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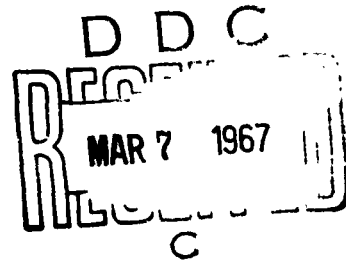
**Digital Hydraulic Actuator Study**

**Phase III  
Final Report**

Sponsored by:  
Air Programs, Office of Naval Research  
Contract Nonr 4375(00)

By:  
G. W. Scott

IBM NO. : 66-L03-005



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November 1966

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**IBM** *Federal Systems Division, Electronics Systems Center,  
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## ABSTRACT

To further support the practicability of the digital hydraulic actuator as a control component, IBM has successfully demonstrated operation of the Phase III laboratory model in a simulated digital flight control system. Performance using the laboratory model is compared with the performance when using a mathematical model. Recorded transients and the values obtained for a maximum stable step and gain change are presented. The effect of varying the actuator parameters and the validity of a linearized model is also established. Agreement of the results shows the mathematical model to accurately represent the actual hardware. Hence, this study verified the results of both Phase I and Phase II.

## ACKNOWLEDGEMENTS

**Mr. J. W. Raider, the originator of the digital hydraulic concept investigated, significantly contributed to the success of this program by his participation during the initial part of Phase III and the earlier phases.**

**The mathematical model and simulated flight control system was programmed by Mr. N. L. Pleszkoch.**

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## Section I

### INTRODUCTION

#### A. SUMMARY

Completion of Phase III yields results which further support the practicability of a digital hydraulic actuator (DHA) for flight control. A laboratory model of the DHA was operated in a closed loop simulating the digital flight control of the Polaris missile. Performance of the simulated control system using the actual hardware is compared with the performance obtained with the mathematical model. Results presented show the mathematical model to accurately describe hardware dynamics.

Due to the ram area ratio, the system performance could not be determined with the required friction load. However, having established the validity of the mathematical model, the performance of the system with the required ram area and friction load was determined by simulation. The effect of varying the actuator parameters and the performance for a "worst" case parameter condition was also established. Analog flight control, which was simulated in Phase I, is used to provide a basis for evaluating the digital flight control.

A linearized model of the DHA is derived. The model is shown to be a valid approximation when operation is not velocity saturated and quantization is ignored. Frequency response, phase shift, and response to a step command is used as a basis to show the linearized model is a good approximation.

#### B. PURPOSE AND OBJECTIVES OF PROGRAM

Control of an aerospace vehicle can potentially be simplified by using the capabilities of the digital guidance computer for performing those control functions now being accomplished by analog techniques. To study the impact of digitally controlled actuators on flight control systems and to ascertain those requirements of the DHA, ONR initiated Contract No. Nonr 4375(00). The total objective of this program is to demonstrate the feasibility of a DHA as a flight control component. The program consists of three phases whose objectives are:

- Phase I - To ascertain those DHA requirements that are necessary in an aerospace application such as Polaris

- Phase II - To design and evaluate DHA meeting the requirements found necessary in Phase I
- Phase III - To demonstrate the performance of the DHA hardware in a simulated digital flight control system and to establish the accuracy of the mathematical model.

The use of an incremental DHA will result in:

- System simplification by the elimination of digital-to-analog conversion equipment required for communicating between the digital computer and the actuator
- Elimination of an output transducer and a summing amplifier in the analog hydraulic servo loop
- Substitution of bi-stable control valves for the analog control valves, the latter being more susceptible to null shift and oil contamination
- Increased versatility to perform such operations as programmed gain changes or adaptive functions
- A significant step toward realizing an all-digital control system.

### C. DESCRIPTION

The IBM Digital Metering Unit complemented by a hydraulic actuator make up the DHA. The metering unit actuated by digital commands produces a required change of position by the transfer of calibrated fluid volumes. Each digital command produces a volume of fluid equal to one quantum of position. The DHA thus provides a capability of transforming digital commands without conversion into related output positions. A detailed description of the operational concept is presented in Appendix A.

A mathematical model of the DHA is compared with the actual hardware by the arrangement depicted schematically in Figure 1-1. The arrangement provides a capability of monitoring the unused model. Equations describing the flight control system and the DHA are implemented by a hybrid combination of an IBM 709 EDPM and a EAI Analog Computer. The arrangement of the hardware is shown in Figure 1-2.

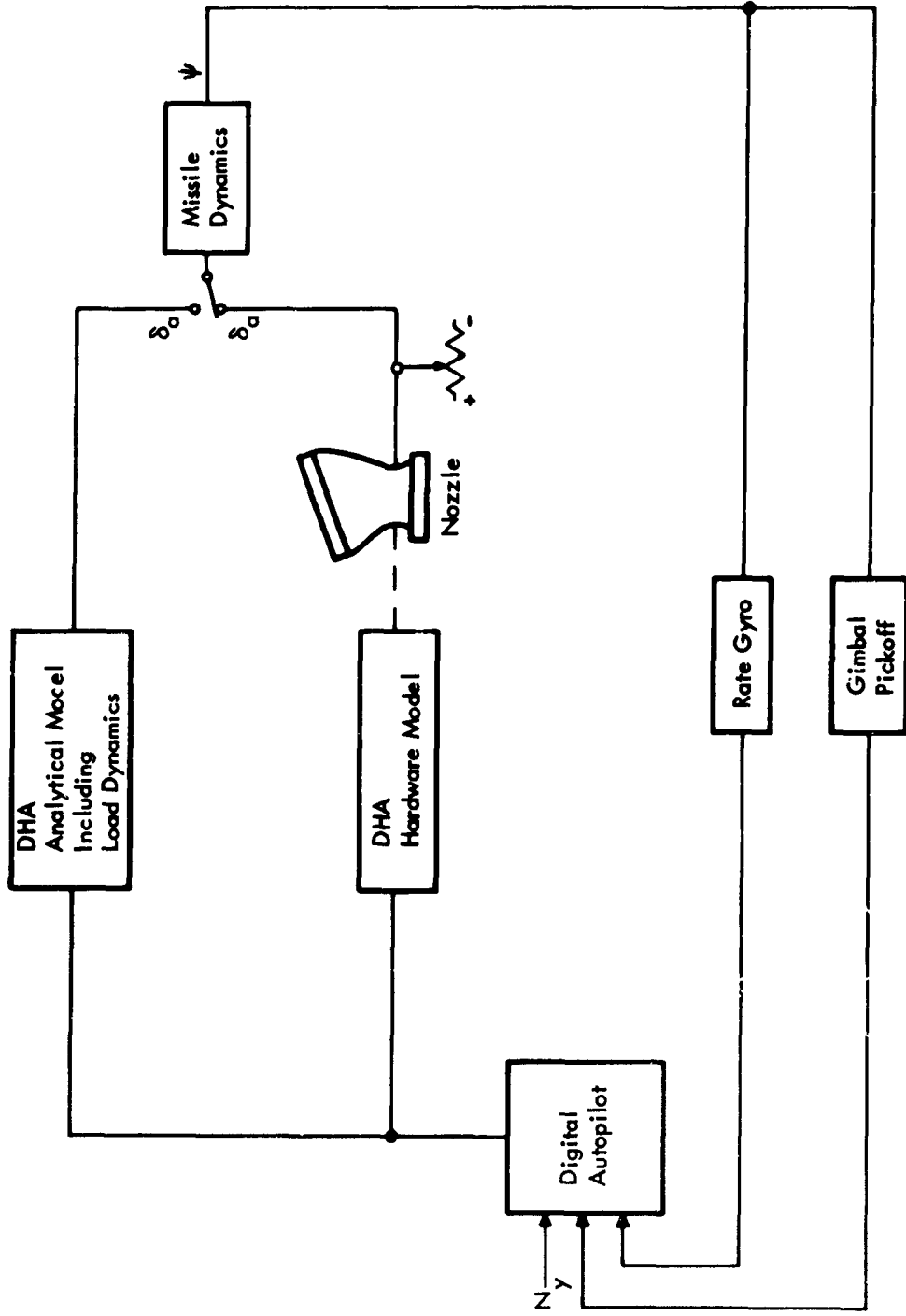


Figure 1-1. Simulation Arrangement



Figure 1-2. Laboratory Arrangement

#### **D. CONCLUSIONS**

Completion of Phase III yielded the following conclusions:

- The mathematical model of the DHA is an accurate representation of the actual hardware
- Results obtained by the Phase I simulation are valid
- Parameter values to attain a required system performance can be accurately determined with the mathematical model of a simulated system.
- A DHA is feasible for an aerospace application, such as Polaris
- For an application such as the Polaris, the acceptable tolerance on the leakage parameters,  $q_L$ , and  $q_{LC}$ , is relatively large. Hence leakage variation due to production tolerances and wear should not present a problem
- The suitability of the DHA to a given application can be initially determined by means of a linearized model.

#### **E. RECOMMENDATIONS**

The DHA for this study was tailored to the requirements of the Polaris Missile. Other applications may require a DHA capable of producing a smaller resolution and a higher velocity. For some applications such as aircraft, a two-speed actuator may be necessary to achieve both high resolution and high velocity of the controlled surface.

The following is recommended for future study:

- Ascertain by simulation the requirements and performance when using a DHA for the control of an aircraft, including the effect of the oscillatory motion of the control surface during steady state on the vibratory modes of the structure.
- Evaluate the performance of a two-speed actuator having the capability of changing the direction of drift\*

\*Raider, Scott, "Digital Hydraulic Study Engineering Summary Report Phase II; Contract No. Nonr 4375(00), IBM No. 66-928-7.

- **Evaluate the design of the laboratory model of the DHA. Based on the results design a DHA which is representative of a deliverable item, meeting reliability and environment specifications.**
- **Design of a metering unit which uses a double-ended ram. This will increase the output power of the actuator for any selected flow and pressure.**



## Section II

### TECHNICAL APPROACH

This section describes the equipment, and implementation of the equations. The Phase III Study consisted of the following effort:

- Design logic interface between the hardware and simulated flight control system
- Implement equations defining the DHA and flight control system
- Compare performance of simulated control system when using actual hardware with the performance when using the mathematical model
- Establish the performance of the Polaris missile when using a DHA which provides a force independent of the direction of motion and opposed by a 600-pound coulomb friction load
- Ascertain the effect of parameters on performance of the simulated system
- Determine the validity of approximating a DHA and digital control system by a linearized model.

Phase III is consistent with Phase I in that:

- Missile dynamics are when the missile is subjected to maximum aerodynamic pressure which corresponds to the least controllable portion of the flight trajectory
- The yaw angle, the loop of highest gain, is studied
- Feedback components are assumed to be ideal in that no error is contributed to the system by the resolution or drift of the attitude sensors

- The transfer function of the Polaris missile is derived for the short period oscillation mode, assuming:
  - Rigid Structure
  - Stationary environment
  - Small perturbations
  - Missile aligned with the equilibrium position of the velocity vector (zero sideslip)
  - Constant mass.

#### A. EQUIPMENT - ARRANGEMENT AND DESCRIPTION

Arrangement of the equipment for the Phase III simulation is shown in Figure 2-1. Two modes of operation are provided, the analog mode and simulation mode. The analog mode permits the DHA to be operationally checked without the computer. A commanded position is compared with the actual position to produce an error signal which is converted into digital signals; a sign, and a volume command. The simulation mode permits the DHA to be operated open loop to control a simulated plant (the Polaris missile). Position error is determined by the control loop about the plant.

##### 1. VALVE CONTROL LOGIC

The control logic permits evaluation, in either the simulation or analog mode, of a single-speed actuator, two-speed actuator or an actuator for achieving accurate positioning, i. e., operation at the discontinuous point of the flow curve (Figure 2-2). Schematic and detailed logic is presented in Appendix B.

Logic required for the Phase III Study is depicted in Figure 2-3. The logic requires that a sign command be received in parallel with each volume command. Sign commands following the last sign change produce the gating signal,  $\bar{\Delta}$ . A volume command when accompanied with the signal,  $\bar{\Delta}$ , is gated to the actuating driver. The actuating driver, upon receipt of a digital command, de-energizes the valve latch to initiate the transfer of a calibrated fluid volume. When changing the direction of motion, the signal,  $\bar{\Delta}$ , does not occur, and the volume command in parallel with the sign command is inhibited. The sign command switches the sign driver, and the transfer of a calibrated volume follows the switching of the sign valve. Sign commands following the last sign change are transmitted to the same sign driver. However, the sign valve is now controlled by the sign driver associated with the latch magnets holding the armature.

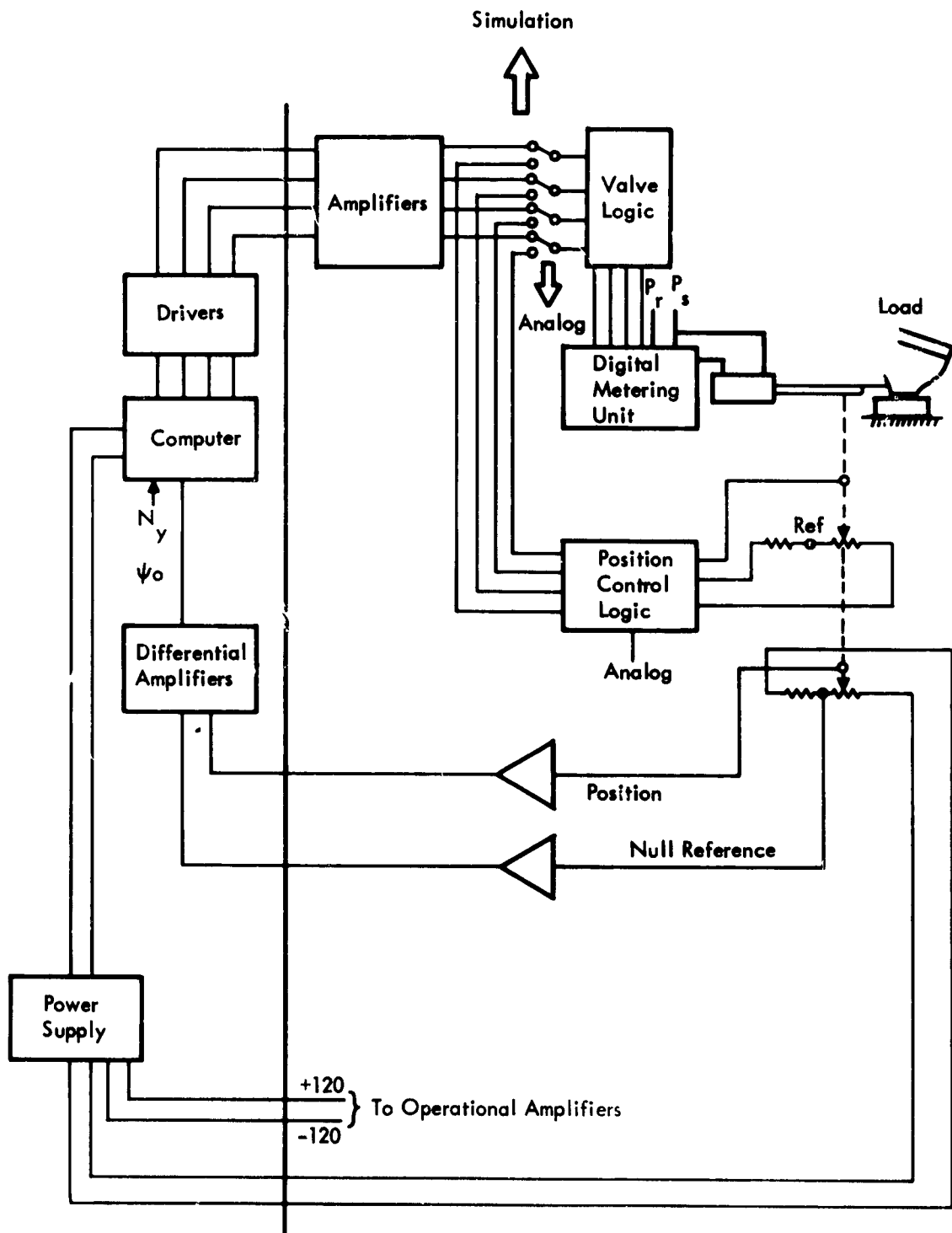


Figure 2-1. Arrangement of Equipment

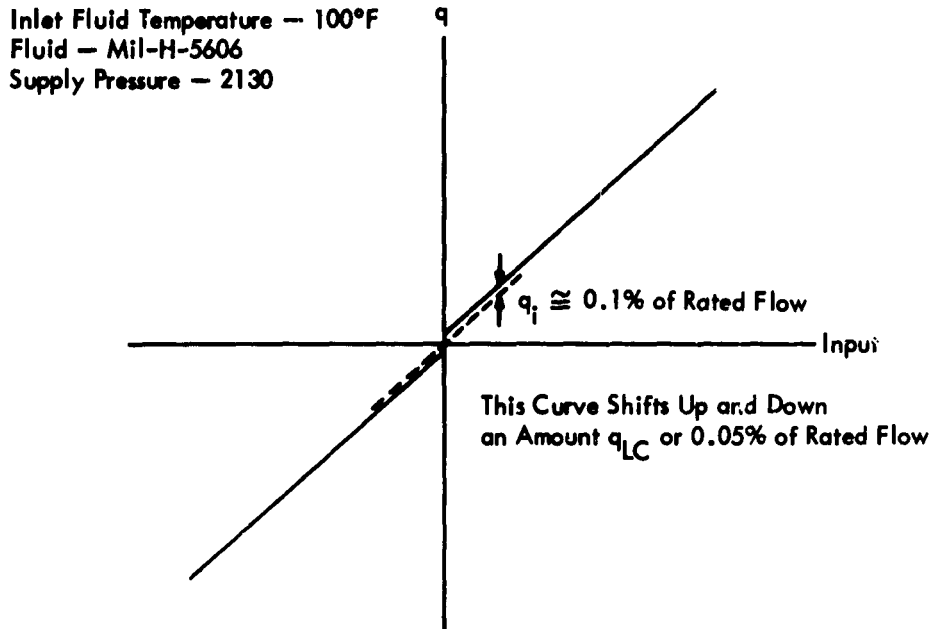


Figure 2-2. Flow Curve for Digital Unit

## 2. POSITION CONTROL LOGIC

The position control logic shown in Figure 2-3 is used when operating in the analog mode to produce the sign and volume commands. The error detector determines the correction required by predicting the error that will exist after effecting the last command. This is accomplished by updating the error signal, based on present position, with the signal produced by the current driver, representing the position change commanded. Hence, the time-lag due to the time required to position the load does not introduce a false error. The error detector outputs (sign and volume commands) are gated to the pulse generators to produce pulses compatible with the valve logic input requirements.

## 3. DIGITAL HYDRAULIC ACTUATOR

As previously stated, the DHA consists of the prototype digital metering unit and a commercial actuator cylinder. The following modifications were

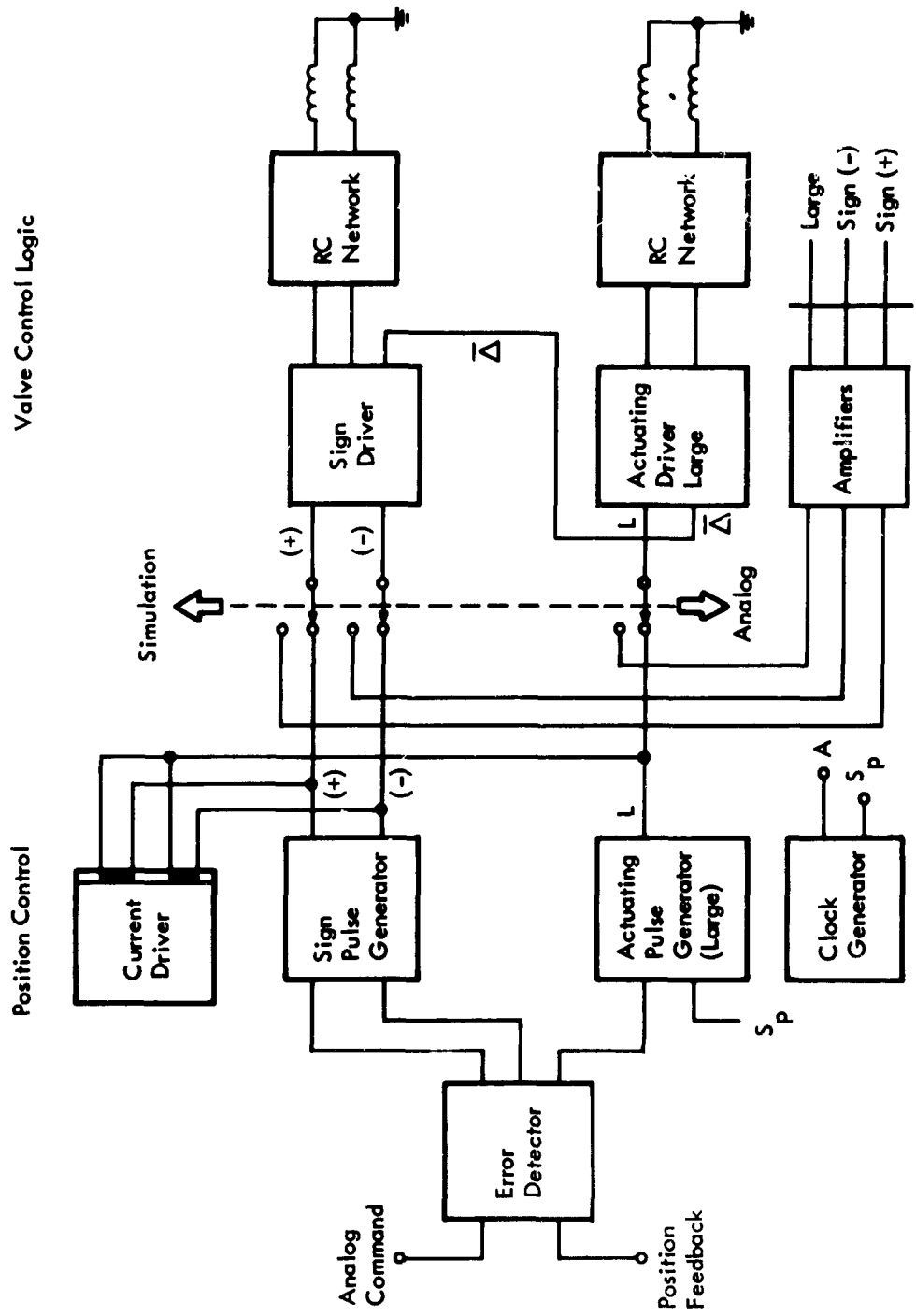


Figure 2-3. Phase III Control Logic

incorporated to improve performance and overcome operation problems experienced during Phase II:

- Relative motion between the pilot spools and armature bearing play was minimized by the use of shims and removing the bearing located on the eccentric
- New magnets were designed to provide a larger holding force and to eliminate the problem of lead wire breakage
- A new manifold was designed to eliminate the excessive leakage due to the location of the port to ram. In addition, the manifold provides ports for an additional valve unit and calibrating cylinder. Hence a capability for two-speed operation.

A commercial cylinder having a ram area of 0.994 square inch and an area ratio of 1.59:1 was used. Since this ratio differs from that required, the force produced is not the same for positive and negative motion.

#### 4. COULOMB FRICTION

Coulomb friction is generated by the bearing and seals when firing the nozzle. To simulate coulomb friction, a phenolic pad was hydraulically loaded against an aluminum drum segment connected to the nozzle. Radial loading of the bearings was minimized by placing the back of the drum segment against the outer race.

Because the area ratio of the ram limited the force capability, the required coulomb friction could not be used when operating with the hardware.

#### B. METHOD OF SIMULATION

The mathematical model for the Phase III Study of the digital autopilot, DHA and missile dynamics is shown in Figure 2-4.

##### 1. DIGITAL AUTOPILOT

The digital autopilot is programmed as shown in Figure 2-5. The yaw command,  $N_y(t)$ , can be either a step  $|N_y|$  at  $t = 0$  or  $|N_y| \sin \omega t$ .

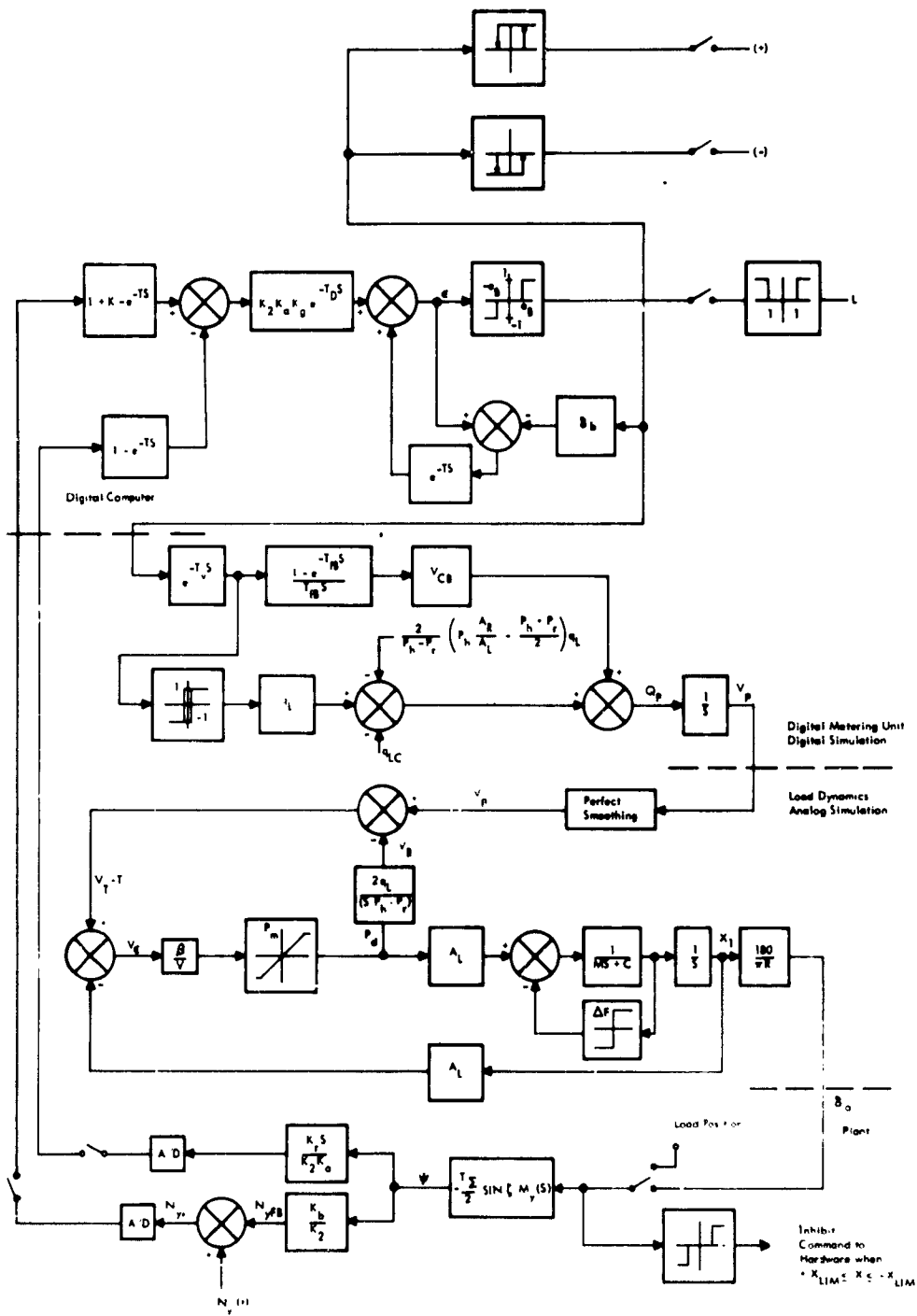


Figure 2-4. Mathematical Model of Digital Autopilot, Digital Actuator, and Missile Dynamics

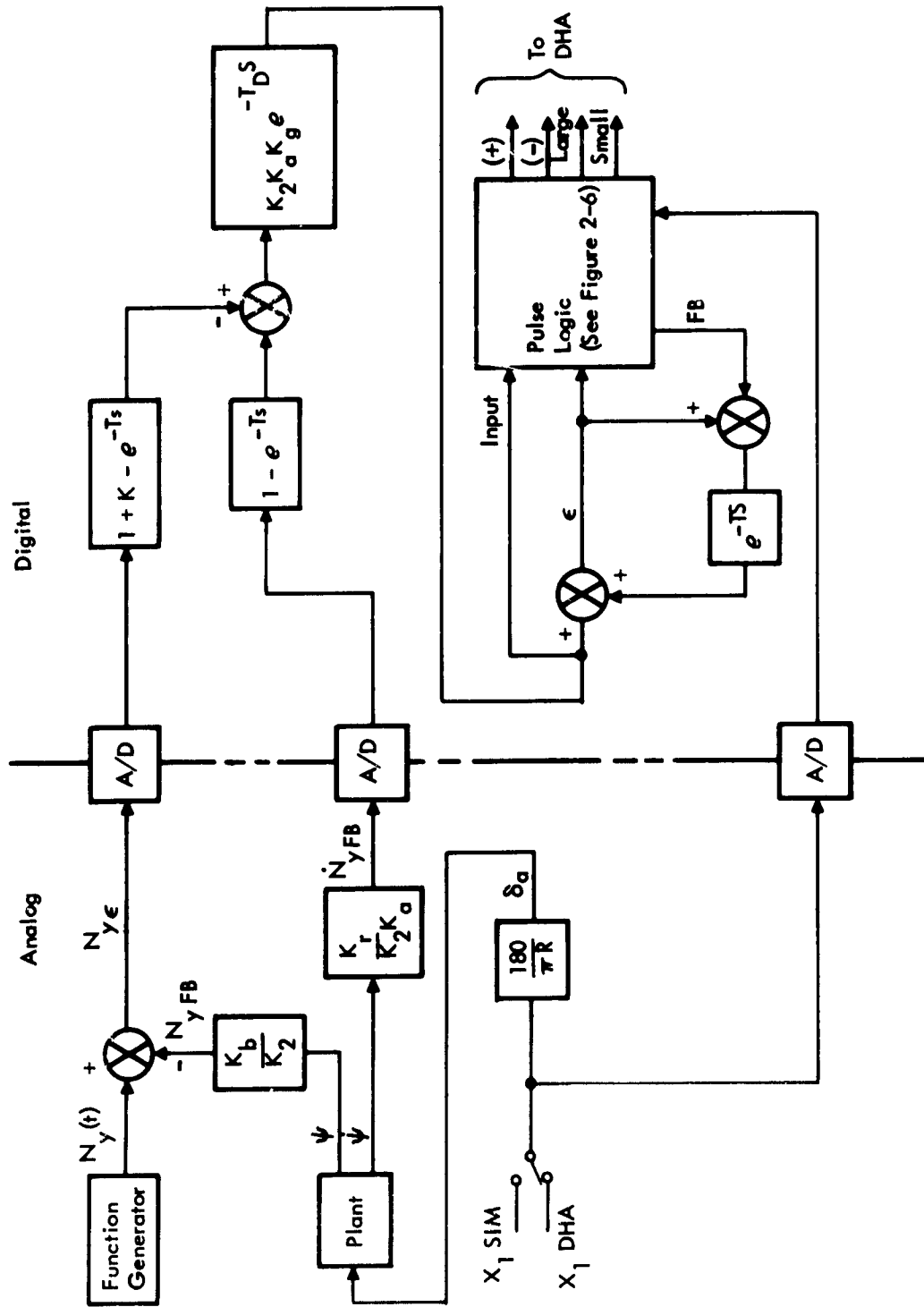


Figure 2-5. Digital Autopilot



The pulse logic box, which is depicted in detail in Figure 2-6, has been generalized to allow for the following autopilot options:

- Single-Speed Operation — Single-speed operation was used for the Phase III Study. This option is attained by setting  $e_s = e_b$ . Note that the condition imposed on  $\epsilon$  to select a small volume command is then  $e_b > |\epsilon| > e_s$  which cannot be satisfied since  $e_s = e_b$ .
- Two-Speed Operation — This option makes it possible to simulate an actuator having two volume sizes, a large volume for slew, and a small volume for fine quantization.

