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TECHNICAL REPORT
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ADVANCED FLIGHT CONTROL ACTUATION SYSTEM (AFCAS - E/P)

Fabrication And Design Integration Of An Electronic Control Unit For A Dual Mode Electro/Pneumatic Actuator For The T-2C Aircraft

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Teterboro, New Jersey

MAY 1981

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

Report of the design, fabrication and test of Electronic Control Unit (ECU) for Dual Mode Electro/Pneumatic Actuator. Integration tests establish control capability of ECU in both pneumatic and electric modes. Closed-loop operation fully implemented in design. Evaluation restricted to open-loop due to limited actuator performance.

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EXECUTIVE SUMMARY

1.0 INTRODUCTION

This report presents the results of an effort conducted at Bendix Flight Systems Division, Teterboro, New Jersey, in compliance with Contract No. N62269-80-C-0241, issued by the Naval Air Development Center, Warminster, Penna. to design, fabricate, test, and deliver an electronic breadboard system capable of controlling a dual mode Electro/Pneumatic actuator. The actuator houses a pneumatic motor and an electric stepper motor with a single rotary assembly. Since this is a dual mode actuator, it provides a higher degree of survivability than does a single mode actuator.

Electrical design concepts, breadboard construction, and system operation are discussed in detail in the body of this report.

2.0 BACKGROUND INFORMATION

This development effort is related to two earlier contract awards described below. Under these, Bendix formulated the design concepts and produced hardware for a Dual Mode Electro/Pneumatic Actuator.

Under NADC Contract No. N62269-77-C-0171, the feasibility aspects of a dual mode actuator were studied. This established the actuator's design details and performance predictions. The results of this study are documented in a final report entitled "Feasibility Investigation of an Electro/Pneumatic Dual Power Driver Concept"(NADC Technical Report (77001-60) dated June 1978).

Under NADC Contract No. 62269-78-C-0247, a report entitled "Fabrication and Design Verification Testing of the Dual Mode Electro/Pneumatic Actuator", dated April 1981 was written which documents its events. This report has been transmitted in preliminary form for NADC approval. This effort resulted in the fabrication and assembly of a Dual Mode Electro/Pneumatic Actuator. It reported the test methods and their results on the completed unit.

3.0 FINDINGS

The design of an electronic engineering breadboard system (hereafter referred to as ECU) was undertaken to control and supply electrical power to operate a Dual Mode Electro/Pneumatic Actuator. Hardware was fabricated from the design details and performance tests conducted on a completed ECU. Figures 1 and 2 are photos of the ECU (Bendix P/N 2806345-1) and the actuator (Bendix P/N 3854020-1), respectively. A flexible hardware configuration was chosen so that various electronic parameters could be easily changed in accordance with the experimental and development nature of this effort.

Performance of the ECU in the electric mode was first evaluated with respect to coil sequencing operation using a resistor bank to simulate the actuator's eight electro-magnetic coils. The test results indicated that the ECU was capable of generating the correct sequence of pulse waveforms. The ECU was then integrated with the actuator to establish their compatability. In the Electric mode, the ECU was capable of sequencing the actuator in either direction of rotation at different rates. In the Pneumatic mode, control of the actuator by commanding the actuator's servo value was demonstrated.

During the ECU and Actuator integration tests in the Electric mode, it was necessary to restrict the actuator input power level to 30% of the 270 VDC design goal due to excessive mechanical interference exhibited by the actuator which resulted in actuator stall. This condition which also affected the actuator performance in the pneumatic mode, persisted throughout the testing period. Due to these operational restrictions, close-loop tests of the ECU and the dual mode actuator that would have resulted from its integration with a T2-C aircraft load rig were deferred. However, the results of the tests that were accomplished did not indicate any characteristics that would preclude the ECU meeting its performance objectives.

One problem was identified with the ECU in the electric mode. It concerns an excessive current drawn for small command inputs. The present overload current detector located in the power input line causes oscillatory power surges. As a corrective measure, it is recommended that foldback current limiting be incorporated in the detector's design.

