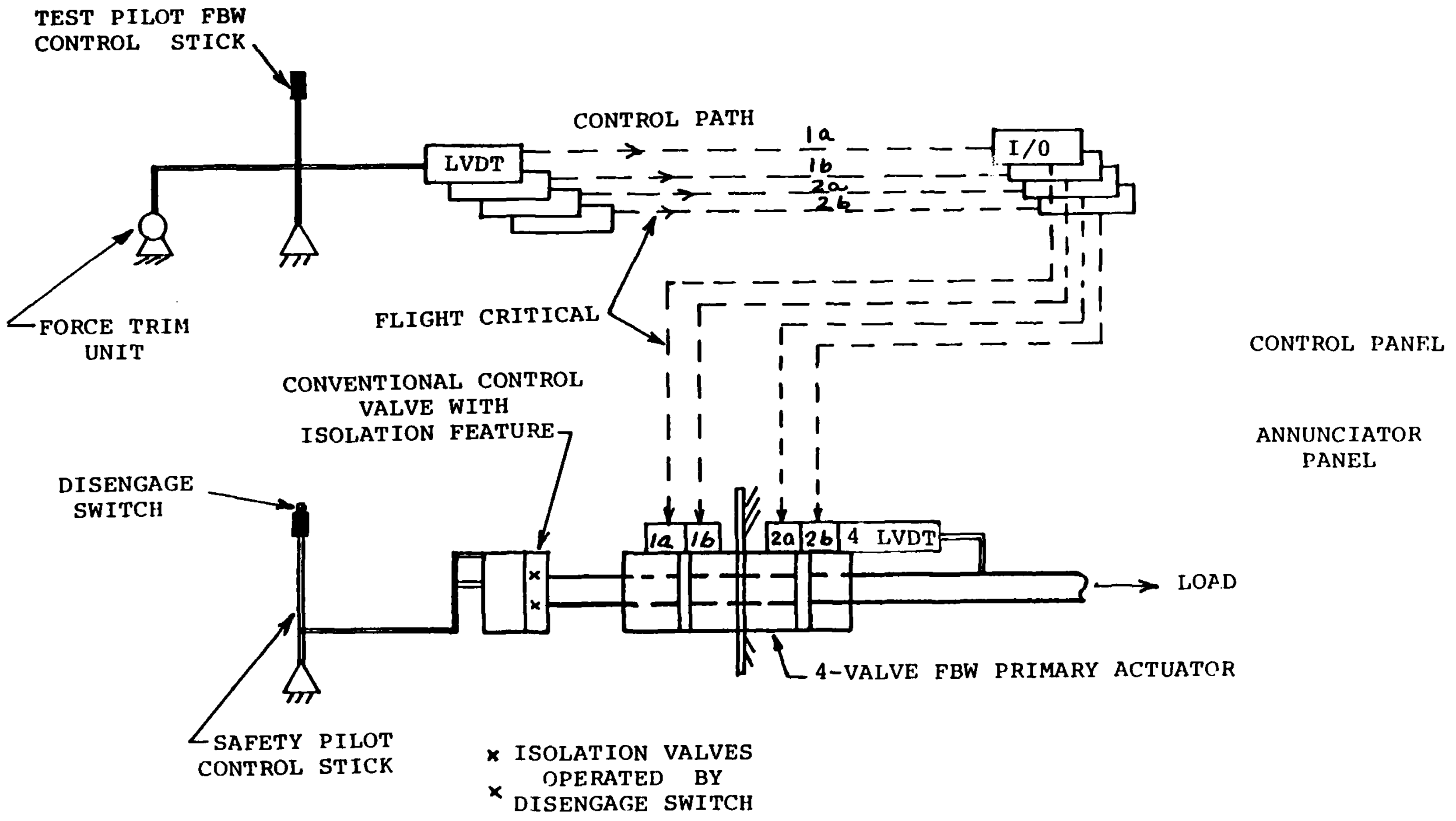


Figure 1. Simplified Block Diagram of FBW Control System With Mechanical Reversion.

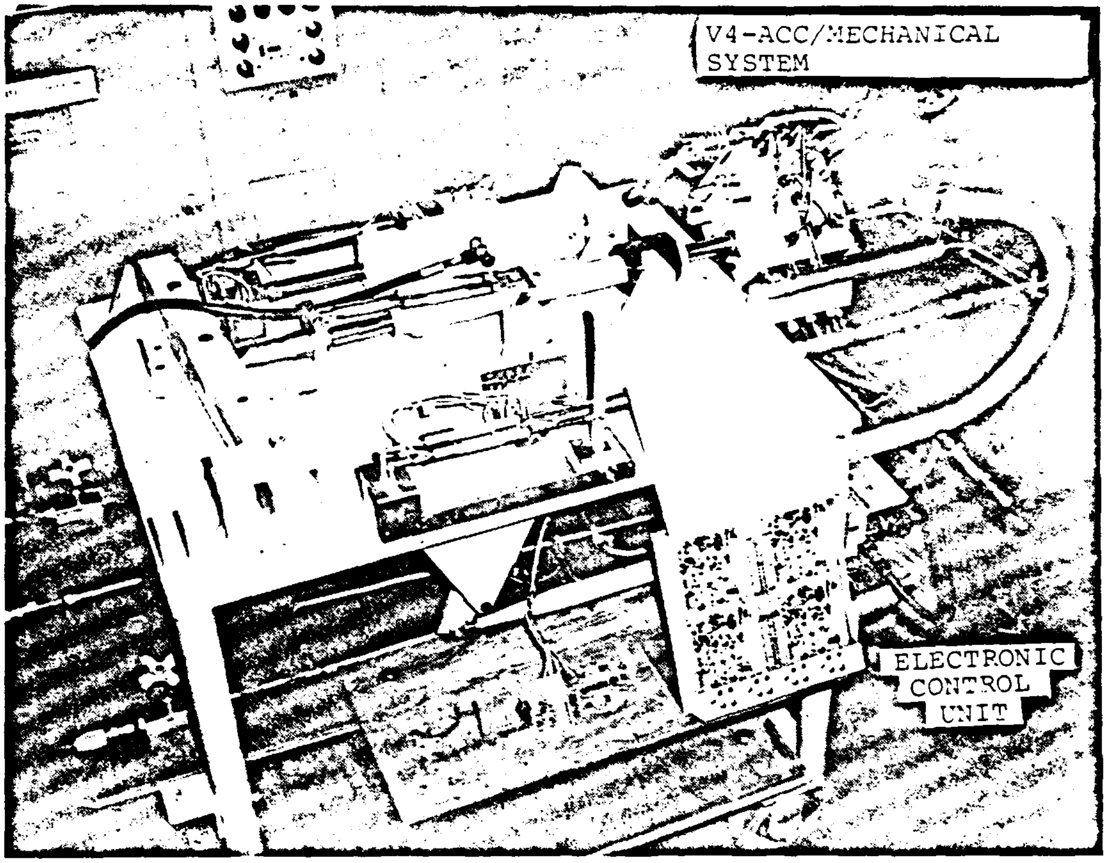


Figure 2. Laboratory Test Installation.

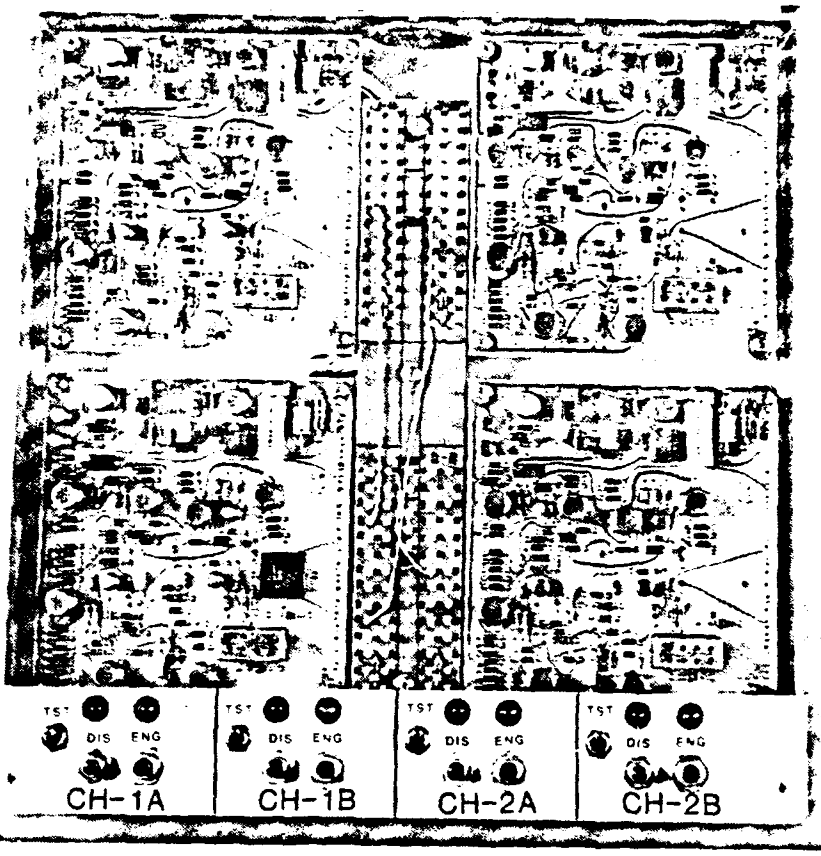


Figure 3. Electronic Control Unit.

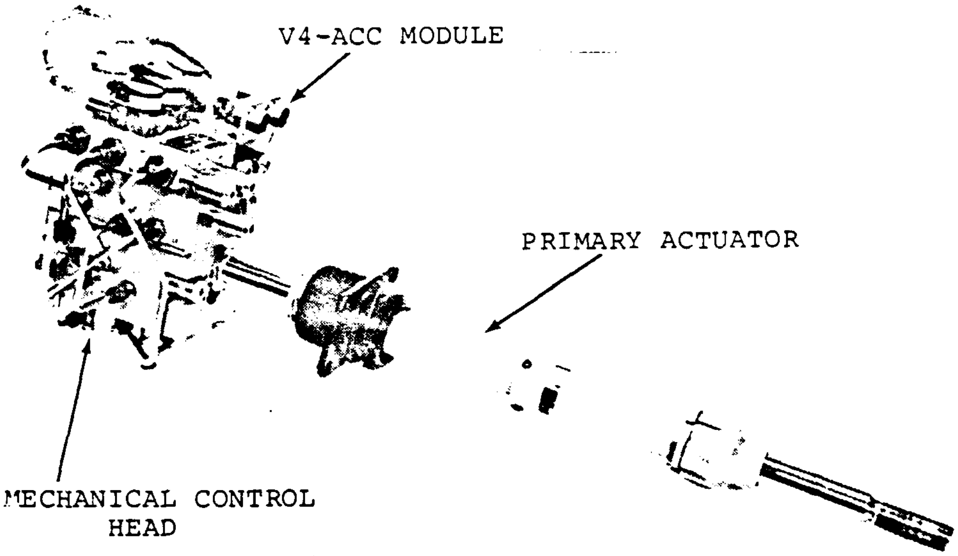


Figure 4. Hydraulic Actuator With a V4-ACC Module/ Mechanical Head.

mechanical reversion (back-up) feature was easily accomplished and could be used as a permanent part of the control concept; however, because of the predicted low failure rate and positive redundancy management characteristics offered by the V4-ACC, it is recommended that the mechanical back-up mode be used during the development phase of any future application and then removed after the integrity of the V4-ACC has been established.

The above recommendations are based on the pertinent attributes listed below.

- Simplicity - functionally, as well as low parts count, relates to low failure rates, low cost, and low weight.
- Failure Tolerance - basic system is single fail-operate; addition of a simple failure management system provides dual fail-operate for control paths.
- Unique Multiple-Path Tracking Feature - makes the system less sensitive to tolerance build-up in control path elements; provides a well defined actuator output impedance about null.
- Efficient Configuration - Electronic Control Unit (ECU) provides control, auto-tracking, and failure management as well as actuator drive control to effect an operationally, self-contained, actuation system.
- Self-Contained Features - allows the V4-ACC to be used as a part of a distributed control system as well as a centrally controlled actuation system.
- EMP Tolerance Potential - location of an ECU as an integral part of the actuator assembly allows the housing to be used to reduce vulnerability to man-made and meteorological electrical interferences.
- Application - V4-ACC can be used in almost any helicopter or fixed wing control system.

2. INTRODUCTION

2.1 GENERAL BACKGROUND

To be effective, a Navy helicopter needs the capability of terminal operation from the deck of a ship under adverse visibility and wind conditions. The approach and touch-down part of the operation presents a much greater problem than taking off. It can be divided into three phases: approach; close-in approach and hover; and touchdown. One solution to the problem is to use a fly-through, fault-tolerant Automatic Flight Control System (AFCS) with sophisticated cockpit displays. A second solution is to use a full-authority, fault-tolerant AFCS with automatic landing capability, but leaving the pilot with override capability and less sophisticated displays for monitoring the landing operation. This program is directed toward validating the V4-ACC incorporating an auxiliary mechanical reversion mode as a candidate actuation system for an AUTOLAND program.

The V4-ACC was initially investigated to determine feasibility, and later evaluated for two other applications in addition to AUTOLAND. Feasibility of the concept was determined under a Bell Helicopter Textron (BHT) IR&D program. This program was followed by a contract with the Naval Air Development Center to evaluate the V4-ACC for use as a fault-tolerant, high authority, series-type actuator in the Navy shipboard landing program. In a later contracted program with NASA/Ames, the concept was used in the predesign of a FBW system for the XV-15 tilt rotor aircraft. In addition to the predesign, the program included the design, fabrication, and laboratory testing of the V4-ACC for use in the collective control channel of the XV-15. This concept has been laboratory tested and performed exceptionally well. It could be installed using the existing mounting points in the XV-15, and is operationally equivalent to the existing collective actuator.

The engineering accomplished during the above programs has yielded a technology base that warrants going directly into the development of a flight test model of the V4-ACC. The AH-1S helicopter has been investigated as a possible candidate for the test helicopter. The findings were very favorable in that the V4-ACC/mechanical system can be installed as a replacement for the existing AH-1S actuators without major modification. Also, the AH-1S helicopter is considered to be a "low maintenance" helicopter and would therefore be a comparatively low cost flight test vehicle.

2.2 SUMMARY DESCRIPTION OF THE 4-VALVE ACTUATION CONTROL CONCEPT

A summary description of the V4-ACC has been included in this section to facilitate the presentation of the material in the subsequent sections. A more detailed description of the concept is provided in Appendix A.

The V4-ACC is, to some degree, an operationally self-contained actuation system. Each ECU is dedicated to a specific actuator and hence can be installed at or in the actuator. The ECU operates in conjunction with the actuator to effect a self-contained function in that it drives the actuator in a closed-loop configuration as well as provides automatic tracking and redundancy management of the quad-redundant control paths.

The V4-ACC uses four active electrical control paths to control a dualized hydraulic actuator. A simple failure management unit operates in conjunction with some of the inherent features of the basic system to provide a Failure Tolerance Level (FTL) for the control paths of dual fail-operate. This actuation system is characterized by fundamental simplicity and its inherent ability to tolerate failures; it is in essence a forgiving-type system.

The electronic control paths can be analog, digital, or digital/optical and use Electrohydraulic Servovalves (EHSV) for direct interfaces with the two primary cylinders. Each control channel uses four electrical links (2 per piston), four electronic drivers, four failure management units, and a dual primary hydraulic actuator (tandem or parallel). In a flight test model, all control channels would be operated with a control/reporting panel located in the cockpit.

This system offers the following features:

- Single fail-operate is inherent (without failure management).
- Dual fail-operate provided by adding a simple failure management system.
- Electrohydraulic servovalves provide a direct interface between the electrical links and the power cylinder (no drive actuation function required).

- Provides automatic tracking of the multiple electrical control links.
- Includes unique feature for protection against intermittent type inputs (e.g., electrical transients) that could effect an unwarranted disengagement.
- Easily retrofitted using the mounting points of the existing actuator.
- Has application to high-performance airplane controls as well as helicopter controls.
- Is essentially "self-contained" and can be driven directly by the pilot through electrical links or other control media.

A simplified schematic of a tandem dual actuator and the driving circuit is shown in Figure 5. All electrical control paths operate simultaneously and are automatically tracked to provide the desired stiffness at null. The tracking signals are inherently generated in the failure sensing circuitry in the failure management system.

The failure management system uses position sensors on the porting stage of the EHSV (see Figure 5) to provide the intelligence needed for the failure logic. The failure circuitry uses a simple logic for failure detection and has the intelligence to differentiate between an inert-type failure and a hard-type failure. Protection against an unwarranted disengagement of a control path (i.e., apparent intermittent failure) has been included for protection against induced transients.

Figure 2 is a photograph of the laboratory test model of the V4-ACC configured for dual fail-operate application. As described later, this hardware was used in the program to evaluate the V4-ACC with a mechanical back-up as part of a candidate control system for use in automatic shipboard landing systems.

2.3 DESCRIPTION OF ACTUATION SYSTEM

The actuation system is shown in simple block diagram form in Figure 1 and in more detail in Figure 6. Reference can be made to Figures 2, 3, and 4 to establish a physical relationship between the "blocks" in Figures 1 and 6 and the actual

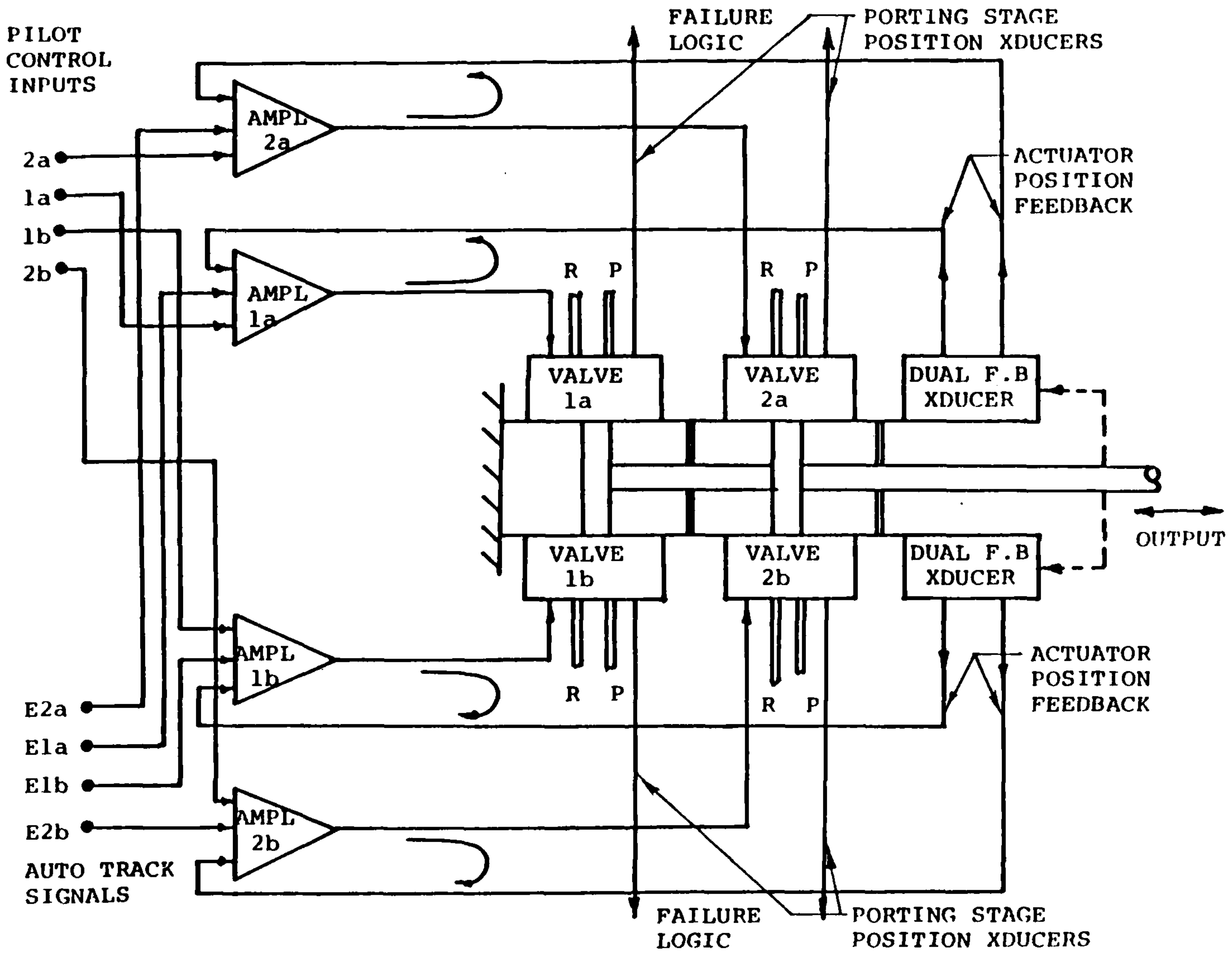


Figure 5. Dual Fail-Operate FBW Concept for Dual Piston Configuration.

