

**NASA CONTRACTOR
REPORT**



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**FLIGHT CONTROL SYSTEMS
PROPERTIES AND PROBLEMS**

Volume II - Block Diagram Compendium

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Prepared by
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16. Abstract <p style="text-align: center;">The purpose of this program was to document and pass on experience to current and future generations of flight control engineers, hopefully, to prevent costly rediscovery of past mistakes and to stimulate trade studies between possible competing mechanizational approaches.</p> <p style="text-align: center;">The documentation is divided into two volumes. Volume I (NASA CR-2500) contains the technical discussion while this volume is a compendium of stability augmentation system and autopilot block diagrams and descriptive material for 48 different types of aircraft. These provide a broad representation of the many mechanizational approaches which have been employed in the past.</p>					
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SECTION I

INTRODUCTION

This volume contains a compendium of SAS and autopilot block diagrams for some 48 attack, bomber, cargo, drone, fighter, research, and transport type aircraft. It also contains references to specific documents from which information was gleaned for this study.

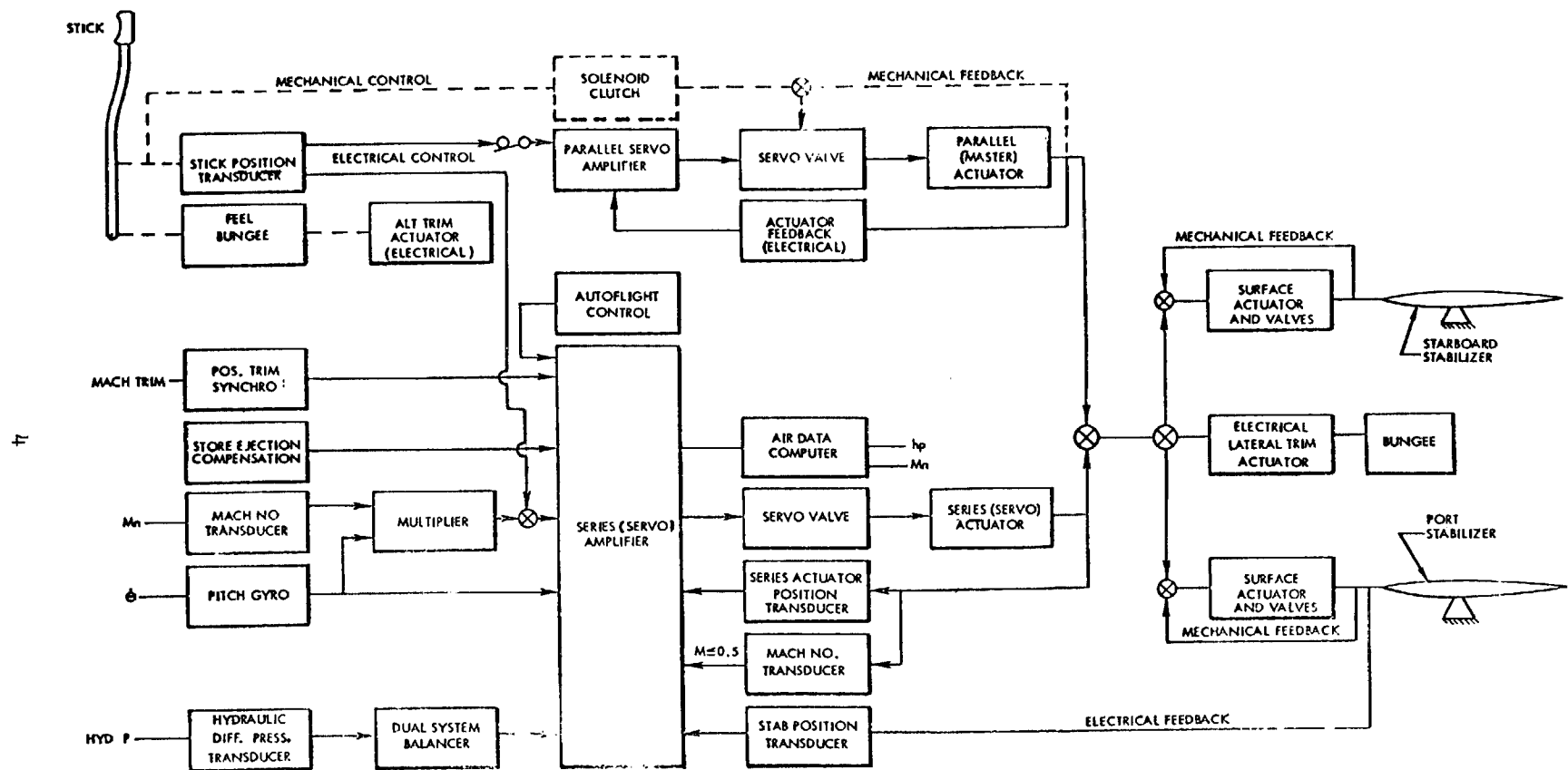
This compendium incorporates and expands upon an earlier effort (Ref. 67) initiated by the A-18 Aerospace Control and Guidance Systems Committee of the Society of Automotive Engineers. It is by no means a complete exposition of systems past and present. There are many systems for which no information was available, and there are others for which the information available was incomplete or conflicting, and therefore not included here.

An initial attempt was made to put all block diagrams into a consistent format which identified functional blocks and associated transfer characteristics, functional switching, etc. However, it rapidly became apparent that such a task was beyond the scope of this program. Therefore in most instances the diagrams presented here have been reproduced directly from the original documents listed in the references. In all probability they reflect but one version of systems which may have undergone several modifications. Consequently, additions or revisions are solicited from those who make use of these volumes.

SECTION II
BLOCK DIAGRAMS

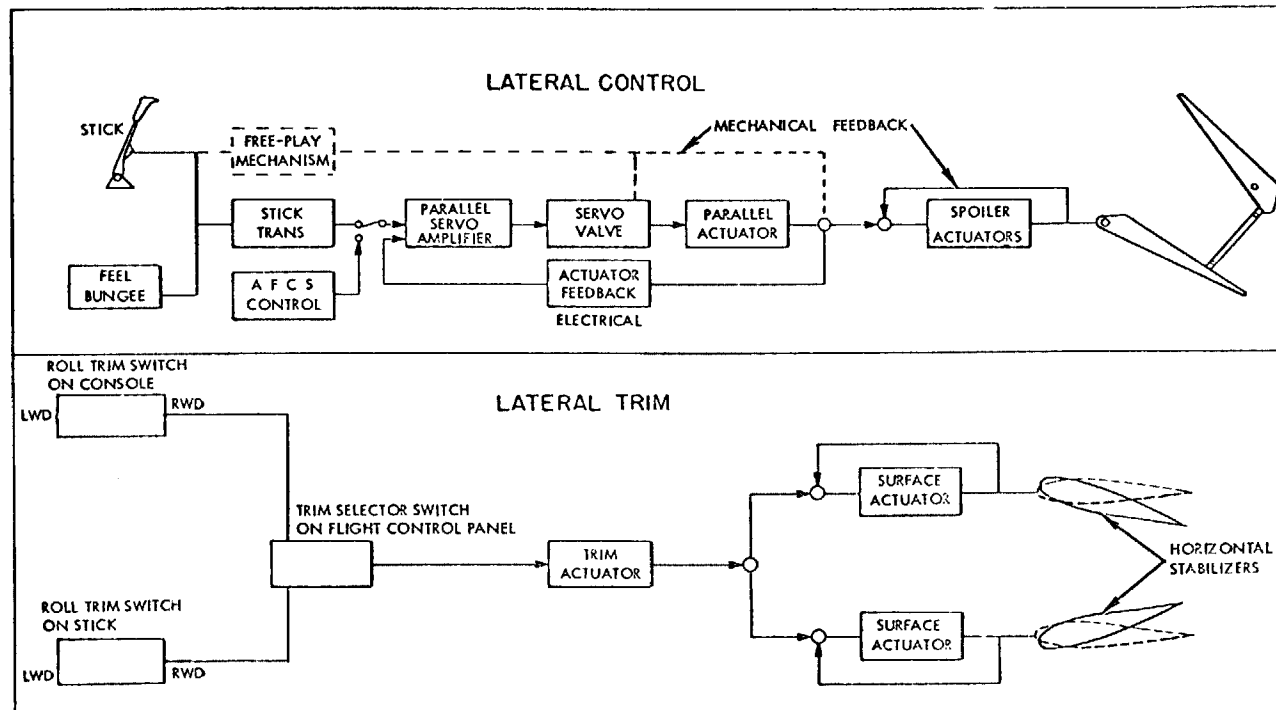
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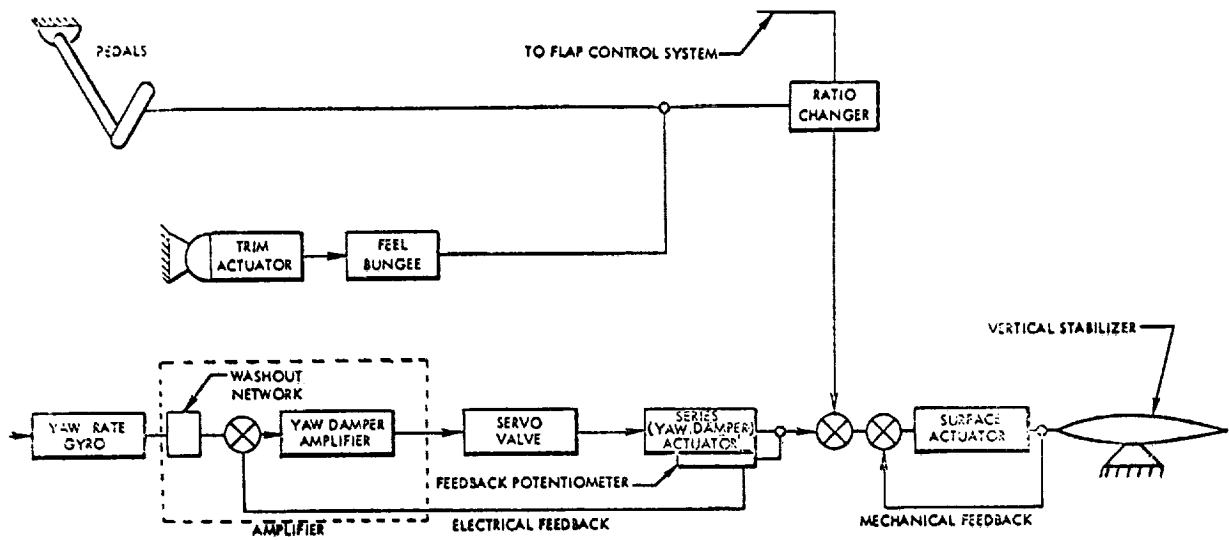
BLOCK DIAGRAM

A3J-1 LONGITUDINAL CONTROL SYSTEM

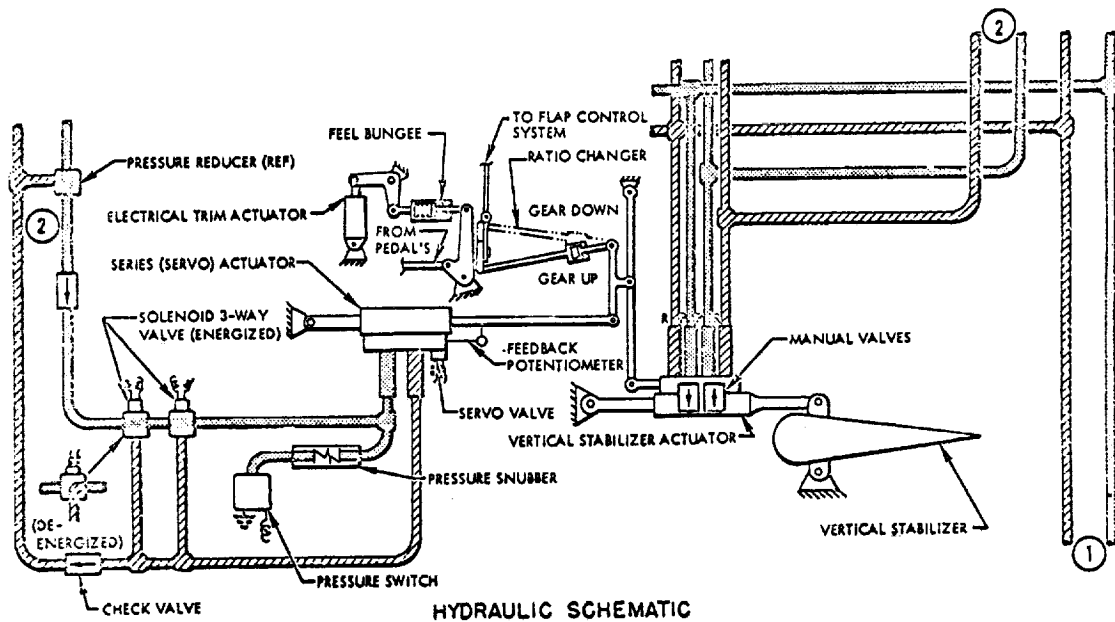


BLOCK DIAGRAMS

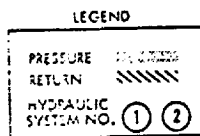
A3J-1 LATERAL CONTROL SYSTEM



BLOCK DIAGRAM

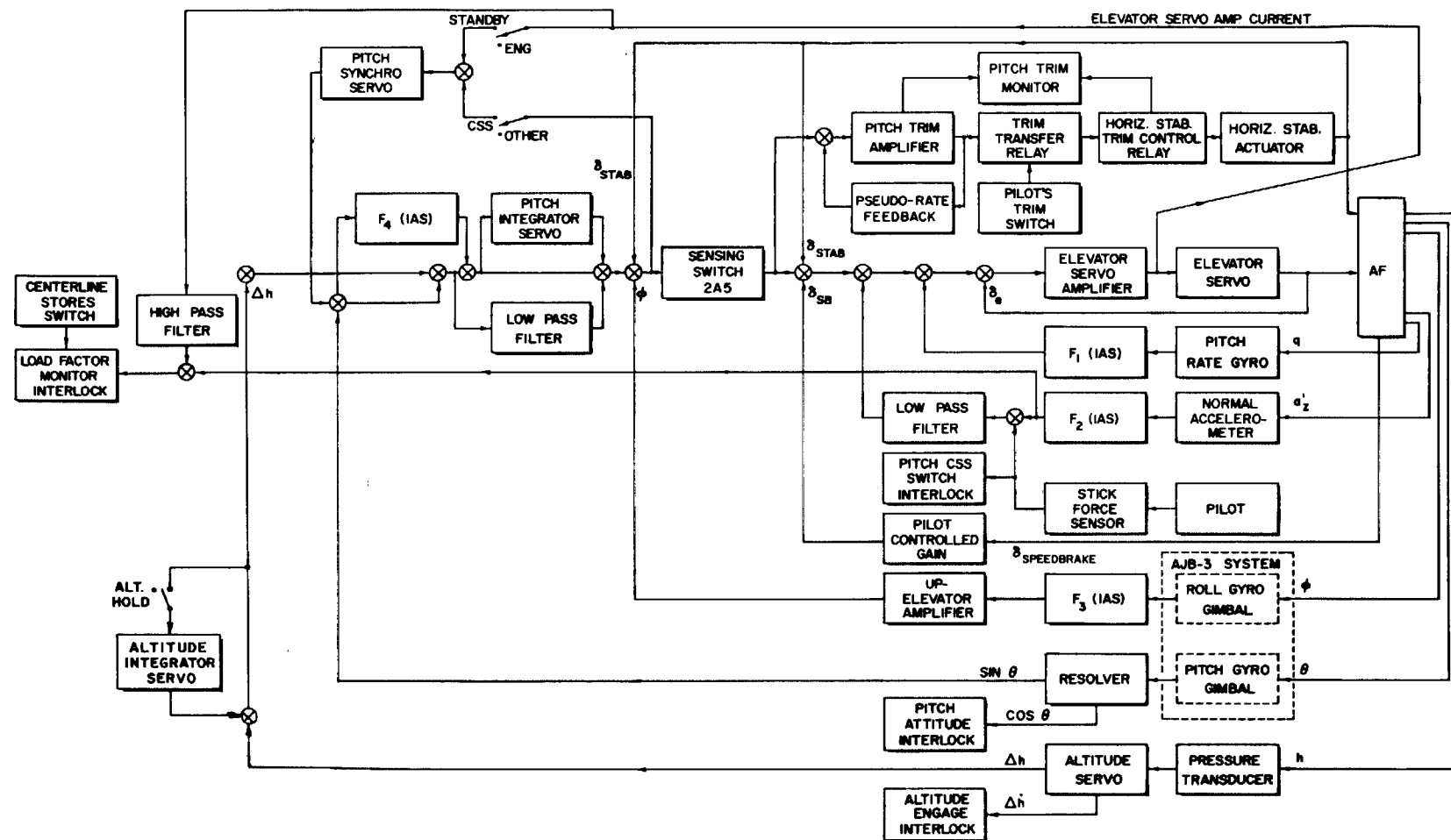


HYDRAULIC SCHEMATIC

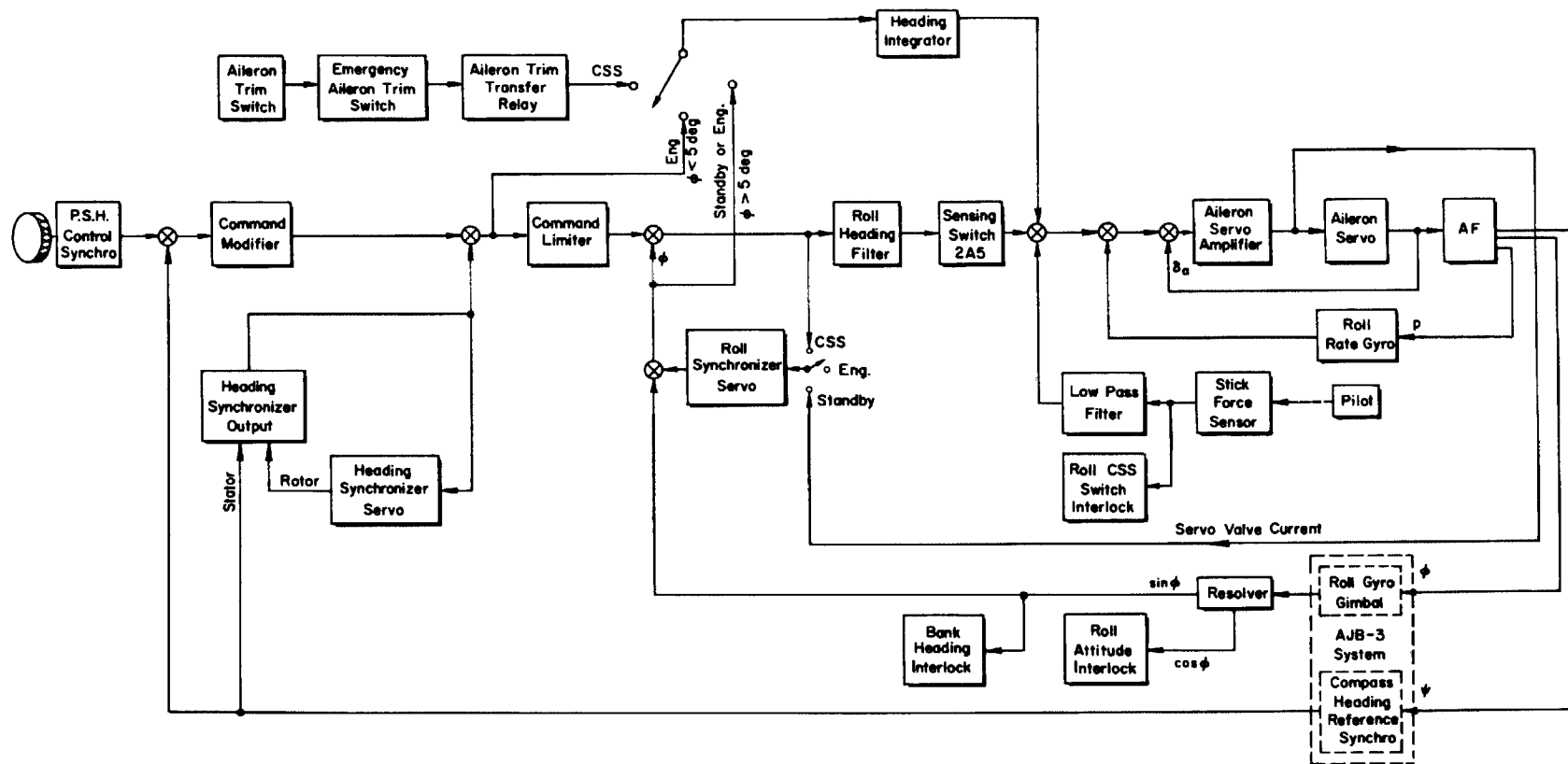


A3J-1 DIRECTIONAL CONTROL SYSTEM

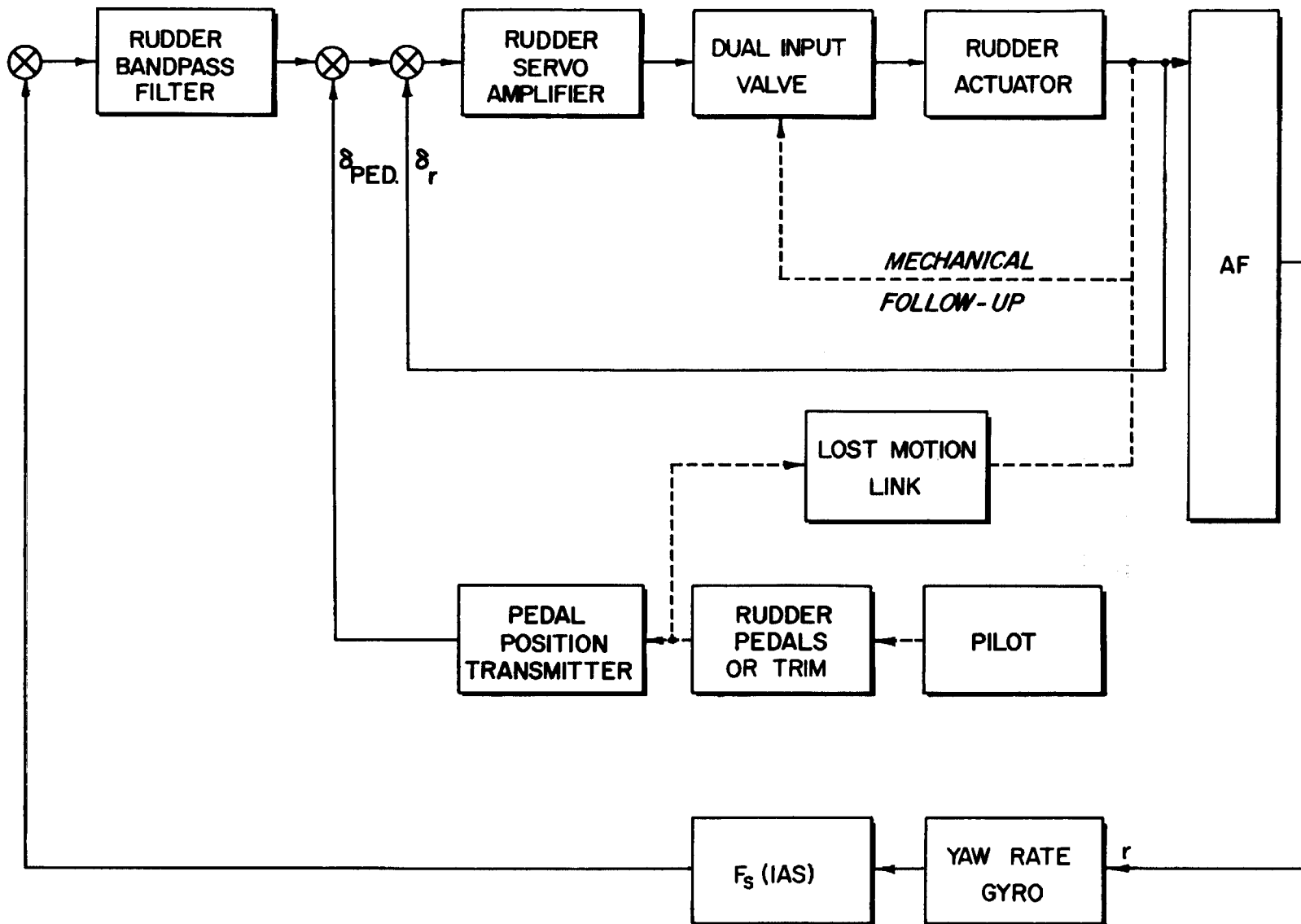
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A-4 Elevator Channel



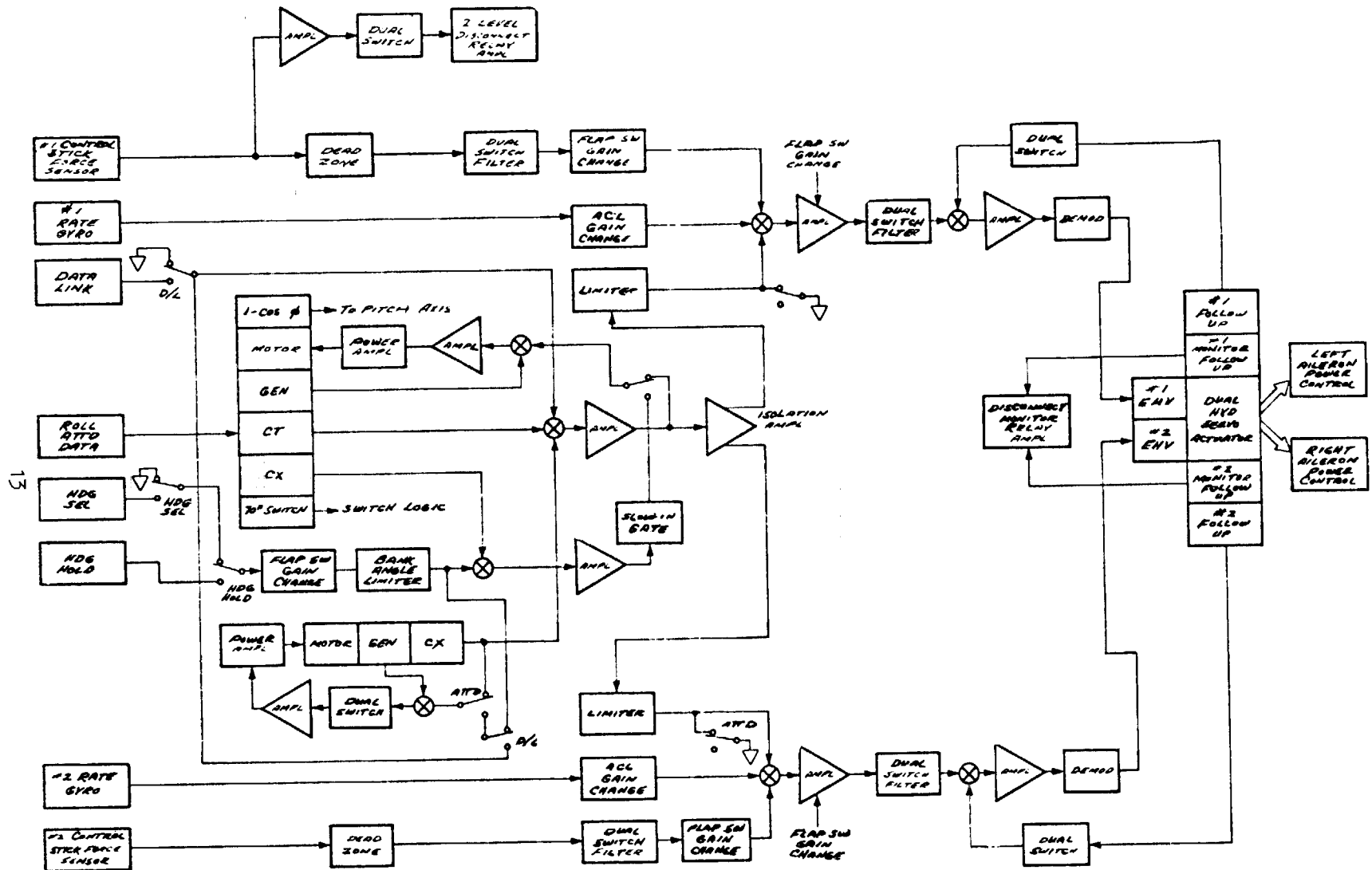
A-4 Roll Channel



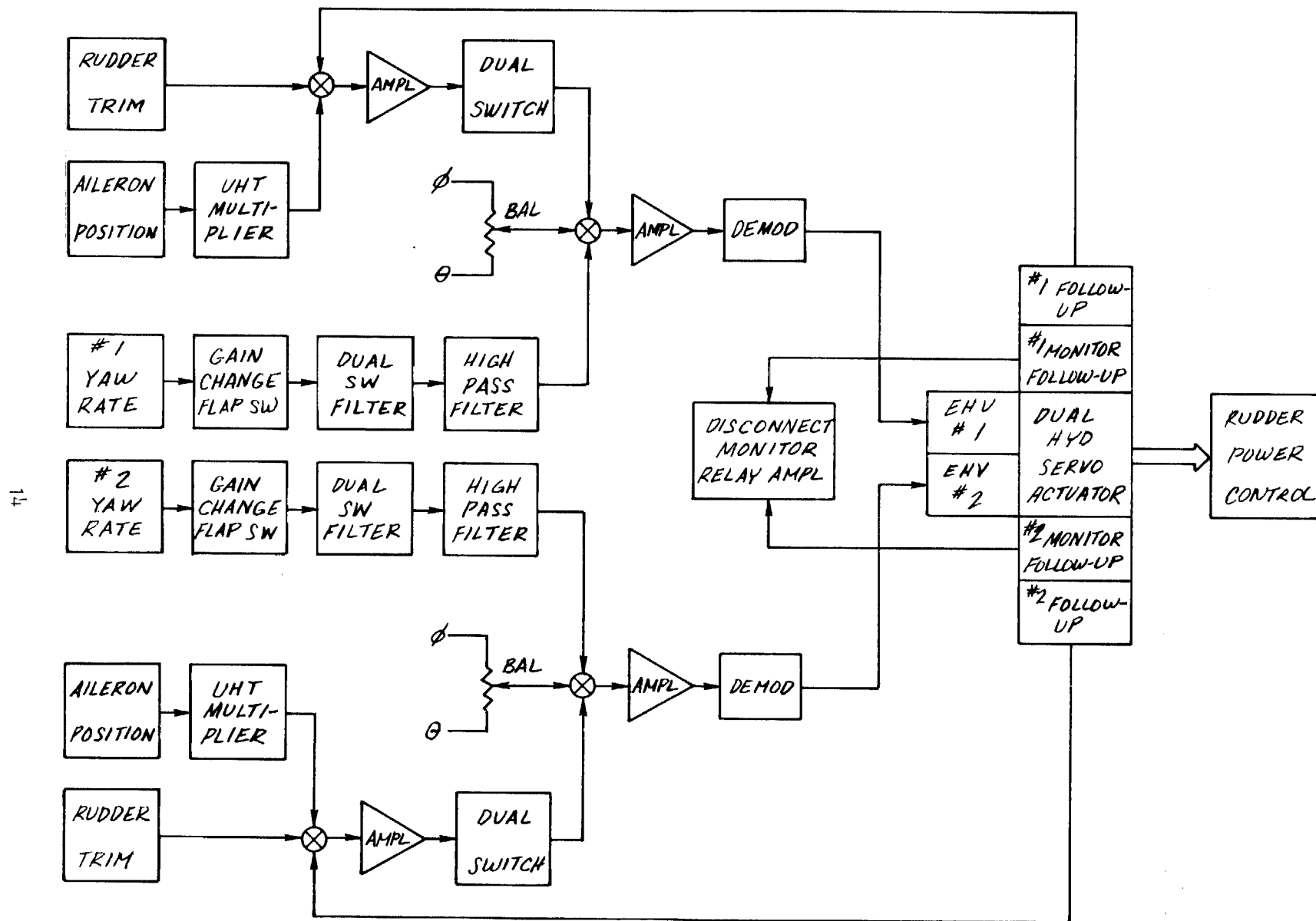
A-4 Yaw Channel



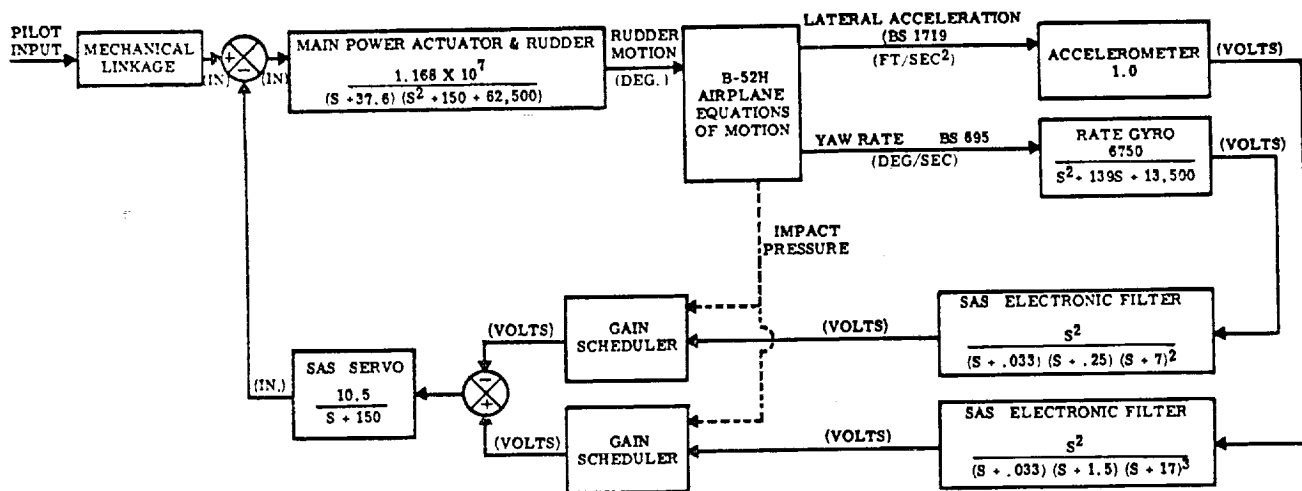
A-7A Pitch Axis



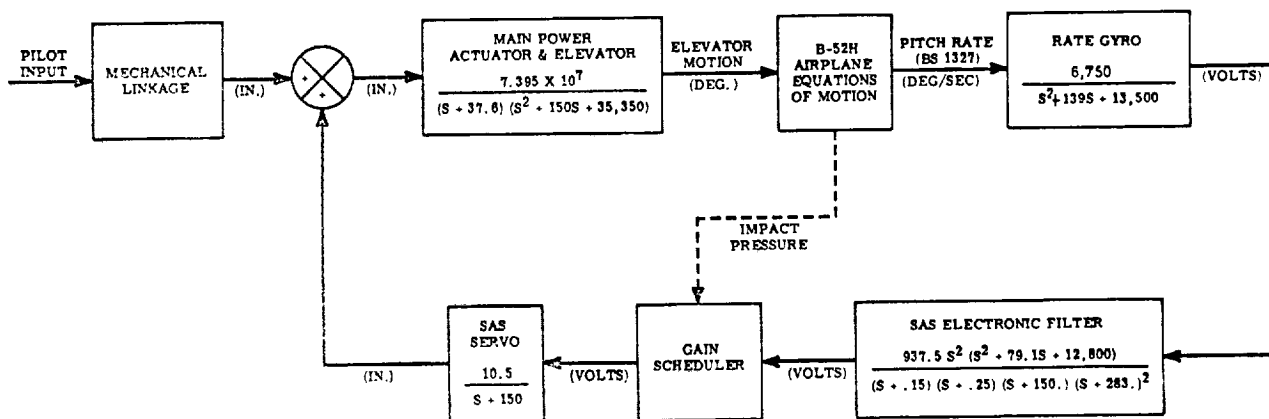
A-7A Roll Axis



A-7A Yaw Axis

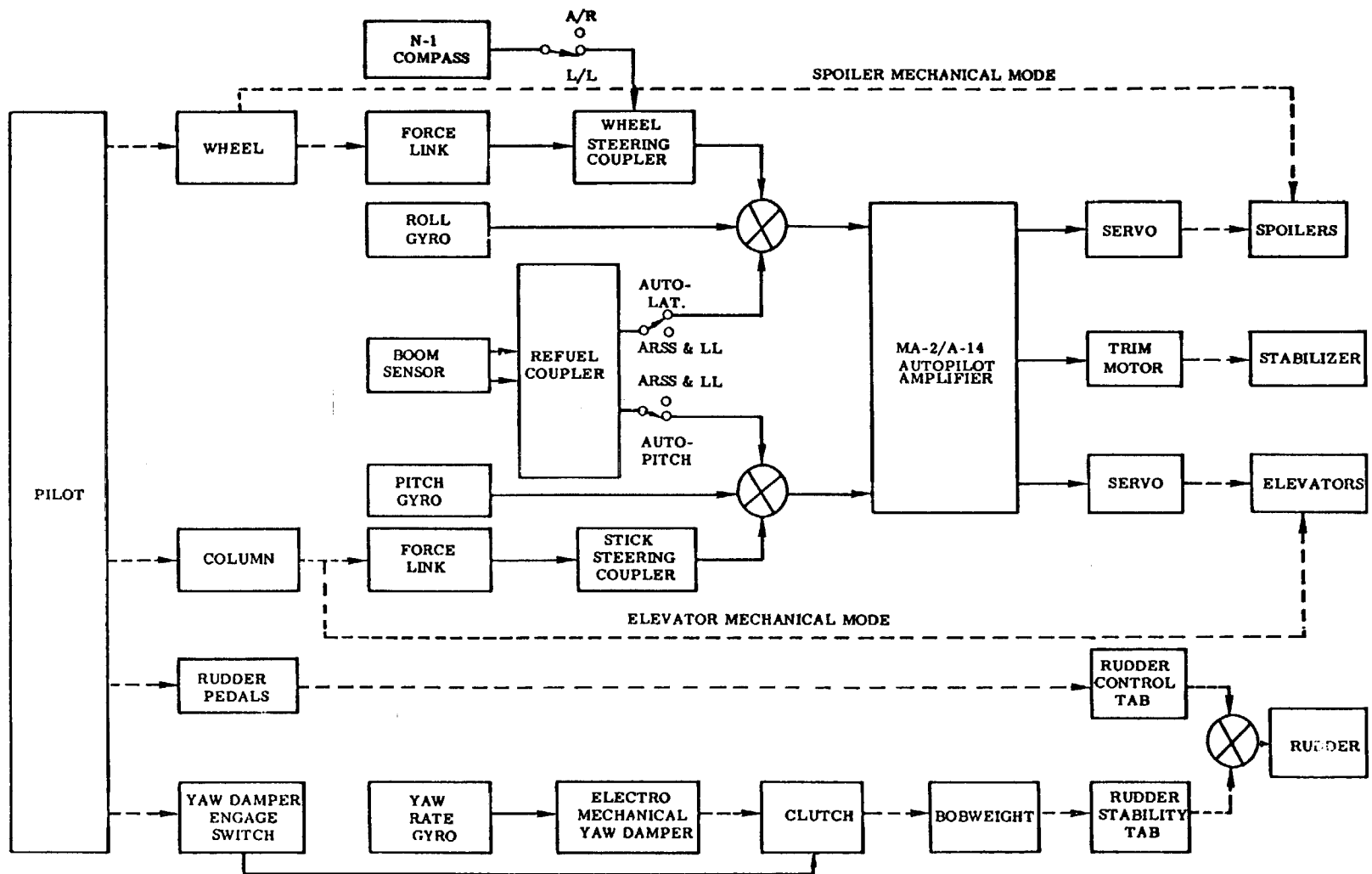


B-52 Modified Yaw SAS Block Diagram

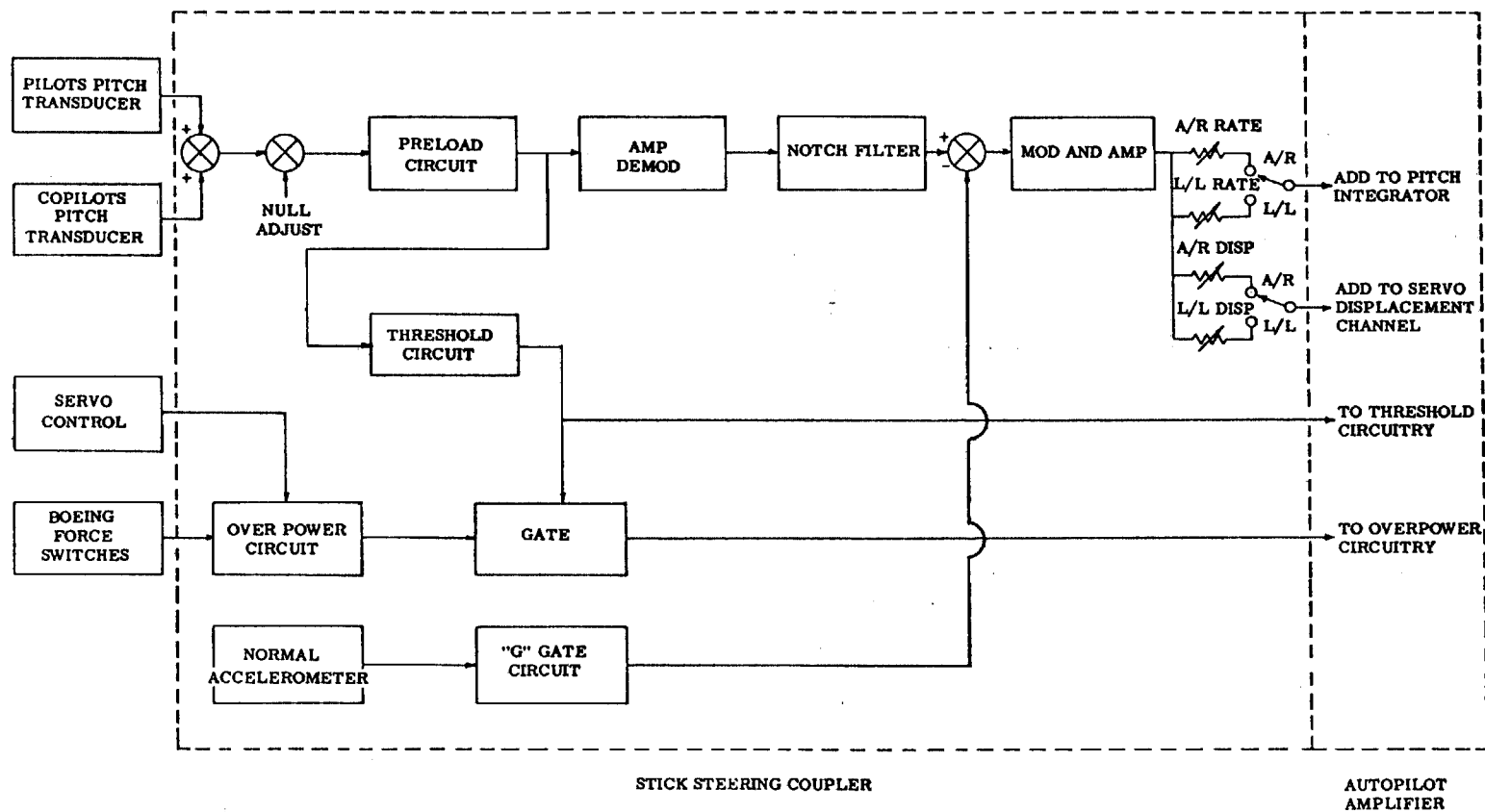


B-52 Modified Pitch SAS Block Diagram

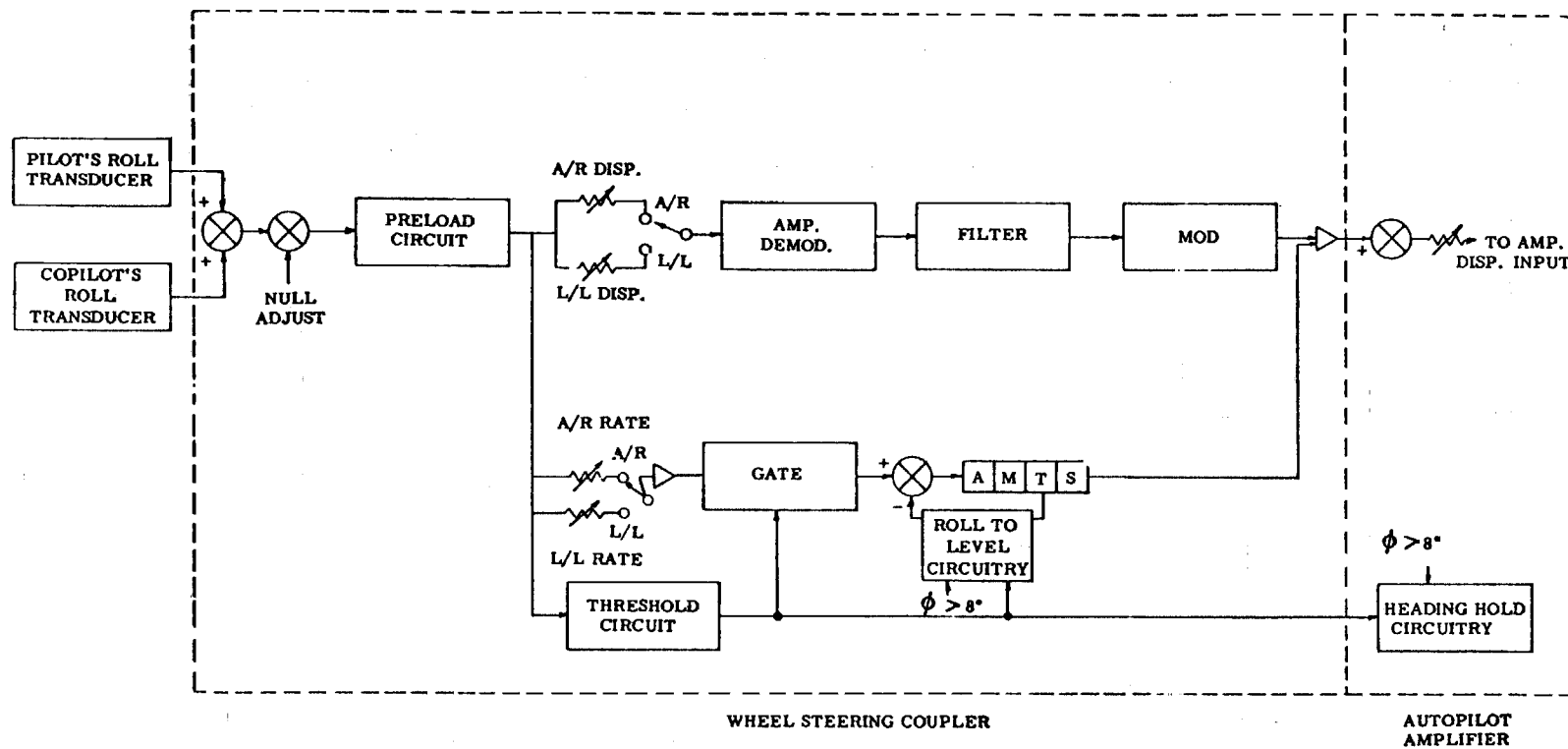
B-52 Original Yaw Damper



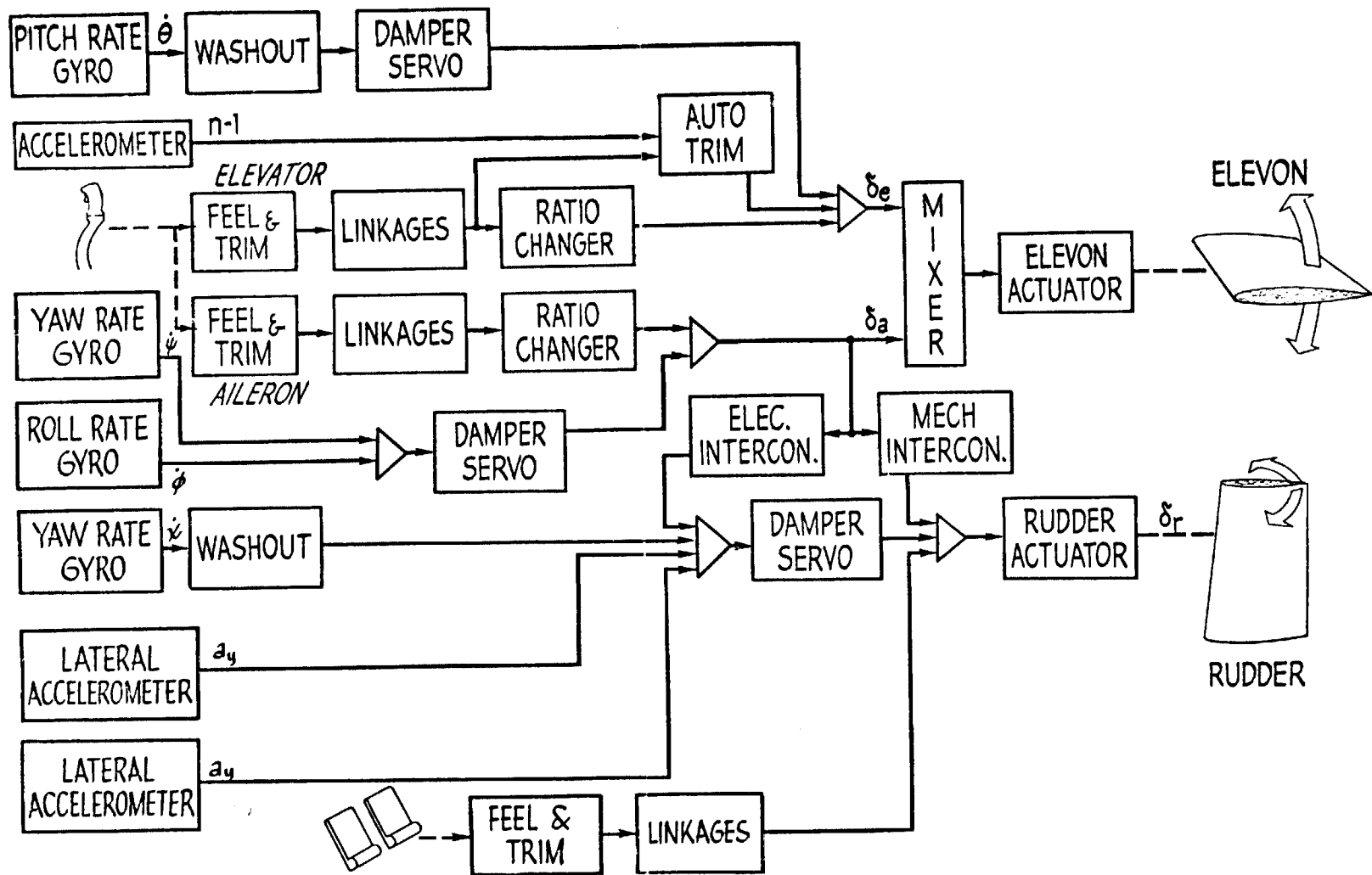
B-52 Original AFCS



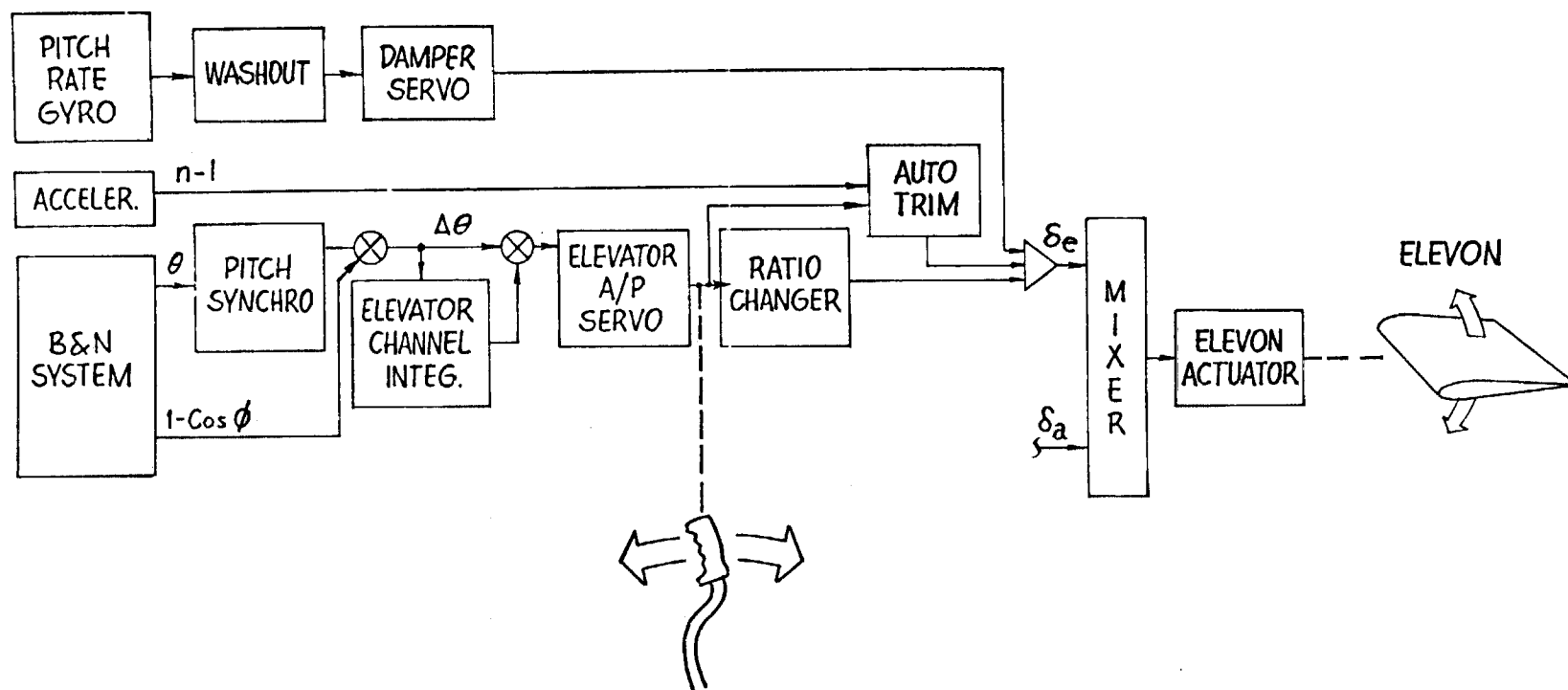
B-52 Longitudinal Control Wheel Steering