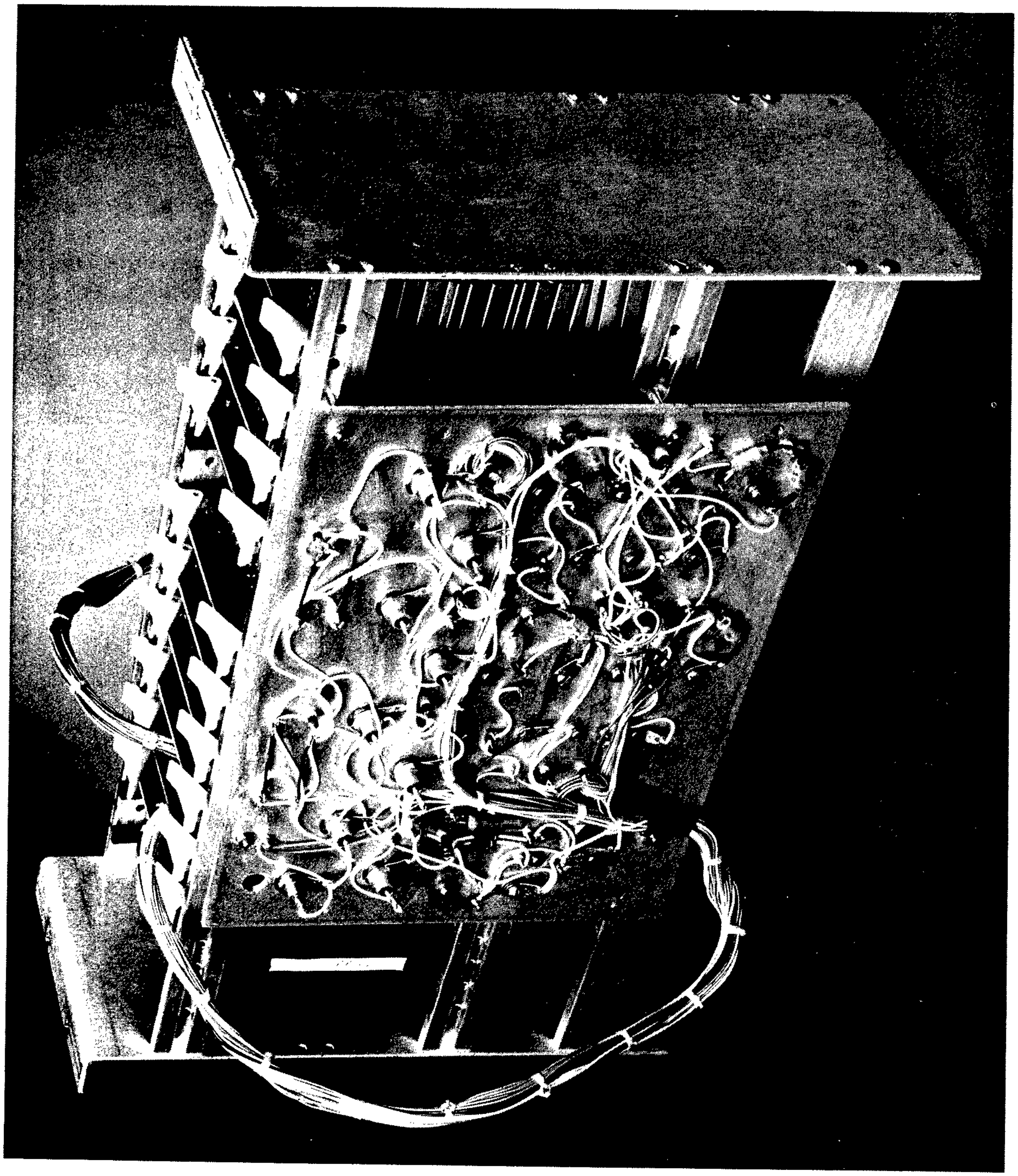


FIGURE 1 ELECTRONIC CONTROL UNIT

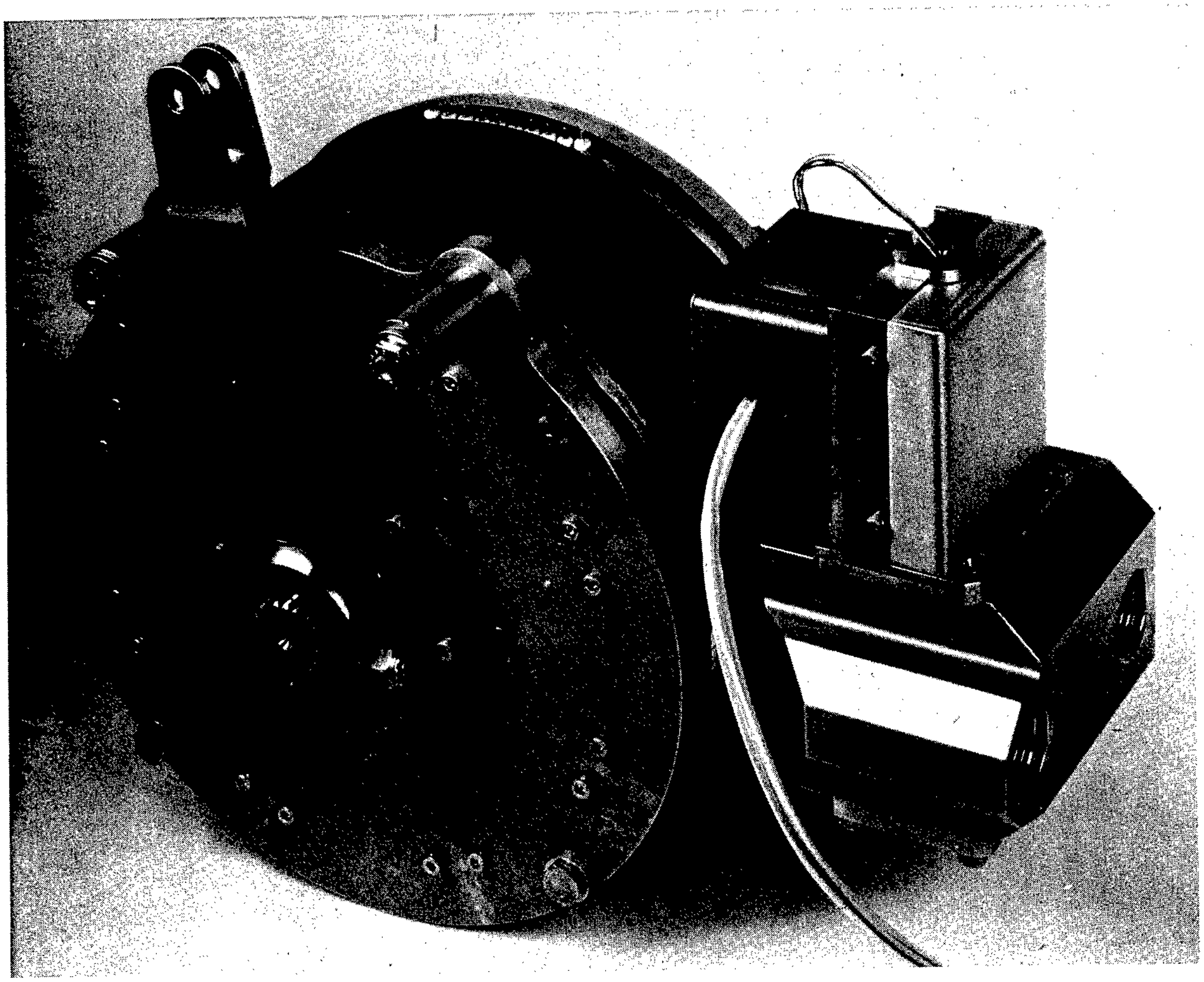


FIGURE 2 ELECTRO/PNEUMATIC ACTUATOR

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

DISCUSSION

4.0 ELECTRONIC CONTROL UNIT

The object of this technical task was to design, fabricate, and integrate an electronic control unit (ECU) capable of controlling a dual E/P (Electro/Pneumatic) actuator. The major components of the actuator assembly consists of an electric stepper motor combined with a vane operated pneumatic motor and a unique epicyclic gear transmission for delivering power to the output shaft. Figure 3 shows an implementation block diagram for the dual mode actuator and the ECU.

In the Electric Mode, the ECU provides a sequential bidirectional output to the actuator coils to cause rotation. It converts an analog input voltage to a variable frequency pulse train which causes logical switching of current to the eight actuator electro-magnetic coils or phases. A polarity detector determines the direction of rotation. When the ECU logic circuitry turns on four adjacent phases at a time in sequence in response to the pulse train, it produces a motor "step". The phase sequence in Figure 4 depicts this operation and shows eight "steps".

In the Pneumatic Mode, the ECU provides a voltage-to-current amplifier which converts the analog input voltage to a dc servo valve command.

5.0 ECU BLOCK DIAGRAM OVERVIEW

Figure 5 is a block diagram of the ECU. It contains five blocks:

1. Analog Signal Conditioning
2. Phase Sequencer
3. Power Control
4. Actuator Power Stage
5. Power Supply

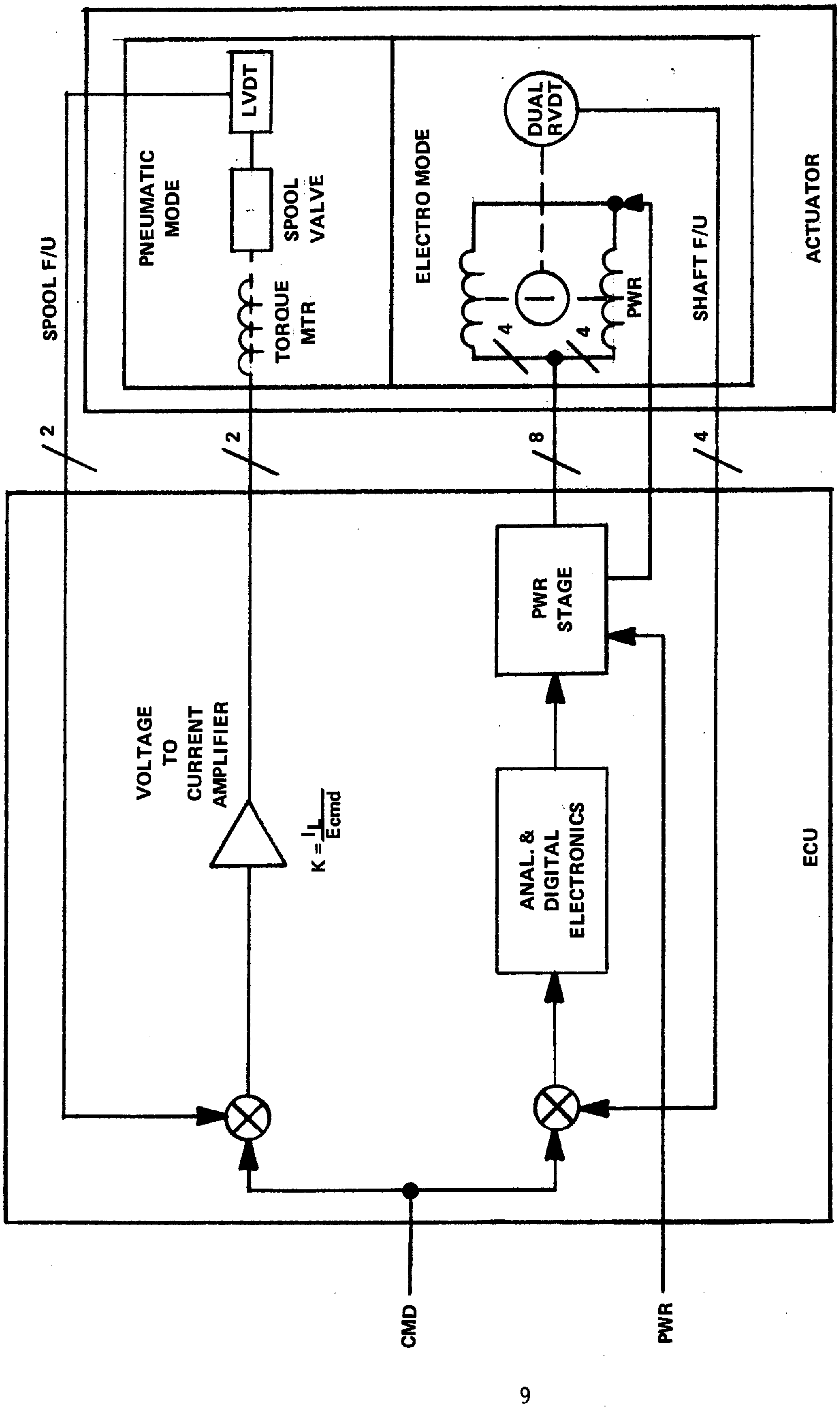


FIGURE 3
DUAL MODE ACTUATOR
IMPLEMENTATION BLOCK DIAGRAM

ECU PHASE SEQUENCE

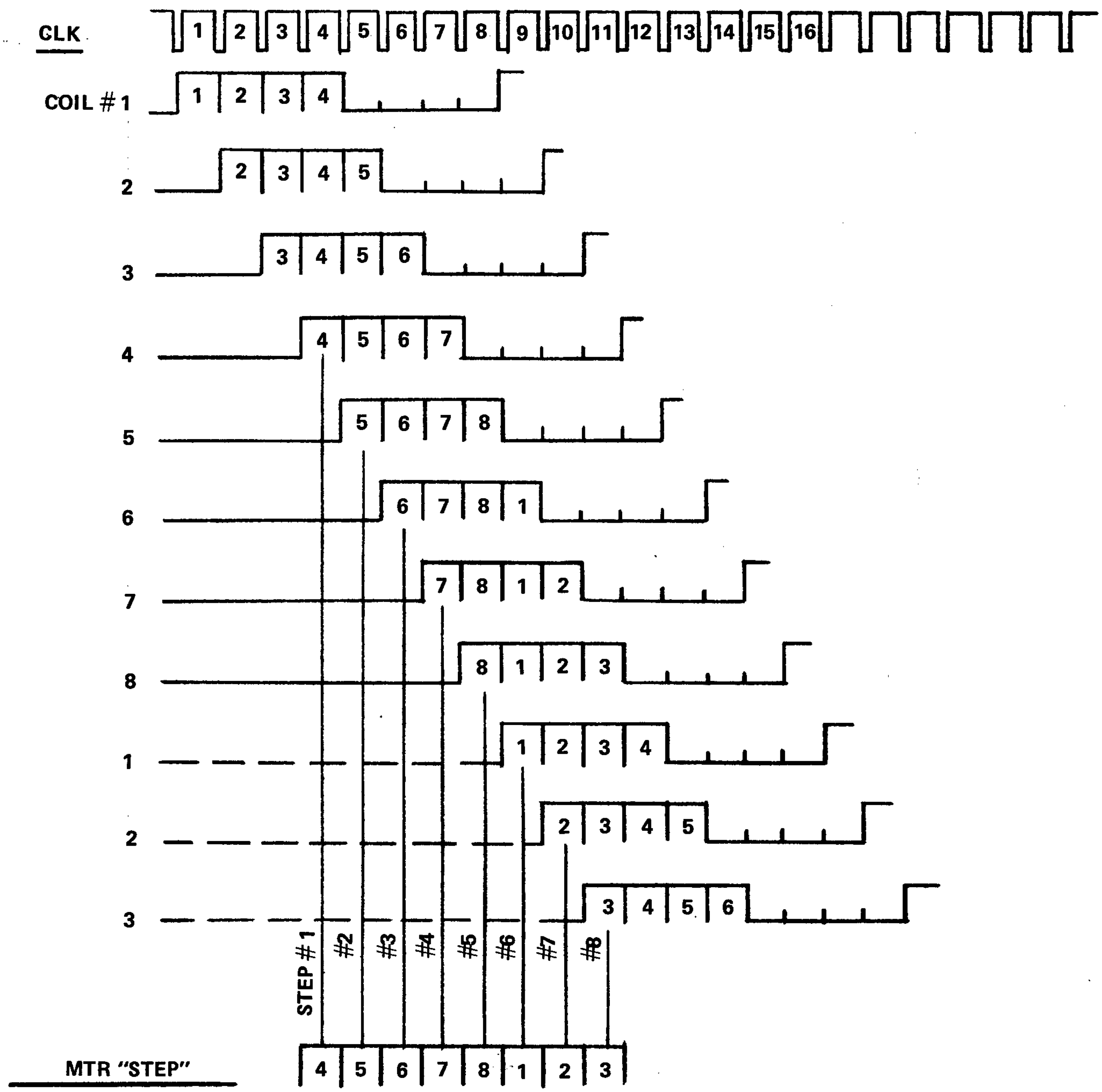
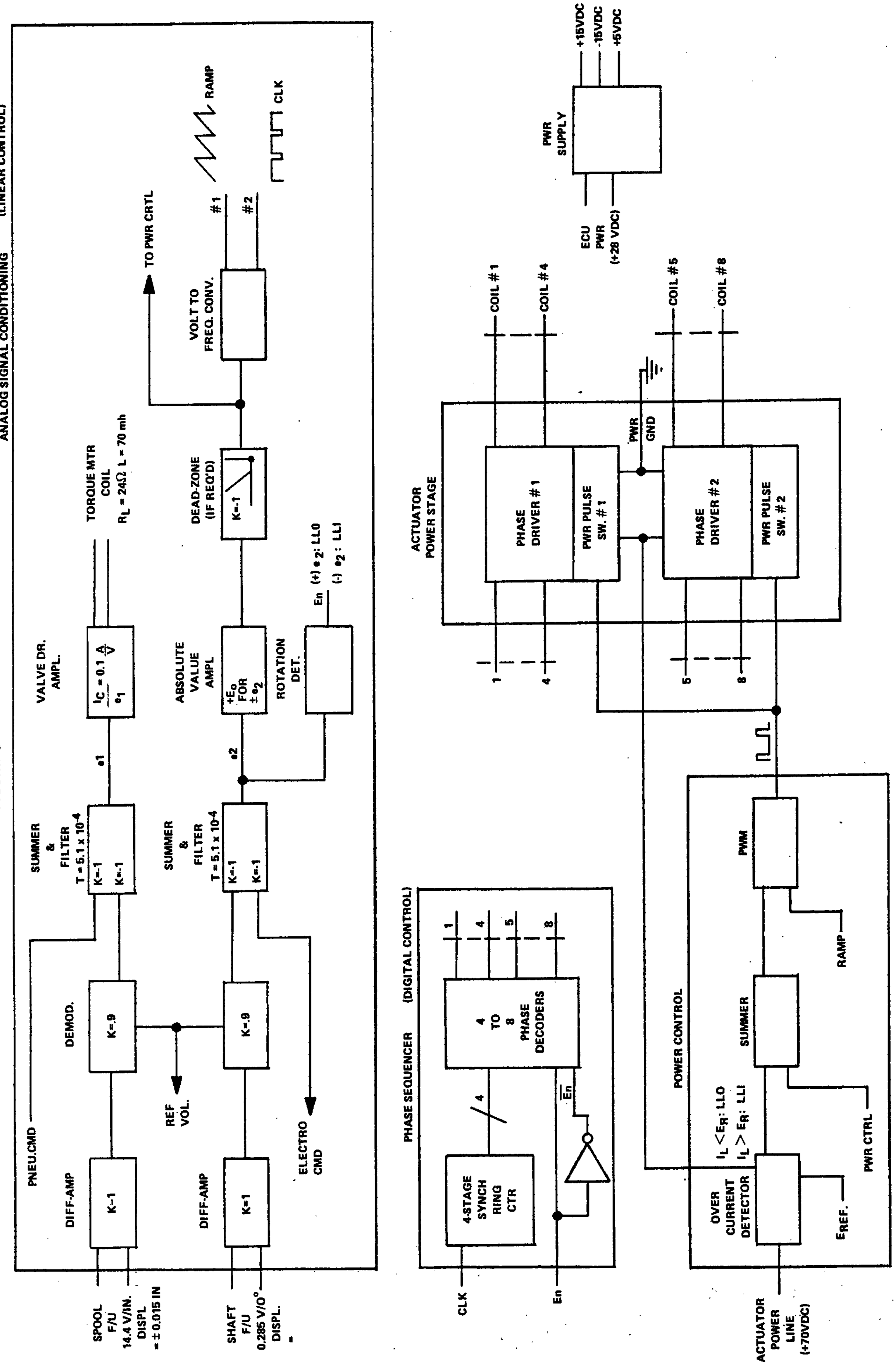


FIGURE 4

FIGURE 5 ECU BLOCK DIAGRAM



5.1 ANALOG SIGNAL CONDITIONING

This block has a two-fold purpose:

1. Pneumatic Operation

   It provides a bipolar current drive to a linear displacement torque motor as a function of the control system error signal.

2. Electric Operation

   A linear voltage-to-frequency conversion is made as a function of the control system error signal. The conversion provides a variable clock pulse for the phase sequence and a reference voltage to the Power Control block.

5.2 PHASE SEQUENCER

The sequencer block contains the necessary counters and decoders to sequence the correct adjacent motor phases. It receives the variable clock pulse and a logic enable to determine direction of rotation. The decoder outputs gate the switching transistors in the Actuator Power Stage.

5.3 POWER CONTROL

The Power Control block contains the pulse width modulator (PWM) circuitry which enables the controller to operate with a variable duty cycle mode. This type of operation reduces the heat dissipation of the switching transistors and controls the speed of the actuator. The PWM is a function of the reference sawtooth generated by the voltage-to-frequency converter (VFC) and control error voltage.

5.4 ACTUATOR POWER STAGE

The Power Stage has eight sets of power transistors split into two groups of four and an associated Power Pulse Switch. These transistors perform the coil switching as directed by the Phase Sequencer outputs. The Power Pulse Switch modulates the input power to each transistor set in response to the amount of On-Off time of the Power Control.

5.5 POWER SUPPLY

This block supplies ±15 VDC and +5 VDC to the ECU from an internal inverter using +28 VDC power input. This powers the analog signal conditioning and the digital circuitry.

6.0 ECU BREADBOARD CONSTRUCTION

The exact ECU requirements would not be known until it was integrated with an actuator. It was therefore desirable to build a controller so that parameters could be easily varied to suit the situation. In order to do this, a MUPAC rack assembly was chosen to house the breadboard. The assembly has a 19" x 5" open style aluminum frame which accommodates a wire wrap chassis and the insertion of 13 panels. Each panel becomes an electronic component assembly (ECA) and features:

1. Wire wrap IC socket patterns totaling 14 rows for dual-in-line IC or carriers containing discrete electronic components such as resistor, diodes, capacitors, etc.

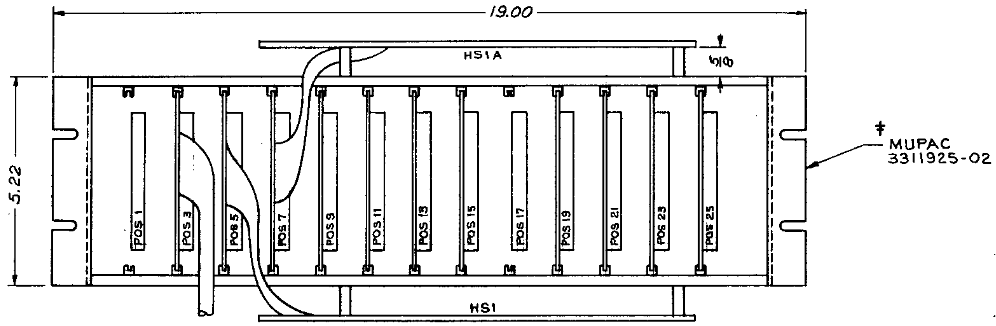
2. Multiple planes for power and ground

3. A 72 pin wire wrap connector.

The key feature to the chassis and ECA's is the wire wrap technique which permits ease of construction and change.

The heat sink assemblies (HSA) which house the components of the Actuator Power Stage are attached to each side of the rack's open frame by means of tubular posts. They are 11" x 8" x 1/8" aluminum plates. The interconnect wiring for each HSA is made via a short cable terminating on a dedicated ECA.

Figure 6 is an assembly drawing (BDX #2806345-1) of the ECU complete with ECA's and HSA's. There are eleven ECA's used in the ECU with two spare slots. Their order is:



POS	CONN	PART Nº	DESCRIPTION
1		(SPARE)	
3	J1	SEE NOTE 1	INTERFACE CARD
5		2805911-1	HS1
7		2805912-1	HS1A
9	J5	2806425-1	COIL DRIVE CARD
11	J6	2806425-1	COIL DRIVE CARD
13	J7	2806425-1	COIL DRIVE CARD
15	J8	2806425-1	COIL DRIVE CARD
17		(SPARE)	
19	J2	2806426-1	POWER CONTROL CARD
21	J3	2806427-1	LINEAR CONTROL CARD
23	J4	2806428-1	DIGITAL CONTROL CARD
25	J9	2806429-1	± POWER SUPPLY CARD

NOTES:
1- ALL LEADS SHALL BE *20 AWG - 3FT LONG - AND WIRED AS PER 2806343-POS 3.
2- FOR ECU SCHEMATIC, SEE 2806344
3- FOR ECU WIRING DIAGRAM, SEE 2806343.

PART NO

REVISIONS: ZONE | REV | DESCRIPTION | DATE | APPROVED

SYSTEM CODE: E/P ACTUATOR

NEXT ASSY | USED ON

FIRST APPLICATION

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COMMODITY CODE

MATERIAL:

HARDNESS:

FINISH:

UNLESS OTHERWISE SPECIFIED
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— TOLERANCES ON DECIMALS
2 PLACE ±.03 3 PLACE ±.005
— INTERPRETATION OF DWG TERMS AND DIMENSIONING PER FLIGHT SYSTEMS DIVISION STD 2795325

* - INDICATES ASSEMBLY
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THE BENDIX CORPORATION
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ELECTRONIC CONTROL UNIT

SIZE C | FSCM NO 55972 | DWG NO 2806345

SCALE 1/2 | SHEET

FORM 10408/8

FIGURE 6 ELECTRONIC CONTROL UNIT (ECU) (BDX P/N 2806345-1)

SLOT NO.	ECA NAME	
1	Spare #1	
3	External (System Interface)	
5	HSA 1	
7	HSA 2	
9	Coil Drive #1	Digital Interface for SW. Transistor
11	Coil Drive #2	
13	Coil Drive #3	
15	Coil Drive #4	
17	Spare #2	
19	Power Control	
21	Analog Signal Conditioning (Linear CNTRL)	
23	Phase Sequencer (Digital CNTRL)	
25	Power Supply	

Figure 7 is a photo of a layout of various ECA's extracted from the ECU. Figure 8 is a close-up photograph of the Analog Signal Conditioner which shows the mix of 12 integrated circuits and 16 discrete component carriers.