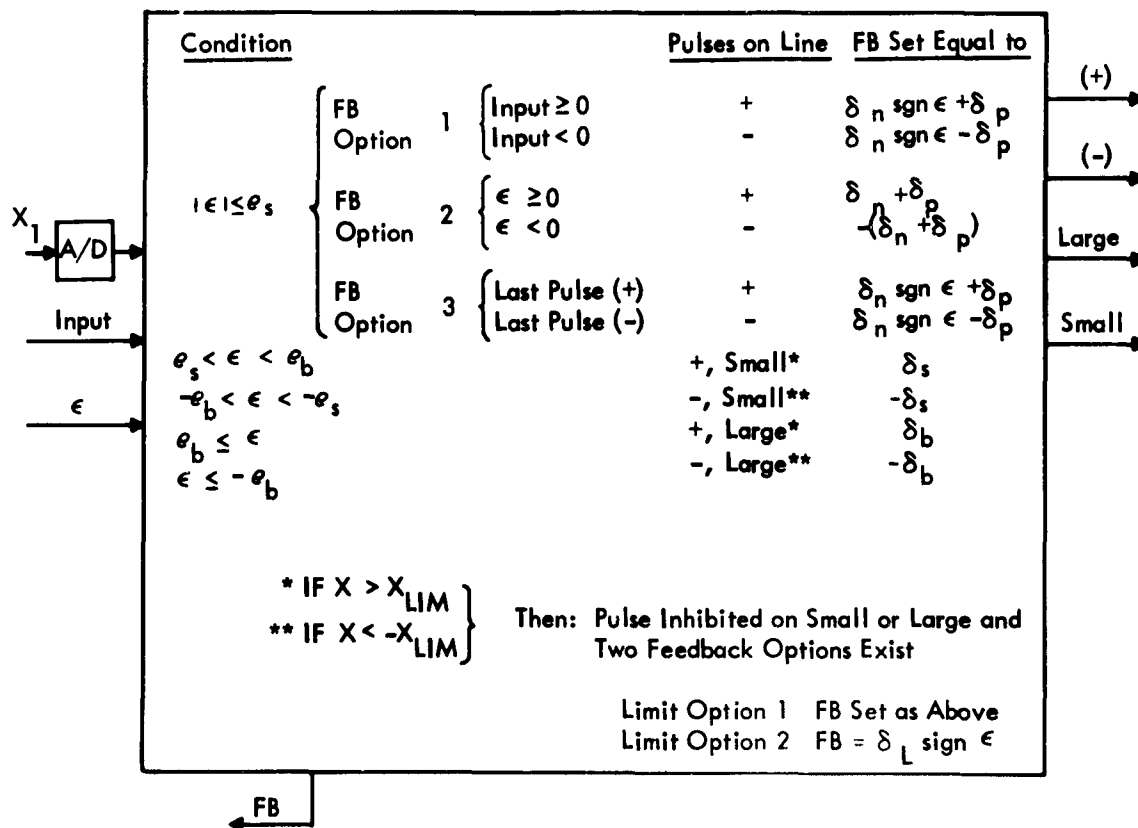


Figure 2-6. Pulse Logic

- Accurate Positioning (Precision Mode) — This option provides the capability of changing the direction of ram motion without displacing a calibrated volume.

If  $|\epsilon| \leq e_s$  the drift option allows the drift polarity to be determined by the polarity of "Input",  $\epsilon$ , or the last command.

- Feedback Flexibility — The polarity of  $\epsilon$  may be the opposite of the DHA sign pulse for  $|\epsilon| \leq e_s$ . To provide the flexibility of attaining a feedback (FB) polarity equal to the polarity of  $\epsilon$  or the polarity of the sign pulse, FB is set equal to

$$\delta_n \operatorname{sgn} \epsilon + \delta_p \operatorname{sgn} (\text{sign pulse}).$$

For small volume commands

$$\text{FB} = \delta_s \operatorname{sgn} \epsilon,$$

and for large volume commands

$$\text{FB} = \delta_b \operatorname{sgn} \epsilon.$$

Hammering of the actuator into its stops by the control computer is prevented during check out and stability check runs by inhibiting the volume commands if the ram position magnitude,  $|X_1|$ , exceeds  $X_{\text{Lim}}$ . A value of  $X_{\text{Lim}}$  was selected so that  $|X_1| = X_{\text{Lim}}$  when the ram is 0.3 inch from the stop. (This distance allows for the displacement produced by the volume stored by the auxiliary pistons.) Since the plant may recover from short periods of  $\delta_a$  saturation, two limit options are provided. Limit option 1 assumes the control computer has no feedback from the actuator and does not alter FB. Option 2 allows for a special FB equal to  $\delta_L \operatorname{sgn} \epsilon$  assuming some sort of limit detection. In summary, Phase I is duplicated if:

$$\epsilon_b = e_s = \frac{1 \text{ quantum} + \text{hysteresis}}{2} = 0.681 \text{ for a quantizer hysteresis of } \delta_q/4$$

drift option = 3

limit option = 1

## 2. DIGITAL HYDRAULIC ACTUATOR (DIGITAL PORTION)

After transmitting the DHA pulses, the digital computer calculates  $Q_{p1}$ ,  $Q_{p2}$ ,  $Q_{p3}$  and  $\Delta V$  as shown in Figure 2-7. Where:

$Q_{p1}$  is the flow for  $t$  in the interval  $(t_v, t_{fs})$

$Q_{p2}$  is the flow for  $t$  in the interval  $(t_{fs}, t_{fB})$

$Q_{p3}$  is the flow for  $t$  in the interval  $(t_{fB}, t_v)$

$$\Delta V = \int_{t_v}^{t_v + T} Q_{p_i} dt \quad (i = 1, 2, 3)$$

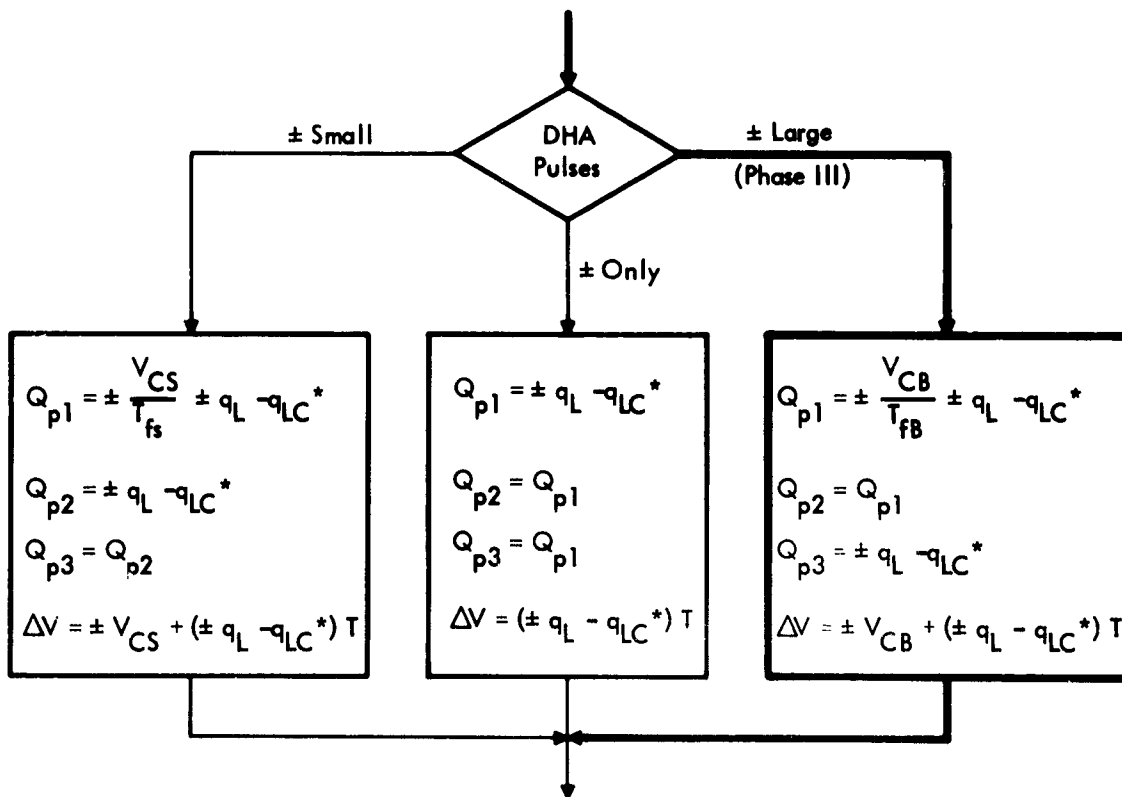


Figure 2-7. Flow Calculations

With reference to the timing chart shown in Figure 2-8, the  $Q_{pi}$  ( $i = 1, 2, 3$ ) are converted from digital to analog at the proper time and fed to an analog integrator to get  $V_p$ . To prevent drift in this open-loop integration, the  $\Delta V$ s are summed to form a digital representation of  $V_p$ . A drift correction ( $Q_{corr}$ ) is added to the  $Q_{pi}$  to force the analog value of  $V_p$  to match the digital value  $V_{dig}$  at sampling times (Figure 2-9).

Transfer of the volume commanded during the interval  $T_{(n-1)}$  is completed during the time interval  $T_{(n)}$ . Therefore, to make  $V_{dig}$  assume values correct at the analog-to-digital version time,  $T_{A/D}$ , of  $V_p$ ,  $\Delta V$  is divided so that

$$\Delta V = \int_{t_v}^{t_v + T(n)} Q_p dt = \Delta V_1 + \Delta V_2$$

where

$$\Delta V_1 = \int_{t_v}^{t_{A/D} + T} Q_p dt$$

$$\Delta V_2 = \int_{t_{A/D} + T}^{t_v + T} Q_p dt$$

Thus during the  $n$ th DHA cycle, the volume added to the integration summer is:

$$\Delta V' = \Delta V_1(n) + \Delta V_2(n-1)$$

or

$$\Delta V' = \int_{t_{A/D}}^{t_{A/D} + T} Q_p dt$$

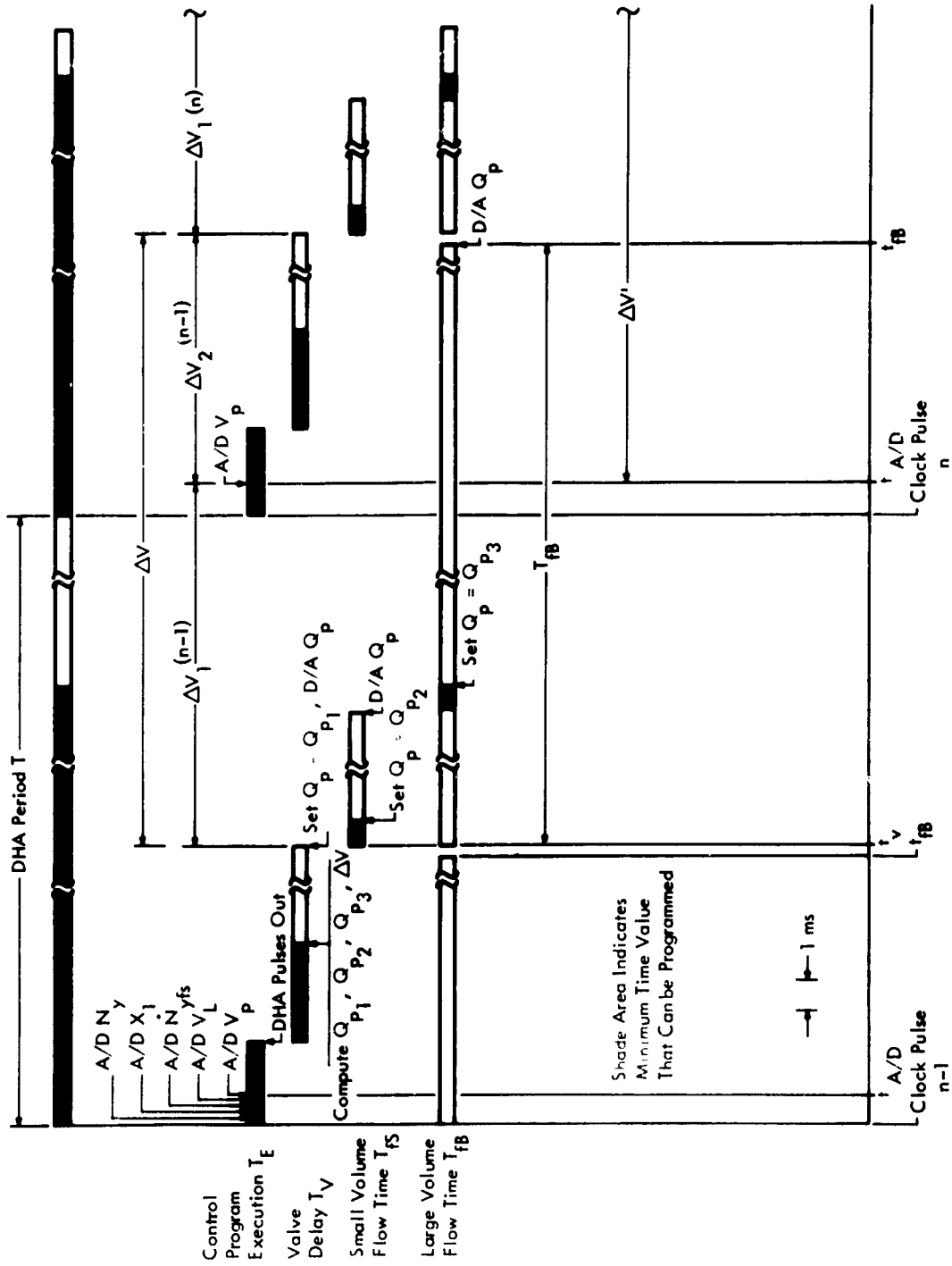


Figure 2-8. Timing Chart

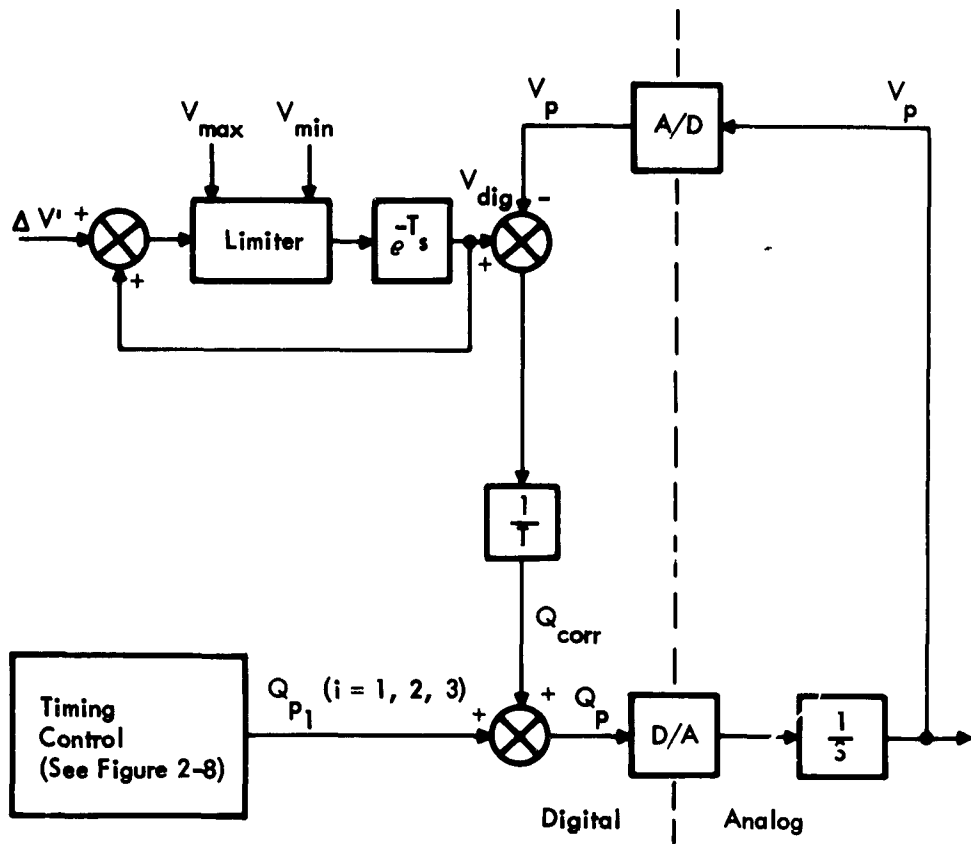


Figure 2-9. Digital Integration

The limiting values,  $V_{max}$  and  $V_{min}$ , for the digital integrator (Figure 2-9) are variable and are obtained from the following relationships:

$$V_T = V_p - \frac{2q_L}{P_h} \int_0^t P_d dt = V_p - V_B$$

which is depicted by block diagram in Figure 2-10. Since  $V_T$  has a fixed limit,  $V_{Lim}$ ,

$$-V_{Lim} < V_T < V_{Lim}$$

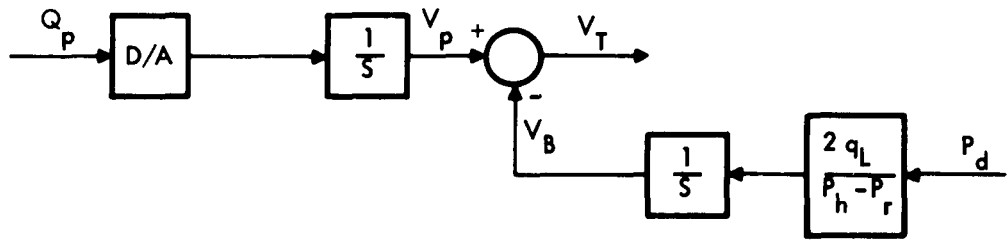


Figure 2-10. Method of Obtaining Limiting Values for the Digital Integrator

or

$$-V_{Lim} < V_p - V_B < V_{Lim}$$

or

$$-V_{Lim} + V_B < V_p < V_{Lim} + V_B$$

Therefore,  $V_B$ , an analog quantity, is converted from analog to digital form, and the limits on  $V_{dig}$  are computed by the digital computer as

$$V_{min} = -V_{Lim} + V_B$$

$$V_{max} = V_{Lim} + V_B$$

### 3. DIGITAL HYDRAULIC ACTUATOR (ANALOG PORTION)

The analog simulation of the actuator dynamics is programmed as in Phase I, (Figure 2-11) with the exception of the coulomb friction. As a result of simulating in real time (Phase I simulation was 1/10 as fast) the limited frequency response, and amplifier phase shift caused the coulomb feedback loop to oscillate when used as a simple bang-bang amplifier as illustrated in Figure 2-12. Hence during a steady state, large-amplitude oscillations of the pressure,  $P_d$ , resulted. To overcome this problem, a latching electronic switch is used at the input of the  $\dot{X}$  integrator (Figure 2-13).

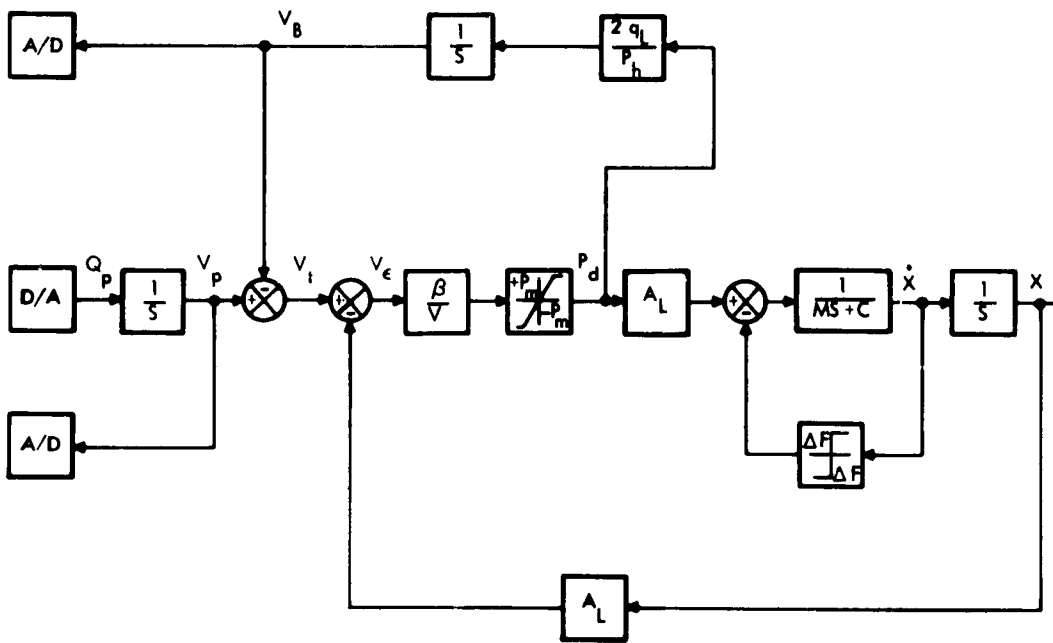


Figure 2-11. Actuator Dynamics

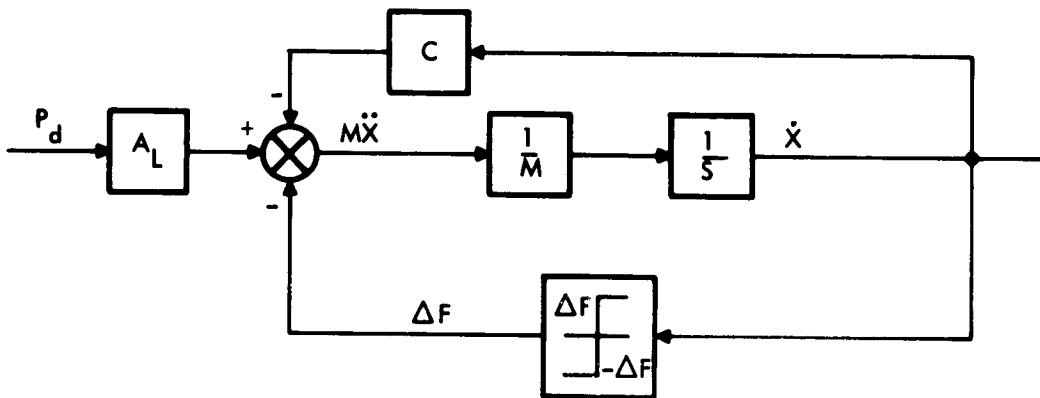


Figure 2-12. Simulation of Coulomb Friction (Phase I)



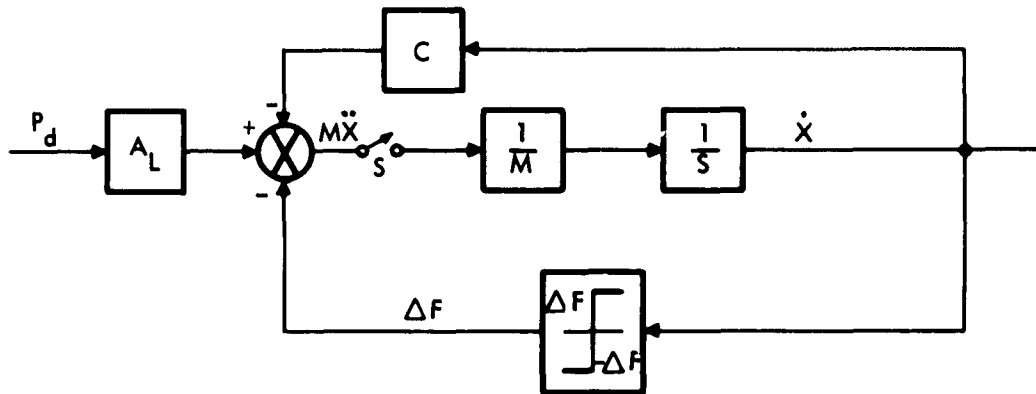


Figure 2-13. Simulation of Coulomb Friction (Phase III)

The logic that operates switch S is:

- S closes and latches whenever  $|P_d A_L| \geq F$
- S unlatches when both  $|P_d A_L| < F$

$$\dot{X} = 0$$

This prevents  $\Delta F$  from acting as an accelerating force because of phase shift.

#### 4. COMPARISON

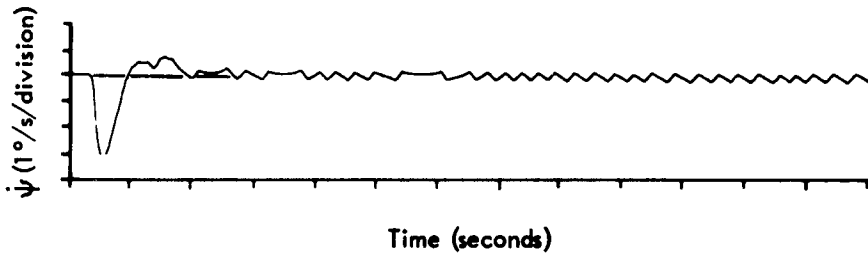
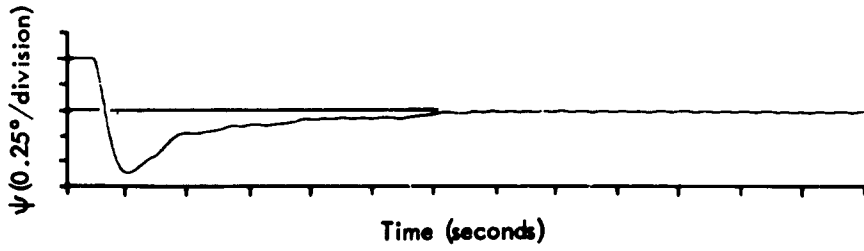
This method of simulating the digital autopilot and DHA for Phase III differed from Phase I. To establish that the results obtained with the present model agreed with the results obtained during Phase I, several simulation runs depicting significant characteristics were rerun. Parameter values used for the reruns were identical to those used for the Phase I Study except for the fluid flow time,  $T_{fB}$ . The parameter  $T_{fB}$  is not readily modified in the program; therefore,  $T_{fB}$  was programmed for the value obtained by test and does not significantly influence the results.

The results attained are compared in Table 2-1 with the results of Phase I. The agreement of the two methods of implementing the equations is further illustrated by the recorded transients shown in Figure 2-14.

