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(R) Description of Actuation Systems for Aircraft With Fly-By-Wire Flight Control Systems

RATIONALE

The purpose of revision B of this document is to expand its scope to add descriptions of the flight control actuation systems for additional aircraft developed recently. Those new aircraft are the A380, Eurofighter, BA609 Tiltrotor and A400M.

TABLE OF CONTENTS

1. SCOPE

This SAE Aerospace Information Report (AIR) provides design information of various contemporary aircraft fly-by-wire (FBW) flight control actuation systems that may be useful in the design of future systems for similar applications. It is primarily applicable to manned aircraft. It presents the basic characteristics, hardware descriptions, redundancy concepts, functional schematics, and discussions of the servo controls, failure monitoring, and fault tolerance. All existing FBW actuation systems are not described herein; however, those most representing the latest designs are included. While this AIR is intended as a reference source of information for aircraft actuation system designs, the exclusion or omission of any other appropriate actuation system or subsystem should not limit consideration of their use on future aircraft.

2. REFERENCES

Some of the data in this information report have been collected from material presented at previous SAE A-6 meetings. If more detailed information is desired, contact with the authors of the following references may be rewarding. It is, however, reasonable to expect, and appreciate, that certain proprietary rights may be exercised with respect to certain data and/or information.

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- F-15 S/MTD Flight Control Actuators, R. Harlow, Oct. 1986
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- X-29 Digital Flight Control System Design, A. Whitaker and J. Chin, Oct. 15, 1984, Symposium on Active Control Systems, Toronto

- Airbus A330/A340 Primary Flight Control Actuation System, Presented at SAE Committee A-6 in Atlanta, GA, April 29-May 3, 1991

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3. ACTUATION SYSTEM DESCRIPTION

The development of fly-by-wire (FBW) flight control systems started in the late 1960s. Today most of the aircraft (both civil and military) are being designed and developed based on FBW technology. A key element in these FBW systems is the FBW actuation system. The early FBW research/development and prototype aircraft used redundant secondary actuators to replace the mechanical linkage between the pilot's controls and the control surface power actuators. Later FBW aircraft were designed with the redundant servos integrated on the power actuator. This AIR presents descriptions of selected secondary and primary representations of aircraft actuation systems as a reference base for providing design information on various FBW actuation systems. The selected aircraft are: the NASA F-8 DFBW, USAF F-4 SFCS, YF-16, F-16, F/A-18 A/B/C/D, F-15 S/MTD, Tornado, Space Shuttle, Lavi, JAS-39, V-22, Saab 2000, IDF, B-2, C-17, X-31A, Boeing 777, X-29A, Airbus A320/330/330, F-117, and N-250.

3.1 Summary of Characteristics

A summary of these aircraft FBW actuation systems is contained in Tables 1 through 21, where:

Table 1 - NASA F-8 DFBW Secondary Actuator Characteristics
Table 2 - F-4 SFCS Secondary Actuator Characteristics
Table 3 - YF-16 Command Servoactuator Characteristics (F-111 SAS Actuator)
Table 4 - F-16 Actuator Characteristics
Table 5 - F/A-18 Actuator Characteristics
Table 6 - F-15 S/MTD Actuator Characteristics
Table 7 - Tornado Actuator Characteristics
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Table 22B - A380 Actuator Characteristics (Spoiler Surfaces)
Table 23A - BA609 Rotor and Conversion Actuator Characteristics
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Table 25B - A400M Actuator Characteristics (Spoiler Surfaces)

TABLE 1 - NASA F-8 DFBW SECONDARY ACTUATOR CHARACTERISTICS

Characteristics	Phase I	Phase II
Hydraulics Pressure (psi) Fluid	 3000 MIL-H-5606	 3000 MIL-H-5606
Redundancy Hydraulic Electrical	 Dual Quad	 Triplex Triplex
Electrical Failure Capability	Two-Fail Operate	Fail-Operate/ Fail-Off
Fail-Safe Modes	---	Fail Neutral
Servovalves	A	B
Output Force (lb)	462	2340
Stroke (in)	2.0	2.0
Output Velocity (No-Load) in/s	12.5 (active) 1.6 (standby)	15.1
Loop Gain (rad/s)	156 (active) 54 (standby)	125
Hysteresis (Percent Full Stroke)	0.15 (active) 0.25 (standby)	0.08

NOTES:

A - Active mode: two two-stage flapper-nozzle servovalves in an active and monitor configuration. Standby mode: three single stage jet-pipe servovalves in force summing configuration.

B - Three two-stage flapper-nozzle servovalves in force summing configuration.

TABLE 2 - F-4 SFCS SECONDARY ACTUATOR CHARACTERISTICS

Characteristics	
Hydraulics Pressure (psi) Fluid	 3000 A MIL-H-83282
Redundancy Hydraulic Electrical	 Quad Quad
Failure Capability Hydromechanical Electrical	 Two-Fail-Op/Fail-Safe Two-Fail-Op/Fail-Safe
Backup/Fail-Safe Modes	B
Servovalves	C
Output Force (lb)	640
Stroke (in)	1.0
Output Velocity (No Load) in/s	 0.6
Loop Gain (rad/s)	122
Hysteresis (Percent Full Stroke)	 0.04

NOTES:

A - 1600 psi to one element
B - Lateral and directional actuators driven to center, longitudinal actuator holds last position
C - Single stage jet-pipe servovalve

TABLE 3 - YF-16 COMMAND SERVOACTUATOR CHARACTERISTICS
(F-111 SAS ACTUATOR)

Characteristics	SAS SERVO
Hydraulics Pressure (psi) Fluid	 3000 MIL-H-5606
Redundancy Hydraulic Electrical	 Dual Triplex
Failure Capability Hydromechanical Electrical	 Fail-Op/Fail-Safe Fail-Op/Fail-Safe
Backup/Fail-Safe Modes	---
Servovalves	A
Output Force (lb)	15 300
Stroke (in)	1.5
Output Velocity (No Load) in/s	 5.2
Loop Gain (rad/s)	40 B
Hysteresis (Percent Full Stroke)	 3.0

NOTES:

A - Three, two-stage flapper nozzle servovalves
B - Mechanical feedback

TABLE 4 - F-16 ACTUATOR CHARACTERISTICS

Characteristics	Horizontal Tail	Flaperon	Rudder	L.E. Flap
Hydraulics Pressure (psi) Fluid	 A B	 A B	 A B	 A B
Redundancy Hydraulic Electrical	 Dual Triplex	 Dual Triplex	 Dual Triplex	 Dual Dual
Failure Capability Hydromechanical Electrical	Fail-Op/ Fail-Safe Two-Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe Two-Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe Two-Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe Fail-Op/ Fail-Safe
Backup/ Fail-Safe Modes	Drive to Zero	Drive to Zero	Drive to Zero	Lock in Place
Servovalves	C	C	C	D
Output Force (lb)	34 900	34 900	21 700	350 000 (in-lb)
Stroke (in)	4.25	4.25	2.65	27 (deg)
Output Velocity (No Load) in/s deg/s	 5.10 50	 5.10 52	 5.30 120	 --- 27
Loop Gain (rad/s)	14.4	14.4	14.4	10
Hysteresis (Percent Full Stroke)	3.0	3.0	3.0	4.5

NOTES:

A - 3000 psi
B - MIL-H-5606
C - Three, two-stage jet pipe servovalves
D - Dual electro-mechanical command servo

TABLE 5 - F/A-18 A/B/C/D ACTUATOR CHARACTERISTICS

Characteristics	Aileron	Rudder	L.E. Flap	Stabilator	T.E. Flap
Hydraulics Pressure (psi) Fluid	 A B	 A B	 A B	 A B	 A B
Redundancy Hydraulic Electrical	 Simplex Dual	 Simplex Dual	 Simplex Dual	 Dual Quad	 Dual Quad
Electrical Failure Capability	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Two Fail-Op/Fail-Safe	Two Fail-Op/Fail-Safe
Backup/ Fail-Safe Modes	Damper	Damper	Lock in Place	Mechanical	Neutral Lock
Servovalves	C	C	D	E	E
Output Force (lb) Compression Tension	 13 100 12 090	 15 740 13 880	Torque (in/lb) 346 050 346 050	 29 940 27 540	 18 070 14 330
Stroke (in)	4.38	1.43	37.0 (deg)	7.12	8.12
Output Velocity (No Load) in/s deg/s	 6.70 100.0	 1.33 60	 --- 18.0	 7.4 40	 2.76 18.0
Loop Gain (rad/s)	48.0	37.0	20.0	30.0	18.0
Hysteresis (Percent Full Stroke)	0.1	0.1	0.2	0.2	0.2

NOTES:

A - 3000 psi
B - MIL-H-83282
C - Two-stage jet pipe servovalves
D - One pair of single-stage jet pipe servovalves
E - Two pair of single-stage jet pipe servovalves

TABLE 6 - F-15 S/MTD ACTUATOR CHARACTERISTICS

Characteristics	Canard/ Stabilator	Aileron/ Flaperon	Rudder (Rotary)
Hydraulics Pressure (psi) Fluid	 A B	 A B	 A B
Redundancy Hydraulic Electrical	 Dual Quad	 Dual Dual	 Simplex Dual
Electrical Failure Capability	Two-Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe
Fail-Safe Modes	Free Float (canard) Neutral Lock (stabilator)	Damper	Damper
Servovalves	C	D	D
Output Force (lb) Compression Tension	 42 200 38 600	 23 100 18 500	 22 000 (in-lb)
Stroke (in)	7.8	1.4	60 (deg)
Output Velocity in/s deg/s	 8.4 ---	 3.3 ---	 --- 105
Loop Gain (rad/s)	30	40	30
Hysteresis (Percent Full Stroke)	0.1	0.36	0.1

NOTES:

A - 3000 psi
B - MIL-H-83282
C - Quad coil rotary direct drive force motor
D - Dual coil rotary direct drive force motor

TABLE 7 - TORNADO ACTUATOR CHARACTERISTICS

Characteristics	Taileron	Rudder	Spoiler
Hydraulics Pressure Fluid	 A B	 A B	 A B
Redundancy Hydraulic Electrical	 Dual Quad	 Dual Quad	 Simplex Dual
Electrical Failure Capability	 Two-Fail-Op/ Fail-Safe	 Fail-Op/ Fail-Safe	 Fail-Op/ Fail-Safe
Fail-Safe Modes	Mechanical	Power to Center	Damper
Servovalves	C	C	D
Output Force (lb) Compression Tension	 76 291 79 652	 17 985 16793	 39 278 36 253
Stroke (in)	7.21	5.35	2.44
Output Velocity in/s	 7.28	 4.80	 ---
Loop Gain (rad/s)	---	---	---
Hysteresis (Percent Full Stroke)	---	---	---

NOTES:

A - 4000 psi
B - MIL-H-5606
C - Two-stage electrohydraulic servovalves
D - Dual coil, two-stage electrohydraulic servovalve

TABLE 8A - SPACE SHUTTLE TVC ACTUATOR CHARACTERISTICS

Characteristics	SSME TVC Upper Pitch	SSME TVC Lower Pitch	SSME TVC Yaw	SRB TVC
Hydraulics Pressure (psi) Fluid	 A B	 A B	 A B	 A B
Redundancy Hydraulic Electrical	 Triplex Quad	 Triplex Quad	 Triplex Quad	 Dual Quad
Electrical Failure Capability	Two-Fail-Op	Two-Fail-Op	Two-Fail-Op	Two-Fail-Op
Backup Fail-Safe Modes	---	---	---	---
Servovalves	C	C	C	C
Output Force (lb) Compression Tension	 74 400 74 400	 60 000 60 000	 60 000 60 000	 96 900 96 900
Stroke (in)	10.9	10.9	8.8	12.8
Output Velocity (No Load) in/s	 5.2	 5.2	 5.2	 6.7
Loop Gain (rad/s)				18.5
Hysteresis (Percent Full Stroke)				3.0

NOTES:

A - 3000 psi
B - MIL-H-83282
C - Four, two-stage, flapper-nozzle, pressure-feedback drivers for single, four-way power stage
D - Mechanical feedback

TABLE 8B - SPACE SHUTTLE ORBITOR ACTUATOR CHARACTERISTICS

Characteristics	Inbd Elevon	Outbd Elevon	Rudder
Hydraulics Pressure (psi) Fluid	 A B	 A B	 A B
Redundancy Hydraulic Electrical	 Simplex Quad	 Simplex Quad	 Triplex Quad
Electrical Failure Capability	Two-Fail-Op	Two-Fail-Op	Two-Fail-Op
Backup Fail-Safe Modes	---	---	---
Servovalves	C	C	C
Output Force (lb) Compression Tension	 65 400 65 400	 54 000 54 000	
Stroke (in)	14.6	8.5	
Output Velocity (No-Load) in/s	5.3	3.1	
Loop Gain (rad/s) D			
Hysteresis (Percent Full Stroke)			

NOTES:

A - 3000 psi
B - MIL-H-83282
C - Four, two-stage, flapper-nozzle, pressure-feedback drivers for single, four-way power stage
D - Electrical feedback

TABLE 9 - LAVI PRIMARY FLIGHT CONTROL SERVOACTUATOR CHARACTERISTICS

Characteristics	Elevon	Rudder	Canard
Hydraulics Pressure (psi) Fluid	 3,000 MIL–H–83282	 3,000 MIL–H–83282	 3,000 MIL–H–83282
Redundancy Hydraulic Electrical	 Dual Quad	 Dual Quad	 Dual Quad
Electrical Failure Capability	Two-Fail-Op / Fail-Safe	Two-Fail-Op / Fail-Safe	Two-Fail-Op / Fail-Safe
Fail-Safe Modes	Power-to-Center	Power-to-Center	Power-to-Center
Servovalves	A	A	A
Output Force (lb) Compression Tension	 25,300 25,300	 19,200 19,200	 16,400 16,400
Stroke (in)	4.0	2.4	5.0
Output Velocity (in/s)	5.0	4.9	10.1
Loop Gain (rad/s)	50	50	50
Hysteresis (% Full Stroke)	<.01	<.01	<.01

NOTES:

A - Two pairs of quad-coil, single-stage servovalves

TABLE 10 - JAS-39 ACTUATOR CHARACTERISTICS

Characteristics	Inboard Elevon	Outboard Elevon	Canard	Rudder
Hydraulics Pressure (psi) Fluid	 4000 psi MIL-H-5606	 4000 psi MIL-H-5606	 4000 psi MIL-H-5606	 4000 psi MIL-H-5606
Redundancy Hydraulic Electrical	 Dual Triplex	 Dual Triplex	 Dual Triplex	 Dual Triplex
Electrical Failure Capability	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe
Fail-Safe Modes	Damped Bypass	Damped Bypass	Damped Bypass	Damped Bypass
Servovalves	Linear Direct Drive	Linear Direct Drive	Linear Direct Drive	Linear Direct Drive
Output Force (lb) Compression Tension	 38,400 38,400	 15,700 13,900	 21,600 21,600	 11,700 11,700
Stroke (in)	4.19	4.08	6.00	2.80
Output Velocity in/s deg/s	 4.3 60	 4.0 60	 4.6 60	 2.8 60
Loop Gain (rad/s)	25	25	25	25
Hysteresis (% Full Stroke)	0.1	0.1	0.1	0.1

TABLE 11 - V-22 PRIMARY FLIGHT CONTROL ACTUATOR CHARACTERISTICS

Characteristics	Swashplate	Flaperon	Elevator	Rudder	Conversion
Hydraulics					
Pressure (psi)	5,000	5,000	5,000	5,000	5,000
Fluid (see Note D)	MIL-H-83282	MIL-H-83282	MIL-H-83282	MIL-H-83282	MIL-H-83282
Redundancy					
Hydraulic	Dual	Simplex	Simplex	Simplex	Dual
Electrical	Triplex	Simplex	Simplex	Simplex	Triplex
Electrical Failure Capability	Fail-Op/ Fail-Op	Fail-Safe	Fail-Safe	Fail-Safe	Fail-Op/ Fail-Op
Fail-Safe Modes	None	Bypass	Bypass	Bypass	None
Servovalves	A	B	B	B	C
Output Force (lb)					
Compression	8,697	4,832	6,487		33,000
Tension	13,160	3,682	6,487		33,000
Stroke (in)	16.45	8.50	4.92		45.0
Output Velocity					
in/s	6.5	13.0 Ext./ 11.0 Ret.	11.0		3.8
deg/s					7.5
Loop Gain (rad/s)	50.0	31.4	31.4	31.4	20.0
Hysteresis (% Full Stroke)	<0.04	<0.075	<0.12		<1.5

NOTES:

A - Three 2-stage nozzle-flapper EHSVs
B - Single 2-stage nozzle-flapper EHSV
C - Two 2-stage nozzle-flapper EHSVs
D - Referenced fluid applies above -40 °F. MIL-H-5606 is qualified for temperatures down to -65 °F.

TABLE 12 - SAAB 2000 ACTUATOR CHARACTERISTICS

Characteristics	Rudder	Elevator
Hydraulics Pressure (psi) Fluid	 3000 MIL-H-5606	 3000 MIL-H-5606
Redundancy Hydraulic Electrical	 Dual Dual	 Dual Dual
Electrical Failure Capability	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe
Fail-Safe Modes	Damped Bypass	A
Servovalves	B	B
Output Force (lb) Compression Tension	 11,800 11,800	 4,600 4,600
Stroke (in)	7.40	2.46
Output Velocity (in/s)	2.6	1.4
Loop Gain (rad/s)	20	20

NOTES:

A - Damped bypass for each actuator; emergency electromechanical pitch trim actuator engages if both primary elevator actuators bypass

B - 2-stage nozzle-flapper pressure-flow (P-Q) control EHV with electrical spool position feedback

TABLE 13 - IDF ACTUATOR CHARACTERISTICS

Characteristics	Flaperon	Horizontal Tail	Rudder	Leading Edge Flap
Hydraulics Pressure (psi) Fluid	 3,000 MIL-H-5606	 3,000 MIL-H-5606	 3,000 MIL-H-5606	 3,000 MIL-H-5606
Redundancy Hydraulic Electrical	 Dual Triplex	 Dual Triplex	 Dual Triplex	 Dual Triplex
Electrical Failure Capability	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe
Fail-Safe Modes	Damped Bypass	Damped Bypass	Damped Bypass	Damped Bypass
Servovalves	A	A	A	A
Output Force (lb) Compression Tension	 36,000 36,000	 27,000 27,000	 25,000 25,000	210,000 in-lb
Stroke (in)	3.72	4.06	2.62	30°
Output Velocity (in/s)	4.0	6.1	5.4	28°/s
Loop Gain (rad/s)	25	25	25	20
Hysteresis (% Full Stroke)	<0.2	<0.2	<0.3	<1.5

NOTES:

A - Linear direct-drive valve

TABLE 14 - B-2 ACTUATOR CHARACTERISTICS

Characteristics	GLAS	Inboard Elevon	Middle Elevon	Outboard Elevon	Lower Rudder	Upper Rudder
Hydraulics						
Pressure (psi)	4000	4000	4000	4000	4000	4000
Fluid	MIL-H-5606	MIL-H-5606	MIL-H-5606	MIL-H-5606	MIL-H-5606	MIL-H-5606
Redundancy						
Hydraulic	Dual	Dual	Dual	Dual	Dual	Dual
Electrical	Quad	Quad	Quad	Quad	Quad	Quad
Electrical Failure Capability	Three-Fail-Op/ Fail-Safe	Three-Fail-Op/ Fail-Safe	Three-Fail-Op/ Fail-Safe	Three-Fail-Op/ Fail-Safe	Three-Fail-Op/ Fail-Safe	Three-Fail-Op/ Fail-Safe
Backup/ Fail-Safe Modes	A	A	A	A	A	A
Servovalves	B	B	B	B	B	B
Output Force* (lb)						
Compression	19,913	20,000	21,282	17,000	45,187	23,231
Tension	21,335	25,800	43,800	25,716	18,500	7,500
Stroke (in)	2.585	6.221	6.215	5.215	6.075	6.075
Output Velocity (No Load)						
in/s	10.42	10.12	5.06	4.22	6.56	6.56
deg/s	100	100	50	50	80	80
Loop Gain (rad/sec)	25	35	45	35	40	40
Hysteresis (Percent Full Stroke)	0.1	0.1	0.1	0.1	0.1	0.1
Actuators per Surface	2	3	2	2	2	2

NOTES:

A - Since multi-actuators per surface, first actuator goes to bypass. Last actuator on surface remains engaged.
B - Quad coil linear direct drive valve
* - Steady-state software limits, not hydraulic stall limits

TABLE 15 - C-17 ACTUATOR CHARACTERISTICS

Characteristics	Aileron	Rudder	Elevator	Spoiler	Flap	Slat	Pitch Trim
Hydraulics Pressure (psi) Fluid	4,000 MIL-H-83282	4,000 MIL-H-83282	4,000 MIL-H-83282	4,000 MIL-H-83282	4,000 MIL-H-83282	4,000 MIL-H-83282	4,000 MIL-H-83282
Redundancy Hydraulic Electrical	Dual Quad	Dual Quad	Dual Quad	Simplex Dual	Dual Dual	Dual Simplex	Dual Dual
Electrical Failure Capability	Fail-Op/ Fail-Op/ Fail-Safe	Fail-Op/ Fail-Op/ Fail-Safe	Fail-Op/ Fail-Op/ Fail-Safe	Fail-Safe	Fail-Op/ Fail-Safe	Fail-Safe	Fail-Op/ Fail-Safe
Fail-Safe Modes	A	A	A	Power to Retract	B	B	B
Servovalves	Jet-Pipe EHSV	Jet-Pipe EHSV	Jet-Pipe EHSV	3-Way Jet-Pipe EHSV	Jet-Pipe EHSV	N/A	N/A
Output Force (lb) Compression	94,000	65,700	25,000	23,600 I.B. 14,100 O.B.	171,000 I.B. 127,000 O.B.	N/A	N/A
Tension	72,000	65,700	13,000	32,800 I.B. 21,500 O.B.	124,000 I.B. 98,000 O.B.	N/A	N/A
Stroke (in)	5.9	4.9	4.5 I.B. 2.6 O.B.	5.1	17.9 I.B. 13.3 O.B.	17.3-23.3	N/A
Output Velocity deg/s	41.2	37.4	26.2 I.B. 45.9 O.B.	60	3.0 Ext. 2.0 Ret.	N/A	N/A
@ % Stall	25	75	25	25			

NOTES:

A - Mechanical back-up or damped bypass if all hydraulic power to actuator is lost
B - Locked in last position

TABLE 16 - X-31A ACTUATOR CHARACTERISTICS

Characteristics	Trailing Edge	Rudder/ Canard	Speed Brake/ Thrust Vector	Air Inlet	Leading Edge
Hydraulics					
Pressure (psi)	3000	3000	3000	3000	3000
Fluid	MIL-H-83282	MIL-H-83282	MIL-H-83282	MIL-H-83282	MIL-H-83282
Redundancy					
Hydraulic	Dual	Dual	Simplex	Simplex	Simplex
Electrical	Triplex	Triplex	Dual	Dual	Dual
Electrical Failure Capability	Two Fail-Op	Two Fail-Op/ Fail-Safe	Two Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe
Fail-Safe Modes	None	Damped Bypass	Damped Bypass	Damped Bypass	Lock in Place
Servovalves	A	B	C	C	C
Output Force (lb)					
Compression	10,595	10,595	17,262	10,595	110,000 in-lb
Tension	10,595	10,595	17,262	10,595	110,000 in-lb
Stroke (in)	4.6	4.0	5.7	1.25	40°
Output Velocity					
in/s	5.6	5.6	6.0	1.6	N/A
deg/s	80	80 (Rudder) 100 (Canard)	50 (Speed Brake) 87 (Thrust Vector)	30	31
Loop Gain (rad/s)	63	63	50	50	20
Hysteresis (% Full Stroke)	0.1	0.1	0.1	0.1	0.25

NOTES:

A - Three 2-stage flapper-nozzle EHSVs
B - Tandem rotary-rotary direct drive valve
C - Single 2-stage deflector-jet EHSV

TABLE 17 - BOEING 777-200 ACTUATOR CHARACTERISTICS

Characteristics	Elevator	Rudder	Aileron	Flaperon	Spoiler, Outboard	Spoiler, Inboard
Actuators Per Surface	2	3	2	2	1	1
Hydraulics Sys. Pressure (psi) Hydraulic Fluid	3000 A	3000 A	3000 A	3000 A	3000 A	3000 A
Hydraulic System Failure Capability *	Fail - op/ Fail - safe	Fail - op/ Fail - op/ Fail - safe	Fail - op/ Fail - safe	Fail - op/ Fail - safe	Fail - safe	Fail - safe
Electrical System Failure Capability *	Fail - op/ Fail - safe	Fail - op/ Fail - op/ Fail - safe	Fail - op/ Fail - safe	Fail - op/ Fail - safe	Fail - safe	Fail - safe
Servovalve	B	B	B	B	B	B
Max. Output Force (lbs) Extend Retract	28,900 28,900	28,900 28,900	11,600 11,600	6,500 4,100	10,200 7,300	22,900 22,900
Max. Rate (in/sec) Extend Retract	6.7 6.7	9.1 9.1	3.5 3.5	17.4 13.5	6.7 5.5	5.6 5.6
Stroke (in) Extend Retract	3.49 2.99	3.23 3.25	1.59 0.92	10.25 2.35	6.20 -	4.79 -

NOTES:

A - AS1241 Type IV phosphate ester
B - 2-stage deflector jet servovalve
* - Capability at surface level

TABLE 18 - X-29A ACTUATOR CHARACTERISTICS

Characteristics	Canard	Rudder	Flaperon	Strake
Hydraulics Pressure (psi) Fluid	 3000 MIL-H-5606	 3000 MIL-H-5606	 3000 MIL-H-5606	 3000 MIL-H-5606
Redundancy Hydraulic Electrical	 Dual Triplex	 Dual Triplex	 Dual Triplex	 Dual Triplex
Electrical Failure Capability	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe
Fail-Safe Modes	A	A	A	A
Servovalves	B	B	B	C
Output Force (lb) (Compression & Tension)	34,900	21,700	21,700	8,940
Stroke (in)	4.25	2.65	2.65	3.2
Output Velocity in/s deg/s	 5.1 118	 5.1 155	 5.1 75	 1.1 30
Loop Gain (rad/s)	24	24	24	35
Hysteresis (% Full Stroke)	3.0	3.0	3.0	3.0

NOTES:

A - Drive to stowed position
B - Three 2-stage jet pipe servovalves
C - Two pairs of series nozzle-flapper servovalves

TABLE 19A - AIRBUS A319/320/321 ACTUATOR CHARACTERISTICS

Characteristics	**Elevator**	**Rudder**	**Aileron**	**Spoiler**
Actuators per Surface	2	3	2	1
Hydraulics Pressure (psi) Fluid	 3000 A	 3000 A	 3000 A	 3000 A
Hydraulic System Failure Capability*	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Safe
Electrical System Failure Capability*	Fail-Op/ Fail-Op/ Fail-Op/ Fail-Safe	Fail-Op/ Fail-Op	Fail-Op/ Fail-Safe	Fail-Safe
Fail-Safe Modes	Centering/ Damped Bypass	Damped Bypass	Damped Bypass	Surface Down
Servovalves	B	B (Yaw Damper)	B	B
Output Force (lb) Extend Retract	 6,230 6,230	 9,960 9,960	 10,200 10,200	 10,100 8,230
Max. Rate (in/sec)	2.4	4.3	3.5	3.9
Total Stroke (in)	2.4	4.3	1.7	3.3

NOTES:

A - AS1241 Type IV phosphate ester
B - 2-stage single inlet servovalve
* - Capability at surface level

TABLE 19B - AIRBUS A330/340 ACTUATOR CHARACTERISTICS

Characteristics	Elevator	Rudder	Inboard Aileron	Outboard Aileron	Spoiler
Actuators per Surface	2	3	2	2	1
Hydraulics Pressure (psi) Fluid	 3000 A	 3000 A	 3000 A	 3000 A	 3000 A
Hydraulic System Failure Capability*	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Safe
Electrical System Failure Capability*	Fail-Op/ Fail-Op/ Fail-Op/ Fail-Safe	Fail-Op/ Fail-Op	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Safe
Fail-Safe Modes	Centering/ Damped Bypass	Damped Bypass	Damped Bypass	Damped Bypass	Surface Down
Servovalves	B	B	B (Yaw Damper)	B	B
Output Force (lb) Extend Retract	 22,900 22,900	 21,100 21,100	 37,100 37,100	 23,800 23,800	 25,000 19,400
Max. Rate (in/sec)	4.7	5.3	4.3	4.3	2.4
Total Stroke (in)	3.9	6.2	3.3	3.0	2.8

NOTES:

A - type IV phosphate ester
B - 2-stage single inlet servovalve
* - Capability at surface level

TABLE 20 - F-117 ACTUATOR CHARACTERISTICS

Characteristics	Inboard Elevon	Outboard Elevon	Tail Fin
Hydraulics Pressure (psi) Fluid	 3000 MIL-H-5606	 3000 MIL-H-5606	 3000 MIL-H-5606
Redundancy Hydraulic Electrical	 Dual Triplex	 Dual Triplex	 Dual Triplex
Electrical Failure Capability	Two Fail-Op/ Fail-Safe	Two Fail-Op/ Fail-Safe	Two Fail-Op/ Fail-Safe
Fail-Safe Modes	Drive to Center	Drive to Center	Drive to Center
Servovalves	A	A	A
Outout Force (lb) Compression Tension	 34,900 34,900	 21,700 21,700	 21,700 21,700
Stroke (in)	3.35		
Output Velocity in/s deg/s	 5.1 125	 5.3 	 5.3
Loop Gain (rad/s)	14.4	14.4	14.4
Hysteresis (% Full Stroke)	3.0	3.0	3.0

NOTES:

A - Three 2-stage jet pipe EHSVs

TABLE 21 - N-250 ACTUATOR CHARACTERISTICS

Characteristics	Aileron	Elevator	Rudder	Spoiler
Actuators per Surface	2 (FBW)	2 (1 FBW, 1 Mech. Input)	2 (1 FBW, 1 Mech. Input)	1 (FBW)
Hydraulics				
Pressure (psi)	3,000	3,000	3,000	3,000
Fluid	A	A	A	A
Hydraulic System Failure Capability*	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Safe
Electrical System Failure Capability*	Fail-Op	Fail-Op	Fail-Op/ Fail-Safe	Fail-Safe
Fail-Safe Modes	Damped Bypass	Centering/ Damped Bypass	Damped Bypass	Surface Down
Servovalves	B	B	B	B
Output Force (lb)				
Extend	10,700	11,000	4,900	7,100
Retract	10,700	11,000	4,900	5,500
Stroke (in)	3.54	2.50	1.70	2.25
Max. No Load Rate				
Extend (in/sec)	4.1	2.09	1.77	2.7
Retract (in/sec)	4.1	2.09	1.77	2.3

NOTES:

A - AS1241 Type IV phosphate ester
B - 2-stage single inlet servovalve
* - Capability at surface level

TABLE 22A - A380 ACTUATOR CHARACTERISTICS (PRIMARY SURFACES)

Characterstic	Outboard Aileron	Inboard & Middle Aileron		Upper & Lower Rudder	Inboard & Outboard Elevator	
Actuators per Surface	2 Conventional FBW Actuators	1 Conventional FBW Actuator	1 EHA	2 EBHA	1 Conventional FBW Actuator	1 EHA
Hydraulics Pressure Fluid	 5000 psi Phosphate Ester Type IV / V	 5000 psi Phosphate Ester Type IV / V	 5000 psi Phosphate Ester Type IV / V	 5000 psi Phosphate Ester Type IV / V	 5000 psi Phosphate Ester Type IV / V	 5000 psi Phosphate Ester Type IV / V
Electrical Power	N / A	N / A	115 VAC-VF	115 VAC-VF	N / A	115 VAC-VF
Hyd / Elec Power Supply Failure Capability *	Fail-Op / Fail-Safe	Fail-Op / Fail-Safe		Fail-Op / Fail-Op /Fail-Op /Fail-Op /Fail-Safe	Fail-Op / Fail-Safe	
Computer Failure Capability *	Fail-Op / Fail-Safe	Fail-Op / Fail-Op /Fail-Op /Fail-Op /Fail-Op /Fail-Safe		Fail-Op / Fail-Op /Fail-Op /Fail-Op /Fail-Op /Fail-Safe	Fail-Op / Fail-Op /Fail-Op /Fail-Op /Fail-Op /Fail-Safe	
Fail-Safe Modes	Damped Bypass	Damped Bypass	Damped Bypass	Damped Bypass	Damped Bypass	Damped Bypass
Servovalves	2 stage Single Inlet	2 stage Single Inlet	N / A	2 stage Single Inlet	2 stage Single Inlet	N / A
Output force Extend Retract	 135 kN 135 kN	 135 kN 135 kN	 135 kN 135 kN	 225 kN 225 kN	 180 kN 180 kN	 180 kN 180 kN
Max Rate	81 mm/S	81 mm/S	81 mm/S	120 mm/s (hyd) 45 mm/s (elec)	107 mm/s	107 mm/s
Total Stroke	115 mm	115 mm	115 mm	186 mm	149 mm	149 mm

NOTES:

EHA = Electrohydrostatic Actuator
EBHA = Electrical Back-up Hydraulic Actuator
* Failure capability is at surface level

TABLE 22B - A380 ACTUATOR CHARACTERISTICS (SPOILER SURFACES)

Characterstic	Spoiler 1 - 4 & 7 - 8	Spoiler 5-6
Actuators per Surface	1 Conventional FBW Actuator	1 EBHA
Hydraulics Pressure Fluid	 5000 psi Phosphate Ester Type IV / V	 5000 psi Phosphate Ester Type IV / V
Electrical Power	N / A	115 VAC-VF
Hyd / Elec Power Supply Failure Capability	Fail-Safe	Fail-Op / Fail-Safe
Computer Failure Capability	Fail-Safe	Fail-Safe
Fail-Safe Modes	Surface Down	Surface Down
Servovalves	2 stage Single Inlet	2 stage Single Inlet
Output force Extend Retract	215 kN 145 kN	215 kN 145 kN
Max Rate	100/80 mm/s	100/80 mm/s (hyd) 26 mm/s (elec)
Total Stroke	116 mm	116 mm

NOTES:

EHA = Electrohydrostatic Actuator
EBHA = Electrical Back-up Hydraulic Actuator

TABLE 23A - BA609 ROTOR AND CONVERSION ACTUATOR CHARACTERISTICS

Characteristic	Collective	Longitudinal	Conversion
Hydraulics Pressure (psi) Fluid	 3000 MIL-PRF-87257	 3000 MIL-PRF-87257	 3000 MIL-PRF-87257
Redundancy Hydraulic Electrical	 Triplex Triplex	 Triplex Triplex	 Triplex[A] Triplex
Hydraulic/Electrical Failure Capability	 Two Fail-Op	 Two Fail-Op	 Two Fail-Op
Fail-Safe Modes	None	None	Locked
Servovalve	3 nozzle-flapper	3 nozzle-flapper	2 jet-pipe
Manifold Configuration	Dual Solenoid Dual ITFV[B]	Dual Solenoid Single ITFV[B]	Three Solenoid Integral Motor & Manifold
Output Force (lb) Compression Tension	Total/Single 24 714/8238 24 714/8238	Total/Single 6645/2215 6645/2215	 17 700 17 700
Stroke (in)	5.43	6.36	30.90
Output Velocity in/s deg/s	 2.3	 6.1	 2.9 8.0
Hysteresis (% Full Stroke)	<0.11	<0.09	<0.20

TABLE 23B - BA609 CONTROL SURFACE ACTUATOR CHARACTERISTICS

Characteristics	Flaperon	Elevator
Hydraulics Pressure (psi) Fluid	 3000 MIL-PRF-87257	 3000 MIL-PRF-87257
Redundancy Hydraulic Electrical	 Simplex Simplex	 Simplex Simplex
Hydraulic/Electrical Failure Capability	 Single Fail-Safe	 Single Fail-Safe
Fail-Safe Modes	Bypass	Bypass
Servovalve	1 nozzle-flapper	1 nozzle-flapper
Manifold Configuration	Single Solenoid Single ITFV[B]	Single Solenoid Single ITFV[B]
Output Force (lb) Compression Tension	 6639 5343	 2356 1729
Stroke (in)	4.59	1.58
Output Velocity in/s deg/s	Extend/Retract 4.8/4.5	Extend/Retract 3.3/2.8
Hysteresis (% Full Stroke)	<0.13	<0.38

TABLE 24 - EUROFIGHTER ACTUATOR CHARACTERISTICS

Characteristics		Foreplane	Inboard Flaperon	Outboard Flaperon	Rudder	Airbrake
Hydraulics						
Pressure	MPa (psi)	27.5 (4000)				
Fluid		Mil-PRF-5606/83282/87257				
Redundancy						
Hydraulic		Dual				Single
Electrical		Quadruplex				Single
Valve						
Type		Direct Drive Valve (Quadruplex Motor)				EHSV
Output Force						
Compression	kN (lbf)	134 (30,125)	208 (46,761)	191 (42,939)	253 (56,877)	104 (23,380)
Tension	kN (lbf)	126 (28,326)	182 (40,916)	167 (37,543)	234 (52,606)	58 (13,039)
Stroke						
Nominal	mm (in)	154 (6.06)	115 (4.53)	103 (4.06)	145 (5.71)	526 (20.71)
Speed						
No Load	mm/s (in/s)	180 (7.09)	222 (8.74)	206 (8.11)	242 (9.53)	232 (9.13)

TABLE 25A - A400M ACTUATOR CHARACTERISTICS (PRIMARY SURFACES)

Characterstic	Aileron		Rudder	Elevator	
Actuators per surface	1 Conventional FBW Actuator	1 EHA	2 EBHA	1 Conventional FBW Actuator	1 EHA
Hydraulics Pressure Fluid	3000 psi Phosphate ester type IV / V	3000 psi Phosphate ester type IV / V	3000 psi Phosphate ester type IV / V	3000 psi Phosphate ester type IV / V	3000 psi Phosphate ester type IV / V
Electrical power	N / A	115 VAC-VF	115 VAC-VF	N / A	115 VAC-VF
Hyd / elec power supply failure capability *	Fail-Op / Fail-Safe		Fail-Op / Fail-Op /Fail-Op /Fail-Op /Fail-Safe	Fail-Op / Fail-Safe	
Computer failure capability *	Fail-Op / Fail-Op /Fail-Op /Fail-Op /Fail-Safe		Fail-Op / Fail-Op /Fail-Op /Fail-Op /Fail-Safe	Fail-Op / Fail-Op /Fail-Op /Fail-Op /Fail-Safe	
Fail-safe modes	Damped by-pass	Damped by-pass	Damped by-pass	Damped by-pass	Damped by-pass
Servovalves	2 stage single inlet	N / A	2 stage single inlet	2 stage single inlet	N / A
Output force Extend Retract	148 kN 148 kN	120 kN 120 kN	120 kN 120 kN	148 kN 148 kN	82 kN 82 kN
Max Rate	115 mm/S	64 mm/S	133 mm/s (hyd) 54 mm/s (elec)	115 mm/s	38 mm/s
Total Stroke	88 mm	84 mm	178 mm	88 mm	84 mm

TABLE 25B - A400M ACTUATOR CHARACTERISTICS (SPOILER SURFACES)

Characterstic	Spoiler 3-5	Spoiler 2	Spoiler 1
Actuators per surface	1 Conventional FBW Actuator	1 Conventional FBW Actuator	1 EBHA
Hydraulics Pressure Fluid	3000 psi Phosphate ester type IV / V	3000 psi Phosphate ester type IV / V	3000 psi Phosphate ester type IV / V
Electrical power	N / A	N / A	115 VAC-VF
Hyd / elec power supply failure capability *	Fail-Safe	Fail-Safe	Fail-Op / Fail-Safe
Computer failure capability *	Fail-Safe	Fail-Op/Fail-Safe	Fail-Safe
Fail-safe modes	Surface down	Surface down	Surface down
Servovalves	2 stage single inlet	2 stage single inlet	2 stage single inlet
Output force Extend Retract	110 kN 87 kN	96 kN 96 kN	90 kN 90 kN
Max Rate	125/110 mm/s	168 mm/s	147 mm/s (hyd) 75 mm/s (elec)
Total Stroke	116 mm	78 mm	78 mm

3.2 NASA F-8 DFBW Secondary Actuators

The NASA F-8 digital fly-by-wire (DFBW) program was a research and development program which was used to provide the foundation for the technology in terms of design criteria and practical DFBW experience. Secondary servoactuators were used to replace the linkage between the pilot's stick and the power actuators on a converted Navy F-8C aircraft.

The F-8 DFBW program was accomplished in two phases. Phase I consisted of a single DFBW primary control system witih an analog backup control system which provided two-fail-operate/fail-off capability. Phase II consisted of a triplex DFBW system with single fail-operate/fail-neutral capability.

3.2.1 Phase I Servoactuator Configuration

The Phase I secondary servoactuator was designed to provide reliability equivalent to the conventional mechanical linkage system. To achieve this, the secondary servoactuator was designed with a quadruplex redundant capability to provide a two-fail-operate/fail-off performance. Thus, if any two channels became inoperative, the secondary servoactuator would continue to operate normally.

The secondary servoactuator consists of four electrohydraulic control channels, a triple tandem piston and a quadruplex LVDT for feedback loop closure. The servoactuator is shown schematically in Figure 1. The system is an active/standby configuration consisting of a monitored primary channel witih hydraulic logic failure detection in servo system 1 and three force-summed standby channels with electronic failure detection (servo systems 2, 3, and 4). Servo system 1 is designed to be a relatively high response system and uses a pair of two-stage flapper nozzle servovalves in an active/monitor configuration. The backup or standby channels, servo systems 2, 3, and 4, are designed for lower response requirements and use three single-stage jet-pipe servovalves in a force-summing configuration. The low pressure gain of the single-stage jet-pipe servovalve permits force shraing without a force equalization network. The servoactuator is supplied by two independent hydraulic supplies, and the design provides complete hydraulic system isolation with rip stop construction. A cross-section of the Phase I servoactuator is shown in Figure 2.

Servo system 1, which provides the normal and primary mode of operation, has an active electrohydraulic servovalve plus a monitor servovalve. The servovalves are modified two-stage, flapper-nozzle valves. The active valve controls the actuator output and is monitored hydraulically by the monitor servovalve and hydraulic comparator. The only difference between the active servovalve and the monitor valve is that the monitor valve has a blank spool in place of the second stage spool and sleeve.

3.2.2 Phase I Servoactuator Redundancy Management

If a failure occurs in the servoactuator or its servo loop electronics, the outputs of the active and monitor valves will differ. This will result in a pressure difference on the comparator spool, causing spool displacement. When the pressure difference exceeds a predetermined threshold, displacement of the comparator spool will dump the supply pressure to return. This allows the engage valve of servo system 1 to be shuttled, by the spring force, into a blocked position. The blocked position blocks the output of the active servovalve of system 1.

Upon a failure of the primary channel, the servo system 1 failure indicator will provide an electrical signal to automatically energize the solenoids of the standby channels 2, 3, and 4. Thus, a control transfer to the three-channel force-summed standby mode of operation takes place. Differential pressure transducers are provided across each cylinder port in order to provide signals which can be used to determine failure status.

Second failure (first failure in the standby system) will result in control with some degree of degradation. With one of the three channels deactivated, the servoactuator force ouptut is degraded by one-third, while the system response remains unchanged. When the second channel is deactivated, the system response is unchanged, while the force output is reduced by an additional third. Upon complete de-energizing of all solenoid valves, the total actuator is by-passed. Piston and seal friction are the only constraints on the piston when totally de-energized.

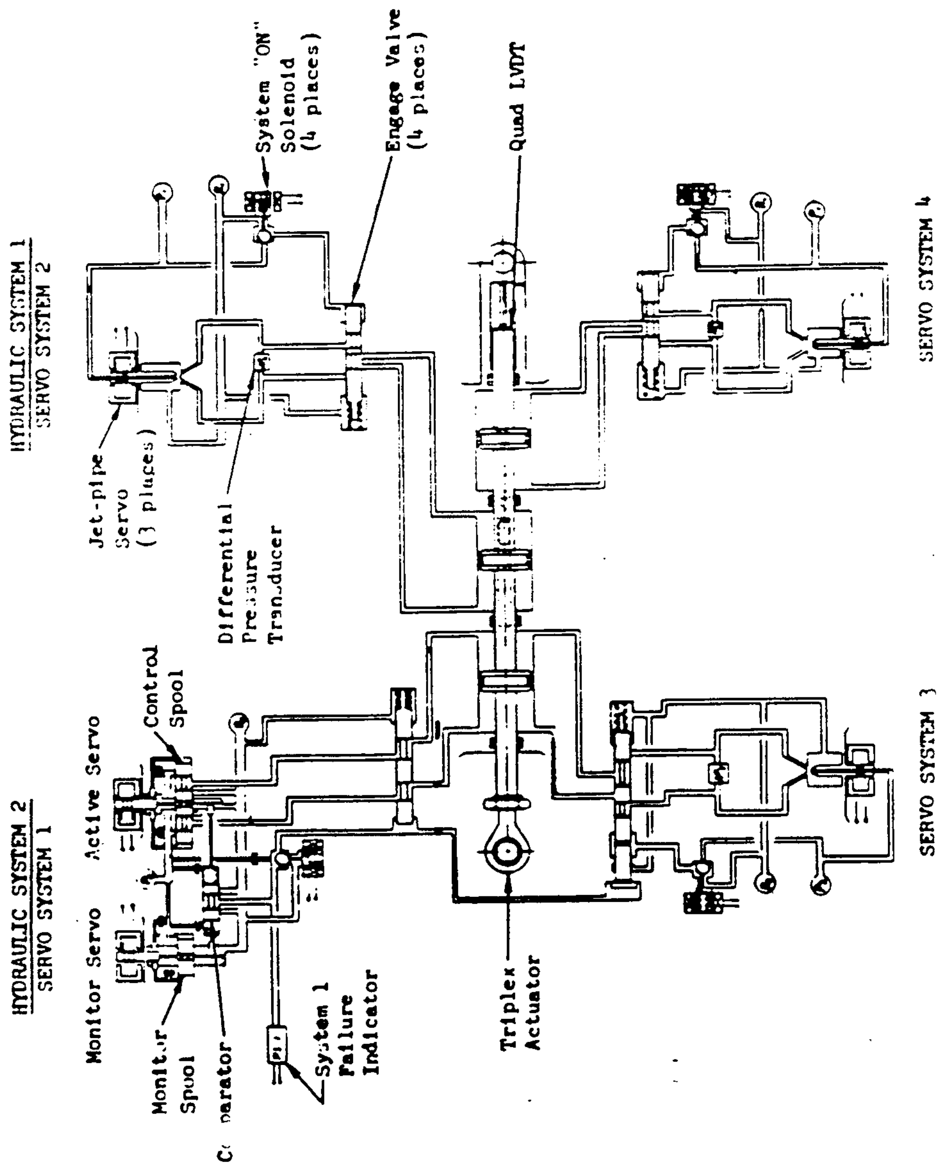


FIGURE 1 - PHASE I HYDRAULIC SCHEMATIC
QUAD REDUNDANT SECONDARY ACTUATOR

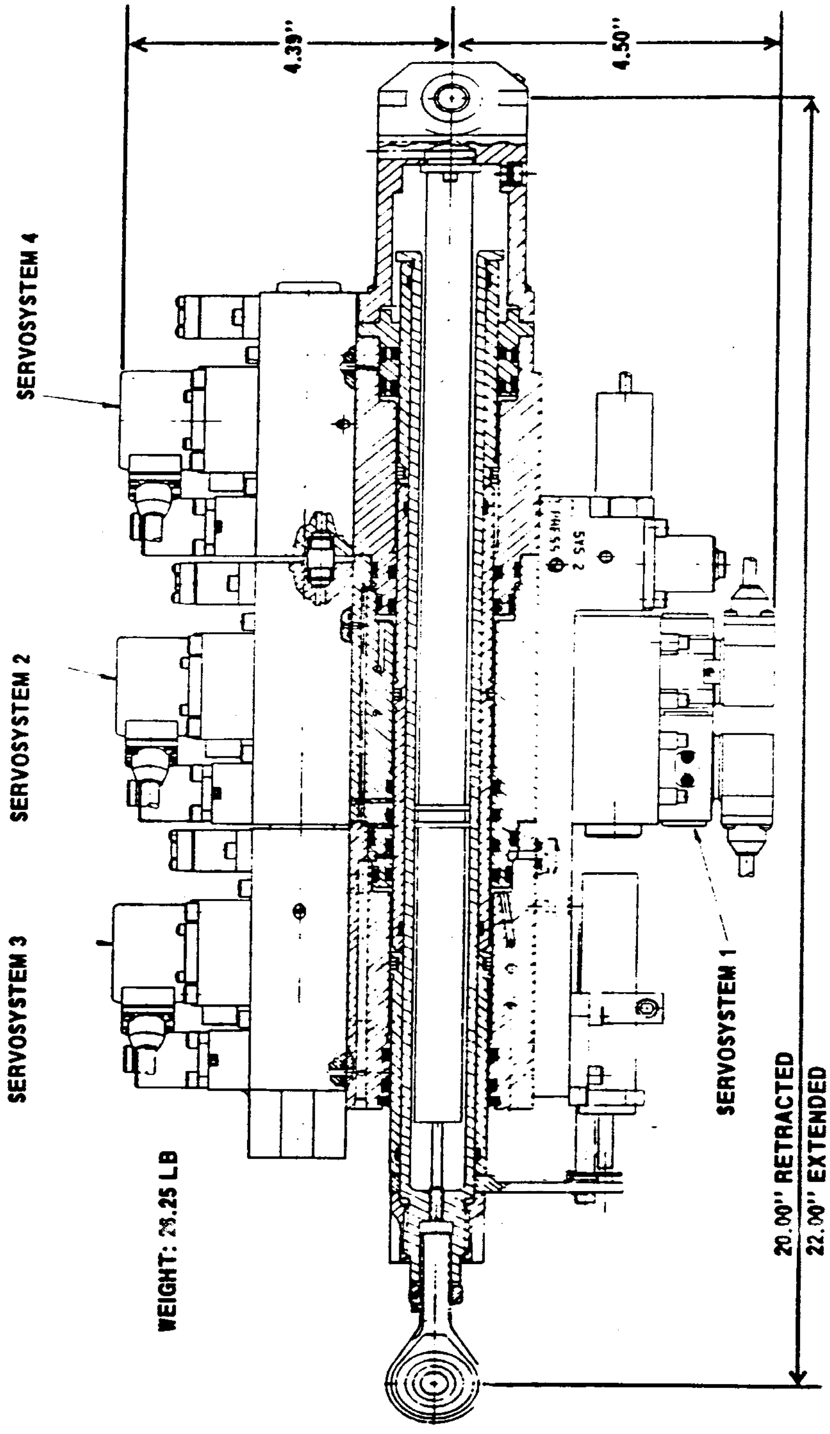


FIGURE 2 - PHASE J SECONDARY SERVOACTUATOR
CROSS-SECTION

3.2.3 Phase II Servoactuator Configuration

The Phase II secondary servoactuator was designed as a triplex redundant actuator capable of providing a single fail-operate/fail-neutral. The Phase II servoactuator configuration resulted from the following aircraft modifications:

- Installation of a triplex digital flight control computer.
- Addition of a third independent hydraulic supply to provide complete hydraulic supply redundancy.
- Addition of an external "spring bungee" assembly to drive the surface actuator to neutral (faired) position after total shutdown of the servoactuator.

The Phase II servoactuator consists of three electrohydraulic channels "A", "B", and "C" operating in tandem on a common shaft as shown in Figure 3. Each electrohydraulic channel incorporates the following features and components:

- A two-stage electrohydraulic flapper-nozzle servovalve to control the actuator motion.
- A solenoid valve to port pressurized fluid to the servovalve and to the actuator chambers.
- An engage valve, which allows the servovalve ports into the actuator chambers to be interconnected when disengaged providing a bypass mode which prevents a hydraulic lock.
- A differential pressure sensor and transducer for failure detection and channel synchronization.

The triple tandem piston contains a triplex LVDT for position output sensing and feedback loop closure. A cross-section of the triplex redundant Phase II secondary servoactuator is shown in Figure 4.

The normal operational configuratioin of the secondary servoactuator is three channels ON simultaneously. The full benefits of a multi-channel force summing can only be realized if all channels tend to work in harmony or synchronization. To guarantee this condition, a pressure feedback equalization scheme is required particularly in a servo system using high pressure gain valves. The incorporation of this feedback loop with a high DC gain serves to reduce any force fight among the various channels to tolerable limits.

3.2.4 Phase II Servoactuator Redundancy Management

If a failure occurs in a channel of the servoactuator or its servo loop electronics, a force fight will develop among the channels. This force fight is detected by the differential pressure sensors and the solenoid on the failed channel is de-energized.

The Phase II servoactuator was designed with some internal features which addressed passive failures and prevention of hydraulic lock. In the event a servovalve loses its electrical signal or has a passive failure, detection is accomplished by providing a mechanical null bias on the servovalve’s first stage. Thus, a bias in the servo loop electronics is needed to keep the servovalve at null. If a lead wire breaks or there is a short in the coil, the servovalve cannot be nulled. This will result in an immediate large pressure signal at the differential pressure sensor and the failed channel will be disengaged.

The solenoid valve is designed to be engaged only when energized with an electrical signal. In the event a solenoid valve loses its electrical signal, the solenoid valve is de-energized and pressure is shut off. This places the servoactuator channel in its fail-safe state.

A basic requirement for the Phase II servoactuator was that "no single hydraulic channel failure shall result in a hydraulic lock." In the event an engaged valve fails to close as the result of a mechanical failure of the spring or jamming of the spool, a hydraulic lock could occur by virtue of the electrohydraulic servovalve being at its null position. To preclude such a failure, a spring is provided in the servovalve second stage spool which will mechanically bias the spool to a hard-over position when pressure is removed by de-energizing the solenoid valve. This connects one of the cylinder ports directly to return and the other cylinder port is connected to return via the solenoid valve.

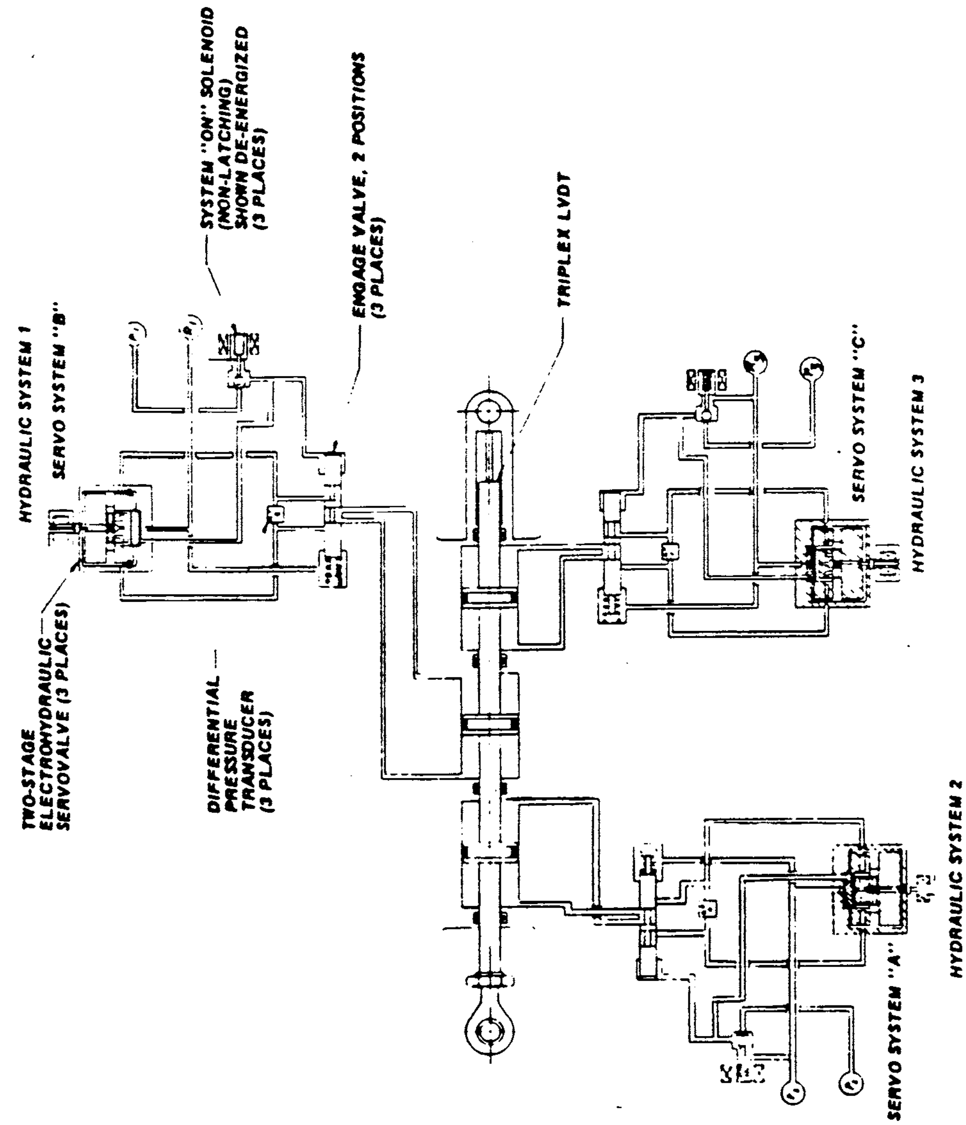


FIGURE 3 - PHASE II HYDRAULIC SCHEMATIC
TRIPLEX REDUNDANT SECONDARY SERVOACTUATOR

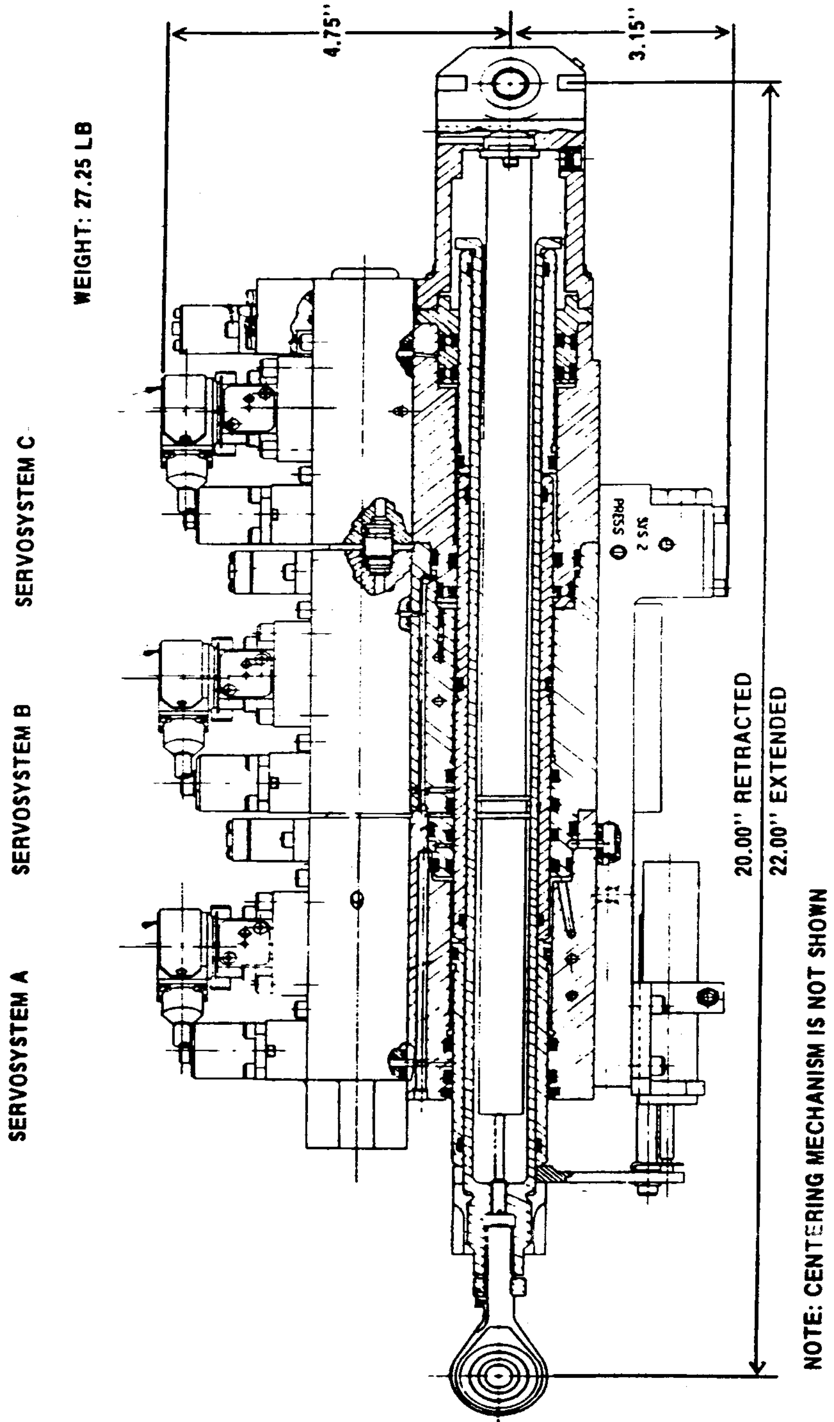


FIGURE 4 - PHASE II SECONDARY SERVOACTUATOR CROSS-SECTION

3.3 F-4 SFCS Secondary Actuators

The F-4 Survivable Flight Control System (SFCS) program was an Air Force flight control advanced development program, program No. 680J. The control system is a fully quadruplex, three axis system with two-fail operational capability. The quadruplex electrohydraulic secondary actuators converted the electrical signals into mechanical commands to the existing power actuator of the F-4 test aircraft. Three hydraulic power sources are normally available in the F-4 aircraft, power control system No. 1, No. 2, and utility. An electrically driven 1600 psi hydraulic pump was added as a fourth hydraulic system for the secondary actuators.

