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DEVELOPMENT OF AN ACTUATOR SIMULATOR CONSOLE FOR THE SPACE SHUTTLE ELEVON SUBSYSTEM

Job Order 35-489

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LEC-7181
SHUTTLE

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DEVELOPMENT OF AN ACTUATOR SIMULATOR CONSOLE FOR THE SPACE SHUTTLE ELEVON SUBSYSTEM

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13. ABSTRACT

This report discusses the development, design, construction and testing of an elevon simulator console (ASC). The ASC is an electronic analog of the elevon hydraulic servoactuator subsystem to be used in the Space Shuttle flight control system (FCS).

14. SUBJECT TERMS

# Flight Control	UF Servoactuator	Analogs
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	BT # Control Surfaces	RT # Simulation

ABSTRACT

This report discusses the development, design, construction and testing of an elevon actuator simulator console (ASC). The ASC is an electronic analog of the elevon hydraulic servoactuator subsystem to be used in the Space Shuttle flight control system (FCS). A mathematical model of the elevon servoactuator subsystem, developed by J. W. Hoke of Rockwell/Space Division, provided the basis for the ASC development.

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ABBREVIATIONS AND ACRONYMS

ASA	Aerosurface servo amplifier
ASC	Actuator simulator console
CBH	Current buffer and hysteresis
CSMP	Continuous System Modeling Program
CVM	Control valve module
FCS	Flight control system
HRM	Hydraulic Research and Manufacturing Company
IBM	International Business Machines
IVS	Isolation valve simulator
LVDT	Linear variable differential transformer
MDM	Multiplexer-demultiplexer
OPTS	Output position transducer simulator
PA	Primary actuator
PFC	Position to flow conversion
PPTS	Primary pressure transducer simulator
R/SD	Rockwell/Space Division
SAS	Secondary actuator secondary spool
SPS	Secondary power spool
SPTS	Secondary pressure transducer simulator
op amp	Operational amplifier

1. SUMMARY

An important part of the Space Shuttle flight control system, especially in the landing mode, is the elevon servoactuator subsystem. This subsystem consists of the aerosurface servoamplifier (ASA), the servoactuator package, containing a secondary actuator and a power ram, and the elevon. Testing of the subsystem required development of an accurate analog model of the secondary actuator or control valve module (CVM) and the ram. The model of the actuator was based on a complex mathematical model developed by J. W. Hoke of Rockwell/Space Division (R/SD). The Hoke model was simplified and scaled to operational voltage levels. Operation of the resulting model was then compared with that of the Hoke model using a digital computer program, the Continuous System Modeling Program (CSMP), developed by International Business Machine (IBM). After verification of proper operation, the simplified model was used as a basis for the design and construction of an actuator simulator console (ASC). Part of the ASC was to be interchangeable with a prototype hydraulic secondary actuator constructed by Hydraulic Research and Manufacturing Company (HRM). The secondary actuator section of the ASC was intended to be a black box replacement for the CVM.

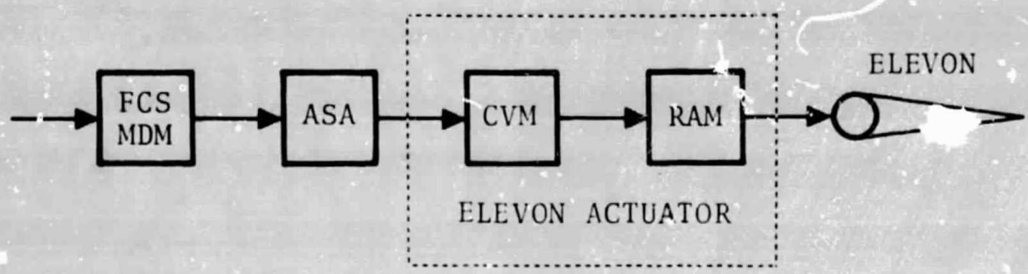
Testing of the ASC and comparison with the CSMP outputs of the Hoke model showed that the ASC is a valid replacement for its hydraulic counterpart. The advantages of using the ASC in subsystem testing are many: No hydraulic pumps or supply lines are required; configuration changes are easily made in the electronics; the ASC does not require much space; and it costs less than its hydraulic counterpart.

2. INTRODUCTION

Guidance and control of the Space Shuttle in the landing mode is accomplished by positioning a set of four elevons attached to the delta wing trailing edge. These elevons are controlled by electrohydraulic actuators which are commanded electronically by the pilot or autopilot through an electronic flight control computer.

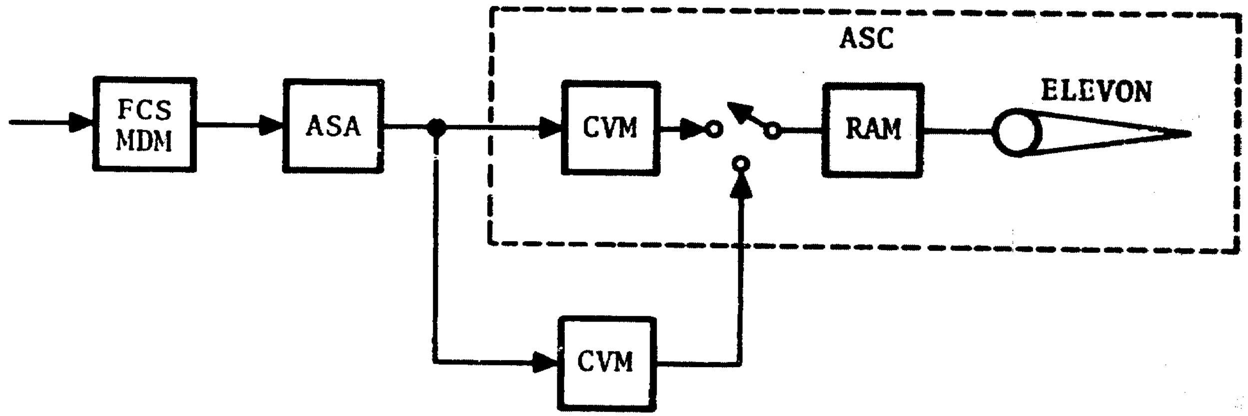
Accurate and timely positioning of the elevons is critical to stable control of the Space Shuttle in the landing configuration. Consequently, performance of the elevon actuator subsystem is subject to stringent specifications. The actuator subsystem proposed for the Space Shuttle consists of a set of four aerosurface servo amplifiers (ASA's) coupled to several quadruple redundant hydraulic servoactuators. Each ASA drives one channel of each servoactuator in a cross-coupling scheme providing redundancy. The secondary actuator or CVM commands a hydraulic power ram which deflects the elevon. A simple schematic of this command chain is shown in figure 2-1. Note that in the flight hardware, the CVM and the ram are packaged in one unit (elevon actuator).