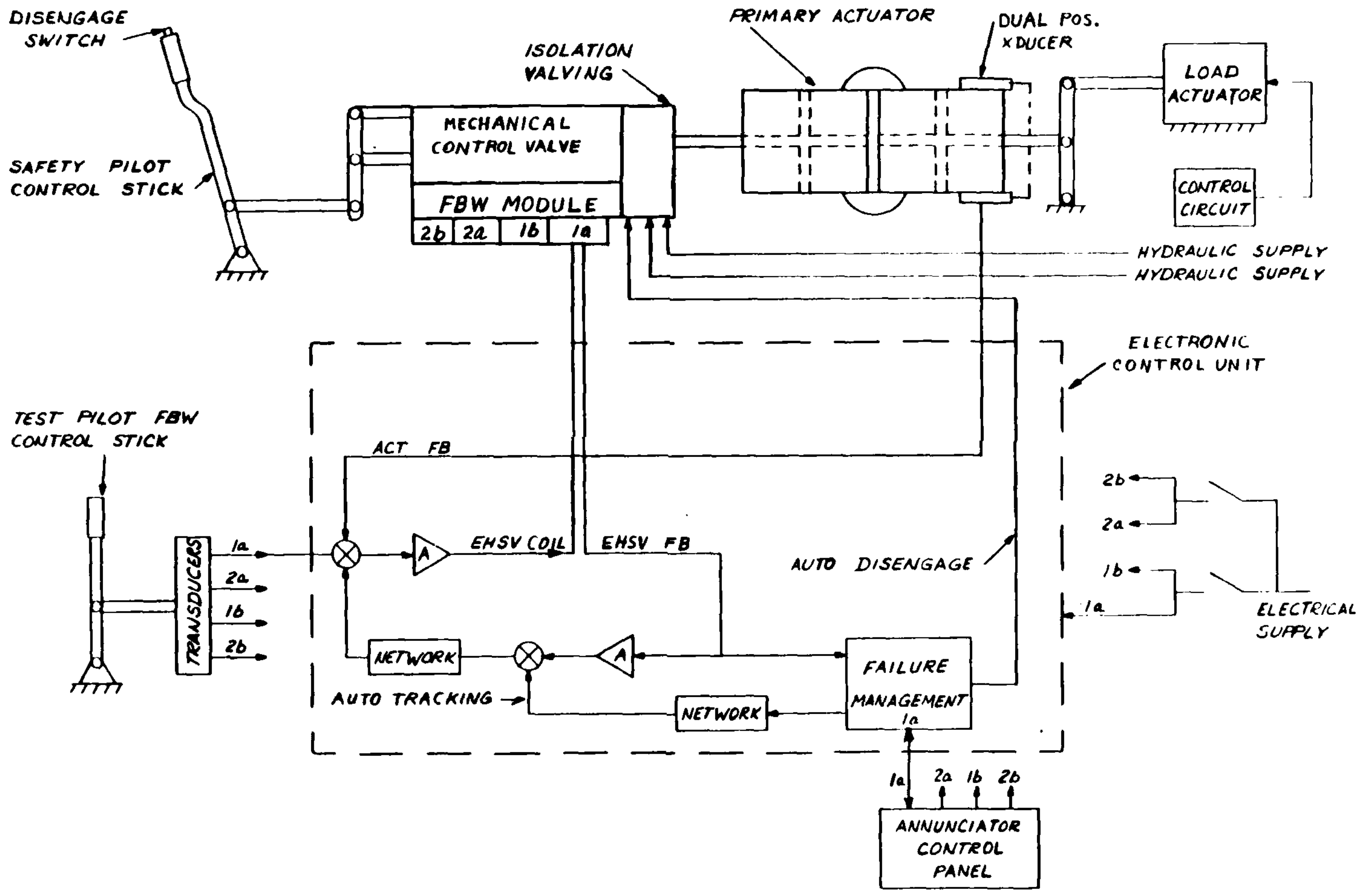


Figure 6. Simplified System Schematic of Control Path 1a.

equipment. The test model of the actuation system, as shown in Figure 6, consists of the basic equipment listed below.

- Control/Annunciator Panel
- FBW/Controller and Electrical Links
- Mechanical Control Unit
- FBW/Mechanical Actuator Assembly

In accordance with the test program requirements, these equipments were installed on a test stand and evaluated as an integrated system. The test stand was equipped with a load actuator, 28 Vdc supply, and a 1500 psi hydraulic supply (see Figure 2). Each control path includes a dedicated 4 KHz ac supply and a regulated 14 Vdc supply which, for the laboratory test, was derived from the 28 Vdc on the test stand.

The Control/Annunciator Panel is equipped so that the control paths (1a, 1b, 2a, and 2b) can be engaged and disengaged individually. This panel is also equipped to display the engage/disengage status of each control path. After engagement of one or more of the control paths, the V4-ACC/mechanical system is slaved to the FBW controller. The mechanical controller will inherently follow the actuator since it is physically connected through the mechanical linkage and mechanical control head. Hence, it is always in a synchronized position in the event of a reversion from FBW to mechanical control. Reversion is accomplished with the manually operated switch on the mechanical controller. Reversion automatically occurs if all FBW control paths are disengaged. The system process can be mentally integrated into an operable system by following through a step-by-step operation.

With the quad FBW control paths engaged, assume a pilot input from the FBW controller. The four analog signals are amplified by the actuator drive circuitry in the ECU and, in turn, simultaneously drive the four EHSVs which port fluid into the actuator cylinders. The actuator moves until the four LVDT actuator position feedback transducers produce signals that cancel the four pilot input signals. Continuous tracking and failure monitoring of the control paths are provided by the Auto-Track and Failure Management Block in the ECU. If a control path fails, it is disengaged and annunciated to the pilot. If a second failure should occur, it is likewise disengaged. In the event of a third failure, the operable control path, as well as the failed path, will probably disengage. The system will sense and disengage some third failures without disengaging the remaining operable control path, e.g., an open EHSV coil.

If the copilot elects to take over, the "kill switch" on the mechanical controller is depressed. This operates valving in the isolation stage of the hybrid mechanical valve that switches the hydraulic flow control from the FBW module to the mechanical control valves. As pointed out earlier, the conversion to mechanical control is automatic if the quad control paths are disengaged.

The basic equipments mentioned above and shown in Figure 6 are described in more detail in Section 3.

3. TASK DESCRIPTION

The work covered in this section is for the procurement of hardware, design, fabrication, and test of a laboratory test model of a FBW actuation system equipped with an auxiliary (back-up) mechanical control system. The test includes integration of the equipments, failure modes and effects analysis, and evaluation relative to use in automatic shipboard landing systems. The work was accomplished as described below in the work statement.

3.1 DESIGN TASK (0001)

3.1.1 Design of the Basic Configuration of the Control/Actuation System

The V4-ACC/mechanical system was designed to functionally operate as described in Section 2.3. It was functionally configured as shown in Figure 6 and physically configured as pictorally shown in Figure 2. Some of the equipments and the test stand from the earlier program were modified and used cost reduction. The laboratory test configuration included the equipments listed below:

- V4-ACC/mechanical system
- Electronic control unit
- Load actuator and control circuitry
- Safety pilot's mechanical controls
- Pilot's FBW control assembly
- Control/annunciator panel
- Test stand

Narration and illustrations are used in the following subsections to describe the physical and operational characteristics of the above equipments.

3.1.2 Design of Required Equipments

3.1.2.1 V4-ACC/Mechanical System. The V4-ACC used in the previous program was provided to minimize cost. A modification design was required to configure this actuator into a V4-ACC/mechanical system suitable for use in this program.

A plan view of the V4-ACC/mechanical system and associated test hardware is shown in Figure 7. Figure 8 is a hydraulic schematic of the basic actuator, mechanical control head, and the V4-ACC module. As shown in this figure, the mechanical control head consists of the conventional spool and sleeve assembly and two mode select valves. The spool and sleeve assembly includes the mechanical input and its output ports are connected to the mode select valves. The two mode select valves are also connected to the output ports of the V4-ACC module. Two solenoids are used to hydraulically operate the two mode-select valves to effect mechanical reversion. Mechanical reversion occurs if the pilot depresses the kill switch, if all FBW control paths are disengaged, or if all electrical power is cut off.

The hybrid actuator is depicted schematically as an integral part of the actuation system in Figure 6 and pictorially shown in Figure 4. This actuator was configured in the most economical manner to provide a laboratory model that would satisfy the functional requirements. Physically, however, the finalized version would be significantly different. In later prototypes, the components in the V4-ACC module could be integrated into the barrel of the actuator. Also, the mechanical control head could be considerably reduced and would not have the exposed plumbing as can be seen in Figure 4.

As shown in Figure 6, the hydraulic supplies are connected to the mode select stage of the mechanical valve. The mode select stage contains valving that blocks the ports of the mechanical valve (see Figure 8) while operating in the FBW mode. The kill switch is connected to control an electro-hydraulic solenoid that, in turn, controls the position of the mode select valving. In the FBW mode, the solenoid is energized. Mechanical reversion is obtained by three means: depressing the kill switch, disengagement of the quad control paths, or loss of all electrical power. Operation of the kill switch or loss of electrical power disengages the control paths which, in turn, automatically operate their respective mode select valves that blocks the EHSV ports so that the

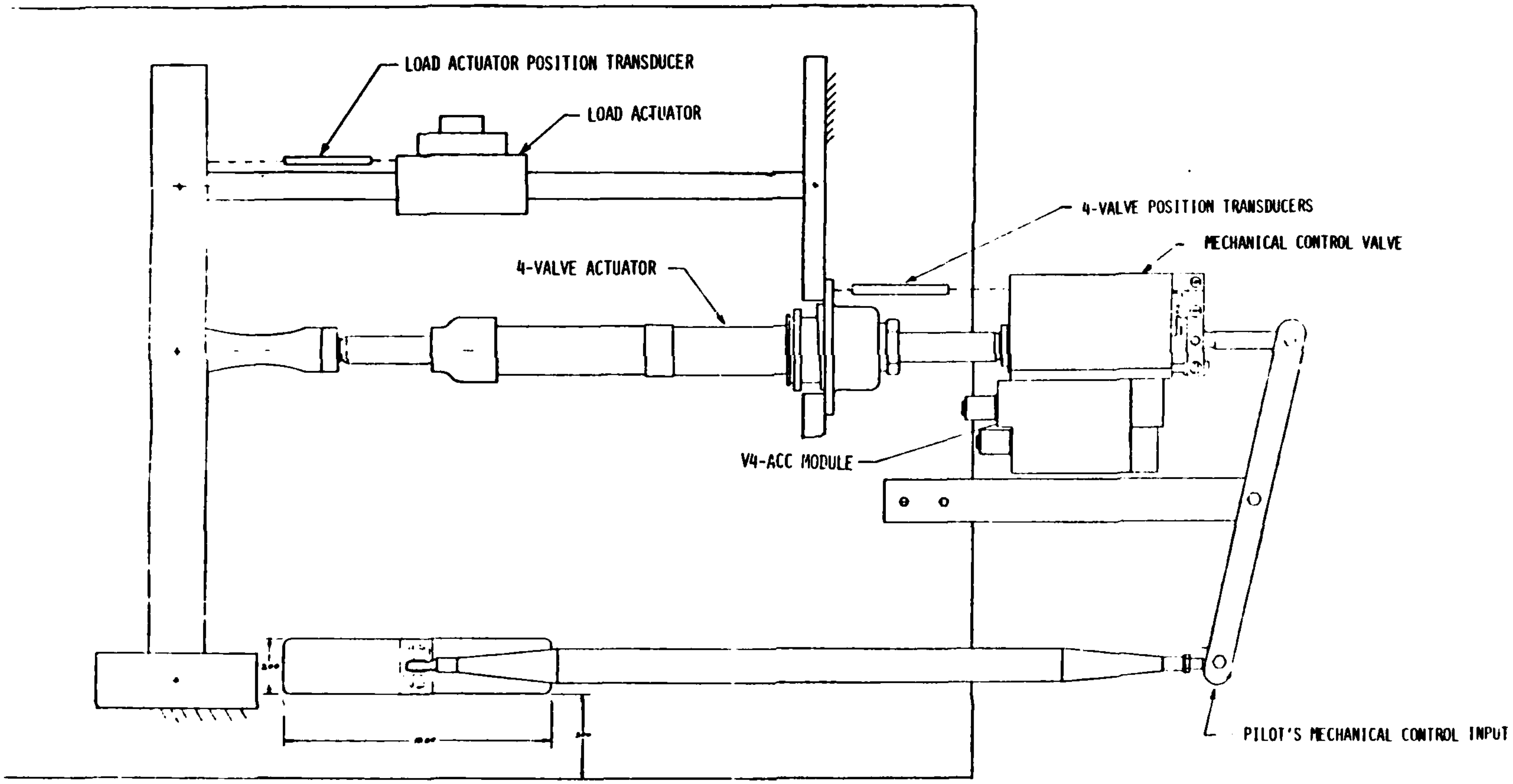


Figure 7. Plan View of Actuator Installation and Control Link Mechanism.

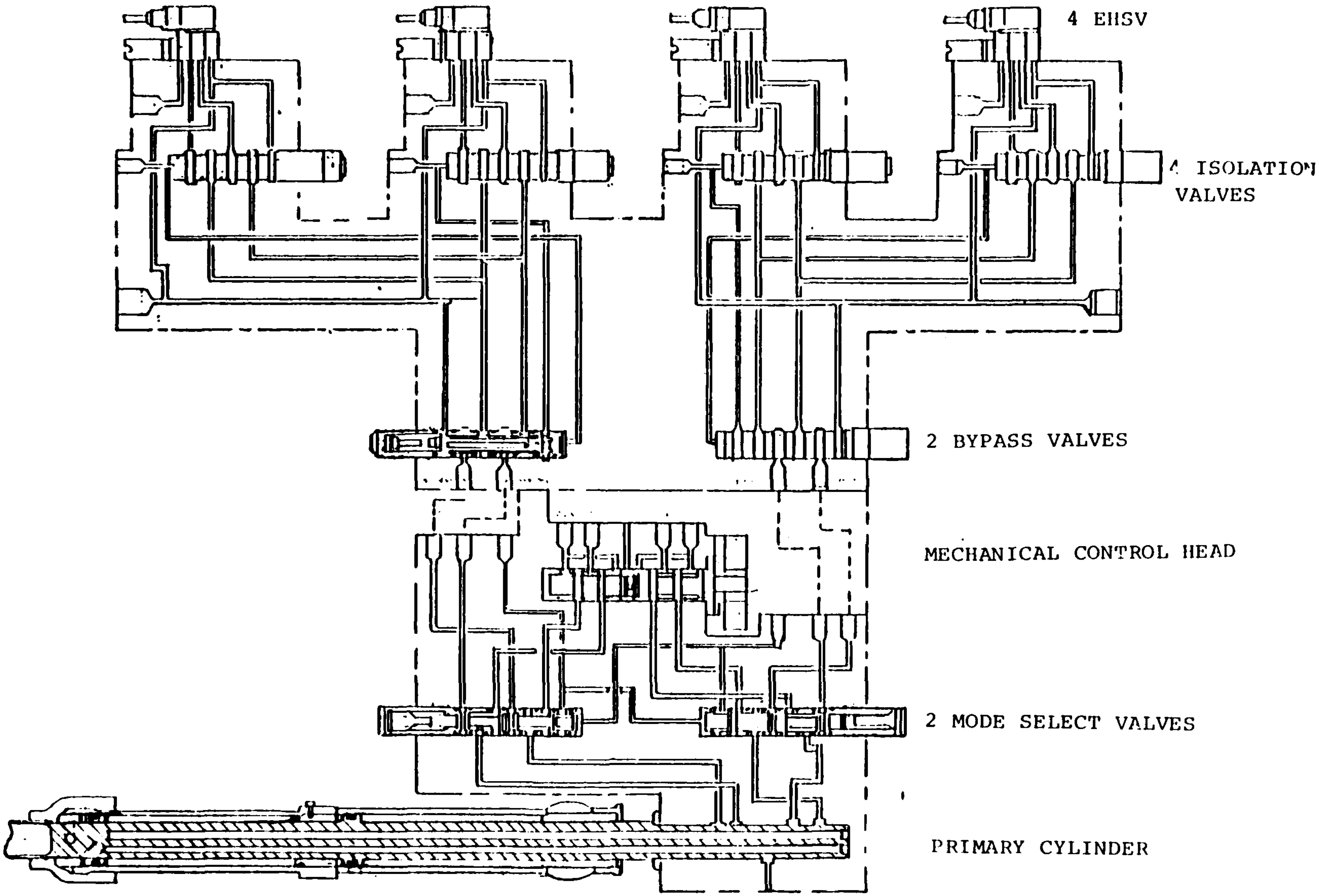


Figure 8. Hydraulic Schematic of Hydraulic Actuator With V4-ACC/Mechanical System.

fluid does not have a path around the pistons. A flight test version will include a standby hydraulic system and probably some redundancy in the mechanical reversion process.

3.1.2.2 Electronic Control Unit. The electronic package configuration was designed to facilitate the laboratory test program. The circuitry was designed also to accommodate the laboratory test; however, it is considered suitable for use in a flightworthy model. A flightworthy version can be obtained by conformal coating the circuit boards shown in Figure 3 and then repackaging the boards into a configuration more suitable for flight test.