B-52 Lateral Control Wheel Steering

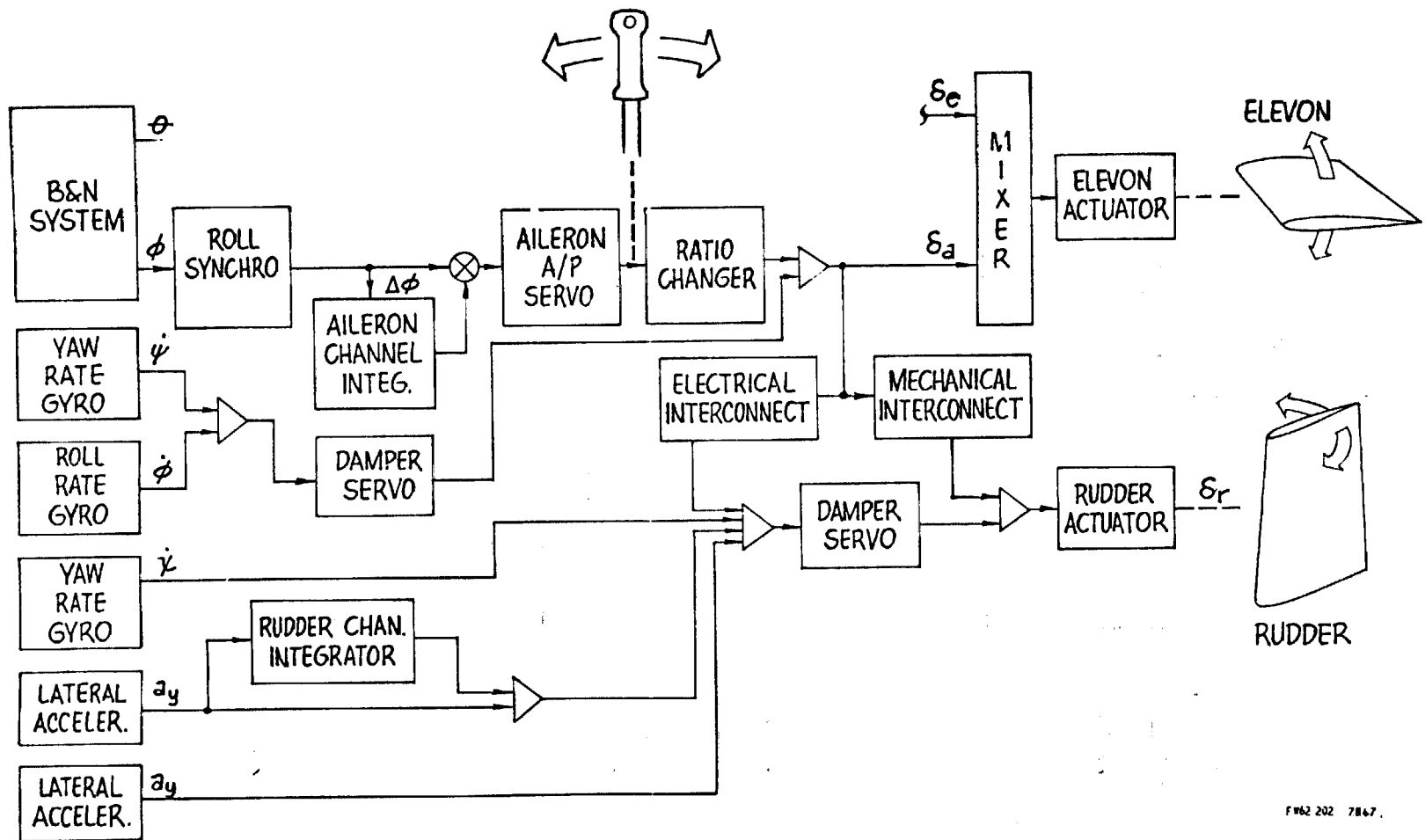


B-58 Stability Augmentation

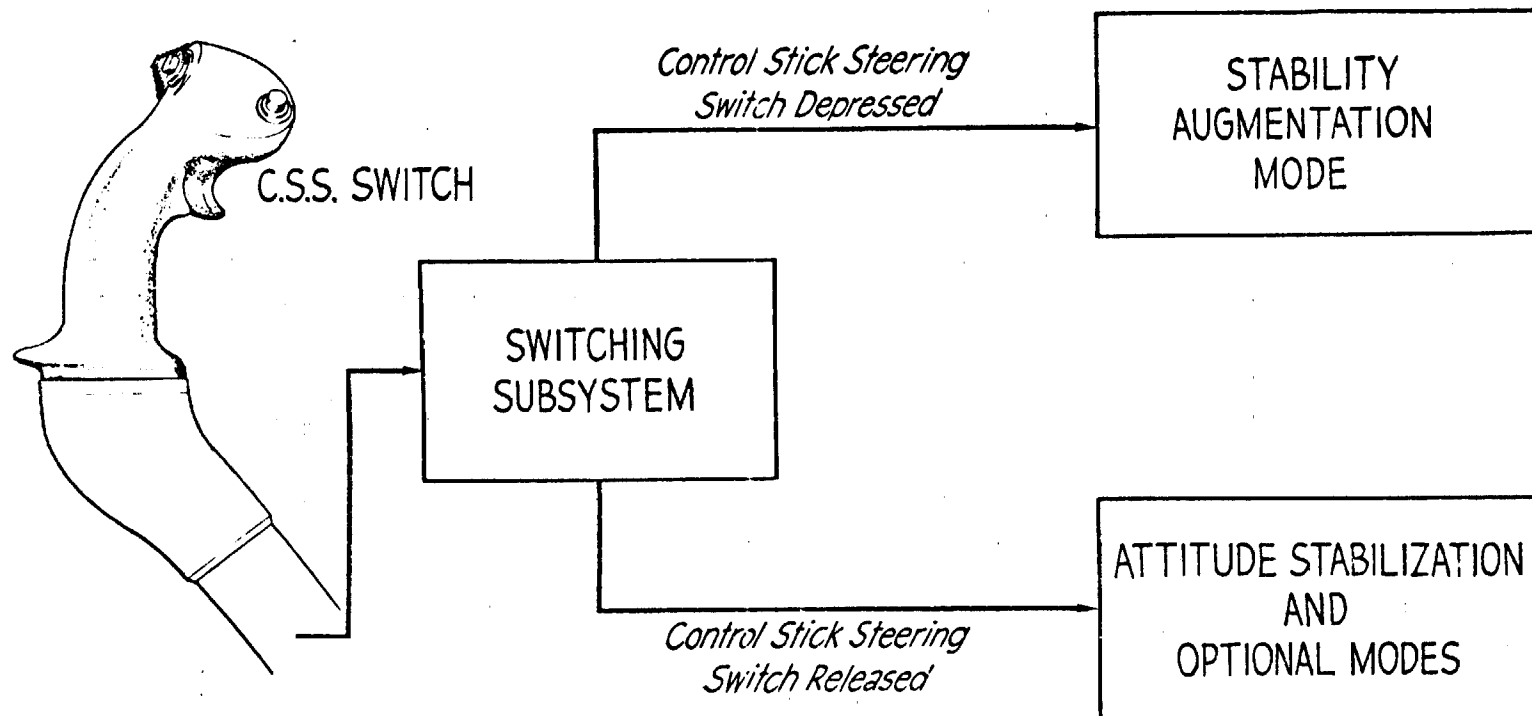


B-58 Attitude Stabilization Mode

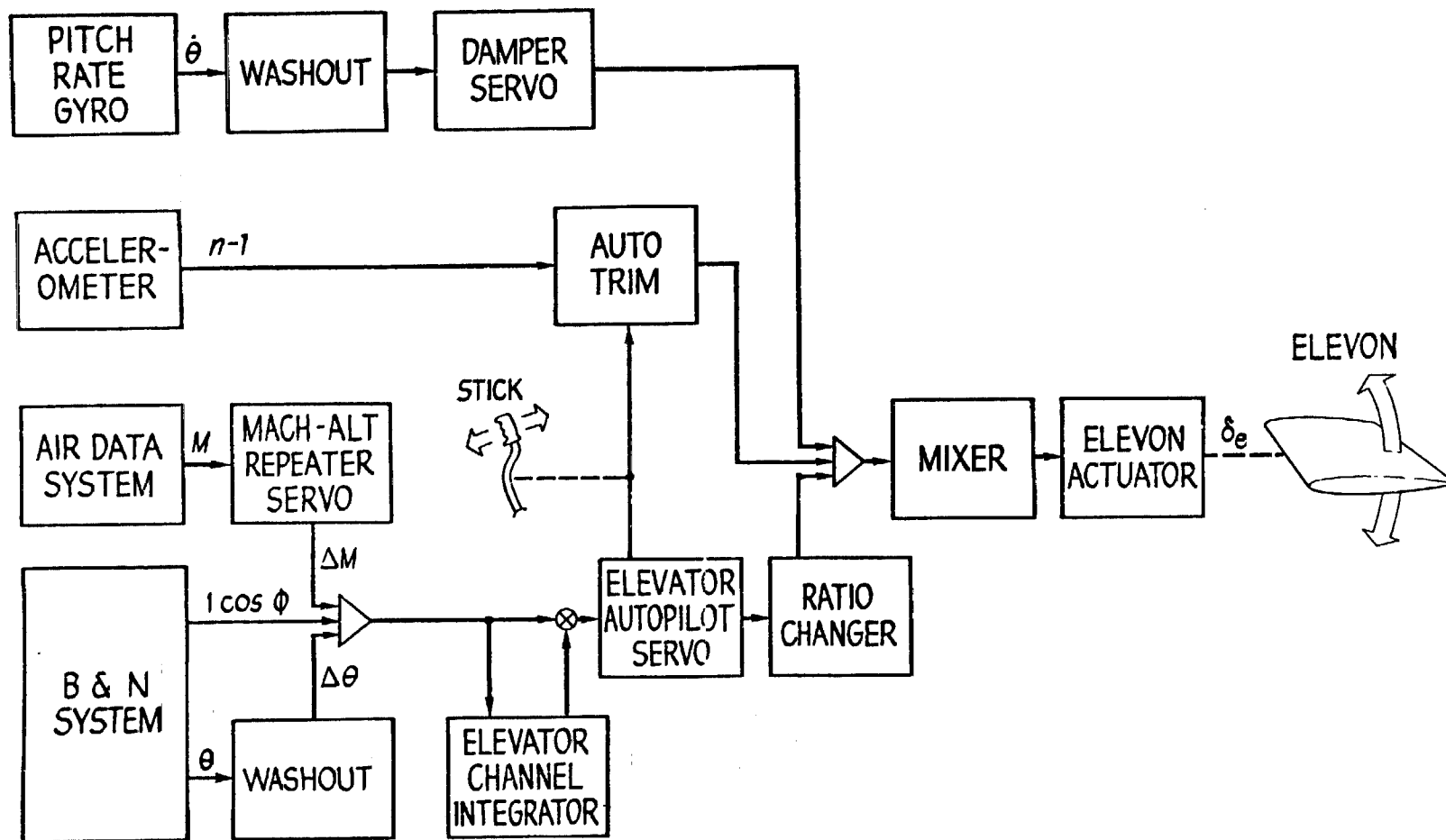
Pitch



B-58 Attitude Stabilization Mode
Lateral

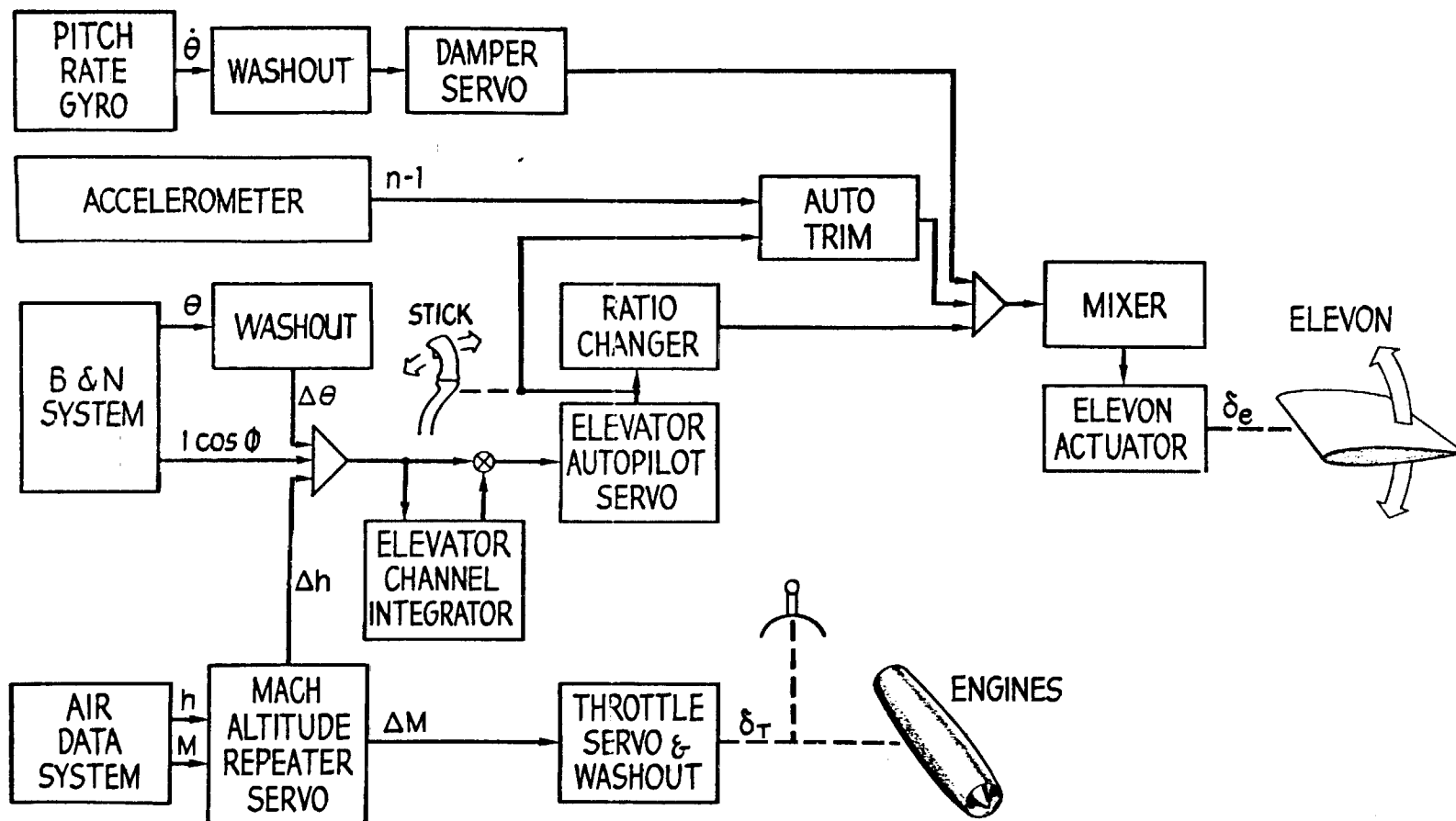


B-58 Control Stick Steering Mode

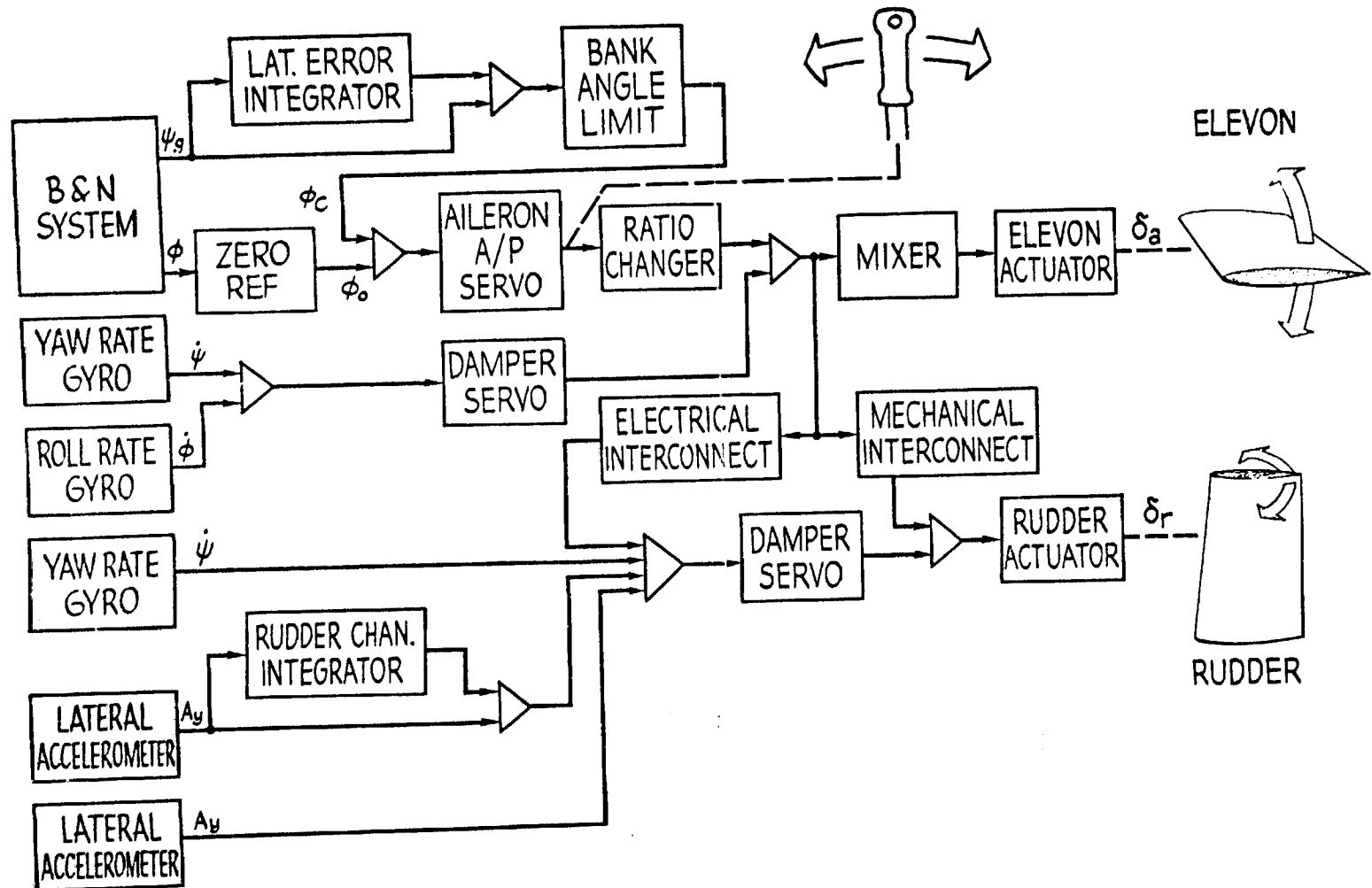


B-58 Mach Mode

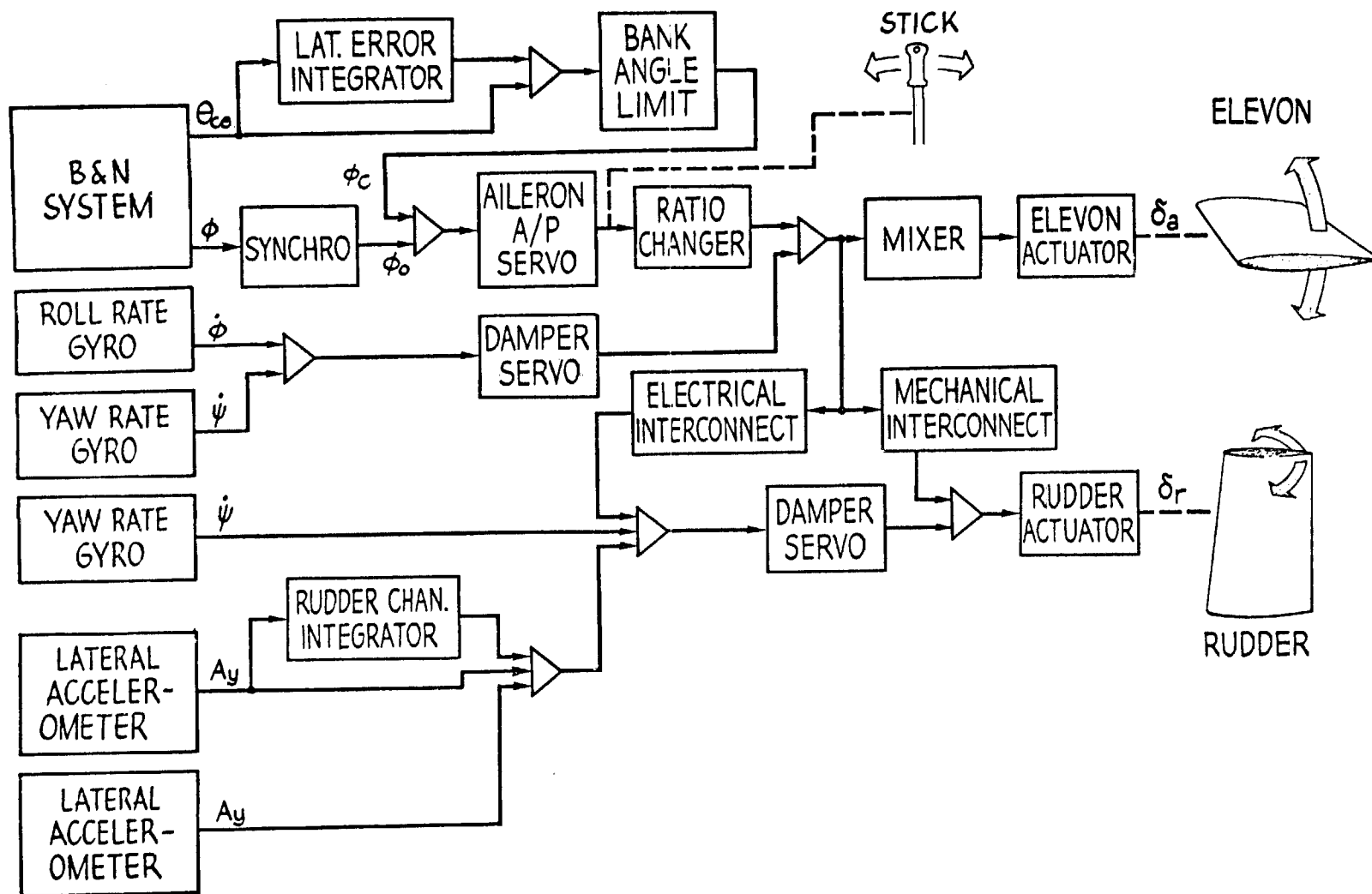
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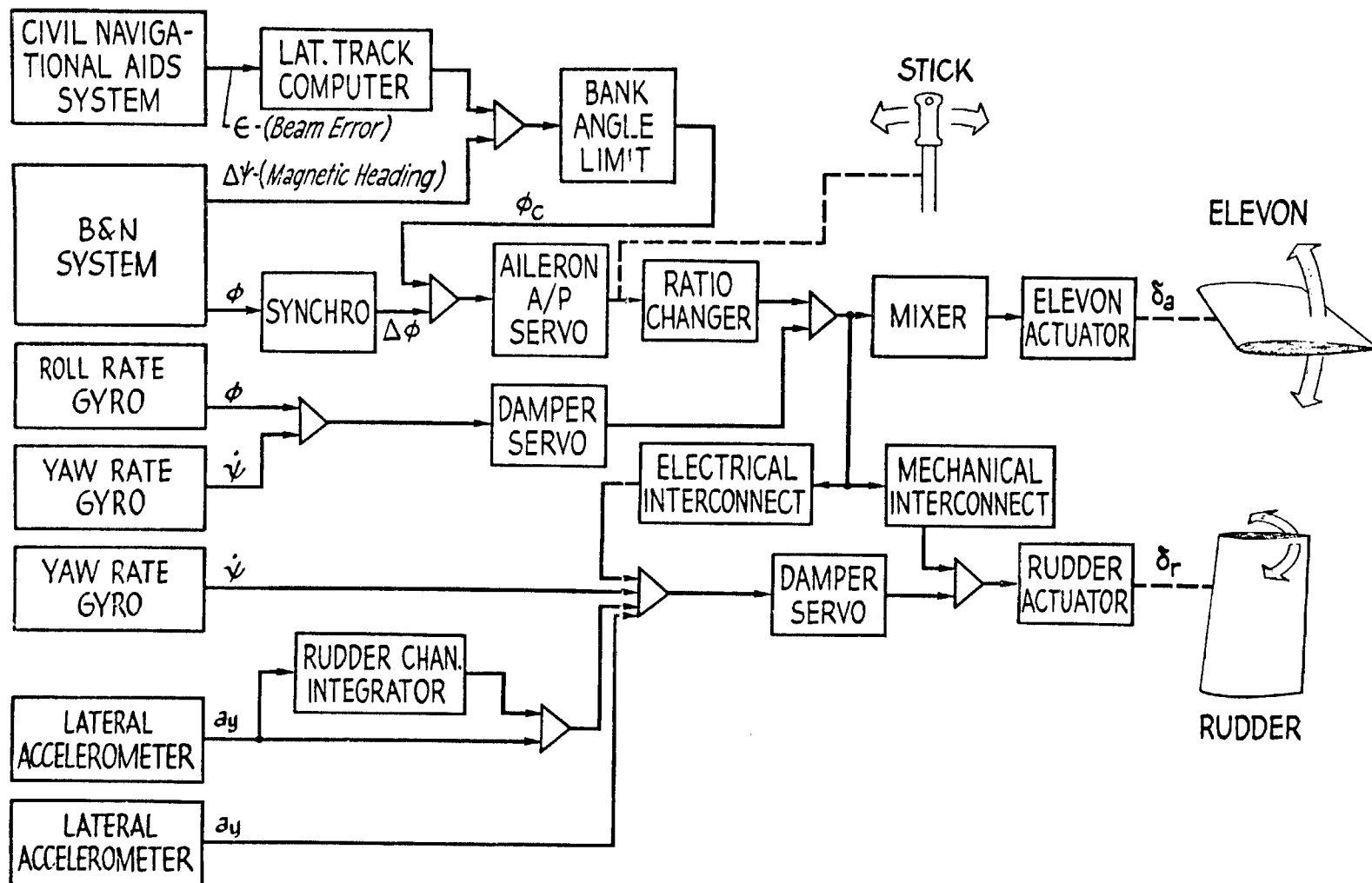
B-58 Mach-Altitude Mode



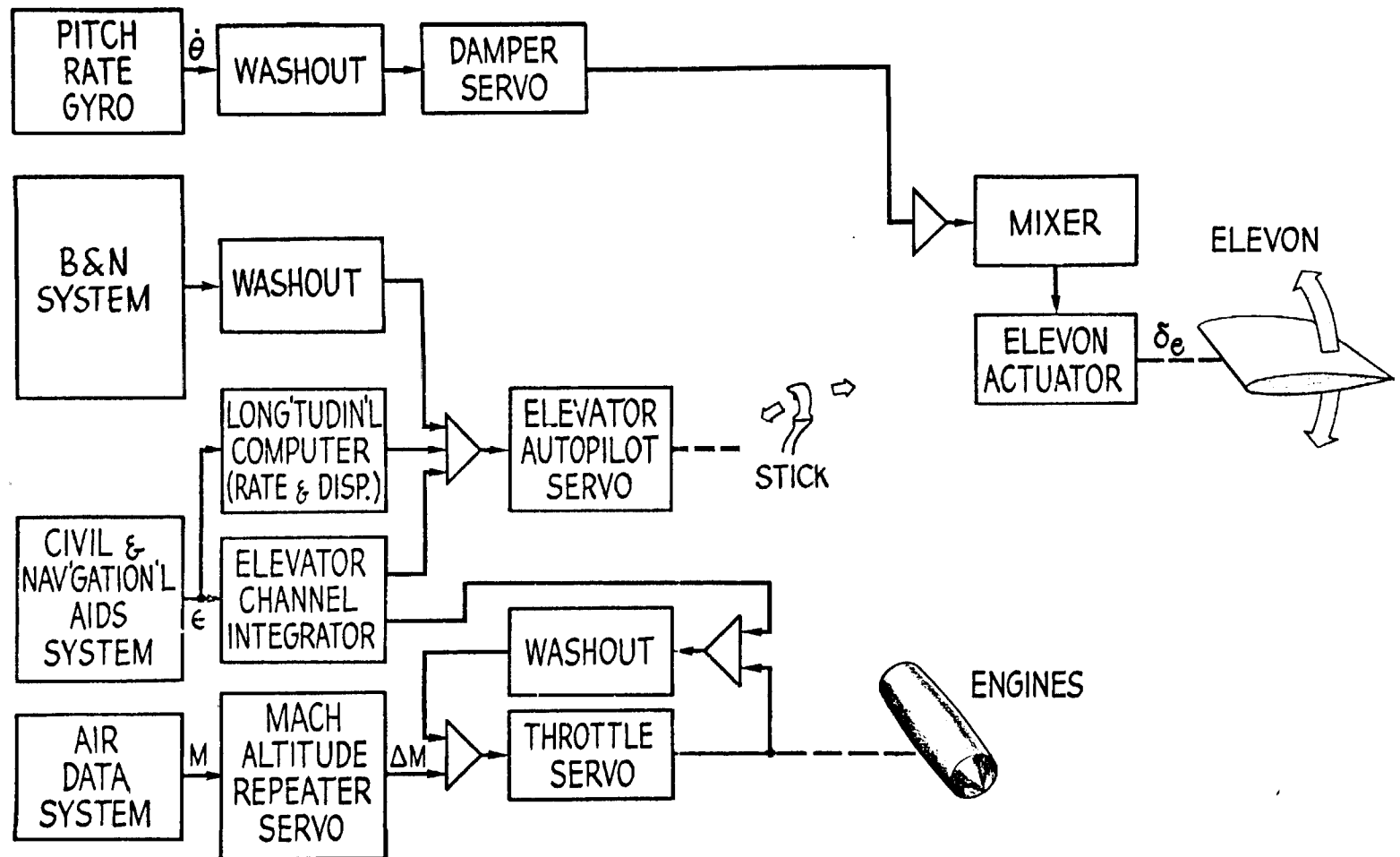
B-58 Constant Heading



B-58 Heading Nav Mode

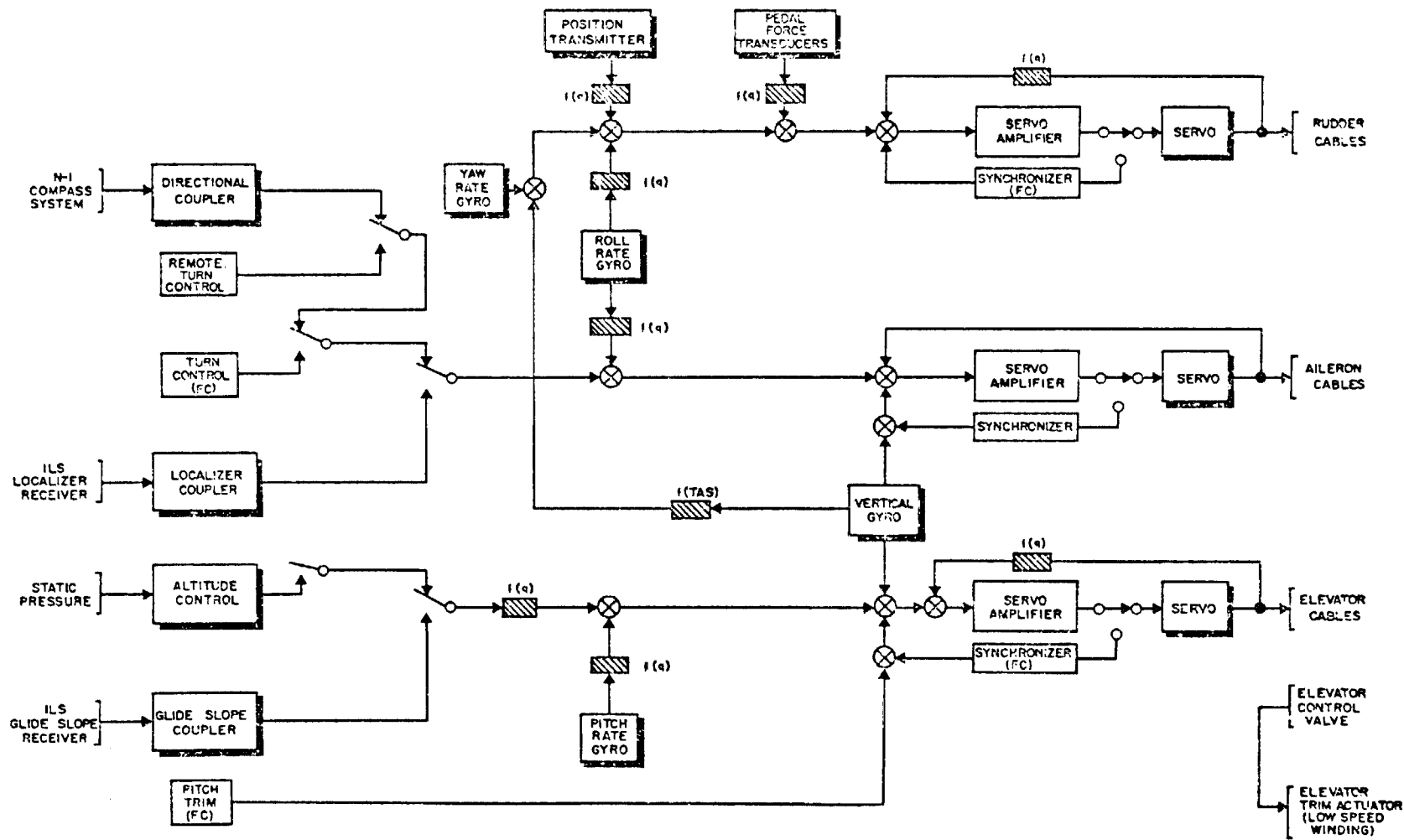


B-58 Localizer Mode



B-58 Automatic Glide Path Mode

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(FC) INDICATES BLOCK FUNCTIONS WHICH ARE PART OF THE FLIGHT CONTROLLER

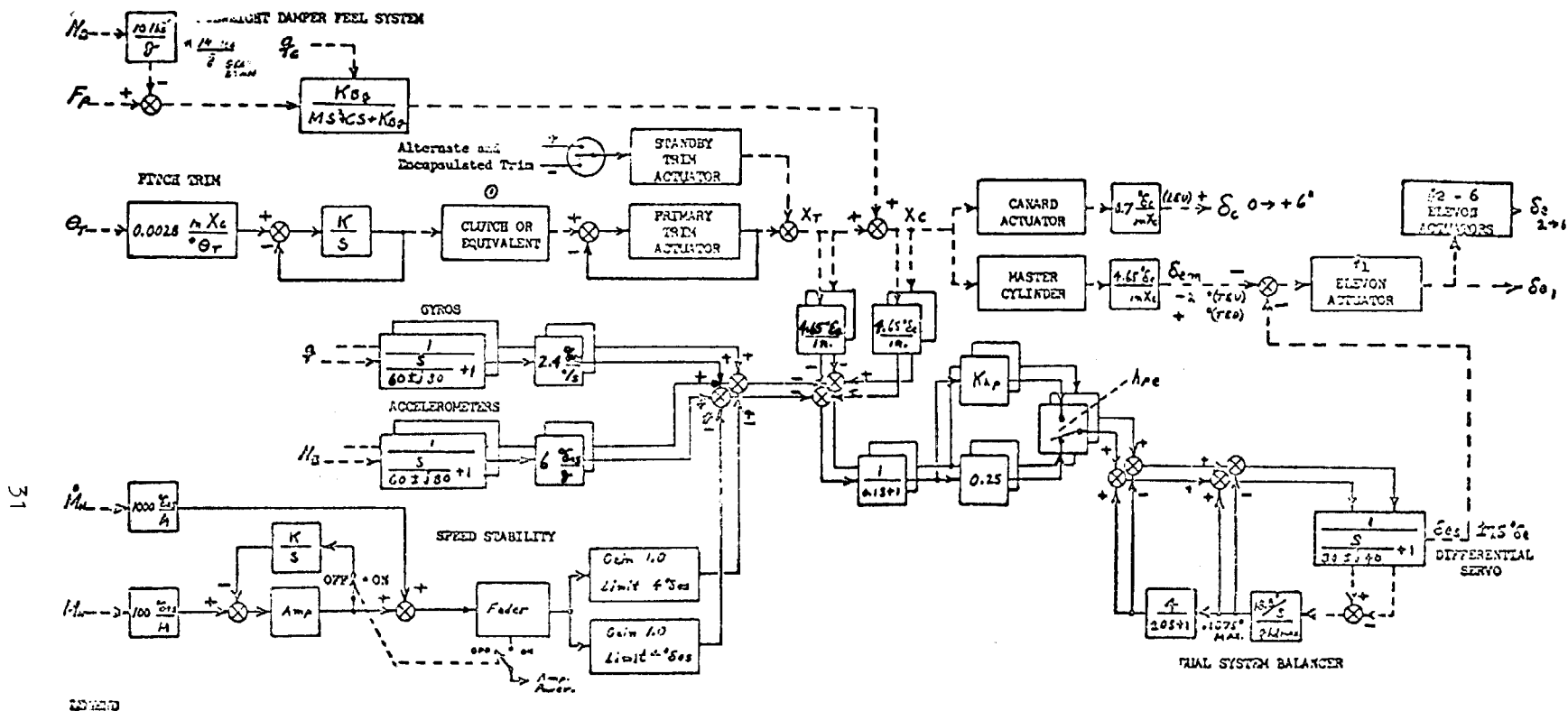
SHADED BLOCKS INDICATE AUTOMATIC GAIN CONTROL FUNCTIONS OF THE AIRSPEED COMPENSATOR

$I(q)$ INDICATES GAIN IS VARIED AS A FUNCTION OF DIFFERENTIAL PRESSURE

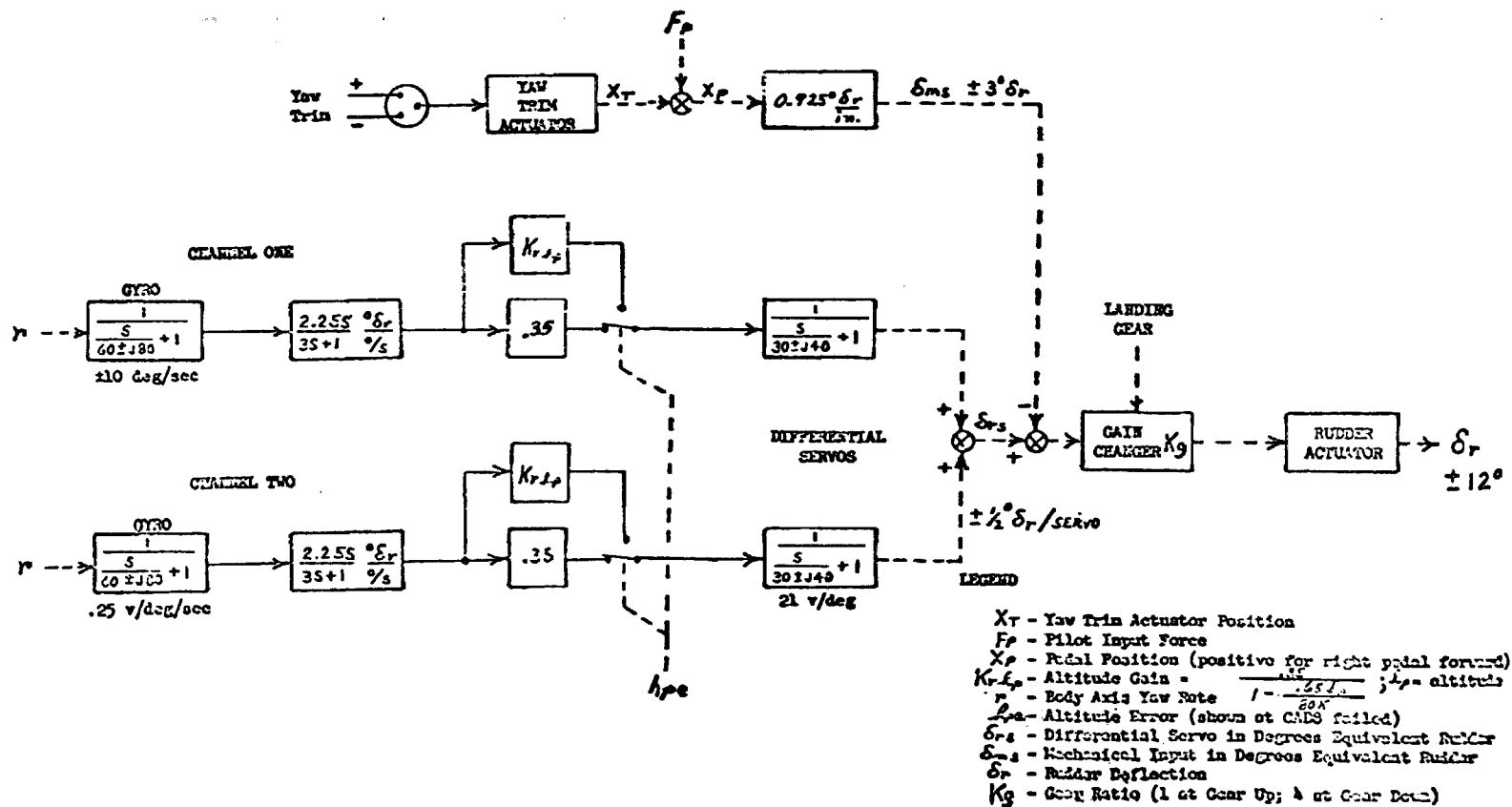
$I(TAS)$ INDICATES GAIN IS VARIED AS A FUNCTION OF TRUE AIR SPEED

⊗ SYMBOL INDICATES SIGNAL SUMMING

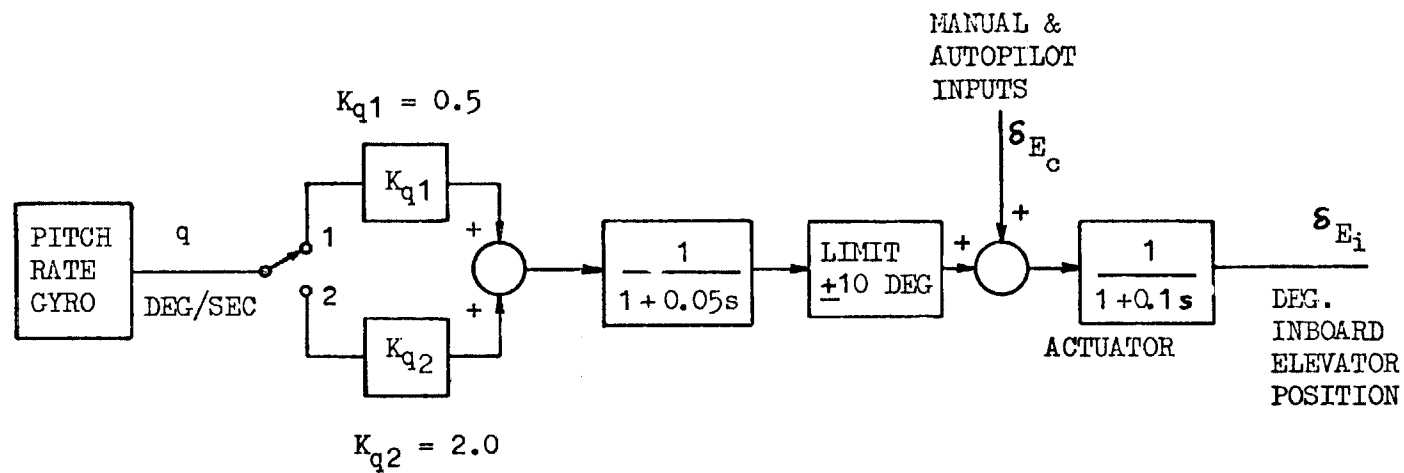
▨ INDICATES COMPONENTS CONTAINING SENSING ELEMENTS



XB-70 Pitch Axis Augmentation



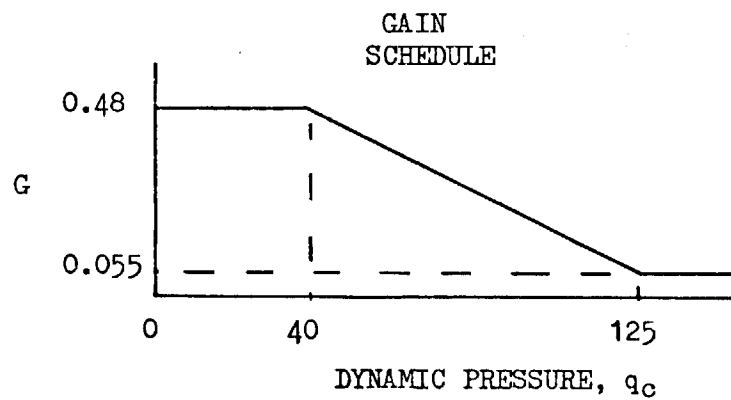
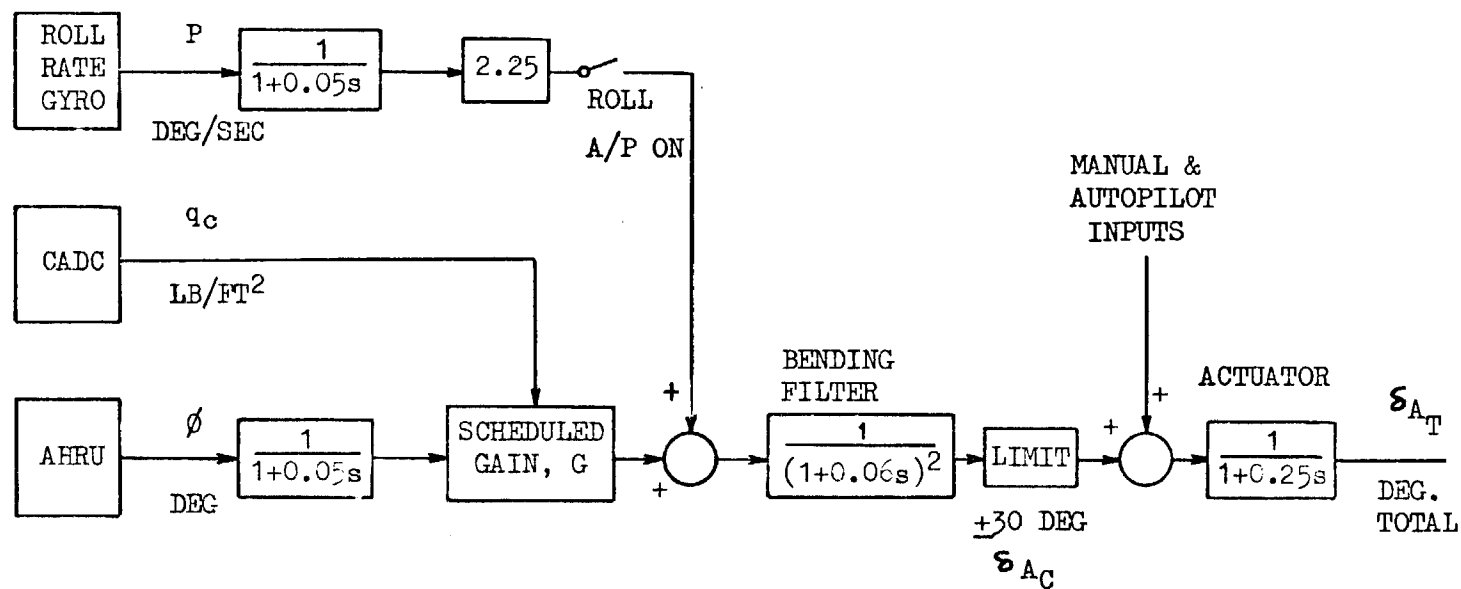
XB-70 Yaw Axis Augmentation



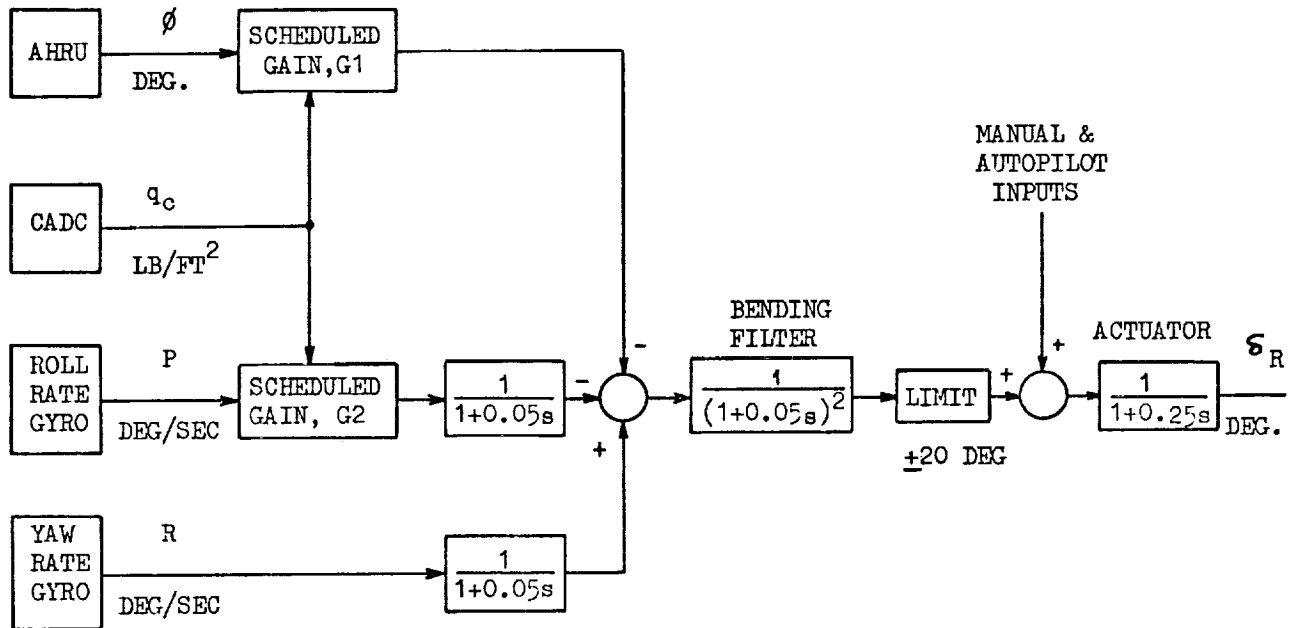
SWITCH POSITION: 1 PITCH AUTOPILOT OFF

 2 PITCH AUTOPILOT ENGAGED

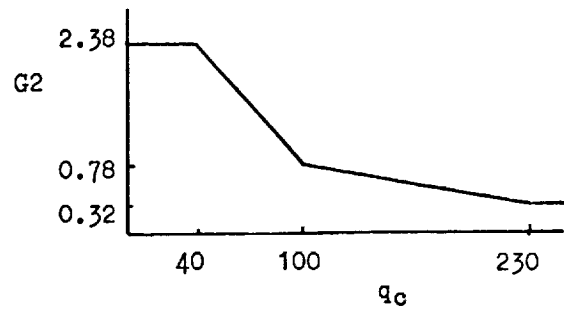
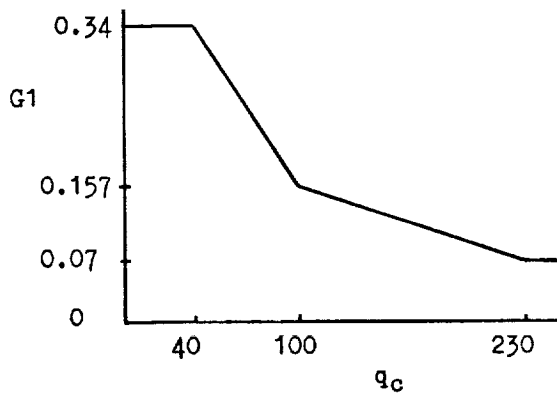
C-5A Pitch Stability Augmentation System



C-5A Roll Stability Augmentation System (SAS)

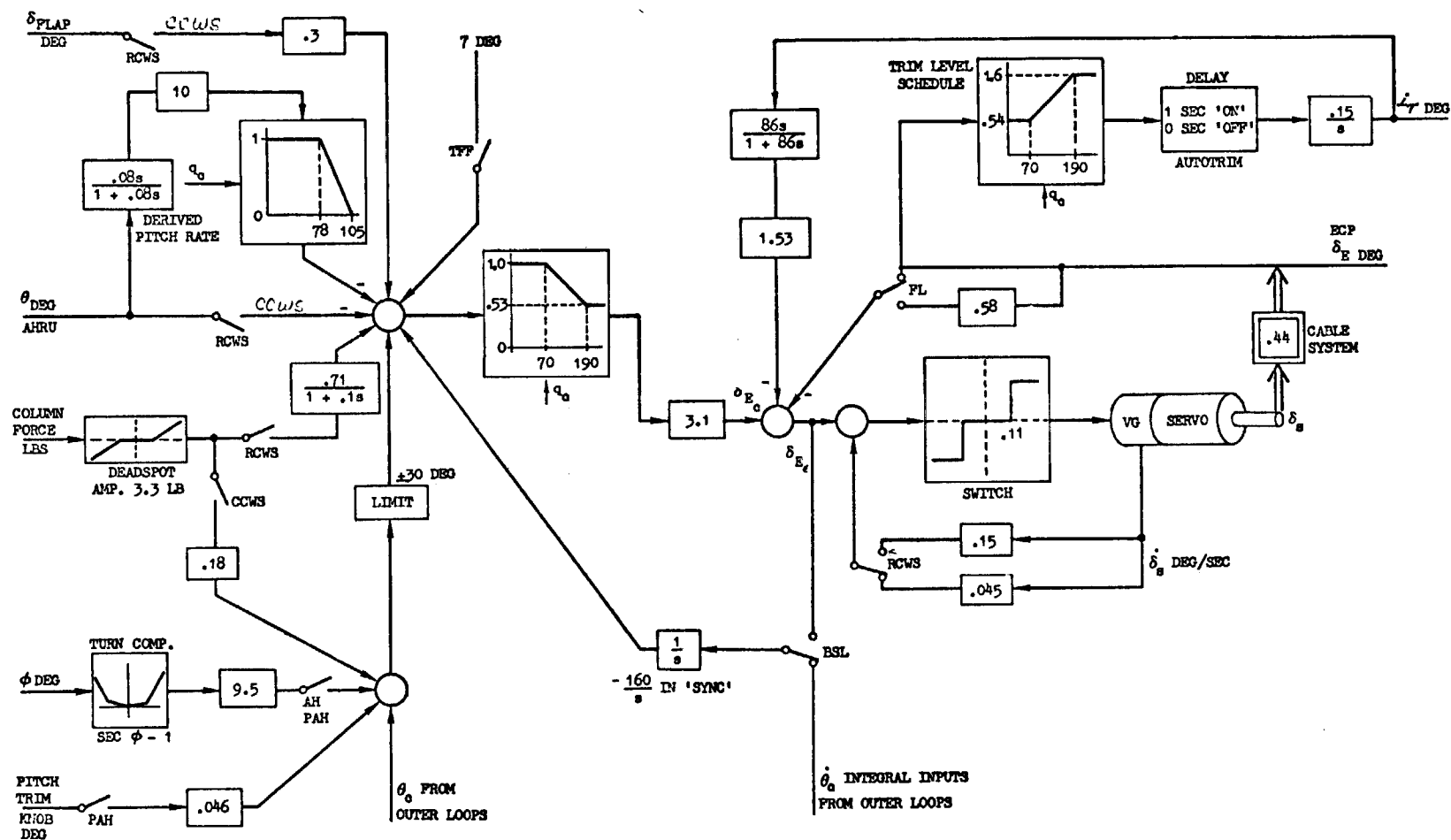


GAIN SCHEDULES

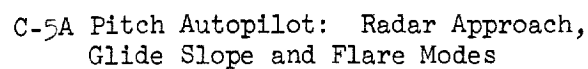


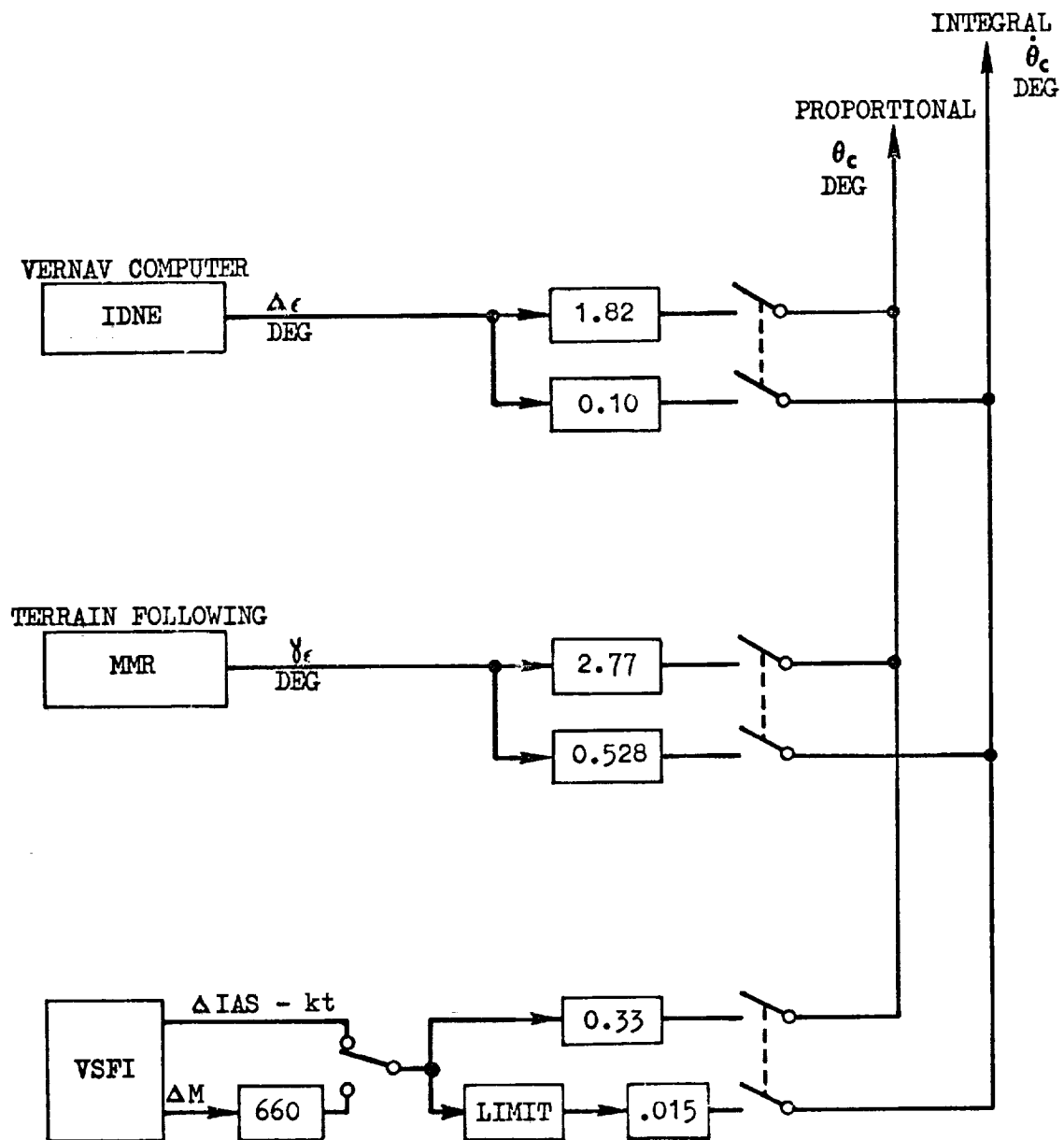
C-5A Yaw Stability Augmentation System (SAS)

