NAVAIRDEVCEN-79156-60

DESIGN AND TEST OF A HYDRA-OPTIC FLIGHT CONTROL ACTUATION SYSTEM (HOFCAS) CONCEPT

DECEMBER 1980

FINAL REPORT FOR PERIOD
SEPTEMBER 1979–DECEMBER 1980

Prepared For:

NAVAL AIR SYSTEMS COMMAND (AIR 340D)
Department of the Navy
Washington, DC 20361

AIRCRAFT AND CREW SYSTEMS TECHNOLOGY DIRECTORATE (CODE 6012)
Naval Air Development Center
Warminster, PA 18974

Rockwell International
North American Aircraft Division

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER NADC-79156-60	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) DESIGN AND TEST OF A HYDRA-OPTIC FLIGHT CONTROL ACTUATION SYSTEM (HOFCAS) CONCEPT		5. TYPE OF REPORT & PERIOD COVERED Final Report 18 SEP 1979 - 17 DEC 1980 6. PERFORMING ORG. REPORT NUMBER NR80H-87
7. AUTHOR(s) Lloyd L. Kohnhorst Domenic A. Magnacca		8. CONTRACT OR GRANT NUMBER(s) N62269-79-C-0709
9. PERFORMING ORGANIZATION NAME AND ADDRESS Rockwell International North American Aircraft Division 4300 E. Fifth Avenue, Columbus, OH 43216		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Air Development Center Warminster, PA 18974		12. REPORT DATE December 1980 13. NUMBER OF PAGES 105
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office) AIR-530311 and AIR-340D Naval Air Systems Command Department of the Navy Washington, DC 20361		15. SECURITY CLASS. (of this report) Unclassified 15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for Public Release; Distribution Unlimited

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

18. SUPPLEMENTARY NOTES

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

Direct Digital Drive Flight Control Actuation
Digital Fly-By-Light
EMI Immunity
Hydra-Powered Alternator
Optical Control

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

The feasibility of the Hydra-Optic Flight Control Actuation System (HOFCAS) concept was demonstrated in a laboratory program. The concept offers a realistic approach for reducing susceptibility to electromagnetic hazards in fly-by-wire control systems. The system features a modular design, digital direct drive actuator that will offer improved performance and reliability by reducing system complexity. The laboratory testing demonstrated the concept functions satisfactorily and is ready for flight testing in a T-2C aircraft.

SUMMARY

This report describes the development, testing and demonstration of a Hydra-Optic Flight Control Actuation System (HOFCAS) suitable for the actuation tasks of a Digital Fly-By-Wire flight control system. HOFCAS offers a realistic, cost effective approach to reducing the susceptibility of aircraft fly-by-wire systems to EMP, EMI, RFI, lightning, etc. By removing the conventional wiring to the actuation areas of an aircraft, the concept eliminates the opportunity for electromagnetic hazards to enter the system.

The HOFCAS concept provides a direct drive, hydraulically powered surface actuation system that provides immunity to electromagnetic radiation. The direct drive actuator, developed in a previous multiphase Navy Advanced Flight Control Actuation System (AFCAS) program, uses an electrical torque motor to power a single stage hydraulic valve for control of the actuator. A hydraulically powered alternator supplies the electrical power needed to operate the torque motor. The actuator command signal is supplied by a fiber optic link. The HOFCAS was configured to operate the directional control system in a T-2C aircraft. The AFCAS program demonstrated direct digital control of a surface actuator, and the HOFCAS extends this technology to demonstrate that conventional interconnecting electrical wiring to the surface actuators can be eliminated.

The HOFCAS was laboratory tested using T-2C flight hardware and the results demonstrated the system to be completely acceptable for flight testing. The laboratory setup, including controls and signal paths, simulated the T-2C installation. Additional testing was performed on various components to establish areas where design improvements could be added to extend the capability of the concept. This was especially true with the Hydra-Powered Alternator (HPA) where the data indicates a significant improvement can be obtained with an alternator and electronics specifically designed for this application.

PREFACE

This report documents research conducted by the North American Aircraft Division of Rockwell International Corporation, Columbus, Ohio, under contract N62269-79-C-0709 with the Naval Air Development Center, Warminster, Pennsylvania. Technical direction was provided by Mr. C. Abrams, the Program Manager for Navy Flight Control (Code 6012).

This report discusses the development, test, and demonstration of a Hydra-Optic Flight Control Actuation System (HOFCAS) for Digital Fly-By-Light control. The HOFCAS utilized the assets from the previous AFCAS programs and was designed to be flight tested and evaluated in a T-2C aircraft.

Acknowledgement is given to the following for participation on this project:

Mr. E. Solomon - System Engineer
Mr. B. Holland - Hydraulic Engineer

Appreciation is extended to the many individuals who provided helpful support and constructive criticism of the program; in particular Mr. C. Abrams, Mr. T. Jansen, and Mr. W. Kaniuka of the Naval Air Development Center.

Discussions in this report of components and material supplied by various manufacturers shall not be construed as either an endorsement or criticism of any item. The Government incurs no liability or obligation to any supplier from the information presented herein.

TABLE OF CONTENTS

TABLE OF CONTENTS (Cont'd)

LIST OF FIGURES

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

LIST OF FIGURES (Cont'd)

LIST OF TABLES

1.0 INTRODUCTION

1.1 BACKGROUND INFORMATION

The development of Advanced Flight Control Actuation Systems (AFCAS) for the next generation aircraft has been a joint undertaking by the Navy and Rockwell International Corporation since 1972. The Navy recognized the need for advanced high performance flight control actuation systems as used for Fly-By-Wire but without the increased complexity normally associated with these systems. The AFCAS program investigated totally new approaches for surface actuation instead of using the traditional actuators with added accessories and functions. As a result, the AFCAS program offers an approach to surface actuator standardization and reduced actuator complexity. This in turn produces reduced cost, size and weight while still providing improved performance.

The AFCAS concept being developed by the Naval Air Development Center (NADC) is a direct-drive, lightweight, hydraulic surface actuation system capable of being controlled with a direct digital command. This Direct Digital Drive (D^3) actuation system and the lightweight hydraulics, have been successfully flight tested and shown to be a practical approach to surface actuation. This project utilizes AFCAS with new approaches incorporated to eliminate the conventional interconnecting cabling to the surface actuator.

A major concern for future fly-by-wire aircraft is protection against electronic hazards such as EMI, EMP, lightning, high energy radiation, and spurious signals. If control signals can be transmitted via light pulses, particularly to the actuation regions, then electromagnetic transient protection can be greatly enhanced. By removing all electrical connections to the actuator, electromagnetic coupling which would allow RFI, lightning or other transient signals to enter would be eliminated. The electrical power required to receive and utilize the light pulses would be generated hydraulically within the actuator. The electronics to restore the digital signal and drive the electrohydraulic valve would also be contained within or on the actuator. The system developed for this project offers an approach for meeting the goal of a direct drive surface actuator with no interconnecting cabling.

The AFCAS program that preceded this study was a six phase program (References 1 through 6) that explored the feasibility of direct drive, developed the concept, and evaluated it in a series of laboratory and flight test programs. Phase VI of this program incorporated the microcomputer and successfully demonstrated the D^3 capability of the AFCAS. Pulse modulated signals, generated in the microcomputer, were power amplified in an Electronic Drive Unit (EDU) and used to control the direct drive actuator. An analog backup capability was also provided, whereby the EDU controlled the actuator directly and the microcomputer was not in the control loop.

1.2 OBJECTIVE

The general objective of this program was to assemble and test a direct-drive, lightweight, hydraulic surface actuator system that provides immunity to all forms of electromagnetic radiation. The specific goal was to operate the Navy's digital AFCAS without the need for electrical power being transmitted to the actuator. This was accomplished by modifying the Navy's AFCAS to operate with a hydraulically-driven alternator supplying the electrical power, and adding an optical command link between the microcomputer and the direct drive actuator electronics.

1.3 TECHNICAL APPROACH

The technical approach used to develop the Hydra-Optic Flight Control Actuation System (HOFCAS) was to utilize assets developed under the previous six-phase AFCAS program and to demonstrate, through laboratory testing, that the HOFCAS concept is suitable for flight in the T-2C Demonstrator Aircraft. The AFCAS actuator, the transducers, and the microcomputer power supply were used without change. The microcomputer and the EDU were modified to incorporate optical data transmission. A Hydra-Powered Alternator (HPA) was added to supply the electrical power needed for the actuator drive unit. Additional changes were made to the system switching and interconnecting wiring to incorporate the new modes of operation.

The system configuration was designed and tested to verify that the HOFCAS is suitable for controlling the rudder of a T-2C aircraft, shown in Figure 1-1. For this application the T-2C control system will be modified from a mechanically powered cable system to a full powered Digital Fly-By-Light (DFBL) system with an Analog Back-Up (ABU) mode of operation. The original cable system between the rudder pedals and the rudder will be removed. The rudder pedal will be attached to force transducers. Force on the rudder pedal is converted to a proportional electrical signal by these force transducers. This signal is supplied to a microcomputer where it is summed with the feedback signal and processed into a pulse modulated error signal. The pulse modulated error signal is transmitted optically through fiber optic cables to the EDU where it is converted to electrical signals, power amplified, and used to control the torque motor of a direct drive hydraulic rudder actuator. This modified system provided full power DFBL control of the rudder, instead of the manually operated rudder of the basic T-2C aircraft.

The HOFCAS mounting requirements, lead length, and hydraulic and electrical power sources were selected to be compatible with the T-2C. The HOFCAS evaluation criteria were selected to meet the dynamic performance requirement of the T-2C aircraft. Safety provisions, including failure mode evaluation, were based on T-2C flight safety requirements. The previous AFCAS flight test program included a hydraulic bypass valve on the direct drive actuator. This device allows the rudder to seek a trail position if the rudder control system were lost. Flight testing has established the aircraft can be safely landed with the rudder in the trail position. This feature establishes a third level of redundancy beyond the DFBL and the ABU modes of control.

Figure 1-1. T-2C Demonstrator Aircraft

All the major components needed to fly the HOFCAS in the T-2C were assembled in the laboratory for the system testing. System and component tests were performed to insure satisfactory operation in the T-2C. Additional system tests were performed that exceeded T-2C requirements. These tests were performed to establish the performance levels possible with the present HOFCAS and to identify areas where improvements could be made if necessary.

This approach makes use of existing Navy hardware to test and evaluate several critical portions of an actuation system that eliminates the need for wiring to transmit power and signal to the actuation region. The Navy currently has a separate program for developing an optical position sensor to provide a feedback for this direct drive hardware. After the optical sensor, the HPA, and the EDU are integrated into a common actuation package with the D^3 actuator, the general objectives of this program will be achieved.

2.0 HYDRA-OPTIC FLIGHT CONTROL ACTUATION SYSTEM (HOFCAS)

2.1 GENERAL DESCRIPTION

The HOFCAS utilizes a direct drive actuation system, commanded by light, with self contained electrical power to control an aircraft rudder actuation system. The system hardware for this program is a modification of the Phase VI Direct Digital Drive AFCAS program hardware previously evaluated and described in Reference 6.

A simplified block diagram showing the major components of the HOFCAS system is contained in Figure 2-1. The shaded areas in Figure 2-1 indicate the units modified or added for the HOFCAS. The microcomputer and the EDU were modified to incorporate the optical command link (new) and the HOFCAS Hydra-Powered Alternator (HPA) is a new unit added to provide electrical power for the EDU in the Digital Fly-By-Light (DFBL) mode.

2.2 SYSTEM DESCRIPTION

Two modes of system operation are provided, the DFBL and the ABU modes. Figure 2-2 contains a block diagram that illustrates the two modes of operation, and a functional schematic of the system is shown in Figure 2-3.

The DFBL mode is selected by momentarily holding the cockpit DFBL ENGAGE switch to ON, energizing the DFBL control relays and resulting in the following:

- The pedal command and actuator feedback transducer outputs are connected to the microcomputer input.
- The microcomputer output is connected to the EDU via the fiber optic control link.
- Hydraulic pressure is supplied to the HOFCAS HPA, and the 26 VAC, 1000 HZ HPA output is used to power the EDU via a 26 VAC to 115 VAC step-up transformer. The EDU input power is utilized to provide excitation for the transducers and to condition, amplify, and convert the optical signals into electrical signals which are power amplified and used to drive the torque motor coils.

If the microcomputer senses the system is functioning properly, a power ground is continuously supplied to the DFBL ENGAGE switch holding coil by the microcomputer and the system remains in the DFBL mode.

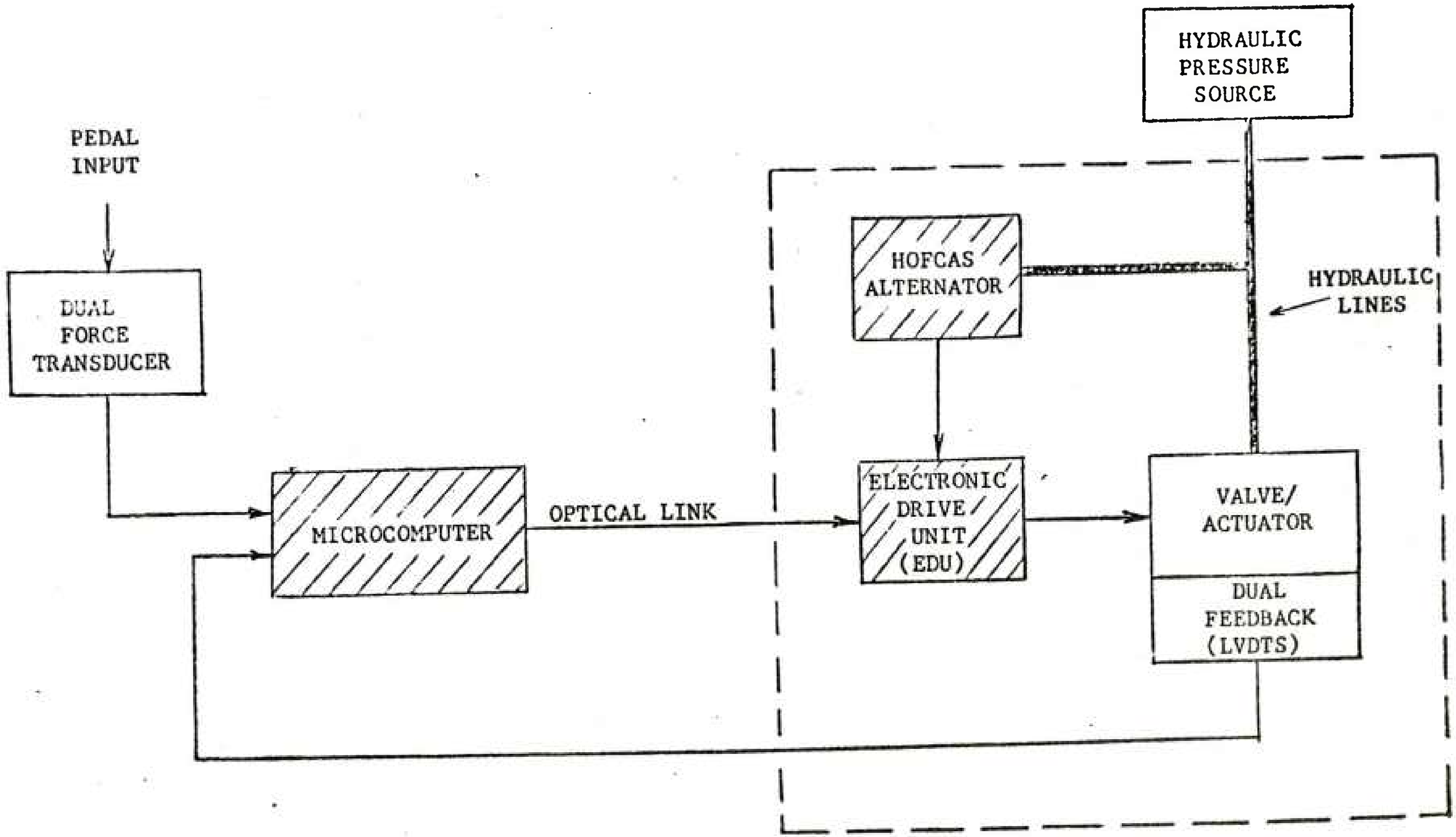


Figure 2-1. HOFCAS Simplified Block Diagram

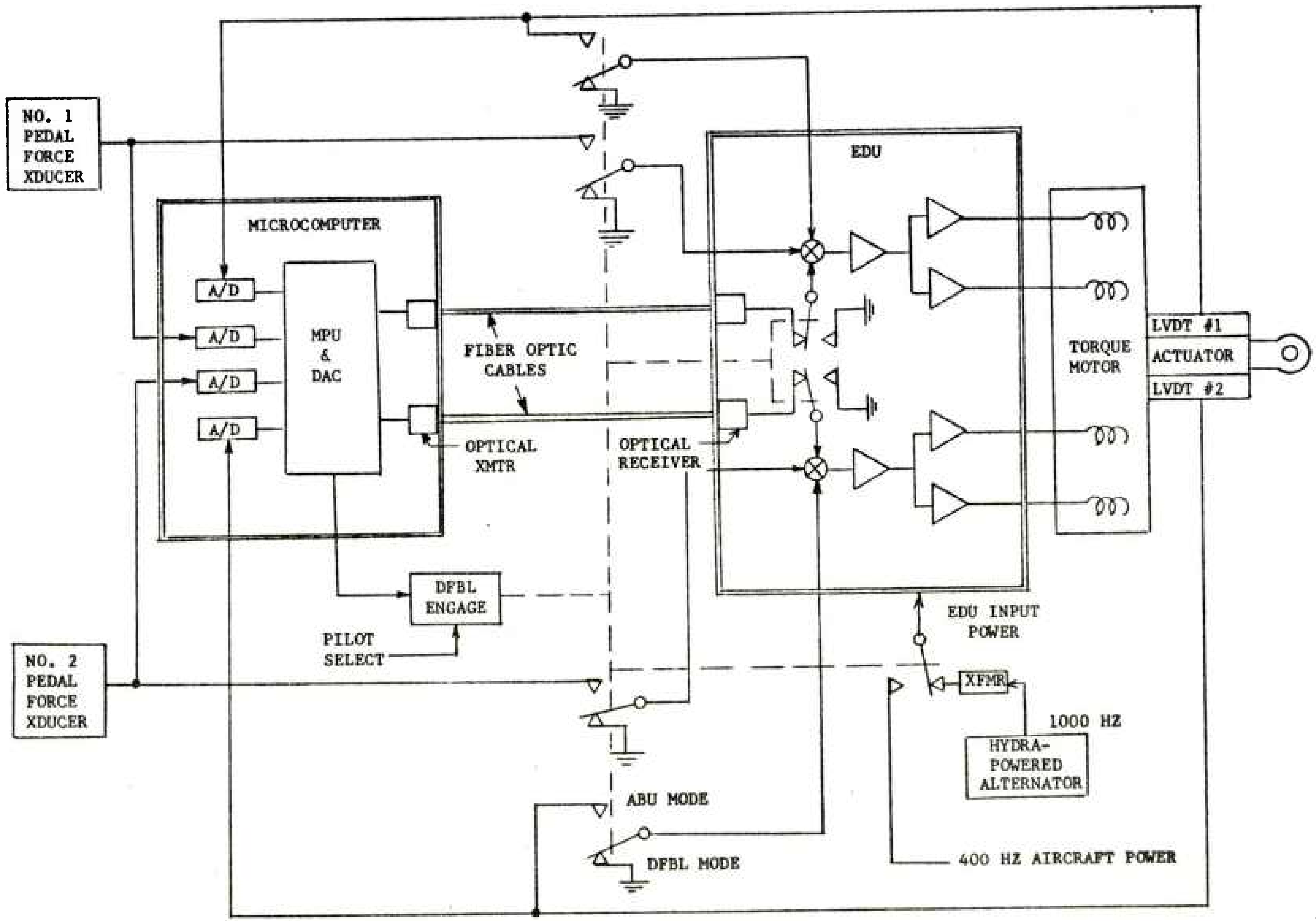


Figure 2-2. HOFCAS Operational Modes, Simplified Block Diagram

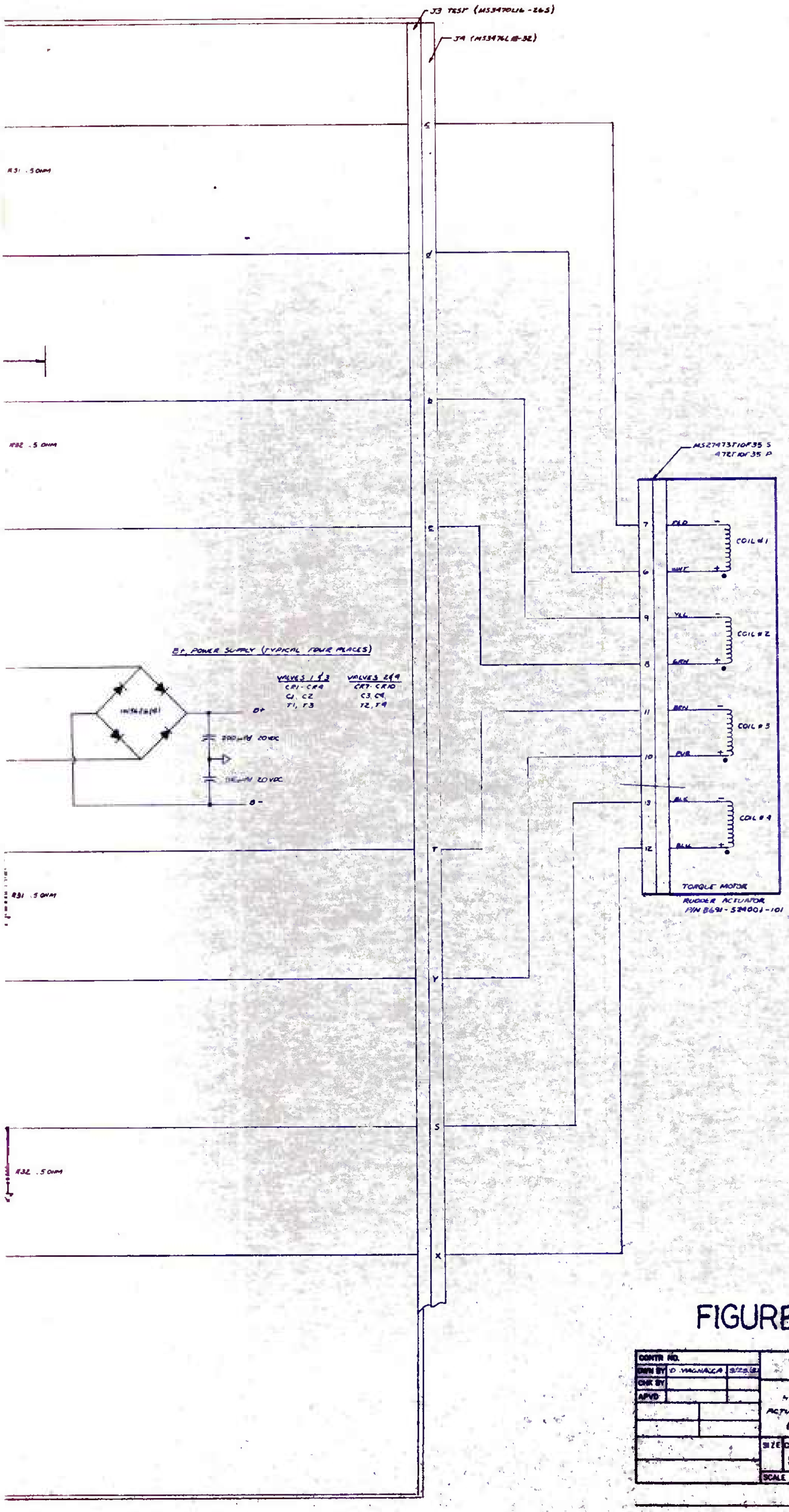


FIGURE 2-3

CONTR NO.		Columbus Aircraft Division North American Rockwell
DWN BY	D. VAGNALCA	
CHK BY		HYDRA-OPT.C FLIGHT CONTROL ACTUATION SYSTEM (HOFCAS) T-2C (INSTALL SCHEMATIC)
APVD		
SIZE	CODE IDENT NO. 89372	INFORMATION PRINT
SCALE		SHEET

The ABU mode can be selected by manually placing the DFBL ENGAGE switch to OFF, or automatically by the microcomputer removing the power ground from the DFBL ENGAGE switch holding coil if abnormal system operating errors occur.

Switching to the ABU mode results in the following:

- The fiber optic control link output from the microcomputer is disconnected from the EDU, and the pedal command and actuator feedback transducer outputs are connected directly to the EDU where they are summed and amplified to drive the four torque motor coils of the actuator direct drive valve.

- Hydraulic pressure is removed from the HOFCAS HPA, and the EDU is powered by 115 VAC, 400 HZ aircraft power.

The various system components are discussed in the following paragraphs.

2.3 HYDRA-POWERED ALTERNATOR (HPA)

The HOFCAS HPA assembly, Bertea P/N 287700, supplies electrical power to the EDU in the DFBL mode. The alternator rated output, at 3000 psi (21 MPa) ΔP and a fluid flow of 0.72 gpm (2.7 L/min), is 25 watts @ 26 VAC, 1000 HZ. The HPA was not used in the previous Phase VI of the Digital AFCAS program and has been added for HOFCAS.

The unit consists of a hydraulically driven 2" (5.1 cm) diameter turbine wheel coupled to a conventional permanent magnet electric alternator, spun by fluid discharged from a .020" (.05 cm) diameter orifice. The 6-pole configuration of the alternator, Electro-Kinetics Model No. 4922-2, provides a frequency of 1000 HZ at 10,000 rpm.

The alternator output is nearly sinusoidal with a resistance load, and distorts to a pseudo square wave when inductive loads are applied (detailed data describing alternator output and waveforms are contained in section 3.3.1 of this report).

The HPA turbine wheel and alternator are shown in Figure 2-4 and the HPA assembly is shown in Figure 2-5. Additional alternator data is supplied in Appendix B.

2.4 ELECTRONIC DRIVE UNIT (EDU)

The EDU contains the electronics required for converting optical inputs to electrical input signals, signal conditioning and amplification, signal summation, and power amplification to current drive the actuator torque motor. The unit was designed by the North American Aircraft Division (NAAD) and contains two independent channels, each sub-divided into dual valve driver circuits.

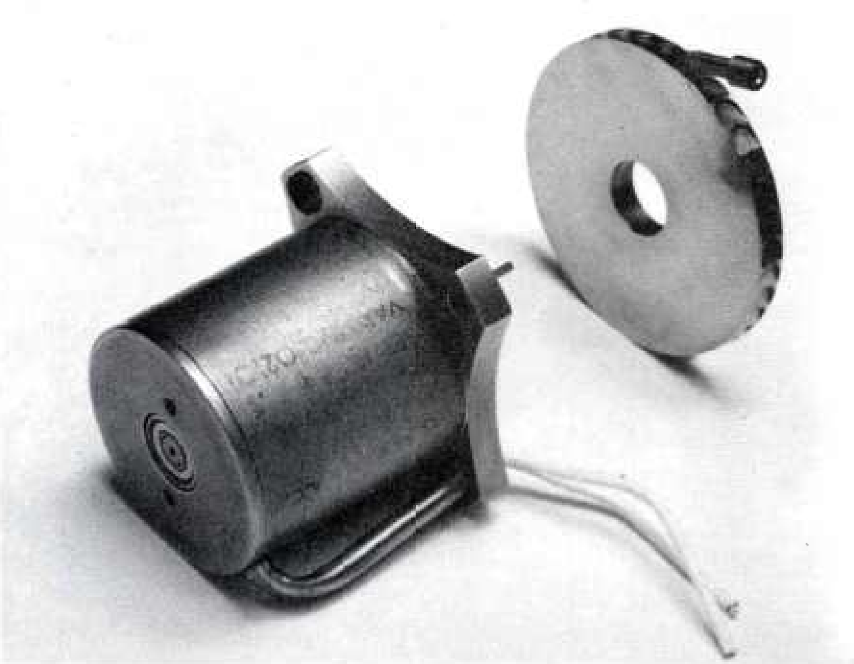


Figure 2-4. HPA Turbine Wheel and Alternator

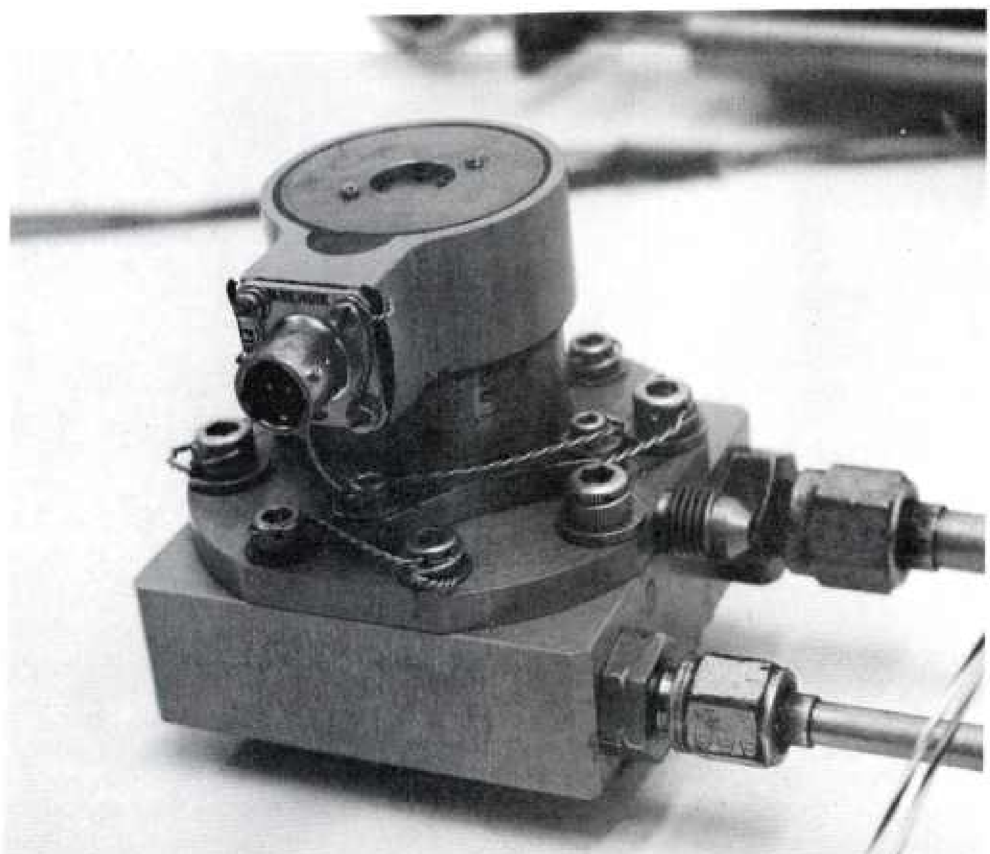


Figure 2-5. HPA Assembly

Each of the dual valve driver circuits employ current feedback with a highly reliable "Darlington" power transistor configuration. Redundant power supplies are used. The circuitry is designed so that in the event an output stage fails "hardover", the voltage applied to a motor coil will not exceed its rated value. This limiting feature permits a subunit failure to be compensated or nullified by another subunit. Closed loop tests showed that operation of the redundant subunits provided high immunity to component failures as reported in Reference 3, NR75H-1 Control by Wire Modular Actuator Tests (AFCAS).

The dual channel fiber optic receiver amplifier added for HOFCAS converts the microcomputer optical output signals to electrical input signals for the EDU. Each receiver amplifier channel contains a detector, two stages of gain, and a passive isolation circuit. The optical signals received consist of PWM information, and the passive isolation feature prevents a hardover of the rudder actuator if the drive signal is lost due to a microcomputer or fiber optic loop failure.

The dual channel fiber optic receiver amplifier and associated detectors are located on a single module board, contained in a housing mounted on the EDU. All electrical and optical connections to the module board were made to permit easy removal if return of the EDU to its original configuration is desired.

The modified EDU with fiber optic cables is depicted in Figure 2-6 and a functional schematic, including the fiber optic receiver amplifier, is included in Figure 2-3.

2.5 TRANSDUCERS

2.5.1 Pedal Force Transducers

Two force transducers, Schaevitz Model FTD-IT-500, are used to convert pedal forces into DC signals. Excitation is provided by the EDU $\pm$ 15 VDC power supplies. The force transducers are connected to the pedals through a cable/sector assembly having a mechanical advantage of 2.28 (pedal force x 2.28 = transducer force). The transducers have a maximum capacity of 500 lbs. (2.2 kN), a spring rate of approximately 8000 lb/in (1.4 MN/m), and a design scale factor of 0.01 v/lb (.002 v/N). The force transducers are shown in Figure 2-7.