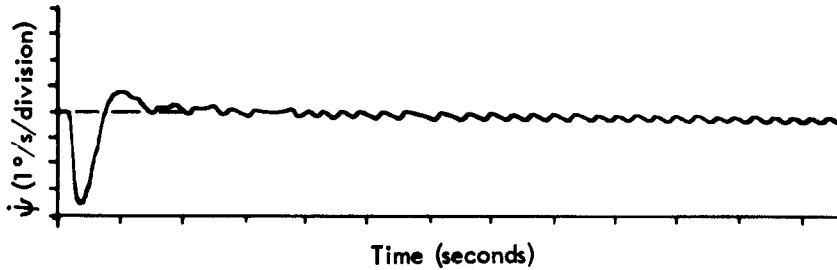
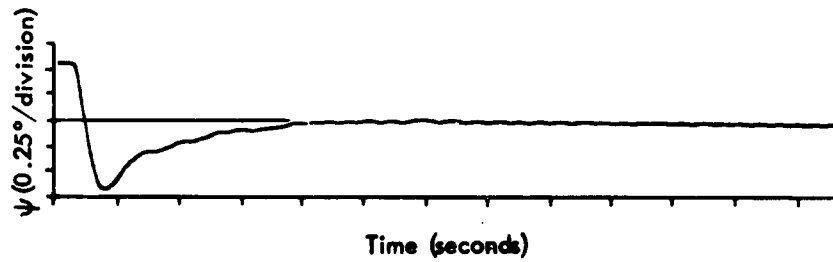
Table 2-1

SIMULATION RUNS TO DETERMINE AGREEMENT BETWEEN THE METHODS OF IMPLEMENTING THE MATHEMATICAL MODEL

Model	Results			Parameters								Reference Run (Phase I)
	Stable k g	Unstable k g	Input	K (K <sub>1</sub> g)	q <sub>L</sub> in <sup>3</sup> / sec	q <sub>LC</sub> in <sup>3</sup> / sec	δ <sub>q</sub> deg	T 10 <sup>-3</sup> sec	M Slugs	Quantizer Hysteresis		
Phase I	5.55	5.90	0	0	0	0	1.09	12.1	3.55	δq/4	180	
Phase III	5	5.55										
Phase I	5.55	5.90	0	0	0.14	0.01	1.09	12.1	3.55	δq/4	182	
Phase III	5	5.55										
Phase I	Maximum Stable Step			0.01	0.14	0.01	1.09	12.1	3.55	δq/4	193	
Phase III												
Phase I	Unstable Step			0.01	0.14	0.01	1.09	12.1	3.55	δq/4	194	
Phase III												
Phase I	Figure 2-14 a			0.002	0.14	0.01	1.09	12.1	3.55	δq/4	207	
Phase III	Figure 2-14 b											



a) Phase I Simulation



b) Phase III Simulation

Figure 2-14. Recorded Transients for  $\psi = -1/2^\circ$   
(Run 207 Table 2-1)

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### Section III

#### MATHEMATICAL MODEL EVALUATION

Performance of the simulated control loop when using the mathematical model of the DHA is compared with the performance when using the laboratory hardware. Accuracy of the model is established by correspondence of the recorded ram motion and agreement of the results for:

- Maximum stable step
- Response to a step command,  $N_y = 10$
- Response with an initial yaw condition
- Gain margin for initial conditions less than one quantum
- Limit cycle
- Frequency response and phase shift.

Plant transients presented in this section are of significance only for the purpose of comparison since the ram used did not produce the same force for both directions of motion.

With the DHA in the loop the initial condition of the ram is obtained by allowing the ram to drift from a positive to a negative value. The position is sampled at the operating frequency (82.5 Hz) and the run is started when a zero or negative ram position is detected.

The unpredictable behavior of an unstable plant with zero initial conditions, quantization effects, and the method of initializing the position of the physical load will produce variations in the plant response. Therefore, small variations of the plant transient when using the mathematical model from the transient generated when using the hardware does not necessarily indicate an inaccuracy of the mathematical model.

#### A. PARAMETER VALUES

Parameter values defining the actuator and load dynamics are shown in Table 3-1. The parameter values were established by test when practicable. Values not measured are indicated. Accurate values are not readily

Table 3-1

## PARAMETER VALUES

Parameter	Units	Value	Parameter	Units	Value
$\Delta F$	lb	380	$e_b$	deg	0.681
M	lb-s <sup>2</sup> /in	0.25	Quant. Hys.	deg	$\delta q/4$
R	in	8.125	$\delta_b$	deg	1.09
$\frac{* \beta}{V}$	lb-in <sup>-5</sup>	26,600	K	—	$2^{-7}$
*C	lb-s/in	12			
$q_L$	in <sup>3</sup> /s	0.107			
$q_{LC}$	in <sup>3</sup> /s	-0.006			
$q_{LC}^*$	in <sup>3</sup> /s	-0.0165			
$V_{CB}$	in <sup>3</sup>	0.152			
$f_c$	Hz	82.5			
$T_V$	in <sup>-3</sup>	5.5			
$t_f$	in <sup>-3</sup>	10			
$P_M$	lbf/in <sup>2</sup>	+540 -960			
$P_R$	lbf/in <sup>2</sup>	130			
$P_h$	lbf/in <sup>2</sup>	2,130			
$A_L$	in <sup>2</sup>	0.994			
$A_L/A_R$	—	1.59			
*Value Approximated					

## B. RESULTS

Simulation results when using the parameter values of Table 3-1 are shown in Table 3-2. Table 3-2 also shows the results when changing the parameter value of Table 3-1 to that indicated.

Table 3-2

### PERFORMANCE OF SIMULATED FLIGHT CONTROL SYSTEM

Parameter Value	Maximum Stable Step	Unstable Step	$K_G$ ( $N_y = \psi_o = 0$ )		Reference: Figure No.	
			Stable	Unstable	$N_y = 10$	Limit Cycle
Hardware						
Digital	11	12			3-2	3-5
Hydraulic			4	4.5		
Actuator	-8	-9			3-8	
Mathematical Model						
Table 3-1	11	12	4	4.5	3-6	3-7
	-8	-9				
Mathematical Model with:						
C = 6	11	12	4	4.5	3-9	3-11 a
	-9	-10				
C = 18	11	12	3.5	4	3-10	3-11 b
	-6	-7				
$\frac{\beta}{V} = 13,300$	11	12	4	4.5	3-12 a	3-13 a
	-8	-9				
$\frac{\beta}{V} = 100,000$	11	12	4	4.5	3-12 b	3-13 b
	-8	-9				
$\Delta F = 0$	11	12	4.5	5		
	-9	-10				

Recorded transients which further support the accuracy of the mathematical model and the effect when varying the parameters are shown.

As shown by Table 3-1, the maximum stable step is dependent on the sign of the steering pulse command  $N_y$ . The difference between the maximum positive and maximum negative stable step is a consequence of the ram force being different for positive and negative motion. The higher negative force produces a larger effective moment due to faster response and increased overshoot. Recorded transients of the ram for positive and negative yaw step commands are shown in Figure 3-1. For the negative step command the ram is seen to be velocity saturated during the positive motion.

Figure 3-2 shows the recorded ram motion of the laboratory model and mathematical model for a yaw step command when closing the simulated loop with the laboratory model (Figure 3-3). It is significant that the transients are parallel. With the mathematical model operated open loop, and error in the leakage rate,  $q_{LC}$ , will cause the ram transient for the mathematical model to converge or diverge relative to the transient recorded for the actual ram. Hence the parallel transients verify the value of  $q_{LC}$  to be reasonably correct.

Although the agreement is good the transients differ when changing from negative ram motion to positive ram motion, detail A, Figure 3-2. This difference is due to the velocity produced with the mathematical model for negative motion being greater than that achieved with the hardware. A lumped parameter approximation is used to describe damping in the mathematical model. Accuracy of the approximation is decreased when the damping is significantly different for positive and negative motion. With the larger accelerating force for negative commands, Figure 3-4, a larger force acts on the ram before the auxiliary piston is displaced. Until the calibrating piston stroke is completed, the return lines effect damping of the ram motion. Hence, because of the unequal ram force, the damping realized when initiating negative motion is greater than that produced by the mathematical model.

The value used for the damping coefficient ( $C = 12$ ) better represents the damping for positive motion. This is shown by the agreement when the order of ram motion is reversed, see detail B, Figure 3-2.

Limit cycles produced with the hardware and mathematical model in parallel are shown in Figure 3-5. With the simulated loop closed about the hardware, the higher velocity achieved with the mathematical model for negative commands can be seen. Also of interest is the "stepping" characteristic produced with the mathematical model during drift (see detail A of Figure 3-5). This characteristic is due to the method of implementing coulomb friction. Steps occur when the condition  $P_d A_L \geq \Delta F$  is obtained, thus closing the switch (Figure 2-13). Oscillations of  $P_d$  which result



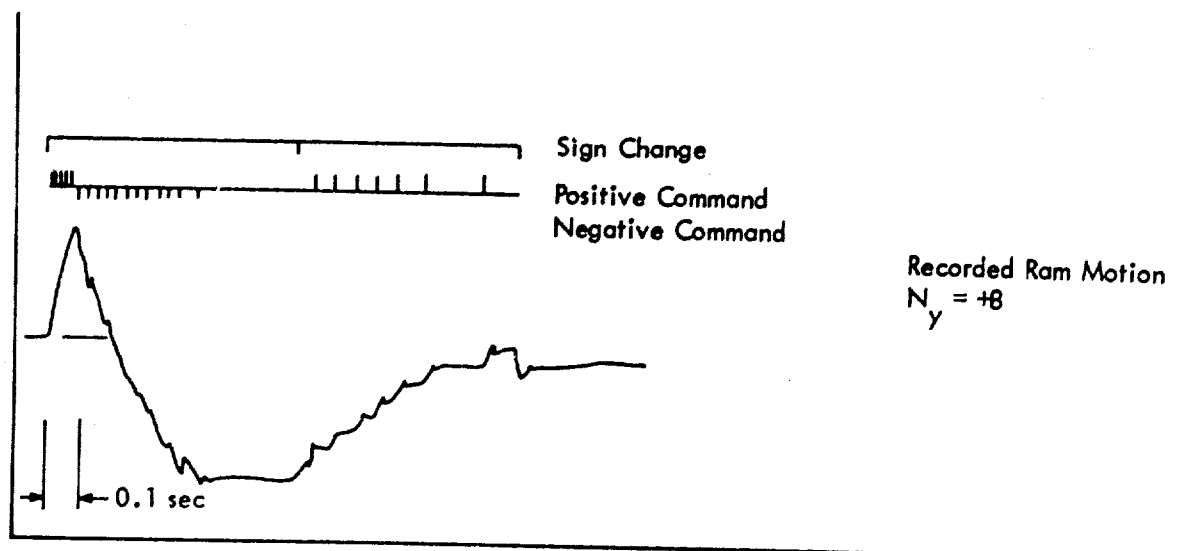
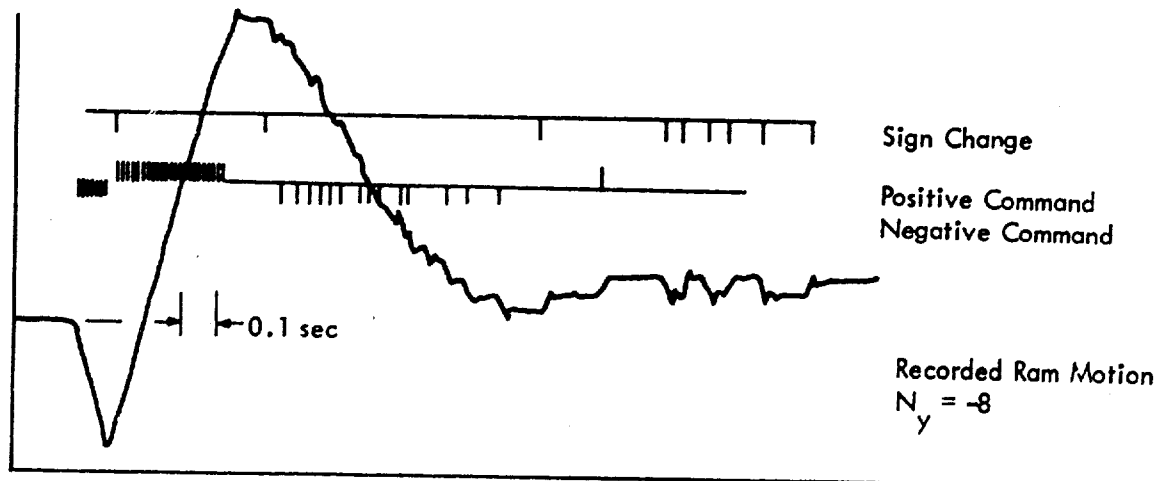


Figure 3-1. Recorded Motion of Ram with Digital Hydraulic Actuator in Simulated Control Loop ( $\Delta F = 60$  lbs)

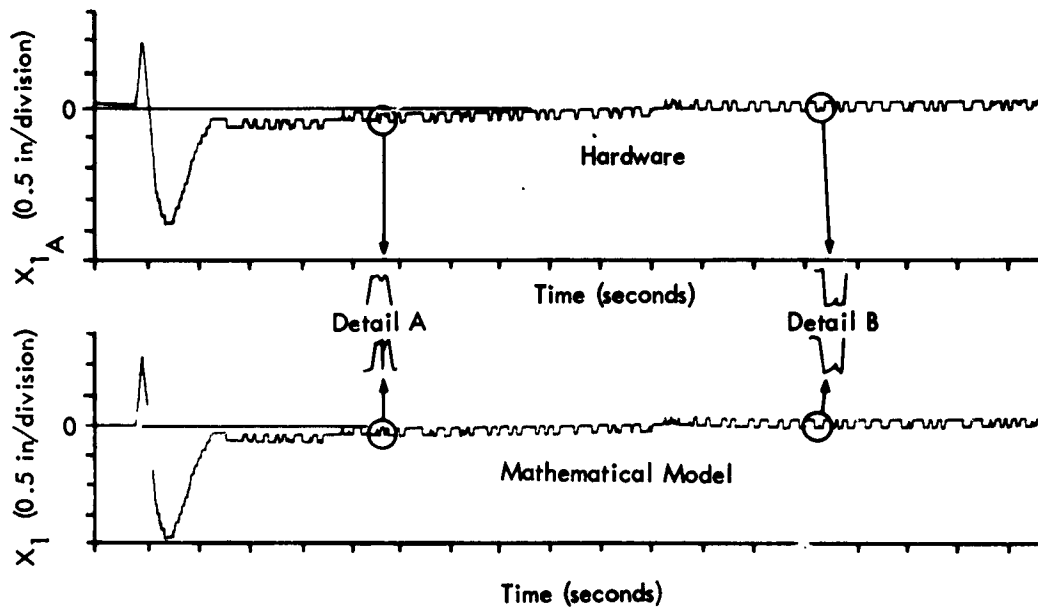


Figure 3-2. Ram Motion for a Yaw Step Command ( $N_y = 10$ )

create the conditions required to open the switch, i. e.,  $P_d A_L < \Delta F$ ,  $X_1 = 0$ . The stepping characteristic can also be noted in Figure 3-13 showing the effect of the parameter  $\beta/V$  on the limit cycle. With the increased resonance frequency (larger  $\beta/V$ ) the stepping frequency increases.

The ram transient for a yaw step command using the mathematical model in the simulated loop is shown in Figure 3-6. Limit cycle characteristics are shown in Figure 3-7. Comparison with Figures 3-2 and 3-5 shows the recorded ram motion to exhibit the same characteristics as that produced by the hardware. Comparison of the plant transients shown in Figures 3-6 with Figure 3-8 show the response characteristics of the simulated loop with the mathematical model of the DHA to be the same as that achieved with the laboratory hardware.

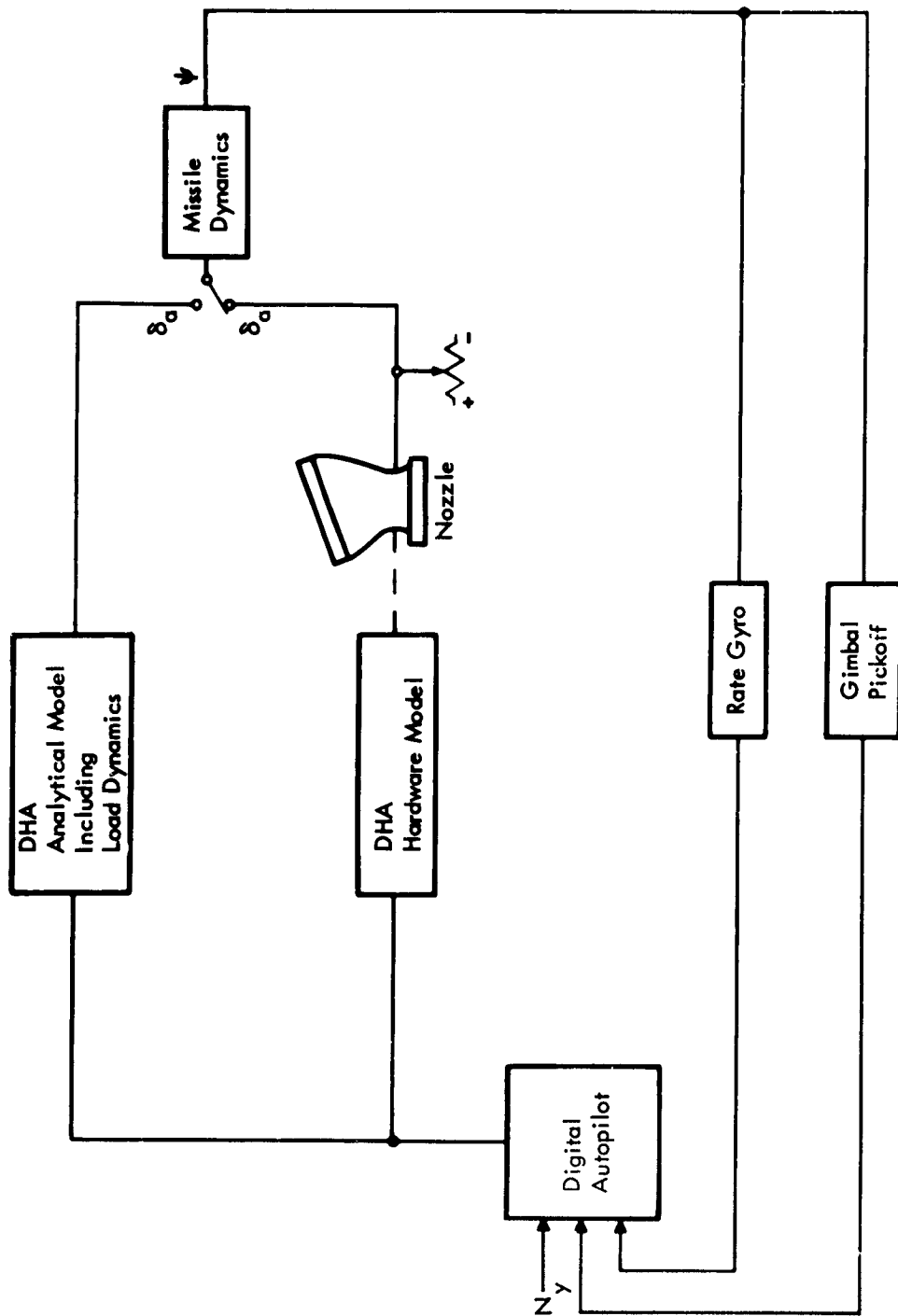


Figure 3-3. Simulation Arrangement

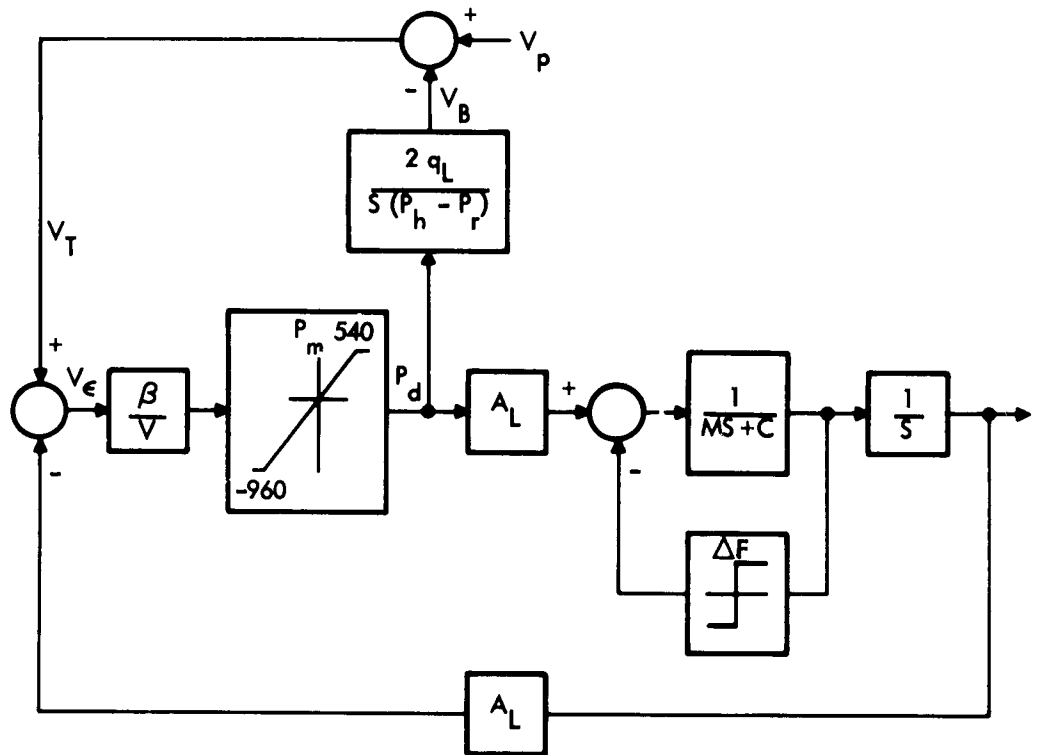


Figure 3-4. Block Diagram for DHA Load Dynamics

### 1. EFFECT OF THE PARAMETER C

The effect of parameter C on loop performance is shown by the results in Table 3-2. The values of C represent a variation  $\pm 50$  percent from that used when comparing the mathematical model with the hardware. For both increased and decreased damping, the maximum negative stable step differed from the result obtained with the laboratory model. However, the maximum positive stable step was not changed. As shown by Figure 3-1 negative ram motion is required to stabilize the missile after initiating a positive step command. For the values of damping investigated the relation:

$$\frac{V_c f_c}{A_L} < \frac{P_m A_L - \Delta F}{C}$$

existed with negative motion. Hence the slew velocity required to attain the maximum positive stable step was not effected by the values of C investigated.

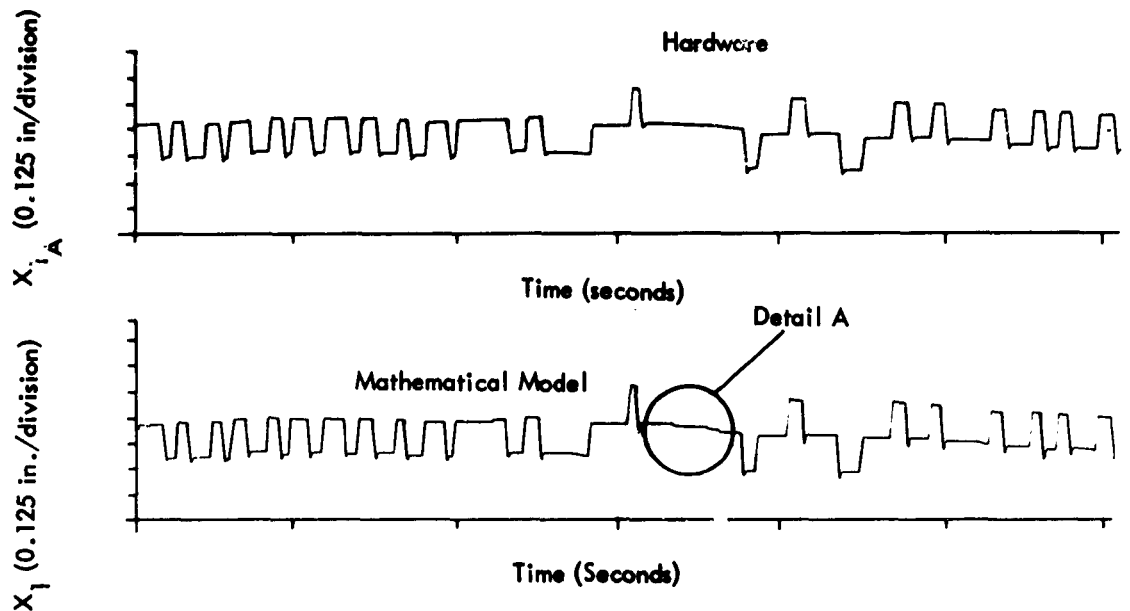


Figure 3-5. Recorded Transients Showing Actual Motion of Digital Hydraulic Actuator and the Motion Generated with the Mathematical Model

Figures 3-9 and 3-10 show the response to a yaw step command for  $C = 6$  and  $C = 18$ . The variation of the damping parameter produces no significant change in the transient response. The effect of the damping on the ram motion is shown in Figure 3-11. As to be expected, the overshoot of ram position is greater for decreased damping. However, the limit cycle characteristics as shown in Figures 3-9 and 3-10 do not significantly differ.

## 2. EFFECT OF THE PARAMETER $\beta/V$

The effect of the parameter  $\beta/V$  was determined for values of 13,300 lb/in<sup>5</sup> and 100,000 lb/in<sup>5</sup>. As indicated by Table 3-2 the variations had no effect on gain margin or maximum stable step. Transients recorded for a yaw command  $N_y = 10$  are shown in Figure 3-12 for the variations of the parameter  $\beta/V$ . Both transients are in satisfactory agreement with the

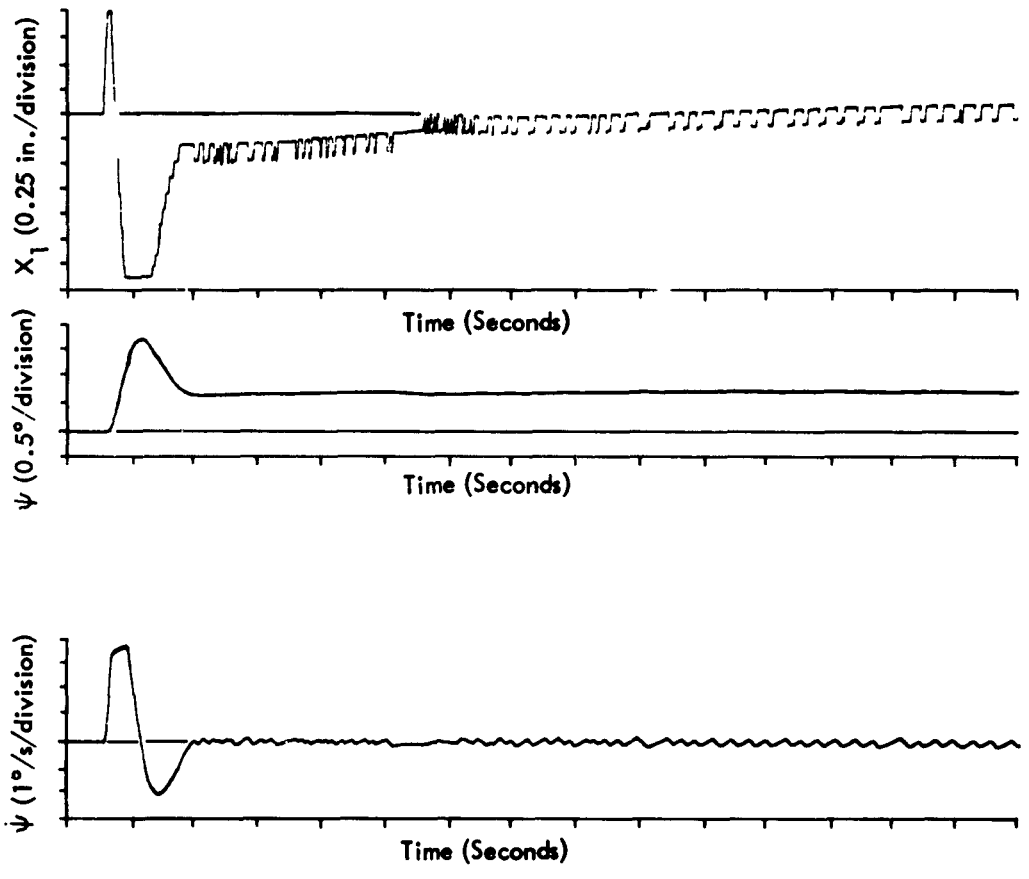


Figure 3-6. Recorded Transients for a Yaw Step Command ( $N_y = 10$ ) Using Mathematical Model

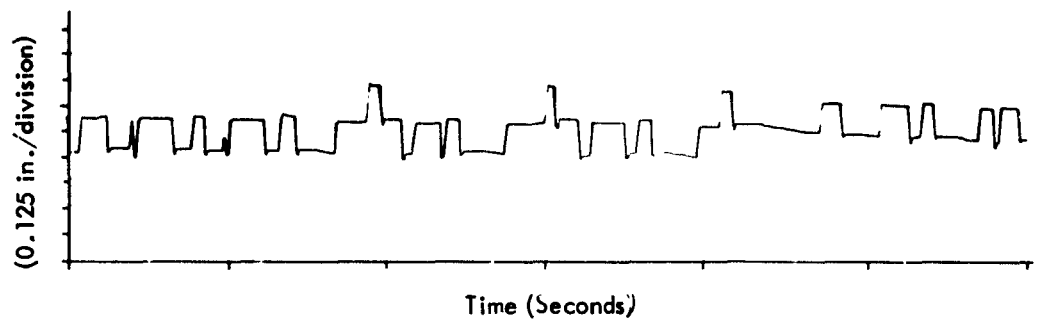


Figure 3-7. Limit Cycle Generated with the Mathematical Model in the Simulated Control System