The unit is depicted in Figure 6 as a functional part of the actuation system. Figure 3 is a photograph of a laboratory model of this unit, and Figure 9 is a detail circuit schematic of the circuitry for one control path; hence, each of the four circuit boards displayed in Figure 3 represents the electronics required for one control path. Each circuit board includes a dedicated 4 KHz ac supply; dedicated 14 Vdc supply; drive circuitry for the EHSV; high gain position feedback loop around the EHSV; automatic tracking loop for synchronizing the EHSV with the other operating EHSVs; failure management circuitry for the respective control paths; and outgoing vote signals to the other circuit boards. The circuit boards also include test circuitry for simulating failures needed for the Failure Modes and Effects Analysis (FMEA) test.

EHSV Drive Circuitry. As shown in Figure 9, the drive signal for the EHSV follows the path: Q_{1a}-Q_{1b}-Q_{2a}-Q_{2b}-EHSV coil. The gain of this path is set up to produce 100 percent flow from the EHSV for four percent pilot input. This flow gain should be adequate if only one control path on each piston is operating.

EHSV Position Feedback Loop. The high gain feedback loop around the EHSV follows the path: EHSV position feedback (LVDT) - Q_8-Q_{6b}-Q_{3a}-Q_{3b}-Q_{2a}-Q_{2a}-Q_{2b}-EHSV coil. This feedback loop reduces the effects of hysteresis, null shift, threshold, and nonlinearity. The loop has been designed to reduce these characteristics by a factor of 5; e.g., five percent hysteresis effect would be reduced to one percent. The intent, of course, is to improve the valve characteristics as well as to obtain a better match of the four valves. The payoff is that manufacturing tolerances of off-the-shelf valves are acceptable for the V4-ACC. This valve matching plus the automatic

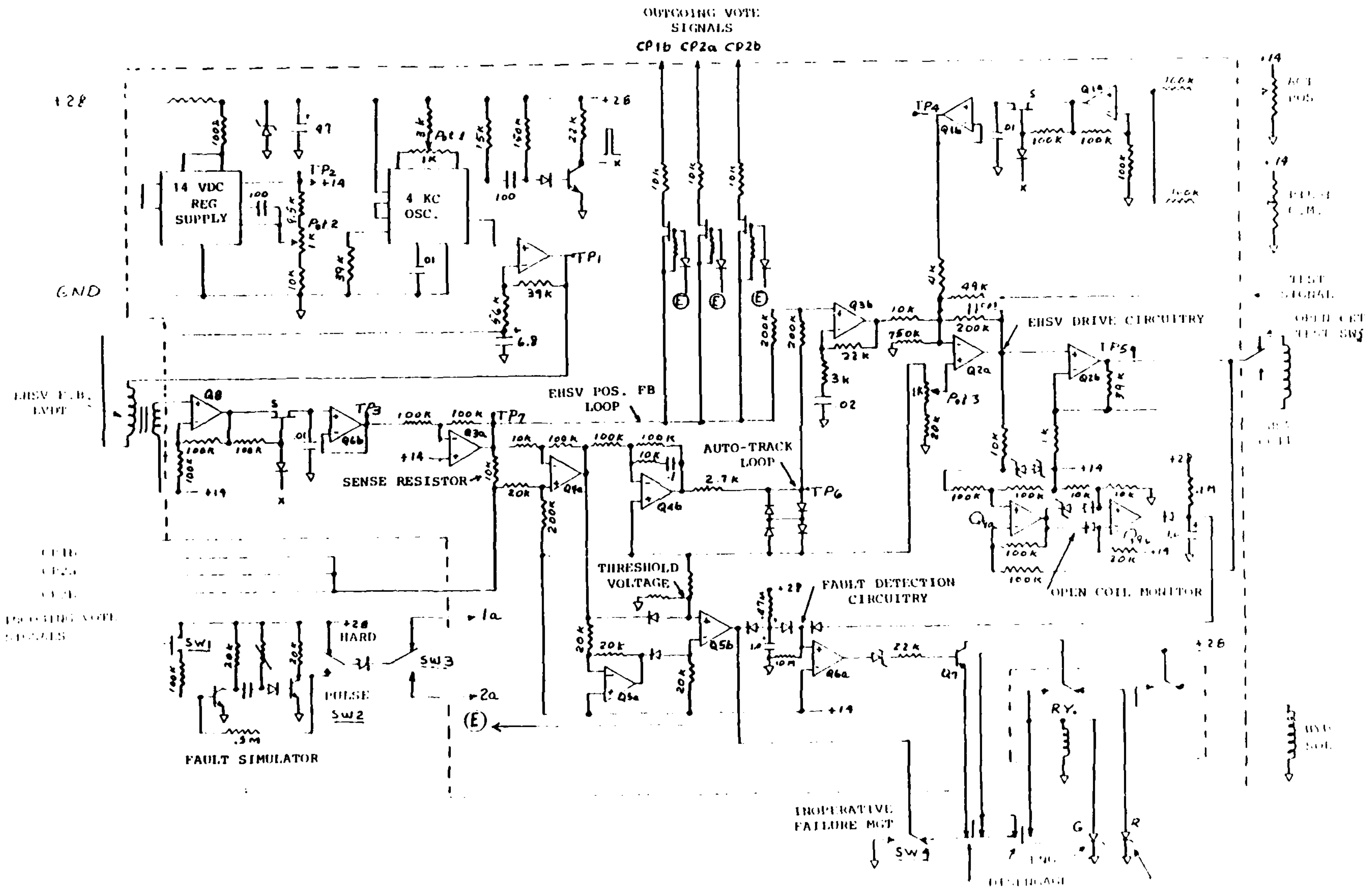


Figure 9. Detail Circuit Schematic of Control Path 1a.

tracking loops provide a primary actuator with a well defined null with controllable characteristics if desired.

Automatic Tracking Loop. The automatic tracking loop follows the path: Sense Resistor - Q_{4a}-Q_{4b}-Q_{3b}-Q_{2a}-Q_{2b}-EHSV coil. The error signal across the sense resistor represents the level of disagreement of the EHSV of the respective control path and the other EHSVs. This loop operates at a high gain and can provide valve track out past the main rotor frequencies (1/rev, 2/rev, etc.). The control of the tracking signal is limited to an equivalent of about fifty percent EHSV displacement. That is, the dynamic track range of the track loop is equivalent to fifty percent of EHSV stroke or about two percent of primary actuator stroke (depending on the actuator position loop gain). If the track signal exceeds the limit but is less than the value required for displacement, it is considered a "soft-failure" and should be annunciated as such.

Failure/Management Loop. The failure/management loop follows the path: Sense Resistor - Q_{4a}-Q_{5a}-Q_{5b}-Q_{6a}-Q_7-Disengage Relay - Engage/Disengage Solenoid Valve. Q_{5a}, Q_{5b}, the diodes and resistors, constitute a double-ended threshold circuit. The resistor pad establishes the threshold. If the signal exceeds the threshold, Q_{5b} swings from ground potential to 28 Vdc which provides a back bias to the diode which allows the 1 μf capacitor to start charging through the 470K resistor. When the capacitor charges to the 14 Vdc level, Q_{6a} swings from ground potential to 28 Vdc. This turns off Q_7 which disengages the engage/disengage relay and, in turn, the engage/disengage electrohydraulic solenoid. The solenoid cuts the hydraulic pressure off to the associated slide valve in the FBW hydraulic module which isolates the failed control path. The above RC timing circuit effects a time inhibit of 0.25 second. The reset time for this circuit is about 0.00025 second. The purpose of this circuit is to protect against electrical interferences; the time delay requires the interference to be present for a set time while the quick reset prevents the time circuit from integrating a series of short interferences.

Inert Failure Protection. As shown in Figure 9, 14 Vdc is used as the reference voltage; i.e., all the signals are referenced to the 14 Vdc supply and hence swing ± about this reference. The circuitry has been designed so any open or short of the signal up to the EHSV coil creates a hard signal and will effect a disengagement of the respective control path. An open of the EHSV coil, however, results in an inert type failure. This type failure is not easily detected while flying in smooth air since the EHSVs are not being appreciably displaced from null and the disagreement with the failed control path and the operable control paths is comparatively small. Low disengagement thresholds would have to be used to assure that a coil failure would be sensed and result in a subsequent disengagement of the associated control path. Low thresholds, however, make the system vulnerable to false failure type disengagements and it was elected to incorporate an additional simple circuit to monitor the EHSV coil. This circuit consists of Q_{9a}, Q_{9b}, and the associated circuit hardware in Figure 9. It operates as an adjunct to the basic failure/management system in that it can sense EHSV coil failures and can output a fail signal to Q_{6a} to effect a disengagement of the associated control path.

An improved EHSV coil monitor concept that will sense a "shorted" coil as well as an "open" coil has been recently conceived. It was not incorporated into the hardware since it was conceived after the laboratory test had been completed. The improved concept is a simple modification of the existing monitor and is presented below as supplemental information.

The improved version of the EHSV coil monitor is shown in Figure 10. The driver signal is amplified and processed through two paths to Q_{9a}. For normal operation the gains of Path No. 1 and Path No. 2 are the same and, hence, the output of Q_{9a} is essentially zero. An appreciable difference in the gains of the two paths will produce an output from Q_{9a} when a driver signal is present. If this output exceeds the set threshold (4 Vdc), Q_{9b} will output a hard signal that operates through a time constant to provide a discharging signal to the basic failure/management unit. For example, the coil has a dc impedance of 2000 ohms and if it opens, the gain of Path No. 1 is high compared to Path No. 2 (by a factor of 80/6) and will effect a disengagement when there is an adequate driver signal. On the other hand, if the coil is shorted, Path No. 2 has a higher gain (by a factor of 3) and will effect a disengagement when there is an adequate driver signal. Obviously, for the latter condition it will require a larger

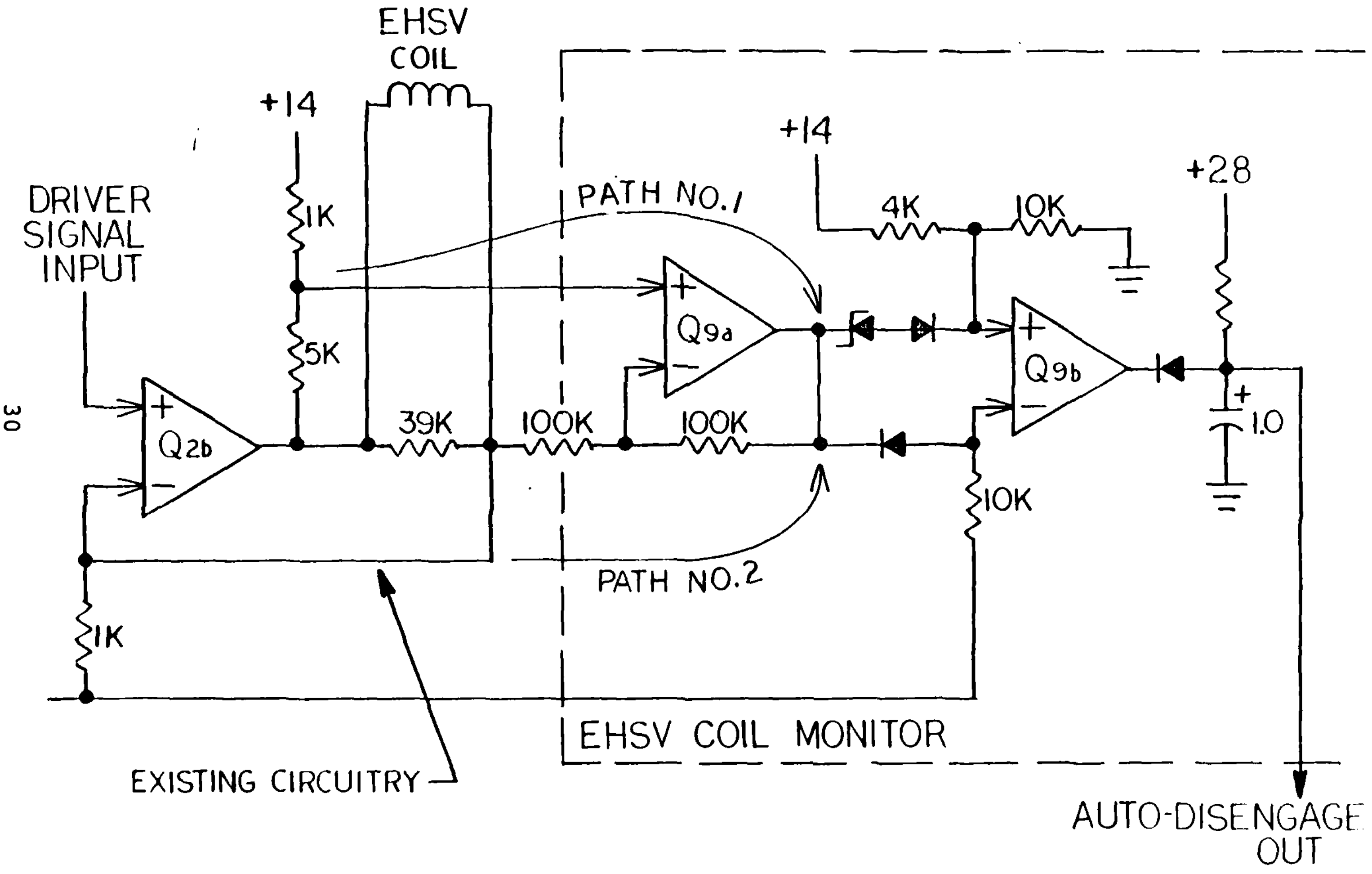


Figure 10. Open/Short EHSV Coil Monitor.

signal to effect a disengagement; for the gains as shown it would require a driver signal of 6 volts. This is equivalent to about two percent pilot input and does not present a problem since it will disengage on demand for flow.

Outgoing Vote Signals. These three signals paths are used to inform the other control paths of the position of EHSV 1a. Each of the other control paths will use this information to establish a vote in the same manner that control Path 1a uses the incoming signals from the other three control paths identified as "Incoming Vote Signals" in Figure 9. A detailed description of the voting technique is covered in Appendix A.

FMEA Test Circuitry. Test circuitry has been included on the circuit boards to simulate failures within the ECU. This includes simulation of a hard signal failure, hard short pulse, inert failure management circuitry, and open EHSV coil failure.

The fault simulator in the lower left corner of Figure 9 is used to generate the hard signal failure and hard short pulse. A transient-type error signal is generated by positioning SW3 to "1a," SW2 to PULSE, and momentarily depressing SW1. This generates 0.2 second, 28 volt pulse. Since the disengage time delay is 0.25 second, the 0.2 second pulse should not effect a disengagement. The hard fail signal is generated by positioning SW2 to HARD. This applies a 28 volt error signal to the test signal input and should effect a disengagement of Control Path 1a. SW3 can be positioned to 2a to generate a second failure.

SW4 in the lower center of Figure 9 is used to simulate an inert type failure in the failure management circuitry. Positioning this switch to the fail position "shorts" the failure signal to ground and hence causes a loss of the failure management function for Control Path 1a. With this condition existing, a failure in Control Path 1a will not effect a disengagement; the basic system, however, will tolerate one failure and continue working as discussed in Appendix A.

SW5 in the right center of Figure 9 is used to simulate an open EHSV coil. Positioning this switch to the open position will effect a disengagement as discussed earlier under Inert Failure Protection in this section.

3.1.2.3 Load Actuator and Control Circuitry. The load actuator and associated electronic control circuitry used in the previous program were transferred to this program. These equipments were used without major modification.

The load actuator and associated control circuitry are identified in Figure 2. Figure 7 shows how the load actuator is connected to the V4-ACC/mechanical system. It has a larger piston area and can therefore stall the hybrid actuator. Maximum force is accomplished by adjusting the supply pressure. The electronic control circuitry operates in conjunction with the load actuator to effect a simple position feedback control system.

3.1.2.4 Safety Pilot's Mechanical Controls. A conventional cyclic control stick and grip are used in conjunction with simple linkage to provide the mechanical back-up control function (see Figures 2 and 7). The cyclic stick and control linkages used in the previous program were modified and used as shown in the mentioned figures.

3.1.2.5 FBW Controller and Electric Links. The FBW controller consists of a simple lever connected to two dual, film potentiometers (see Figures 1 and 2). A flight test model would obviously use a suitably configured FBW controller and four independent, inductive-type transducers. For convenience, the transducers are excited from a single-source electrical supply. The output signals are connected to the ECU and, in turn, are amplified and used as the drive signals for the actuator.

3.1.2.6 Control/Annunciator Panel. This panel is an integral part of the ECU as shown in Figure 3. Functionally, it consists of four independent panels, one for each control path. Each panel consists of button-type engage and disengage switches, engage and disengage annunciators, and a momentary switch for simulating electrical transients and "hard" failures.

3.1.2.7 Test Stand. The test stand is shown in Figure 2 with the laboratory test installation of equipment. Figure 7 is a plan view of the test stand, actuators, and mechanical controls. The test stand existed but modification was necessary to accommodate the mechanical control linkages. Also, two electrohydraulic solenoids were added for the mechanical reversion feature.

3.2 PROCUREMENT TASK (0002)

3.2.1 V4-ACC/Mechanical System

The services and material for the modification of the existing V4-ACC were procured from Hydraulic Research Textron in accordance with a BHT specification. This procurement was at no cost to the contract.

3.2.2 Mechanical Hardware

Existing mechanical hardware was used; no procurement was required.

3.2.3 Electrical Hardware

This program required the procurement of photographic services for the circuit boards, integrated circuits, discrete transistors, relays, switches, capacitors, resistors, etc.

3.3 FABRICATION TASKS (0003)

3.3.1 Test Stand

The existing test stand used in the previous program was modified to accommodate the new equipment. The modification to the basic test stand was very minor. Some new installation hardware was required for the V4-ACC/mechanical system and the control linkages. The linkages were configured so that the existing cyclic stick could be used. Figure 7 is a plan view of the test stand and shows the V4-ACC/mechanical system installation and the control linkages. Reference should also be made to Figure 2, which is a pictorial presentation of the test stand and the equipment.

3.3.2 Mechanical Controls and V4-ACC/Mechanical System

The V4-ACC/mechanical system installation and the mechanical control linkages are shown in Figure 7. Reference can also be made to Figure 2, which is a pictorial presentation of the installed equipment. The control linkage installation included an adjustable friction device to prevent having a "limp stick" when the controls are switched from FBW to mechanical back-up.

3.3.3 Electronic Hardware

The electronic hardware was fabricated as shown in Figures 2 and 3. As shown, the electrical control and annunciator functions were fabricated as an integral part of the ECU. Also, the test switches and associated circuitry used for simulating failures were fabricated as a part of the ECU. The ECU was fabricated as shown in Figure 3 to facilitate testing the laboratory model. The four circuit boards are flightworthy and hence can be repackaged and used in a flight test program.

3.4 EQUIPMENT INTEGRATION TASK (0004)

The Integration Test Plan was prepared as a contracted item and has been included in the Appendices as a deliverable item. Some minor circuit changes have been incorporated in the ECU since the test plan was submitted for approval. The test instructions have been updated accordingly and included in this section along with the associated results of each test. Figures 6 and 9 can be used to supplement the stated test and results.