2.5.2 Actuator LVDT Position Feedback Transducers

Two Schaevitz Model 2000 HCD DC Linear Variable Differential Transformers (LVDT's) provide dual position rudder actuator feedback signals. Excitation is provided by the EDU $\pm$ 15 VDC power supply. Actuator position travel, $\pm$ 1.75 in. ($\pm$ 4.45 cm) max., is converted through a bellcrank and push rod to angular travel of the rudder, $\pm$ 12° max. The design scale factor for both LVDT's is 5.0 VDC/inch (1.97 VDC/cm). The position transducers are shown mounted on the rudder actuator in Figure 2-8.

Figure 2-6. EDU With Fiber Optic Cables Attached

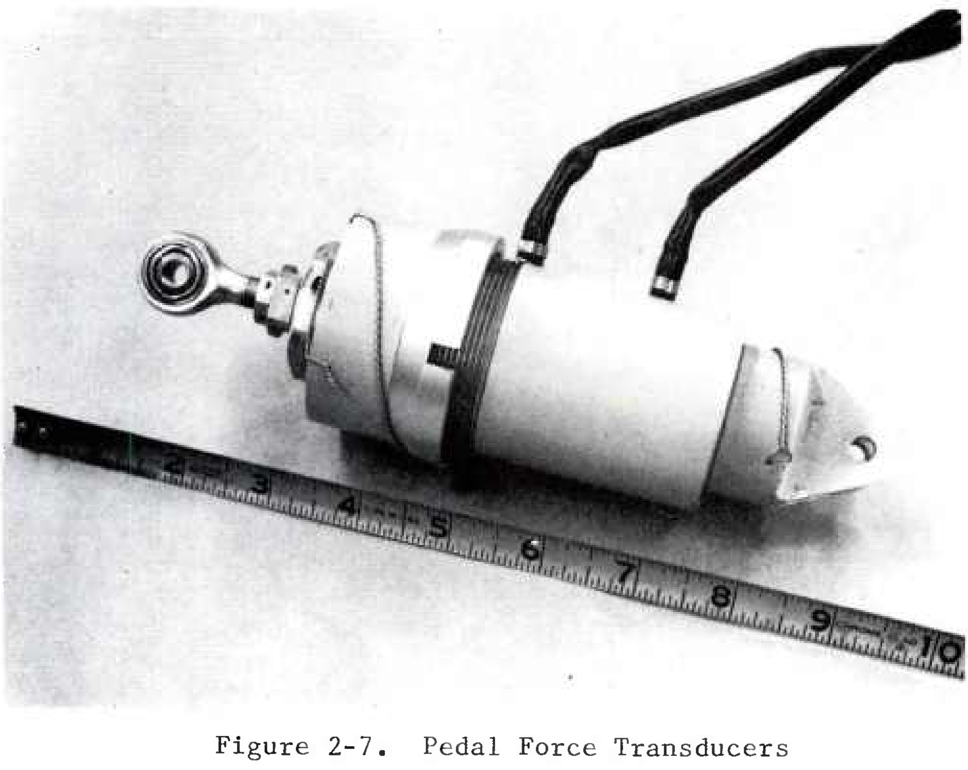


Figure 2-7. Pedal Force Transducers

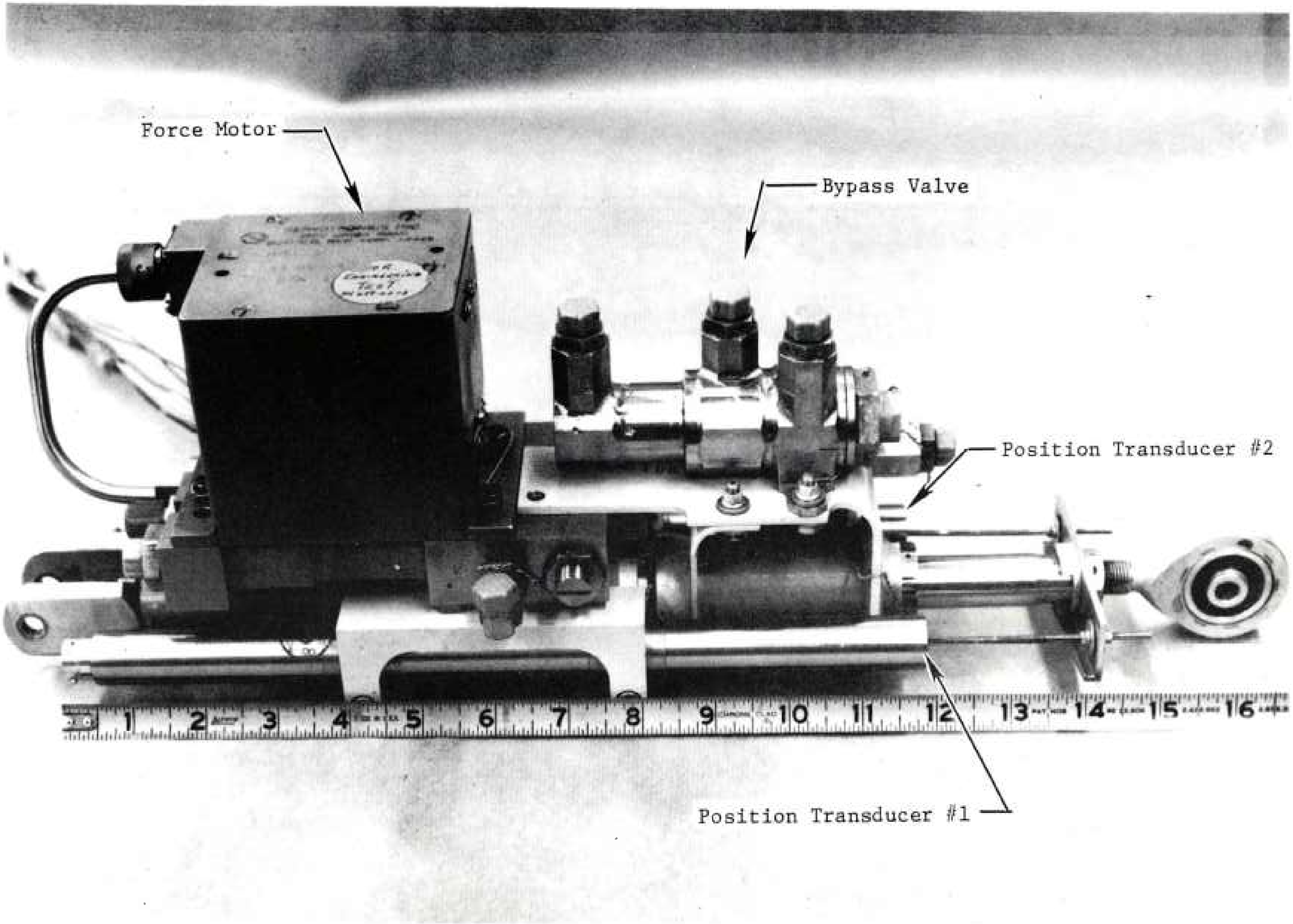


Figure 2-8. Rudder Actuator Assembly

2.6 AFCAS ACTUATOR

The fly-by-wire AFCAS rudder actuator, P/N 8691-524001-101, is directly driven by a permanent magnet force motor having four independent coils for redundancy. The force motor armature is mechanically coupled to a spool/sleeve flow control valve which commands actuator piston rate. Piston feedback is provided by dual DC LVDT's mounted externally on opposite sides of the actuator housing. A hydraulic bypass valve was added to automatically interconnect the two cylinder chambers and allow the rudder to "trail", in the event hydraulic power is lost. The T-2C rudder has a travel of $\pm$ 25°. For safety reasons, rudder travel was reduced to $\pm$ 12° in the test installation by limiting actuator stroke. This permits the pilot to land safely with a "hardover" rudder, opposite engine out, and three knot cross-wind.

Actuator constants are listed below:

Operating Pressure	8000 psi (55 MPa)
Piston Stroke (Total)	3.5 In. (8.9 cm)
Cylinder Bore	0.926 In. (2.3 cm)
Rod Diameter	0.748 In. (1.9 cm)
Piston Effective Area	0.234 $In.^2$ (1.5 cm^2)
Force Output (Max.)	1870 Lb. (8.3 kN)
Piston Velocity (Max.)	5.5 In./Sec. (14 cm/s)
Actuator Length (Extended)	18.375 In. (46.7 cm)

Manufacturers and major components of the actuator were:

Part No.	Description	Manufacturer
8691-524001-101	Rudder Actuator Assembly	North American Aircraft Division-Columbus Plant, Rockwell International
8691-524001-051	Bypass Valve	" " "
SO 4262-03-21	Control Valve	Ronson Hydraulic Units Corporation Charlotte, North Carolina
99-D0234 (M/N 21-6-200)	Force Motor	Servotronics, Inc. Buffalo, New York
2000 HCD	Position Transducer	Schaevitz Engineering Camden, New Jersey

The actuator assembly is shown in Figure 2-8.

2.7 MICROCOMPUTER ASSEMBLY AND POWER SUPPLY

The microcomputer assembly is housed in an enclosed unit, and consists of the following subassemblies:

Part No.	Nomenclature
M68MM01A	Motorola Monoboard Microcomputer Module
M68MM05A	Analog-To-Digital (A/D) Converter Module
M68MM05C	Digital-To-Analog (D/A) Converter Module
M68MMCC05	Card Cage & Mother Board Assembly
EO H383246-11	Signal Conditioning Board
EO H383888	Fiber Optics Transmitter Board Assembly

The microcomputer module is a complete computer-on-a-board having all the processing and control required for a microcomputer-based system. It incorporates the MC 6800 MPU, 1 K of Random Access Memory (RAM), provisions for 4 K of Programmable Read Only Memory (PROM), timing and control, buffers, an Asychronous Interface Adapter (ACIA) and two Peripheral Interface Adapters (PIA).

The A/D converter module consists of eight channels of A/D conversion of which four are utilized. The D/A converter module consists of four channels of D/A conversion of which three are utilized.

The signal conditioning board contains four channels of sensor signal conditioning and a relay driver that interfaces the microcomputer monitor output with the system control logic.

The dual channel fiber optic transmitter board was added for HOFCAS. Located in the microcomputer housing, the board contains a fiber optic photo diode and dropping resistor for each channel, to convert the microcomputer PWM output to optical form for transmission to the EDU. Two fiber optic cables, each 10 feet (3.05 m) long, interconnect the microcomputer and EDU. The 10 foot (3.05 m) cables simulate the length required to connect an actuator, with its electronic EDU located at the rudder, to the microcomputer located in the equipment bay. The microcomputer unit with the fiber optic cables attached is shown in Figure 2-9.

A separate power supply (Motorola P/N M68MMPS1) is provided to supply power to the microcomputer. The power supply converts single-phase, 115 VAC, 400 HZ to + 5 VDC and $\pm$ 12 VDC.

Additional information on the microcomputer is contained in Appendix A.

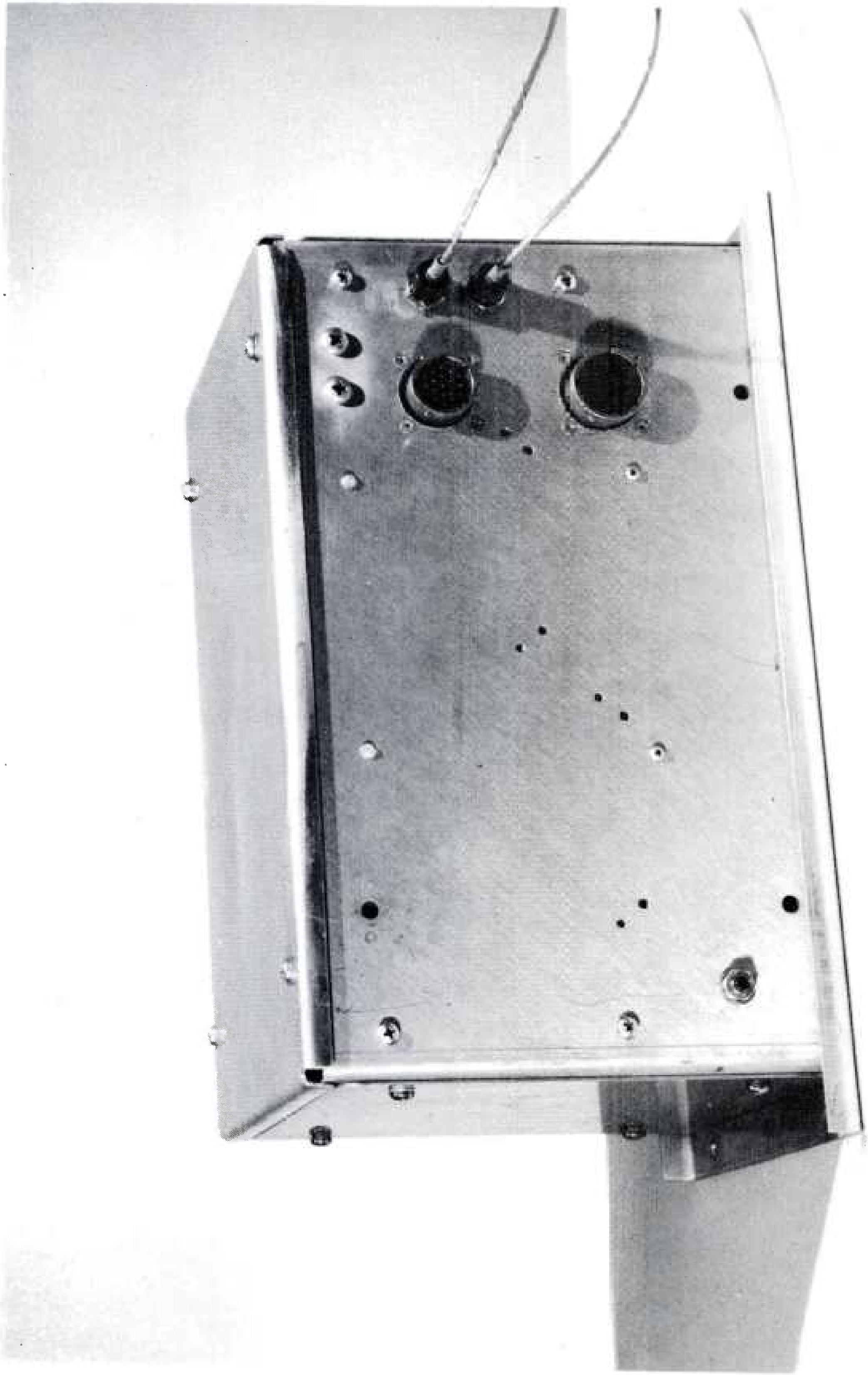


Figure 2-9. Microcomputer Unit With Fiber Optic Cables Attached

2.8 SOFTWARE DESCRIPTION

2.8.1 Function

The microcomputer software performs two basic functions; a command/feedback control function and a control monitor function.

The command/feedback control function sums the pilot command and rudder position signals to produce an output signal proportional to the difference to drive the actuator.

The control monitor function measures the level of error between the pedal command and the rudder actuator position feedback, and if a preset level is exceeded for a given period of time, the engage command will be removed. Actuator control will then revert to the ABU mode. A continuous check is also made on the transducer input A/D conversion hardware by comparing the two digital feedback signals with each other and in a similar manner comparing the digital pedal signals. Any differences exceeding preset levels for a given period of time will result in switching system control to the ABU mode.

The control monitor function was incorporated as the Motorola microcomputer is a single channel device which could generate a "hardover" command under certain failure conditions. The dual-channel redundancy of the ABU mode prevents a "hardover" command of the rudder even if a pedal transducer or rudder position transducer fails in a "hardover" condition.

2.8.2 Program Modules

The DFBL Microcomputer Program Flow Chart, Figure 2-10, illustrates the modular nature of the software and the sequence in which the modules function. The program modules were designed, coded, and initially checked as individual entities prior to being integrated.

Following is a brief description of the program modules:

Initialize - The Initialize module sets the Digital-To-Analog Converter (DAC) channel 4 to provide +5 VDC to hold in relay K1 (ref. Figure 2-3). The K1 relay, in turn, holds the DFBL ENGAGE switch in the engage position. This module also sets timing counters to ensure that the Monitor function does not immediately turn off the DFBL ENGAGE switch.

Input 1 - The Input 1 module, as the first in the repetitive loop, is used to start the PWM output signals. This is done by setting both DAC-1 and DAC-2 at +10 VDC. It then controls the A/D conversions of pilot command (CMD1) and rudder position (POS1). Inputs are scaled so that

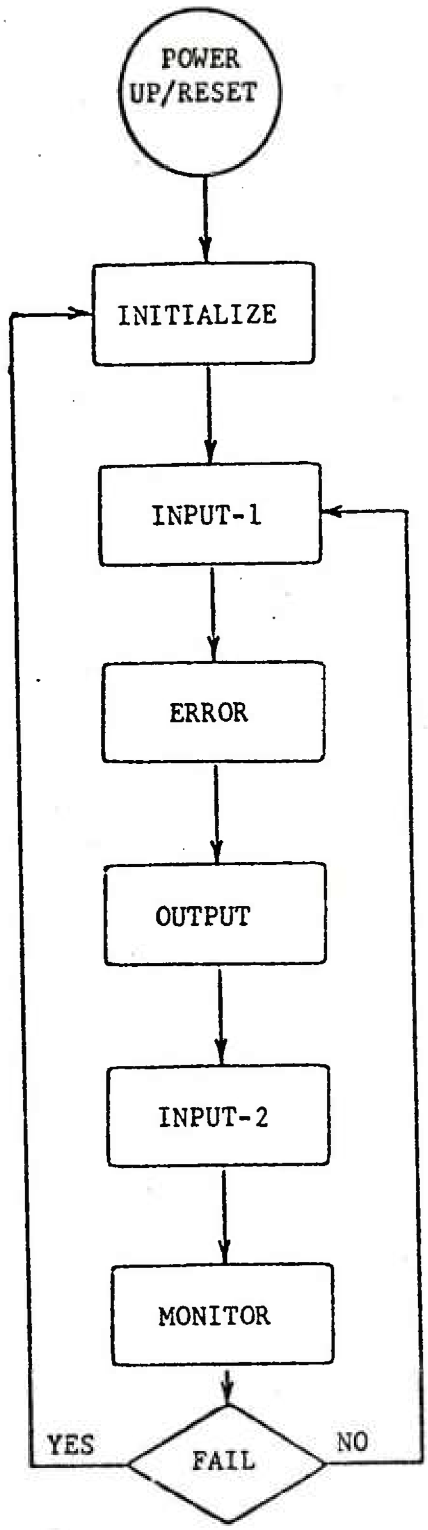


Figure 2-10. DFBL Microcomputer Program Flow Chart

full scale, $\pm 12°$ of rudder is ± 5 VDC, which is one-half of full range for the A/D channels. Since the force transducer that provides CMD1 is not mechanically or electrically limited to ± 5 VDC, a software limit is provided to set CMD1 at either ± 5 VDC, as appropriate, when that value is exceeded. Output of the A/D converter is a 12 bit word, proportional to the voltage.

Error - The error module performs a double precision subtract of CMD1 from POS1 and sets computer gain through a series of shifts. It then determines polarity of the error and transfers to the appropriate output module.

Output - The output module sets countdown timers that establish the duration of the plus and minus portions of the PWM output signal. It switches DAC-1 and DAC-2 to -10 VDC when the "positive" counters have timed-out. When the "minus" counters time-out, it transfers control to the Input 2 module.

Input 2 - The Input 2 module controls the conversion of CMD2 and POS2 and provides limits on CMD2 in the same manner as Input 1. CMD2 and POS2 are for use in the Monitor functions.

Monitor - The Monitor module compares the redundant pilot command and rudder position input signals. If a difference in either of 1.5° is detected for a period of 0.128 seconds, the program is set to deenergize the DFBL holding relay (K1 in Figure 2-3) and reverts control of the system into the ABU mode. The monitor also checks the magnitude of the error signal. If it exceeds 1.5° for 2 seconds, the DFBL holding relay is deenergized, and control of the system again reverts to the ABU mode. As long as the monitor does not detect an error, it transfers control back to the Input 1 module.

A listing of the flight program software is contained in Appendix A. The program was designed to function at a rate of 500 HZ, and occupies 462 bytes of the available 4096 bytes of PROM and 18 bytes of the 1024 bytes of "scratch pad" RAM. The PROM map is also contained in Appendix A.

2.9 HYDRAULIC SUPPLY

The hydraulic supply used for the laboratory testing utilized a variable displacement, axial piston, 3000 psi (21 MPa) pump. An accumulator of approximately 50 in^3 (820 cm^3) was used in the supply line to minimize supply pressure transients. Complete instrumentation was provided to measure pressures and flows to the actuator and HPA. The hydraulic equipment is included in the laboratory setup pictorial, Figure 2-11.

Figure 2-11. Laboratory Test Setup Pictorial

3.0 LABORATORY TESTS

3.1 TEST OBJECTIVES

Laboratory tests were accomplished to integrate the HOFCAS with the existing Phase VI digital AFCAS system, perform system functional tests, evaluate system performance and compatibility with the HOFCAS modification, and to determine the effects of the HOFCAS modification on system performance. Temperature tests were also performed to verify the equipment would function properly in the T-2C aircraft operating environment.

3.2 TECHNICAL APPROACH

3.2.1 Components

Laboratory tests were accomplished using the actual aircraft components to simulate flight conditions in preparation for flight testing of the system at a later date.

Included in the lab setup were the rudder LVDT feedback transducers, rudder actuator, EDU, microcomputer and associated power supply, hydra-alternator, fiber optic link including emitters, detectors and fiber optic cables, and the switches and control relays used in the aircraft.

3.2.2 Lab Setup

The lab wire harness was configured to simulate the aircraft wiring, and a terminal strip/interconnection board provided control, test points, and the interface between the wire harness, system components, and lab test equipment. The Lab Signal Simulator Box (LSSB) was included as part of the lab test setup, and provided simulated pedal force commands, LVDT feedback signals, and microcomputer PWM output signals during certain phases of system testing. The two fiber optic cables, connecting the microcomputer output to the EDU, were each 10 feet (3.05 m) in length simulating the actual aircraft cable length requirements. The portable lab hydraulic pressure source, described in paragraph 2.9, was used for all lab testing. A pictorial of the lab setup is shown in Figure 2-11.

3.3 FUNCTIONAL TESTS

3.3.1 Hydra-Powered Alternator (HPA)

3.3.1.1 HPA No-Load Tests - No-load tests were performed with the HPA connected to the lab hydraulic pressure source and test equipment as shown in Figure 3-1. Voltage, frequency, hydraulic flow and temperature were monitored for input pressures ranging from 500 to 3000 psi (3.5 to 21 MPa).

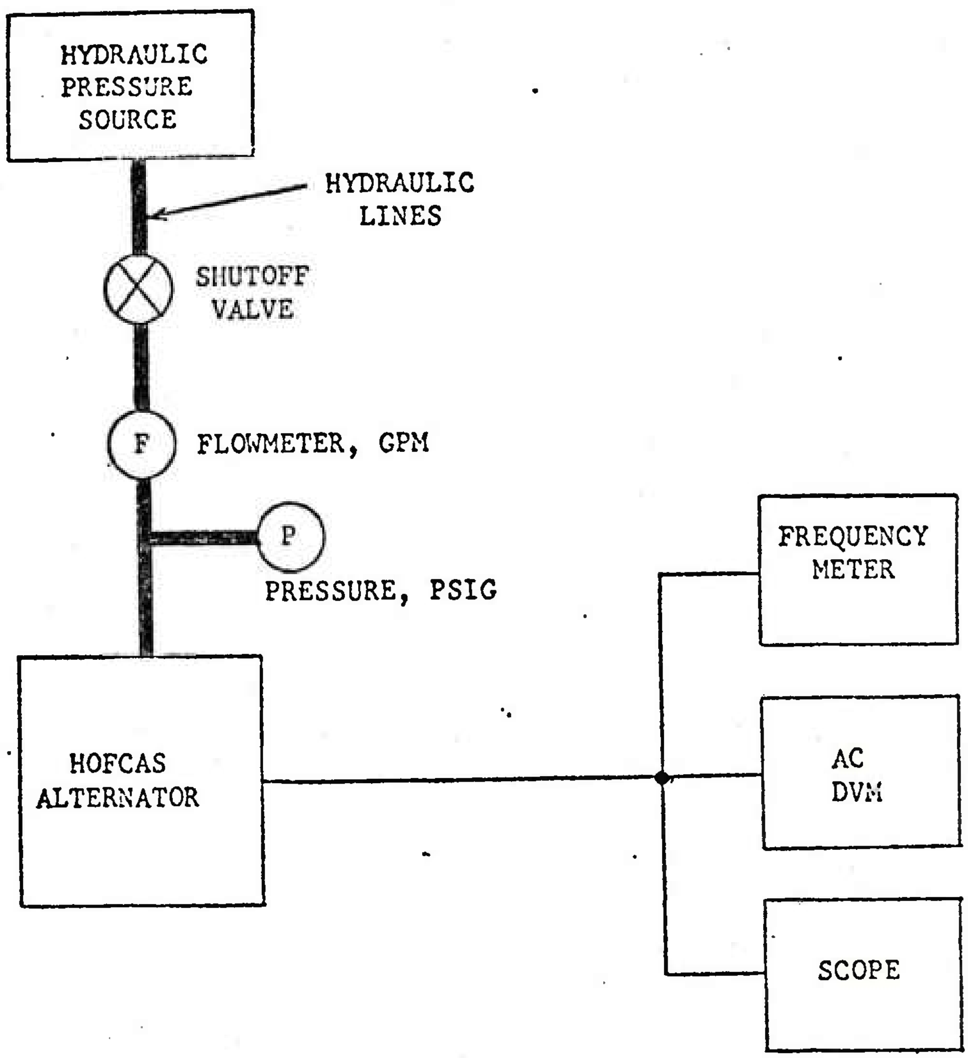


Figure 3-1. HPA No-Load Test Setup

The no-load HPA output voltage and frequency versus HPA ΔP are plotted in Figure 3-2, and show a linear rise as inlet pressure is increased. With an HPA ΔP of 3000 psi (21 MPa), the output voltage was 35.7 VAC at a frequency of 1187 HZ.

The HPA fluid flow and fluid outlet temperature versus HPA ΔP are plotted in Figure 3-3, and show a flow of 0.73 gpm (2.8 L/min.) at 3000 psi (21 MPa) with a fluid temperature of 114°F (45.5°C).

The HPA output voltage waveforms were observed on the oscilloscope. The waveforms were nearly sinusoidal and were identical for all ΔP's except for increased voltage amplitude as ΔP was increased. The 3000 psi (21 MPa) waveform is shown in Figure 3-4.

3.3.1.2 <u>HPA Load Tests, Constant Pressure</u> - Load tests were performed with the HPA connected as shown in Figure 3-5. The step-up transformer, added for HOFCAS to match the HPA 26 VAC output to the EDU 115 VAC input power requirement, was connected to the HPA output and a variable resistance load connected to the transformer secondary. The HPA ΔP was maintained at 3000 psi (21 MPa) for all load settings.

HPA output voltage and frequency versus HPA output current are plotted in Figure 3-6. The HPA output voltage decreased 33% (33.5 VAC to 22.1 VAC) and the frequency decreased 6% (1135 HZ to 1064 HZ) as the load was increased from 0 to full load.

The transformer secondary current and voltage versus HPA output current are plotted in Figure 3-7. The transformer secondary voltage decreased 35% (152.2 VAC to 98.5 VAC) as the load was increased from 0 to full load, nearly identical to the 33% decrease in HPA output voltage (transformer primary) for the same load settings.

The HPA output and transformer secondary voltage waveforms were photographed using the oscilloscope. The no-load waveforms, Figure 3-8, are nearly sinusoidal and are identical except for voltage amplitude. The full-load waveforms, Figure 3-9, show slight distortion at the peaks and are again identical except for voltage amplitude.

The HPA fluid discharge temperature remained at 110 ± 2°F (43.3 ± 1°C) and the HPA hydraulic flow was 0.73 gpm (2.8 L/min.) for the entire test. Load data taken at time 0 and again after 30 minutes of running time at full load showed no significant change.

3.3.1.3 <u>HPA Output Versus Hydraulic Pressure, Constant Load</u> - The HPA was connected to the lab hydraulic source and lab test equipment as shown in Figure 3-5. The load resistor was set for 1 ampere HPA output current at ΔP of 3000 psi (21 MPa), and this resistance value held constant while reducing the HPA P to 2500 psi (17 MPa), in 100 psi (0.7 MPa) increments. The HPA fluid discharge temperature remained at 113 ± 2°F (45 ± 1°C) for the entire test.

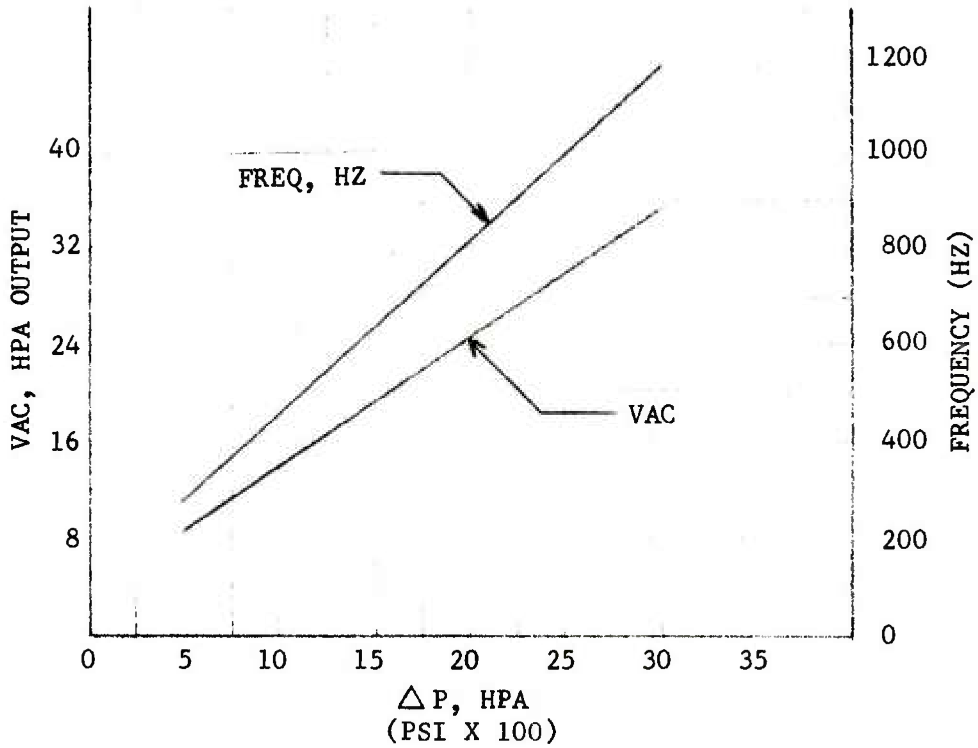


Figure 3-2. HPA VAC & Frequency Versus HPA △P, No Load

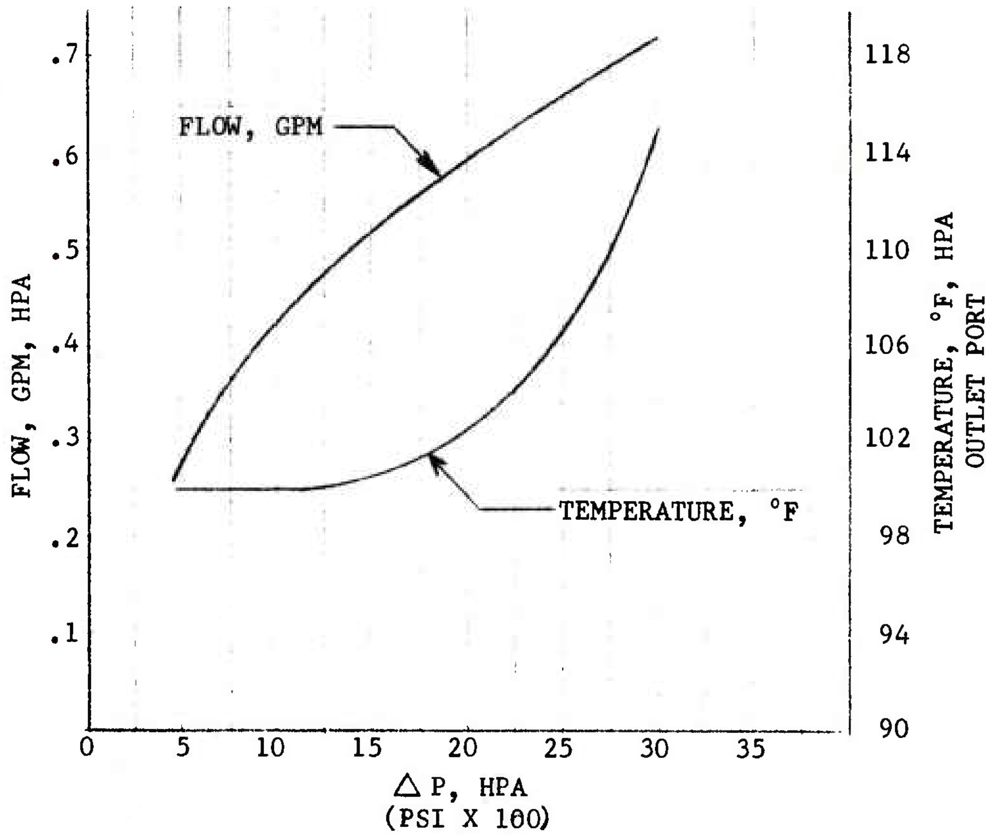
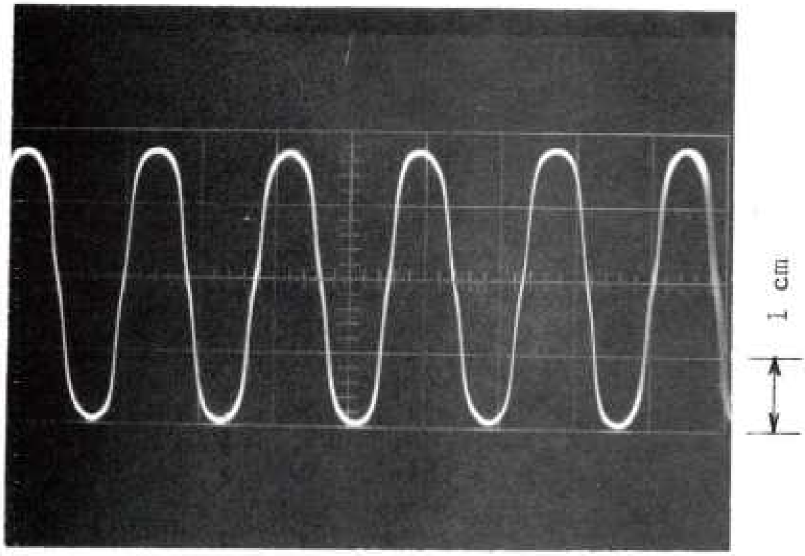


Figure 3-3. HPA Fluid Flow & Temperature Versus HPA △P, No Load



HPA ΔP = 3000 PSI
20 V/cm, .5 ms/cm

Figure 3-4. No-Load HPA Output Voltage Waveform

The HPA output (transformer primary) and transformer secondary output, in volt-amps (VA), versus HPA ΔP are plotted in Figure 3-10, and show a 15% reduction in power output at 2500 psi (17 MPa) ΔP compared to the nominal 3000 psi (21 MPa) ΔP operating pressure.