The operation of the ECU and the Dual Mode Actuator can be demonstrated through use of the Electro/Pneumatic Test Console. Figure 9 displays the placement of the ECU and its Control Panel within the console. Figure 10 is a photo of a bench test set-up. Figure 11 is the wiring diagram for this actuation system. It ties together the ECU, the Test Console and the actuator.

The Control Panel in the Test Console has three switches and a ten turn potentiometer.

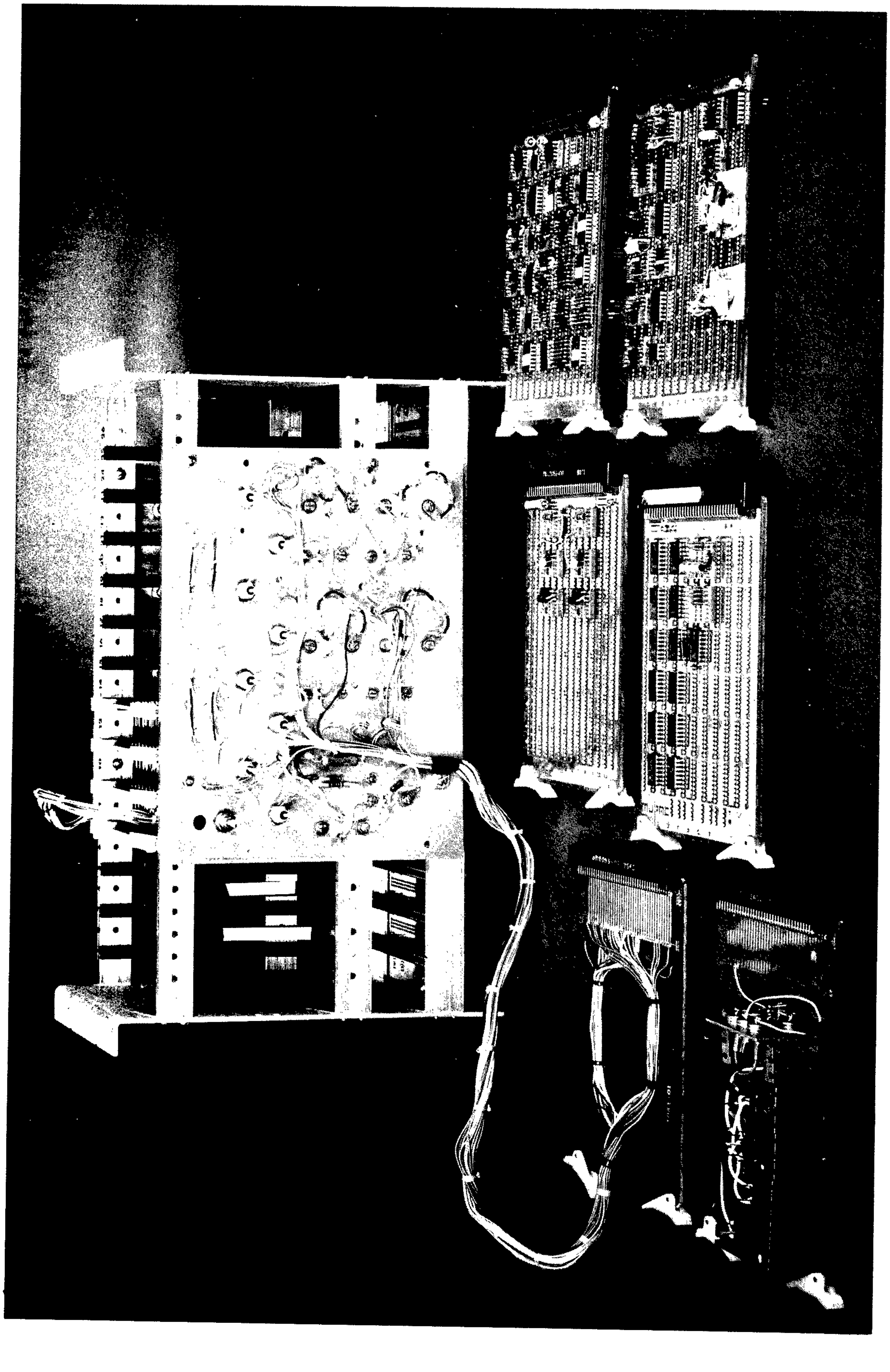

FIGURE 7 ECU MODULE BREAKOUT

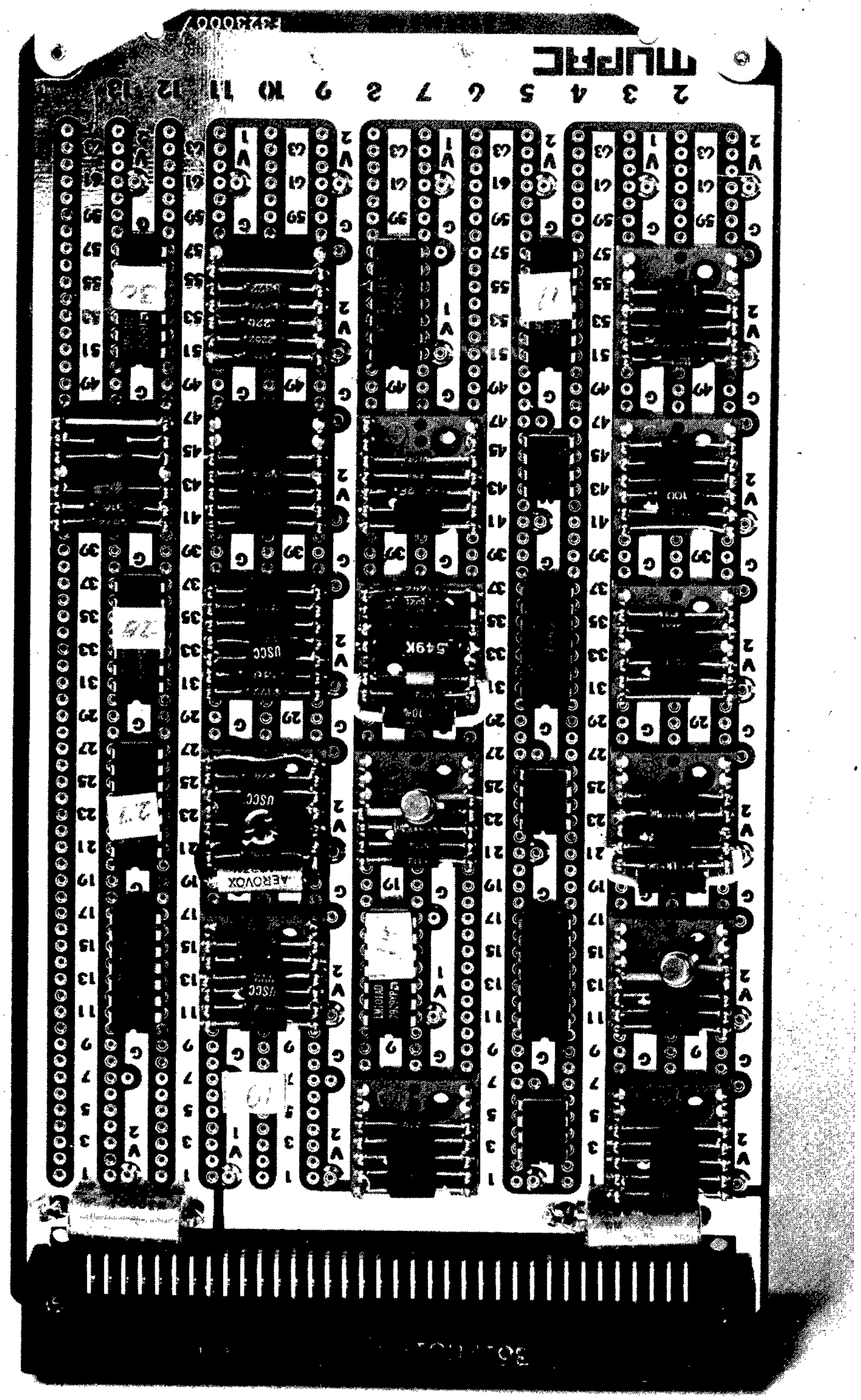

FIGURE 8 ANALOG SIGNAL CONDITIONER MODULE

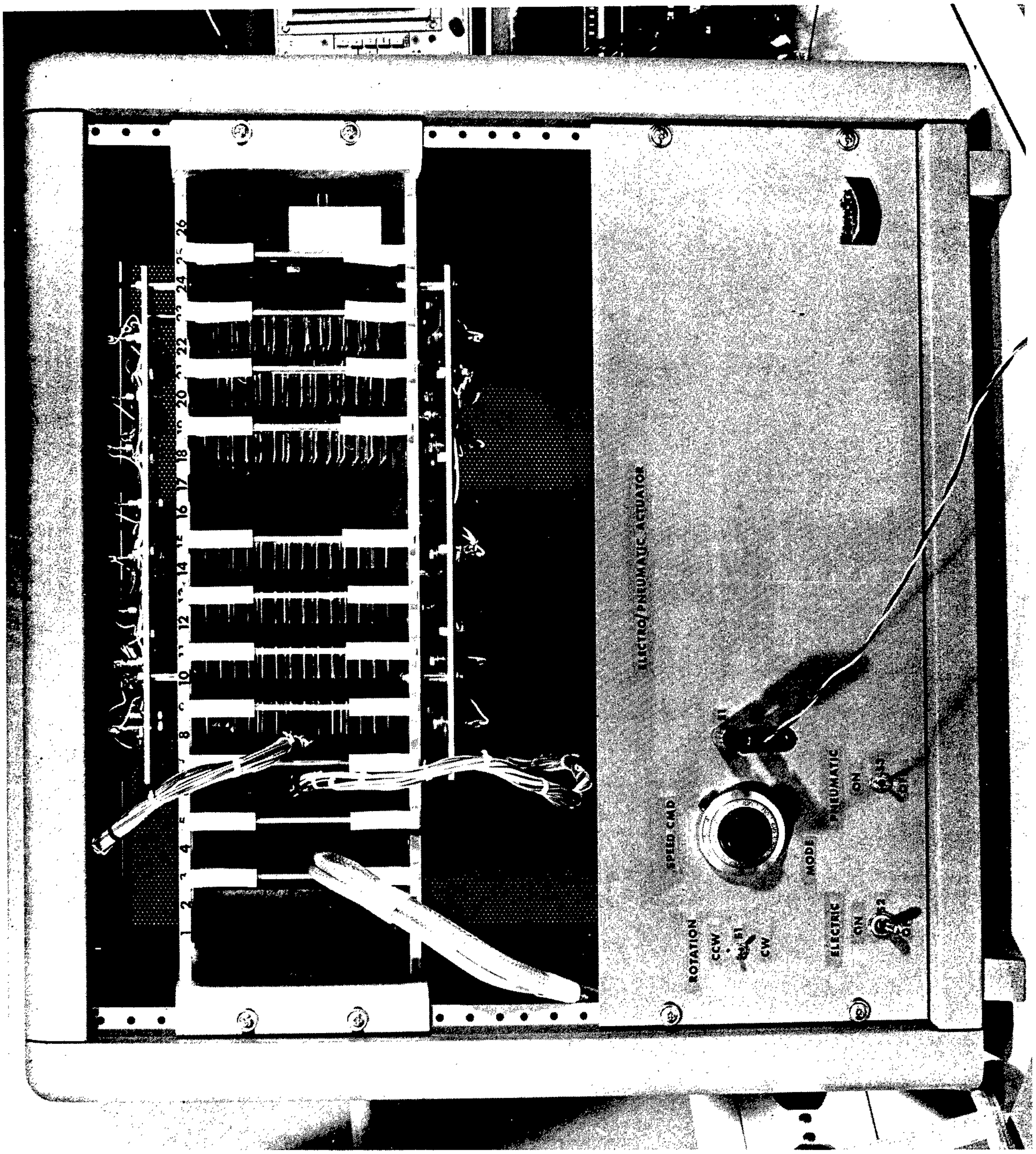

FIGURE 9 ELECTRO/PNEUMATIC (E/P) ACTUATOR TEST CONSOLE

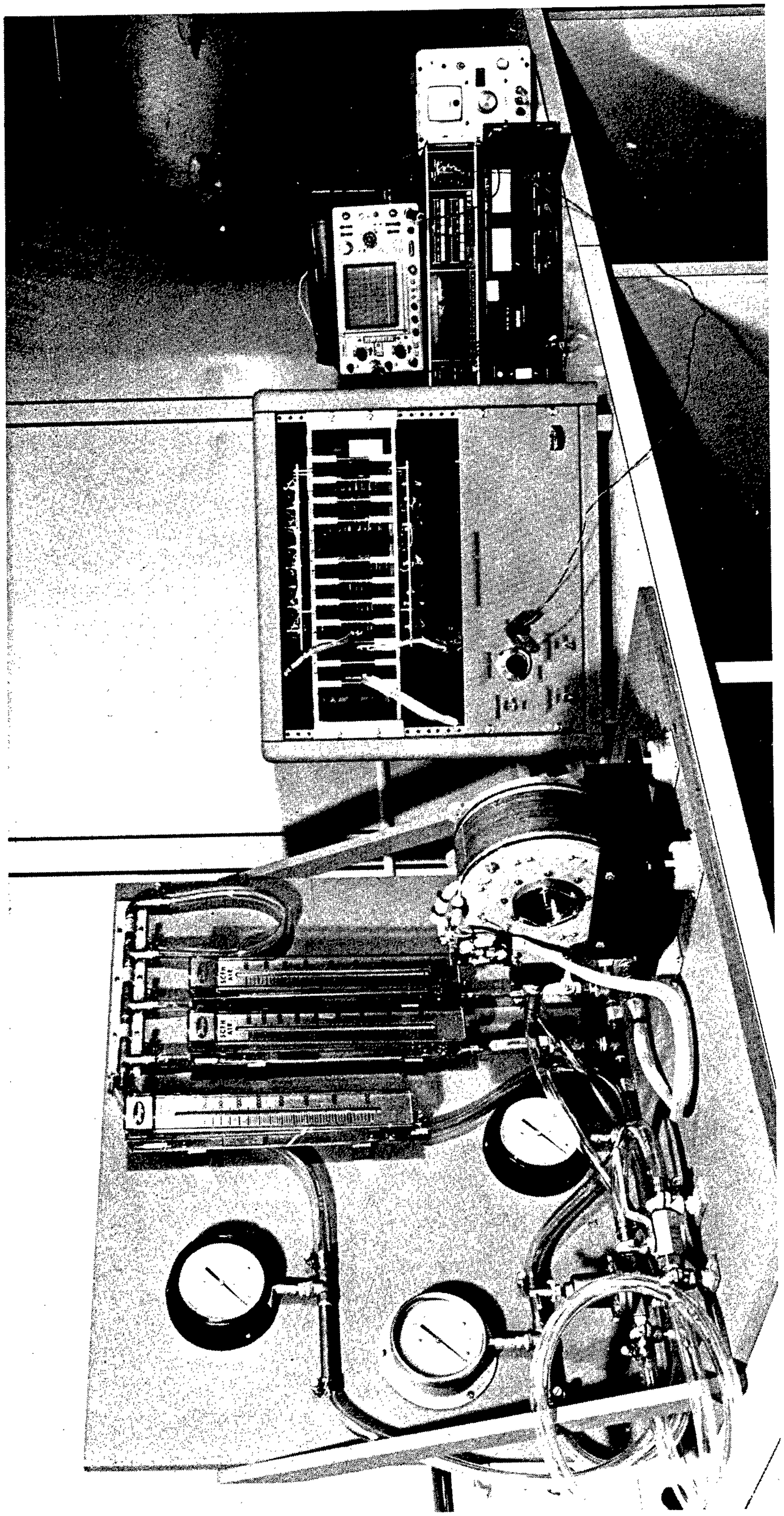