Testing of the actuator subsystem is required to determine its operating characteristics. Individual components such as the ASA and the CVM also must be tested to verify that their performance meets the specifications. To facilitate performing these tests, an electronic model was proposed which would function analogous to the CVM-power ram-elevon combination (fig. 2-2). This would enable actuator subsystem testing using a breadboard ASA, which was built at JSC. After successfully testing the ASA using the actuator model, a hardware hydraulic CVM could be inserted in the subsystem, with only the electronic analog power ram-elevon combination remaining. The CVM model would not be used in this test. The electronic actuator model would have two



Note: For simplicity only a single-channel chain is shown.

Figure 2-1. – Basic elevon actuator subsystem.



Note: Either hydraulic or analog CVM may be used.

Figure 2-2. – Basic elevon actuator subsystem using ASC.

functions: (1) to verify ASA operation in a closed-loop subsystem test, and (2) to perform closed-loop subsystem tests using the hydraulic CVM.

3. REQUIREMENTS OF THE ELEVON ACTUATOR MODEL

Meaningful tests on the elevon actuator subsystem can only be performed if the electronic analog actuator model accurately represents its hydraulic counterparts, the CVM and power ram. Since all signals to and from the prototype CVM are electrical, a black box approach was selected for the model. The black box or actuator simulator console (ASC) would respond like a CVM with a ram, as far as the ASA was concerned. Thus, the ASC had to present not only the same input and output impedances to the ASA as the CVM-ram combination, but it also had to respond dynamically as a CVM with a ram.

The Space Shuttle elevon actuator subsystem is designed and manufactured by HRM to specifications set by R/SD, (ref. 1). A prototype CVM has been supplied to NASA for subsystem testing. This hydraulic prototype replaces the analog secondary actuator of the ASC in the subsystem.

A mathematical model of the elevon servoactuator has been developed by J. W. Hoke of R/SD (ref. 2). It is this model which forms the basis for the analog actuator design. A block diagram of this model is shown in figure 3-1. The interface requirements of the actuator with the ASA are specified by R/SD and are listed in tables I and II. These specifications are incorporated in the design of the analog actuator, so that the ASC appears as a hydraulic actuator to the ASA (ref. 1).

In addition to the response characteristics and interface requirements of the analog model, it appeared desirable to make several of the model parameters variable. These parameters are specifically actuator position and pressure transducer offset and gain, analog hydraulic supply pressure (P_S), elevon viscous damping (B_E), aerodynamic torque on elevon (T_A), and elevon aerodynamic spring rate (K_δ).

TABLE I. – ELEVON ACTUATOR SIGNAL OUTPUTS TO ASA

Output	Primary Actuator Surface Position	Secondary Actuator Differential Pressure	Primary Actuator Differential Pressure
Transducer Type	Linear variable differential transformer (LVDT) excited by ASA		
Output Range	5 ± 0.2 Vrms (nominal excitation) no load open circuit, in-phase and out-of-phase		
Phase Shift	5° maximum lag w.r.t reference		
Null Voltage	Total: 100 mVrms maximum Harmonic: 20 mVrms maximum		
Scale Factor	0.182 Vrms / degree surface	0.00167 Vrms / psi differential hydraulic pressure	
Scale Factor Accuracy	±2% ±5% tracking among redundant transducers	±2%	
Phasing	In-phase output = Positive Cmd = Elevon Trailing Edge Down = Ram extended	= Positive Diff. Press.	= Positive Diff. Press.
Transducer Impedance	Pri: 430 + j300 + 20%/-0% at 400 Hz Sec: 240 + j170 + 20%/-0% at 400 Hz Power Dissipation: 1 watt max. at 0.8 pF min. and nom. voltage Pri. and line Cap.: 4000 pF max., distributed		

TABLE II. – ASA SIGNAL INPUTS TO ELEVON ACTUATOR

Electrohydraulic Valve Drive 2 Wire Current Source Current Range: ±9.2 mA max., ±7.6 mA dc linear Null: less than ±0.5 mA dc with all ASA input signals at 0V Load Impedance: 1000 ± 10% ohms resistance 2.5 ± 10% H inductance 4000 pF max. distributed capacitance Phasing: Pos. drive current = Pri. Act. extension
Hydraulic Isolation Valve Drive Single Wire Excitation Voltage Drop: <1.5 Vdc Excitation Voltage: 28 Vdc +4 Vdc / -6 Vdc Load Power: 15 watts max. Load Impedance: 250 ± 10% mH inductance 4000 pF max. capacitance Phasing: Excitation = Valve Closed = Isolate Transient Data: Pull-in current 150 mA max. Drop-out current 50 mA max. Pull-in time 50 msec max. Drop-out time 50 msec max.
Transducer Excitation One twisted pair. 26 Vrms ± 2.3% 400 ± 14 Hz sine wave less than 3% harmonic distortion ±10 mV max. dc offset