BSL - BUMP SYNC LATCH
 RCWS - RATE CONTROL WHEEL STEERING
 CCWS - COUPLED CONTROL WHEEL STEERING (attitude)
 TFF - TERRAIN FOLLOWING FAILURE

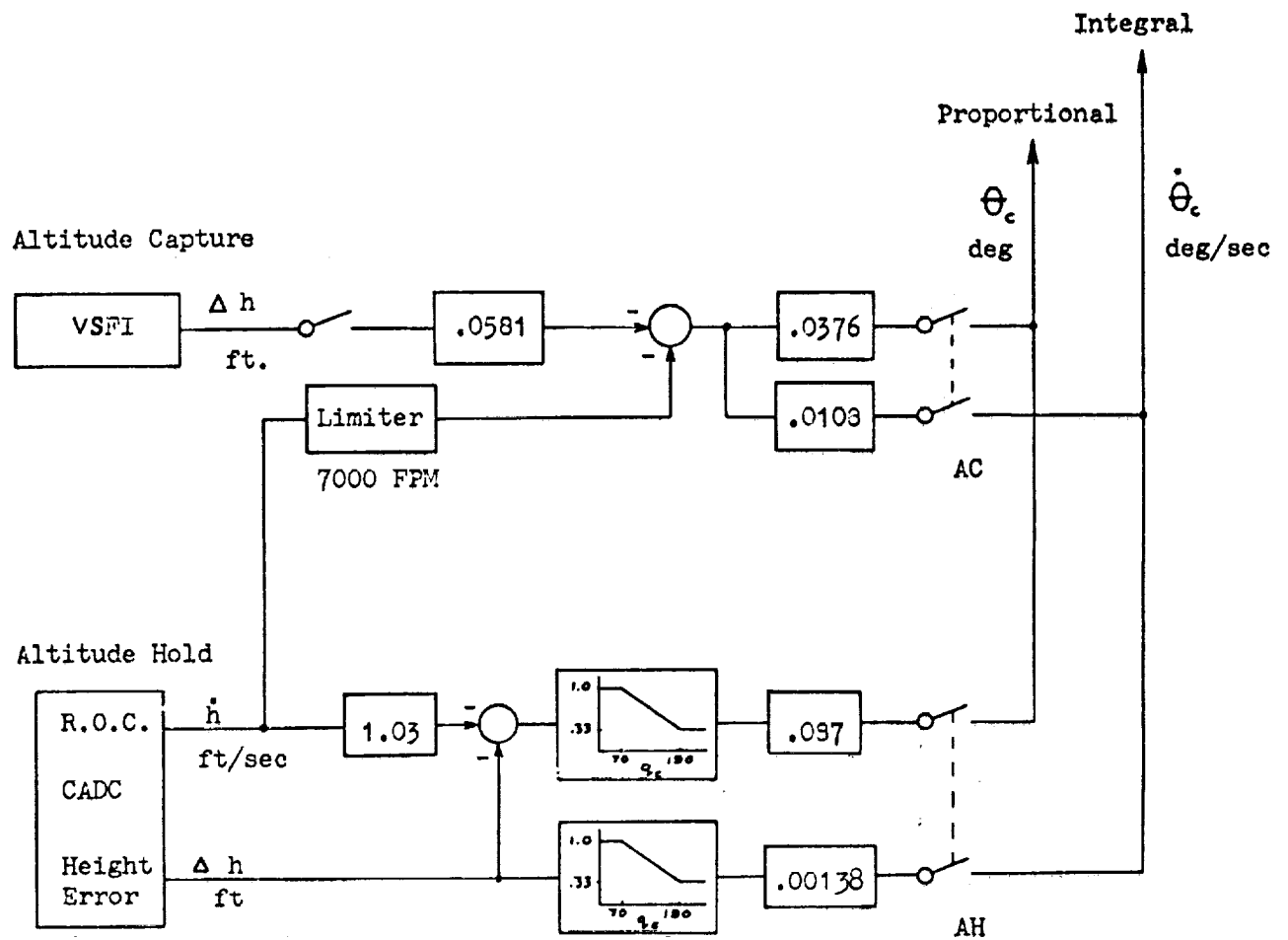


C-5A Pitch Autopilot: Inner Loops

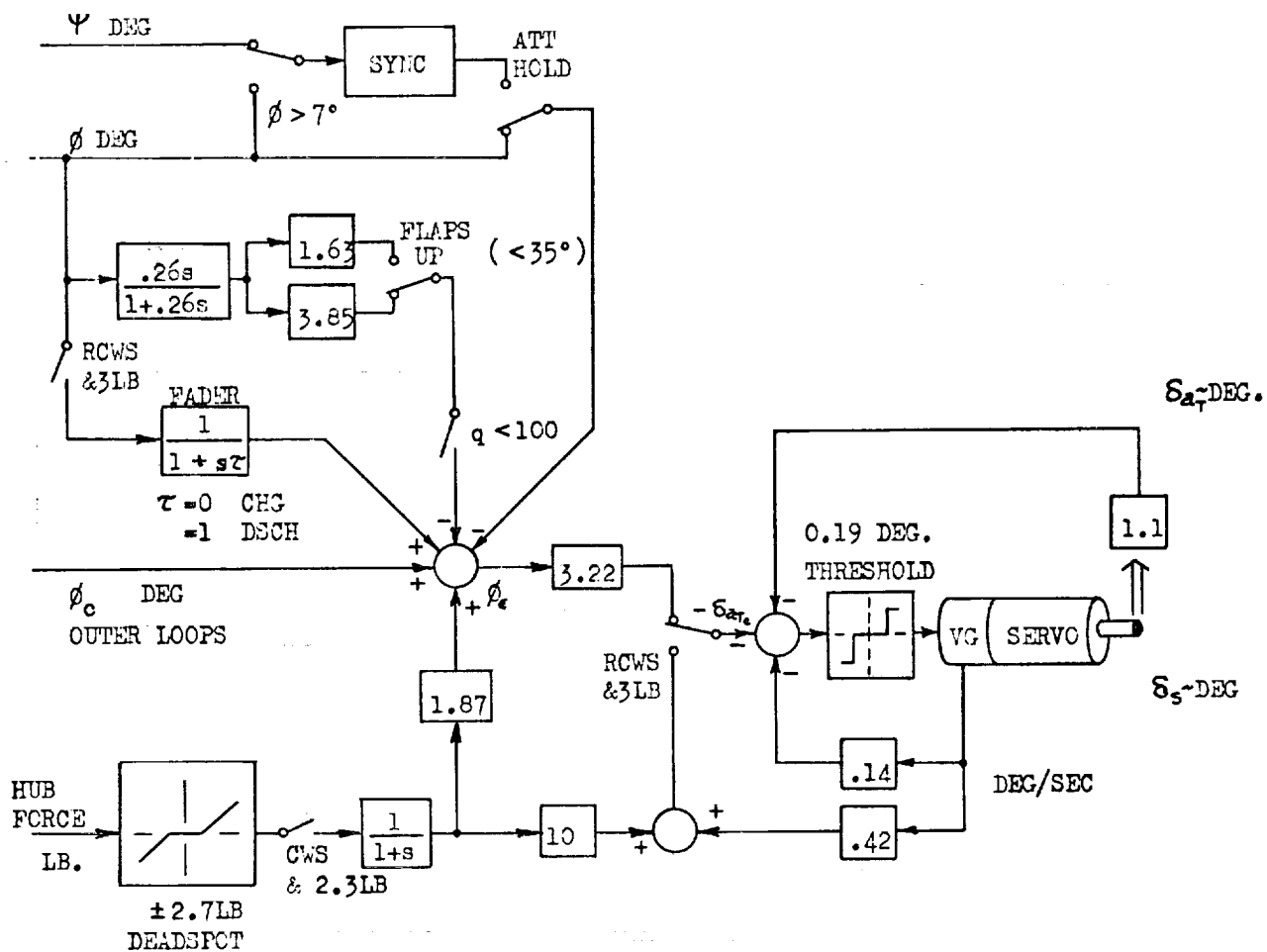




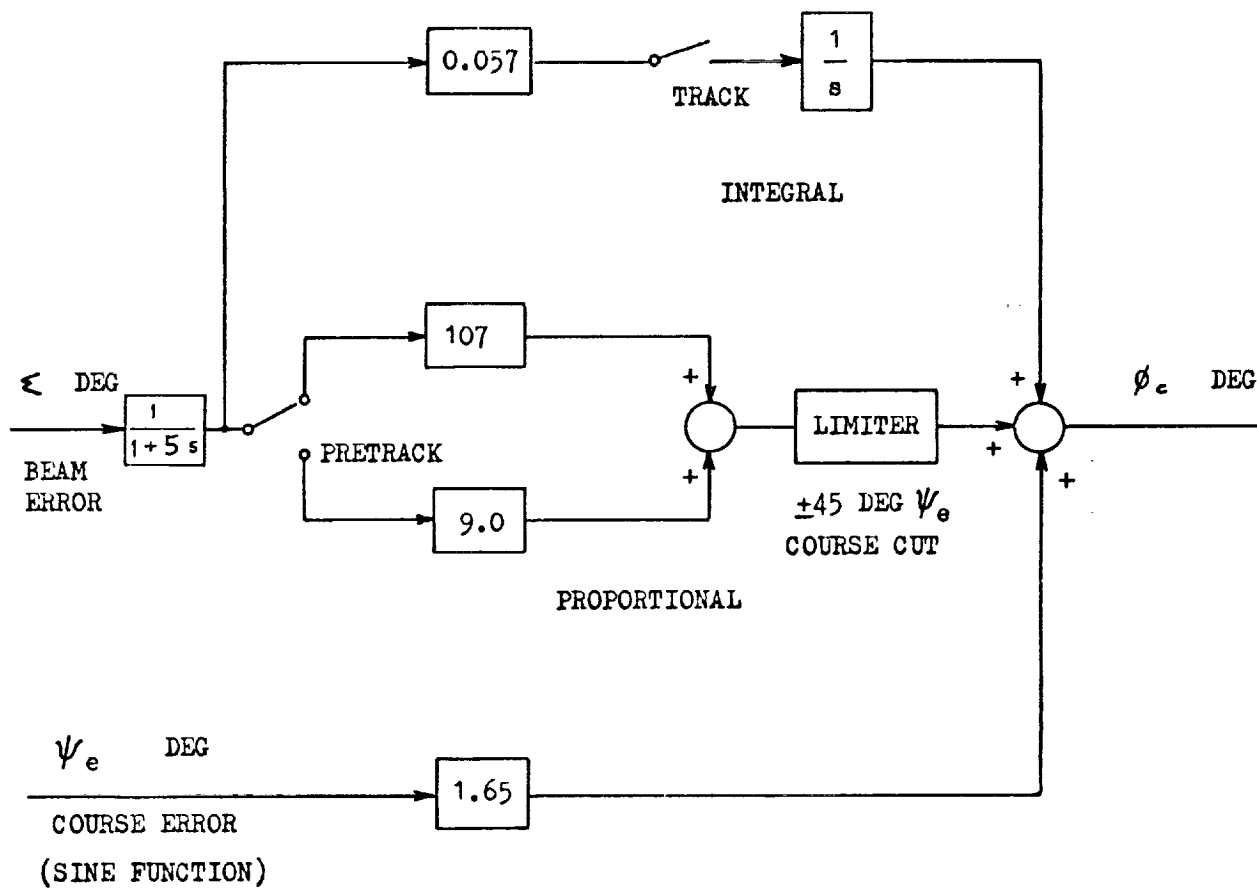
C-5A Pitch Autopilot: Vernav, Terrain Following
and Mach/IAS Modes



C-5A Pitch Autopilot: Altitude Capture and Altitude Hold Modes

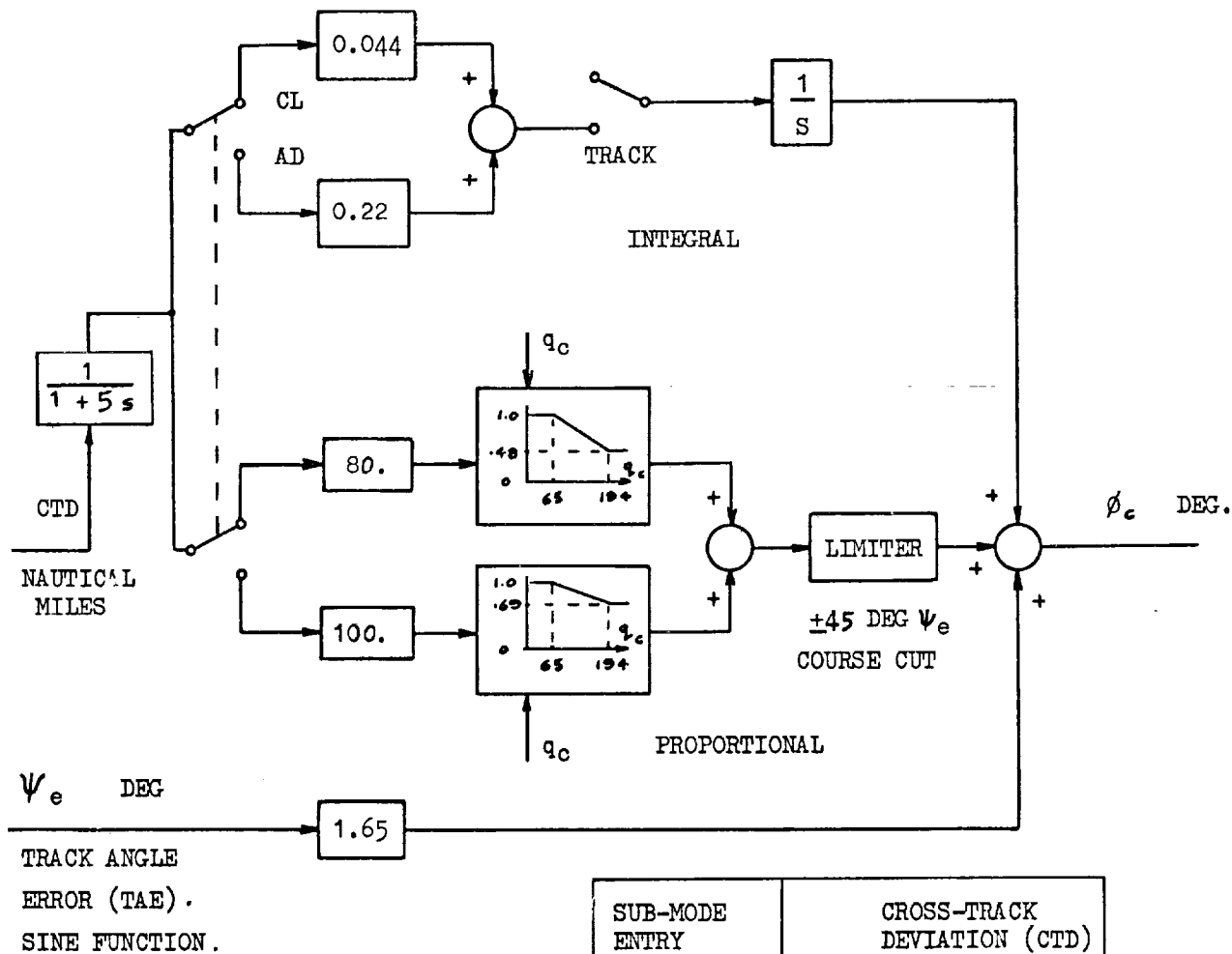


C-5A Roll Autopilot: Inner Loops Including Control Wheel Steering



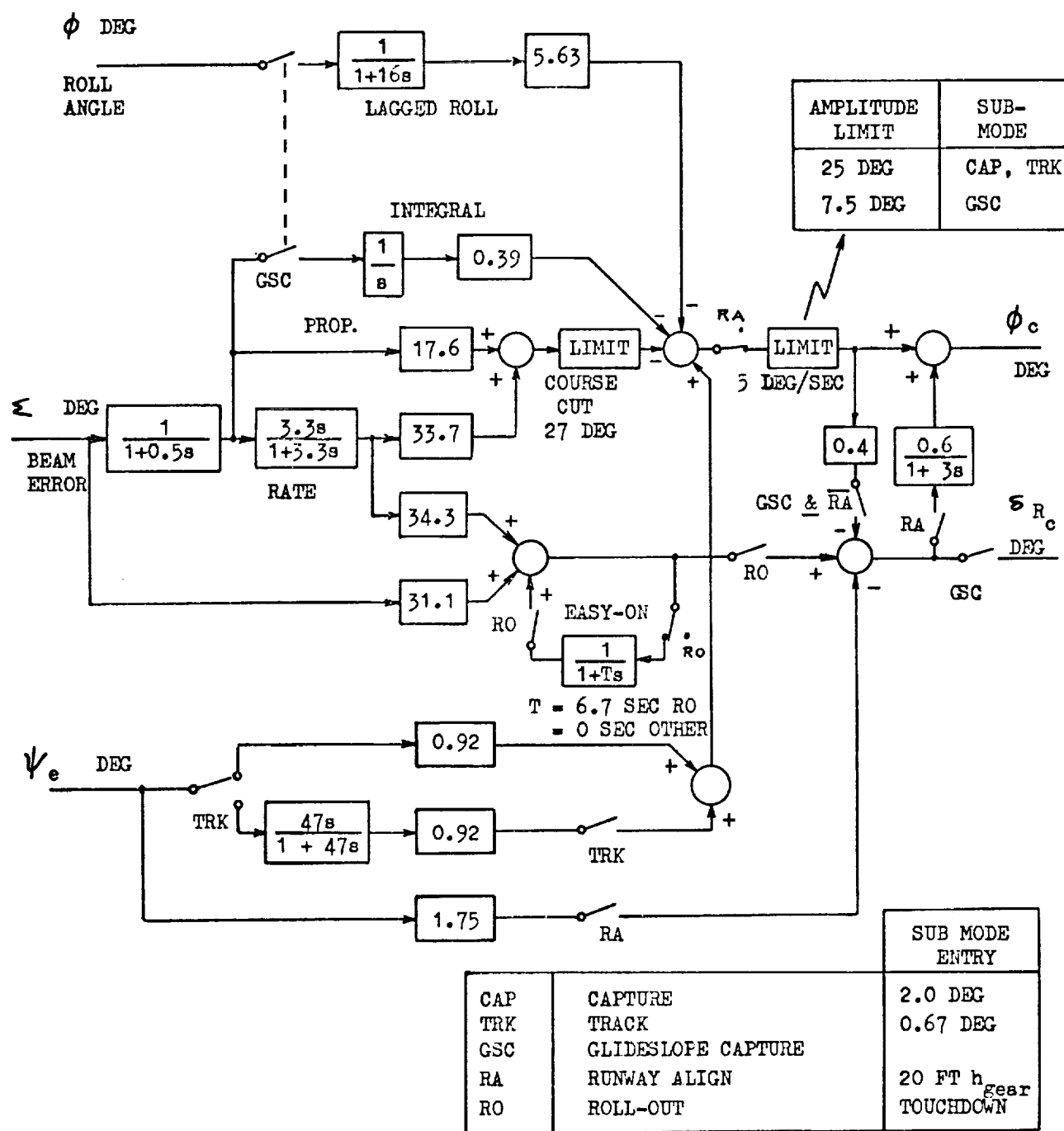
SUB-MODE ENTRY	VOR, TACAN \leq 62 NM	TACAN > 62 NM
CAPTURE	5.0 DEG	5.4 NM
PRE-TRACK	2.1 DEG	2.3 NM
TRACK	1.2 DEG	1.3 NM

C-5A Roll Autopilot: VOR and TACAN Modes

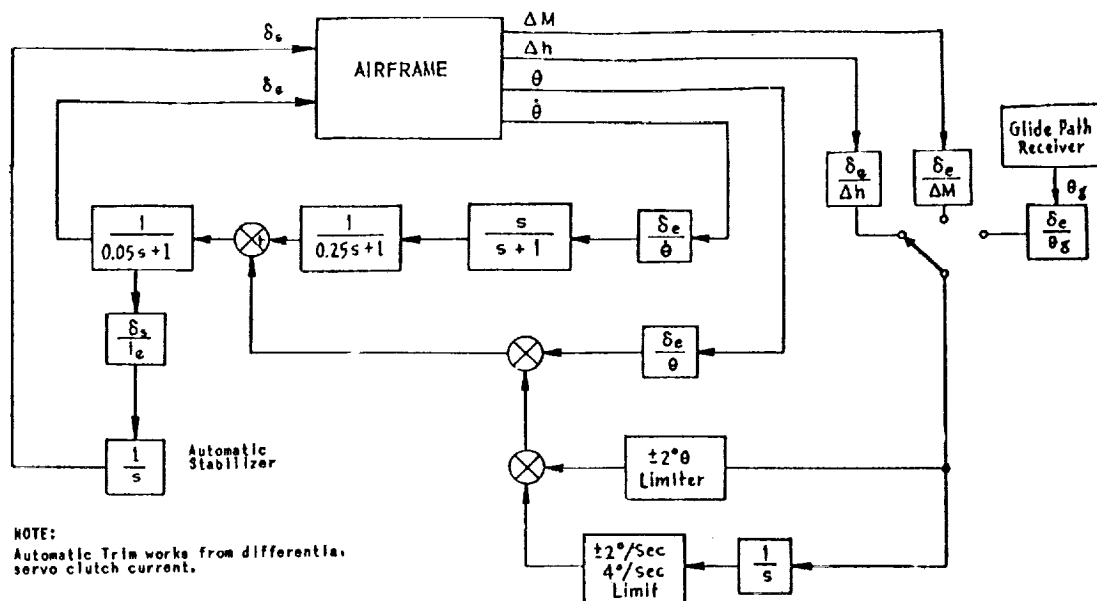


SUB-MODE ENTRY	CROSS-TRACK DEVIATION (CTD)
CAPTURE	5.8 NM
TRACK	0.4 NM

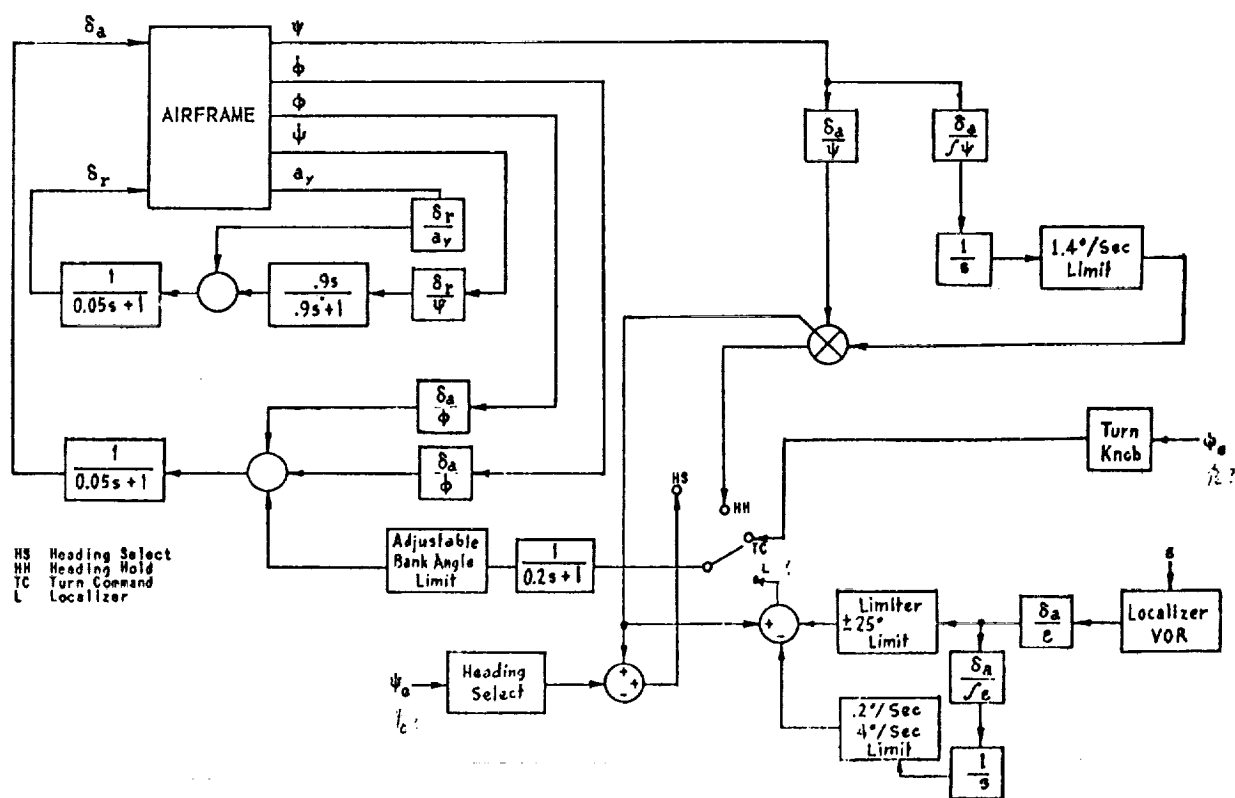
C-5A Roll Autopilot: Courseline and Air-Drop Modes



C-5A Roll Autopilot: Localizer Mode, Including Autoland

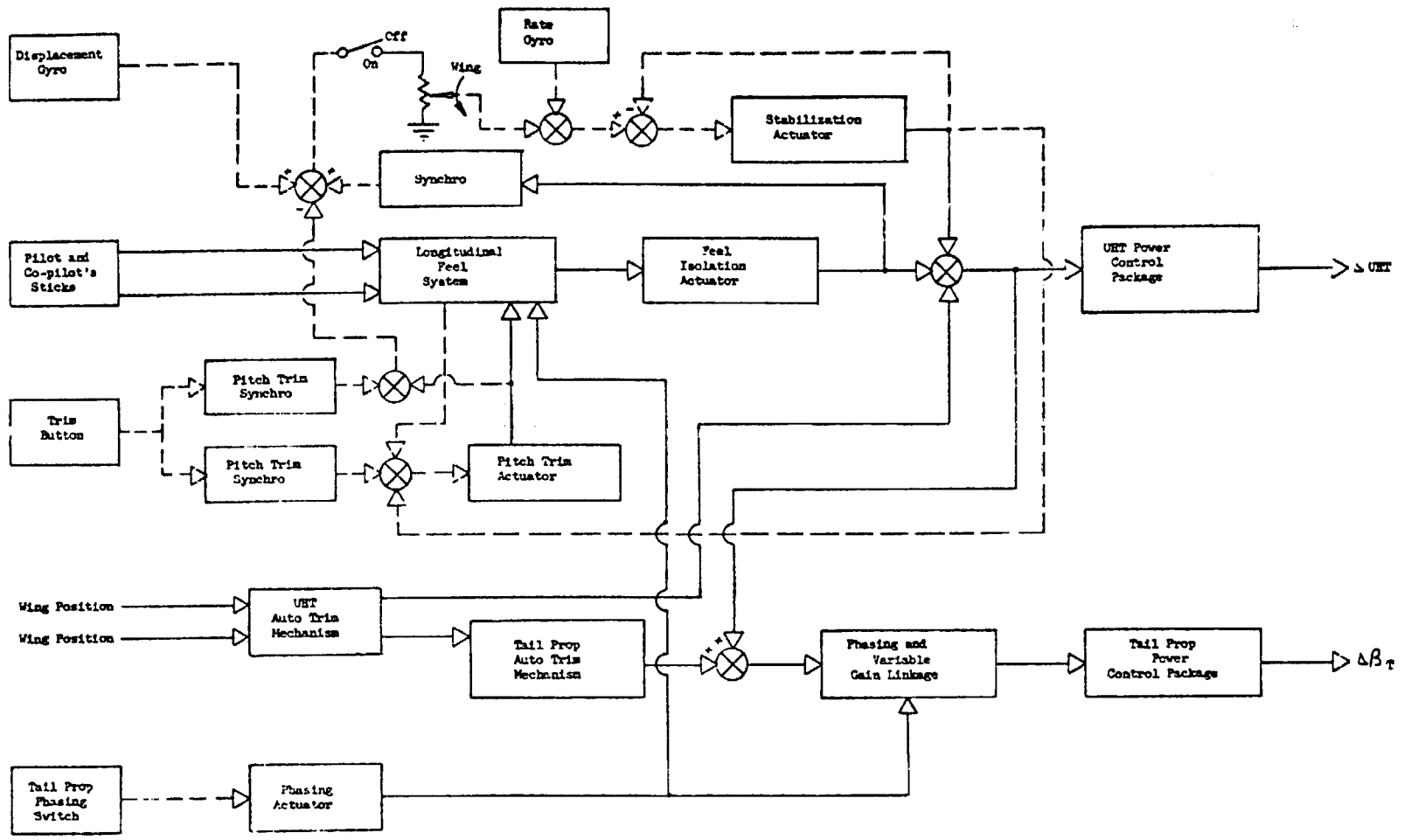


KC-135 Pitch Diagram

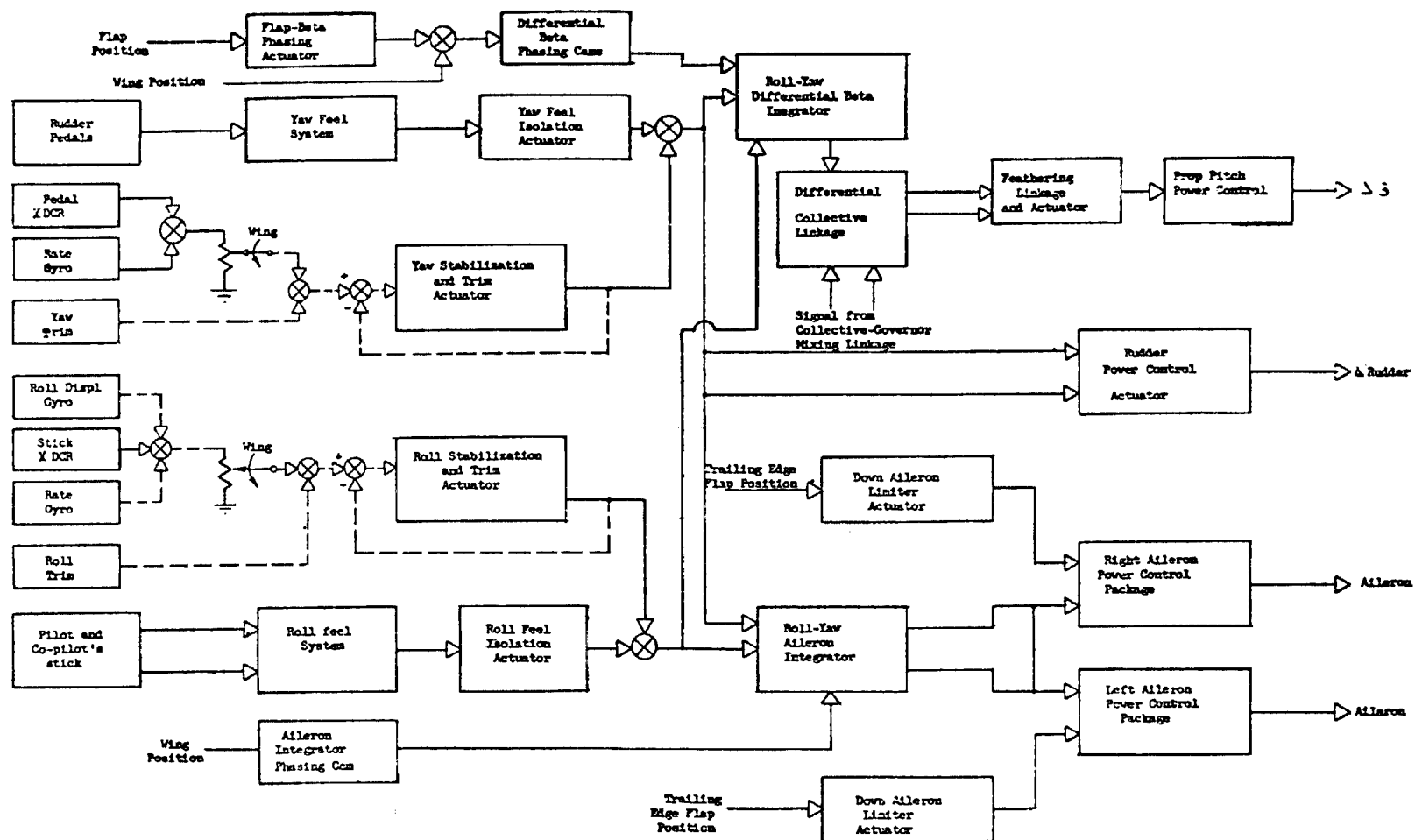


KC-135 Lateral-Directional Axis Diagram

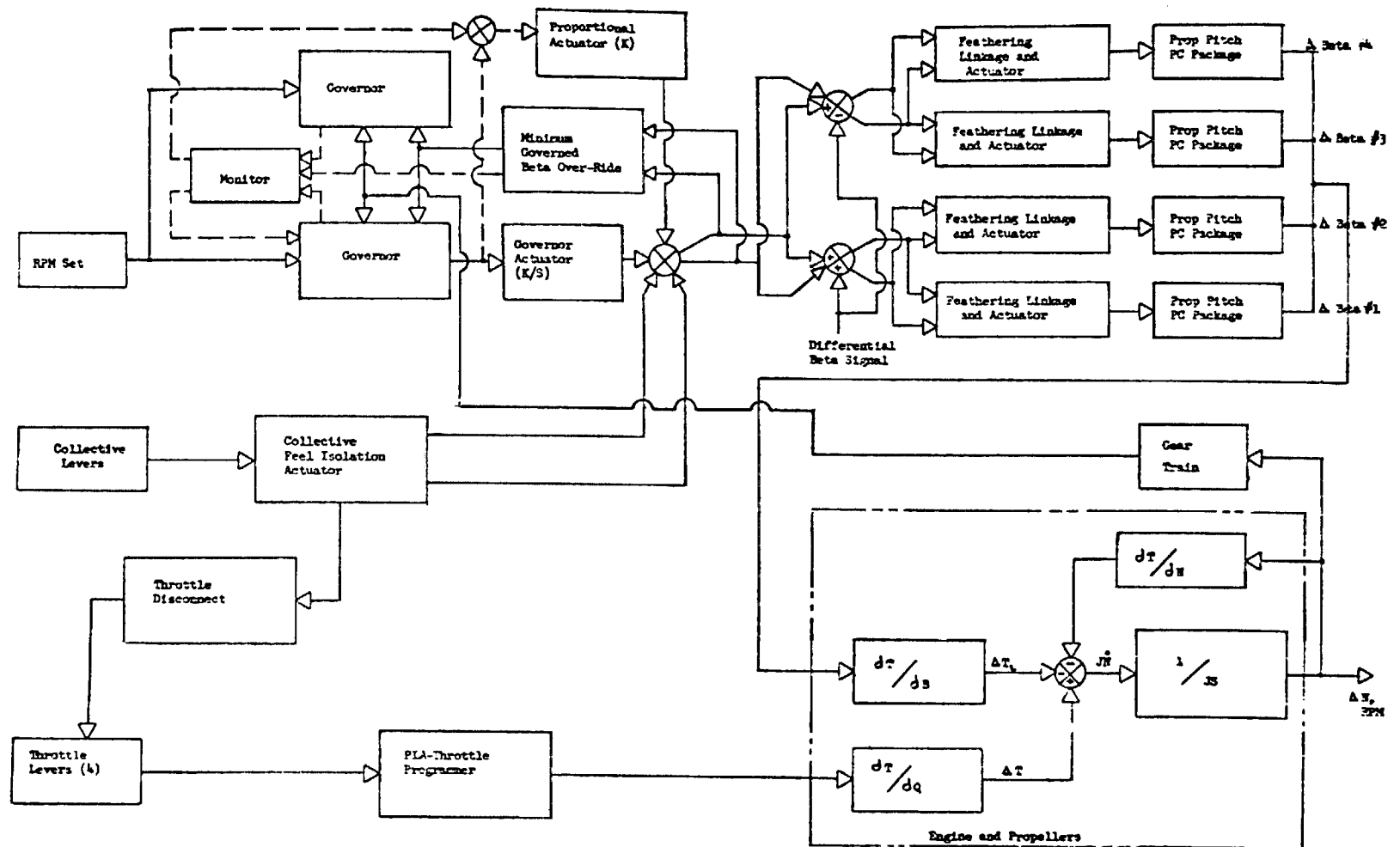
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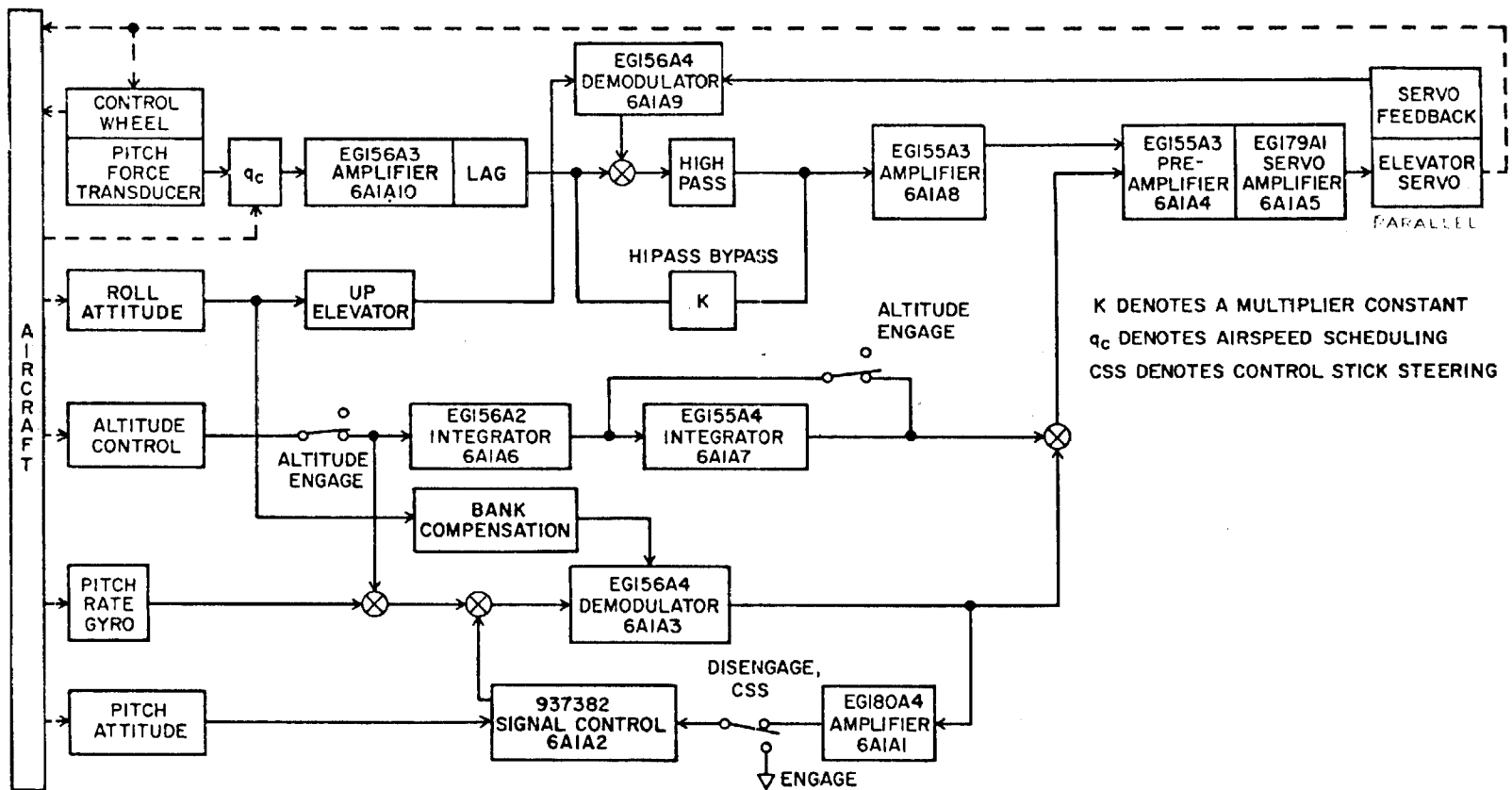
XC-142A Pitch Control System Block Diagram



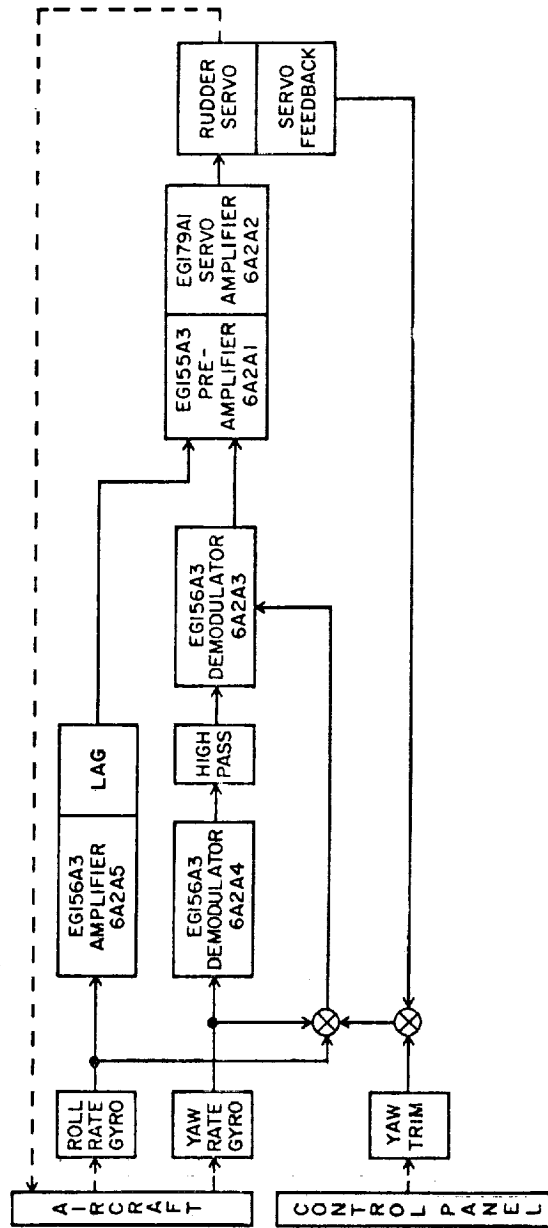
XC-142A Roll and Yaw Control System Block Diagram



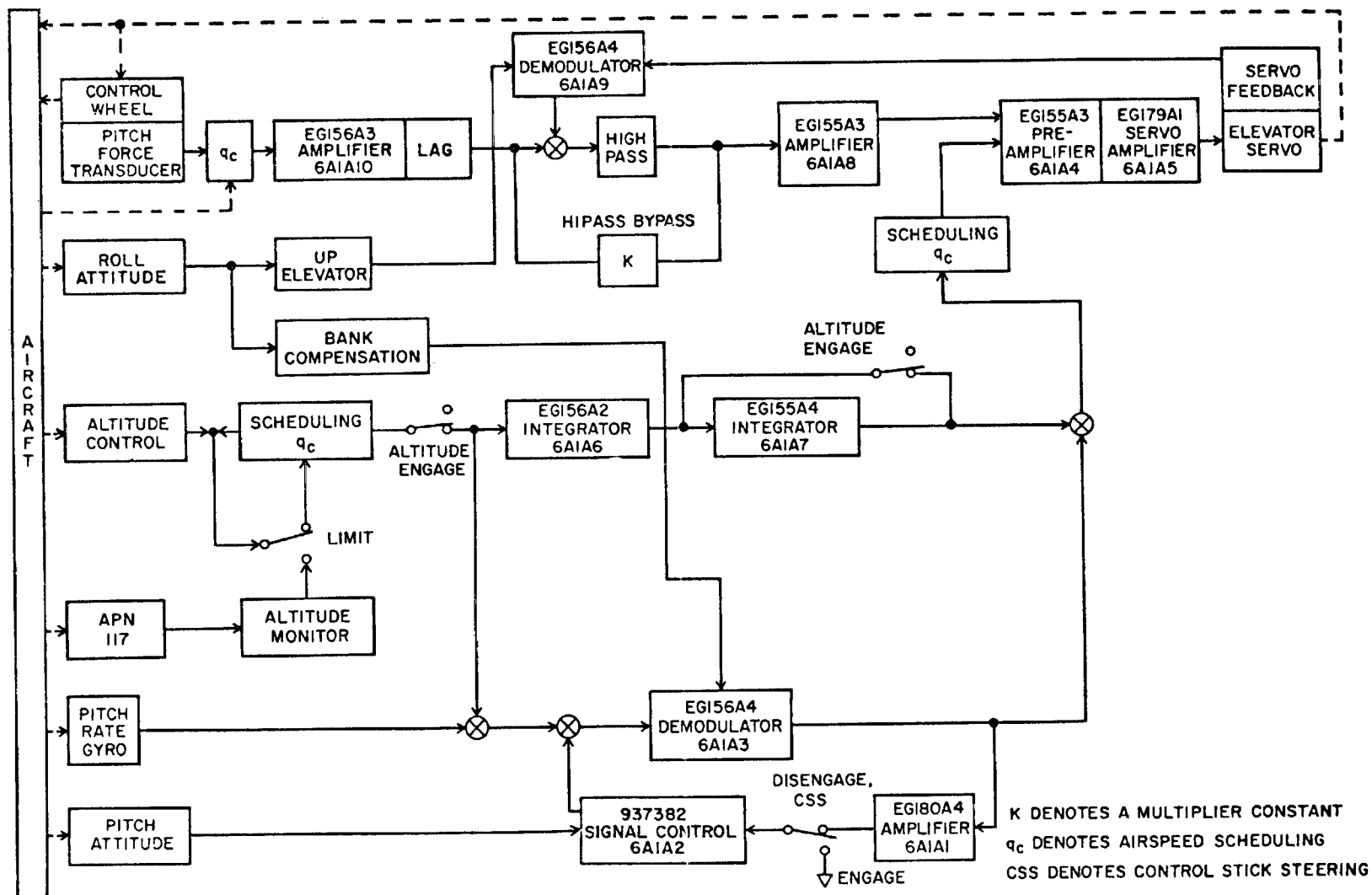
XC-142A Collective-Throttle System Block Diagram