Scope

This test program included the integration and test of the FBW control mode as well as the mechanical reversion mode. It covers the alignment, functional test, operational suitability test, and FMEA.

3.4.1 Functional Test

3.4.1.1 Hybrid Actuator Mechanical Control. With hydraulic power on and FBW module disengaged, move pilot's controls from stop to stop and qualitatively check for operational suitability. Note dead spots, thresholds, breakout forces, etc. Turn off Supply No. 1; Supply No. 2 should automatically take over. Apply pressure to load actuator, and with an appreciable amount of load, move actuator from stop-to-stop to assure proper operation.

Results. The primary actuator operated in a normal manner. Other than some slop that was attributed to the loose "fit" of the cyclic stick, the motion was smooth and had no discernable dead spots.

3.4.1.2 Hybrid Actuator FBW Control. The loop gains and compensation networks are essentially the same as were used in the previous program. There are some changes, however, in circuit configuration, and it is necessary to realign the control paths. Each control path is to be aligned and tested separately under the conditions outlined below, which have been changed as required to accommodate the changes in circuit configuration. Reference should be made to Figure 9 for supplemental information. It is pointed out that the operational amplifiers are operated from +28 Vdc to ground with +14 Vdc as the common.

3.4.1.2.1 Alignment and Test of Control Paths

4 KHz Supply

Conditions: Electrical power ON

- Connect oscilloscope to TP1 and adjust Pot 1 to effect a uniform sine wave output. Output should be approximately 3 volts rms. There is no amplitude adjustment. Adjust all four 4 KHz supplies.

Results: All supplies adjusted to obtain sine wave output. The voltage magnitudes are recorded below.

4 KHz Supply 1a - 2.95 Vrms
4 KHz Supply 1b - 2.92 Vrms
4 KHz Supply 2a - 2.91 Vrms
4 KHz Supply 2b - 2.97 Vrms

14 Vdc Regulated Supply

Conditions: Electrical power ON

- Connect voltmeter to TP2 and adjust Pot 2 to obtain +14 Vdc. Adjust all four supplies.

Results: Voltage magnitudes of the supplies were adjusted to obtain the voltages recorded below.

DC Supply 1a - 13.99 Vdc
DC Supply 1b - 13.99 Vdc
DC Supply 2a - 13.99 Vdc
DC Supply 2b - 13.99 Vdc

Control Path 1a

Conditions: Hydraulic power ON
Electrical power ON
TP4 shorted to 14 Vdc

EHSV Feedback Loops

The purpose of this loop is to improve the linearity of the EHSVs as well as to reduce hysteresis effect, null shift, and thresholds.

- Adjust Pot 3 to null TP3 (referenced to +14 Vdc). This adjustment is performed with the EHSV position feedback loop closed which compensates for any electrical null shift caused by the circuitry, EHSV coil, or misalignment of the position feedback transducer (LVDT or EHSV). The adjustment aligns the electrical null with the assumed mechanical null of the EHSV which is accurate to ±two percent of total EHSV output.

Results: Pot 3 was adjusted to null TP3. This adjustment also compensates for offsets caused by the tracking loop.

Frequency Response Test

Conditions: Hydraulic power ON
Electrical power ON
Shorted TP4 to 14 Vdc

- Connect frequency generator to the Test Input (pin 18)
- Conduct closed loop frequency response on EHSV 1a by incrementally varying frequency of input from zero to well passed the first break frequency. Measure and record the magnitude of the input signal and the EHSV LVDT output signal.

Control Paths 1b, 2a, and 2b

Same as Control Path 1a.

Results: Closed loop frequency response data for the four EHSVs are in Figures 11a, 11b, 11c, and 11d. As noted, the four curves are essentially identical. This confirms that the static and dynamic characteristics of the control paths are the same and are in accordance with the design.

3.4.1.3 Alignment of Electromechanical Transducers

Actuator Feedback Transducers

Conditions: Hydraulic power ON
Electrical power ON
Shorts on TP4 removed
Control Path 1a engaged

- Use FBW controller and position V4-ACC module in increments and determine sensitivity in terms of volts per inch of actuator travel.

Results: Sensitivity was measured and recorded to be 3.2 volts-per-inch of actuator travel.

- Use controller and drive V4-ACC module in increments and measure track error between the control paths.

Results: Actuator position tracking data were recorded from stop-to-stop in five increments. The readings for the four actuator feedback transducers are presented in Table 1a. The alignment of these transducers was considered to be within the control range of the auto-tracking circuitry and that no trimming was necessary.

FBW Controller Transducers

Conditions: Hydraulic power ON
Electrical power ON
Control Path 1a engaged

- Use FBW controller and position V4-ACC module in increments and determine sensitivity in terms of volts per inch of actuator travel.

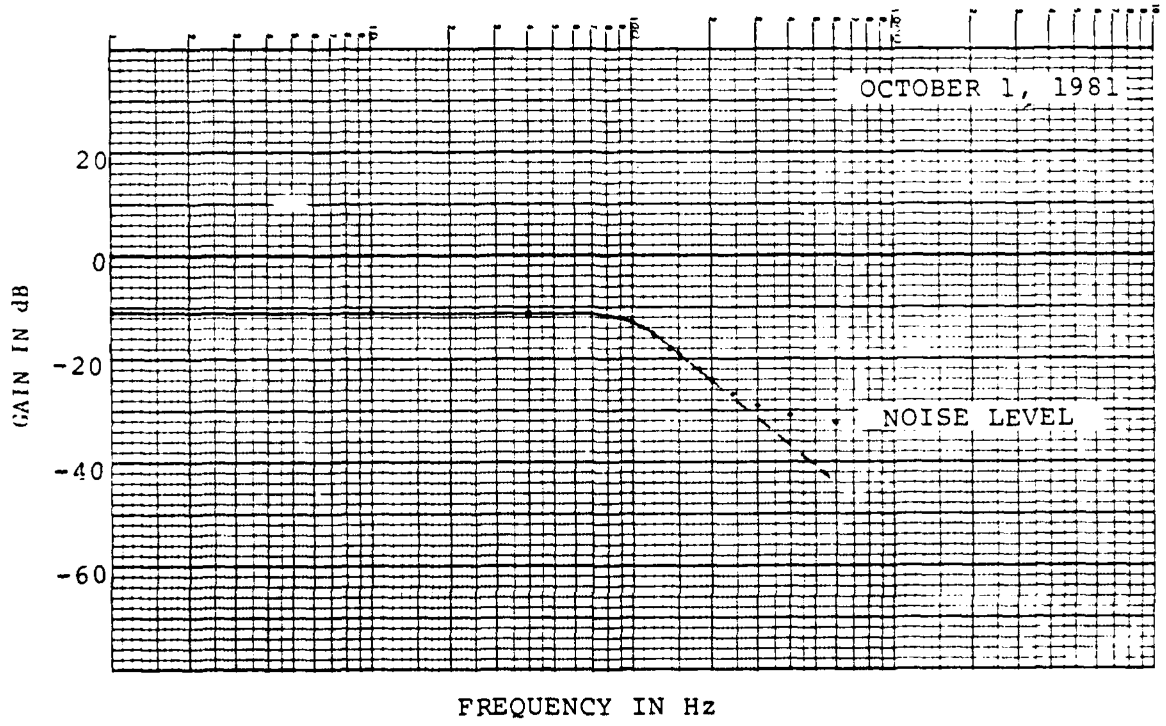


Figure 11a. Closed Loop Frequency Response of EHSV 1a.

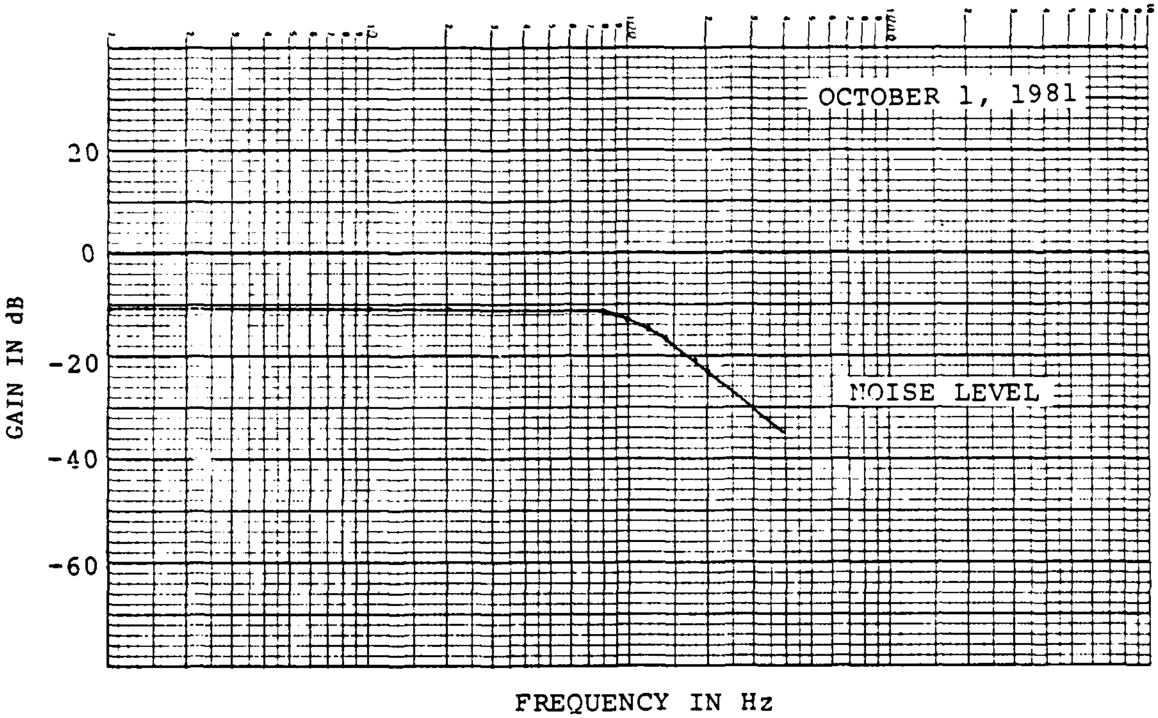


Figure 11b. Closed Loop Frequency Response of EHSV 1b.

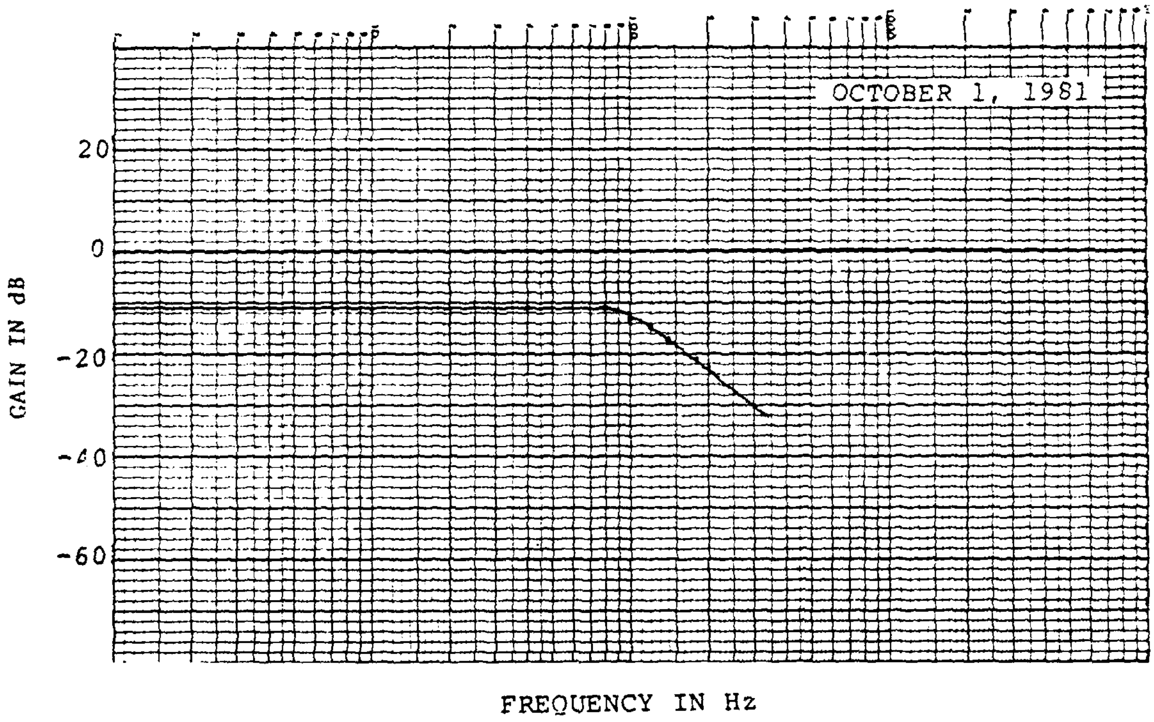


Figure 11c. Closed Loop Frequency Response of EHSV 2a.

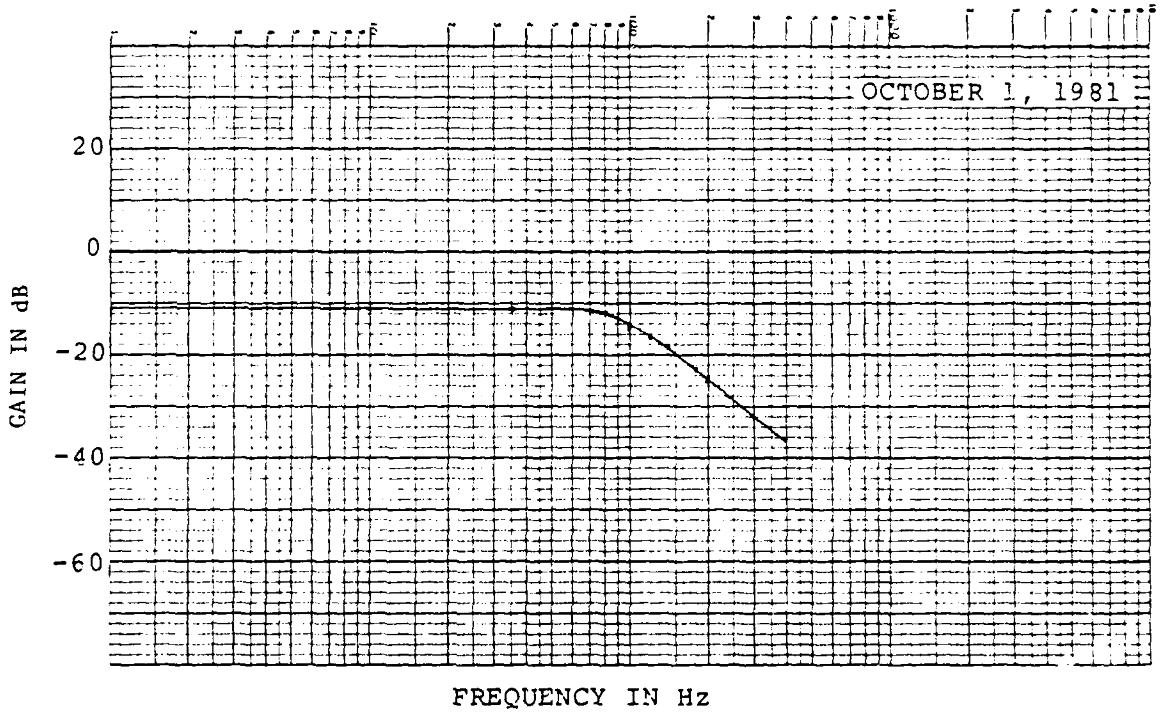


Figure 11d. Closed Loop Frequency Response of EHSV 2b.

TABLE 1. ELECTROMECHANICAL TRANSDUCER ALIGNMENT DATA

	1a				1b			
Actuator Travel (Inches)	Actuator Feedback Transducers (Volts)				FBW Control Transducers (Volts)			
	1a	1b	2a	2b	1a	1b	2a	2b
0.00	-3.42	-3.36	-3.49	-3.65	-10.40	-10.55	-10.53	-10.66
0.49	-4.98	-4.97	-5.02	-4.99	-9.04	-9.08	-9.12	-9.19
1.21	-7.30	-7.30	-7.29	-7.29	-6.74	-6.75	-6.79	-6.79
1.88	-9.44	-9.39	-9.36	-9.62	-4.61	-4.67	-4.70	-4.67
2.00	-9.82	-9.74	-9.72	-9.80	-4.27	-4.33	-4.36	-4.33

Results: Control transducer tracking data were recorded from stop-to-stop in five increments. The readings for the four FBW controller transducers are presented in Table 1b. The alignment of these transducers were considered to be within the control range of the auto-tracking circuitry and that no trimming was necessary. The sensitivity measured and recorded to be 3.07 volts per inch of actuator travel.

3.4.1.4 Auto-Tracking Loop Test

Conditions: Hydraulic power ON
Electrical power ON
All control paths disengaged

Note: The procedures in this section differ to some extent from the Integration Test Plan. The changes in the procedures were necessary to accommodate the added redundancy in the auto-tracking circuitry.

- Open test SW5 on EHSV coil 1a and null LVDT on EHSV with dc voltmeter on TP3. Signal at this point has been demodulated and provides much better null data than an ac voltmeter reading across LVDT secondary.

Results: LVDT was nulled to 0.003 volt.

- Short TP4 to 14 Vdc in Control Path 1a to isolate the control input.

- Close SW5 on EHSV coil 1a. This closes EHSV loop; dc voltmeter at TP3 will now indicate any stand-off voltage. Null TP3 by adjusting "Pot" 3.

Results: Adjusted TP3 to zero volts.

- Apply pulse to EHSV 1a loop by positioning SW2 to PULSE and depressing SW1. Qualitatively observe the results at TP3 and note stability characteristics.

Results: Transient response observed at TP3 qualitatively indicated good loop stability.

- Repeat procedure for Control Paths 1b, 2a, and 2b.

Results: Same as 1a.

- Remove short from TP4 in Control Path 1a; engage Control Path 1a; and apply a pulse by positioning SW3 to 1a, SW2 to PULSE, and depressing SW1. Note closed loop stability characteristics.

Results: Transient response observed on actuator feedback transducer qualitatively indicated good actuator loop stability.

- Remove all shorts from TP4 to 14 Vdc and engage other control paths; V4-ACC system will now track the FBW control input.

- Drive the V4-ACC system from stop-to-stop with the FBW controller, examine for interferences over the complete range of travel.

Results: The actuator tracked the FBW controller very smoothly and no interference was noted.

- Drive actuator in increments over operating range and record voltages at TP3 and TP6. This test is to examine tracking characteristics of the auto-tracking circuitry.