3.3.1 Secondary Actuator Configuration

The secondary actuator is comprised of four individual elements, which are small actuators, whose force outputs are summed through a rotary linkage to provide the single mechanical input to the surface actuator, as shown in Figure 5. The actuators used in the lateral and directional axes are designed with a centering mechanism after three failures. The actuator used in the longitudinal axis has a similar mechanism which holds it in the last position after the third failure. The front frame of the actuator assembly contains a spring-operated plunger which operates the centering or brake mechanism. The individual element of the actuators also contain a centering/brake release piston which is designed to totally disengage this function by compressing the spring plunger during normal operation and avoid affecting actuator performance.

Each individual actuator element is part of one of the electronic channels. Figure 6 shows a cross section of a typical econdary actuator element. Each element is driven by a single-stage jet pipe servoavle. The jet pipe servovalve was used because it has sufficient flow recovery to meet the actuator slew rate requirement while the low pressure gain allows the elements to force sum without the need for pressure equalization. Each element has a LVDT to provide position feedback to its channel of the electronics.

3.3.2 Secondary Actuator Redundancy Management

The elements contain a differential pressure sensor assembly which is used for failure monitoring. The sensor assembly performs several functions; it monitors the working pressure or differential pressure across the piston head, provides an indication of loss of pressure, and limits the differential. A LVDT in the sensor measures its position and provides electrical information for failure detection. The servovalve coils on the element supplied by the 1600 psi hydraulic system are connected in series while the coils on the other elements are wired in parallel. This tends to equalize the pressure gain of elements and the pressure limit in the differential pressure sensor prevents the 1600 psi element from being overpowered.

A failure or error in an element or its servo loop electronics will result in a force fight with the other elements and its differential pressure will increase relative to the others. When the differential pressure exceeds a predetermined level, failure logic in the electronics will indicate that the element has failed and initiate a shut-down by de-energizing the element’s solenoid-operated shutoff valve. A second failure will result in a similar sequence in another element. However, when the third element fails, the electronics will shut down both remaining elements. The element with the third failure fights the remaining element and the differential pressures in both increase toward the failure voting level. It is very difficult to determine which of the remaining two elements is good, thus necessitating the shut down of both elements in the event of the third failure. When a lateral or directional secondary actuator has been totally shut down, a spring-driven system centers the output. In the case of a longitudinal secondary actuator, a brake holds the actuator in its last position.

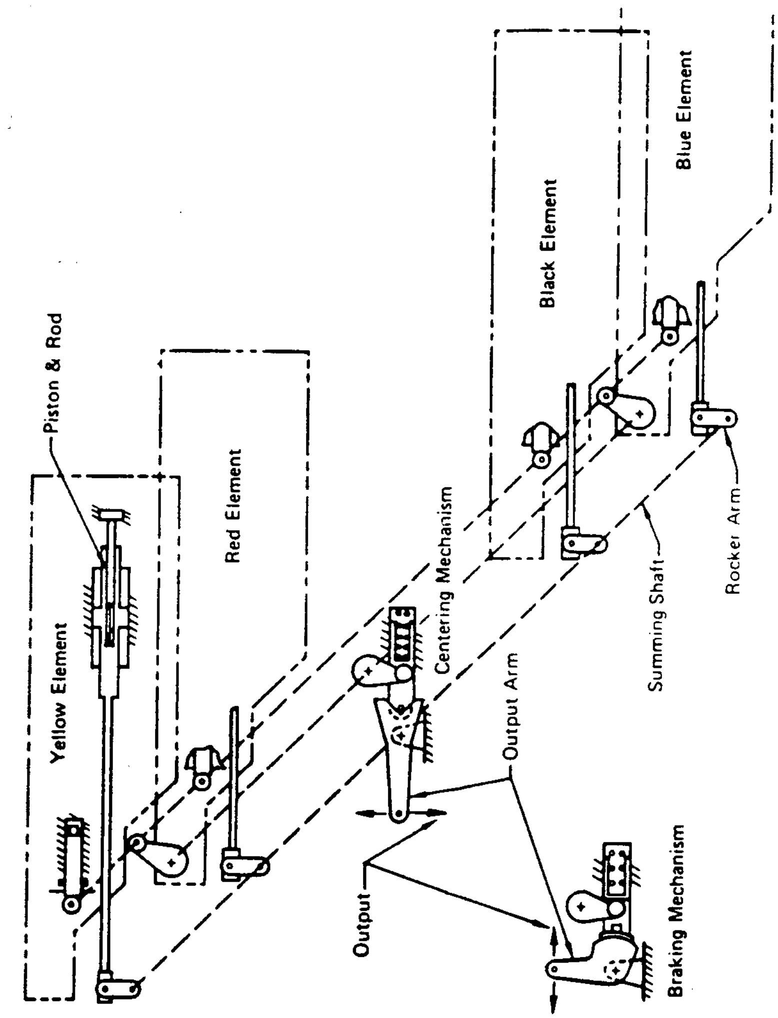


FIGURE 5 - MECHANICAL SCHEMATIC, SECONDARY ACTUATOR

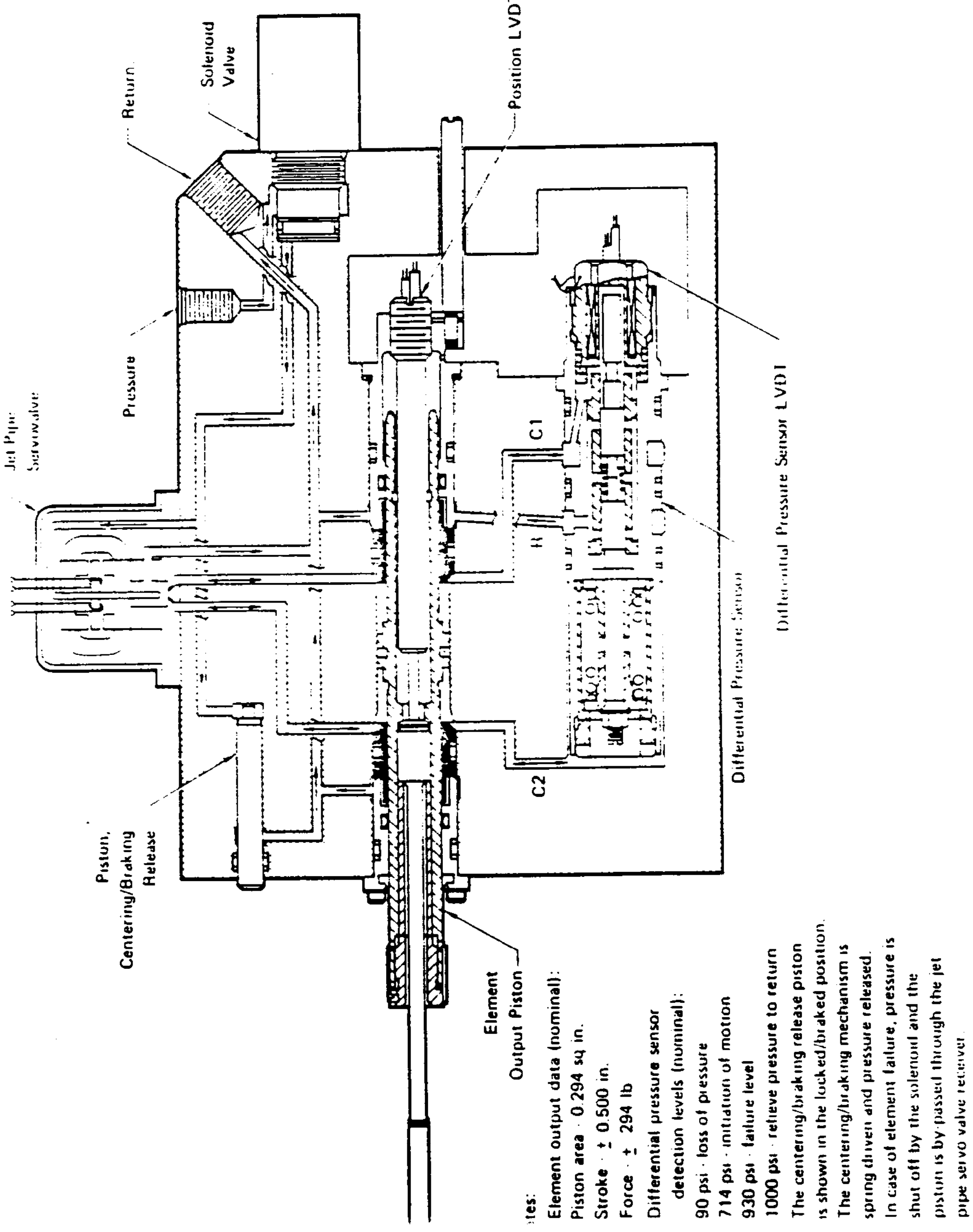


FIGURE 6 - HYDRAULIC SCHEMATIC, SINGLE ACTUATOR ELEMENT

3.4 YF-16 Command Servoactuator

The YF-16 prototype was one of the first aircraft designed to employ a fly-by-wire (FBW) control system. The YF-16 prototype FBW system was designed to use existing state-of-the-art components with little or no development required to provide the necessary redundancy and reliability levels needed for a FBW system. The quadruplex analog flight control electronics system was designed for two-fail-operate capability. The design scheme of the actuation system was to use the production F-111 stability augmentation system (SAS) damper servo as a full authority command servo (secondary actuator). The servo drives mechanical linkage to provide positional inputs to a conventional tandem valve-on-ram arrangement at each primary surface. The prototype aircraft redundancy requirements for the primary surfaces are fail-operative/fail-safe for the rudder and flaperons and dual-fail-operative for the horizontal tails. In the case of the rudder and flaperons, this redundancy was achieved completely through the hydraulic logic within the damper servo. The electrical interface with the rudder and flaperon systems is shown in Figure 7. The horizontal tail actuation system includes a mechanical cross-over linkage shown in Figure 8 to provide the desired redundancy. The linkage allows either command servo to drive both horizontal tails in the event of a second failure of one of the command servos.

The F-111 SAS servoactuator is a triplex configuration with an all hydromechanical failure logic (self-error sensing and correction) unit. The actuator was designed to provide single-fail operate (SFO) capability.

3.4.1 F-111 SAS Servoactuator Configuration

The actuator configuration, shown in Figure 9, has three two-stage electrohydraulic servovalves with mechanical feedback from the main ram to the torque motor of the servovalves. The actuator receives three electrical command signals and two hydraulic supplies. All of the mechanization necessary to produce actuator displacement in response to command signals, and continued operation after failure of any input or internal component, is contained within the package.

3.4.2 Failure Monitoring

The failure monitoring is basically an active/active detection-correction configuration, together with an electrohydraulic model servo. Continuous equalization of the two active servovalves (No. 1 and 2) is performed by an integrator spool which cross-compares the flow outputs of the two valves. The position of this integrator spool is fed back to each servovalve by feedback spring wires so that any differences in command inputs, or valve null shifts, are washed out. The actuator schematic diagram in Figure 9 shows the function of this equalizer (called the differential sensor spool). The position of this spool is a measure of the mismatch between the two active servovalves, so it contains valving elements which open when servovalve mismatch exceeds a preset amount. This failure logic, together with a comparison between the model servo position and the actual servo position, provides the failure detection function.

The model includes another servovalve together witih a separate piston and mechanical feedback arrangement. The piston is scaled down from the actual piston size to save envelope and weight. Use of an electrohydraulic servo model gives good reproduction of many actuator nonlinearities, including piston stroke limits, velocity saturation, servoloop dynamics, servovalve dynamics, and torque motor hysteresis. Loading on this SAS actuator is small so the model need not include provisions for load induced nonlinearities.

The servovalve error sensor and the model sensor are interconnected hydraulically so that a failure of either actuation channel, or of the model, will produce a corresponding hydraulic signal. This signal is used to cut off an active servo if it has failed, or to provide just a failure indication if the model has failed. The failure indicator provides an electrical signal for a pilot warning light.

Two solenoid controlled start-up valves are included in the package and these must be energized to reset the failure logic upon start-up or following self-shut-off. Although a number of double failure capabilities exist for this servoactuator, not every possible double failure is protected, so the actuator rates only a single-fail-operate capability.

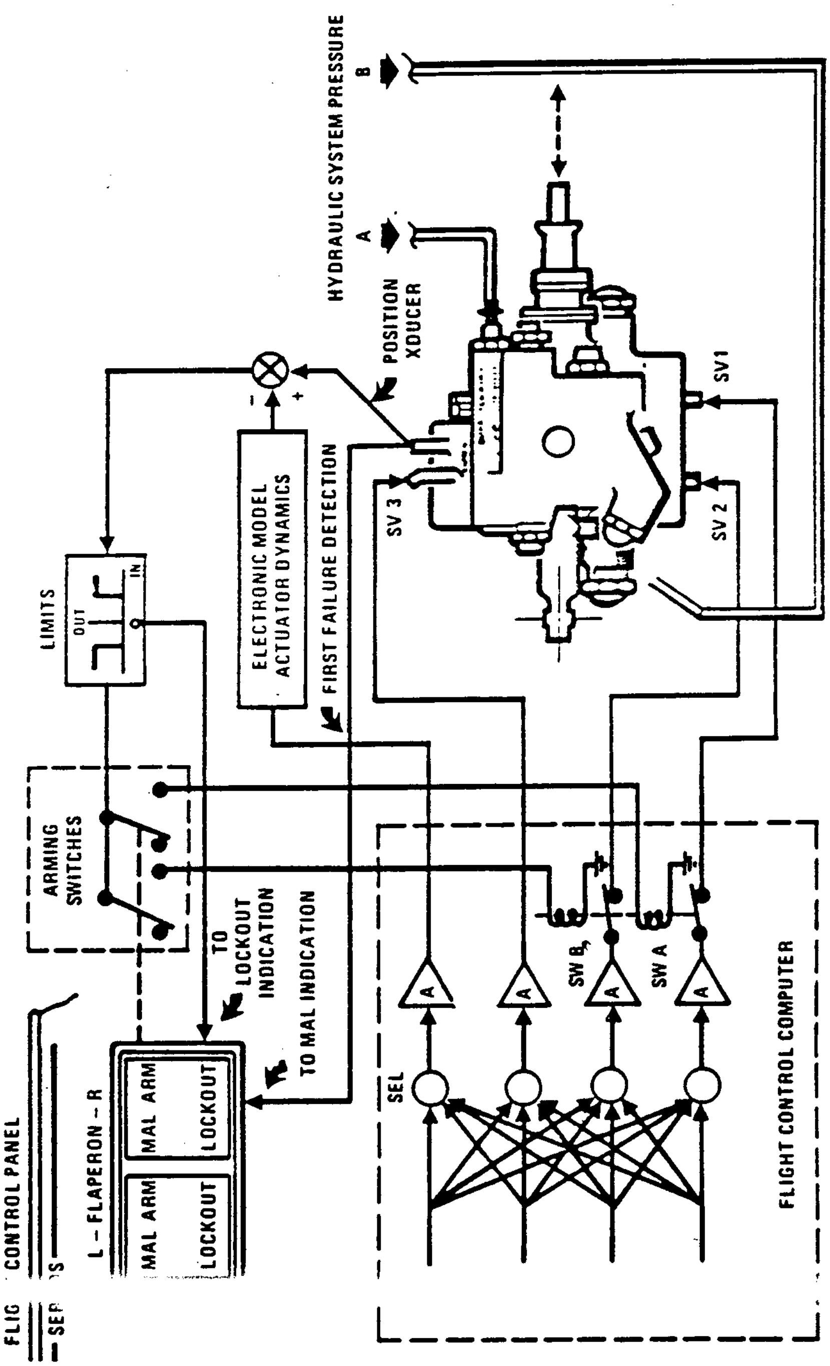


FIGURE 7 - ELECTRICAL INTERFACE WITH YF-16
FLAPERON AND RUDDER SURFACE ACTUATION

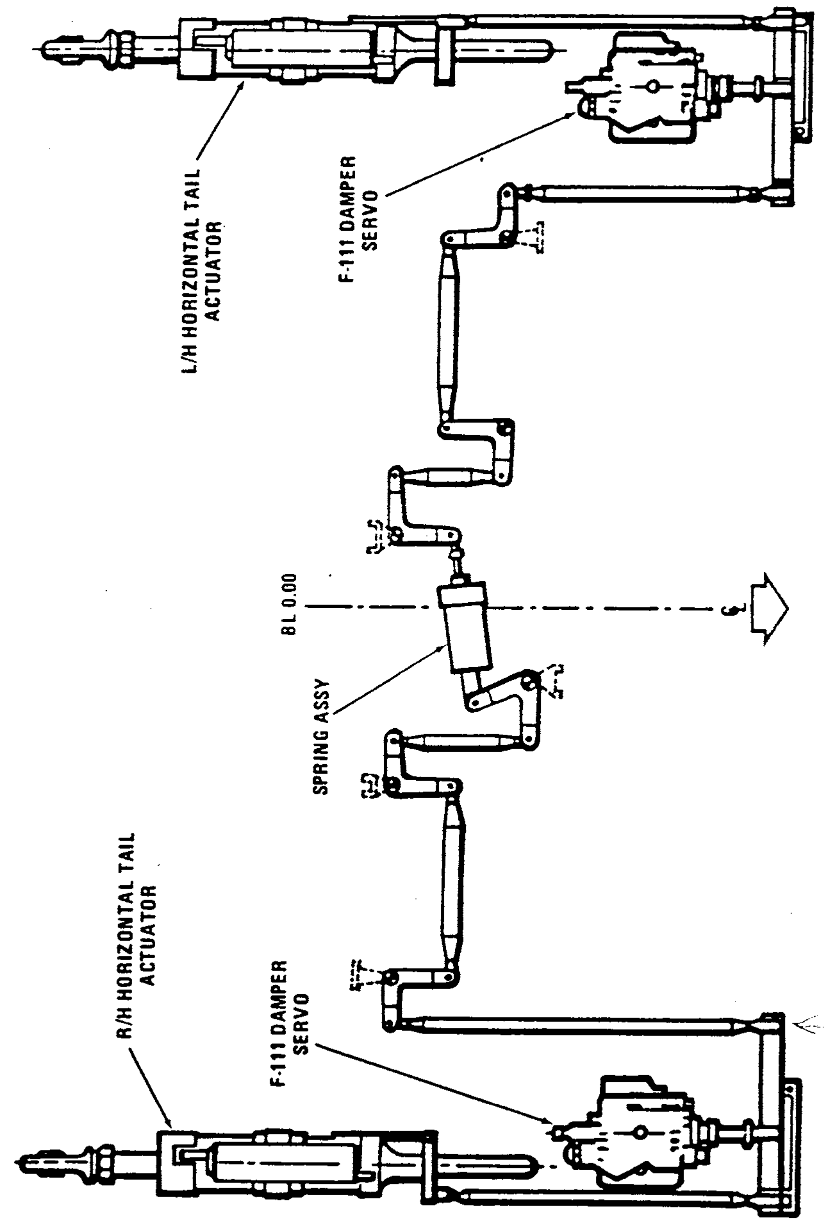


FIGURE 8 - YF-16 HORIZONTAL TAIL SURFACE ACTUATION CROSSOVER LINKAGE

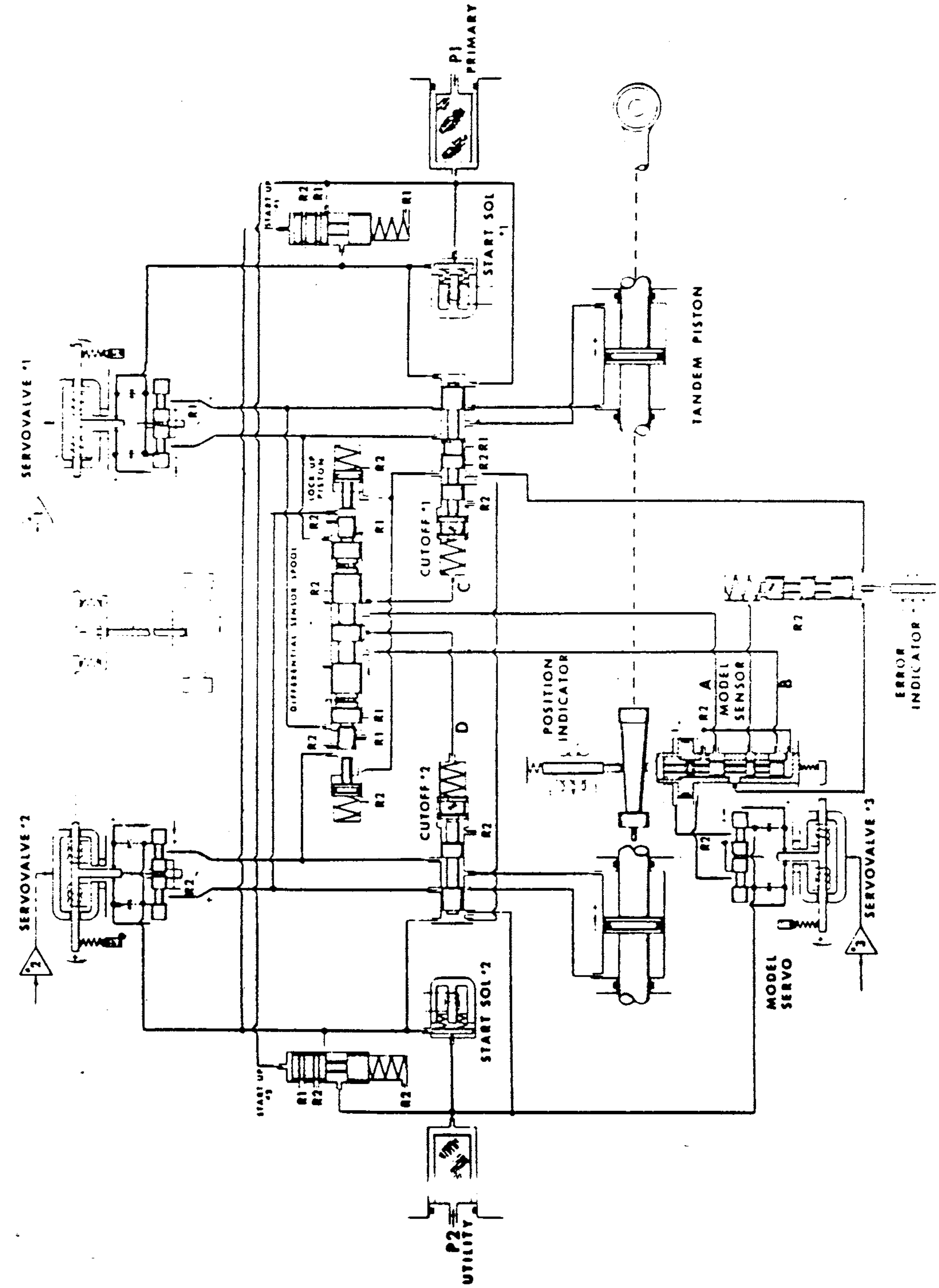


FIGURE 9 - F-111 SAS SERVOACTUATOR SCHEMATIC

3.5 F-16 Actuators

Several ground rules were important in the development of the F-16 integrated servoactuator (ISA). Commonality between various surface locations would be desirable. Both the command servo and power stages had to be operational after a hydraulic system failure. The ISA should perform like the YF-16 system. The YF-16 flight control system adapted the F-111 stability augmentation system (SAS) servoactuator to drive conventional surface actuators via mechanical linkage. The SAS servo had shown excellent reliability during the F-111 and the YF-16 programs. The SAS servo is a dual-tandem hydraulic design utilizing mechanical position feedback and self-contained logic to detect and correct hydromechanical failures. The decision for mechanical feedback was made because of the following reasons:

- Compatibility with YF-16 FCs design
- Less vulnerable to damage
- Minimum electrical interface with actuator
- Easier to implement fail-safe feature

The decision to use fail-operative/fail-safe hydromechanical redundancy was selected because greater redundancy did not yield a significant improvement in aircraft safety. However, two-fail-operate electrical failure detection was still necessary.

The production F-16 ISA functional schematic is shown in Figure 10. Features of the ISA configuration are as follows:

- Same actuator used at flaperon and horizontal tail locations. Rudder actuator identical except for smaller power ram
- Mechanical rate (main valve spool position) and ram position feedback
- Three EHVs: two active averaging, one standby
- Internal hydromechanical failure detection/correction

3.5.1 Electrical Failure Monitoring

The two-fail-operate electrical failure protection is accomplished by the electrical monitor and logic interface scheme shown in Figure 11. Each of the three servovalves contain two identical windings independently capable of full servovalve control. Three electrical channels within the computer provide signals to the primary coils in the servovalves. These signals are simultaneously compared to detect failures which occur anywhere within a command circuit. After a failure, the fourth computer servoamplifier, which is normally in standby, is switched in to control the secondary coil of the servovalve. If the servovalve coil current monitor voting level and time are set lower than that in the ISA voting logic, then a first electrical failure will be detected in the computer. A subsequent electrical failure will be corrected within the ISA; hence, the desired electrical two-fail-operative redundancy is achieved.

3.5.2 Hydromechanical Failure Monitoring

The hydromechanical fail detection and correction logic is shown in Figure 11. Detection is accomplished by monitoring of servovalve first stage "T" pressure by a hydromechanical monitor valve. Failure isolation is accomplished by the voting spool. A first failure of one of the active valves (SV1 or SV2) causes transfer to the standby servovalve (SV3). A first failure of SV3 locks on SV1 and SV2 control. During dual hydraulic system operation, servovalves SV1 and SV2 operate on one hydraulic system and SV3 operates on the other system. Hydraulic system failure correction has precedence over servovalve failures. The ISA has second-fail-safe capability which is activated by excitation of two solenoid valves upon receipt of command from an external monitor comparing ISA position with an electronic model position. Engagement of solenoids allows a feedback linkage centering spring to command the actuator to a zero position.

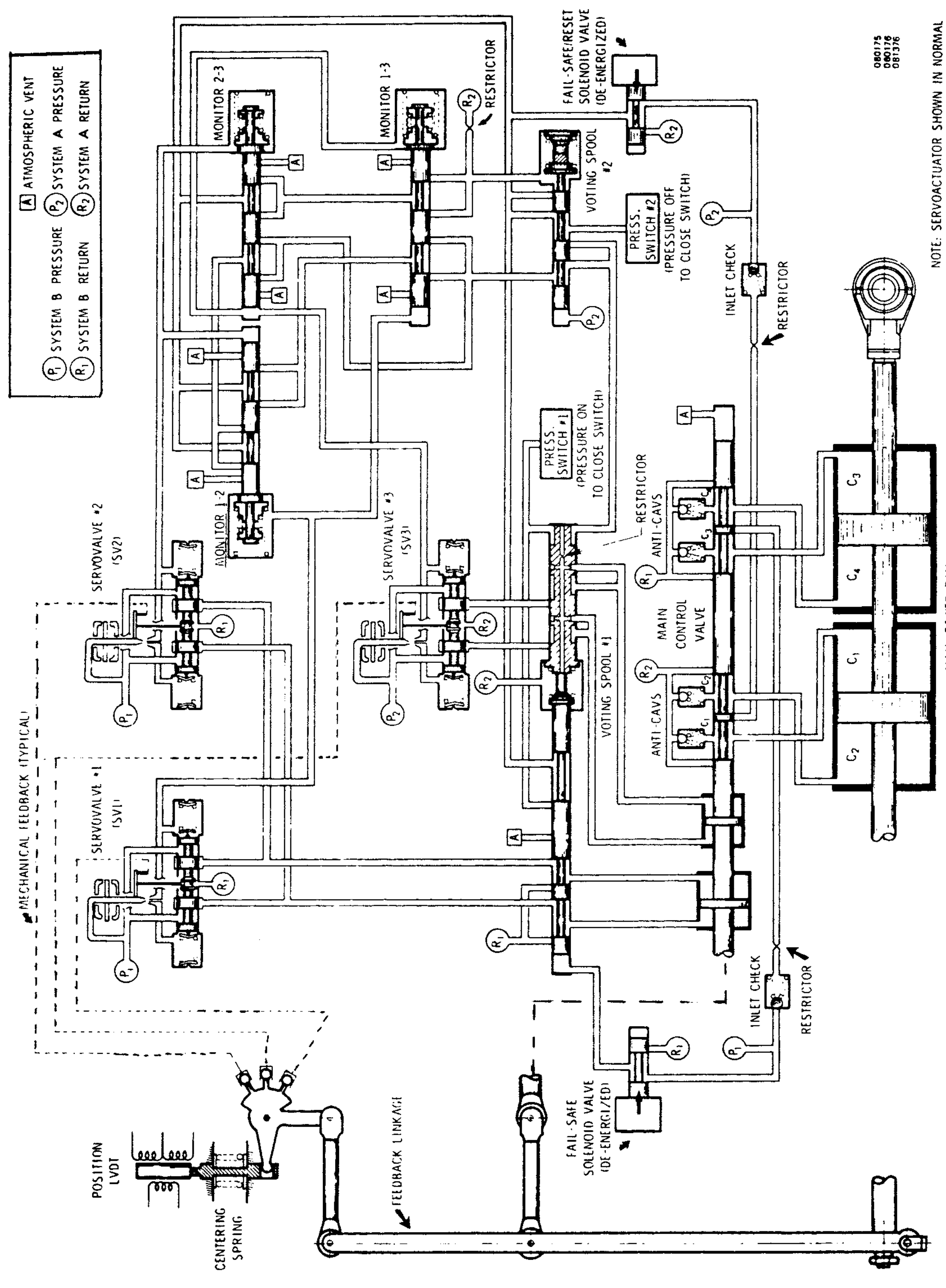


FIGURE 10 - F-16 PRIMARY CONTROL SERVOACTUATOR

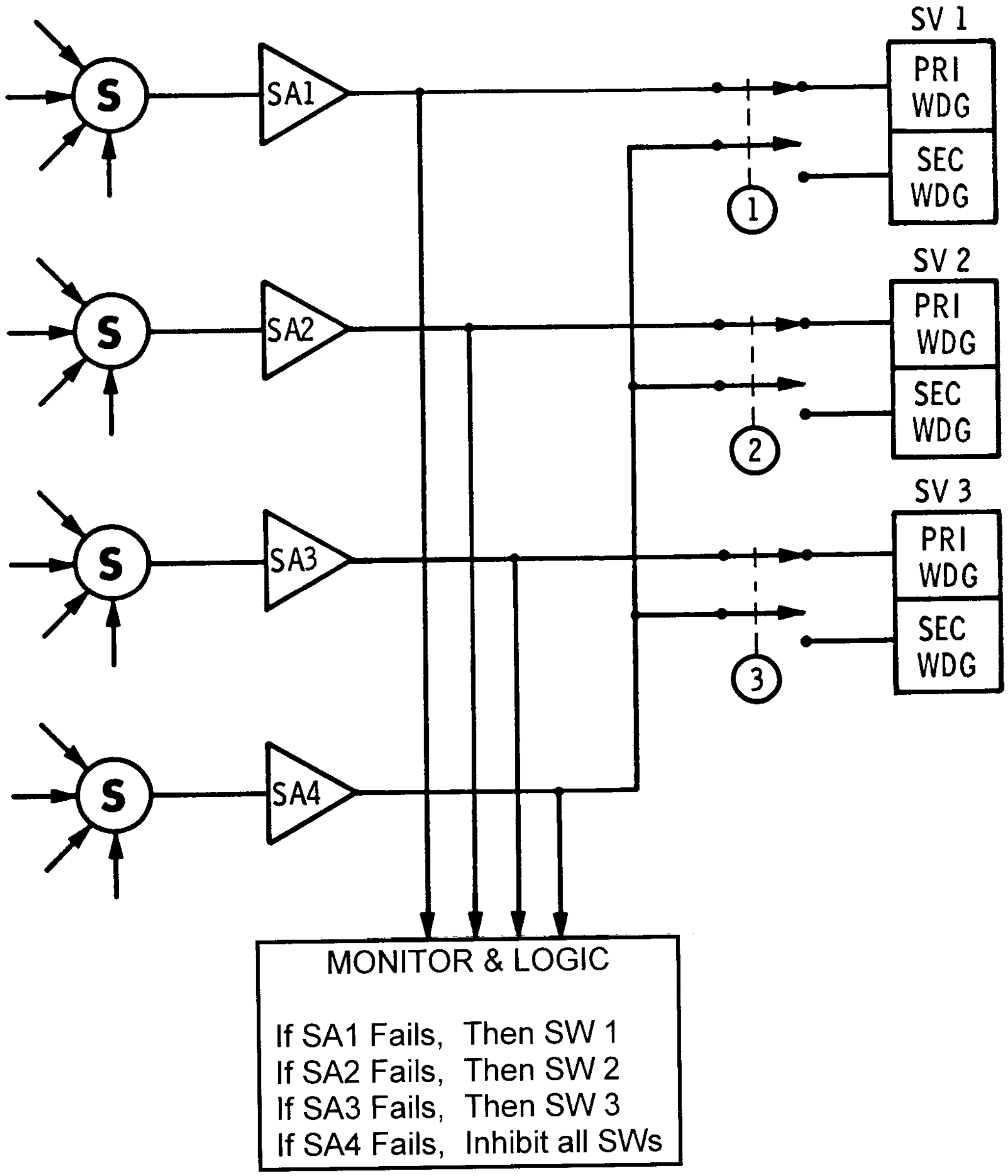


FIGURE 11 - ELECTRICAL INTERFACE WITH F-16 ISA FOR FIRST ELECTRICAL FAILURE CORRECTION

3.5.3 Leading Edge Flap Actuation System

Each wing of the F-16 aircraft has a single leading edge flap (LEF) panel which runs the full span of the wing. Rotary mechanical actuators intermittently spaced along each flap panel provide attachment of the flap to the wing structure and allow the flap to be rotated as a function of Mach number and angle-of-attack.

Two sizes of rotary actuator units are utilized - two of the larger sizes on the inboard portion of each wing and two smaller units on the outboard portion (a total of four actuator units per wing). The remainder of the drive system consists of two angle gear boxes, a centrally located power drive unit (PDU), an asymmetry brake assembly at the outer tip of each panel, and multiple torque shafts interconnecting all of these devices.

The PDU consists of two hydraulic motors torque summing into a single gearbox. Each motor receives power from separate hydraulic systems through a tandem main control valve. Inputs to the valve are accomplished with a command servo through mechanical linkage. Flap position feedback is accomplished mechanically on the PDU through the mechanical linkage arrangement. The command servo is powered by two independent electrical motors giving the system fail operation/fail safe performance.

3.6 F/A-18 A/B/C/D Actuators

The redundancy requirements of the F/A-18 A/B/C/D actuators were established in association with the aircraft aerodynamic redundancy. The servo configurations are simplified by the summing of the redundant electrical channels in the magnetic flux of the torque motor in the electrohydraulic servovalve. Flux summing of the electrical channels permitted separation of the redundancy management into electrical failure monitors and hydromechanical failure monitors. The redundancy management of the F/A-18 flight control actuators performs failure detection and failure isolation of the actuator components and the associated servo electrical systems. Electrical feedback was chosen for the main ram and servo position to improve resolution and to permit higher loop gains.

3.6.1 Aileron Actuator Configuration

The aileron actuator is a fail-operate/fail-safe configuration. As shown in Figure 12, the aileron actuator consists of single main ram with one dual-coil two-stage, electrohydraulic servovalve. Dual main ram linear variable differential transformers (LVDTs) provide the feedback for closed loop position control. Dual contact pressure switches and dual LVDTs on the servovalve spool provide inputs to the flight control computers for failure monitoring. Each actuator is controlled by two electrical channels with different channel pairs controlling the left and right ailerons. Dual hydraulic power sources are provided via an upstream switching valve. Failure of both electrical channels or both normal and backup hydraulic supplies will result in the actuator reverting to a damper mode. The actuator contains an integral accumulator in the return system to provide a hydraulic fluid supply for the damping mode of operation.

3.6.2 Rudder Actuator Configuration

The rudder actuator is functionally equivalent to the aileron actuator. The tandem main ram was required due to envelope considerations.

3.6.3 Leading Edge Flap Actuation System

Leading edge flap actuation is accomplished by mechanical transmissions spaced spanwise along the surface as shown in Figure 13. These transmissions are driven by a central hydraulic drive unit whose output to the transmissions is transmitted by rotating shafts. Two hydraulic motors powered by two independent hydraulic supplies provide torque and rotational velocity to the hydraulic drive unit outputs.

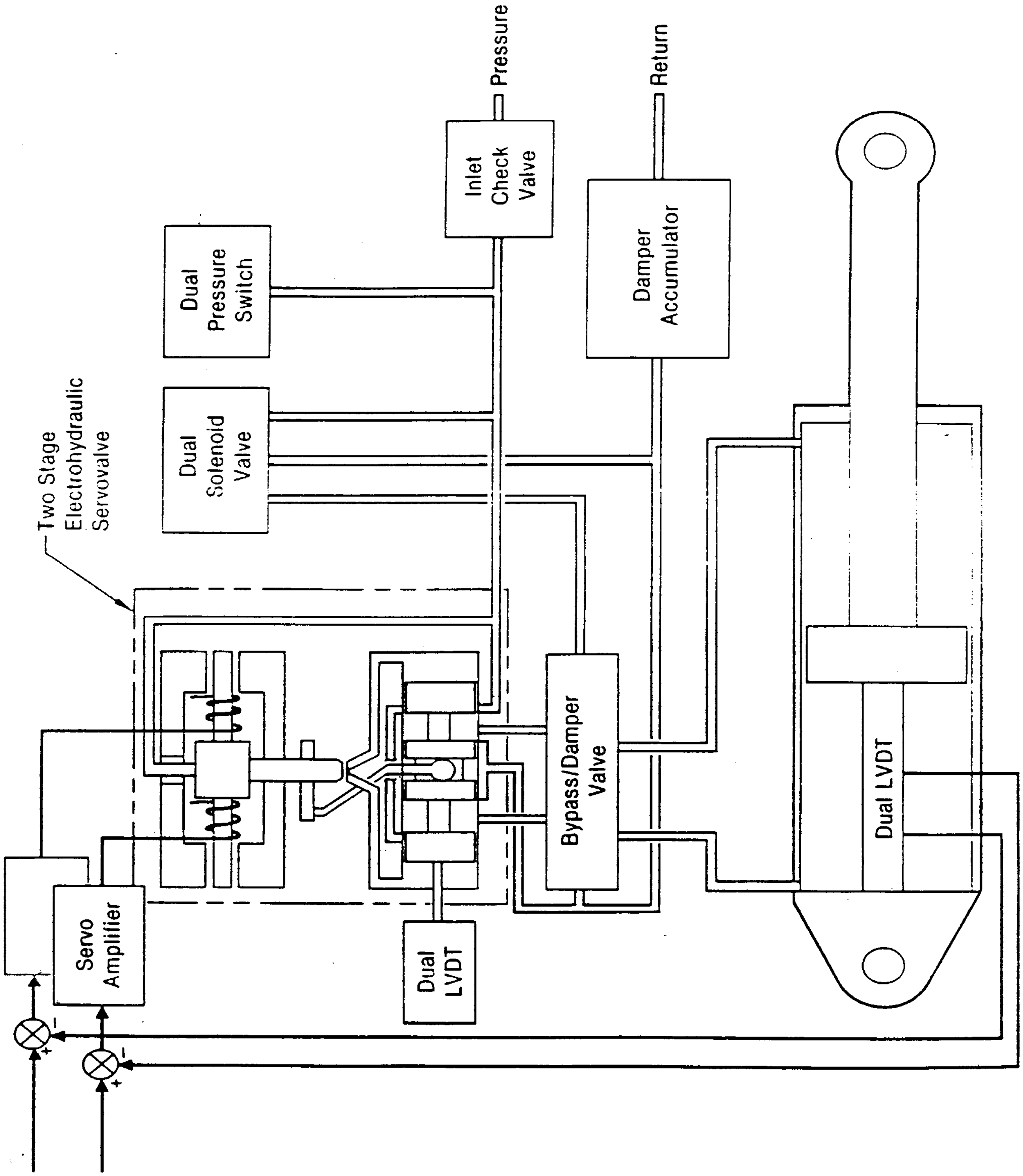
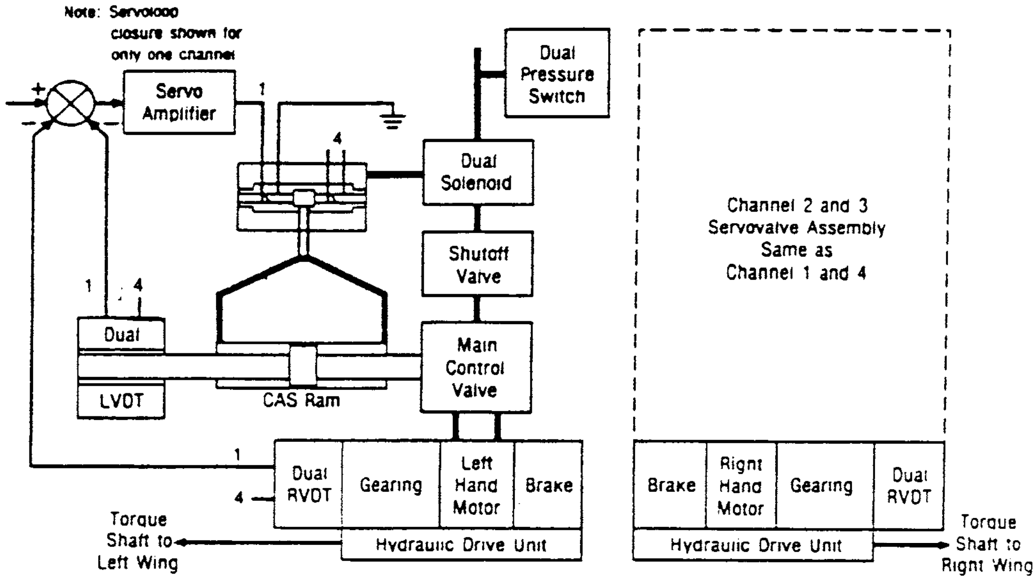


FIGURE 12 - F/A-18 A/B/C/D AILERON ACTUATOR SCHEMATIC



LEADING EDGE FLAP SERVOVALVE ASSEMBLY

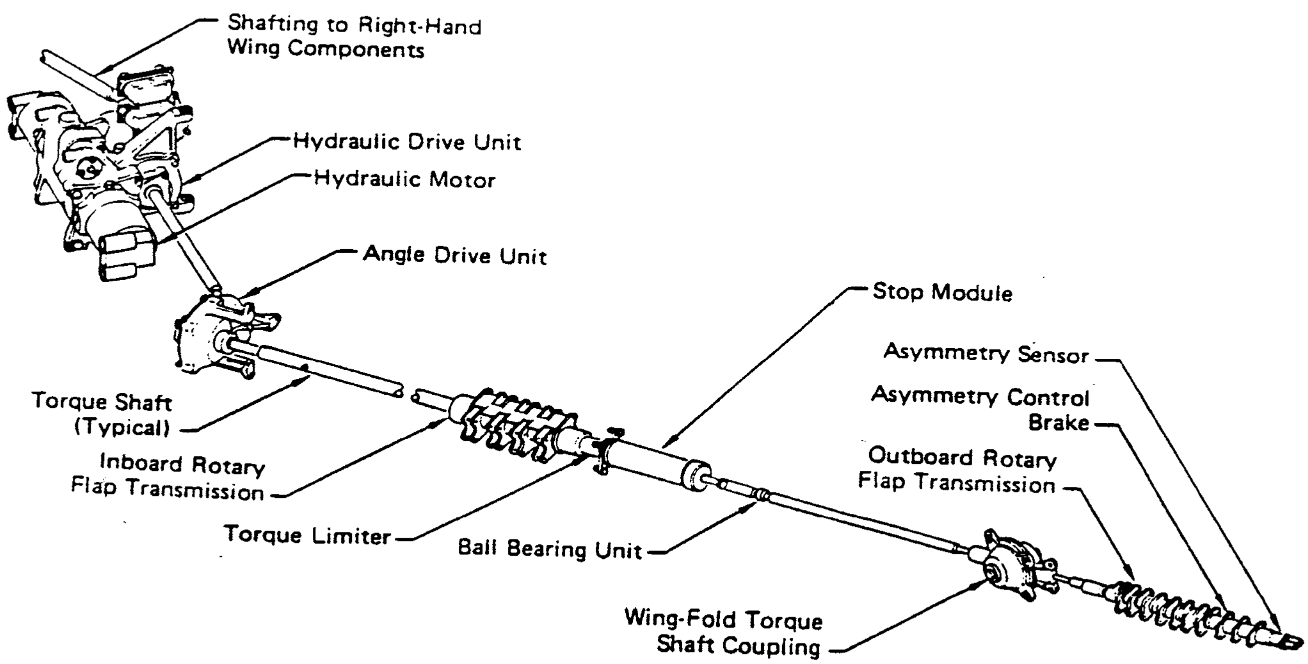


FIGURE 13 - F/A-18 A/B/C/D LEADING EDGE FLAP DRIVE SYSTEM

Each motor drives one half of the leading edge flap system and is mechanically independent of the other half. Flow to each hydraulic motor is provided by separate servocontrol units shown in Figure 13. Each servocontrol includes a main control valve positioned by two dual-coil, single-stage electrohydraulic servovalves. Switching valves provide backup hydraulic power to each motor. Each actuator system will sustain operation following an electrical command failure and one hydraulic supply failure. In the event of a second electrical failure on the same side, that side is shut down and the collective flap command to the other side is frozen. In the event of a dual hydraulic system failure, the flaps will remain in the last position at the time of failure. Asymmetry control units are installed on the outboard transmissions. These units contain a brake, a dual-coil solenoid and dual-rotary variable differential transformers (RVDTs).

3.6.4 Aileron and Rudder Actuator Servo Loop Electronics and Redundancy Management

The actuator servo loop electronics and redundancy management is typical of the aileron and rudder actuator configurations. As shown in Figure 14, each electrical channel commands one of the dual coils in the electrohydraulic servovalve. The servovalve is designed to provide full performance capability when operating on a single channel. The servoamplifier gain is doubled for single channel failure. As shown in Figure 14, each channel of the computer contains four basic actuator monitor functions: servoamplifier, command signal, main ram LVDT, and servovalve. Failure monitoring of the electrical components in the actuator can provide fail-operate/fail-safe capability by comparing servoamplifier currents between an active path and a model path. The actuator servoamplifier monitor compares the actual current through the electrohydraulic servovalve with a model of the servoamplifier current. The command signal to both the servo loop and the servo loop model is failure detected by the digital-to-analog converter monitor. The main ram LVDT secondary winding has a center tap failure detection. A failure detected by any one of these monitors will disengage the servoamplifer in that channel and de-energize the corresponding coil in the solenoid operated hydraulic shutoff valve. A second failure will remove all excitation from the solenoid valve coils, which will cause the shutoff valve to close and the bypass damper valve to shift to the damper position. A servovalve failure or hydraulic pressure loss indication will shut down two channels.

The servovalve is monitored for hydromechanical failures by the servovalve monitor. The servovalve is a conventional two-stage valve with mechanical feedback between the second stage spool and the torque motor. The servo-valve monitor compares actual spool position with the spool position which is commanded by the sum of the currents in both channels driving the valve. A simple lag filter is used to simulate the servovalve dynamics for the commanded valve position path. When this monitor declares a failure, it shuts off both channels. The hydraulic pressure switch is used in conjunction with the monitors to eliminate transients and nuisance failure indications during operation of the hydraulic switching valve.

3.6.5 Leading Edge Flap Actuation System Redundancy Management

Redundancy management system for the leading edge flap system servovalve assembly is functionally equivalent to the system used for aileron and rudder. The leading edge flap system has two additional monitors because of failure modes of the hydraulic motors, mechanical transmissions, and rotating shafts. The monitors are flap asymmetry monitor and hydraulic motor monitor. The flap asymmetry monitor is designed to detect broken torque shafts, and compares inboard and outboard flap positions on each wing. The hydraulic motor monitor, designed to detect hydraulic motor failures or jams in the gear train, compares commanded flap position with actual flap position.

3.6.6 Stabilator Actuator Configuration

The stabilator actuator is a two-fail-operate/fail-safe configuration. As shown in Figure 15, the stabilator actuator consists of a dual-tandem main ram configuration with an integral quadruplex servo and a mechanical manual command input. The actuator contains a Command Select mechanism (CSM) which provides electrical control during normal operation and mechanical control as a backup. The actuator is normally commanded by four electrical commands. The mechanical backup command capability is provided in the event of electrical command or electrohydraulic servovalve failures. The servos and the dual main rams are powered by two independent hydraulic supplies. The servo rams are positioned by two pairs of quad-coil single-stage electrohydraulic servovalves. Quadruplex main ram and servo ram LVDTs provide feedback for closed loop position control. Two quadruplex fail solenoid sare used for failure isolation. The actuator will sustain normal operation following two electrical command failures and one hydraulic supply failure.

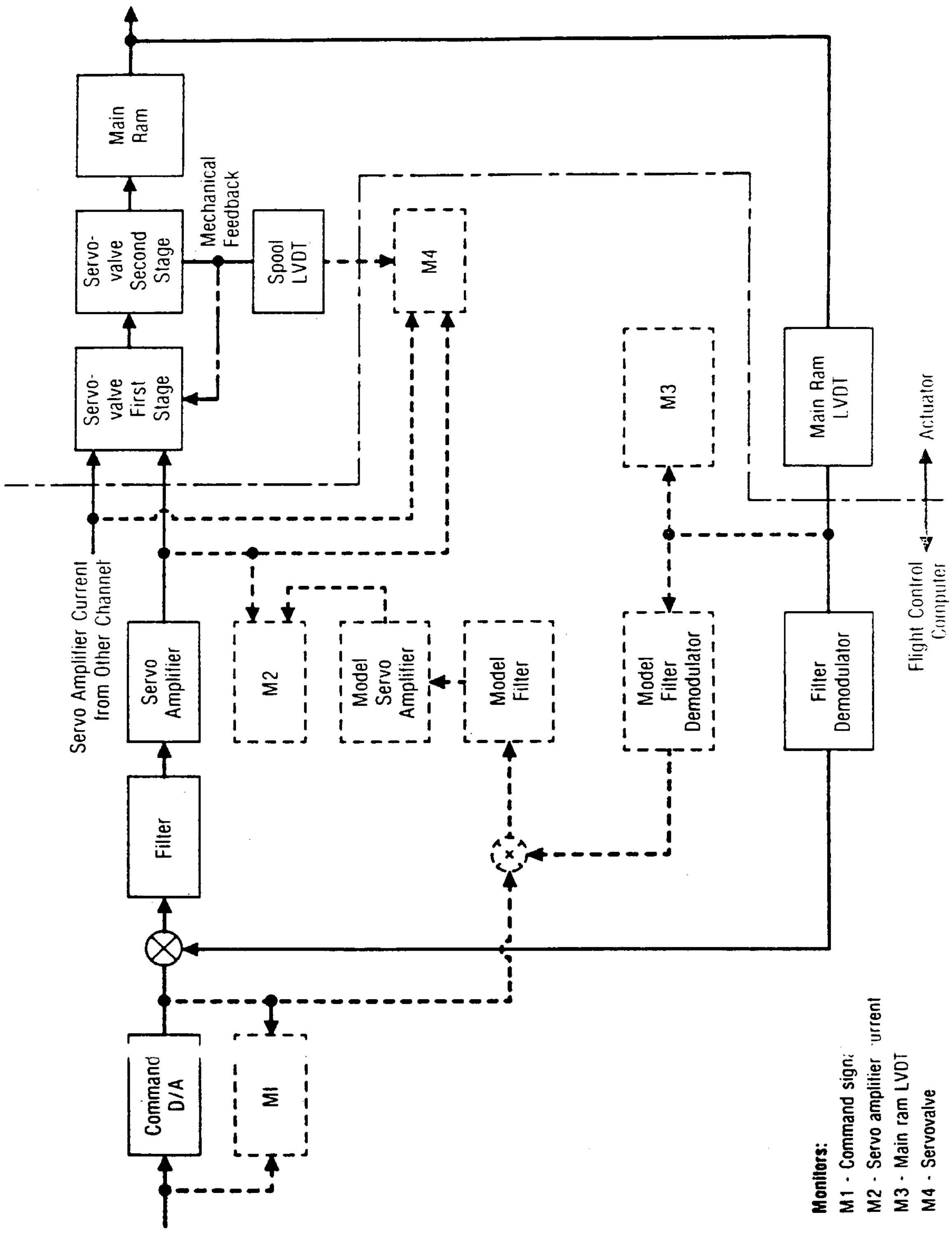


FIGURE 14 - F/A-18 A/B/C/D AILERON ACTUATOR MONITORS

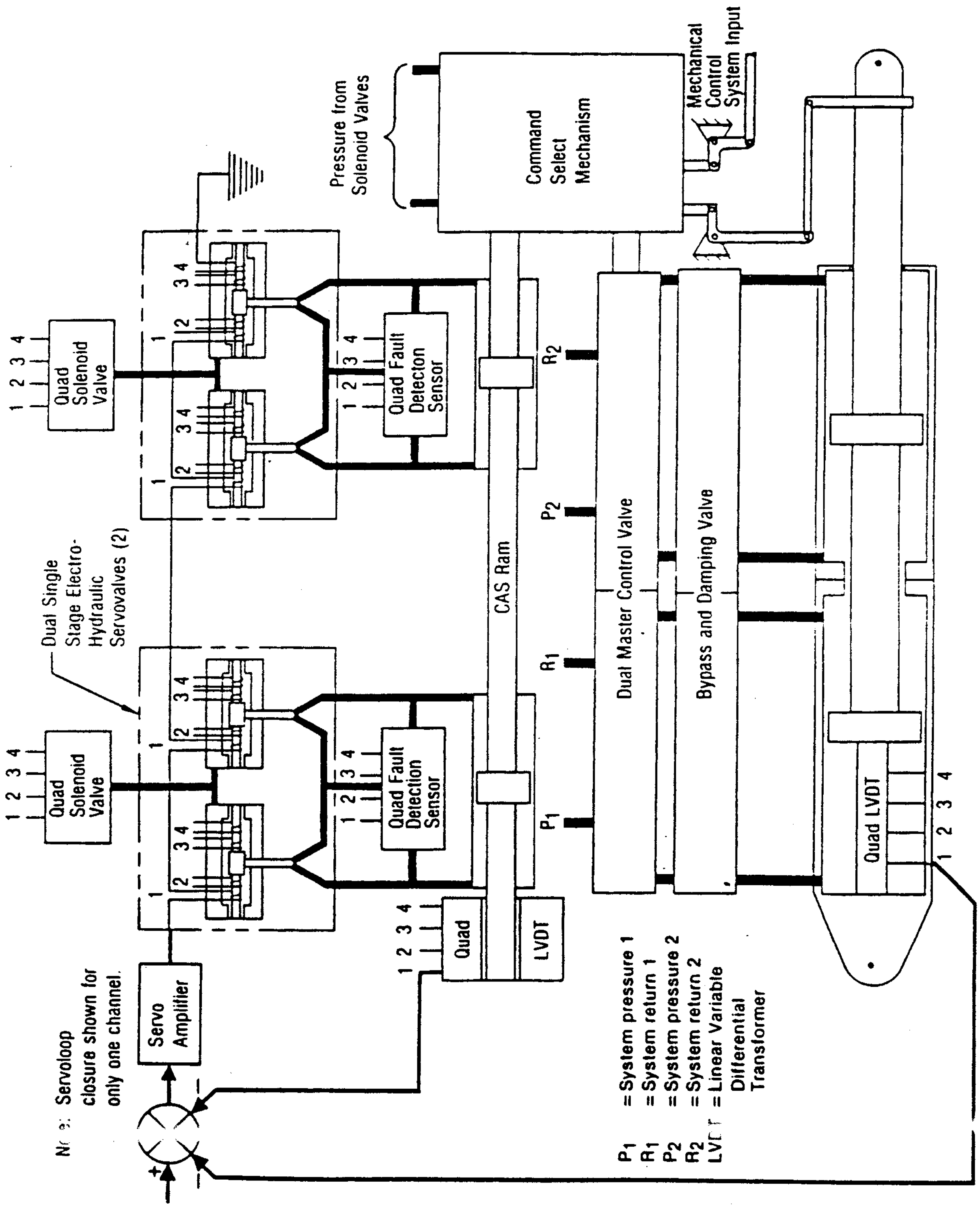


FIGURE 15 - F/A-18 A/B/C/D STABILATOR ACTUATOR SCHEMATIC

The electrohydraulic servovalves are commanded by four independent channels which are combined by magnetic flux summing in the torque motors. Full performance capability can be obtained with any two coils energized. The two valves on each hydraulic system are operated in pairs to permit failure detection for hydromechanical failures. In the event of failures that result in shutoff of all the electrical commands, full command capability is transferred to the mechanical system. The mechanical input will not affect actuator position during normal mode of operation. A third hydraulic power source is provided to the aft half of the dual tandem cylinder via an upstream switching valve. Failure of all the hydraulic supplies will result in the unit reverting to a damper mode.

3.6.7 Trailing Edge Flap Actuator

The trailing edge flap actuator is a dual-parallel main ram configuration with an integral quadruplex servo as shown in Figure 16. The servo rams are positioned by two pairs of quad-coil single-stage electrohydraulic servovalves, similar to the stabilator. The actuator is commanded by four electrical channels and powered by two independent hydraulic supplies. The actuator will sustain operation following two electrical command failures and one hydraulic supply failure. In the event of a third electrical failure, the actuator will be driven to zero degree or neutral lock flap position. In the event of failure of both hydraulic supplies, the actuator will move to a dampened trail position.

3.6.8 Quadruplex Actuator Servo Loop Electronic and Redundancy Management

The stabilator and trailing edge flap actuator servo loop electronics and redundancy management are functionally equivalent. These actuation systems were designed to provide two-fail-operate/fail-safe capability. As shown in Figure 17, each electrical channel commands one coil in each of the electrohydraulic servovalves, and the coils of the two pairs of servovalves are connected in series. Failure detection and failure isolation are performed by monitors in the flight control computers. As shown in Figure 17, each channel contains three monitor functions: servoamplifier current, cross servo, and electrohydraulic valve failure detector. The servoamplifier current monitor will detect failures in the servo loop electronics including the amplifier. This is done by a model current using the same actuator command, main ram feedback, and servo ram feedback which is used to generate the actual servoamplifier current to the servovalve. A failure detected by this monitor will disengage the servoamplifier and remove the excitation from both solenoid valves in the failed channel. After a third failure the actuators revert to fail-safe mode. The cross servo monitor detects failures in the servo ram, the main ram LVDT, the servo ram LVDT or the command signal. Because the servo ram position is the average of all operating channels, a single channel failure can be detected by comparing the commanded servo ram position with the actual servo ram position. The shutdown logic for the cross servo monitor is the same as for the servoamplifier current monitor. The failure of one electrical channel does not affect the steady-state relationship between the commanded servo position and the actual servo position because the flux summing takes place in the forward path of the servo loop. The actuator servo loop gains were designed to meet all aircraft performance requirements when operating on only two channels without gain changing.

Failures in the electrohydraulic valves are detected by two differential pressure sensors, one in each of the two hydraulic systems of the actuator. The servo ram is controlled by two pairs of electrohydraulic valves. Each pair is powered by a separate hydraulic system. Each electrohydraulic valve contains an active output pressure and an inactive output pressure. The active outputs in each pair differentially drive the servo ram. The inactive outputs are connected together to provide a reference pressure, PSUM. The differential pressure sensor compares PSUM with the average active pressure. Any failure in the electrohydraulic valve, such as a plugged nozzle or receiver, will unbalance the pressure measured by the differential pressure sensor. This unbalance will change the voltage output of the pressure sensor and will be sensed by a level detector. A failed electrohydraulc valve will result in the removal of all four channels of excitation to one solenoid valve. This will disengage one pair of electrohydraulic valves and the servo ram will continue to be controlled by the other pair of electrohydraulic valves.