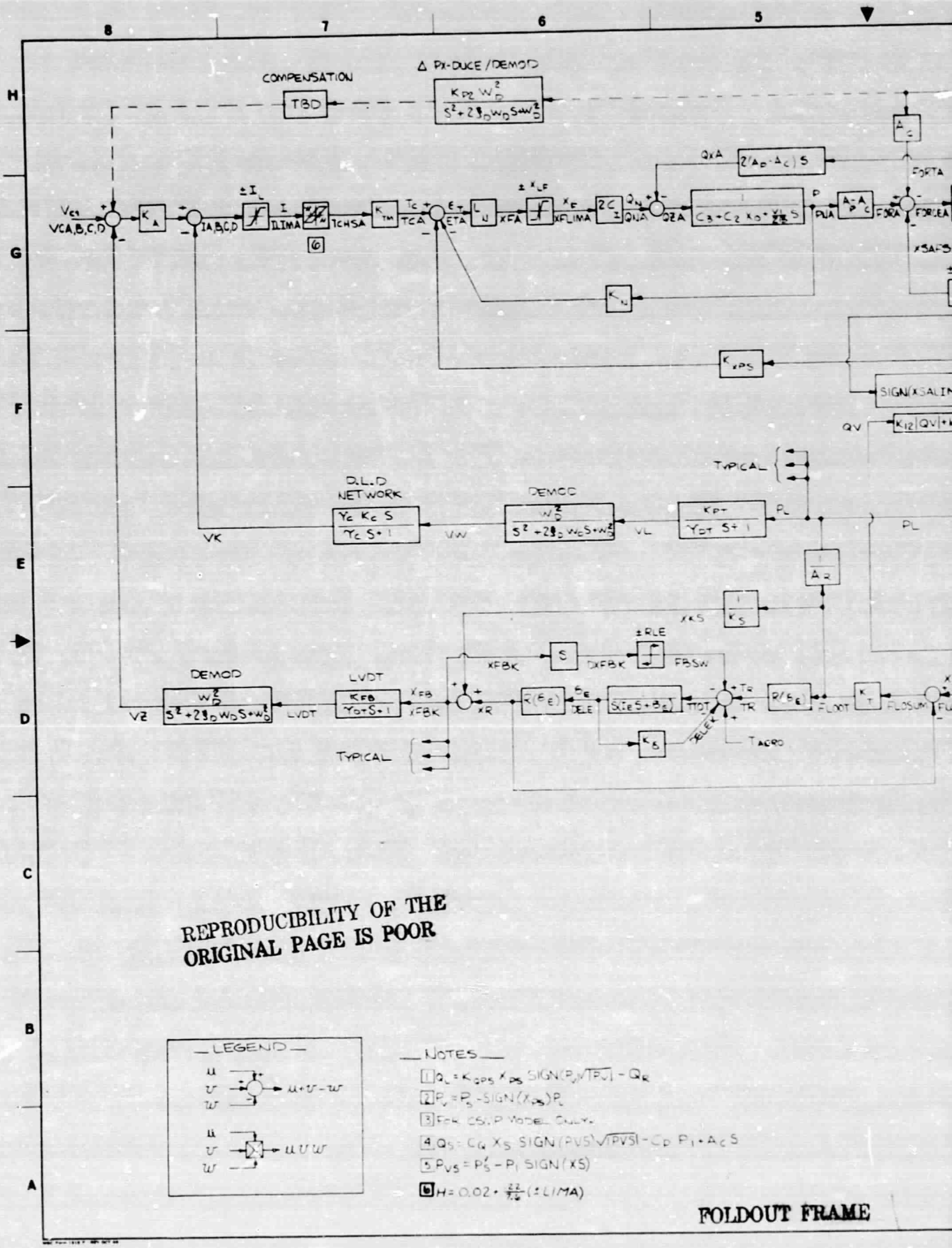


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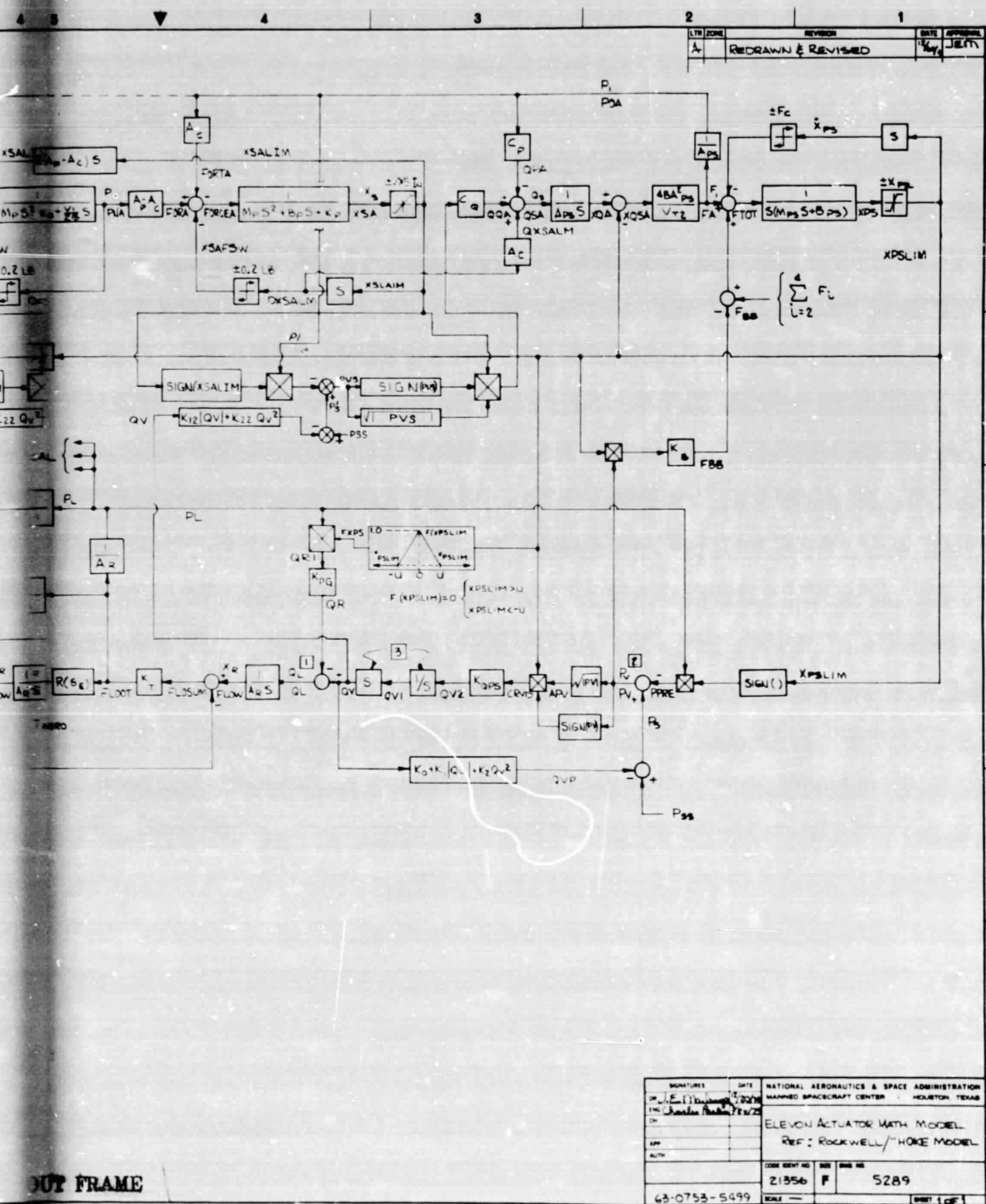
Figure 3-1. – Elevon actuato