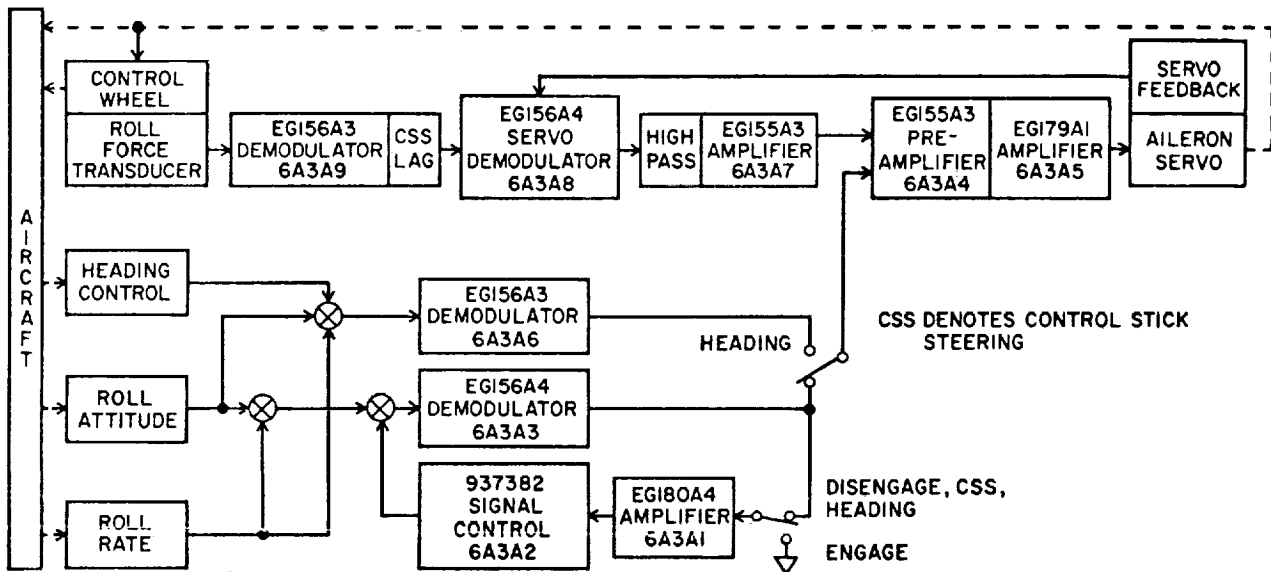


E-1B Pitch Axis

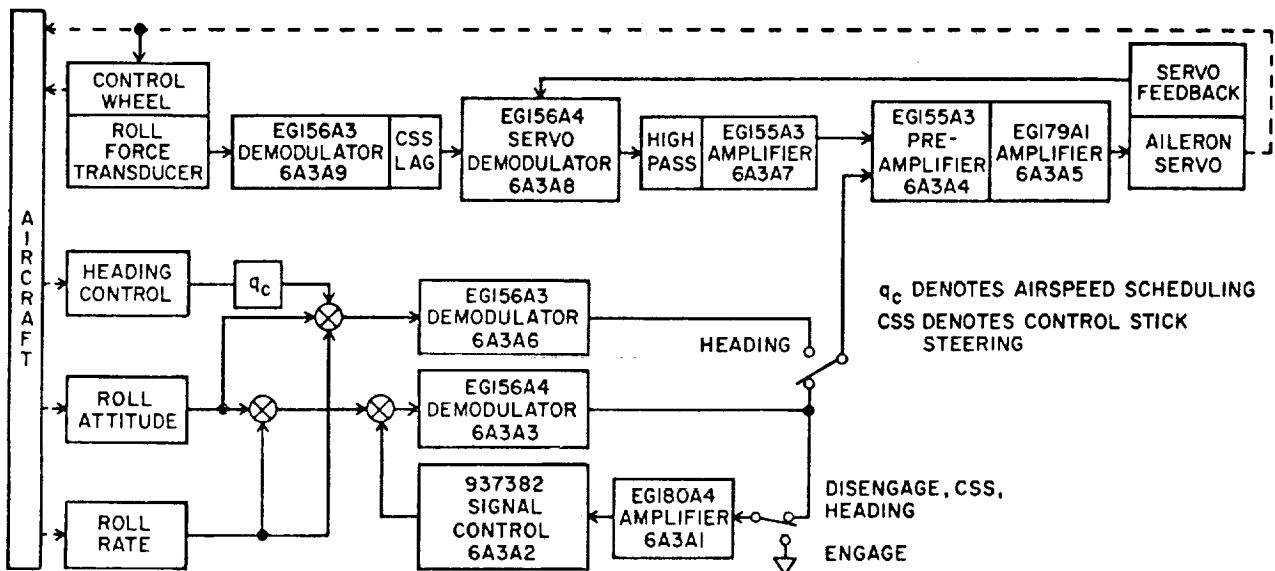


E-1B Yaw Axis Block Diagram

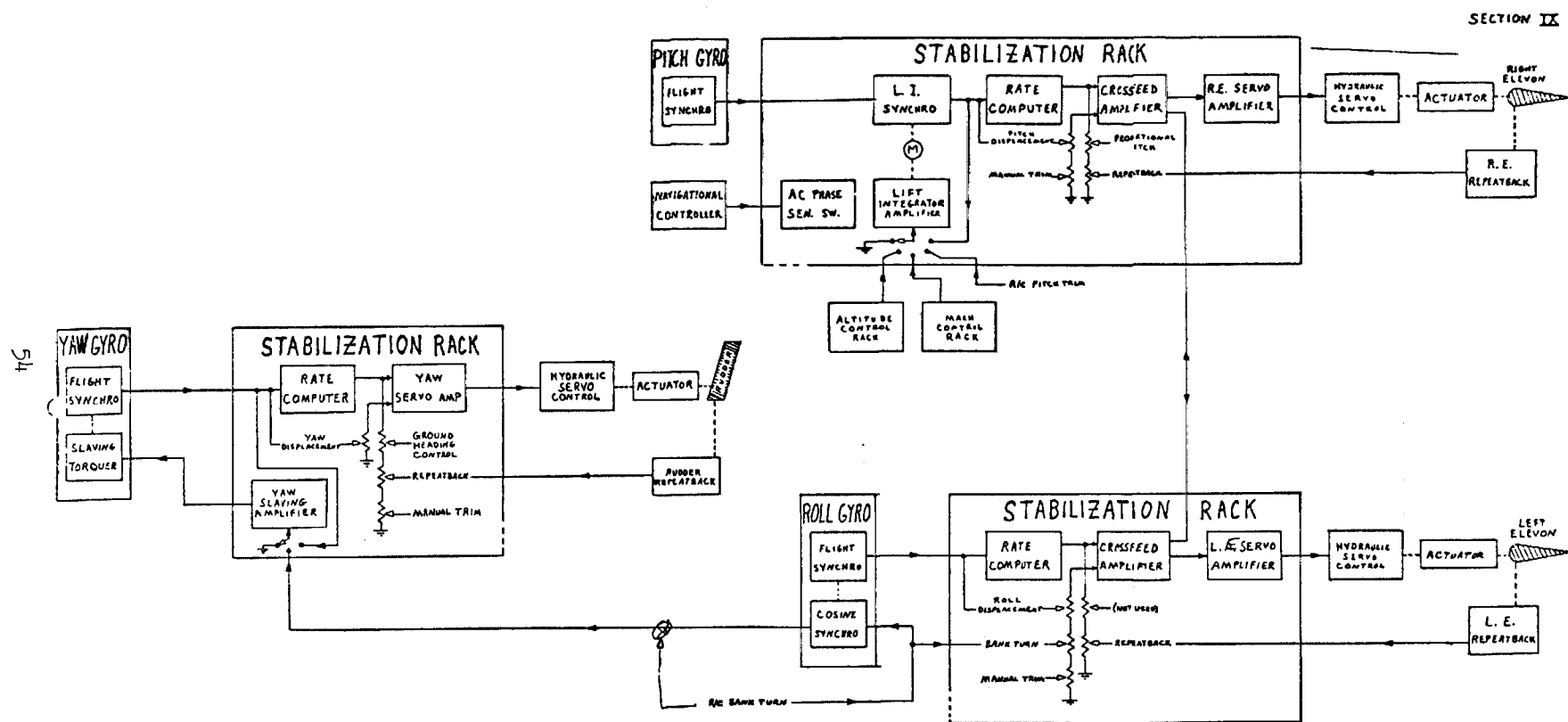




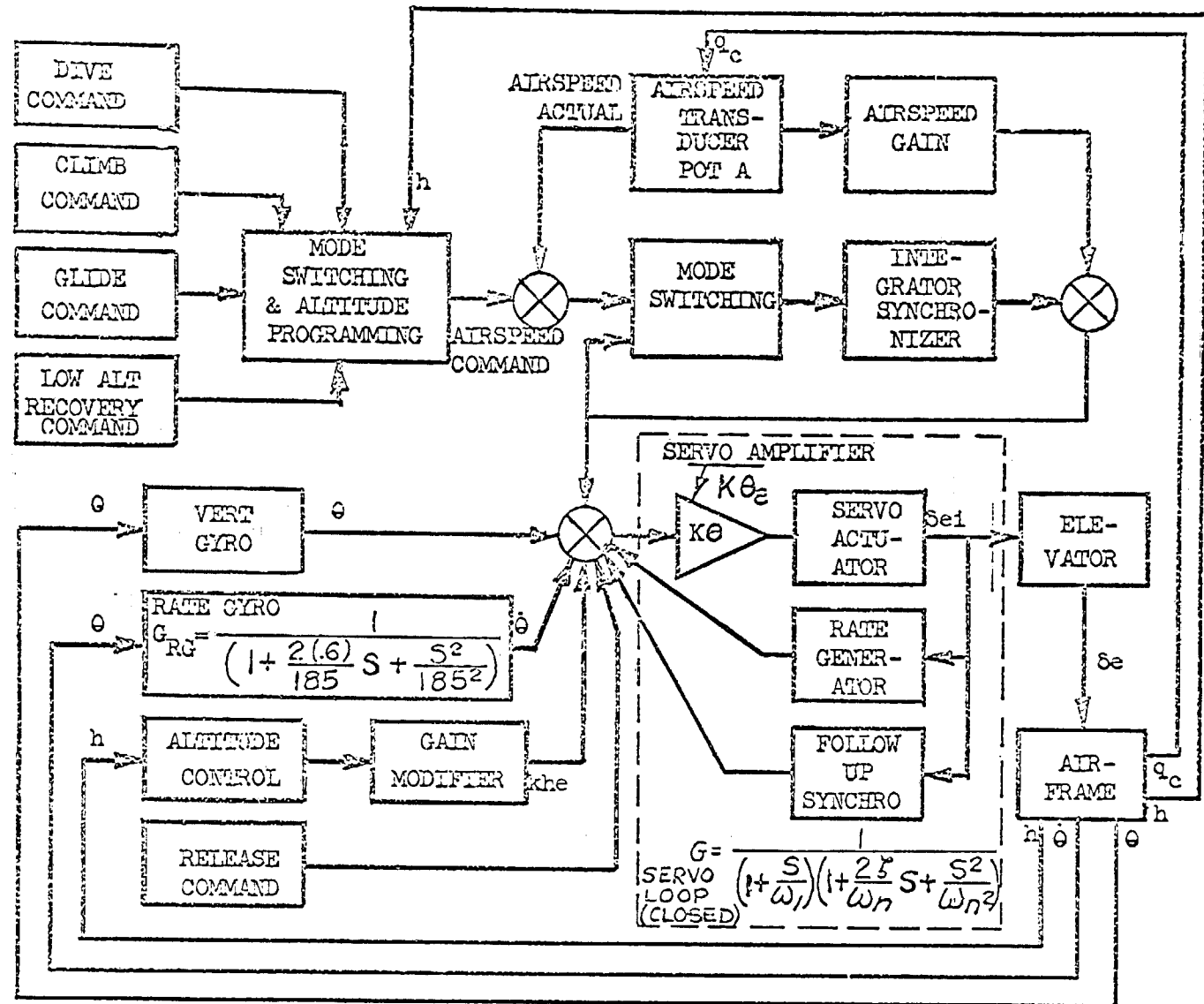
E-1B Roll Axis



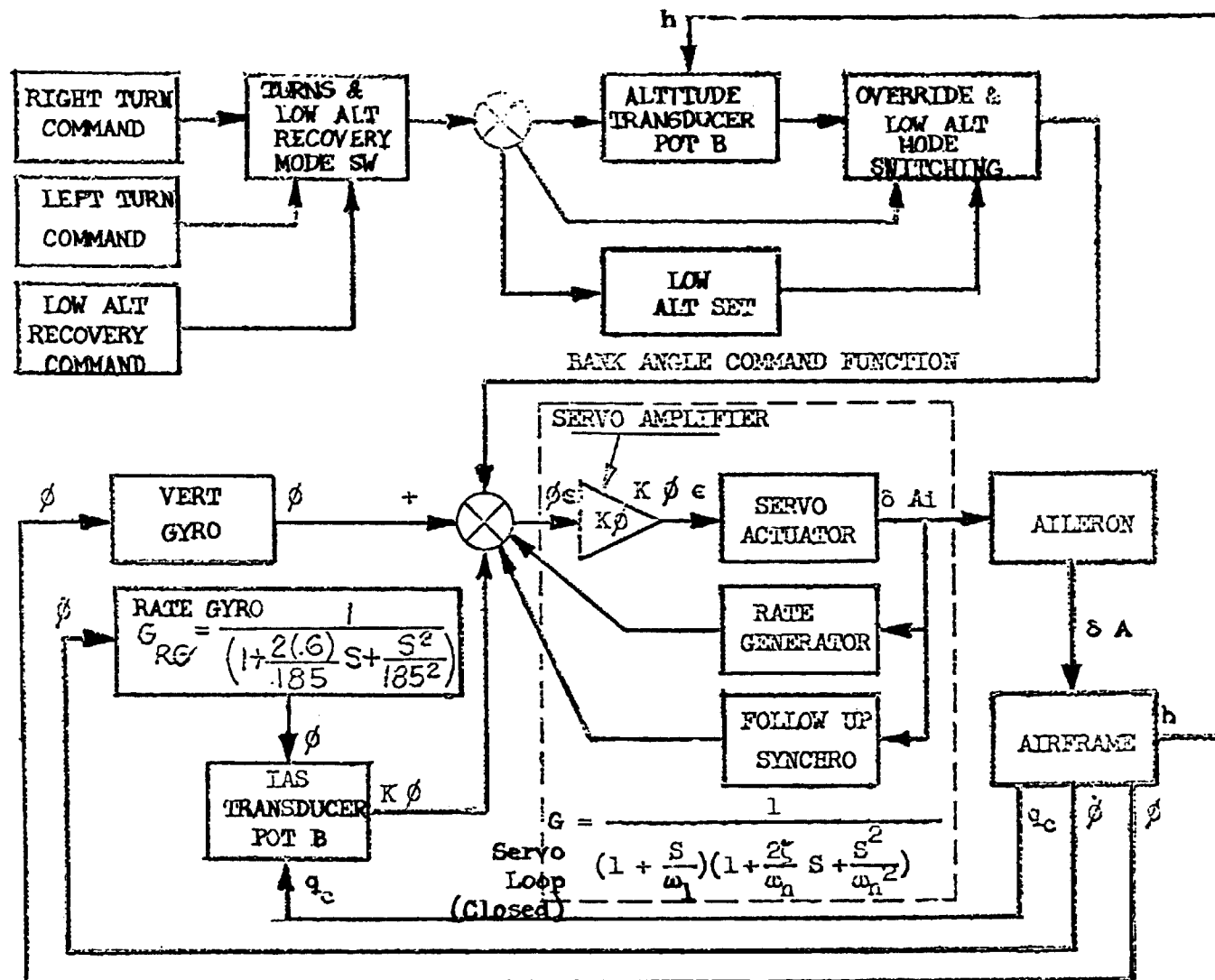
S-2D/S-2E Roll Axis



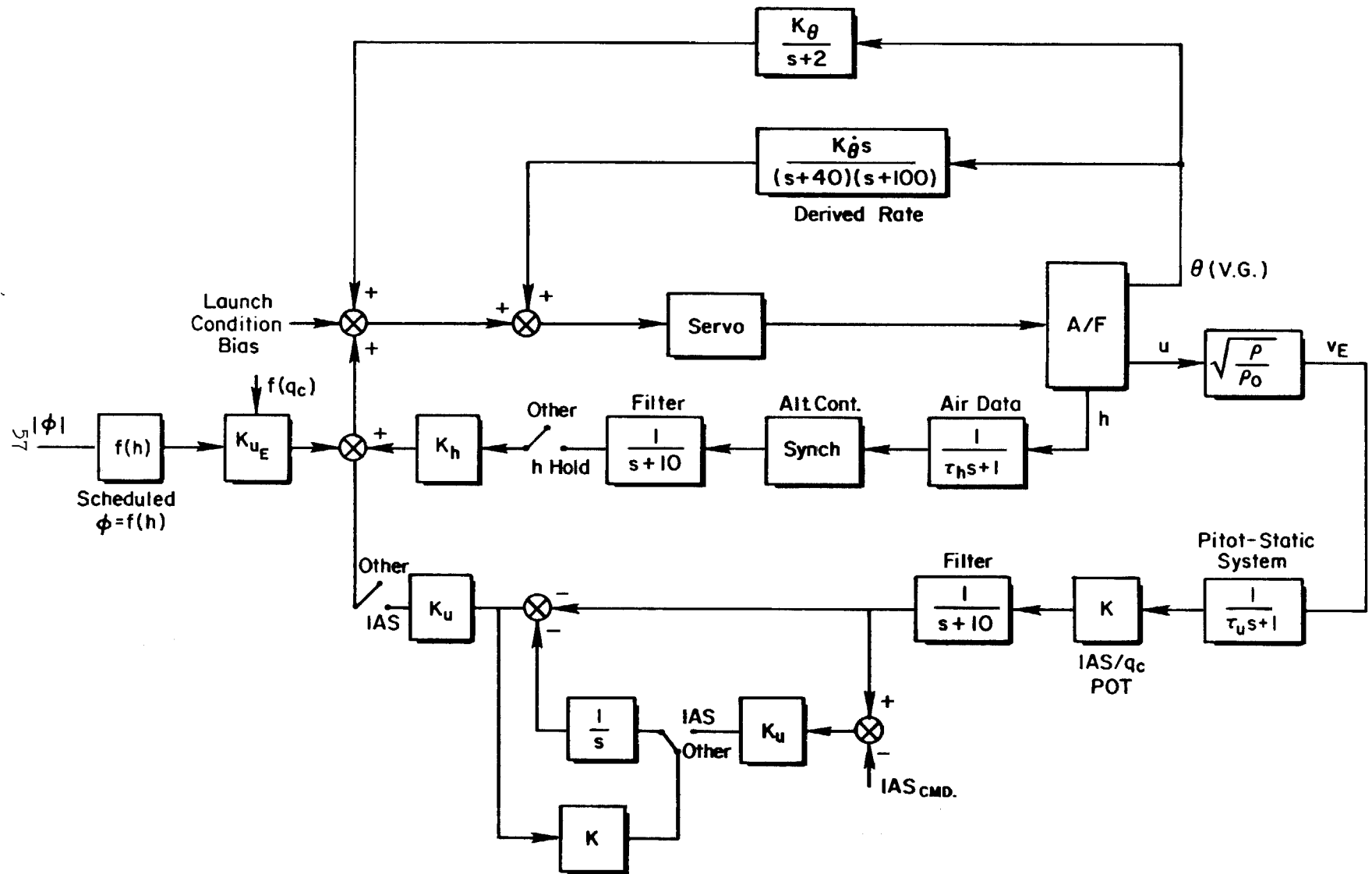
Regulus II Lot I Autopilot



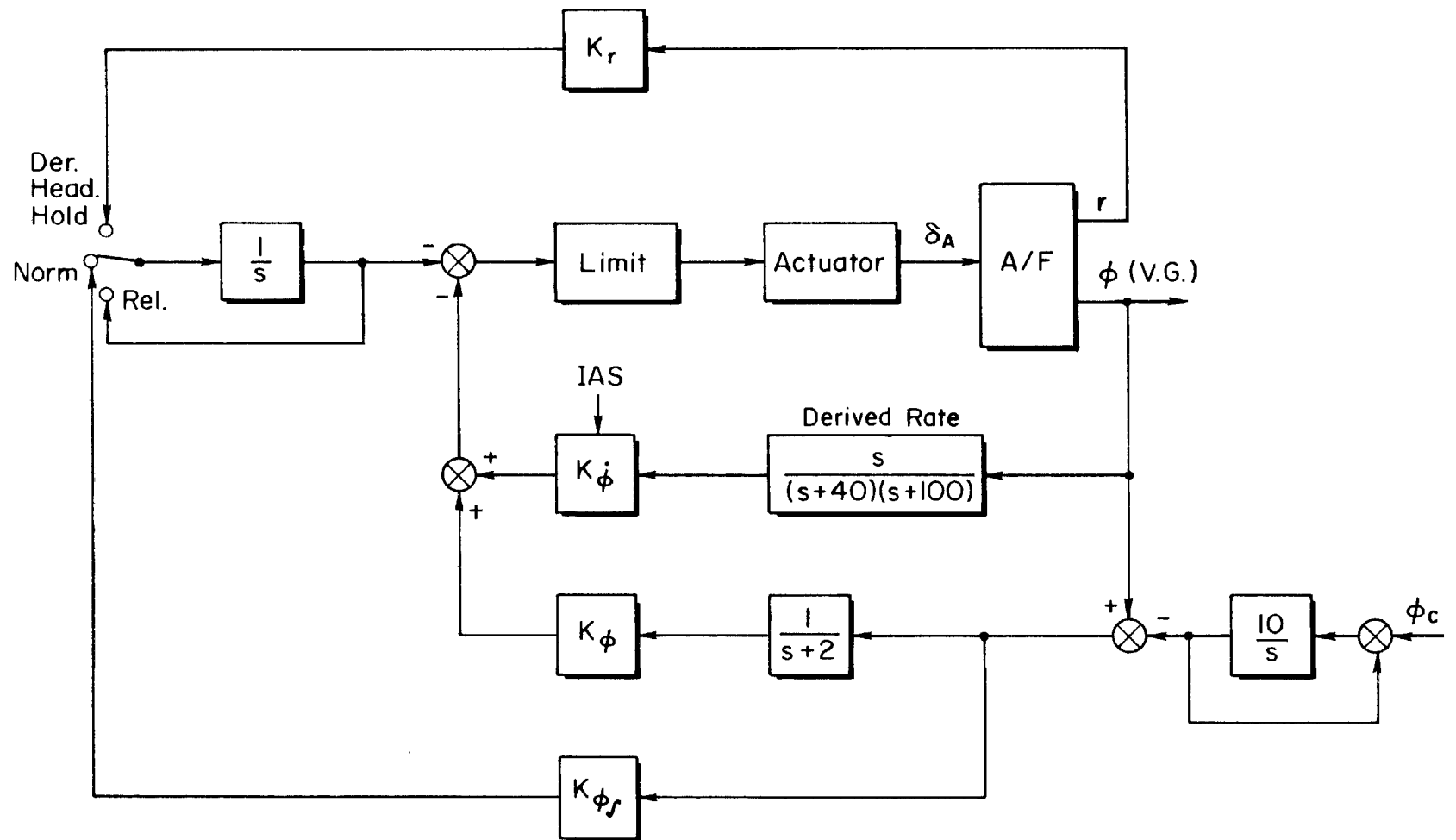
Q-2C Longitudinal Control System



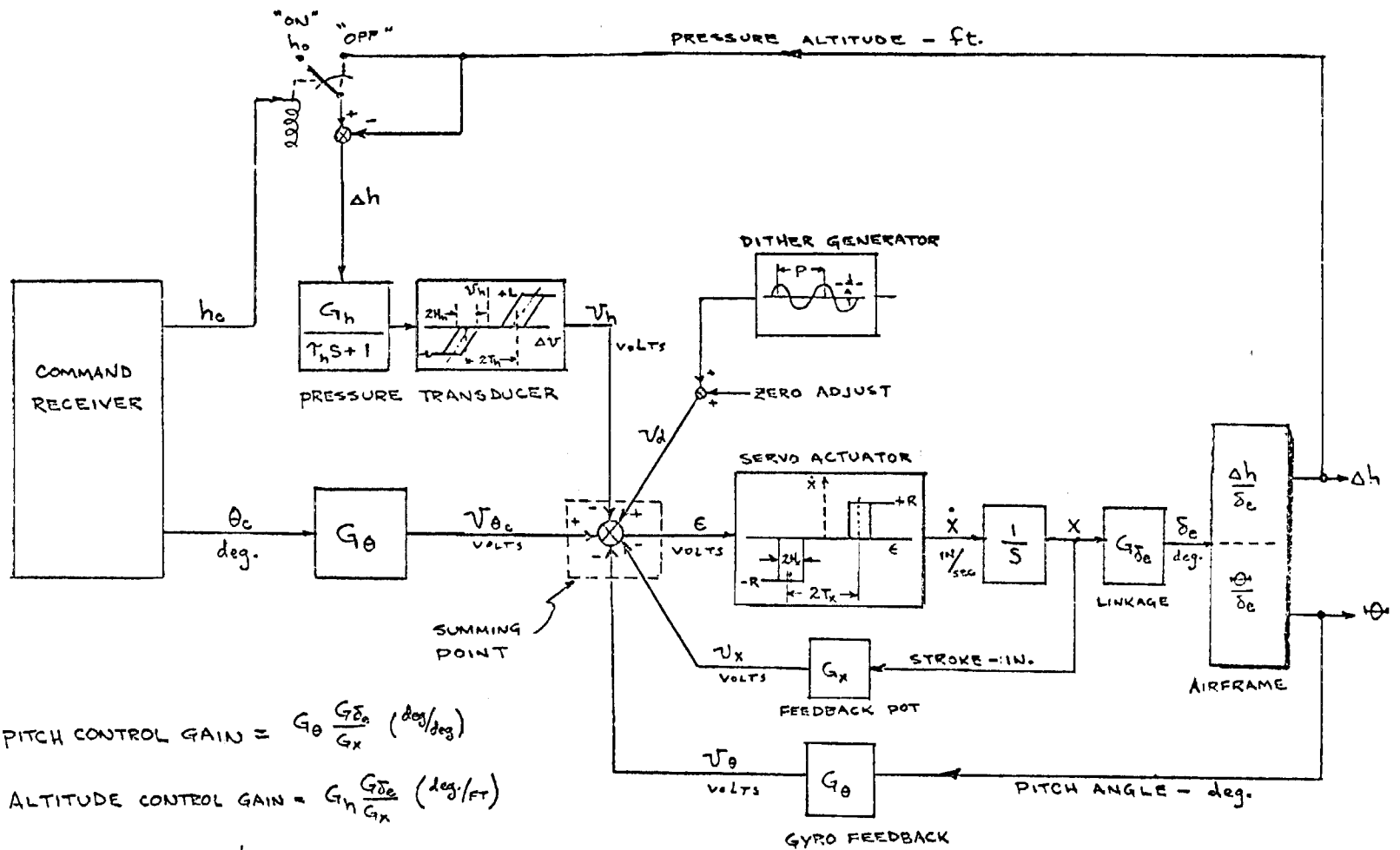
Q-2C Roll Control System



BQM-34 Pitch Axis



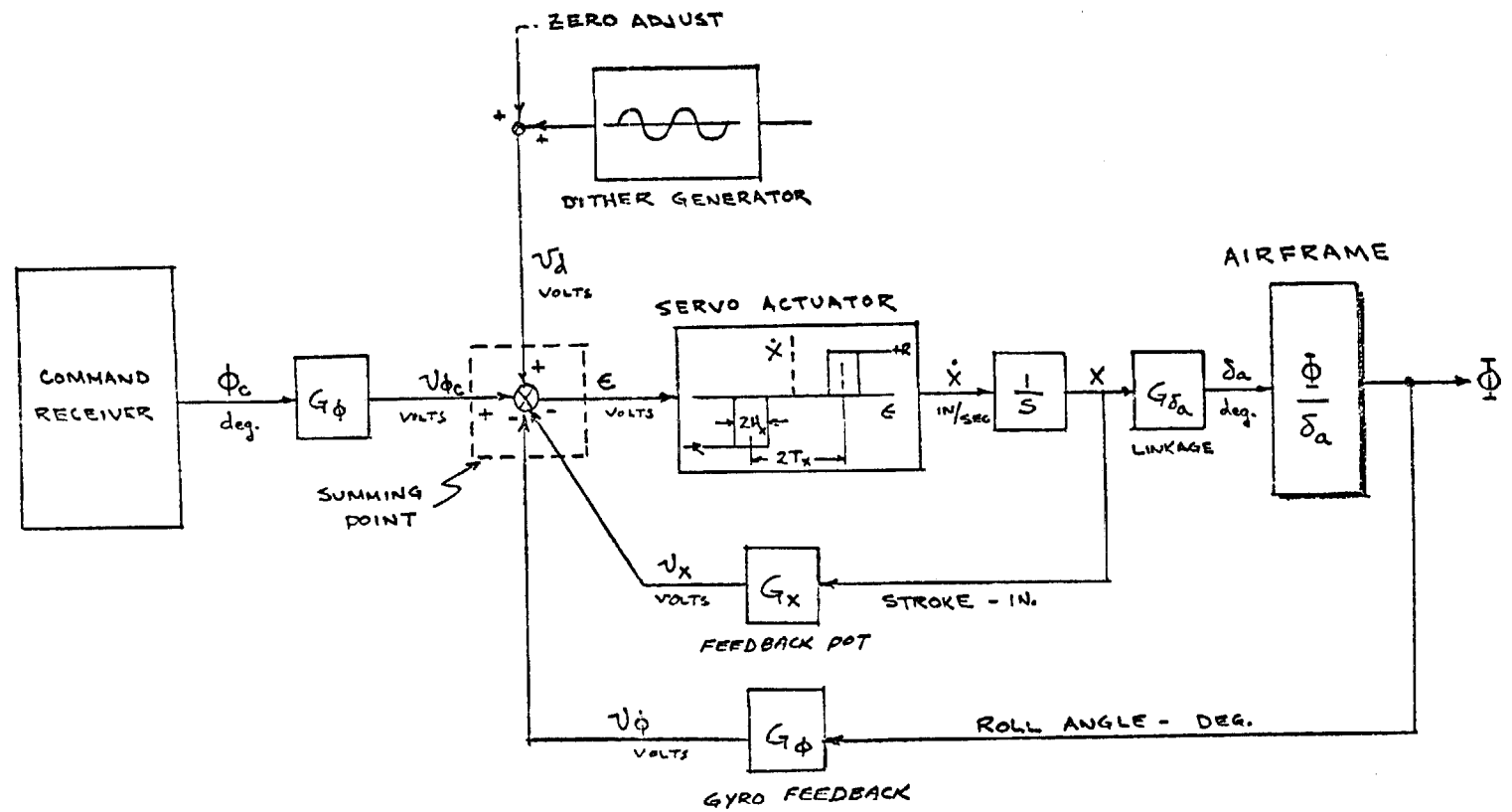
BQM-34 Roll Axis



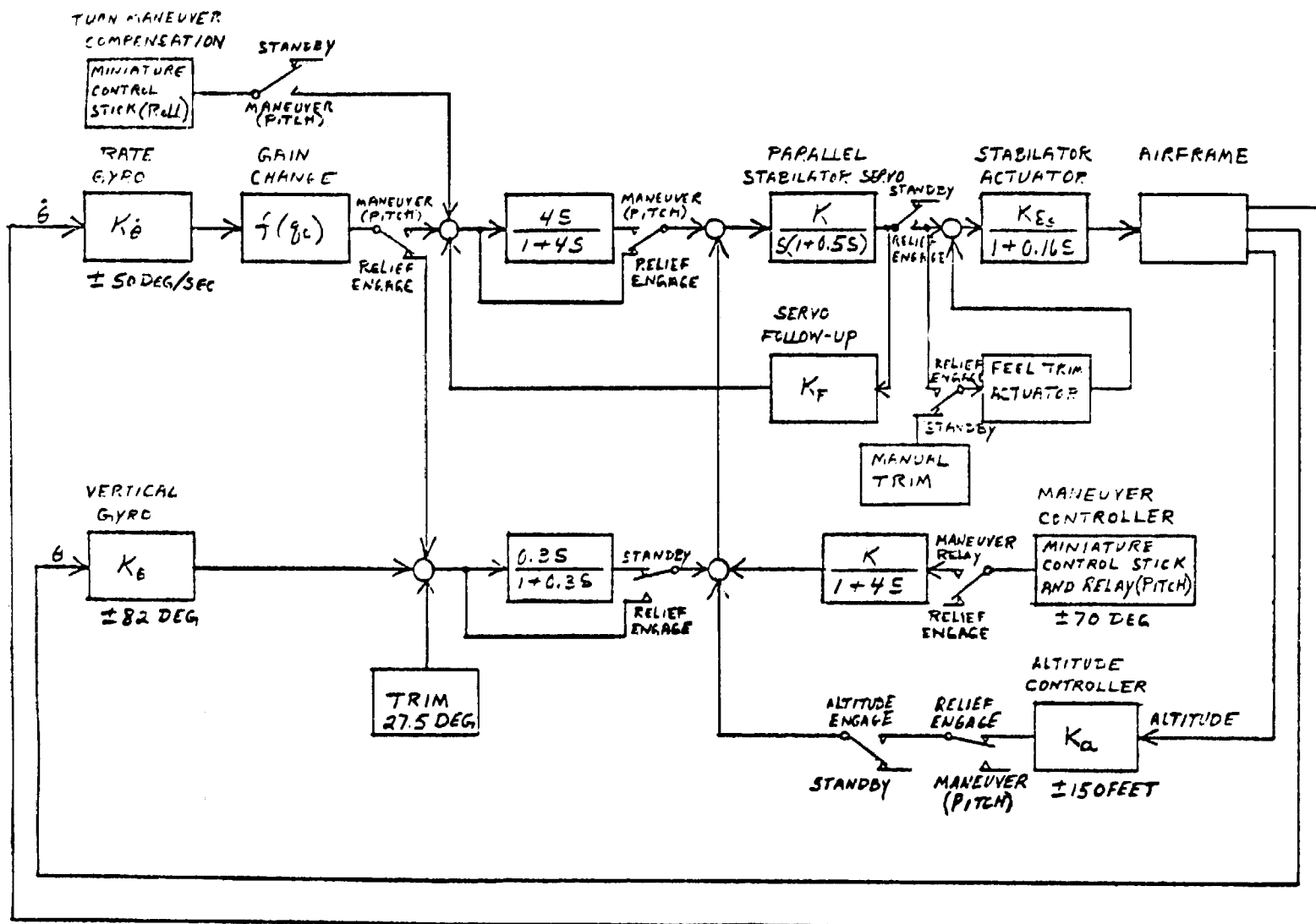
$$K_\theta = \text{PITCH CONTROL GAIN} = G_\theta \frac{G_{\delta_e}}{G_x} \left(\frac{\text{deg}}{\text{deg}} \right)$$

$$K_h = \text{ALTITUDE CONTROL GAIN} = G_h \frac{G_{\delta_e}}{G_x} \left(\frac{\text{deg}}{\text{ft}} \right)$$

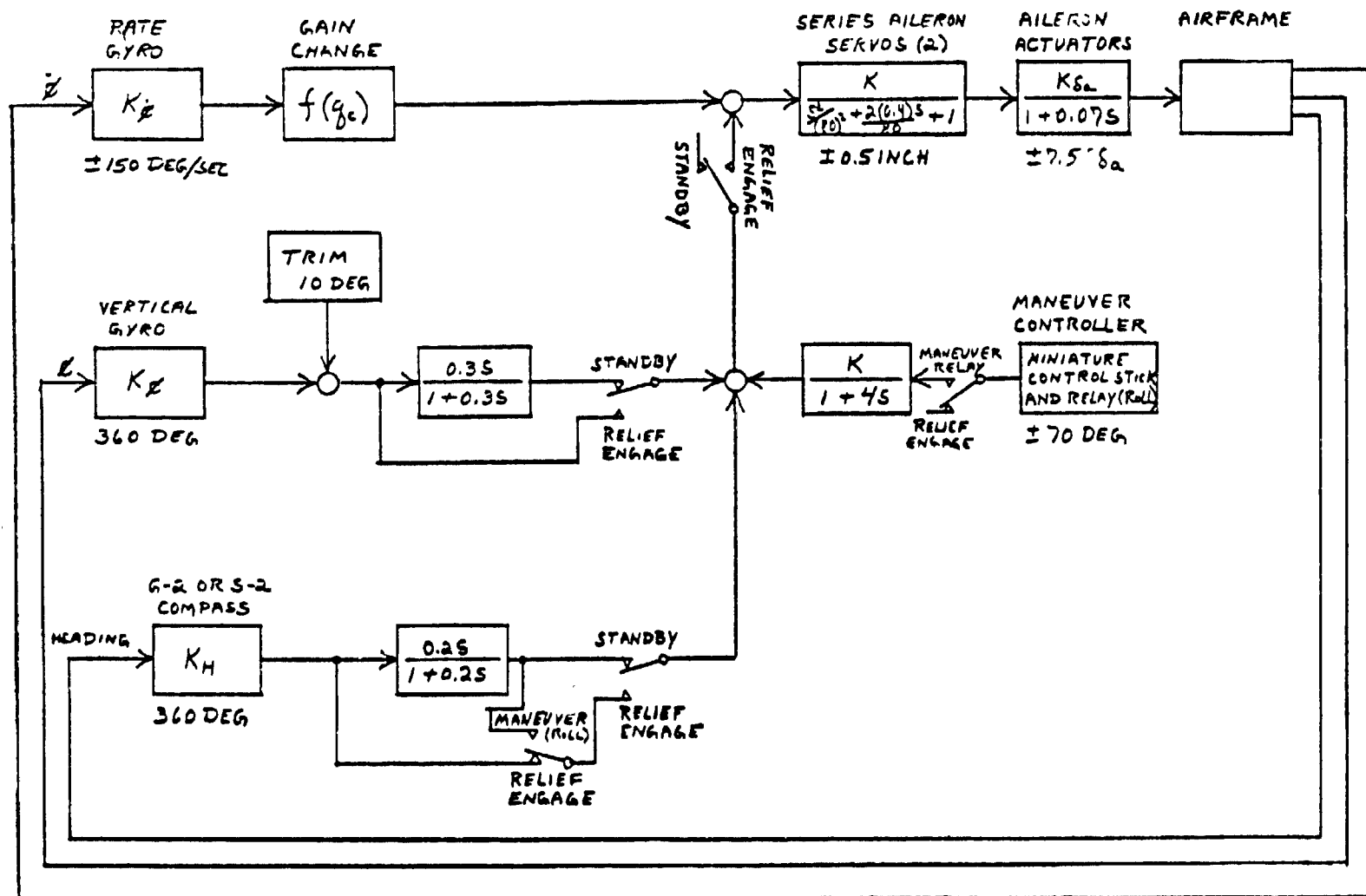
NOTE: G_h IS FUNCTION OF h_0
 (i.e. $G_h = \frac{\Delta V}{\Delta P} \cdot \frac{dp}{dh} \bigg|_{h=h_0}$)



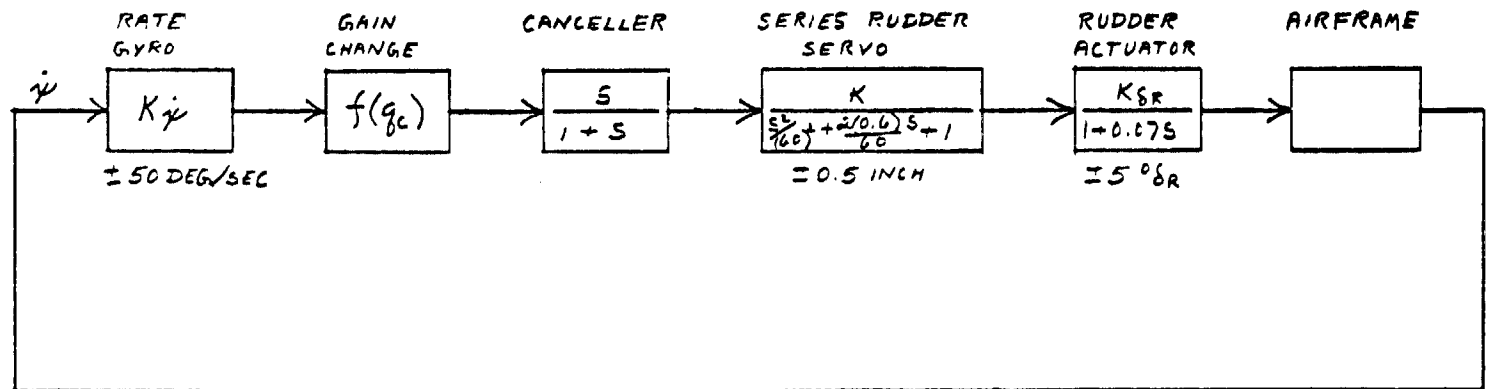
$$K_\phi = \text{ROLL CONTROL GAIN} = G_\phi \frac{G_{\delta a}}{G_x}$$



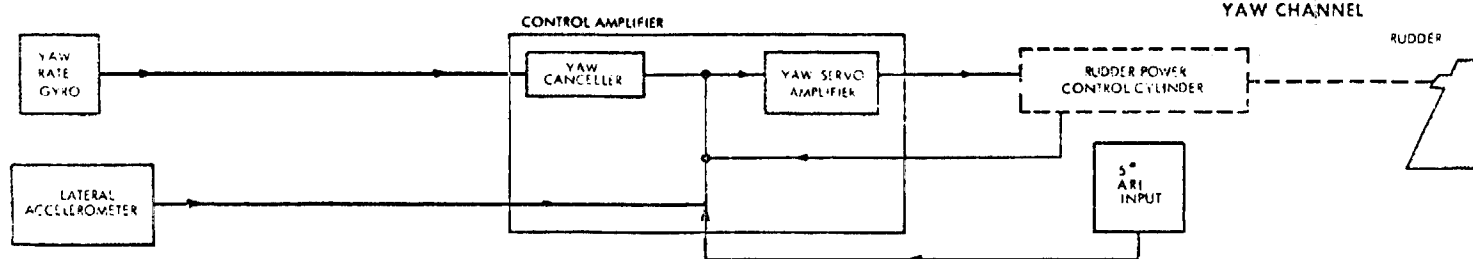
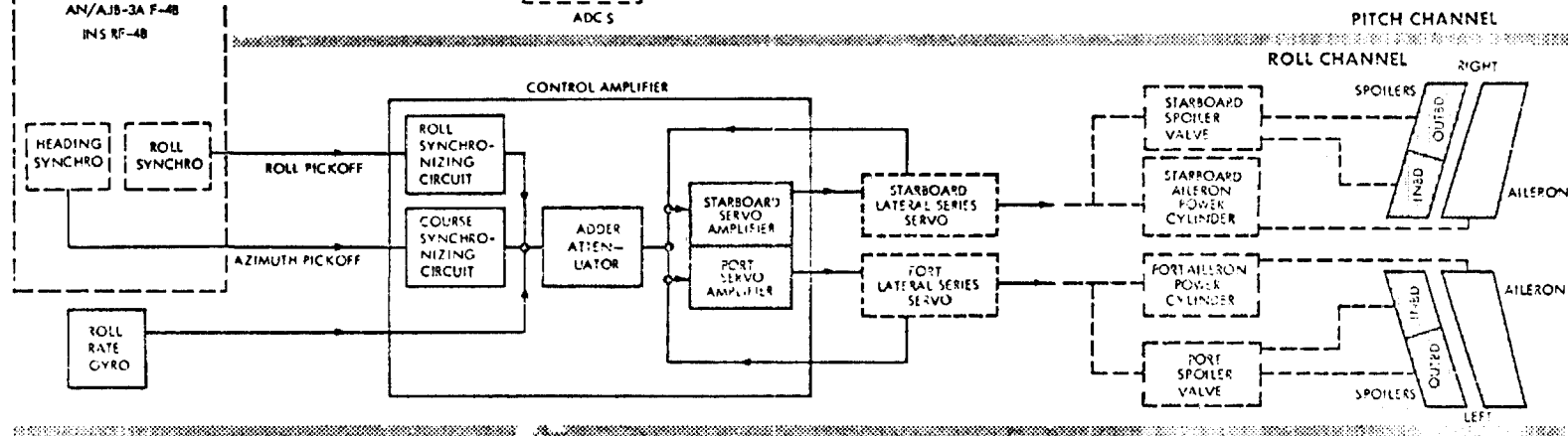
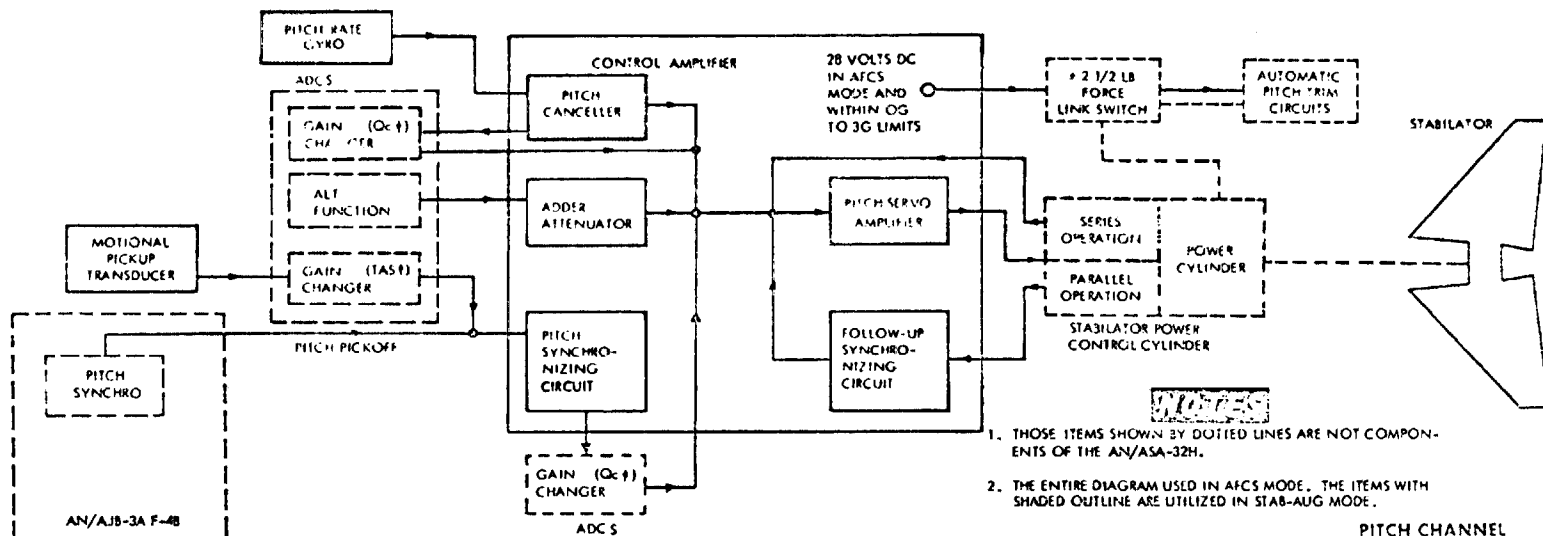
F3H PITCH CHANNEL

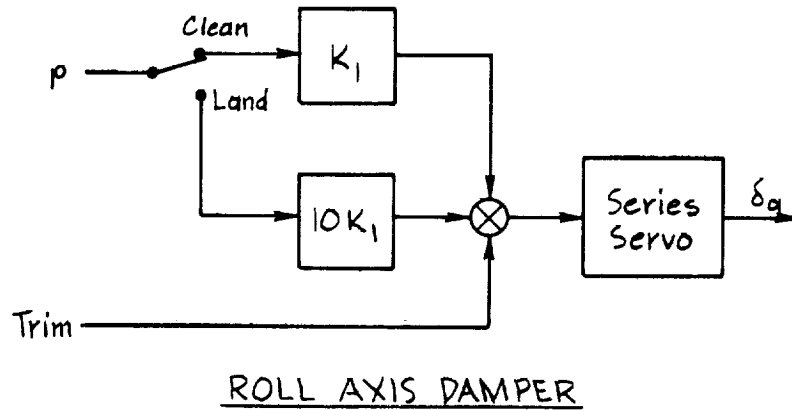
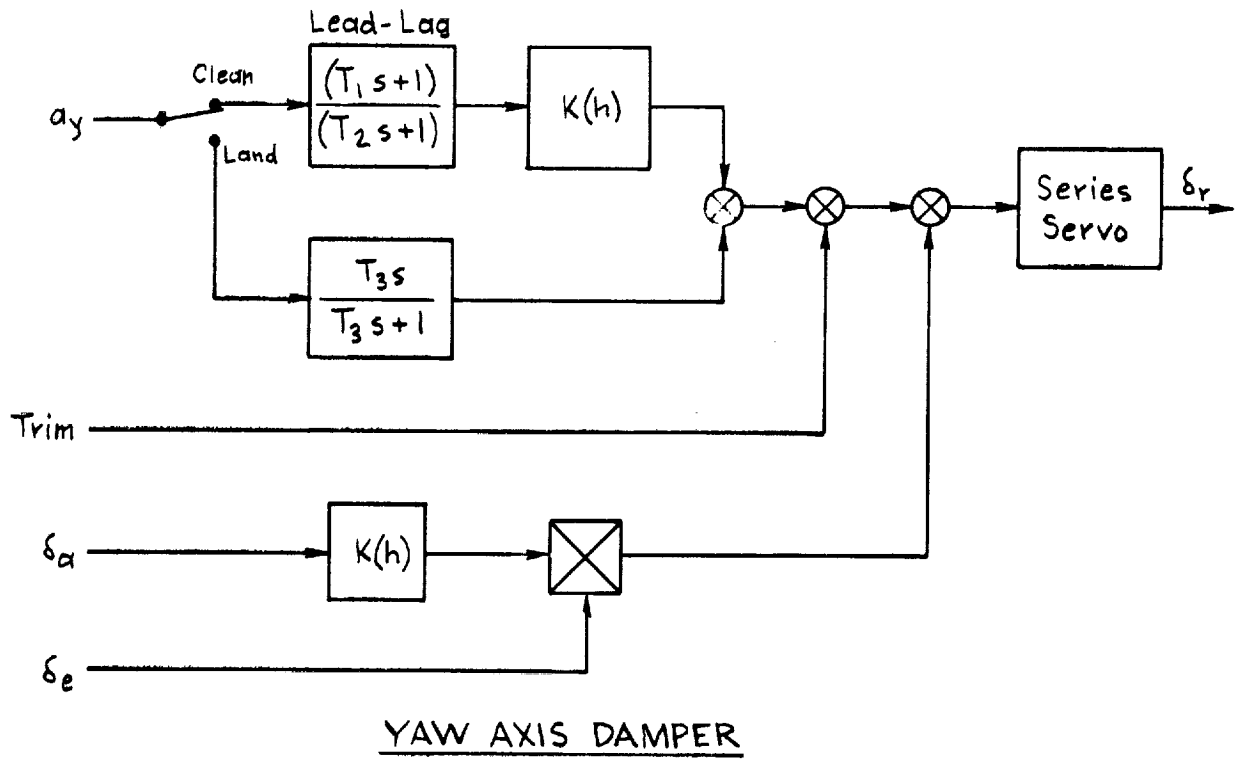


F3H ROLL CHANNEL

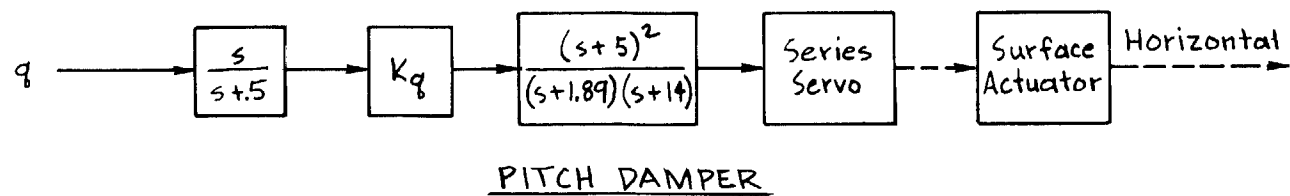
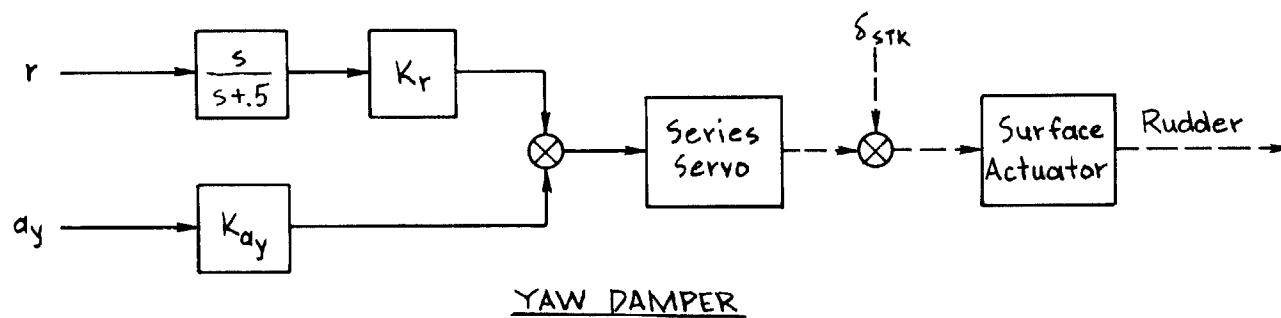
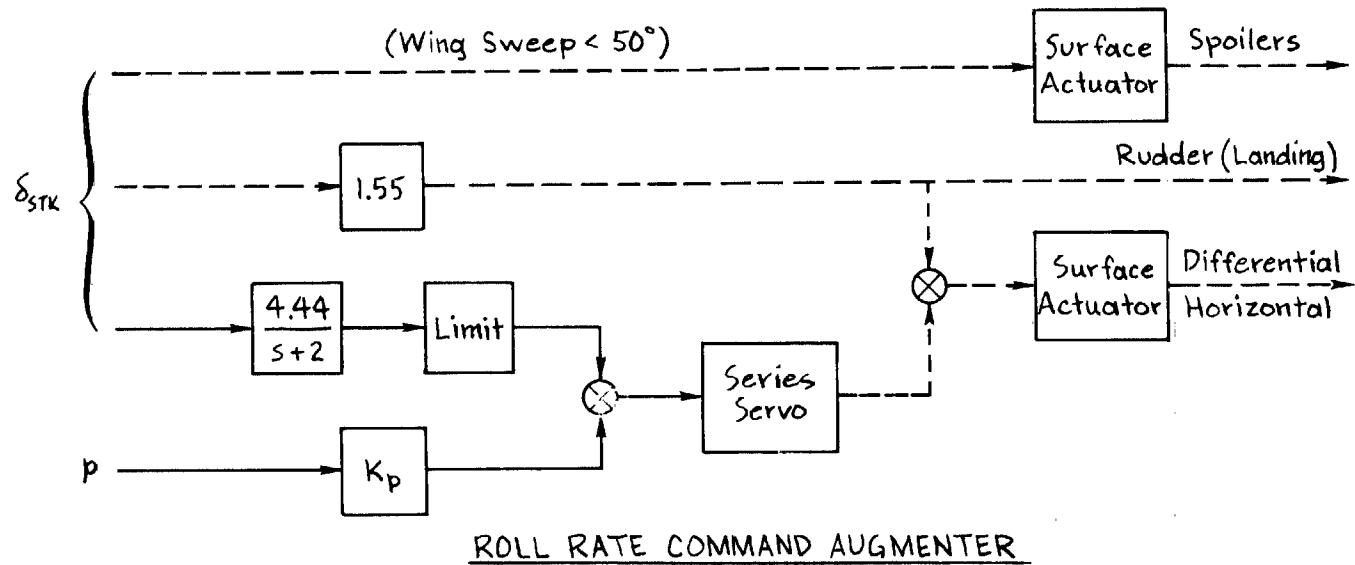


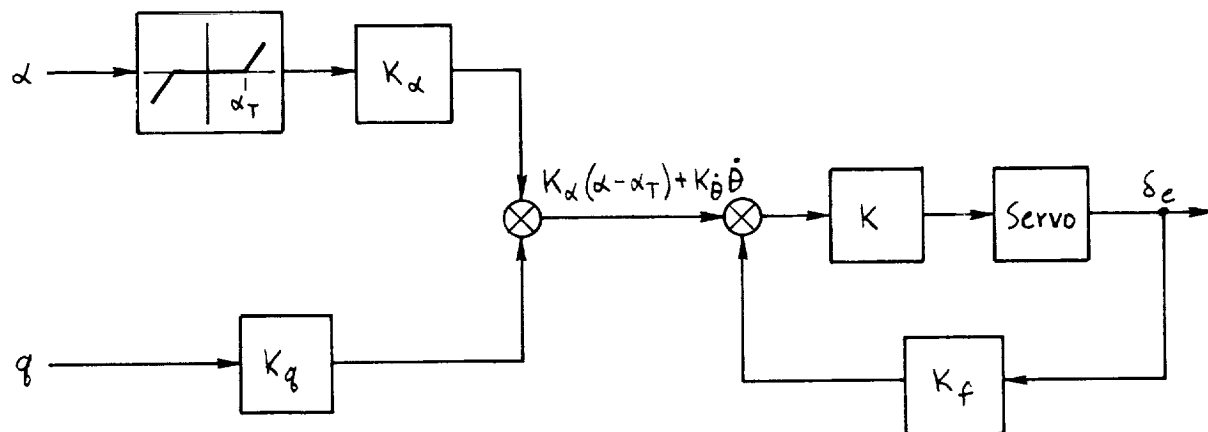
F3H YAW CHANNEL





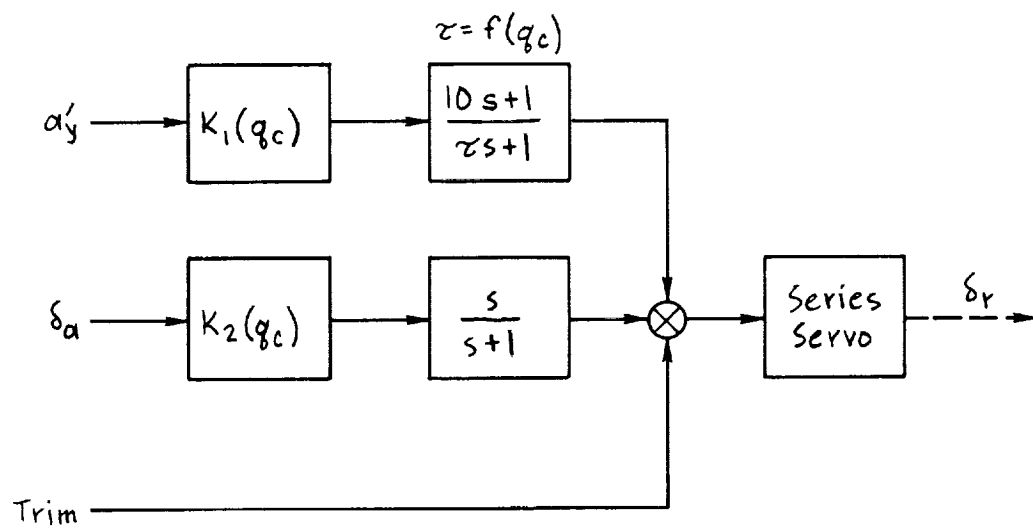
F-8D





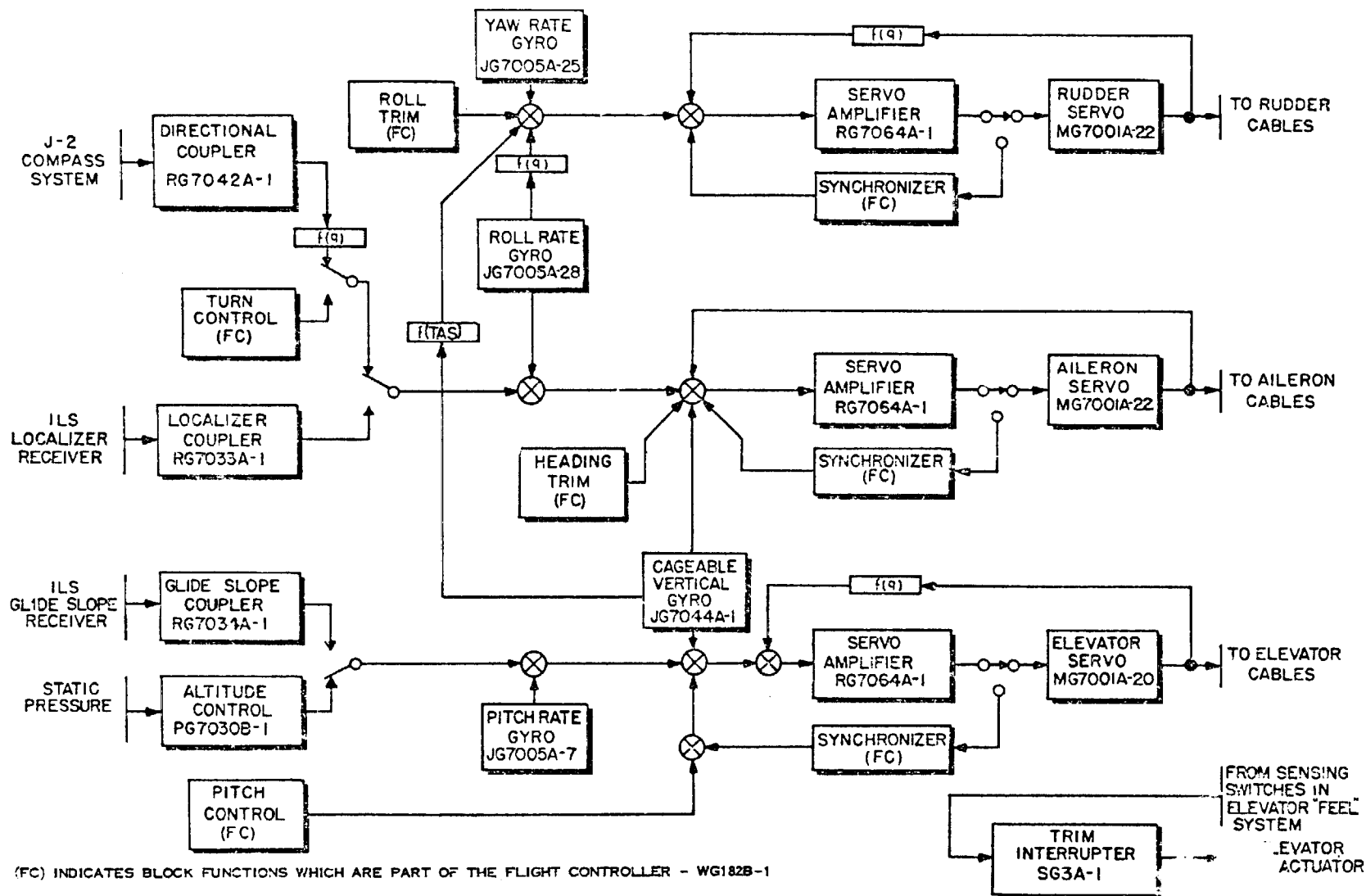
$$\begin{aligned} \delta_e &= K_\alpha(\alpha - \alpha_T) + K_{\dot{\theta}}\dot{\theta} & \text{when } K_\alpha(\alpha - \alpha_T) + K_{\dot{\theta}}\dot{\theta} > 0 \\ \delta_e &= 0 & \text{when } K_\alpha(\alpha - \alpha_T) + K_{\dot{\theta}}\dot{\theta} < 0 \end{aligned}$$