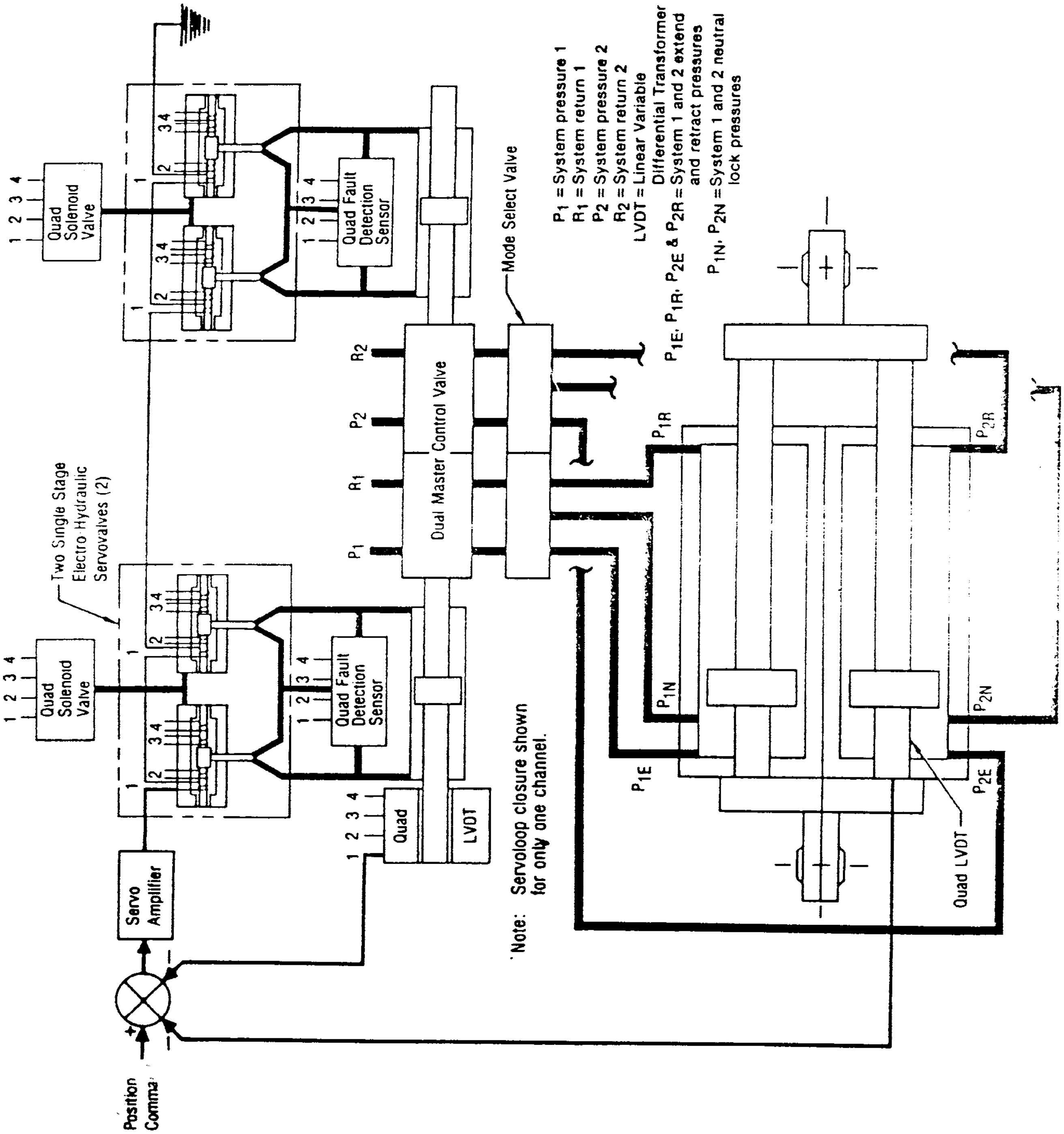


FIGURE 16 - F/A-18 A/B/C/D TRAILING EDGE FLAP ACTUATOR SCHEMATIC

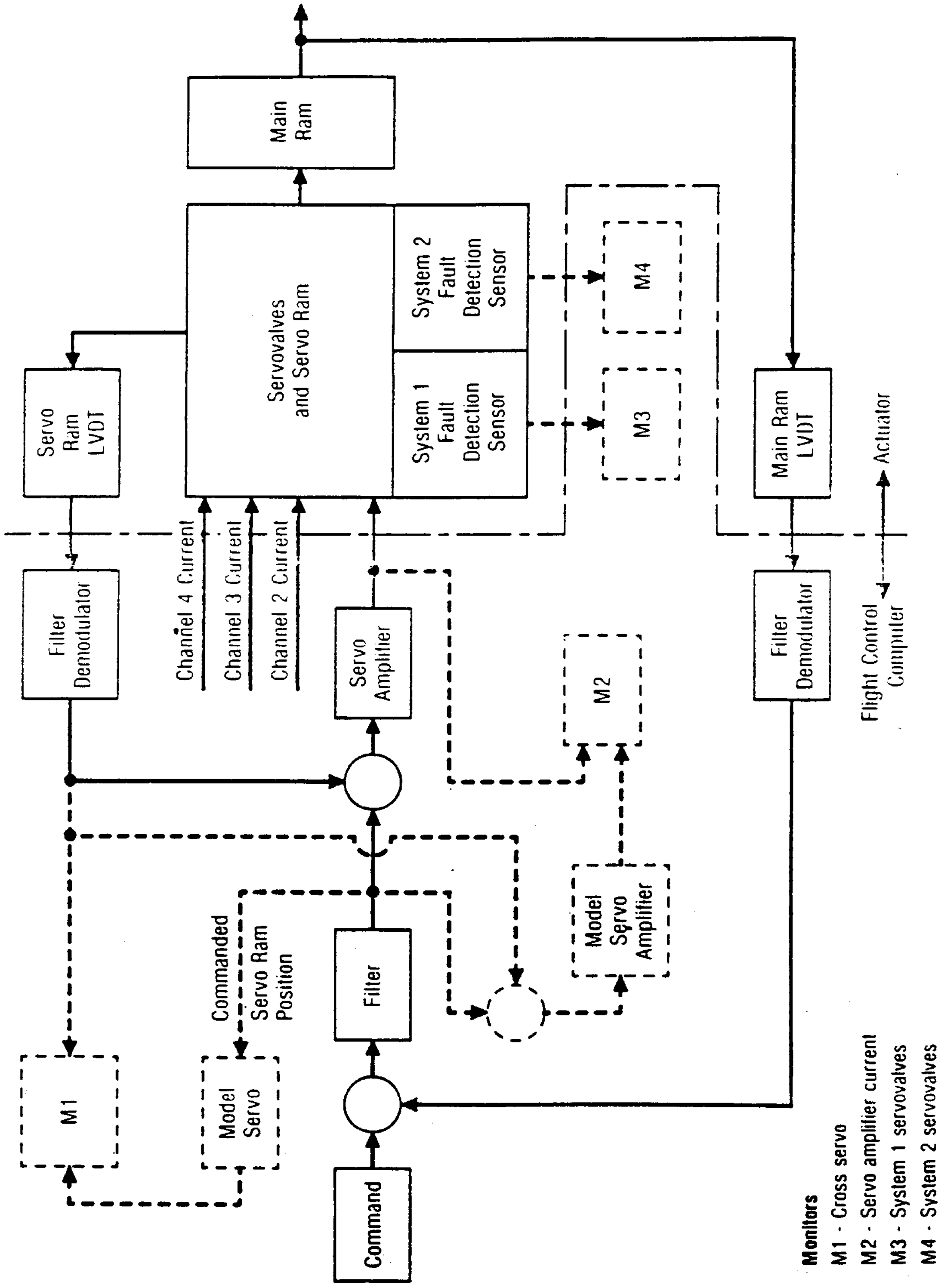


FIGURE 17 - F/A-18 A/B/C/D STABILATOR ACTUATOR MONITORS

3.7 F-15 S/MTD Actuators

This description is restricted to the aerodynamic surface servocylinders for the F-15 STOL/Maneuver Technology Demonstrator, all of which are controlled directly by outputs from the flight controllers of the flight path control set (FPCS). The nozzle actuators, under the control of the nozzle controllers, and the nose landing gear steering servocylinder are the balance of the actuators controlled by the integrated flight/propulsion control (IFPC) system. The redundancy concepts for the F-15 S/MTD surface actuators were based on the aircraft aerodynamic redundancy and control system degraded mode requirements. Commonality between the various actuators was a major consideration. The force motor servo configuration was chosen to improve reliability by eliminating the hydromechanical failure detection sensors required in most redundant electrohydraulic servovalve configurations. Electrical feedback was chosen for the main ram and servo position for good actuator resolution and to permit higher loop gains.

3.7.1 Canard/Stabilator Actuator Configurations

The canard and the stabilator actuators are essentially a common configuration; they have two-fail-operate/fail-safe capability. The actuators are powered by two independent hydraulic supplies. As shown in Figure 18, these actuators consist of a dual-tandem main ram, a single stage dual tandem spool-sleeve main control valve, a quad coil rotary direct drive force motor, and mode selector valves. Quadruplex linear variable differential transformers (LVDTs) provide main ram and main control valve position signals for closed loop control. Two quad-coil solenoid valves are used for failure isolation. After three electrical failures, the stabilator actuator is powered to a neutral lock position. After three electrical failures, the canard actuator is allowed to free float to an unloaded position. The modification to achieve that mode was done by changes to the main control valve and mode select valve.

3.7.2 Aileron/Flaperon Actuator Configurations

The aileron and flaperon actuators are a common configuration, with the exception of unique rod ends. They have fail-operate/fail-safe capability. The actuators are powered by two independent hydraulic supplies. As shown in Figure 19, these actuators consist of a dual-tandem main ram, a single stage, dual-tandem spool-sleeve main control valve, a dual-coil rotary direct-drive force motor, a mode selector valve, and an integral damper accumulator. Dual-coil LVDTs provide main ram and main control valve positions for closed loop control. Two dual-coil solenoid valves are used for failure isolation. After two electrical failures, the actuators revert to a damper mode.

3.7.3 Rudder Actuator Configuration

The rudder actuator is a rotary configuration with fail-operate/fail-safe capability. It is powered by a single hydraulic supply. As shown in Figure 20, the actuator consists of a three-chamber rotary ram and cylinder, a single stage spool-sleeve main control valve, a dual-coil rotary direct drive force motor, a mode selector valve, and an integral damper accumulator. Closed loop control is provided by a dual-coil rotary variable differential transformer (RVDT) for main ram position and a LVDT for main control valve position. Two dual-coil solenoid valves are used for failure isolation. After two electrical failures, the actuator reverts to a damper mode.

3.7.4 Servo Loop Electronics and Redundancy Management

The servo loop electronics and the redundancy management for the flight control actuators is contained within the quadruplex flight path control set (FPCS) computers. The servo loop-closure electronics is analog. The IFPC redundancy management uses a combination of cross-channel monitoring and inline comparison of active elements and models.

3.8 Tornado Actuators

The most fundamental advance in the Tornado actuators is that the system is normally electrically signalled ("fly-by-wire"). This means that the actuators must incorporate means of interfacing with the signal output from the Command and Stability Augmentation System (CSAS). In the system there is also a completely separate provision for conventional mechanical signalling to one set of control surfaces (the tailerons), and so in this part of the system, means must be provided for immediate and smooth mode changeover from electrical to mechanical signalling either upon pilot command or automatically in the event of sufficiently severe malfunction.

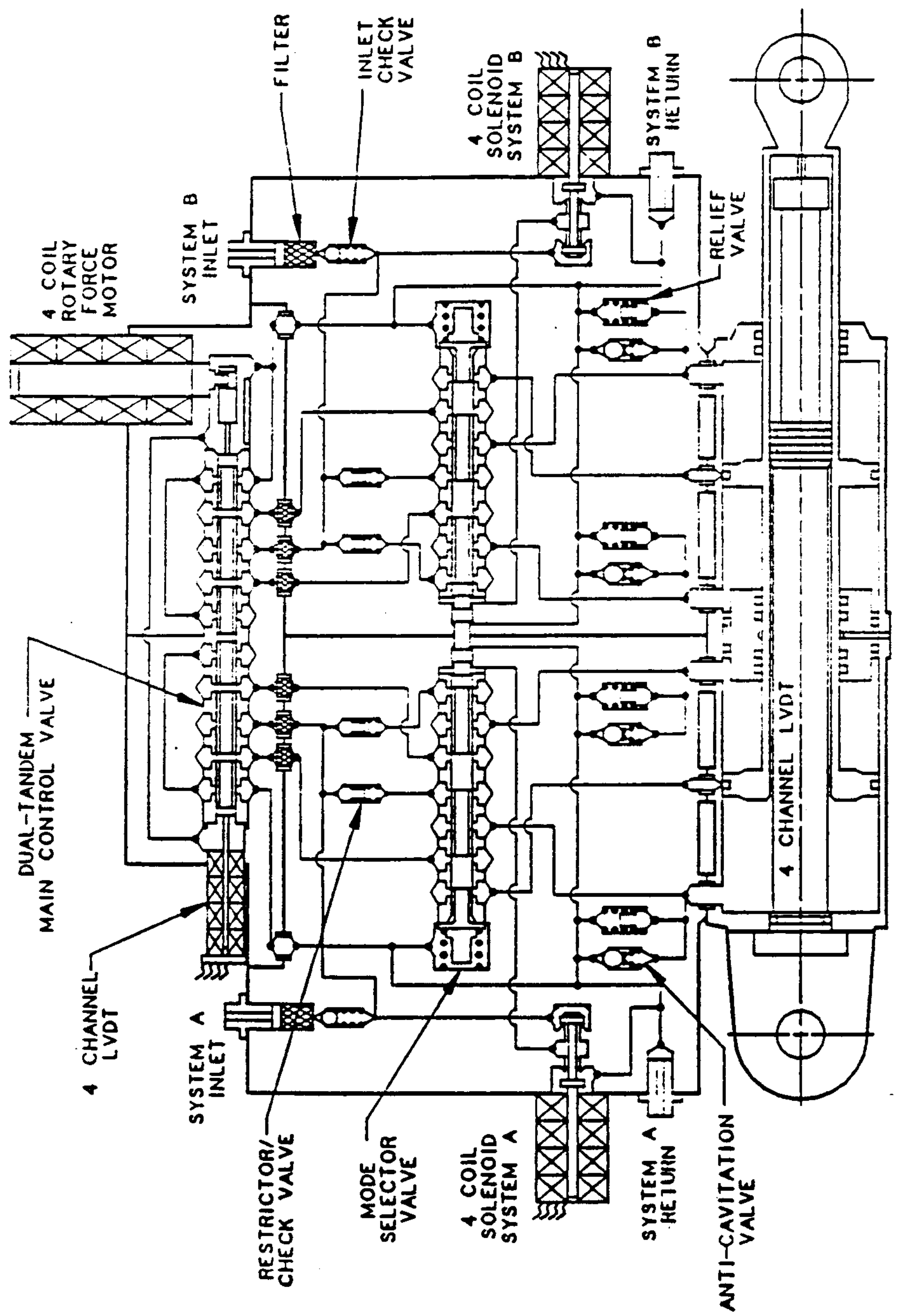


FIGURE 18 - F-15 S/MTD STABILATOR/CANARD SERVOACTUATOR

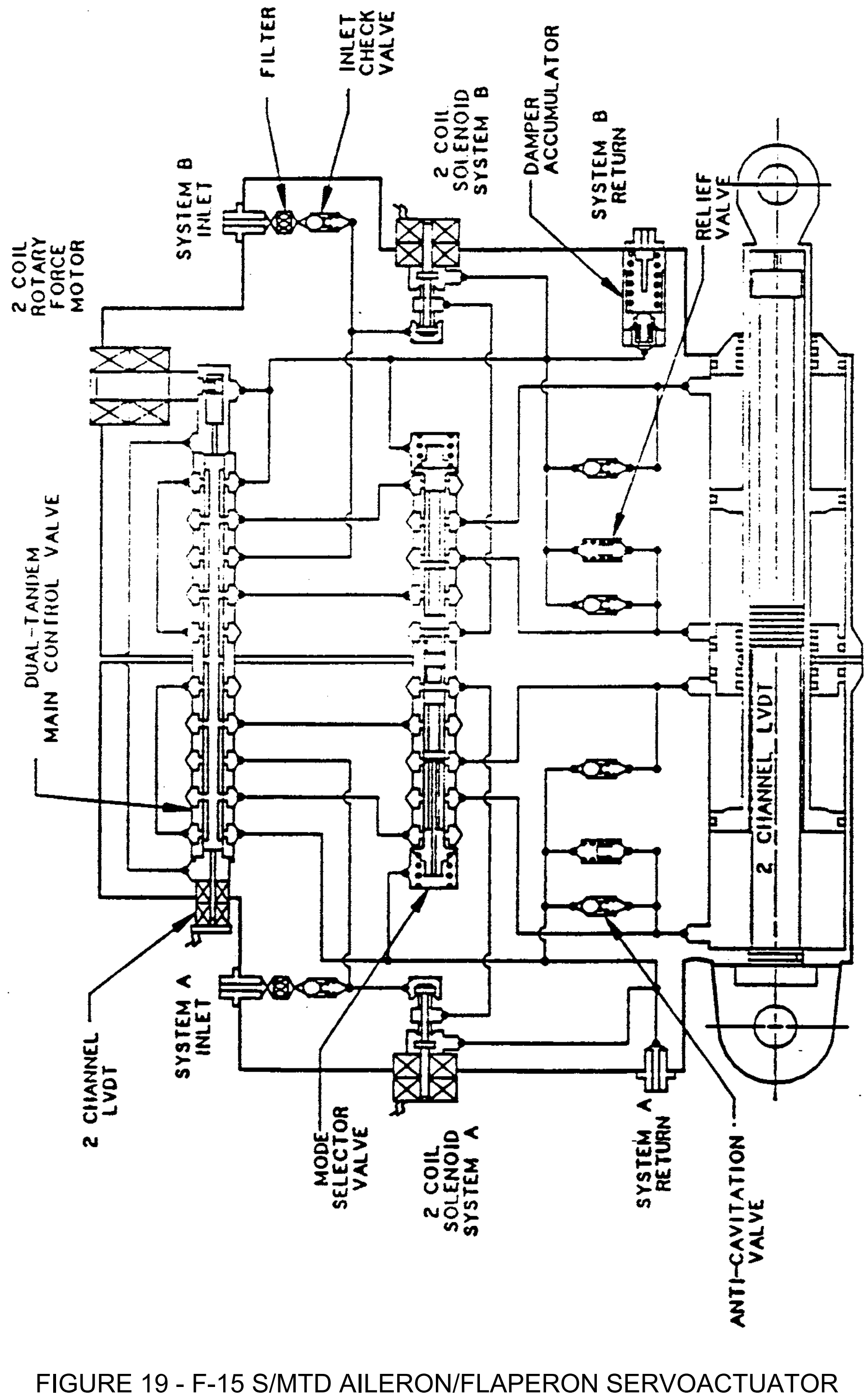


FIGURE 19 - F-15 S/MTD AILERON/FLAPERON SERVOACTUATOR

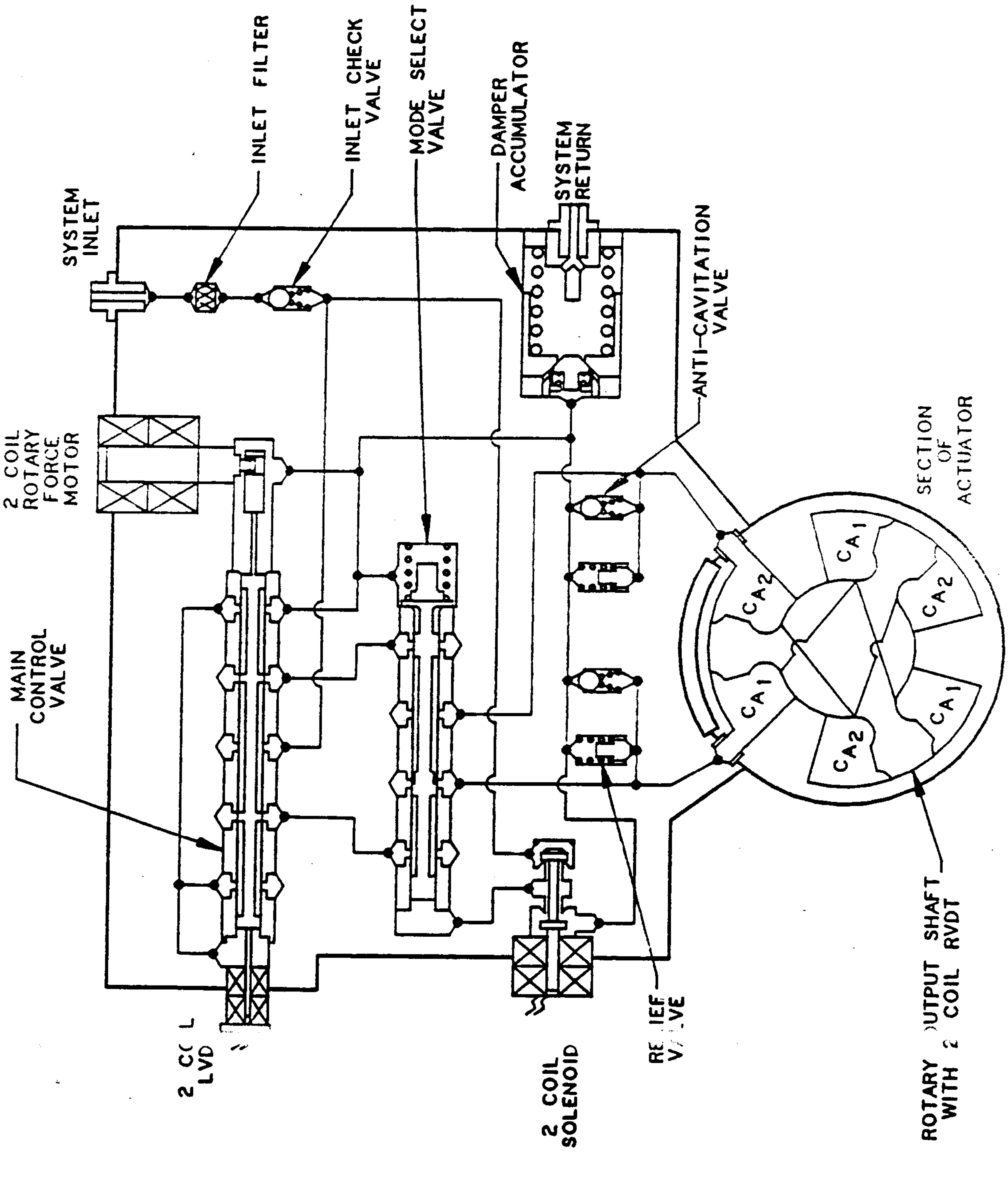


FIGURE 20 - F-15 S/MTD RUDDER SERVOACTUATOR

The hydraulic parts of the Tornado flying-control system have very adequate failure survival at the duplex level. The basic electrical control is triplex with the internal control loop quadruplexed to align with the duplex hydraulic system. The arrangement is shown diagrammatically in the block diagram shown in Figure 21.

3.8.1 Taileron Actuator Configuration

Each taileron (or half horizontal stabilizer) is separately driven by its own power unit incorporating a tandem hydraulic actuator, Figure 22. The taileron actuator schematic is shown in Figure 23. Each actuator piston is served by a separate hydraulic system. The position of the surface is controlled by a mechanical servo-valve equipped with a low-frequency-blocked pressure-feedback device. Motion of the ram rod is sensed by a three-track plastic-film potentiometer, or, in the mechanical mode, by a mechanical feedback link. In the mechanical mode, this link acts directly on the servovalves to cancel the input demand. In the normal, electrical, mode the surface power unit is governed by a quadruplex actuator, which is mounted on the power unit and serves as a high-integrity interface between the FBW electrics and CSAS electronics on the one hand and the mechanical powered flying control unit on the other.

3.8.2 Taileron Actuator Redundancy Management

In the normal (electrically signalled) mode of operation, the quadruplex actuator performs two main functions. It converts the summed electrical demand inputs into a medium-power mechanical output to control the surface power unit, and it allows for variations between the signals in the four electrical lanes. Should there be a substantial error in one lane, it automatically isolates that lane from the common mechanical output.

The deviations between the four signals originating from the voter monitor would, in the absence of faults, be small.

Other errors between the four quadruplex lanes may arise from the implementation of these demands or failures of valves or potentiometers in the actuator or wiring faults in the aircraft. Any major deviation of any one lane from the position of the other three is signalled to the pilot as a "fail operate" warning. The actuator can tolerate a second electrical lane failure and remain fully operational. A third electrical failure or combination of one hydraulic failure with an electrical failure results in a reversion to the mechanical signalling mode of control with a "fail-safe" warning to the pilot.

Each of the quadruplex actuator input lanes commands the movement of a separate electro-hydraulic servovalve. In turn, this governs the position of a small hydraulic subactuator. Thus, the four electrical inputs are converted to four independent mechanical movements. The four sub-actuator drive "connecting rod" links, each of which rotates a clutch plate which is hydromechanically loaded onto a driven plate secured to the consolidated output shaft. The variable degree of coupling between the clutch plates and the output shaft enables the quadruplex actuator to:

1. operate with four lanes functioning, despite minor disagreements,

2. disconnect any lane whose degree of disagreement exceeds a critical value, and

3. disconnect all electrical lanes in the event of a nonsurvivable fault condition.

The variable coupling takes the form of conical pegs projecting axially from the face of each driven plate and normally mating with detent sockets in the corresponding face of each clutch plate. With hydraulic power on and all lanes operative, the four sub-actuators drive four clutch plates arranged in two pairs, each pair gripping a driven plate between them. The whole assembly moves together and establishes a consolidation of the output displacements of all four control lanes in the inner loop. In the event of the output of one lane seriously differing from the other three, the output consolidation favors the three good lanes. Minor deviations are accommodated by the detent sockets of the clutch plates, riding away from the conical pegs on the driven plates against the clamping force of hydraulic clutching pistons inside the hollow output shaft. This allows each clutch plate to move through an angle of about 4 degrees relative to its mating driven plate. This represents 20% total lane displacement in that direction. The total system is, therefore, very tolerant of minor deviations arising from component tolerances within the actuator and the avionic driving system. Relative motion is always possible because the torque imparted to each clutch plate substantially exceeds the opposing force of the clutching pistons.

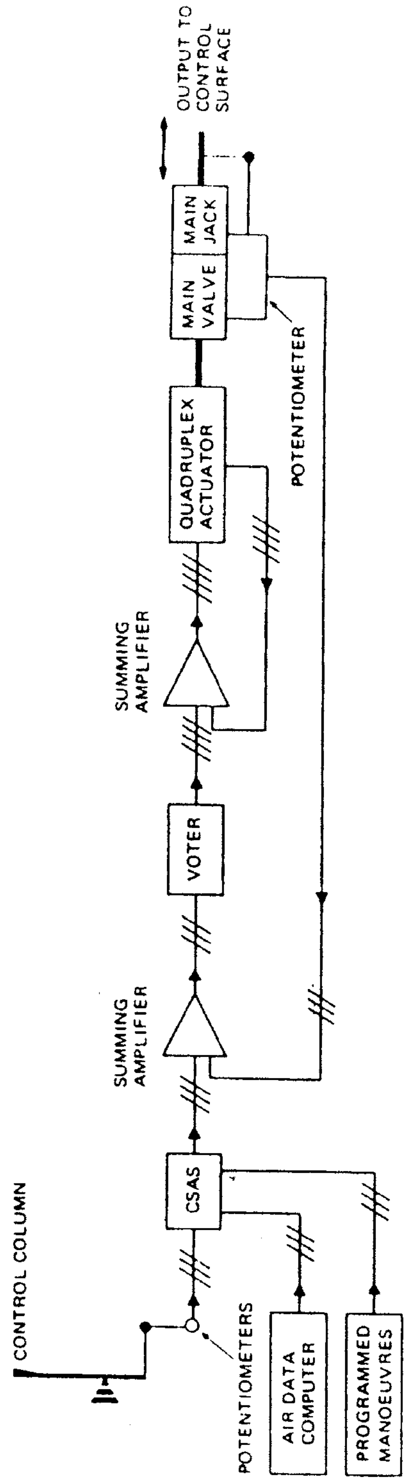


FIGURE 21 - TORNADO CONTROL SYSTEM REDUNDANCY

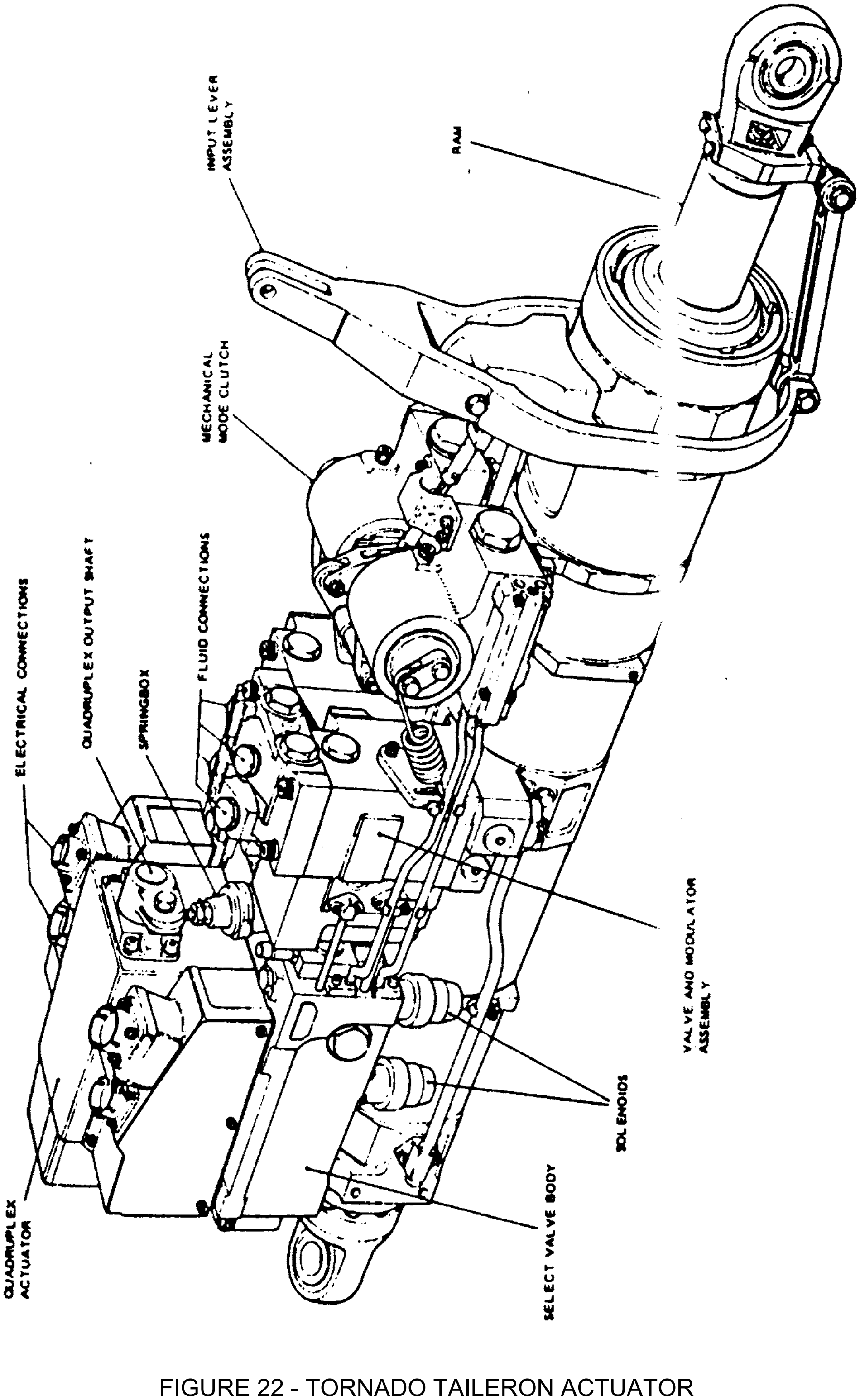


FIGURE 22 - TORNADO TAILERON ACTUATOR

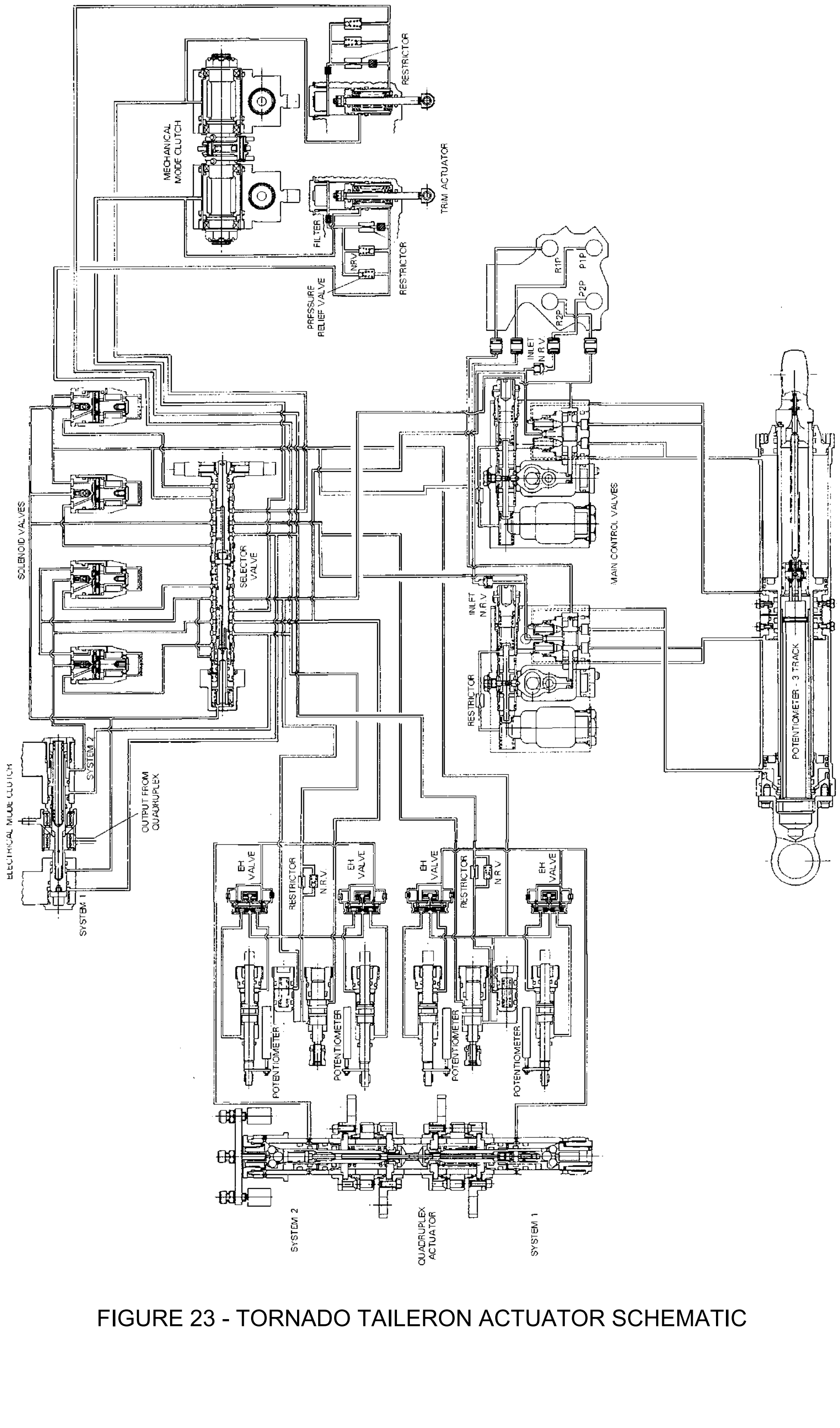


FIGURE 23 - TORNADO TAILERON ACTUATOR SCHEMATIC

Once the disagreement in any lane causes the relevant clutch plate to move through a relative angular distance greater than 5 degrees the axial travel of that clutch plate along the output shaft becomes great enough to cause effective disengagement. A latch plate drops between the clutch plate and driven plate preventing the drive from that plate being applied to the consolidated output and preventing the faulty plate from being re-engaged (until the latch plate is deliberately raised). The axial travel of the clutch plate closes a switch signalling an amber fail-operate warning on the pilot's panel. Further rotation of that clutch plate, such as would occur with a faulty hard-over signal, carries the detent sockets out of engagement with the conical pegs of the driven plate, so that the torque it can transmit is effectively zero. The output, thus, continues to be determined by the three surviving channels.

Two of the input lanes drive their clutch plates through one hydraulic system and the other two lanes drive through the other. In the same way, the clutch-plate loading pistons are energized in pairs from the two hydraulic systems, and clamp the assembly axially against an opposing force from the concentric pairs of coil springs. In the event of failure of either hydraulic system, these springs push apart the two affected clutch plates until they are no longer in engagement with their driven plate. This is again signalled as a fail-operate condition (if no other failure has previously taken place). An amber warning is interpreted by the pilot as one of the following:

1. one lane well outside normal operating limits,

2. two lanes well outside normal operating limits,

3. failure of one hydraulic system.

Such a warning calls for no mandatory action by the pilot unless he is in an unnecessarily hazardous flight mode (for example, mission in a severe terrain-clearance regime) in which sudden reversion to mechanical signalling might be undesirable.

With any fault condition giving an amber fail-operate warning, the system continues to function on at least one hydraulic system and at least two correctly operating electrical channels. Any further fault, however, must cause an immediate reversion to mechanical signalling.

Reversion is brought about by microswitches being opened, thus cutting off current to solenoids in the reject selector assembly. there are four fail-safe solenoids provided to control the mode selector valve, which is a two-position tandem hydraulic spool valve with one half operating in each hydraulic system. With the solenoids in the de-energized condition, the selector is held in the mechanical mode position by spring pressure.

The taileron actuator also includes two types of clutch and trim actuators. The clutches and the trim actuators are needed to provide two independent actuator control linkages, one for use with electrical signalling and the other for mechanical signalling, and for engaging only that which is demanded. The trim actuators are needed to take out any difference between the electrical and mechanical control demands at the moment of reversion, and re-align the geometric datum settings of the surface and the pilot's control column. The importance of this function is evident from the fact that, in the worst case, at the moment of changeover the pilot might be making a 10% demand in one direction while the surface may actually be at the limit of its travel in the opposite direction in accordance with control demands from the CSAS.

The electrical mode clutch has a fixed geometry with which it engages or disengages the linkage between the quadruplex actuator output shaft and the power unit servovalves and is pressurized by the two hydraulic systems.

In contrast, the mechanical mode clutches are of unusual design to meet the challenging requirement that mechanical reversion must be almost instantaneous, with no insignificant transient. This sudden take-up of the mechanical system might also occur at a time of rapid relative motion between the mating members. The solution is an infinite position device with which to engage the mechanical system and transmit the control movements while the trimming function takes place.

The trim actuators, which are needed to wash out the difference between surface positioni and pilot's stick position at the moment of changeover, must not bring the two into immediate alignment. To do so might cause a sudden deflection of the tailerons which at high IAS could break the aircraft. A time of 9 s is, therefore, allowed for trimming out the difference. The pilot has control authority throughout this period, but at the moment of reversion, he may find that his neutral stick position is displaced. This would not cause immediate embarrassment, but the stick and surface must be brought to a common datum to permit full control surface displacement when required by the pilot.

3.8.3 Rudder Actuator Configuration

The single rudder is driven by a power unit of slim design housed within the rudder itself, driving on to the fixed fin. The rudder actuator is shown in Figure 23. Its operation is similar to that of the taileron power units, apart from the fact that there is no provision for manual signalling. The rudder is less important as a control surface since the aircraft can, under normal conditions, be controlled without the rudder. Accordingly, its reversionary mode is a centering action back to the streaming position.

3.8.3.1 Rudder Actuator Redundancy Management

The rejector selector is "signalled over" to the reversionary position by solenoids, as in the taileron system. In this position, the main mechanical servovalves are isolated from the cylinder, which are then commanded by a local mechanical closed loop. This lever system signals two secondary valves, one in each hydraulic system, to bring the rudder to the central position. Subsequently, it is held "stiff" by hydraulic pressure to prevent flutter.

3.8.4 Spoiler Actuator Configuration

Each wing carries two spoiler surfaces above its trailing edge, the inner spoilers being driven by one hydraulic system and the outer by the other. Each panel is positioned by a double-acting actuator with a duplex electrical feedback potentiometer. The actuator, shown in Figure 24, is governed by a separate package, alongside it in the thin wing. This contains a single electro-hydraulic valve with separate coils receiving two demand signals fed through duplex electrical control links. The coil in the first stage determines the position of the flow stage of the valve which controls the actuator.

3.8.4.1 Spoiler Actuator Redundancy Management

The potentiometer feedback signals are continuously compared with the duplex input signals, and any sufficiently large disagreement serves to trigger the reject system. This applies hydraulic power on the retraction side of the ram to drive the surface fully home. The movement is completed in 0.5 s to prevent undesired roll being imparted by a faulty hardover signal. Simultaneously, the corresponding spoiler on the other wing is housed and deactivated to preserve symmetry of roll power in both directions.

When the wings are swept to a supersonic angle, the same system is triggered for all spoiler sections, since at maximum sweep the inner panels are within the fuselage. In the event of hydraulic failure, the spoilers are allowed to close under aerodynamic load.

3.9 Space Shuttle Actuators

The Space Shuttle Main Engine (SSME) servoactuators and the Solid Rocket Booster (SRB) servoactuators provide Thrust Vector Control (TVC) for the shuttle engines. The actuator configuration is common among the various applications and there are four actuator sizes. The servoactuators consist of a single cylinder and piston with mechanical feedback and a quadruplex majority voting servo assembly. The mechanical design phhilosophy for these large power output elements is conservative to provide adequate reliability. The alternative of using redundant power output elements involves unreasonable size and weight. The servo design is a four servovalve configuration with electrical failure sensing and shutoff to give two-fail-operate capability. The SSME servoactuators have three hydraulic supplies and the SRB servoactuators have two supplies. In each case, however, only one hydraulic system is used at a time within each servoactuator.

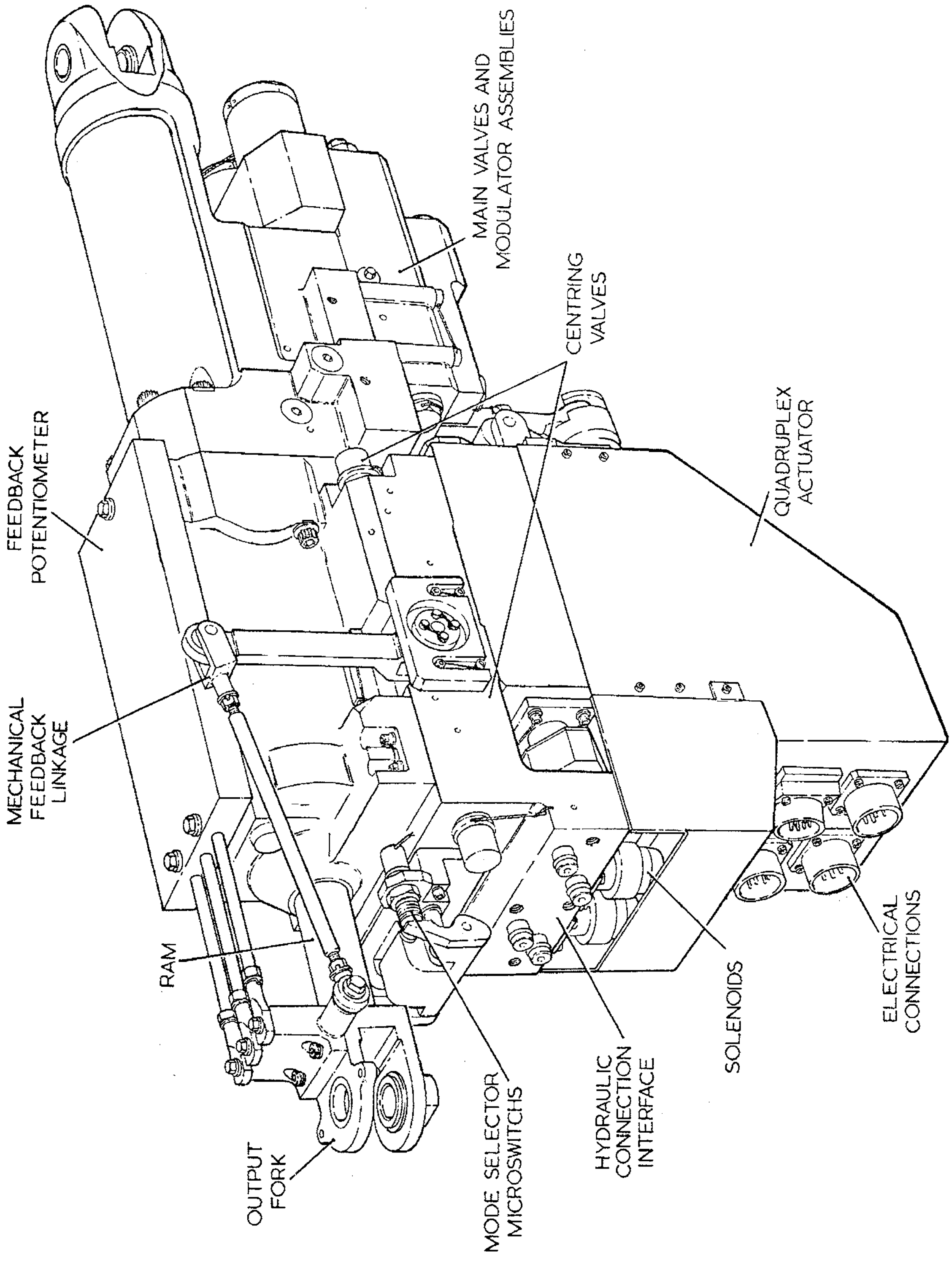


FIGURE 24 - TORNADO RUDDER ACTUATOR

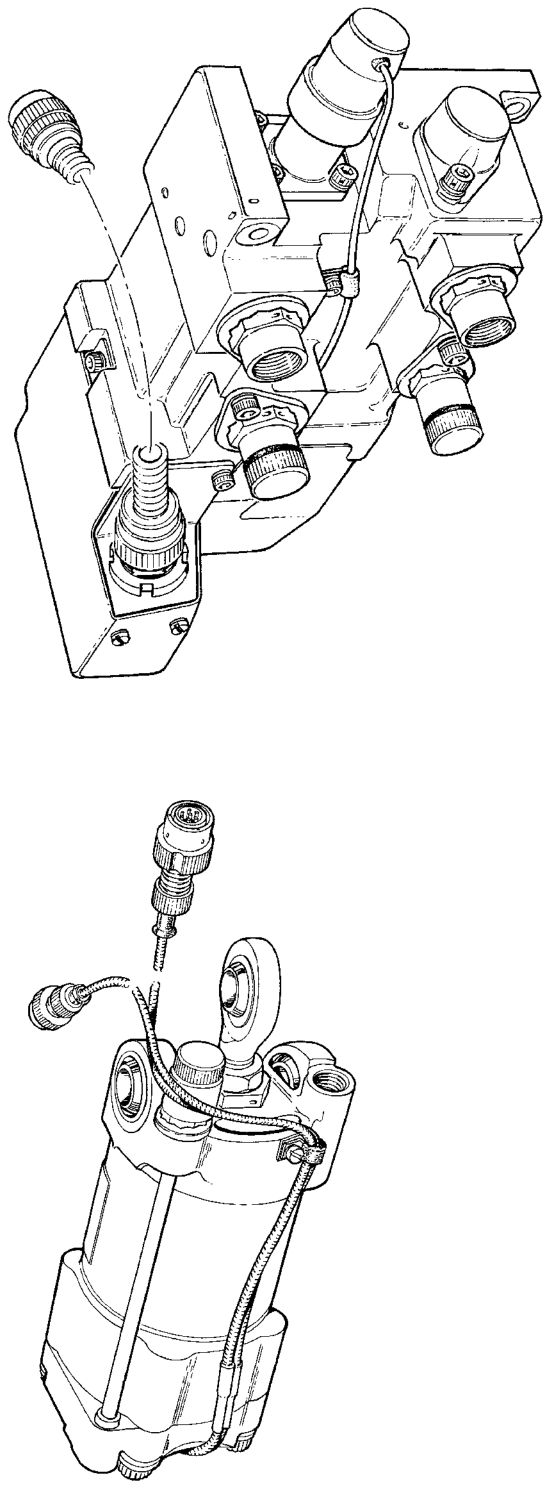


FIGURE 25 - TORNADO SPOILER ACTUATOR AND VALVE PACKAGE

3.9.1 Thrust Vector Actuator Configurations

A diagram of the TVC actuators is shown in Figure 26. Overall actuator position feedback is provided mechanically by a conical cam, cam follower and linkage arrangement that positions springs that act on the torque motor of each servovalve. Internal cantilever spring wires within each servovalve provide mechanical feedback from the second-stage spools and from the power-valve spool. The four servovalves are arranged in a V-4 configuration about the single power valve spool (see Figures 26 and 27). A concentric drive piston is used at each end of the power valve to create four separate drive areas at each end. The drive pistons couple to the power valve through flex rods to reduce concentricity problems. The entire power valve drive assembly is immersed in fluid and no elastomeric dynamic seals are used.

Separate modular differential-pressure sensors and solenoid shutoff-valves are used. Each servovalve has twin feedback wires to provide mechanical feedback from the second-stage spool and from the power valve. The servovalves also have pressure feedback to stub shafts on their second-stage spools to give load sharing. Each servovalve has a second pair of hydraulic amplifier nozzles that connect to dynamic pressure feedback (DPF) pistons. The DPF from the actuator piston differential pressure provides stabilization for the resonant load formed by the engine and structure. A simplified schematic of the TVC servoacatuator pressure loop is shown in Figure 28.

3.9.2 TVC Servo Loop Redundancy Management

The output pressures from the four servovalves are monitored for failure sensing by four differential pressure electrical sensors. These signals are supplied to the electrical failure monitoring circuitry, shown in Figure 29. This circuitry incorporates lagged integrator equalization to reduce the transient associated with channel shut-off when interchannel mismatch is present. The time constant of the equalization filter is approximately 8 s, which is longer than the period of the low frequency vehicle mode.

If the monitored pressure from any one channel exceeds a preset threshold level for a preset period of time, a channel shut-off signal occurs. This signal energizes the shut-off solenoid valve for that channel. The valve removes hydraulic pressure from the corresponding servovalve and opens a bypass across the servovalve output. Electrical signal limits are imposed on the actuator commands to avoid common mode failures associated with excessive rate and stroke commands.

3.9.3 Orbitor Flight Surface Actuators Redundancy Concepts

The orbital flight surface actuators are conventional liinear actuators for the inboard and outboard elevons and a differential gear summation system for the rudder two-fail-operate capability.

3.9.4 Orbitor Elevon Actuator Configuration

The elevon servoactuators consist of a single cylinder and piston with a quadruplex valve assembly similar to the TVC actuators; however, there is no mechanical feedback mechanism between the main piston and the quad valve assembly. Instead, these servoactuators use electrical feedback from a quad LVDT located inside the piston rod. The only significant difference between the inboard and outboard elevon actuators are the force and velocity capabilities.

3.9.5 Orbitor Rudder/Speed Brake Actuation System Configuration

The rudder and speed brake actuation system is a differential gear summation configuration driven by hydraulic motors and controlled by quad servovalve assemblies. The rudder/speed-brake gear train schematic is shown in Figure 30. The schematic of the rudder/speed-brake valve module is shown in Figure 31.

3.9.6 Orbitor Servo Loop Redundancy Management

The redundancy management for the orbitor elevon and rudder/speed-brake servoactuators is the same as that used for the TVC servoactuators.