The HPA hydraulic flow and frequency versus HPA ΔP are plotted in Figure 3-11, and show an 8% reduction in hydraulic flow, 0.72 gpm (2.7 L/min.) to 0.66 gpm (2.5 L/min.), and a 14% decrease in frequency (1089 HZ to 936 HZ) as the HPA ΔP is reduced from 3000 psi (21 MPa) to 2500 psi (17 MPa).

The transformer primary and secondary voltage waveforms at the HPA 2500 psi (17 MPa) ΔP operating point are contained in Figure 3-12, and show a slight distortion at the peaks and are identical except for voltage amplitude.

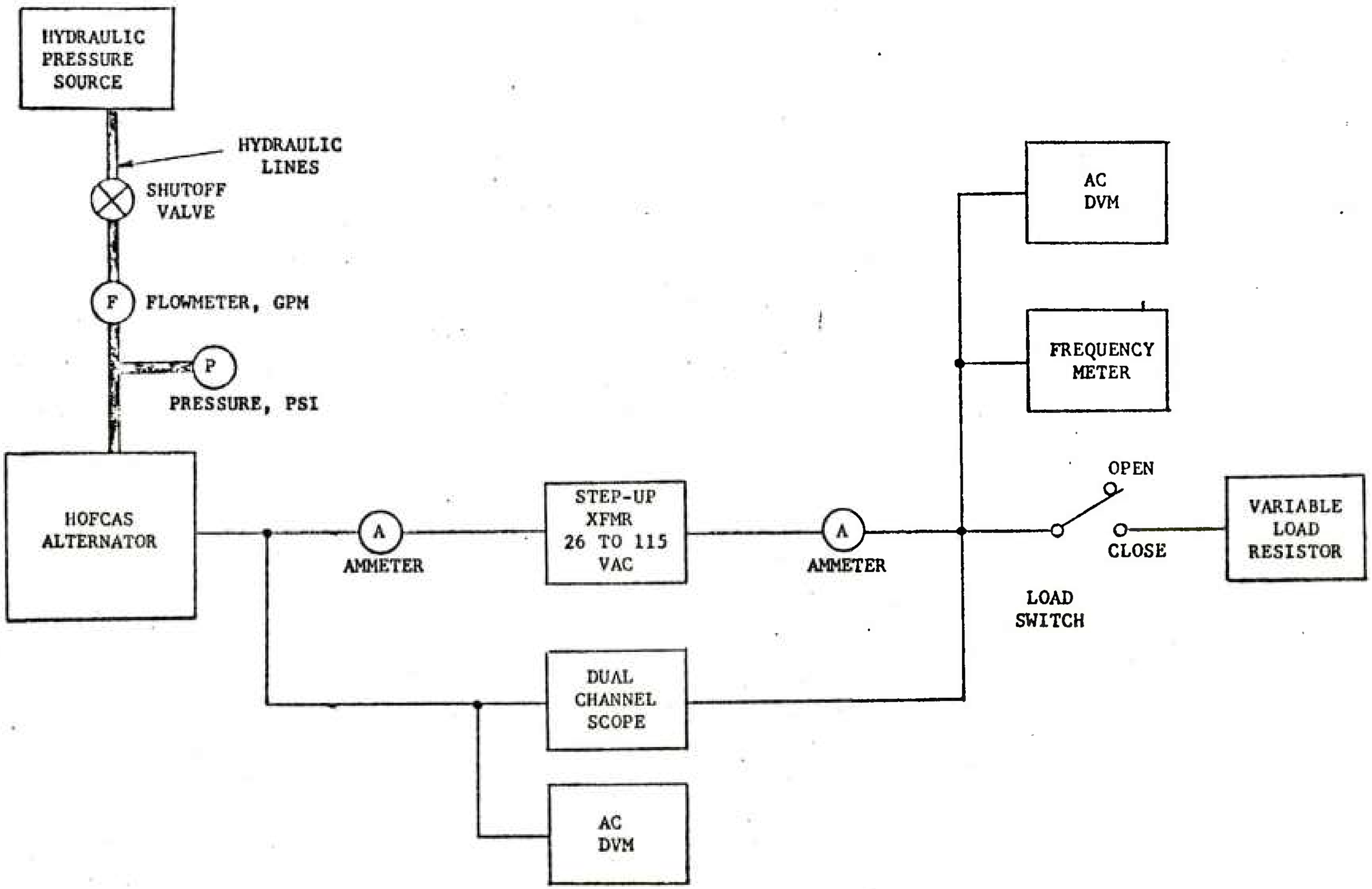


Figure 3-5. HPA Load Test Setup

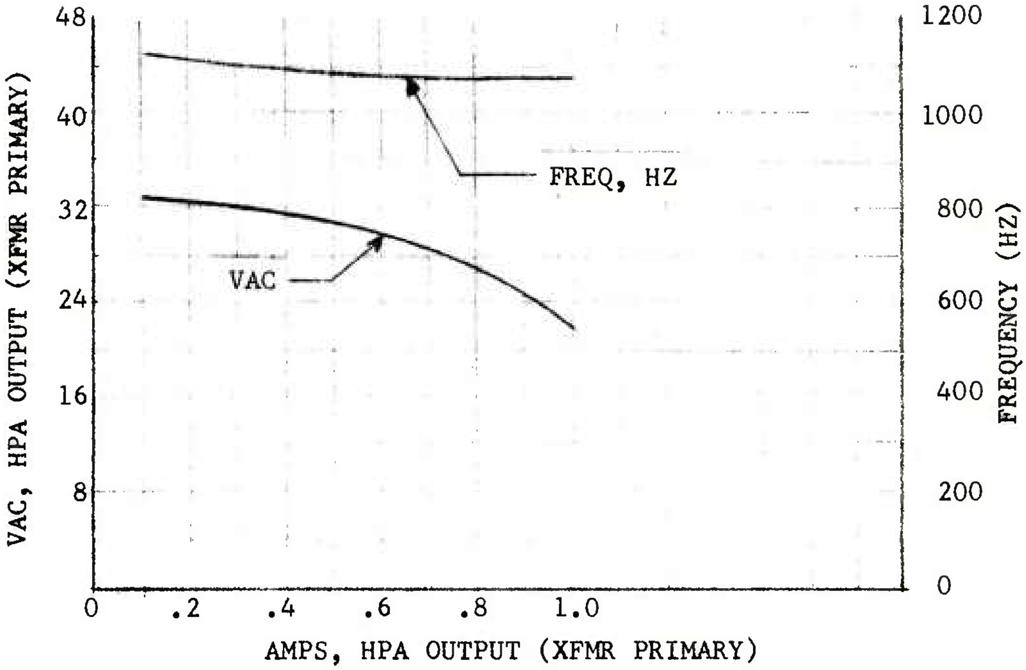


Figure 3-6. HPA VAC & Frequency Versus HPA Output Current

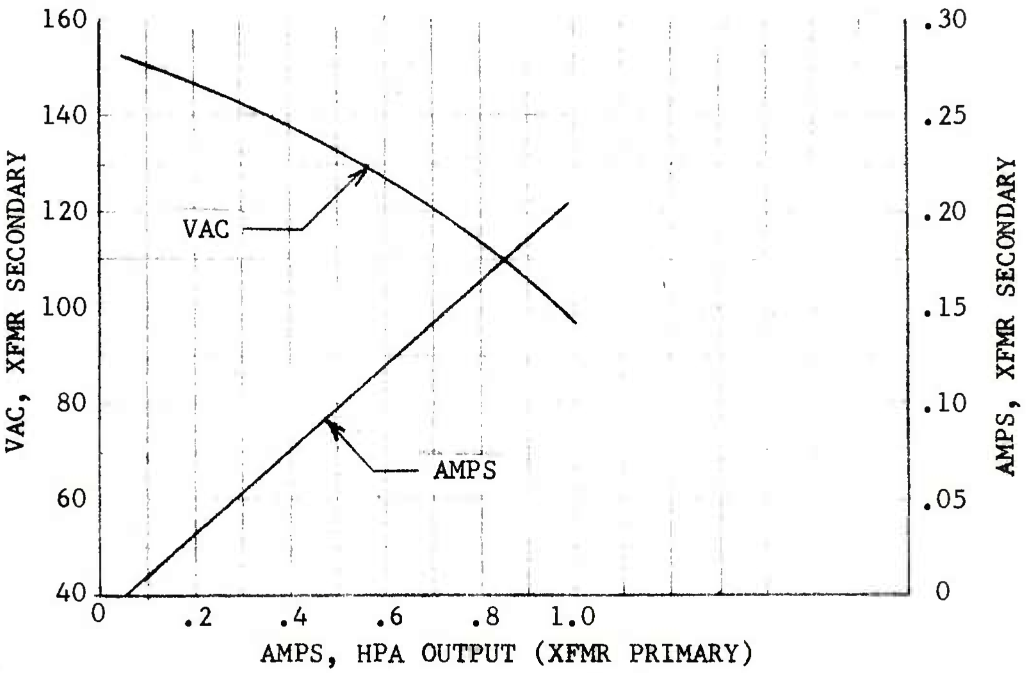
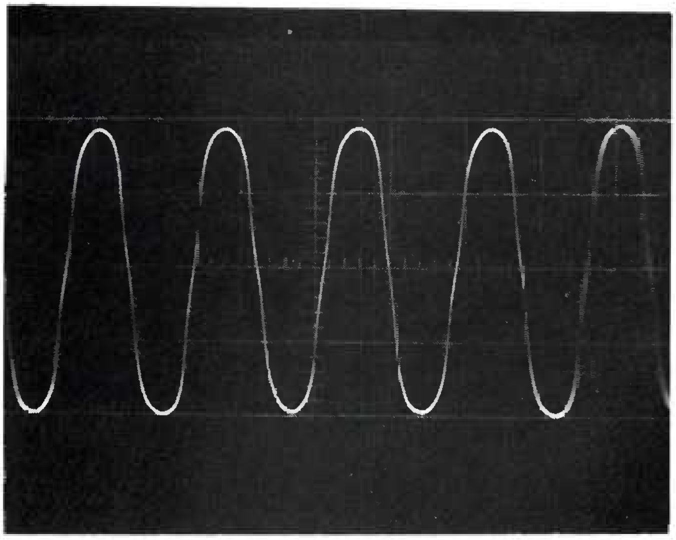
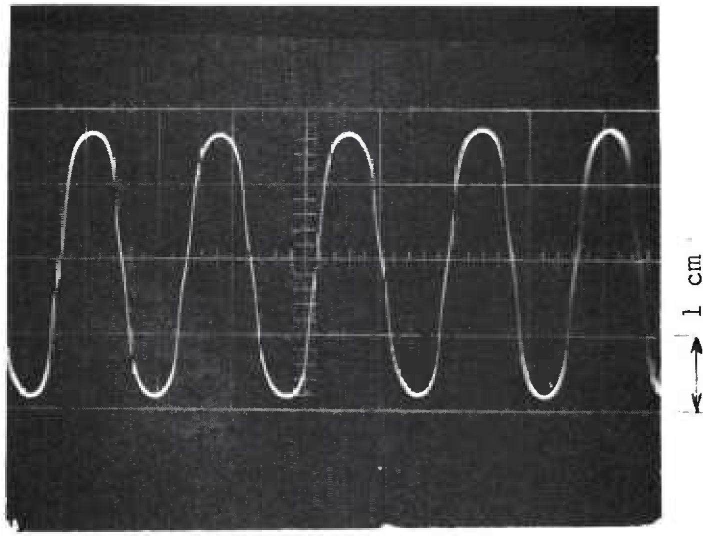


Figure 3-7. Transformer Secondary VAC & Current Versus HPA Output Current (Transformer Primary)

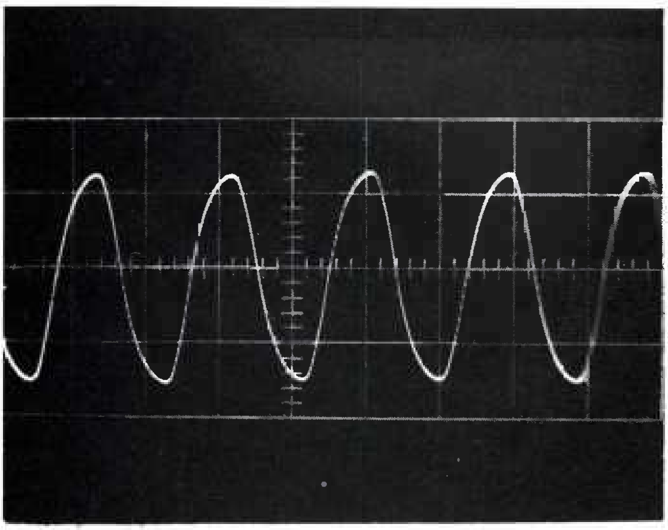


XFMR PRIMARY, I = .06a
20 V/cm, .5 ms/cm

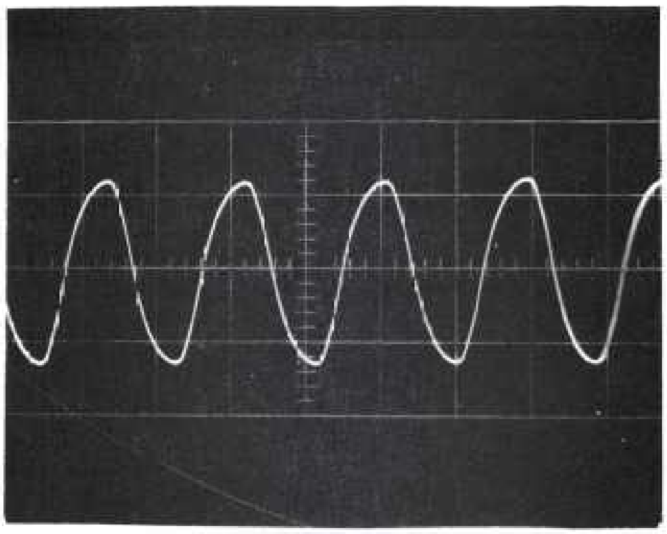


XFMR SECONDARY, I = 0a
100 V/cm, .5 ms/cm

Figure 3-8. Transformer Primary and Secondary No-Load Voltage Waveforms



XFMR PRIMARY, I = 1.0a
20 V/cm, .5 ms/cm



XFMR SECONDARY, I = .21a
100 V/cm, .5 ms/cm

Figure 3-9. Transformer Primary and Secondary Full-Load Voltage Waveforms

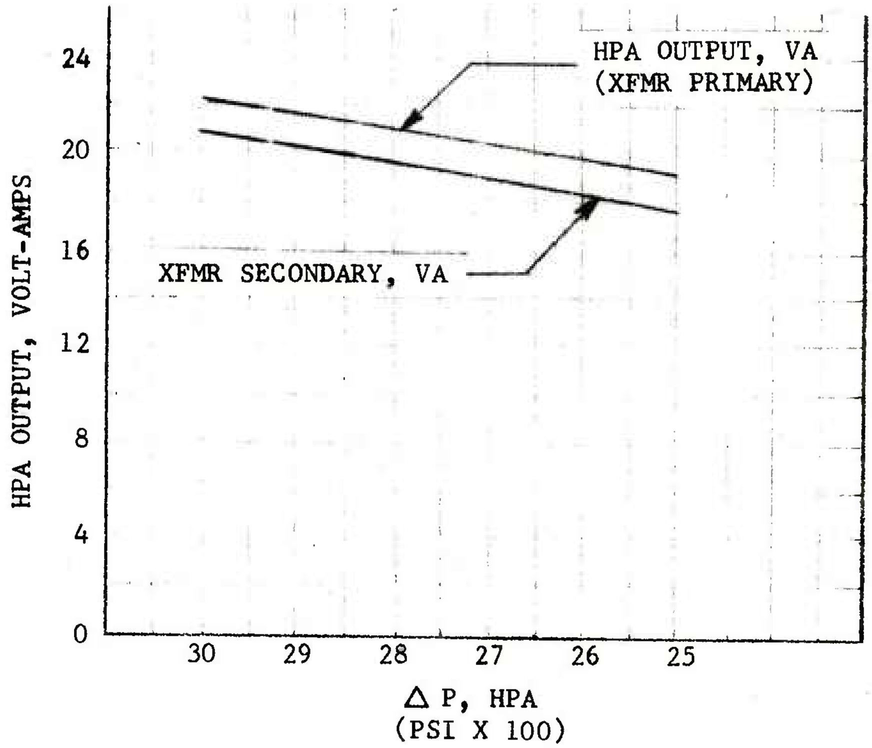


Figure 3-10. HPA VA Output Versus HPA △P, Constant Resistive Load

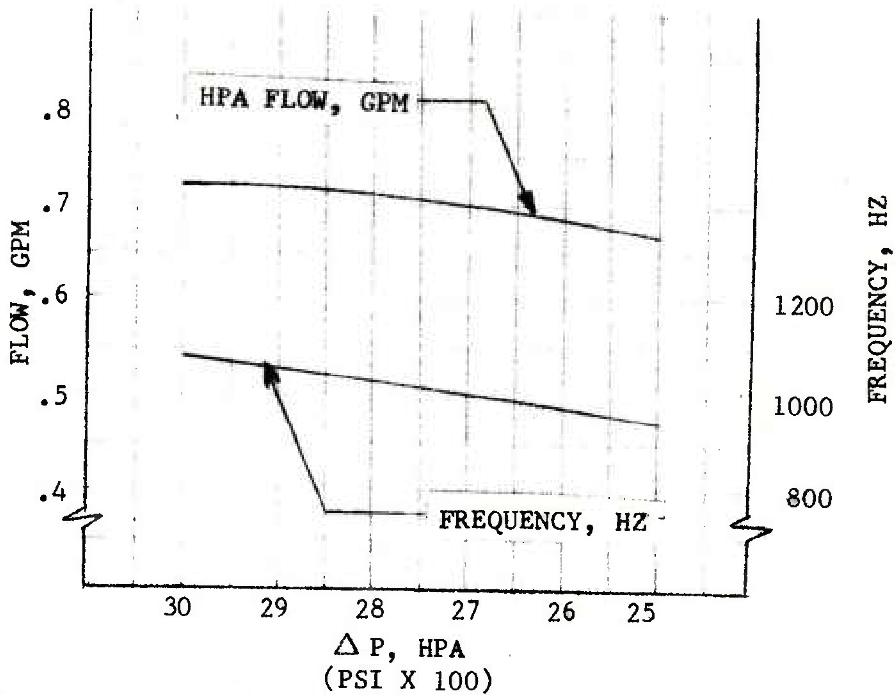
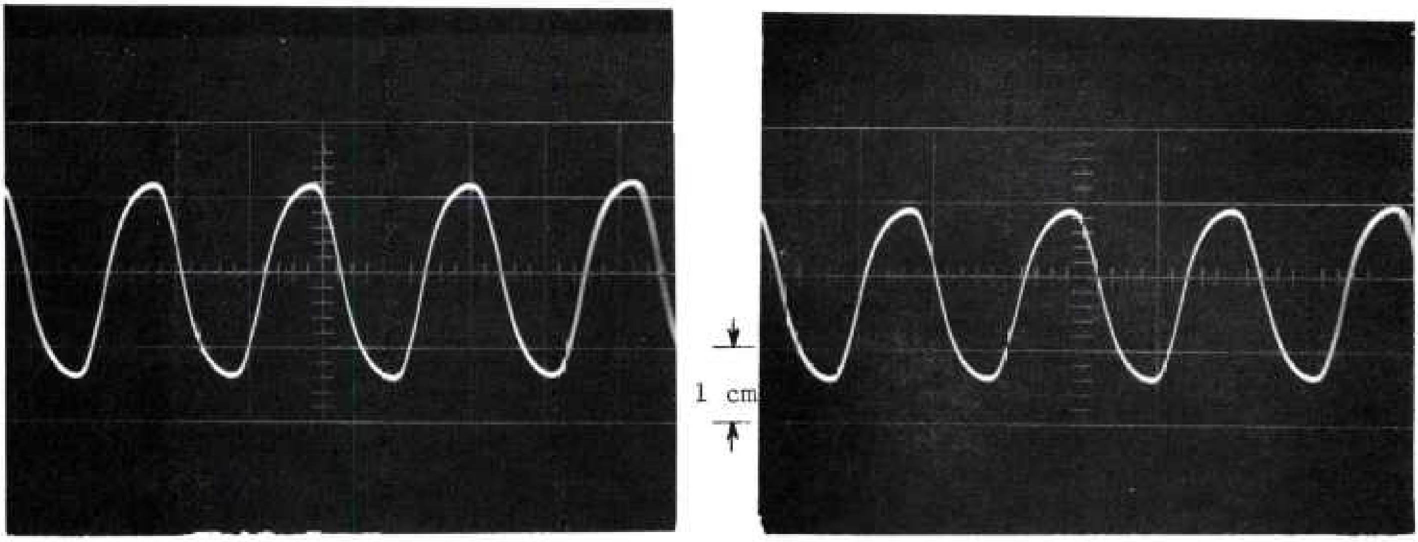


Figure 3-11. HPA Flow & Frequency Versus HPA △P, Constant Resistive Load



XFMR PRIMARY
20 V/cm, .5 ms/cm

XFMR SECONDARY
100 V/cm, .5 ms/cm

Figure 3-12. Transformer Primary and Secondary Voltage Waveforms, 2500 PSI HPA ΔP

3.3.2 System Null and Gain Tests

3.3.2.1 Static Null, DFBL Mode, EDU 1000 HZ and 400 HZ Power - The system was connected as shown in Figure 3-13, with the Lab Signal Simulator Box (LSSB) connected to the microcomputer inputs, to obtain comparison data for HPA 1000 HZ and lab 400 HZ EDU power.

The microcomputer simulated force transducer (pedal command) and actuator feedback inputs were set to 0 $\pm$ .01 VDC. The EDU was powered by HPA 1000 HZ, and the individual motor coil currents set for 0 $\pm$ .01 amperes, using the R9, R10, R11, and R12 bias pots on the EDU as required. HPA voltage, fiber optic control link, and actuator motor coil current waveforms were photographed. The EDU input power was then switched to 400 HZ and without further adjustments the data points, including coil currents and waveforms, were repeated.

Results showed the channels 1 and 2 fiber optic loop transmitter input and receiver output waveforms were identical for both HPA 1000 HZ and lab 400 HZ EDU power (the channel 1 waveforms are contained in Figure 3-14).

The motor coil current readings and waveforms for 1000 HZ and 400 HZ EDU power were also identical. Coil #1 current waveforms are contained in Figure 3-15 (waveforms for all four coils were identical) and show the current is nearly zero, due to the inductance of the motor coils (the oscilloscope vertical gain for the current waveforms was set at 100 ma/cm for expanding the waveforms to facilitate comparison of results). The individual coil currents (rms values) were measured with an ammeter and are recorded in Table I.

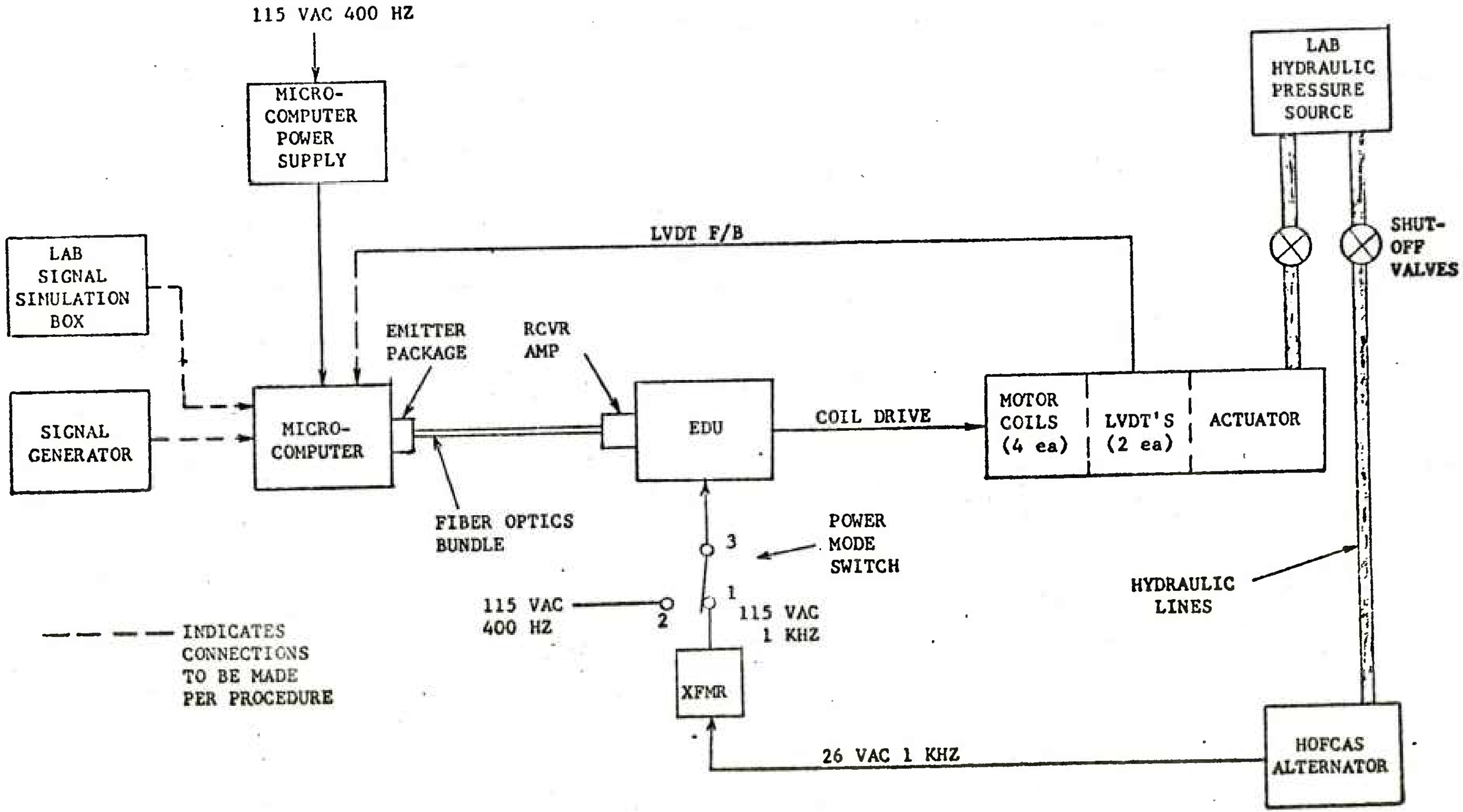
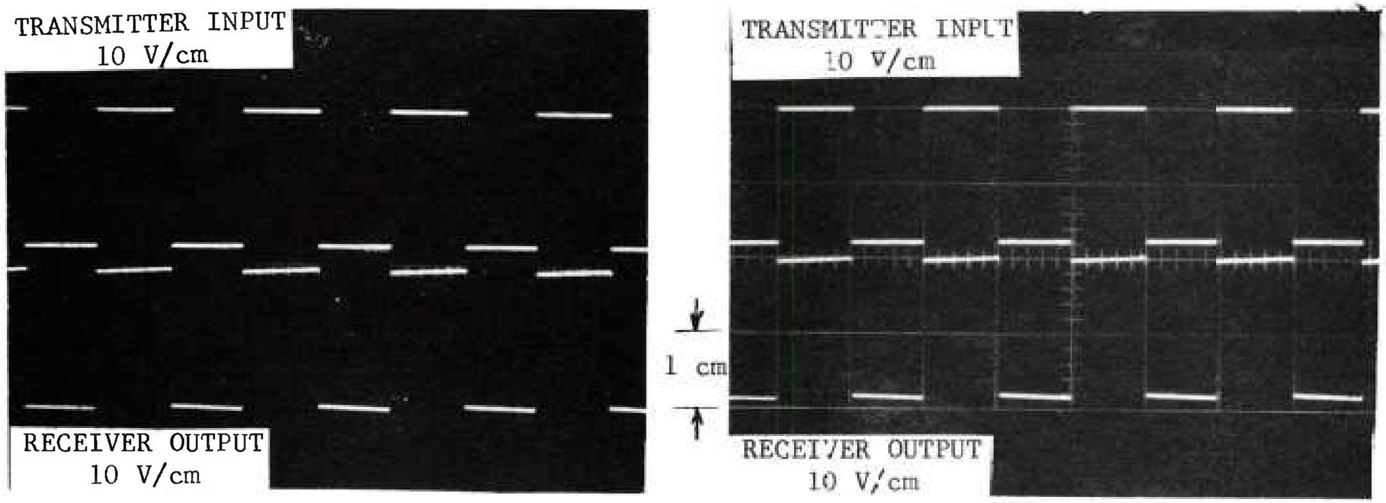


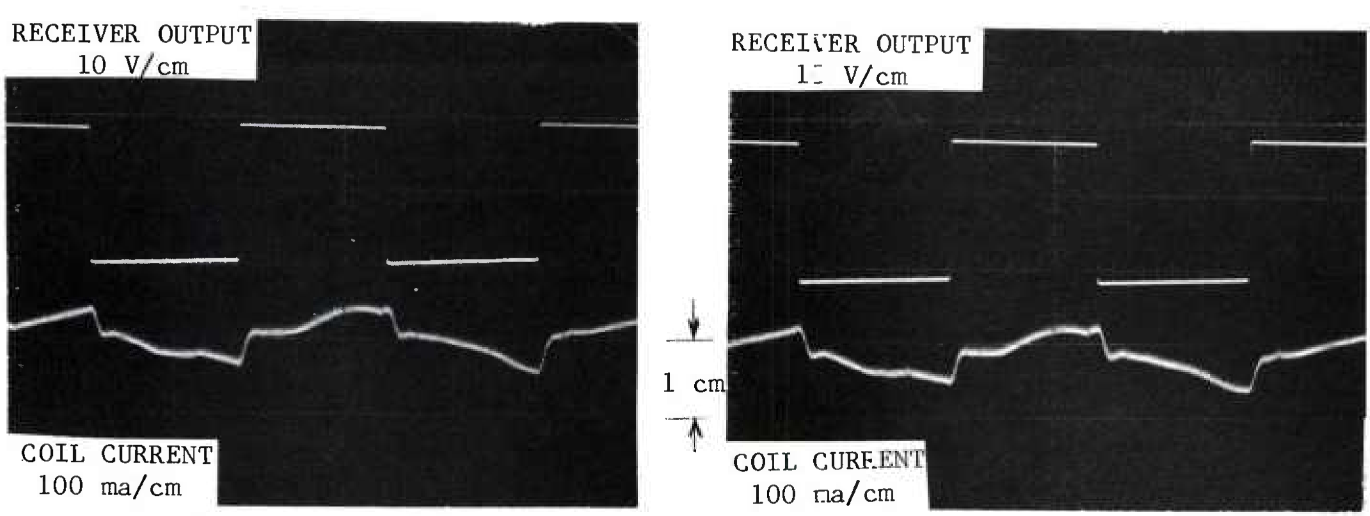
Figure 3-13. Null and Gain Test Setup



1000 HZ EDU POWER

400 HZ EDU POWER

Figure 3-14. Fiber Optic Loop Transmitter Input and Receiver Output Waveforms, Channel #1



1000 HZ EDU POWER

400 HZ EDU POWER

Figure 3-15. Fiber Optic Receiver Output and Motor Coil #1 Current Waveforms

Table I. Motor Coil Currents, System Null

MOTOR COIL NO.	MILLIAMPS, 1000 HZ EDU POWER	MILLIAMPS, 400 HZ EDU POWER
1	18	17
2	17	15
3	12	8
4	-8	-10

3.3.2.2 Static Gain, Fiber Optic Control Loop Waveforms and EDU Input Voltage - The Lab Signal Simulator Box (LSSB) was connected to the microcomputer force transducer and LVDT feedback inputs (see Figure 3-13). The fiber optic control link waveform pulse width modulation and amplitude, and the EDU input voltage (1000 HZ, DFBL mode) were measured and recorded for various combinations of signal inputs. The resultant data is recorded in Table II. All PWM waveforms and amplitudes were within specified values. The fiber optic link input and output 88% and 12% modulation waveforms are shown in Figure 3-16.