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r Elevon actuator math model.

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These variables with their limits and nominal values are listed in table III. Front-panel test points are listed in table IV, which also indicates the scale factor at each test point.

TABLE III. – POT ADJUSTMENT DATA

Variable Units	Lower Limit Unit / Pot Setting	Upper Limit Unit / Pot Setting	Variable Change per Unit Pot Setting	Nominal Pos. Units / Pot Setting	Remarks
Supply Press. (P_S) psi	0 psi	3000 psi	300 psi	3000 psi	
	0	10		10	
Aero Torque (T_{AERO}) in-lb	0 in-lb	10^6 in-lb	10^5 in-lb	0 in-lb	
	0	10		0	
Aero Spring Rate (K_δ) in-lb/rad	0 in-lb/rad	8×10^6 in-lb/rad	8×10^5 in-lb/rad	10^6 in-lb/rad	
	0	10		1.25	
Elevon Viscous Damping (B_E) in-lb-sec	10^6 in-lb-sec	9.1×10^4 in-lb-sec	$B_E = \left(\frac{10^6}{1+P.S.}\right)$ in-lb-sec P.S. = Pot Setting	9.1×10^4 in-lb-sec	B_E is not a linear function of the Pot Setting
	0	10		10	
Transducer Gain % Nominal	105% Nom. Gain	95% Nom. Gain	1% Nom. Gain	100% Nom. Gain	
	0	10		5	
Transducer Offset % Full Scale	-5% FS	+5% FS	1% FS	0% FS	
	0	10		5	

TABLE IV. – FRONT PANEL TEST POINTS

Variable	Symbol	Units	Test Point	Scale Factor	Remarks
Torquer Current	I	mA	I1-I4	2 mA/volt	
Mod Piston Pressure Force	F	lb	F1-F4	100 lb/volt	
Mod Piston Differential Pressure	P	psi	F1-F4	525 psi/volt	
Mod Piston Power Spool Displ.	X_{PS}	in	XPS	5×10^{-3} in/volt	
Ram Load Flow	Q_L	cis	QL	20 cis/volt	
Ram Piston Displacement	X_{FB}	in	XFB	1 in/volt	
Elevon Position Angle	δ_E	degree	DE	2.5°/volt	
Hydraulic Supply Pressure	P_{SS}	psi	PSS	500 psi/volt	
Ram Load Pressure	P_L	psi	PL	500 psi/volt	
Front Panel Inputs					
Hydraulic Supply Pressure	P_{SS}	psi	PSS	500 psi/volt	Input Voltage is neg.
Aero Torque	T_A	in-lb	TA	10^5 in-lb/volt	

4. DESCRIPTION OF THE HOKE MODEL

The mathematical model of the actuator system developed by J. W. Hoke may be subdivided into the major physical units of the corresponding actuator subsystem. These units are identified as the secondary actuator, primary actuator or ram with elevon, the pressure and position transducers, and a simple ASA model which closes the control loop.

The secondary actuator is the most complex part of the actuator system. Four first-stage electrohydraulic servovalves are individually driven by electrical current commands. Each first-stage servovalve converts this electrical current command into a differential pressure which is applied to a secondary servovalve. Movement of the secondary servovalve in response to the applied pressure causes flow of hydraulic fluid into a mod piston. The mod piston integrates this fluid flow into a displacement. There are four sets of first-stage servovalves, secondary servovalves, and mod pistons. The four mod piston displacement outputs are coupled together mechanically. Motion of the mod pistons causes power spool displacement. Power spool displacement causes fluid flow into the power ram and resulting extension or retraction of the ram piston, which deflects the elevon. Ram position is fed back electrically to close the loop, as is the ram hydraulic load pressure.

Linear transfer function blocks representing sets of differential equations are shown in the s-domain or frequency domain for simplicity, so that Laplace transformations can be made (figure 3-1).