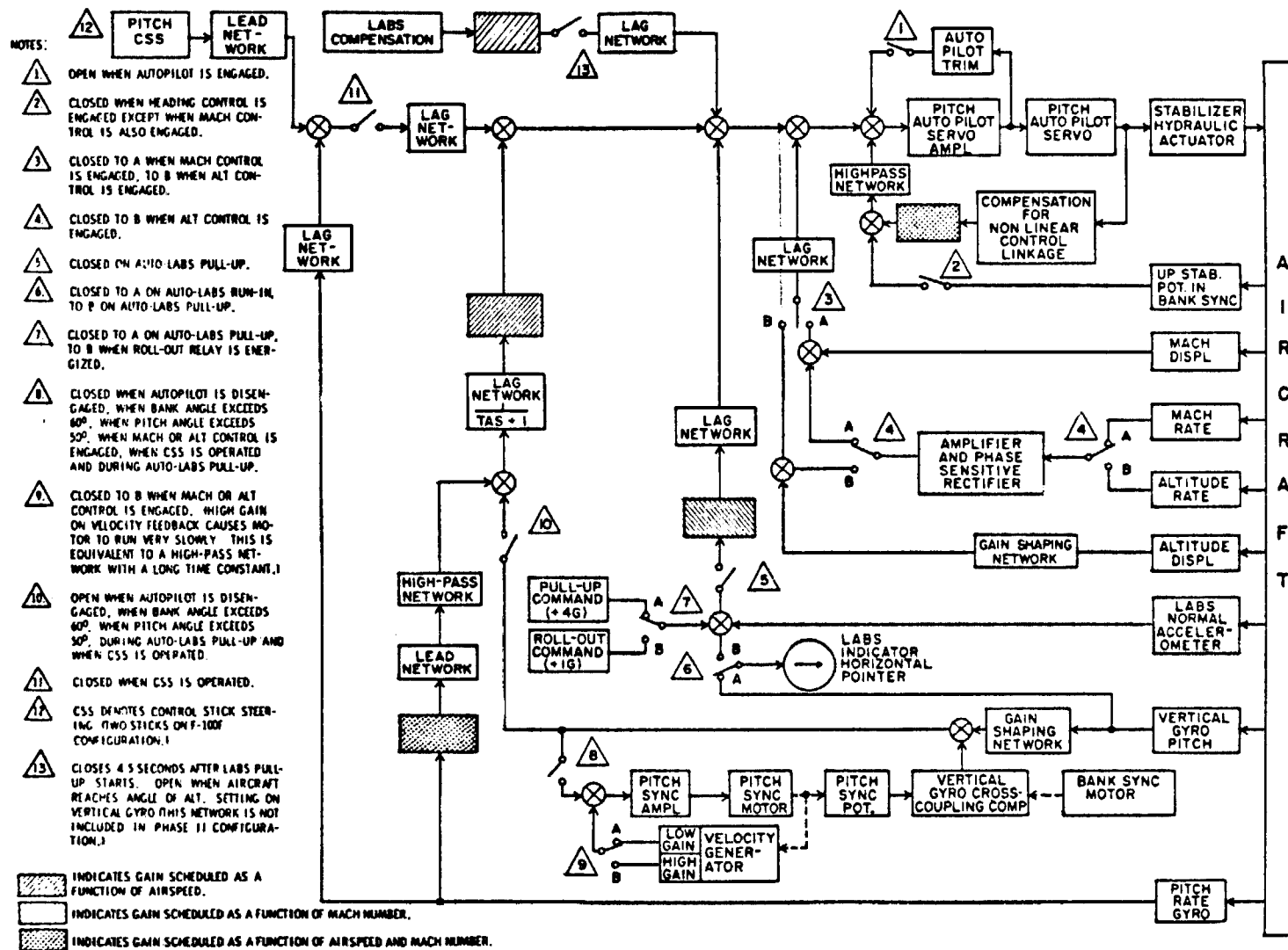
F-86 Pitch-up Preventer



F-89 Sideslip Stability Augmenter

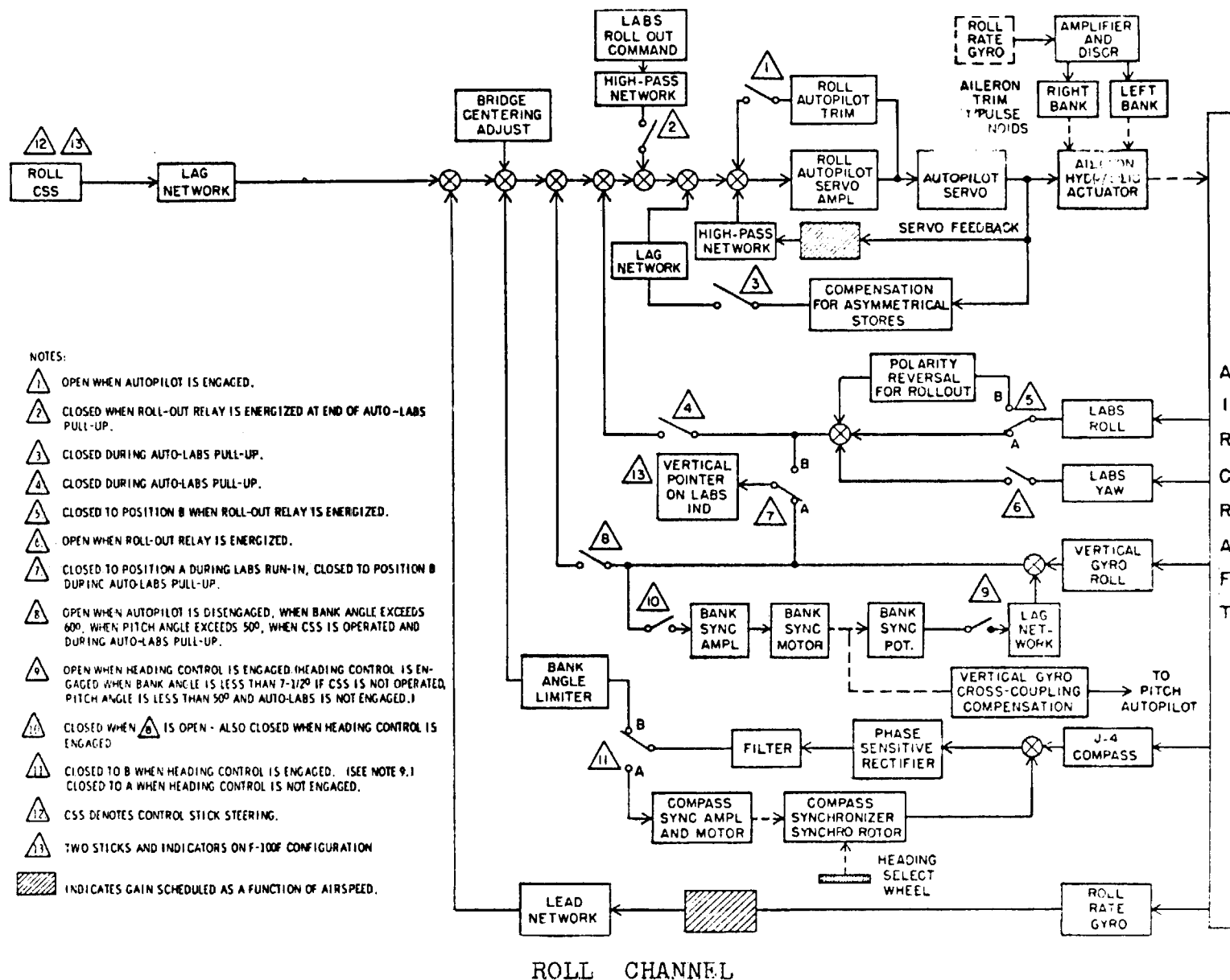
69

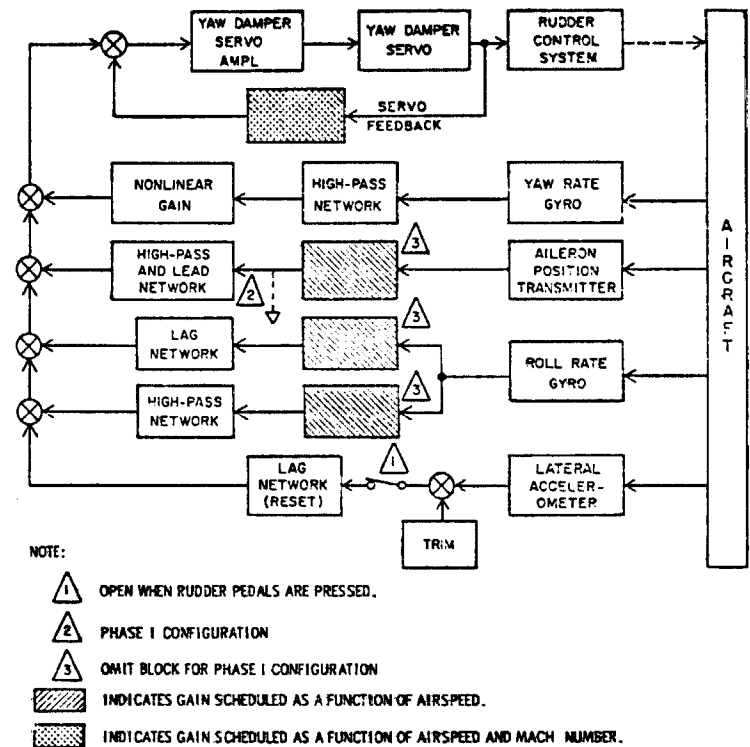
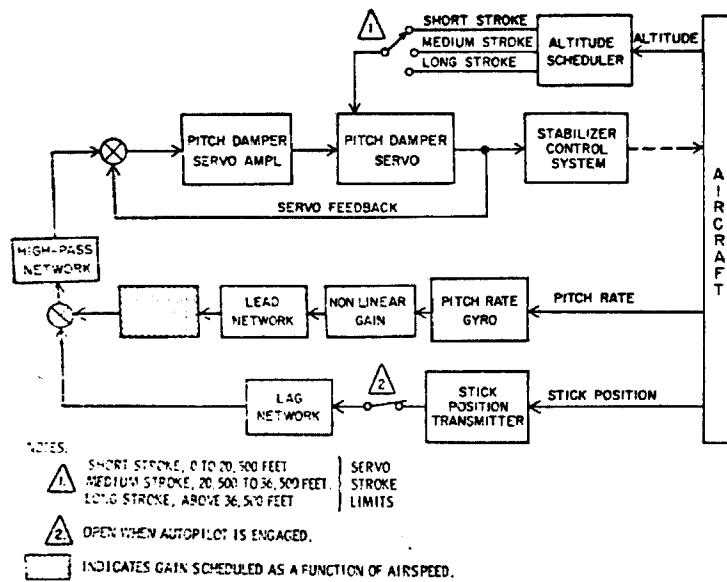


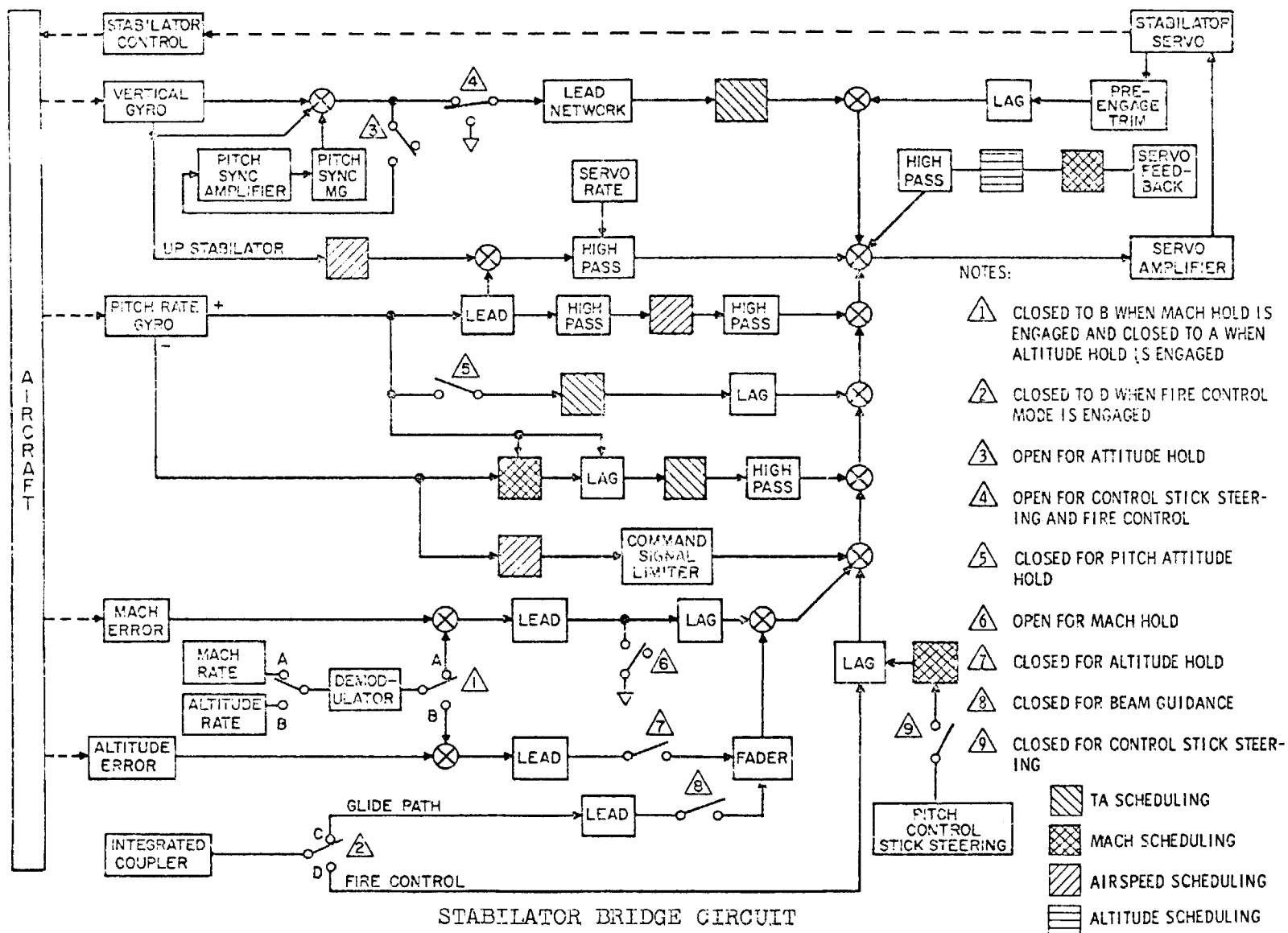


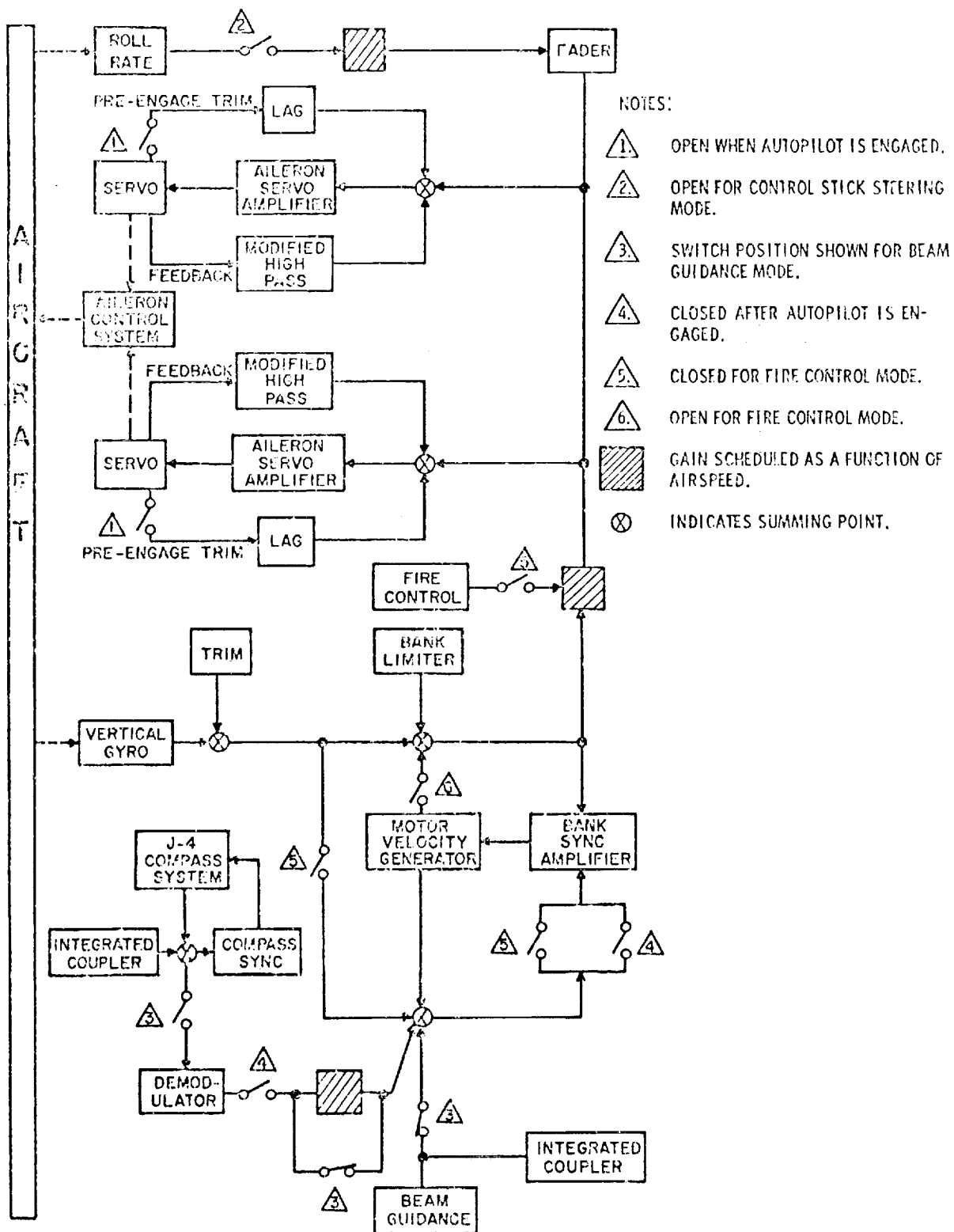
PITCH CHANNEL

F-100 D/F Autopilot



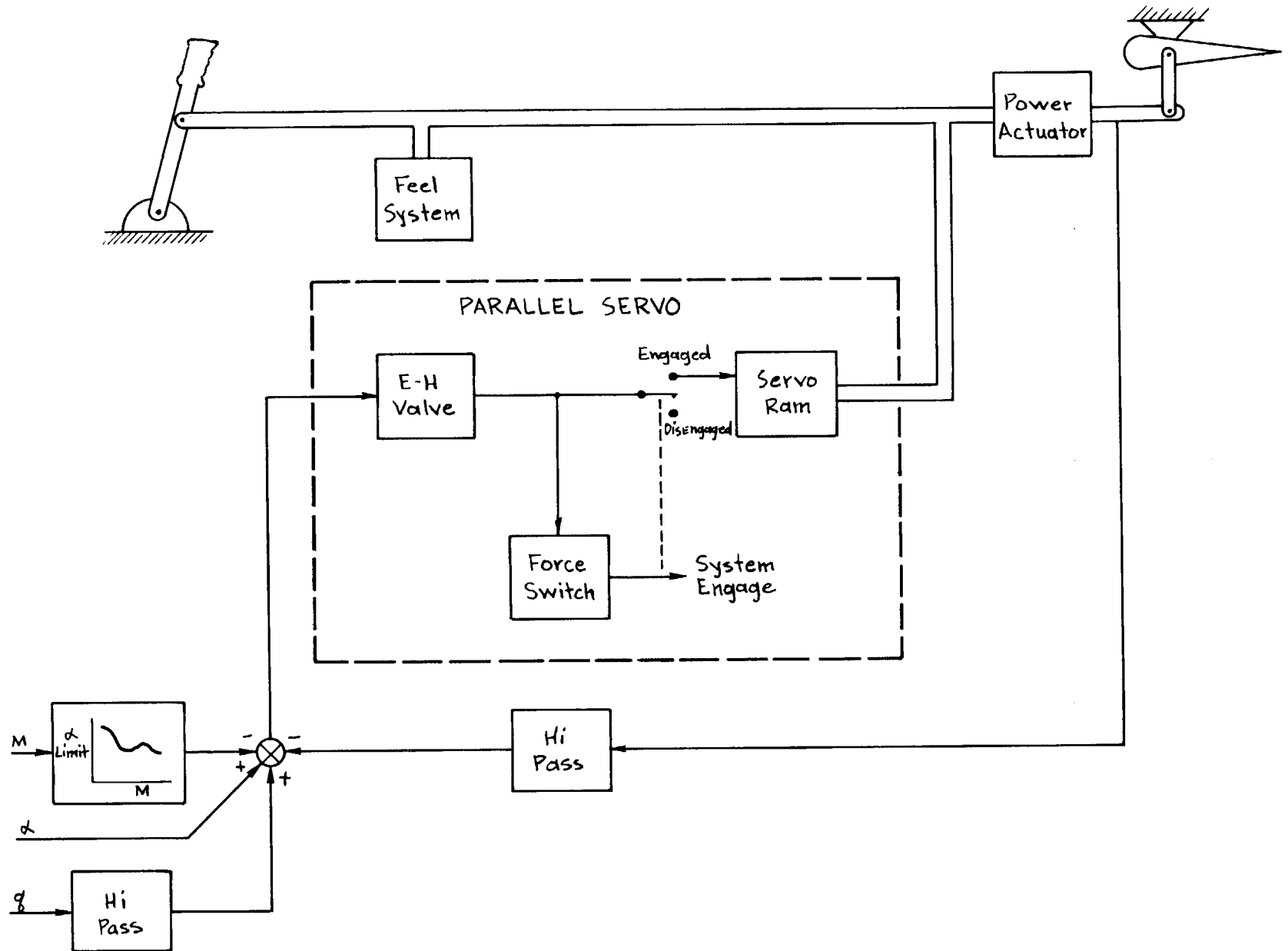






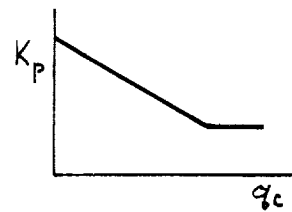
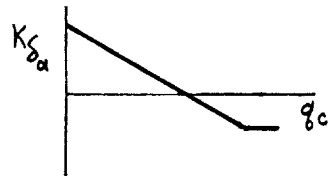
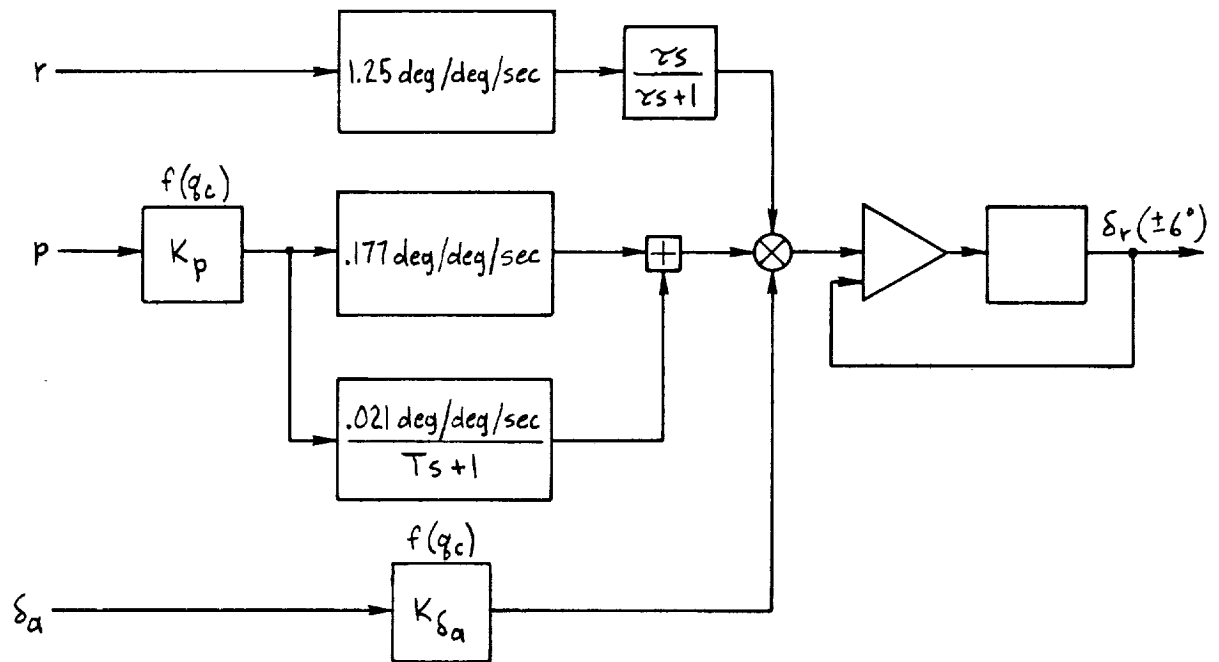
AILERON BRIDGE CIRCUIT