FIGURE 10 PNEUMATIC AND ELECTRIC MODE OPEN LOOP TEST SET-UP

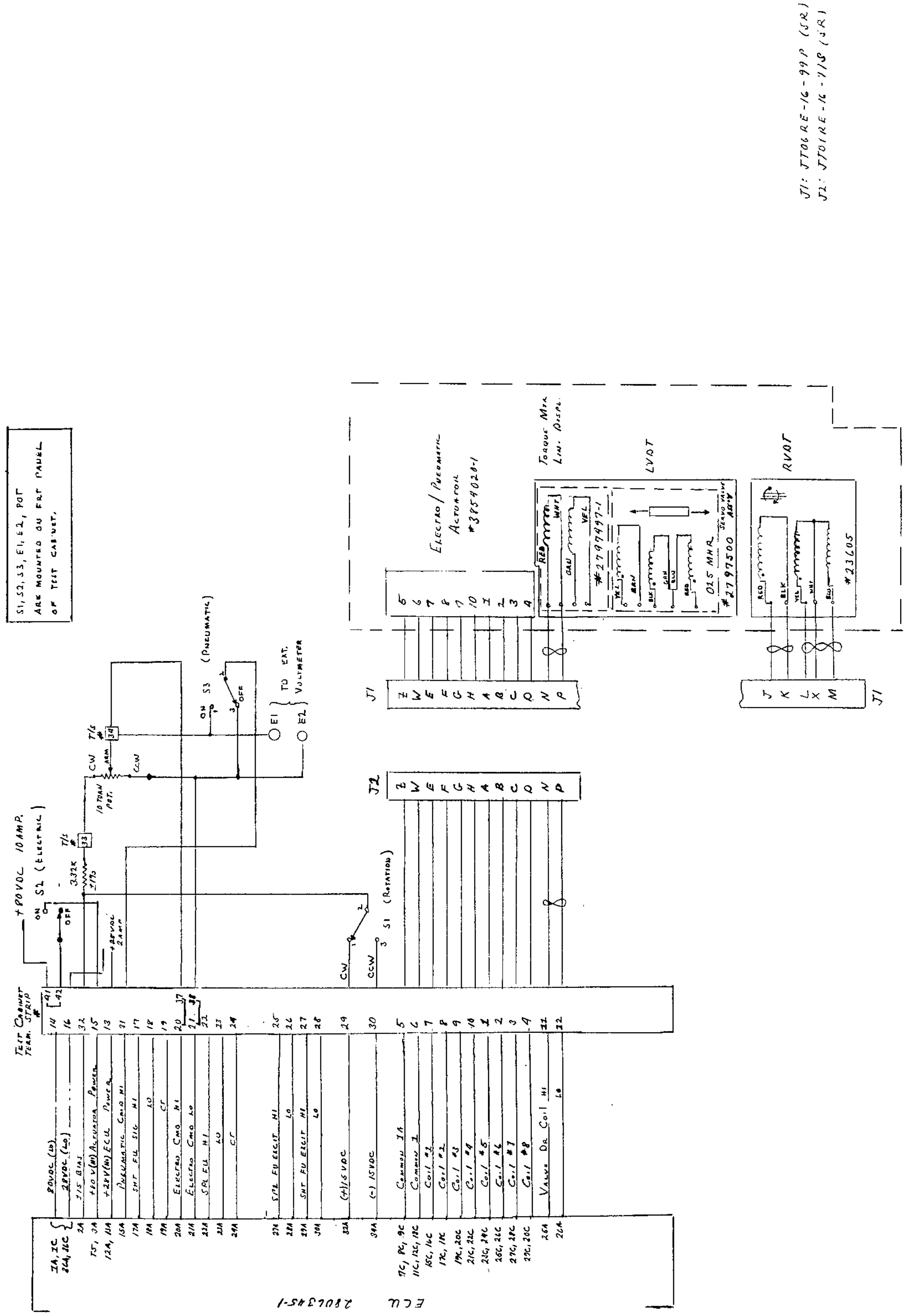

FIGURE 11 E/P ACTUATION SYSTEM WIRING DIAGRAM

SN NO.	FUNCTION
S1	Rotation CW/CCW
S2	Electric Mode ON/OFF
S3	Pneumatic Mode ON/OFF

Switches S2 and S3 can be engaged separately or together. The Speed Command is the signal source whose voltage can be read out by connecting a voltmeter to terminals E1/E2. It is generated from the power supply internal to the ECU. The console requires two external dc power sources to power the system.

1. (+)80 VDC @ 10 amp for Actuator

2. (+)28 VDC @ 2 amp for ECU Power

The actuator air supply with inlet/outlet hoses also come directly from an external source. There are no pneumatic controls or pressure indicators within the console; these must be supplied externally.