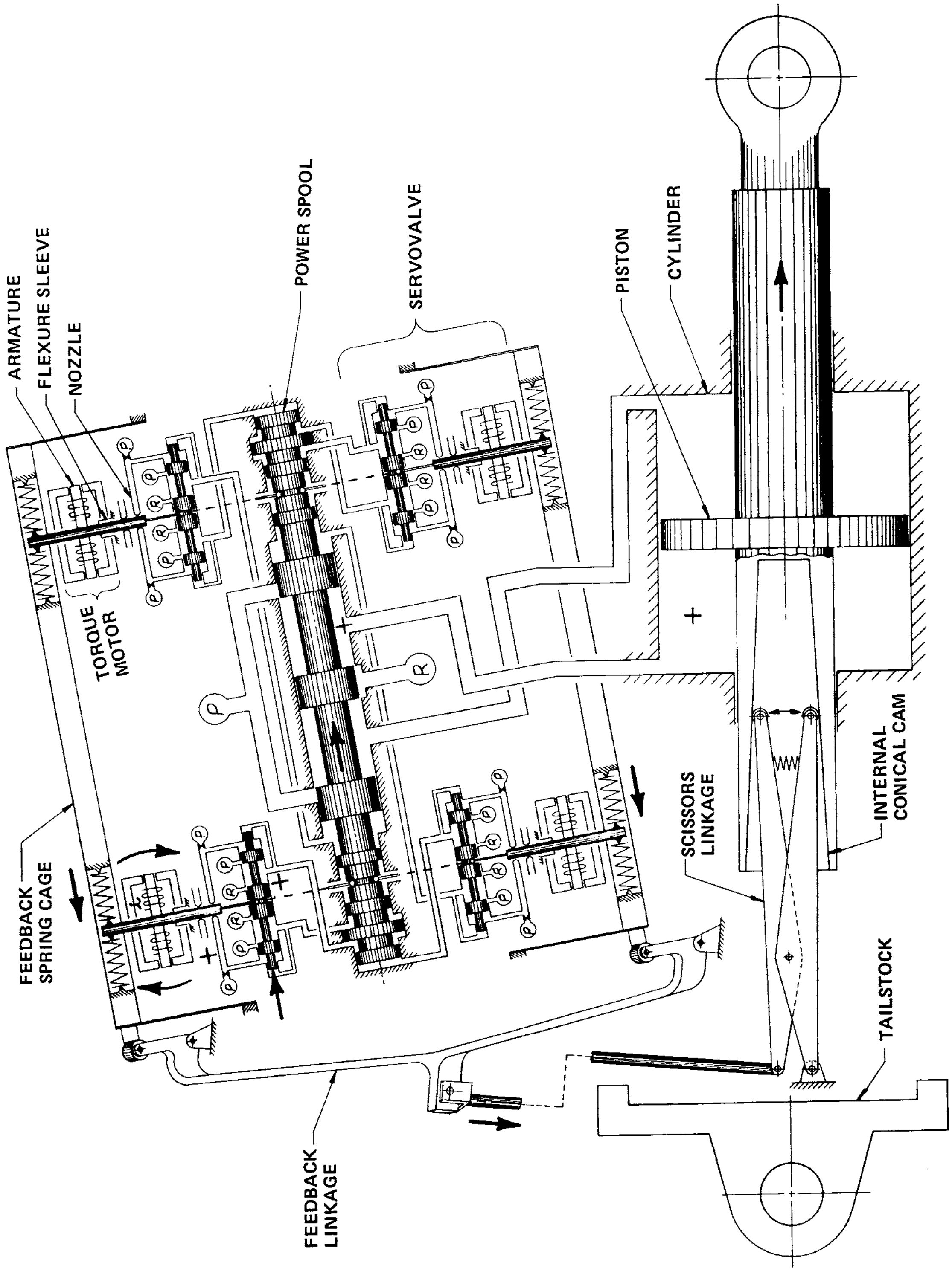


FIGURE 26 - SIMPLIFIED SCHEMATIC OF TVC SERVOACTUATOR POSITION LOOP

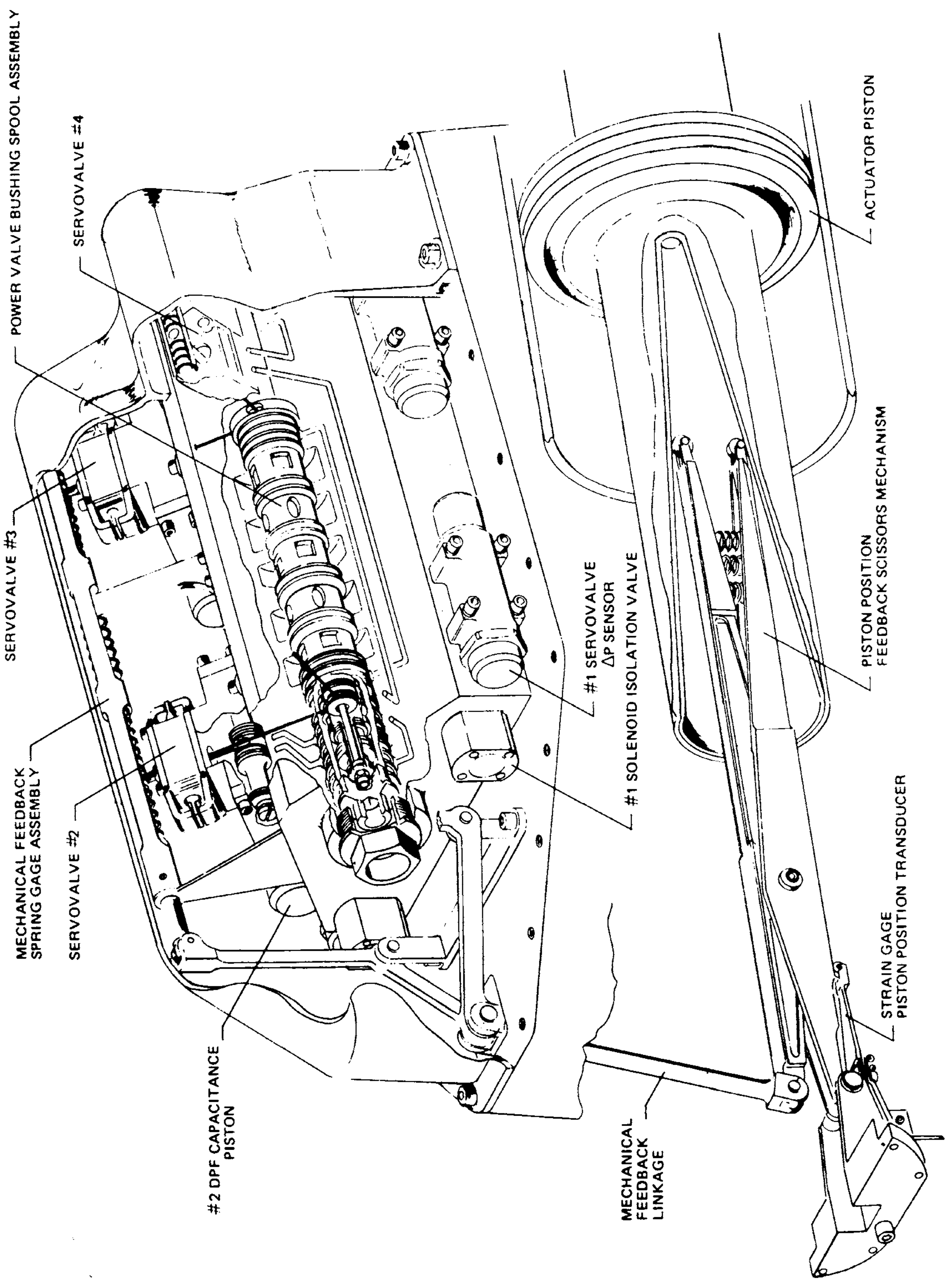


FIGURE 27 - SSME TVC SERVOACTUATOR CONFIGURATION

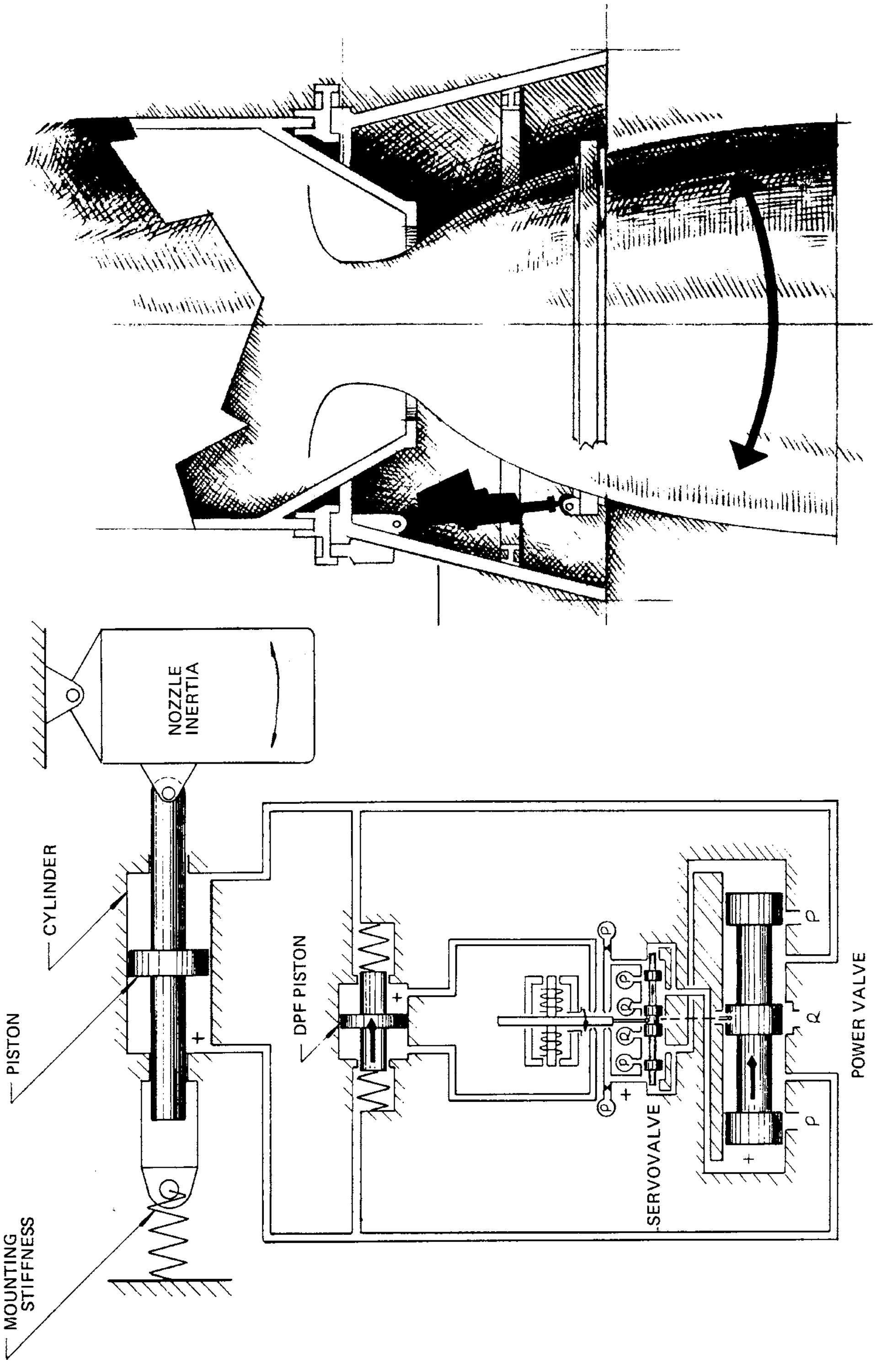


FIGURE 28 - SIMPLIFIED SCHEMATIC OF TVC SERVOACTUATOR PRESSURE LOOP

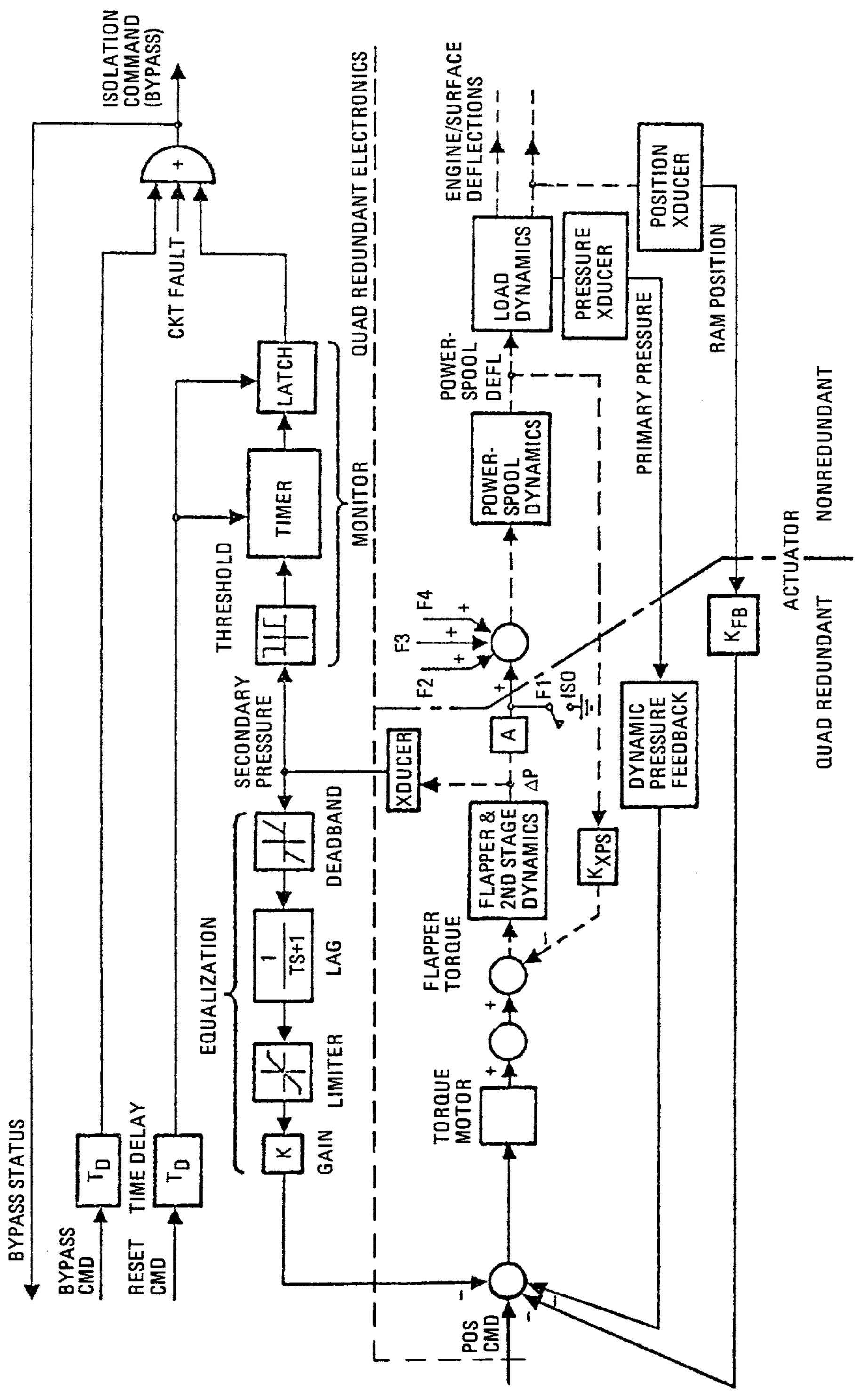


FIGURE 29 - EQUALIZATION AND FAULT DETECTION SCHEME

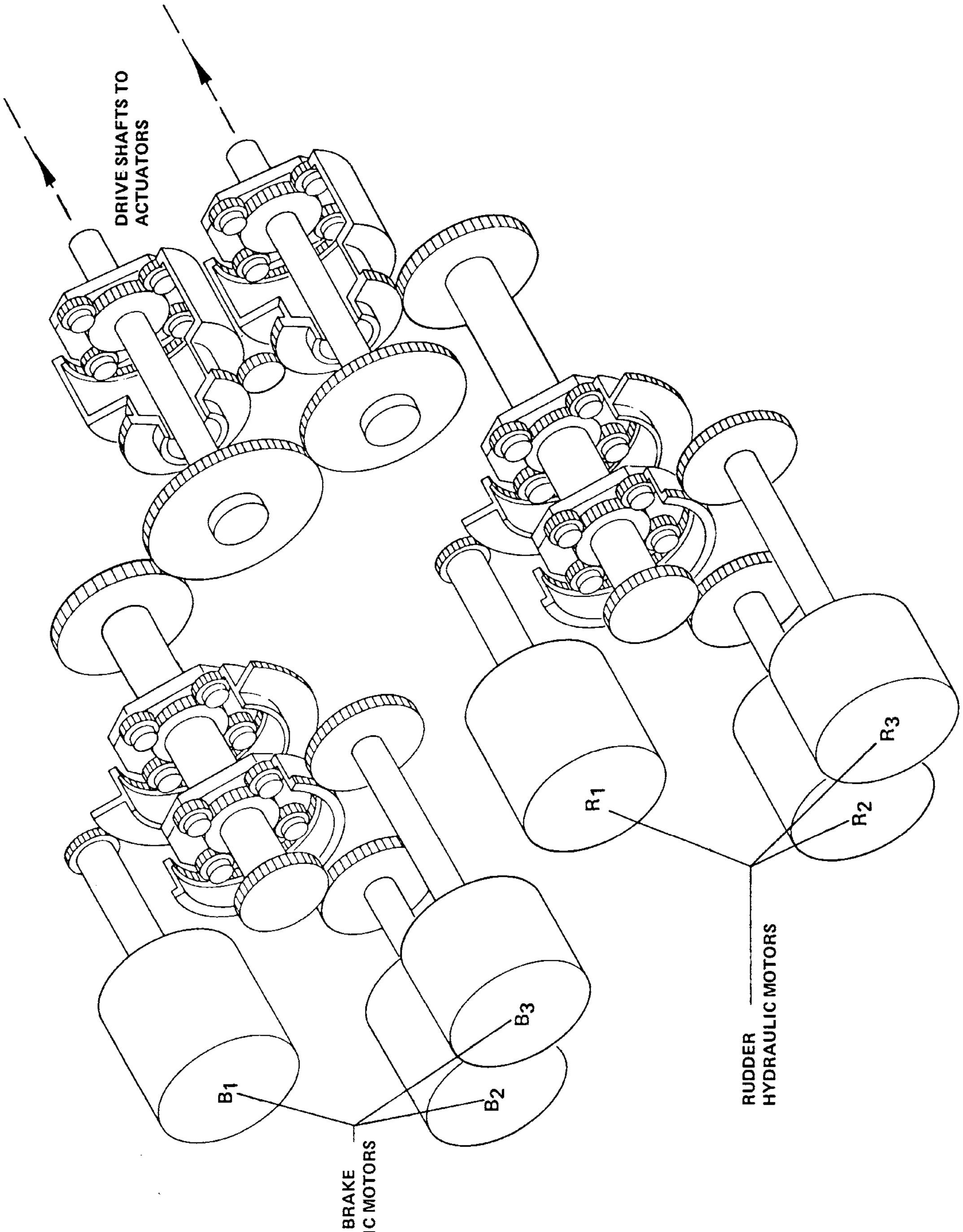


FIGURE 30 - RUDDER/SPEED BRAKE GEARTRAIN SCHEMATIC

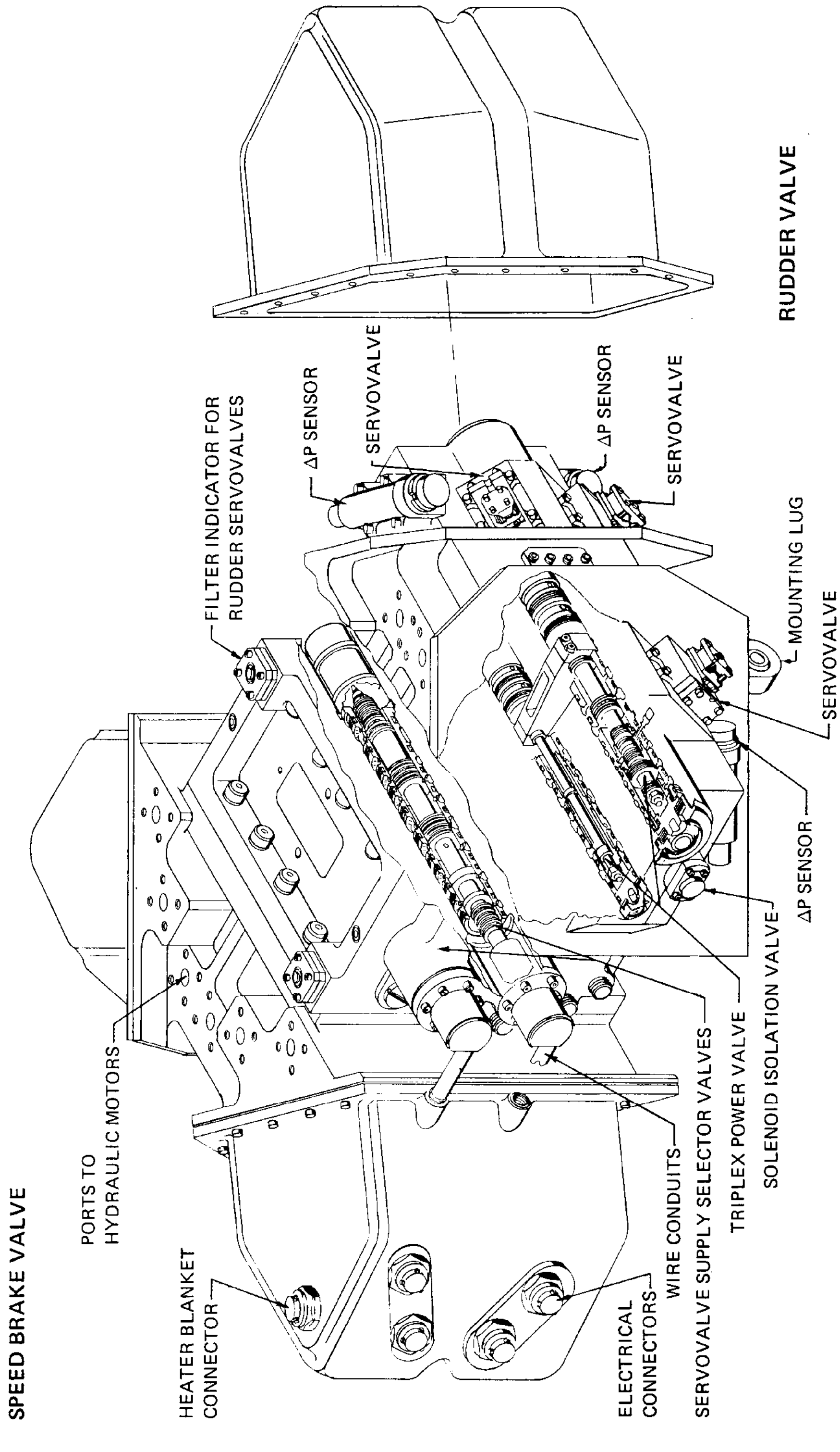


FIGURE 31 - RUDDER/SPEED BRAKE VALVE MODULE

3.10 LAVI Actuators

The LAVI fighter fly-by-wire primary flight control system consists of quadraplex flight control computers commanding dual tandem actuators for two canard, four elevon, and one rudder surface. The hydraulic system consists of dual 3000 psi supplies using MIL-H-83282 fluid.

3.10.1 Actuator Configuration

All three designs are equal area, dual-tandem actuators, pin-joint mounted at rod end and tailstock. Pressure vessel “ripstop” protection is provided by separate cylinder barrels and manifolds. The actuators are full Fly-By-Wire designs and use conventional Electrohydraulic Servovalves (EHSVs) rather than Direct-Drive Valves (DDVs). The EHSVs are single stage valves, force summed on separate drive areas on the dual-tandem, spool-type Main Control Valve (MCV) which controls the flow from the two hydraulic systems to power the actuator.

3.10.2 Architecture and Redundancy Management

The flight control system is centralized and the Digital Flight Control Computer (DFCC) has four cross-compared channels. The actuators achieve double-fail-operate/fail-safe performance (FO^2/FS), with respect to electrical failures, and this electrical redundancy is independent of the dual-system hydraulic redundancy, through the use of multiple-coil EHSVs. The actuator commands generated by all four channels of the DFCC are provided to all of the servovalves in series so that, following loss of one hydraulic system, the valves pressurized by the remaining good system continue to be commanded by all four channels.

As shown in Figure 32, there are four EHSVs per actuator in a dual-pair arrangment, one pair presurized by each of the two hydraulic systems. Each pair of valves generates two control pressures, like a single four-way servovalve, which are used to drive a pair of areas on the MCV. The pressures are also summed, and compared with the differential supply pressure to the servovalve pair, for EHSV failure detection. This failure detection can only detect EHSV failures and cannot detect command failures since each of the two summed pressures is controlled by all four command signals from the DFCC. DFCC failures then are detected upstream by a combination of self-monitoring and cross-comparison.

Each EHSV pair is turned on and off with a quad coil solenoid operated valve (SOV). The hydraulic output of the SOV is amplified with a second stage, poppet-type for jam-free performance and the pressure supplied to the EHSV pair is regulated to allow reliable failure-detection performance over a wide range of hydraulic system supply pressure.

To minimize the analog wiring to each actuator the inner loop around the MCV position is closed mechanically, through a spring-type feedback wire to each EHSV. For the same reason, the position of the comparator centerline which detects EHSV failures is sensed, and conveyed to each channel of the DFCC, with a cam mechanism and four switches, rather than LVDTs.

3.10.3 Fail-Safe Mode

At loss of three DFCC commands, or loss of both EHSV pairs or loss of one pair of EHSVs and the opposite hydraulic system, the actuators fail-safe to a hydraulically powered, centered position. This is achieved with a lightweight linkage, contained within protected cavities, which engages the MCV and provides mechanical actuator position feedback of limited range. The linkage is normally held disengaged by a NOR-type mechanism, as long as either or both of the SOVs are energized and pressurized. If both SOVs are denergized or depressurized the linkage engages and the actuator drives at a controlled rate towards the centered position where it finds equilibrium in a regulator fashion. When the actuator is completely depressurized it will not power to the centered position but it will tend to ratchet towards center because the combination of inlet check valves and the mechanically driven MCV allows free motion towards center but blocks any attempt to move away from (and hence past) the centered position.

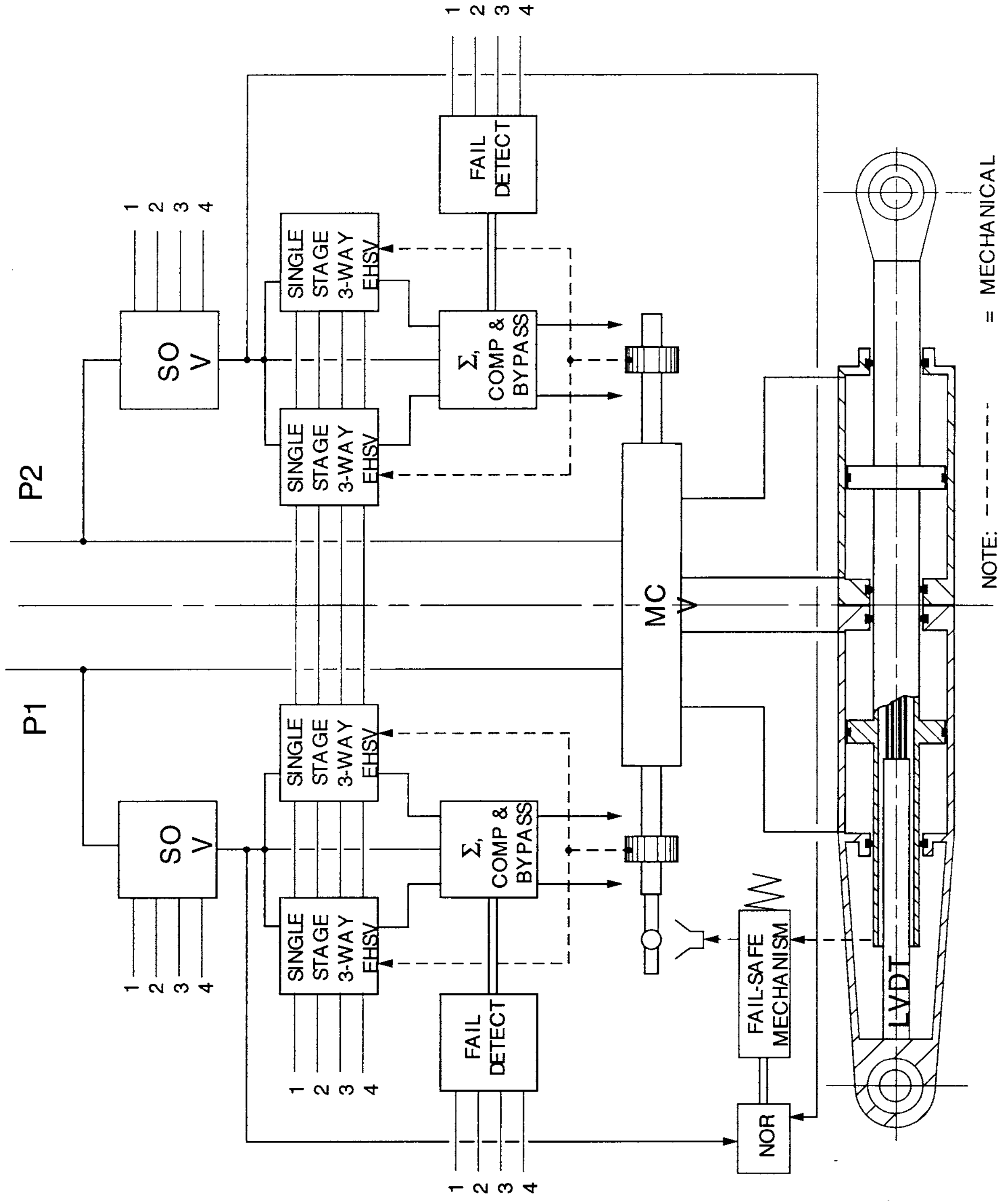


FIGURE 32 - LAVI PRIMARY FLIGHT CONTROL ACTUATOR SCHEMATIC

3.10.4 Performance

The actuators are required to achieve a phase shift of better than 45 degrees at 30 rad/s, to show zero peaking within the bandwidth and to provide stable operation and zero peaking in the presence of a moderately demanding inertial load giving a load resonance at about seven times the frequency at which 45 degrees must not be exceeded. This performance was achieved with nominal inner and outer loop gains of 120 and 50 s^{-1}, repectively, together with a notch filter in the forward path.

Because of the mechanical loop closure around the inner loop, loss of one electrical command channel could cause a 25% reduction of the gain in the outer loop and a consequent proportional decrease in actuator bandwidth. To avoid this, at first electrical failure, the gain of each channel is increased by 33% so the loop gain remains unchanged. At second electrical loss, however, the loop gain is allowed to decrease to 2/3 of the normal 50 s^{-1}.

The failure transients which result from the first EHSV hardover failure and the first DFCC hardover failure are held to less than 1.5 and 3.5% of full stroke, respectively, and the normal operating threshold is less than 0.05% of full stroke.

3.11 JAS-39 Actuators

The Swedish JAS-39 Gripen fighter primary flight control actuation system consists of two servoactuators each for the inboard elevon and outboard elevon surfaces and a single rudder surface. The servoactuator architecture is simplified by the use of direct-drive valves (DDV). This aircraft marks the first production application of DDVs for primary flight controls. The DDV actuation system uses redundant electronic inner-loop (spool position) feedback and failure detection of the single Main Control Valve. The high electrical power demands of the DDV require the use of pulse width-modulated (PWM) servoamplifiers. Each DDV force motor is configured with three separate coils in a flux summed arrangement such that the valve flow is proportional to the sum of the three currents. The valves are capable of performing at full capability with any two coils active and with slight degradation on just one coil.

3.11.1 Canard Actuator Configuration

The canard actuator is a fail-op/fail-safe configuration. As shown in Figure 33, this actuator consists of dual tandem pistons with a triplex coil, single-stage direct drive servovalve. Each piston chamber is powered by a separate hydraulic system. A triplex main ram linear variable differential transducer (LVDT) provides feedback for closed loop position control. Mode select valves piloted by triplex solenoids are employed to provide safe control under fault conditions. Complete failure of either half of the tandem actuator results in a free-flow bypass of the failed side of the piston, resulting in half the hinge moment capability and slightly degraded no-load rate. Failure of both sides results in a damped bypass mode. The actuator contains an integral accumulator in the return system to ensure a hydraulic fluid supply for the damped bypass mode.

3.11.2 Inboard Elevon Configuration

The canard actuator is functionally equivalent to the canard actuator. Due to installation constraints the inboard elevon valve control module, containing the aforementioned valving and accumulator is mounted remotely from the main piston/cylinder assembly.

3.11.3 Rudder Configuration

The rudder actuator is functionally equivalent to the canard actuator. As with the inboard elevon the valve control module is mounted remotely.

3.11.4 Outboard Elevon Configuration

The outboard elevon is the simplex hydraulic system functional equivalent of the tandem canard actuator. However, its valve control module is mounted remotely from the main piston/cylinder assembly.

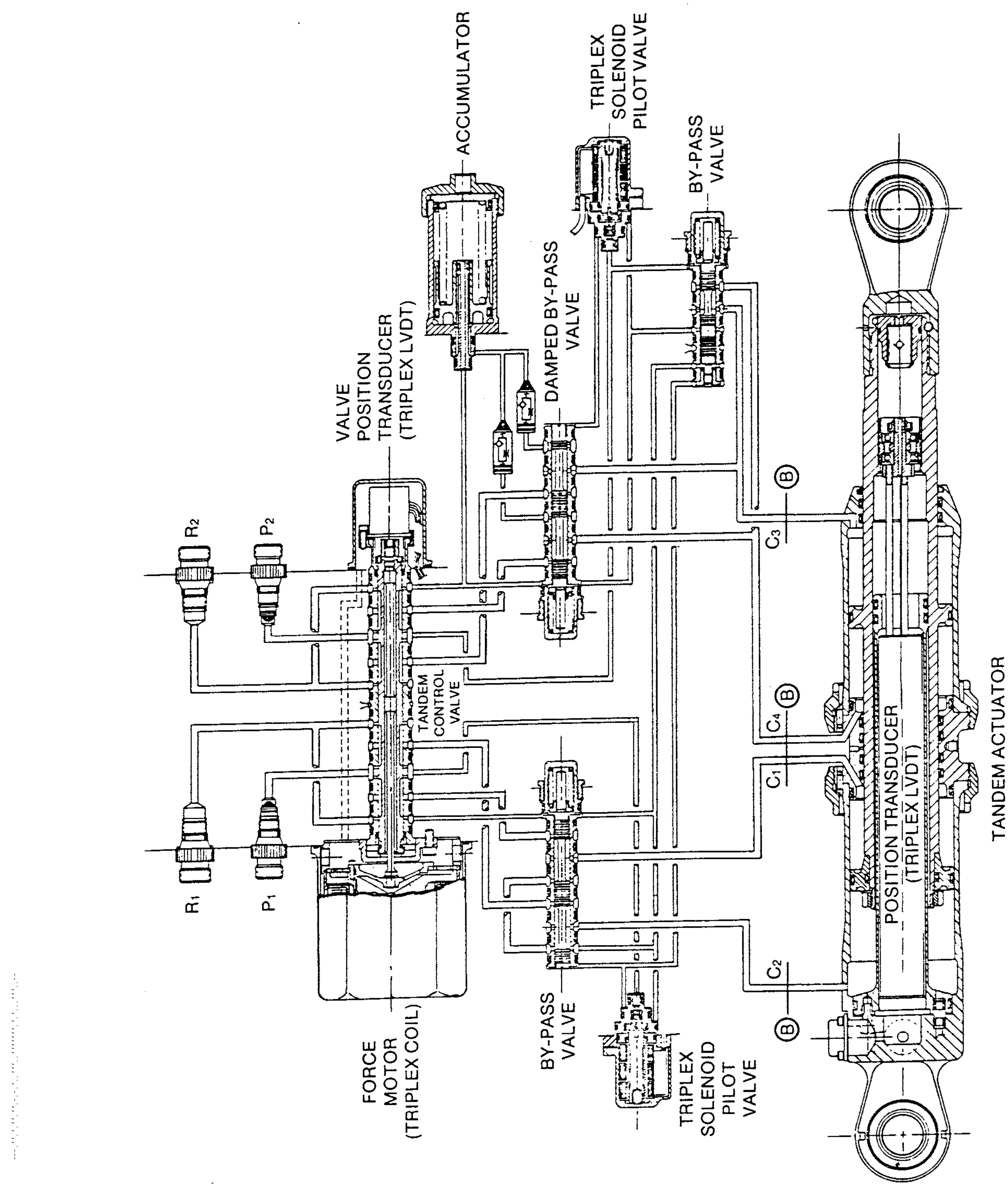


FIGURE 33 - JAS-39 CANARD, INBOARD ELEVON AND RUDDER ACTUATOR FUNCTIONAL SCHEMATIC

3.11.5 Primary Actuator Servo Loop Electronics and Redundancy Management

The actuator servo loop electronics and redundancy management is typical of the three primary actuator configurations, flaperon, horizontal tail and rudder. As shown in Figure 34, each electrical channel generates current commands to one of the DDV triplex coils in a flux summing fashion. There are three loop closures within the electronics, the current loop, the inner (valve) loop and the outer (ram) loop. Each of these loops is triplex. The outer loop is driven by the mid-level selected command from control laws. Failure of one channel reduces the forward gain of the system by one third. The failure of a second channel will send the actuator into a damped bypass mode. Three failure monitors are utilized: the coil current monitor, the position feedback monitor and the main control valve monitor. Failures attributable to the coil current and position feedback are determined through majority vote of the three channels. The detection of a jammed MCV is uncovered by comparing coil current inputs to MCV position feedback. Upon detection of an MCV jam the actuator is placed into damped bypass mode.

3.12 V-22 Flight Control Actuators

The V-22 Osprey Tilt Rotor hydraulic system has been designed in accordance with MIL-H-5440 Type 2 systems and includes a total of 21 flight control servoactuators, comprised of six swashplate, eight flaperon, three elevator, two rudder and two conversion actuators. Figure 35 shows a diagram of the aircraft's hydraulic distribution and flight control actuators. MIL-H-83282 hydraulic fluid is specified for temperatures above -40 °F and MIL-H-5606 at colder temperatures, down to -65 °F. There are three independent 5000 psi hydraulic systems with systems 1 and 2 dedicated to flight controls. System 3 is used for ground check-out of all flight control actuators, inflight power for all utility systems, one elevator and two flaperon actuators and is a backup for the swashplate actuators in the event of a failure of either system 1 or 2 by means of a switching valve. Each of system 1 and 2 provide hydraulic power to both conversion, all swashplate, three flaperon, one elevator and one rudder actuator. Each of the three systems are powered by a 32 gpm gearbox driven box. The gearboxes are interconnected such that they all operate any time either rotor is turning. All hard hydraulic tubing is made of Ti-3Al-2.5V, pressure line flexible hoses are kevlar reinforced PTFE lined and return line flexible hoses are CRES reinforced and PTFE lined.

Table 11 in 3.1 summarizes characteristics of the V-22 primary flight control servoactuators.

3.12.1 Swashplate Actuator Configuration

There are a total of six swashplate servoactuators; three for each rotor. By controlling collective and cyclic pitch they provide all directional control while the aircraft is in helicopter mode and forward thrust when in the airplane mode. These actuators are quite critical in that loss of function of any one of the six swashplate actuators will result in loss of rotor control and thus loss of the aircraft. To minimize the chance of this event the servoactuator redundancy is dual hydraulic and triplex electrically. As shown in Figure 36 the actuator is a tandem piston/cylinder design with system 1 having unbalanced area pistons and system 2 with balance pistons. Actuator position feedback for loop closure is provided by a triplex LVDT housed within the actuator. The actuator is partially ballistic tolerant with the system 1 cylinder designed to completely defeat a ballistic threat and system 2 designed not to jam after being hit.

Control of hydraulic fluid to the cylinders is provided by means of a piloted main control valve (MCV). The MCV is a tandem assembly that controls flow to both piston/cylinders in parallel and it is designed with dual load paths, an extensive use of ripstop and dual locking for each component part. The MCV is driven by two modulating pistons, one of which is twice the area of the other. This minimizes force fight and provides the capability of overcoming a hard-over EHV failure. EHVs drive the MCV through the modulating pistons. The mod pistons are of a size to provide generous chip shearing capability to the MCV. MCV spool position feedback to the flight control computer (FCC) is provided by three individual LVDTs which are housed within the MCV.

The system 2 control module is mounted approximately midway along the actuator and it contains the MCV, a dual channel EHV, a dual coil solenoid valve and a bypass/shutoff valve. When energized the solenoid valve supplies control pressure to the bypass/shutoff valve so that it provides EHV supply pressure and directs control fluid from the EHV to its corresponding mod pistons of the MCV. In the event of an electrical failure of either channels A or C the system 1 EHV and solenoid valve will be driven by channel B.

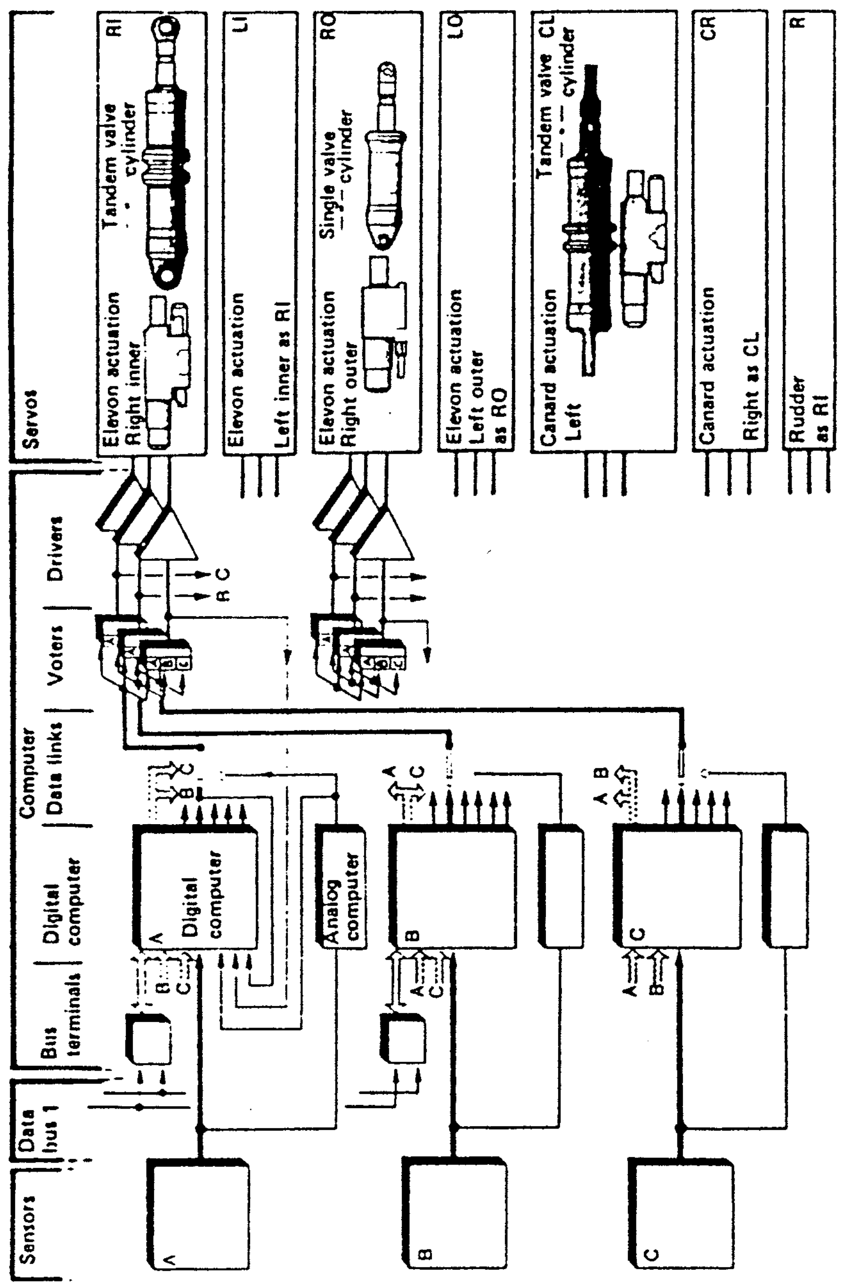


FIGURE 34 - JAS-39 ELECTRICAL FLIGHT CONTROL SYSTEM

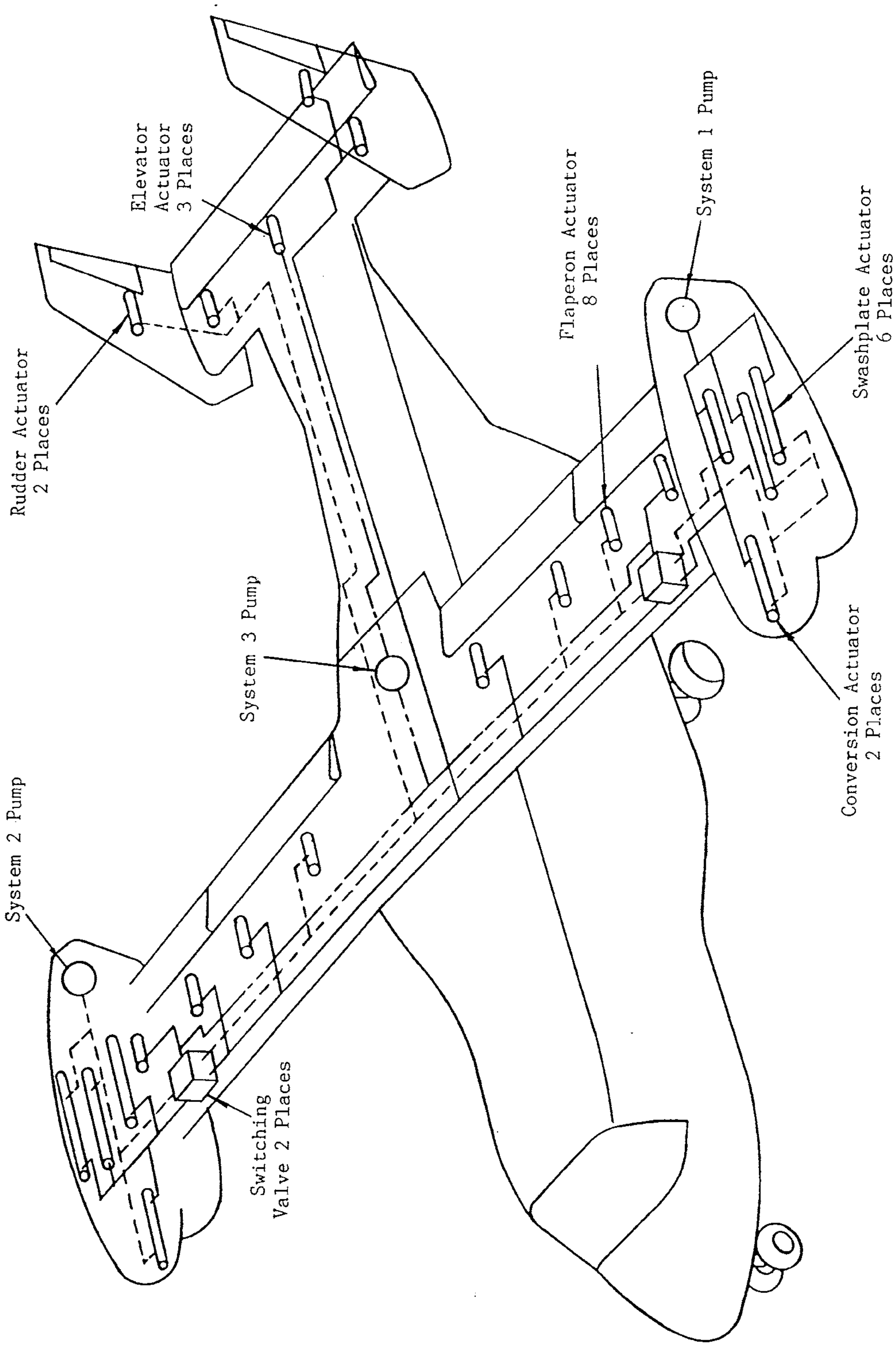


FIGURE 35 - V-22 FLIGHT CONTROL AND HYDRAULIC SYSTEM LAYOUT

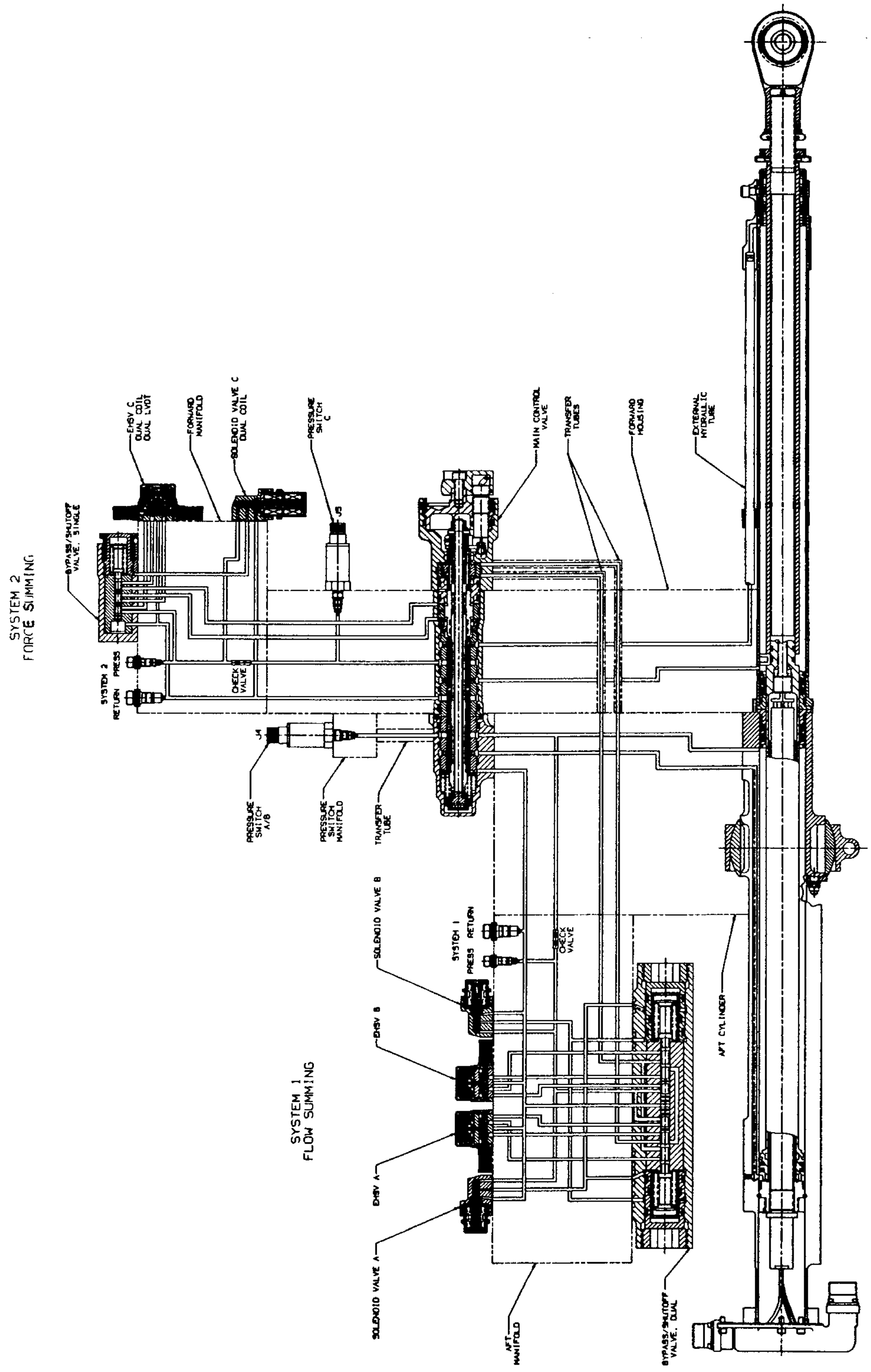


FIGURE 36 - V-22 SWASHPLATE ACTUATOR PICTORIAL SCHEMATIC

EHV failure detection is accomplished by running a real time EHV software model in the FCCs which compares EHV command (current) to EHV spool position, as measured by a dual LVDT. If there is a difference between the two by more than a predetermined threshold the EHV is declared failed and is disconnected from the MCV by its corresponding solenoid valve.

The system 1 control module is located at the aft end of the actuator. This provides maximum ballistic separation from the system 2 control module. The system 1 control module comprises two EHVs, two solenoid valves and a dual bypass/shutoff valve. In a similar fashion as with the system 2 control module the solenoid valves enable or disable the function of their corresponding EHVs except in system one their are two EHVs and solenoid valves with a dual bypass/shutoff valve.

In the event of an electrical failure of either channels A or B the corresponding bypass/shutoff valve will move to the position that shuts off system pressure to the servovalve. If both channels A and B fail then both of the bypass/shutoff valve spools will move into a position which will shut off system pressure to the EHVs and also interconnect both sides of mod piston 1.

The integrity of all LVDTs are checked by continuous monitoring of each transducer’s summed output voltage. If a summed voltage falls out of acceptable tolerance its corresponding electrical channel is declared failed and the channel is turned off.

3.12.2 Flaperon Actuator Configuration

The V-22 has a total of eight flaperon actuators positioning four surfaces (2 actuators each). Figure 37 shows a pictorial schematic of a flaperon actuator. The actuator piston rides on a balance tube so that the net piston areas are slightly unbalanced. Housed within the balance tube is a simplex LVDT which provides ram position feedback to the FCC. An actuator mounted control module houses an EHV with a spool monitoring LVDT, a solenoid valve, a shutoff/bypass valve and a force transducer.

The solenoid valve pilots the shutoff/bypass valve such that an energized solenoid valve causes the shutoff/bypass valve to connect the EHV control ports to the actuator cylinder so that the actuator position responds to servovalve commands. When the solenoid valve is deenergized hydraulic power is removed from the EHV and the cylinder chambers are interconnected and connected to return pressure so that the actuator is in a free bypass state.

The force transducer provides force feedback to a FCC-embedded surface load equalizer that is designed to minimize force fights between actuators on a flaperon surface. The force equalizer also measures force from the other actuator on the same surface and alters the actuator position commands so their force outputs are equal. The transducer consists of a piston with unequal areas in proportion to the actuator piston areas caged between springs and connected to a LVDT. Thus the piston position, as measured by the LVDT, is proportional to the hydraulic force generated at the piston.

3.12.3 Elevator Actuator Configuration

The V-22 has a single elevator surface powered by three actuators. As with the flaperon actuators, the elevator actuators have force transducers for enabling load equalization between these actuators. Configuration of the elevator actuators is very similar to that of the flaperon actuators described in 3.12.2. Aside from differences in size (shown in Table 11) the elevator actuator differs also in that it has balanced piston areas and the actuator is designed with ballistic tolerance. The ballistic tolerance attribute is that if a projectile passes through an elevator actuator the force capability of one of the sister elevator actuators is sufficient to clear the resulting jam so that the surface can be maneuvered by the remaining healthy actuators.

3.12.4 Rudder Actuator Configuration

The V-22 has dual rudder surfaces with each one powered by a single actuator. Each rudder actuator is similar to the flaperon actuator described in 3.12.2 except that there is no force transducer since no force equalization is required.

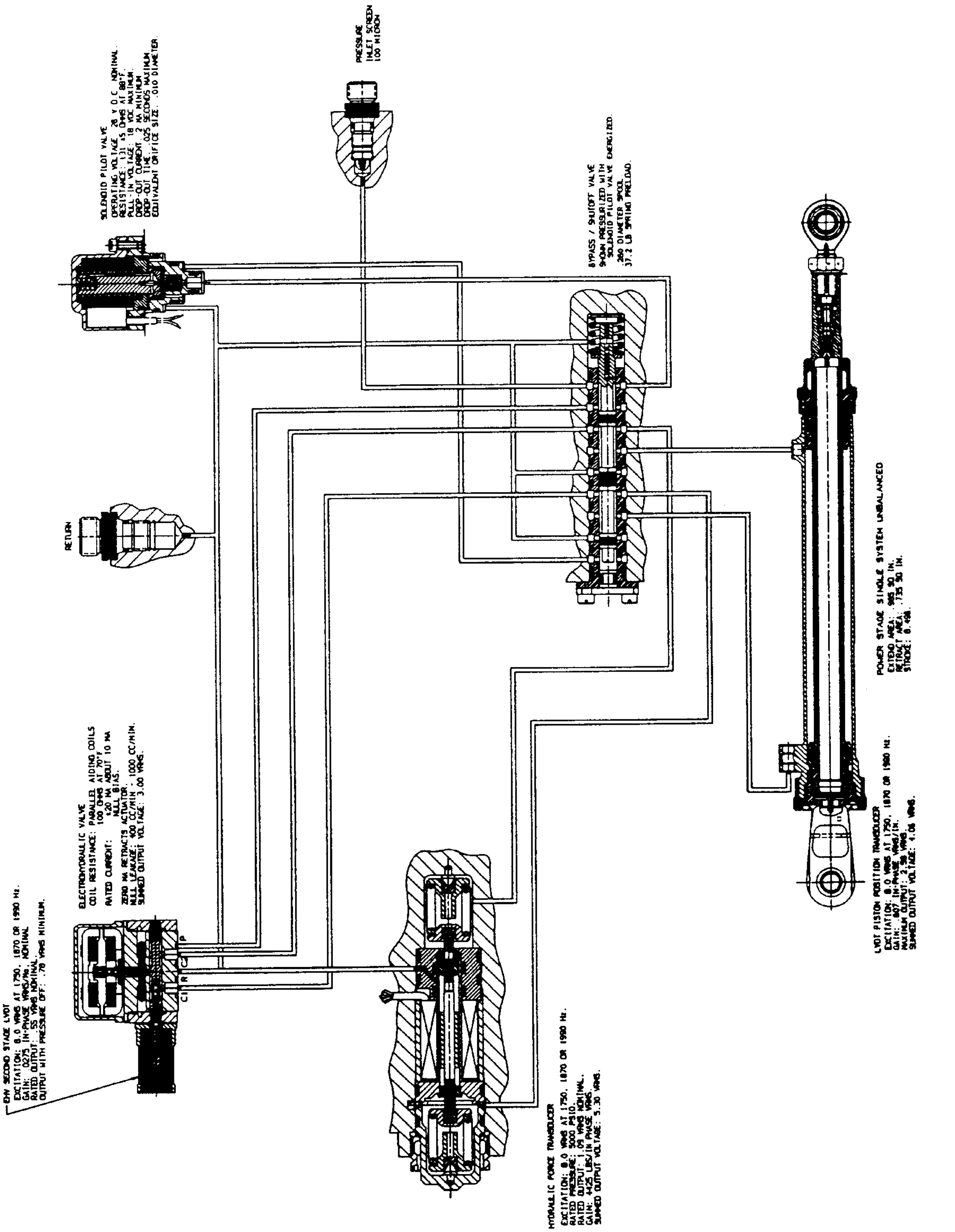


FIGURE 37 - V-22 FLAPERON ACTUATOR PICTORIAL SCHEMATIC

3.12.5 V-22 Conversion Actuator Configuration

Two conversion actuators, one for each nacelle, are used to transition the V-22 aircraft between airplane and helicopter modes. Loss of either actuator can prevent conversion to helicopter mode for landing which is essential to clear the 32 ft diameter rotors from the ground. Thus the conversion actuators are considered flight (or should we say landing) critical and incorporate extensive redundancy.

Each actuator, shown schematically in Figure 38, is capable of generating 33 000 lb stall force over its 45 in stroke and consists of a telescoping ballscrew normally powered by redundant hydraulic drive units (HPDUs) which are powered by hydraulic systems 1 and 2 and controlled by dual redundant channels of the FCCs. The conversion actuators incorporate dual hydraulic and dual electric brakes, solenoid operated shutoff valves for each HPDU, and a differential force transducer. The force transducers allow the FCCs to match the force outputs of each HPDU, and to permit preloading the actuators on the downstops to minimize nacelle motion in the airplane mode. With both HPDUs operating, the V-22 can convert from helicopter to airplane mode in as little as 12 s. The EHVs that control the HPDUs each have a simplex LVDT for spool position inner loop closure and failure detection. Separate quad redundant nacelle position resolvers are used for nacelle position loop closure.

For normal HPDU operation the electric brakes are set for preventing relative rotation of the lug end and inner screw. The hydraulic brakes are released allowing the HPDUs to rotate the outer nut and extend or retract the ballscrew. Each hydraulic brake utilizes dual brake calipers fed by both the number 1 and 2 hydraulic systems. This permits releasing both brakes after a single hydraulic system failure, allowing the remaining HPDU to drive the actuator. Backup operation at half rate is provided by an electric power drive unit (EPDU) and an analog backup computer in the event of two flight control computer or two hydraulic system failures. During backup operation pressure is disconnected from the hydraulic brakes causing them to set and fix the outer nut. Electrical power is applied to release the electric brakes, permitting the EPDU to rotate the inner screw and thereby extend and retract the ballscrew as if the outer nut was being turned.

3.13 Saab 2000 Actuators

The Saab 2000 primary flight control actuation system consists of two fly-by-wire (FBW) rudder actuators, two FBW elevator actuators and dual electronic control modules. Both the rudder and elevators have single surfaces driven by two parallel actuators in a force sharing configuration. The two aileron surfaces are non-powered and positioned by a lateral control cable network and implemented with a geared tabs. The FBW actuators are powered by dual hydraulic supplies and controlled by dual electronics. For a given surface each actuator is connected to separate hydraulic supplies while both electronic channels support each actuator.

3.13.1 Rudder Actuator

Figure 39 is a rudder control system functional schematic showing the push-pull arrangement of the two actuators acting on the single rudder surface. As shown in Figure 40 the rudder actuator is a single balanced area piston design. A mode select valve piloted by a solenoid valve is a two-position valve that configures the actuator either in operate mode with control provided by a servovalve or damped bypass mode. In bypass mode the two cylinder chambers are connected through a damping orifice to provide flutter suppression. The damping function is ensured by anticavitation valves and an integral emergency return line reservoir so that the damping circuit is kept full with hydraulic fluid at a minimum pressure.

Dual LVDTs provide ram position feedback. The servovalve by itself is a pressure control valve (i.e., pressure is proportional to current). Additionally, a spool position LVDT enables an inner spool position control loop whose net effect is a pressure-flow (P-Q) control servovalve. The P-Q feature provides a softer pressure gain than that of a flow control valve so that force fighting between the two surface actuators is greatly reduced. Potential force fight is diminished further by autorigging biases out using servovalve currents as the means for inferring delta-pressures. The servovalve LVDT also provides a means for failure monitoring.

3.13.2 Elevator Actuator

The Saab 2000 elevator actuator is functionally equivalent to the rudder actuator described above. Table 12 in 3.1 tabulates its unique performance parameters. In the event multiple failures cause both elevator actuators to be commanded to bypass an emergency pitch trim electromechanical actuator engages the surface to maintain adequate longitudinal control.

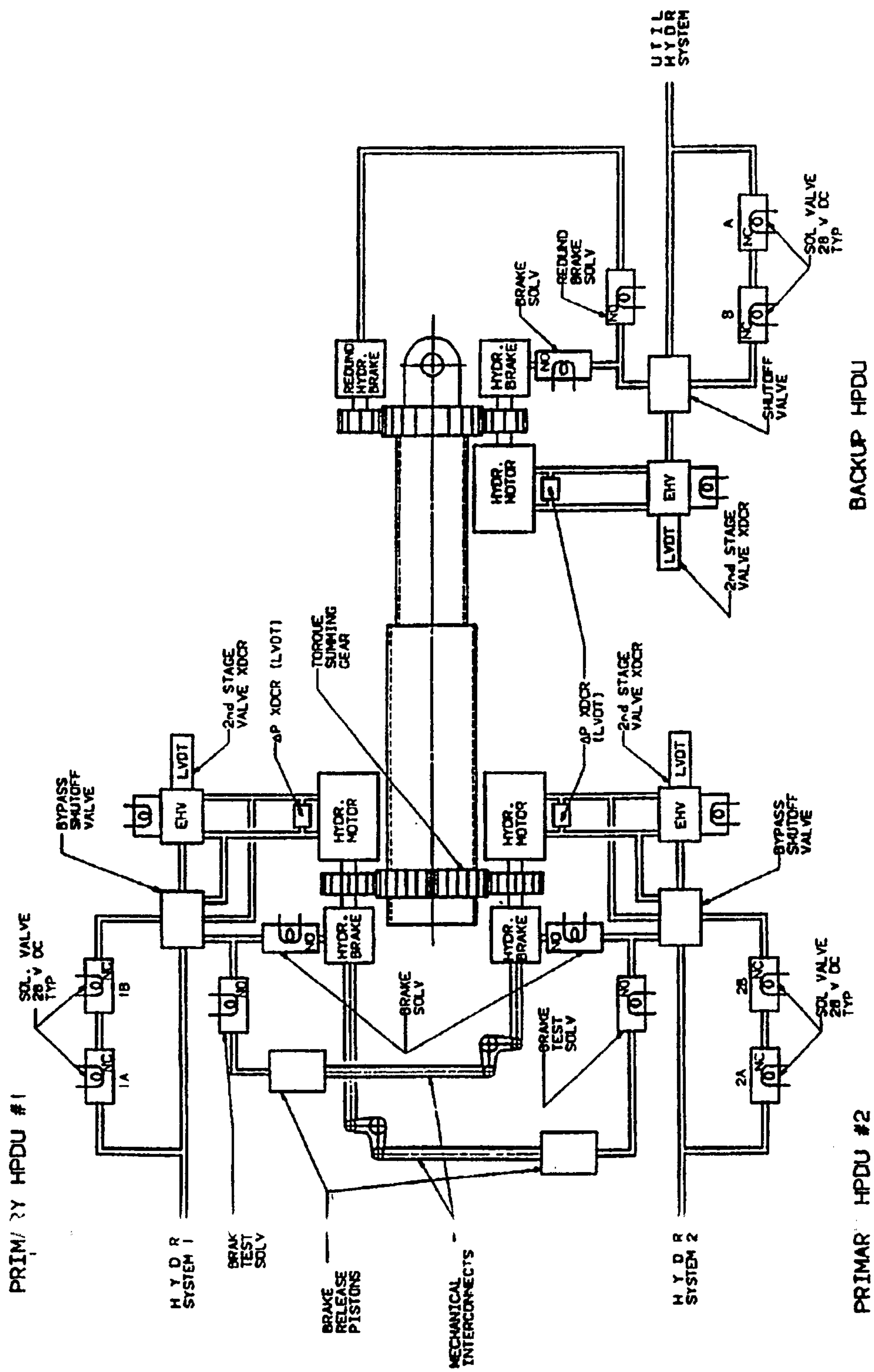


FIGURE 38 - V-22 CONVERSION ACTUATOR FUNCTIONAL SCHEMATIC

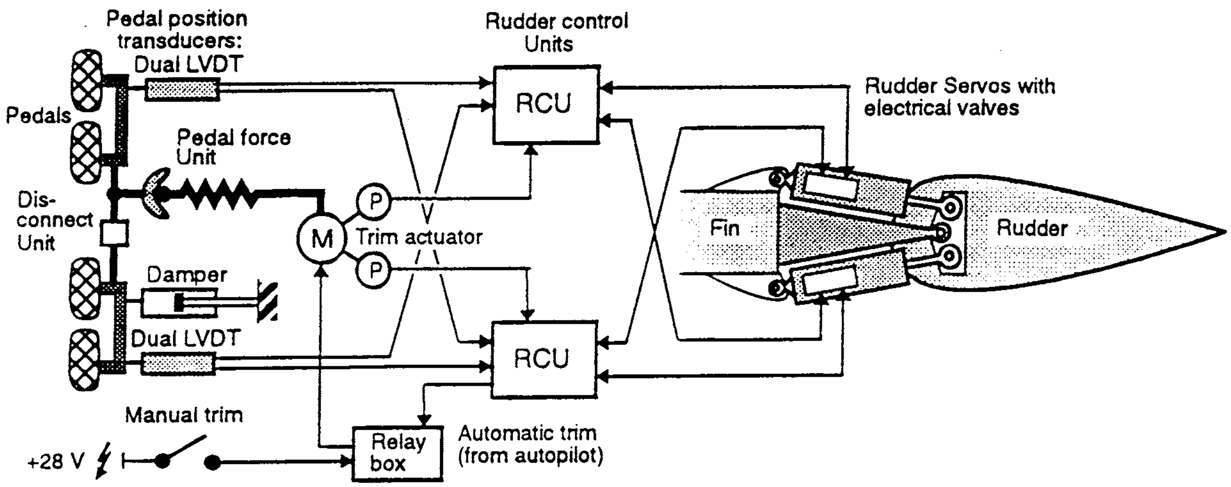


FIGURE 39 - SAAB 2000 RUDDER CONTROL SYSTEM FUNCTIONAL SCHEMATIC

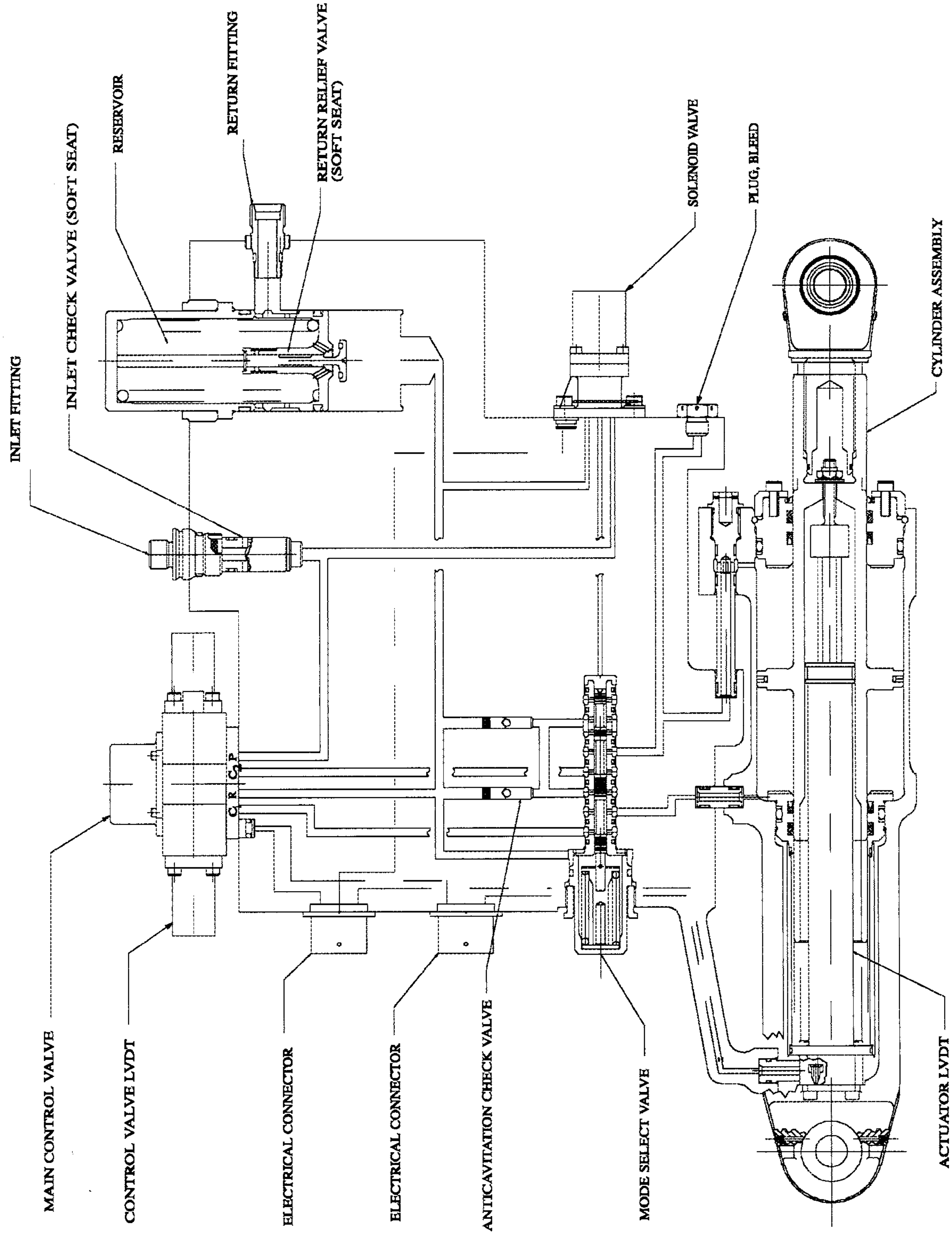


FIGURE 40 - SAAB 2000 RUDDER SERVOACTUATOR HYDRAULIC SCHEMATIC

3.14 IDF Actuators

The Indigenous Defense Fighter (IDF) primary flight control actuation system consists of two servoactuators each for the flaperon and horizontal tail surfaces and a single rudder surface. The servoactuator architecture is simplified by the use of direct-drive valves (DDV). The DDV actuation system uses redundant electronic inner-loop (spool position) feedback and failure detection of the single Main Control Valve. The high electrical power demands of the DDV require the use of pulse width-modulated (PWM) servoamplifiers. Each DDV force motor is configured with three separate coils in a flux summed arrangement such that the valve flow is proportional to the sum of the three currents. The valves are capable of performing at full capability with any two coils active and with slight degradation on just one coil.