The EDU 1000 HZ input voltage waveform for system null (50% pulse width modulation) is contained in Figure 3-17. Figure 3-17a shows the EDU input with the oscilloscope vertical deflection set at 100 V/cm. Figure 3-17b shows the same EDU waveform and the control link drive signal to the EDU (50% modulation) with the scope vertical gain for the EDU input set at 200 V/cm, to permit simultaneous display of both waveforms. The EDU input waveform tends to distort to a pseudo square wave due to the inductive load of the direct drive torque motor.

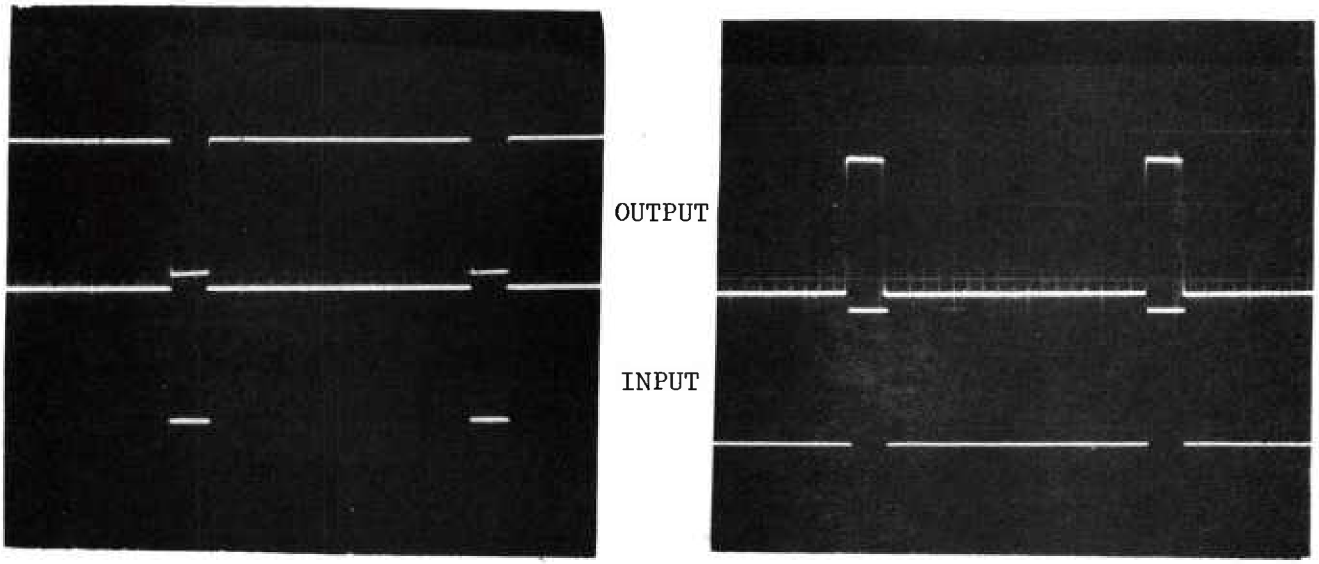
The 1000 HZ EDU input voltage readings are included in Table II for information only since the Dana Model 5400 AC digital voltmeter used to obtain the readings is an average detecting instrument and is accurate for sinusoidal waveforms only.

3.3.2.3 Position Gain, DFBL Mode - The rudder actuator LVDT feedback and the LSSB pedal command outputs were connected to the microcomputer (see Figure 3-13) and the rudder actuator was manually positioned to the midstroke (null) position. With actuator hydraulic pressure OFF and the system energized in the DFBL mode (1000 HZ EDU power), the actuator feedback linkage was adjusted for 0 $\pm$ .01 VDC LVDT output. With hydraulic pressure applied to the actuator, actuator piston travel (with respect to the null position) was then recorded for various pedal command inputs. All readings were within specified values, and are recorded in Table III of this report.

Table II. Fiber Optic Link Input/Output Signals Versus Simulated LVDT and Pedal Command Inputs

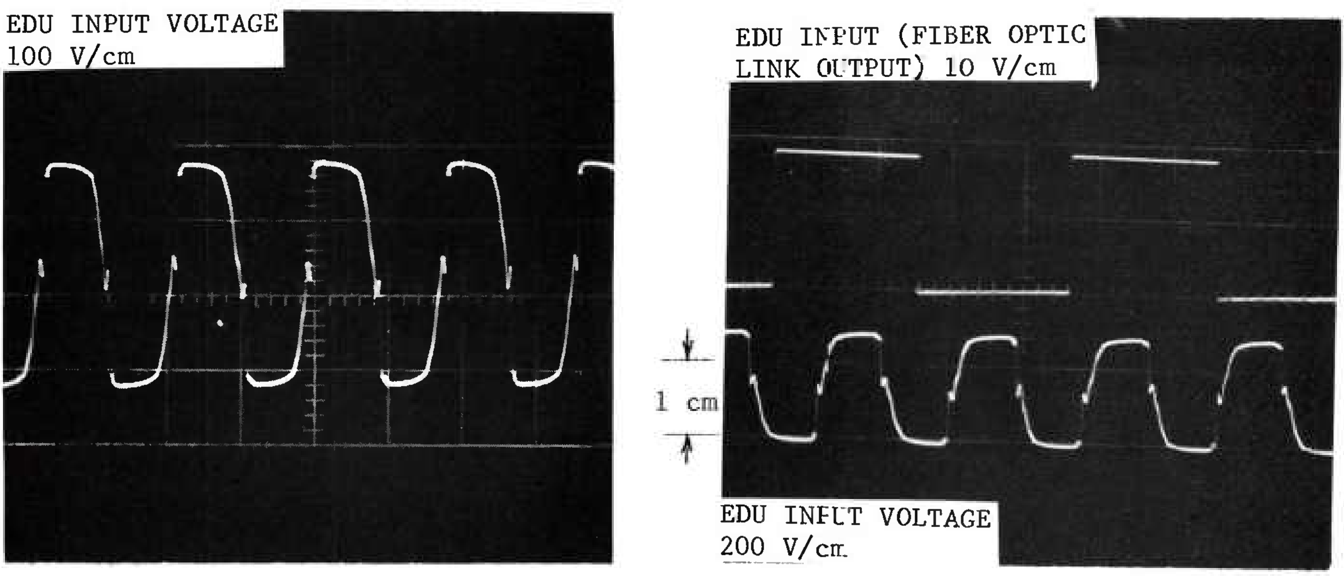
LSSB SIMULATED INPUTS			FIBER OPTIC XMTR INPUT		FIBER OPTIC RCVR OUTPUT		
MICROCOMPUTER, LVDT INPUT, VOLTS DC	MICROCOMPUTER PEDAL COMMAND INPUT, VOLTS DC	% MODULATION REQ'D, ±10%	% MODULATION, MEASURED	PK TO PK AMPL (20±2V REQ'D)	% MODULATION, MEASURED	PK TO PK AMPL (20±2V REQ'D)	XFMR SECONDARY (EDU INPUT) VOLTAGE, VAC
0	0	* 50	50	19	50	19	142.6
4.37	0	* 88	88	19	88	19	129.6
4.37	-1.0	50	48	19	48	19	142.6
0	-1.0	* 12	12	19	12	19	132.7
0	1.0	88	88	19	88	19	133.1
-4.37	1.0	50	50	19	50	19	142.0
-4.37	0	12	12	19	12	19	133.3

*PHOTOGRAPH WAVEFORMS FOR THESE SETTINGS WITH SCOPE CAMERA.



88% MODULATION (DRIVE POSITIVE) 12% MODULATION (DRIVE NEGATIVE)

Figure 3-16. Fiber Optic Link Input/Output Waveforms, Static Gain Test



a. b.

Figure 3-17. EDU Input Voltage Waveform, System Null
(Microcomputer PWM Output @ 50% Modulation)

Table III. Actuator Position Versus Pedal Command

LSSB PEDAL COMMAND OUTPUT, VDC	ACTUATOR POSITION, INCHES	
	DESIRED (±5%)	MEASURED
0	0 (MIDSTROKE POSITION)	0 (MIDSTROKE POSITION)
1.7	1.5 (EXTEND)	1.52 (EXTEND)
-1.7	1.5 (RETRACT)	1.56 (RETRACT)
2.0	1.75 (EXTEND)	1.74 (EXTEND)
-2.0	1.75 (RETRACT)	1.80 (RETRACT)
0	0 (MIDSTROKE POSITION)	0 (MIDSTROKE POSITION)

3.4 INTEGRATION TESTS

3.4.1 System Response

The bandpass requirements and therefore the system loop gain were established by T-2C aircraft dynamic requirements for the integration tests. System dynamic response tests were performed to demonstrate that the HOFCAS operational modes meet these dynamic requirements and are satisfactory for controlling the rudder of the T-2C aircraft. The lab test setup, Figure 3-18, was configured to provide either HPA 1000 HZ or simulated aircraft 400 HZ power for the EDU in the HOFCAS DFBL and ABU modes, and a DFBW mode of operation. A function generator provided sinusoidal and step input signals to the system force transducer inputs and a 2-channel strip chart recorder was used to record the function generator output and rudder actuator feedback signal.

3.4.1.1 System Frequency Response, DFBL Mode, Flight Gain Configuration - DFBL mode system frequency response tests, with the system in the flight gain configuration, were performed for both HPA 1000 HZ and 400 HZ EDU power inputs.

System frequency response for 400 HZ power input to the EDU is contained in Figure 3-19, with the 3 db point occurring at 3.6 HZ. Response for HPA 1000 HZ power input to the EDU is contained in Figure 3-20, with the 3 db point occurring at 2.5 HZ. The lower response for the HPA 1000 HZ EDU input is due to loading effects of the EDU reducing the HPA output voltage.

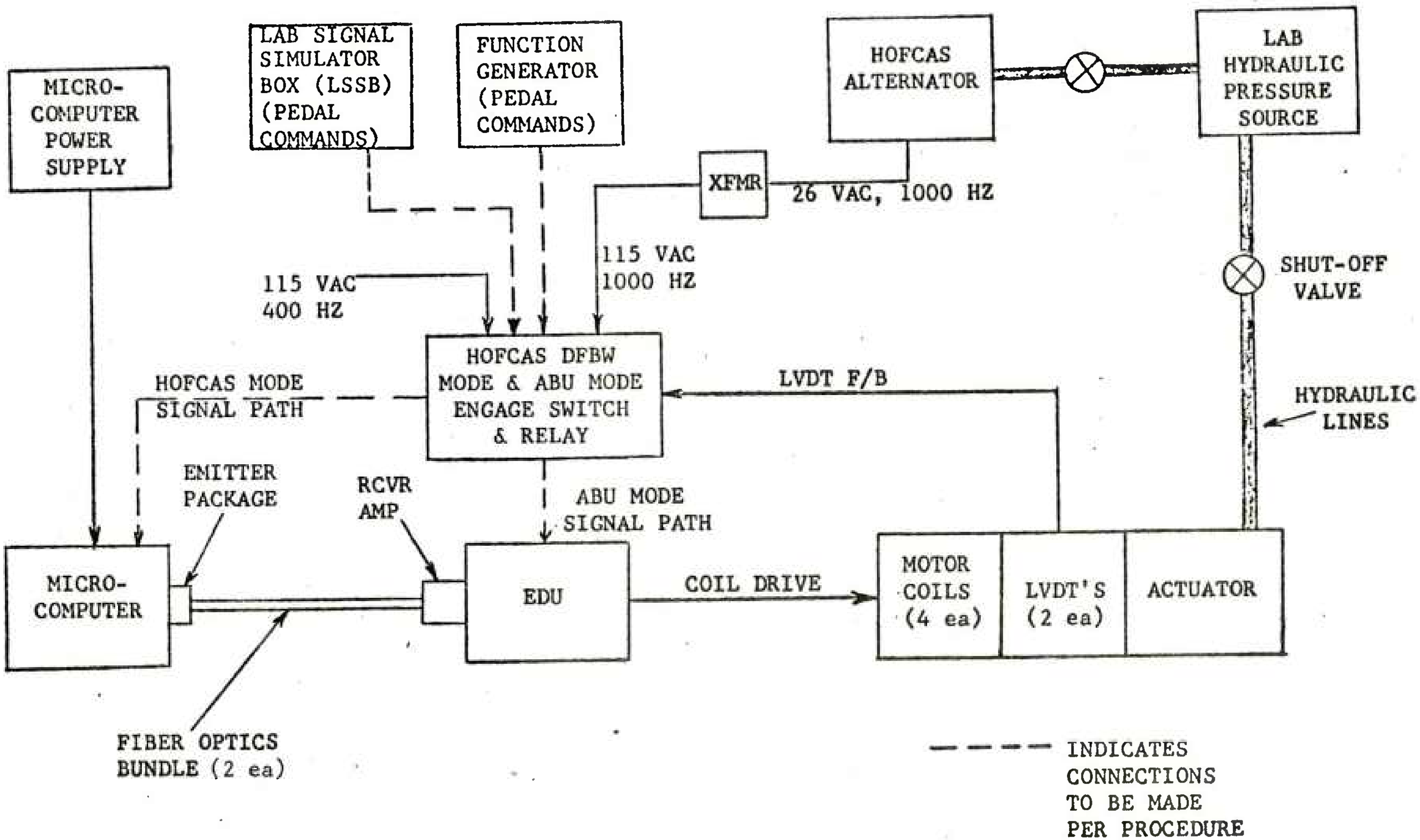


Figure 3-18. System Dynamic Test Lab Setup

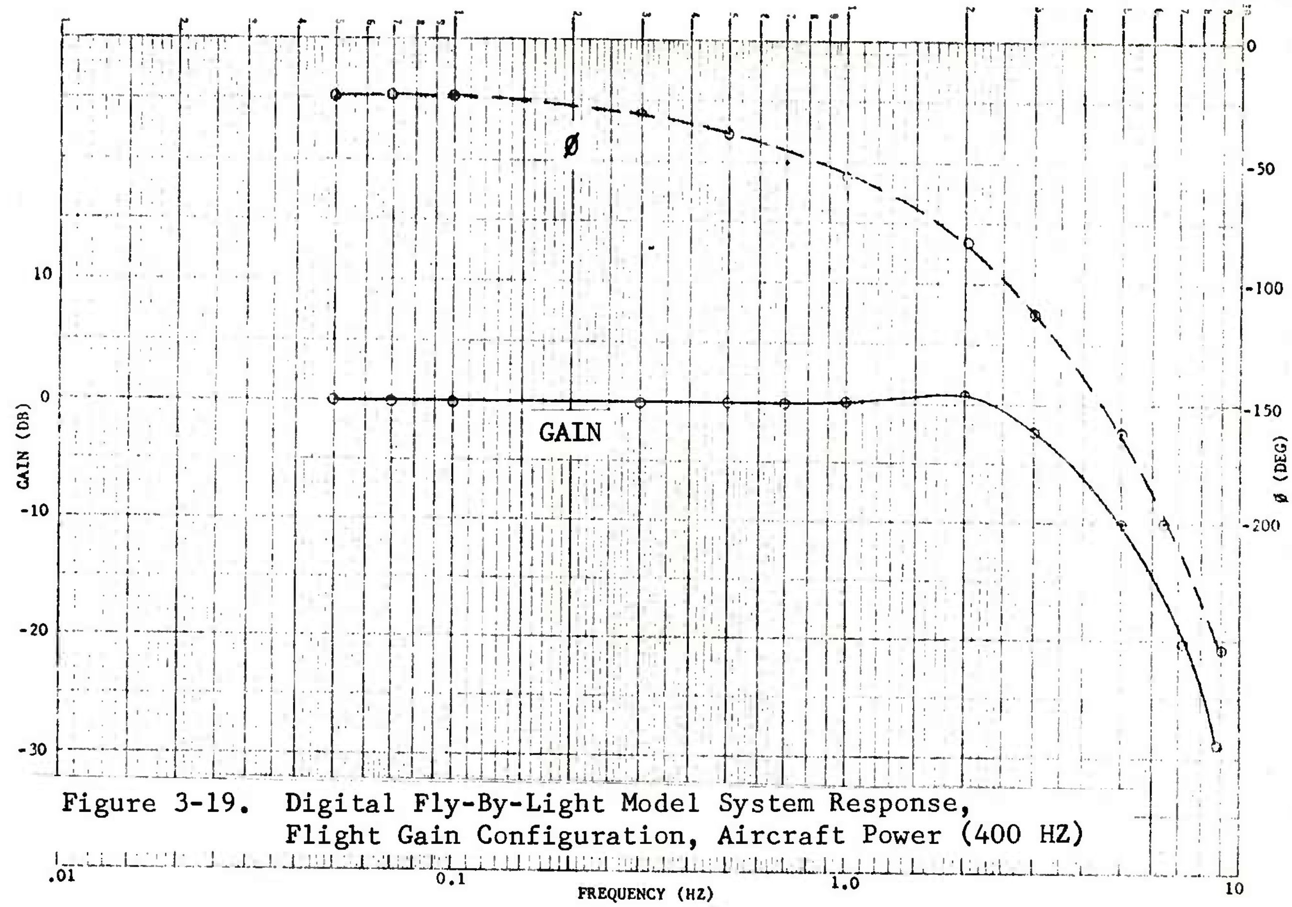


Figure 3-19. Digital Fly-By-Light Model System Response, Flight Gain Configuration, Aircraft Power (400 HZ)

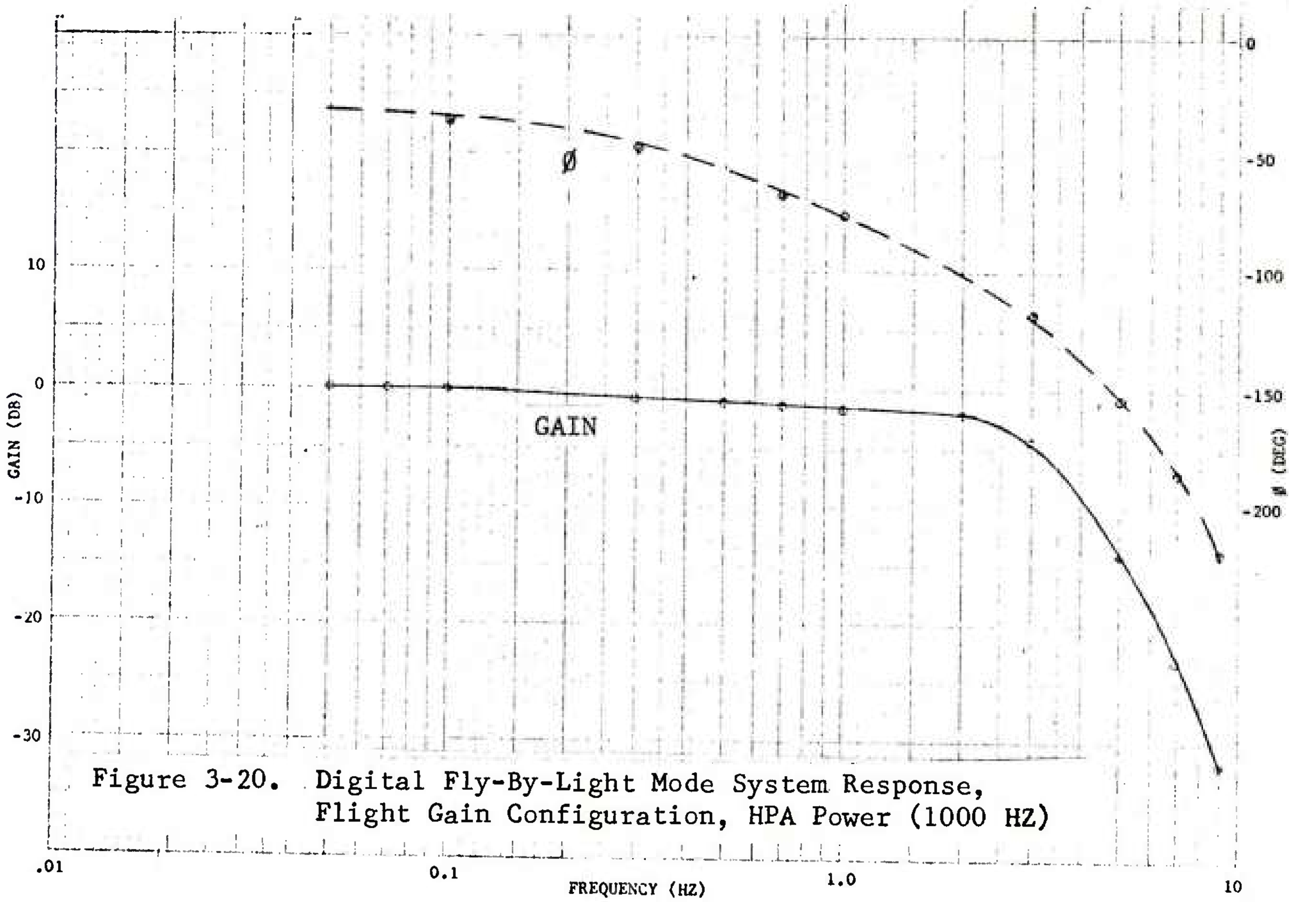


Figure 3-20. Digital Fly-By-Light Mode System Response, Flight Gain Configuration, HPA Power (1000 HZ)

3.4.1.2 System Frequency Response, Digital Fly-By-Wire Mode - System frequency response tests were also performed for a Digital Fly-By-Wire test configuration. This configuration was achieved by direct wiring the EDU to the microcomputer and provides comparison frequency response data for the optical control link.

The microcomputer Digital-To-Analog Converter (DAC) Pulse-Width-Modulated (PWM) outputs were disconnected from the fiber optic link transmitter assembly, and the fiber optic control link outputs were disconnected from R23 and R24 inputs to operational amplifiers U5 and U6, EDU channels 1 and 2 (reference Figure 2-3). The microcomputer DAC output was then directly wired to resistors R23 and R24, channels 1 and 2, in the EDU to configure the system in the Phase VI AFCAS DFBW mode.

Response tests were performed with the system in the flight gain configuration for both HPA 1000 HZ and aircraft 400 HZ EDU power. The EDU 400 HZ response curve is contained in Figure 3-21, with the 3 db point at 3.5 HZ. The EDU 1000 HZ response curve is shown in Figure 3-22, with the 3 db point at 2.6 HZ. Results were the same as the DFBL mode system response (reference Figures 3-19 and 3-20) and show no degradation due to the incorporation of the fiber optic loop into the system.

3.4.1.3 System Step Response, DFBL and DFBW Modes, Flight Gain Configuration - System step response tests were performed for the HOFCAS DFBL and the DFBW modes of operation, in the flight gain configuration (modification of the system to obtain DFBW mode response is included in paragraph 3.4.1.2 of this report). A lab function generator supplied a .2 HZ square wave input to the system force transducer input, with the signal amplitude set for ± .4" actuator travel.

Step response for the DFBL mode is contained in Figure 3-23, and the DFBW mode is contained in Figure 3-24. Actuator LVDT feedback waveforms for both modes are essentially the same, showing no degradation in system operation with the fiber optic loop in the circuit (DFBL mode). The actuator LVDT feedback waveforms for HPA 1000 HZ EDU input power are slightly degraded compared to lab 400 HZ EDU power due to loading effects of the EDU on the HPA output.

3.4.2 EDU Power Supplies

The ± 15 VDC EDU channels 1 and 2 power supply outputs were monitored during system operation in the DFBL mode (1000 HZ EDU power) at system null (50% PWM EDU input signal). The corresponding readings are contained in Table IV and show the HPA voltage had no effect on the EDU power supplies.

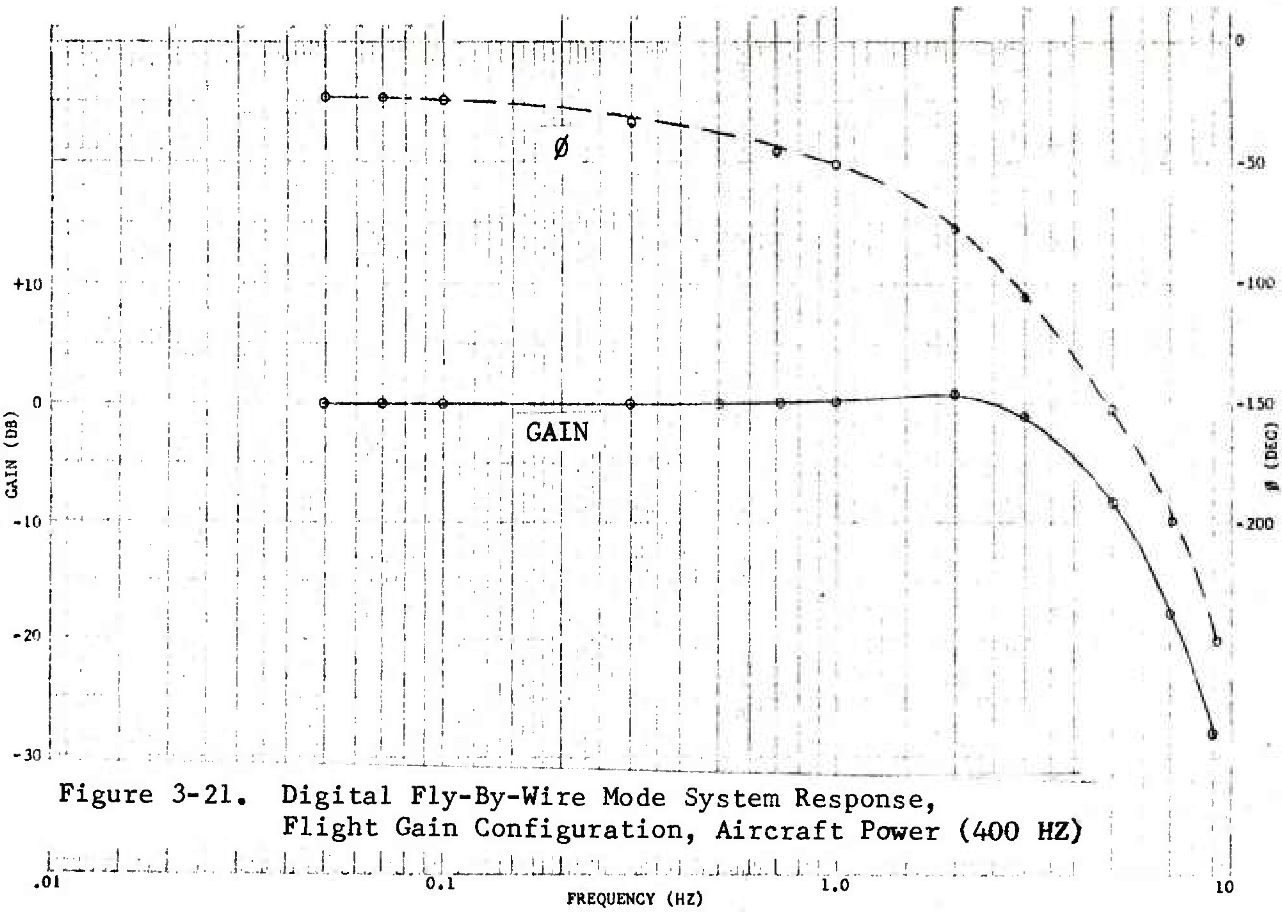


Figure 3-21. Digital Fly-By-Wire Mode System Response, Flight Gain Configuration, Aircraft Power (400 HZ)

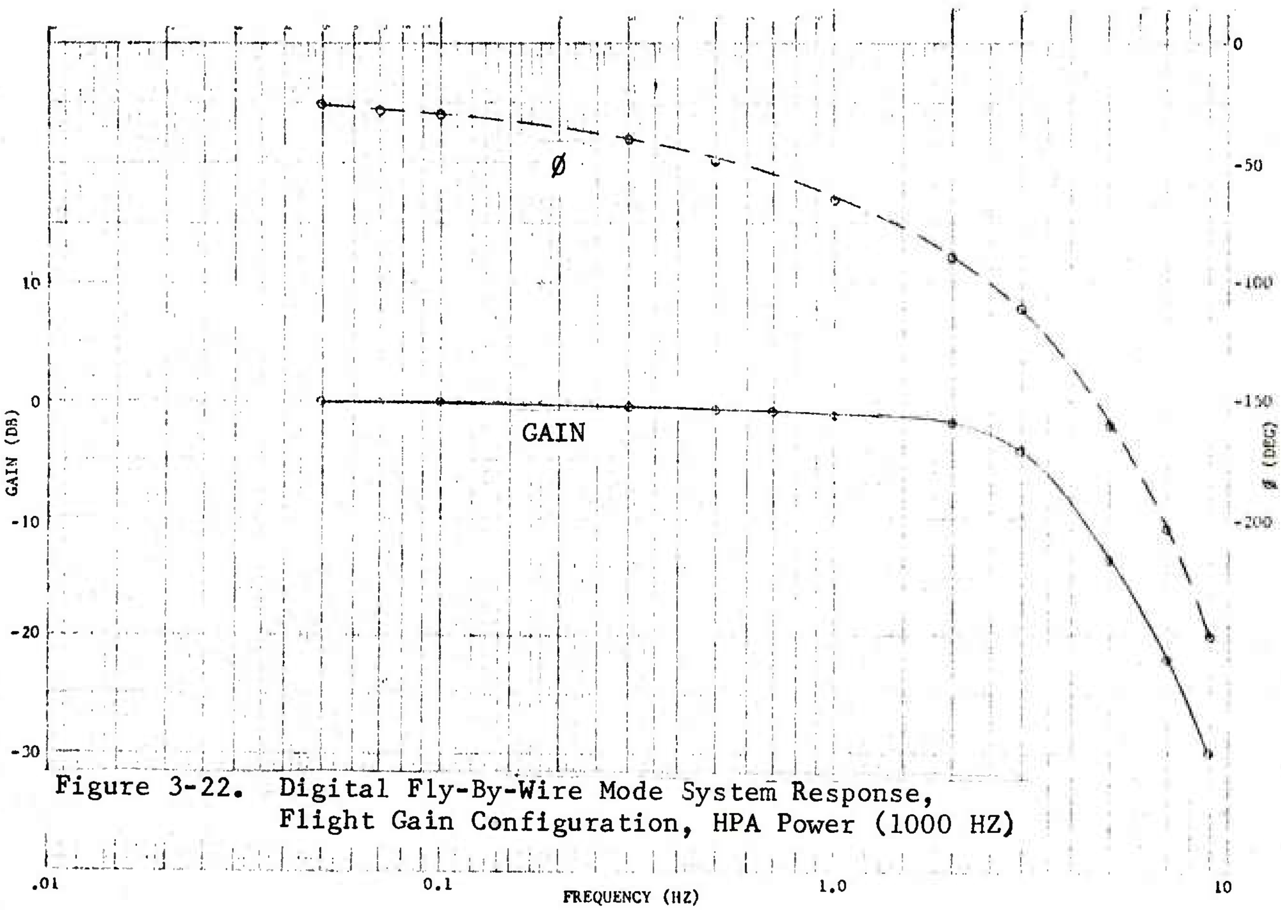
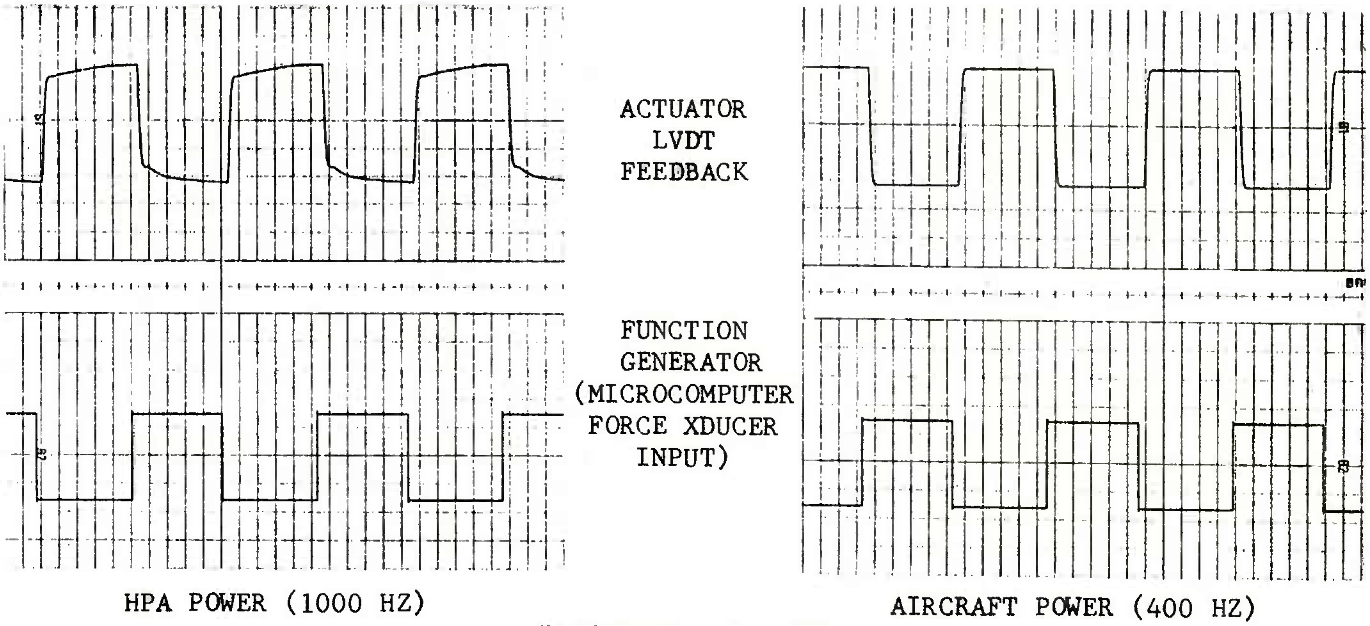
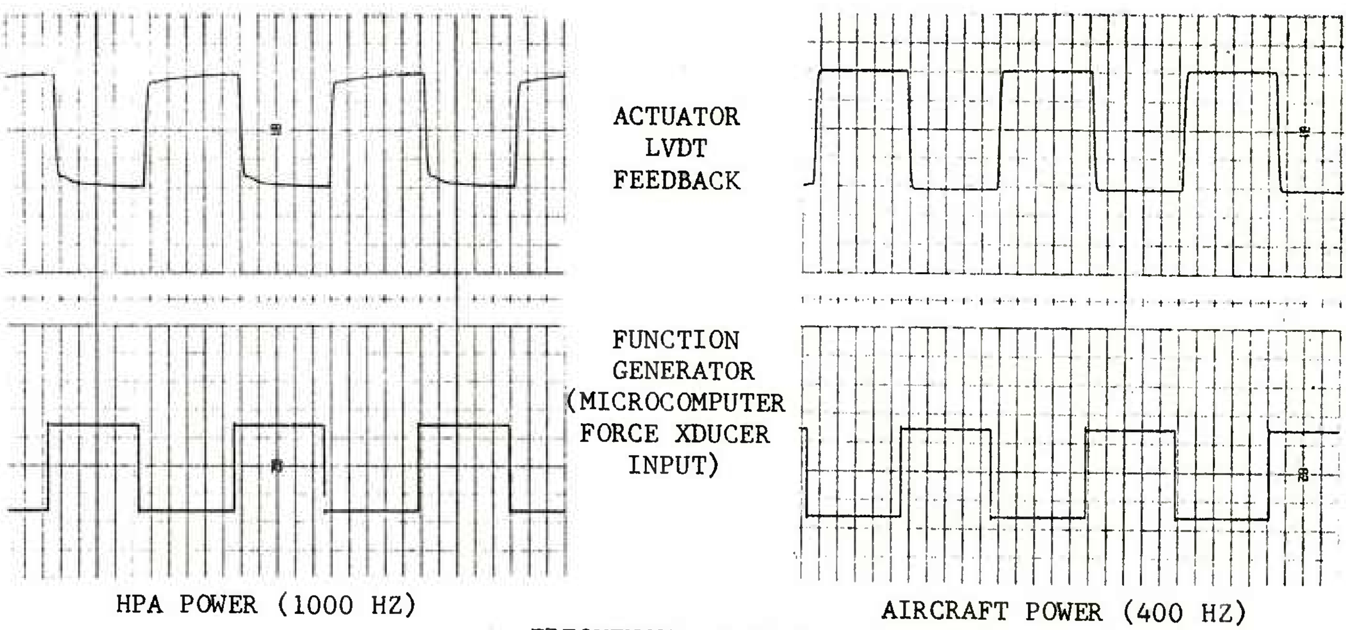