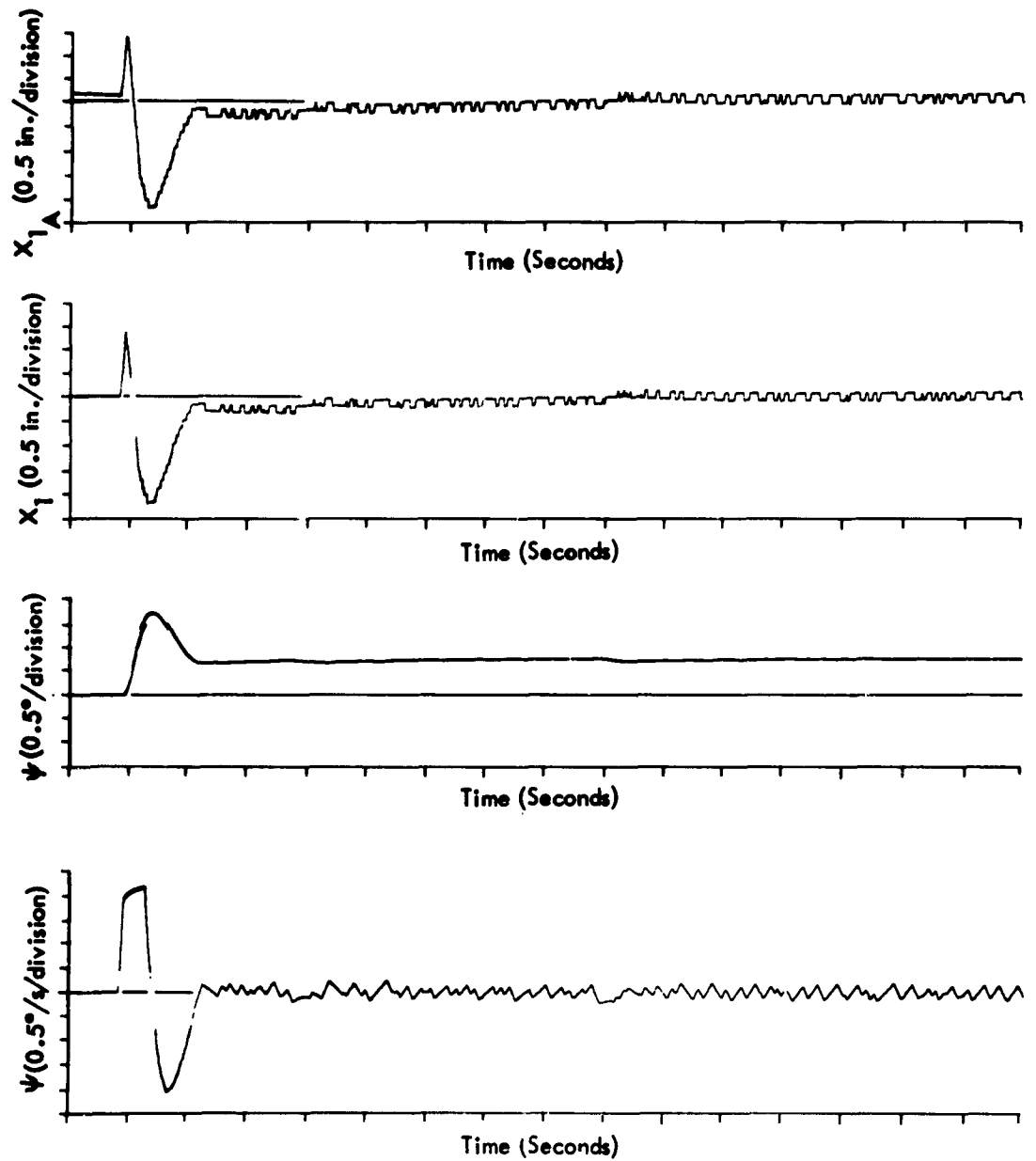


Figure 3-8. Recorded Transients for a Yaw Step Command ( $N_y = 10$ )  
 Using Actual Hardware with Mathematical Model Operated Open Loop  
 (Ref - Figure 3-3)

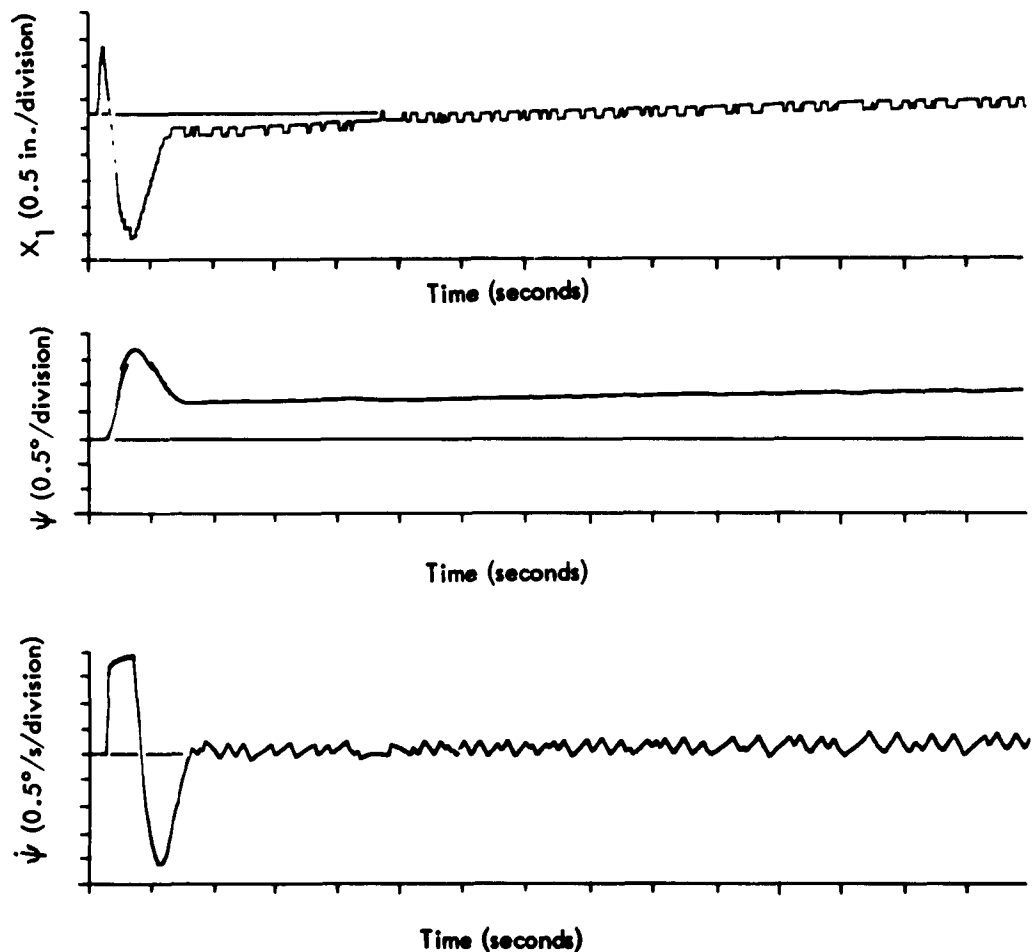


Figure 3-9. Response to a Yaw Step Command  
with  $C = 6 \text{ lb-s/in}$

transients recorded for the hardware and the mathematical model. The difference in the settling time of the plant relative to that depicted in Figure 3-6 is noted. However, due to the correspondence between the transients of Figure 3-12 the difference in settling time is attributed to a change of conditions within the simulated loop.

With reference to Figure 3-13, the effect of the parameter  $\beta/V$  on drift characteristics of the ram and ram overshoot is shown. Comparison with Figure 3-7 shows the value for  $\beta/V = 26,600 \text{ lb/in}^5$  to provide better agreement with the hardware.



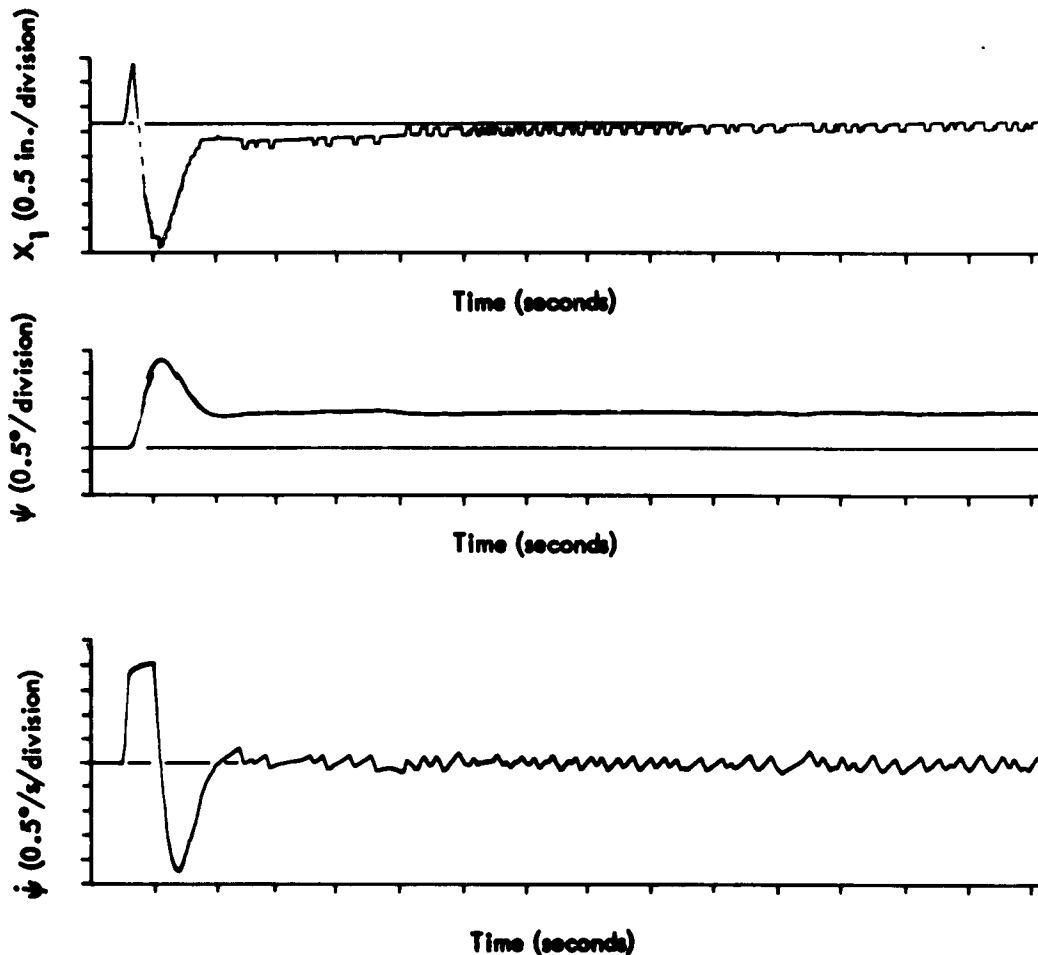


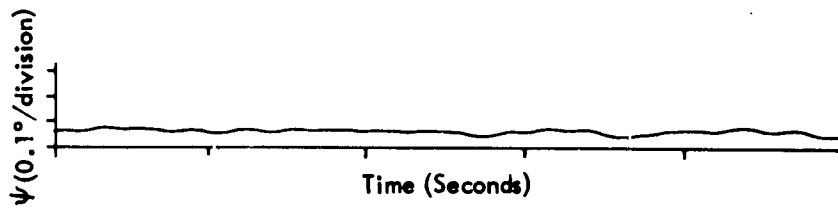
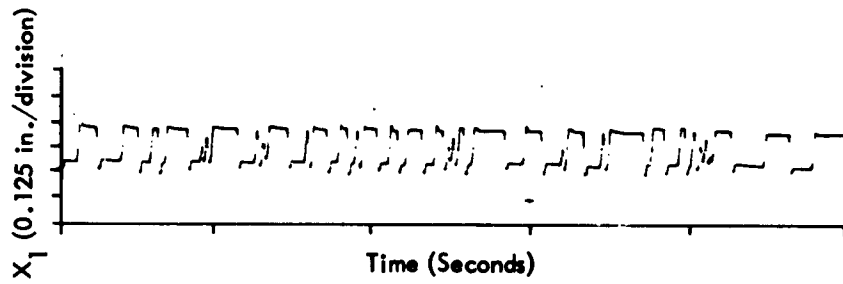
Figure 3-10. Response to a Yaw Step Command  
with  $C = 18 \text{ lb-s/in}$

The parameter  $\beta/V$  for the values stated produced little change in the steady state frequency of the ram, see Figure 3-13.

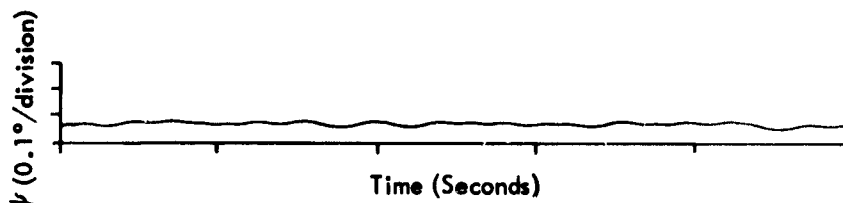
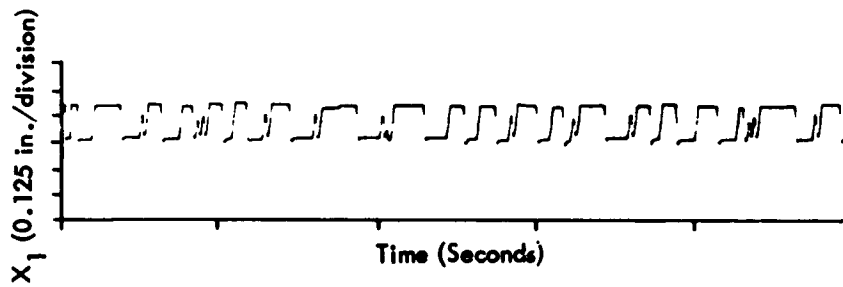
### 3. GAIN-PHASE

Closed loop frequency response and phase characteristics of the simulated loop were obtained when using the laboratory model and the hardware. Results are depicted in Figures 3-14 and 3-15. Inputs were restricted in amplitude to eliminate the nonlinear effect of velocity saturation. Differences when comparing results are attributed more to the accuracy of measuring the data than to a difference in the models.

The agreement of results further establishes the accuracy of the mathematical model describing the digital hydraulic actuator.

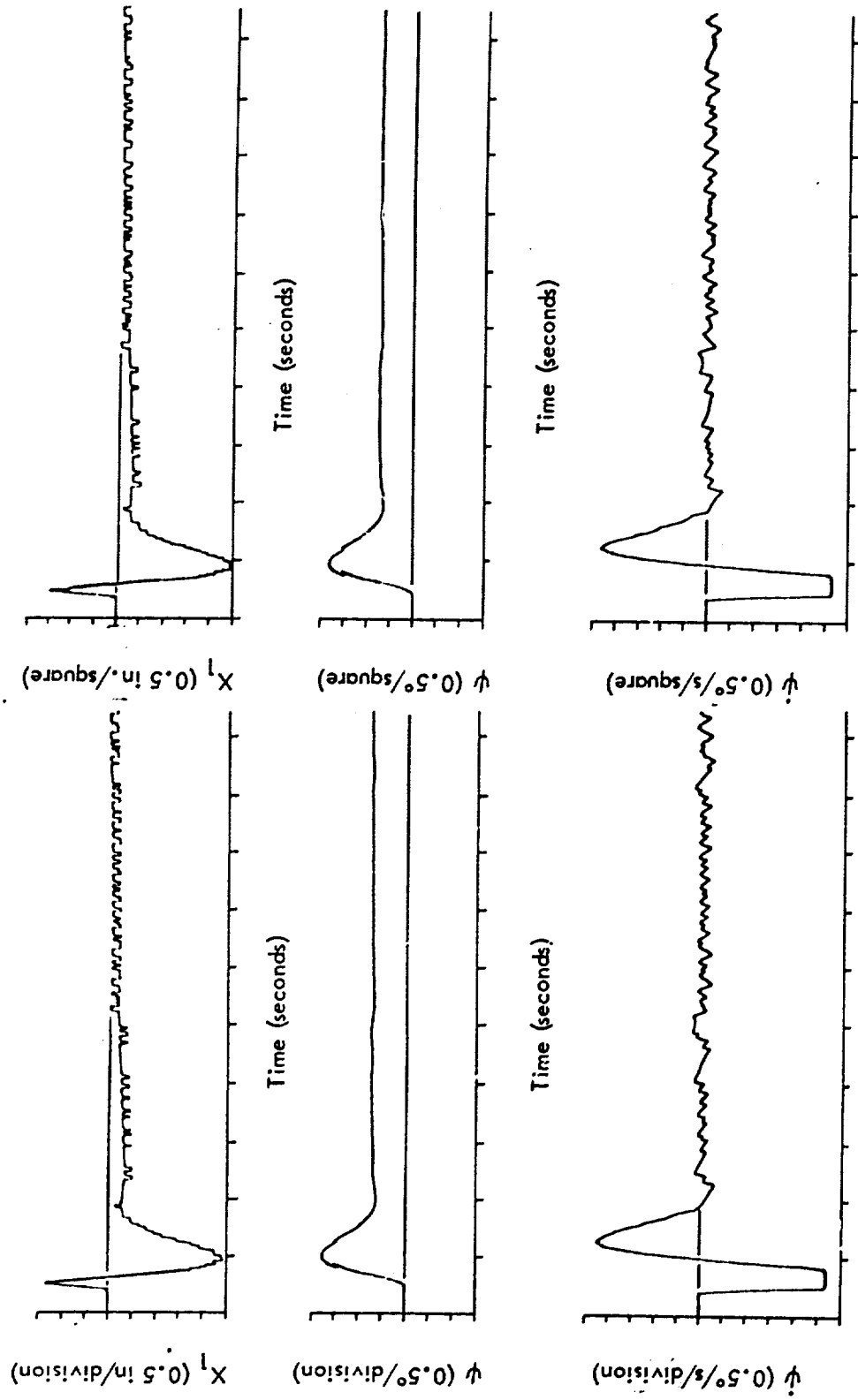


a)  $C = 6 \text{ lb-s/in}$



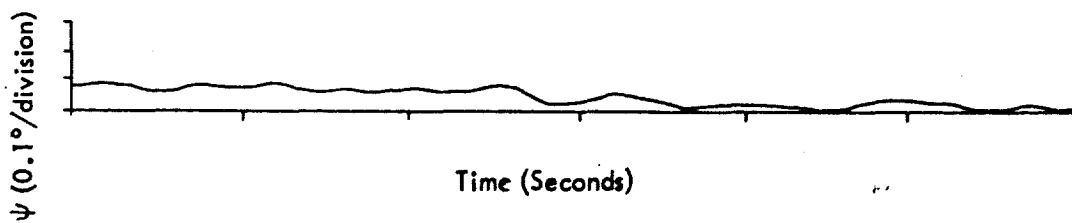
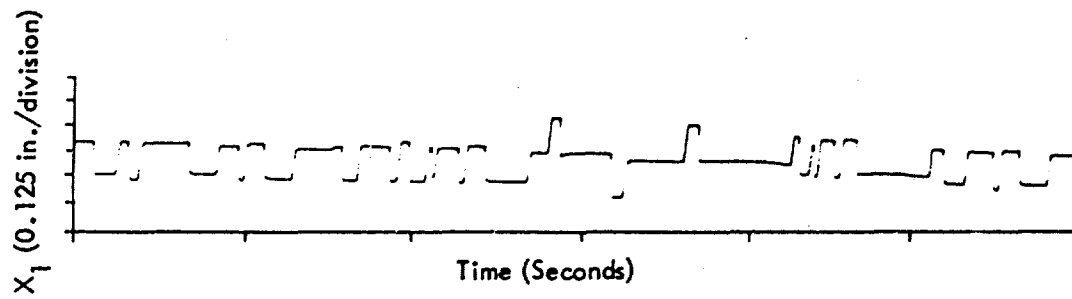
b)  $C = 18 \text{ lb-s/in}$

Figure 3-11. Limit Cycle

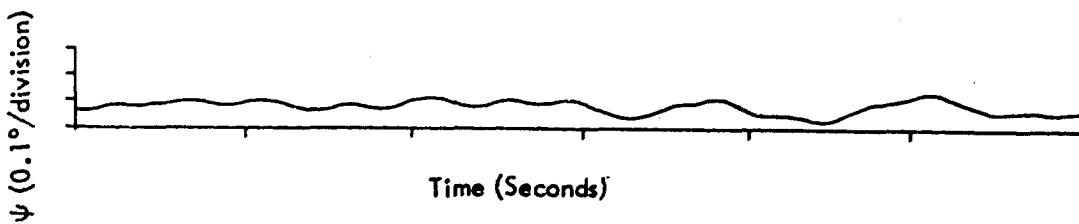
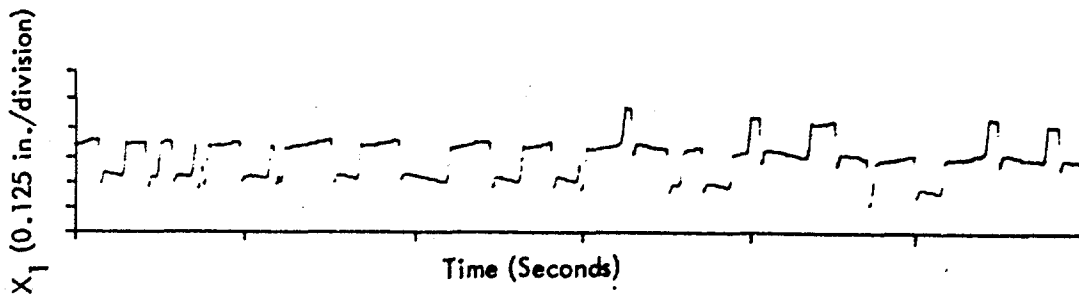


a)  $\frac{\beta}{V} = 13,300 \text{ lb/in}^5$       b)  $\frac{\beta}{V} = 100,000 \text{ lb/in}^5$

Figure 3-12. Response to a Yaw Step Command for (a)  $\frac{\beta}{V} = 13,300$  lb/in<sup>5</sup> (b)  $\frac{\beta}{V} = 100,000$  lb/in<sup>5</sup>



a)  $\frac{\beta}{V} = 13,300 \text{ lb/in}^5$



b)  $\frac{\beta}{V} = 100,000 \text{ lb/in}^5$

Figure 3-13. Limit Cycle

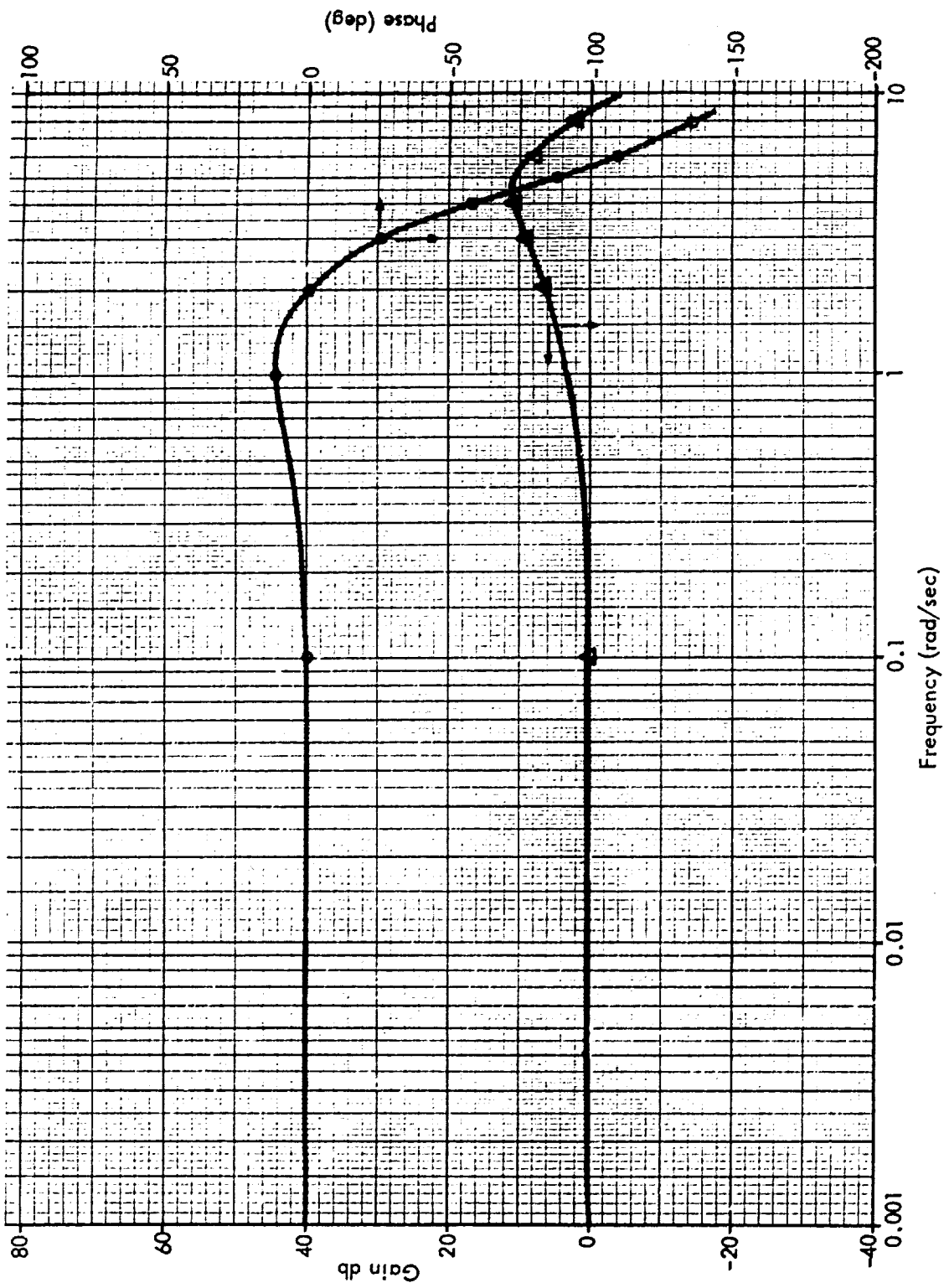


Figure 3-14. Closed Loop Amplitude and Phase Characteristics of Simulated Digital Control System when Closing the Loop with the Laboratory Model

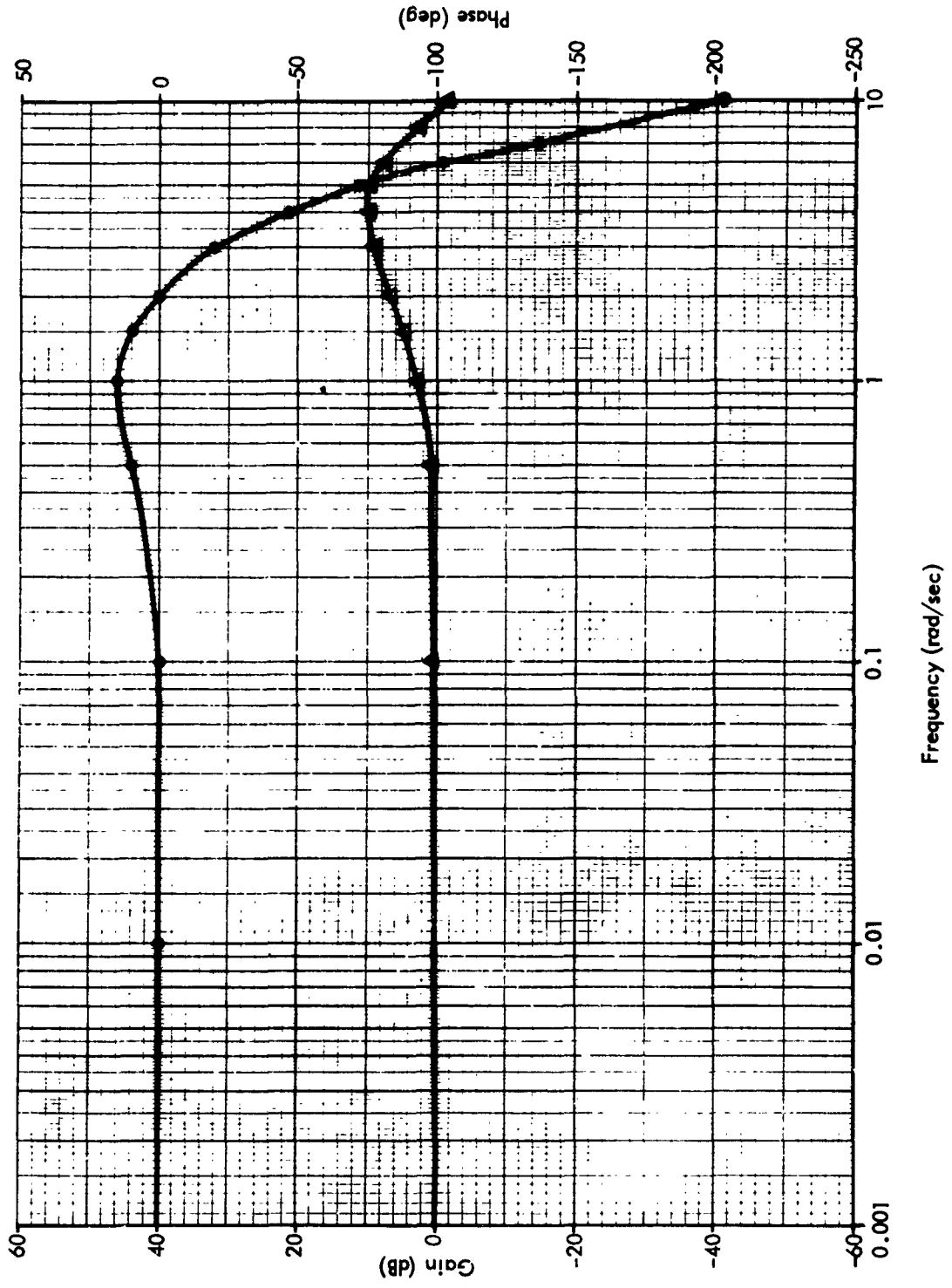


Figure 3-15. Closed Loop Amplitude and Phase Characteristics of Simulated Digital Flight Control System Using Mathematical Model (See Table 3-1)

## Section IV

### DIGITAL FLIGHT CONTROL SIMULATION

#### A. DESCRIPTION

Performance of the Polaris missile was determined when using a DHA which provides the same force for both directions of motion. A nozzle torque independent of velocity, producing an axial load of 600 pounds, is assumed. Results were obtained with the mathematical model for the actuator parameters of the actual hardware and a ram area ratio of 1.885:1. The equivalent mass load differs from that used when evaluating the mathematical model due to the longer moment arm used with the hardware. Parameter values are summarized in Table 4-1.