Results: Voltmeter readings for TP3 and TP6 for five actuator positions are shown in Table 2. Full EHSV displacement produces an output at TP3 of 1.30 Vdc. As can be appreciated from Table 2, the EHSVs tracked within about ±0.7 percent in terms of maximum EHSV travel and 0.028 percent in terms of total actuator travel. The worst case, which occurred at 95 percent actuator travel, was ±2.3 percent in terms of EHSV and 0.09 percent in terms of actuator travel; for a travel of four inches, this would be equivalent to 0.0036 inch. The tracking function can be appreciated by noting the last incremental change of TP3 from +0.018 to 0.000 and relating this change to the track signal at TP6 which had an associated change from -0.048 to -0.256. The auto-track function is considered to be very effective in reducing "force-fight" between pistons as well as flow disagreements between companion valves; e.g., EHSVs 1a and 1b.

TABLE 2. AUTO-TRACK LOOP DATA

Actuator Travel (Inches)	TP3 (Volts)				TP6 (Volts)			
	1a	1b	2a	2b	1a	1b	2a	2b
0.35	+0.015	+0.027	+0.018	+0.038	-0.088	+0.020	-0.065	+0.145
0.50	+0.015	+0.035	+0.027	+0.031	-0.092	+0.058	-0.010	+0.052
1.02	+0.022	+0.027	+0.029	+0.031	-0.040	-0.025	+0.020	+0.050
1.58	+0.018	+0.003	+0.033	+0.040	-0.048	-0.195	+0.086	+0.156
1.9	+0.00	+0.017	+0.028	+0.059	-0.256	-0.096	+0.020	+0.332

3.4.2 Operational Suitability Test

3.4.2.1 Characteristics Under Normal Conditions

Conditions: Electrical power ON
Hydraulic power ON
All control paths disengaged (mechanical mode)
Load actuator adjusted for typical static load

- Measure displacement threshold of pilot controls in terms of inches at top of stick. This will actually show up as a "dead spot" in the controls. For this to be meaningful, the measurement should be corrected to reflect the difference in the short linkage control ratio and control ratio in the test helicopter.

Results: The threshold measurement was accomplished by displacing control stick in one direction; stopping and recording actuator position from Actuator Feedback Transducer 1a in volts; and the measuring the required control stick displacement in the other direction to effect an actuator movement as indicated by a change on the feedback transducer.

The threshold at the top of the stick and corrected to the proper control ratio was ±0.06 inch or 0.6 percent of total travel.

- Measure the FBW input threshold in volts required from the simulated inputs to effect a displacement of the V4-ACC system. As in the above case, this measurement should be corrected to read in terms of percent of the actual capable travel of the V4-ACC system.

Results: The FBW input threshold was measured by moving the FBW controller in one direction; stopping and recording Actuator Feedback Transducer 1a position in volts as well as the FBW Control Transducer 1a in volts; moving the FBW controller in the opposite direction until the feedback transducer indicated a change; and then reading the voltage change on FBW Control Transducer 1a. The threshold voltage corrected to read in terms of the actual capable travel of the actuator is ±0.016 percent of total travel.

3.4.2.2 Characteristics Under Single-Failure Conditions

Conditions: Same as 3.4.2.1, except that Control Path 2a is disengaged

Procedures: Same as 3.4.2.1

Results: 0.006 ± percent of total actuator travel

3.4.2.3 Characteristics Under Dual-Failure Conditions

3.4.2.3.1 Two Companion Control Paths (sharing same piston)

Conditions: Same as 3.4.2.1, except that Control Paths 2a and 2b are disengaged

Procedures: Same as 3.4.2.1

Results: 0.012 ± percent of total actuator travel

3.4.2.3.2 Two Control Paths not Sharing Same Piston

Conditions: Same as 3.4.2.1, except that Control Paths 1b and 2b are disengaged

Procedures: Same as 3.4.2.1

Results: ±0.009 percent of total actuator travel

3.4.2.3.3 One Control Path and Associated Failure Management Circuit

Conditions: Same as 3.4.2.1, except that Control Path 1b is failed hard and failure management circuit 1b is inoperative

Procedures: Same as 3.4.2.1

Results: ±0.006 percent of total actuator travel

3.4.2.4 Characteristics Under Failure of One Electrical Supply

Conditions: Same as 3.4.2.1, except that electrical supply to Control Paths 2a and 2b is off

Procedures: Same as 3.4.2.1

Results: Loss of this power supply disengages Control Paths 2a and 2b. Hence, results are same as 3.4.2.3.1 and the threshold is ±0.012 percent of total actuator travel.

3.4.2.5 Characteristics Under Complete Failure of Electrical and Hydraulic Power

Conditions: Same as 3.4.2.1, except that all electrical and hydraulic power is turned off

Results: Loss of hydraulic pressure allows the by-pass valves on both pistons to go to the "by-pass" position which allows freedom of motion as far as the hydraulics are concerned. The combined friction of the V4-ACC system and the load actuator requires about 100 pounds at the cyclic grip to produce motion. This obviously is not considered suitable for flight.

3.4.2.6 FBW to Mechanical Control Switching Transients. The purpose of this test is to check the transients induced into the control system when the safety pilot switches from FBW control to mechanical control.

Conditions: Electrical power ON

Hydraulic power ON

Quad control paths engaged

Load actuator adjusted for typical static load

Connect voltmeter to actuator position signal for path 1a, using +14 Vdc as reference

- Note voltmeter reading prior to FBW mode disengagement and compare with reading after disengagement. The difference in these two measurements can be attributed to the amount of motion in the safety pilot's hydraulic valve displacement translated into an analog signal read on the voltmeter.

Results: Test was made with the mechanical valve against the stops to test for the worst condition. When the FBW mode was disengaged, the motion of the cyclic grip when corrected for the proper control ratio was 0.15 inch. If flight test should indicate that this transient is not acceptable, preloaded centering springs can be added to the mechanical valve. The preload would have to be high enough to drag the mechanical control along.

3.4.3 Failure Modes and Effects Analysis Test

The tests in this section cover the basic types of failures that can occur. The intent is to validate the V4-ACC as a viable fault-tolerant actuation system. The FBW control paths, up to and including the EHSVs, will be tested to assure a failure tolerance level of dual fail-operate for the worst conditions.

The failure modes covered in the subsequent subsections will be simulated using the switches on the failure simulation panel; two hydraulic hand valves; and combinations of these input devices. Pertinent parameters will be measured and recorded to define failure effects. The measurements will be made using an oscilloscope and digital voltmeter. Except as noted, all initial conditions will be for all control paths and power supplies operating.

3.4.3.1 Control Paths and Failure Management System

3.4.3.1.1 Transient Disturbances. The purpose of this is to show tolerance to EMI type disturbances.

- Position SW2 to PULSE position and use momentary SW1 to apply short pulse (0.2 second) to Control Path 1a.

Results: Actuator displaced 0.086 inch (2.2 percent of total stroke) for about 0.2 second and then returned to original position which confirmed tolerance to a 0.2 second, or less, hard transient.

- Re-engage Control Path 1a.
- Adjust pulse width to about 0.4 second and apply pulse to Control Path 1a.

Results: Control Path 1a displaced 0.086 inch, disengaged, and returned to original position in about 0.35 second.

3.4.3.1.2 Second Hard Failure. This test is to demonstrate the ability of the system to manage a second failure and continue operating.

- Simulate second failure in Control Path 2a by positioning SW3 to 2a and positioning SW2 to HARD.

Results: Control Path 2a displaced about 0.088 inch, disengaged, and returned to original position in about 0.35 second.

- Re-engage Control Paths 1a and 2a.

3.4.3.1.3 Single Inert Control Path Failure. This test is to demonstrate the ability of the system to manage inert type failures.

- Simulate inert failure by positioning SW5 to OPEN which simulates an open in EHSV coil 1a.

Results: If there is an appreciable load on the actuator, Control Path 1a immediately disengages. Under a no-load condition, however, Control Path 1a does not normally disengage until an appreciable actuator displacement is commanded. This cannot present a problem since it will always disengage on demand, i.e., if additional force is needed from the actuator, a position error signal is created that disengages Control Path 1a.

- Re-engage Control Path 1a.

3.4.3.1.4 Second EHSV Coil Failure. This test is to demonstrate the ability of the system to manage two inert type failures. If two such failures are not properly managed, a "two-and-two" vote condition can occur. This system recognizes the condition and disengages both faulty control paths.

- Simulate two open EHSV coil failures by positioning SW5 in Control Paths 1a and 1b to OPEN

Results: For a no-load condition, a command for 0.056 inch of actuator displacement was required to disengage the two control paths. With an appreciable actuator load, the control paths disengaged immediately without a displacement command.

- Close SW5 on Control Paths 1a and 1b.

- Re-engage Control Paths 1a and 1b.

3.4.3.1.5 Failure Management Circuitry Failure Plus Associated Control Path Failure. This test is to demonstrate the capability of the system to operate with one control path failed and not disengaged, and hence not isolated, as a result of the associated failure management unit having failed "inert."

- Close SW4, Control Path 1a, to simulate an inert failure management unit.

- Position SW3 to 1a and SW2 to HARD to simulate a hard failure in Control Path 1a.

Results: The actuator displaced 0.13 inch and continued to operate normally with the exception of the 0.13 inch offset. This is a means of demonstrating that the basic system (without failure management) will inherently tolerate one failure and continue to operate.

- Measure and record the stall load for this condition in terms of pressure on the load actuator.

Results: Stall pressure was 500 psi.

- Open SW4 which allows Failure Management Unit 1a to become operative.

Results: Control Path 1a disengaged as expected.

- Disengage Control Path 1b.

- Measure and record stall load for this condition in terms of pressure on the load actuator.

Results: Stall load pressure was 500 psi, which is the same as the above stall load pressure. This indicates that if a first failure is a failure management unit and the second failure is the associated control path, the effect of the EHSV in the faulty control path is essentially cancelled by the comparison valve; i.e., the companion EHSV effects a hydraulic "short" circuit that results in zero pressure across the associated piston.

3.4.3.1.6 Failure Management Circuitry Shorted to Ground. This failure was considered to be the worst case failure prior to some improvements that were incorporated into the failure management circuitry. With the improved circuitry, this failure mode was deleted. The failure mode discussed above in 3.4.3.1.5 is now considered the worst case failure, which as discussed, presents no problem.

3.4.3.2 Reversion to Mechanical Control. The objective of this test is to demonstrate the capability of the actuation system to automatically switch to mechanical backup control if all FBW control paths should experience failures and subsequent disengagements.

- Insert failure in Control Paths 1a, 2a, and 2b.
- System should automatically revert to mechanical backup. Measure and record transit.

Result: The third failure insert does not necessarily mean that both of the remaining control paths disengage. However, when all four control paths are disengaged, the system automatically reverts to mechanical control. A short actuator jump was experienced which was measured in terms of top of the cyclic and grip and correct for proper control motion ratio. The corrected value of the reversion jump was 0.127 inch or 1.27 percent of total travel.

3.4.3.3 Electrical Power Supply. Three or more electrical supplies would normally be used for flight test hardware. For the laboratory test, however, only two sources are simulated. The objective of this test is to demonstrate that after a failure of electrical power to two related control paths (e.g., 1a, 1b), the actuation system continues to operate. And, after the loss of electrical power to the other two controls paths (total loss of electrical power), the hybrid actuation system automatically reverts to manual backup control.

3.4.3.3.1 Single Failure. Power Supply No. 1 provides power to Control Paths 1a and 1b while Supply No. 2 provides electrical power to Control Paths 2a and 2b. The existing power switches on the Engage/Disengage Panel will be used to simulate Electrical Power Supplies Nos. 1 and 2.

- Position power switches for Control Paths 1a and 1b to OFF.

Result: The engage/disengage relays for Control Paths 1a and 1b operate from Electrical Supply No. 1 and, hence, the two control paths disengaged. Control Paths 2a and 2b continued to operate in a normal manner.

3.4.3.3.2 Dual Failure. The purpose of this test is to demonstrate that if both electrical supplies fail, the hybrid actuator will automatically provide the pilot with the backup mechanical input.

- Position power switches for all control paths to OFF.

Results: Control Paths 2a and 2b disengaged which, in turn, automatically effected a reversion to mechanical controls since Control Paths 1a and 1b had been previously disengaged.

3.4.3.4 Hydraulic Power Supply. Three or more hydraulic supplies would normally be used for flight test hardware. For the laboratory test, however, only two sources are simulated. The objective is to demonstrate that after the hydraulic power to one piston is lost, the actuation system will continue to operate, and that after the loss of hydraulic power to the other piston (total loss of hydraulic power), the actuation system reverts to pure mechanical non-boosted controls.

3.4.3.4.1 Single Failure

- Cut off Hydraulic Supply No. 1.

Results: Loss of pressure for Piston No. 1 relieves force on by-pass valve as well as the two isolation valves for Control Paths 1a and 1b. Control Paths 2a and 2b continue working with Piston No. 2 in a normal manner. Failure of hydraulic pressure to Control Paths 1a and 1b and, hence, Piston No. 1, creates the same failure mode as if the two control paths had failed and disengaged with one exception. The exception is that if hydraulics should come back on, the two control paths would be operable again since the electronics remain engaged. A backup hydraulic supply, of course, would be used in a flyable system and would take over in the event one of the primary supplies failed.

3.4.3.4.2 Dual Failure

- Cut off Hydraulic Supply No. 2.

Results: Loss of Supply No. 2 affects Control Paths 2a and 2b in the manner as described above relative to Control Paths 1a and 1b. Both by-pass valves across the two pistons are open as a result of the loss of both hydraulic systems; however, the mechanical, unboosted controls require too much force to overcome the friction of the V4-ACC system plus the load actuator to be considered as operable. As stated above, a backup hydraulic supply would be used to effect a dual fail-operate hydraulic system for a flyable system.

3.4.3.5 Summary Discussion on Failure Mode Testing. The V4-ACC with mechanical reversion performed the failure management function in a very positive manner for all failure modes. Due to the inherent characteristics of the basic concept, the failure management does not have to effect an instant disengagement of a failed control path. Hence, it can afford a time delay to confirm the presence and continued existence of a failure as well as require a comparatively high fail-signal for a more positive failure identification.

The failure modes covered in the test program represents major type failures. An informal BHT-funded failure analysis on the electronic control and failure management circuitry was conducted apart from this program which covered detail failures such as: shorted op-amp inputs, voltage breakdown of FET switches, open limiting diodes in the auto-tracking circuitry, 14 Vdc supply, 4 KHz electrical supply, etc. None of the failures presented a failed condition that was different from the simulated failures covered in the preceding subsection. Also, none of the failures were of the type that propagated other failures.

The BHT program also covered auto-preflight requirements that were considered necessary to locate inert type failures in the failure management circuitry. It was concluded that only four test points per control path would be needed to assure that these circuits were operable. With the failure management units in an operable state, failure protection is assured and the control paths can be safely engaged.

4. RECOMMENDATION

The feasibility of the V4-ACC was determined on a Bell Helicopter IR&D program. Under Contract No. NAS2-10289 Mod 1 with NASA/Ames, the actuation concept was confirmed as a valid candidate for use in a FBW control system for the XV-15 tilt rotor aircraft. Under Contract No. N62269-79-C-0292 with the Naval Air Development Center, the concept was confirmed as a candidate for use as a fault-tolerant actuation system for a potential helicopter test vehicle. The extensive laboratory testing under this contract further confirms the results from the preceding programs and specifically confirms its application with mechanical reversion for use in automatic shipboard landing systems. To obtain the best return from the foregoing technological investments, a follow-up program is needed to develop flightworthy hardware and proceed with a flight test validation program. A recommended program is discussed below.

The most profitable approach to such a program is to take necessary steps to make the existing laboratory equipment flightworthy and to install and flight test this equipment in the collective channel of a helicopter, preferably an AH-1S Cobra. The Cobra collective channel is equipped with two primary hydraulic pumps and a third electrically driven pump that can be used to effect a dual fail-operate system. Redundant electrical power can be provided by adding another starter/generator to the transmission and two dedicated batteries connected to the generators through charging circuits. The collective stick in the gunner station (front seat) can be mechanically disconnected from the pilot's controls and used as the FBW controller. The pilot's collective controls would then be used for the mechanical back-up mode.

The plan is to reconfigure the existing equipment into flightworthy equipment by:

- Separating the FBW hydraulic module (see Figure 4) from the actuator and mount it to the structure in a close-by location.
- Building a new mechanical control head (see Figure 4) that is much smaller and flightworthy.
- Adapting the existing mechanical input linkage for compatibility with the new mechanical control head.

- Connecting the FBW hydraulic module to the mechanical control head with "flex-lines."

- Repackaging the existing circuit boards (see Figure 3) into an ECU that is more suitable for flight test.

- Designing and fabricating a control panel with provisions for preflight test.

The program will include the necessary analysis and test to assure that the above equipment configurations are flight-worthy. Adequate equipment and installation drawings as well as documentation of tests and analysis will be provided to satisfy the safety of flight release. The flight test program will include ground run, operational suitability test, and in-flight failure mode effects tests.

The recommended program should result in a flight-validated actuation concept and should also provide the necessary technology to develop a multi-axis prototype control system.

APPENDIX A

TECHNICAL DISCUSSION OF A V4-ACC

INTRODUCTORY COMMENTS

This section describes the basic V4-ACC as it relates to the basic control elements. It provides a conceptual description of the electrical links, electrohydraulic interface, power actuators, and failure management system. The actuator configuration may be a redundant tandem piston, a parallel actuator configuration, or a redundant rotary actuator. The FBW module can be an integral part of the hydraulic cylinder or the FBW module can replace the mechanical control head as shown in Figure A1. To facilitate the description of the concept in the subsequent subsections, a conventional dual tandem piston configuration will be used (see Figures A1 and A2).

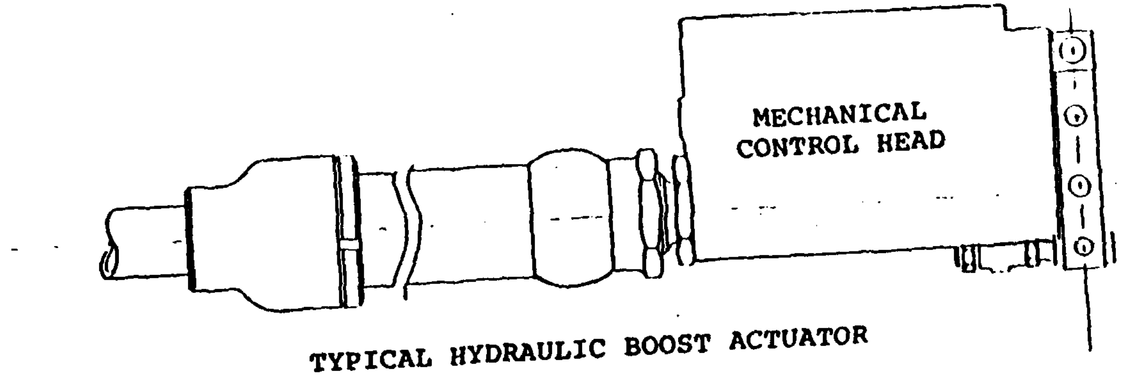
To provide a viable fault-tolerant control system, it is necessary to have an adequate number of reliable control paths and actuators for each control channel and, also, a compatible, secure failure management system. The system described in the following material satisfies the control channel requirement and includes a unique concept for sensing and isolating a failed and/or degraded control path.