7.0 ECU ELECTRICAL DESIGN

The functional blocks that make-up the ECU are built up around standard "off-the-shelf" electronic components. Most of the analog functions are implemented around 741 and 101A operational amplifiers. The family of logic parts chosen for the digital functions was the 54 LSXX or Low Power Schottky TTL. Actuator coil switching and power switching is by discrete power transistors. A schematic of the ECU circuitry is shown in Figure 12. The ECU's internal wiring which interconnects the various modules is shown in Figure 13.

7.1 ANALOG SIGNAL CONDITIONING DESIGN

The Spool F/U and Shaft F/U voltage are generated by ac-excited electromechanical transducers using a carrier frequency of 1.8 KC. These two 3-wire inputs are interfaced at the ECU by a differential amplifier/demodulator combinations; U7/U8A for Spool and U14/U10A for Shaft. The differential amplifiers

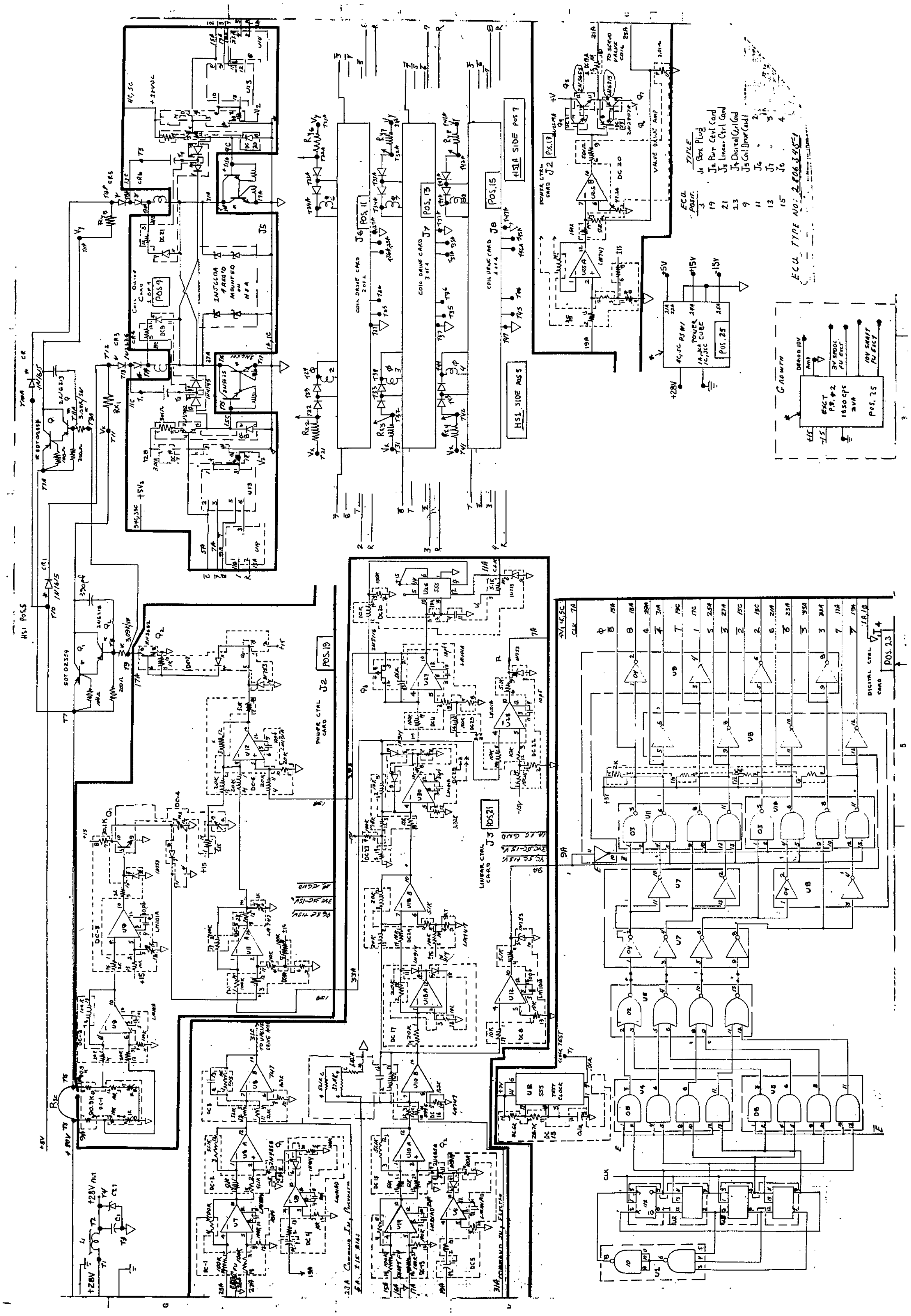

FIGURE 12 SCHEMATIC, ELECTRONIC CONTROL UNIT

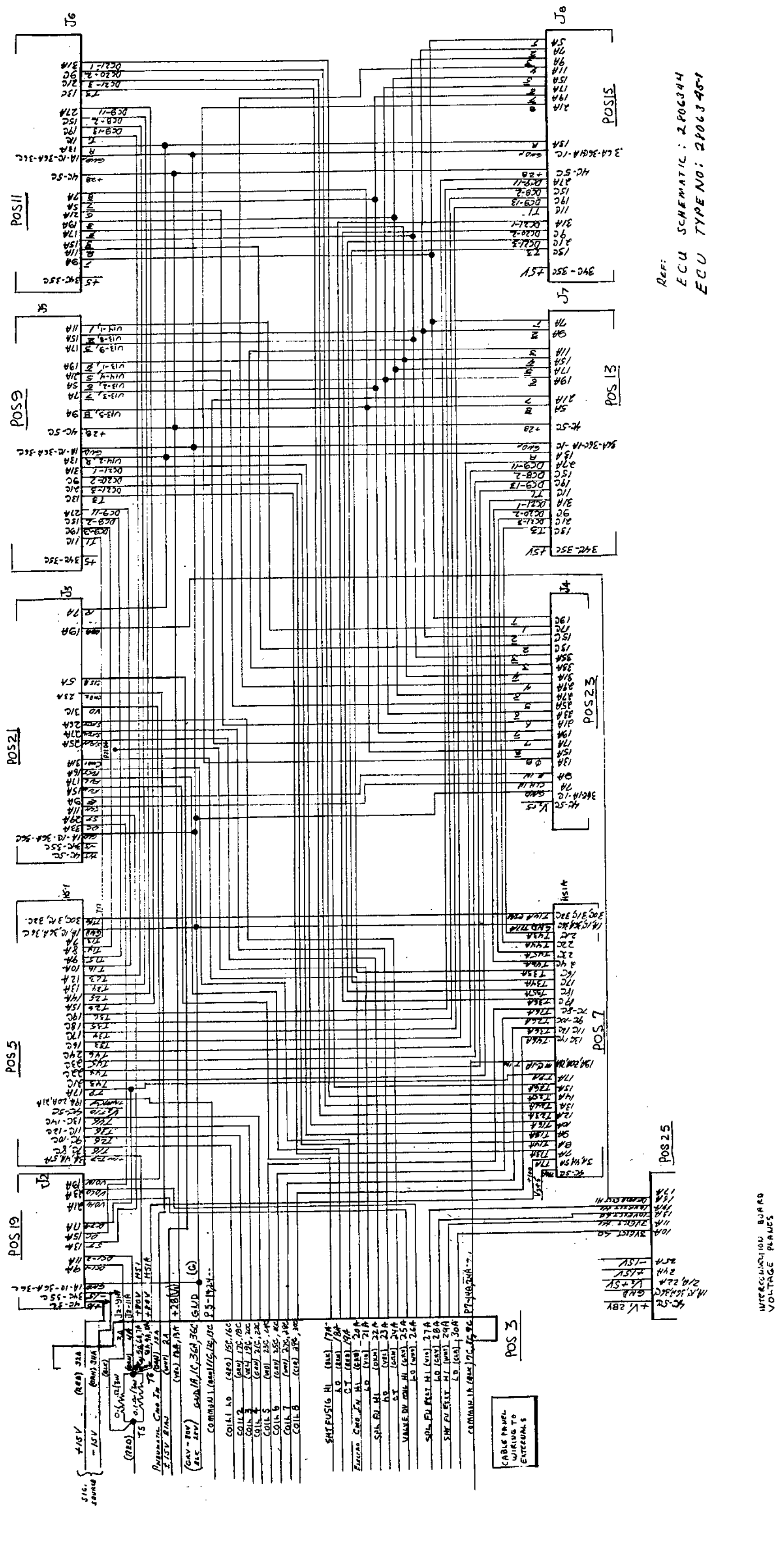

FIGURE 13 ECU WIRING DIAGRAM

acts as an impedance buffer on analog signal transfer. The phase sensitive demodulator transforms the carrier input signal to a bipolar dc output proportional to the input signal. Demodulation is obtained by first switching the sine wave input at carrier frequency using a FET (Q1 or Q2) located at the non-inverting op-amp input and then recombining the inputs. The Pneumatic and Electric control error signals are a result of the summation of F/U and COMMAND. Their respective gain scalings are performed by the input resistors at summing amplifiers U8B and U10B. A single order lag filter to minimize demodulator ripple appears in the feedback loop of each summer.

U18A/B form an absolute value amplifier; U18A with diodes in the feedback loop acts as the precision rectifier and U18B is a two input summer which recombines the signal. The result is that the polarity of the output voltage is always positive for either input polarity.

Op-amp U30 provides a dead zone capability if required. A negative bias voltage for creating the break point is summed at the inverting input of this stage.

The voltage-to-frequency converter (VFC) is a two stage affair. It pairs an op-amp integrator (U27) which ramps into a 555 timer (U26). The purpose of the VFC is to provide two different outputs.

1) A linear sawtooth waveform from the integrator which is frequency dependent on the input voltage. This waveform is required as a reference for a PWM application in the Power Control block.

2) A series of clock pulses outputting from the timer whose repetition rate is directly proportional to the input voltage. These pulses are required for advancing the counter in the Phase Sequencer block.

The 555's output is fed back to form a rapid discharge circuit. This IC timer consists of a voltage divider network, two voltage comparators, and a bistable flip-flop. The comparators along with the divider network detect the level of the ramp and set the F/F state to a LL = 0. This shorts a P-channel FET in shunt with the integrator's capacitor and forces the abrupt drop back to zero of the ramping voltage wave.