5. REDUCTION OF THE HOKE MODEL

Preliminary design of an analog actuator model required simplification of the Hoke math model, which was considered to be too complex to be practical. Reduction of the Hoke model greatly simplified the resulting electronic hardware. Only those functions of the model which were unessential and had minimal affect on the operation and fidelity were reduced or eliminated.

Guidelines used in the reduction of the Hoke model will now be discussed. Although many nonlinearities exist in the mathematical model, such as stroke limits, pressure limits, hysteresis, etc., an attempt was made to combine each linear section of the model between irreducible nonlinearities into a single higher-order transfer function. High frequency poles and zeros (greater than 1000 radians per second) were rejected, since the open-loop gain of the system is negligible at these frequencies. All summing junctions then were investigated. The maximum possible value at each input was compared, and those which contributed less than one percent of the largest input were neglected. Integrity of the physical units of the actuator was maintained in the reduction process whenever possible.

In order to make the analog actuator model represent all relevant physical quantities of the control system as voltages, each variable had to be scaled, such that its maximum value was within the available voltage range. This range is ±12 volts, since most quantities will be operational amplifier (op amp) outputs, and this is the nominal maximum linear output for op amps operating from ±15 volt supply voltages. To get optimum resolution, the voltages were scaled to make them as large as possible and still be within limits. This also had the advantage that all amplifier sections had voltage gains near unity. The resulting scaled and reduced Hoke model could now be implemented into a hardware electronic system, the actuator simulator console (ASC). A block diagram of the reduced and scaled system is shown in figure 5-1.

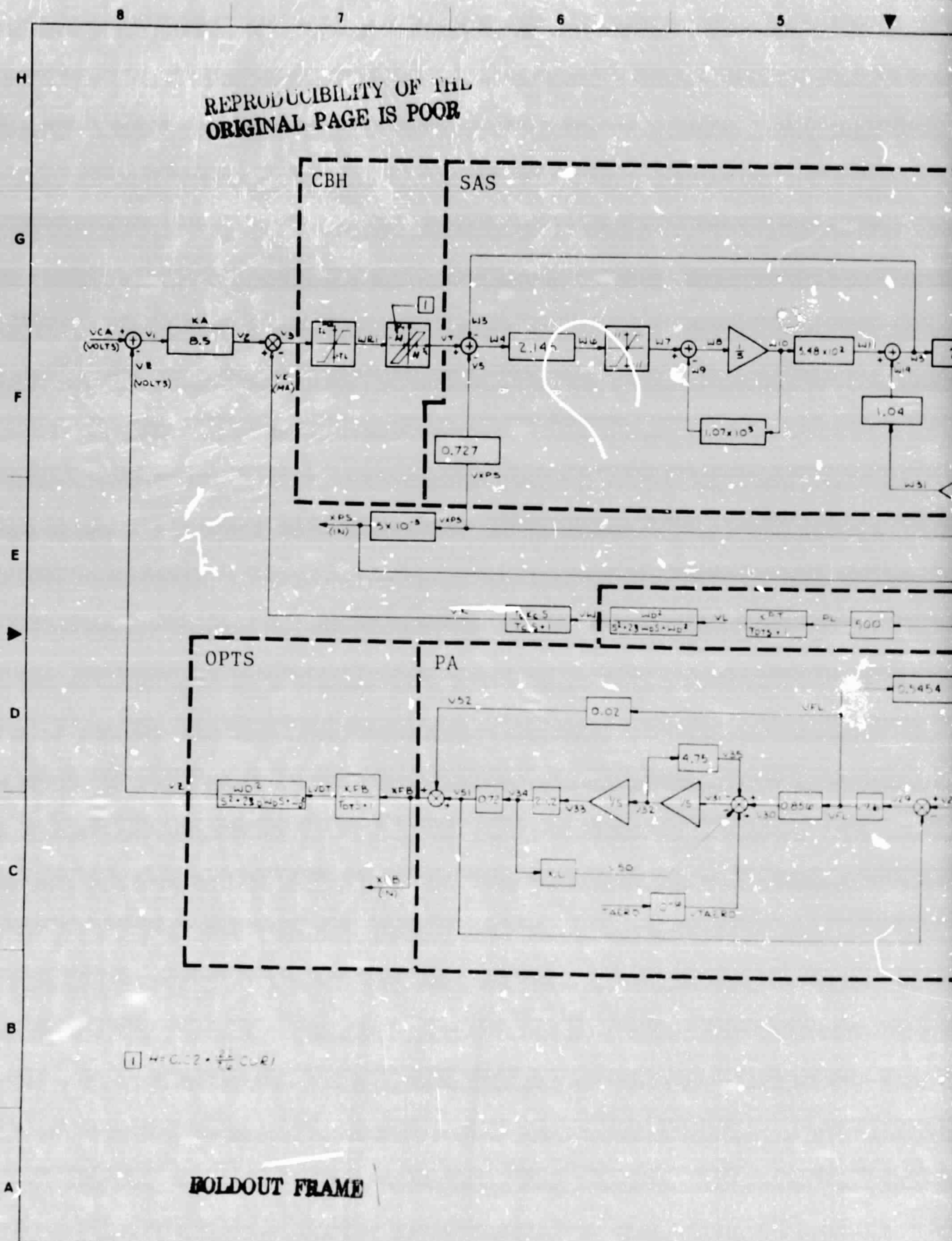
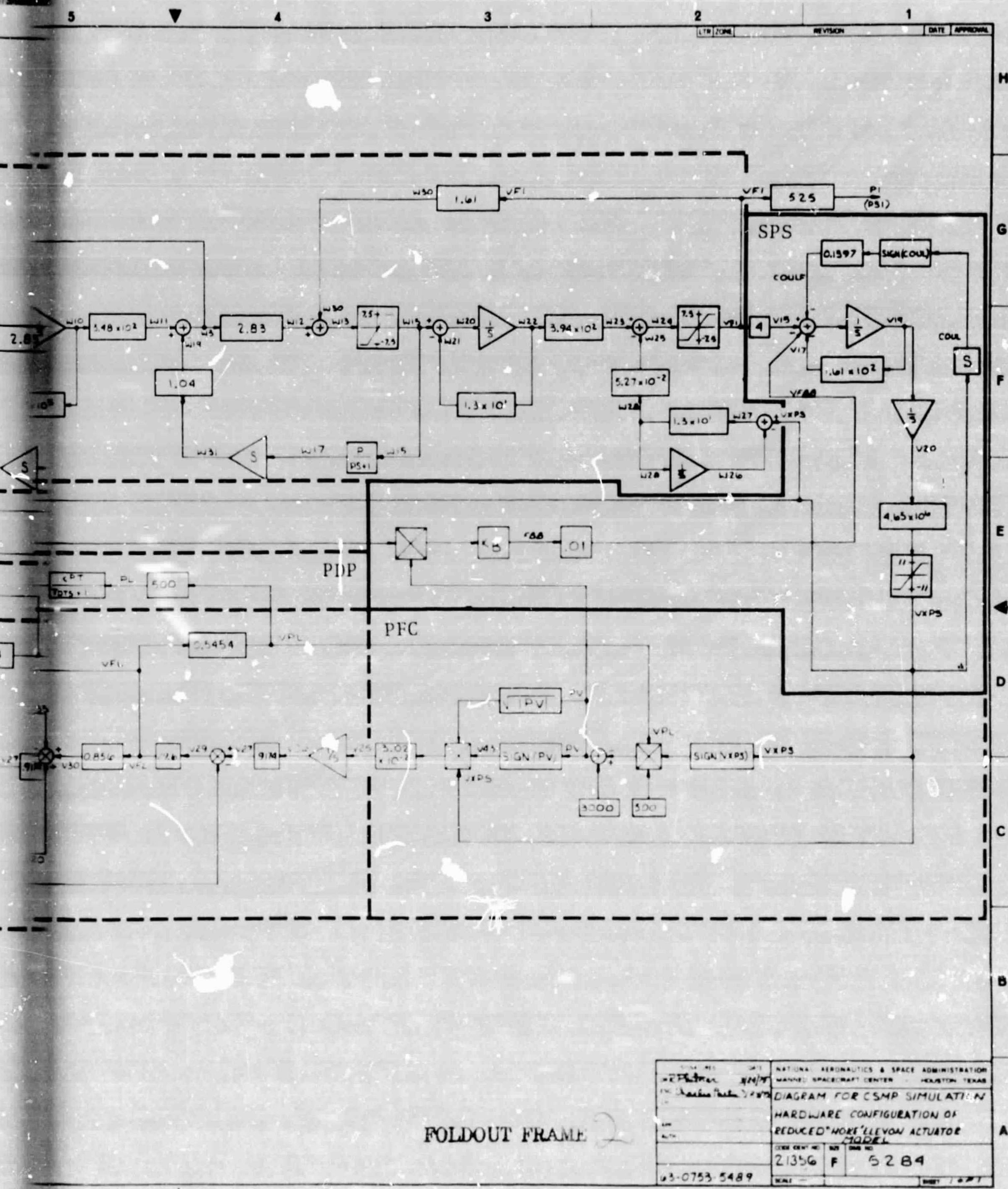