DESCRIPTION OF CONCEPT

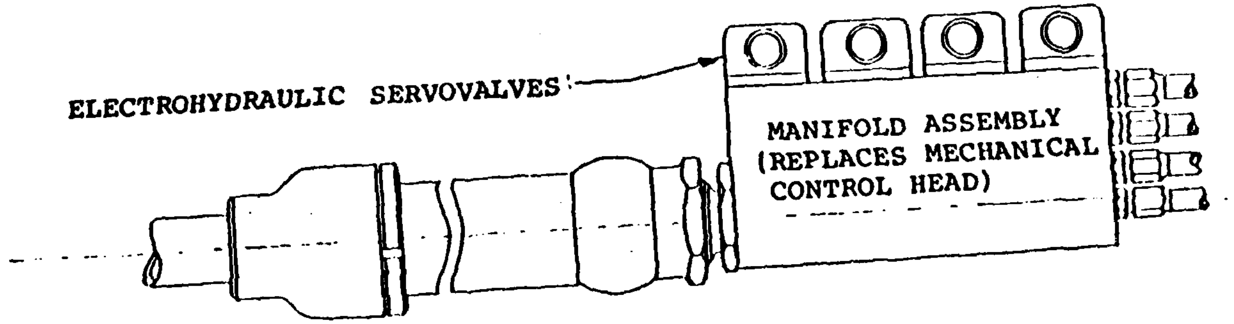
Summary

The basic fault-tolerant actuation system consists of dual hydraulic primary actuators, quadruplex electrical control paths, a failure management system, and electrical drive signals. Two electrical control paths are used for each piston. The failure management system is mechanically interfaced with the electrical control paths to provide maximum security. It provides automatic disengagement of a control path and also provides track error signals that are used in the control paths for automatic alignment of the four valves.

A flight test model of this system would include a master control panel and an annunciator panel. The control panel would provide the necessary control functions, preflight checkout capability, and a manual reset for each control channel. The annunciator panel would indicate the operating



TYPICAL HYDRAULIC BOOST ACTUATOR



BOOST CYLINDER MODIFIED TO FLY-BY-WIRE CONFIGURATION

Figure A1. Conventional Hydraulic Boost Actuator and Proposed V4-ACC Configuration.

condition of the control paths and would operate in conjunction with the control panel for the preflight checkout.

FBW Control Paths

A control axis of the basic V4-ACC consists of four FBW control paths and a dual piston power cylinder. The four control paths connect the pilot's control input to the power actuator cylinder and include the four electrohydraulic servovalves as shown in Figure A2.

The dual actuator schematically depicted is conventional, except that the control head (spool valve assembly) has been replaced with the four electrohydraulic servovalves.

Figure A2 is a functional schematic of the follow-up system; i.e., the dual boost actuator is slaved to the pilot's control inputs. All control paths are identical and operate simultaneously. A control input to the amplifiers proportionally opens the valves and drives the actuator until the dual feedback transducers provide feedback signals that cancel the command signals at the amplifier, which closes the valves and hence stops the actuator at a new position. The four valves are continuously and automatically aligned by a limited authority signal that is inherent in the failure management system (this feature is discussed in more detail later). The dual feedback transducers can be single elements and separately located to reduce vulnerability to battle damage if desired. The response of the actuator can be shaped to improve handling qualities as required.

The failure logic for the system shown in Figure A2 operates in the following manner. If a control path fails (e.g., path 1a), the path is automatically disengaged and Valve 1a is cut off to prevent leakage of fluid from one side of the piston to the other. A second path failure will be disengaged in the same manner. If the second failure should be path 1b, the logic circuitry will automatically engage a pressure-operated hydraulic bypass across the common piston so that the failure will not restrict the operation of the other piston. It is pointed out that if a first failure should disable the failure management system (described in the next section), the control path system, shown in Figure A2, has the inherent capability of absorbing a second failure. This is possible because, for example, if Valve 1a should fail and remain hardover, the other three valves will go in the opposite direction to oppose the actuator motion. This will effect a bypass around the

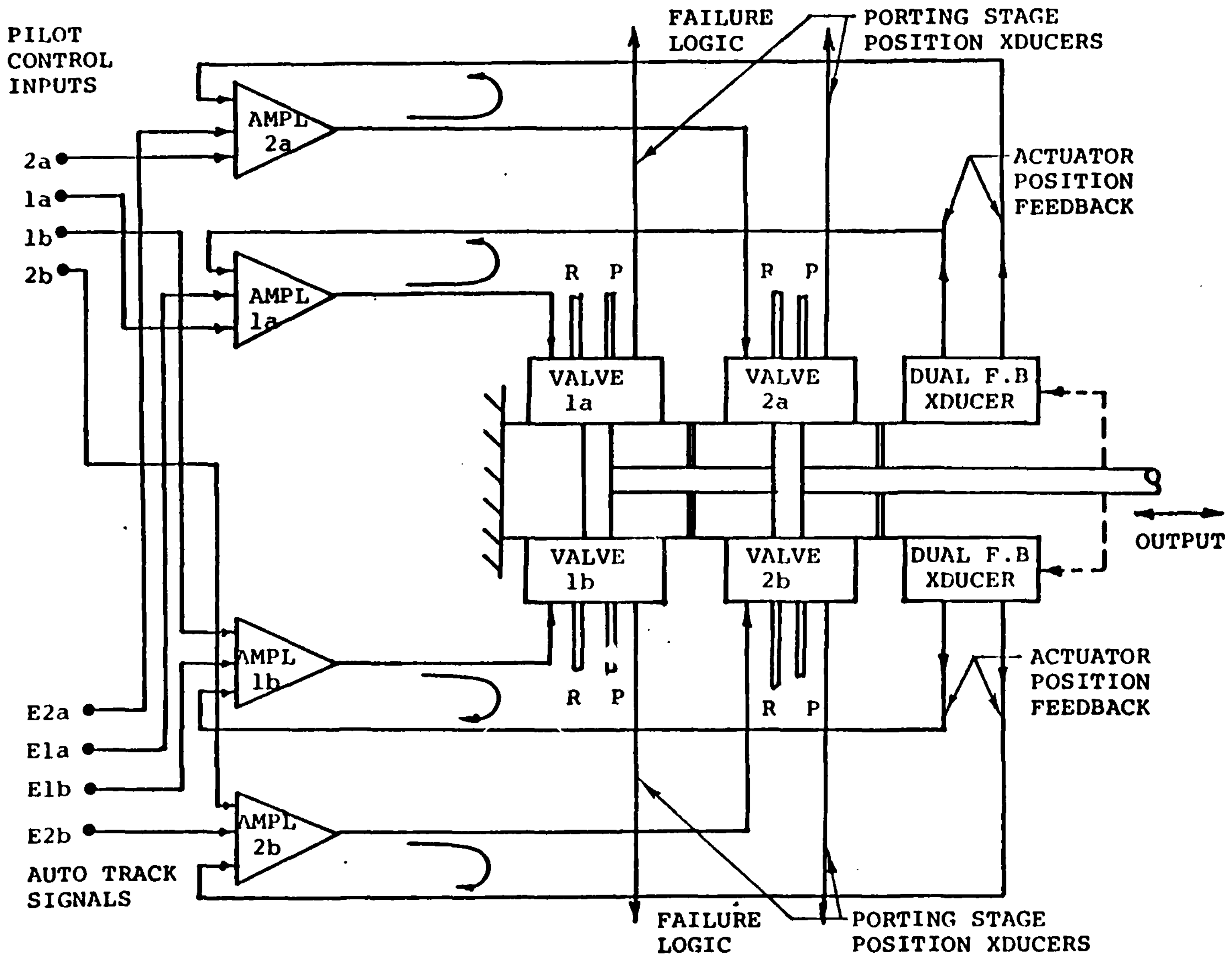


Figure A2. Dual Fail-Operate FBW Concept for Dual Piston Configuration.

piston common to Valves 1a and 1b and, hence, will allow the other piston to operate without any appreciable degradation. This inherent feature appreciably improves the overall reliability of the system and allows a comparatively simple failure management system to be used in place of a conventional voting scheme. The overall actuation system can be characterized as a forgiving type system.

Failure Management System

The failure management system complements the control paths to provide a control system with a failure tolerance level of dual fail-operate. It also includes an inherent signal in each control path that is used to effect a limited authority, automatic alignment function for the control paths which compensates for differences in component tolerance build-up. The failure management system consists of a failure sensing function and an automatic detection/disengage function. These functions are conceptually described in the following paragraphs.

Failure Sensing. The addition of an LVDT-type position transducer to the porting stage of the servovalves (second stage on conventional servovalves) allows the failure management circuitry to be mechanically interfaced with the control paths. This feature affords a more secure means of sensing a failed or degraded control path without reducing the reliability of the control path, and, hence, the transducer can be used to cover failures up to the power piston. Several other ways to provide a valve feedback signal for this failure monitor concept were considered. For example, differential pressure across the second stage of a conventional servovalve can be used. Also, the current flow through the first stage (flapper valve coil) can be used and is more economical. However, neither of these approaches will provide 100 percent failure coverage and were discarded in favor of the valve position transducer approach. Valves of this type are currently available.

The basic failure sensing function for each power actuator channel is provided simply by using four equal value resistors in conjunction with the 4-valve position transducers. Connection of the resistors as shown in Figure A3 constitutes a very simple and reliable voting concept that allows each control path to comparatively monitor itself, determine a failure, and disengage itself.

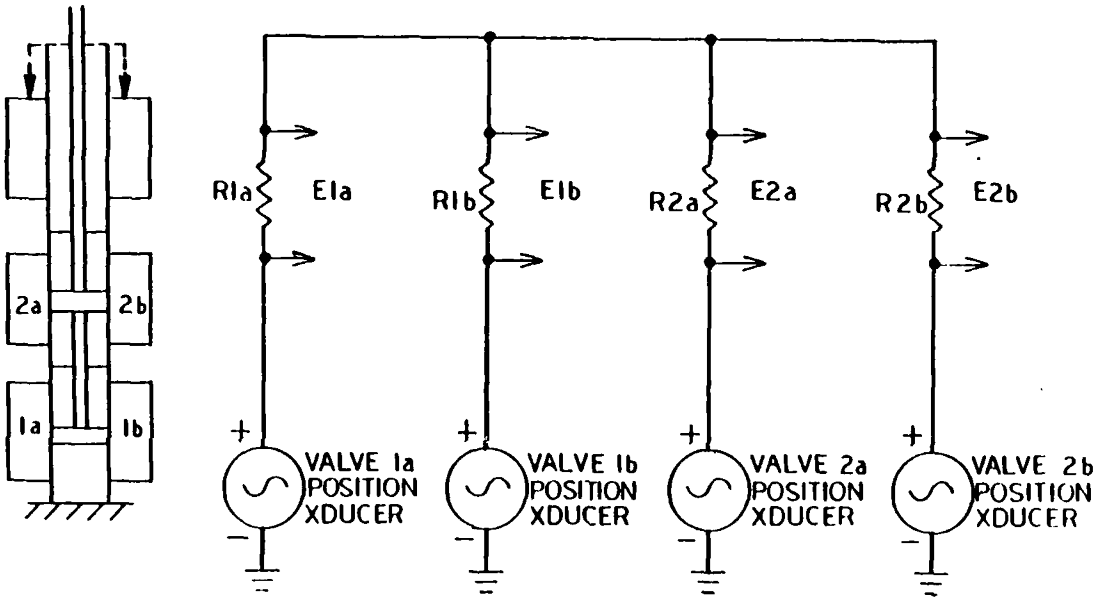
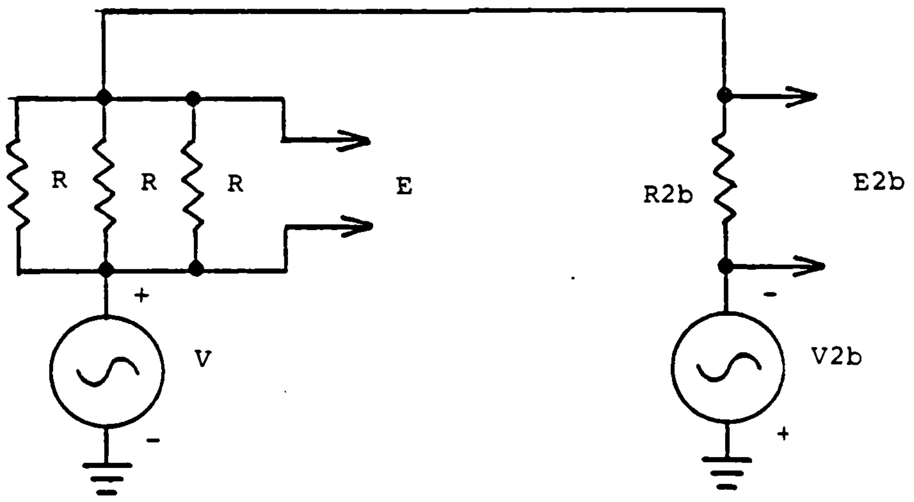


Figure A3. Fault Sensing Concept.

Figure A3 is a simplified schematic of the basic concept for sensing a failure. For normal operation, the voltage across the valve position transducers should be the same. Since the voltages across the transducers are the same regardless of valve position, there will be no appreciable current in the resistors. Current will flow only in the resistors when the valve positions are not in agreement. If one control path has a "hard" failure, the respective porting stage will fully displace while the others will partially displace in the opposite direction. The voltage differences will cause a current in the resistor associated with the failed control path that is several times higher than the current in the other resistors, thus providing a means for identifying the failed path. For example, if Valve 2b is hardover, the other three will be displaced a small amount (depending on the actuator load) in the opposite direction and each will produce a transducer output voltage. The equivalent circuit would be as shown in Figure A3.



As indicated in the equivalent circuit, the voltage from the valve transducer in the failed control path is opposite in polarity from the other three transducers and, in effect, is in series and will be additive.

The current $I_{2b} = \frac{(V-V_{2b})}{R/3+R}$ Where: $R_{1a} = R_{1b} = R_{2a} = R_{2b} = R$

$$= \frac{3}{4} \frac{(V-V_{2b})}{R}$$

The current in each of the other three resistors would be

$$\frac{1}{4} \frac{(V-V_{2b})}{R}$$

or 1/3 the current in R_{2b}. A second failure would produce the following current condition (assuming the second failure is in path E_{1b} and the switch, S_{2b}, has opened):

$$I_{Lb} = \frac{(V-V_{1b})}{R/3+R} = \frac{2}{3} \frac{(V-V_{1b})}{R}$$

The current in the other two resistors would be 1/3 $\frac{(V-V_{1b})}{R}$ or one-half the current in the resistor of the failed path.

In both cases, the failure current associated with the failed path is high enough (compared to the other currents) to provide a means of positive identification of a failure or degraded condition.

The quad-resistor network can be looked upon as an element that interfaces the failure intelligence of the four control paths. One common quad-resistor network can be used to accommodate the failure management units for the four control paths or one can be used for each of the control paths to provide additional redundancy; the trade-off is additional redundancy and failure isolation for additional cross coupling. The individual resistor network for each control path was selected because of the addition redundancy and the improved isolation of failure modes.

Automatic Detection/Disengage. This function is the part of the failure management system that detects the occurrence of a failure and isolates the fault by disengaging the affected control path. If the fault is not of sufficient magnitude to warrant a disengagement, it is presented to the pilot as a soft-fail (e.g., high null) indication. The soft-fail feature is a cautionary device for the pilot and constitutes a BITE function.

Several approaches for detecting failures were considered. One approach was to simply compare the magnitude of the failure voltage across each sense resistor (R_{1a}, R_{1b}, R_{2a}, R_{2b}) with a set threshold. The second approach used a scheme for comparing the four failure voltages to determine a failure. This approach is not as simple as the first approach, but it appeared to be more tolerant to failures and was successfully used in the BHT V4-ACC feasibility program. Subsequent studies, however, indicate that an improved arrangement of the first approach has some advantages and, as stated above, was selected as the preferred approach. The major advantage of the first approach is that it has less failure modes and has a high degree of operational independence. The selected failure detection technique affords a failure/management system that is very simple when compared to the more conventional voting schemes. This failure detection scheme and the associated automatic disengage function is shown in Figure A4 and discussed below.

Figure A4 is a simplified block diagram of the failure management unit for Control Path 2b and the quad-resistor configuration which provides an interface with the failure detection systems for the other control paths. All four control paths are identical to Control Path 2b. The three resistors and associated FET switches designated as "Outgoing Vote Signals" are an integral part of Control Path 2b Electronic Unit. These signals are connected as designated to the other electronic units to communicate the second stage position of EHSV 2b. Hence, each control path provides a status "vote" to the failure of management system of the other control paths. These signals are used in the electronic units of each control path for auto-track of the EHSV's and for detecting a failure condition.

The signal symbol depicted in Figure A4 as EHSV POSN XDUCER is the secondary winding of the LVDT that senses the position of the second stage of the EHSV. The EHSV position transducer for a control path is excited with a dedicated 4KC oscillator. Since each of these oscillators will have some difference in frequency and, hence cannot be mixed directly as shown in the fault detection schematic (Figure A3), it is necessary to demodulate the outputs so that dc mixing can be used. As

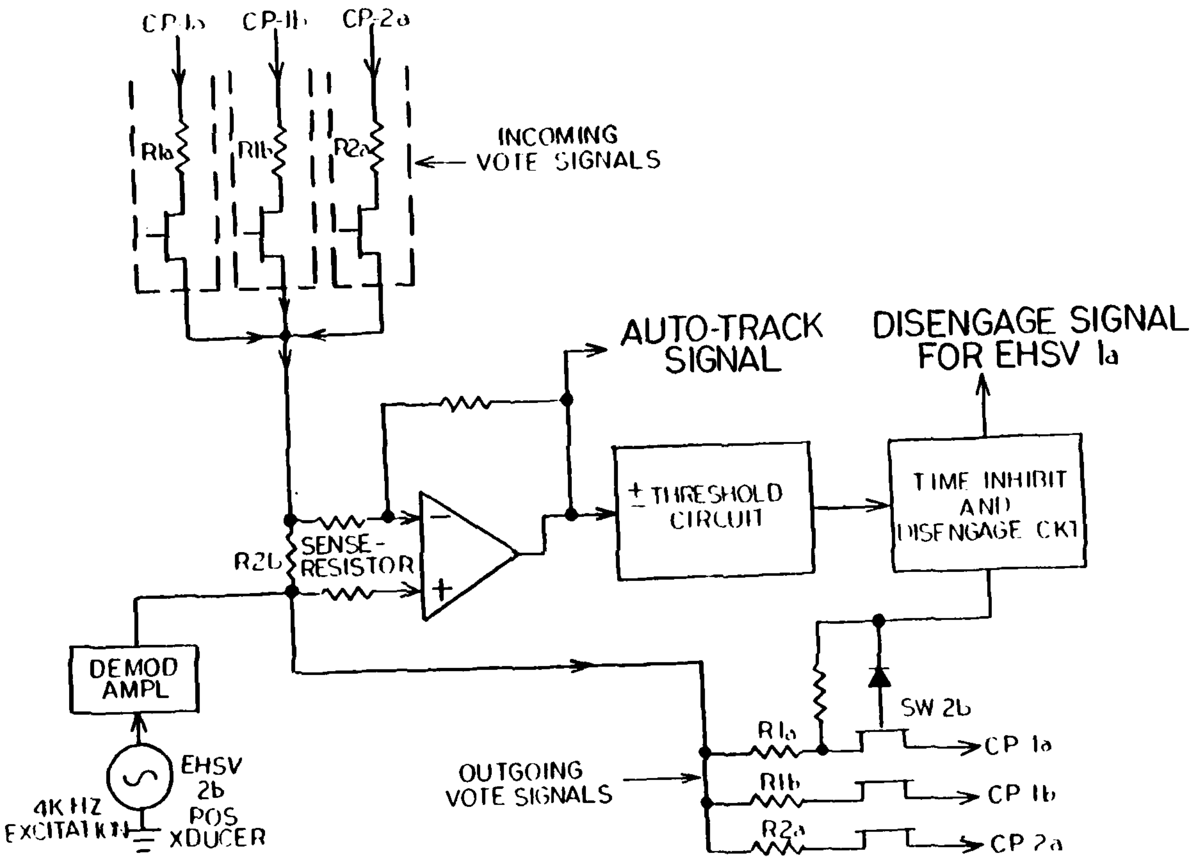


Figure A4. Failure Management Concept for a V4-ACC System.

shown, the failure signal for Control Path 2b is sensed across resistor R_{2b} and applied to a differential amplifier. The amplifier outputs a signal for two functions. It provides an auto-track signal which is limited and applied to the actuator drive amplifier for Control Path 2b (see Figure A2). The other signal is applied to a double ended threshold circuit that outputs a hard positive signal if the failure signal exceeds the set threshold. The hard signal operates on the time delay circuit which effects an autodisengage after a set time delay. This action disengages the electrohydraulic solenoid valve for the Control Path 2b and also isolates the failure logic by opening the FET switches in the "Outgoing Vote Signals" as shown in Figure A4.