The Rotation Detector (U12) provides an Enable logic level to the Phase Sequencer. It is an open-loop amplifier which changes saturation state as a function of the error voltage polarity. TTL translation is through a series resistor-shunt zener diode.

The valve drive amplifier (U25) is a standard voltage-to-current configuration using a complimentary emitter-follower output stage. It uses Darlington NPN-PNP transistors (Q5 thru Q7) to supply the 300 ma of valve current. The transfer gain I_L/E_{IN} = 0.1 amp/volt. The transfer function is independent of load.

7.2 PHASE SEQUENCER DESIGN

The phase sequencer is made up of a four stage synchronous counter (U2/U3) which feeds back on itself and a 4-to-8 phase decoder. These are J-K flip-flops (LS112) and are driven in parallel by a clock pulse derived from the VFC. The outputs of the counter are:

1. Logically combined with the Enable (En) from the Rotation Detector block which establishes the direction of phase sequence.

2. Decoded from 4 to 8 lines using wired-OR nand gate (U10/U11) in order to gate the power transistors located in the Actuator Power Stage.

7.3 POWER CONTROL DESIGN

This contains Pulse Width Modulation (PWM) circuitry. The PWM is an open-loop op-amp (U12) which sees at its inputs the sawtooth reference voltage and the control system error signal. Their relationship produces pulses whose ON-OFF time varies the duty cycle of the two parallel Pulse Power Switches located in the actuator power line. The ON-time of the PWM decreases with increasing error signal. This assures that a maximum voltage pulse is applied to the actuator coils for fast current build-up to develop starting torque.

An Over-Current Detector (U8/U9) is incorporated in this stage for the purpose of limiting the actuator input current to a safe level. This feature affords protection for the coil switching transistors. Diff-amp U8 senses the line current passing through a balance bridge. Level Detector U9 will change state when the current exceeds its reference. This will provide a large bias input via transistor Q1 and summing amplifier U11 and drive the PWM's to OFF. The PWM remains in this state until the overcurrent condition clears itself.

7.4 ACTUATOR POWER STAGE DESIGN

The Actuator Power Stage was split into two halves to distribute the power dissipation. Each half contains four sets of NPN power transistors in the Darlington configuration for switching the motor coil and a PNP Darlington Power Pulse Switch for modulating the input power. The switching transistors were selected to operate at the 270 VDC supply voltage. The output transistors are shunted by Transzorbs for "despiking" during their off-period. These devices are transient voltage suppressors which handle large power pulses with fast response time.

A capacitor doubler circuit for each coil was envisioned for this stage. This would provide a surge of current at a very high voltage to aid coil turn on and develop the necessary torque. This voltage pulse would be equal to twice the supply voltage. Steering diodes were incorporated between alternate sets of coils. The operational sequence dictates that one coil is on and that its alternate is off. This permits two occurrences for the transfer of energy:

1. The capacitor across the OFF-coil will charge up when the alternate coil is turned on by its associated switching transistor.
2. The shunt capacitor across the ON-coil discharges its stored energy into that coil.

7.5 POWER SUPPLY DESIGN

This block utilizes a 20KC inverter for converting the 28 VDC input into:

1. $\pm$15 VDC for biasing the various operational amplifiers that comprise the analog circuitry.
2. +5 VDC for powering the digital logic circuits used in the phase sequencer block.

The 20KC inverter makes use of four standard Power Cube modules wired together on an ECA to form the ECU supply. They are:

	PART NO.	DESCRIPTION
1)	811FTA	EMI Module
2)	22G100W40	DC Input/HF Generator
3)	15TRC10	$\pm$15 VDC @ 1 amp.
4)	5TR65	+5 VAC @ 6.5 amp.

Power Cube modules were selected because their availability. Growth area on the ECA was provided for a 1.8KC oscillator which would excite the actuator's LVDT/RVDT and the ECU's demodulators. The ECU's harness contains the necessary wiring for these electrical connections.

7.6 ECU OPERATION

It was possible to demonstrate through use of the Test Console that the ECU drove the actuator under the following open-loop conditions:

1. Dual mode operation with 80 VDC and 28 VDC electrical power and 20 PSI of pneumatic power.
2. Electric mode operation at 80 VDC and 28 VDC electrical power.
3. Pneumatic mode with 20 PSI of pneumatic power and 28 VDC electrical power.

Figure 14 is a plot of the actuator output shaft speed as a function of ECU command signal. This shows a linear relationship. The highest no-load speed attained was 19.8 deg/sec. A higher command (increase in coil sequencing ratio) results in actuator stall-out. Tests were not conducted below 5 deg/sec because of the oscillatory input power problem. This was due to the overload current detector sensing the increase in power supplied to the actuator as a result of greater on-time of the coils for small magnitude of command inputs. The present detector trips out at around 8 amps.

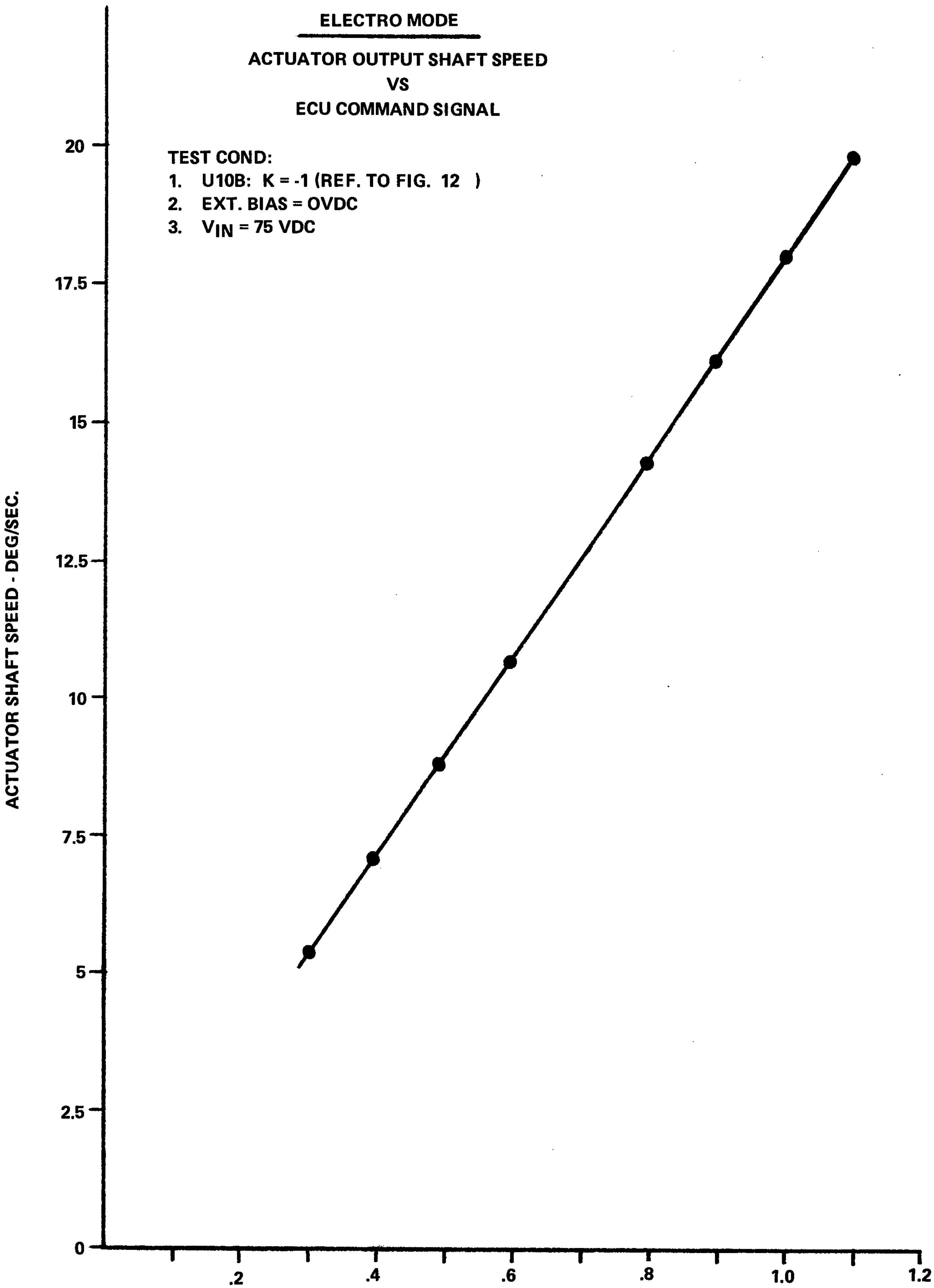

FIGURE 14 ECU CMD - VDC

The nominal power drawn by the ECU and actuator during the no-load speed run was:

1. 80 VAC @ 5 amps: This 400 watts is dissipated mostly in the actuator.

2. 28 VDC @ 1.1 amps: The 31 watts is dissipated within the ECU.

The ECU operation in the Electric Mode was observed by taking a series of Polaroid photographs of various waveforms using a Tektronix 465 dual scope.

Figure 15 is the output of the Power Pulse Switch in response to the sawtooth generated by the VFC. The actuator power is switched between gnd and 80 VDC at a frequency of 100 Hz. Its ON-TIME/(ON + OFF) TIME ratio is 0.6.

Figure 16 is a photo of actuator coil turn-on. It has two traces. The top trace is the waveform (V_{CE}) across phase switching transistor Q4-4 on heat sink assembly HSA1. It controls actuator coil #8. The bottom trace represents the modulated voltage out of the Power Pulse Switch. Coil #8's on-time ($V_{CE} = 0$) is about 40 msecs.

Figures 17(A) and 17(B) depict the actuator phase sequence. The top trace in both photos is V_{CE} of Q4-4; (Coil #8). In (A), the bottom trace is V_{CE} of Q4-3; (Coil #7). It has turned on 10 msecs ahead of Q4-4. In (B), the bottom trace is V_{CE} of Q4-2; (Coil #6). This coil is on 20 msecs ahead of Q4-4.

In 80 msec, the stepper motor orbits 1 revolution. This corresponds to 12.5 RPS or

$$\frac{360^\circ}{0.08} = 4500 \frac{\text{deg}}{\text{sec}}$$

Since the actuator has a gear ratio of 468.4 to 1, the shaft speed is:

$$\frac{4500}{468.4} = 9.6 \frac{\text{deg}}{\text{sec}}$$

This correlates with the measured actuator shaft speed.