Figure 3-22. Digital Fly-By-Wire Mode System Response, Flight Gain Configuration, HPA Power (1000 HZ)



FREQUENCY: 0.2 HZ
OUTPUT
AMPLITUDE: $\pm$.4 IN

Figure 3-23. Step Input Response, Flight Gain Configuration, DFBL Mode



FREQUENCY: 0.2 HZ
OUTPUT
AMPLITUDE: $\pm$.4 IN

Figure 3-24. Step Input Response, Flight Gain Configuration, DFBW Mode

Table IV. EDU Channels 1 & 2 Power Supply Outputs, System Null

PARAMETER, VDC	CHAN #1 POWER SUPPLY VDC	CHAN #1 POWER SUPPLY PEAK-TO-PEAK RIPPLE, mv	CHAN #2 POWER SUPPLY VDC	CHAN #2 POWER SUPPLY PEAK-TO-PEAK RIPPLE, mv
+15	+15.1	50	+15.0	50
-15	-15.1	50	-15.0	50

3.4.3 Simulated Failures

3.4.3.1 Fiber Optic Loop, Null Input - The system was connected as shown in Figure 3-18, with the LSSB connected to the microcomputer pedal command input. With the pedal command set at 0 $\pm$ .1 VDC and the system engaged in the DFBL mode, one of the fiber optic loop cables was disconnected from the EDU. A simultaneous 0.15 inch (0.38 cm) transient in actuator position (retract) occurred followed by the actuator immediately returning to the null position. This transient is equivalent to a momentary 1° change in aircraft rudder position (total T-2C rudder travel capability for AFCAS is $\pm$ 12°) and is not considered significant.

With both fiber optic inputs to the EDU disabled in the DFBL mode, system operation will revert to the ABU mode when the pedal command signal or LVDT feedback (due to actuator drift with no EDU input signal) results in a microcomputer error output exceeding 1.5° for 2 seconds, minimum.

3.4.3.2 Fiber Optic Loop, Dynamic Input - The system was connected as shown in Figure 3-18, with the function generator connected to the microcomputer pedal command input. The function generator output was set for $\pm$ 1.25" actuator travel at .5 HZ, in the DFBL mode. One of the two fiber optic cables was disconnected from the EDU. The actuator continued cycling, with loop gain reduced by one half and a corresponding reduction in bandpass.

3.4.3.3 Hydra-Powered Alternator (HPA) - The system was connected as shown in Figure 3-18, with the function generator connected to the microcomputer pedal command input and set for $\pm$ 1.25" actuator travel at .5 HZ, DFBL mode. Hydraulic pressure was removed from the HPA. No transients occurred, and the system subsequently reverted to the ABU mode of operation after two seconds.

In the full aircraft configuration, the system will not automatically revert to the ABU mode with loss of HPA power to the EDU. Since both the pedal and feedback transducers are powered from the EDU, their outputs would go to zero and the microcomputer monitor program would not sense an error great enough to de-energize the DFBL control relays.

3.5 PERFORMANCE TESTS

3.5.1 System Frequency Response, Maximum Gain, DFBL Mode

Tests were performed to establish the bandpass capability of the system when the loop gains are increased beyond those desired for T-2C flight testing. To perform these tests, computer gain (percent modulation per volt of error signal) was increased until the system dynamics became limited by system components and not the loop gain. DFBL mode frequency response tests were performed with the system in the increased gain configuration for HPA 1000 HZ and lab 400 HZ EDU power inputs. The results are contained in Figure 3-25, and show the 3 db point occurring at 2.5 HZ for HPA 1000 HZ power and 6.2 HZ for lab 400 HZ power. The difference in performance for the two power sources is produced by the limited power available from the HPA. This is discussed further in section 4.4.

3.5.2 System Frequency Response, ABU Mode

The frequency response of the ABU mode is established by the analog gain of the EDU. After the completion of other dynamic tests, the ABU mode was evaluated to ensure operation was unchanged by incorporation of the HOFCAS. ABU mode frequency response with the system in the flight gain configuration and 400 HZ EDU power is shown in Figure 3-26. Results show the 3 db point occurring at .7 HZ, and is the same performance capability obtained in Phase VI of the AFCAS program.

3.6 ENVIRONMENTAL TESTS

3.6.1 Fiber Optic Loop

Temperature tests were performed on the HOFCAS fiber optic control link utilizing the lab temperature chamber. Components located in the chamber included the fiber optic transmitters, detectors, associated circuitry, and fiber optic cabling.

The tests consisted of a 2-hour 32°F (0°C) "cold soak" followed by a 2-hour "soak" at 122°F (50°C). The system was energized at the end of each 2-hour period and the input and output waveforms for null, negative, and positive drive input signals displayed on the oscilloscope. Results showed no change in the output waveforms due to temperature. The null and drive negative signal waveforms are contained in Figure 3-27.

3.6.2 Hydra-Powered Alternator (HPA)

The HOFCAS HPA temperature tests had previously been performed on this unit by the supplier (Bertea). The resultant data is included in Appendix B, paragraph B.5 (Bertea Corporation Acceptance Test Procedure No. 287700-T) of this report.

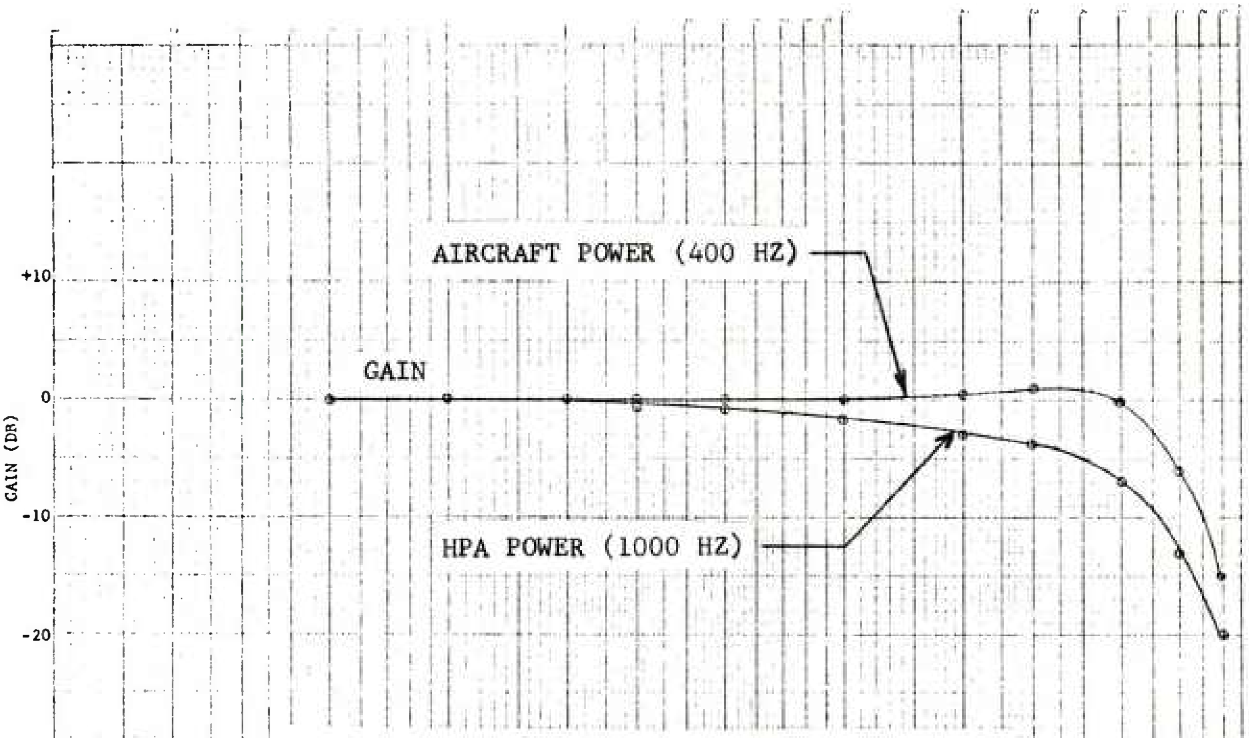


Figure 3-25. Digital Fly-By-Light Mode System Response, Maximum Capability, HPA Power (1000 HZ) and Aircraft Power (400 HZ)

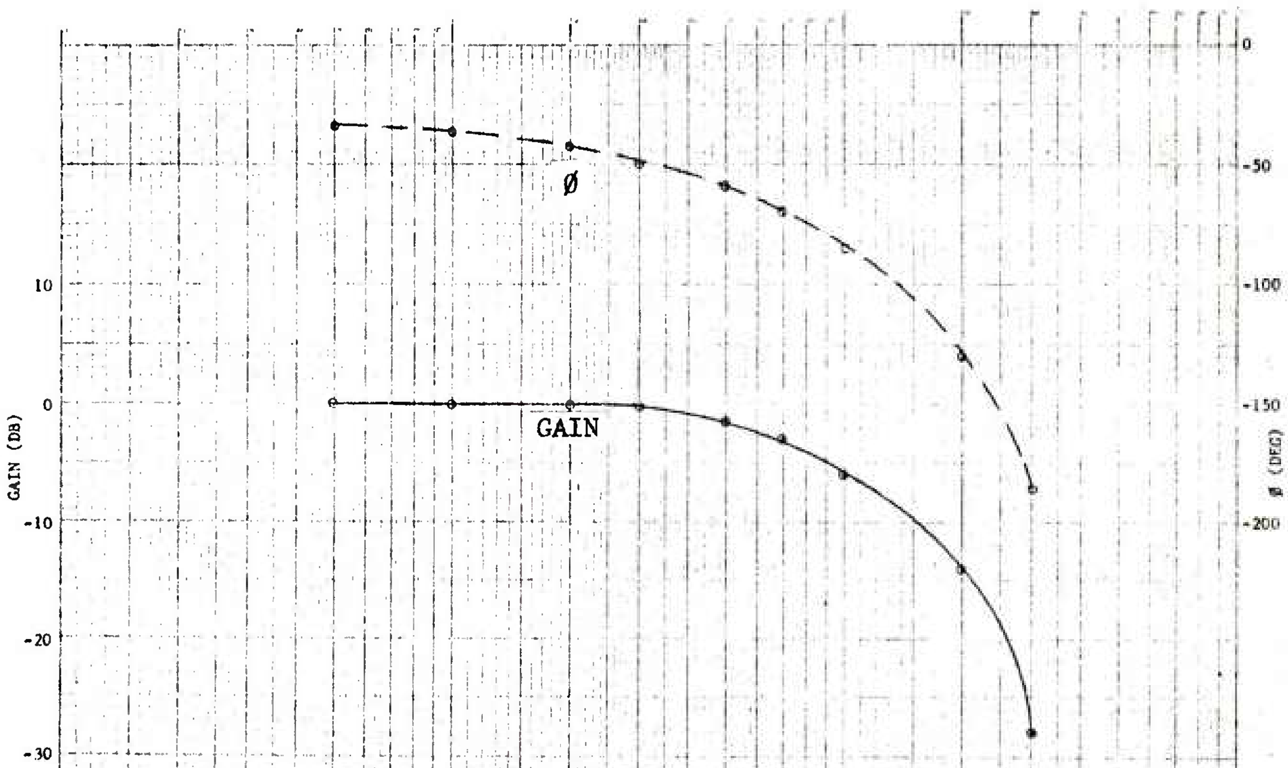


Figure 3-26. Analog Back-Up Mode System Response, Flight Gain Configuration, Aircraft Power (400 HZ)

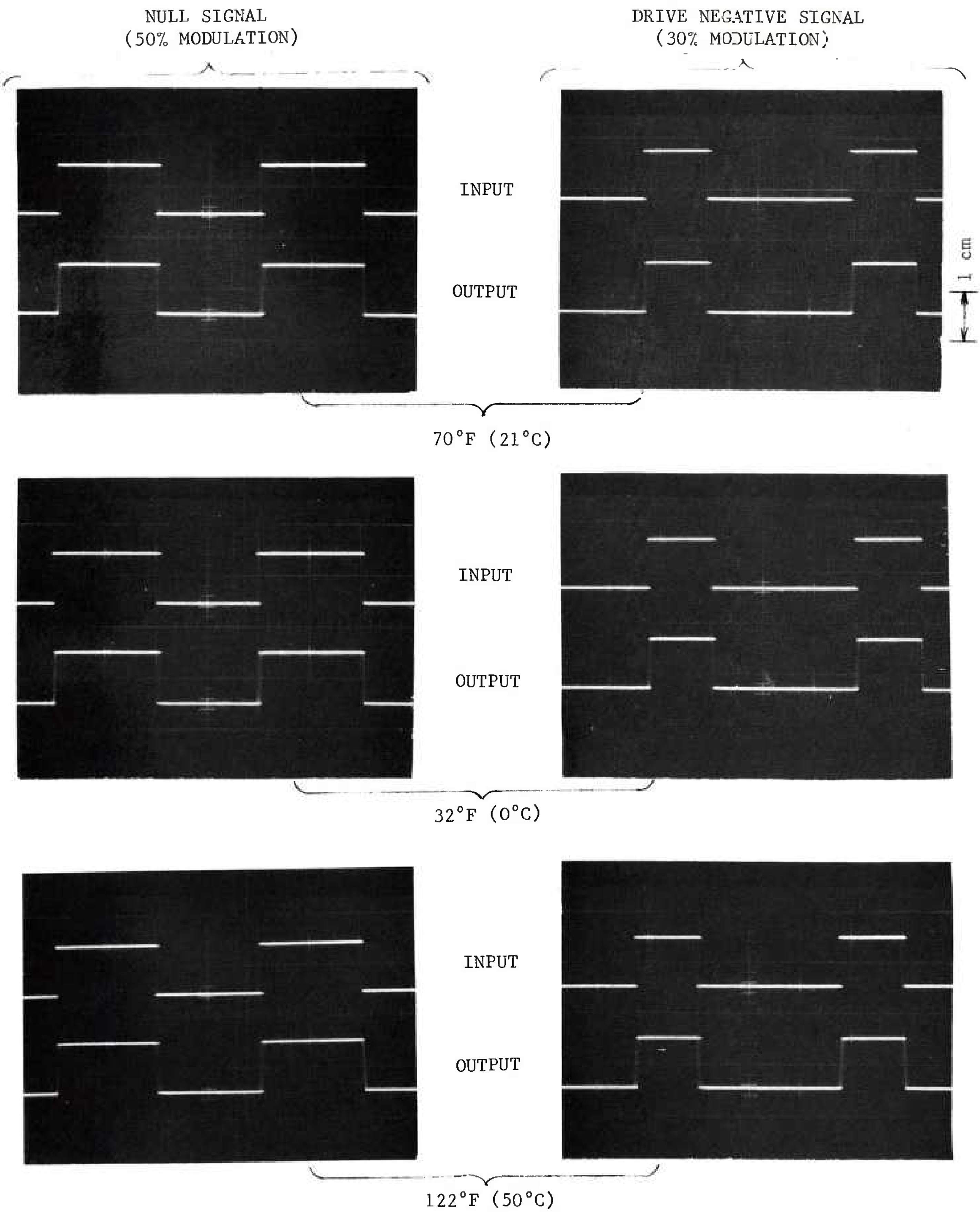


Figure 3-27. Temperature Test Fiber Optic Loop Input and Output Waveforms

4.0 ANALYSIS OF RESULTS

The test results demonstrate that the HOFCAS is satisfactory for operation in the rudder system of the T-2C aircraft. The testing was divided into three categories. The first group of tests accomplished the functional testing of the added system components, especially the HPA. The second group of tests evaluated the HOFCAS for operation with the T-2C rudder. The third set of tests established performance limits and provided data for suggested improvements in the HOFCAS concept.

4.1 HYDRA-POWERED ALTERNATOR (HPA)

The functional tests established the HPA operational capability and demonstrated the unit is adequate to supply the electrical power needed to operate the rudder actuator of a T-2C aircraft. The data, contained in paragraph 3.3, has the characteristics expected for the HPA design. The design is described in Appendix B.

The speed (frequency) and the no load voltage of the alternator are directly related to hydraulic flow, which is controlled by the turbine nozzle diameter and the applied hydraulic pressure (reference Figure 3-2). Increased flow through the fixed nozzle results in increased losses and additional heating of the hydraulic fluid, as shown in Figure 3-3.

The alternator used for this project was an adaptation of an existing missile power source and is wound to provide alternator protection against overloads. This characteristic becomes apparent in the data of Figures 3-6 and 3-7. As the output current is increased, the voltage decreases and total power output remains the same. At the same time, the unit shows very little change in speed (frequency) with increased current. As the power output remains constant at rated load, it is apparent the hydraulic turbine load is constant and the speed would not vary. In addition, the HPA has a very low efficiency (Appendix B) so that slight variations in extracted power have very little effect on total torque required to drive the alternator.

Wave shapes of the alternator output showed the waveform with a resistive load to be nearly sinusoidal. For this system application the output power is supplied to power supplies in the EDU through a transformer and the wave shape is not critical to system operation. When the HPA was used to power the EDU, the load became highly inductive and the wave shape approached a square wave (Figure 3-17). While this does not directly affect system operation, the distorted wave shape reduces transformer and power supply efficiencies and further increases the loading effects on the alternator.

The HPA used for this project is satisfactory for flight testing, and will demonstrate the concept of a D^3 actuation system without electrical power and signals routed to the actuation surface. Several areas of improvement in the HPA performance are desirable and are discussed in Appendix B.

4.2 FIBER OPTIC LINK

The fiber optic link performed satisfactorily as expected. No difference in system performance was noted between the fiber optic link or direct wiring method of connecting the microcomputer output to the EDU, reference Figures 3-20 and 3-22, and Figures 3-23 and 3-24.

4.3 FLIGHT TEST CONFIGURATION

HOFCAS integration tests were performed using the hardware configured to the T-2C aircraft installation. These tests consisted primarily of dynamic response and failure mode evaluation. Frequency response tests showed a slight reduction in system performance with the EDU powered by the HPA 1000 HZ output compared to 400 HZ power (reference Figures 3-19 and 3-20).

The slight reduction in dynamic response, when the EDU is powered by the HPA 1000 HZ output, is due to the limited power capability of the HPA which results in a voltage drop at the torque motor coils when additional power is requested. The voltage drop causes a reduction in loop gain and a corresponding loss of bandpass.

The HPA used in this project is capable of a steady state 26 watt output with no capability of handling higher power demand transients (see Appendix B for further discussion). The EDU peak power requirement is 50 watts, consisting of 32 watts for the torque motor and 18 watts for EDU amplifiers, power supplies, and transducer excitation. The torque motor characteristics (see Figure 4-1) are such that at 26 watts total power (8 watts at the torque motor) the major portion of the spool travel has occurred and the rated flow of the valve is already obtained. The additional power requirement to the torque motor is needed to obtain the full particle shear out capability and is not required for full hydraulic flow. For the T-2C application, if the full torque motor force is required, the system will revert to the ABU mode with aircraft power and full shear force will be available.

The step response characteristics shown in Figures 3-23 and 3-24 again show the effects of limited power to the EDU. This effect is more pronounced with step demands as they require high power peaks.

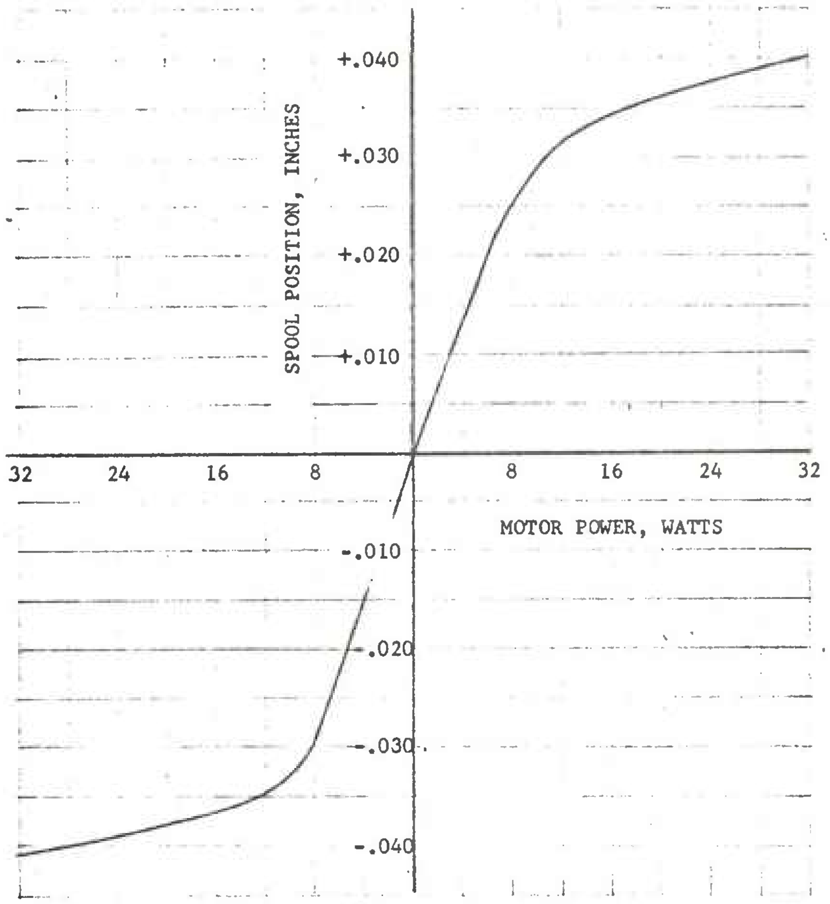


Figure 4-1. Torque Motor Characteristics

4.4 HOFCAS PERFORMANCE

Results of the dynamic tests performed in this project successfully demonstrated the suitability for HOFCAS operation in a T-2C aircraft and provided additional data to demonstrate the potential of a HOFCAS design.

The performance of the AFCAS actuator was evaluated in a previous flight test program (Reference 5). The measured frequency response shown in Figure 4-2 is approximately 13 HZ. This response was considerably above that required for the flight test program. The D^3 operation of this actuator (Reference 6) used the same analog EDU to drive the torque motor of the actuator. Since the EDU was not optimized for digital drive some bandpass was lost and the response is that shown on Figure 3-25 for aircraft power. Rockwell laboratory tests of a circuit optimized for direct digital drive have produced the frequency response (25 HZ) shown in Figure 4-3. As the natural frequency of the torque motor is approximately 230 HZ, the dynamic response is limited either by the valve design or the electronic drive design.

The data of Figure 3-25 shows the dynamic response obtained with the present D^3 design and that obtained with the HOFCAS design. As mentioned above the bandpass with aircraft power matches that of Phase VI of the AFCAS program (Reference 6). The reduced response of the HOFCAS design is produced by the limited power available from the HPA. The limited HPA power reduces the power available to the torque motor coils resulting in a reduced loop gain under dynamic conditions. This produces reduced response but no decrease in static accuracy.

For comparison purposes the response curve of the ABU mode is shown in Figure 3-26. This response is the same as that of the two previous flight test programs and demonstrates that the modifications for HOFCAS did not affect the ABU operation.

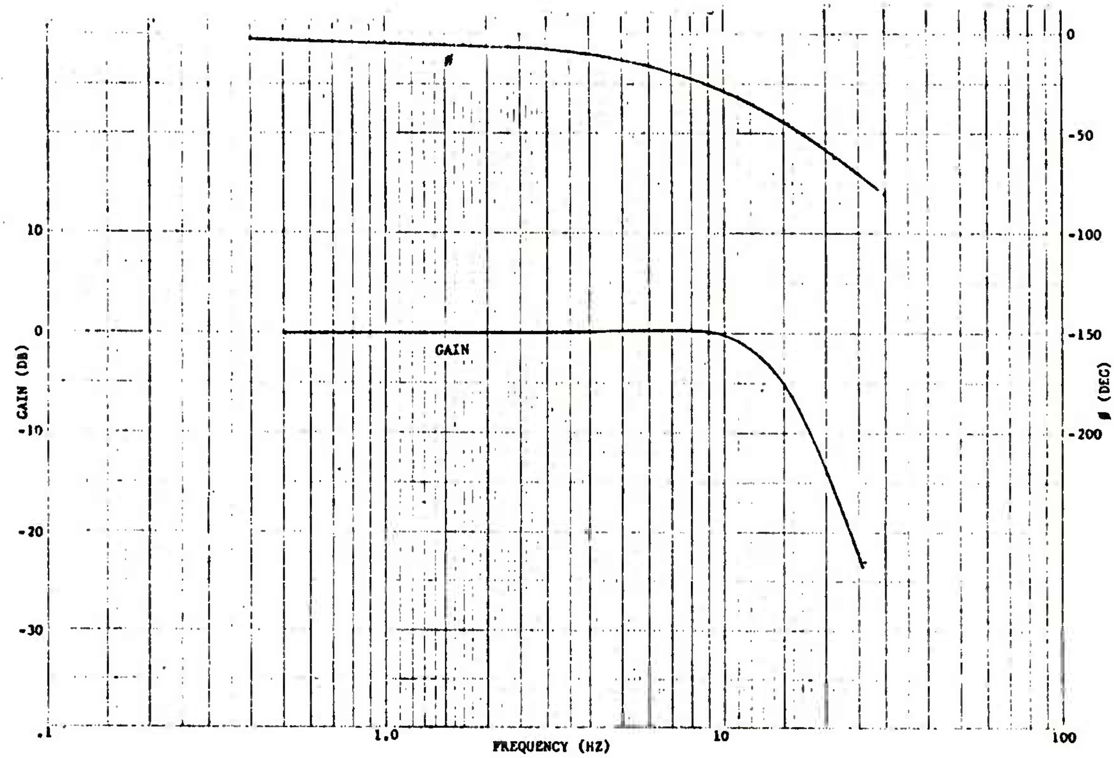


Figure 4-2. AFCAS Frequency Response

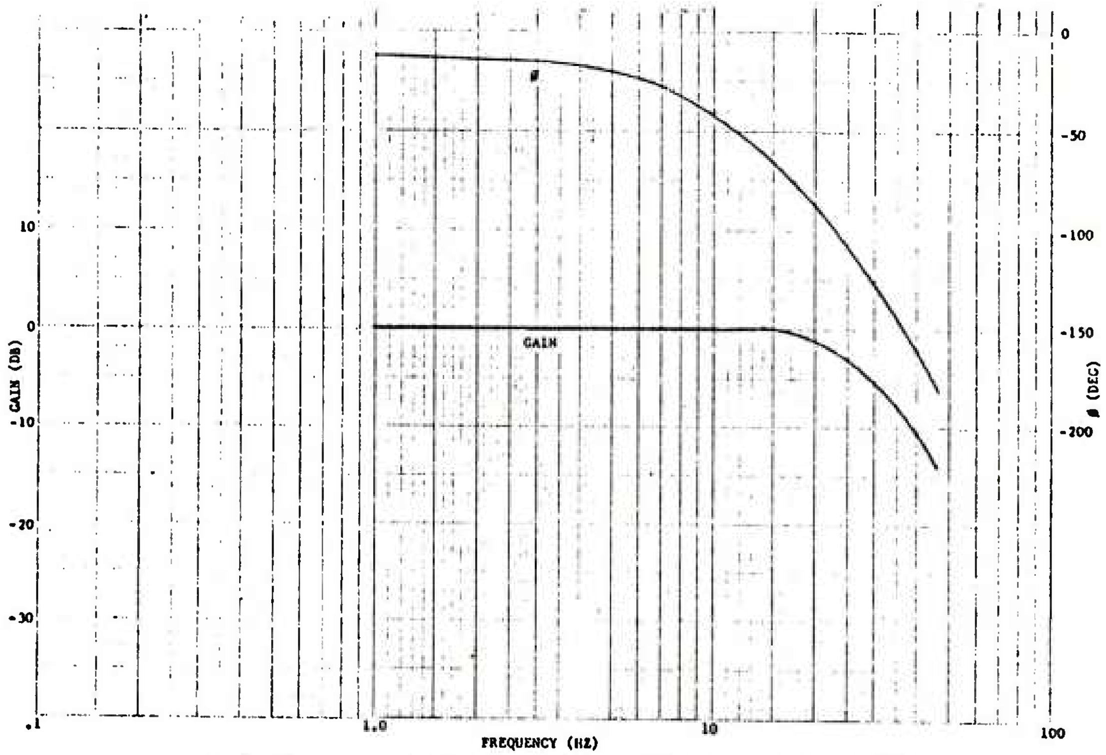


Figure 4-3. Frequency Response, AFCAS Designed For Direct Digital Drive

5.0 CONCLUSIONS AND RECOMMENDATIONS

The results of the laboratory tests demonstrate that the HOFCAS configuration is satisfactory for flight testing in a T-2C aircraft. The tests prove the HOFCAS concept is a practical approach for operating remotely located surface actuation with immunity to electromagnetic interference. The D^3 actuator is ideally suited for this application because of the integrated actuator concept and the ease of adapting optical control to the actuator.