The effect of the leakage parameters and the gain, K, of the autopilot compensation is shown. Performance is evaluated by comparison with the performance of the analog flight control simulated during Phase I.

#### B. RESULTS

Simulation results for the parameter values of Table 4-1 are shown in Table 4-2. Also shown are results for the parameter values indicated.

##### 1. EFFECT OF LEAKAGE PARAMETERS

As shown by the results of Table 4-2 system performance of the flight control system was not decreased for the assumed values of the leakage parameters,  $q_L$ , and  $q_{LC}$ . A worst-case condition was assumed by using the larger of the values for both  $q_L$  and  $q_{LC}$ . Values greater than shown could be used, however, the variation from that of the actual hardware is believed to represent a reasonable tolerance. Figure 4-1 shows the recorded transients for a yaw step command using the parameter values of Table 4-1. The transient of  $X_1$  in Figure 4-1, is typical of that recorded for the leakage conditions shown in Table 4-2.

The recorded transients for an initial condition  $\psi_0 = -1/2$  degree are shown in Figure 4-2 for the parameter values of Table 4-1. Results for a no

Table 4-1

PARAMETER VALUES FOR SIMULATION OF  
DIGITAL FLIGHT CONTROL

Parameter	Units	Value	Parameter	Units	Value
$\Delta F$	lb	600	$e_b$	deg	0.681
M	lb-s <sup>2</sup> /in	0.296	Quant. Hys.	deg	$\delta q/4$
R	in	8.00	$\delta_b$	deg	1.09
$\frac{\beta}{V}$	lb-in <sup>-5</sup>	26,600	K	—	$2^{-7}$
C	lb-s/in	12			
$q_L$	in <sup>3</sup> /s	0.107			
$q_{LC}$	in <sup>3</sup> /s	-0.006			
$q_{LC}^*$	in <sup>3</sup> /s	-0.0165			
$V_{CB}$	in <sup>3</sup>	0.152			
$f_c$	Hz	82.5			
$T_V$	in <sup>-3</sup>	5.5			
$T_f$	in <sup>-3</sup>	10			
$P_M$	psi	+750			
$P_R$	psi	130			
$P_h$	psi	2130			
$A_L$	in <sup>2</sup>	1.00			
$A_L/A_R$	—	1.885			



leakage condition are shown in Figure 4-3 and for the worst-case leakage in Figure 4-4. Power during steady state can be expressed by:

$$W = X_1 A_L P_h \frac{A_R}{A_L} f_c,$$

where  $f_c$  is the actuator frequency.

Table 4-2

SUMMARY OF RESULTS -  
SIMULATION OF DIGITAL FLIGHT CONTROL

Parameter Value	Maximum Stable Step	Unstable Step	Stable Unstable $K_G$ $K_G$ ( $N_y = \psi_o = 0$ )		Reference Figure No.	
					$N_y = 10$	$\psi_o = -\frac{1}{2}$
Table 4-1	10	11	4.0		4-1	4-2
$q_L = .150$	10	11	4.5	5.0		
$q_{LC} = -.0165$	+11	12	4.5	5.0		
	-10	-11				
$q_L = q_{LC} = 0$	10	11	4.5	5.0		4-3
$q_L = .150$ $q_{LC} = -.0165$	11	12	4.5	5.0		4-4
	-10	-11				
$K = 12^{-16}$	11	12	4.5	5.0	4-5	
$K = 2^{-5}$	7	8	4.0	4.5		4-6
$K = 2^{-9}$	11	12	4.5	5.0	4-9	4-10

With reference to Figures 4-2 through 4-4, the frequency,  $f_o$ , during steady state averaged from 6 to 11 Hz. The lowest average frequency was obtained with the condition:  $q_L = q_{LC} = 0$ . However, for the no leakage condition the peak to peak amplitude of  $\psi$  approached 0.07 degree as compared to approximately 0.03 degree with leakage. The variation of  $\psi$  and  $f_o$  produced with the assumed worst case leakage, did not noticeably differ from the variation obtained with the hardware parameters.

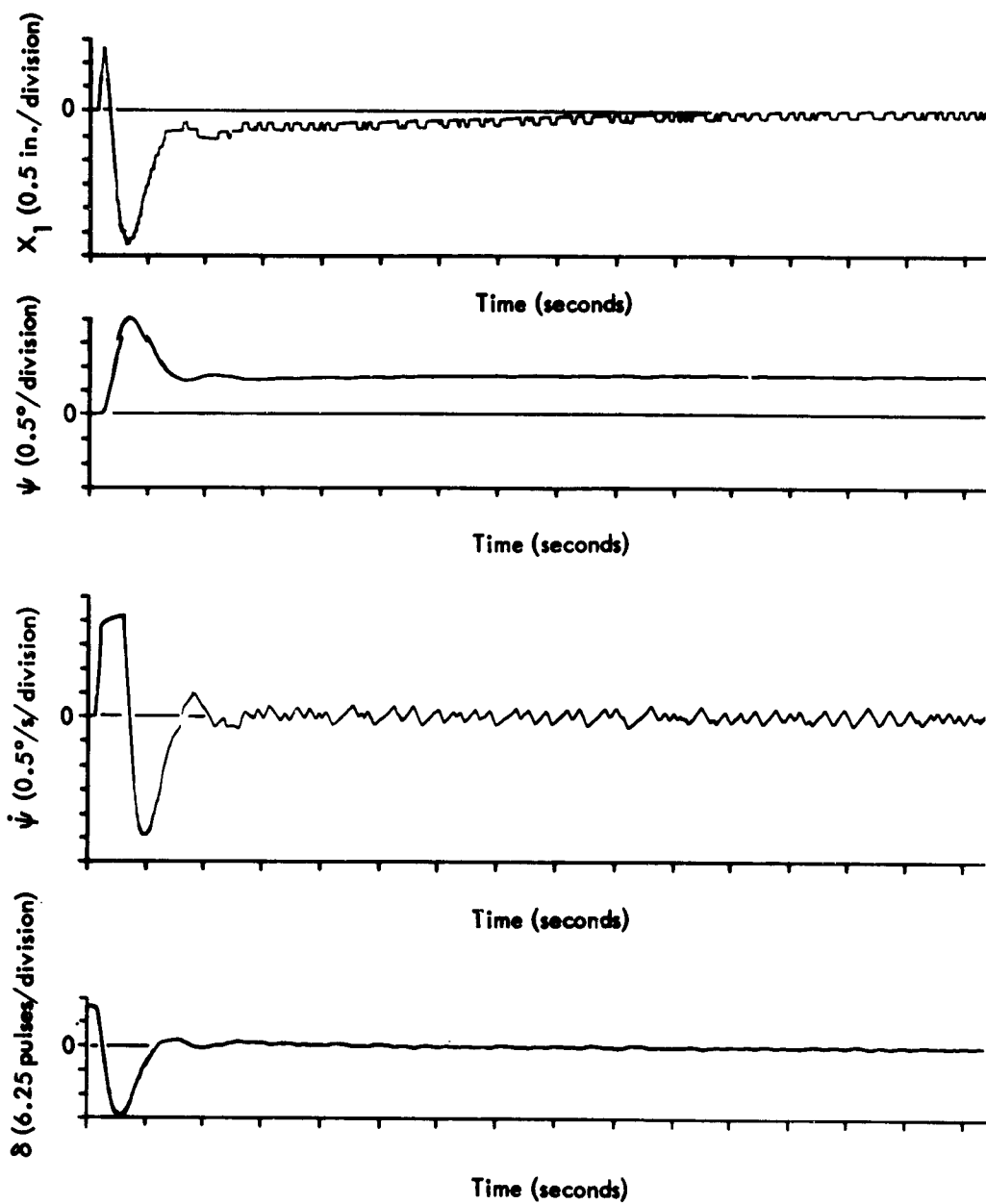


Figure 4-1. Recorded Transients for a Yaw Step Command  
 $N_y = 10$  (See Table 4-1)

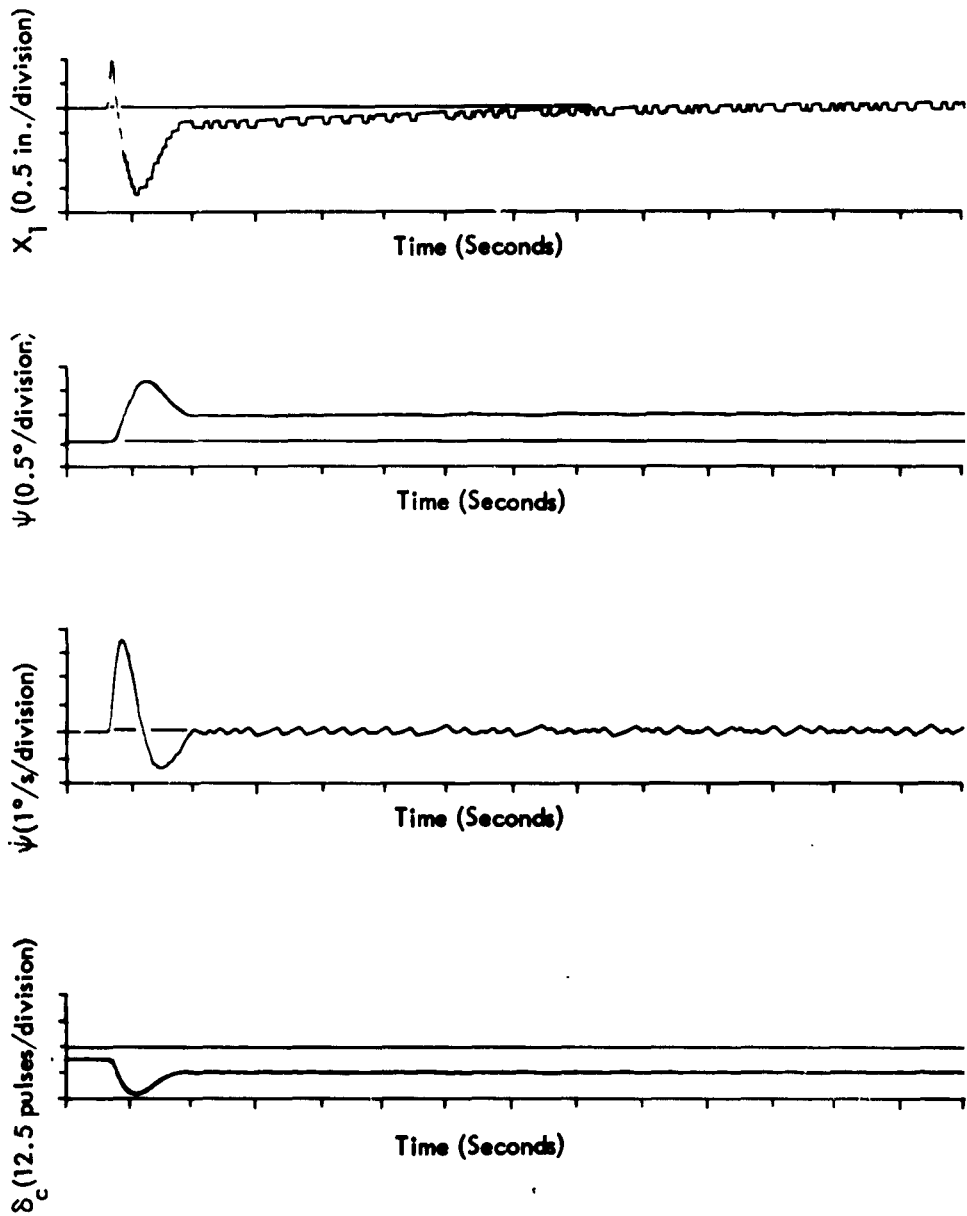


Figure 4-2. Recorded Transients for an Initial Yaw Condition,  
 $\psi_0 = -1/2^\circ$  (Ref: Table 4-1)

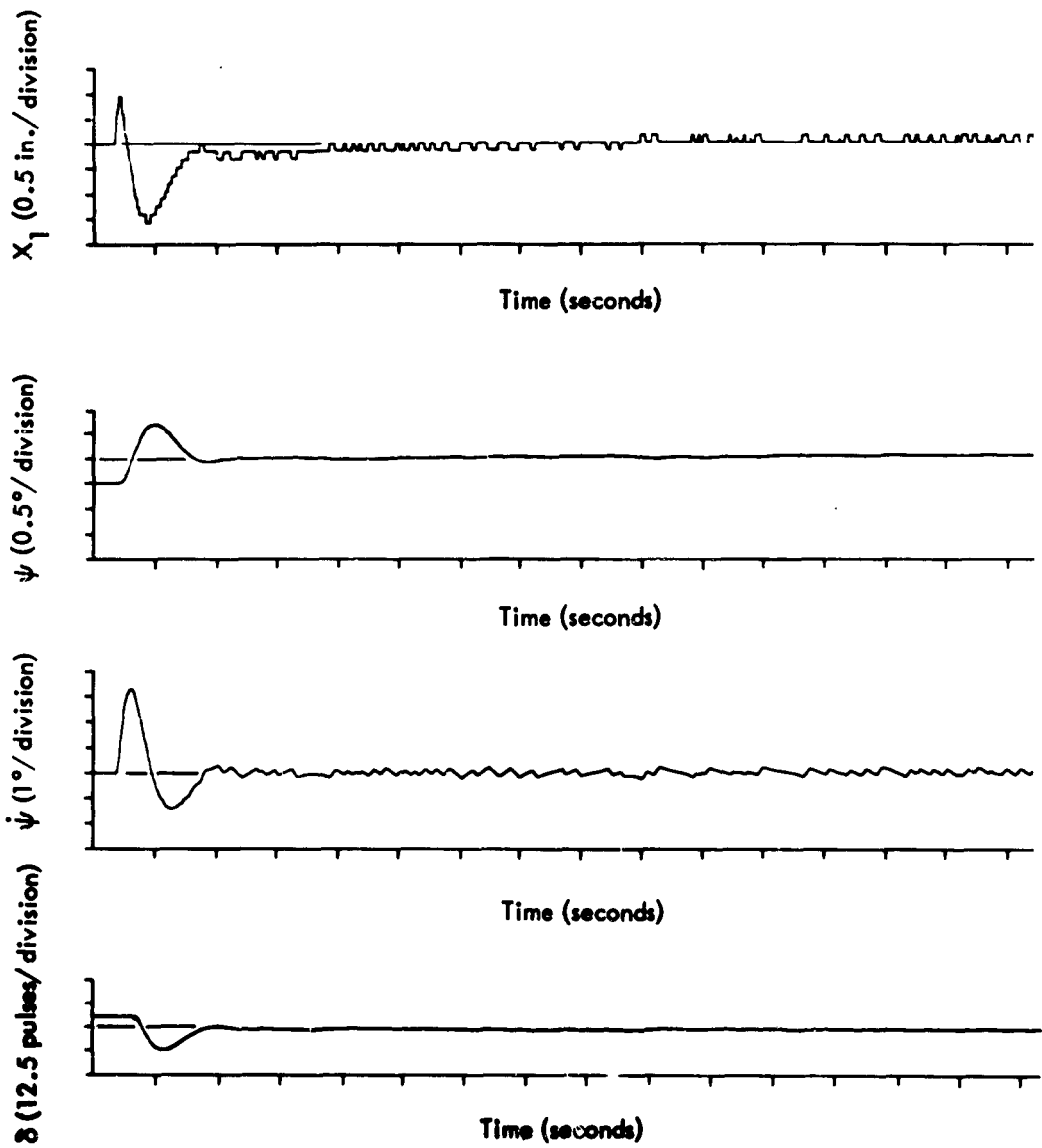


Figure 4-3. Recorded Transients for an Initial Yaw Condition ( $\psi_o = -1/2^\circ$ ) and no Leakage ( $q_L = q_{LC} = 0$ )

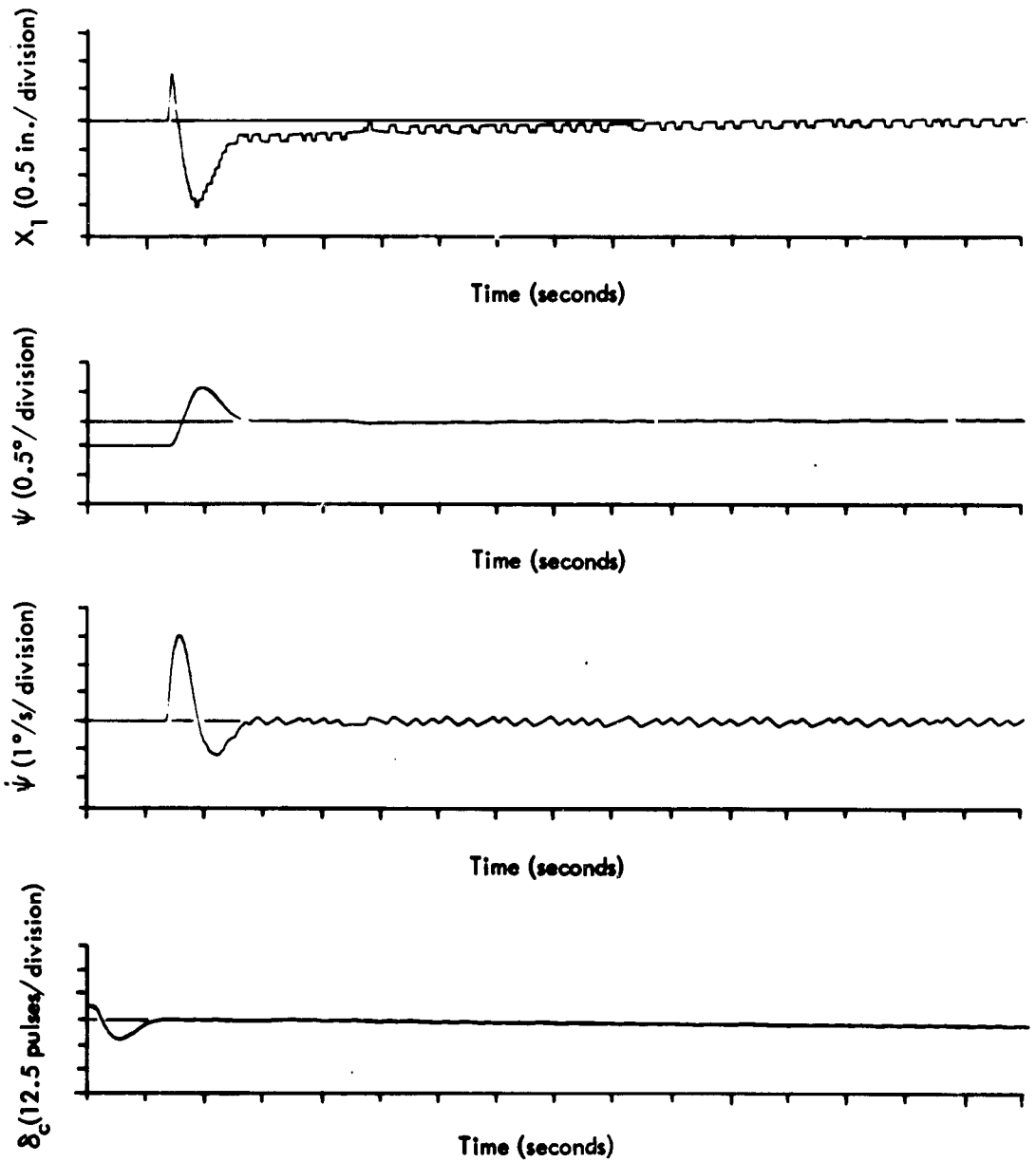


Figure 4-4. Recorded Transients for an Initial Yaw Condition  
 $(\psi_0 = -1/2^\circ)$ , Assuming the "Worst" Case Leakage  
 $(q_L = 0.150 \text{ in}^3/\text{s}, q_{LC} = -0.0165 \text{ in}^3/\text{s})$

## 2. EFFECT OF COMPENSATION GAIN, K

System performance and response characteristics of the missile can be readily modified by changing the gain, K, of the autopilot compensation. Transients for  $K = 2^{-16}$  are shown in Figure 4-5 and for  $K = 2^{-5}$  in Figure 4-6. As K approaches zero ( $K = 2^{-16}$ ) a steady state error of  $\psi$  results due to the presence of leakage. For large K ( $K = 2^{-5}$ ) the missile transient is highly oscillatory.

## 3. COMPARISON WITH ANALOG FLIGHT CONTROL

Table 4-3 shows the performance of the analog flight control system simulated as part of the Phase I study. Transients for a yaw step command and an initial yaw condition are shown respectively in Figures 4-7 and 4-8. Similar performance and transient characteristics are achieved with the digital flight control with the compensation gain K equal to  $2^{-9}$  (Figures 4-9 and 4-10). The maximum stable step for the analog system is 0.075 degree larger, a difference of 8 percent. This is attributed to the change in implementation, (see Table 2-1). With the digital flight control, oscillations of  $\psi$  during steady state approached a peak-to-peak value of 0.04 degree, a consequence of a nonlinearities and quantization. Because of the dynamics of the vehicle, the effect of the oscillations of  $\psi$  on the flight path angle is attenuated.

As discussed in Reference 1, the no-input condition used to investigate gain of the digital flight control is not analogous to the no-input condition used with the analog flight control. A 0.109 degree oscillation of the nozzle exists during the steady-state condition of the digital system. Hence, the maximum gain of the analog system is higher. The gain of the analog system approaches that of the digital system when measured with an input of  $N_y = 1$ . Although maximum gain of the digital system is lower, the gain changed required to produce instability provides a credible margin.

## 4. GAIN-PHASE

The frequency response and phase shift characteristics of the closed loop system is depicted in Figure 4-11 when using the parameter values of Table 4-1. To minimize the effect of velocity saturation the input was restricted to small signals.

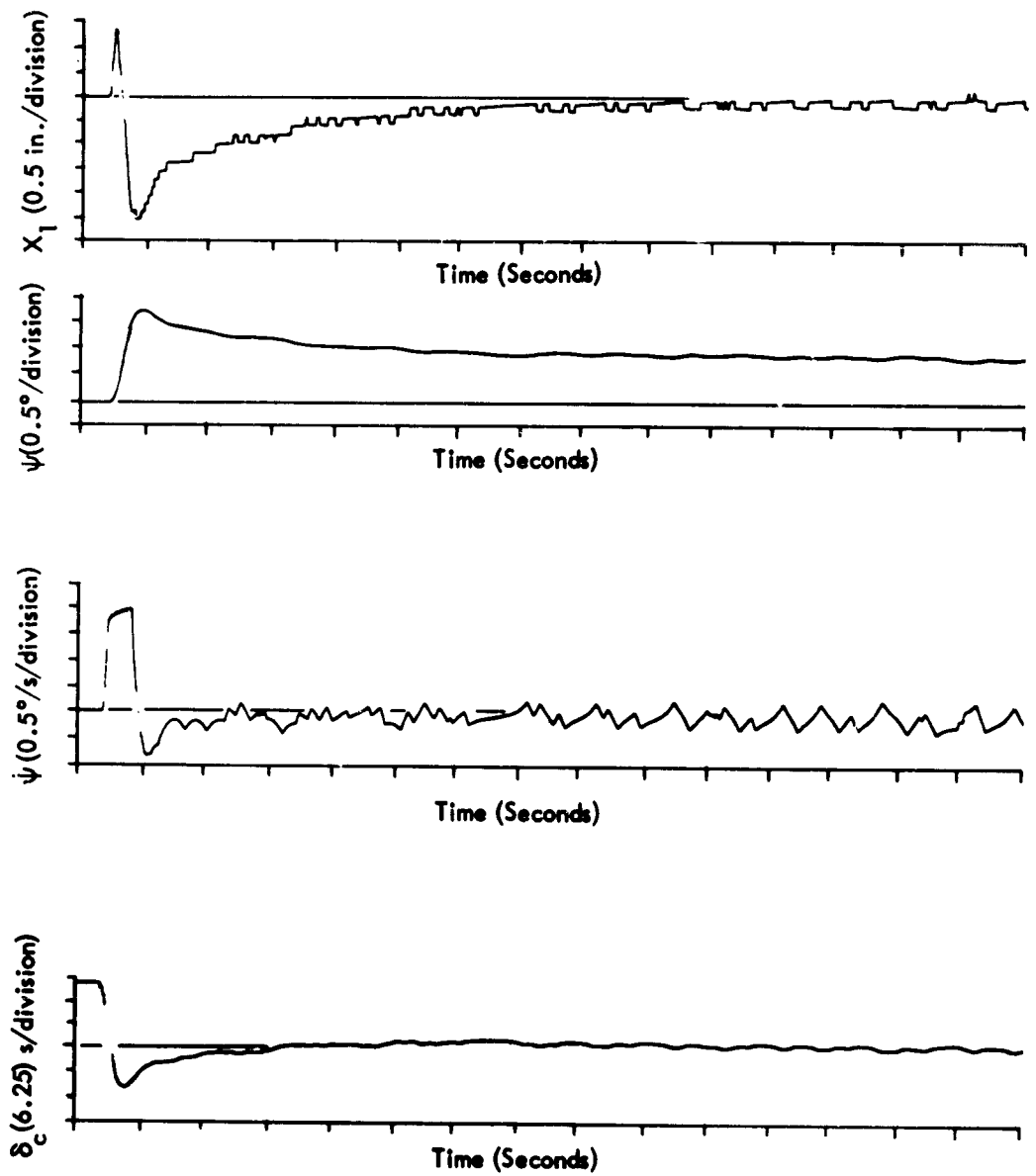


Figure 4-5. Recorded Transients for a Yaw Step Command  
 ( $N_y = 10$ ) Showing Steady State Error of  $\psi$  when  $K \rightarrow 0$   
 ( $K = 2^{-16}$ )