In addition to the primary flight control actuators the IDF has a maneuvering leading edge flap system which also is controlled by direct drive valves.

3.14.1 Primary Flight Control Actuator Configuration

The primary flight control actuators are identical in function, although different in size. The actuators are a fail-op/fail-safe configuration. As shown in Figure 41, they consist of dual tandem pistons with a triplex coil, single-stage direct drive servovalve. Each piston chamber is powered by a separate hydraulic system. A triplex main ram linear variable differential transducer (LVDT) provides feedback for closed loop position control. Mode select valves piloted by triplex solenoids are employed to provide safe control under fault conditions. Complete failure of either half of the tandem actuator results in a free-flow bypass of the failed side of the piston, resulting in half the hinge moment capability and slightly degraded no-load rate. Failure of both sides results in a damped bypass mode. The actuator contains an integral accumulator in the return system to ensure a hydraulic fluid supply for the damped bypass mode.

3.14.2 Primary Actuator Servoloop Electronics and Redundancy Management

The actuator servoloop electronics and redundancy management are typical of the three primary actuator configurations. Each electrical channel generates current commands to one of the DDV triplex coils in a flux summing fashion. There are three loop closures within the electronics, the current loop, the inner (valve) loop and the outer (ram) loop. Each of these loops is triplex. The outer loop is driven by the mid-level selected command from control laws. Failure of one channel reduces the forward gain of the system by one third. The failure of a second channel will send the actuator into a damped bypass mode. Three failure monitors are utilized: the coil current monitor, the position feedback monitor and the main control valve monitor. Failures attributable to the coil current and position feedback are determined through majority vote of the three channels. The detection of a jammed MCV is uncovered by comparing coil current inputs to MCV position feedback. Upon detection of an MCV jam the actuator is placed into damped bypass mode.

3.14.3 Leading Edge Flap Actuation System

The IDF leading edge flap system reacts to the angle of attack giving the aircraft enhanced maneuverability. A centrally located Power Drive Unit (PDU) drives four rotary mechanical actuators located along the hingeline of the leading edge flap on each wing. Two angle gearboxes, one in each wing root, provide direction change in the drive path. The PDU, angle gear boxes, and actuators are connected via torque shafts.

The PDU is powered by two 3000 psi hydraulic motors which are each controlled by a direct drive valve. The motors are connected in a torque summing arrangement to a pinion in mesh with a bull gear which drives two output shafts through bevel gears. The PDU incorporates an integral overtravel stop module and a triplex rotary position transducer.

The rotary mechanical actuators convert the high speed moderate torque of the PDU to moderate speed very high torque at the flaps. The hingeline actuators provide high stiffness at the surface in a compact design. An asymmetry brake and duplex position feedback module have been integrated into the outboard actuator. The brake can be activated electrically when the asymmetry exceeds prescribed limits or will activate automatically in case of a runaway flap.

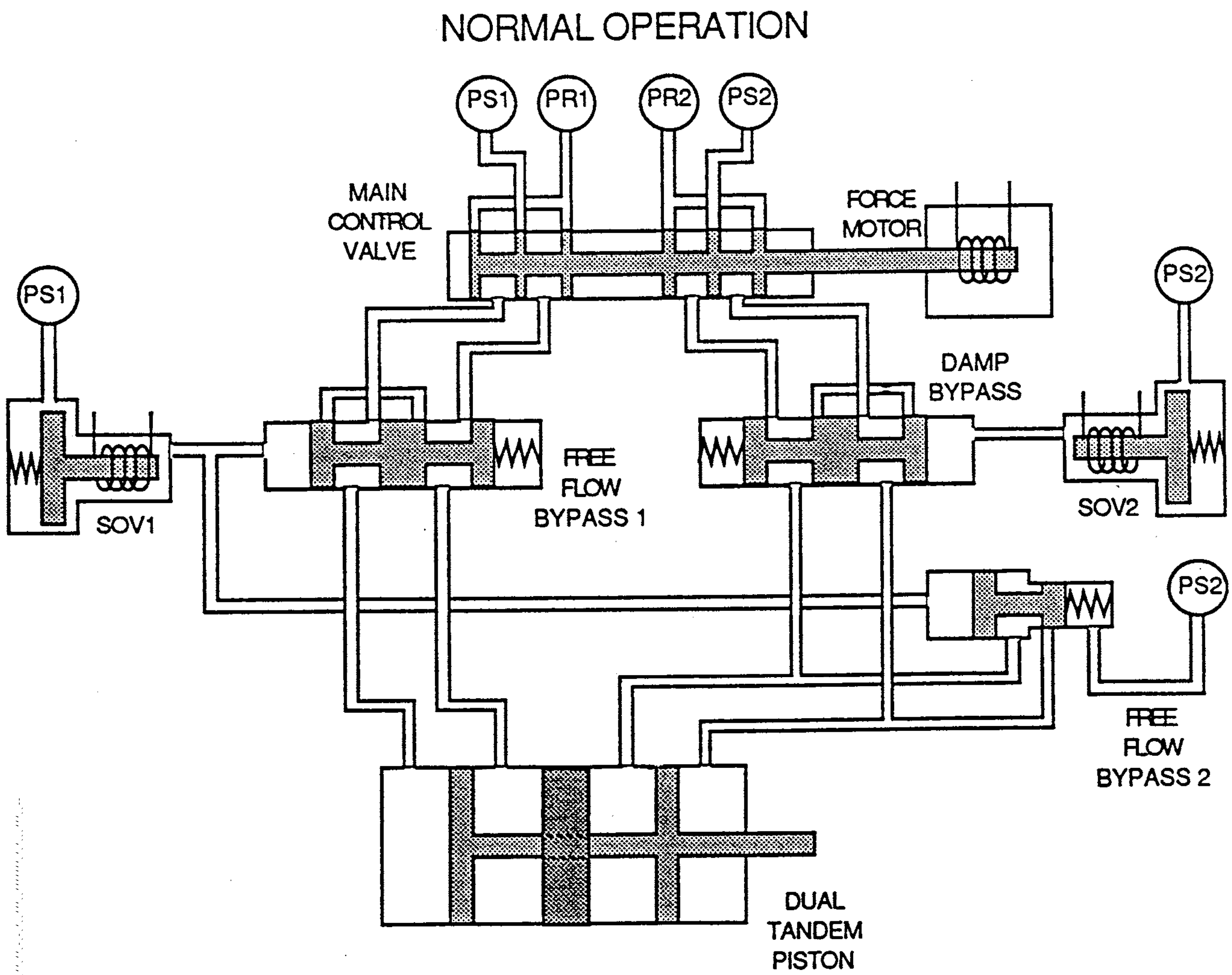


FIGURE 41 - IDF FLAPERON, HORIZONTAL TAIL AND RUDDER ACTUATOR FUNCTIONAL SCHEMATIC

3.15 B-2 Actuators

The B-2 Flight Control Actuation System (FCAS) is a self contained quadruplex system. The FCAS includes simplex piston, direct drive servovalve, hydraulic actuator designs for all surfaces with numerous quadruplex transducers. The B-2 normally has four (4) hydraulic systems available. Each actuator is plumbed to two hydraulic systems. A mode control switch valve selects one of three operating modes: Primary, Alternate and Bypass. At least two identical actuators drive each of the B-2's eleven (11) primary flight control surfaces. The surfaces are: (a) the Gust Load Alleviation Surface (GLAS), (b) inboard, middle, and outboard elevons, and (c) the upper and lower split rudders. A design challenge of the B-2's FCAS was high bandwidth control of the unbalanced, high inertia, surfaces.

3.15.1 Actuator Construction

All of the primary flight control actuators for the B-2 are a simplex design. Depending on the surface, a balanced or unbalanced area piston is used. Figure 42 depicts a balanced area piston design used for the GLAS, inboard and middle elevons. The installation envelopes for the outboard elevon and both rudders demanded minimum length actuators, so unbalanced area designs were specified. These actuators incorporate balance tubes to minimize area imbalance.

Depending on the health of the hydraulic systems an actuator is commanded to select either of two hydraulic systems or bypass mode. The selection is controlled by energizing either of two solenoid valves (or neither for bypass) which, in turn, positions the switching valve to one of three positions. The center position represents bypass mode.

Since each actuator is connected to two hydraulic systems, complete rip-stop construction is embodied from the supply ports to the switching valve. To minimize internal leakage and servovalve fault detection hardware, direct drive valves are utilized.

3.15.2 Actuation System Interfaces

Actuator Remote Terminals (ARTs) receive MIL-STD-1553 multiplex data bus information from the quadruplex Flight Control Computers and provide the actuator electronic loop closure and redundancy management for the actuation system. The ARTs are distributed on the airframe such that a set of four (4) redundant ARTs operate on each side of the aircraft, for a total of eight. The Operation Flight Program software for the Flight Control Actuation System resides in the Actuator Remote Terminals. Figure 43 depicts the FCAS architecture.

3.15.3 Actuator Control Loops

Figure 44 outlines the loop closures used for control of the primary flight control actuators on the B-2. Each actuator has an outer position loop, dynamic pressure feedback, main control valve (MCV) rate, MCV position, force limiting, force equalization, snubbing, and rate limiting.

The actuator position loop uses quad-redundant linear variable differential transformers (LVDTs) to sense actuator position and provide feedback for the electronic loop closure. The actuator position feedback signal is also used for position snubbing near the end of actuator stroke and for rate limiting of the surface commands.

Quad-redundant differential pressure transducers provide feedback used to dampen the load reasonance mode necessary for the B-2's relatively high loop gain. The loop gains are driven by the high system bandwidth requirements: Approximately 8 Hz for the unbalanced, high inertia, surfaces. The pressure transducer also is used for force limiting. Due to the B-2's relatively unsymmetrical loading requirement (see Table 14) the force limiter has a dramatic effect on reducing structural weight. Finally, the pressure transducer is also used for force equalization between actuators on a surface.

The main control valve uses a quad-redundant LVDT for position and a quad-redundant linear variable transformer (LVT) for spool velocity loop closure. The electronic feedback of the spool position and rate provides for the stable, accurate, and very high bandwidth servovalve response necessary for the B-2 actuation system.

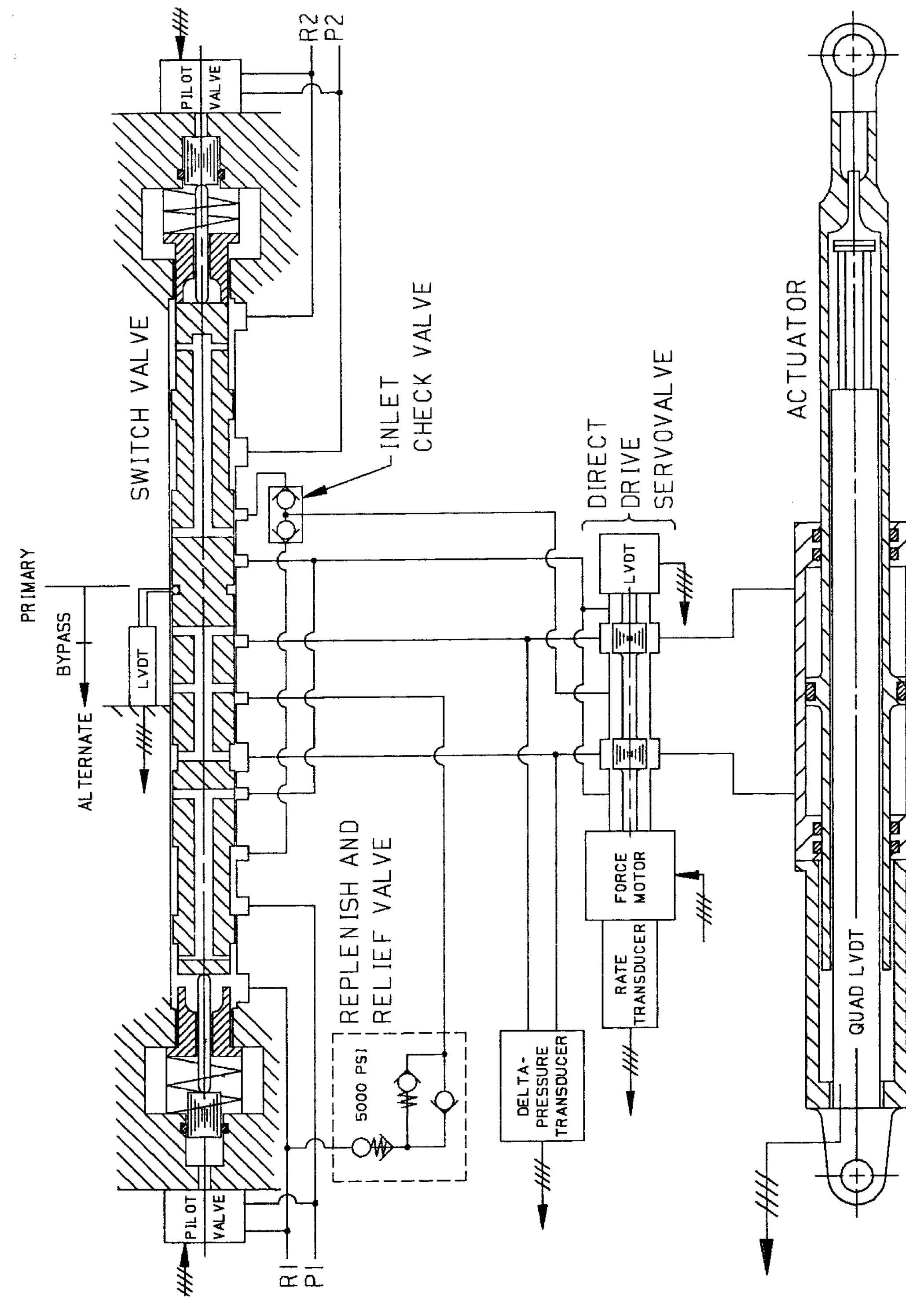


FIGURE 42 - B-2 GUST LOAD ALLEVIATION SURFACE ACTUATOR PICTORIAL SCHEMATIC

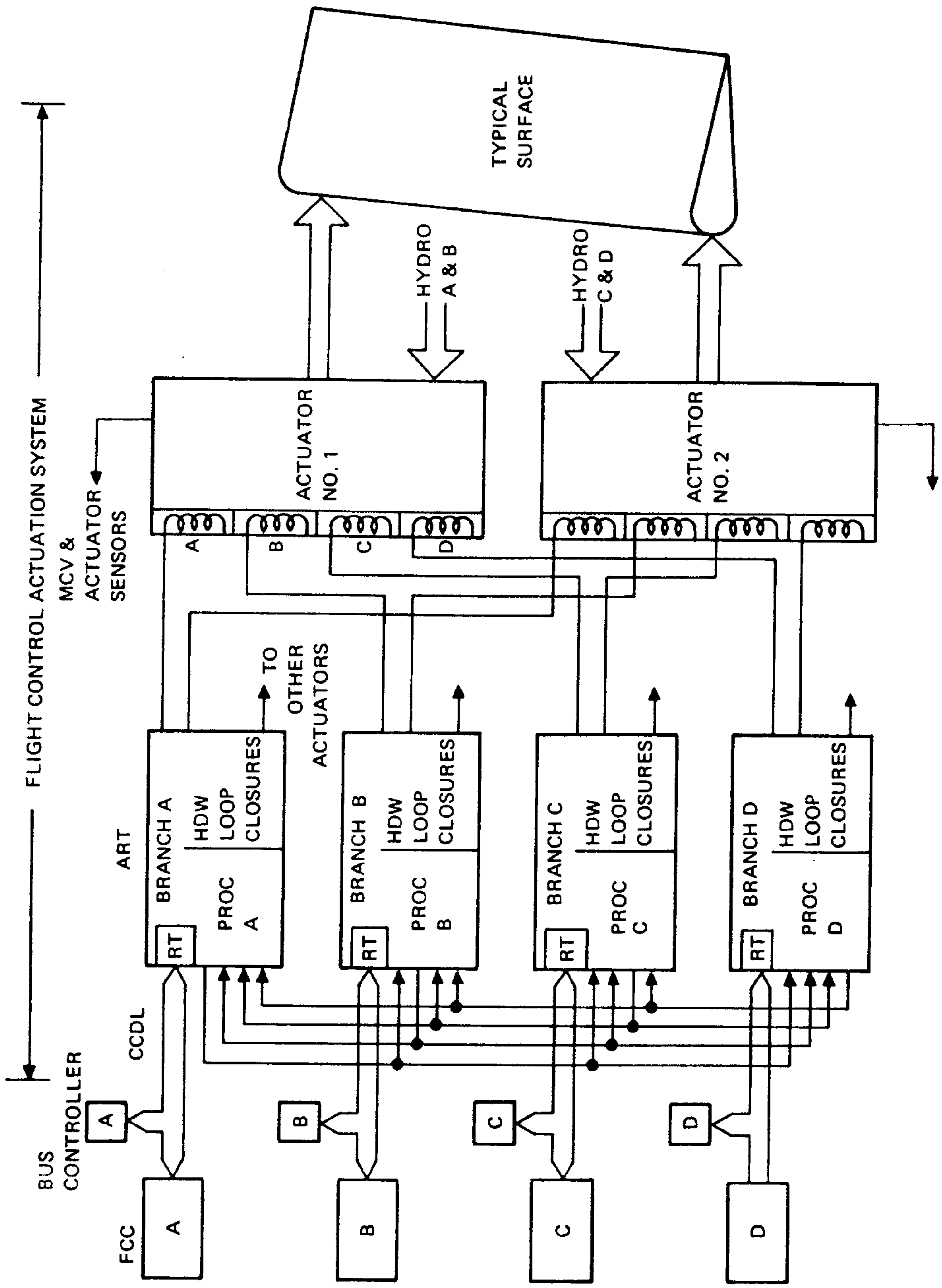


FIGURE 43 - B-2 FCAS ARCHITECTURE BLOCK DIAGRAM

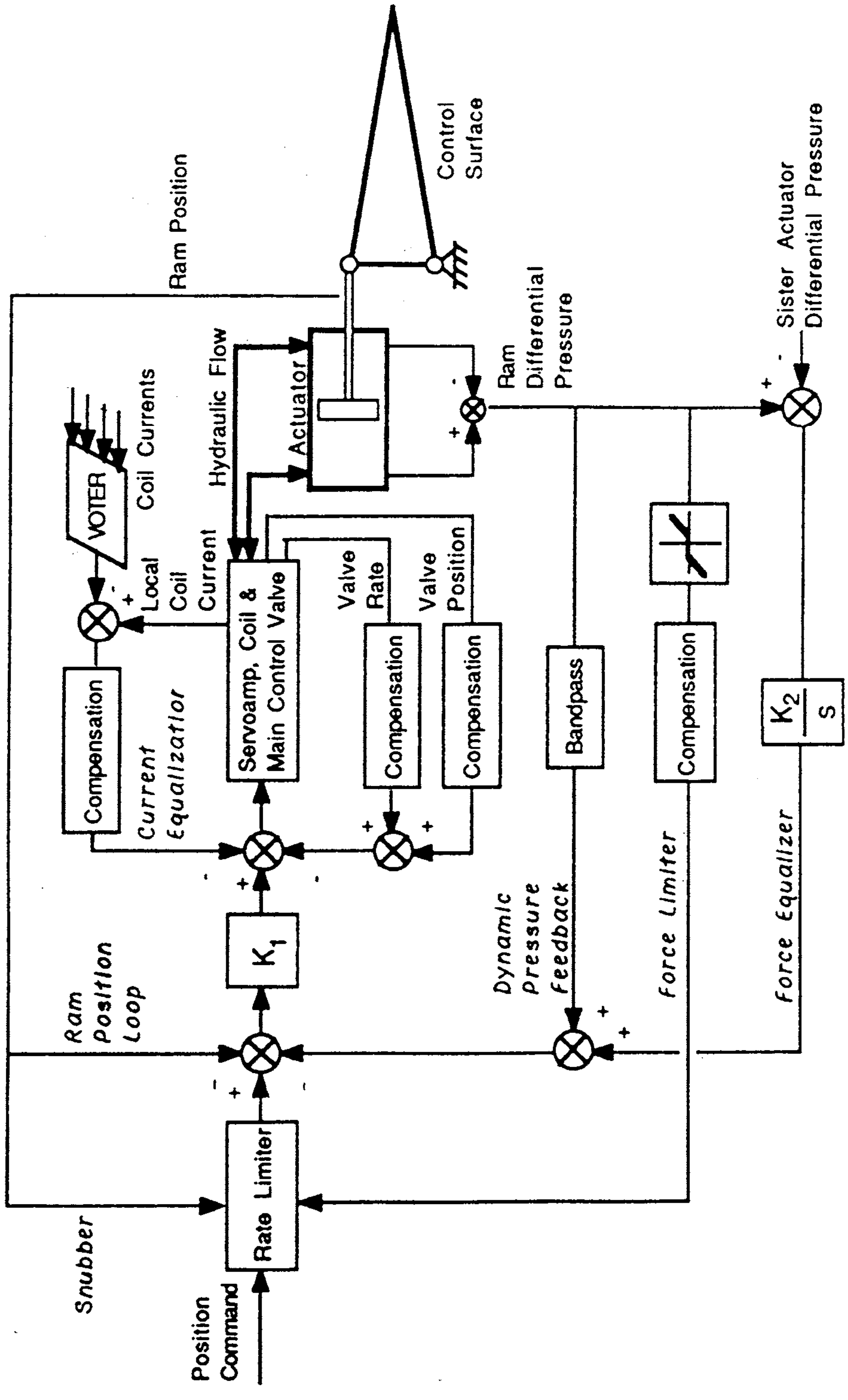


FIGURE 44 - B-2 ACTUATOR LOOP CLOSURES

3.15.4 Actuator Redundancy Management

The quadruplex hydraulic and electronic architecture of the FCAS allows it to tolerate up to three electronic system and three hydraulic system failures. System reconfiguration is completed to remove the effects of any detected failures. The FCAS implements a combination of hardware and software monitoring, all completed in the ARTs. These include analog and discrete cross channel monitors and analog and discrete in-line monitors.

A monitor detecting a sensor path fault on a branch reduces the actuator loop closure by one level of redundancy. However, since the feedbacks from the other sensors remains valid, the other sensor data continues to be used in the voting algorithms. This improves failure detection capability. The ART adjusts individual actuator loop closure gains as a function of the valid control loops. This reconfiguration, a gain change, is to maintain actuator performance with less than four channels being available.

Should sufficient actuator loop failures occur, and a sister actuator is currently engaged on the surface, the actuator is commanded to bypass. This reconfiguration allows for removal of the faulty FCAS component but continues to allow for surface control (albeit with reduced hinge moment capability).

3.16 C-17 Actuators

C-17 flight control surfaces are actuated by electrohydraulic devices. Control surfaces for C-17 are: eight (8) slats, eight (8) spoilers, four (4) flaps, two (2) ailerons, two (2) rudders, four (4) elevators and horizontal stabilizer. The layout of these surfaces is illustrated in Figure 45.

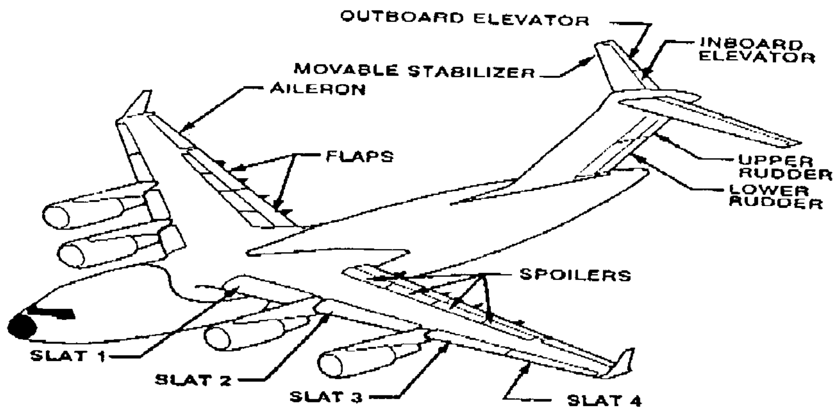


FIGURE 45 - C-17 FLIGHT CONTROL SURFACES

The flight control actuators are all dual redundant servomechanisms with the exception of those for the spoilers and slats. All flight controls are electrically commanded in their main mode of operation, with the Elevator, Aileron, Lower Rudder, and Horizontal Stabilizer Systems having an additional mechanical back-up mode. In the mechanical mode, the pilot inputs are directly connected to the Integrated Flight Control Modules (IFCMs) and to the Horizontal Stabilizer control valves. There is no mechanical backup control for spoilers, flaps, nor slats. The spoiler actuators are simplex. The slats are commanded either fully extended or fully retracted with no intermediate positions.

The flight control actuators are powered by the normal aircraft hydraulic supply of 4000 psi pressure and 85 psi return. All four hydraulic systems are used to power the flight control actuation devices with the distribution designed to give maximum control authority following failures within the supply system. The Spoiler actuators are self-contained electrohydraulic servomechanisms with the control valve manifold mounted directly on the actuating cylinder. The Elevator, Ailerons, Rudders, Flaps and Slats have remote cylinders which are connected to their control modules with hydraulic tubing. These control modules are supplied by two hydraulic systems simultaneously and have rip-stop construction to prevent a single structural failure causing loss of both systems. The individual cylinders are made from high strength steel to provide good load carrying capability along with high fatigue life.

3.16.1 Primary Flight Control Actuator Configuration

A functional layout of a typical C-17 primary flight control actuator is shown in Figure 46. The elevator, aileron, and rudder actuation systems use similar control valve modules and actuators. Each control valve assembly is an Integrated Flight Control Module (IFCM) which provides both direction and rate control for two remote cylinder assemblies. The IFCMs are each powered by two hydraulic systems and interface with the four Flight Control Computers (FCCs). The FCC interface is via four external electrical connectors, one for each channel. The remote cylinder assemblies have an internal dual Linear Variable Differential Transformer (LVDT) which is used for position feedback to the FCCs.

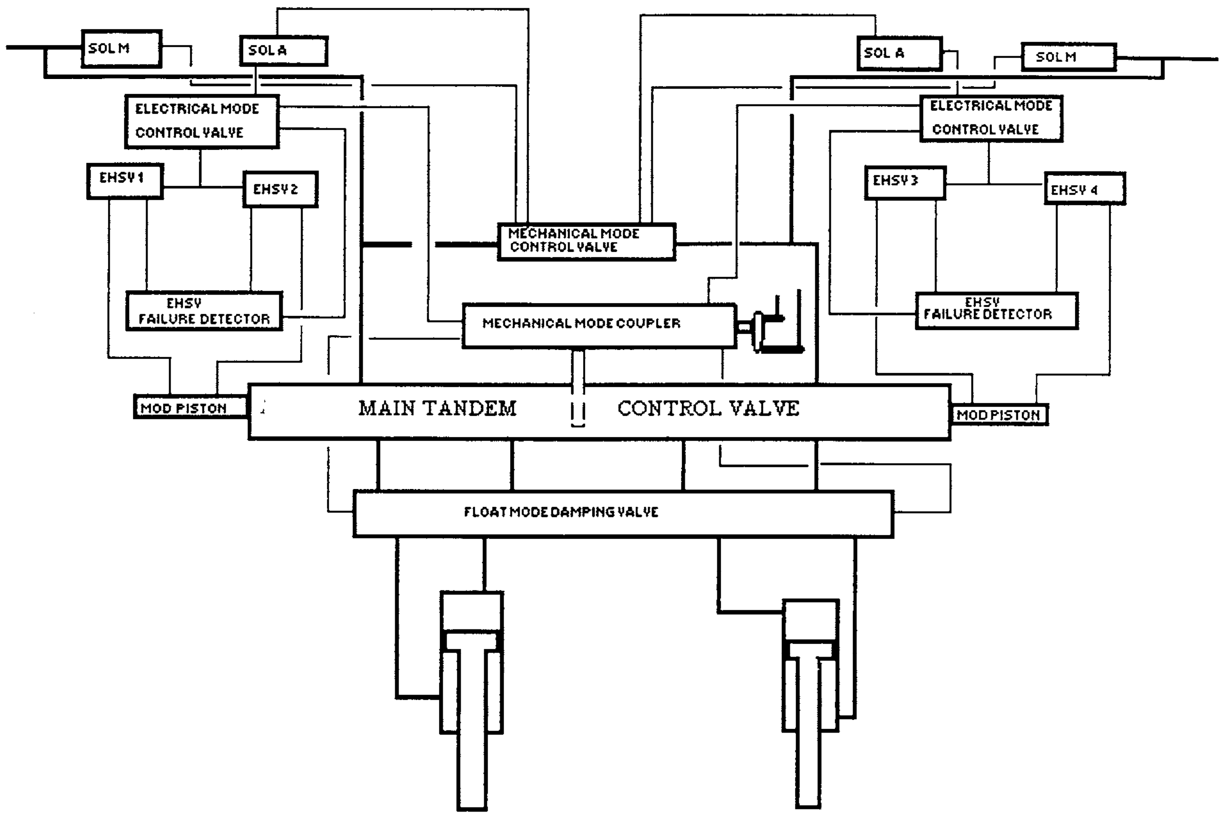


FIGURE 46 - C-17 PRIMARY FLIGHT CONTROL ACTUATION

There are three modes of operation: Electrical Control, Float mode, and Mechanical Control. The Electrical Control Mode is the primary mode of operation for the IFCMs. In this mode the FCCs have control of the surfaces. The Electrical mode is engaged by the FCC energizing the "M" solenoids and then, 100 ms later, energizing the "A" solenoids. Each FCC provides a 28 V DC discrete to drive one of four coils in each "M" and "A" solenoid. For monitoring purposes, current from two or more FCCs is required to keep the solenoids engaged.

The "M" solenoids disengage the mechanical mode input and the "A" solenoids allow pressure to be ported to the Electrohydraulic Servovalves (EHSVs). The hydraulic sequencing prevents the Electrical and Mechanical Modes from being commanded simultaneously. In the Electrical Control Mode, the electronic inputs from the four FCCs command the EHSVs which in turn position the main tandem control valve. The EHSVs (two per hydraulic system) are force summed at the main tandem control valve and mod piston. The position of the main tandem control valve controls the rate and position of the remote surface cylinders. The main control valve spool has an anti-jamming feature which can shear a chip of 73 Kpsi material totally occupying a flow slot. The EHSVs on the IFCM contain four coils each, which are driven by the FCCs. Each FCC drives one coil in each of the EHSVs connected in series.

The surface position feedback to the FCCs for the Electrical Control Mode is from internal dual LVDTs in the cylinders. Each LVDT channel receives its excitation from and sends its output signals to one FCC. The LVDTs in one cylinder interface with FCCs 1 and 2 and the LVDTs in the other cylinder interface with FCCs 3 and 4.

The Electrical Mode Control Valve provides four discrete signals, one to each FCC, to indicate that the EHSV Failure Detector valve has detected a servovalve failure and that it has shut off hydraulic pressure to that pair of EHSVs.

The float mode is a transitory mode between the electrical mode and the mechanical mode, and prevents impacts on alpha limiting in the pitch axis and rudder limiting in the yaw axis. In the roll axis, the float mode is limited to a short time span (approximately 1 s) in order to avoid the adverse aileron surface aerodynamic neutral position.

The float mode is engaged when the FCCs de-energize the "A" solenoids, while the "M" solenoids still remain energized.

The float mode also is engaged if both EHSV failure detectors are tripped and consequently disengage both electrical mode control valves, while the "M" solenoids remain energized.

The float mode is also the default mode when pressure in both hydraulic systems is lost.

In the float mode, the remote cylinders are isolated from the main control valve and system pressure. In addition, both cylinder control lines are interconnected through an orifice in the float mode damping valve to return.

In the Mechanical Control Mode, the pilot has a direct mechanical input from the control stick/rudder pedals to the main tandem control valve in the IFCM. Surface position is mechanically summed with the pilot input at the IFCM to provide the servo control.

This mode is commanded by de-energizing the "M" solenoids or if all electrical power to the IFCM is lost, the EHSV's are depressurized to prevent any electrical inputs from fighting the mechanical input. Pressure is ported through the mechanical mode control valve to the mechanical mode coupler which provides a fixed pivot for the pilot input. In the Electrical Control Mode, this pivot is allowed to float, preventing the pilot mechanical input from commanding the main tandem control valve.

3.16.2 Primary Flight Control Actuator Redundancy Management

The IFCM incorporates an EHSV failure detector valve in each hydraulic system. This valve detects output pressure differences above a predetermined threshold between the pair of EHSVs in that system. If this threshold is exceeded due to either a mechanical failure of one EHSV or a large null shift, then the failure detector valve will port pressure to the Electrical Mode Control (EMC) valve. This commands the EMC valve to the failed mode. The electrical mode control valve depressurizes the pair of EHSVs and self-latches in this failed mode. Simultaneously a quad discrete electrical signal is transmitted to the four FCCs to announce this failure. The IFCM continues to function normally, controlled by the remaining pair of EHSVs in the other hydraulic system. This failure does not degrade performance of hinge moment capability as both remote cylinders are still controlled by the main tandem control valve. Following a further failure, either loss of hydraulic pressure to the remaining controlling EHSVs or tripping off their failure logic will result in the Float mode.

The FCCs command the Mechanical Control mode by de-energizing the "M" solenoids which allows the mechanical mode control valves to port fluid to the mechanical mode coupler. During transition to Mechanical Mode, the IFCM remains in the Float Mode until the mechanical coupler has moved to provide the input linkage with a hard point (either hydraulic system can provide the hard point). As soon as the hard point is provided, pressure is ported to the float mode damping valve taking it out of the damping mode at a controlled rate. The rate is controlled by an orifice restricting the return flow from the end of the valve as it moves out of bypass. The total reversion time is 0.6 to 1.0 s. A quad discrete signal from a position switch on each mechanical mode control valve is transmitted to the four FCCs to indicate that the IFCM is in the mechanical mode.

3.16.3 Spoiler Actuator Configuration

Figure 47 shows a pictorial schematic of a C-17 spoiler actuator. The spoiler servoactuator consists of a self-contained, pivoting body, unequal area unit, comprised of a cylinder assembly, a manifold assembly, and a three-way Electrohydraulic Servovalve (EHSV). A mechanical input is not provided. Each spoiler servoactuator assembly is a "fly-by-wire" servoactuator that provides positional control of a spoiler surface , for both on-ground and in-flight operations. Each spoiler interfaces with two parallel electrical command inputs from the Spoiler Control/Electronic Flap Computers (SC/EFCs) and a single hydraulic power supply. A total of eight spoiler servoactuators are used on the C-17 aircraft; four inboard (two per wing) and four outboard (two per wing). The inboard and outboard cylinder assemblies are similar, the main difference being the bore diameters. Both cylinder assemblies consist of a power ram, end gland and dual LVDTs. The center-tap LVDT is incorporated to close the electrohydraulic servo loop. The LVDT provides an electrical signal proportional in amplitude to the displacement of the ram from its retracted position.

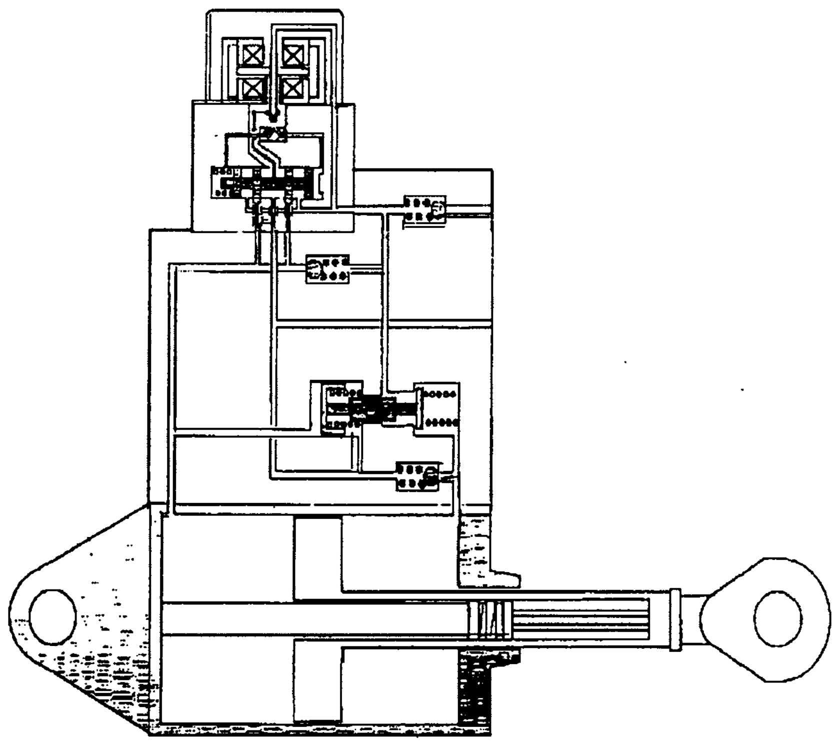


FIGURE 47 - C-17 SPOILER ACTUATION

The EHSV assembly is identical for both servoactuators (inboard and outboard). Each EHSV-controlled actuator performs as a conventional three-way actuation system. The double-acting ram drives the spoiler surface. The retract end of the ram, which is always subjected to full system pressure, has an effective area less than the extend end. The two-stage, three-way jet-pipe EHSV is an adaption of a standard two-stage, four-way, jet-pipe EHSV. In the retract mode, a single flow path is used because of lower flow requirements.

3.16.4 Spoiler Actuator Failure Management

The dual channel LVDTs provide the surface position feedback to the SC/EFC. To monitor the integrity of the spoiler LVDT, the center tap voltage is used by the SC/EFC.

In the control valve, the first stage contains a bias on the torque motor to assure that, in the event of a total electrical system failure, hydraulic pressure is ported to the retract side of the ram to fully retract the spoiler surface. The second-stage spool is spring-biased to assure that in the event of a hydraulic system failure, it will port hydraulic fluid from the extend side of the piston to system return, allowing the aerodynamic load to push the spoiler surface to a trail position.

3.16.5 Flap Actuator Configuration

The Flap Actuation System consists of four surface panels each panel positioned by two remote hydraulic actuators and one Tandem Control Valve Module (TCVM), as shown schematically in Figure 48. Each TCVM is supplied by two independent hydraulic systems which are controlled by two dual-coiled solenoid valves, one active/one standby. The module housing provides a complete structural separation between the two independent hydraulic systems to prevent a crack or rip from propagating from one system to another. The main spool chip shear force will shear a chip of 73 Kpsi material totally occupying a flow slot, hence providing an anti-jamming feature. The TCVM is controlled by two electrical input channels from each of the SC/EFCs in response to pilot selection of the Flap/Slat handle, Flap Index Switch, or Speedbrake switch. The flaps have the capability of extending to 42 degrees, but are electronically limited within the SC/EFCs control laws to a maximum deflection of 40.5 degrees. The normal flap range is 0 to 40.5 degrees, the range in speedbrake mode is 0 to 8 degrees. Mechanical feedback from the main power stage to the electrohydraulic servovalve (EHSV) is used for proportional flow control. A dual LVDT on the main power stage is used for failure monitoring. Panel to panel synchronization and rate control of the flap surfaces is carried out by the SC/EFCs, which in turn control the TCVMs. The system is active/standby hydraulically with only one EHSV controlling the main valve spool at any one time. The system is active/active electrically with each SC/EFC driving a separate coil in each EHSV, each with 50% authority. When one SC/EFC becomes inoperative, the remaining SC/EFC servo amplifier gain is doubled to maintain the same response. The electrical command signals are applied to both servovalves in series so that both servovalves will be synchronized at all times to minimize transients when the other servovalve is brought on-line. The two actuators (cylinders) per flap surface have dual LVDTs to provide flap position feedback to the SC/EFCs. While the actuators are in stow position (fully retracted) a piston cross flow of approximately 0.12 gpm maintains a warming flow within the actuation loop to improve performance under low temperature conditions. This recirculating flow is shut off during operation and only becomes active during the last 0.1 in of fully retracted stroke. While in operation, if one of the two flap surface panel actuators fails to deliver force, the other actuator has full design capability to supply 100% hinge moment.

3.16.6 Flap Actuator Redundancy Management

The flaps use Hydraulic Systems No. 1 and No. 4. Following failure of either system, the flaps still operate normally. Following loss of the remaining system, the flaps are locked in the last commanded position. The flaps are kept in synchronization by the SC/EFCs by speeding up slow flap surfaces and slowing down fast surfaces. If due to a failure and/or damage, the split between flap surfaces exceeds a set threshold, the SC/EFCs will shut the flap surfaces down and the flaps will remain locked in the existing position.

3.16.7 Slat Actuation System Configuration

The slat system consists of eight surface panels, four per wing, as illustrated in Figure 49. All panels are positioned simultaneously by a single Tandem Control Valve Module (TCVM) and each panel is powered by two unbalanced actuators. The TCVM is supplied by two independent hydraulic systems No. 2 and No. 3. The module housing provides a complete structural separation between the two systems to prevent a crack from propagating from one system to the other. The TCVM is controlled by the mechanical input from an electrical actuator which in turn is controlled by the input signal from the SC/EFCs in response to pilot selection of the flap/slat handle. Each slat panel uses a Hydraulic Lock Valve Module (HLVM) and two identical actuators working in parallel. With the hydraulic systems pressurized, the slat extend or retract pressure commands the lockvalves to the unlock position, permitting extension or retraction of both actuators.

Each actuator incorporates pressure compensated flow control valves at the cylinder extend and retract ports which provide a constant flow over a wide pressure drop range across the ports. Along with the snubbing feature at the actuator first 1/4 in of stroke, it accomplishes the synchronization of the panels. The slats are designed to fully extend in 4 to 6 s and fully retract in 8 to 10 s.

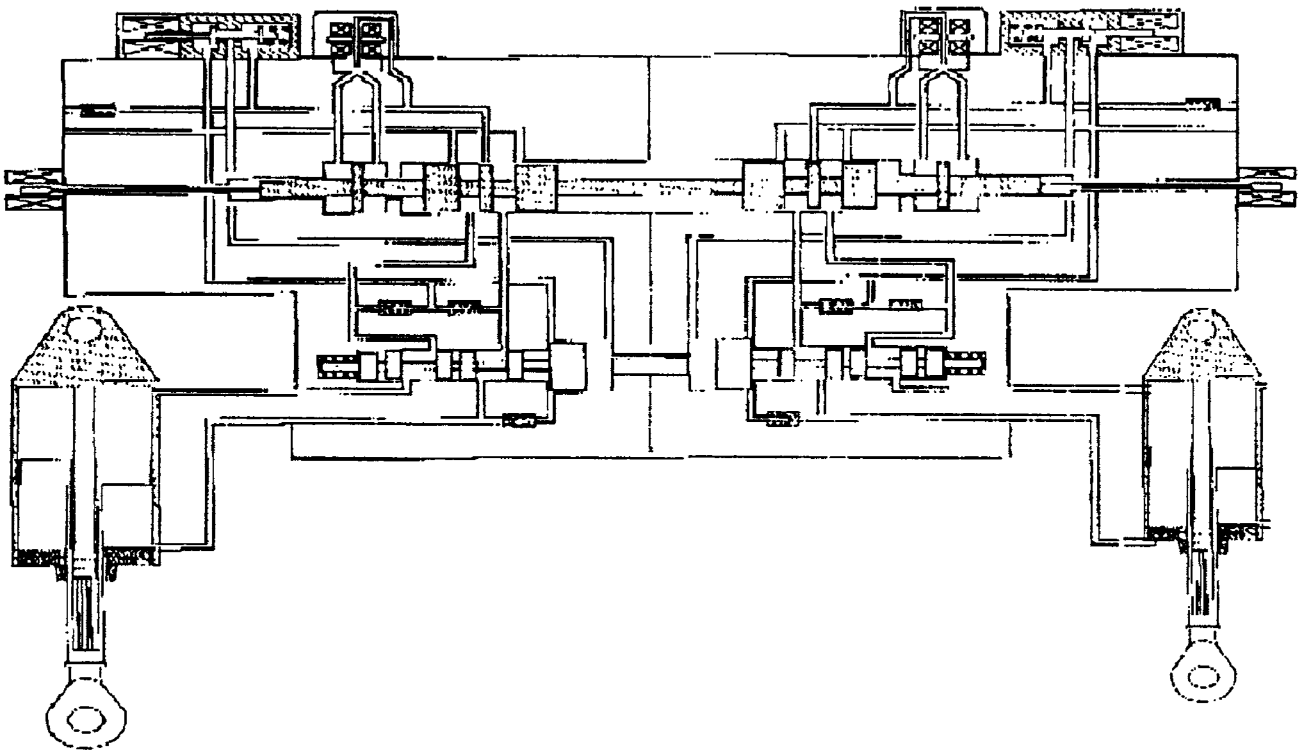


FIGURE 48 - C-17 FLAP ACTUATION PICTORIAL SCHEMATIC

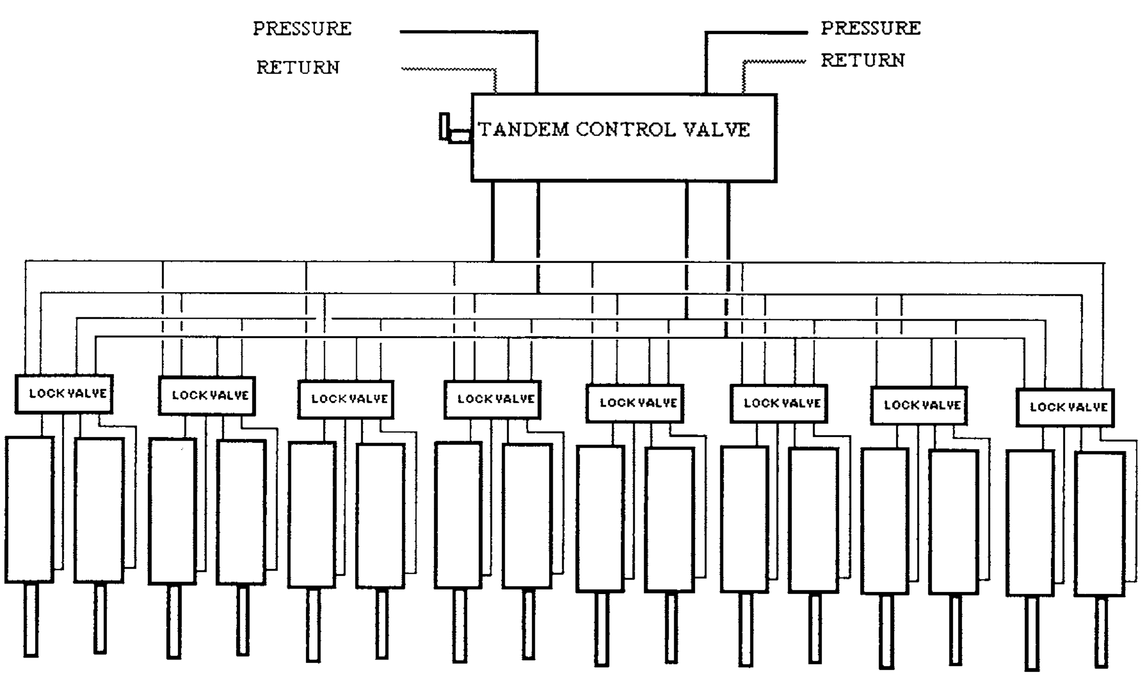


FIGURE 49 - C-17 SLAT ACTUATION

3.16.8 Slat Actuation Redundancy Management

An over-center spring on the TCVM prevents uncommanded extension or retraction in case of mechanical input link failure; the spring will hold the valve in the last commanded position. Each slat panel uses a Hydraulic Lock Valve Module (HLVM) and two identical actuators working in parallel. The HLVM prevents uncommanded extension or retraction due to air loads, in case of dual hydraulic system failure, by trapping the fluid in both actuator chambers.

The HLVM also permits the panel to operate in the event one hydraulic system has failed. It also incorporates a thermal relief valve in both retract and extend chamber which limits the pressure rise in the actuator due to temperature rise of the trapped fluid.

3.16.9 C-17 Pitch Trim Actuator Configuration

Figure 50 shows a hydraulic schematic of the C-17 pitch trim actuation system. The hydraulic portion of the Pitch Trim Actuation (PTA) system consists of two single speed hydraulic motors, two hydraulic brakes, and two solenoid operated Dual Control Valves (DCVs). One motor, brake and DCV combination is supplied by Hydraulic system No. 1 and the other by System No. 4. The hydraulic motor outputs are differentially summed by a gearbox that combines their speed to drive one output that rotates the ballscrew. A brake is provided with each motor to prevent one motor from back-driving the other in case of a hydraulic failure. The horizontal stabilizer is prevented from back-driving the drive system by a ratcheting type "no-back" load device.

Directional as well as shutoff flow control to the motors is provided by the DCVs. Each contains a directional control valve spool and a shutoff valve spool which can be driven either electronically or mechanically.

In electronic operation mode, the FCC's electrical signals command a given solenoid valve to port pressure to one of the solenoid pistons. A damping orifice controls the actuation speed of the solenoid piston. The piston drives a push rod which compresses a centering spring (override spring does not compress) and moves the directional or shutoff control valve spool to the commanded position. The spool also moves the mechanical crank assembly. When the electrical command is removed, the solenoid valve ports the piston to return. The centering spring then drives the push rod to return the piston and spool to neutral. Two simultaneous commands in the same direction of trim are required to open each Dual Control Valve and operate each motor. The directional control valve spool and shutoff control valve spool move in opposite directions.

During mechanical operation of the Dual Control Valve, a command is transmitted from the pitch trim control handle through the mechanical control system to the crank assembly which moves the spool to the commanded position. Spool movement compresses the override spring (centering spring does not compress). When the control handle is released, the override spring returns the spool and the mechanical control system, including the control handle, to neutral. Each trim handle controls one spool in each valve. Both pitch trim control handles must be moved simultaneously, in the same direction, to provide flow to the motor.

3.16.10 Pitch Trim Actuator Redundancy Management

The hydraulically powered PTA system contains a ballscrew with a dual load path construction throughout its structural load path. The secondary load path tie rod is located in the center of the ballscrew. the ballscrew drive incorporates a ratcheting "no-back" load brake which prevents the horizontal stabilizer from back-driving the drive system. The load brake prevents rotation of the ballscrew during static load applications and absorbs the energy in the aiding mode. In the event of a structural failure between a hydraulic brake and the differential drive train, the no-back load brake drive will hold the horizontal stabilizer in the last commanded position.

The ballscrew has mechanical stops to limit travel. The mechanical stops consists of a pair of stops on each end of the ballscrew that contact corresponding stops on the nut. There also are electronic stops provided in the FCC's software that limit surface movement to 1 degree less than the mechanical stops.

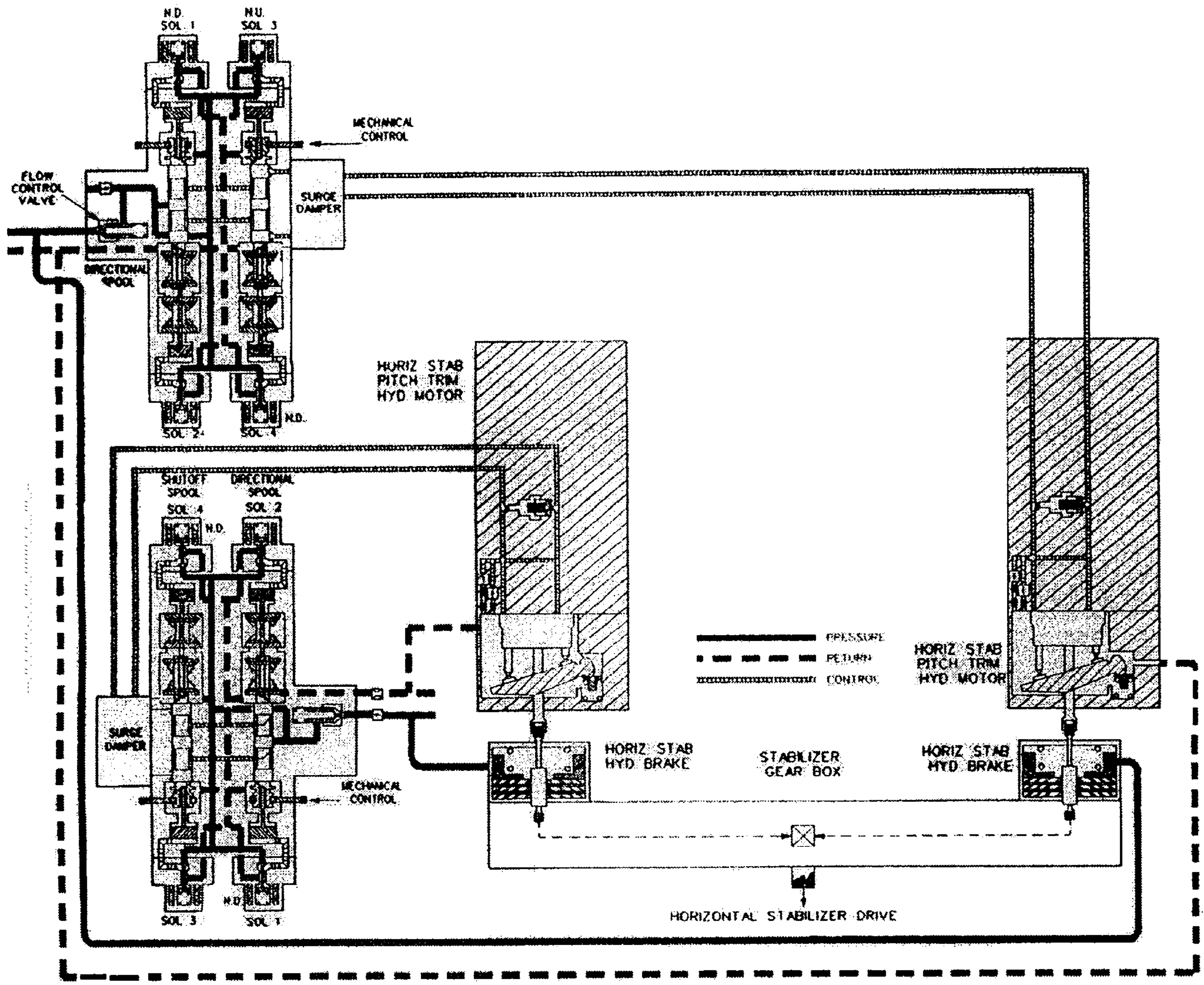


FIGURE 50 - C-17 PITCH TRIM ACTUATION

3.17 X-31A Actuators

The X-31A actuators are of two types, redundant and single channel. The redundant actuators control the trailing edge, rudder, and canard surfaces; while the single channel actuators control the air intake, thrust vectoring, speed brake and leading edge surfaces. All surfaces except for the leading edge, are controlled by linear actuators with remote hydraulic control modules. The leading edge control consists of a hydraulic control module, remote hydraulic motors, planetary gear actuators and associated shafting.

3.17.1 Redundant X-31A Actuators

3.17.1.1 Trailing Edge Actuation System

These actuators are the most flight critical surfaces on the aircraft. They provide the only roll axis control and the major pitch axis control. All four trailing edge surfaces (inboard and outboard on each wing) must function for the aircraft to remain controllable.

3.17.1.1.1 Trailing Edge Control Module

A hydraulic schematic of the trailing edge control module is shown in Figure 51. There are three electrohydraulic servovalves, one for each electrical channel, driving a tandem main control valve. The tandem main control valve is powered from two separate hydraulic supplies. There are three bypass/shutoff valves for the three EHVs, an inlet filter and check valve, a fluid compensator, and four anti-cavitation check valves.

3.17.1.1.1.1 EHVs

The EHVs are standard two stage flapper-nozzle valves with LVDTs attached to their second stages for monitoring purposes.

3.17.1.1.1.2 Main Control Valve Drive Pistons

Here is where the problem of mixing three electrical channels with two hydraulic systems is solved. The 'C' channel EHV drives a mod-piston that is connected directly to the main control valve, the 'A' and 'B' EHVs are both connected to a mod-piston that is twice the area of the ‘C’ mod-piston (‘A’ and ‘B’ are flow summed). The “A”/“B” mod-piston is directly connected to the ‘C’ mod-piston, which is directly connected to the main control valve. Thus, ‘A’ and ‘B’ are “flow summed” together and then “force summed” with ‘C’ to drive the main control valve.

3.17.1.1.1.3 Main Control Valve

The main control valve is a tandem configuration with two hydraulically independent four-way servo control valves machined onto the same shaft. Because the two servo control valves are machined into the same part, the force fight between the two systems can be held to a very small level by careful synchronization during the overlap process. A small orifice is fitted between each pair of cylinder ports to reduce the effective pressure gain of the main control valve, and thus minimize the force fight between the trailing edge actuators.

3.17.1.1.1.4 Shutoff-Bypass Valves

When a fault is declared in channel ‘C’, the EHV must be isolated from its main control valve mod-piston, and the mod-piston must be bypassed so the other mod-piston can drive the main control valve without added resistance.

When a fault is declared in channel ‘A’ or ‘B’, the EHV must be isolated from its main control valve mod-piston and the other EHV, so that the remaining EHV can move the main control valve with no loss in flow or added resistance from the failed channels. With only the ‘A’ or ‘B’ EHV driving, it is recognized that the maximum velocity of the main control valve is only half of that achieved by channels ‘A’ and ‘B’, or channel ‘C’ only, or channels ‘A’, ‘B’, and ‘C’.

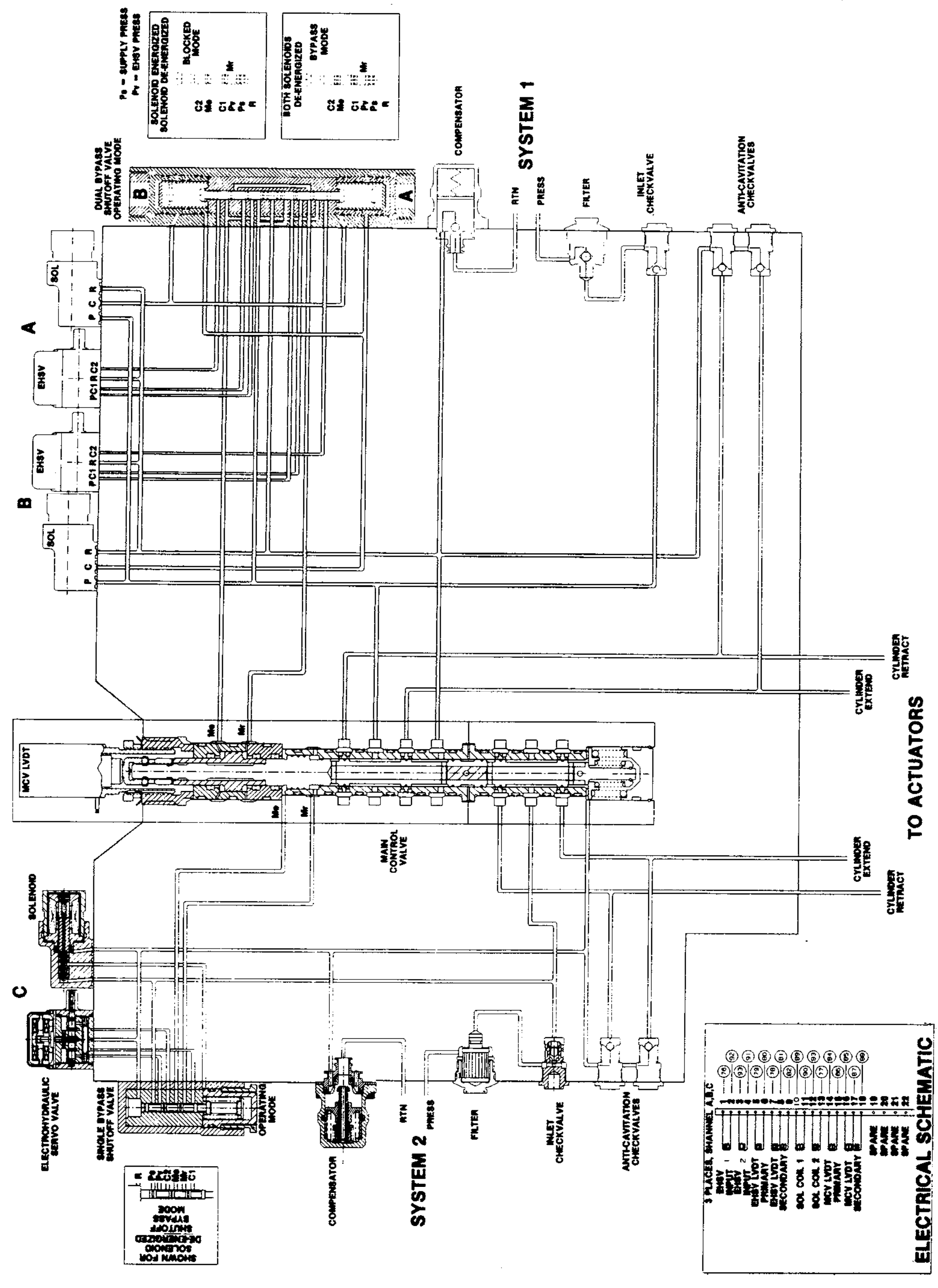


FIGURE 51 - X-31A TRAILING EDGE CONTROL MODULE HYDRAULIC SCHEMATIC

When a fault is declared in both channel ‘A’ and channel ‘B’, both EHVs must be isolated from the mod-piston, and the mod-piston must be bypassed so that the ‘C’ channel can drive the main control valve unrestricted.