As an adjunct to the above described failure detection concept, an additional feature was incorporated in the design of the failure-sensing circuitry that affords it the intelligence to differentiate between the inert-type failure and a hard-signal failure. This feature was tested in the BHT FBW laboratory model and proved to be an asset to the concept. The EHSV drive circuitry has been designed so that any open circuit up to the valve coil would create a hard failure. Hence, the most probable cause of an inert failure in a control path would be an "open" or "short" in the EHSV coil.

During a cruise condition, and especially in calm air, the EHSV's displacements are comparatively small. Hence, if one path becomes inert, the disagreement between the inert control path and the operating paths may not be of sufficient magnitude to overcome the set threshold and effect a disengagement. This suggests that a failed EHSV coil failure could exist for some time without disengaging the respective channel. Hence, a simple circuit was included as a part of the failure management system to monitor the EHSV coil (see Figure A5). It simply relates the EHSV coil current with input signal to determine an open EHSV coil and, in turn, disengages the respective control path.

The driver signal is amplified and is processed through two paths to the Monitor Amplifier. For normal operation the gain of the two paths are equal and, hence, the output of the monitor amplifier is essentially zero. An appreciable difference in the gain of the two paths will produce an output from the Monitor Amplifier when a driver signal is present. If this output signal exceeds the set threshold (e.g., 4 VDC), the threshold amplifier will output a hard signal that will

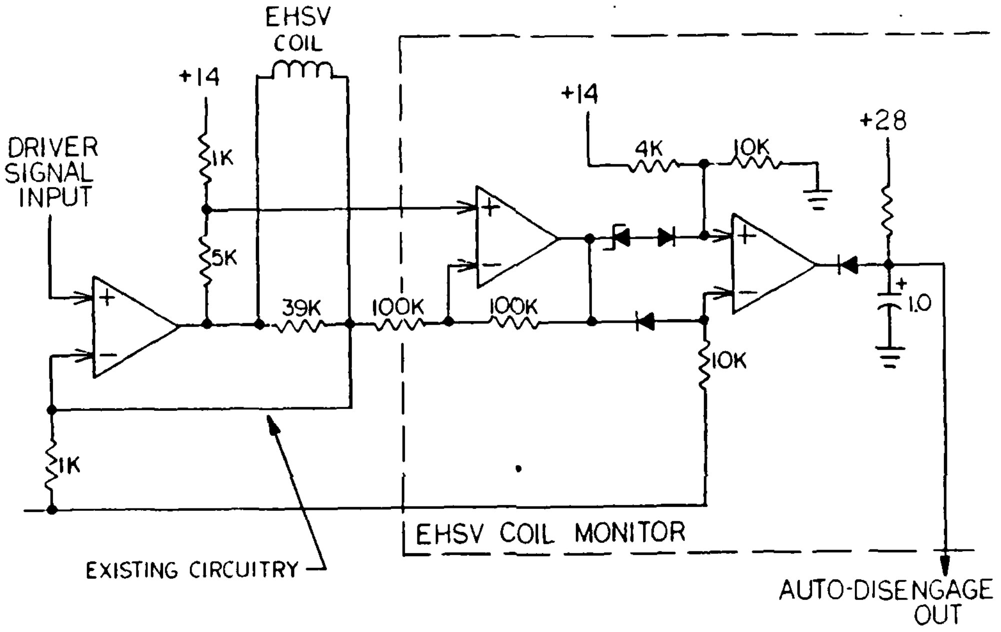


Figure A5. Open/Short EHSV Coil Monitor.

operate through a time constant to provide a disengage signal. For example, the coil has a dc impedance of 2000 ohms and if it opens, the gain of the path going to the noninverting stage of the Monitor Amplifier is very high gain compared to the other path and will effect a disengagement when there is adequate driver signal. On the other hand, if the coil is shorted, the other path has a higher gain (by a factor of 3) and will effect a disengagement when there is an adequate driver signal. Obviously, for the latter condition it will require a much larger signal to effect a disengagement; for the gains as shown, it would require a driver signal of 6 volts. This does not present a problem, however, since it will produce a disengagement on demand.

SUMMARY COMMENTS: V4-ACC

Is a comparatively simple-low parts count system

Is a forgiving type system

Requires only one monitoring plane

Installation requires no special provisions

Is easily retrofitted

Flexible - has application to any rotating controls configuration as well as conventional control surfaces

Affords the capability of leaving mechanical controls in copilot station during the development period

APPENDIX B
INTEGRATION TEST PLAN

Bell Helicopter TEXTRON
Division of Textron Inc

CODE IDENT NO. 97499

TECHNICAL DATA

BY Delbert E Haskins DATE 4-29-81
CHECKED Bruce A Hart DATE 4-29-81
APPROVED M R Murphy DATE 4/30/81
APPROVED DATE
APPROVED DATE
APPROVED DATE

NO. OF PAGES 22

REPORT NO. 699-099-031 DATE 4-29-81

INTEGRATION TEST PLAN FOR AUTOLAND FLY-BY-WIRE FLIGHT CONTROL SYSTEM

PREPARED UNDER CONTRACT N62269-80C-0128

7842-59136 Rev 276

INTEGRATION TEST PLAN FOR AUTOLAND FLY-BY-WIRE FLIGHT CONTROL SYSTEM

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LIST OF ILLUSTRATIONS

1. SCOPE

The intent of the integrated systems test is to validate the operation of the 4-valve fly-by-wire/mechanical actuator concept as a viable actuation concept for the Autoland Test Vehicle. The laboratory model of the actuator as tested per this document is functionally the same as a flight model, but to reduce cost, the physical configuration is different. A flight model will be much more compact. The circuit configuration of the failure/management and actuator drive circuitry is suitable for subsequent use in a flight test model.

This system is a full authority FBW system that may be overridden by the safety pilot's mechanical system. A "kill" or override function is provided on the safety pilots mechanical control to completely isolate the fly-by-wire system. This override function is provided as a third level failure consideration.

The following sections describe the subject equipment, test stand, auxiliary equipment, procedures for integrating the equipment, and means for determining operational suitability, failure mode testing, and failure effects.

2. DESCRIPTION OF HARDWARE

2.1 GENERAL DESCRIPTION

The test system consists of a hybrid 4-valve fly-by-wire/mechanical actuator assembly, load actuator, control circuitry for both actuators, and a control/failure simulation panel. These equipments are installed on a laboratory test stand having hydraulic and electrical supplies that are configured to simulate dual supplies. Either hydraulic supply will operate the 4-valve actuator through a pressure-operated selector valve. The fly-by-wire actuator is equipped with a mechanical input that can be activated by a control-stick-mounted switch. Figures 1 through 4 describe the test system.

2.2 HYBRID FLY-BY-WIRE/MECHANICAL

The basic actuator is equipped with a fly-by-wire electro-hydraulic module, and a mechanical control valve. The actuator can be controlled electrically or mechanically. In either case, the pilot control stick moves when the actuator moves. The pilot's control stick is equipped with a switch that activates a hydraulic solenoid in the mechanical isolating valve to disengage the 4-valve fly-by-wire control. Existing 4-valve fly-by-wire actuator hardware has been used when feasible to reduce cost. The resultant hybrid actuator is functionally the same as a flight test model but the physical configuration is different. It primarily differs in that the fly-by-wire module is hydraulically connected to the cylinder through the isolation stage in the mechanical control head. This approach was used in place of developing a new actuator barrel with fly-by-wire module integrally connected. Figure 1 is a schematic of the laboratory configuration. A flight test module with the fly-by-wire module fabricated as an integral part of the barrel will be much more compact.

Existing hardware has been used in the test stand where practical. The actuator has four inches travel and is compatible with the pilot's controller for full travel.

2.3 LOAD ACTUATOR AND CONTROL CIRCUITRY

The load actuator is shown schematically in Figure 1 and can be identified in Figure 2 as the actuator connected to the end of the pivoted beam. As shown, it is connected so that it can be used for simulating reactionary loads from the output control elements. The load actuator is controlled by appropriate circuitry in a closed-loop configuration. Reactionary loads are simulated by adjusting the hydraulic pressure and electrically driving the acuator with a signal generator.

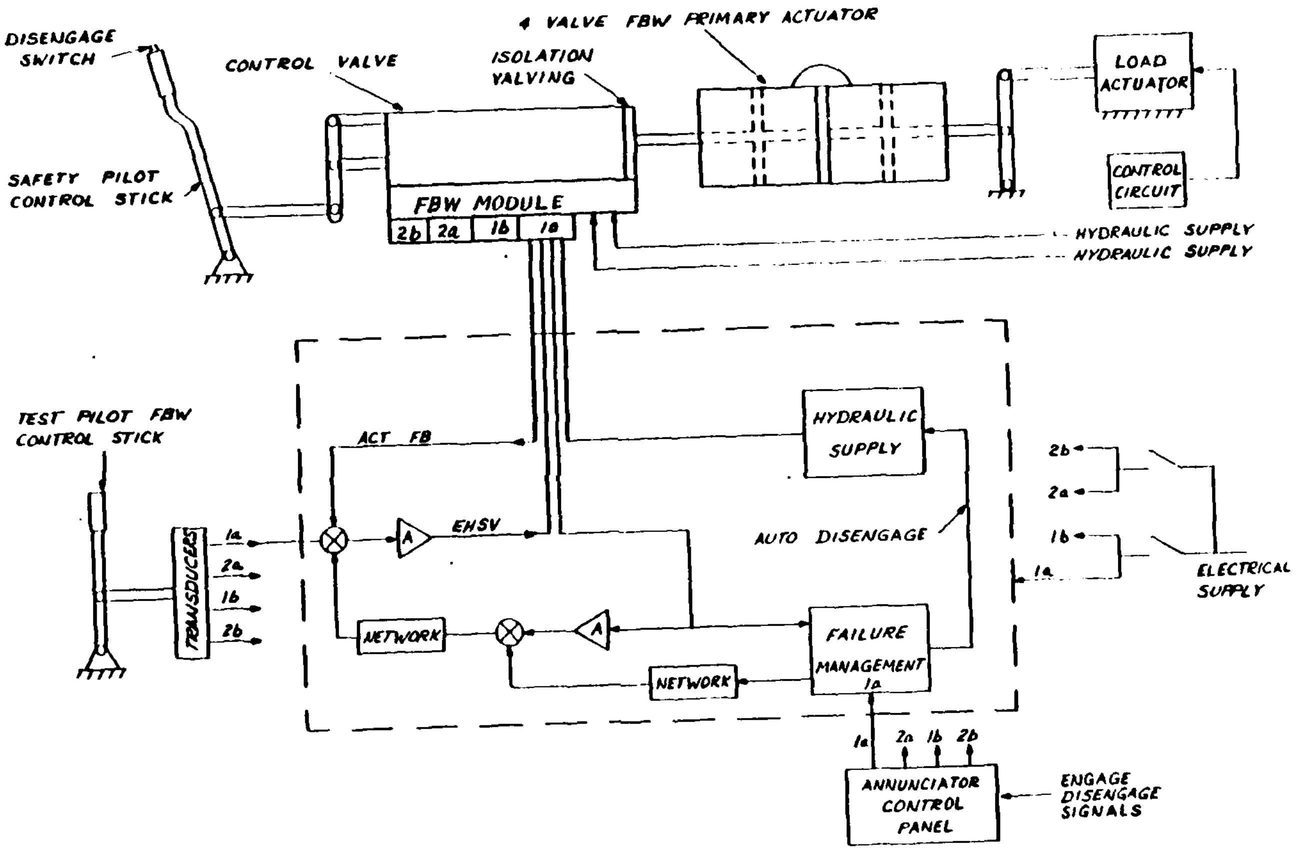

Figure 1. System Schematic of Laboratory Test Model.

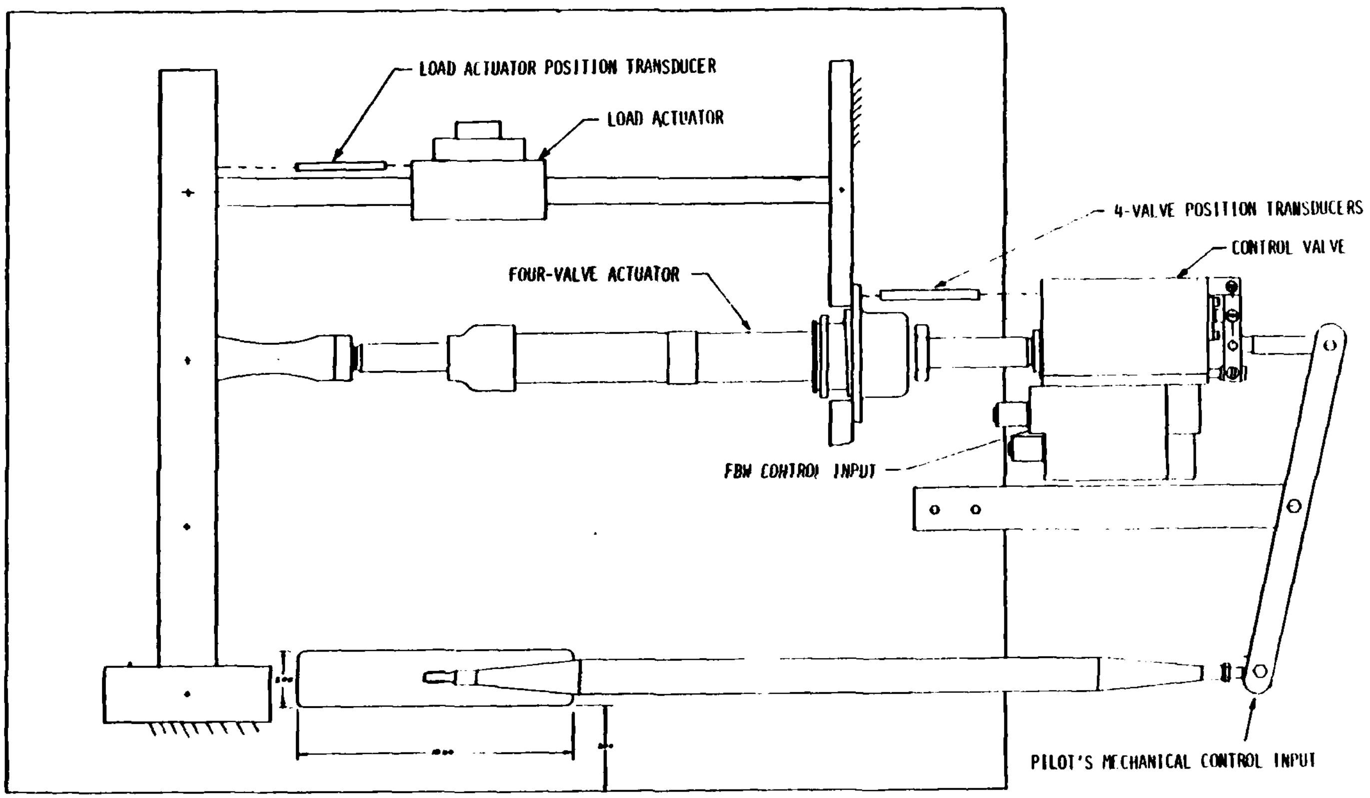

Figure 2. Plan Layout of Equipment - Test Stand.

2.4 FAILURE MANAGEMENT AND ELECTRONIC CONTROL CIRCUITRY

Figure 3 is a schematic of the failure management and electronic control circuitry as well as the test circuitry for simulating failures. The hand controller simulates test pilot inputs and is mechanized with four parallel potentiometers. AFCS signals can be accommodated through an auxiliary input. A photograph of the electronic circuitry is shown in Figure 4. Each circuit board includes the failure management circuitry, control circuitry, and failure simulation circuitry for one control path.

2.5 CONTROL/ANNUNCIATOR PANEL

The control/annunciator panel is shown in Figure 4 as an integral part of the housing for the electronic circuitry. It provides the capability of engaging/disengaging individual control paths, annunciation states of each control path, and simulating the following failure mode for each control path.

- Transient input (pulse)
- Hard control path failure
- Open EHSV coil
- Inert failure of failure management circuitry.