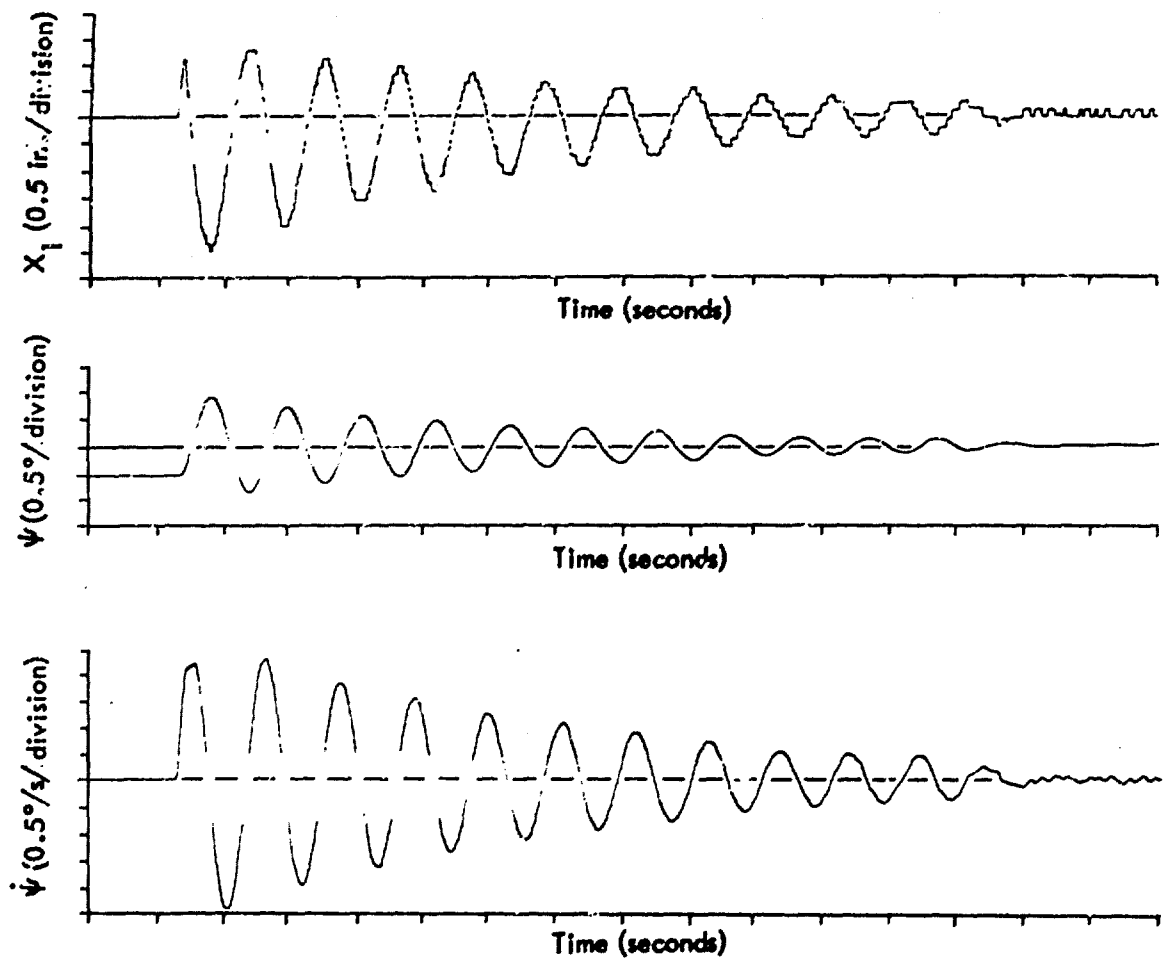


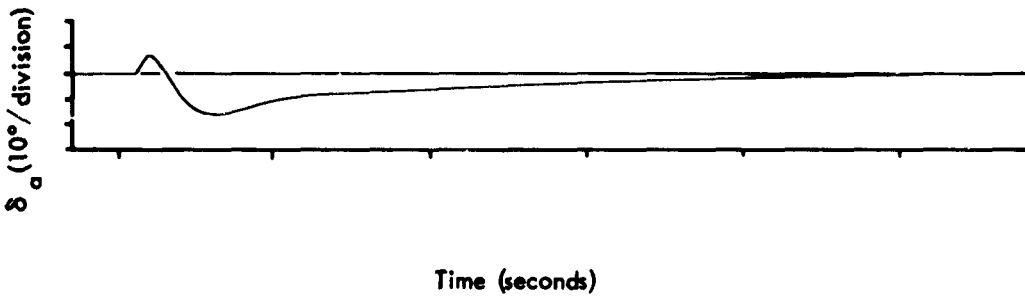
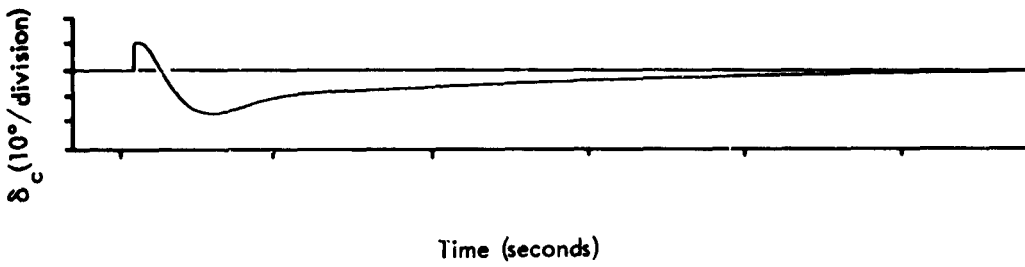
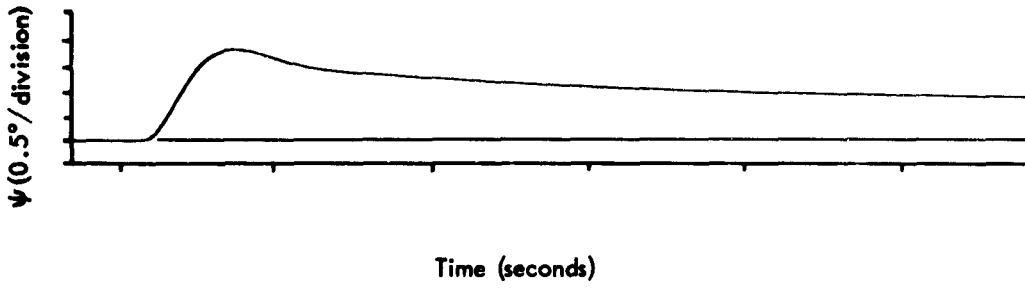
Figure 4-6. Recorded Transients for a Yaw Condition  
 $(\Psi_0 = -1/2^\circ)$  with  $K = 2^{-5}$



Table 4-3

RESULTS OF ANALOG FLIGHT CONTROL  
SIMULATION (PHASE I)

Run	Input	Results	Time Histories
C-13A	None	Stable with $K_g = 18.2$	Figure 4-8  Figure 4-7
C-13B	None	Unstable with $K_g = 18.9$	
C-14	Step of $N_y = 12$	Stable	
C-15	Step of $N_y = 13$	Unstable	
C-16	Initial $\psi_o = 0.5^\circ$	Stable	
C-17	Step of $N_y = 10$	Stable	
C-18	Step of $N_y = 1$	Stable	
C-19A	Step of $N_y = 1$	Stable with $K_g = 7.0$	
C-19B	Step of $N_y = 1$	Unstable with $K_g = 7.25$	
C-20A	Step of $N_y = 2$	Stable with $K_g = 4.5$	
C-20B	Step of $N_y = 2$	Unstable with $K_g = 4.75$	



**Figure 4-7. Recorded Transients Using Analog Flight Control for a Yaw Step Command ( $N_y = 10$ )**

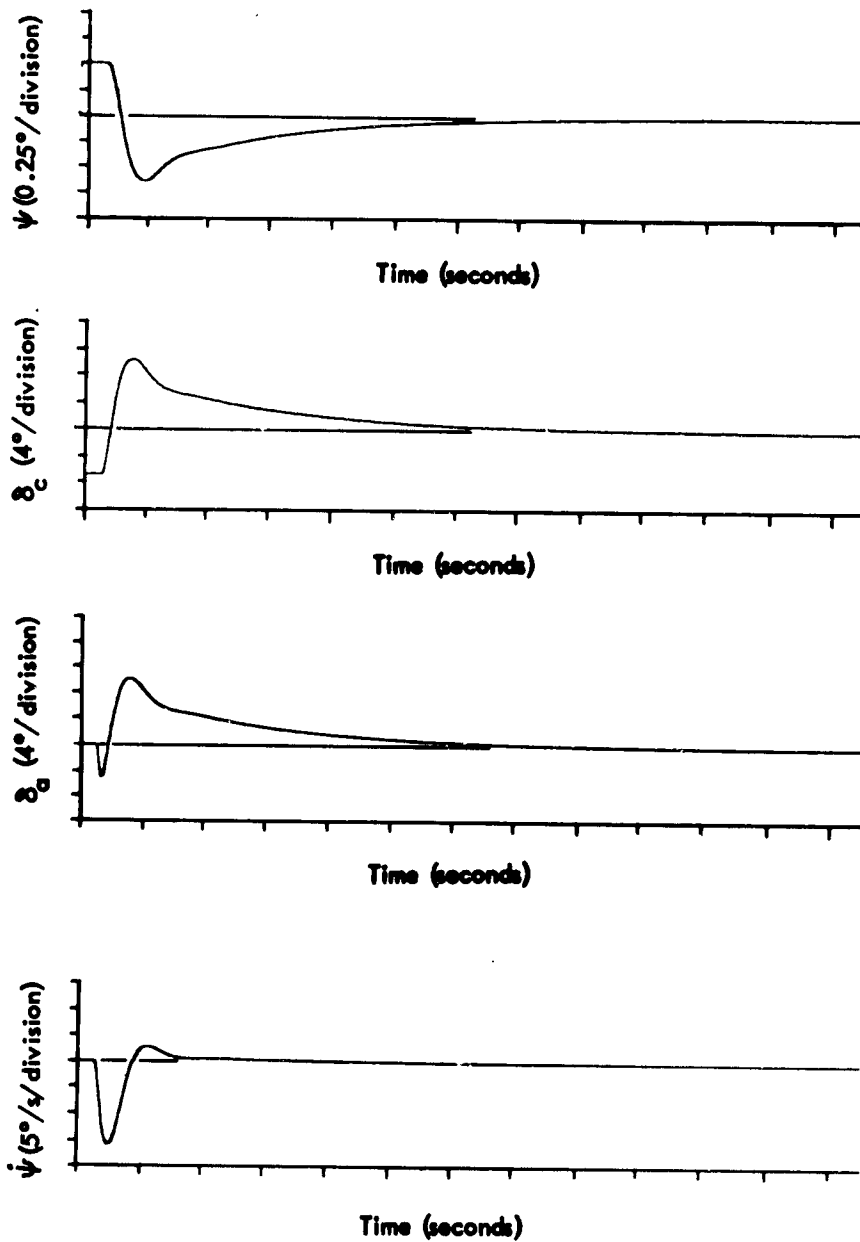


Figure 4-8. Recorded Transients Using Analog Flight Control System for an Initial Yaw Condition ( $\psi_0 = +1/2^\circ$ )

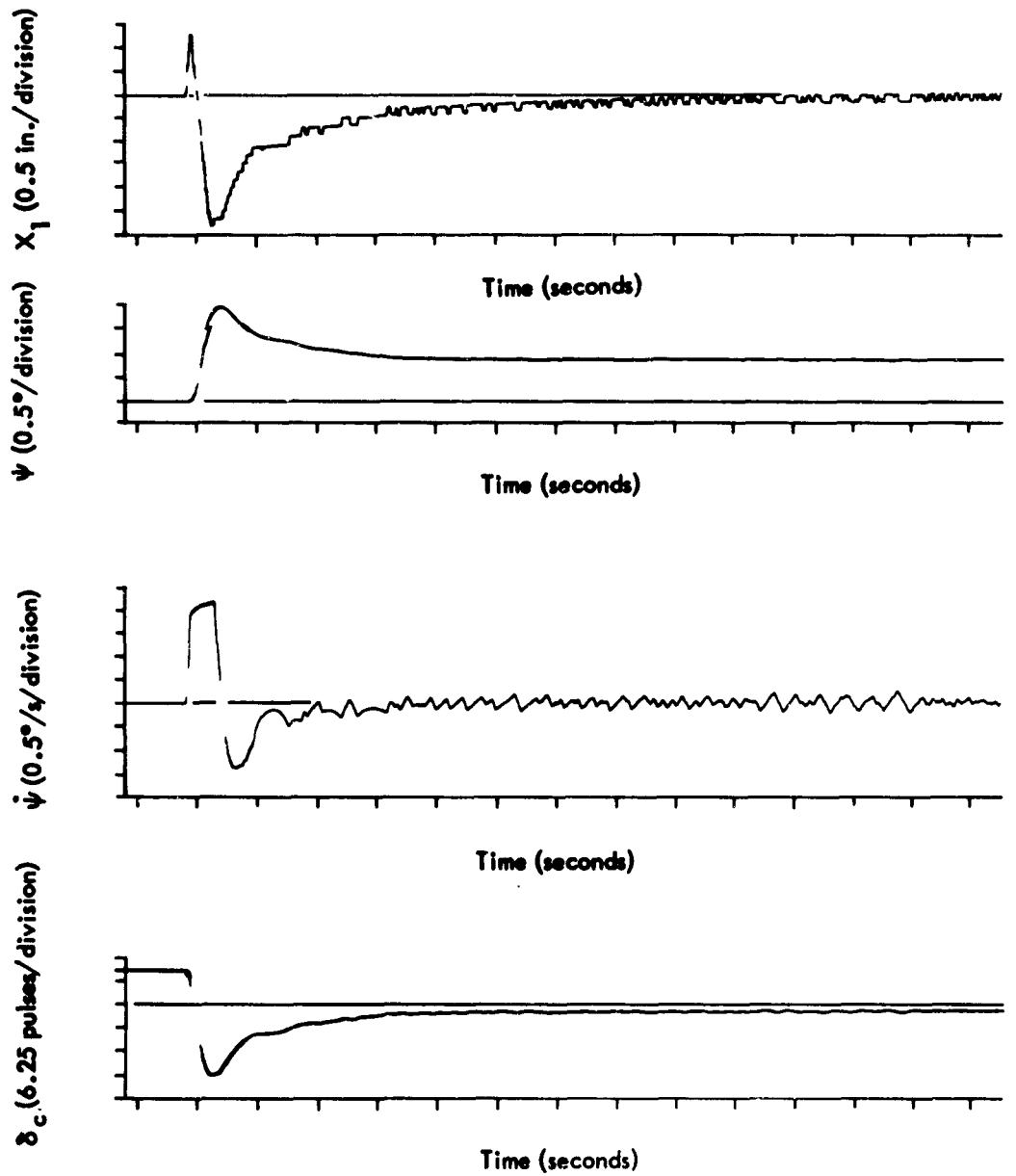


Figure 4-9. Recorded Transients for a Yaw Step Command ( $N_y = 10$ ) with  $K = 2^{-9}$  (Ref - Table 4-1)

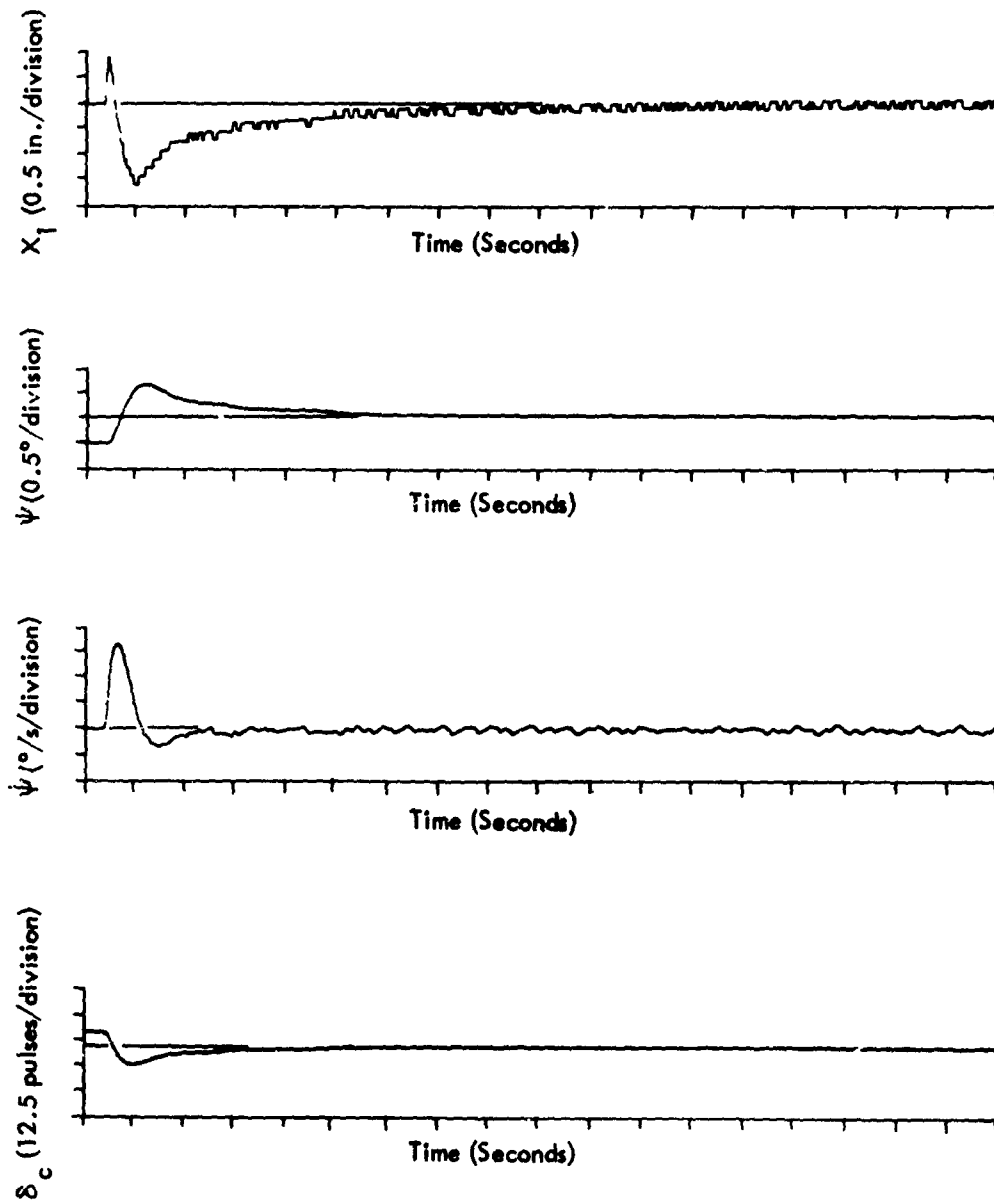


Figure 4-10. Recorded Transients for an Initial Yaw Condition ( $\psi_0 = -1/2^\circ$ ) with  $K = 2^{-9}$  (Ref - Table 4-1)

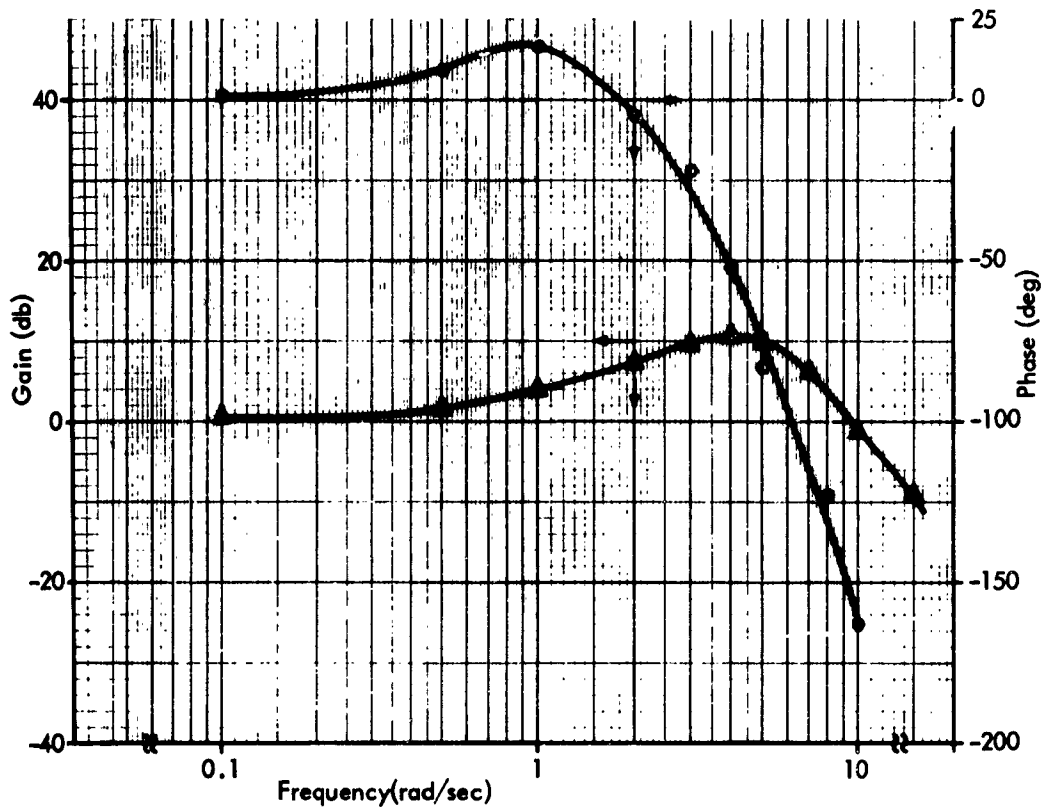


Figure 4-11. Closed-Loop Amplitude and Phase Characteristics of Simulated Polaris Digital Flight Control

## Section V

### LINEARIZED MODEL

As a first approximation, a linearized model provides a convenient means of determining the suitability of the DHA to a given application. To ascertain the validity of using a linear model, the mathematical model of Figure 2-3 is reduced to a linear form. Performance of the linear model is compared to the performance of the simulated system when closing the loop with the laboratory model. Validity is established by the agreement of performance characteristics for frequency response, phase shift, and step response.

#### A. DEVELOPMENT

Figure 5-1 shows the block diagram of the digital flight control system when load dynamics are neglected. Restricting the commands so that the input to the non-linear block never exceeds one quantum and neglecting quantization Figure 5-2 is equivalent to Figure 5-1. By use of the identity shown in Figure 5-3 the model can be represented by the diagram of Figure 5-4 which also includes the approximation:

$$\frac{1 - e^{-T_f S}}{T_f S} \cong e^{-\frac{T_f S}{2}}$$

Zero-order holds can be formed in the feed forward path and minor loop by combining the integration of the DHA with the first difference computation. The sampling frequency is approximately two orders of magnitude higher than the frequency of the missile poles. Hence, a sample and hold can be approximated by the time delay,  $e^{-\frac{TS}{2}}$ . Using this approximation and rearranging the terms yields the linearized model shown in Figure 5-5.

The linearized model is based on small signal inputs, i. e. , velocity saturation does not exist. The magnitude of missile poles are small relative to the poles of the actuator. As a consequence loop dynamics even in the presence of slow saturation are dominated by the characteristics of the missile. Therefore, the linearized model can be used with inputs which produce

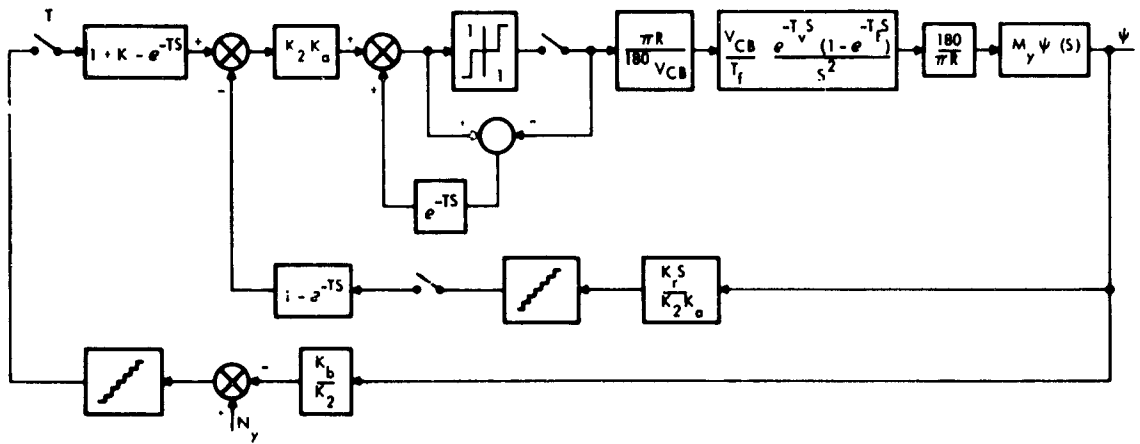


Figure 5-1. Block Diagram of Digital Flight Control System Neglecting Load Dynamics

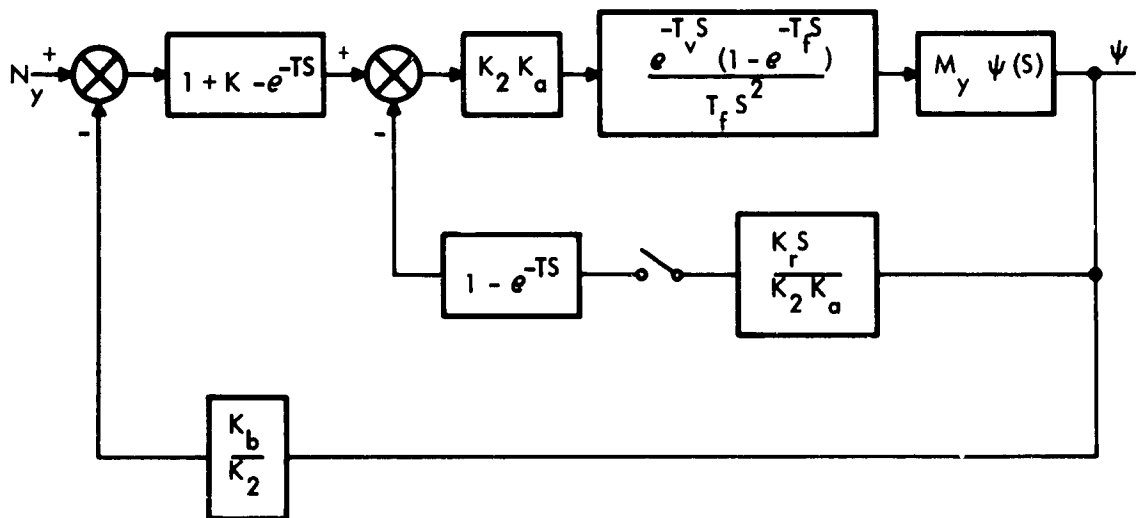


Figure 5-2. Block Diagram Equivalent of Figure 5-1 When Neglecting Quantization and Restricting Input to Small Signals



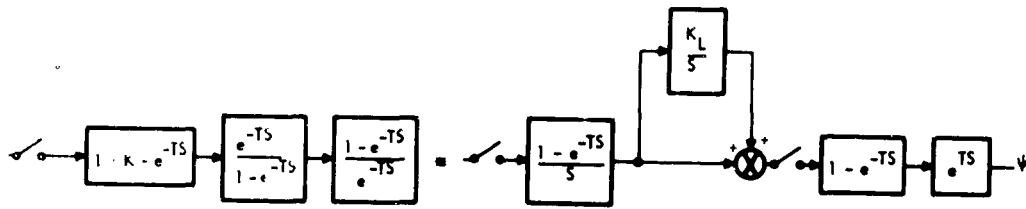


Figure 5-3. Identity Used to Reduce Figure 5-2 to Figure 5-4

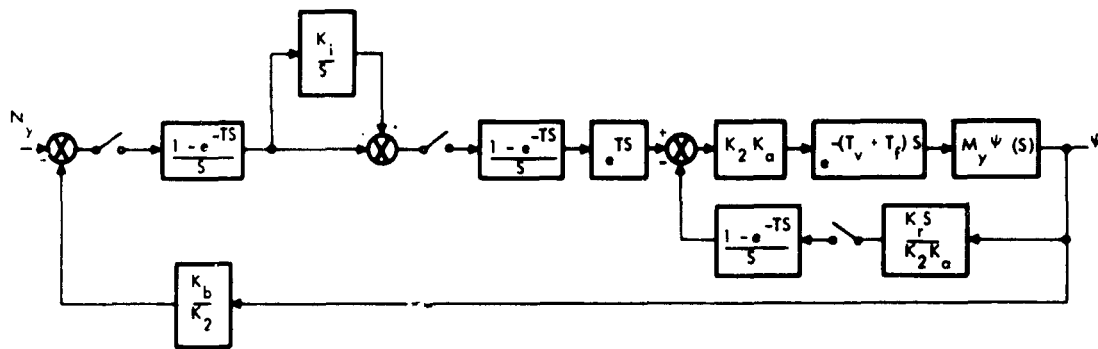


Figure 5-4. Equivalent Form of Figure 5-2

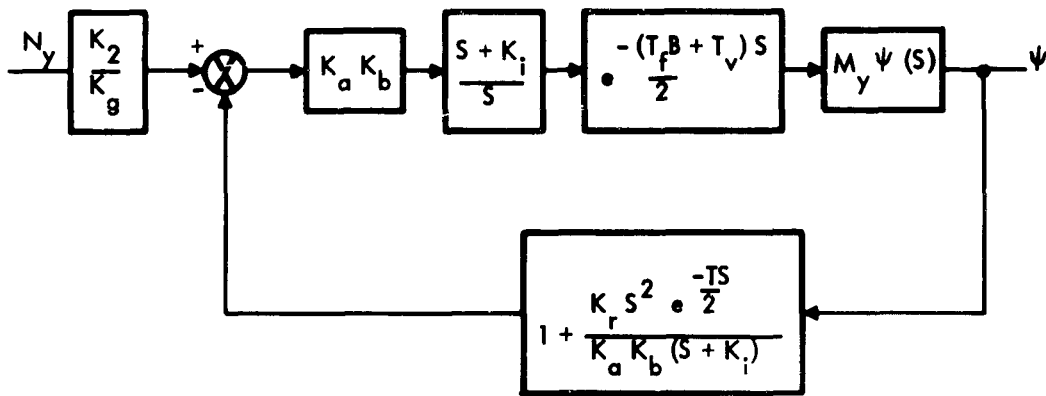


Figure 5-5. Linearized Model of Digital Flight Control System

velocity saturation. The magnitude of the input, however, is limited by the stability condition:

$$\left[ T_{\Sigma} \sin \zeta l_e \right] \delta_{\max} > C_{N\beta} \bar{q} S l_{p\beta} (t)$$

$$\text{and } \left[ T_{\Sigma} \sin \zeta l_e \right] \delta(t) > C_{N\beta} \bar{q} S l_{p\beta}^{\circ}(t) \text{ for } \text{sgn } \delta(t) = - \text{sgn } \beta(t)$$

## B. RESULTS

Results presented in Figure 5-6 and 5-7 were obtained using the linearized model of Figure 5-5. Although not included in this report, satisfactory results were also achieved with a model which included the approximation:

$$e^{-\tau S} = \frac{1}{\tau S + 1}$$

which was used to obtain the response curve of Figure 5-7. Comparison of Figure 5-6 and 5-7 with Figures 4-11 and 4-1 shows the linearized model to be a good approximation.