Figure 5-1. – Diagram for CSMP simulat
of reduced Hoke elevon actu



...am for CSMP simulation hardware configuration
...ed Hoke elevon actuator model.

6. VERIFICATION OF THE REDUCED MODEL

Operation of the ASC should simulate that of the Hoke model and corresponding hydraulic actuator systems. To verify operation of the reduced and scaled Hoke model before finalizing the ASC hardware design, both the Hoke math model and its reduced and scaled version were simulated on a digital computer. A special purpose modeling program developed by IBM, the Continuous System Modeling Program (CSMP), was used to program both models from their block diagrams. Equal step inputs were applied to both models in the simulation programs, and the resulting outputs were compared. Of particular interest were the ram feedback position, primary load pressure and the secondary actuator power spool position. All results verified that the reduced model is a close representation of the Hoke model.

7. HARDWARE DESIGN AND DESCRIPTION

After verification of the scaled and reduced Hoke model was completed, a detailed electronic design was started. The basic philosophy was to generate an electronic black box which would resemble the actuator and elevon in dynamic response characteristics, as well as input and output impedances. Thus, the CVM could be interchanged with its electronic equivalent in the ASC. Connectors from the ASA to the ASC were made compatible with those on the CVM. Input and output impedances of the ASC were equivalent to those of the CVM as specified by R/SD. All signals to and from the ASA were isolated, so that no common ground connection existed.

Standard analog design techniques were employed, since most of the circuits contain operational amplifiers. Components used were all commercially available. Integrated circuits were utilized as much as possible.

The reduced Hoke model was divided into physically identifiable blocks, each of which was to be contained on a circuit card. A total of 19 circuit cards were required to construct the ASC. This way the design remains flexible, so that minor changes in the math model can be incorporated in the ASC without much difficulty.

The reduced and scaled Hoke model is mechanized by electronic circuit cards as shown in figure 5-1. The dotted lines separate sections of the reduced Hoke model which are identifiable circuit cards. Figure 7-1 is a diagram showing the basic signal flow and interconnections between circuit cards.