ECU OPERATION

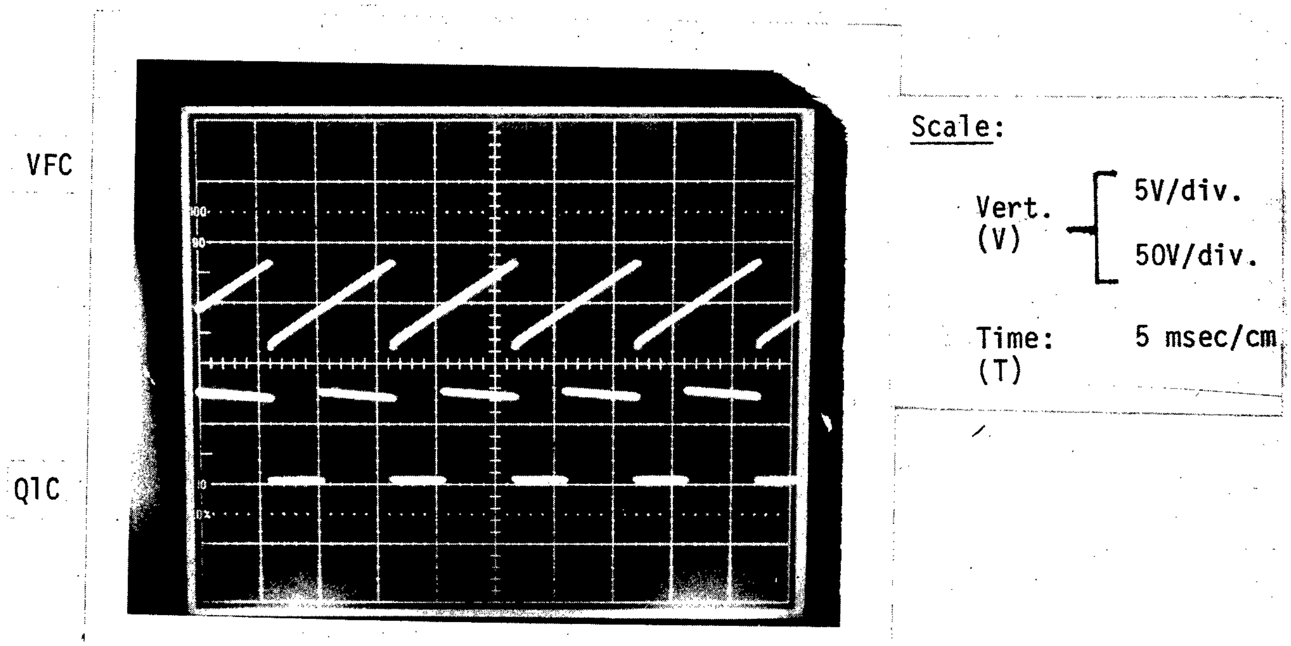

FIGURE 15 MODULATION OF POWER PULSE SWITCH

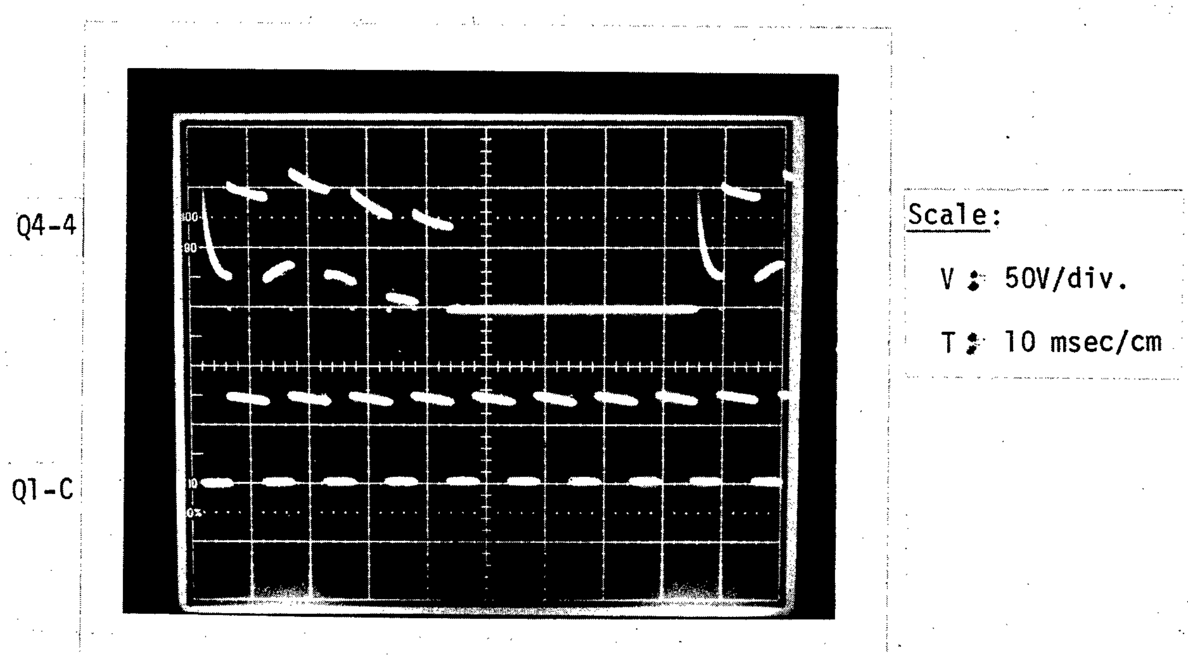

FIGURE 16 ACTUATOR COIL TURN-ON

ASSEMBLY
HSA1

P_{WR} = 80 vdc

Actuator S_{PD}:

9.5°/sec

Q4-4

Q4-3

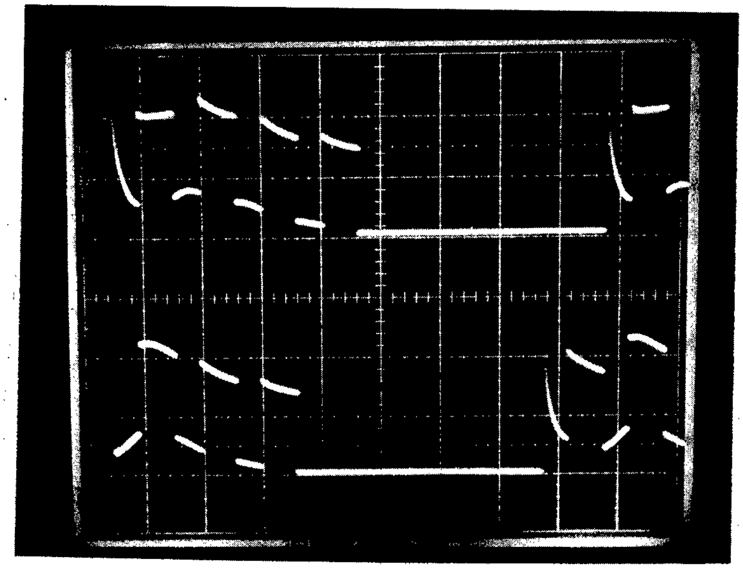

FIGURE 17A ECU PHASE SEQUENCE

Scale:

V : 50V/div.

T : 10 msec/cm

Q4-4

Q4-2

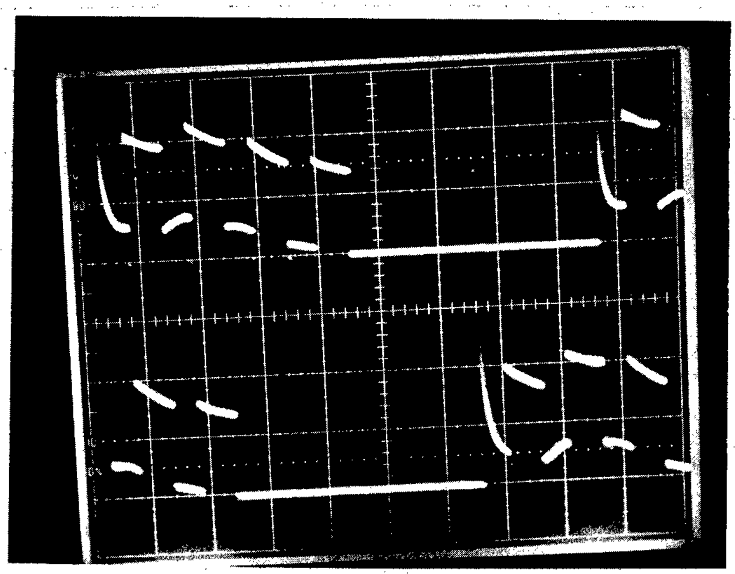

FIGURE 17B ECU PHASE SEQUENCE

8.0 CONCLUSIONS AND RECOMMENDATIONS

The ECU demonstrated that it could drive an actuator in both the electric and pneumatic modes. It had to operate the actuator within a window which restricted its performance. Corrective measures applicable to the actuator would permit full use of the ECU's operational capability since it has:

1. An output stage which was designed to operate at a supply voltage of 270 VDC.

2. Pulse width modulation technique for motor control and minimum internal heat dissipation.

3. An energy transfer network within the output stage for developing high starting torque.

4. Shaft/Spool F.U. circuitry for a closed-loop servo configuration.

A temporary solution to the ECU's oscillatory input power problem was put in on the Analog Signal Conditioning Module. This was done to facilitate the ongoing integration testing. A bias network was located on the operational amplifier that sums Command and Shaft Follow-Up (See DC16 on Figure 12). This meant that with the E_{CMD} = 0 VDC, the actuator will rotate at a very slow rate with the 80 VDC current drain stable. The polarity of the bias is the same as that of the E_{CMD} so that it always adds.

The oscillatory surge problem is a response of the aforementioned overload current detector located in the power input line. This type of detector shuts the Power Pulse Switch off on an overload and immediately clears when the overload is removed. A recommended design change would be a detector which has foldback current limiting. This should eliminate the oscillatory power surges generated by the original circuit. It would:

1. Permit the actuator to draw the necessary current at maximum torque and foldback to a fraction of that current at zero command.

2. Provide a smooth transition during the turn-on of the actuator from this steady state point and still protect the switching transistors from overload due to any cause of failure, be it the ECU or the actuator.

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