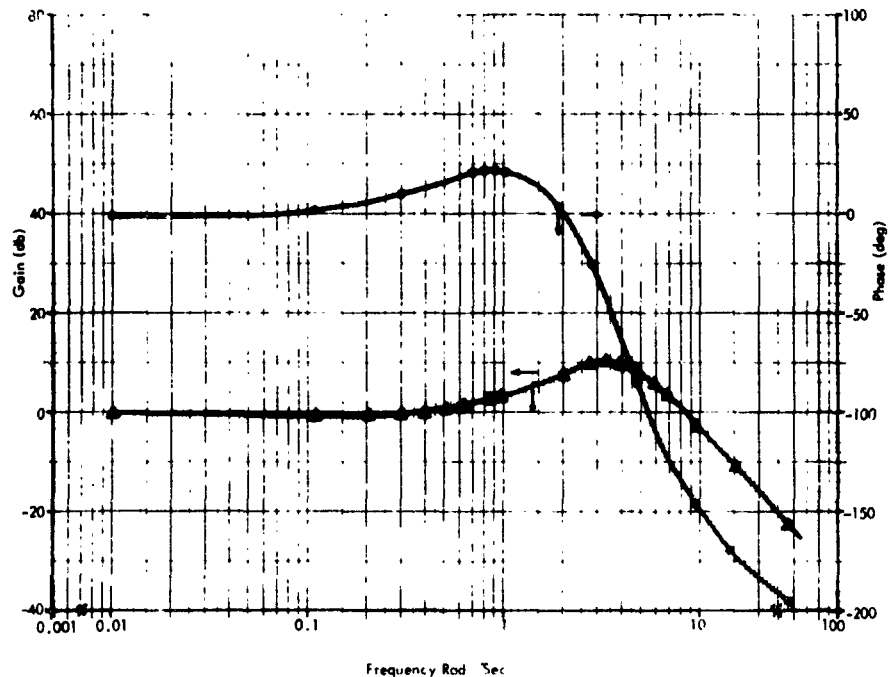


Figure 5-6. Closed Loop Amplitude and Phase Characteristics of Linearized Model (Ref Fig. 5-5)

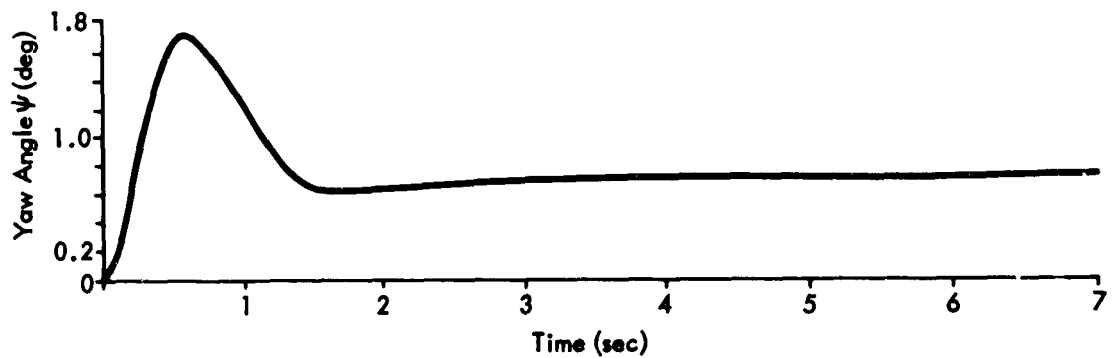


Figure 5-7. Computed Response to a Yaw Command ( $N_y = 10$ )  
Using Linearized Model (Figure 5-5)

#### REFERENCES

1. "Digital Hydraulic Actuator Study Final Report (U)," Contract No. Nonr 4375(00), IBM CD No. 3-260-6036, August 1964.
2. Raider, Scott, "Digital Hydraulic Study Engineering Summary Report Phase II", Contract No. Nonr 4375(00), IBM No. 66-928-7.
3. "Digital Hydraulic Actuator Phase III Proposal," IBM No. 65-947-085, August 1965.
4. Raider, Scott, "A Digital Hydraulic Actuator," IBM No. 65-825-1467, April 1965.
5. "Polaris A3 Preliminary Flight Performance Report, Polaris A3P (MK 3 MODO) Missile (U)," 15 March 1962.

**Appendix A**

**DIGITAL HYDRAULIC ACTUATOR  
OPERATIONAL CONCEPT**

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Appendix A  
DIGITAL HYDRAULIC ACTUATOR  
OPERATIONAL CONCEPT

The digital hydraulic actuator (DHA) design concept used in this study is shown in Figure A-1. Calibrated fluid volumes, transferred by displacing the calibrating piston, are summed to achieve a load position corresponding to a digital command. Auxiliary pistons permit the calibrated volume to be displaced at a rate independent of the mass load.

For simplicity, the operation of the DHA (Figure A-2) will be described neglecting the auxiliary pistons. The high pressure is directed to force the volume piston to its extreme upper position. When the actuating valve is moved down, the fluid pressure will move the volume piston to its extreme bottom position and displace fluid into the actuating cylinder. This in turn will cause the output ram to move a calibrated distance to the right. Because of the larger area on the left side of the ram piston, the high-pressure fluid on the right side of the cylinder will be forced into the high-pressure line. A restriction placed in this line will damp the output ram. Further movement of the actuating valve will cause the output ram to continue discrete motions to the right.

To see how motion to the left is achieved, assume that both valves are again in the upper position, but this time move the direction valve down. The return pressure will now propagate to the bottom side of the volume piston, causing the volume piston to move down. This will withdraw one calibrated volume from the actuating cylinder, and the output ram will be forced to the left by the high pressure on the right side of the actuator cylinder. Motion to the left is continued by moving the actuating valve. Hence, the output ram is moved to the right by moving the direction valve up, or, if it is already in its upper position, by changing the position of the actuating valve. Output ram motion to the left is achieved by moving the direction valve down, or, if it is already down, by changing the position of the actuating valve.

Accuracy requires that the valve iteration interval,  $T_c$ , be greater than the time required to transfer the calibrated volume,  $V_c$ . The maximum valve iteration rate,  $f_c$ , for a given pressure is thus dictated by the magnitude of the mass load. The addition of auxiliary pistons (Figure A-1) permits the calibrated volume to be displaced at a rate independent of the mass load.

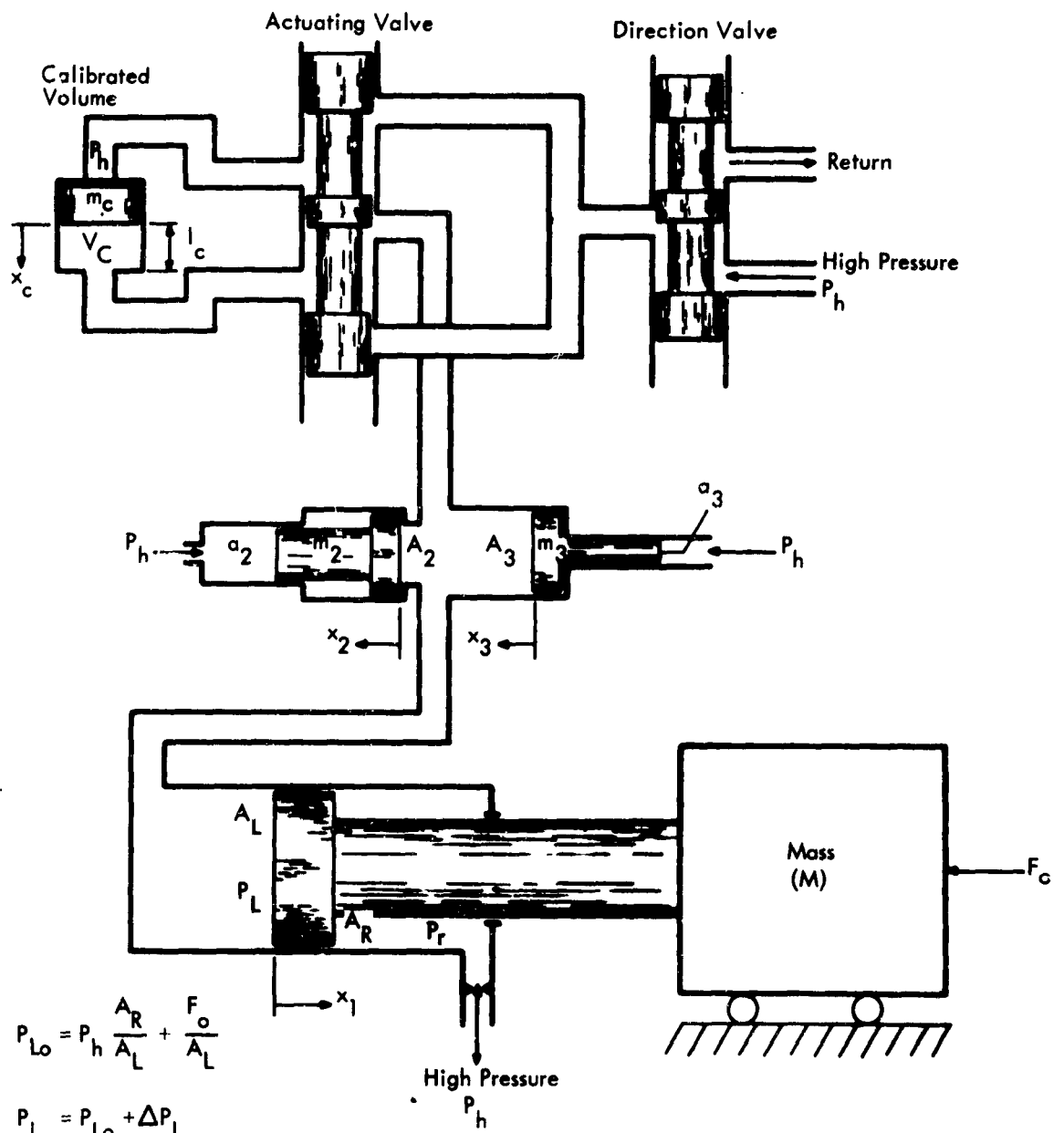


Figure A-1. Schematic of the Basic Digital Hydraulic Actuator

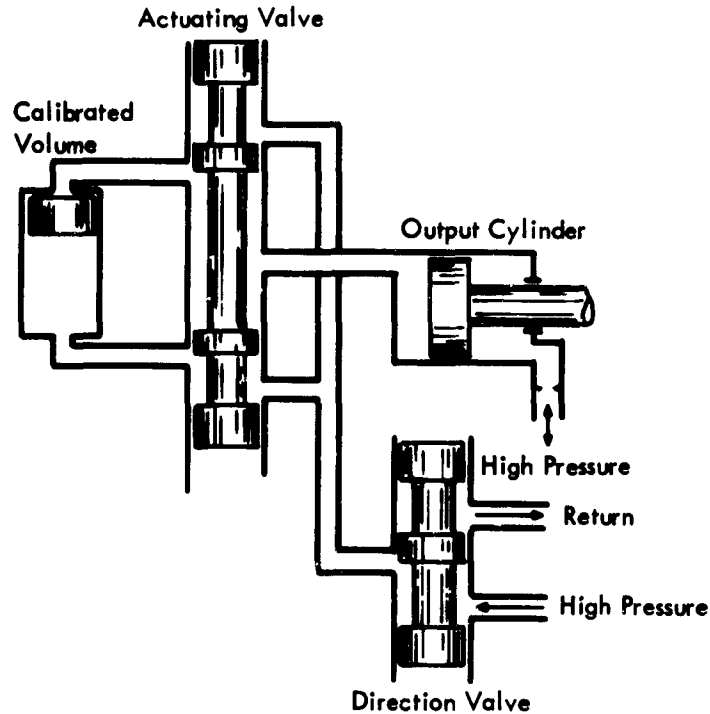


Figure A-2 Digital Hydraulic Actuator

Hence, the iteration rate is limited only by: (1) the maximum switching speed of the valve; (2) the time required to transfer  $V_C$ ; and (3) the time required to decay the transient pressures displacing the volume piston. Since the mass of each auxiliary piston is much less than that of the mass load, fluid transfer time is greatly reduced. Consequently, the mass rate,  $m_r$ , acting to displace the mass,  $M$ , approaches a step function.

If the actuating valve is positioned so that high pressure,  $P_h$ , forces the calibrating piston from the position shown in Figure A-1 to the bottom position, a calibrated volume of fluid,  $V_C$ , will be displaced. The volume displaced can be considered as being divided into three unequal parts:

- A volume necessary to increase the transient total internal pressure,  $P_L$ , from

$$P_h \frac{A_R}{A_L} \quad \text{to} \quad P_h \frac{a_2}{A_2} .$$

- A volume which displaces the ram piston the right.
- A volume which displaces the auxiliary piston of area  $A_2$ .

Because the mass,  $M$ , driven by the ram piston is large relative to the mass of the auxiliary piston, the response of the auxiliary piston is high. Hence, the larger portion of the displaced volume is used to displace the auxiliary piston. The ram piston, initially accelerated by a portion of the volume displaced by the calibrating piston, is further displaced by the transfer of the volume stored by the auxiliary piston due to  $P_h$  acting to restore auxiliary piston 2 to its rest position. Motion of the ram piston is completed when the volume required to increase  $P_L$  is transferred to ram piston motion, thus returning  $P_L$  to its original value,  $P_h A_R/A_L$ . Hence, the ram piston displacement  $X_1$  is:

$$X_1 = \frac{V_c}{A_L} .$$

Additional calibrated volumes displaced by the calibrating piston are stored by displacing auxiliary piston 2.

Over-travel of the ram piston as it moved to the right reduced  $P_L$ . As a consequence, auxiliary piston 3 is displaced, thus limiting  $P_L$  to minimize the effect of cavitation. Displacement of auxiliary piston 3 creates a pressure differential that acts to return the auxiliary piston to its rest position. Hence, over-travel of the ram piston is limited. Auxiliary piston 3 is restored to its rest position and returns the ram piston to a position such that

$$X_1 = \frac{V_c}{A_L} .$$

Positioning the sign valve so that the return is connected to the calibrated volume permits the ram piston to be displaced to the left. Displacing the actuating valve allows  $P_L$  to displace the calibrating piston. Due to the magnitude of the mass,  $M$ , the initial volume of fluid required to displace the calibrating piston is furnished by the motion of auxiliary piston 3. Operation is therefore identical in principle to the motion of the ram piston to the right. However, when ram piston motion is to the left, auxiliary piston 3 provides the storage capability and auxiliary piston 2 returns the ram piston to its commanded position when over-travel occurs.

Hydraulically actuated pilot valves operate both the sign and actuating valves. In addition, by using hydraulic power to move the pilot valve, the magnet is not required to perform any work, and this permits the use of small, low-power magnets controlled by electrical commands. Energized, the magnets act as latches, holding the spool of the pilot valve at a fixed position. When de-energized, a magnetic latch permits the hydraulic force to move the



pilot spool, which in turn allows a hydraulic force to move the main spool. A schematic diagram of the pilot and actuator valves is shown in Figure A-3. The pilot valve is shown held in its left hand position by magnetic latch A. Hydraulic pressure acts through the pilot valve to the end of the actuator valve, forcing it to the extreme right. It also acts through the actuator valve to the left end of the pilot spool. De-energizing magnetic latch A allows the hydraulic pressure to move the pilot to the extreme right-hand position, where it is held by latch B. Moving the pilot to the right-hand position switches the pressure to the right-hand end of the actuator valve and connects the left end to the sump. The actuator valve is therefore moved to the extreme left. In an extreme left position, the pressure switches to force the pilot to the left. The left end of the pilot is now connected to the sump, and movement of the pilot is prevented by magnetic latch B. De-energizing latch B allows both valves to move back to the initial position.

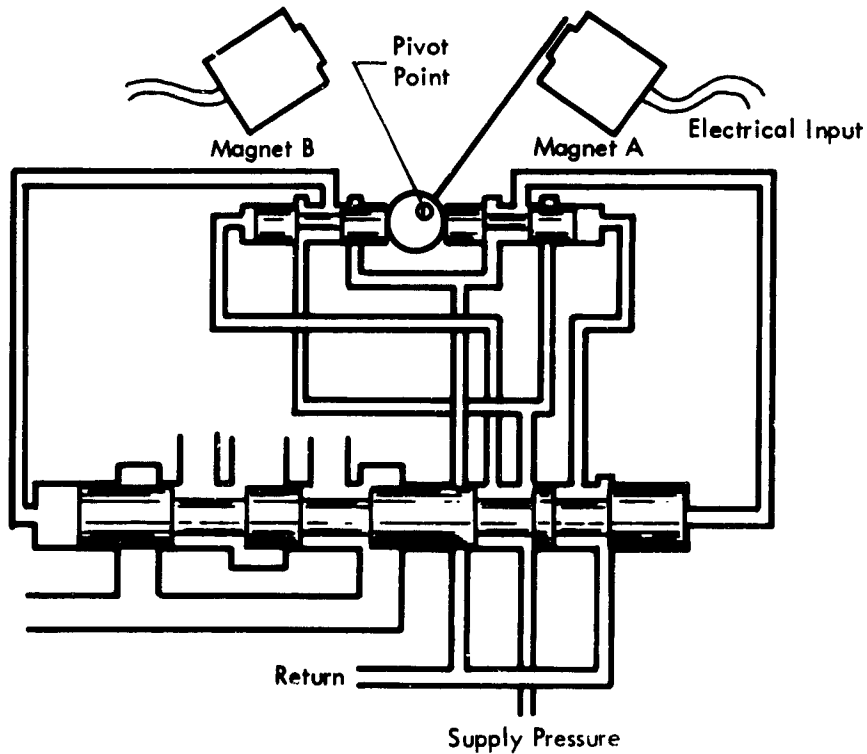
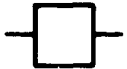



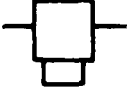




Figure A-3. Pilot Drive Schematic

**Appendix B**  
**CIRCUITS**  
**CONTROL LOGIC**

### Description of Symbols

Symbol	Description	Type - IBM No.
	Inverter	370348
	2-Input NAND Inverter	370216
	3-Input NAND Inverter	370378
	Trigger	37022
	Singleshot	370262
	Driver	371633
	Load Card	37032

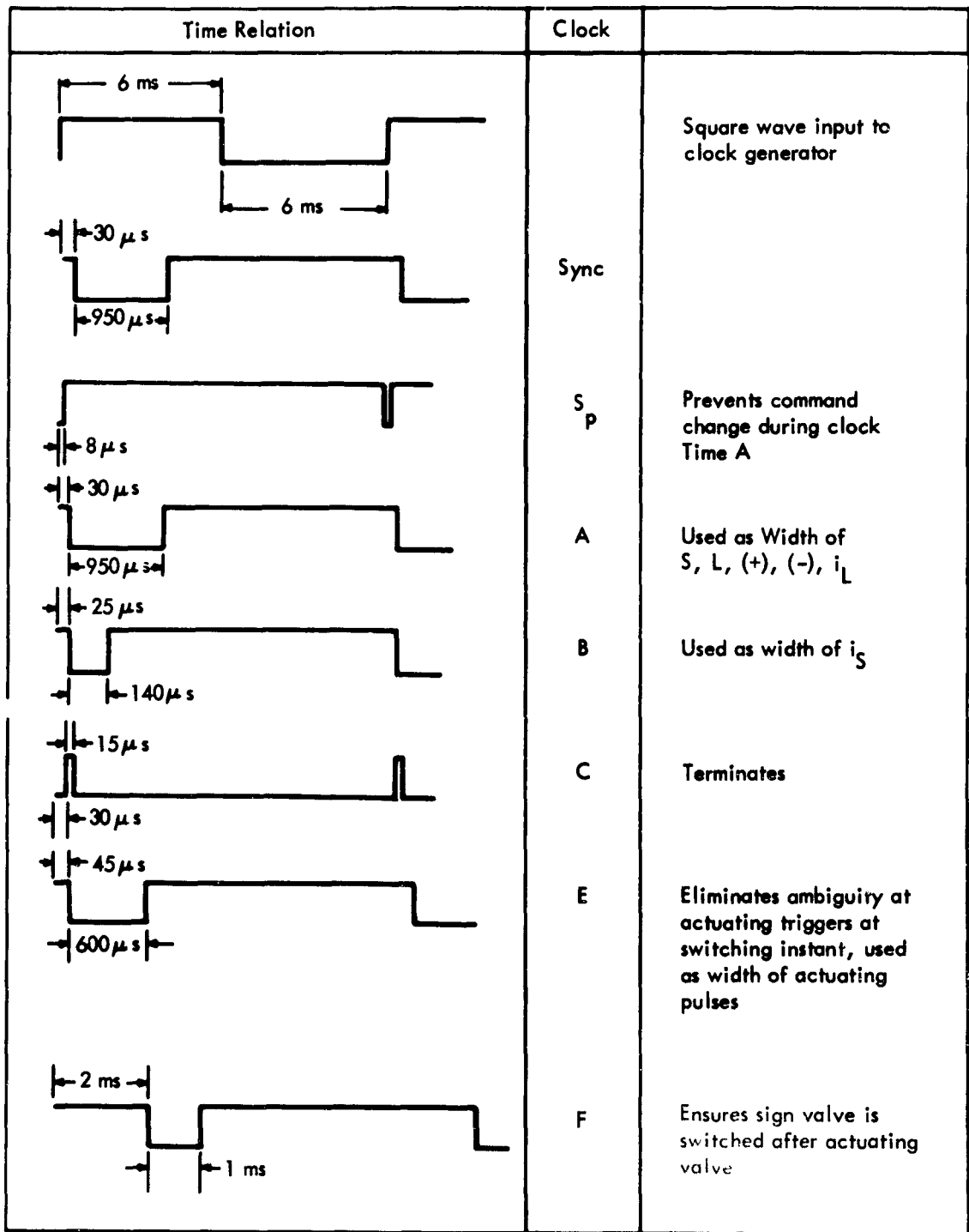


Figure B-1. Clock Pulses - Function and Time Relation (Revised)