The preceding group of actions are achieved using the shut-off bypass valve setup shown in the hydraulic schematic Figure 51.

3.17.1.1.1.5 Compensators

There are inlet check valves and fluid compensation modules for each hydraulic system in each trailing edge manifold. These components insure that the actuators and control stages are always full of hydraulic fluid, even if a hydraulic system has been lost.

3.17.1.1.1.6 Anti-Cavitation Check Valves

All four cylinder ports are connected to return pressure through check valves, so that if any cylinder pressure should drop below return pressure, fluid would flow into that cylinder from return, and avoid cavitation and the possibility of aerating the cylinder through the dynamic rod seals.

3.17.1.1.2 Trailing Edge Actuators

The actuators that drive each trailing edge surface are two single hydraulic system, balanced area actuators, mounted in parallel. In order to minimize the mismatch between the two actuators, one has a quad LVDT (for surface position feedback to the three electrical channels), and the other has no LVDTs.

The fourth LVDT is used as a fourth vote “tie breaker” so that the system can determine the faulty LVDT after a second failure. The fourth LVDT is not used for loop closure.

3.17.1.2 Rudder and Canard Actuation

These axes are important but the aircraft is controllable if these surfaces are allowed to drift to some “trail” position. There is only one rudder surface, and although there are two canard surfaces, they are connected together mechanically, so from a control standpoint they represent only one surface.

3.17.1.2.1 Control Module

A hydraulic schematic of the rudder/canard control module is shown in Figure 52. The control modules consist of one triple coil, tandem, Direct Drive Valve (DDV); two dual coil solenoid operated bypass valves, an inlet filter and check valve, fluid compensator and check valves.

3.17.1.2.1.1 Direct Drive Valve

The DDV is a rotary-rotary configuration. That is, the DDV consists of a rotary torque motor capable of ±11 degree rotation against a torsion centering spring and the limited flow force from the control valve. The control valve is a tandem rotary hydraulic slide and sleeve valve. The rotary slide position is sensed by three Linear Output Hall Effect Transducers (LOHET) which are used to close a position control loop around the slide valve. Thus the DDV can achieve high response with low hysteresis and threshold.

Each of the three independent coils is capable of driving the slide to its full rotation position. A low response current equalization loop is used to keep all three channels driving with approximately the same current into each coil.

3.17.1.2.1.2 Solenoid Operated Bypass Valve

There are three Flight Control Computers which drive four solenoid valve coils, so FCC No. 2 has two solenoid coil drivers. The logic is that any active channel switches the bypass valve to its active mode, and only if no channels are active will the valves go to their bypass position. In the bypass position the surfaces will “trail” to their aerodynamic center positions. In the bypass position there is some damping to achieve a measure of flutter resistance during bypass.

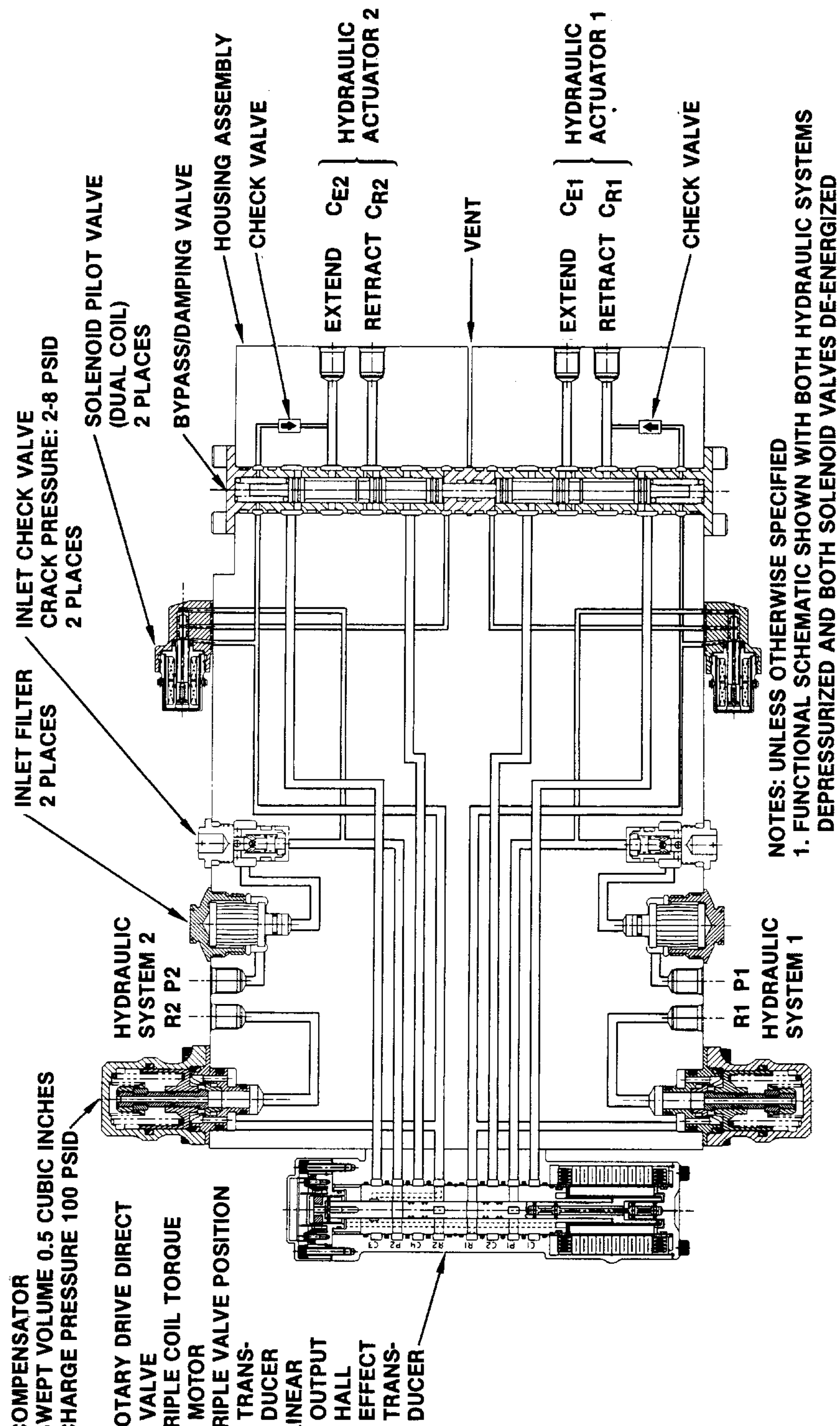


FIGURE 52 - X-31A RUDDER/CANARD CONTROL MODULE HYDRAULIC SCHEMATIC

3.17.1.2.1.3 Compensator

The rudder/canard inlet check valves and fluid compensation modules are identical to that of the trailing edge modules.

3.17.1.2.1.4 Anti-Cavitation Check Valves

There are no actual “anti-cavitation check valves” as there are in the trailing edge module, but there are small check valves that allow connection of two of the four actuator cylinder ports to return. The other actuator port is connected only through the bypass valve.

3.17.1.2.2 Actuators

Except for drive areas, the rudder/canard actuators are identical to the trailing edge actuators.

3.17.2 Simplex Actuators

3.17.2.1 Speed Brake, Thrust Vector, and Air Inlet Actuation

These surfaces are less critical then either the trailing edge or the rudder/canard surfaces and as such have only a single hydraulic system for controlling each surface. Redundancy is limited to two electrical channels driving each surface. There are two speed brake surfaces (one on each side of the aircraft), three thrust vector surfaces, and one air inlet surface.

3.17.2.1.1 Control Module

A hydraulic schematic for the thrust vector module assembly is shown in Figure 53. The control module consists of one dual coil electrohydraulic servovalve, one dual coil solenoid operated pilot valve, one pressure operated bypass/damping valve, an inlet filter and check valve, and a fluid compensator.

3.17.2.1.1.1 EHV

The EHV is a deflector-jet two stage, dual coil valve. There is no LVDT connected to the second stage.

3.17.2.1.1.2 Solenoid Operated Pilot Valve

This valve is identical to the pilot valves used for the rudder/canard control modules. It has two coils each driven from a separate flight control computer. It has a single output that is connected to return pressure when no coils are energized and connected to supply pressure when either coil is energized.

3.17.2.1.1.3 Pressure Operated Bypass Valve

This valve performs the same function as the bypass valve on the rudder/canard module, but in the bypass mode it supplies both the damping resistance from actuator cylinder to cylinder and a high resistance path from actuator retract to return.

3.17.2.1.1.4 Compensator

The inlet check valves and fluid compensators are common to the other control modules.

3.17.2.1.2 Actuators

The actuators for the thrust vector and speed brake systems are balanced area actuators with dual LVDTs for position indication and loop closure. A single actuator is assigned to each EHV.

The actuators for the air intake system are partially balanced with each EHV driving two actuators. Only one of the actuators has the dual LVDTs for the position indication and loop closure.

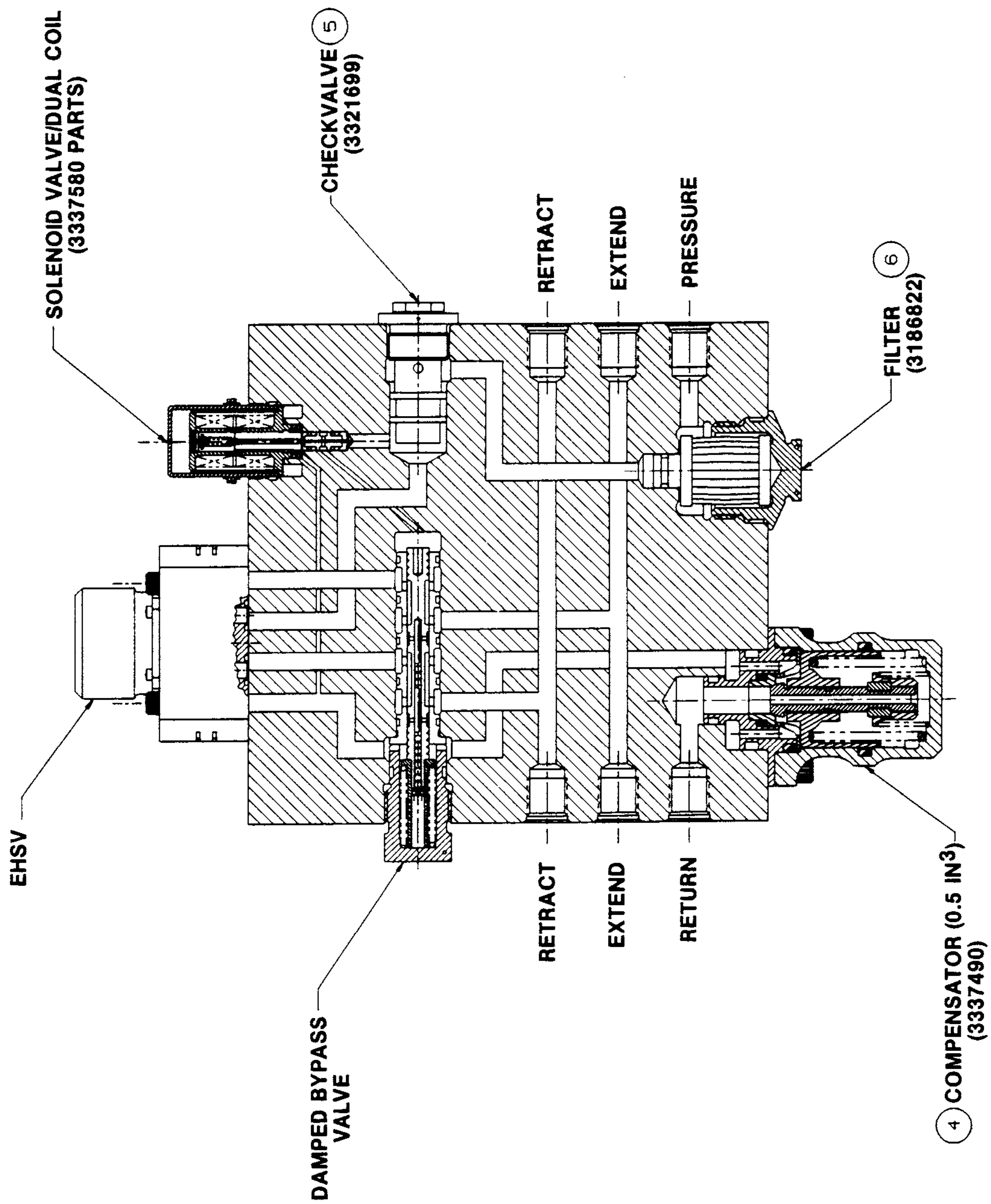


FIGURE 53 - X-31A THRUST VECTOR CONTROL MODULE HYDRAULIC SCHEMATIC

3.17.2.2 Leading Edge Actuation

The same redundancy requirements for the speed brake, thrust vector, and air inlet systems; also apply to the leading edge system. As with the speed brake there are two surfaces to drive, one on each wing. Each surface has its own control module and remotely mounted hydraulic power drive unit.

3.17.2.2.1 Control Module

The hydraulic schematic for the leading edge control module is shown in Figure 54. The control module consists of one dual coil electrohydraulic servovalve, one dual coil solenoid operated pilot valve, one pressure operated enable valve, an inlet filter and check valve, and two crossover relief valves.

3.17.2.2.1.1 EHV

The leading edge flap EHV is a deflector-jet two stage, dual coil valve. There is no LVDT connected to the second stage. Each coil is controlled from a separate flight control computer.

3.17.2.2.1.2 Solenoid Operated Pilot Valve

This valve which pilots the enable valve is identical to the pilot valve used on the rudder/canard modules. It has two coils each driven from a separate flight control computer. It has a single output that is connected to return pressure when no coils are energized, and connected to supply pressure when either coil is energized.

3.17.2.2.1.3 Enable Valve

This valve is a two position pressure operated slide and sleeve valve that is controlled by the pressure output of the solenoid operated pilot valve. In its enabled mode, it connects the inlet of the EHV to system supply pressure. In its disabled mode, it connects the inlet of the EHV to system return pressure.

3.17.2.2.1.4 Crossover Relief Valves

These valves limit the magnitude of the differential pressure that can be developed across the hydraulic motor cylinder ports. The relief valves are set at 3600 psid cracking pressure.

3.17.2.2.2 Power Drive Unit

This unit contains a hydraulic motor that supplies the power to the leading edge system, an initial stage of gear reduction and a dual RVDT used for flap position feedback.

3.17.2.2.3 Torque Shafts

There are various torque shafts that connect the power drive unit to the two gear leading edge flap actuators on each wing.

3.17.2.2.4 Torque Limiter

Between the output of the PDU and the inboard gear actuator there is a brake that stops the whole system in the case of excessive torque. The brake is actuated by a ball-ramp mechanism that unlocks upon application of reverse torque.

3.17.2.2.5 Over-Travel Stop

Since the hydraulic motors and gear actuators are continuous rotation devices and the surface has definite travel limits, a means of limiting the stroke of the system is necessary in the case of a system failure that would drive the actuators into the surface stroke limits. This unit applies a mechanical brake to the torque shaft between the two gear actuators if the PDU inadvertently drives the system beyond its stroke limits. Its action is all mechanical, requiring no electrical connections. A traveling nut presses on brake plates at each end of its stroke.

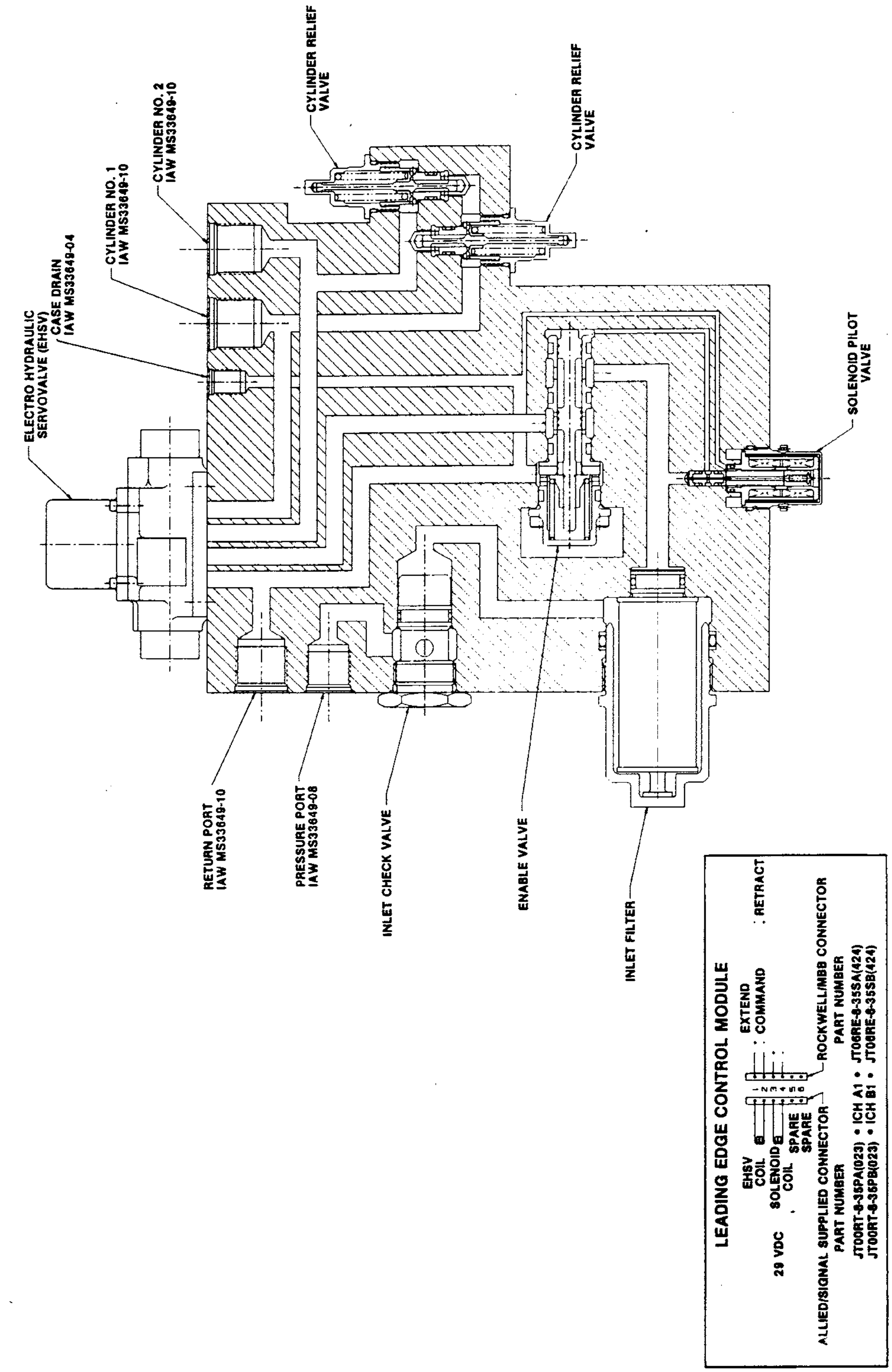


FIGURE 54 - X-31A LEADING EDGE FLAP CONTROL MODULE HYDRAULIC SCHEMATIC

3.17.2.2.6 Gear Actuators

These are planetary gear rotary actuators with very high gear ratios. The overall ratio between hydraulic motor speed and surface speed is 974.453 to 1 for the inboard flap and 1196.203 to 1 for the outboard flap. Since the shafting that connects the two gear actuators is all interconnected, the inboard and outboard flaps move at different rates and through different angles.

3.17.2.2.7 Asymmetry Brake

This unit consists of an electrically actuated brake and an RVDT. The RVDT signal from each wing is sent to the flight control computer and if an out of symmetry condition is detected, both leading edge controls are de-activated and the asymmetry brakes are applied to hold the leading edge actuators in their last reached positions.

3.18 Boeing 777 Actuators

The control surfaces of the Boeing 777 are positioned by hydraulically powered actuators. The elevators, ailerons, and flaperons are controlled by two actuators on each surface and the rudder is controlled by three. Each spoiler panel is powered by a single actuator. The horizontal stabilizer is positioned by two hydraulic motors driving the stabilizer jackscrew.

The Primary Flight Control actuators are controlled by the Actuator Control Electronics (ACEs) as shown in Figure 55. Four identical ACEs are used in the system, referred to as L1, L2, C, and R. These designations correspond roughly to the left, center, and right hydraulic systems on the airplane. The flight control functions are distributed among the four ACEs, such that a total failure of a single ACE will leave the major functionality of the flight control system intact. An ACE failure of this nature will have much the same impact to the Primary Flight Control System as that of a hydraulic system failure.

The ACEs decode the signals received from the transducers used in the pilot controls and the primary actuation. The ACEs convert the transducer position into a digital value and then transmit that over the ARINC 629 busses for use by the Primary Flight Computers (PFCs). The PFCs use these pilot control positions and surfaces positions to calculate the surface commands. The PFCs then transmit the surface commands over the same ARINC 629 busses back to the ACEs, which convert them into analog commands for each actuator.

The key Boeing 777 airplane flight control actuator characteristics are listed in Table 17 found in 3.1.

3.18.1 Actuator Modes of Operation

The actuators on the elevators, ailerons, flaperons, and rudder have several operational modes which are described below:

a. Normal - Normally, all actuators on the elevators, ailerons, flaperons, and rudder receive commands from their respective ACEs and position the surfaces accordingly. The actuators will remain in the normal mode until commanded into another mode by the ACEs.

b. Bypass - In this mode, the actuator does not respond to commands from the ACE. The actuator is allowed to move freely, so that one or more sister actuators on the surface can move the surface unencumbered. This mode is available on aileron, flaperon, and rudder actuators.

c. Damped - In this mode, the actuator does not respond to commands from the ACE. The actuator is allowed to move, but at a restricted rate which provides flutter damping. This mode allows the other actuator or actuators on the surface to continue to operate the surface at a rate sufficient for airplane control. This mode is available on elevator and rudder actuators.

d. Blocked - In this mode, the actuator does not respond to commands from the ACE, and is not allowed to move. When both actuators on a surface controlled by two actuators have failed, they both enter the Blocked mode to provide a hydraulic lock on the surface. This mode is available on the elevator and aileron actuators.

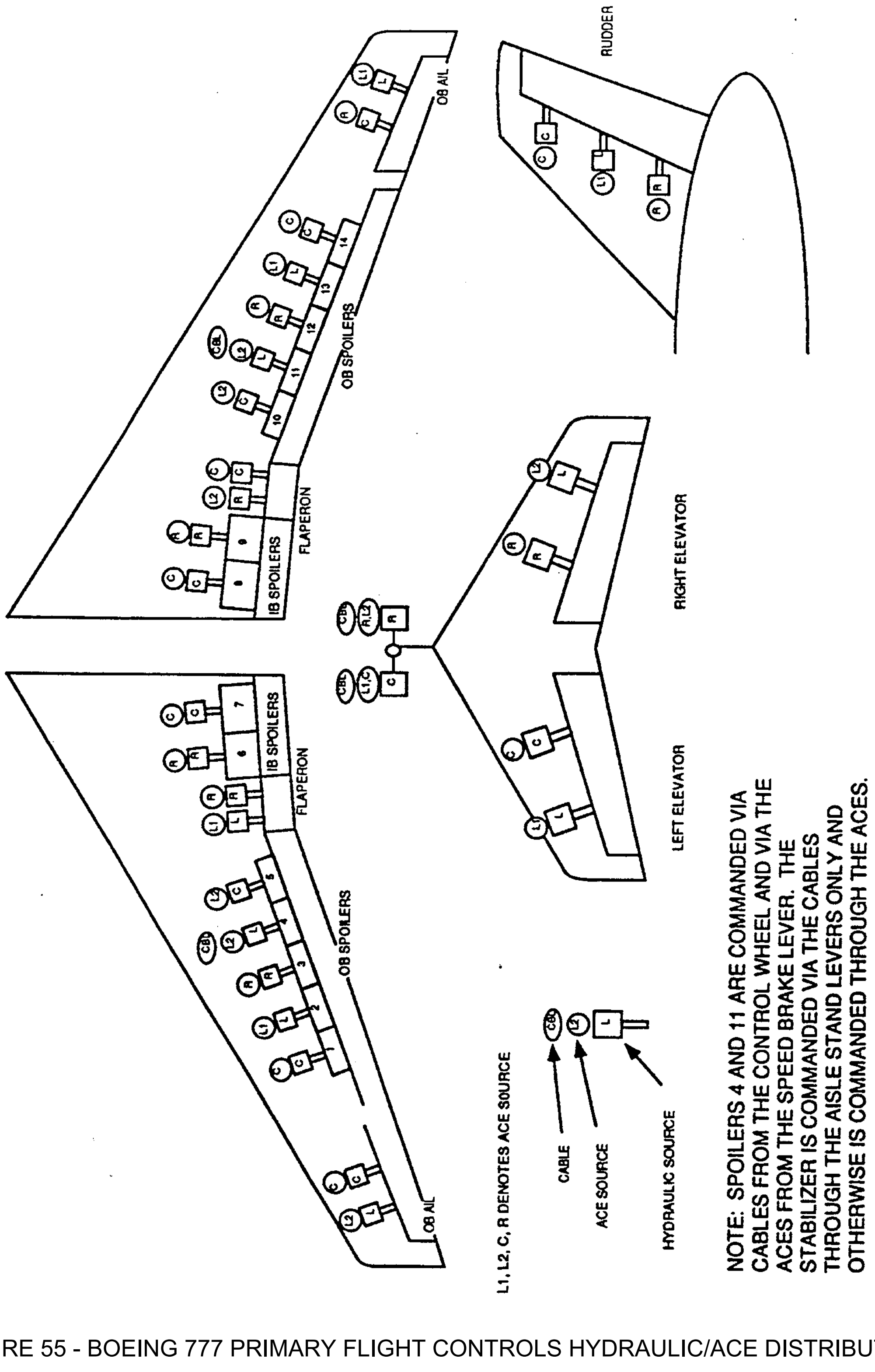


FIGURE 55 - BOEING 777 PRIMARY FLIGHT CONTROLS HYDRAULIC/ACE DISTRIBUTION

An example using the elevator surface illustrates how these modes are used. If the inboard actuator on an elevator fails, the ACE controlling that actuator will place the actuator in the Damped mode. This allows the surface to move at a limited rate under the control of the outboard actuator. Concurrent with this action, the ACE also arms the Blocked mode on the outboard actuator on the same surface. If a subsequent failure occurs which will cause the outboard actuator to be placed in the Damped mode by its ACE, both actuators will then be in the Damped mode and have their Blocked modes armed. An elevator actuator in this configuration enters the blocked mode, which hydraulically locks the surface in place for flutter protection.

3.18.2 777 Power Control Units

As an example of the Power Control Units (PCUs) used on the 777, the aileron PCU is described below.

Figure 56 is a functional diagram of an aileron PCU. This three-mode PCU is a linear, electrohydraulic actuator with a two-stage servovalve and a balanced area piston. The PCU control module and cylinder are integrated and form a single LRU. The electrohydraulic servovalve responds to a current command from ACE by metering hydraulic fluid to the actuator ram. The actuator rod end is connected directly to the control surface.

An aileron PCU module contains a servovalve, a mode selector valve, two solenoid valves, two position transducers, a compensator, load and thermal relief valves, and check valves as shown in Figure 56. Bypass and blocking solenoid valves are operated by ACEs to achieve, via the mode selector valve, one of three modes: normal, bypass, and blocked. The two transducers provide servovalve position, and ram position to the corresponding ACE.

An extension check and relief valve is installed in the actuator hydraulic line to prevent aileron up-float following certain failures. The aileron surface is mass-balanced and does not need special flutter damping.

A manual bypass valve that allows fluid to circulate around the piston is provided to aid in actuator installation. In case of water or fluid accumulation, air cavities in aileron actuators are self draining via drain holes.

3.19 X-29A Actuators

The X-29A flight control system is a triplex digital fly-by-wire system with dual hydraulic systems positioning two canards, six segmented trailing edge flaperons driven by four actuators which provide variable camber and roll control, a single rudder and two strake surfaces. Each of the two canards and two strake surfaces has separate actuators. A hydraulic schematic of the X-29A flight control system is shown in Figure 57. Where possible the aircraft used off-the-shelf hardware. As such, all surfaces except the strake use F-16 ISAs (integrated servoactuators). Refer to 3.5 and Figure 10 for details on the ISAs.

3.19.1 Strake Actuator

Because of the unavailability of existing actuators which meet both the performance and envelop requirements of the strakes a new design was developed for this application. As shown by the pictorial hydraulic schematic in Figure 58 the strake actuator is an active/standby dual tandem design to support the fail-operate/fail-safe philosophy of the aircraft. The fail-safe mode fully extends the actuator at a restricted rate with a force limitation controlled by built-in pressure regulators. Each half of the dual actuator contains separate mode control valving and a pair of two-stage electrohydraulic servovalves (EHSVs).

Each EHV pair is a unique arrangement with built-in failure detection. Each valve of the pair is plumbed in series such that the output of the first EHV serves as the supply to the second EHV's second stage. Furthermore, the first EHV has a 50% underlap to supply pressure while the second valve is axis cut. Since all EHVs on an actuator receive the same current commands the second servovalve is the controlling valve while the first (underlapped) servovalve "goes along for the ride" as long as both servovalves are functioning properly. If one of the two EHVs misfunctions and does not respond to commands the actuator position loop commands the valves toward the opposite quadrant from the actual position of the failed valve. Thus the "good" valve spool is opposite in polarity from the failed valve which cuts off the flow to the actuator, thereby stopping its motion since the two EHVs of a pair are plumbed in series.

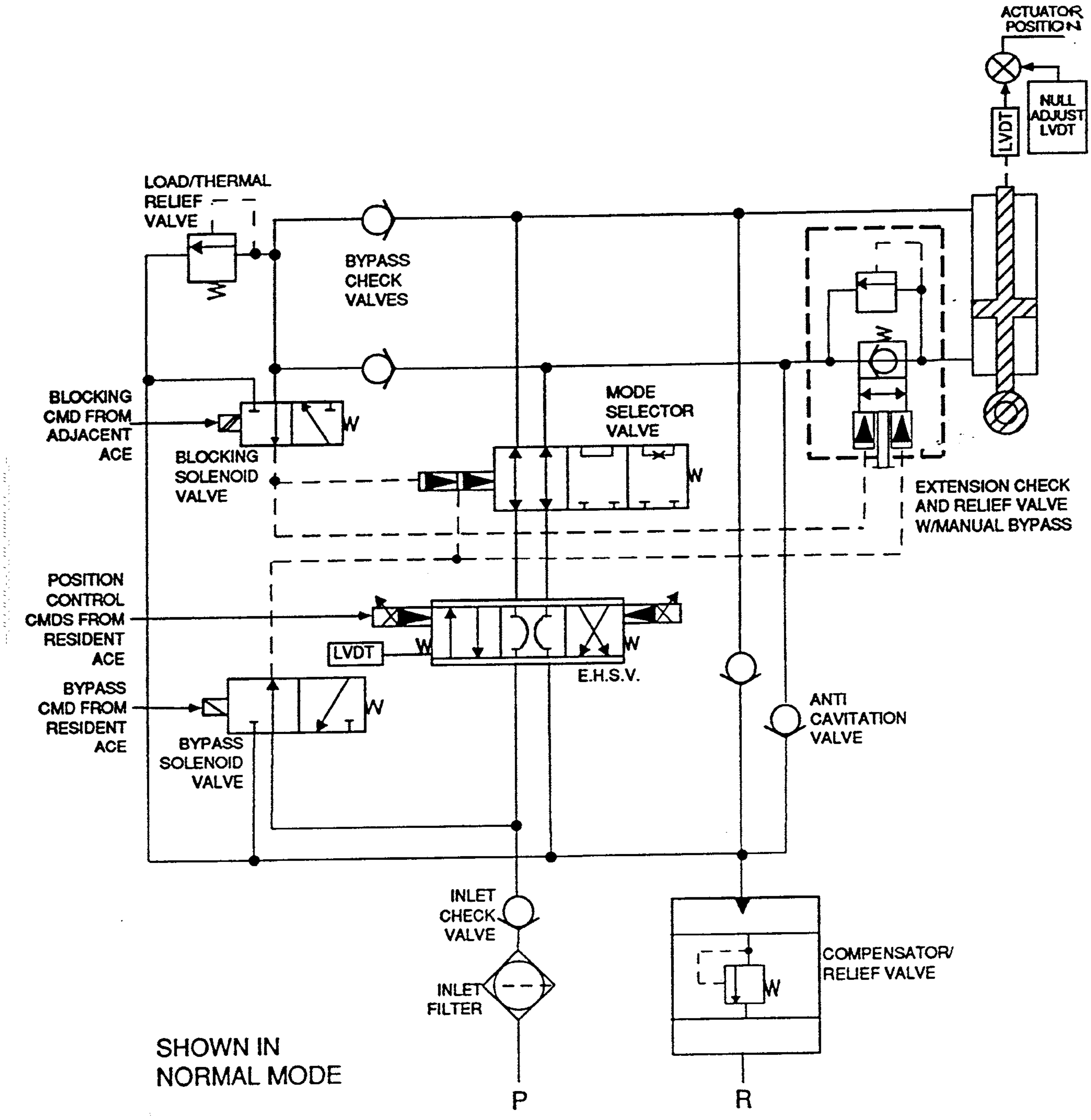


FIGURE 56 - BOEING 777 AILERON PCU HYDRAULIC SCHEMATIC

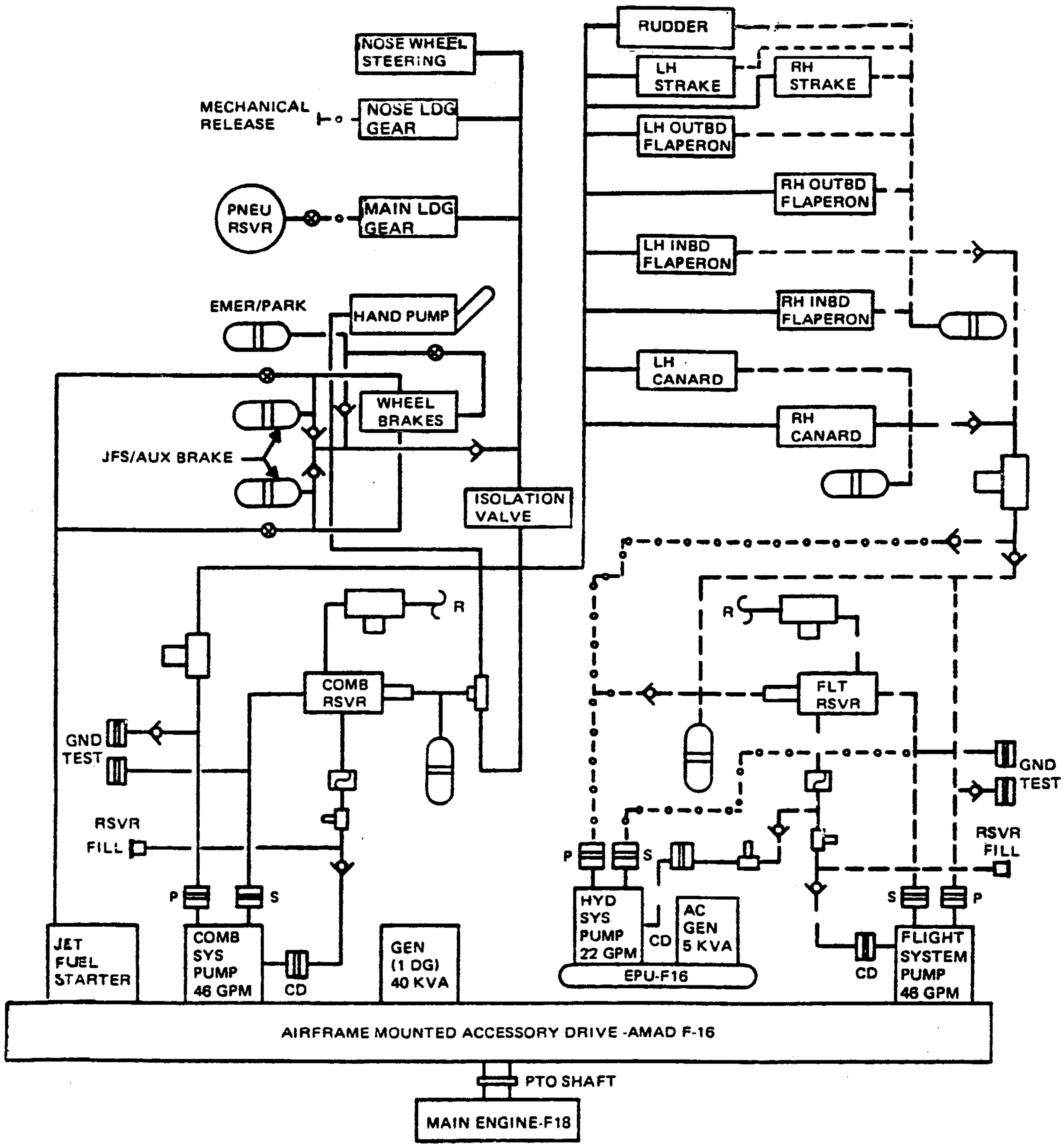


FIGURE 57 - X-29A FLIGHT CONTROL SYSTEM HYDRAULIC SCHEMATIC

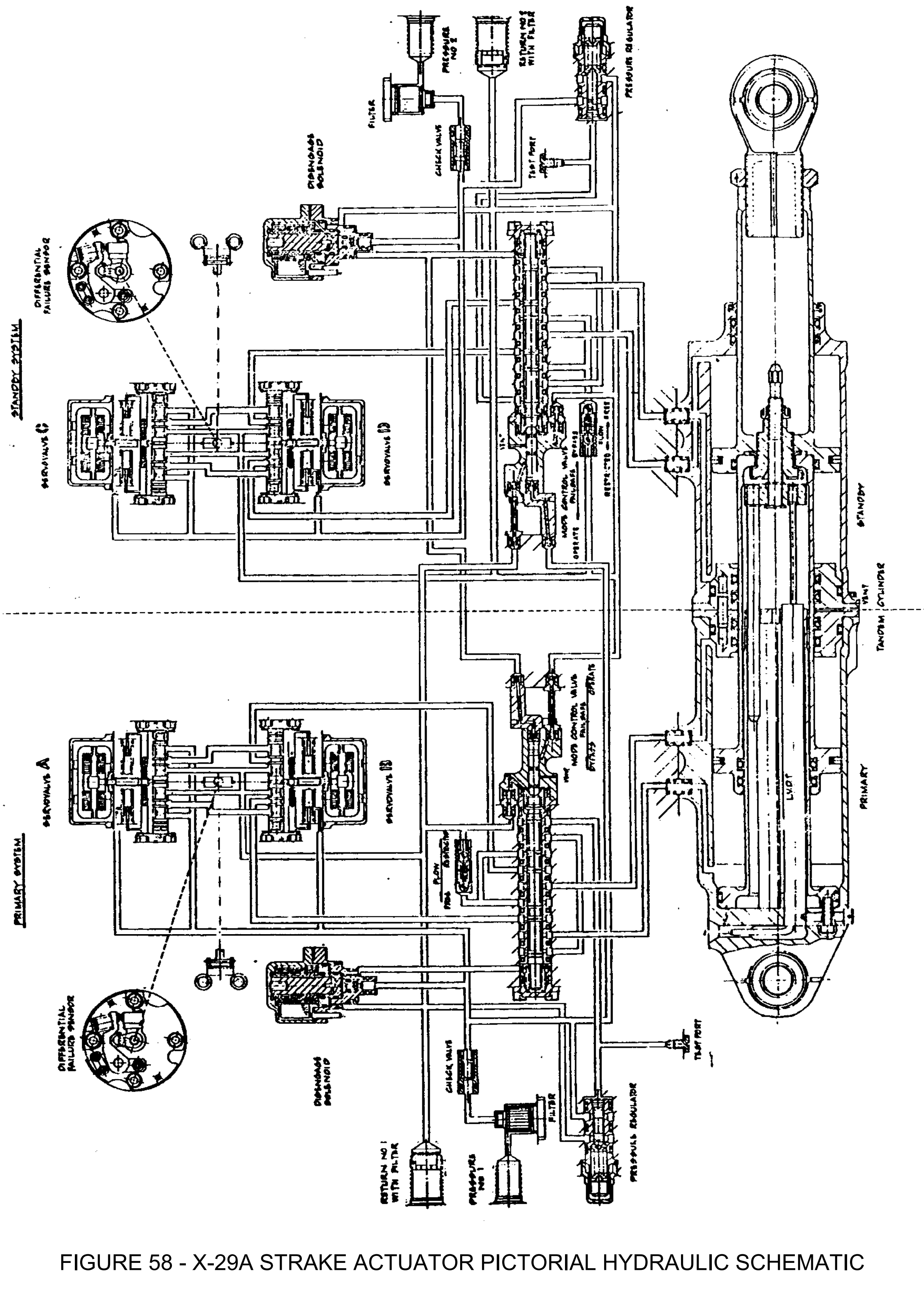


FIGURE 58 - X-29A STRAKE ACTUATOR PICTORIAL HYDRAULIC SCHEMATIC

Figure 58 also shows a mechanism within each EHV assembly pair that senses a discrepancy between the two EHV spool positions. For differences larger than 25% of stroke a microswitch is actuated which alerts the flight control computer of an EHV failure at which point the corresponding half of the tandem strake actuator is commanded to bypass.

3.20 Airbus A320/330/340 Actuators

The general architectures of the actuation systems for the Airbus Standard Body and Long Range families are very similar in principle to each other, the differences being limited to the number of aileron and spoiler surfaces. The servoactuators are similar in their operating functions, but are different in sizes between the two aircraft families. The description below and Figure 59 reflect the Long Range configuration (A330/340) while Tables 19A and 19B list the characteristics of both the Standard Body (A319/320/321) and Long Range flight control actuators, respectively.

All surfaces are hydraulically powered. The ailerons and elevators are each fitted with two servoactuators, the rudder with three, the spoiler surfaces each with one, and the Trimmable Horizontal Surface (THS) ball screw is driven by two hydraulic motors. The actuators are powered by three independent hydraulic systems, designated Green, Yellow and Blue.

The fly-by-wire ailerons, elevator and spoilers are controlled directly by the flight control computers. The rudder takes commands from the yaw damper servoactuators which drive input levers on the hydromechanical rudder servoactuators. The THS actuator is a “smart” (has onboard electronics) whose position commands come from the flight control computers through digital data buses. Servoloops and control laws are shared between five digital computers of two dissimilar types, the three Flight Control Primary Computers (FCPC) and the two Flight Control Secondary Computers (FCSC).

Additionally, the rudder and the THS actuators can be mechanically controlled via cables from the pedals and the pitch trim handwheel, respectively.

3.20.1 Servoactuator Operating Modes and System Reconfigurations

Aileron elevator, rudder and spoiler servoactuators achieve different operating modes by selectively energizing the solenoid valves found on each actuator. The operating modes for each surface are described as follows:

Ailerons: One actuator in active mode positions the surface while the adjacent actuator on the same surface is in damped bypass mode. In the event of a failure on the active actuator it switches to damped bypass mode while the adjacent actuator switches to active mode. In the event that both actuators of the surface fail they both are commanded to damped bypass. There is sufficient damping to provide flutter protection.

Elevator: One actuator in active mode positions the surface while the adjacent actuator on the same surface is in damped bypass mode. In the event of a failure on the active actuator it switches to damped bypass mode while the adjacent actuator switches to active mode. In the event that both actuators of the surface fail those in centering mode hold the surface at neutral. In the event of loss of hydraulic pressure to both actuators they revert to damped bypass mode for flutter protection.

Rudder: The three actuators simultaneously drive the rudder surface in parallel. If an actuator fails it switches to bypass mode.

Spoiler: Each spoiler surface is positioned by a single actuator when the actuator is in normal mode. If a failure occurs the actuator is driven to retract (surface down) by supply pressure. If the hydraulic supply fails the actuator prevents the surface from raising by means of a hydraulic lock and allows aerodynamic forces to retract the actuator. A maintenance mode enables the surface to be manually moved when depressurized.

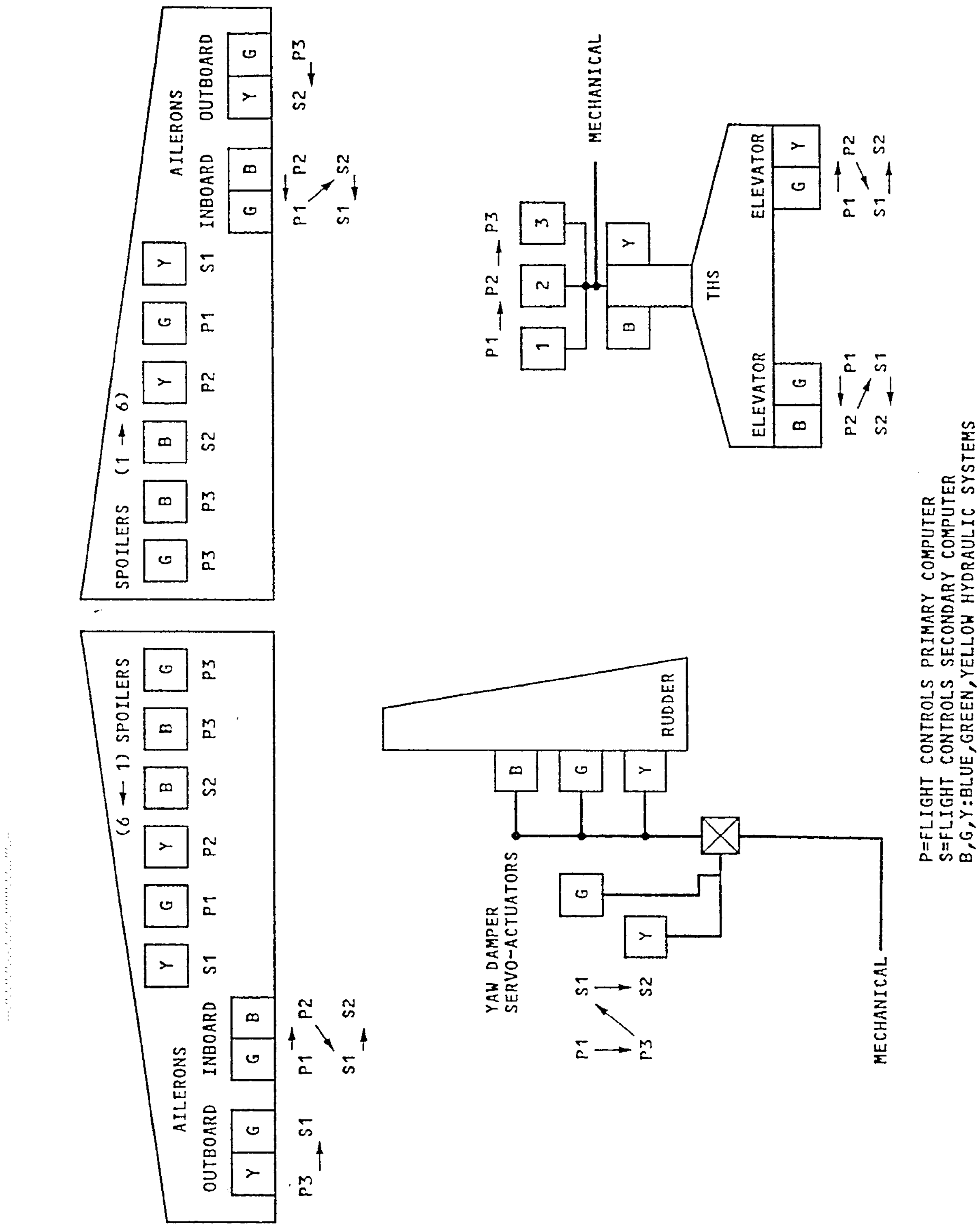


FIGURE 59 - AIRBUS A330/340 FLIGHT CONTROL ACTUATION SYSTEM LAYOUT

3.20.2 Airbus Servoactuator Description

The fly-by-wire servoactuator functions used on the Airbus Standard Body and Long Range Families are illustrated in Figure 60 and described below:

The actuator body and equal area piston rod are connected to the fixed structure and surface through spherical bearings. A piston position transducer (LVDT) is mounted internally to the piston rod. A manifold housing the hydraulic components includes the following LRUs:

- An inlet filter
- A two-stage electrohydraulic single inlet servovalve
- A solenoid valve for piloting the mode selector valve
- A mode selector valve position transducer for monitoring the valve spool position
- A differential pressure transducer for preflight BIT checking of the damped bypass mode

The hydromechanical rudder servoactuator is shown schematically in Figure 61.

3.21 F-117 Actuators

The F-117 flight control actuation system consists of six actuators driven by a triplex set of flight control computers (FCCs). The flight control surfaces are two inboard elevons, two outboard elevons and two tail fins. Each surface is positioned by a dual tandem hydraulic actuator. Because of the aircraft’s low observable requirements and the resulting unusual airframe the aircraft’s development program faced a number of high risk challenges in the areas of aerodynamics, avionics, low observable technology and flight controls. To minimize the flight control risk the F-117 designers chose to utilize the F-16 actuators and FCC chassis, applying only modest modifications to them. The actuators are integrated servoactuators (ISAs) which are described in 3.5. The F-117 inboard elevons utilize F-16 horizontal tail servoactuators, but with shortened stroke. The F-117 outboard elevons and tail fins use the F-16 rudder servoactuator. See Table 20 in 3.1 for a tabulation of the F-117 actuator characteristics.

3.22 N-250 Flight Control Actuation System

The N-250 turboprop commuter airliner flight control surfaces consist of one rudder, two ailerons, two elevators, and four spoiler/ground spoiler panels. The system is all fly-by-wire except the aileron and elevator systems have standby mechanically signaled reversion modes. There are two actuators on each surface, except for the spoilers, which has one each. A system overview is shown in Figure 62. The aircraft has triplex hydraulic supplies and two normal DC electrical busses plus two battery-backed essential DC electrical busses.

N-250 flight control actuator characteristics are tabulated in Table 21 found in 3.1.

3.22.1 Aileron Actuators

Normally, the aileron is positioned by the outboard actuator, which is a simplex electrohydraulic actuator that receives servovalve and mode command signals from an Electronic Control Unit (ECU). There is a dedicated ECU for each aileron surface, providing control and monitoring for both actuators. The ECU receives position commands from an RVDT that senses the pilot's control wheel position.

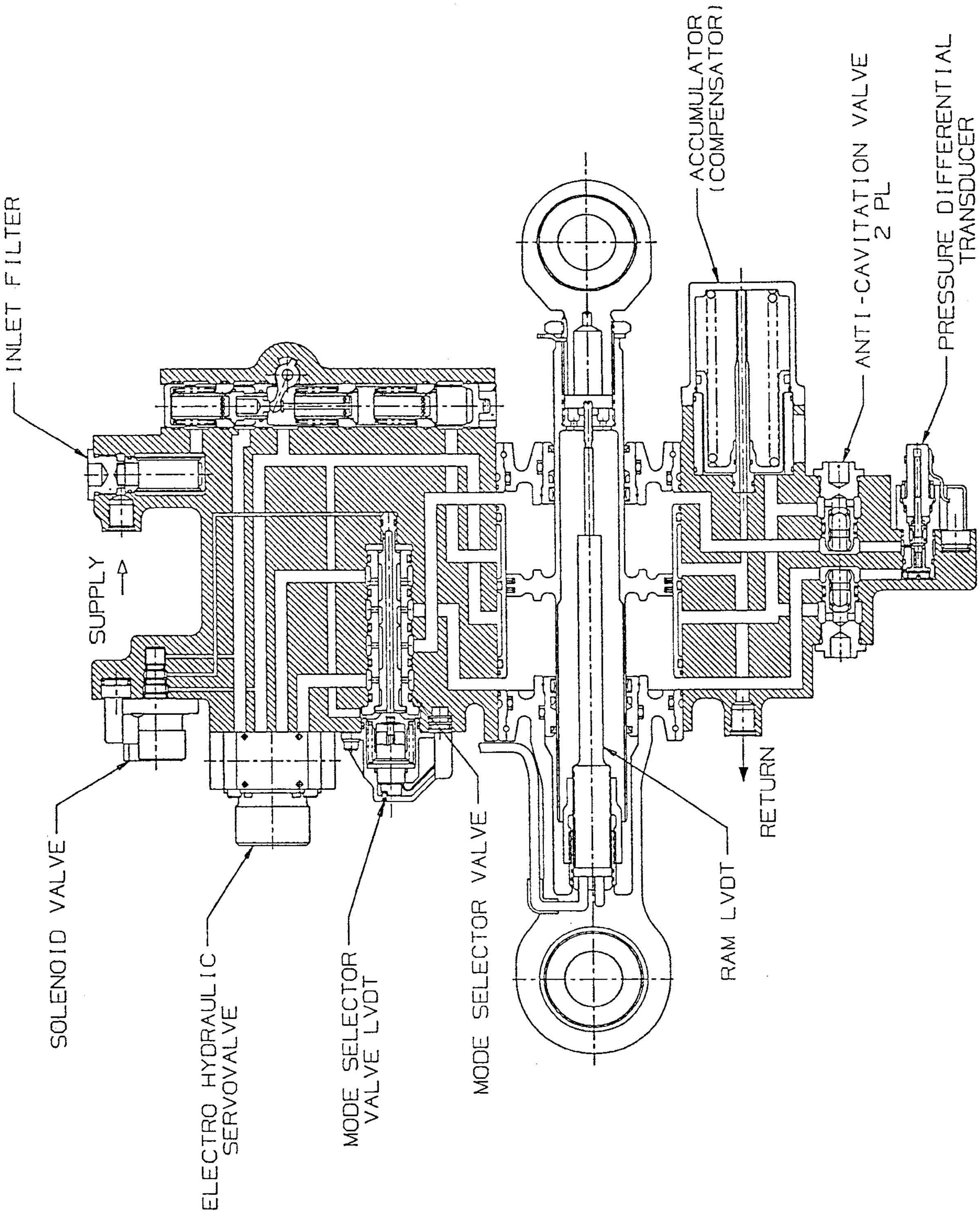


FIGURE 60 - AIRBUS A330/340 FLY-BY-WIRE FLIGHT CONTROL ACTUATOR PICTORIAL SCHEMATIC

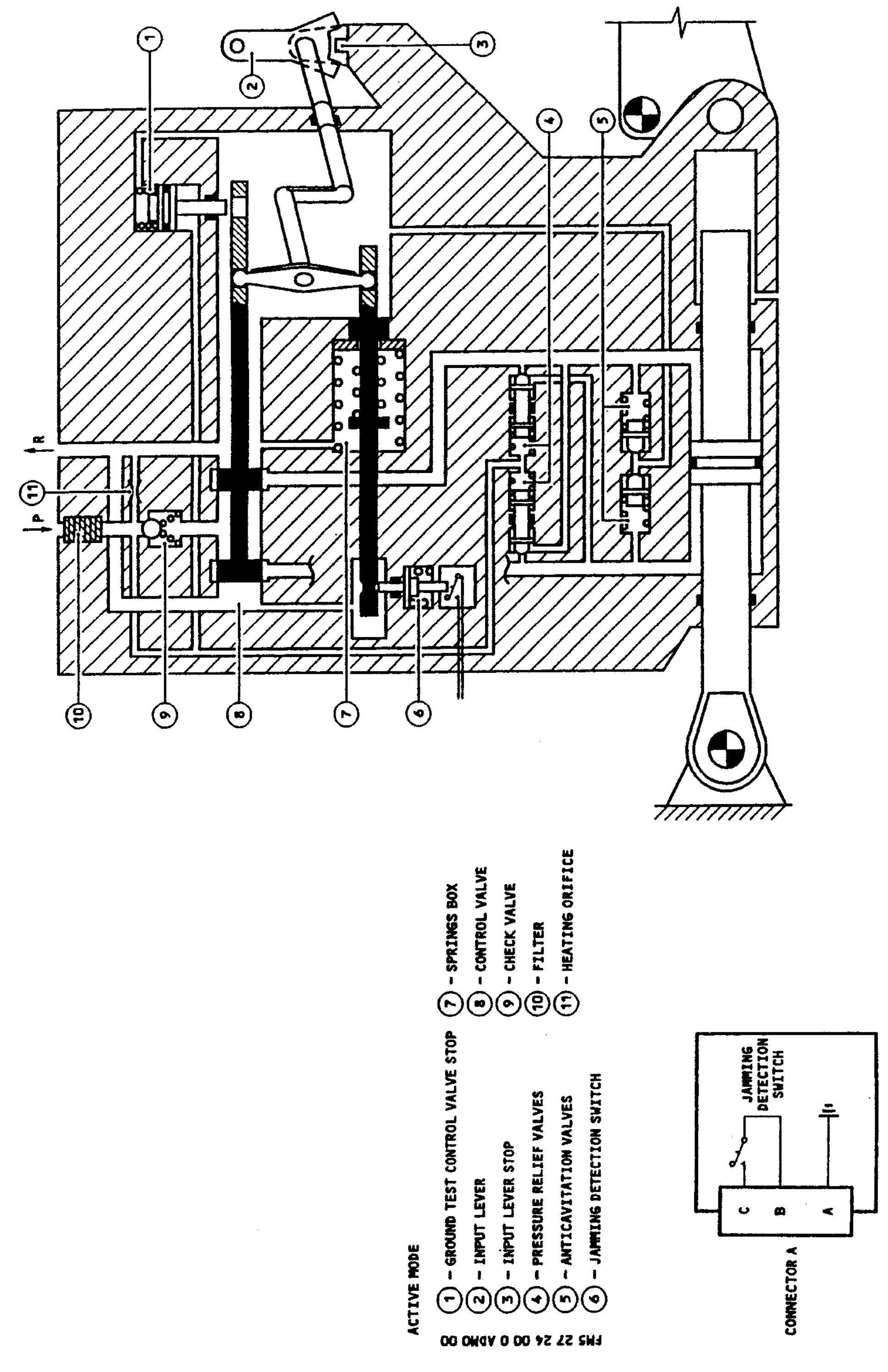


FIGURE 61 - AIRBUS A330/340 RUDDER ACTUATOR PICTORIAL SCHEMATIC

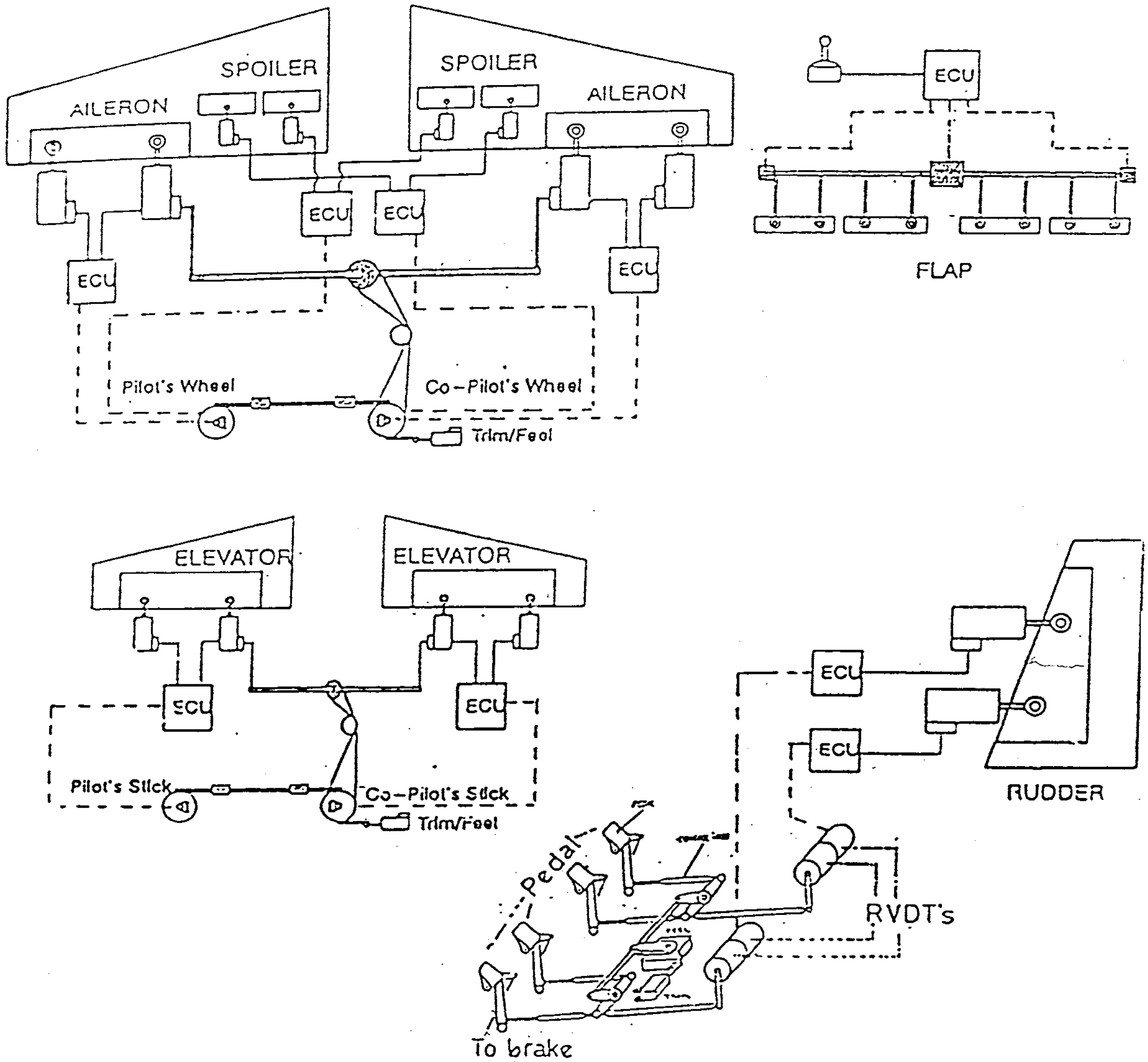


FIGURE 62 - N-250 FLIGHT CONTROL SYSTEM OVERVIEW

A pictorial schematic of the outboard aileron actuator is shown in Figure 63. In normal mode the ECU energizes the solenoid valve which in turn, shifts the bypass valve to connect the cylinder chambers to the servovalve, making this actuator active. Electronic loop closure is provided by the ECU which receives ram position feedback from a dual LVDT located inside the piston. The servovalve includes a spool position LVDT for monitoring purposes. If the outboard aileron actuator or its ECU experiences a failure the solenoid valves of both the outboard and inboard actuators are deenergized which places the outboard actuator in damped bypass mode and the inboard actuator takes over in active mode. Bypass mode is damped by a damping orifice, which serves to limit velocity on the opposite (active) actuator and provide flutter control if both actuators are bypassed. A compensator is built into the servoactuator to maintain an adequate fluid supply for preserving the damping function if hydraulic power is lost.