F-101B Autopilot

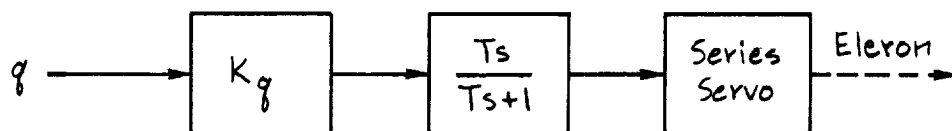


F-101B Stick Pusher

F-102 YAW DAMPER



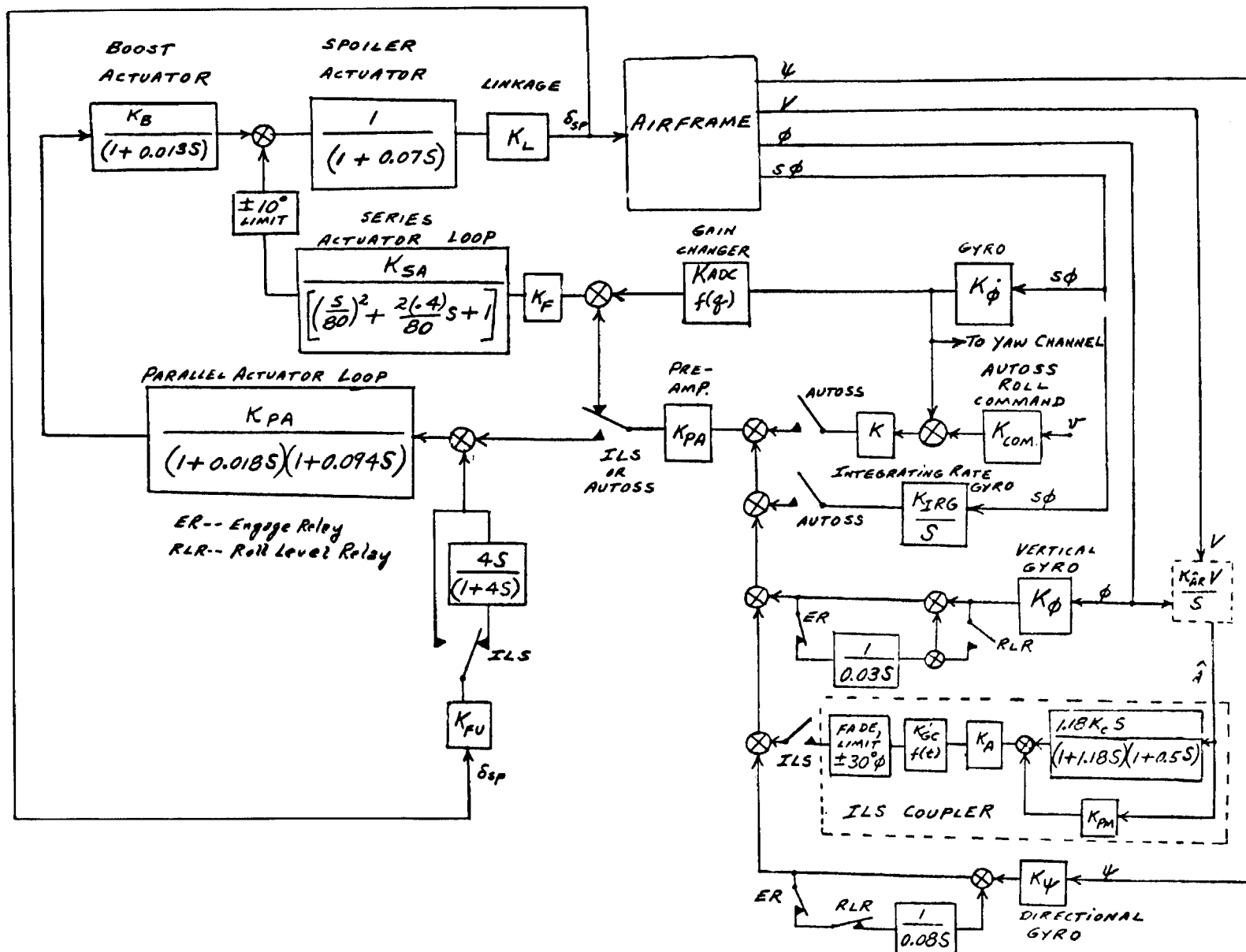
F-102 PITCH DAMPER

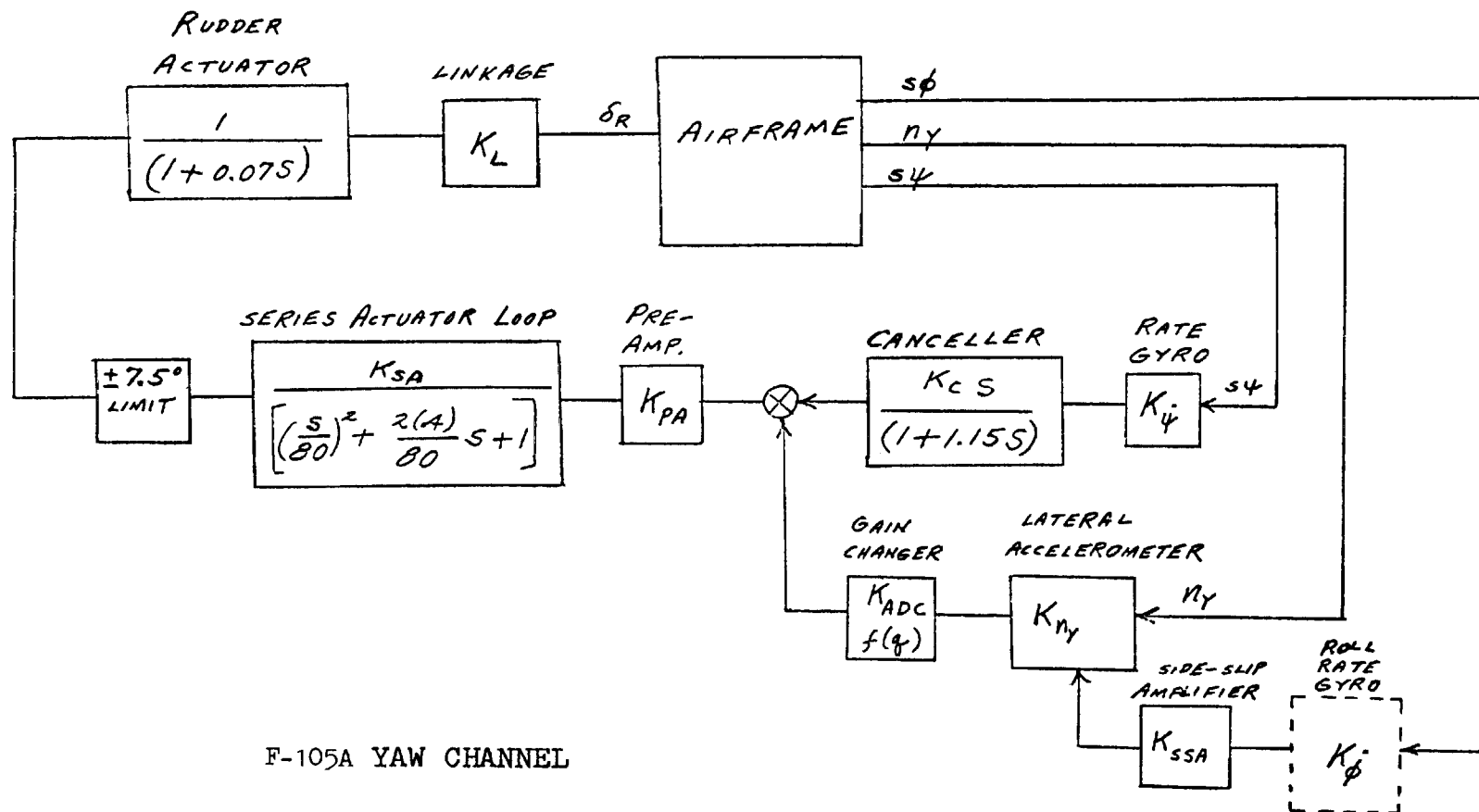


F-102



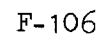
F-105A PITCH CHANNEL



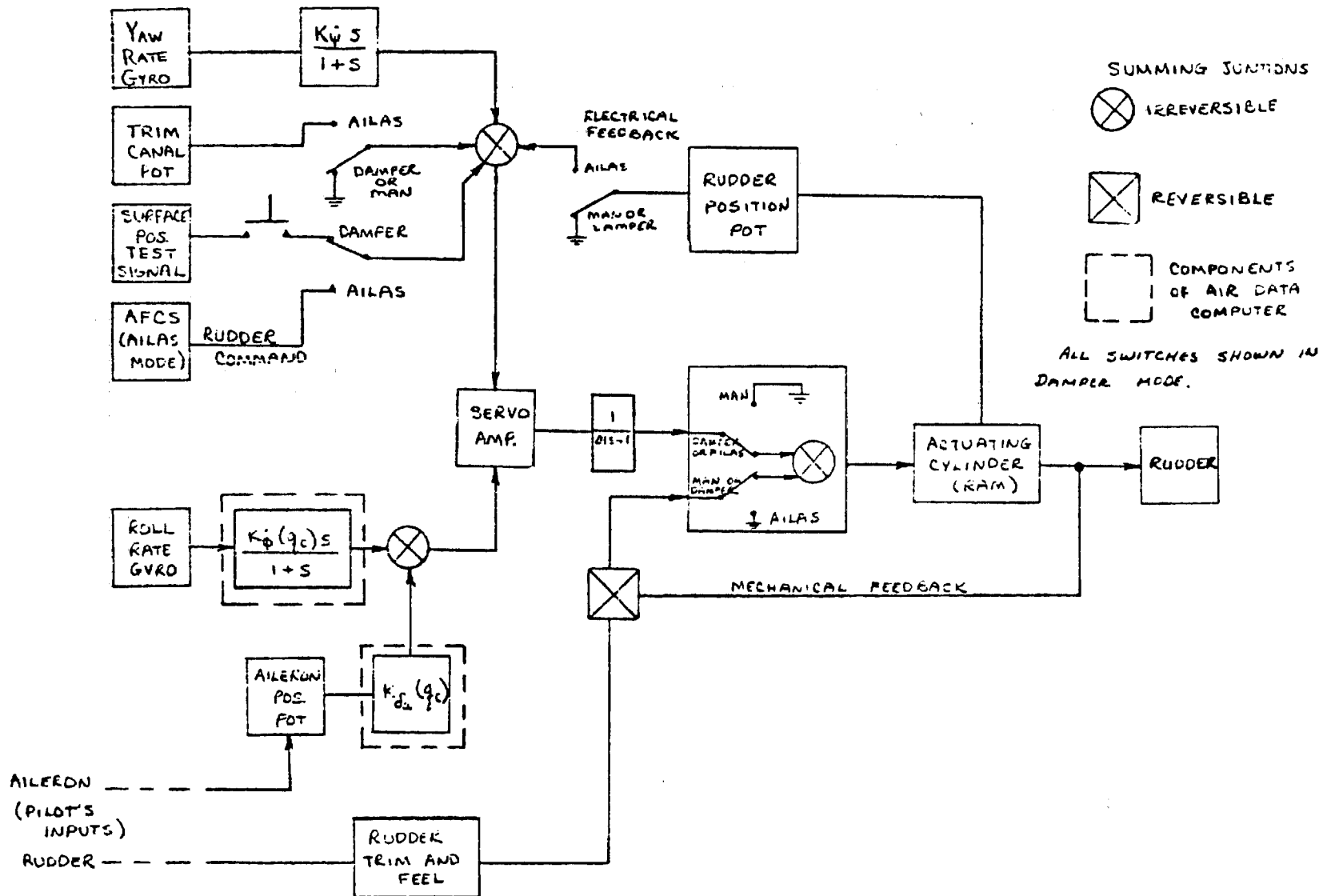


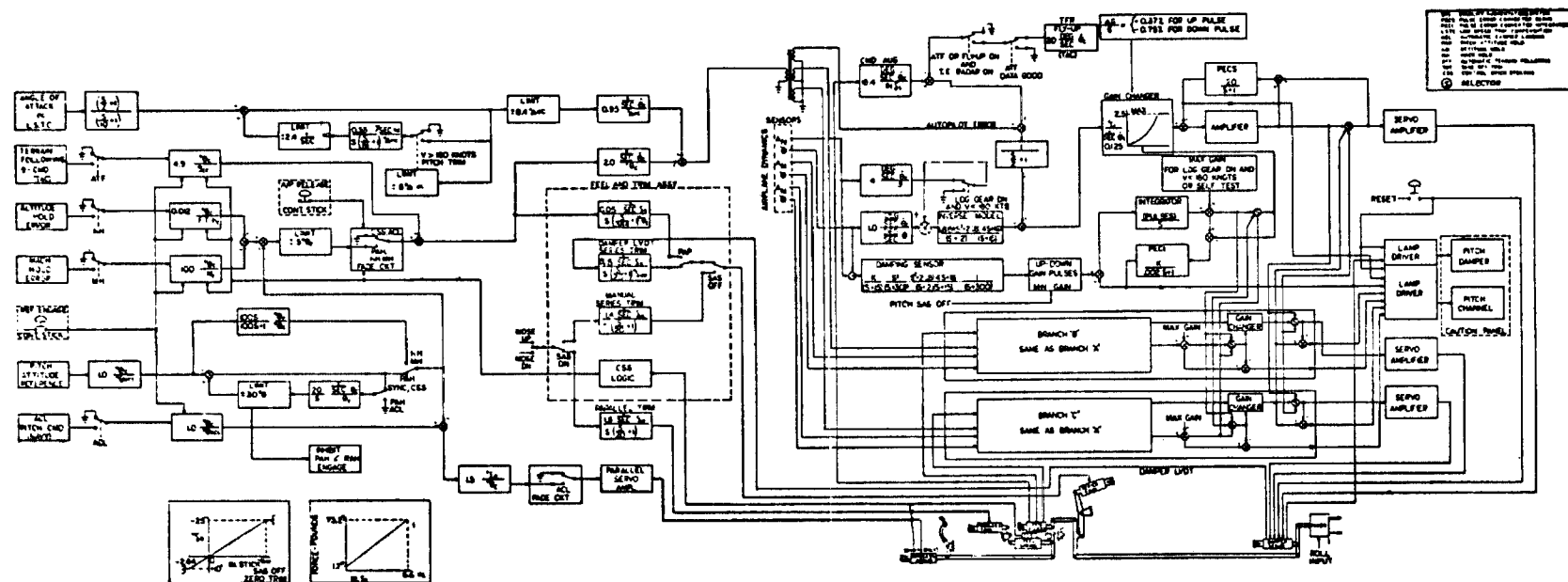
F-105A YAW CHANNEL

82

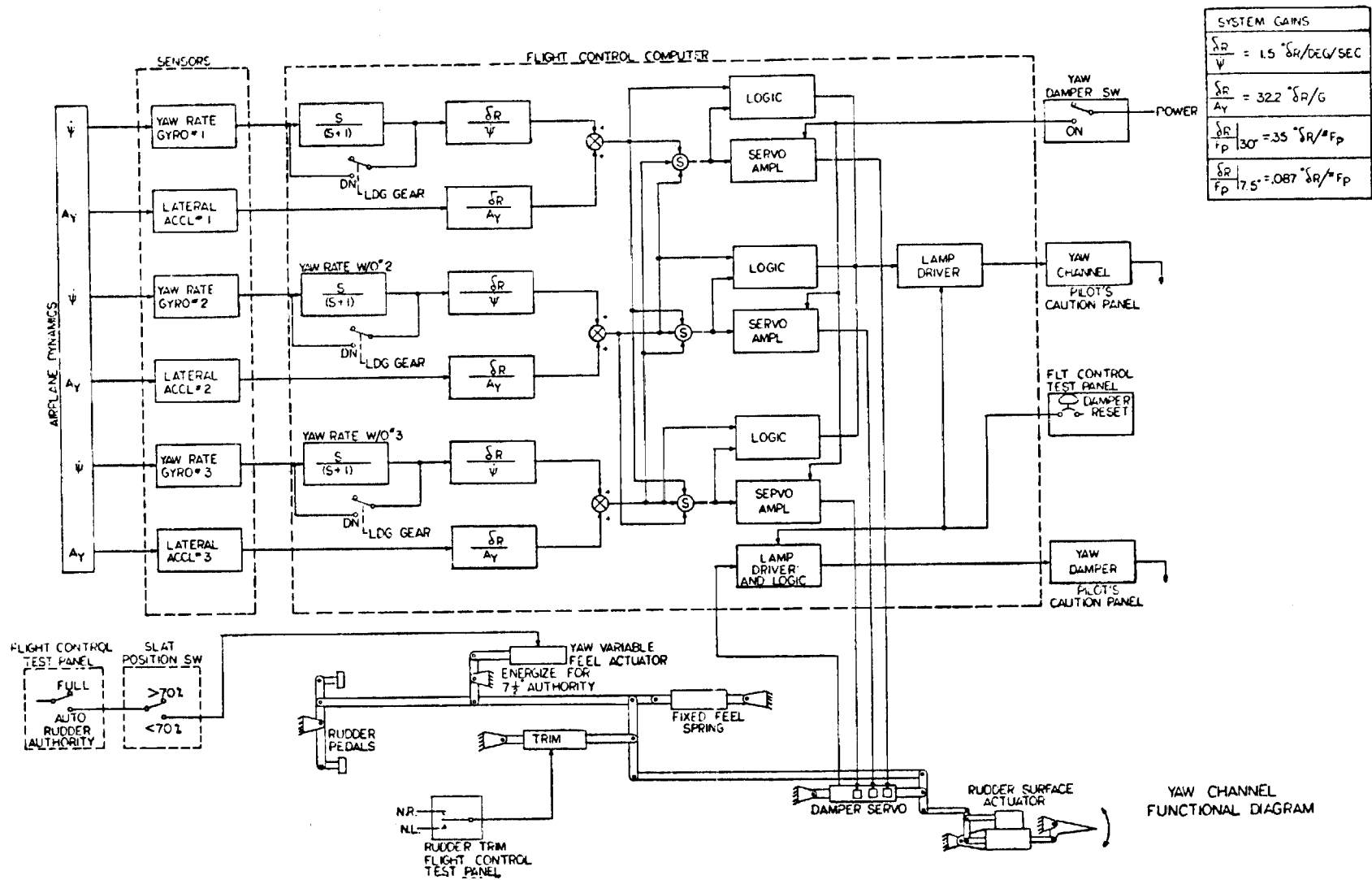


MANUAL MODE, YAW DAMPER AND TURN COORDINATOR MODE, AND AILAS MODE

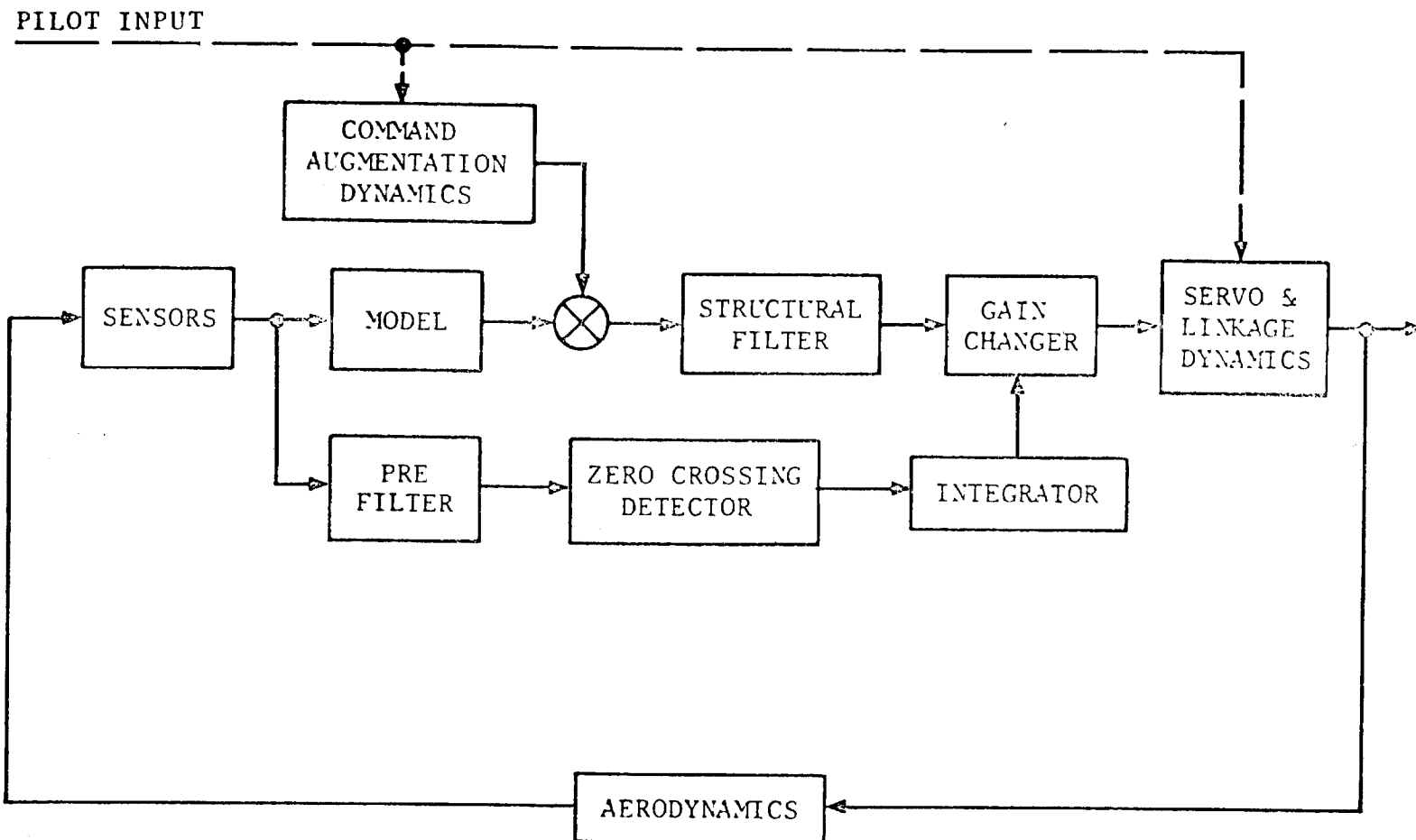




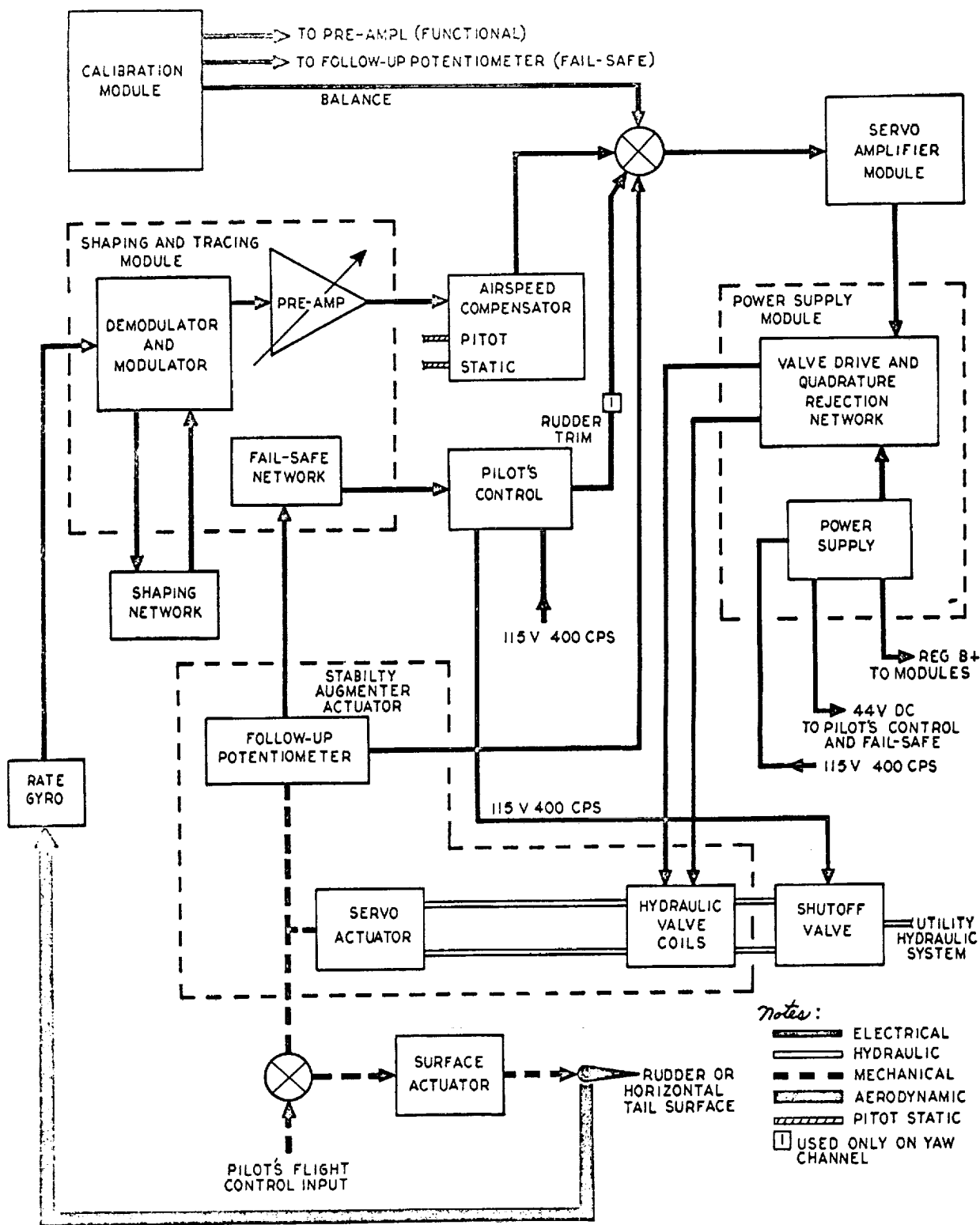
F-111 Pitch Channel Functional Diagram



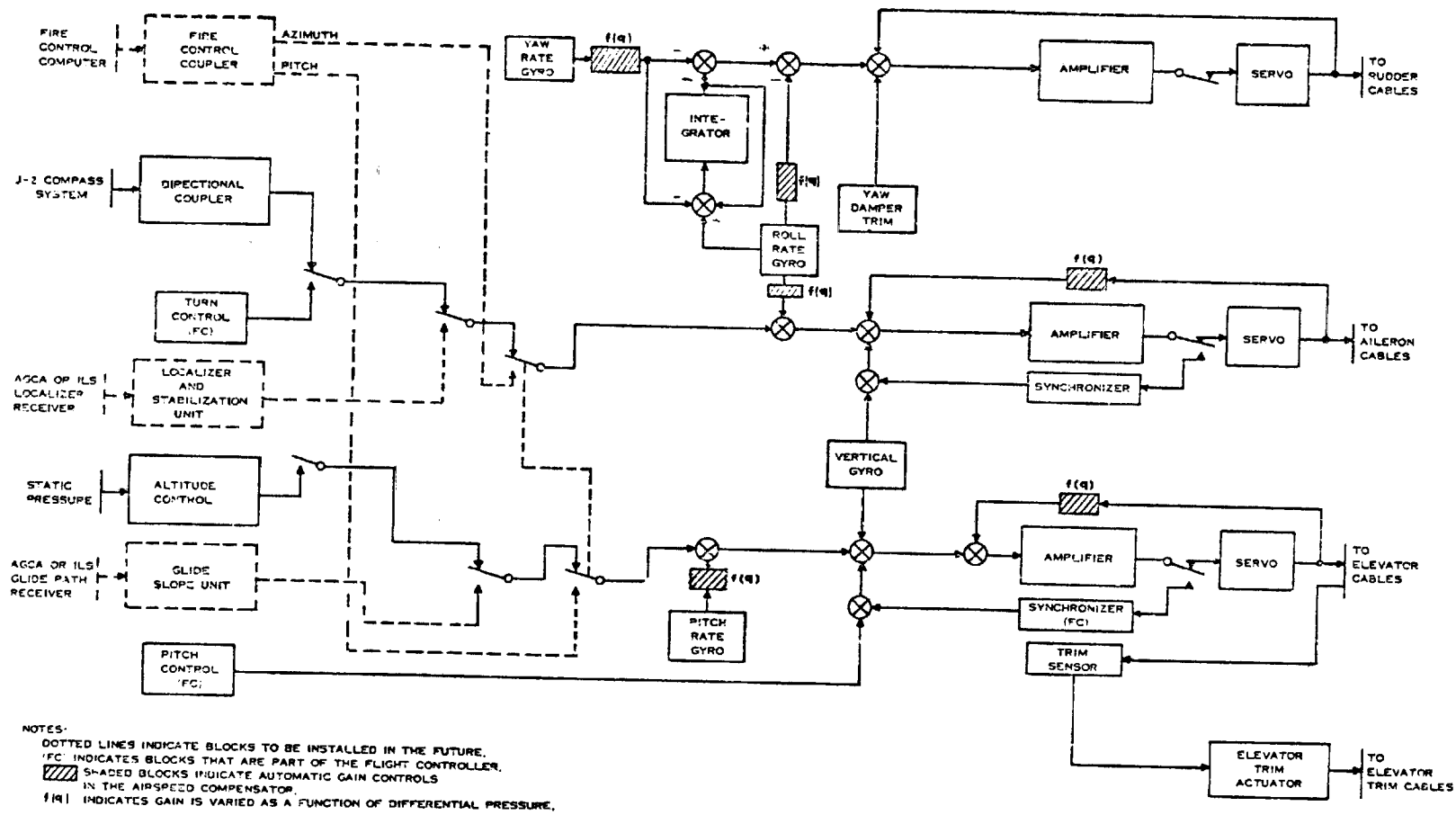
F-111 Yaw Channel Functional Diagram



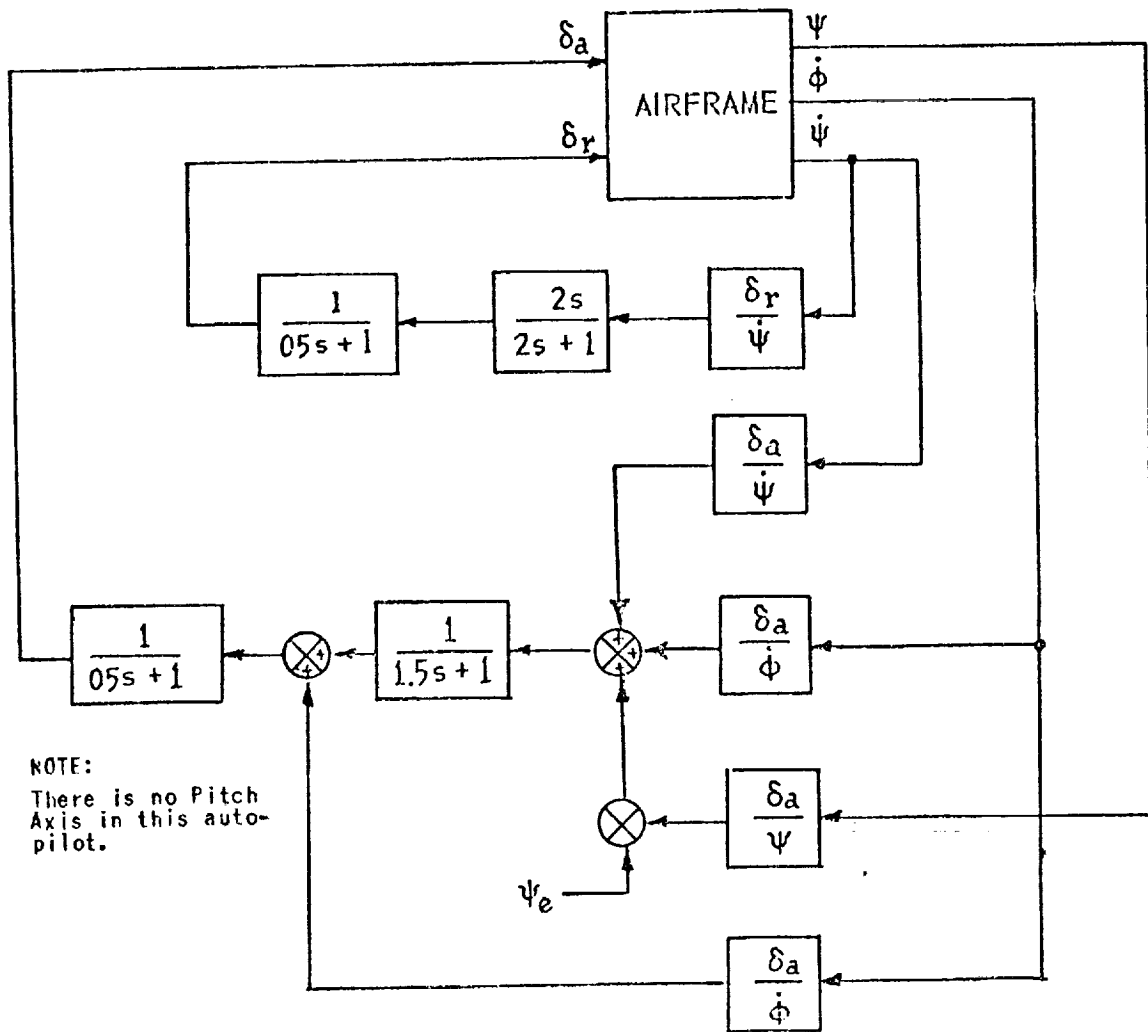
F-111 Adaptive Principle



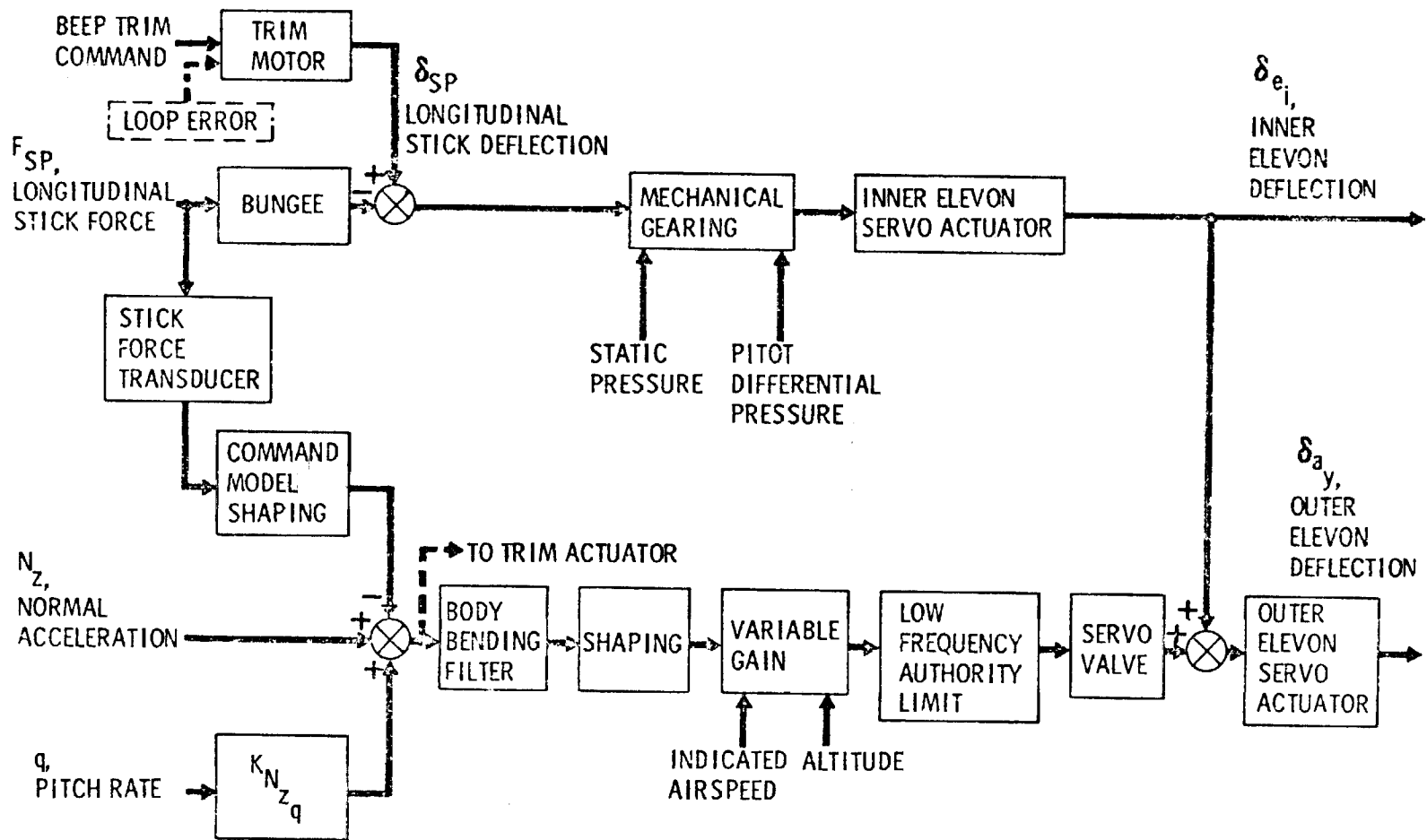
T-38 Stability Augmentation System



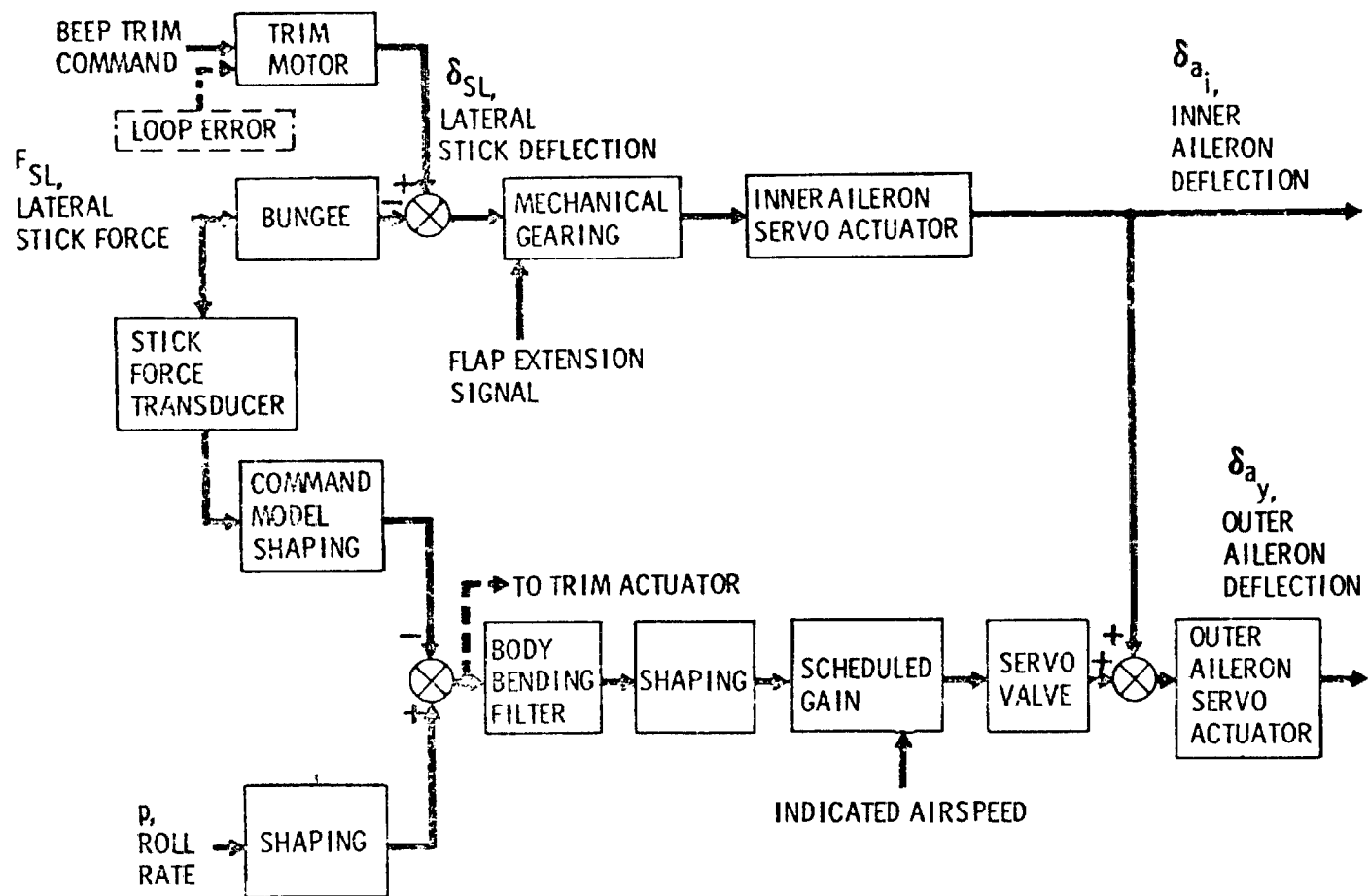
AVRO CF-100 Autopilot



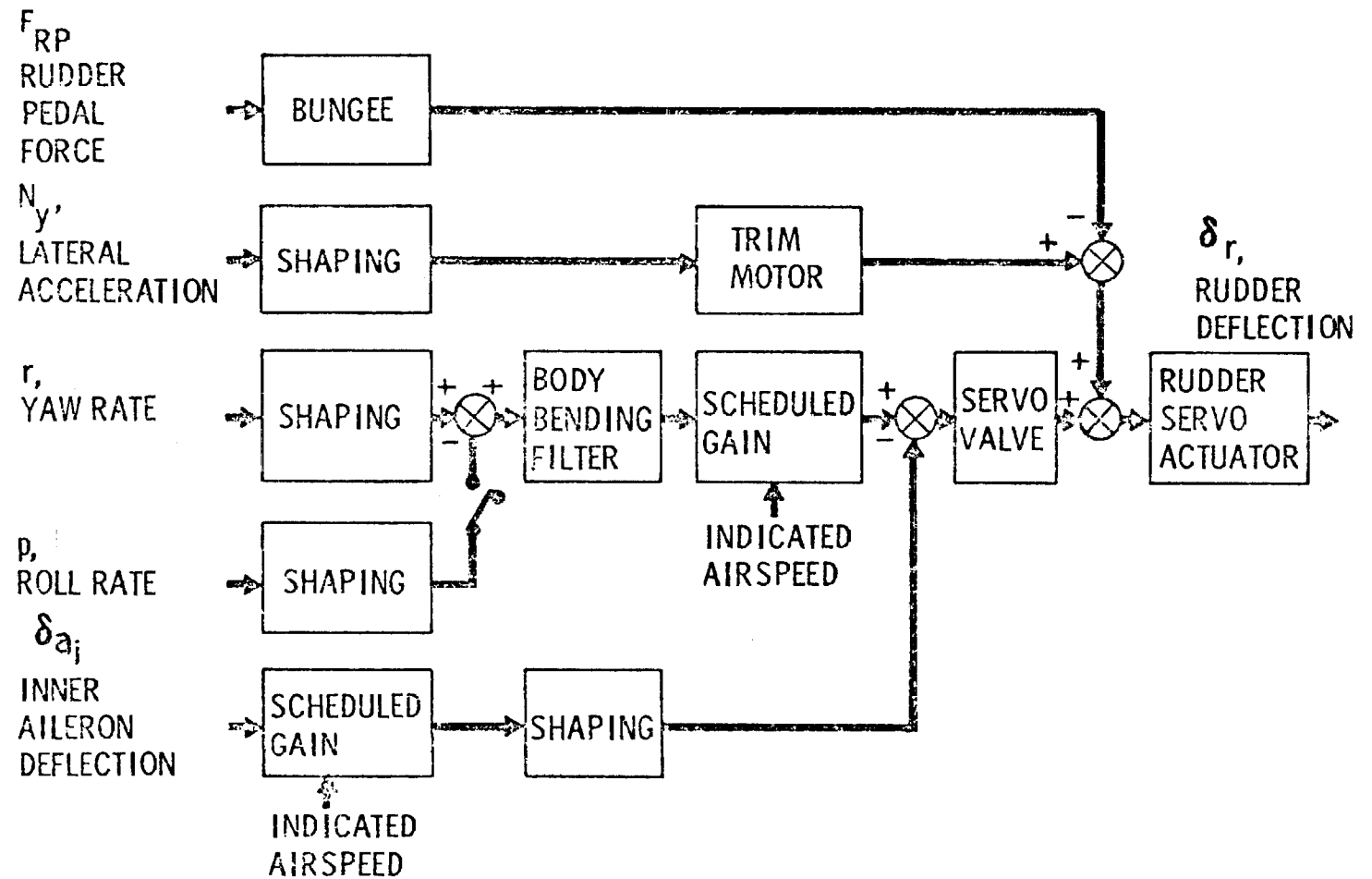
FIAT G-91 Lateral Diagram



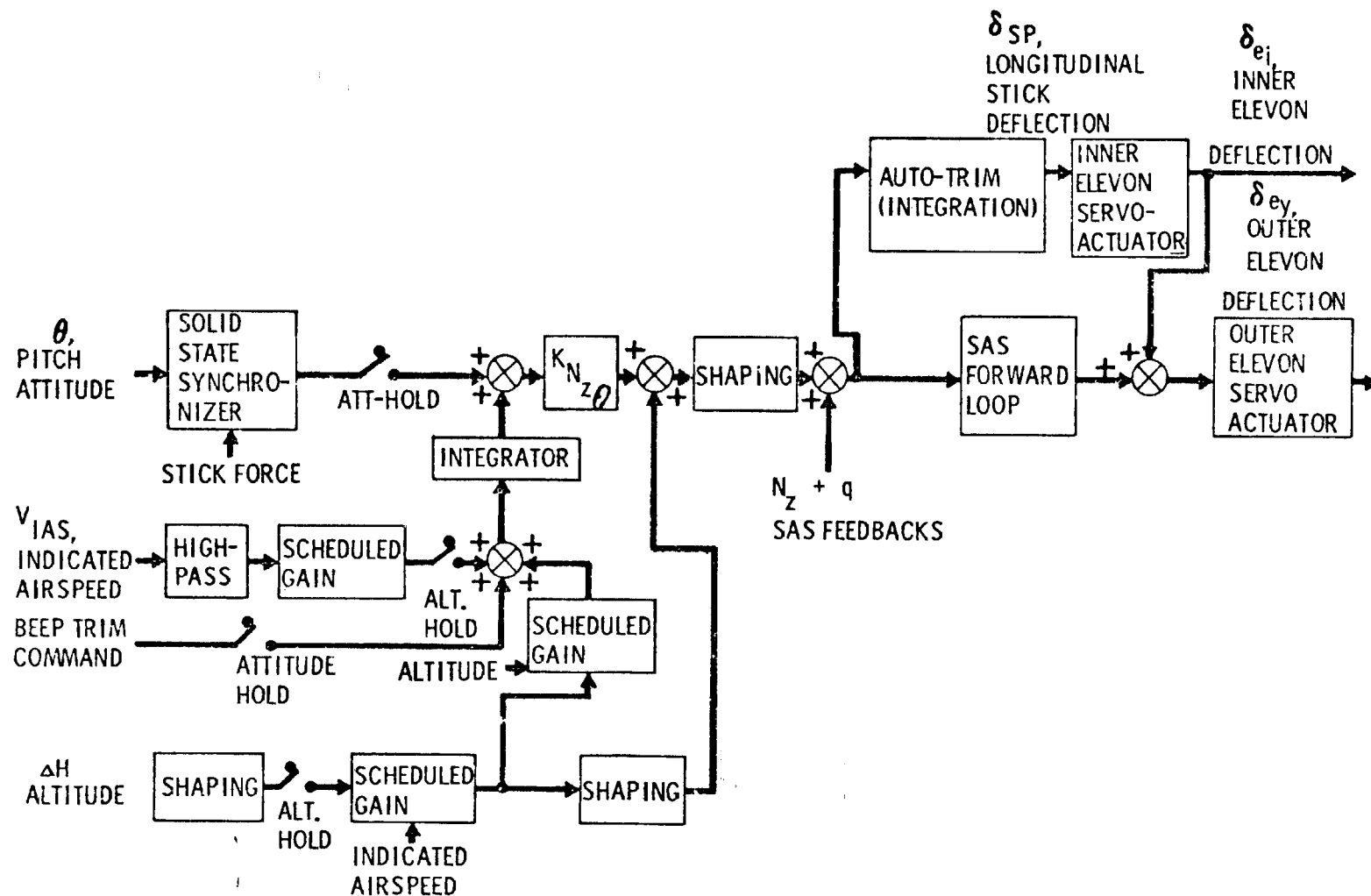
Viggen Pitch Axis Stability Augmentation and Control Stick Steering Mode



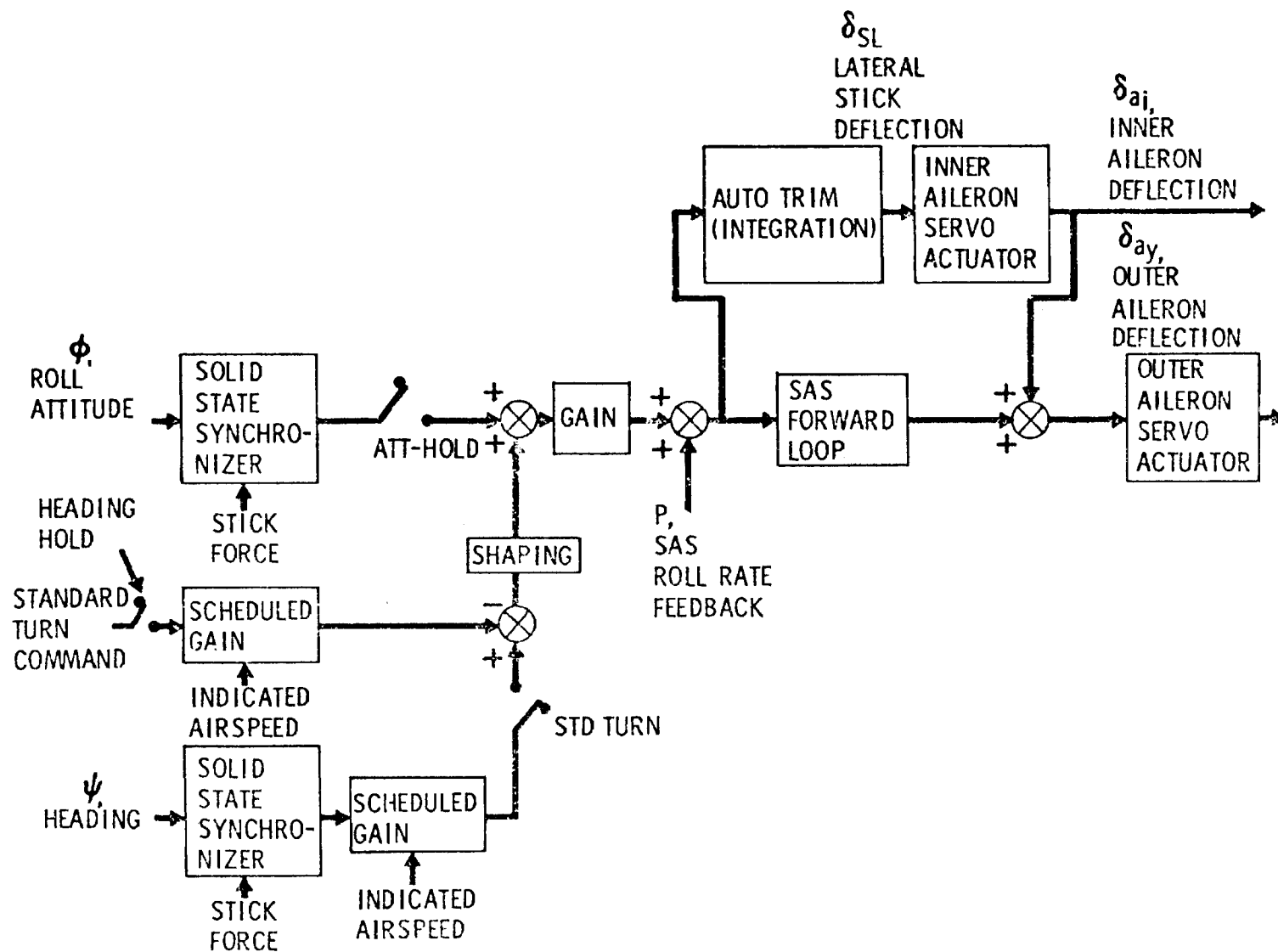
Viggen Roll SAS-CSS Loop



Viggen Yaw Axis Stability Augmentation System

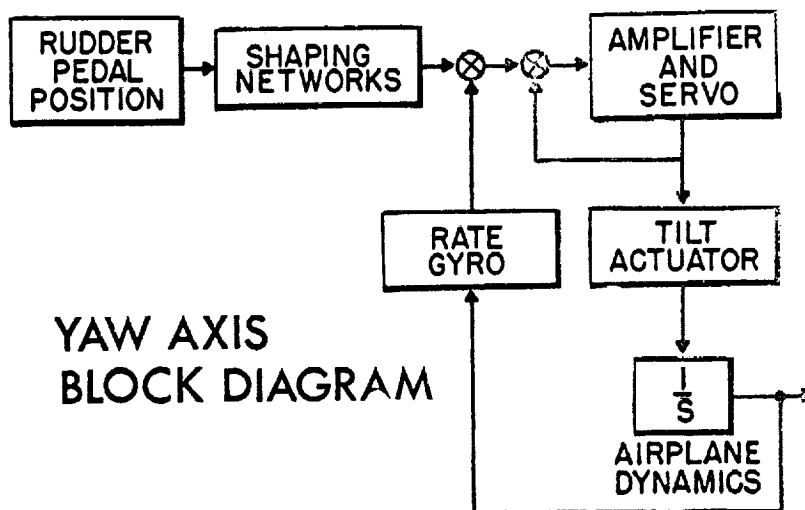
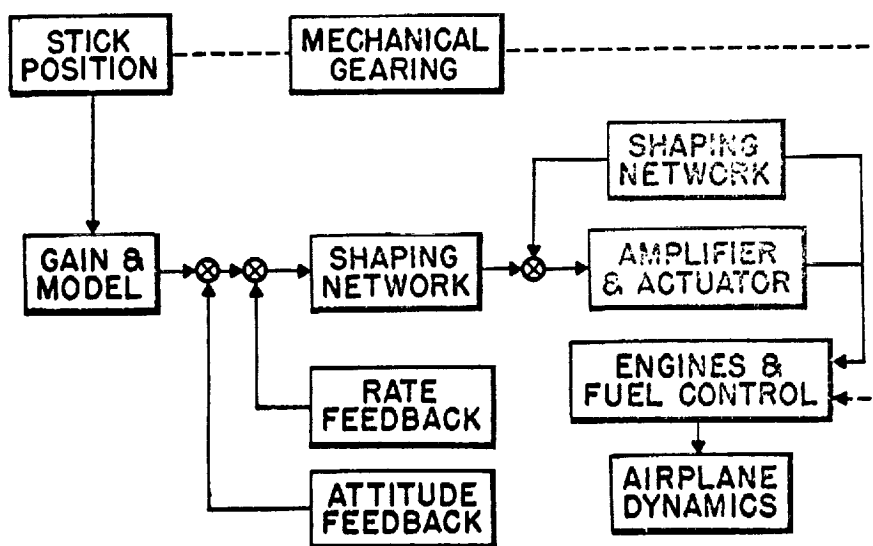


Viggen Pitch Outer Loops

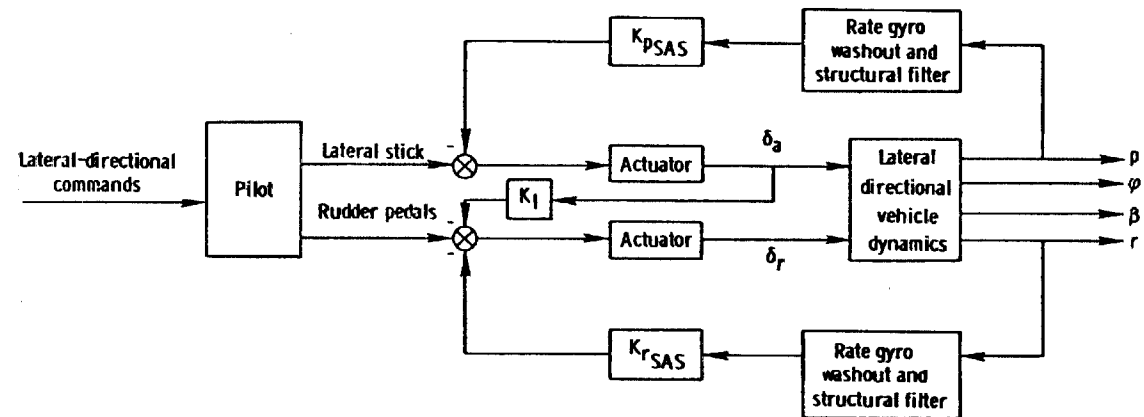


Viggen Lateral Outer Loops

GENERAL BLOCK DIAGRAM FOR ROLL AND PITCH AXES

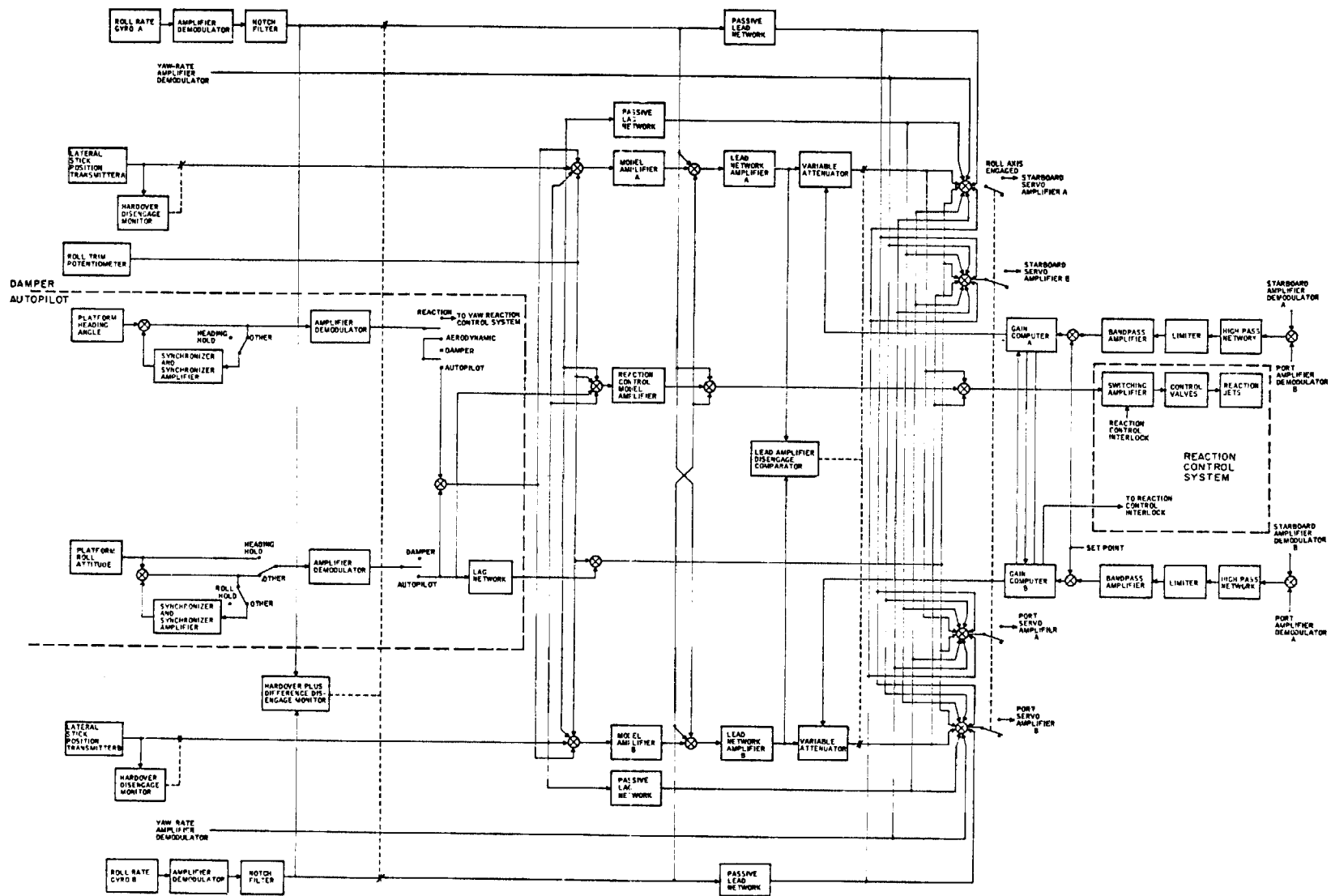


YAW AXIS
BLOCK DIAGRAM

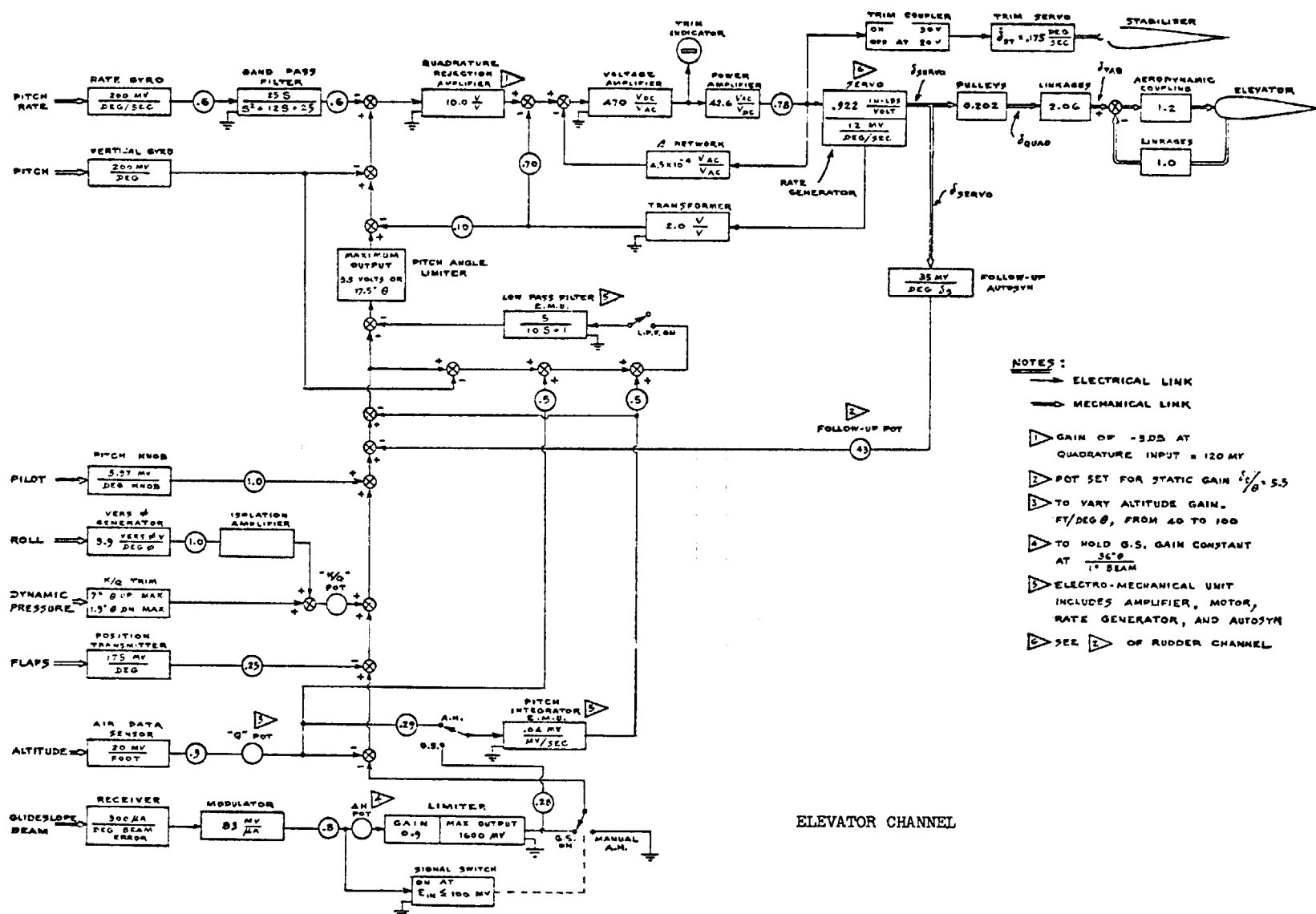


M2-F2 Lateral-Directional Flight Control System

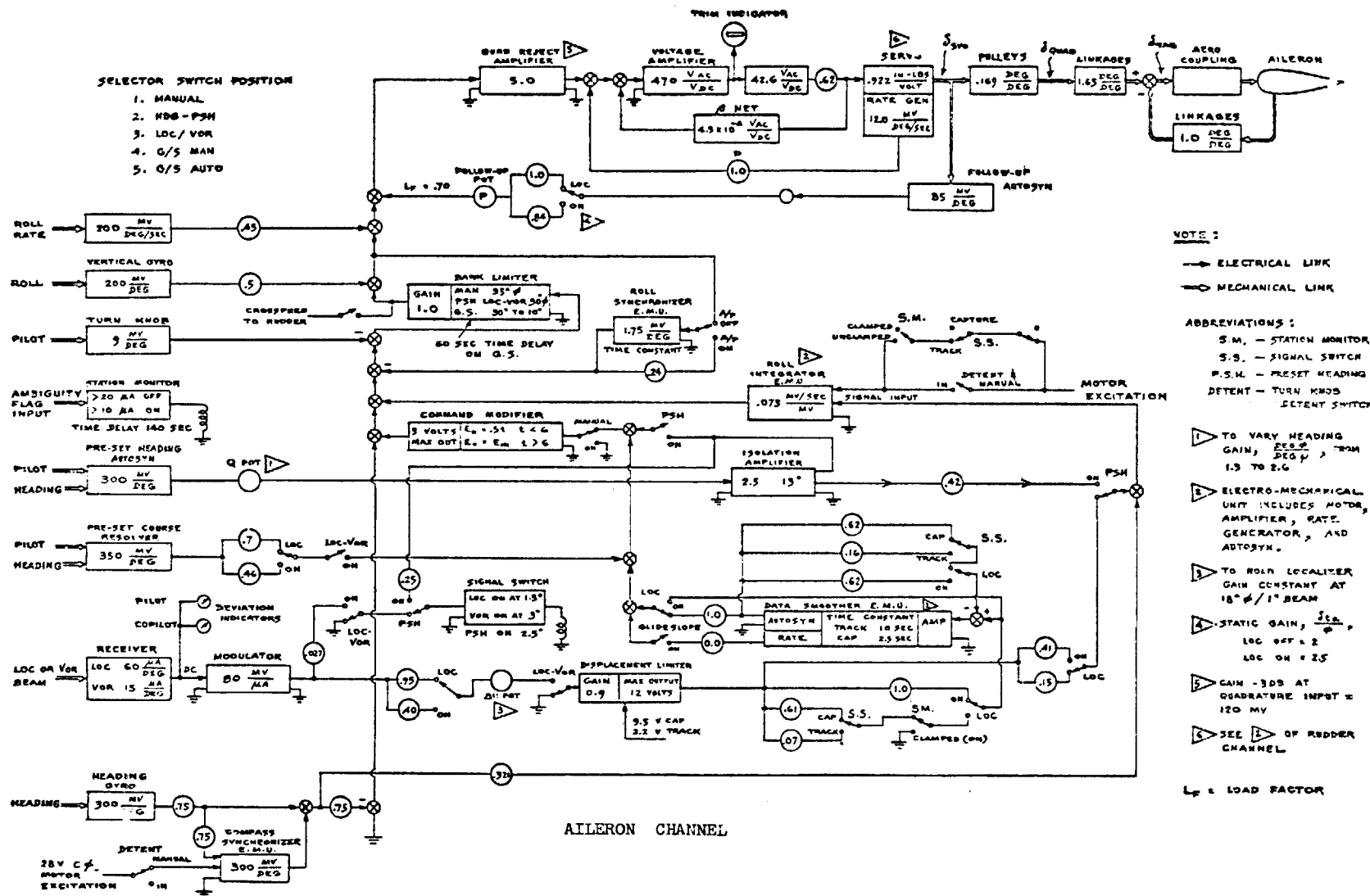
X-15 Pitch Axis Configuration Block Diagram

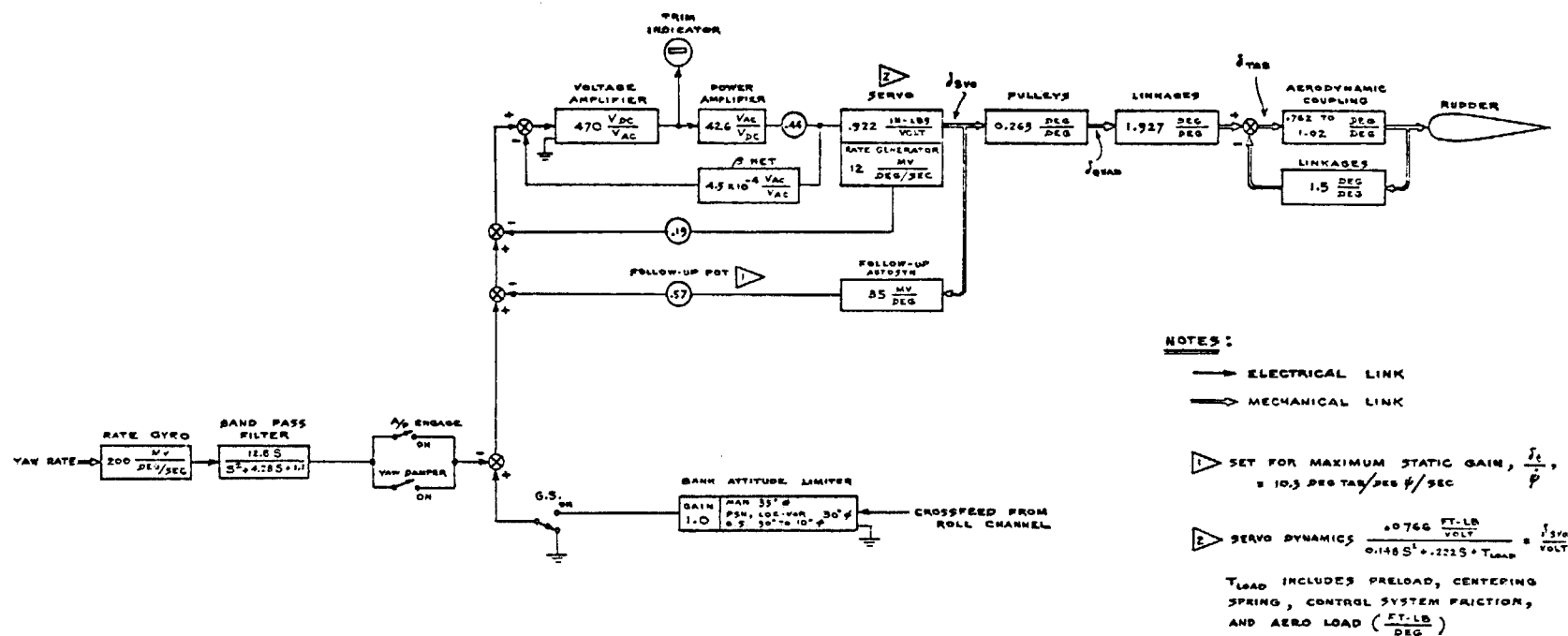


X-15 Roll Axis Configuration



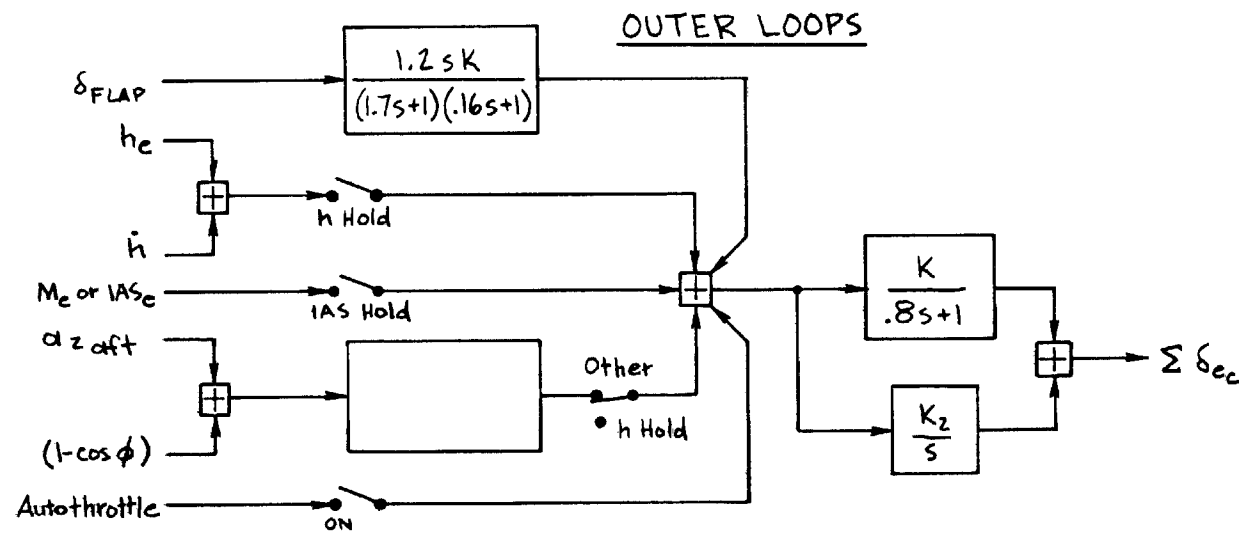
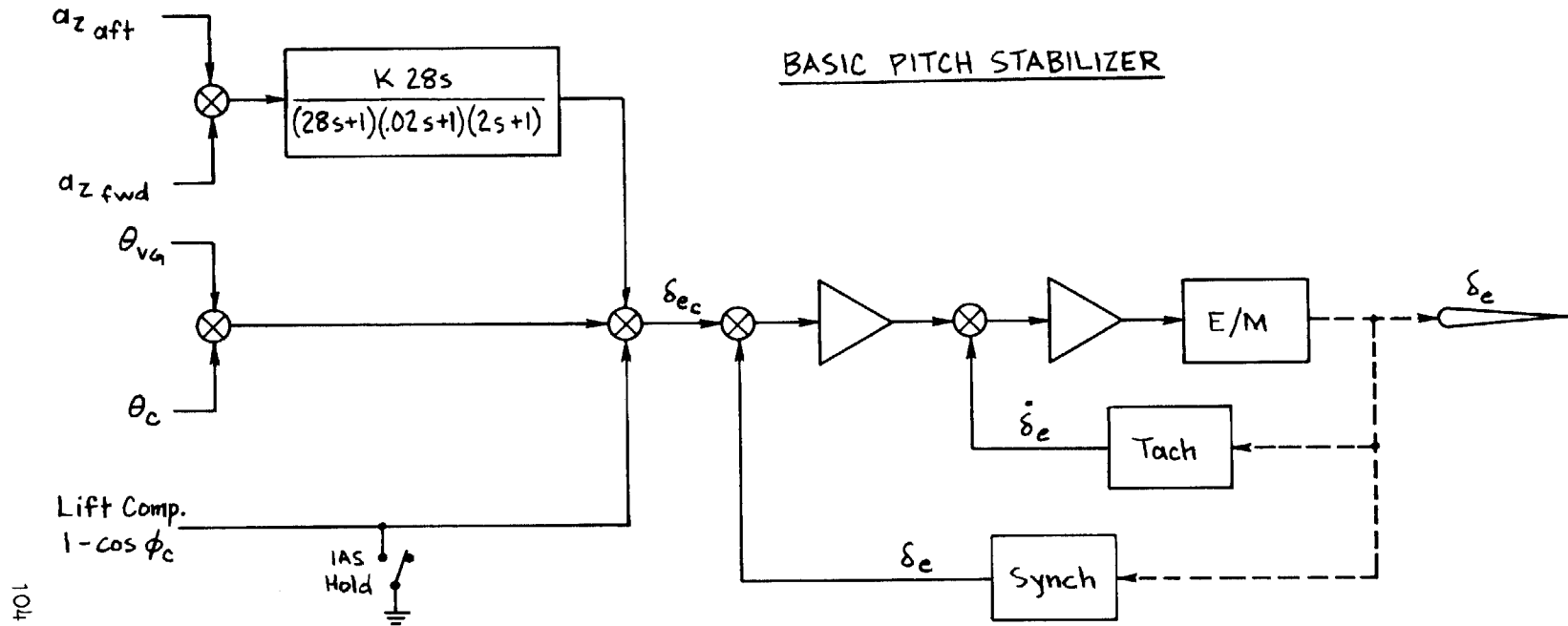
B-707 Autopilot