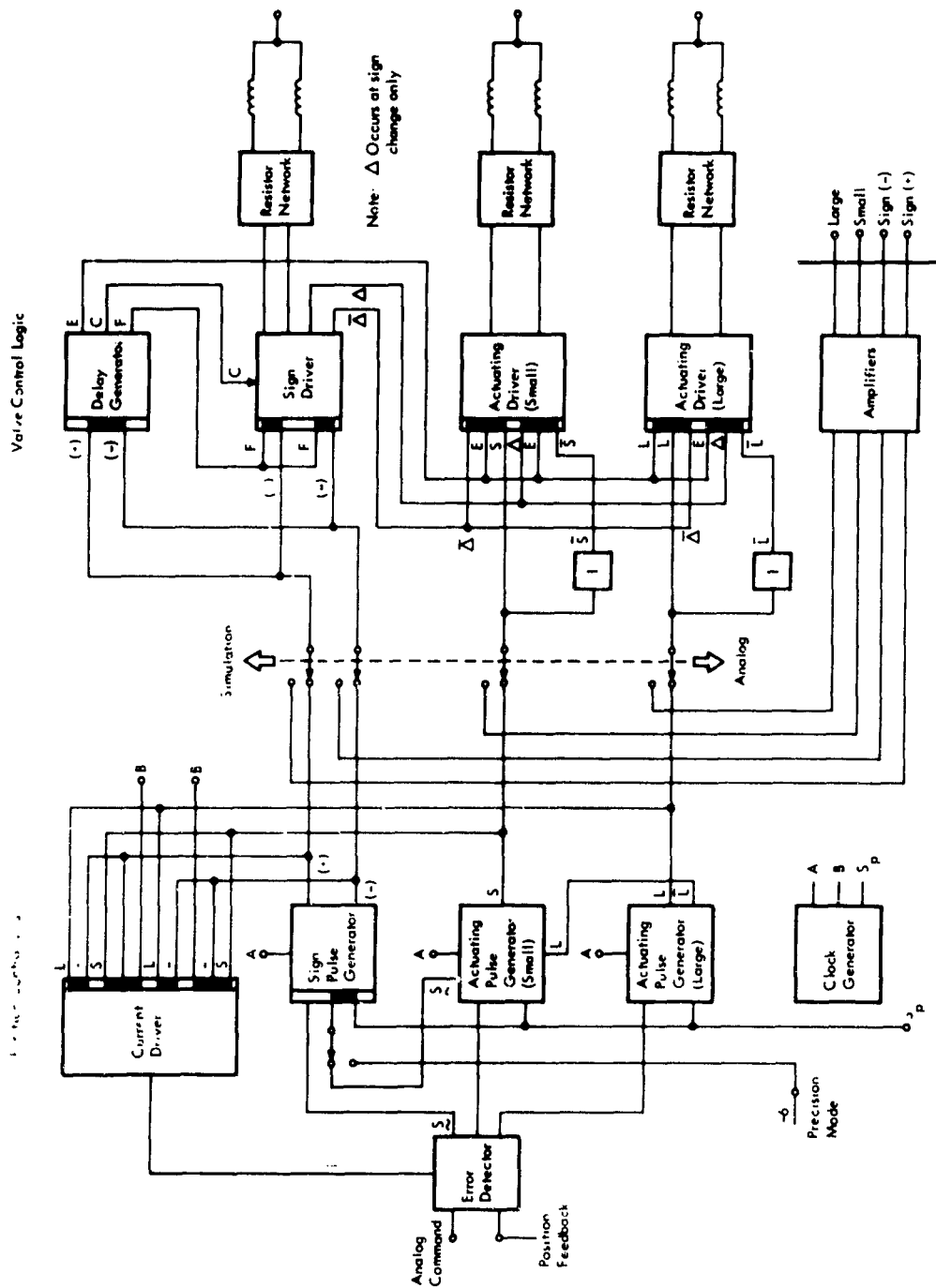


Figure B-2. Central Logic

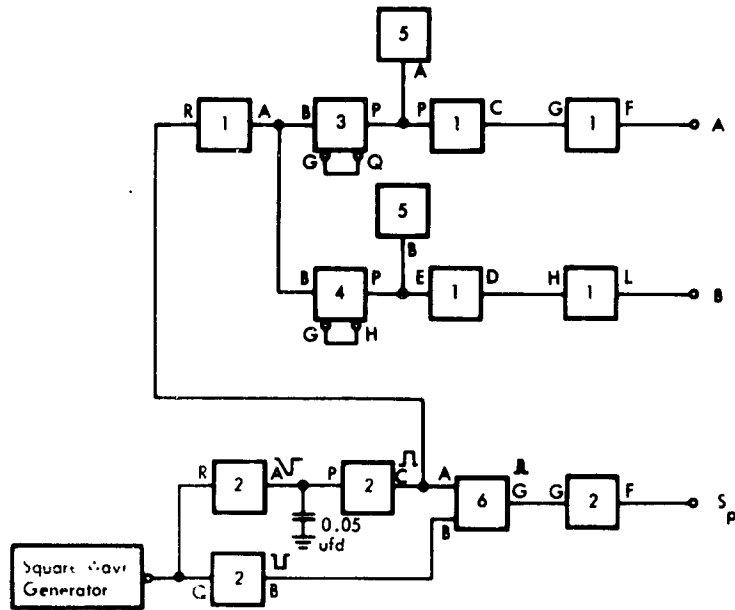


Figure B-3. Clock Generation

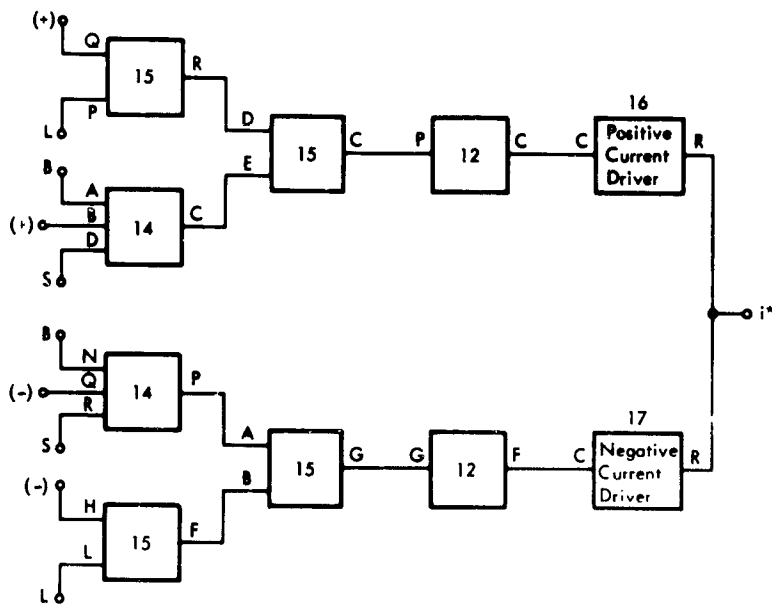


Figure B-4. Current Driver

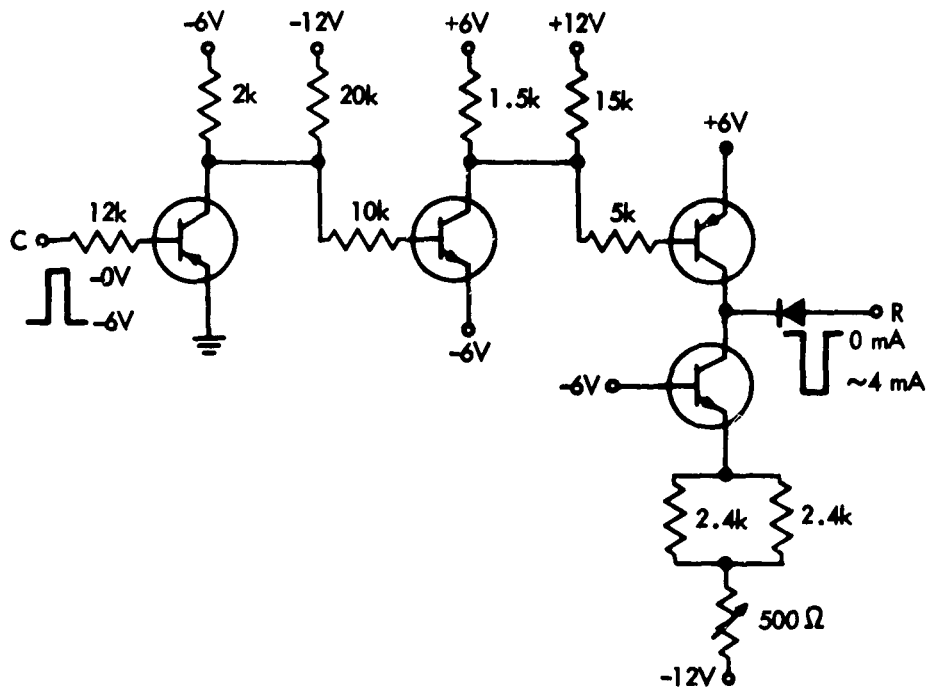


Figure B-5. Negative Current Driver

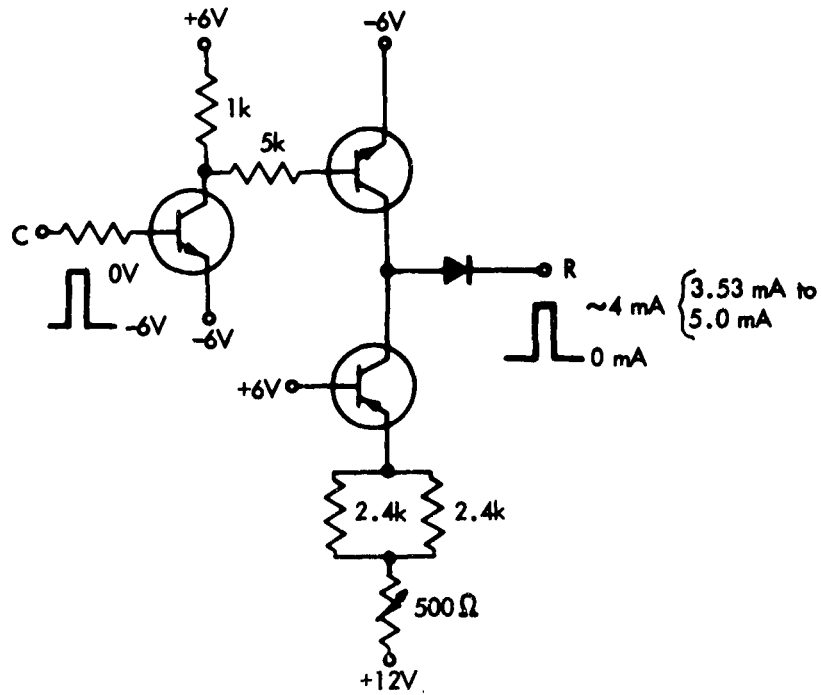


Figure B-6. Positive Current Driver

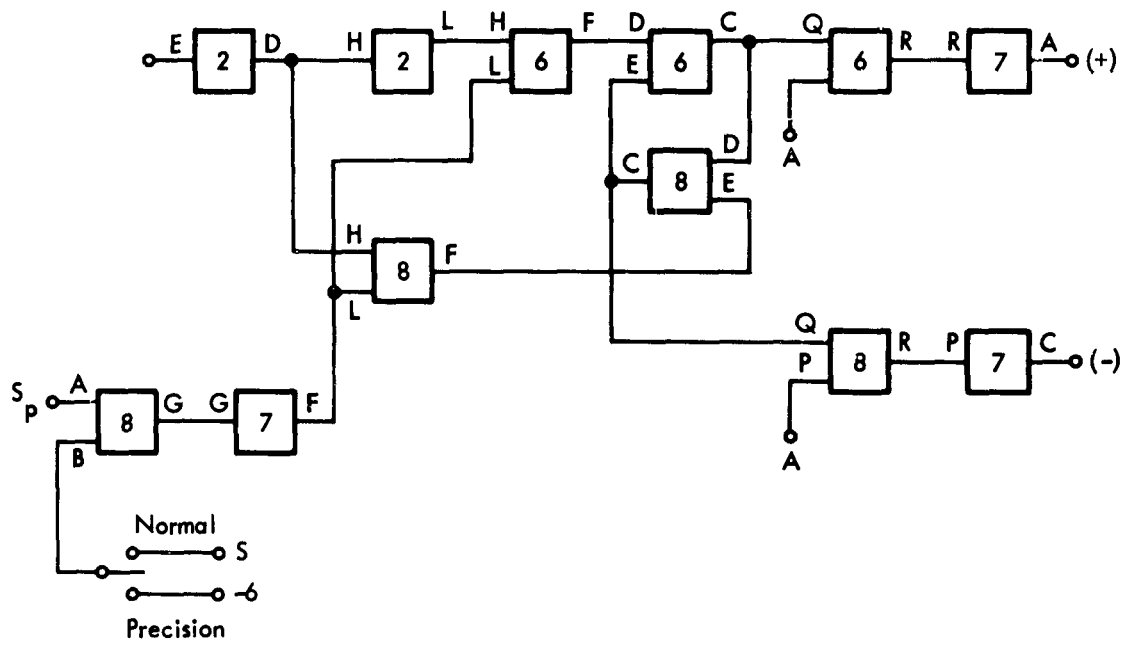


Figure B-7. Sign Pulse Generation

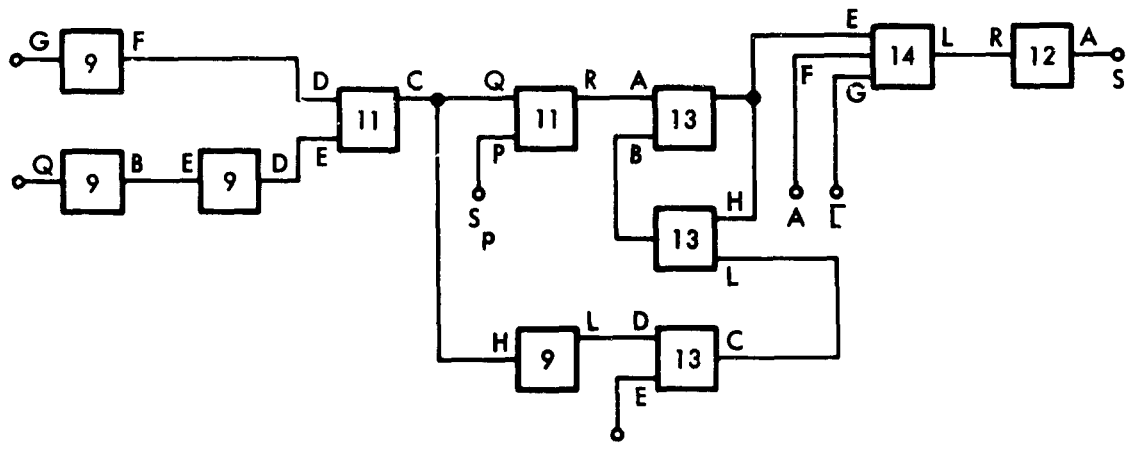


Figure B-8. Small Pulse Generation



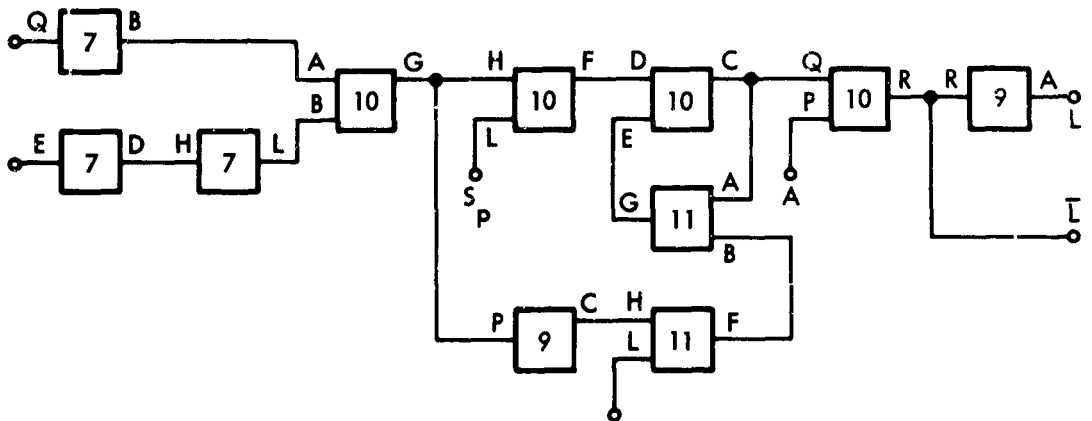


Figure B-2. Large Pulse Generation

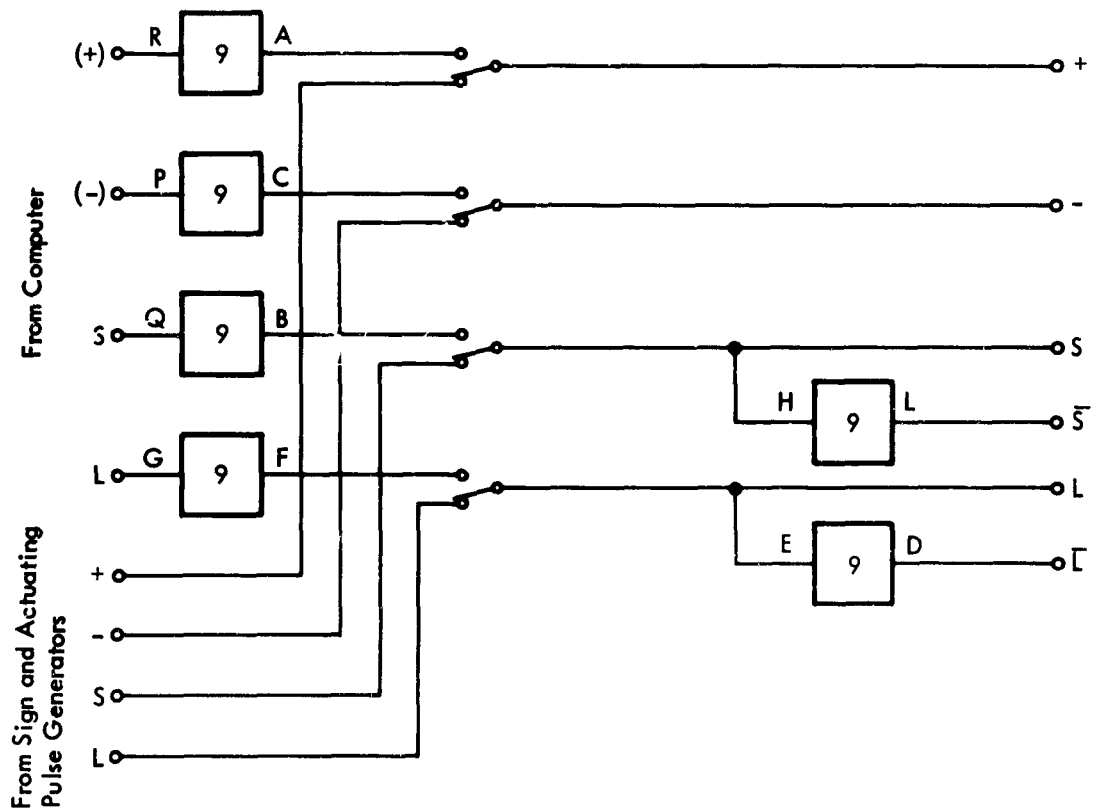


Figure B-10. Amplifiers and Command Inverters

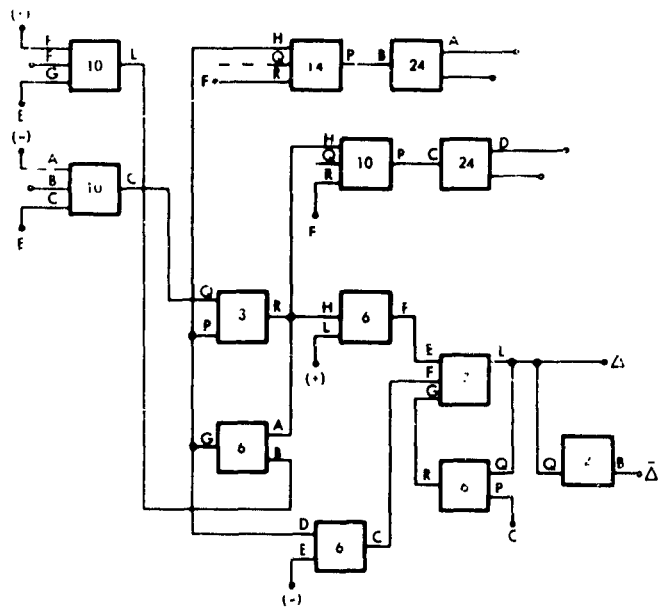


Figure B-11. Sign Driver

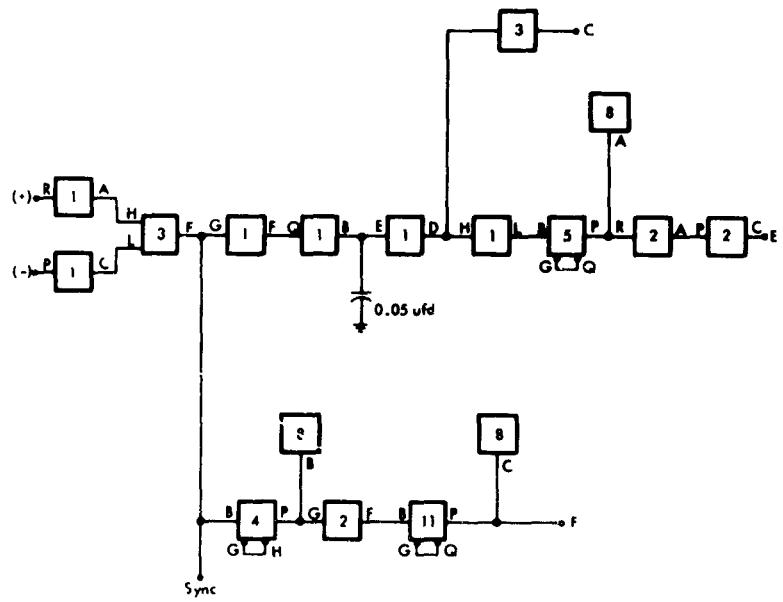


Figure B-12. Delay Generation Logic

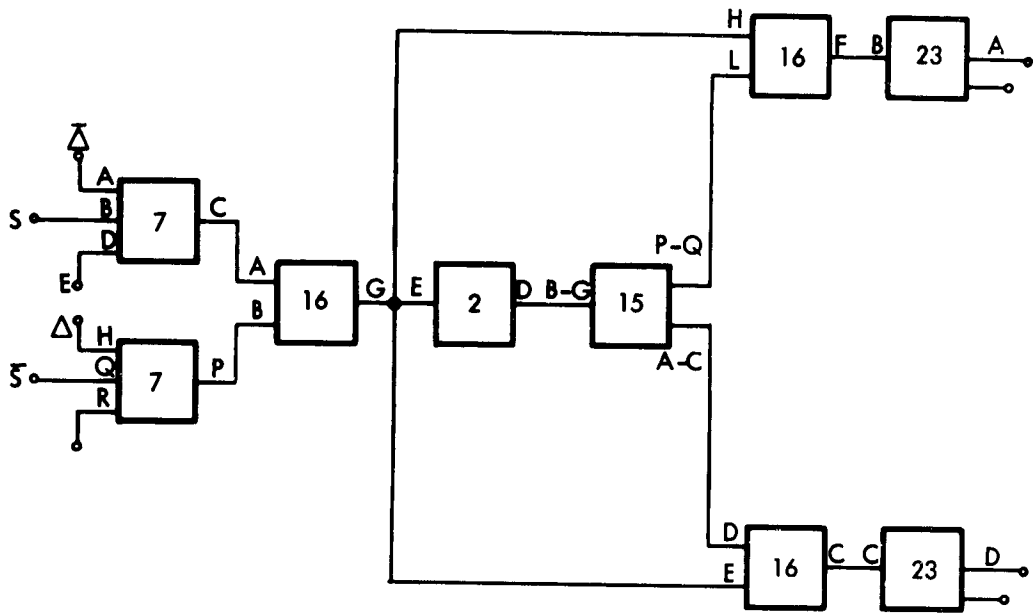


Figure B-13. Small Actuating Driver

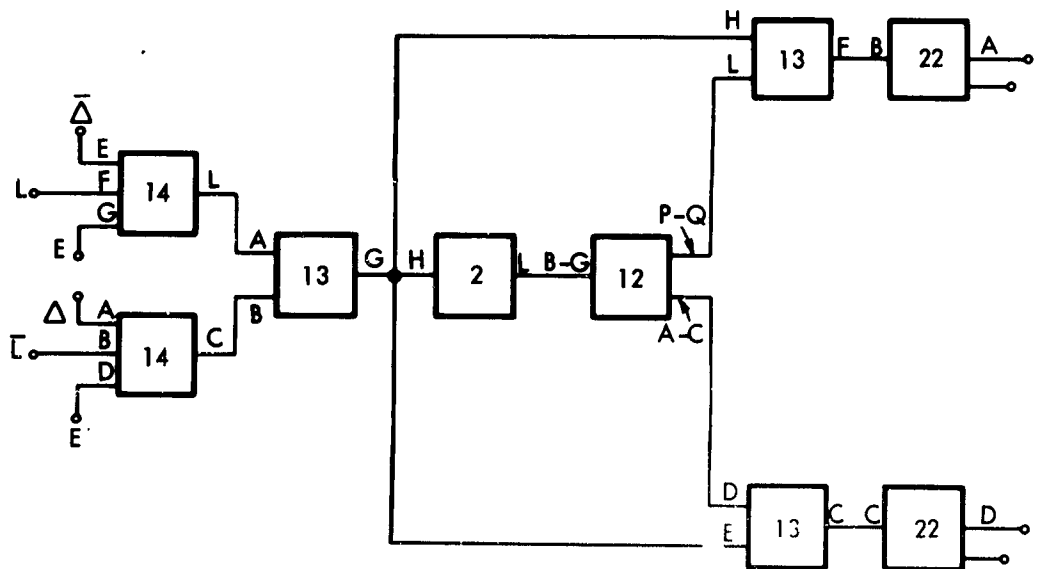


Figure B-14. Large Actuating Driver

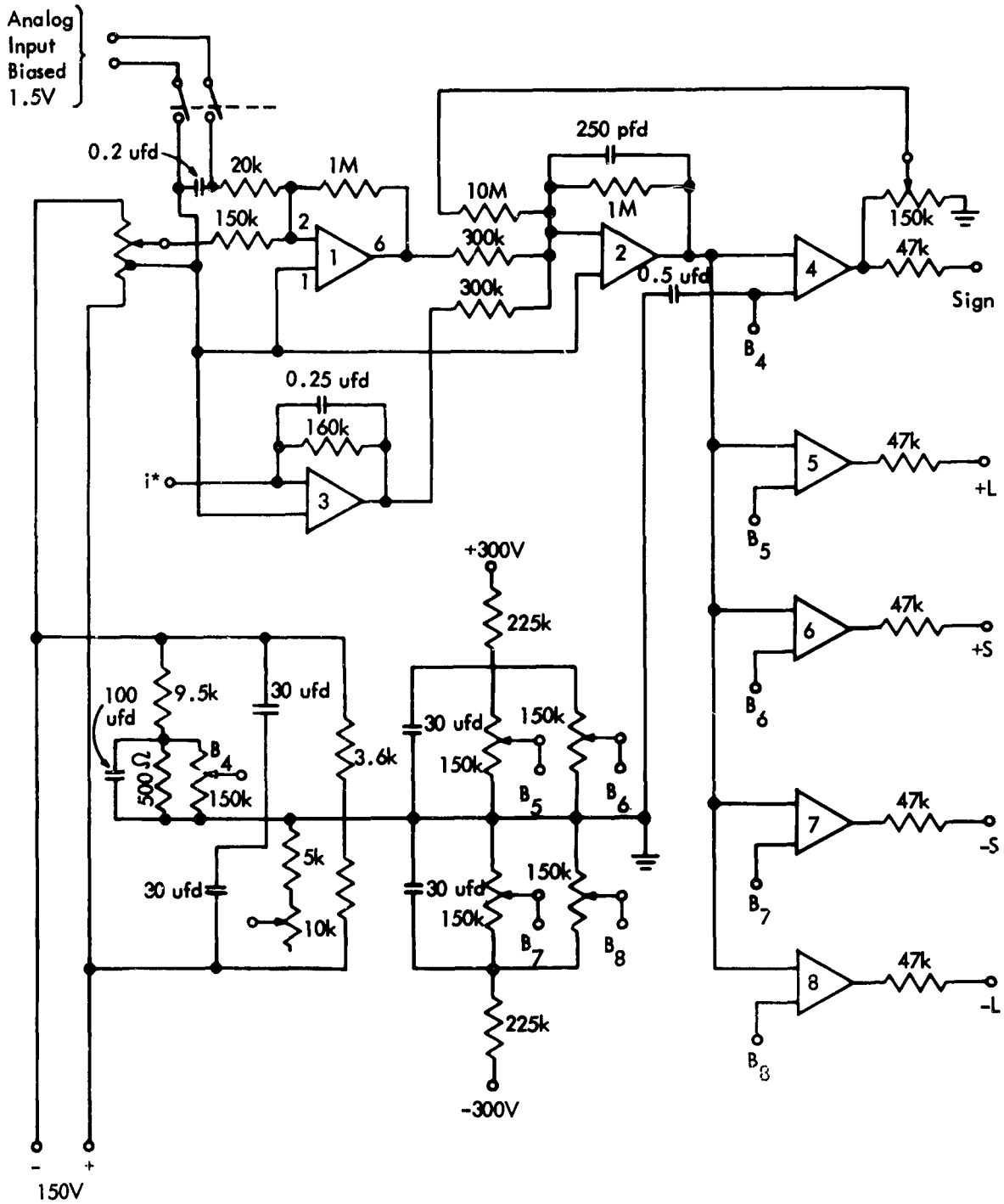


Figure B-15. Error Detector

**Appendix C**  
**LIST OF SYMBOLS**

## Appendix C

### LIST OF SYMBOLS

<u>Symbol</u>	<u>Dimension</u>	<u>Definition</u>
$A_C$	$\text{in}^2$	Area of Calibrating Piston
$A_L$	$\text{in}^2$	Area of Ram Piston Exposed to $P_L$
$A_R$	$\text{in}^2$	Area of Ram Piston - Rod End
$A_2$	$\text{in}^2$	Area of Auxiliary Piston 2 Exposed to $P_L$
$a_2$	$\text{in}^2$	Area of Auxiliary Piston 2 Exposed to $P_S$
$A_3$	$\text{in}^2$	Area of Auxiliary Piston 3 Exposed to $P_L$
$a_3$	$\text{in}^2$	Area of Auxiliary Piston 3 Exposed to $P_S$
$C$	$\text{lb} \cdot \text{s}/\text{in}^{-1}$	Viscous Damping Coefficient
$C_{N\beta}$	—	Gradient of Normal Force Coefficient with Respect to Angle of Sideslip
$e_b$	deg	Error Required to Produce Input - Large
$e_s$	deg	Error Required to Produce Small Volume Command
FB	—	Feedback
$\Delta F$	—	External Force
K	—	Forward Path Gain of Integration Compensation - Equal to $K_1 T$

<u>Symbol</u>	<u>Dimension</u>	<u>Definition</u>
$K_a$	—	Pitch and Yaw Attitude Autopilot Gain
$K_b$	—	Weighting Factor for Yaw Body Angles
$K_g$	—	Variable Gain Used to Determine Gain Margin
$K_i$	$s^{-1}$	Forward Path Gain of Autopilot Integration Compensation
$K_L$	$\text{deg } s^{-1}$	Leakage Rate Gain
$K_r$	$s$	Yaw Rate Autopilot Gain
$K_2$	$\text{deg/pulse}$	Proportionality Factor for Guidance Yaw Command and Pulses
$l_p$	ft	Aerodynamic Control Arm
$l_e$	ft	Axial Control Arm
$M$	$\text{lb} - s^2/\text{in}^{-1}$	Lumped Mass of Output Ram Piston Including Load Inertia
$M_y$	$\text{radians/pound}$	Missile Transfer Function $\psi/T_y$
$N_y$	—	Algebraic Sum of Yaw Steering Pulses
$N_{yFB}$		$\frac{K_B}{K_2} \psi$
$N_{y\epsilon}$		$N_y(t) + N_{yFB}$
$P_d$	$\text{lb/in}^2$	Pressure Change of $P_L$
$P_h$	$\text{lb/in}^2$	High Pressure
$P_L$	$\text{lb/in}^2$	Transient Total Internal Pressure

<u>Symbol</u>	<u>Dimension</u>	<u>Definition</u>
$P_m$	$\text{lb/in}^2$	Maximum Deviation of $P_L$
$P_r$	$\text{lb/in}^2$	Return Pressure
$P_s$	$\text{lb/in}^2$	Supply Pressure
$q$	$\text{in}^3 - \text{s}^{-1}$	Flow
$Q_{\text{corr}}$	$\text{in}^3/\text{s}$	Correction Required to Make Analog Integrated Value $V_B$ Equal to Integrated Value, $V_{\text{dig}}$
$Q_{P_i}$	$\text{in}^3/\text{s}$	Flow for Specified Parts of the Period T
$Q_p$	$\text{in}^3/\text{s}$	Summation $Q_{P_L}$ and $Q_{\text{corr}}$ at Sample Time
$\bar{q}$	$\text{lbf/in}^2$	Dynamic Pressure
$q_{LC}^*$	$\text{in}^3/\text{s}$	$q_{LC} + \frac{2}{P_h - P_r} \left[ P_h \frac{A_R}{A_L} - \frac{P_h + P_r}{2} \right] q_L$
$q_{LC}$	$\text{in}^3/\text{s}^{-1}$	Error Rate Leakage
$q_L$	$\text{in}^3/\text{s}^{-1}$	Leakage Rate Gain
$r_1$	$\text{lb s/in}^{-5}$	Flow Resistance
R	in	Moment Arm
S	$\text{s}^{-1}$	Laplace Transform Variable
$\bar{S}$	$\text{ft}^2$	Missile Reference Area
T	s	Sampling Period
$T_D$	s	Delay



<u>Symbol</u>	<u>Dimension</u>	<u>Definition</u>
$T_v$	s	Valve Operation Period
$T_{fB}$	s	Fluid Flow Period (Large Volume)
$T_{fs}$	s	Fluid Flow Period (Small Volume)
$T_z$	lb	Thrust Along Yaw Axis
$T\Sigma$	lb	Nominal Total Thrust
$\Delta V$	in <sup>3</sup>	Volume Transferred Over Interval $t_v$ to $(t_v + T)$
$\Delta V'$	in <sup>3</sup>	Volume Transferred Over the Interval $t_{A/D}$ to $(t_{A/D} + T)$
$V_{dig}$	in <sup>3</sup>	Digital Summation of $\Delta V'$
$\Delta V_1$	in <sup>3</sup>	Volume Transferred Over the Interval $t_v$ to $(t_{A/D} + T)$
$\Delta V_2$	in <sup>3</sup>	Volume Transferred Over the Interval $(t_{A/D} + T)$ to $(t_v + T)$
$V_p$	in <sup>3</sup>	Analog Integrated Value of the Flow $Q_p$
$V_B$	in <sup>3</sup>	Leakage Volume Change Due to the Pressure $P_d$
$V_T$	in <sup>3</sup>	Total Volume Producing Ram Motion
$V_\epsilon$	in <sup>3</sup>	Volume Generating Pressure $P_d$

<u>Symbol</u>	<u>Dimension</u>	<u>Definition</u>
$V_{CS}$	$\text{in}^3$	Displacement Volume of Calibrating Small Piston
$V$	$\text{in}^3$	Oil Volume of Digital Hydraulic Actuator
$V_{CB}$	$\text{in}^3$	Displacement Volume of Calibrating Piston - Large
$V_T$	$\text{in}^3$	Total Volume Producing Ram Motion
$X_1$	in	Displacement of Output Ram Piston
$X_{1A}$	in	Actual Displacement of Output Ram Piston
$\delta_a$	deg	Actual Nozzle Rotation
$\delta_\beta$	deg	Feedback Gain
$\delta_c$	rad	Desired Nozzle Position
$\delta_n$	deg	Feedback Gain
$\delta_p$	deg	Feedback Gain
$\delta_L$	deg	Feedback Gain
$\dot{\delta}_{LC}$	$\text{deg s}^{-1}$	Error Rate Leakage
$\beta$	$\text{lb/in}^2$	Bulk Modulus
$\beta(t)$	rad	Angle of Sideslip
$\delta_q$	deg	One Quantum
$\zeta$	deg, rad	Rotatable Nozzle Cant Angle
$\psi$	deg, rad	Yaw Angle
$\epsilon$	deg	Desired Change of Nozzle Position

**APPENDIX D**  
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Appendix D

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11 SUPPLEMENTARY NOTES		12 SPONSORING MILITARY ACTIVITY <b>Air Programs, Office at Naval Research</b>
13 ABSTRACT  To further support the practicability of the digital hydraulic actuator as a control component, IFM has successfully demonstrated operation of the Phase III laboratory model in a simulated digital flight control system. Performance using the laboratory model is compared with the performance when using a mathematical model. Recorded transients and the values obtained for a maximum stable step and gain change are presented. The effect of varying the actuator parameters and the validity of a linearized model is also established. Agreement of the results shows the mathematical model to accurately represent the actual hardware. Hence, this study verified the results of both Phase I and Phase II.		

<p>14</p> <p style="text-align: center;">KEY WORDS</p> <p><b>Actuators</b>  <b>Digital Control Valve</b>  <b>Digital Hydraulics</b>  <b>Digital Control</b></p>	LINK A		LINK B		LINK C	
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