The next logical step in developing the HOFCAS would be to demonstrate the concept in flight. Several additional developments, some of which are already in work, are needed to establish this concept for use in future high performance aircraft. These items are:

- A suitable optical actuator feedback link.
- High temperature digital electronics suitable for packaging inside the actuator.
- An improved valve-torque motor suitable for packaging inside the actuator.
- An improved HPA with the capability of handling the peak transient power requirements.
- Design of the integrated actuator package.

The optical feedback link and the valve-torque motor are already under development in separate Navy programs. The drive electronics would be the next needed development. The new electronics and the improved valve-torque motor can be expected to reduce the power requirement of the HPA.

Other studies of interest would include research into methods of improving the HPA efficiency (see Appendix B) without increased size, weight or complexity. A design study to show the advantages of the HPA over the "brute force" approach (shielding, filtering, etc.) to protect against EMP would also be desirable.

The conclusions of this study show that HOFCAS approach incorporating a D^3 actuation system will produce a simple highly reliable actuation system that is immune to the effects of electromagnetic interference.

REFERENCES

Reference No.

1. NR72H-240, Feasibility Study for Advanced Flight Control Actuation System (AFCAS), Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-72-C-0108, June 1972, Unclassified. AD 767 058

2. NR73H-107, Control-By-Wire Actuator Model Development for AFCAS, Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-73-C-0405, January 1974, Unclassified. AD 772 588

3. NR75H-1, Control-By-Wire Modular Actuator Tests (AFCAS), Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-73-C-0405, January 1975, Unclassified. AD A-006 371

4. NR76H-1, Design and Fabrication of an 8000 psi Control-By-Wire Actuator for Flight Testing in a T-2C Airplane, Rockwell International Corporation, Columbus Aircraft Division, Contract N62269-75-C-0311, January 1976, Unclassified. AD A024 487/IGI

5. NAVAIRDEVCEN 75287-60, Flight Verification of the Advanced Flight Control Actuation System (AFCAS) in the T-2C Aircraft, Columbus Aircraft Division, Rockwell International Corporation, Contract N62269-76-C-0201, June 1978, Unclassified.

6. NAVAIRDEVCEN 78207-60, Flight Verification of Direct Digital Drive for an Advanced Flight Control Actuation System (AFCAS) in the T-2C Aircraft, North American Aircraft Division, Rockwell International Corporation, Contract N62269-76-C-0201, November 1979, Unclassified.

APPENDIX A

MICROCOMPUTER AND SOFTWARE

APPENDIX A

MICROCOMPUTER AND SOFTWARE

The microcomputer selected for this program was based on the Motorola MC6800 microprocessor. The assembly consisted primarily of the Motorola Monoboard Microcomputer 1A (Micromodule 1A) which is a complete computer-on-a-board, plus Burr Brown D/A and A/D converters, all mounted on a mother board and housed in a single unit. This unit, shown in Section 2, Figure 2-9, contains all the interfaces and wiring required for the processor and has space for two additional cards for expansion of capability.

The heart of the unit is the monoboard microcomputer which has the following features:

- MC6800 Microprocessing Unit (MPU) with associated clock oscillator, power on reset timer, and memory decoding logic.
- 1024 Bytes of RAM.
- Sockets for up to 4096 bytes of Alterable Read Only Memory (AROM) or mask-programmable ROM (Four of the 2048 x 8-bit ROM's may also be used if the proper jumper connections are made, thus providing over 8K of ROM on this module).
- One RS-232C compatible interface that utilizes a single MC6850 (ACIA).
- Two programmable MC6820 PIA's that provide 40 programmable Input/Output and control lines.
- Address, data, and control bus drivers to interface Monoboard Microcomputer 1A with other modules in the Family or with an EXORciser.
- TTL signal level inputs and TTL signal level, three-state, or open collector outputs.

This monoboard microcomputer is shown in block diagram form in Figure A-1. A photograph of the board is shown in Figure A-2. The MPU, Motorola MC 6800, is contained on a single chip on the board. The organization of the chip is shown in Figure A-3. The complete instruction set is given in Tables A-I, A-II, and A-III.

The A/D and D/A converters make up the other two boards in the micro-computer assembly. Figure A-4 is a block diagram of the A/D converter. Figure A-5 is a block diagram of the D/A converter.

Table A-IV is a summary of the characteristics of the two converters.

Table A-V is the program listing and Figure A-6 contains the PROM map used for this project.

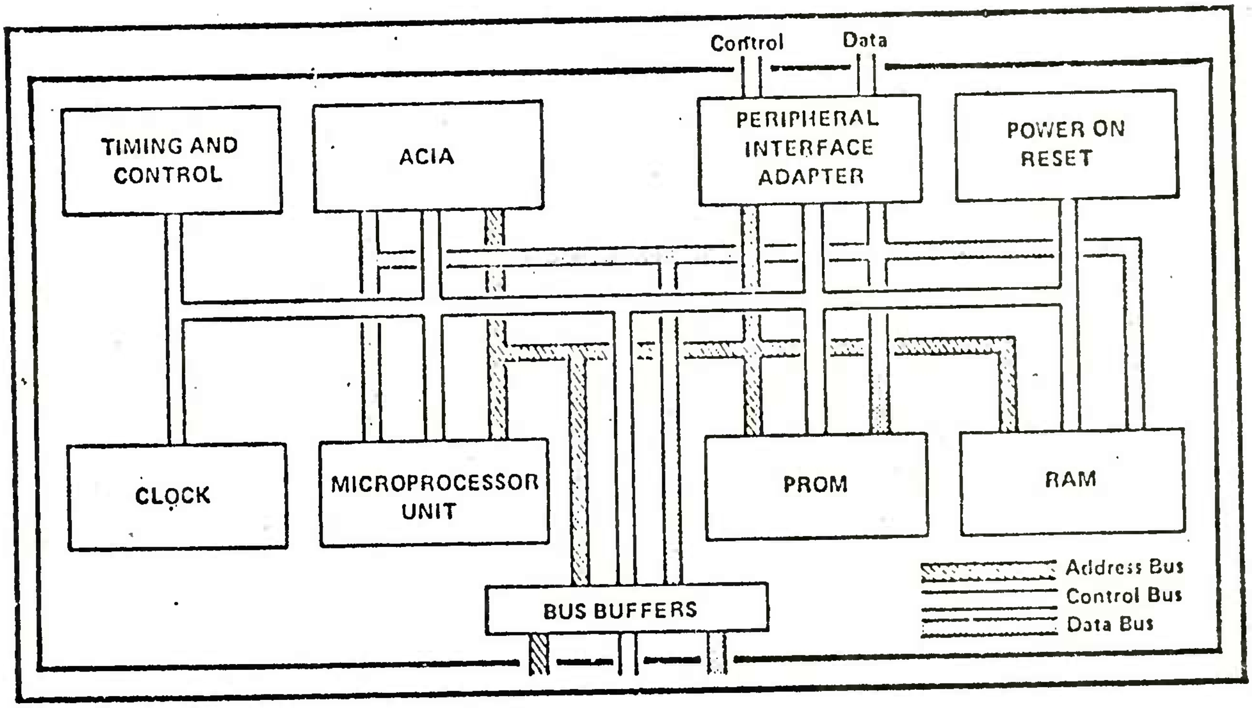


Figure A-1. Monoboard Microcomputer Block Diagram

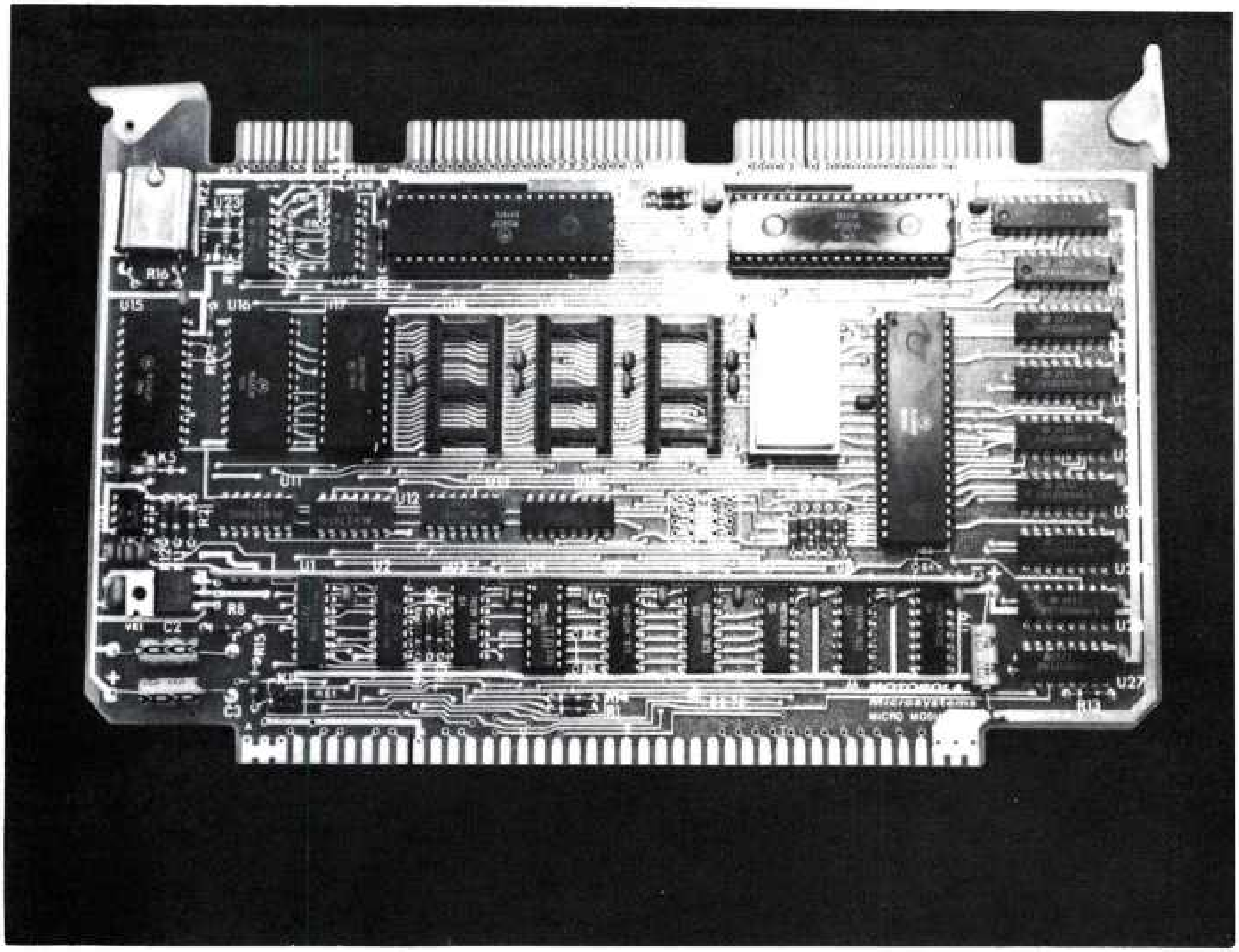


Figure A-2. Monoboard Microcomputer

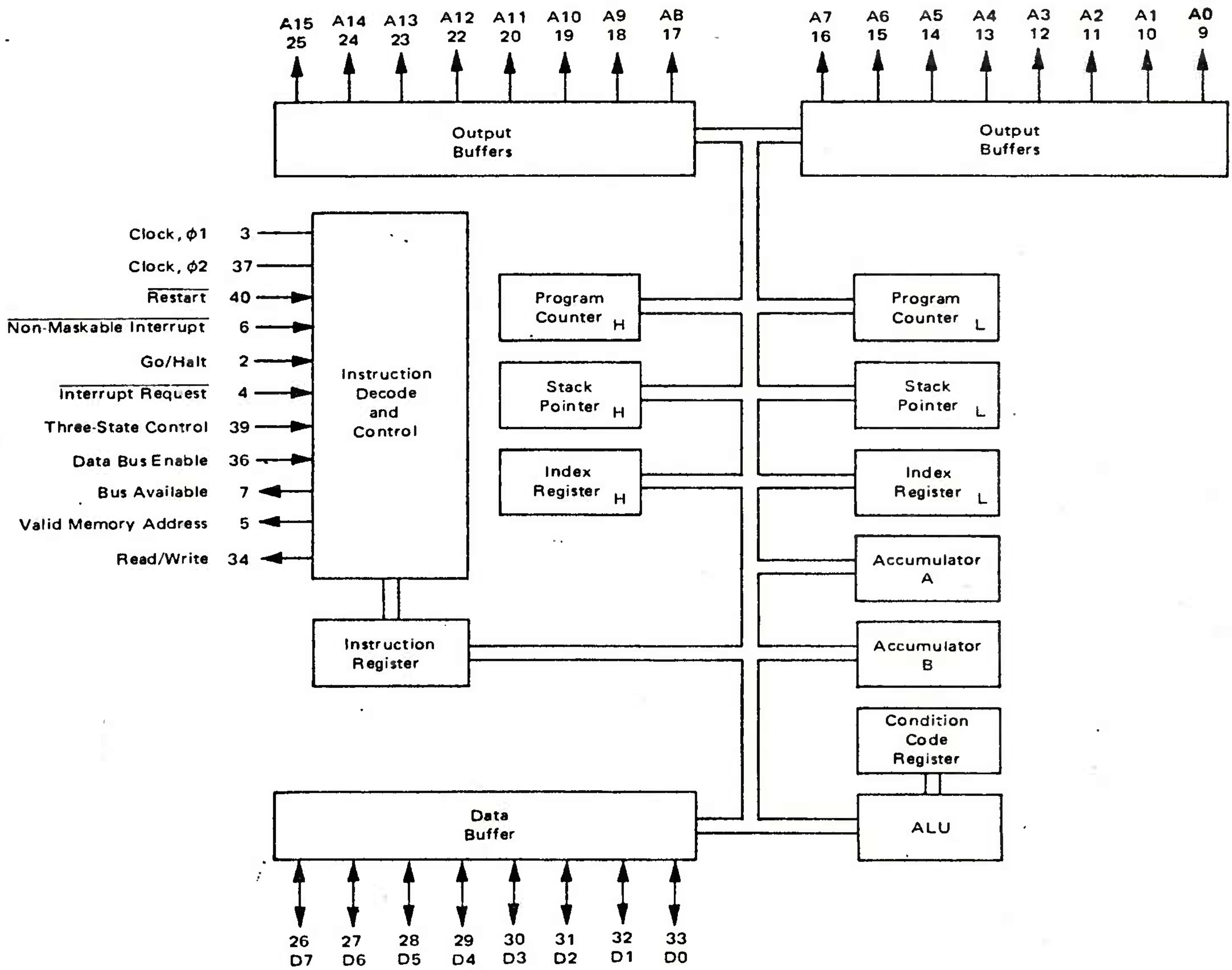


Figure A-3. Microprocessor Unit Organization (MC 6800)

Table A-I. Accumulator and Memory Instructions (MC6800)

OPERATIONS	MNEMONIC	IMMED OP	~	#	DIRECT OP	~	#	INDEX OP	~	#	EXTND OP	~	#	IMPLIED OP	~	#	BOOLEAN/ARITHMETIC OPERATION (All register labels refer to contents)	5 H	4 I	3 N	2 Z	1 V	0 C
Add	ADDA	8B	2	2	9B	3	2	AB	5	2	BB	4	3				A + M → A	↕	●	↕	↕	↕	↕
	ADDB	CB	2	2	DB	3	2	EB	5	2	FB	4	3				B + M → B	↕	●	↕	↕	↕	↕
Add Acmltrs	ABA													1B	2	1	A + B → A	↕	●	↕	↕	↕	↕
Add with Carry	ADCA	89	2	2	99	3	2	A9	5	2	B9	4	3				A + M + C → A	↕	●	↕	↕	↕	↕
	ADCB	C9	2	2	D9	3	2	E9	5	2	F9	4	3				B + M + C → B	↕	●	↕	↕	↕	↕
And	ANDA	84	2	2	94	3	2	A4	5	2	B4	4	3				A · M → A	●	●	↕	↕	R	●
	ANDB	C4	2	2	D4	3	2	E4	5	2	F4	4	3				B · M → B	●	●	↕	↕	R	●
Bit Test	BITA	85	2	2	95	3	2	A5	5	2	B5	4	3				A · M	●	●	↕	↕	R	●
	BITB	C5	2	2	D5	3	2	E5	5	2	F5	4	3				B · M	●	●	↕	↕	R	●
Clear	CLR							6F	7	2	7F	6	3				00 → M	●	●	R	S	R	R
	CLRA													4F	2	1	00 → A	●	●	R	S	R	R
	CLRB													5F	2	1	00 → B	●	●	R	S	R	R
Compare	CMPA	81	2	2	91	3	2	A1	5	2	B1	4	3				A − M	●	●	↕	↕	↕	↕
	CMPB	C1	2	2	D1	3	2	E1	5	2	F1	4	3				B − M	●	●	↕	↕	↕	↕
Compare Acmltrs	CBA													11	2	1	A − B	●	●	↕	↕	↕	↕
Complement, 1's	COM							63	7	2	73	6	3				$\overline{M}$ → M	●	●	↕	↕	R	S
	COMA													43	2	1	$\overline{A}$ → A	●	●	↕	↕	R	S
	COMB													53	2	1	$\overline{B}$ → B	●	●	↕	↕	R	S
Complement, 2's (Negate)	NEG							60	7	2	70	6	3				00 − M → M	●	●	↕	↕	1	2
	NEGA													40	2	1	00 − A → A	●	●	↕	↕	1	2
	NEGB													50	2	1	00 − B → B	●	●	↕	↕	1	2
Decimal Adjust, A	DAA													19	2	1	Converts Binary Add. of BCD Characters into BCD Format	●	●	↕	↕	↕	3
Decrement	DEC							6A	7	2	7A	6	3				M − 1 → M	●	●	↕	↕	4	●
	DECA													4A	2	1	A − 1 → A	●	●	↕	↕	4	●
	DECB													5A	2	1	B − 1 → B	●	●	↕	↕	4	●
Exclusive OR	EORA	88	2	2	98	3	2	A8	5	2	B8	4	3				A⊕M → A	●	●	↕	↕	R	●
	EORB	C8	2	2	D8	3	2	E8	5	2	F8	4	3				B⊕M → B	●	●	↕	↕	R	●
Increment	INC							6C	7	2	7C	6	3				M + 1 → M	●	●	↕	↕	5	●
	INCA													4C	2	1	A + 1 → A	●	●	↕	↕	5	●
	INCB													5C	2	1	B + 1 → B	●	●	↕	↕	5	●
Load Acmltr	LDAA	86	2	2	96	3	2	A6	5	2	B6	4	3				M → A	●	●	↕	↕	R	●
	LDAB	C6	2	2	D6	3	2	E6	5	2	F6	4	3				M → B	●	●	↕	↕	R	●
Or, Inclusive	ORAA	8A	2	2	9A	3	2	AA	5	2	BA	4	3				A + M → A	●	●	↕	↕	R	●
	ORAB	CA	2	2	DA	3	2	EA	5	2	FA	4	3				B + M → B	●	●	↕	↕	R	●
Push Data	PSHA													36	4	1	A → M_{SP}, SP − 1 → SP	●	●	●	●	●	●
	PSHB													37	4	1	B → M_{SP}, SP − 1 → SP	●	●	●	●	●	●
Pull Data	PULA													32	4	1	SP + 1 → SP, M_{SP} → A	●	●	●	●	●	●
	PULB													33	4	1	SP + 1 → SP, M_{SP} → B	●	●	●	●	●	●
Rotate Left	ROL							69	7	2	79	6	3				M	●	●	↕	↕	6	↕
	ROLA													49	2	1	A	●	●	↕	↕	6	↕
	ROLB													59	2	1	B C b7 ← b0	●	●	↕	↕	6	↕
Rotate Right	ROR							66	7	2	76	6	3				M	●	●	↕	↕	6	↕
	RORA													46	2	1	A	●	●	↕	↕	6	↕
	RORB													56	2	1	B C b7 → b0	●	●	↕	↕	6	↕
Shift Left, Arithmetic	ASL							68	7	2	78	6	3				M	●	●	↕	↕	6	↕
	ASLA													48	2	1	A ← 0	●	●	↕	↕	6	↕
	ASLB													58	2	1	B C b7 b0	●	●	↕	↕	6	↕
Shift Right, Arithmetic	ASR							67	7	2	77	6	3				M	●	●	↕	↕	6	↕
	ASRA													47	2	1	A	●	●	↕	↕	6	↕
	ASRB													57	2	1	B b7 b0 C	●	●	↕	↕	6	↕
Shift Right, Logic	LSR							64	7	2	74	6	3				M	●	●	R	↕	6	↕
	LSRA													44	2	1	A 0 →	●	●	R	↕	6	↕
	LSRB													54	2	1	B b7 b0 C	●	●	R	↕	6	↕
Store Acmltr.	STAA				97	4	2	A7	6	2	B7	5	3				A → M	●	●	↕	↕	R	●
	STAB				D7	4	2	E7	6	2	F7	5	3				B → M	●	●	↕	↕	R	●
Subtract	SUBA	80	2	2	90	3	2	A0	5	2	B0	4	3				A − M → A	●	●	↕	↕	↕	↕
	SUBB	C0	2	2	D0	3	2	E0	5	2	F0	4	3				B − M → B	●	●	↕	↕	↕	↕
Subtract Acmltrs.	SBA													10	2	1	A − B → A	●	●	↕	↕	↕	↕
Subtr. with Carry	SBCA	82	2	2	92	3	2	A2	5	2	B2	4	3				A − M − C → A	●	●	↕	↕	↕	↕
	SBCB	C2	2	2	D2	3	2	E2	5	2	F2	4	3				B − M − C → B	●	●	↕	↕	↕	↕
Transfer Acmltrs	TAB													16	2	1	A → B	●	●	↕	↕	R	●
	TBA													17	2	1	B → A	●	●	↕	↕	R	●
Test, Zero or Minus	TST							6D	7	2	7D	6	3				M − 00	●	●	↕	↕	R	R
	TSTA													4D	2	1	A − 00	●	●	↕	↕	R	R
	TSTB													5D	2	1	B − 00	●	●	↕	↕	R	R
																		H	I	N	Z	V	C

LEGEND:

- OP Operation Code (Hexadecimal);
- ~ Number of MPU Cycles;
- # Number of Program Bytes;
- \+ Arithmetic Plus;
- − Arithmetic Minus;
- • Boolean AND;
- M_{SP} Contents of memory location pointed to be Stack Pointer;
- \+ Boolean Inclusive OR;
- ⊕ Boolean Exclusive OR;
- $\overline{M}$ Complement of M;
- → Transfer Into;
- 0 Bit = Zero;
- 00 Byte = Zero;

Note – Accumulator addressing mode instructions are included in the column for IMPLIED addressing

CONDITION CODE SYMBOLS:

- H Half-carry from bit 3;
- I Interrupt mask
- N Negative (sign bit)
- Z Zero (byte)
- V Overflow, 2's complement
- C Carry from bit 7
- R Reset Always
- S Set Always
- ↕ Test and set if true, cleared otherwise
- ● Not Affected

Table A-II. Index Register and Stack Manipulation Instructions (MC6800)

POINTER OPERATIONS	MNEMONIC	IMMED OP	IMMED ~	IMMED #	DIRECT OP	DIRECT ~	DIRECT #	INDEX OP	INDEX ~	INDEX #	EXTND OP	EXTND ~	EXTND #	IMPLIED OP	IMPLIED ~	IMPLIED #	BOOLEAN/ARITHMETIC OPERATION	COND. CODE REG. 5 H	4 I	3 N	2 Z	1 V	0 C
Compare Index Reg	CPX	8C	3	3	9C	4	2	AC	6	2	BC	5	3				$X_H - M, X_L - (M+1)$	•	•	1	↕	2	•
Decrement Index Reg	DEX													09	4	1	$X - 1 \rightarrow X$	•	•	•	↕	•	•
Decrement Stack Pntr	DES													34	4	1	$SP - 1 \rightarrow SP$	•	•	•	•	•	•
Increment Index Reg	INX													08	4	1	$X + 1 \rightarrow X$	•	•	•	↕	•	•
Increment Stack Pntr	INS													31	4	1	$SP + 1 \rightarrow SP$	•	•	•	•	•	•
Load Index Reg	LDX	CE	3	3	DE	4	2	EE	6	2	FE	5	3				$M \rightarrow X_H, (M+1) \rightarrow X_L$	•	•	3	↕	R	•
Load Stack Pntr	LDS	8E	3	3	9E	4	2	AE	6	2	BE	5	3				$M \rightarrow SP_H, (M+1) \rightarrow SP_L$	•	•	3	↕	R	•
Store Index Reg	STX				DF	5	2	EF	7	2	FF	6	3				$X_H \rightarrow M, X_L \rightarrow (M+1)$	•	•	3	↕	R	•
Store Stack Pntr	STS				9F	5	2	AF	7	2	BF	6	3				$SP_H \rightarrow M, SP_L \rightarrow (M+1)$	•	•	3	↕	R	•
Indx Reg → Stack Pntr	TXS													35	4	1	$X - 1 \rightarrow SP$	•	•	•	•	•	•
Stack Pntr → Indx Reg	TSX													30	4	1	$SP + 1 \rightarrow X$	•	•	•	•	•	•

Table A-III. Jump and Branch Instructions (MC6800)

OPERATIONS	MNEMONIC	RELATIVE OP	RELATIVE ~	RELATIVE #	INDEX OP	INDEX ~	INDEX #	EXTND OP	EXTND ~	EXTND #	IMPLIED OP	IMPLIED ~	IMPLIED #	BRANCH TEST	COND. CODE REG. 5 H	4 I	3 N	2 Z	1 V	0 C
Branch Always	BRA	20	4	2										None	•	•	•	•	•	•
Branch If Carry Clear	BCC	24	4	2										$C = 0$	•	•	•	•	•	•
Branch If Carry Set	BCS	25	4	2										$C = 1$	•	•	•	•	•	•
Branch If = Zero	BEQ	27	4	2										$Z = 1$	•	•	•	•	•	•
Branch If ≥ Zero	BGE	2C	4	2										$N \oplus V = 0$	•	•	•	•	•	•
Branch If > Zero	BGT	2E	4	2										$Z + (N \oplus V) = 0$	•	•	•	•	•	•
Branch If Higher	BHI	22	4	2										$C + Z = 0$	•	•	•	•	•	•
Branch If ≤ Zero	BLE	2F	4	2										$Z + (N \oplus V) = 1$	•	•	•	•	•	•
Branch If Lower Or Same	BLS	23	4	2										$C + Z = 1$	•	•	•	•	•	•
Branch If < Zero	BLT	2D	4	2										$N \oplus V = 1$	•	•	•	•	•	•
Branch If Minus	BMI	2B	4	2										$N = 1$	•	•	•	•	•	•
Branch If Not Equal Zero	BNE	26	4	2										$Z = 0$	•	•	•	•	•	•
Branch If Overflow Clear	BVC	28	4	2										$V = 0$	•	•	•	•	•	•
Branch If Overflow Set	BVS	29	4	2										$V = 1$	•	•	•	•	•	•
Branch If Plus	BPL	2A	4	2										$N = 0$	•	•	•	•	•	•
Branch To Subroutine	BSR	8D	B	2										See Special Operations	•	•	•	•	•	•
Jump	JMP				6E	4	2	7E	3	3					•	•	•	•	•	•
Jump To Subroutine	JSR				AD	8	2	BD	9	3					•	•	•	•	•	•
No Operation	NOP										01	2	1	Advances Prog. Cntr. Only	•	•	•	•	•	•
Return From Interrupt	RTI										3B	10	1				1			
Return From Subroutine	RTS										39	5	1	See Special Operations	•	•	•	•	•	•
Software Interrupt	SWI										3F	12	1		•	•	•	•	•	•
Wait for Interrupt*	WAI										3E	9	1		•	2	•	•	•	•

*WAI puts Address Bus, R/W, and Data Bus in the three state mode while VMA is held low.

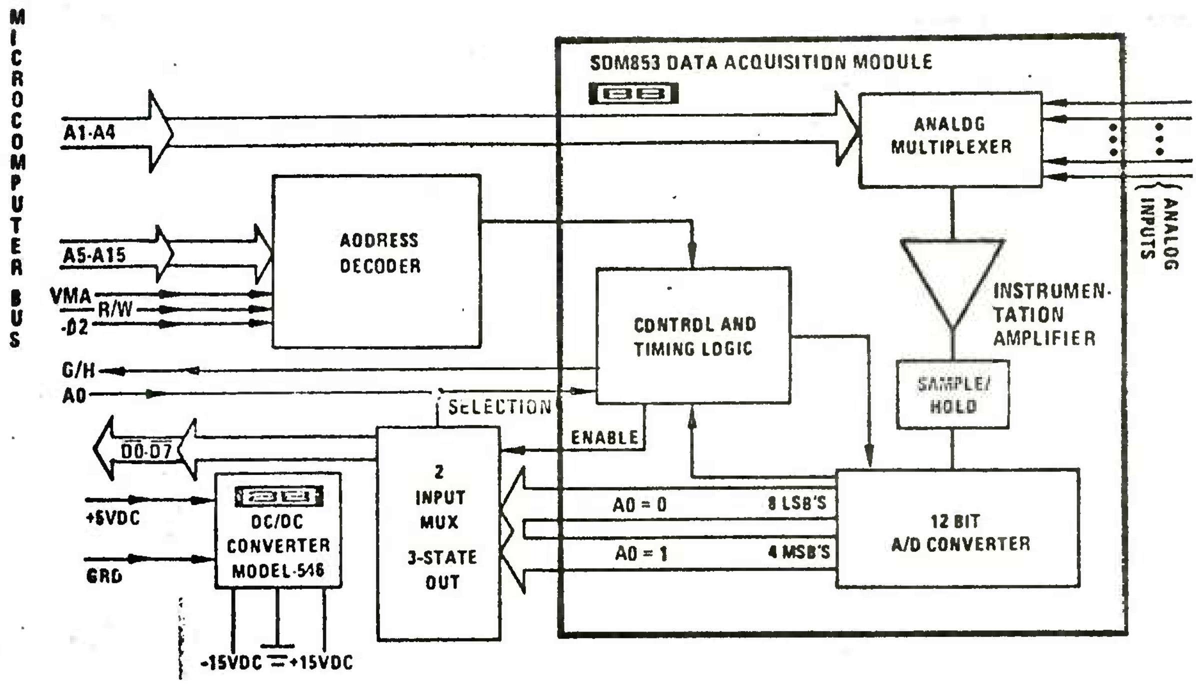


Figure A-4. Analog to Digital Converter - MP7208/7216

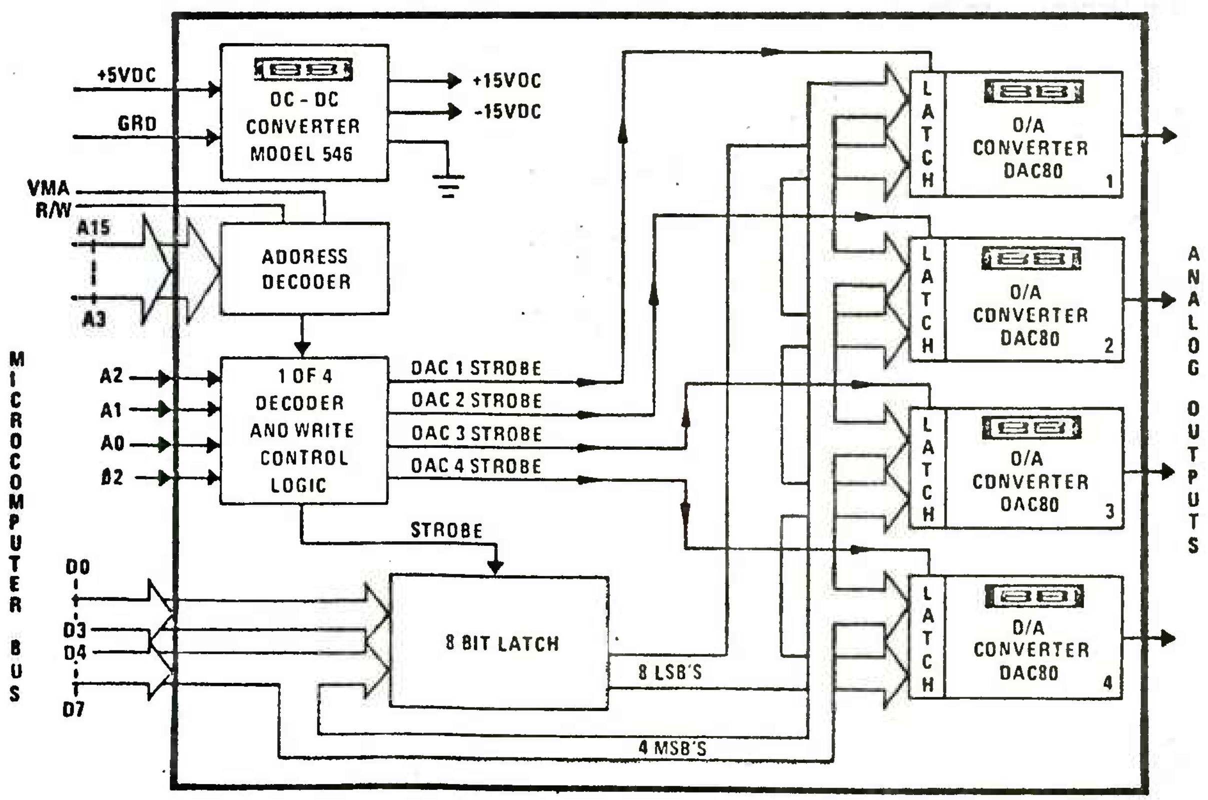


Figure A-5. Digital to Analog Converter - MP7104

Table A-IV. Converter Characteristics

<u>ANALOG TO DIGITAL</u>

NUMBER OF CHANNELS	8
INPUT VOLTAGE	$\pm$ 10 MV TO $\pm$ 10 V
INPUT IMPEDANCE	100 MEGOHMS
RESOLUTION	12 Bits BINARY
CONVERSION TIME ($\pm$ 10 V)	33 MICROSECONDS