A pictorial schematic of the hydromechanical inboard aileron actuator is shown in Figure 64. In normal operation this actuator is commanded to standby (damped bypass) mode when its solenoid valve is energized. In active mode this actuator is controlled by a mechanically driven main control valve (MCV). The input to this valve is a linkage that takes the difference between the actuator ram position and the pilot control wheel command position, as sensed via a cable mechanism between the actuator and the control wheel. The motion of the MCV is such that hydraulic flow moves the piston in the direction to follow the cable input commands. The construction of this actuator is essentially the same as that of the outboard actuator, except that the main control valve and its control linkage replaces the servovalve of the outboard actuator and energizing the inboard actuator places it in damped bypass mode.

The inboard and outboard actuators are powered by two different hydraulic systems. If both hydraulic systems fail or the ECU's electrical power fails both actuators automatically go into damped bypass mode which allows the surface to move with aerodynamic forces, but with sufficient damping to prevent surface flutter.

3.22.2 Elevator Actuators

The two elevator surfaces are controlled functionally the same as the two aileron surfaces previously described in 3.22.1.

3.22.3 Rudder Actuators

The rudder surface is controlled by two identical electrohydraulic actuators in an active-standby arrangement with the upper actuator normally being active. Each actuator is controlled by a dedicated ECU, each with independent electrical power. Each ECU receives commands from the rudder pedals via a dual RVDT, each aileron ECU for turn coordination purposes, and from the autopilot computer to direct both autopilot and yaw damper commands.

The rudder actuators are functionally the same as the outboard electrohydraulic aileron actuator previously described in 3.22.1.

The standby ECU holds its actuator in damped bypass mode but continues to monitor the actuator through its transducers to prevent dormant failures. If the upper rudder or its associated electronics should fail its solenoid valve is deenergized and the lower actuator's solenoid valve is energized, thereby reversing the roles of the two actuators. In the event of a dual hydraulic or dual electrical failure both actuators revert to a damped bypass state with the actuators providing sufficient damping to the surface to inhibit flutter.

Legend

AA Actuator Assembly
AV Anti-Cavitation Valve
BP Bypass Valve
BV Blocker Valve
CP Compensator
CV Check Valve
DL Dual LVDT
DR Damping Restrictor
DV Drain Valve
EC Electrical Connector
FI Filter
PB Pipe Support Bracket
PP Pressure Port
RP Return Port
SO Solenoid Valve
Energized: P ⇒ C
De-Energized: R ⇒ C
SV Servovalve
VB Valve Block
WH Wire Housing

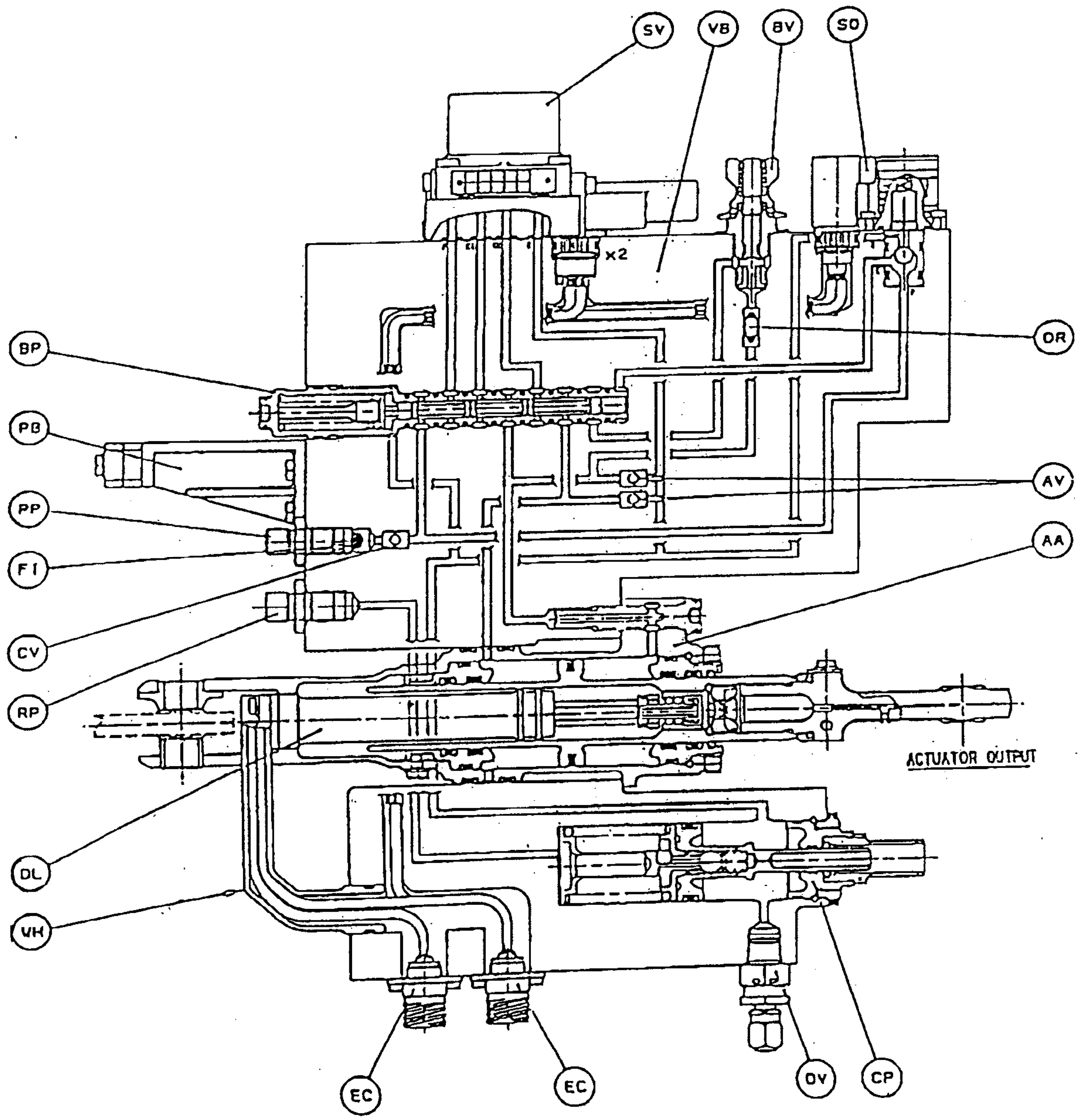


FIGURE 63 - N-250 OUTBOARD AILERON ELECTROHYDRAULIC ACTUATOR

Legend

AA Actuator Assembly	EC Electrical Connector	RP Return Port
AV Anti-Cavitation Valve	FI Filter	SO Solenoid Valve
BP Bypass Valve	FR Fixed Restrictor	Energized: P ⇒ C
BV Blocker Valve	IHS Input Hard Stop	De-Energized: R ⇒ C
CP Compensator	LS LVDT, Simplex	VB Valve Block
CV Check Valve	MCV Main Control Valve	WH Wire Housing
DR Damping Restrictor	PB Pipe Support Bracket	
DV Drain Valve	PP Pressure Port	

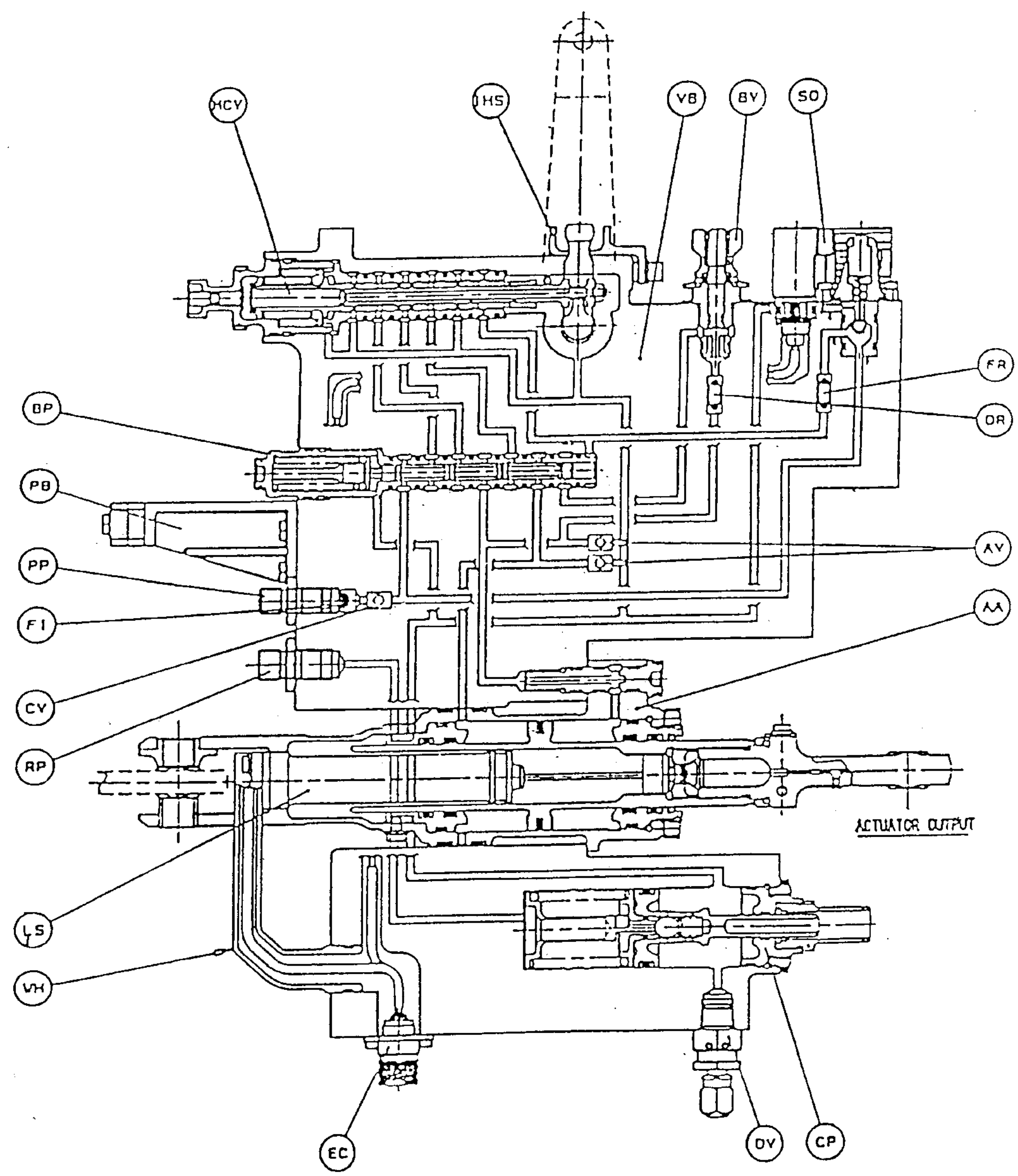


FIGURE 64 - N-250 INBOARD AILERON HYDROMECHANICAL ACTUATOR

3.22.4 Spoiler Actuators

Each of the four spoiler surfaces is positioned by a single fly-by-wire actuator when the actuator is in normal mode. In normal mode position control is maintained by a servovalve as commanded by an ECU which reads the actuator's simplex ram LVDT for position feedback. If a failure occurs the actuator is driven to retract (surface down) by supply pressure. If the hydraulic supply fails the actuator prevents the surface from raising by means of a hydraulic lock and allows aerodynamic forces to retract the actuator. A maintenance mode enables the surface to be manually moved when depressurized.

A single ECU controls both inboard spoilers and a separate ECU controls both outboard spoilers.

3.23 Airbus A380 Flight Control Actuation System

3.23.1 System Lay-Out

The primary flight control surfaces are driven by three types of actuators:

- Conventional hydraulic servocontrols (S/C)
- Electrohydrostatic Actuators (EHA)
- Electrical Back-up Hydraulic Actuators (EBHA).

They are controlled by two different types of digital computers, the Primary Flight Control Computers (PRIM) P1, P2, P3 and Secondary Flight Control Computers (SEC) S1, S2 and S3. The actuators are powered by two 5000 psi hydraulic systems; "Green" and "Yellow" plus three 115VAC variable frequency electrical systems E1, E2 and E3. In the event of failure of all PRIM and SEC, the Back-up Control Module (BCM) B controls selected actuators.

This hybrid distribution of actuators, power sources and computers on the control surfaces is shown in Figure 65.

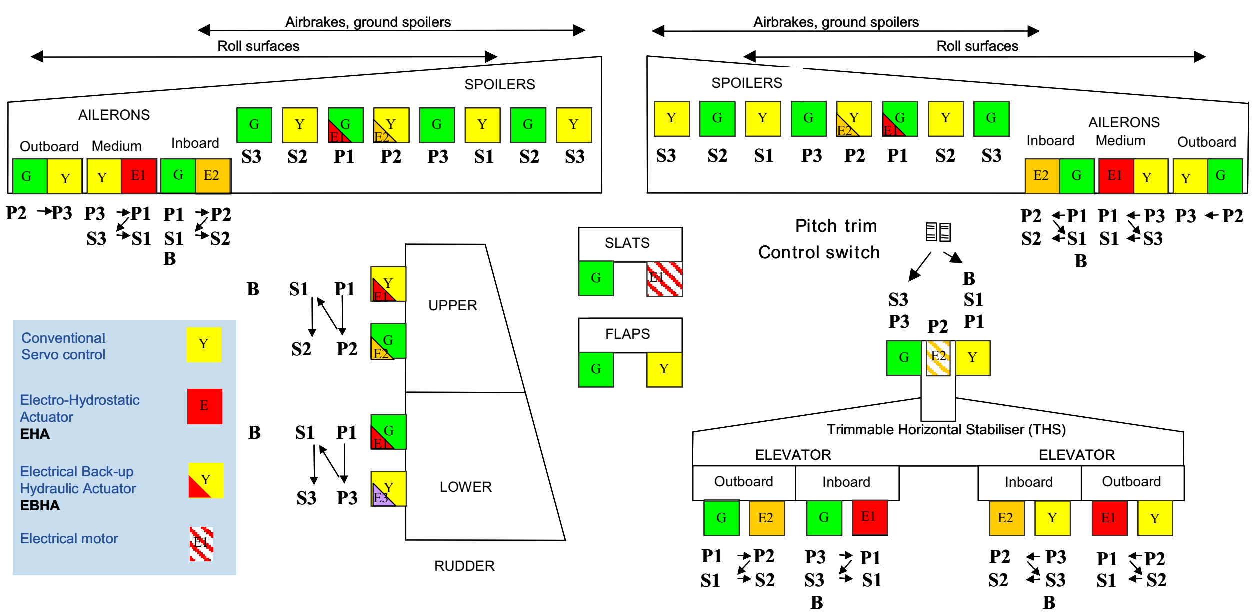


FIGURE 65 - A380 CONTROL SURFACES, ACTUATORS, POWER SOURCES AND COMPUTERS DISTRIBUTION

3.23.2 Aileron Actuation

The aircraft is fitted with three pairs of Aileron actuators (inboard, middle and outboard). A servo control actuator and an electrohydrostatic actuator (EHA) power the inboard and middle surfaces in an active/stand-by arrangement. The outboard surface is powered by two servo controls (S/C), also in an active/stand-by arrangement.

Inboard, middle and outboard Aileron S/Cs are identical and schematically shown in Figure 66.

Inboard and middle Aileron EHAs are identical and schematically shown in Figure 67.

Each actuator is connected to one Primary Flight Control Computer and to one Secondary Flight Control Computer. Furthermore, inboard Aileron S/Cs are connected to the Back-up Control Module.

Each actuator achieves the two main operating modes:

- Active mode: Enables the actuation of the Aileron in accordance with the electrical orders from PRIM or SEC Flight Control Computer.

- Damping mode: Prevents the appearance of flutter in the event of multiple failures, mainly electrical and hydraulic failures.

In the unlikely event of failures of all Flight Control Computers, the BCM controls the inboard Aileron S/C’s through a set of segregated electrical inputs and outputs.

3.23.3 Rudder Actuation

The aircraft is fitted with two Rudder surfaces (upper and lower). Two Electrical Back-up Hydraulic Actuators (EBHA) power each surface in an active/stand-by arrangement.

Upper and lower Rudder EBHAs are identical and schematically shown in Figure 68.

Each actuator is connected to one Primary Flight Control Computer and to one Secondary Flight Control Computer. Furthermore, the top EBHA of each surface is connected to the Back-up Control Module.

Each actuator achieves the three main operating modes:

- Hydraulic Active mode: The actuator is in a hydraulic active mode arrangement and hydraulically powered, that enables the actuation of the rudder in accordance with the electrical commands from the PRIM or SEC Flight Control Computer.

- Damping mode: Prevents the appearance of flutter in the event of multiple failures, mainly electrical and hydraulic failures.

- Electrical Active mode: The actuator is in an electrical active mode arrangement and electrically powered, that enables the actuation of the rudder in accordance with the electrical commands from the PRIM or SEC Flight Control Computer.

If all of the Flight Control Computers are failed, the BCM controls the connected EBHAs through a set of segregated electrical inputs and outputs.

3.23.4 Elevator Actuation

The aircraft is fitted with two pairs of Elevator actuator (inboard and outboard), each with two actuators. A servo control and an Electrohydrostatic Actuator power each surface in an active/stand-by arrangement.

Inboard and outboard Elevator S/Cs are identical and similar to the aileron units and are schematically shown in Figure 66.

Inboard and outboard Elevator EHAs are identical and similar to the aileron units and are schematically shown in Figure 67.

Each actuator is connected to one Primary Flight Control Computer (PRIM) and to one Secondary Flight Control Computer (SEC). Furthermore, inboard elevator S/C's are connected to the Back-up Module (BCM).

Each actuator achieves the two main operating modes:

- Active mode: Enables the actuation of the elevator in accordance with the electrical orders from PRIM or SEC Flight Control Computer.

- Damping mode: Prevents the appearance of flutter in the event of multiple failures, mainly electrical and hydraulic failures.

If all of the Flight Control Computers are failed, the BCM controls the inboard Elevator S/C's through a set of segregated electrical inputs and outputs.

3.23.5 Spoiler Actuation

The aircraft is fitted with eight pairs of spoilers. Each surface is powered by a servo control except Spoiler 5 and 6 surfaces, which are powered by an Electro Back-up Hydraulic Actuator.

Spoiler 1, 2, 3, 7, and 8 servo controls are identical and schematically shown in Figure 69.

A specific S/C, with a different length (equal to the one of the EBHAs), actuates Spoiler 4 surfaces. Both S/C performances are identical.

Spoiler 5 and 6 EBHAs are identical and schematically shown in Figure 70.

Each actuator is connected to one Primary Flight Control Computer or to one Secondary Flight Control Computer.

Each S/C achieves four main operating modes:

<u>Hydraulic Active Mode</u>

The unit, powered by the hydraulic system, actuates the moving surface under the closed loop position control of a flight control computer. When fully retracted the unit applies a permanent load to the surface.

<u>Control Failure Mode</u>

In the event of the loss of the control signal, the unit automatically retracts to its stop.

<u>Supply Failure Mode</u>

In the event of the loss hydraulic power including the loss of the system fluid, the unit prevents the surface from raising and enables it to retract under the air load.

<u>Maintenance Mode</u>

The units include a manually controlled mechanical device to enable the surfaces to be moved for maintenance purpose, with no danger to ground personnel.

Each EBHA achieves five main operating modes:

Hydraulic Active Mode

The unit, powered by the hydraulic system, actuates the moving surface under the closed loop position control of a flight control computer. When fully retracted the unit applies a permanent load to the surface.

Electrical Active Mode

In the event of the loss of aircraft hydraulic circuit the unit, electrically powered, actuates the moving surface under the closed loop position control of a flight control computer. When fully retracted, the unit applies a permanent load to the surface.

Control Failure Mode

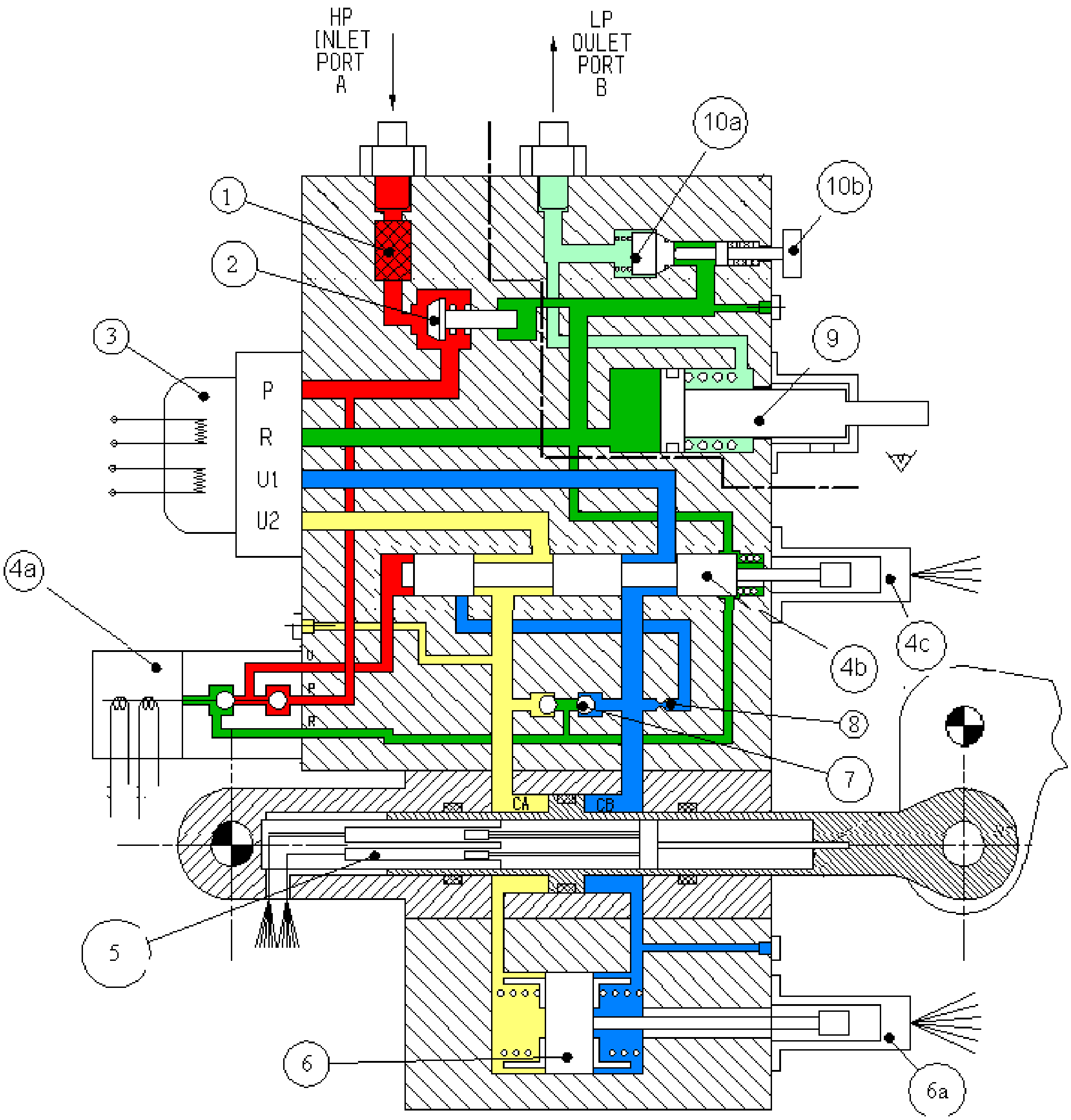
In the event of the loss of the control signal, the unit automatically retracts to its stop.

Supply Failure Mode

When both electrical and hydraulic power are not available, the unit prevents the surface from rising and enables it to retract under the air load.

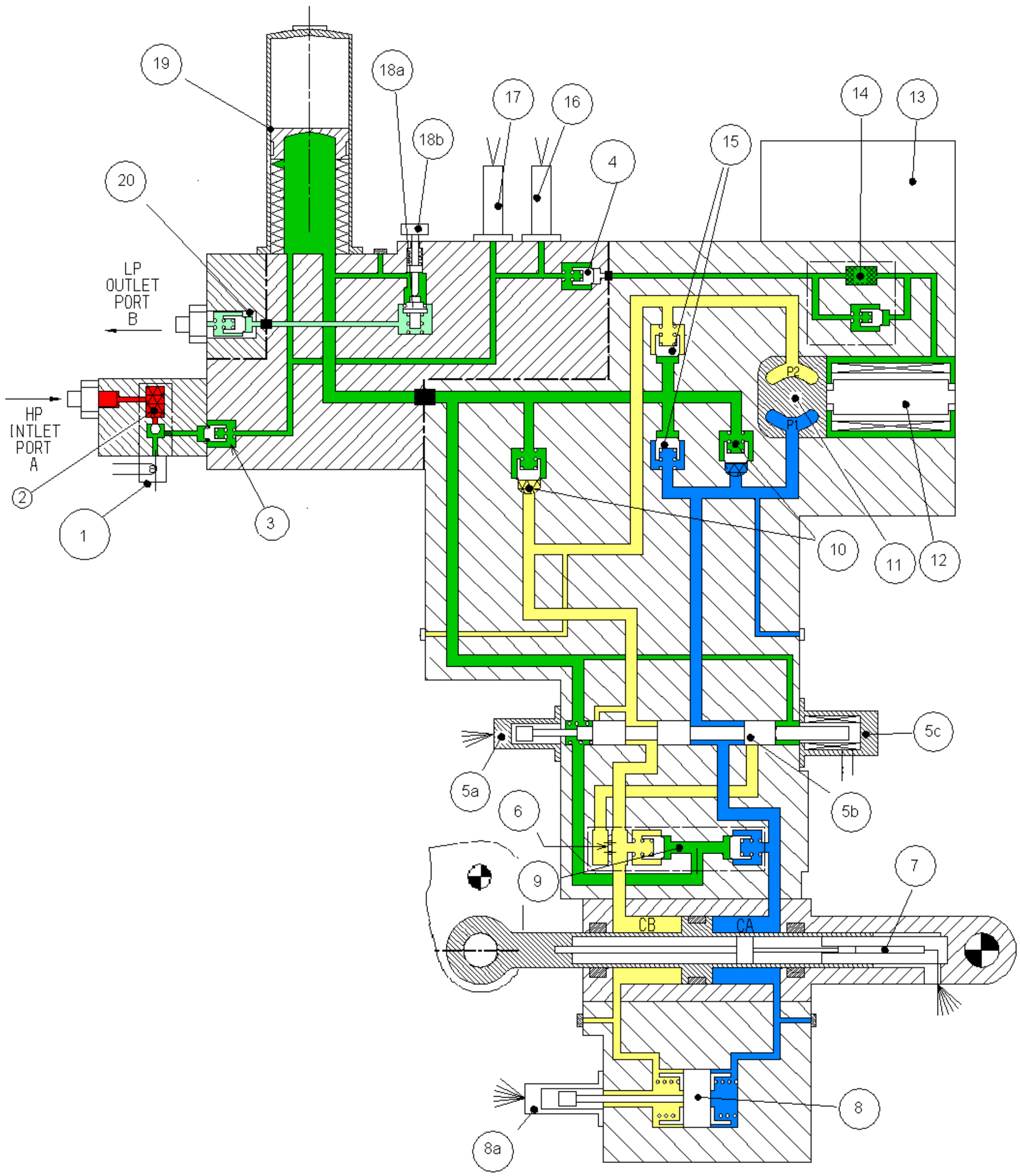
Maintenance Mode

The units include a device to enable the surfaces to be manually moved for maintenance purpose, with no danger to ground personnel.



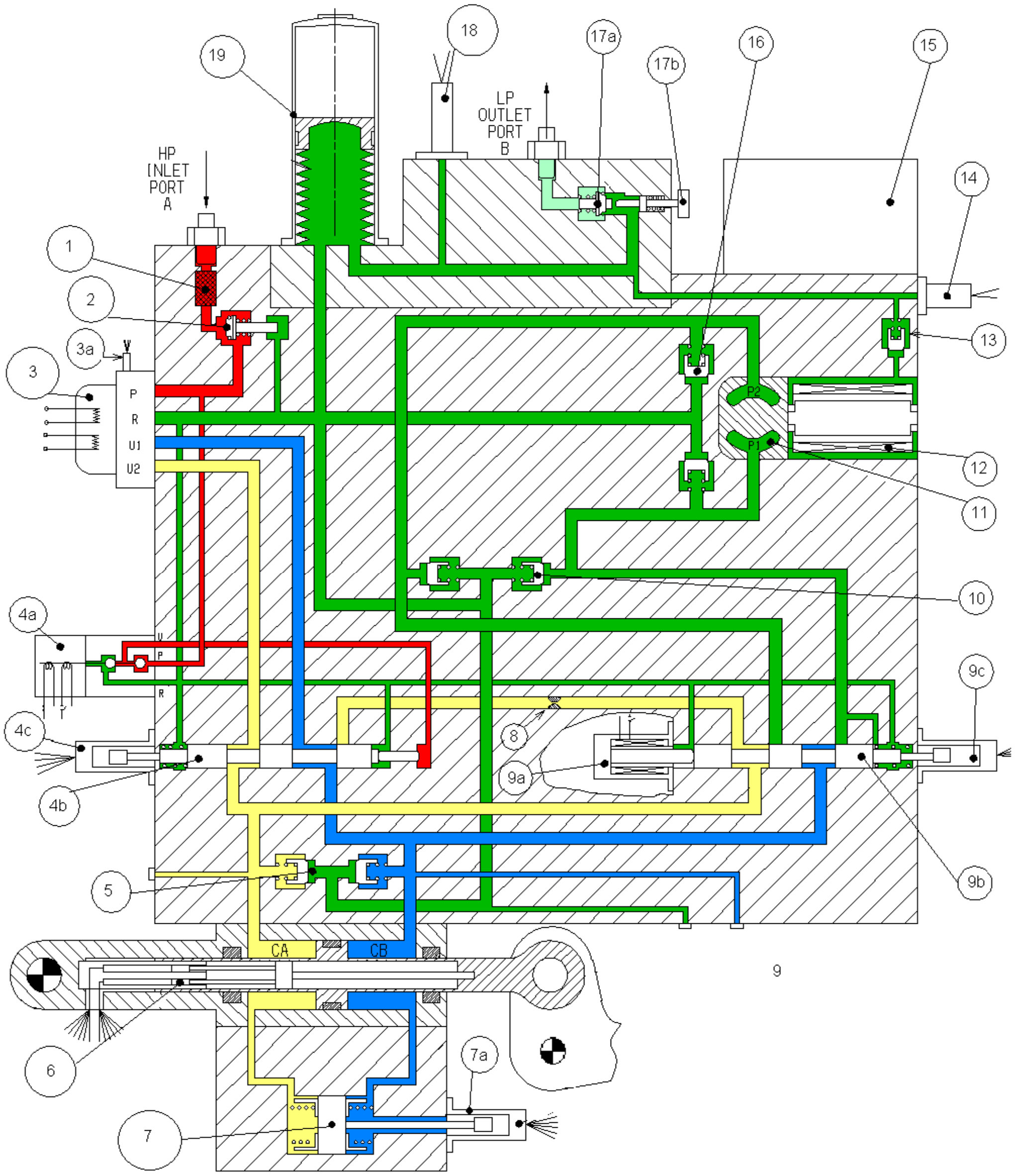
1	HP filter	5	Dual feedback LVDT	10a	LP maintaining valve
2	HP maintaining valve	6	Differential Pressure sensor	10b	Manual bleeding device
3	EHSV	6a	Differential pressure LVDT		
4a	Dual Mode SV	7	Ram anti-cavitation valves		
4b	Mode valve	8	Damping restrictor		
4c	Mode LVT	9	Accumulator		

FIGURE 66 - A380 AILERON S/C IN ACTIVE MODE CONFIGURATION



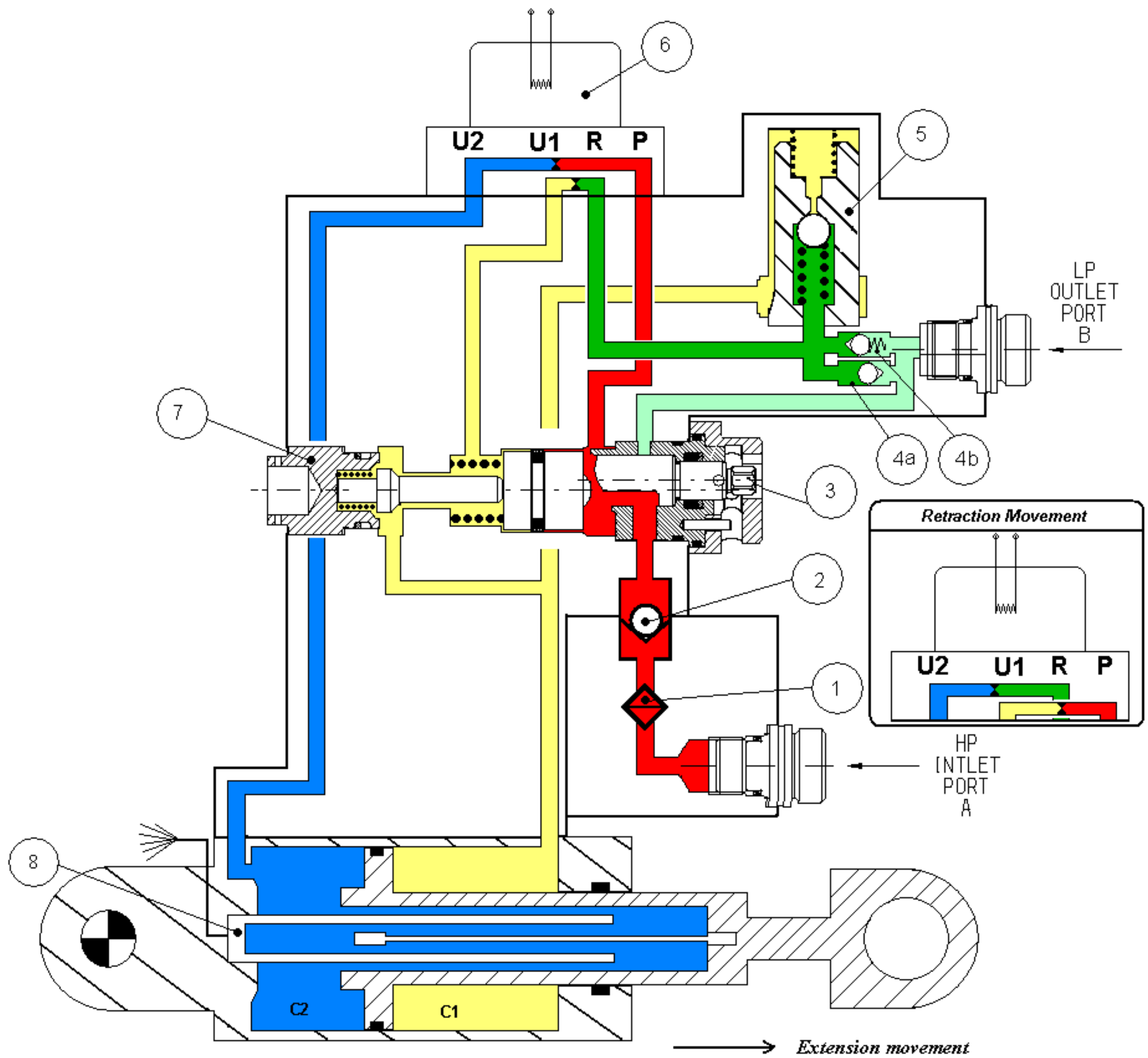
1	Filling SV	7	Feed back LVDT	14	Motor drain filter device
2	HP filter	8	Diff. pressure sensor	15	Pump anti-cavitation valves
3	Filling non return valve	8a	Diff. pressure LVDT	16	Fluid temperature sensor
4	Motor drain non return valve	9	Ram anti-cavitation valves	17	Accumulator pressure transducer
5a 5b 5c	Mode LVT Mode valve Mode SV	10	Load limiting valves	18a	LP maintaining valve
		11	Hydraulic pump	18b	Manual bleeding device
		12	Electrical motor	19	Accumulator
6	Damping restrictor	13	MDE (Motor Drive Electronics)	20	LP non return valve

FIGURE 67 - A380 AILERON EHA IN ACTIVE MODE CONFIGURATION



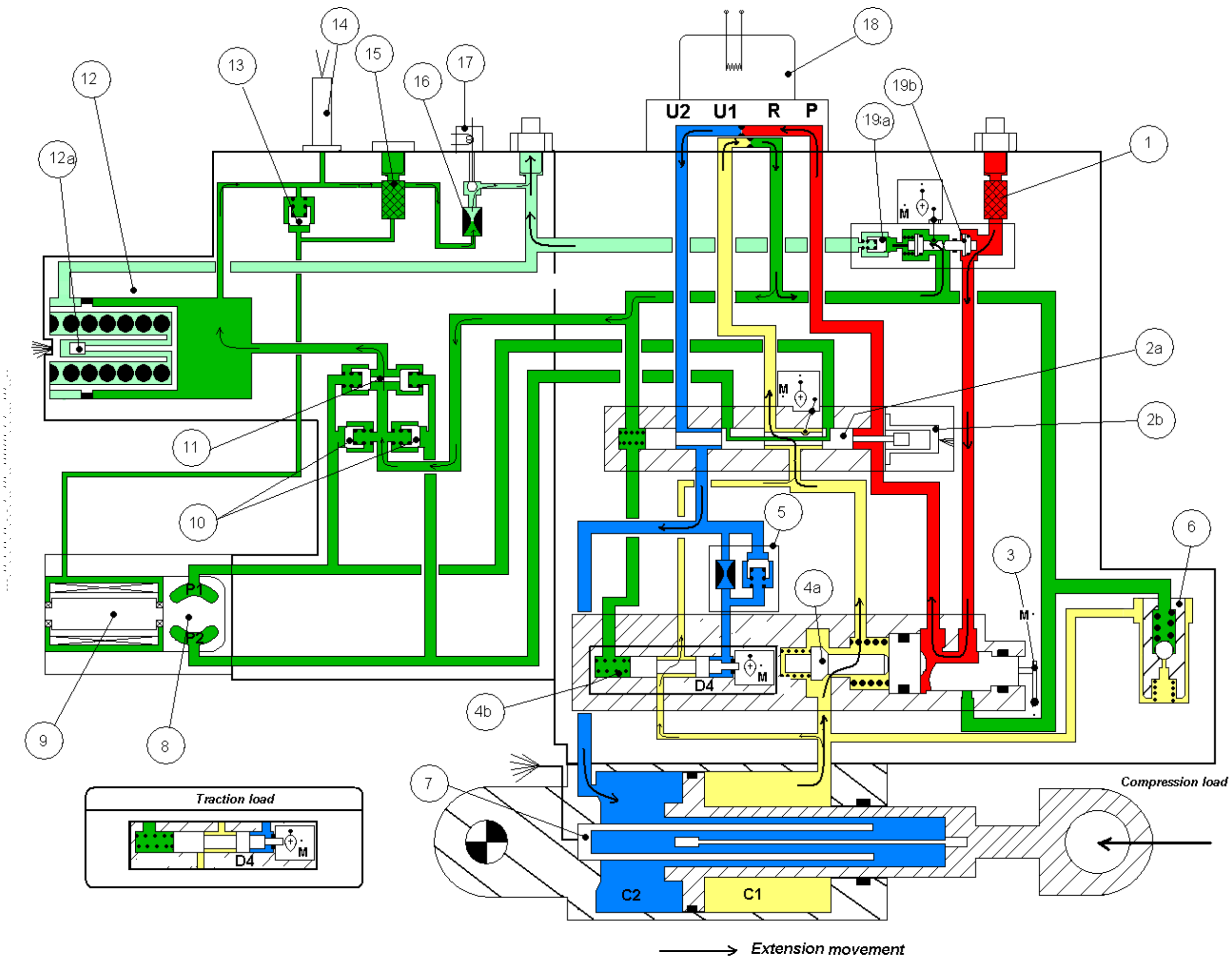
1	HP filter	7	Diff. pressure sensor	13	Motor drain check valve
2	HP maintaining valve	7a	Diff. pressure LVDT	14	Fluid temperature sensor
3 3a	EHSV EHSV spool LVT	8	Damping restrictor	15	MDE
		9a	Electrical mode SV	16	Pump anti-cavitation valves
4a 4b 4c	Dual hydraulic Mode SV Hydraulic mode valve Hydraulic mode LVT	9b 9c	Electrical mode valve Electrical mode LVT	17a 17b	LP maintaining valve Manual bleeding device
		10	Pressure relief valves	18	Accumulator pressure transducer
5	Ram anti-cavitation valves	11	Hydraulic pump	19	Accumulator
6	Dual Feedback LVDT	12	Electrical motor		

FIGURE 68 - A380 RUDDER EBHA IN HYDRAULIC ACTIVE MODE CONFIGURATION



1	HP filter	4a	Return Relief Valves	6	EHSV
2	HP check valve	4b		7	Blocking valve
3	Maintenance operator	5	Load limiting valve	8	Ram LVDT

FIGURE 69 - A380 SPOILER S/C IN ACTIVE MODE CONFIGURATION



1	HP inlet filter	7	RAM LVDT	14	Fluid temperature sensor
2a	Mode selector valve	8	Hydraulic pump	15	Drain filter
2b	Mode selector LVT	9	Electrical motor	16	Restrictor
3	Maintenance operator	10	Relief valve	17	Solenoid valve
4a	Blocking valve-1	11	Shuttle valve (SHV)	18	EHSV
4b	Blocking valve-2	12	Accumulator	19a	Low pressure maintaining valve
5	Restrictor check valve	12a	Accumulator LVDT	19b	High pressure maintaining valve
6	Load limiting valve&Check valve (LLV/CV)	13	Relief valve		

FIGURE 70 - A380 SPOILER EBHA IN HYDRAULIC ACTIVE MODE CONFIGURATION

3.24 BA609 Tilt Rotor Flight Control Actuation System

The BA609 Tilt Rotor hydraulic system has been designed in accordance with MIL-H-5440 Type 2 systems and includes a total of 15 flight control servoactuators, comprised of two triplex collective, two triplex longitudinal, six simplex flaperon, three simplex elevator and two conversion actuators. Figure 71 shows a diagram of the aircraft's hydraulic distribution and flight control actuators. All hard hydraulic tubing is made of Ti-3Al-2.5V, pressure and return line flexible hoses are CRES reinforced PTFE lined. MIL-PRF-87257 hydraulic fluid is specified for all operating temperatures.

There are three parallel and independent 3000 psi hydraulic systems with all three systems utilized simultaneously for flight controls. Pressure and return fluid is filtered to 5 micron and all actuators incorporate 100 to 150 micron screens at supply pressure ports. Hydraulic systems 1 and 2 are powered by 16.4 gpm tilt axis gearbox driven pumps while system 3 is powered by a 14.9 gpm proprotor gearbox driven pump. The gearboxes are interconnected such that they all operate any time the rotors are turning. In operation to perform ground check out of the flight control actuators, the rotors must be turning to drive the pumps. For maintenance a ground cart may be used.

With the exception of the conversion actuators, hydraulic Systems 1, 2 and 3, normally power all flight controls simultaneously. For the conversion actuators, System 1 and 3 provide hydraulic power to the left actuator and System 2 and 3 provide hydraulic power to the right. The conversion actuators are mechanically interconnected by a shaft to permit hydraulic system 1 or 2 to drive both actuators. .

Table 23 summarizes characteristics of the BA609 primary flight control servoactuators.

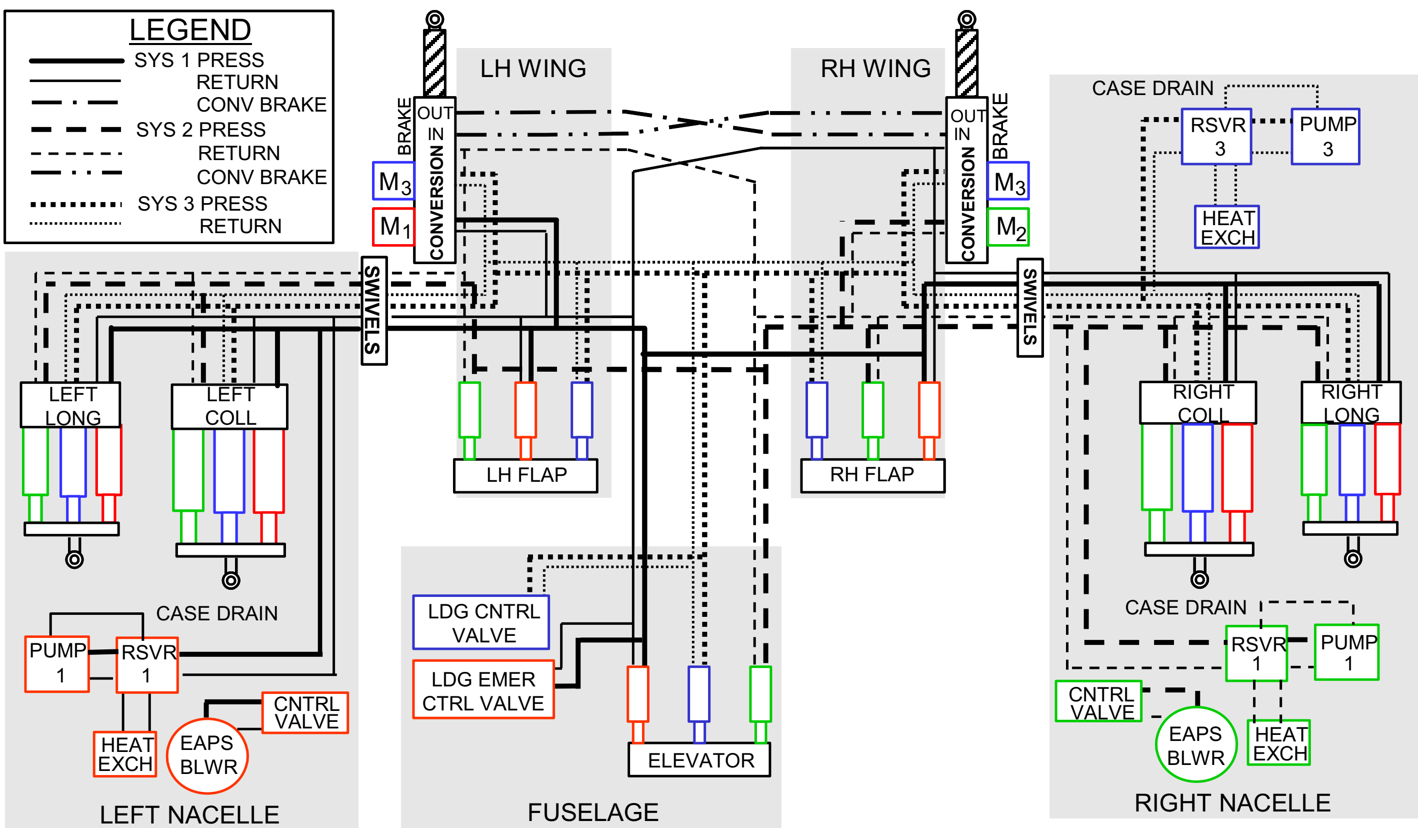


FIGURE 71 - BA609 HYDRAULIC SYSTEM SCHEMATIC

3.24.1 Collective Actuator Configuration

There are 2 triplex collective servoactuators, one for each rotor. By controlling collective cyclic pitch they provide roll and vertical thrust control while the aircraft is in helicopter mode plus yaw and forward thrust when in the airplane mode. These actuators are classified as critical in that loss of function of either of the collective actuators will cause the loss of rotor control resulting in the loss of the aircraft. To minimize the chance of this event the servoactuator redundancy is triplex hydraulically and triplex electrically. The actuator is a triplex side-by-side equal area piston/cylinder design with systems 1, 2, and 3 powering one piston each. Under normal operation, the three share an equal portion of the applied external load. Actuator position feedback for loop closure is provided by a three LVDTs, one housed within each actuator cylinder. The actuator is partially structurally redundant and is designed to not to jam following the fracture separation of a single ram.

Control of hydraulic fluid to each of the three cylinders is provided via three separate manifolds. Each manifold incorporates an electrohydraulic servovalve (EHV) with a second stage spool position monitoring LVDT to control fluid flow, two solenoids for redundant bypass and two Integrated Three Function Valves (ITFVs). Each ITFV functions as a bypass valve, pressure relief valve and a delta pressure transducer. Manifolds can be removed and replaced as LRUs.

As shown schematically in Figure 72, each ITFV assembly consists of a solenoid controlled pilot spool, a solenoid controlled primary spool, two centering springs and a LVDT attached to the primary spool. Along its length, the primary spool incorporate two differential areas of equal size to allow the spool to respond to changes in retract and extend cylinder pressure.

Manifold bypass function is controlled by two solenoid valves that provide a redundant means of achieving bypass mode. Wired in parallel, the solenoids control the engagement and disengagement of the ITFVs. In the event of a hydraulic system control channel failure the solenoid valves de-energize, placing both ITFVs into a bypass mode. This permits unrestricted motion of the bypassed cylinder piston and allows the one or two remaining cylinders to safely control the rotor collective blade pitch. One solenoid, when energized, removes system pressure from the chip shear end of the primary ITFV spool and ports it to return. This allows the primary ITFV spool to be moved to its engaged position with the second solenoid energized. The second solenoid, when energized, ports system pressure to a pilot spool that compresses centering springs to move the primary ITFV spool to its engaged position.

Deenergizing the pilot solenoid causes the primary ITFV spools to be driven by the centering springs to a bypass position. Deenergizing the chip shear solenoid causes the primary ITFV spools to be driven to a bypass position by system pressure. With 2,600 psi of system pressure available, a force in excess of 200 lb is generated to drive the primary ITFV spools to a bypass position. To provide an indication to the FCCs that a pilot solenoid has failed, the ITFV contacts the end of the pilot piston resulting in it stopping short of the full bypass position. To provide an indication to the FCCs that the chip shear solenoid has failed, the ITFV is stop short of the full bypass position by spring washers.

The cylinder extend and retract passages are ported to opposite differential areas on the two ITFVs. This ensures that under a force fight condition in either an extend or retract direction, the time required for one of the two ITFV primary spools to achieve an effective bypass condition will be minimized. In the bypass condition with the solenoids de-energized, the ITFVs in combination block extend and retract EHV ports and connect extend and retract cylinder ports to return.

In the engaged condition with actuator cylinder differential extend or retract pressures exceeding 4111 (during failure conditions), the overload relief function of the ITFVs connects the over pressure cylinder port to return to act as redundant cylinder overload pressure relief valves.

The two differential areas on each energized ITFVs function as spring-centered pistons that vary position in response to changes in differential pressure. Variations in the positions of each ITFV primary spool are monitored by LVDTs. Because the two ITFVs move in opposite directions in response to cylinder differential pressure, the output of the LVDTs is opposite in polarity. The differential pressure signal from the energized ITFVs is used for actuator servo-loop damping and to balance the load sharing of the three cylinders. To permit condition monitoring of the two ITFV's sensor accuracy, the measured differential pressure of the two ITFVs are compared continuously by the FCCs. This eliminates almost all collective actuator PFBIT (Pre-Flight Built In Test) requirements.

EHV failure detection is accomplished by running a real time EHV software model in the FCCs that compares EHV command (current) to EHV spool position. If a discrepancy of more than a predetermined threshold is sensed, the EHV is declared failed and the manifold is placed in bypass.

The integrity of all LVDTs is checked by continuous monitoring of each transducer's summed output voltage. If a summed voltage falls out of acceptable tolerance its corresponding electrical channel is declared failed and the corresponding manifold is placed in bypass.

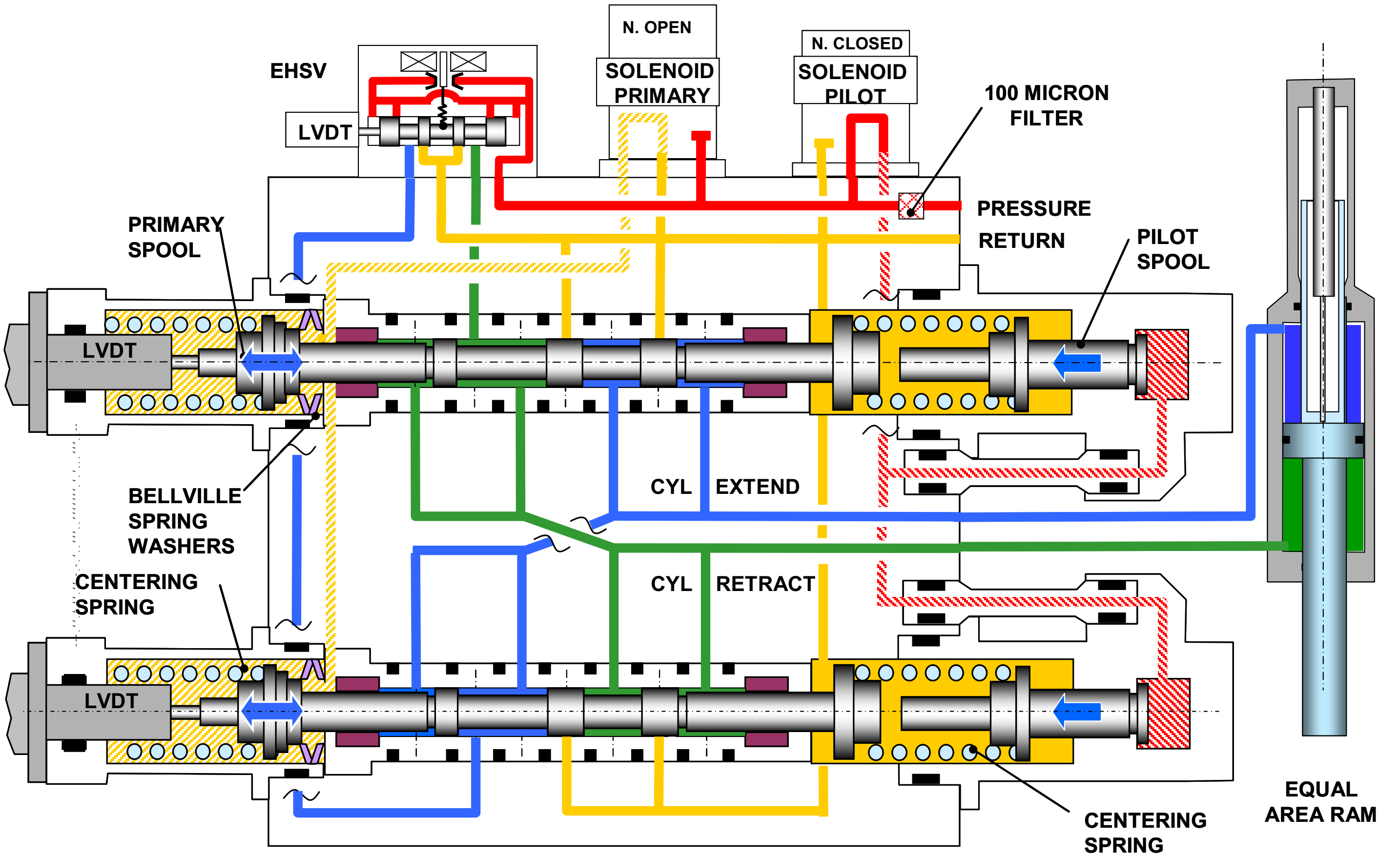


FIGURE 72 - BA609 COLLECTIVE ACTUATOR PICTORIAL SCHEMATIC

3.24.2 Longitudinal Actuator Configuration

There are 2 triplex longitudinal servoactuators; one for each rotor. By controlling longitudinal cyclic they provide pitch and yaw control while the aircraft is in helicopter mode. These actuators are classified as critical in that loss of function of either of the longitudinal actuators will cause the loss of rotor control resulting in the loss of the aircraft. To minimize the chance of this event the servoactuator redundancy is triplex hydraulically and triplex electrically. Like the collective, the longitudinal actuator is a triplex side-by-side equal area piston/cylinder design with systems 1, 2, and 3 powering one piston each. Under normal operation, the three approximately share an equal portion of the applied external load. Actuator position feedback for loop closure is provided by a three LVDTs, one housed within each actuator cylinder. Similar to the collective the actuator is partially structurally redundant and is designed to not to jam following the fracture separation of a single ram.

Control of hydraulic fluid to each of the three cylinders is provided via three separate manifolds shown schematically in Figure 73. Each manifold incorporates an electrohydraulic servovalve (EHV) with second stage spool position monitoring LVDT to control fluid flow. The two solenoids and a single ITFV (Integrated Three Function Valve) used in the longitudinal manifold are identical in design and function to the components used on the collective. Because elapsed time to enter bypass mode and delta-pressure measurement accuracy requirements are not as critical for longitudinal actuator control as they are for the collective, only a single ITFV assembly is required. Manifolds can be removed and replaced as LRUs.

In the bypass condition with the solenoids deenergized, the single ITFV blocks extend EHV port and connects the extend and retract cylinder ports to return. The longitudinal EHV is null biased to the extend direction to connect the EHV retract port to return when current is removed.

To provide condition monitoring of the ITFV sensor accuracy, a controlled force fight between cylinders is used in PFBIT (Pre-Flight Built In Test) for cross comparison.

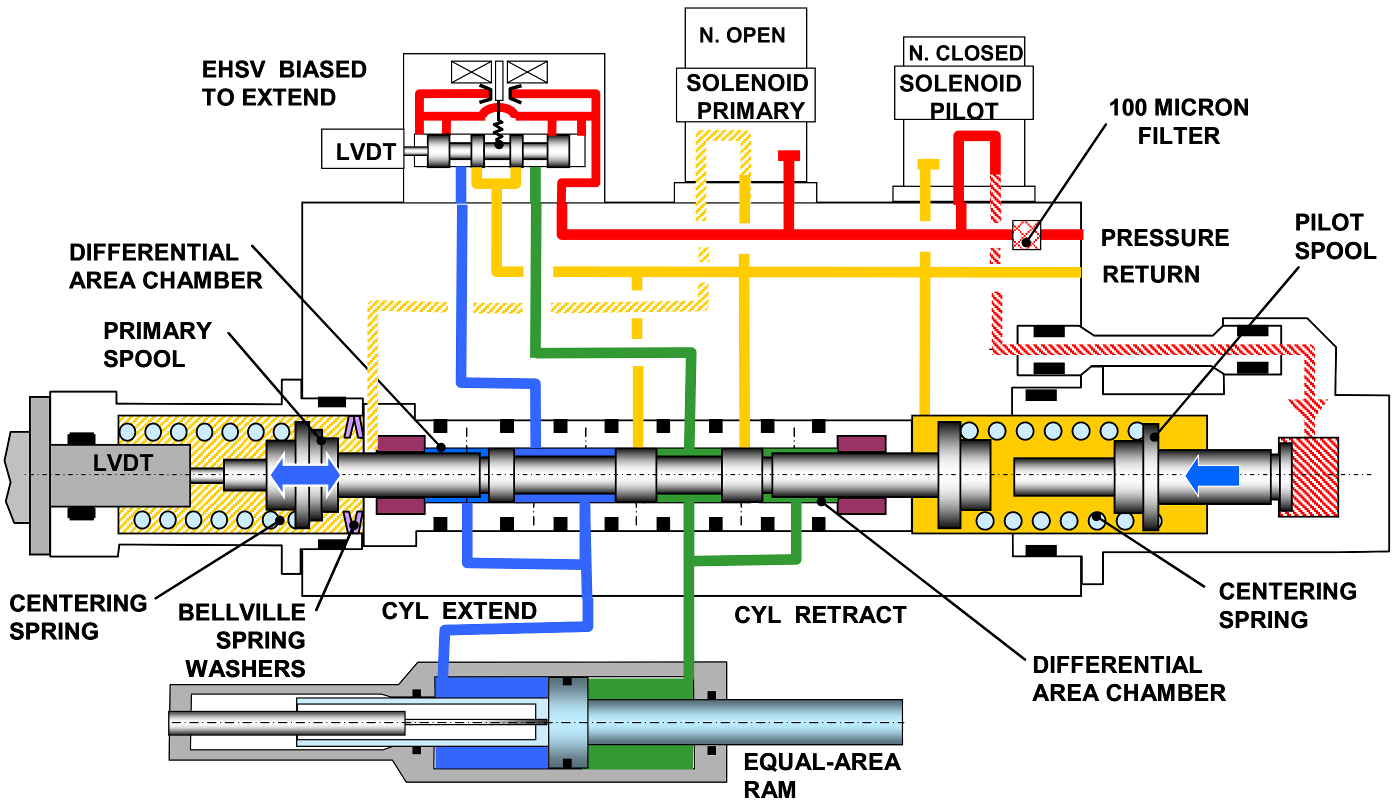


FIGURE 73 - BA609 LONGITUDINAL ACTUATOR PICTORIAL SCHEMATIC

3.24.3 Flaperon Actuator Configuration

The BA609 has three flaperon actuators controlling the left surface and three controlling the right surface for a total of six actuators. Figure 74 shows a pictorial schematic of a flaperon actuator. The actuator piston utilizes a balance tube resulting a net piston area that is slightly unbalanced. Housed within the balance tube is a simplex LVDT that provides ram position feedback to the FCC. An actuator mounted manifold houses an EHV with a spool monitoring LVDT, a single solenoid valve and one ITFV (Integrated Three Function Valve) almost identical in design and function to the ITFV assembly used on the collective.