Referring to figure 7-1, current commands from the aerosurface servo amplifier (ASA) are received by the current buffer and

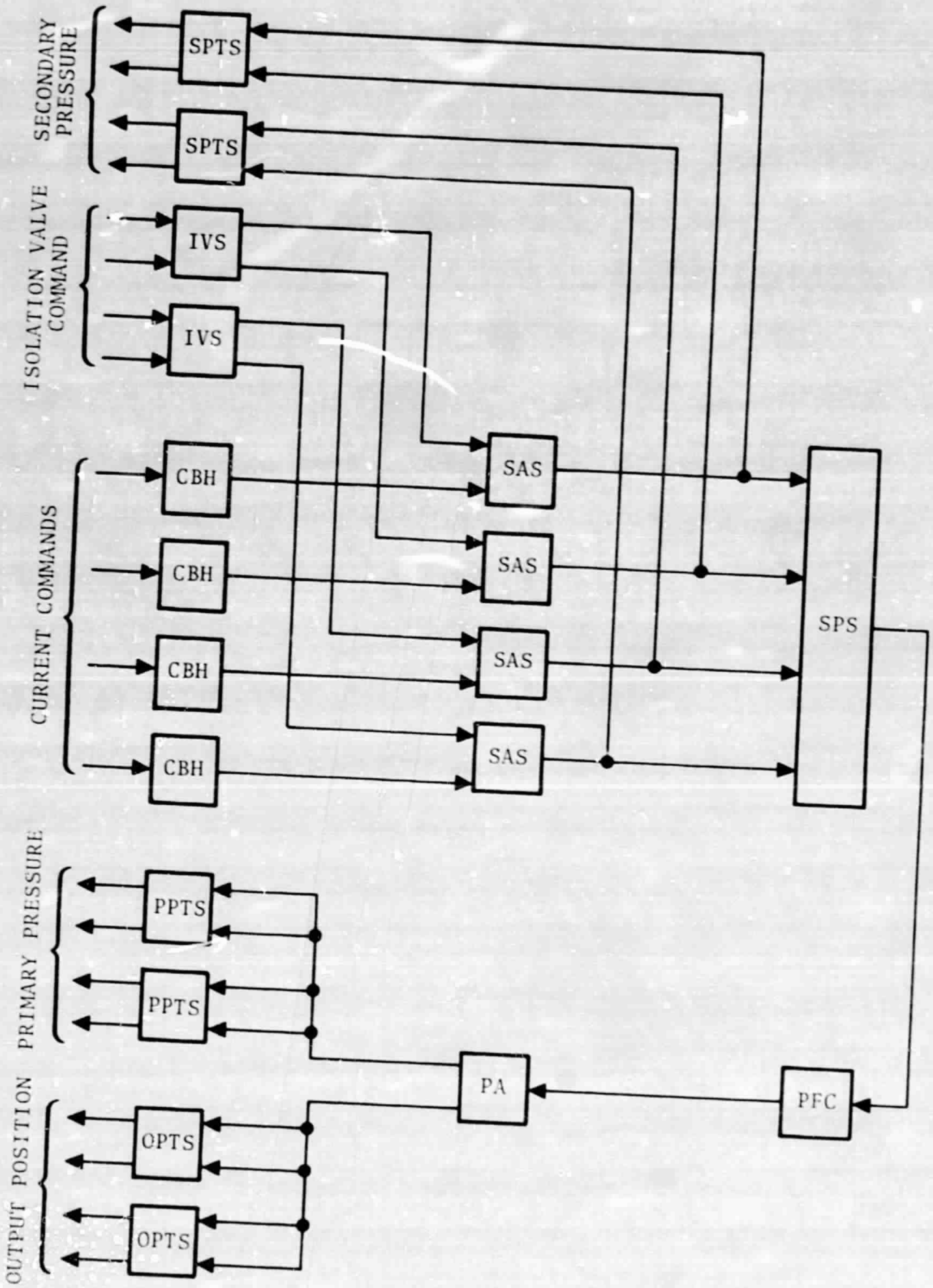


Figure 7-1. – Circuit card interconnect diagram.

hysteresis (CBH) cards. Each CBH card simulates one electrohydraulic servovalve input impedance and hysteresis. The output of each card is the flapper torque analog voltage.

The secondary actuator secondary spool (SAS) analog cards receive the CBH outputs. As the name implies, the SAS cards model the complicated secondary actuator spool dynamics. One of the outputs is the secondary differential pressure which is fed back to the ASA; another output is the applied force.

The outputs of the four SAS cards, representing the four forces generated by the secondary spools, are summed together in the SPS card. The output of this card is the power spool position (X_{PS}), represented by an analog voltage.

In the hardware actuator package, the secondary actuator spool position controls the flow of hydraulic fluid into the primary actuator or ram. The secondary actuator position to primary flow conversion (PFC) board performs this translation. The PFC output is an analog voltage representing hydraulic flow.

The primary actuator plus elevon with its associated structural characteristics is mechanized on the primary actuator (PA) board. Besides the ram position (X_{FB}) output, which is fed back to the ASA, the load pressure (P_L) also is generated and fed back. The signals fed back to the ASA are pressures and positions. On the hardware actuator, linear variable differential transformers (LVDT's) are used as transducers. These LVDT's are modeled by transducer simulator cards which are essentially all the same whether used to represent pressures or positions. The secondary actuator differential pressure transducers are simulated by a secondary pressure transducer simulator (SPTS) card. Similarly, primary load pressure transducers are modeled by the primary pressure transducer simulator (PPTS) and the primary position by the output position transducer simulator (OPTS) card. Each transducer simulator card contains two LVDT simulators. In order to isolate a faulty secondary actuator channel, the hardware CVM uses an electrically operated isolation valve. In the ASC, this valve is simulated by the isolation valve simulator (IVS) card, which also contains two channels per card.

The unit is housed in a 19-inch wide equipment drawer which contains two circuit card racks, a panel with adjustment potentiometers and a dc power supply.

Test points are available on the front panel so that system variables may be sampled and tested. Some system parameters may be adjusted with potentiometers. These parameters are: hydraulic supply pressure, aerodynamic torque, elevon aerodynamic spring rate, and elevon viscous damping. Inside the drawer a special panel provides gain and offset adjustments for all transducer outputs to the ASA. A switch provides for changeover from system operation with the hydraulic CVM to operation with the analog secondary actuator.