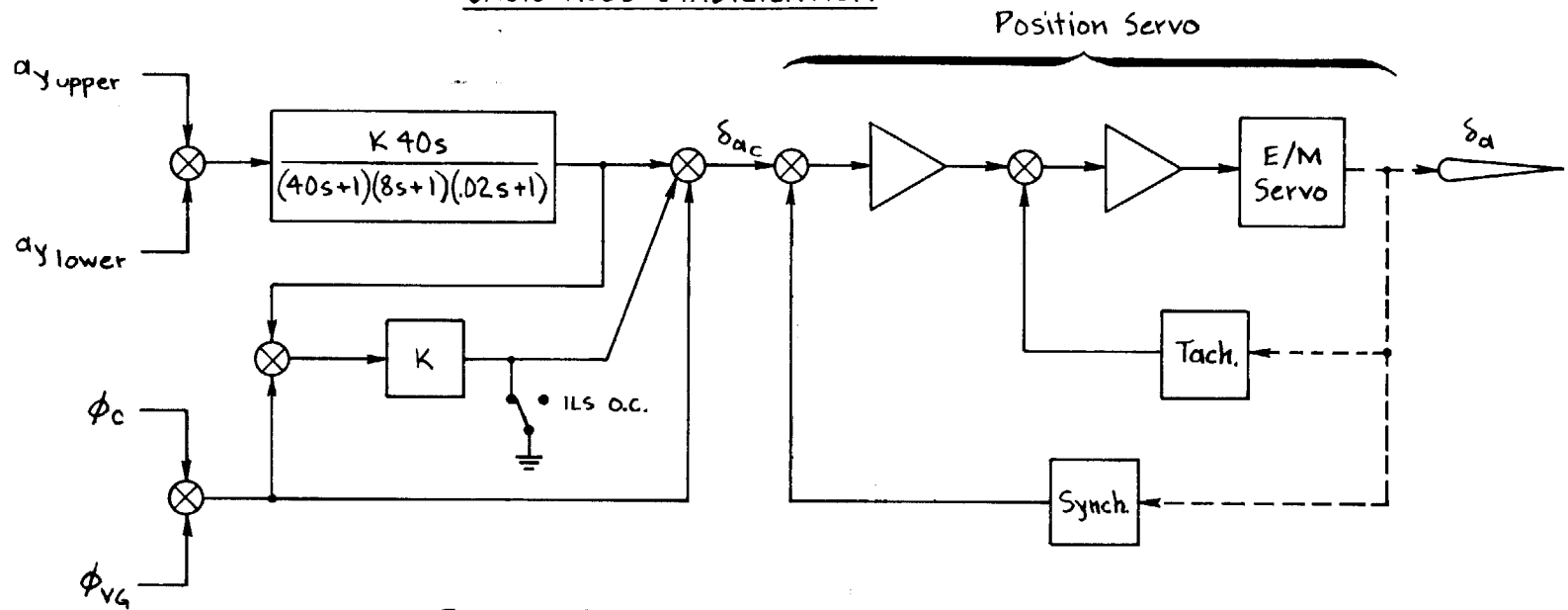
RUDDER CHANNEL

B-707 Autopilot

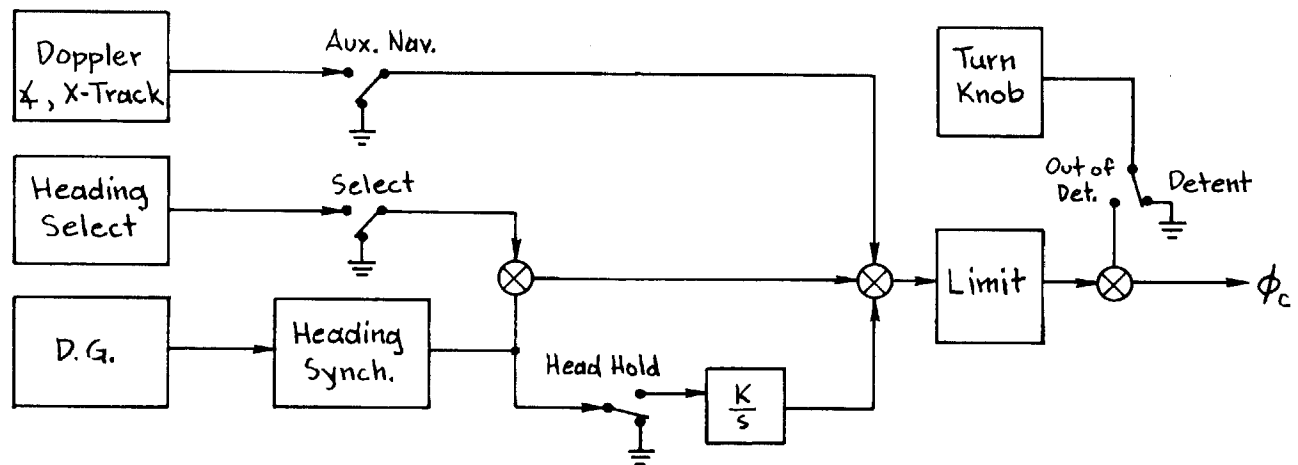


DC-8 Pitch Axis

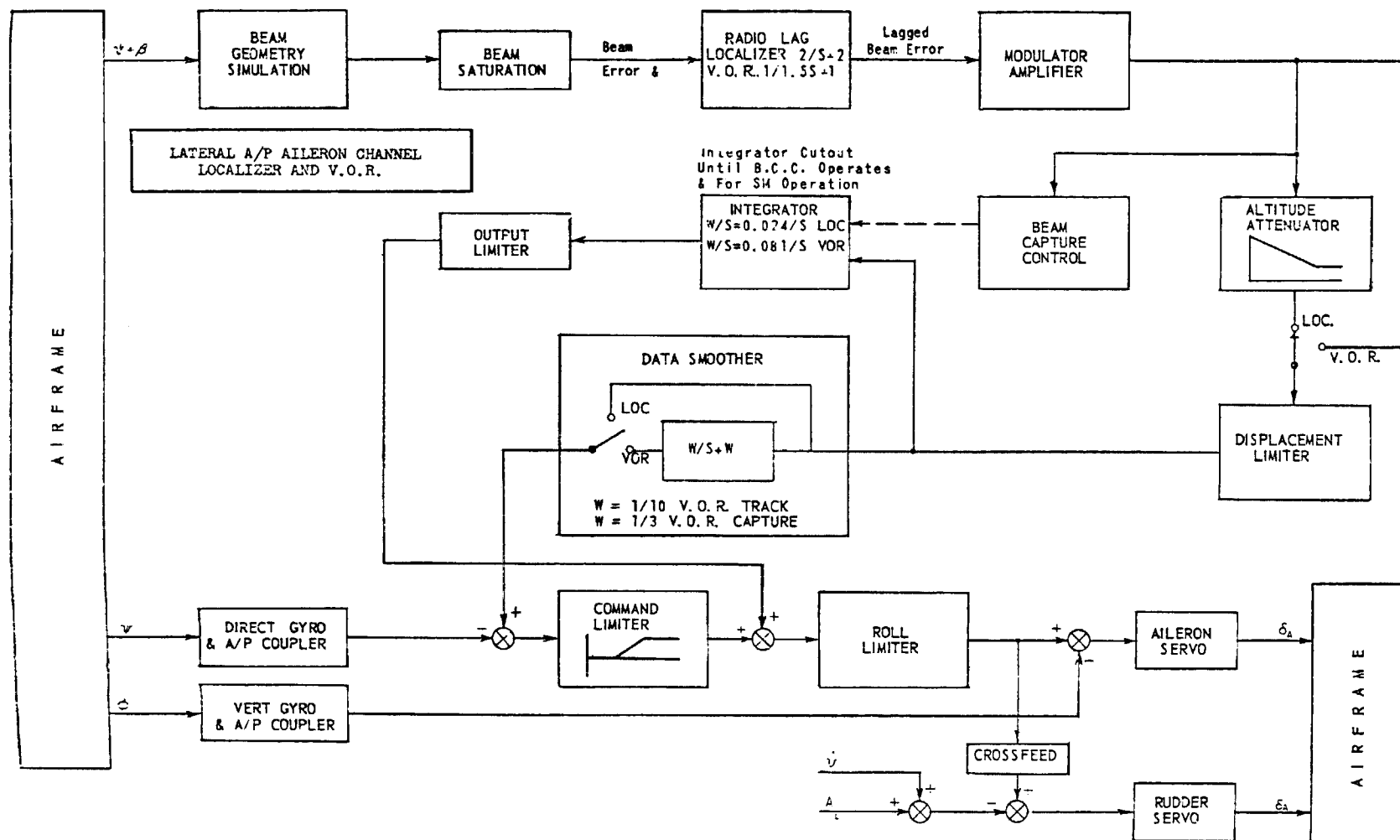
BASIC ROLL STABILIZATION



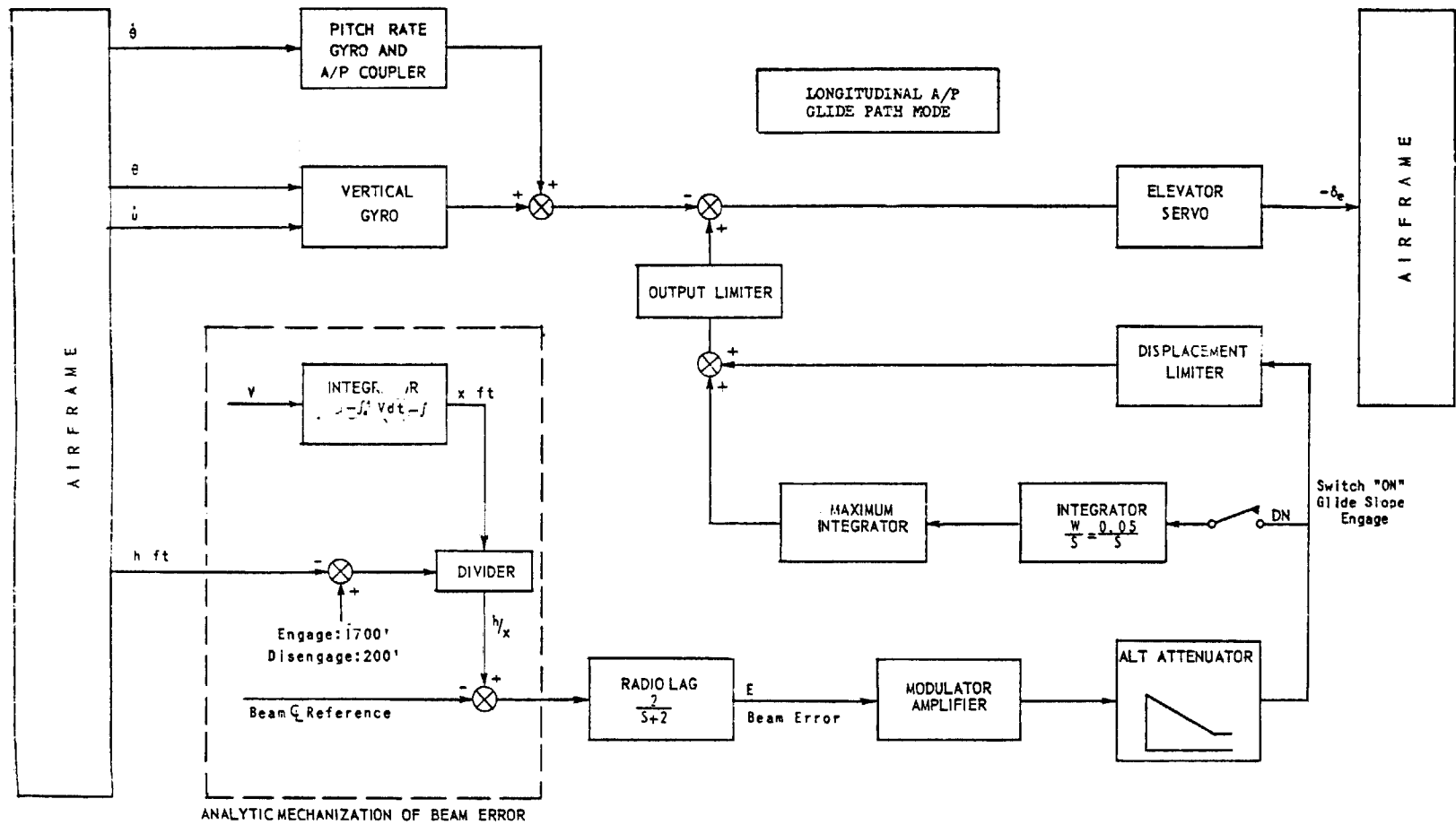
ROLL PATH AND NAV MODES



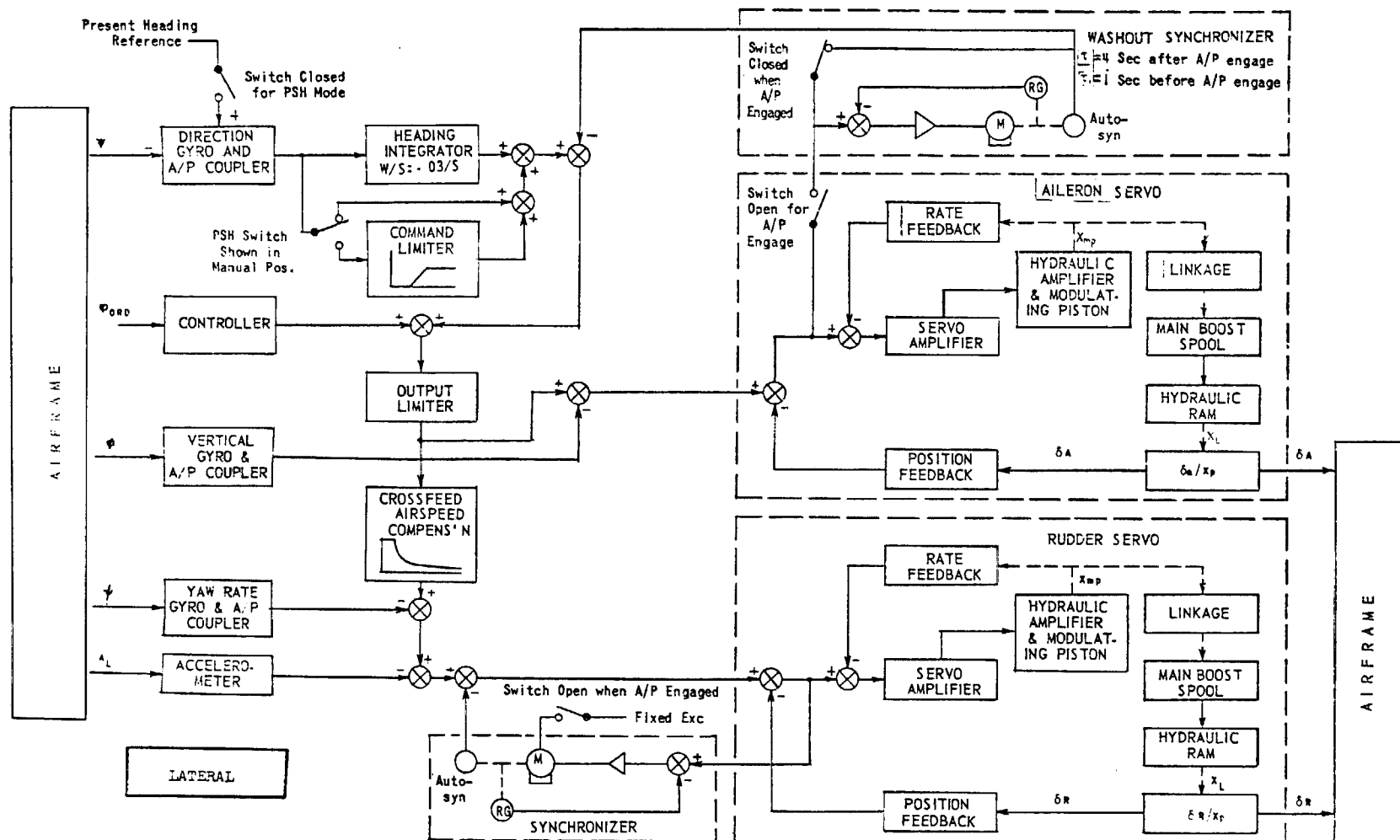
DC-8 Roll Axis



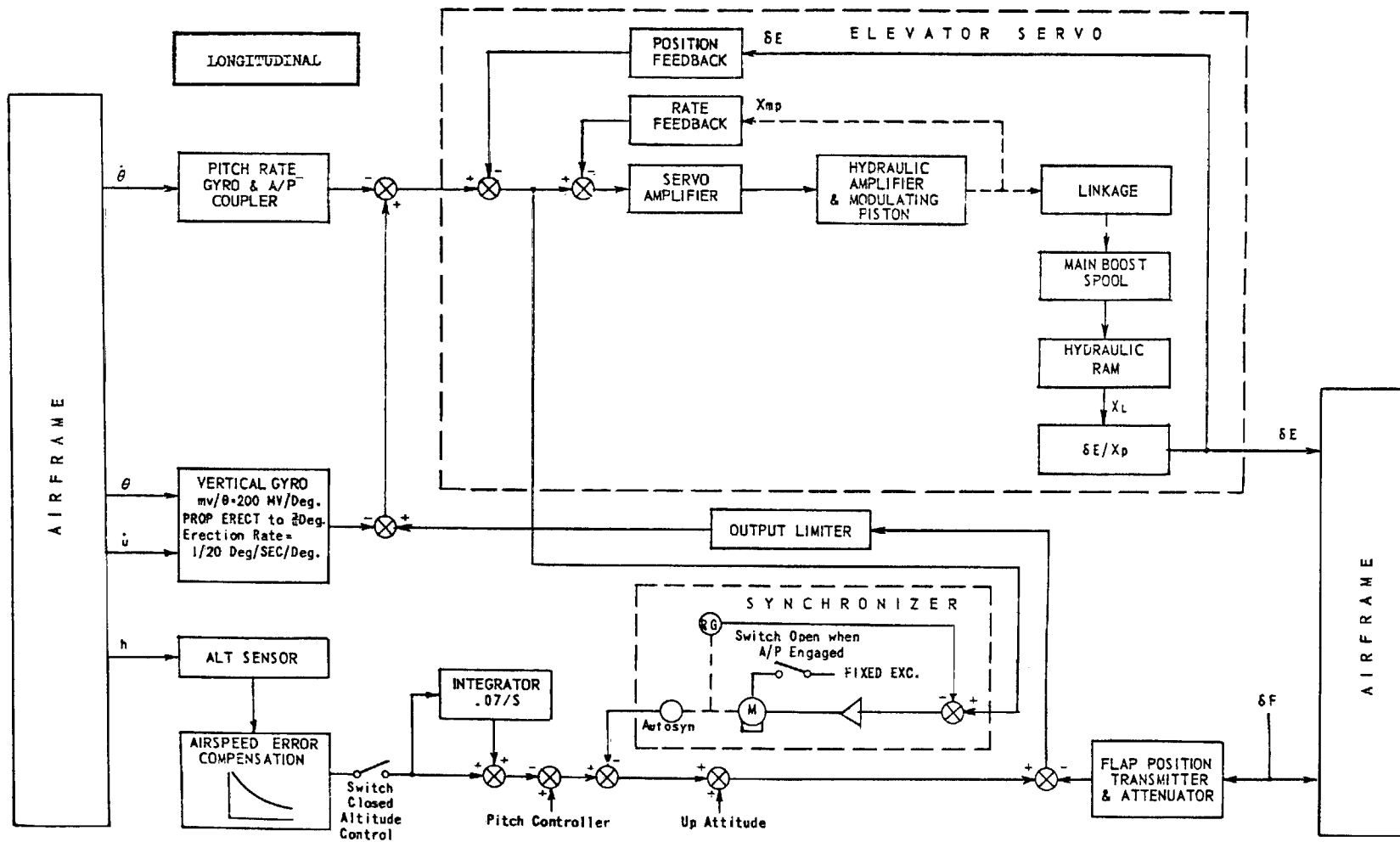
L-188 Autopilot



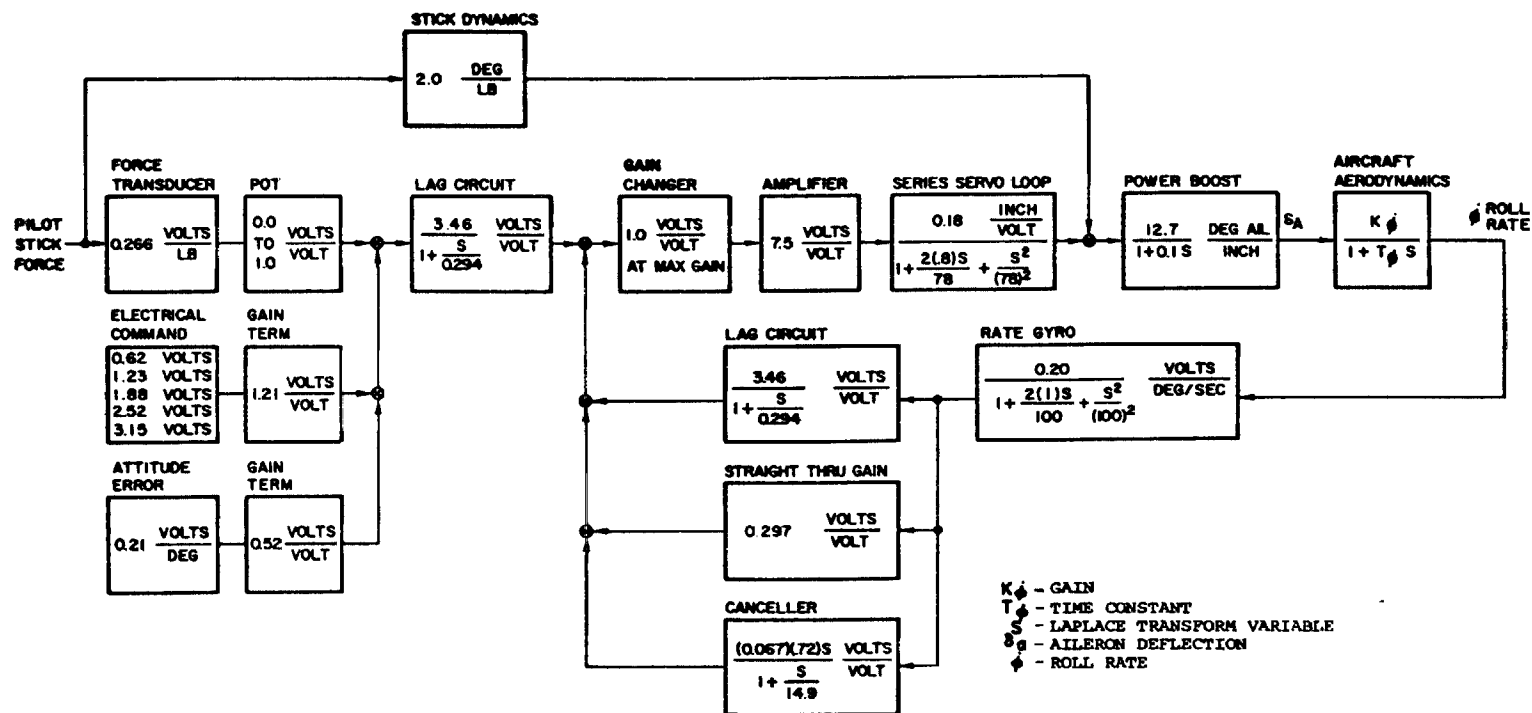
L-188 Autopilot



L-188 Autopilot



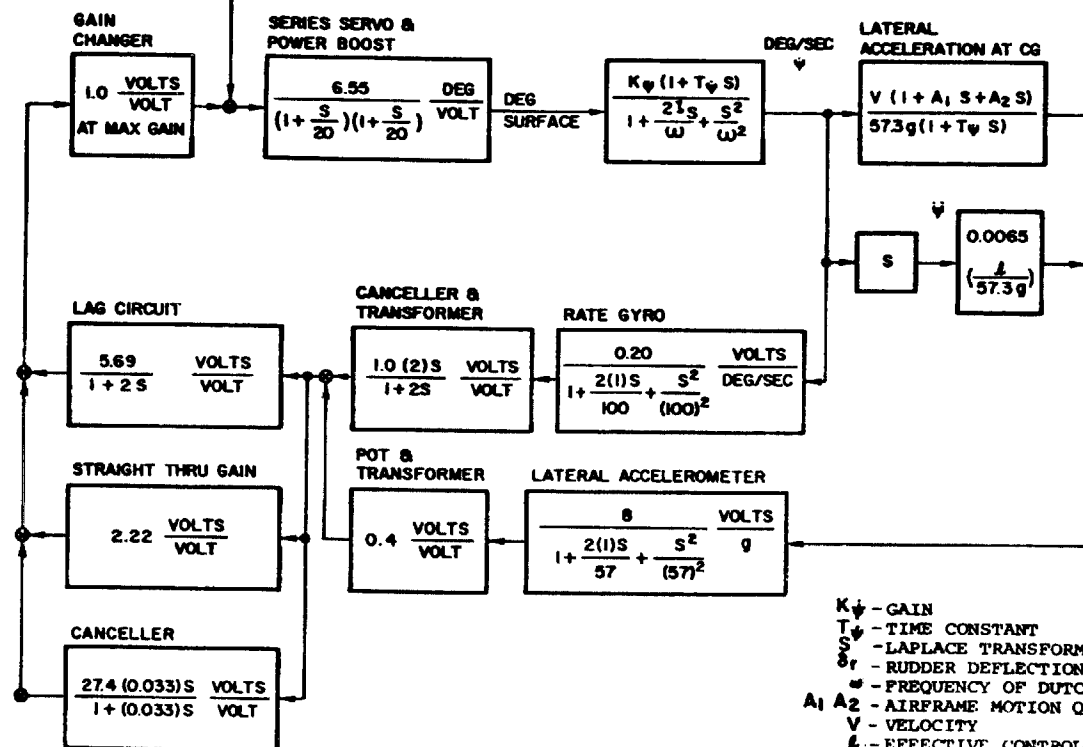
L-188 Autopilot



GESAC Roll Channel (F-4A)

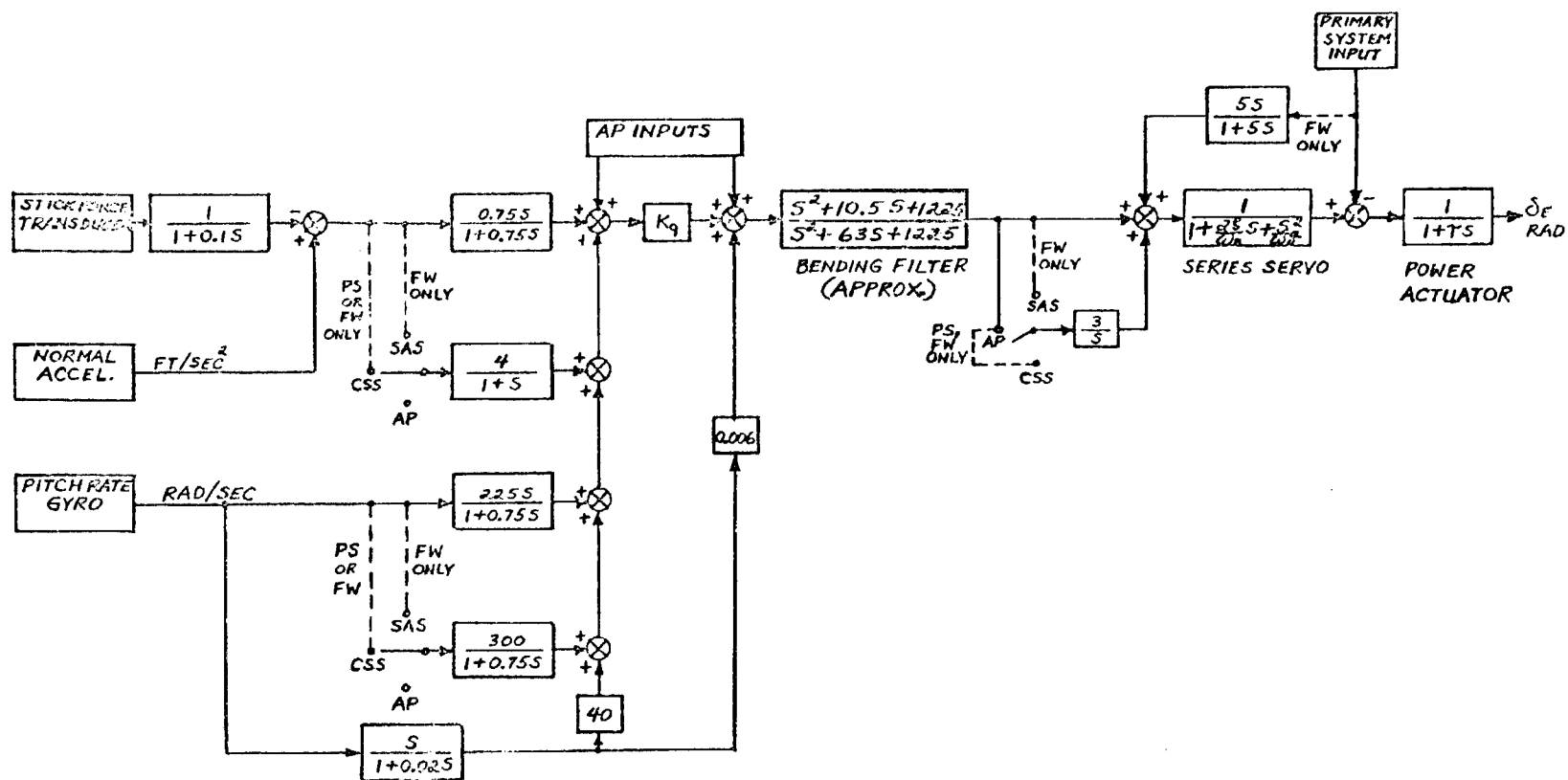
ELECTRICAL BUMP

1 DEG RUD
2 DEG RUD
3 DEG RUD
4 DEG RUD
5 DEG RUD

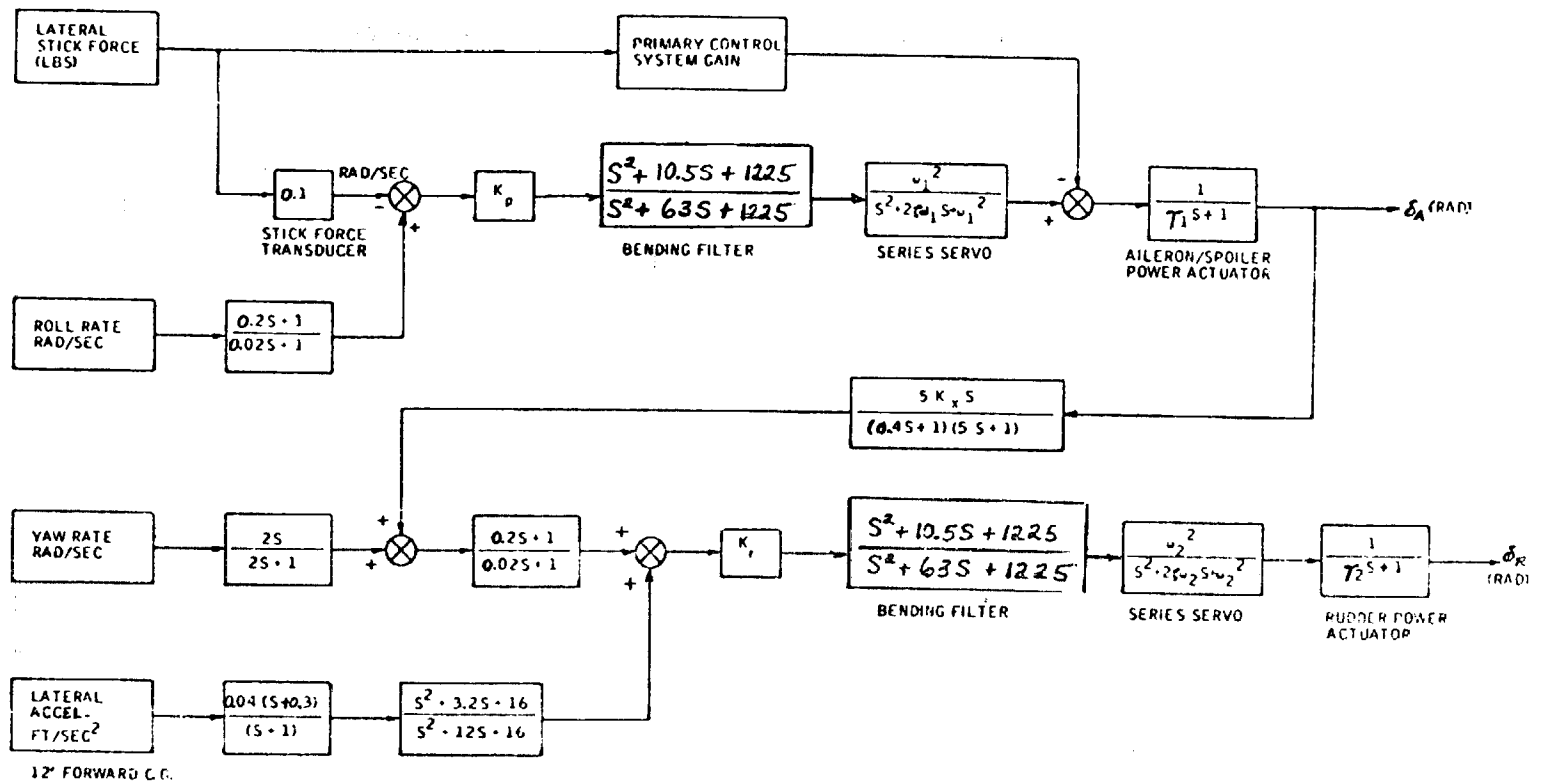


K_ψ - GAIN
 T_ψ - TIME CONSTANT
 s - LAPLACE TRANSFORM VARIABLE
 δ_r - RUDDER DEFLECTION
 ω - FREQUENCY OF DUTCH ROLL MODE
 $A_1 A_2$ - AIRFRAME MOTION QUANTITY
 V - VELOCITY
 l - EFFECTIVE CONTROL MOMENT ARM FROM CG
 $\dot{\psi}$ - YAW RATE
 $\ddot{\psi}$ - YAW ACCELERATION

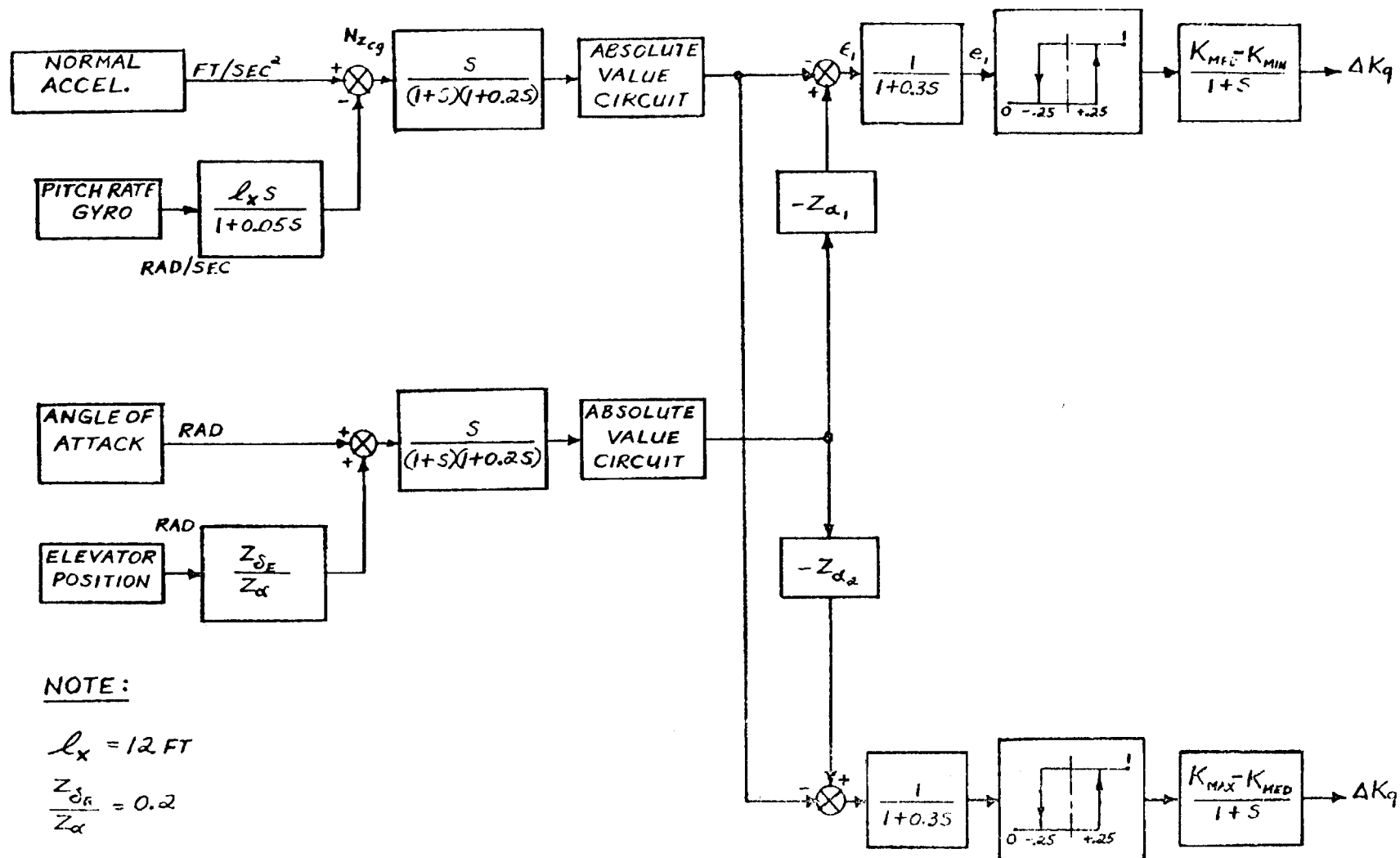
GESAC Yaw Channel (F-4A)



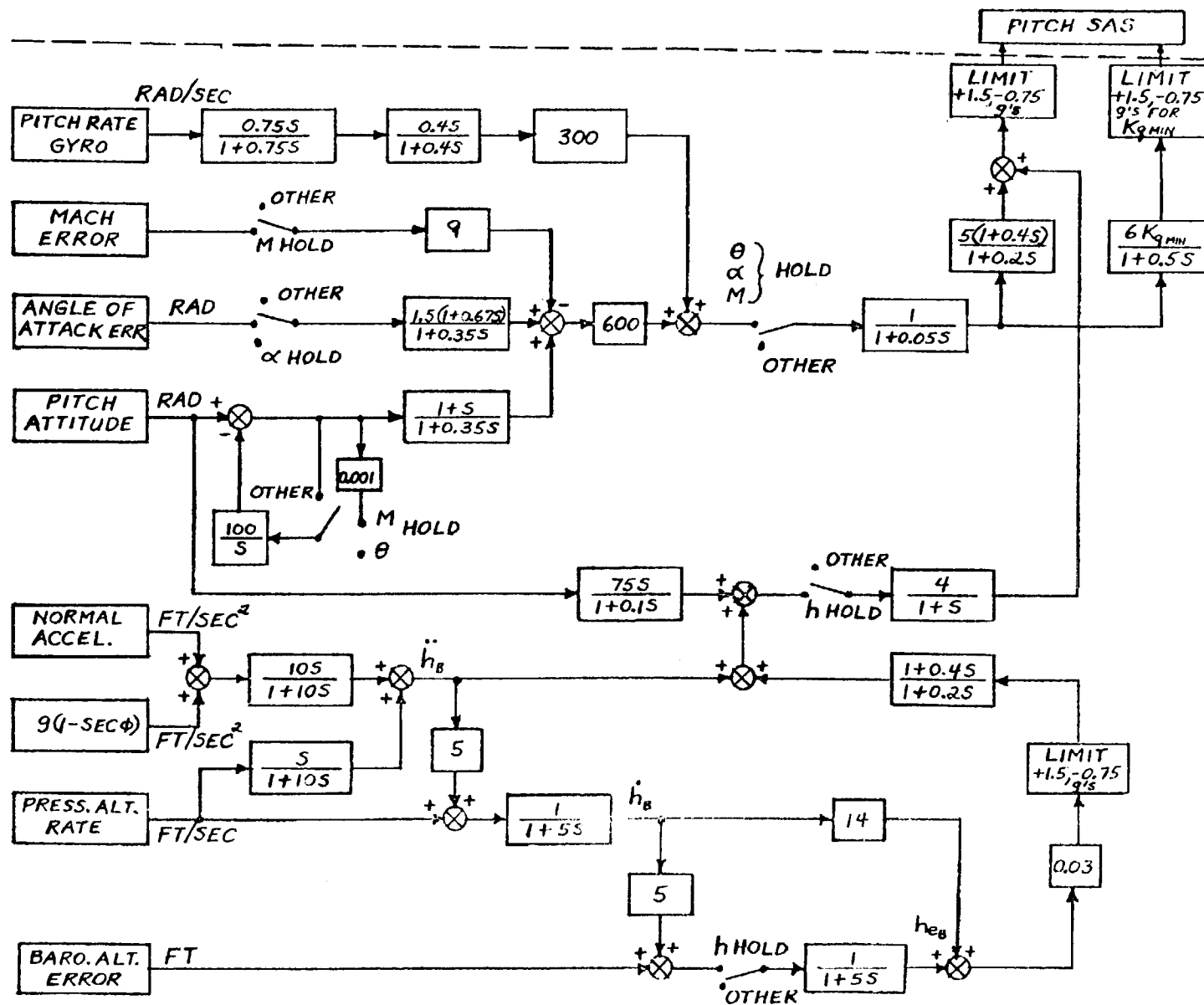
Adaptable FCS Pitch Stability Augmentation System (F-4)



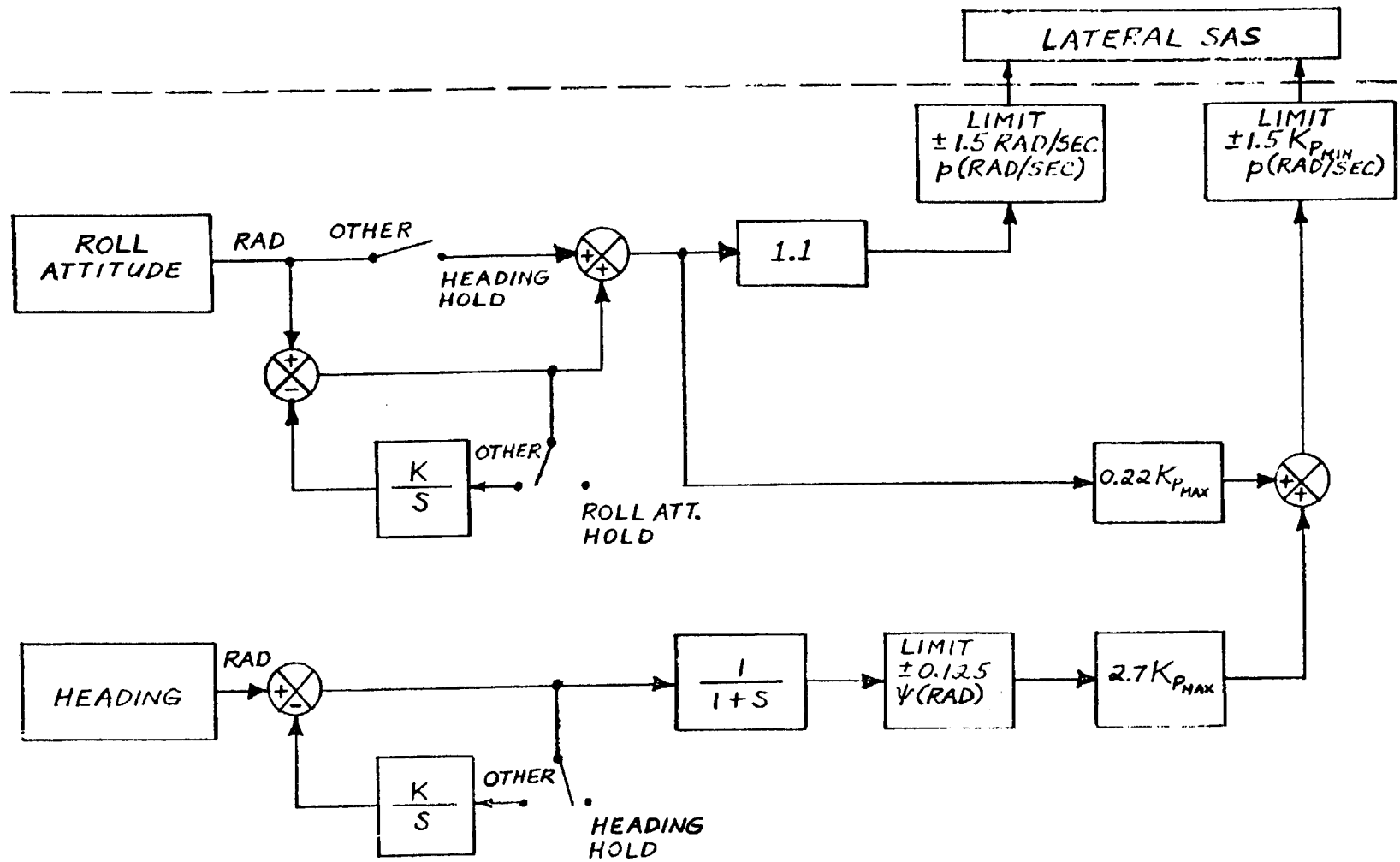
Adaptable FCS Lateral-Directional Stability Augmentation System (F-4)



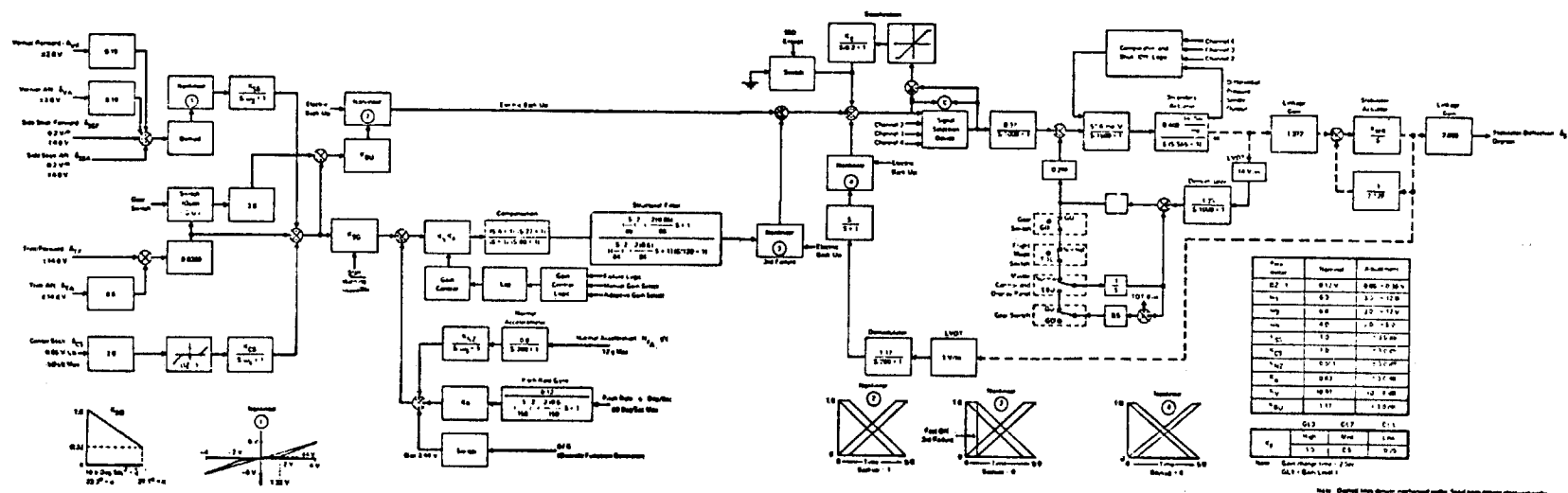
Adaptable FCS Flight Condition Identifier (F-4)



Adaptable FCS Pitch Autopilot Functions (F-4)

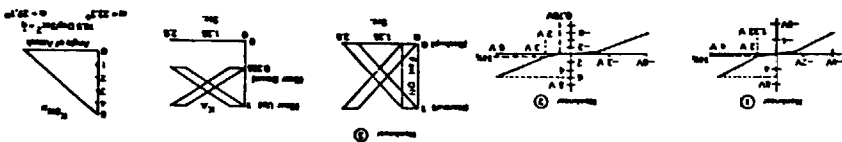


Adaptable FCS Lateral/Directional Autopilot Functions



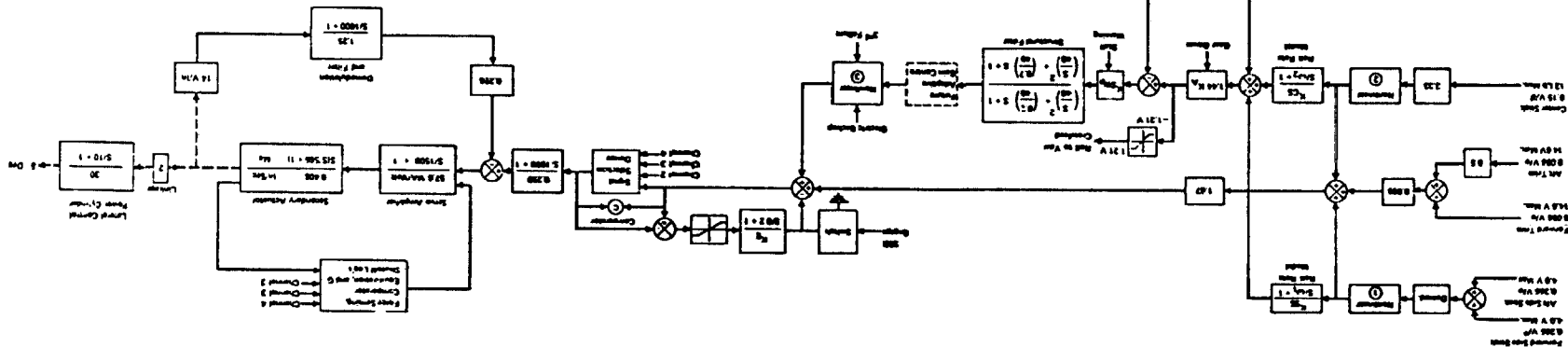
F-4 SFCS Pitch Axis

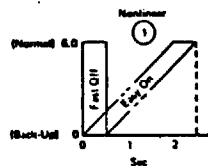
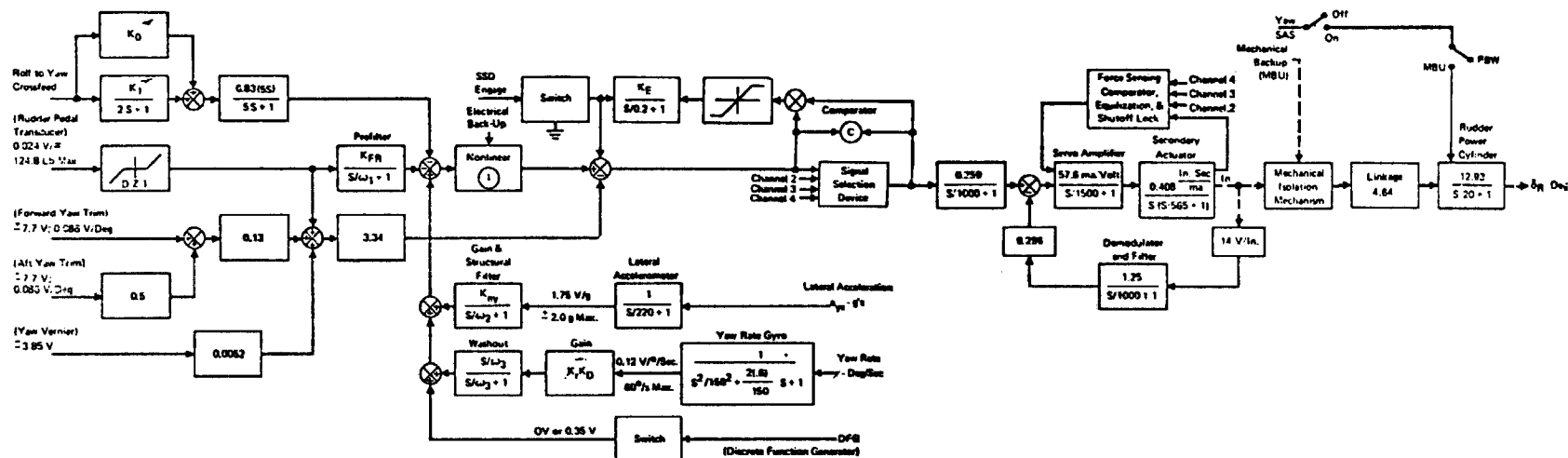
F-4 SFCS Lateral Axis



Parameter	Normal	Adaptive Range
K_1	1.0	1.0
K_2	1.0	1.0
K_3	1.0	1.0
K_4	1.0	1.0
K_5	1.0	1.0
K_6	1.0	1.0
K_7	1.0	1.0
K_8	1.0	1.0
K_9	1.0	1.0
K_{10}	1.0	1.0
K_{11}	1.0	1.0
K_{12}	1.0	1.0
K_{13}	1.0	1.0
K_{14}	1.0	1.0
K_{15}	1.0	1.0
K_{16}	1.0	1.0
K_{17}	1.0	1.0
K_{18}	1.0	1.0
K_{19}	1.0	1.0
K_{20}	1.0	1.0
K_{21}	1.0	1.0
K_{22}	1.0	1.0
K_{23}	1.0	1.0
K_{24}	1.0	1.0
K_{25}	1.0	1.0
K_{26}	1.0	1.0
K_{27}	1.0	1.0
K_{28}	1.0	1.0
K_{29}	1.0	1.0
K_{30}	1.0	1.0
K_{31}	1.0	1.0
K_{32}	1.0	1.0
K_{33}	1.0	1.0
K_{34}	1.0	1.0
K_{35}	1.0	1.0
K_{36}	1.0	1.0
K_{37}	1.0	1.0
K_{38}	1.0	1.0
K_{39}	1.0	1.0
K_{40}	1.0	1.0
K_{41}	1.0	1.0
K_{42}	1.0	1.0
K_{43}	1.0	1.0
K_{44}	1.0	1.0
K_{45}	1.0	1.0
K_{46}	1.0	1.0
K_{47}	1.0	1.0
K_{48}	1.0	1.0
K_{49}	1.0	1.0
K_{50}	1.0	1.0
K_{51}	1.0	1.0
K_{52}	1.0	1.0
K_{53}	1.0	1.0
K_{54}	1.0	1.0
K_{55}	1.0	1.0
K_{56}	1.0	1.0
K_{57}	1.0	1.0
K_{58}	1.0	1.0
K_{59}	1.0	1.0
K_{60}	1.0	1.0
K_{61}	1.0	1.0
K_{62}	1.0	1.0
K_{63}	1.0	1.0
K_{64}	1.0	1.0
K_{65}	1.0	1.0
K_{66}	1.0	1.0
K_{67}	1.0	1.0
K_{68}	1.0	1.0
K_{69}	1.0	1.0
K_{70}	1.0	1.0
K_{71}	1.0	1.0
K_{72}	1.0	1.0
K_{73}	1.0	1.0
K_{74}	1.0	1.0
K_{75}	1.0	1.0
K_{76}	1.0	1.0
K_{77}	1.0	1.0
K_{78}	1.0	1.0
K_{79}	1.0	1.0
K_{80}	1.0	1.0
K_{81}	1.0	1.0
K_{82}	1.0	1.0
K_{83}	1.0	1.0
K_{84}	1.0	1.0
K_{85}	1.0	1.0
K_{86}	1.0	1.0
K_{87}	1.0	1.0
K_{88}	1.0	1.0
K_{89}	1.0	1.0
K_{90}	1.0	1.0
K_{91}	1.0	1.0
K_{92}	1.0	1.0
K_{93}	1.0	1.0
K_{94}	1.0	1.0
K_{95}	1.0	1.0
K_{96}	1.0	1.0
K_{97}	1.0	1.0
K_{98}	1.0	1.0
K_{99}	1.0	1.0
K_{100}	1.0	1.0

Figure 1. Control loop transfer functions with roll rate feedback path.





		Gear Up						Gear Down
		Adaptive				Manual Switch Position		
Level		$M_0 < 6$	$6 < M_0 < 10$	$10 < M_0 < 30$	$M_0 > 30$	High	Mid	Low
Gain								
K_0		0.325	0.15	0.0	0.0	0.375	0.0	0.0
K_1		0.0	0.05	0.2	0.0	0.0	0.2	0.0
K_2		0.83	1.67	1.67	3.33	0.83	1.67	3.33

Note: Gain Change Time = 2 Sec.

Parameter	Normal	Adjust Range
K_{PR}	0.276	
ω_1	3.0	1.5 - 6.0
ω_2	40.0	
ω_3	0.5	0.25 - 1.0
K_{ny}	0.015	± 3.0 dB
K_0	0.42	± 3.0 dB
K_1	20.0	
DZ-1	5.0 ±	2.4 - 5.5 ±

F-4 SFCS Directional Axis

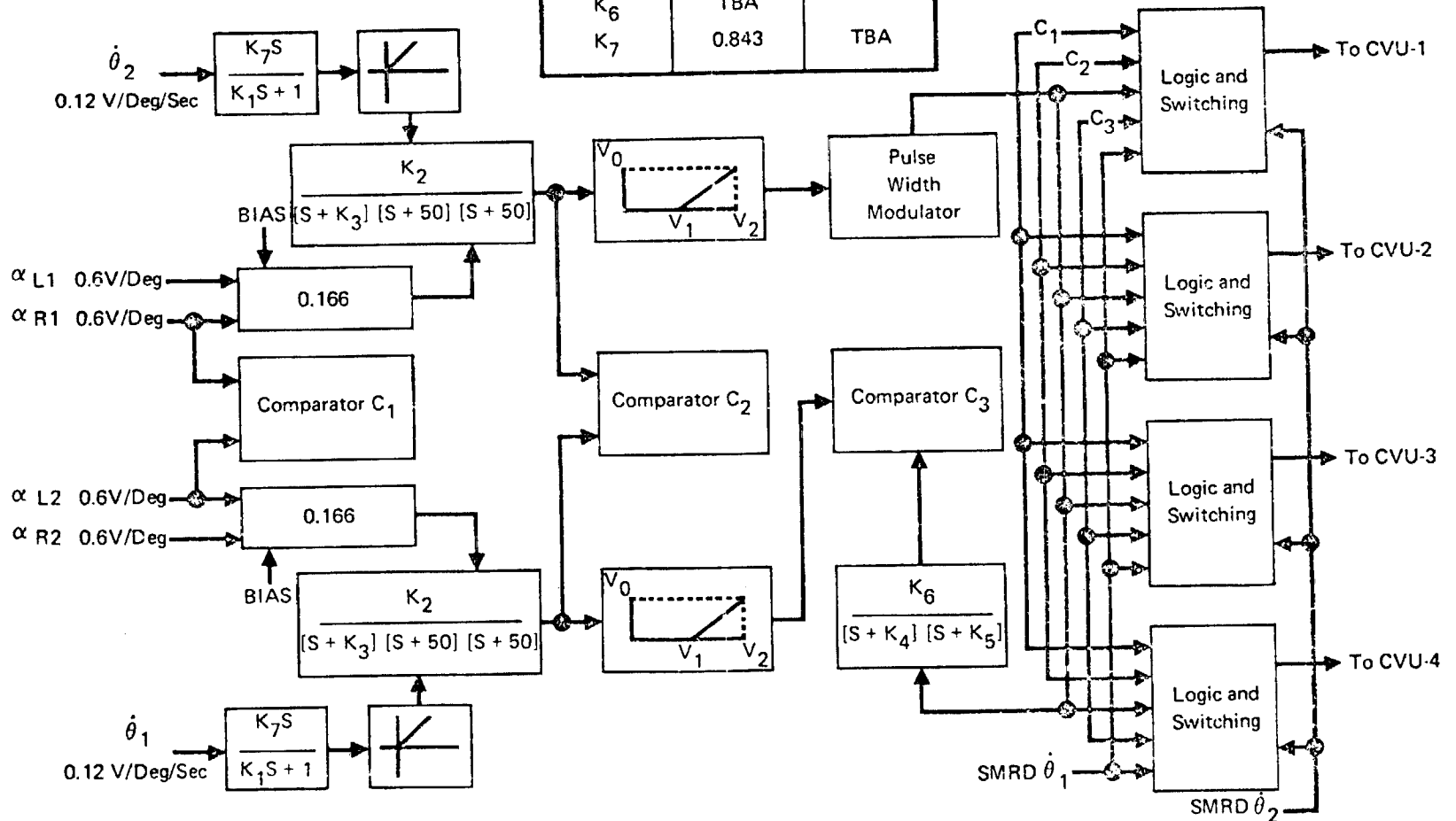
Switching Logic $\overline{SW} = C_1 + C_2 + C_3 + \text{SMRD } \dot{\theta}_1 + \text{SMRD } \dot{\theta}_2$

$V_1 = 1.66\text{V}$
 $V_2 = 2.42\text{V}$
 $V_0 = 4.56\text{V}$
 $\text{BIAS} = 30^\circ \alpha$

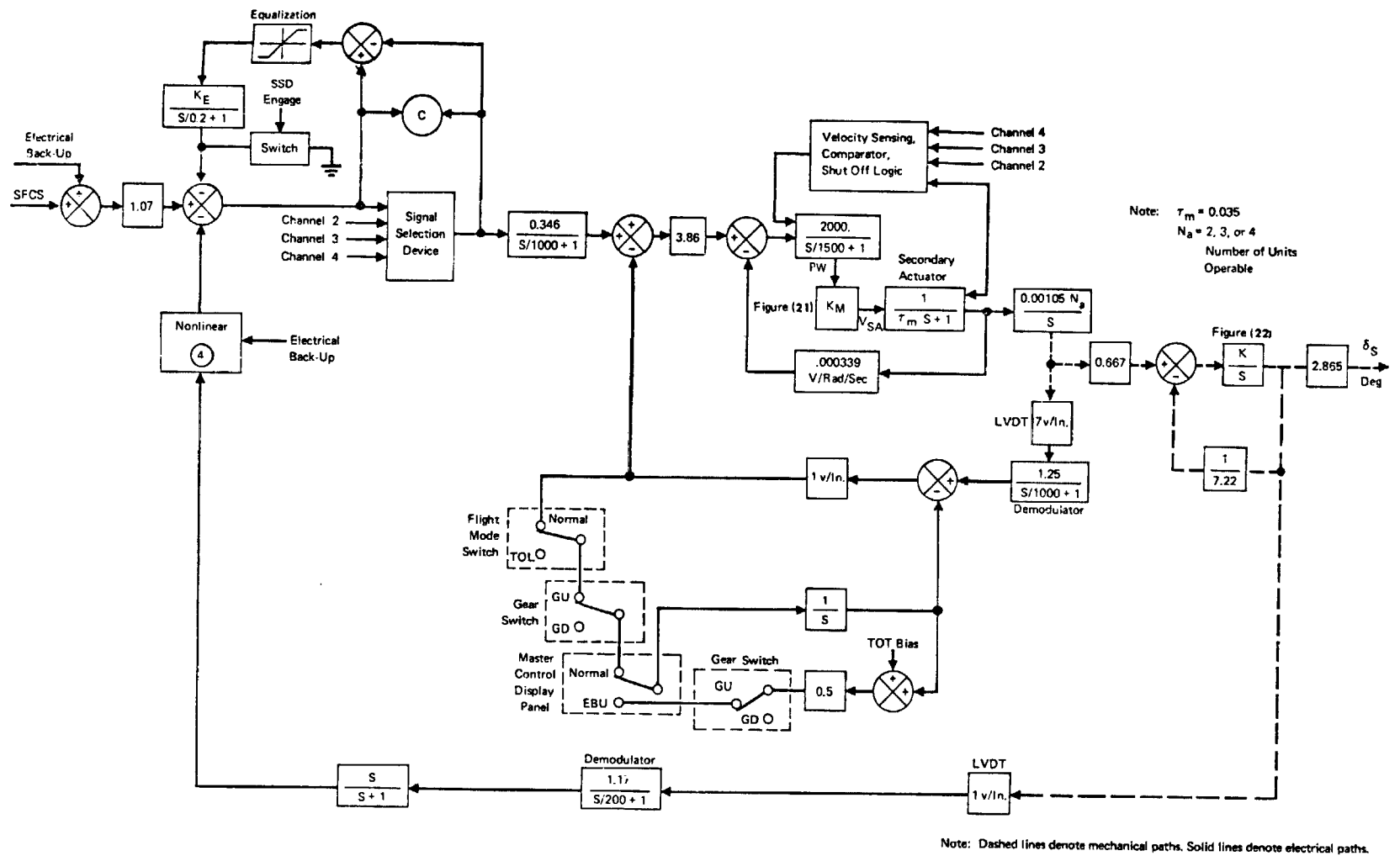
Note: 0 to 100% Modulation Occurs for Range of 0 to V_0 .