In the event of a hydraulic system or control channel failure, the solenoid valve deenergizes, placing the ITFV into a bypass mode. This permits unrestricted motion of the actuator piston, allowing the one or two remaining actuators to safely control the flaperon position. Because manifold bypass function is not as critical for flaperon control as it is for collective and longitudinal control, a redundant means of achieving bypass mode was not required.

With no system pressure supplied to the manifold, the centering springs hold the ITFV spool in the bypass position. As system pressure is increased to operating level, the pilot piston moves to compress it’s centering spring. The ITFV spool however is held in the bypass position by system pressure ported through the solenoid.

In the bypass mode with system pressure available, deenergizing the solenoid removes system pressure from the chip shear end of the ITFV spool and ports it to return. This allows the ITFV spool to be moved by the centering springs to its engaged position.

Similar to the longitudinal manifold, in bypass the flaperon ITFV blocks the extend EHV port and the flaperon EHV is null biased to the extend direction to connect the EHV retract port to return when current is removed. Because only one solenoid is used on the flaperon, the spring washers and stop on the pilot piston for solenoid failure detection found on the collective and longitudinal ITFV assemblies are removed.

To provide condition verification of the ITFV sensor accuracy, flaperon actuators are stalled into the cylinder extend and retract stops during PFBIT (Pre-Flight Built-In-Test) for comparison to system pressure and cross compared at actuator midstroke position.

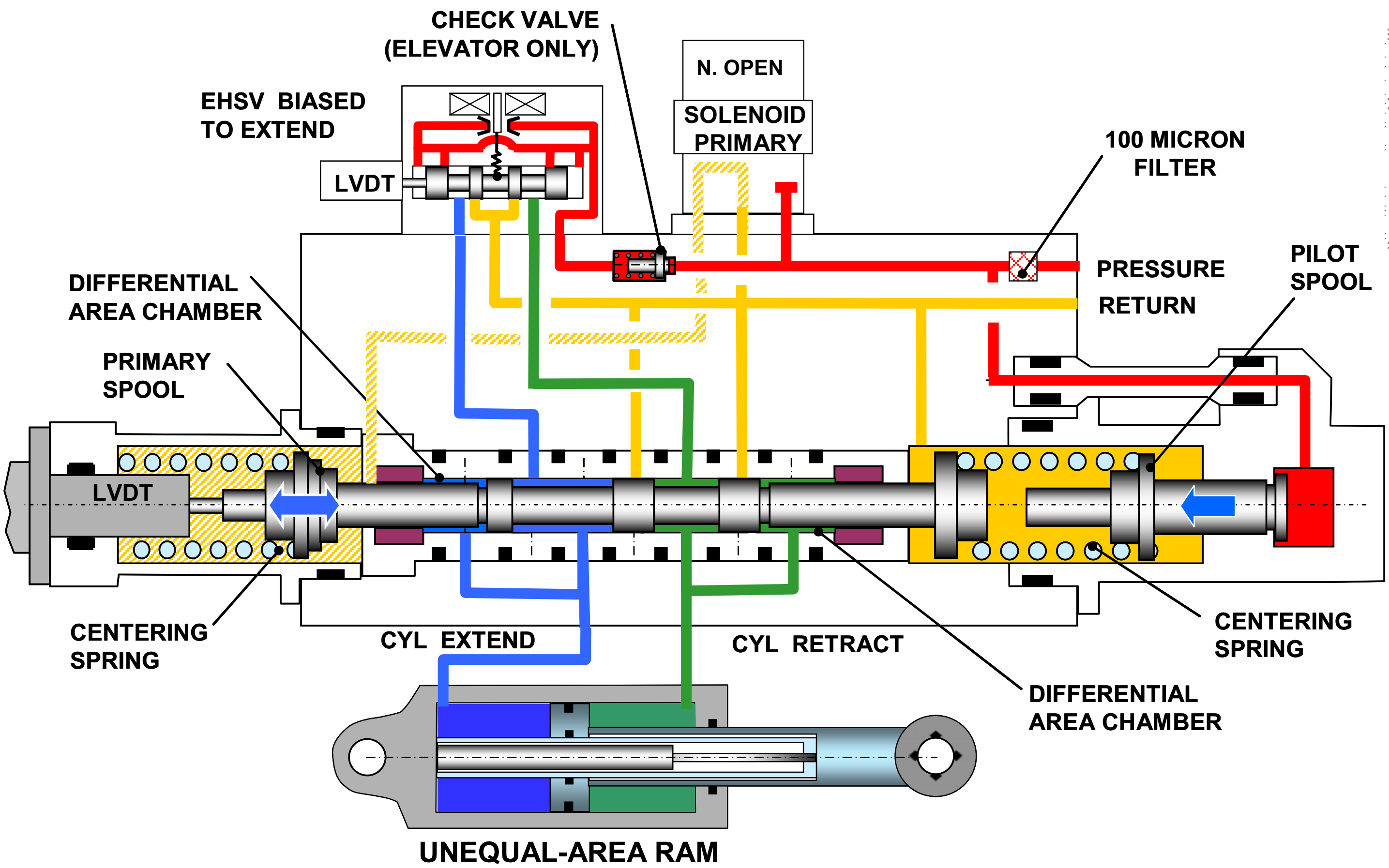


FIGURE 74 - BA609 FLAPERON ACTUATOR PICTORIAL SCHEMATIC

3.24.4 Elevator Actuator Configuration

The BA609 has a single elevator surface powered by three actuators. The configuration and operation of the elevator actuators are identical to the flaperon actuators with the exception of an added check valve installed up stream of the EHV pressure supply (Figure 74). The check valve is installed to prevent the actuator back driving from loads sufficient to force fluid back into the system pressure supply.

3.24.5 Conversion System Configuration

The BA 609 PCS (Pylon Conversion System) is designed as a two-fail-operate system that will continue to operate following the loss of any two hydraulic systems, FCCs, or the components they control. The BA 609 PCS has been designed to meet a mean time between flight-critical failures (MTBFCF) of greater than 1×10^9 flight hours. This reliability value includes the aircraft hydraulic and FCC system reliabilities.

Shown in Figure 75, the PCA (Pylon Conversion Actuator) extend and retract motion is produced by a two-stage telescoping ball screw. The ball screw outer nut is assembled into a gearbox that is mounted to the wing through a trunnion-and-spindle arrangement. The PCA ball screw incorporates redundant load paths within both inner and outer ball screws to provide a PCA stroke capability of at least 49% of stroke (47 degree conversion) in the event of a ball screw fracture.

The PCA gearbox design allows the PCA to continue to operate without jamming following the failure of any gear tooth or the seizure of any single internal component. The gearbox consists of a housing with support bearings for the main shaft/outer ball nut, a planetary gear reduction, a 90-degree gear reduction, a hydraulic clutch, a redundant bull gear with two pinion gears, and two hydraulic brakes. FCC monitoring of gearbox condition is provided by resolvers, chip detectors, and seized-bearing sensors. The gearbox main shaft is supported both radially and axially by angular contact ball bearings. The ball bearing assemblies and their retainers are designed to retain the ball screw assembly (outer ball nut) in the event of a bearing or structural failure. To prevent actuator seizure in the event of an angular contact bearing failure, redundant needle bearings for thrust loads and bushings for radial loads provide a back up to the angular contact bearings. Sensors connected in parallel with the chip detectors provide indications of primary bearing seizures.

When mounted in the aircraft the lower half of the gearbox contains a planetary gear set that is used as a gear reduction and differential for the Primary and Backup HPDUs (Hydraulic Power Drive Units). The bearings supporting the differential have been arranged to prevent an actuator jam in the event of a bearing seizure. The differential carrier output to main shaft is supported solely by bearings attached to the sun and ring gears. In the event of a locked differential, the resulting gear ratio allows the combined primary and backup HPDU inputs to drive the PCA. The upper half of the gearbox contains a 90-degree angle gear reduction that aligns the Interconnect Drive Train (IDT) input with the main shaft bull gear. A hydraulically released clutch is employed to allow disengagement of the 90-degree bevel gear set and IDT in the event of a gear set or IDT jam. When de-clutched, all gears, shafts and bearings that are between the IDT pinion gear and the main shaft (where a failure would prevent conversion actuator operation) are released. A jam-resistant redundant bull gear and two pinion gears are used to provide the final reduction from both the planetary and 90-degree bevel gear sets. The bull and pinion gears are redundant and separated to prevent the loss of one gear tooth from compromising both meshes. Gearbox lubrication utilizes an oil bath splash with oil level windows for inspection. All gearbox components have been designed to provide 20 complete conversion cycles with the gearbox oil completely drained.

To measure pylon position, three nacelle position resolvers with reduction gear heads are mounted to the gearbox and are driven by a gear on the gearbox main shaft. To monitor HPDU, brake, clutch and gearbox performance both in-flight and during Pre-Flight Built-In Test (PFBIT), an additional resolver geared directly to the Primary HPDU output is also used. To control PCA force fight as well as aid in monitoring system condition, a two-channel (transformer/transmitter) resolver is geared to the IDT shaft input.

Each PCA gearbox can be driven directly by either the Primary or Backup HPDU, or indirectly by the opposite PCA through an Interconnect Drive Train (IDT). As shown in Figure 76, HPDUs contain a bent axis hydraulic motor and all the hydraulic and electrical components required for motor control and operation. Primary and Backup HPDUs are identical components, however they perform different functions based on where they are installed. Solenoid 3 on PHPDUs is used to control a Remote Brake Piston (RBP) that permits one PHPDU to drive both actuators through the IDT by releasing the non-driving PHPDUs brake. On BHPDUs, Solenoid 3 is used to disengage the IDT clutches allowing a jammed IDT to be bypassed.

During normal operation the PCS is driven by the PHPDUs and the BHPDUs are in bypass with their brakes engaged. PCS speed and position are FCC controlled using control loops that monitor each PCA's position using three pylon position resolvers on each PCA. Force fight between PCA's is minimized by control loops and two channel resolvers that measure angular twist in the IDT. In the event of system or component failures the FCCs identify the failure and reconfigure the PCS to allow it continue to operate.

To ensure that all PCS components are operating within specifications prior to flight, the FCCs command the HPDUs to perform a series of PFBIT. These tests utilize the same sensors that are used for in-flight monitoring. During PFBIT, the HPDUs are driven to stall capacity, resulting in the application of proof loads to the brakes, clutches, and IDT shafts. The FCCs then compare the resolver readings to predicted values to determine if a component has failed.

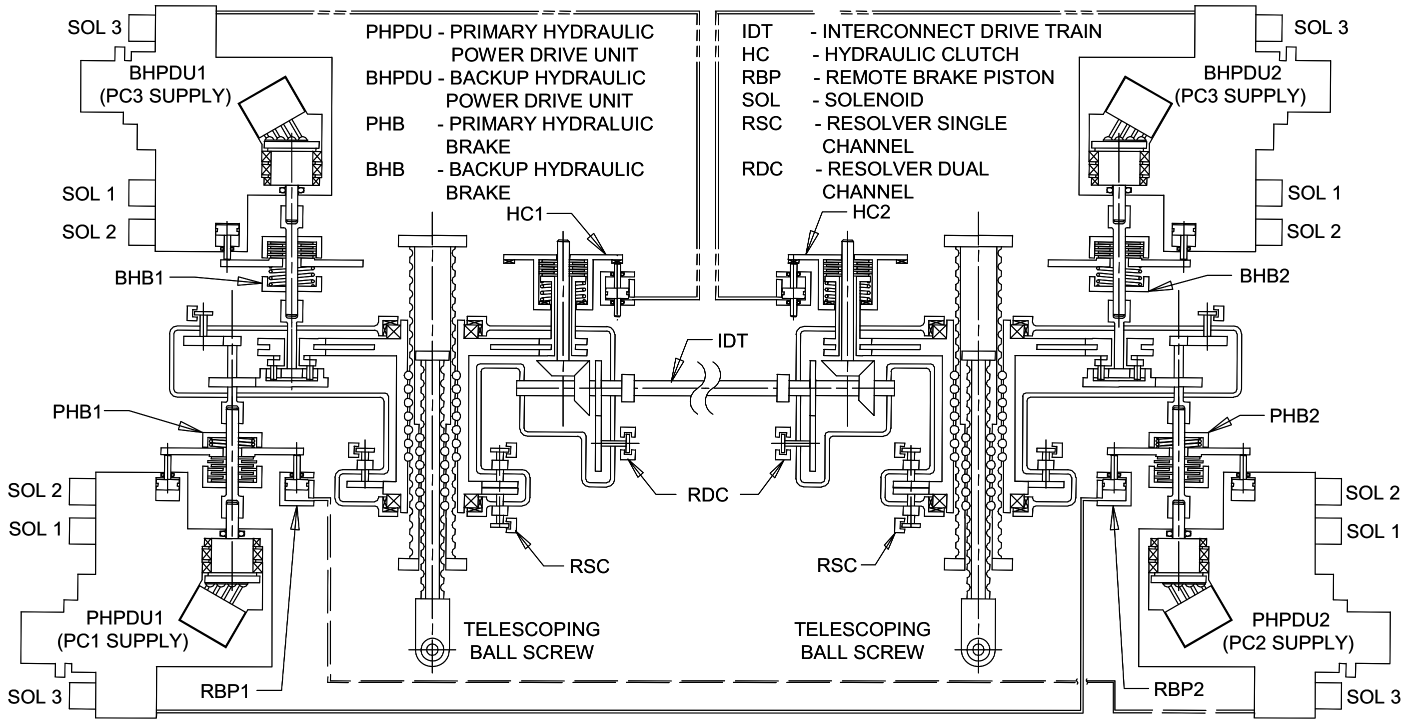
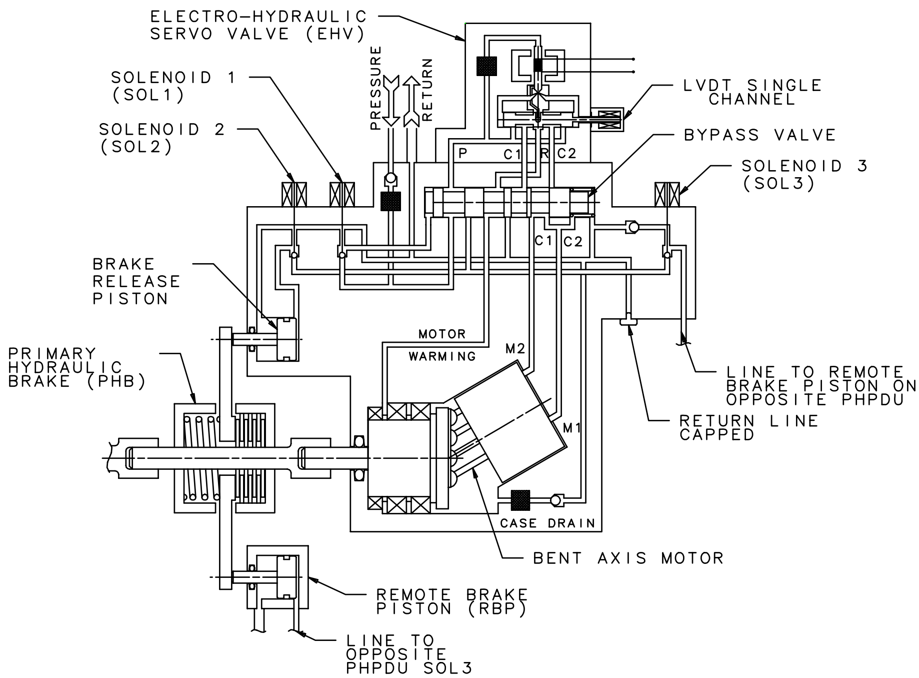
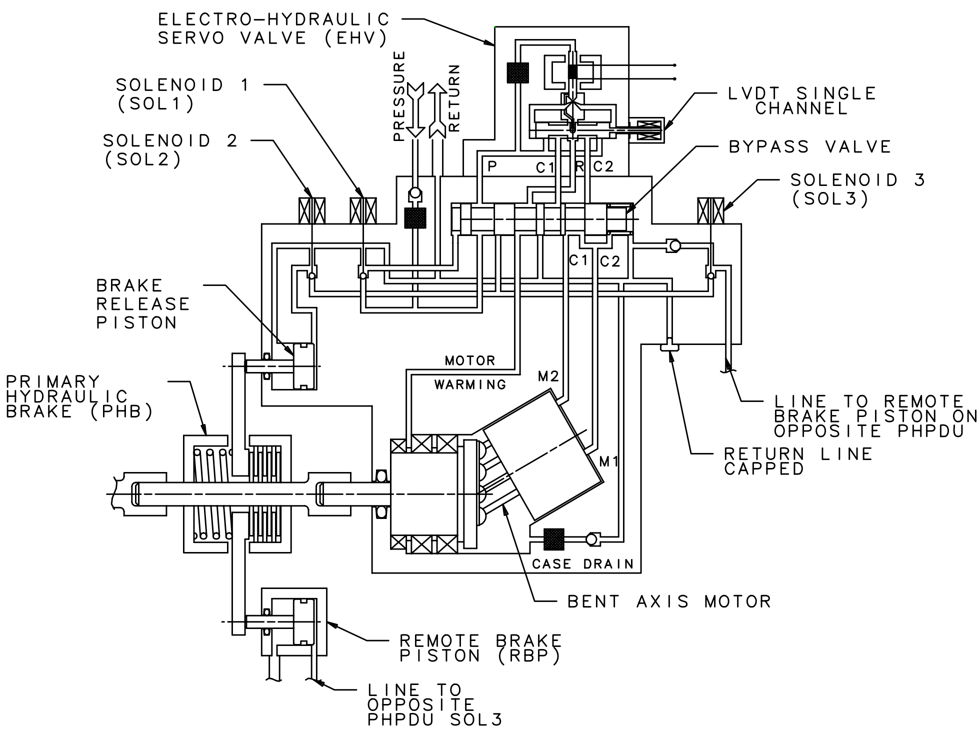


FIGURE 75 - BA609 PYLON CONVERSION ACTUATOR PICTORIAL SCHEMATIC



PRIMARY HYDRAULIC POWER DRIVE UNIT



BACKUP HYDRAULIC POWER DRIVE UNIT

FIGURE 76 - BA609 PRIMARY AND BACKUP HYDRAULIC POWER DRIVE UNIT PICTORIAL SCHEMATICS

3.25 Eurofighter Flight Control Actuation System

The Eurofighter Flight Control Actuation System is part of a quadruplex redundant Fly-by-Wire Flight Control System. The Actuation System includes tandem configuration hydraulic actuator designs controlled by linear Direct Drive Valves (DDVs) for all surfaces with the exception of the Airbrake Actuator which is hydraulically simplex and controlled by an electrohydraulic Servovalve. The Eurofighter power supply is based on two (2) hydraulic systems with a system pressure of 4000 psi. Each tandem actuator is plumbed to two hydraulic systems. There is one actuator each on each of the seven (7) primary flight control surfaces and one actuator on the Airbrake.

The surfaces, illustrated in Figure 77, are: (a) the Foreplane for Pitch Control, (b) Inboard and Outboard Flaperons for Pitch and Roll Control, (c) the Rudder for Yaw Control and (d) the Airbrake as a means to reduce velocity.

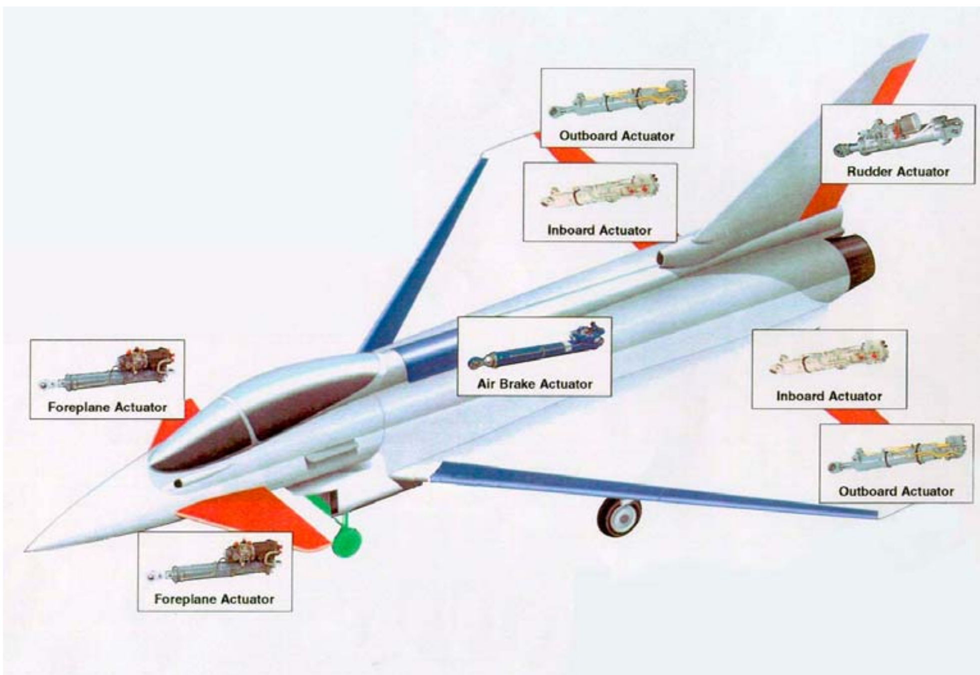


FIGURE 77 - EUROFIGHTER FLIGHT CONTROL ACTUATORS

3.25.1 Actuator Layout

All of the primary flight control actuators for the Eurofighter are a duplex tandem design; the Airbrake Actuator is of a simplex design. Unbalanced area pistons are used in any case whereas area imbalance is minimized for all primary actuators. Figure 78 shows a pictorial schematic representative of all actuators.

The main control valve defaults to Bypass Mode in case of loss of pressure or failure within the control logic. The bypass mode limits any influence of the failed channel to the intact actuator part.

The layout requirement for the Direct Drive Valve motor was derived from the load needed to overcome the chip shear force. Two out of four channels of the DDV are sufficient to provide the dynamic response needed for the specific actuator.

The primary actuation is connected to all four lanes of the flight control computers and functions in a fail-operational logic. The Airbrake is based on fail safe logic and connected to one control channel.

3.25.2 Actuator Control Loops

Figure 79 outlines the loop closures used for control of the primary flight control actuators on the Eurofighter.

The actuator position loop (outer loop) uses quad-redundant linear variable differential transformers (LVDTs) to sense actuator position and provide feedback for the electronic loop closure. The digitally closed actuator control loop is used for positioning and rate limiting of the surface commands.

Also the Direct Drive Valve uses quad-redundant LVDTs for main control valve position and velocity loop closure providing stability to the valve response. The innermost loop is the current feedback loop of the Direct Drive Valve controlling the Pulse Width Modulation of the DDV motor. Both control loops are realized in analog technology.

The loop gains are driven by the system bandwidth requirements of approximately 7 Hz for the unbalanced surfaces. The bandwidth of the Direct Drive Valve is more than ten times higher.

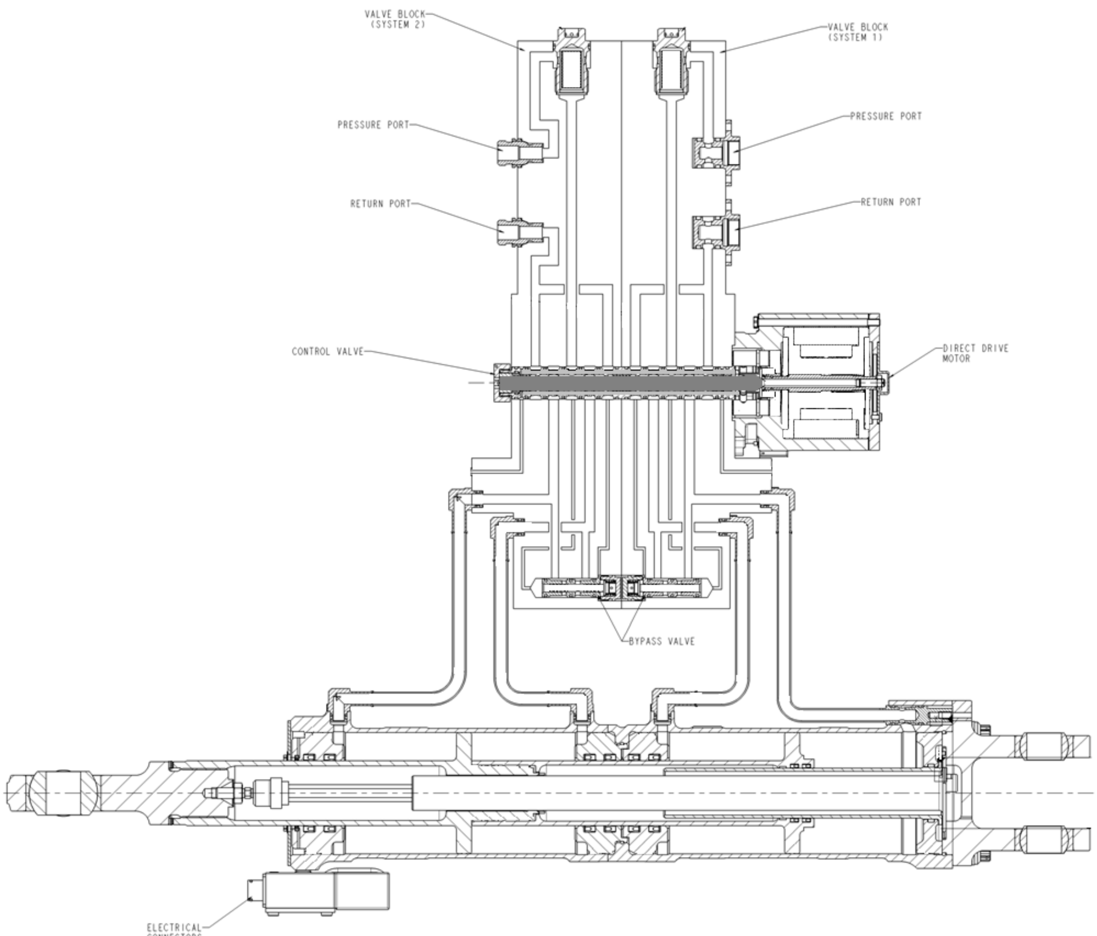


FIGURE 78 - EUROFIGHTER TANDEM ACTUATOR PICTORIAL SCHEMATIC

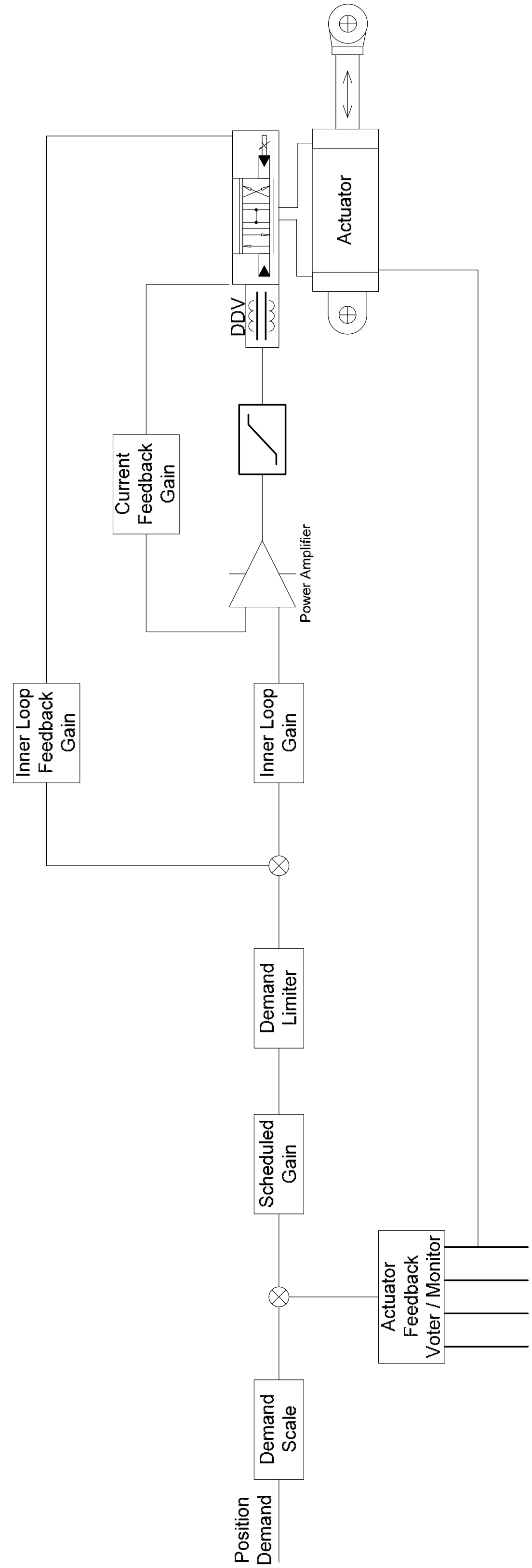


FIGURE 79 - EUROFIGHTER - SCHEMATIC ACTUATOR LOOP CLOSURE DIAGRAM

3.26 A400M Flight Control Actuation System

3.26.1 System Layout

The primary flight control surfaces are driven by three types of actuators:

- conventional hydraulic servocontrols (S/C)
- Electrohydrostatic Actuators (EHA)
- Electrical Back-up Hydraulic Actuators (EBHA)

They are controlled by four identical digital computers C1 to C4 and powered by two 3000 psi hydraulic systems “Blue” and “Yellow” plus three 115 VAC variable frequency electrical systems E1, E2 and EM. In the event of failure of all computers, the Back-up Control Module (BCM) controls selected actuators.

This hybrid distribution of actuators, power sources and computers on the control surfaces is shown in Figure 80.

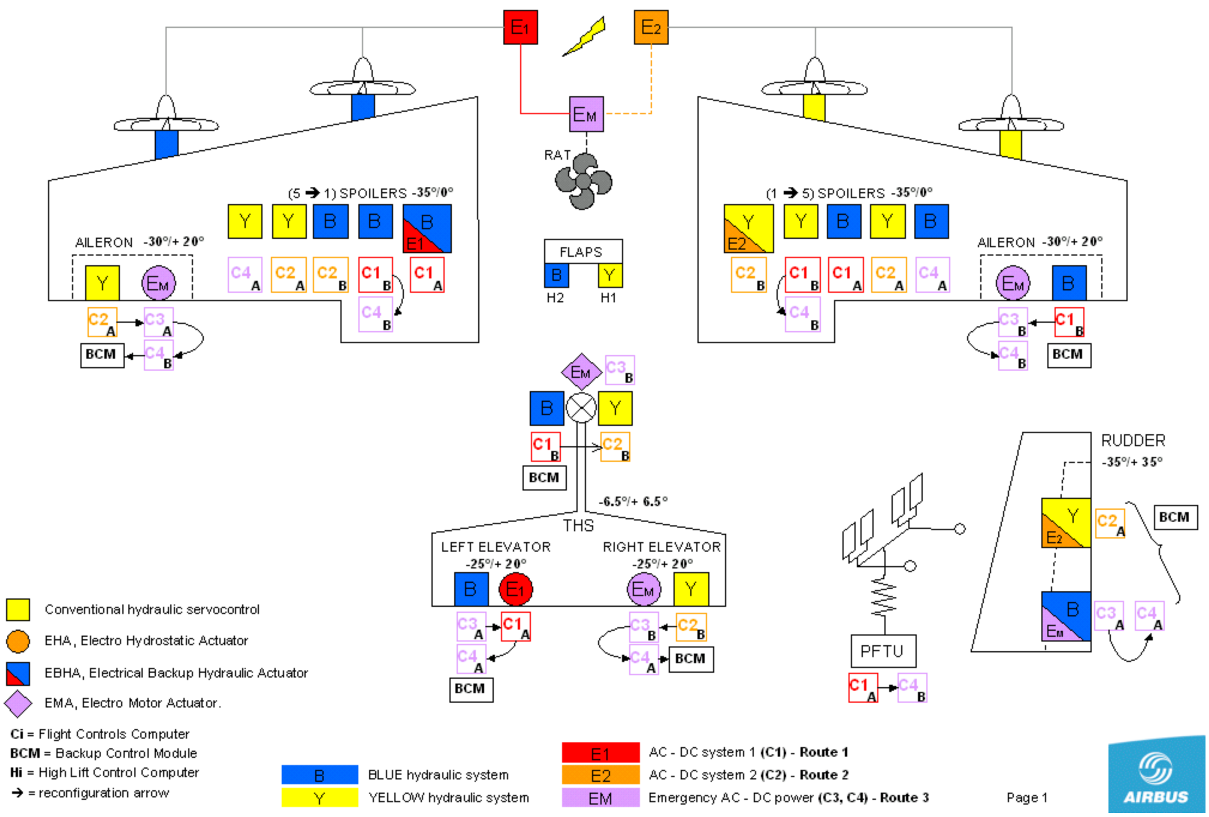


FIGURE 80 - A400M CONTROL SURFACES, ACTUATORS, POWER SOURCES AND COMPUTERS DISTRIBUTION

3.26.2 Aileron Actuation

The aircraft is fitted with one pair of ailerons. A servocontrol and an Electrohydrostatic Actuator (EHA) power each surface in an active/stand-by arrangement.

Aileron servocontrols are schematically shown in Figure 81.

Aileron EHAs are schematically shown in Figure 82.

Each actuator achieves the two main operating modes:

- Active mode: Enables the actuation of the Aileron in accordance with the electrical orders from the Flight Control Computers
- Damping mode: Prevents the appearance of flutter in the event of multiple failures

In the unlikely event of failures of all Flight Control Computers, the BCM controls the Aileron S/C's through a set of segregated electrical inputs and outputs.

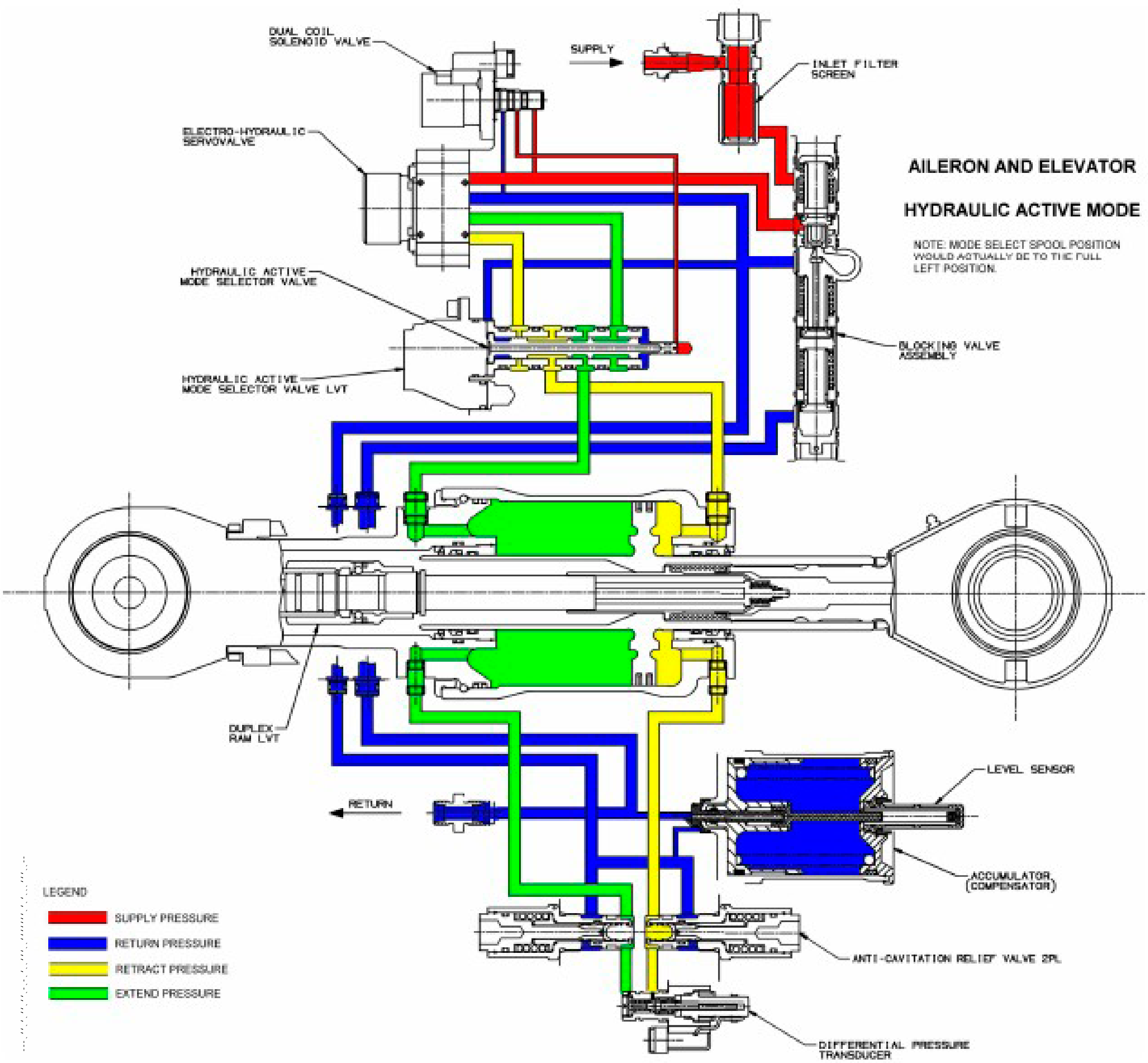


FIGURE 81 - AILERON/ELEVATOR SERVOCONTROL ACTUATOR IN ACTIVE MODE CONFIGURATION

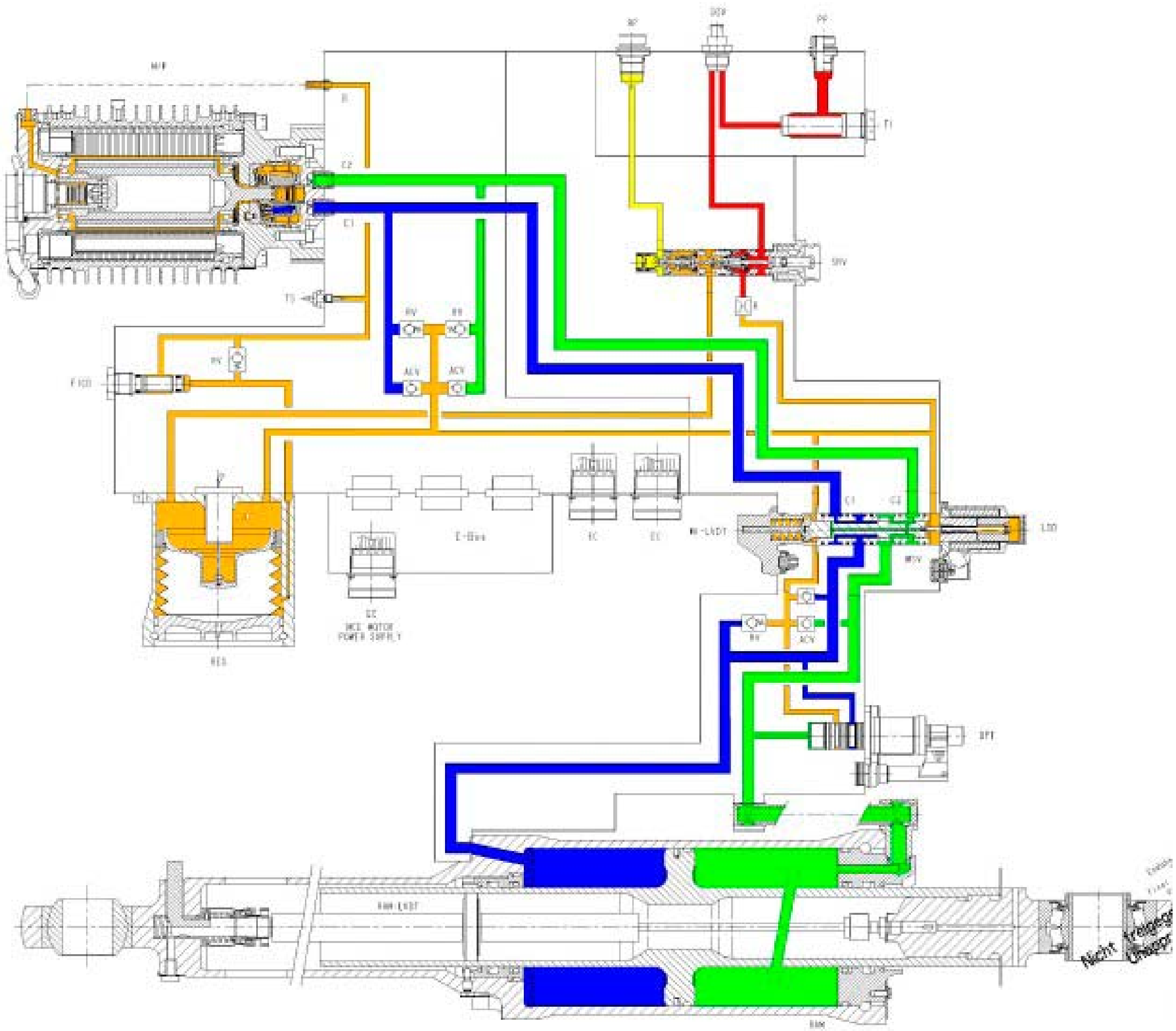


FIGURE 82 - AILERON/ELEVATOR EHA IN ACTIVE MODE CONFIGURATION

3.26.3 Rudder Actuation

The aircraft is fitted with one rudder panel. Two Electrical Back-up Hydraulic Actuators (EBHA) powers the surface in an active/stand-by arrangement.

EBHAs are schematically shown in Figure 83.

Each actuator achieves the three main operating modes:

- Hydraulic Active mode: The actuator is in an hydraulic active mode arrangement and hydraulically powered, that enables the actuation of the rudder in accordance with the electrical commands from the Flight Control Computer

- Damping mode: Prevents the appearance of flutter in the event of multiple failures

- Electrical Active mode: The actuator is in an electrical active mode arrangement and electrically powered, that enables the actuation of the rudder in accordance with the electrical orders from the Flight Control Computer

When all of the Flight Control Computers are out of order, the BCM controls the upper EBHA through a set of segregated electrical inputs and outputs.

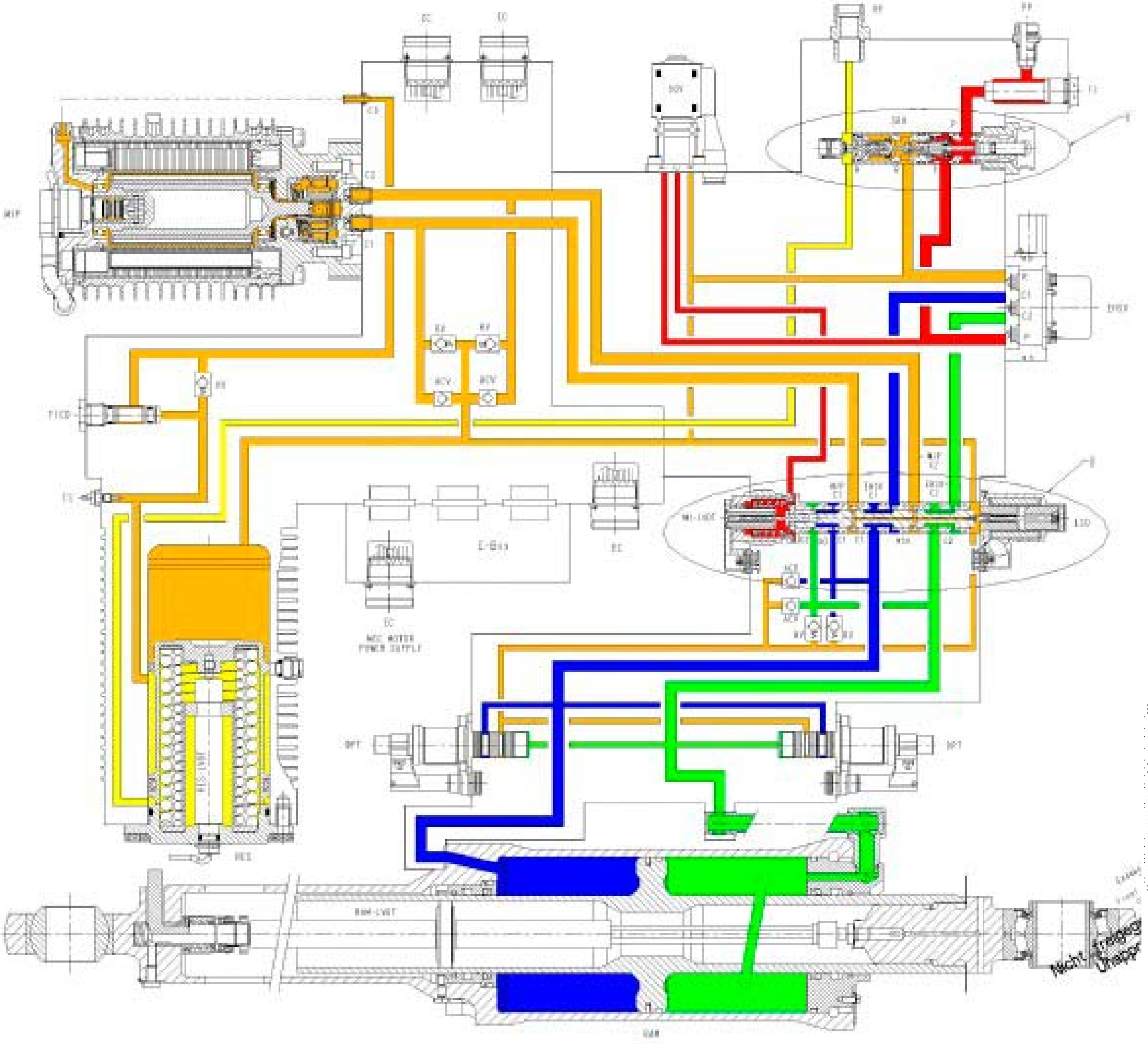


FIGURE 83 - RUDDER EBHA IN HYDRAULIC ACTIVE MODE CONFIGURATION

3.26.4 Elevator Actuation

The aircraft is fitted with one pair of elevators. A servo control and an Electrohydrostatic Actuator power each surface in an active/stand-by arrangement.

Elevator servocontrols are similar to the aileron units and are schematically shown in Figure 81.

Elevator EHAs are similar to the aileron units and are schematically shown in Figure 82.

Each actuator achieves the two main operating modes:

- Active mode: Enables the actuation of the elevator in accordance with the electrical orders from the Flight Control Computer

- Damping mode: Prevents the appearance of flutter in the event of multiple failures

If all of the Flight Control Computers are failed, the BCM controls the elevator S/C's through a set of segregated electrical inputs and outputs.

3.26.5 Spoiler Actuation

The aircraft is fitted with five pairs of spoilers. Each surface is powered by a servo control except Spoiler 1 surfaces, which are powered by an Electro Back-up Hydraulic Actuator.

Spoiler 2 and Spoiler 3/4/5 servo controls are schematically shown in Figures 84 and 85.

Spoiler 1 EBHA is schematically shown in Fig 86.

Each S/C achieves the four main operating modes:

Hydraulic Active Mode

The unit, powered by the hydraulic system, actuates the moving surface under the closed loop position control of a flight control computer. When fully retracted the unit applies a permanent load to the surface.

Control Failure Mode

In the event of the loss of the control signal, the unit automatically retracts to its stop.

Supply Failure Mode

In the event of the loss hydraulic power including the loss of the system fluid, the unit prevents the surface from rising and enables it to retract under the air load.

Maintenance Mode

The units include a manually controlled mechanical device to enable the surfaces to be moved for maintenance purpose, with no danger to ground personnel.

Each EBHA achieves the five main operating modes:

Hydraulic Active Mode

The unit, powered by the hydraulic system, actuates the moving surface under the closed loop position control of a flight control computer. When fully retracted the unit applies a permanent load to the surface.

Electrical Active Mode

In the event of the loss of A/C hydraulic circuit, the unit electrically powered, actuates the moving surface under the closed loop position control of a flight control computer. When fully retracted, the unit applies a permanent load to the surface.

Control Failure Mode

In the event of the loss of the control signal, the unit automatically retracts to its stop.

Supply Failure Mode

When both electrical and hydraulic power are not available, the unit prevents the surface from rising and enables it to retract under the air load.

Maintenance Mode

The units include a device to enable the surfaces to be manually moved for maintenance purpose, with no danger to ground personnel.

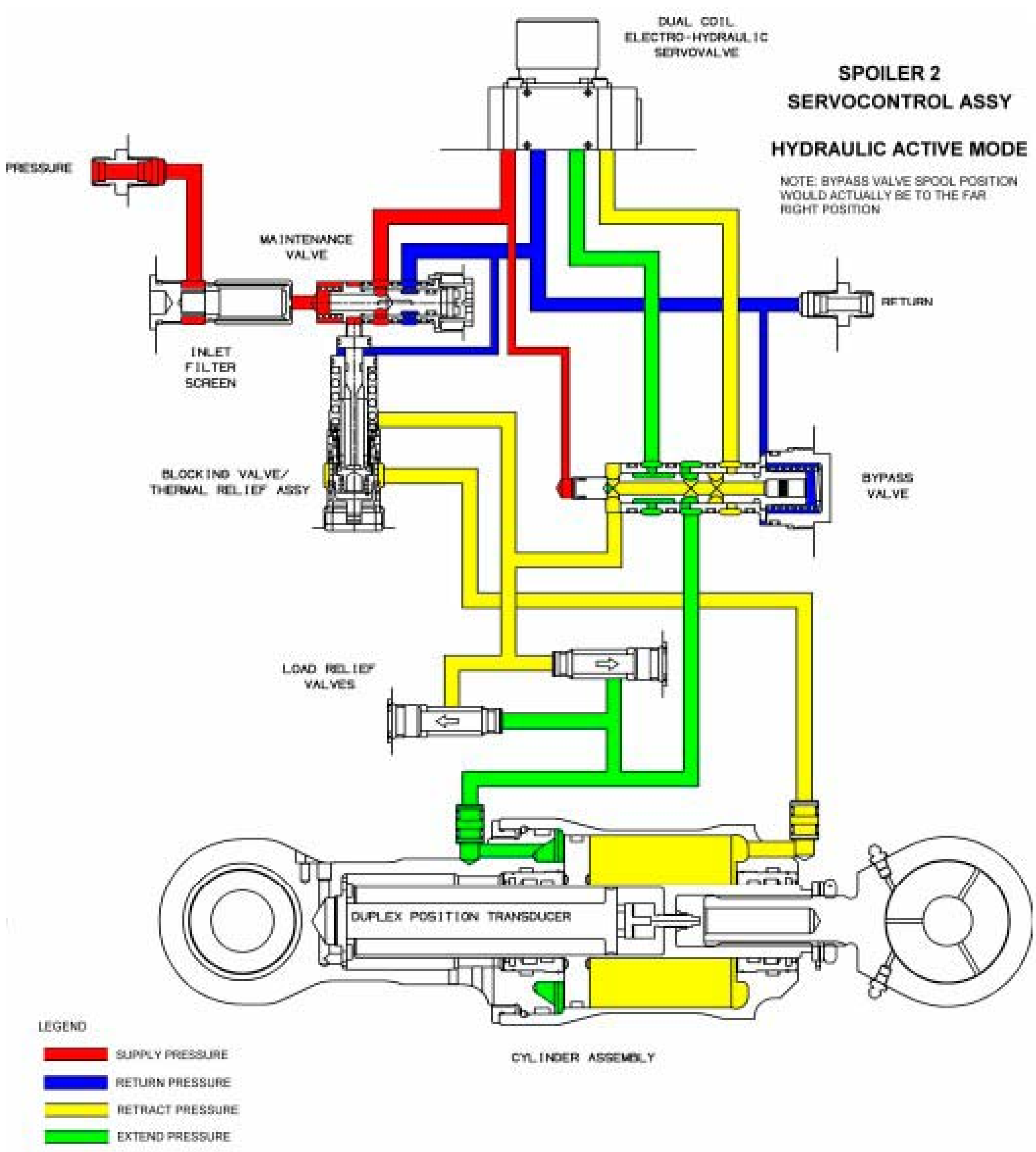


FIGURE 84 - SPOILER 2 SERVOCONTROL IN ACTIVE MODE CONFIGURATION

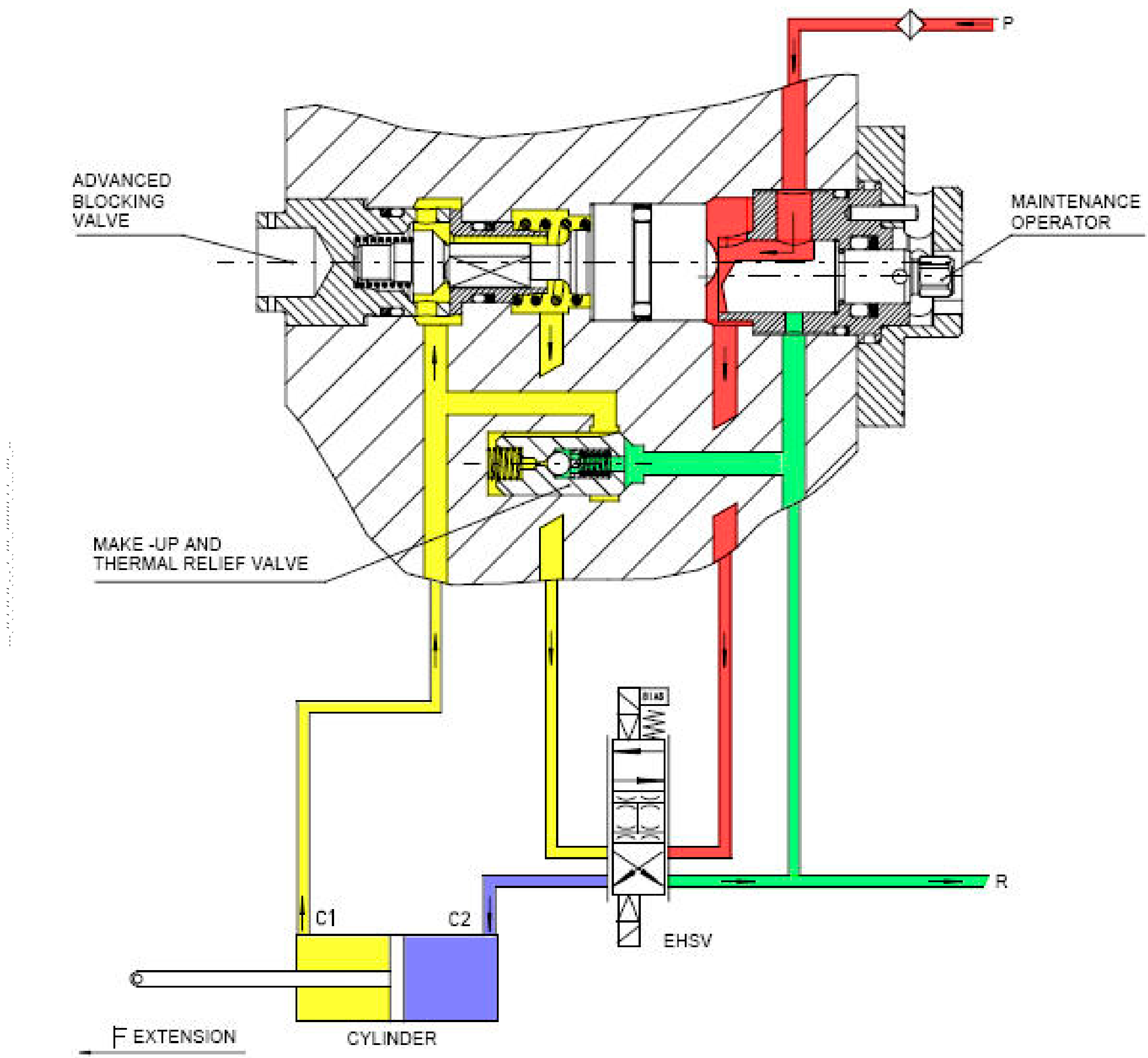


FIGURE 85 - SPOILER 3/4/5 SERVOCONTROL IN ACTIVE MODE CONFIGURATION

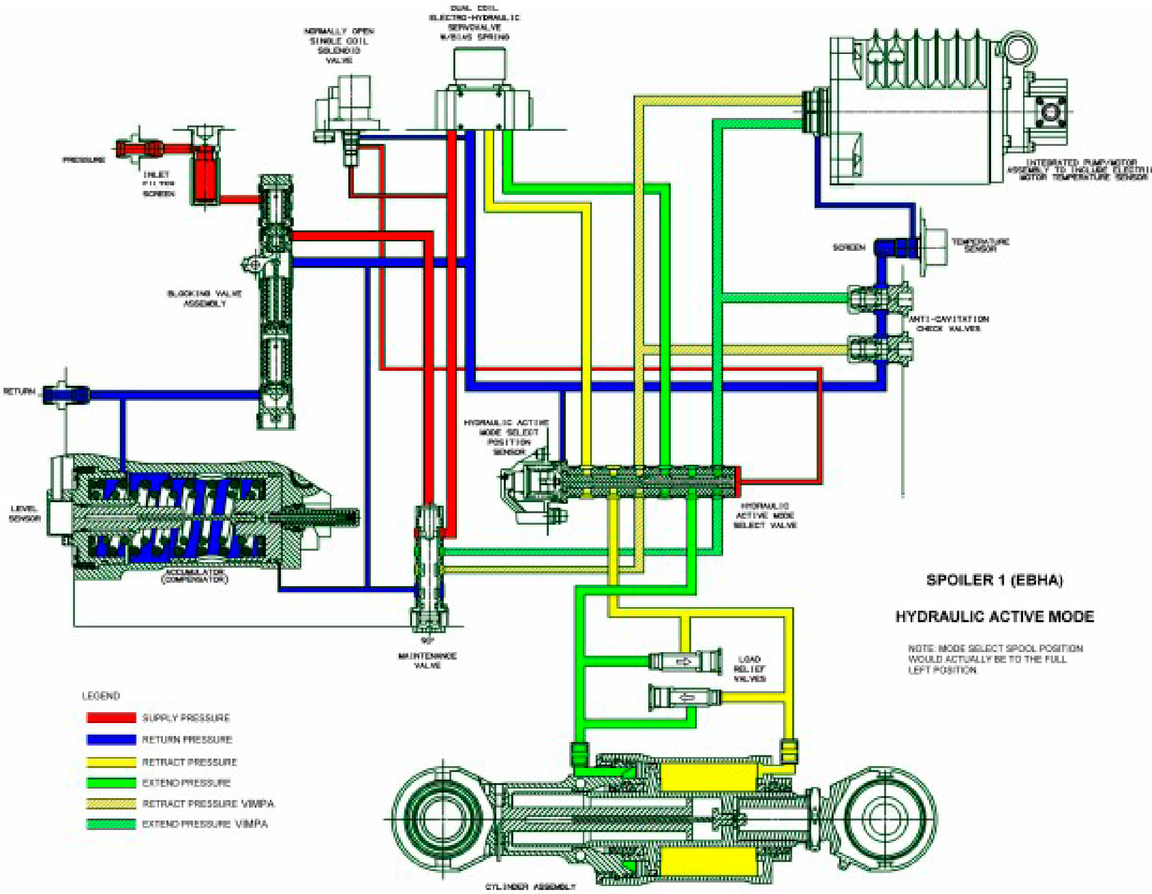


FIGURE 86 - SPOILER EBHA IN HYDRAULIC ACTIVE MODE CONFIGURATION

4. NOTES

4.1 A change bar (l) located in the left margin is for the convenience of the user in locating areas where technical revisions, not editorial changes, have been made to the previous issue of this document. An (R) symbol to the left of the document title indicates a complete revision of the document, including technical revisions. Change bars and (R) are not used in original publications, nor in documents that contain editorial changes only.

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