<u>DIGITAL TO ANALOG</u>

NUMBER OF CHANNELS	4
OUTPUT VOLTAGE, VDC	$\pm$2.5, $\pm$5, $\pm$10, 0 TO 5, 0 TO 10
OUTPUT IMPEDANCE	1 OHM
RESOLUTION	12 Bits BINARY

Table A-V. Program Listing

PROGRAM LISTING - DFBL

SUBROUTINE - TEMP STORAGE

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
00 50		XX XX		CMD1
00 52		XX XX		POS1
00 54		XX XX		CMD2
00 56		XX XX		POS2
00 58		XX XX		ERROR
00 5A		XX --		CARRY
00 5C				
00 5E		XX --		MONITOR CONTROL
00 60		XX --		CMD CTR
00 62		XX --		POS CTR
00 64		XX XX		ERROR CTR
00 66		XX YY		XX, PLUS ON TIME; YY, MINUS ON TIME

INSTRUCTION			EXECUTION TIME	COMMENTS	
LOCATION	OP. CODE	OPERANDS			
CC 6A	CE	04 00		LDX	+5VDC
CC 6D	FF	EF 06		STX	TURN ON DAC-4
CC 70	OF	-- --		SEI	SET INTERRUPT MASK
CC 71	86	1F --		LDA	10
CC 73	97	60 --		STA	CMD CTR
CC 75	97	62 --		STA	POS CTR
CC 77	CE	04 00		LDX	1 SEC
CC 7A	DF	64 --		STA	ERROR CTR
CC 7C	20	02 --		BRA	TO PROG START

PROGRAM LISTING - DFBL SUBROUTINE - INPUT 1

INSTRUCTION			EXECUTION TIME	COMMENTS	
LOCATION	OP. CODE	OPERANDS			
CC 80	CE	07 FF	3/ 3	LDX	+10VDC
CC 83	FF	EF 00	6/ 9	STX	DAC-1
CC 86	FF	EF 02	6/ 15	STX	DAC-2
CC 89	B6	EC 00	4/ 19	LDA-A	START A-D CH. 0 CMD
CC 8C	01	-- --	*2/ 54	NOP	WAIT FOR CONVERSION
CC 8D	FE	EC 00	5/ 59	LDX	CMD IN "X"
CC 90	DF	50 --	5/ 64	STX	
CC 92	B6	EC 04	4/ 68	LDA-A	START A-D CH. 2 POS.
CC 95	01	-- --	*2/ 105	NOP	WAIT FOR CONVERSION
CC 96	FE	EC 04	5/ 110	LDX	POS IN "X"
CC 99	DF	52 --	5/ 115	STX	

* 33 μ sec for A/D Conversion

SUBROUTINE - CMD1 LIMITS

INSTRUCTION			EXECUTION TIME	COMMENTS	
LOCATION	OP. CODE	OPERANDS			
CC 9B	96	50 --	3/ 118	LDA-A	CMD-1
CC 9D	2B	0B --	4/ 122	BMI	TO AA
CC 9F	81	04 --	2/ 124	CMP	
CC A1	2B	13 --	4/ 128	BMI	TO B6
CC A3	CE	04 00	3/ 131	LDX	+5V
CC A6	DF	50 --	5/ 136	STX	CMD1
CC A8	20	12 --	4/ 140	BRA	TO BC
CC AA	40	-- --	2/ 124	NEG	
CC AB	81	05 --	2/ 126	CMP	
CC AD	2B	07 --	4/ 130	BMI	TO B6
CC AF	CE	FC 00	3/ 133	LDX	-5V
CC B2	DF	50 --	5/ 138	STX	CMD1
CC B4	20	06 --	4/ 142	BRA	TO BC
CC B6	73	00 00	6/ 134	COM	
CC B9	73	00 00	6/ 140	COM	
CC BC	73	00 00	6/ 148	COM	
CC BF	20	3F --	4/ 152	BRA	

PROGRAM LISTING - DFBL   SUBROUTINE - ERROR

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 00	96	53 --	3/ 3	LDA-A POSITION (L.S. BYTE)
CD 02	43	-- --	2/ 5	COM-A
CD 03	9B	51 --	3/ 8	ADD LS = CMD - POS
CD 05	24	04 --	4/ 12	BCC
CD 07	C6	01	2/ 14	LDA-B 01
CD 09	20	03 --	4/ 18	BRA
CD 0B	01	-- --	2/ 14	NOP
CD 0C	01	-- --	2/ 16	NOP
CD 0D	5F	-- --	2/ 18	CLR-B
CD 0E	D7	5A --	4/ 22	STA-B SAVE CARRY
CD 10	D6	52 --	3/ 25	LDA-B POSITION (M.S. BYTE)
CD 12	53	-- --	2/ 27	COM-B
CD 13	DB	50 --	3/ 30	ADD-B
CD 15	DB	5A --	3/ 33	ADD-B = CMD - POS
CD 17	57	-- --	2/ 35	ASR-B
CD 18	46	-- --	2/ 37	ROR-A
CD 19	57	-- --	2/ 39	ASR-B
CD 1A	46	-- --	2/ 41	ROR-A
CD 1B	D7	58 --	4/ 45	STA-B ERROR (HI)
CD 1D	97	59 --	4/ 49	STA-A ERROR (LO)
CD 1F	01	-- --	2/ 51	NOP

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 20	D6	59 --	3/ 48	LDA-B ERROR, LO
CD 22	96	58 --	3/ 51	LDA-A ERROR, HI
CD 24	01	-- --	2/ 53	NOP
CD 25	01	-- --	2/ 55	NOP
CD 26	4D	-- --	2/ 57	TST-A
CD 27	2B	21 --	4/ 61	BMI TO NEG ERROR

PROGRAM LISTING - DFBL SUBROUTINE - POSITIVE ERROR

INSTRUCTION			EXECUTION TIME	COMMENTS	
LOCATION	OP. CODE	OPERANDS			
CD 29	84	07 --	2/ 63	AND-A	
CD 2B	26	0F --	4/ 67	BNE	TO SET MAX MODULATION TIME
CD 2D	C4	80 --	2/ 69	AND-B	
CD 2F	26	0E --	4/ 73	BNE	TO SET MAX MOD. TIME
CD 31	D6	59 --	3/ 76	LDA-B	ERROR, LO
CD 33	D7	66 --	4/ 80	STA-B	TIME FOR POS. MOD.
CD 35	86	7F --	2/ 82	LDA-A	7F
CD 37	10	-- --	2/ 84	SBA	
CD 38	97	67 --	4/ 88	STA-A	TIME FOR NEG. MOD.
CD 3A	20	34 --	4/ 92	BRA	TO POS. OUTPUT
CD 3C	01	01 01	6/ 73	NOP	
CD 3F	86	7F --	2/ 75	LDA-A	7F
CD 41	97	66 --	4/ 79	STA-A	TIME FOR POS. MOD.
CD 43	C6	00 --	2/ 81	LDA-B	00
CD 45	D7	67 --	4/ 85	STA-B	TIME FOR NEG. MOD.
CD 47	01	-- --	2/ 87	NOP	
CD 48	20	26 --	4/ 91	BRA	TO POS. OUTPUT

PROGRAM LISTING - DFBL SUBROUTINE - NEGATIVE ERROR

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 4A	43	-- --	2/ 63	COM-A
CD 4B	84	07 --	2/ 65	AND
CD 4D	26	11 --	4/ 69	BNE TO SET MAX NEG. MOD. TIME
CD 4F	53	-- --	2/ 71	COM-B
CD 50	C4	80 --	2/ 73	AND
CD 52	26	10 --	4/ 77	BNE TO SET MAX NEG. MOD. TIME
CD 54	D6	59 --	3/ 80	LDA-B ERROR, LO
CD 56	53	-- --	2/ 82	COM-B
CD 57	D7	67 --	4/ 86	STA-B TIME FOR NEG. MOD. TIME
CD 59	86	7F --	2/ 88	LDA-A 7F
CD 5B	10	-- --	2/ 90	SBA
CD 5C	97	66 --	4/ 94	STA-A TIME FOR POS. MOD. TIME
CD 5E	20	30 --	4/ 98	BRA TO NEG. OUTPUT
CD 60	01	01 --	4/ 73	NOP
CD 62	01	01 --	4/ 77	NOP
CD 64	86	7F --	2/ 79	LDA-A 7F
CD 66	97	67 --	4/ 83	STA-A TIME FOR NEG. MOD.
CD 68	C6	00 --	2/ 85	LDA-B 00
CD 6A	D7	66 --	4/ 89	STA-B TIME FOR POS. MOD.
CD 6C	01	01 --	4/ 93	NOP
CD 6E	20	20 --	4/ 97	BRA TO NEG. OUTPUT

PROGRAM LISTING - DFBL

SUBROUTINE - PLUS OUTPUT

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 70	86	7F --	2/ 2	LDA-A
CD 72	4A	-- --	2/ 4	DEC-A
CD 73	2A	FD --	4/ 774	BPL
CD 75	96	66 --	2/ 776	LDA-A PLUS ON TIME
CD 77	4A	-- --	2/	DEC-A
CD 78	2A	FD --	4/ 782*	BPL
CD 7A	CE	F8 00	3/ 785	LDX -10V
CD 7D	FF	EF 00	6/ 791	STX DAC-1
CD 80	FF	EF 02	6/ 797	STX DAC-2
CD 83	96	67 --	2/ 799	LDA-A MINUS ON TIME
CD 85	4A	-- --	2/	DEC-A
CD 86	2A	FD --	4/1567*	BPL
CD 88	20	26 --	4/1571	BRA TO MONITOR

*TIME WITH ZERO ERROR

PROGRAM LISTING - DFBL SUBROUTINE - MINUS OUTPUT

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CD 90	96	66 --	2/ 2	LDA-A TIME FOR PLUS OUTPUT
CD 92	D6	67 --	2/ 4	LDA-B TIME FOR MINUS OUTPUT
CD 94	4A	-- --	2/	DEC-A
CD 95	2A	FD --	4/ 774*	BPL
CD 97	CE	F8 00	3/ 777	LDX -10V
CD 9A	FF	EF 00	6/ 783	STX DAC-1
CD 9D	FF	EF 02	6/ 789	STX DAC-2
CD A0	5A	-- --	2/	DEC-B
CD A1	2A	FD --	4/ 795*	BPL
CD A3	86	7F --	2/ 797	LDA-A
CD A5	4A	-- --	2/	DEC-A
CD A6	2A	FD --	4/1566*	BPL
CD A8	20	06 --	4/1570	BRA TO MONITOR
				*TIME WITH ZERO ERROR

PROGRAM LISTING - DFBL

SUBROUTINE - INPUT 2

INSTRUCTION LOCATION	OP. CODE	OPERANDS	EXECUTION TIME	COMMENTS
CD B0	B6	EC 02	4/ 4	LDA-A START A-D CH. 1 CMD-2
CD B3	01	-- --	*2/ 37	NOP
CD B4	FE	EC 02	5/ 42	LDX CMD-2
CD B7	DF	54 --	5/ 47	STX
CD B9	B6	EC 06	4/ 51	LDA-A START A-D CH. 3 POS-2
CD BC	01	-- --	*2/ 86	NOP
CD BD	FE	EC 06	5/ 91	LDX POS-2
CD C0	DF	56 --	5/ 96	STX
CD C2	96	54 --	3/ 99	LDA-A CMD-2
CD C4	2B	0B --	4/ 103	BMI TO TEST NEG. LIMITS
CD C6	81	04 --	2/ 105	CMP TEST POS. LIMITS
CD C8	2B	13 --	4/ 109	BMI
CD CA	CE	04 00	3/ 112	LDX +5V
CD CD	DF	54 --	4/ 117	STX CMD-2
CD CF	20	12 --	4/ 121	BRA TO EXIT
CD D1	40	-- --	2/ 105	NEG TEST NEG. LIMITS
CD D2	81	05 --	2/ 107	CMP
CD D4	2B	07 --	4/ 111	BMI
CD D6	CE	FC 00	3/ 114	LDX -5V
CD D9	DF	54 --	5/ 119	STX CMD-2
CD DB	20	06 --	4/ 123	BRA
CD DD	73	00 00	6/ 117	COM
CD E0	73	00 00	6/ 123	COM
CD E3	73	00 00	6/ 129	COM
CD E6	96	5E --	3/ 132	LDA-A MONITOR CONTROL
CD E8	2A	16 --	4/ 136	BPL TO CMD MONITOR
CD EA	20	54 --	4/ 140	BRA TO POS. MONITOR

SUBROUTINE - CMD MONITOR

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CE 00	96	51 --	3/ 3	LDA-A CMD1 (LO)
CE 02	43	-- --	2/ 5	COM-A
CE 03	9B	55 --	3/ 8	ADD CMD2 (LO)
CE 05	24	04 --	4/ 12	BCC
CE 07	C6	01 --	2/ 14	LDA-B 01
CE 09	20	03 --	4/ 18	BRA
CE 0B	01	01 --	4/ 16	NOP
CE 0D	5F	-- --	2/ 18	CLR-B
CE 0E	D7	5A --	4/ 22	STA-B SAVE CARRY
CE 10	D6	50 --	3/ 25	LDA-B CMD1 (HI)
CE 12	53	-- --	2/ 27	COM-B
CE 13	DB	54 --	3/ 30	ADD-B CMD2 (HI)
CE 15	DB	5A --	3/ 33	ADD-B CARRY
CE 17	2A	01 --	4/ 37	BPL
CE 19	53	-- --	2/ 39	COM-B
CE 1A	C4	07 --	2/ 41	AND-B
CE 1C	26	06 --	4/ 45	BNE TO DEC CMD CTR
CE 1E	86	1F --	2/ 47	LDA-A
CE 20	97	60 --	4/ 51	STA-A RESET CMD CTR
CE 22	20	07 --	4/ 55	BRA TO ERROR MONITOR
CE 24	7A	00 60	6/ 51	DEC CMD CTR
CE 27	2A	02 --	4/ 55	BPL TO ERROR MONITOR
CE 29	20	76 --	4/	BRA TO TURN OFF RELAY
CE 2B	86	80 --	2/ 57	LDA-A -1
CE 2D	97	5E --	4/ 61	STA-A MONITOR CONTROL
CE 2F	20	4F --	4/ 65	BRA TO ERROR MONITOR

PROGRAM LISTING - DFBL

SUBROUTINE - POS MONITOR

INSTRUCTION			EXECUTION TIME	COMMENTS
LOCATION	OP. CODE	OPERANDS		
CE 40	96	53 --	3/ 3	LDA-A POS1 (LO)
CE 42	43	-- --	2/ 5	COM-A
CE 43	9B	57 --	3/ 8	ADD POS2 (LO)
CE 45	24	04 --	4/ 12	BCC
CE 47	C6	01 --	2/ 14	LDA-B 01
CE 49	20	03 --	4/ 18	BRA
CE 4B	01	01 --	4/ 16	NOP
CE 4D	5F	-- --	2/ 18	CLR-B
CE 4E	D7	5A --	4/ 22	STA-B SAVE CARRY
CE 50	D6	52 --	3/ 25	LDA-B POS1 (HI)
CE 52	53	-- --	2/ 27	COM-B
CE 53	DB	56 --	3/ 30	ADD-B POS2 (HI)
CE 55	DB	5A --	3/ 33	ADD-B CARRY
CE 57	2A	01 --	4/ 37	BPL
CE 59	53	-- --	2/ 39	COM-B.
CE 5A	C4	07	2/ 41	AND-B
CE 5C	26	06 --	4/ 45	BNE TO DEC POS CTR
CE 5E	86	1F --	2/ 47	LDA-A
CE 60	97	62 --	4/ 51	STA-A RESET POS CTR
CE 62	20	07 --	4/ 55	BRA TO ERROR MONITOR
CE 64	7A	00 62	6/ 51	DEC POS CTR
CE 67	2A	02 --	4/ 55	BPL TO ERROR MONITOR
CE 69	20	36 --	4/	BRA TO TURN OFF RELAY
CE 6B	86	08 --	2/ 57	LDA-A +08
CE 6D	97	5E --	4/ 61	STA-A MONITOR CONTROL
CE 6F	20	0F --	4/ 65	BRA TO ERROR MONITOR

PROGRAM LISTING - DFBL   SUBROUTINE - MONITOR ERROR

INSTRUCTION			EXECUTION TIME	COMMENTS	
LOCATION	OP. CODE	OPERANDS			
CE 80	96	58 --	3/ 3	LDA-A	ERROR (HI)
CE 82	2A	04 --	4/ 7	BPL	
CE 84	96	67 --	3/ 10	LDA-A	TIME FOR MINUS ON
CE 86	20	04 --	4/ 14	BRA	TO AND
CE 88	96	66 --	3/ 10	LDA-A	TIME FOR PLUS ON
CE 8A	01	01 --	4/ 14	NOP	
CE 8C	84	40 --	2/ 16	AND	
CE 8E	27	09 --	4/ 20	BEQ	TO RESET COUNTER
CE 90	DE	64 --	3/ 23	LDX	ERROR COUNTER
CE 92	09	-- --	4/ 27	DEX	
CE 93	DF	64 --	4/ 32	STX	
CE 95	26	07 --	4/ 36	BNE	TO PROG START
CE 97	20	08 --	4/ 40	BRA	TO TURN OFF RELAY
CE 99	CE	04 00	3/ 43	LDX	1 SECOND
CE 9C	DF	64 --	5/ 48	STX	
CE 9E	7E	CC 80	3/ 51	JMP	TO PROG START
CE A1	CE	00 00	3/	LDX	OV
CE A4	FF	EF 06		STX	TURN OFF RELAY
CE A7	86	04 --		LDA	4
CE A9	CE	7F FF		LDX	.25 SEC
CE AC	09	-- --		DEX	
CE AD	26	FD --		BNE-3	
CE AF	4A	-- --		DEC A	
CE B0	26	F7 --		BNE-9	TO CEA9
CE B2	7E	CC 6A		JMP	TO START

P SHWP	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
0000	~~36~~	~~3F~~	~~ED~~	~~ED~~	~~37~~	~~36~~	~~FC~~	~~ED~~	~~36~~	~~26~~	~~ED~~	~~FD~~	~~26~~	~~06~~	~~FD~~	~~ED~~
0010	~~07~~	~~D7~~	~~ED~~	~~EC~~	~~36~~	~~17~~	~~ED~~	~~ED~~	~~36~~	~~56~~	~~ED~~	~~ED~~	~~26~~	~~26~~	~~ED~~	~~FD~~
0020	~~17~~	~~37~~	~~EC~~	~~EC~~	~~26~~	~~26~~	~~ED~~	~~FD~~	~~37~~	~~37~~	~~ED~~	~~FD~~	~~36~~	~~27~~	~~ED~~	~~FD~~
0030	~~27~~	~~17~~	~~EC~~	~~ED~~	~~67~~	~~36~~	~~ED~~	~~EC~~	~~36~~	~~16~~	~~ED~~	~~ED~~	~~07~~	~~26~~	~~ED~~	~~FD~~
0040	~~D9~~	~~D8~~	~~12~~	~~12~~	~~F9~~	~~D9~~	~~12~~	~~12~~	~~C9~~	~~C9~~	~~02~~	~~12~~	~~D9~~	~~D9~~	~~12~~	~~12~~
0050	~~C8~~	~~E9~~	~~12~~	~~13~~	~~C9~~	~~D9~~	~~13~~	~~12~~	~~E9~~	~~C9~~	~~02~~	~~12~~	~~CC~~	~~FD~~	~~12~~	~~12~~
0060	~~E8~~	~~F9~~	~~12~~	~~12~~	~~D9~~	~~C9~~	~~12~~	~~02~~	~~D3~~	~~C9~~	CE	04	00	FF	EF	06
0070	0F	86	1F	97	60	97	62	CE	04	00	DF	64	20	02	~~02~~	~~12~~
0080	CE	07	FF	FF	EF	00	FF	EF	02	B6	EC	00	01	FE	EC	00
0090	DF	50	B6	EC	04	01	FE	EC	04	DF	52	96	50	2B	0B	81
00A0	04	2B	13	CE	04	00	DF	50	20	12	40	81	05	2B	07	CE
00B0	FC	00	DF	50	20	06	73	00	00	73	00	00	73	00	00	20
00C0	3F	~~D9~~	~~12~~	~~12~~	~~D9~~	~~C8~~	~~12~~	~~12~~	~~D9~~	~~D8~~	~~16~~	~~12~~	~~C9~~	~~D9~~	~~12~~	~~12~~
00D0	~~C8~~	~~D0~~	~~12~~	~~12~~	~~D9~~	~~C9~~	~~12~~	~~12~~	~~C8~~	~~F9~~	~~12~~	~~12~~	~~D9~~	~~D9~~	~~12~~	~~12~~
00E0	~~C9~~	~~D9~~	~~12~~	~~12~~	~~D1~~	~~D9~~	~~02~~	~~02~~	~~D9~~	~~D8~~	~~12~~	~~12~~	~~D9~~	~~D8~~	~~12~~	~~12~~
00F0	~~D8~~	~~C9~~	~~12~~	~~12~~	~~D8~~	~~D8~~	~~12~~	~~03~~	~~D9~~	~~D9~~	~~12~~	~~12~~	~~C9~~	~~F8~~	~~12~~	~~02~~
0100	96	53	43	9B	51	24	04	C6	01	20	03	01	01	5F	D7	5A
0110	D6	52	53	DB	50	DB	5A	57	46	57	46	D7	58	97	59	01
0120	D6	59	96	58	01	01	4D	2B	21	84	07	26	0F	C4	80	26
0130	0E	D6	59	D7	66	86	7F	10	97	67	20	34	01	01	01	86
0140	7F	97	66	C6	00	D7	67	01	20	26	43	84	07	26	11	53
0150	C4	80	26	10	D6	59	53	D7	67	86	7F	10	97	66	20	30
0160	01	01	01	01	86	7F	97	67	C6	00	D7	66	01	01	20	20
0170	86	7F	4A	2A	FD	96	66	4A	2A	FD	CE	F8	00	FF	EF	00
0180	FF	EF	02	96	67	4A	2A	FD	20	26	~~FF~~	~~FD~~	~~D3~~	~~D3~~	~~FF~~	~~FF~~
0190	96	66	D6	67	4A	2A	FD	CE	F8	00	FF	EF	00	FF	EF	02
01A0	5A	2A	FD	86	7F	4A	2A	FD	20	06	~~FD~~	~~FF~~	~~33~~	~~33~~	~~FF~~	~~FF~~
01B0	B6	EC	02	01	FE	EC	02	DF	54	B6	EC	06	01	FE	EC	06
01C0	DF	56	96	54	2B	0B	81	04	2B	13	CE	04	00	DF	54	20
01D0	12	40	81	05	2B	07	CE	FC	00	DF	54	20	06	73	00	00
01E0	73	00	00	73	00	00	96	5E	2A	16	20	54	~~6C~~	~~6D~~	~~00~~	~~00~~
01F0	2C	2C	10	18	4C	2C	00	00	4C	4C	02	00	6C	2D	00	00
0200	96	51	43	9D	55	24	04	C6	01	20	03	01	01	5F	D7	5A
0210	D6	50	53	DB	54	DB	5A	2A	01	53	C4	07	26	06	86	1F
0220	97	60	20	07	7A	00	60	2A	02	20	76	86	80	97	5E	20
0230	4F	~~06~~	~~ED~~	~~ED~~	~~26~~	~~1F~~	~~ED~~	~~ED~~	~~36~~	~~26~~	~~ED~~	~~ED~~	~~06~~	~~26~~	~~ED~~	~~ED~~
0240	96	53	43	9B	57	24	04	C6	01	20	03	01	01	5F	D7	5A
0250	D6	52	53	DB	56	DB	5A	2A	01	53	C4	07	26	06	86	1F
0260	97	62	20	07	7A	00	62	2A	02	20	36	86	08	97	5E	20
0270	0F	~~F8~~	~~12~~	~~12~~	~~D9~~	~~C9~~	~~12~~	~~12~~	~~C9~~	~~D8~~	~~12~~	~~10~~	~~D9~~	~~C9~~	~~12~~	~~02~~
0280	96	58	2A	04	96	67	20	04	96	66	01	01	84	40	27	09
0290	DE	64	09	DF	64	26	07	20	08	CE	04	00	DF	64	7E	CC
02A0	80	CE	00	00	FF	EF	06	86	04	CE	7F	FF	09	26	FD	4A
02B0	26	F7	7E	CC	6A	~~36~~	~~EC~~	~~ED~~	~~26~~	~~27~~	~~ED~~	~~ED~~	~~36~~	~~06~~	~~FD~~	~~ED~~
02C0	~~D8~~	~~C9~~	~~12~~	~~92~~	~~C8~~	~~C9~~	~~12~~	~~12~~	~~D9~~	~~E9~~	~~02~~	~~02~~	~~E9~~	~~E8~~	~~10~~	~~02~~
02D0	~~C8~~	~~E9~~	~~12~~	~~12~~	~~C9~~	~~C9~~	~~12~~	~~02~~	~~E9~~	~~D8~~	~~12~~	~~12~~	~~E9~~	~~D9~~	~~12~~	~~12~~
02E0	~~C8~~	~~C8~~	~~11~~	~~12~~	~~D9~~	~~89~~	~~12~~	~~12~~	~~E9~~	~~E9~~	~~12~~	~~12~~	~~D9~~	~~D9~~	~~92~~	~~12~~
02F0	~~C9~~	~~F8~~	~~12~~	~~13~~	~~C8~~	~~C9~~	~~12~~	~~12~~	~~D9~~	~~D9~~	~~12~~	~~12~~	~~C8~~	~~F9~~	~~12~~	~~12~~
0300	~~B7~~	~~B7~~	~~FD~~	~~FD~~	~~F7~~	~~77~~	~~FD~~	~~FD~~	~~13~~	~~57~~	~~FD~~	~~FD~~	~~92~~	~~97~~	~~FF~~	~~FD~~
0310	~~77~~	~~93~~	~~ED~~	~~FF~~	~~93~~	~~F7~~	~~FF~~	~~F9~~	~~93~~	~~F3~~	~~FD~~	~~FF~~	~~93~~	~~93~~	~~FD~~	~~FF~~
0320	~~D3~~	~~D3~~	~~FF~~	~~FF~~	~~D3~~	~~D7~~	~~FD~~	~~FD~~	~~53~~	~~B3~~	~~FF~~	~~FD~~	~~D3~~	~~93~~	~~FF~~	~~FF~~
0330	~~B7~~	~~97~~	~~FF~~	~~FF~~	~~92~~	~~D3~~	~~FF~~	~~DD~~	~~33~~	~~92~~	~~FF~~	~~FD~~	~~92~~	~~63~~	~~FF~~	~~FD~~
0340	~~0C~~	~~00~~	~~02~~	~~10~~	~~2C~~	~~60~~	~~10~~	~~20~~	~~6C~~	~~2C~~	~~00~~	~~02~~	~~4C~~	~~2C~~	~~00~~	~~00~~
0350	~~2C~~	~~0C~~	~~02~~	~~02~~	~~AC~~	~~20~~	~~00~~	~~00~~	~~0C~~	~~2C~~	~~02~~	~~00~~	~~6C~~	~~2D~~	~~00~~	~~00~~
0360	~~28~~	~~20~~	~~00~~	~~02~~	~~0C~~	~~EC~~	~~04~~	~~0A~~	~~6C~~	~~4C~~	~~00~~	~~00~~	~~6D~~	~~7C~~	~~00~~	~~10~~
0370	~~6C~~	~~6C~~	~~04~~	~~08~~	~~0C~~	~~0C~~	~~10~~	~~00~~	~~ED~~	~~6C~~	~~00~~	~~00~~	~~4D~~	~~EC~~	~~10~~	~~12~~
0380	~~F3~~	~~D7~~	~~FD~~	~~FD~~	~~93~~	~~D3~~	~~FF~~	~~F3~~	~~13~~	~~92~~	~~FF~~	~~FF~~	~~B3~~	~~D3~~	~~FF~~	~~FF~~
0390	~~D3~~	~~B7~~	~~FF~~	~~FD~~	~~F3~~	~~F3~~	~~FF~~	~~FD~~	~~73~~	~~F3~~	~~FF~~	~~FF~~	~~93~~	~~93~~	~~FF~~	~~FF~~
03A0	~~F7~~	~~B3~~	~~FD~~	~~FD~~	~~F2~~	~~F3~~	~~FF~~	~~ED~~	~~67~~	~~D3~~	~~FF~~	~~F7~~	~~93~~	~~F2~~	~~FF~~	~~EF~~
03B0	~~F7~~	~~B7~~	~~FF~~	~~F9~~	~~F3~~	~~73~~	~~FF~~	~~EF~~	~~F3~~	~~93~~	~~DF~~	~~FF~~	~~53~~	~~D3~~	~~ED~~	~~FF~~
03C0	~~4C~~	~~60~~	~~12~~	~~10~~	~~48~~	~~4C~~	~~00~~	~~02~~	~~6C~~	~~6C~~	~~00~~	~~00~~	~~6C~~	~~4C~~	~~02~~	~~00~~
03D0	~~28~~	~~48~~	~~00~~	~~10~~	~~6C~~	~~6C~~	~~00~~	~~00~~	~~0D~~	~~4C~~	~~00~~	~~00~~	~~4C~~	~~4C~~	~~00~~	~~00~~
03E0	~~08~~	~~08~~	~~02~~	~~00~~	~~4C~~	~~60~~	~~06~~	~~00~~	~~2C~~	~~EC~~	~~00~~	~~00~~	~~6C~~	~~5C~~	~~00~~	~~00~~
03F0	~~03~~	~~6C~~	~~10~~	~~16~~	~~0C~~	~~0D~~	~~00~~	~~00~~	~~6C~~	~~6C~~	~~10~~	~~00~~	~~6C~~	~~6D~~	CC	6A

NOTES:

1. Data lined through is not used.
2. Starting Address is loaded in locations 03FE16 & 03FF16.
3. Addresses and data are hexidecimal notation.

Figure A-6. PROM Map

APPENDIX B

HYDRA-POWERED ALTERNATOR (HPA)

APPENDIX B

HYDRA-POWERED ALTERNATOR (HPA)

This appendix contains detailed information on the HPA used for the HOFCAS including descriptive data, dimensions, and weight. The HPA efficiency, design specification, and test specification are also discussed.

B.1 HPA DESCRIPTION

The HPA used for the HOFCAS program uses a simple, highly reliable, jet-turbine device which is capable of 26 watts of output power with .72 gpm (2.7 L/m) of fluid flow with 3000 psi (21 MPa). A 2" (5.1 cm) diameter turbine wheel coupled to a conventional P.M. electric generator is spun by fluid discharged by an .020" (.05 cm) diameter orifice. (See Figures 2-4 and 2-5). Rotating speeds of 10,000 rpm are achievable while delivering 26 watts of electric power. The selection of a six pole generator provides a frequency of 1000 Hertz. Generator characteristics determine the waveform of the output. The generator used was an Electro Kenetic P/N 4922-2. The output was sinusoidal with a resistance load attached. This tended to distort to a psuedo square wave when inductive loads were applied. The voltage with any given load was proportional to rpm. The design output was 26 volts AC when loaded with a 27Ω resistance.

The HPA, weighing 2.2 pounds, is shown dimensionally in Figures B-1, B-2 and B-3. The unit used for this project was designed and built by Parker-Bertea. An endurance test of over 1000 hours was successfully conducted prior to incorporating the HPA into the HOFCAS. During the HOFCAS laboratory tests approximately 100 hours of additional operating time were accumulated on the HPA.

B.2 HPA EFFICIENCY

The high speed turbine of the hydra-alternator utilizes the mass-momentum of the fluid for drive. While this is the simplest drive form possible, it results in low energy conversion efficiency which produces increased hydraulic flow.