Variable	Nominal	Range
K_1	0.5	0.25 -- 1.0
K_2	15000	TBA
K_3	6.0	3.0 -- 12.0
K_4	TBA	
K_5	TBA	
K_6	TBA	
K_7	0.843	TBA

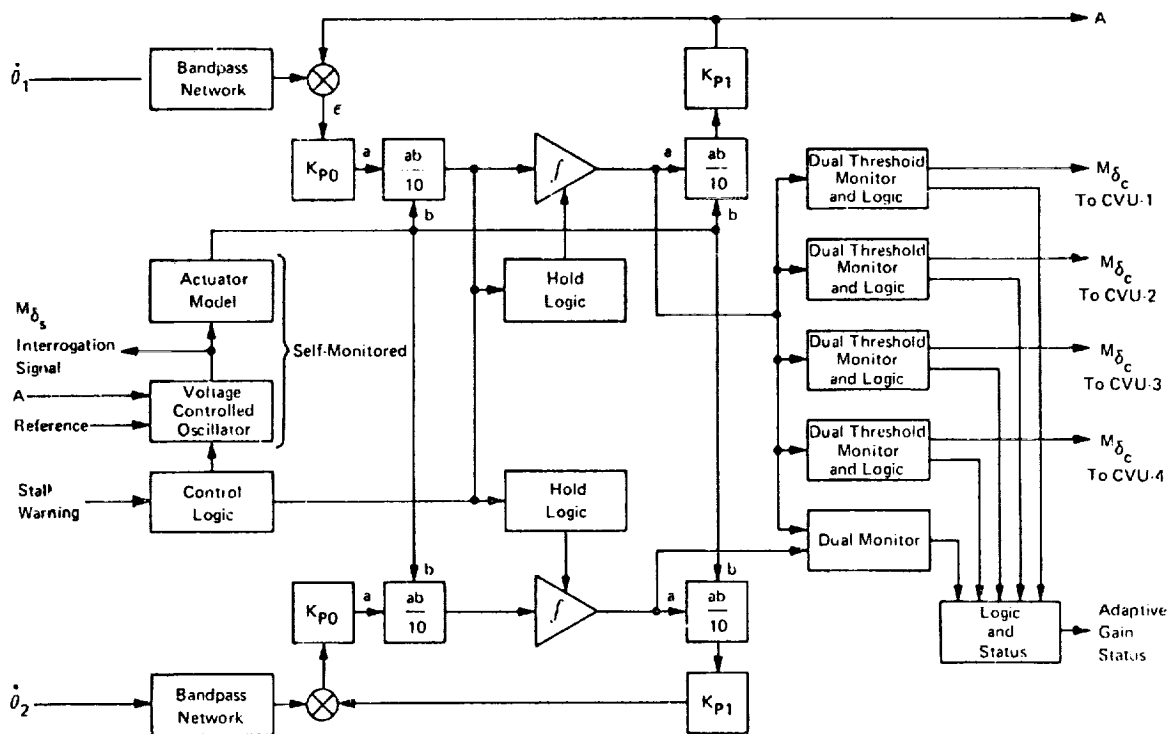
122



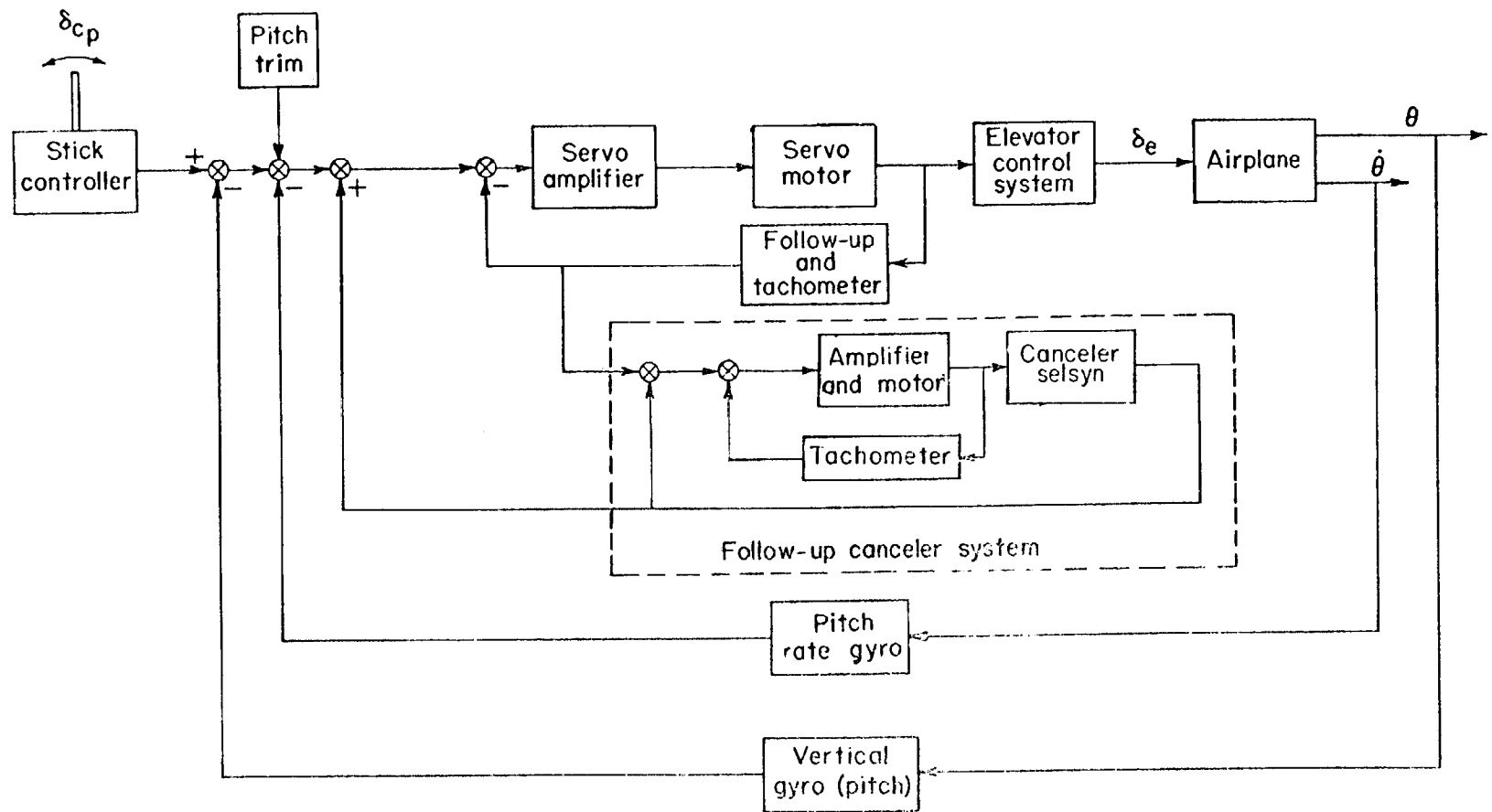
F-4 SFCS Stall Warning



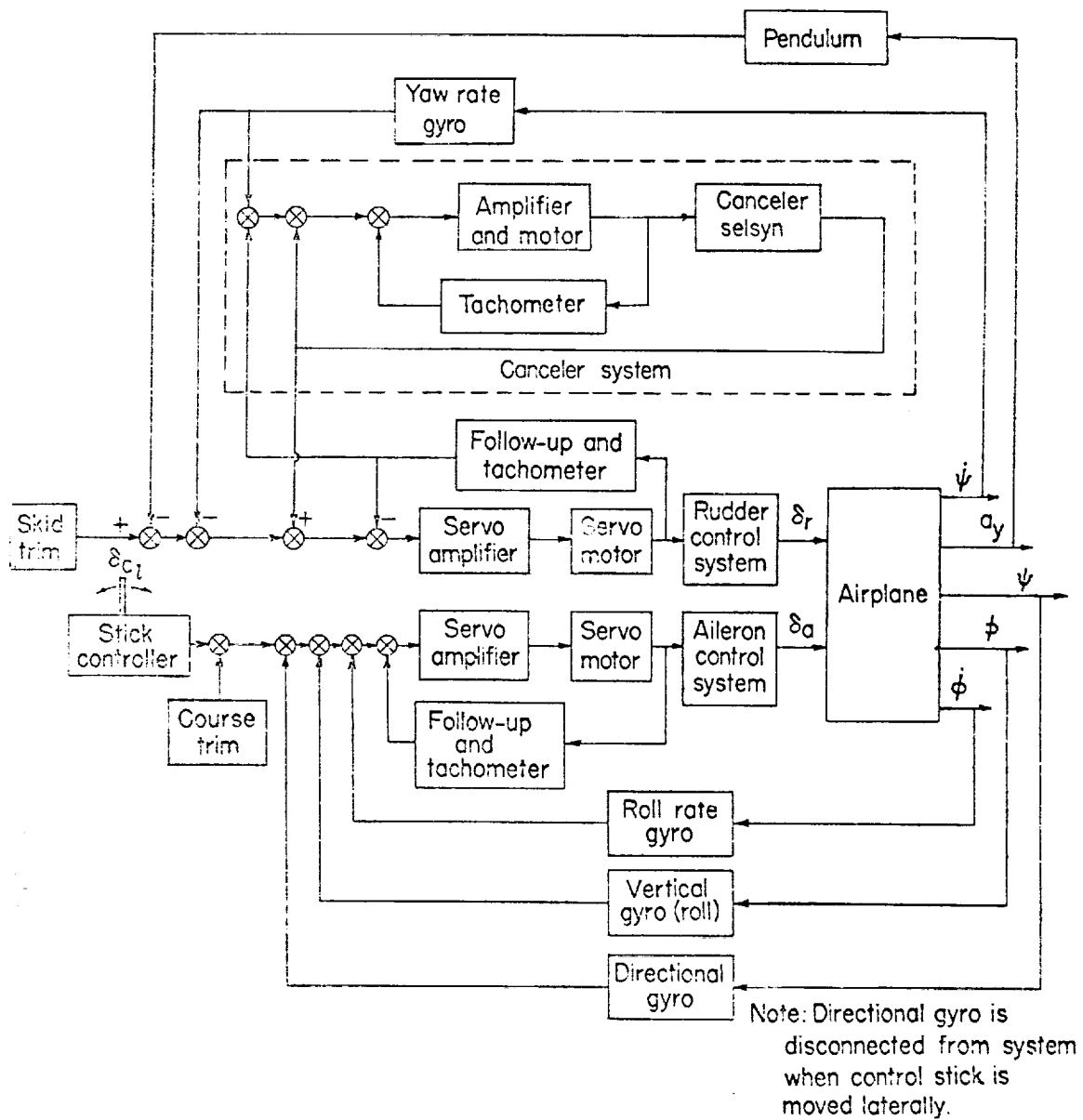
F-4 Survivable Stabilator Actuator Package



F-4 SFCS Adaptive Gain Changer

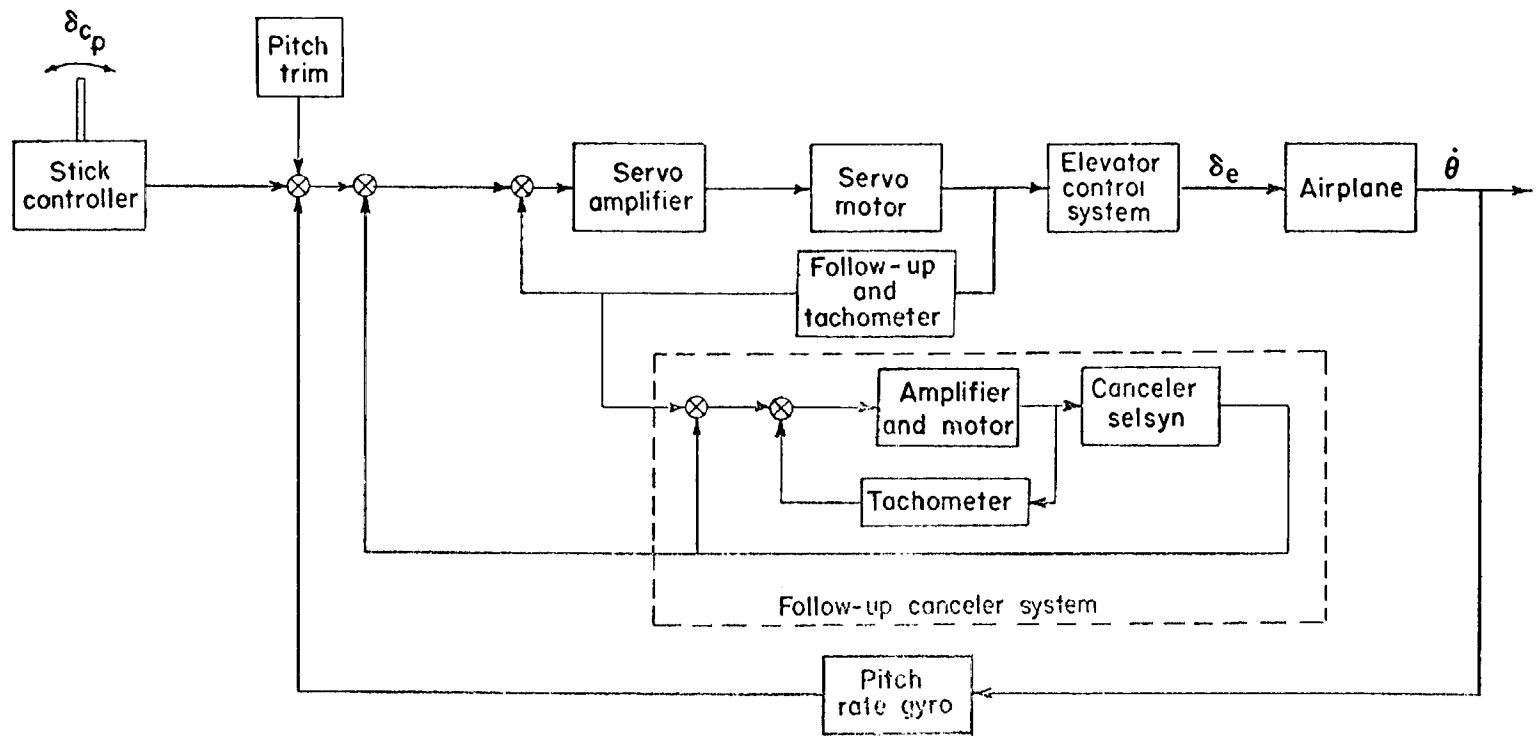


(a) Pitch channel.



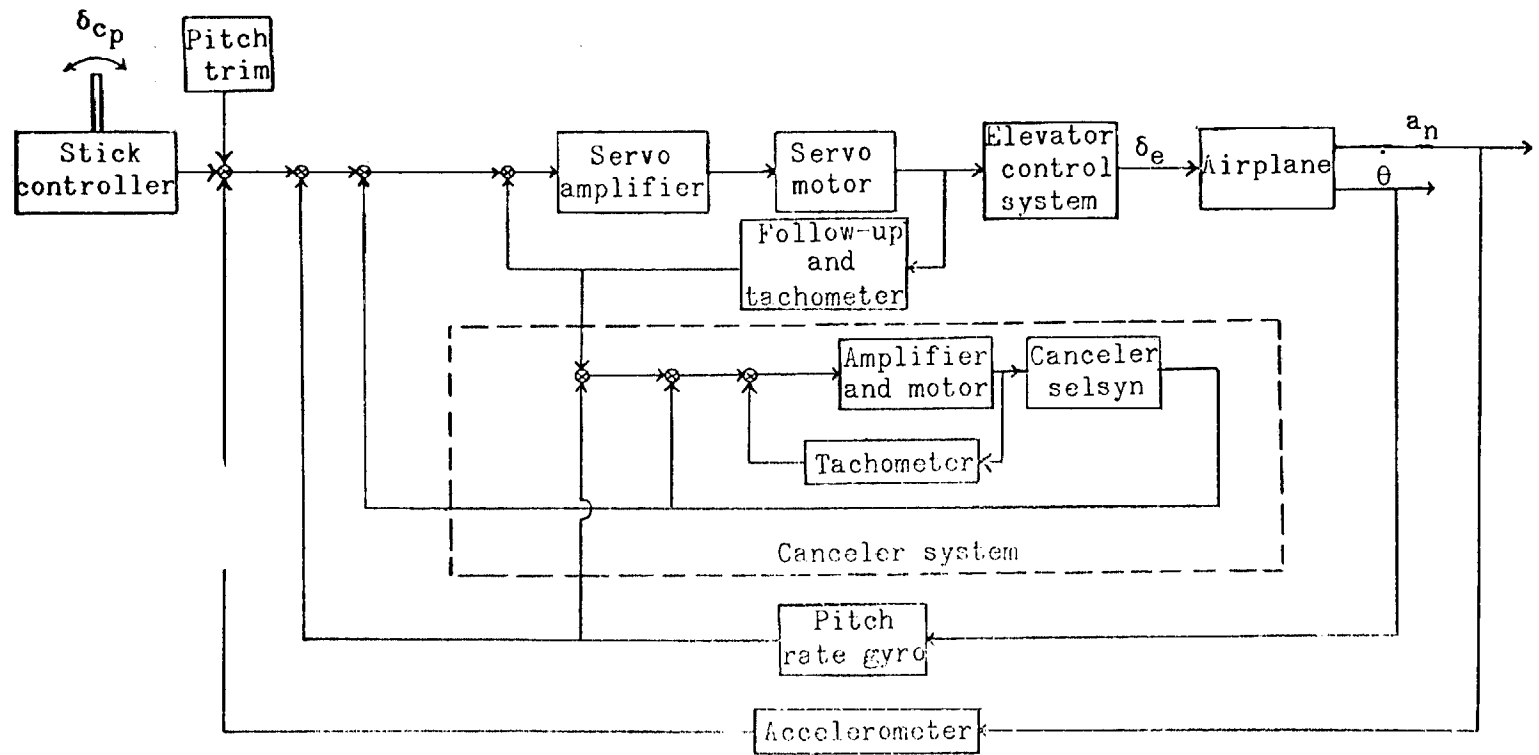
(b) Roll and yaw channels.

Grumman F9F-2 Attitude Command BFW



(a) Pitch channel.

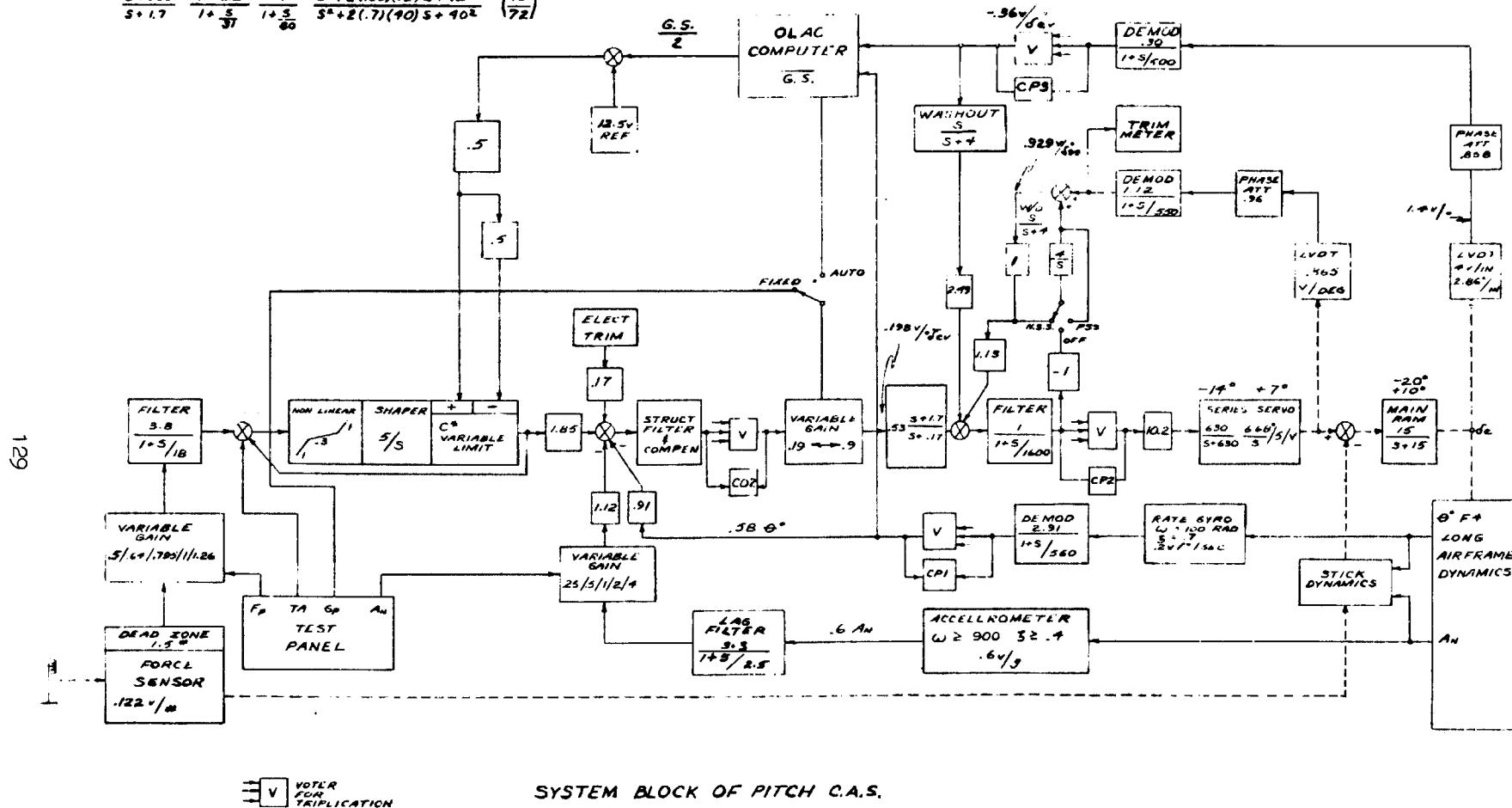
Grumman F9F-2 Rate Command FBW



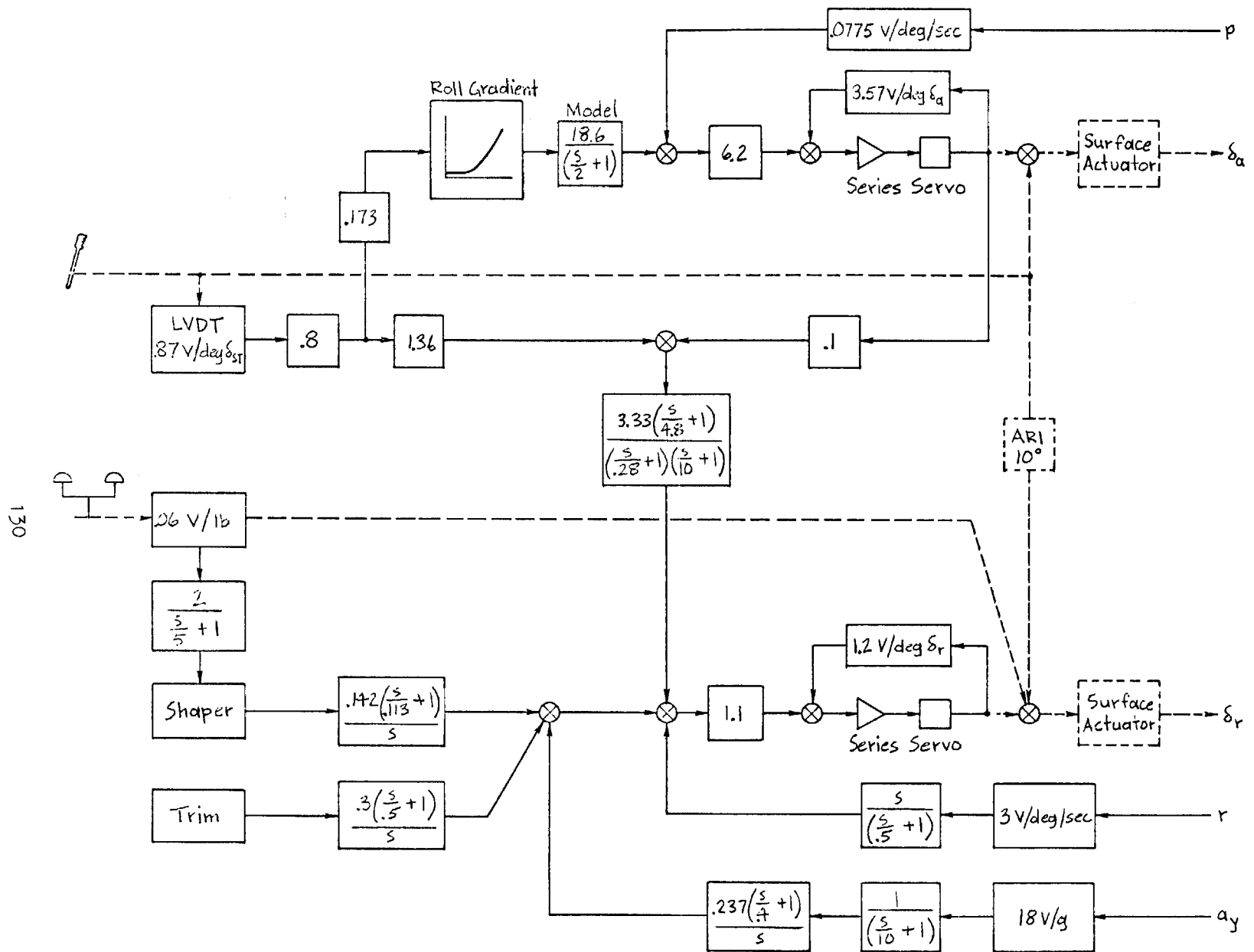
Grumman F9F-2 Normal-Acceleration Control System

STRUCTURAL FILTER

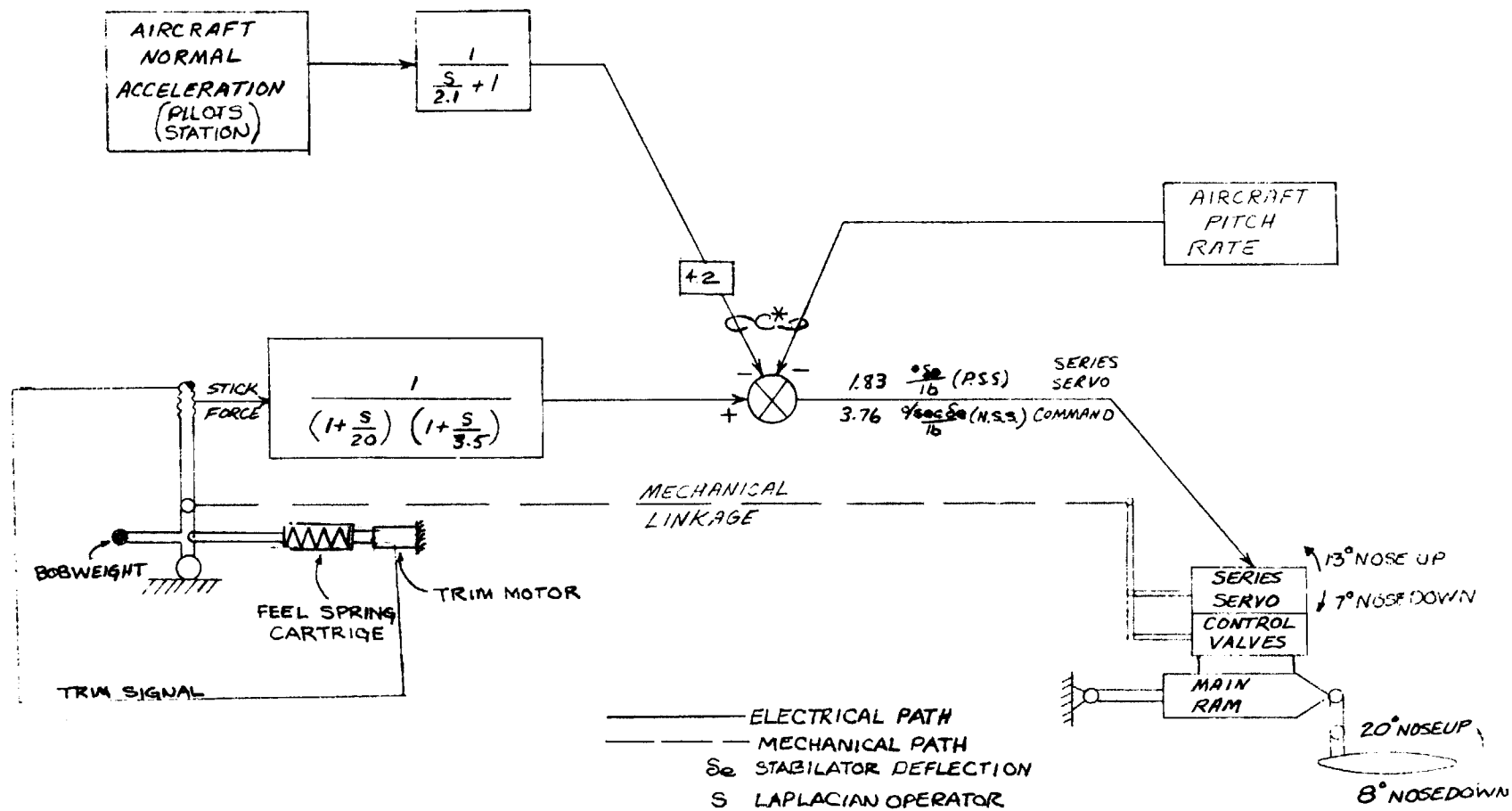
$$\frac{3+155}{s+1.7} \frac{1+\frac{1}{10}s}{1+\frac{s}{31}} \frac{1}{1+\frac{s}{80}} \frac{s^2+2(.09)(72)s+72^2}{s^2+2(.7)(90)s+90^2} \left(\frac{10}{72}\right)^2$$



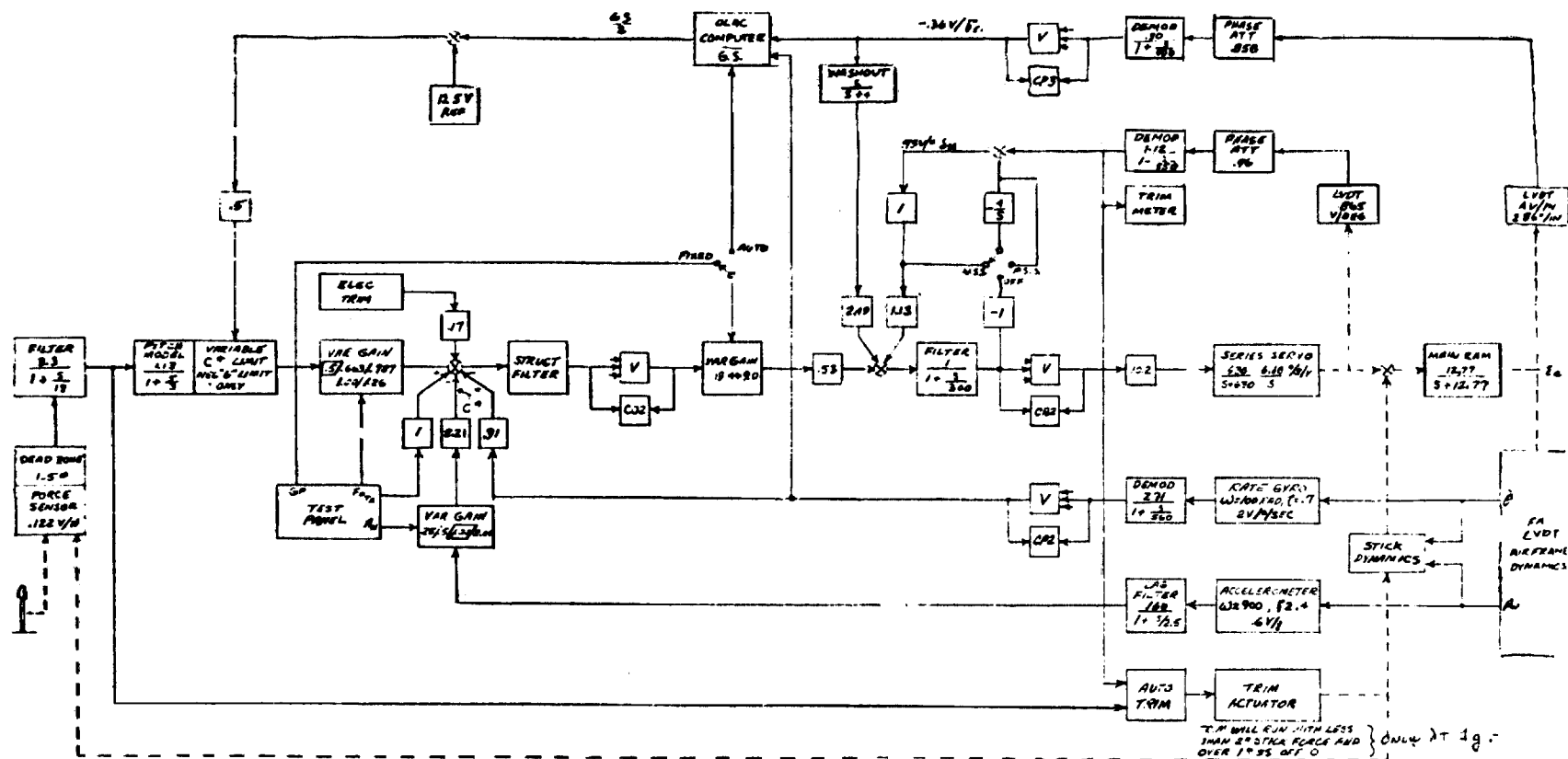
TWEAD I Pitch Axis



TWEAD I Lateral-Directional



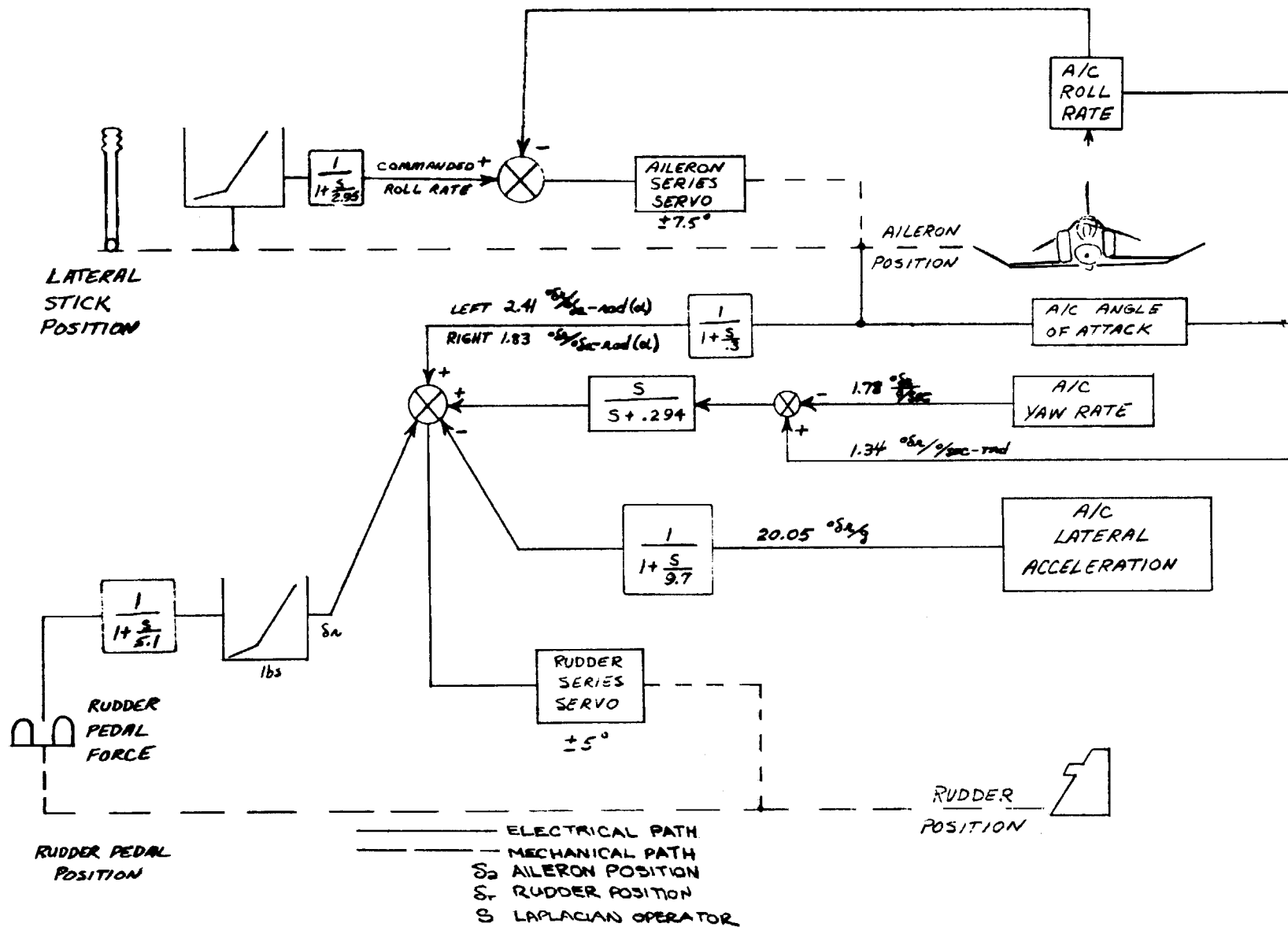
TWEAD II Longitudinal Functional CAS Block Diagram



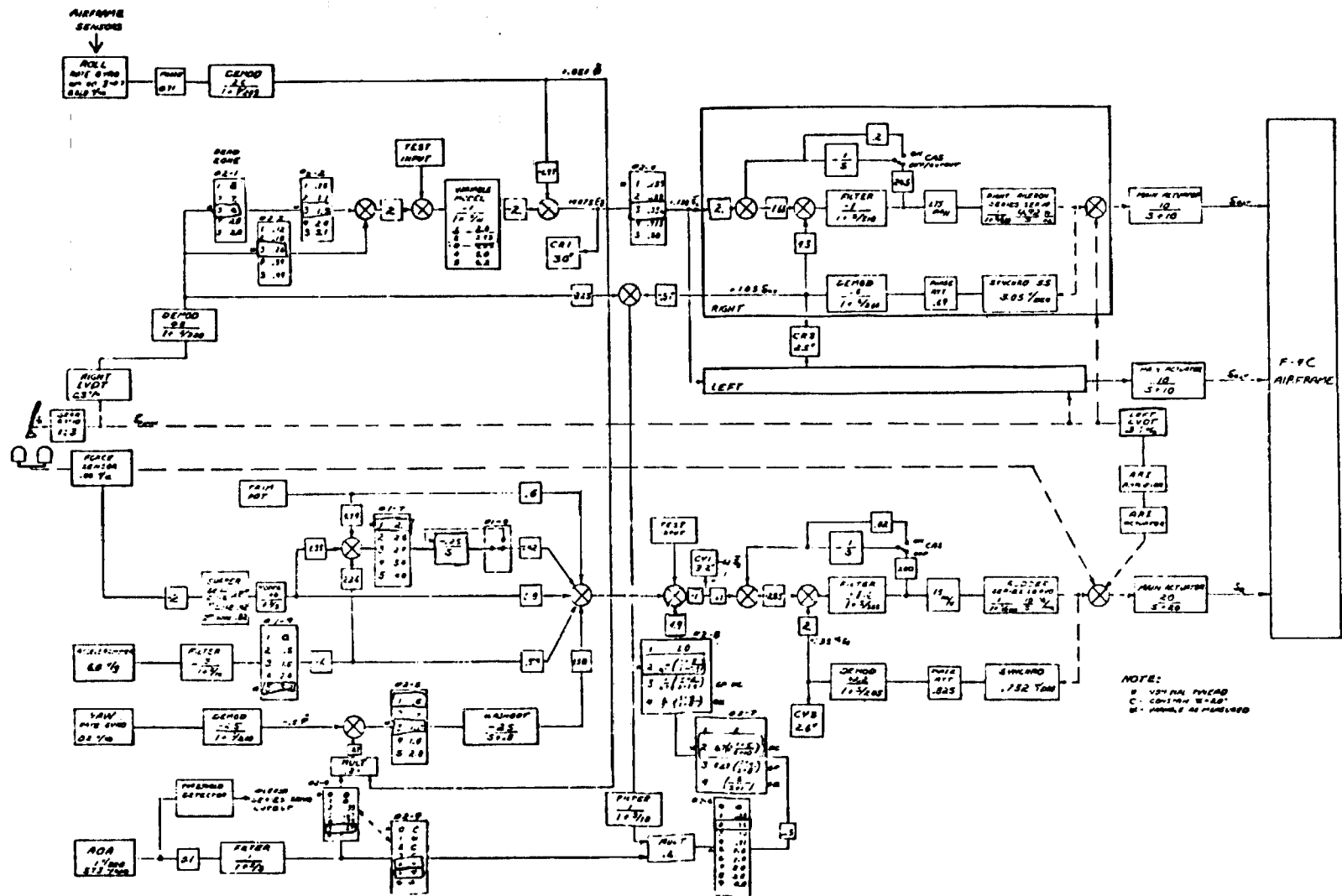
STRUCTURAL FILTER (WITH DOUBLE NOTCH) TRANSFER FUNCTION

$$\begin{aligned}
 \text{REF FCN} &= (1.05) \left[\frac{s^2 + 12.1s + 12.1^2}{s^2 + 102s + 85^2} \right] \left[\frac{-25(s+4)}{s+1} \right] \left[\frac{.993(s^2 + .5s + .66^2)}{s^2 + 102s + 85^2} \right] \left[\frac{.87(s+10.200)}{(s+1)(s+200)} \right] \\
 &= (.665)^2 \left[\frac{s^2 + 12.1s + 12.1^2}{s^2 + 102s + 85^2} \right] \left[\frac{s^2 + .5s + .66^2}{s^2 + 102s + 85^2} \right] \left[\frac{(s+4)(s+5)}{(s+1)(s+87)(s+200)} \right]
 \end{aligned}$$

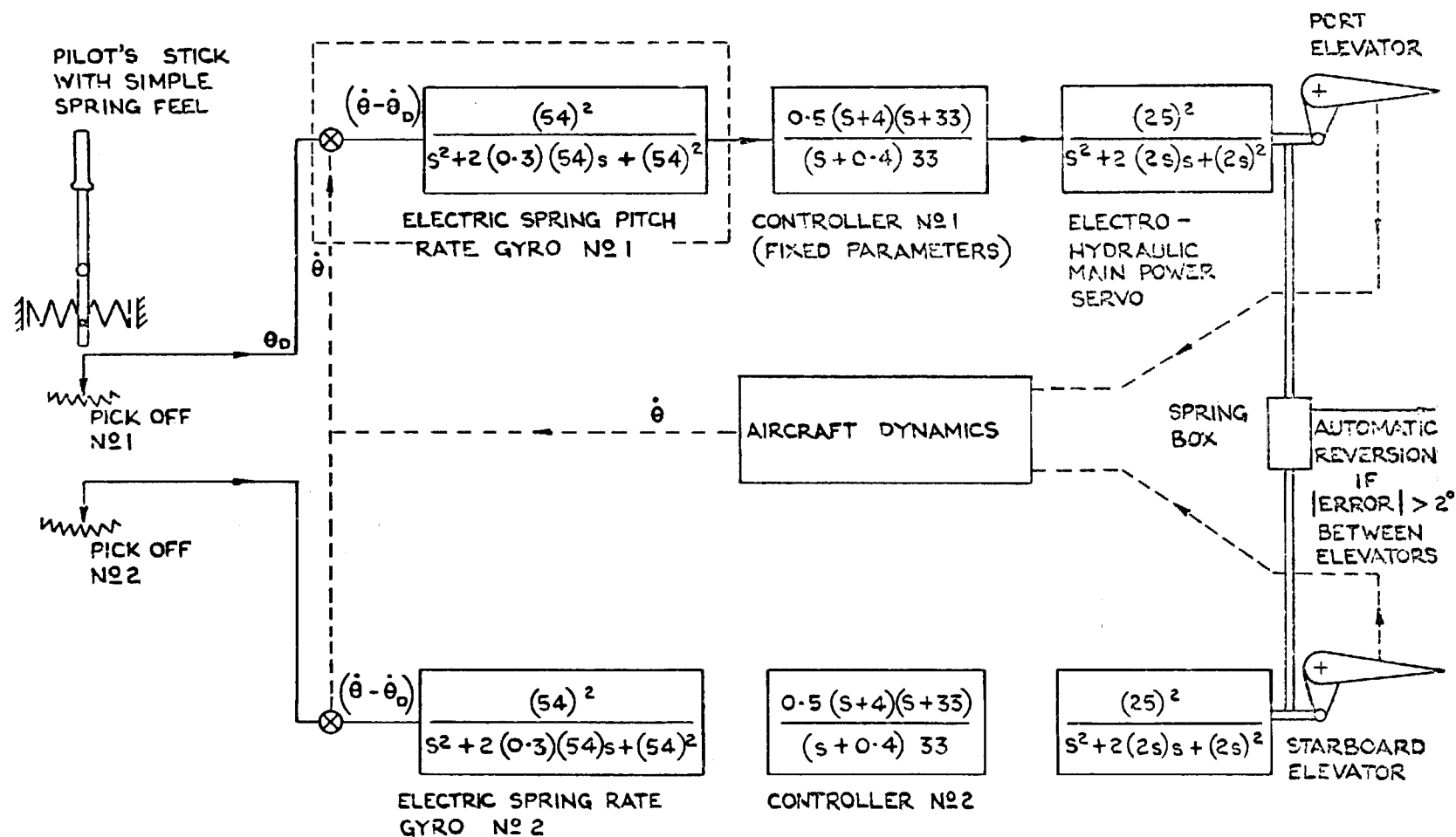
F-4C TWEAD II CAS Longitudinal Block Diagram



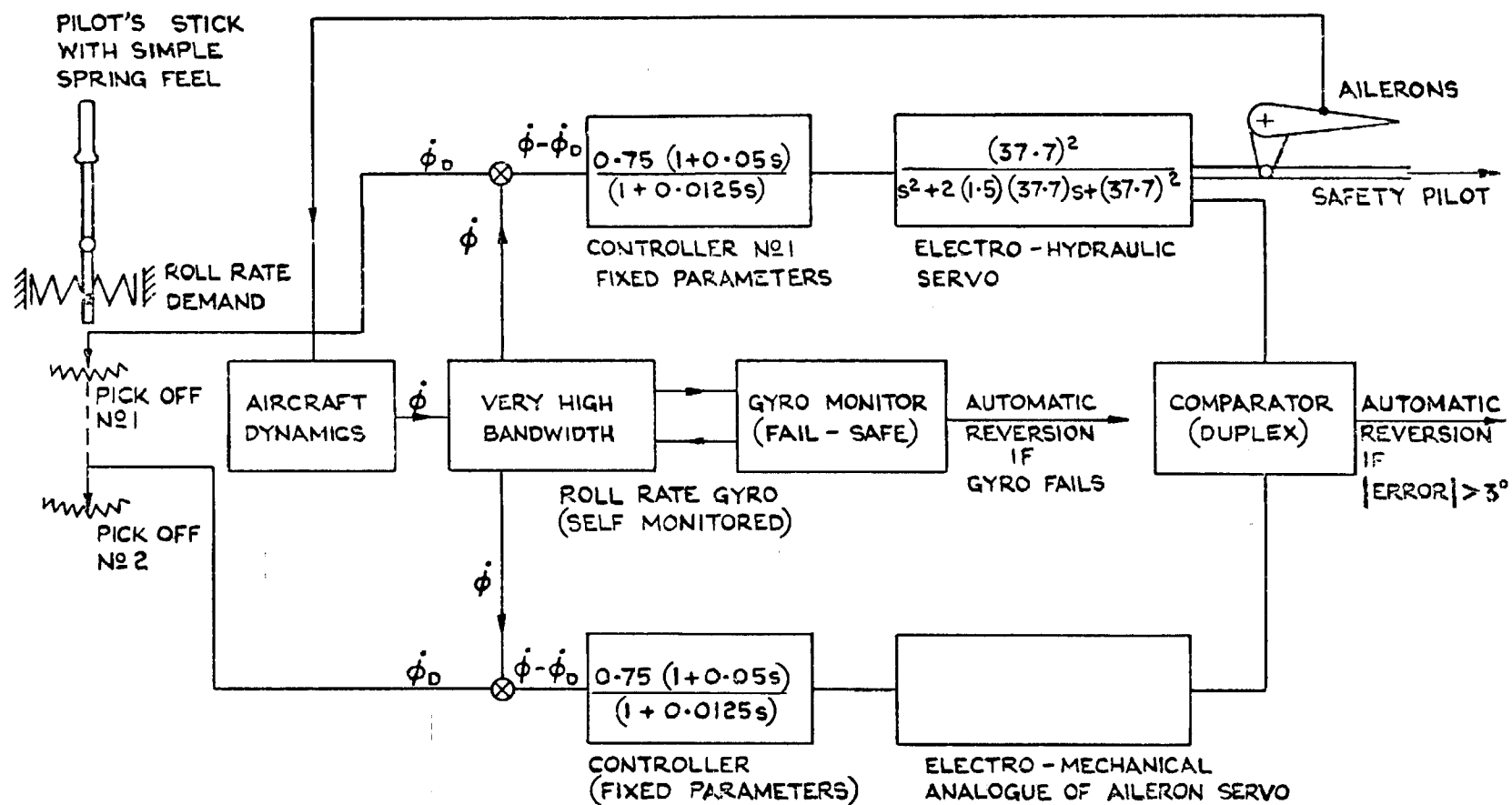
TWEAD II Lateral-Directional Functional CAS Block Diagram



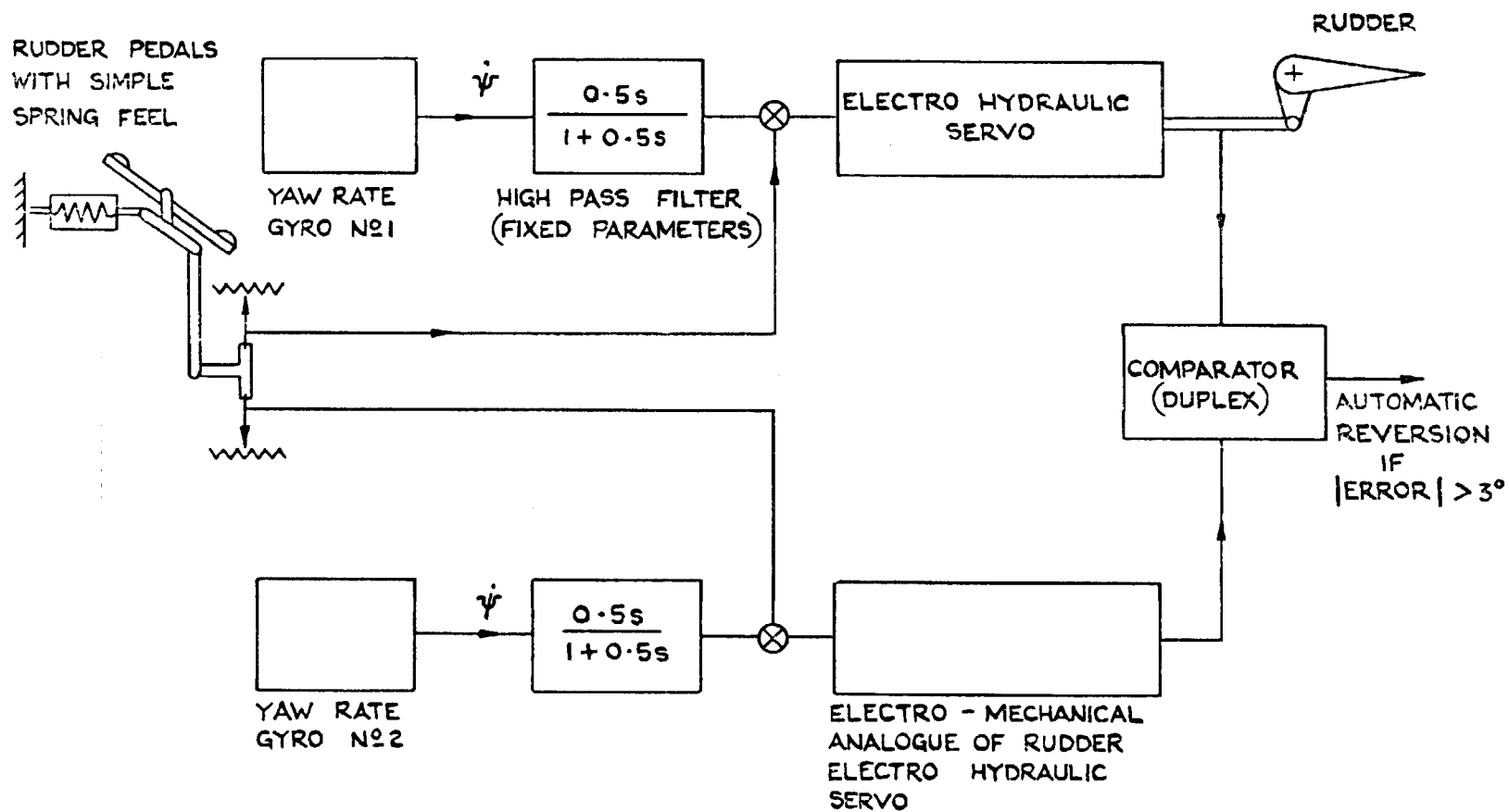
F-4C TWEAD II Lateral Block Diagram



AVRO Pitch Rate Demand Control System (Duplex)

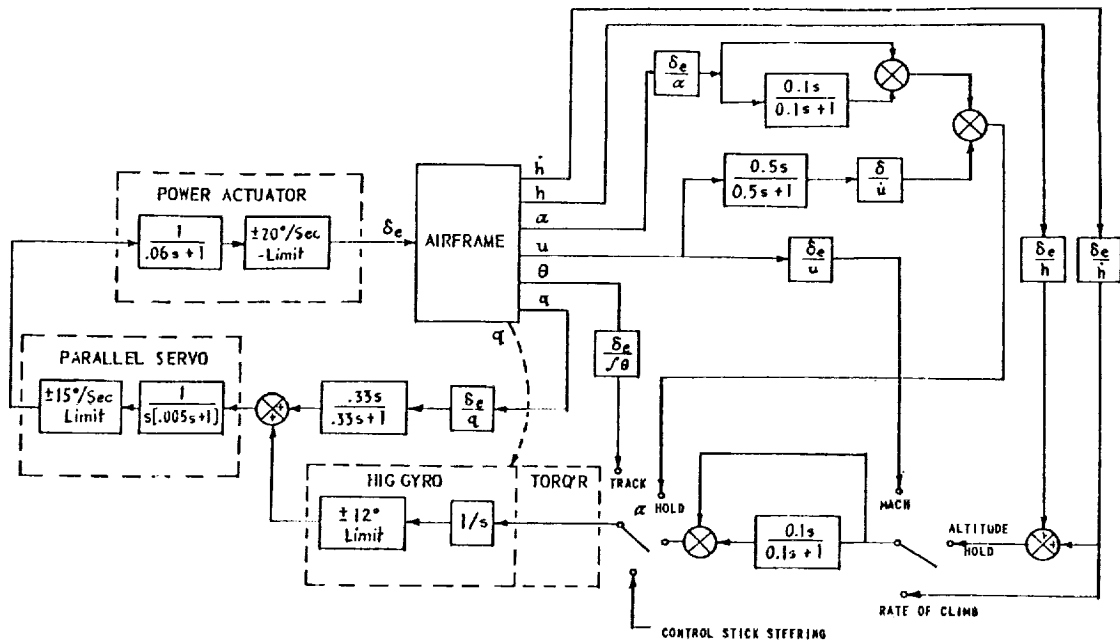


AVRO Roll Rate Demand Control System (Simplex with Comparison Monitor)

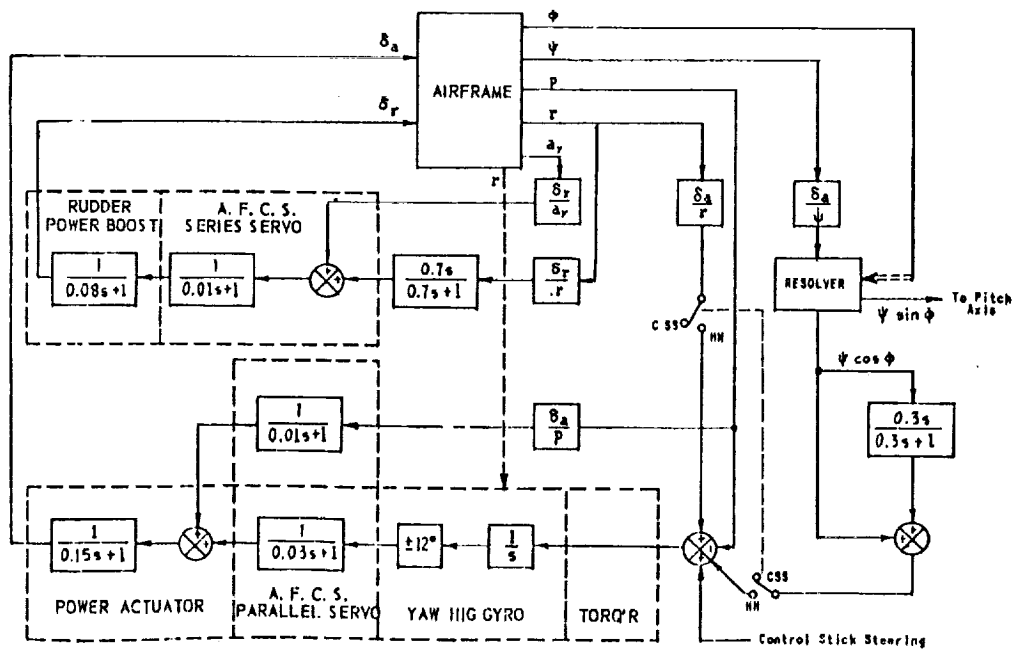


AVRO Rudder Control System Including Yaw Damper
(Simplex with Comparison Monitor)

LONGITUDINAL DIAGRAM



LATERAL DIAGRAM



F-100 Lear Rate Integrating Autopilot

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