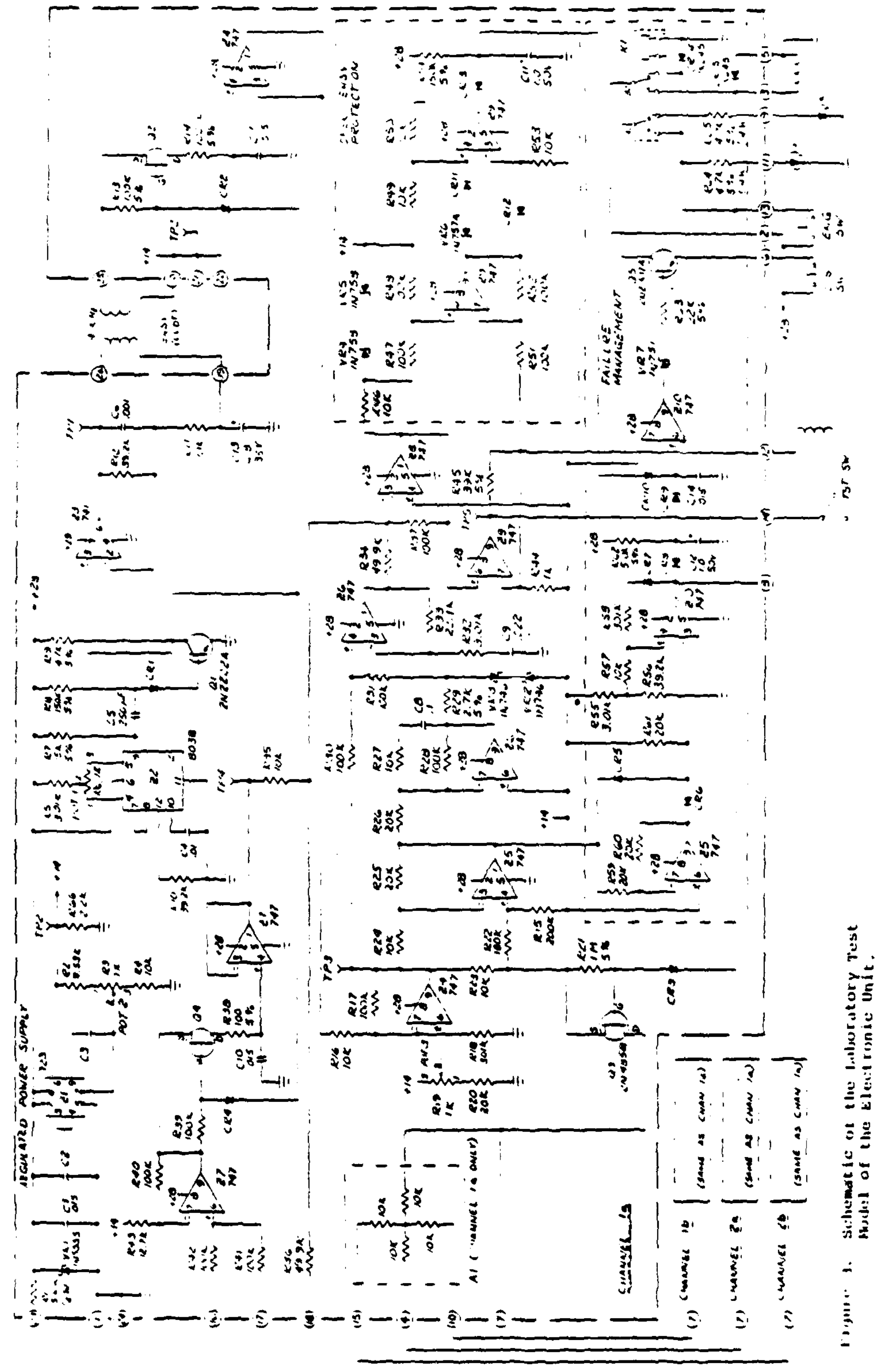

Figure 1. Schematic of the Laboratory Test Model of the Electronic Unit.

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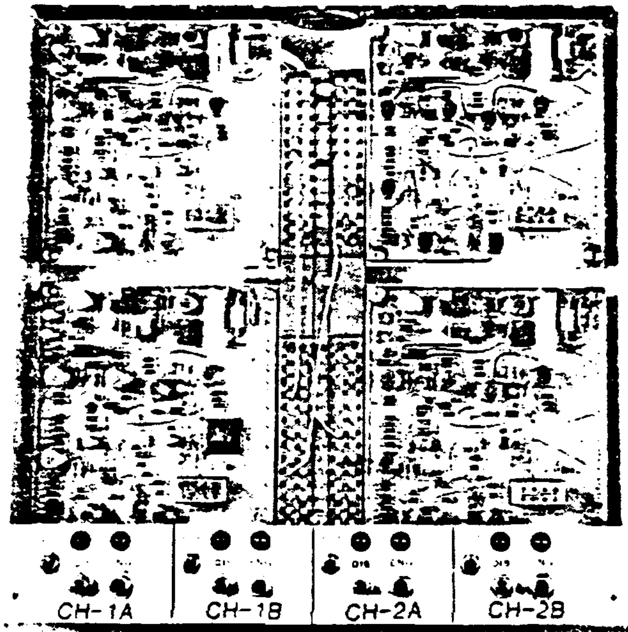

Figure 4. Autoland Fly-by-Wire Electronics Package

3. INTEGRATION TEST OF EQUIPMENT

3.1 FUNCTIONAL TEST

3.1.1 Hybrid Actuator-Mechanical Control

With hydraulics on and fly-by-wire module disengaged, move pilot's controls from stop to stop and quantitatively check for operational suitability. Note dead spots, thresholds, breakout forces, etc. Turn off Supply No. 1; Supply No. 2 should automatically take over. Apply pressure to load actuator, and with an appreciable amount of load, move actuator from stop-to-stop to assure proper operation.

3.1.2 Hybrid Actuator Fly-by Wire Control

The loop gains and compensation networks were used on the NAVTOLAND Program and therefore it is assumed that all the closed loops are stable. The control paths, however, will be realigned to assure proper operation. Each control path will be aligned and tested separately under the conditions stated below. Reference should be made to Figure 3 for supplemental information. It is pointed out that the operational amplifiers are operated from +28 Vdc to ground with +14 Vdc used as common.

3.1.2.1 Alignment and Test of Control Paths

4 K.C. Supply

Conditions: · Electrical power ON.

- Connect oscilloscope to "TP1" and adjust "Pot 1" to effect a uniform sine wave output. Output should be approximately 7 volts RMS. There is no amplitude adjustment requirement. Adjust all four channels.

+14 Vdc Supply

Conditions: · Electrical power ON.

- Connect voltmeter to "TP2" and adjust "Pot 2" to +14 Vdc. This adjustment is made on four channels.

Control Path 1a

Conditions:
- Hydraulic power ON.
- Electrical power ON.
- All solenoid valves disconnected.
- EHSV coil shorted across.
- TP4 shorted to +14 Vdc.
- TP6 shorted to +14 Vdc.
- Control path 1a engaged.

EHSV Feedback Loop

The purpose of this loop is to improve the linearity of the EHSVs and to maintain the null adjustment.

- Adjust "Pot 3" to null "TP3" (reference +14 Vdc). This adjustment aligns the output of the feedback with the assumed mechanical null of the EHSV.

EHSV Tracking Loop

The purpose of the loop is to maintain EHSV track with the other EHSVs.

- This operation assumes the mechanical null of the EHSV is correct and aligns the tracking loop accordingly. The mechanical null is accurate to ±2 percent, which is considered an adequate reference since the second stage of the EHSV has an overlap of ±10 percent.

Frequency Response Test

Conditions:
- Hydraulic power ON
- Electrical power ON
- All solenoid valves disconnected
- Short across EHSV 1a removed
- Control path 1a engaged

  - Connect frequency source to pin 18
  - Short on TP4 and TP6 removed
- Conduct frequency response of the control path and EHSV using the LVDT as the output element.

Control Paths 1b, 2a, and 2b

Same as control path 1a. Only the control path in test should be engaged.

3.1.2.2 Alignment of Electromechanical Transducers

Actuator Feedback Transducers

Conditions:
- Hydraulic power ON
- Electrical power ON
- Solenoid valve 1a (only) connected
- Control path 1a engaged

- Use fly-by-wire simulation controller and position 4-valve actuator in increments and determine sensitivity in terms of volts-per-inch of actuator travel.
- Use controller and drive 4-valve actuator in increments, and measure track error from stop to stop.
- Trim feedback transducers using transducer 1a as reference.

Fly-by-Wire Control Transducers

Conditions:
- Hydraulic power ON
- Electrical power ON
- Solenoid valve 1a (only) connected
- Control path 1a engaged

- Use fly-by-wire simulation controller and position 4-valve actuator in increments and determine sensitivity in terms of volts-per-inch of actuator travel.
- Move controller from stop to stop and measure track error of the 4 controller transducers.

- Trim controller transducers using transducer 1a as reference.

3.1.2.3 Autotracking Loop Test

Control Path 1a

Conditions:
- Hydraulic power ON
- Electrical power ON
- 4 solenoid valves disconnected
- All control paths disengaged

- Short TP4 to 14 Vdc in all control paths to isolate the control input.

- Engage control path 1a, then the other paths one at a time.

- Use pulse key on failure simulation panel and apply pulse to control path 1a. Qualitatively observe the output of LVDT 1a on an oscilloscope and note stability characteristics.

- Remove short from TP4 in all control paths.

- Connect path 1a solenoid.

- Engage control path 1a; 4-valve AFCS actuator will now track simulated fly-by-wire input.

- Drive fly-by-wire actuator from stop-to-stop and examine for interferences over the complete range of the pilot's mechanical input. The friction unit on the pilot's controls will probably have to carry some friction because of the short link arrangements.

- Repeat with some load applied by the load actuator. Apply step input to fly-by-wire actuator and observe stability characteristics on oscilloscope.

- Drive fly-by-wire actuator in increments over full travel and check tracking of each control path by recording voltage on TP6. This is the signal that is used through the limiting diodes at TP6 for autotracking as well as for a signal to the failure management circuitry.

- Tracking is expected to be within 0.05 percent when measured in terms of total actuator displacement capability.

- Connect solenoids for control paths 1b, 2a, and 2b.
- Engage control path 1b.
- Apply step input to fly-by-wire actuator and qualitatively observe stability characteristics.
- Engage control paths 2a and 2b.
- Apply step input to fly-by-wire actuator and qualitatively observe stability characteristics.
- Drive fly-by-wire over full travel in increments.
- Record tracking errors in each path at TP6.

3.2 OPERATIONAL SUITABILITY TEST

This test is similar to the functional test with the exception that the operating conditions will be varied and some parameters will be measured and recorded. The purpose of this test is to provide information pertinent to the judging of the operational suitability of the 4-valve actuation concept for use in a test helicopter.

3.2.1 Characteristics Under Normal Conditions

Conditions:
- Electrical power ON
- Hydraulic power ON
- 4 control paths engaged
- Load actuator adjusted for typical static load

- Measure displacement threshold of pilot controls in terms of inches at top of stick. This will actually show up as a "dead spot" in the controls. For this to be meaningful, the measurement should be corrected to reflect the difference in the short linkage control ratio and control ratio in the test helicopter.
- Measure the fly-by-wire input threshold in volts required from the simulated inputs to effect a displacement of the 4-valve actuator. As in the above case, this measurement should be corrected to read in terms of percent of the actual capable travel of the 4-valve actuator.

3.2.2 Characteristics Under Single-Failure Conditions

Conditions: Same as 3.2.1 except control path 1a is disengaged.

Procedure: Same as 3.2.1.

3.2.3 Characteristics Under Dual Failure Conditions

3.2.3.1 Two Companion Control Paths (share same piston)

Conditions: Same as 3.2.1 except control paths 1a and 1b are disengaged.

Procedures: Same as 3.2.1.

3.2.3.2 Two Control Paths not Sharing Same Piston

Conditions: Same as 3.2.1 except control paths 1a and 2a are disengaged.

Procedures: Same as 3.2.1.

3.2.3.3 One Control Path And Associated Failure Management Circuit

Conditions: Same as 3.2.1 except control path 1a is failed "hard" and failure management circuit 1a is inoperative.

Procedure: Same as 3.2.1.

3.2.4 Characteristics Under Failure of One Electrical Supply

Conditions: Same as 3.2.1 except electrical supply to control paths 1a and 1b are off.

Procedures: Same as 3.2.1.

3.2.5 Characteristics under Complete Failure of Electrical and Hydraulic Power

Conditions: Same as 3.2.1 except all electrical and hydraulic power supply turned off.

Procedure: Same as 3.2.1 except no test required on fly-by-wire actuation unit.

3.2.6 Fly-by-wire to Mechanical Control Switching Transients

The purpose of this test is to check the transients induced into the control system when the safety pilot switches from fly-by-wire control to mechanical control.

3.2.6.1 Transient Characteristics with 4 Control Path Engaged

Conditions:

- Electrical power On
- Hydraulic power ON
- 4 control paths engaged
- Load actuator adjusted for typical static load
- Connect volt meter to actuator position signal for path 1a, using +14V DC as reference
- Increase friction on safety pilot stick to eliminate kickback in stick.

- Note voltmeter reading prior to hybrid actuator disengagement and compare with reading after disengagement. The difference in these two measurements can be attributed to the amount of motion in the safety pilot's hydraulic valve displacement translated into an analog signal read on the volt meter.

3.2.6.2 Transient Characteristics with one Path Disengaged

Conditions: Same as 3.2.6.1 except path 1a disengaged

- Measurements same as in 3.2.6.1

3.2.6.3 Transient Characteristics with two Paths Sharing Same Piston Disengaged.

Conditions: Same as 3.2.6.1 except paths 1a and 1b disengaged

- Measurements same as in 3.2.6.1

3.2.6.4 Transient Characteristics with two Paths Not Sharing Same Piston Disengaged.

Conditions: Same as 3.2.6.1 except paths 1a and 2a disengaged

- Measurements same as in 3.2.6.1

4. FAILURE MODES AND EFFECT TEST

The tests in this section cover the basic type of failures that can occur. The intent is to validate the 4-valve actuation concept as a viable fault-tolerant actuation system. The fly-by-wire control paths, up to and including the EHSVs, will be tested to assure a failure tolerance level (FTL) of dual fail-operate for the worst conditions. The electrical and hydraulic power systems will be tested to assure that the failure effects on the total system will result in an FTL of single fail-operate and dual fail-safe.

The failure modes covered in the subsequent subsections will be simulated using the switches on the failure simulation panel; four electrical power switches, two hydraulic hand valves, and combinations of these input devices. Pertinent parameters will be measured and recorded to define failure effects. The measurements will be made using an oscilloscope. Except as noted, all initial conditions will be for all control paths and power supplies will be operating.

4.1 CONTROL PATHS AND FAILURE MANAGEMENT SYSTEM

4.1.1 Transient Disturbances

The purpose of this test is to show tolerance to EMI-type disturbances.

4.1.1.1 Short Pulse - Control Path 1a Only

- Position SW2 to PULSE position and use momentary SW1 application to apply pulse (about 0.2-second pulse).
- Applied pulse should result in a short duration jump at the actuator. Control path 1a should tolerate this disturbance and not disengage.
- Adjust pulse width to about 0.4 second and apply pulse. Control path 1a should disengage.
- Reengage control path 1a.

4.1.2 First Hard Failure

This test is to demonstrate the ability of the system to manage hard failures.

- Position SW2, control path 1a, to HARD to simulate a hard failure.

- Control path 1a should disengage.
- Use oscilloscope and measure and record actuator displacement and time required for recovery.

4.1.3 Second Hard Failure

This test is to demonstrate the ability of the system to manage dual hard failures.

- Position SW2, control path 2a, to HARD to simulate a second hard failure.
- Control path 2a should disengage.
- Measure and record actuator displacement and time required for recovery.
- Reengage control paths 1a and 2a.

4.1.4 Single Inert Control Path Failure

This test is to demonstrate the ability of the system to manage inert-type failures without requiring large actuator displacements to create an error signal.

- Position SW5, control path 1a, to OPEN to simulate an open EHSV coil.
- Simulate a fly-by-wire control input; control path 1a should disengage immediately.
- Measure the magnitude of the control input required to effect a disengagement.
- Reengage control path 1a.

4.1.5 Dual Inert Control Path Failure

This test is to demonstrate the ability to manage two inert failures. If these are not properly managed, a "two-and-two" vote condition can occur. This system recognizes the condition and will disengage both faulty control paths.

- Position SW5, control paths 1a and 1b, to OPEN to simulate two open EHSV coils.
- Simulate a fly-by-wire control input; control paths 1a and 1b should both disengage.

- Measure the magnitude of the fly-by-wire signal required to effect the disengagement.

- Reengage control paths 1a and 1b.

4.1.6 Failure Management Circuitry Failure Plus Associated Control Path Failure

This test is to demonstrate the capability of the system to operate with one control failed and not isolated by the normal disengagement.

- Close SW6, control path 1a, to simulate an inert Failure Management System.

- Position SW2, control path 1a, to HARD to simulate a hard failure.

  The hard failure will not effect a disengagement since the associated failure management circuitry is inoperative; the fault-tolerant actuation system will still be operable but with a slight static offset.

- Measure and record this offset.

- Measure and record the stall load for this condition in terms of pressure on load actuator.

- Open SW6; control path 1a should disengage.

- Disengage control path 1b.

- Measure stall load; this should be about the same as for the dual failure conditions.

4.1.7 Failure Management Circuitry Shorted to Ground

This test is to demonstrate the capability of the failure management system to handle the worst case type failures.

- Close SW4, control path 1a, to simulate a worst case failure to channel 1a failure management.

The hard failure will effect a disengagement in channel 1a only. The other channels will not disengage as they receive only approximately 40 percent of necessary voltage to disengage.

- Measure and record offset in other channels
- Open SW4
- Engage channel 1a

4.2 REVERSION TO MECHANICAL CONTROL

The objective of this test is to demonstrate the capability of the actuation system to automatically switch to mechanical backup control if all fly-by-wire control paths should experience failure and disengage.

- Insert failure in control path 1a, 2a, and 2b.

  System should automatically revert to mechanical backup. Measure and record transit.

4.3 ELECTRICAL POWER SUPPLY

Three or more electrical supplies would normally be used for flight test hardware. For the laboratory test, however, only two sources are simulated. The objective of this test is to demonstrate that after a failure of electrical power to two related control paths (e.g. 1a, 1b), the actuation system continues to operate. And after the loss of electrical power to the other two controls paths (total loss of electrical power), the hybrid actuation system automatically reverts to manual backup control.

4.3.1 Single Failure

Power Supply No. 1 provides power to control paths 1a and 1b while Supply No. 2 provides electrical power to control paths 2a and 2b. The existing power switches on the Engage/Disengage Panel will be used to simulate Electrical Power Supplies Nos. 1 and 2.

- Position power switches for control paths 1a and 1b to OFF.

  Control paths 1a and 1b will disengage. Control paths 2a and 2b will continue to operate in a normal manner. The loss of the two control paths will not change the "flow gain" of the actuator; however, the "force gain" will be one-half of the normal gain.

4.3.2 Dual Failure

The purpose of this test is to demonstrate that if both electrical supplies fail, the hybrid actuator will automatically provide the pilot with the backup mechanical input.

- Position power switches for all control paths to OFF.

  All control paths will disengage and the mechanical backup control will automatically activate.

4.4 HYDRAULIC POWER SUPPLY

Three or more hydraulic supplies would normally be used for flight test hardware. For the laboratory test, however, only two sources are simulated. The objective is to demonstrate that after the hydraulic power to one piston is lost, the actuation system will continue to operate, and that after the loss of hydraulic power to the other piston (total loss of hydraulic power), the actuation system reverts to pure mechanical nonboosted controls.

4.4.1 Single Failure

De-energize solenoid valves 1 and 2 to simulate loss of system 1. The pressure-operated bypass valve will go to bypass position and system 2 will continue to operate.

4.4.2 Dual Failure

Energize solenoid valves 5 and 6; de-energize solenoid valves 1, 2, 3 and 4. The pressure-operated bypass valves in system 1 and 2 will go to operate position and shutoff valves 1, 2, 3 and 4 will close and the actuator will continue to operate in the pure manual mode.

4.5 SUMMARY DISCUSSION ON FAILURE MODE TESTING

Summary discussion will include all test results and any peculiarities that may occur during testing.

DATE

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