The hydra-alternator for the HOFCAS program, requires a flow of 0.72 gpm at 3000 psi to generate 26 watts of electrical power. If only energy conversion efficiency is considered it can be calculated as follows:

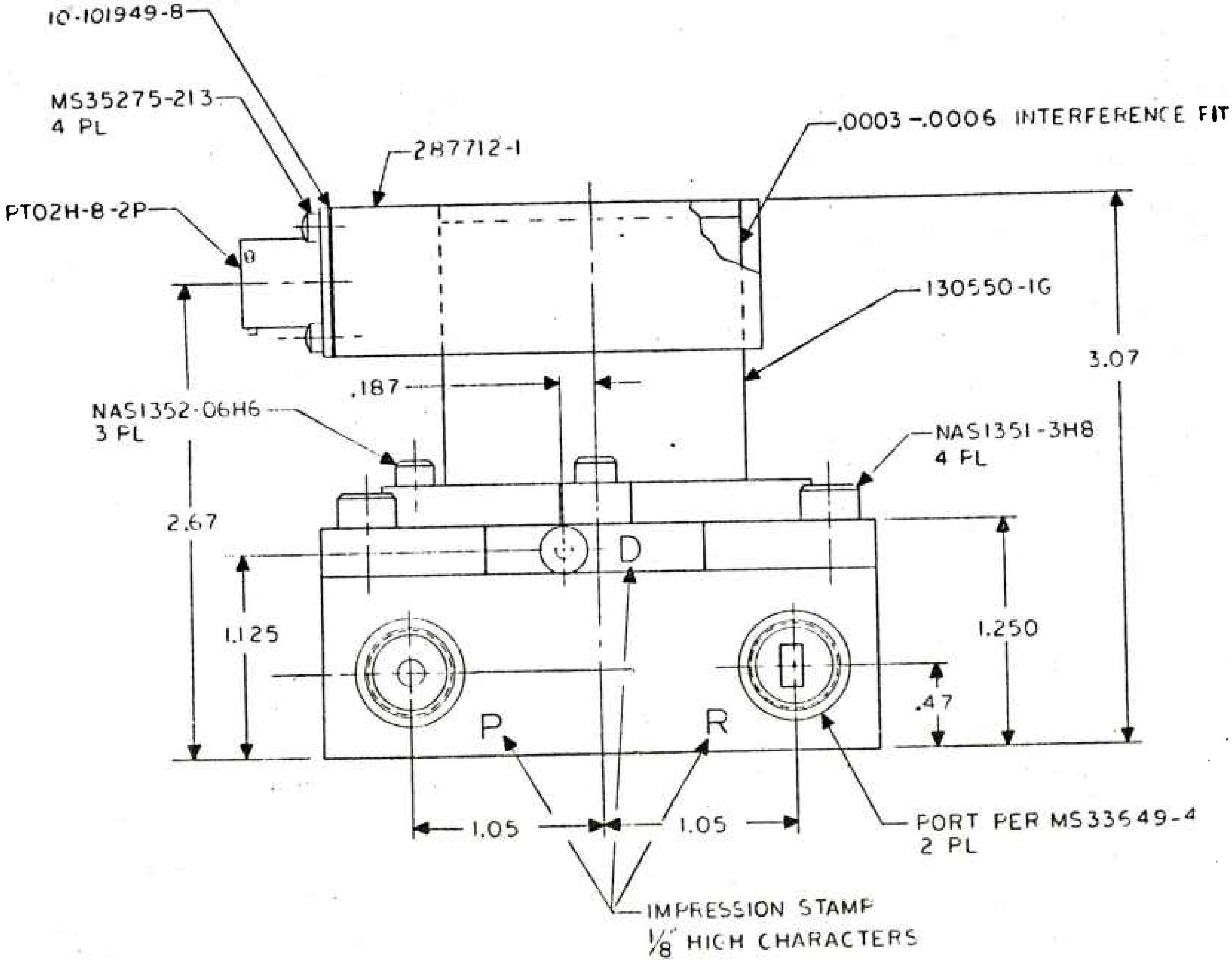


Figure B-1. HPA, Front View

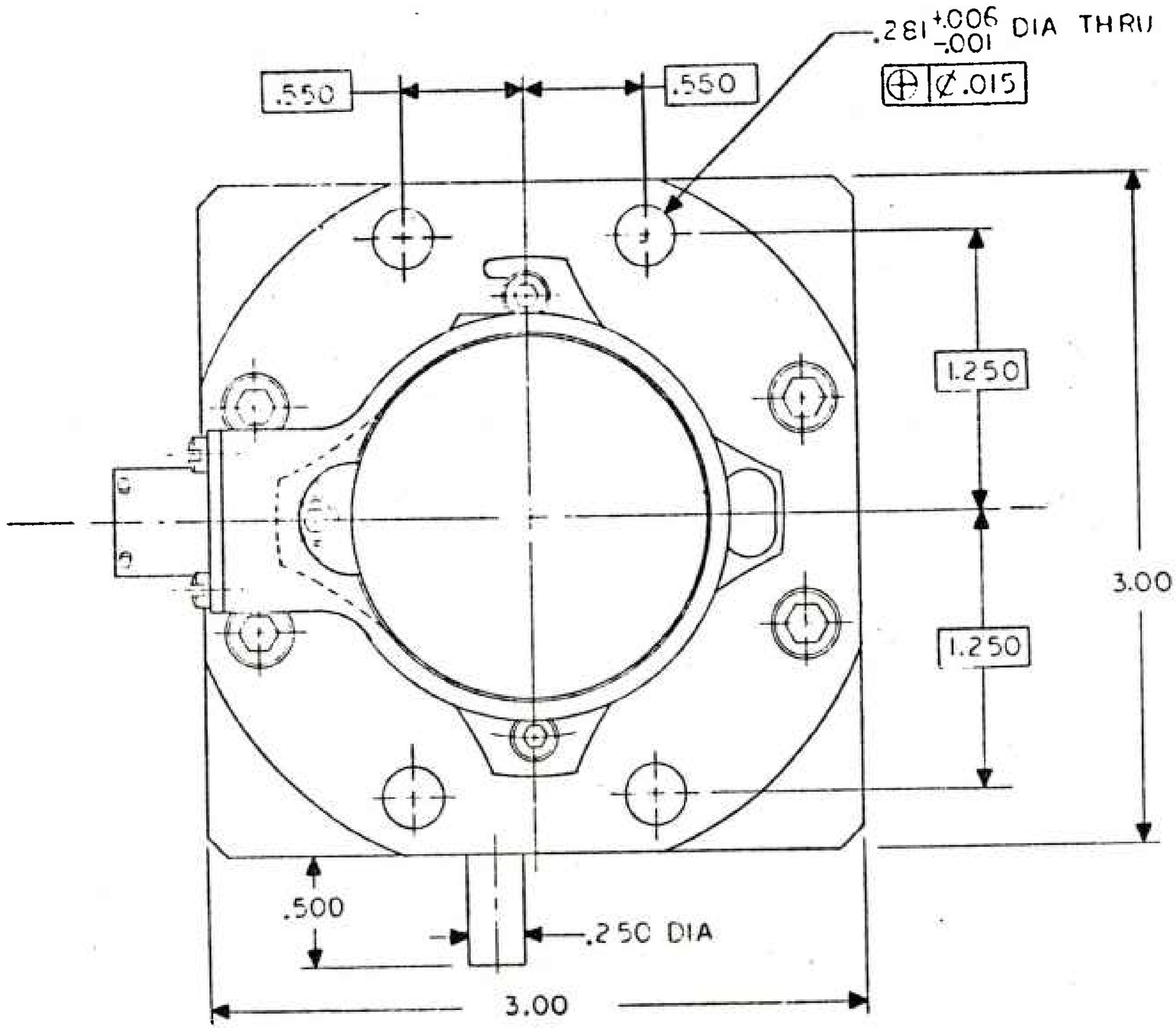


Figure B-2. HPA, Top View

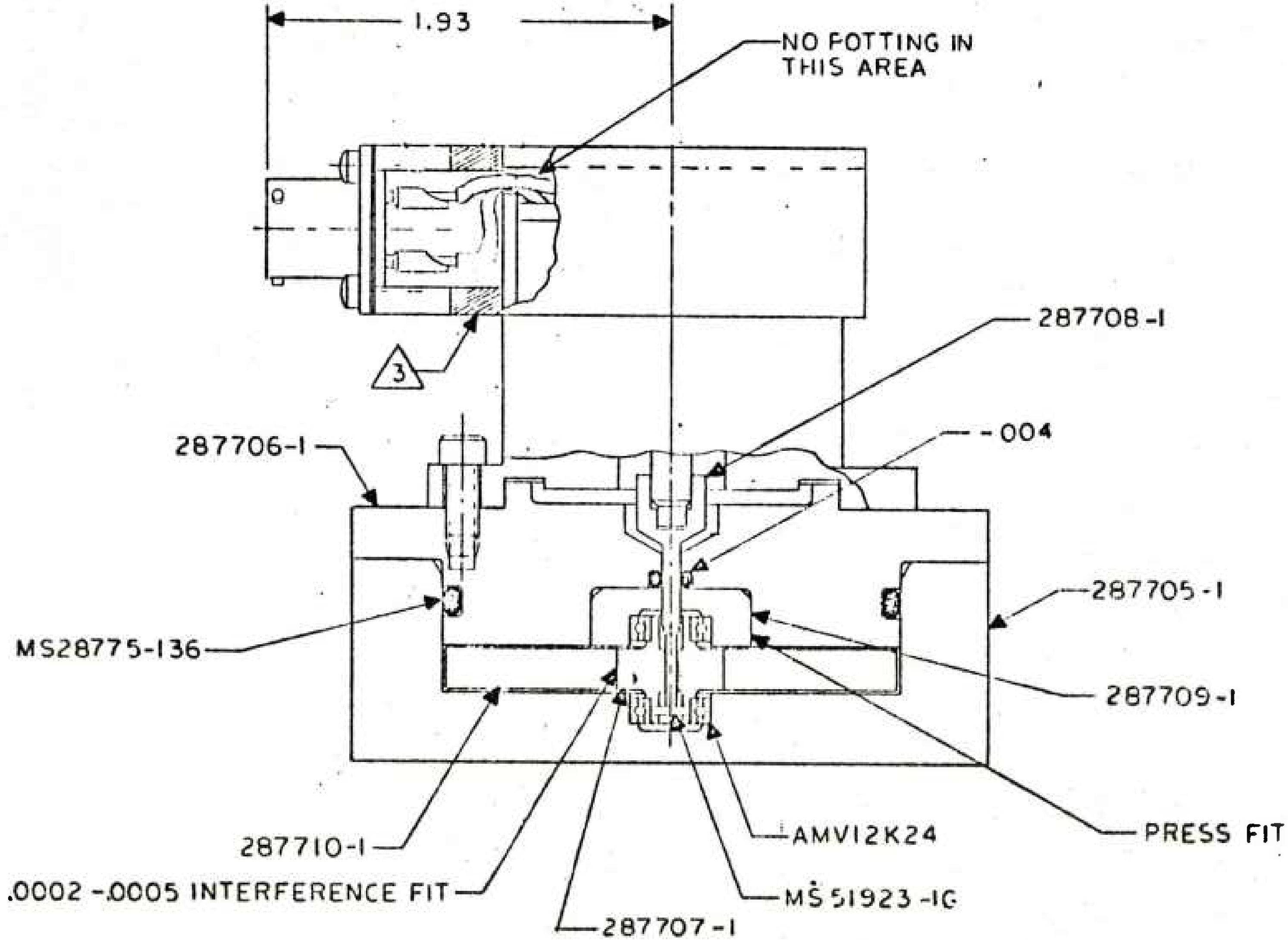


Figure B-3. HPA, Sectioned View

$$HP = \frac{GPM \times \Delta P}{1714} = \frac{0.72 \times 3000}{1714} = 1.26$$

Where HP = horsepower, GPM = gallon per minute flow, ΔP = pressure drop and 1714 is a scaling constant.

As one HP = 746 watts

$$W \text{ input} = 1.26 \times 746 = 940$$

$$\% \text{ efficiency} = \frac{W \text{ output}}{W \text{ input}} \times 100 = \frac{26}{940} \times 100 = 2.8\%$$

Turbine windage in the fluid filled cavity is a major contributor to this inefficiency. The high turbine speed of 10,000 rpm tends to emphasize the turbine losses. Other means of driving the alternator, such as a positive displacement hydraulic motor or a slower turbine speed, have been considered. All of these approaches would increase complexity and add size and weight to the HPA.

Studies by the supplier to reduce the losses of the present design show that a smaller diameter turbine wheel, 0.75 inches (1.9 cm) compared to 2 inches (5.1 cm), could double the output with the same flow. Also a generator has been tested which has smaller air gaps and will supply 20% additional power at the same rpm. Should the efficiency be doubled or tripled, it would still remain a low number. The major advantage of this design is its simplicity and relatively low cost when compared to gear trains and positive displacement hydraulic motors.

When evaluating a device of this type its impact on the aircraft must be considered. While the unit efficiency is very low, the total flow requirement is not significant. To keep this number in perspective some typical aircraft flow capabilities are:

Aircraft	GPM	L/M
F-15	224	848
F-14	168	636
A-7	80	303
A-6	56	212
F-18	112	424
F-16	85	322

Present day actuators for fly-by-wire aircraft have leakage rates of 0.5 gpm (1.9 L/m) to 1.0 gpm (3.8 L/m). Adding 10 to 20 hydra-alternators to an aircraft would not have a major impact on aircraft hydraulic system.

B.3 HPA POWER OUTPUT AND TRANSIENT RESPONSE

When the HPA was designed it was determined that the inertia of the turbine and alternator plus the hydraulic drive design would be sufficient to maintain alternator speed for transient overloads. This proved to be essentially correct. Also with the low efficiency of the hydraulic drive, the alternator output has very little effect on the turbine speed. The alternator selected by the supplier is wound to provide load protection, and any attempt to draw additional current beyond rated value results in an immediate voltage drop. Therefore the design of the alternator selected for the HPA precluded the transient power capability even though the hydraulic turbine was able to maintain speed.

To obtain full actuation system capability, the HPA must be able to supply maximum required power. Sizing the unit to the peak power requirement would result in a noticeable larger alternator. The alternator should be designed so that a short term overload capability, similar to aircraft power systems, is available. This may require an alternator to be designed specifically for this specification.

B.4 HPA SPECIFICATION

The performance specification for the HPA is contained in Table B-I. The requirements for items 2, 5, and 7 of Table B-I were not attainable with the developmental unit, and are as follows:

- Item 2, Operating Pressures

  A proof pressure of 3500 psi was used in lieu of 4500 psi as specified. The supplier expressed concern that the unit might be damaged by the requested proof pressures and therefore the unit was not evaluated at the higher pressures. This is not a major concern for a research unit but would be needed for general production applications.

- Item 5, Transients

  The output peak power requirement was not met and as discussed in Section 4, resulted in the performance limitations of the HOFCAS. The average or steady-state power requirements of the HPA were adequate to power the D^3 actuator for normal system operations. However for step inputs or high frequency response requirements the actuator electronics (EDU) can require up to 50 watts. Without this level of power the transient response performance of the actuator is reduced.

Table B-I. Performance Specification

Performance

1. Rated Inlet Pressure. The rated inlet pressure of the unit shall be 3000 psi. This pressure is defined as the maximum system pressure for which the unit is designed to operate continuously at rated temperature and rated speed.

2. Operating Pressures. The operating pressure limits and peak impulse pressure for the inlet and outlet shall be 4500 psi on the pressure port and 2250 psi on the return port.

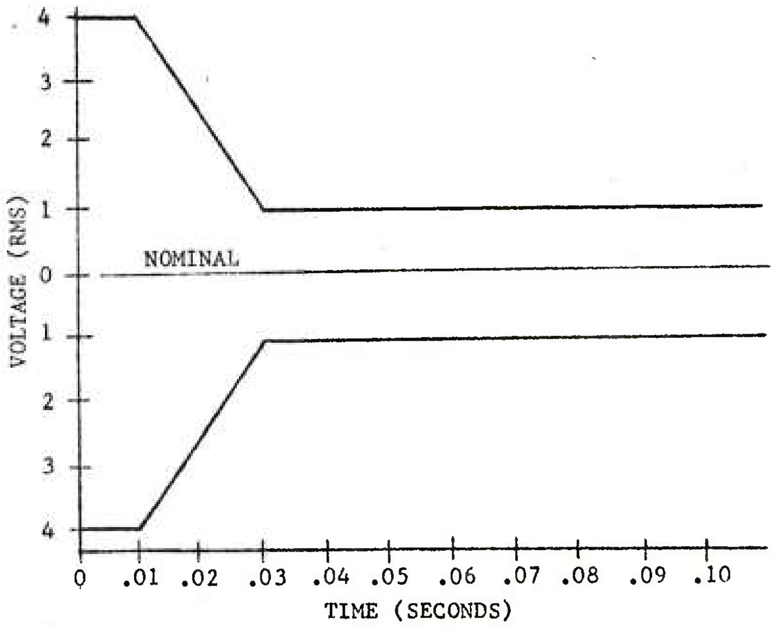
3. Ambient Conditions. The unit shall operate with ambient temperature and pressures of 0°C at 30,000 feet altitude and 50°C at sea level. The alternator shall be designed to operate with a maximum continuous fluid temperature at the inlet port of 135°C.

4. Rated Power Output. The alternator shall deliver 25 watts of average power at 26 VAC 1K Hz.

5. Transients. The transient and steady state voltage shall remain within the limits shown for all normal load conditions while the system is operating under all the environmental conditions.

6. Output Peak Power. The unit shall deliver 50 watts of peak power, 0.2 second maximum. At this peak power output, the voltage and frequency change shall be within 10% of rated power.

7. Rated Power Input. The unit shall not demand more than 0.5 gpm at 3000 psi.



Transient and Steady State Regulation @ Rated Capacity

- Item 7, Rated Power Output

  The rated power requirement was not met, and is discussed in detail in paragraph B.1 of this Appendix.

In writing a new specification for an HPA, all the performance requirements originally specified for this unit should be required and all applicable military specifications should be met. (Table B-II is a list of military specifications used for this unit.) The HPA should be sized for the specific application. The smaller turbine wheel (0.75 inches) design should be included, to improve efficiency and produce a smaller, more compact package. The unit should be modular in design so that it could be easily added to an actuator and can also be readily removed for maintenance actions.

B.5 BERTEA ACCEPTANCE TEST PROCEDURE NO. 287700T HYDRAULIC ALTERNATOR

The enclosed Bertea Acceptance Test Procedure No. 287700T, Hydraulic Alternator, was performed on the HPA by the supplier before shipment to Rockwell. The Acceptance Test Data Sheet with test results is also included.

The results of the temperature performance tests (Item 10) of this procedure demonstrate the effects of hydraulic fluid viscosity on the HPA output. If the speed (frequency) of the alternator is compared to the viscosity of the hydraulic fluid at various temperatures, the results contained in test #10 of the Acceptance Test Procedure are considered normal. The low alternator output at 0°F is not a concern for the T-2C application since the fluid temperature increases rapidly after starting the aircraft engines and hydraulic pumps. The effect of oil viscosity on the HPA power output should not be overlooked, however, since there are potential applications of the HOFCAS concept where the low temperature operation could result in significant operational problems.

Table B-II. Applicable Military Specifications

<u>Federal</u>

QQ-C-320	Chromium Plating (Electrodeposited)
QQ-P-416	Plating, Cadmium (Electrodeposited)
QQ-Z-325	Zinc Coating, Electrodeposited, Requirements for

<u>Military</u>

MIL-P-116	Preservation, Method of
MIL-D-1000	Drawings, Engineering and Associated Lists
MIL-C-5501	Caps and Plugs, Protective, Dust and Moisture Seal
MIL-H-83282	Hydraulic Fluid, Synthetic Hydrocarbon Base, Aircraft, Missile, and Ordnance
MIL-H-6083	Hydraulic Fluid, Petroleum Base, Preservation and Testing
MIL-P-6906	Plates, Information and Identification
MIL-P-7936	Parts and Equipment, Aeronautical, Preparation for Delivery
MIL-A-8625	Anodic Coatings, for Aluminum and Aluminum Alloys
MIL-C-26482	Connector, Electric Circular, Miniature, Quick Disconnect, Environment Resisting, General Specification for
MIL-H-8775	Hydraulic System Components, Aircraft and Missiles, General Specification for
MIL-F-8815	Filter and Filter Elements, Fluid Pressure, Hydraulic Line, 5 Micron Absolute Type II Systems
MIL-S-8879	Screw Threads, Controlled Radius Root with Increased Minor Diameter; General Specification for

<u>STANDARDS</u>

<u>Military</u>

MIL-STD-129	Marking for Shipment and Storage
MIL-STD-143	Specifications and Standards, Order of Precedence for the Selection of
MIL-STD-781	Reliability Tests: Exponential Distribution
MIL-STD-889	Dissimilar Metals
MS33649	Bosses, Fluid Connection - Internal Straight Thread

1. TEST THE FOLLOWING UNIT TO THIS PROCEDURE.

   A. 287700 HYDRAULIC ALTERNATOR

2. TEST EQUIPMENT

   A. ELECTRONIC COUNTER OR EQUIVALENT FREQUENCY COUNTER
   B. AC VOLTMETER
   C. ELECTRONIC PROGRAMMABLE SWITCH

3. TEST FLUID MIL-H-83282 @ 80 TO 130°F CONTAMINATION LEVEL PER BMF 5106.

4. RECORD THE TEST RESULTS ON BERTEA TEST DATA SHEETS. SEND ONE COPY OF RESULTS WITH THE UNIT.

5. UNLESS OTHERWISE NOTED, THE RETURN PART WILL REMAIN OPEN FOR ALL TESTS.

BERTEA CORPORATION IRVINE · CALIFORNIA	CODE IDENT NO. 82106	287700-T	REV A

ACCEPTANCE TEST PROCEDURE

HYDRAULIC ALTERNATOR

SIZE A | P 3

TEST	REQUIREMENTS
1. EXAMINATION OF PRODUCT	THE ASSEMBLY IS TO BE EXAMINED FOR DIMENSIONAL COMPLIANCE WITH BERTEA DRAWING 287700.
2. DIELECTRIC STRENGTH	APPLY 500 VAC BETWEEN THE CONNECTOR PINS AND THE ASSEMBLY CASE. NO ARCING OR FLASHOVER ALLOWED.
3. INSULATION RESISTANCE	APPLY 500 VDC BETWEEN THE CONNECTOR PIN AND THE CASE. INSULATION RESISTANCE TO BE 10 MEGOHMS MINIMUM.
4. ELECTRICAL RESISTANCE	MEASURE THE ELECTRICAL RESISTANCE BETWEEN PINS A & B. RECORD THE ELECTRICAL RESISTANCE AND TEMPERATURE. ELECTRICAL RESISTANCE BETWEEN PINS A & B TO BE 1 Ω ± .15 Ω @ 77°F.
5. PROOF PRESSURE	APPLY 50 PSI TO THE PRESSURE PORT WITH THE RETURN PORT OPEN. BLEED ALL AIR FROM THE UNIT. CLOSE THE RETURN LINE AND INCREASE THE SUPPLY PRESSURE TO 3500 PSI. HOLD THE PRESSURE FOR 2 MIN. NO EXTERNAL LEAKAGE OR PERMANENT SET ALLOWED.
6. BREAK-IN RUN	INSTALL A 5 MICRON FILTER IN THE PRESSURE AND RETURN LINE TO THE UNIT. THE BREAK-IN SHALL BE OF ONE HOUR DURATION. APPLY 3000 PSI AT THE PRESSURE PORT AND 50 PSI AT THE RETURN PORT. THE ELECTRICAL OUTPUT BETWEEN PIN A & B IS TO BE VARIED AS FOLLOWS: .2 SEC - 50 WATTS 1.8 SEC - 25 WATTS AT THE COMPLETION OF THE ONE HOUR TEST, THE DOWNSTREAM FILTER IS TO BE COUNTED TO DETERMINE ANY CONTAMINATION GENERATED BY THE ASSEMBLY. EXTERNAL LEAKAGE DURING THE BREAK-IN RUN IS TO BE INSUFFICIENT TO FORM A DROP.
7. RATED POWER OUTPUT	APPLY 3000 PSI TO THE SUPPLY PORT AND RESTRICT THE RETURN LINE TO INDUCE A 50 PSI RETURN PRESSURE. MEASURE THE FREQUENCY AND RMS VOLTAGE WHEN THE GENERATOR IS DELIVERING 25 WATTS OF AVERAGE POWER BETWEEN PINS A & B (25 WATTS OF POWER IS OBTAINED BY DROPPING THE ELECTRICAL OUTPUT BETWEEN PINS A & B ACROSS A 27.04 Ω RESISTOR) THE FREQUENCY WILL BE 1000 HERTZ ± 100 HERTZ AND THE VOLTAGE IS TO BE 26 ± 1 VAC RMS.

TEST	REQUIREMENTS
8. RATED POWER INPUT	WITH THE CONDITIONS OF TEST 7, MEASURE THE FLOW AT THE RETURN PORT. FLOW SHALL NOT EXCEED .5 GPM.
9. OUTPUT POWER PEAK	WITH THE CONDITIONS OF TEST 7 ESTABLISHED, MOMENTARILY (2 SEC.) INCREASE THE ELECTRICAL OUTPUT BETWEEN PINS A & B FROM 25 WATTS TO 50 WATTS. (THIS IS ACCOMPLISHED BY PARALLELING AN ADDITIONAL 27.04 Ω RESISTOR WITH THE EXISTING 27.04 Ω RESISTOR) DURING THIS TRANSIENT, RECORD OUTPUT VOLTAGE AND FREQUENCY VOLTAGE AND FREQUENCY WILL NOT VARY BY MORE THAN 10% OF THE VALUES RECORDED IN TEST 7.
10. TEMPERATURE PERFORMANCE	WITH THE CONDITIONS OF TEST 7 ESTABLISHED, DECREASE THE FLUID TEMPERATURE TO 0°F. RECORD THE VOLTAGE AND FREQUENCY BETWEEN PINS A & B. RAISE THE FLUID TEMP. TO 275°F. RECORD THE FREQUENCY AND VOLTAGE. BE SURE THE ELECTRICAL LOAD DOES NOT VARY WITH TEMPERATURE CHANGE.
11. FLUSHING	FLUSH AND FILL THE UNIT WITH MIL-H-6083 AND CAP PORTS.

BERTEA CORPORATION IRVINE · CALIFORNIA	CODE IDENT NO 82106	287700T	REV A

ACCEPTANCE TEST DATA SHEET

PART NUMBER	DASH NO	PART NAME	PROJECT	SIZE	P
287700		HYDRAULIC ALTERNATOR	T2C	A	5

PAGE OF ACCEPTANCE TEST DATA SHEETS

SPECIFICATION NO	CONTR NO	DATE TESTED	INSPECTION
HC287-5009	N62269-79-C-0709	6/5/80 [illegible]	

TEST	REQUIREMENTS	RESULTS	ACPT	REJ
1 EXAMINATION OF PRODUCT	COMPLIANCE WITH DRAWING 287700	ACCEPTABLE ✓ NOT ACCPT. ____	✓	
2 DIELECTRIC STRENGTH	NO ARCING OR FLASHOVER PIN A & B TO BODY (500 VAC)	ACCEPTABLE ✓ NOT ACCPT. ____	✓	
3 INSULA-TION RESISTANCE	500 VDC BETWEEN PIN A & B AND CASE. RESISTANCE TO BE 10 MEGOHM MINIMUM	INSULATION RESISTANCE > 10 MEG Ω	✓	
4 ELECTRICAL RESISTANCE	ELECTRICAL RESISTANCE BETWEEN PINS A & B TO BE 1 Ω ± .15 Ω AT 77°F	ELEC. RESISTANCE A-B 1 Ω@ 70 °F CORRECTED 1.057 Ω@ 77°F	✓	
5 PROOF PRESSURE	NO EXTERNAL LEAKAGE OR PERMANENT SET	3500 PSI OK		
6 BREAK-IN RUN	ONE HOUR DURATION. CONTA-MINATION & EXTERNAL LEAKAGE CHECK	CONTAMINATION No Detectable [illegible] EXTERNAL LEAKAGE NONE	✓ ✓	
7 RATED POWER OUTPUT	WHEN DELIVERING 25 WATTS OF POWER THE FREQUENCY IS TO BE 1000 ± 100 HZ AND THE VOLTAGE IS TO BE 26±1 VOLTS	FREQ. 1033 HZ VOLT. 26.4 VAC	✓ ✓	
8 RATED POWER INPUT	WHEN DELIVERING 25 WATTS OF ELECTRICAL POWER, THE RETURN FLOW SHALL NOT EXCEED .5 GPM WITH 3000 PSI AT THE SUPPLY PORT	RETURN FLOW .75 GPM	Acceptable Per [illegible] 6/5/80	
9 OUTPUT POWER PEAK	WITH A MOMENTARY (.2 SEC) INCREASE IN THE OUTPUT, FREQ. & VOLTAGE NOT TO VARY BY MORE THAN 10% OF TEST 7	FREQ. 1011 HZ VOLT. 19.2 VAC	Acceptable Per [illegible]	
10 TEMP.PERF.	RECORD VOLTAGE & FREQ. @ 0°F & 275°F FLUID TEMP.	VOLT. 3.8 FREQ. 141 0 °F VOLT. 28 FREQ. 1133 275 °F		
11 FLUSHING	FLUSH WITH MIL-H-6083. FILL AND CAP PORTS	FLUSHED YES CAPPED YES	✓ ✓	

LIST OF ABBREVIATIONS/ACRONYMS

AC	Alternating Current
ABU	Analog Back-Up
ACIA	Asynchronous Interface Adapter
A/D	Analog to Digital
AFCAS	Advanced Flight Control Actuation System
Amp	Ampere
AROM	Alterable Read Only Memory
°C	Degrees Celsius
cc/min	Cubic Centimeters per Minute
c	Centi (10^{-2})
cm^3	Cubic Centimeters
CMD	Pilot Command
CPU	Central Processing Unit
D^3	Direct Digital Drive
D/A	Digital to Analog
DAC	Digital to Analog Converter
db	Decibel
DC	Direct Current
deg	Degree
DFBL	Digital Fly-By-Light
DFBW	Digital Fly-By-Wire
EDU	Electronic Drive Unit
EMI	Electromagnetic Interference

EMP	Electromagnetic Pulse
°F	Degrees Fahrenheit
ft	Feet
F/T	Force Transducer
ft/sec	Feet per Second
gpm	Gallons per Minute
HOFCAS	Hydra-Optic Flight Control Actuation System
HPA	Hydra-Powered Alternator
hp	Horsepower
HZ	Hertz (Cycles per Second)
in.	Inch
in^2	Square Inches
in^3	Cubic Inches
I/O	Input/Output
k	Kilo (10^3)
kg	Kilogram
kW	Kilowatt
lb	Pound
L	Liter
LED	Light Emitting Diode
L/m	Liters per Minute
LHS	Lightweight Hydraulic System
LSSB	Laboratory Signal Simulator Box
LVDT	Linear Variable Differential Transformer

m	Meter, also Milli (10^{-3}), also Minute
M	Mega (10^6)
max	Maximum
mm	Millimeter
M/N	Model Number
min	Minute (Time)
MPa	Megapascals
MPU	Microprocessing Unit
ms	Millisecond
m/s	Meters per Second
mv	Millivolt
N	Newton (Metric Unit of Force)
NAAD	North American Aircraft Division
NADC	Naval Air Development Center
No.	Number
ΔP	Differential Pressure
Pa	Pascal (Metric Unit of Pressure)
PIA	Peripheral Interface Adapter
POS	Rudder Position
PROM	Programmable Read Only Memory
psi	Pounds per Square Inch
psia	Pounds per Square Inch Absolute Pressure
psig	Pounds per Square Inch Gauge Pressure
PM	Pulse Modulation

P/N	Part Number
PWM	Pulse Width Modulated
RAM	Random Access Memory
R&D	Research and Development
RFI	Radio Frequency Interference
rms	Root-Mean-Square
ROM	Read Only Memory
rpm	Revolutions per Minute
s	Second (Time), also LaPlace Transform Operator
sec	Second (Time)
V	Volt
VDC	Volts Direct Current
W	Watt
XDCR	Transducer
XFMR	Transformer

SUMMARY OF METRIC CONVERSIONS

Area	in^2	x	6.452	=	cm^2
	ft^2	x	.0929	=	m^2
Fluid Flow	gal/min	x	3785	=	cc/min
	gal/min	x	3.785	=	L/min
	in^3/sec	x	16.39	=	cc/sec
Force	lb	x	4.448	=	N
Length	in	x	2.540	=	cm
	ft	x	.3048	=	m
Mass	lb	x	.4536	=	kg
Pressure, Stress	psi	x	6895	=	Pa (=N/m^2)
	psi	x	.06895	=	bar
Velocity, Speed	in/sec	x	2.540	=	cm/sec
	ft/sec	x	.3048	=	m/sec
	knots	x	.5144	=	m/sec
Volume	in^3	x	16.39	=	cm^3 (-cc)
	gal	x	3.785	=	L
	l	x	1000	=	cm^3
	m^3	x	1000	=	L