8. TESTING OF THE ACTUATOR SIMULATOR CONSOLE

Before insertion into the ASC, each card was tested. The linear frequency response for small signals was measured and compared with the theoretical response. Those cards containing nonlinearities, such as the current buffer and hysteresis (CBH) cards or the square root and sign functions of the secondary actuator position to primary flow converter (PFC) card, were tested as required. The transducer simulator cards were tested to insure that all gain, phase shift and impedance specifications were met.

To permit performing a closed-loop checkout of the ASC without using the ASA, an electronic circuit was designed and constructed to close the control loop in a manner similar to the ASA.

After completing a thorough checkout of the ASC and eliminating some minor problems, the closed-loop response of the ASC was measured for comparison with that of the Hoke model using a CSMP simulation. Again a step input was applied. Reference 3 discusses the results of these tests and contains a graphic comparison of the performance of the analog and Hoke models.

It was concluded in the memo (ref. 3) that performance of the electronic model of the elevon actuator agrees essentially with that of the Hoke math model, and that the electronic model is, therefore, a valid representation of the elevon actuator subsystem. To support this conclusion, figure 8-1 is reproduced from reference 3. This graph shows the elevon primary actuator position in degrees as a function of time, when the system is excited by a step command. Three curves are shown, two for the Hoke model with respective high and low gains, and one for the electronic hardware model or ASC. As can be seen, the ASC response falls between the two Hoke model responses.

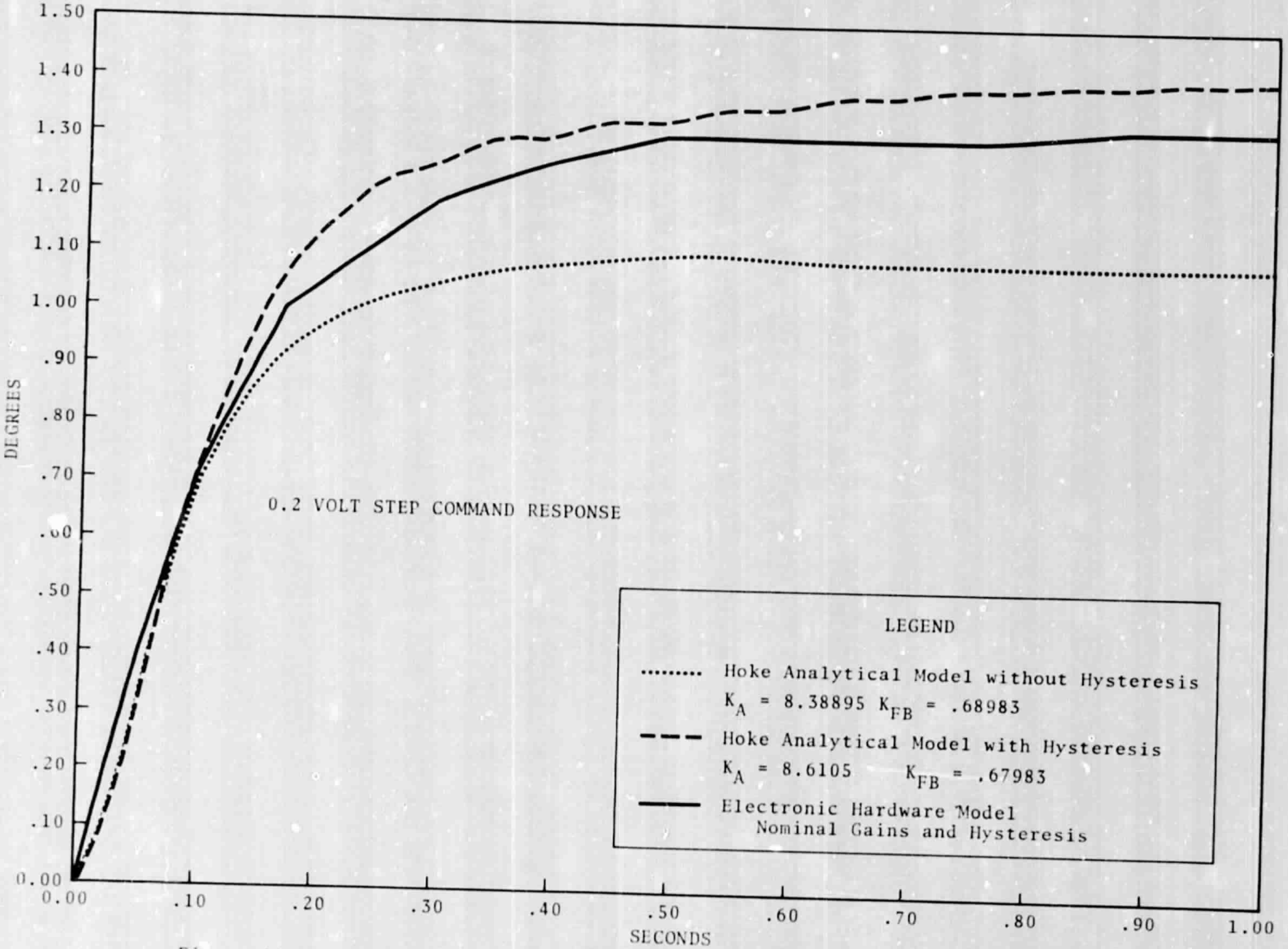


Figure 8-1. – Elevon primary actuator position in degrees versus time in seconds.

9. CONCLUSIONS

The evolution of an actuator subsystem from a detailed mathematical model developed by J. W. Hoke of R/SD to a special purpose analog computer, the actuator simulator console (ASC), was described. It was found that the ASC is a very accurate representation of its hydraulic counterpart. In certain instances, the ASC has definite advantages over its counterpart, such as in the ease of making configuration changes, the elimination of cumbersome hydraulic supplies, and in a lower overall cost.

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