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Superseding AIR4253A

(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.

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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.

- Survivable Flight Control System, D. S. Hooker et al, May 1971, USAF AFFDL-TR-71-20
- Redundant Secondary Servoactuators for the NASA F-8 Digital Fly-By-Wire (DFBW) Aircraft, Avi Mordkowitz, July 1977, Hydraulic Research Technical Bulletin HR 79900075
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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

Table 8 - Space Shuttle Actuator Characteristics

Table 9 - Lavi Actuator Characteristics

Table 10 - JAS-39 Actuator Characteristics

Table 11 - V-22 Actuator Characteristics

Table 12 - Saab 2000 Actuator Characteristics

Table 13 - IDF Actuator Characteristics

Table 14 - B-2 Actuator Characteristics

Table 15 - C-17 Actuator Characteristics

Table 16 - X-31A Actuator Characteristics

Table 17 - Boeing 777 Actuator Characteristics

Table 18 - X-29A Actuator Characteristics

Table 19 - Airbus A320/330/330 Actuator Characteristics

Table 20 - F-117 Actuator Characteristics

Table 21 - N-250 Actuator Characteristics

Table 22A - A380 Actuator Characteristics (Primary Surfaces)

Table 22B - A380 Actuator Characteristics (Spoiler Surfaces)

Table 23A - BA609 Rotor and Conversion Actuator Characteristics

Table 23B - BA609 Control Surface Actuator Characteristics

Table 24 - Eurofighter Actuator Characteristics

Table 25A - A400M Actuator Characteristics (Primary Surfaces)

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
Servovalues	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	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe	Fail-Op/ Fail-Safe
Electrical	Two-Fail-Op/ Fail-Safe	Two-Fail-Op/ Fail-Safe	Two-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 servo valves

D - One pair of single-stage jet pipe servo valves

E - Two pair of single-stage jet pipe servo valves

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
Servovalues	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	---	---	---
Servo valves	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
Servo valves	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) Fluid (see Note D)	5,000 MIL-H-83282	5,000 MIL-H-83282	5,000 MIL-H-83282	5,000 MIL-H-83282	5,000 MIL-H-83282
Redundancy Hydraulic Electrical	Dual Triplex	Simplex Simplex	Simplex Simplex	Simplex Simplex	Dual 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 Tension	8,697 13,160	4,832 3,682	6,487 6,487		33,000 33,000
Stroke (in)	16.45	8.50	4.92		45.0
Output Velocity in/s deg/s	6.5	13.0 Ext./ 11.0 Ret.	11.0		3.8 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) Fluid	4000 MIL-H-5606	4000 MIL-H-5606	4000 MIL-H-5606	4000 MIL-H-5606	4000 MIL-H-5606	4000 MIL-H-5606
Redundancy Hydraulic Electrical	Dual Quad	Dual Quad	Dual Quad	Dual Quad	Dual Quad	Dual 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 Tension	19,913 21,335	20,000 25,800	21,282 43,800	17,000 25,716	45,187 18,500	23,231 7,500
Stroke (in)	2.585	6.221	6.215	5.215	6.075	6.075
Output Velocity (No Load) in/s deg/s	10.42 100	10.12 100	5.06 50	4.22 50	6.56 80	6.56 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) Fluid	3000 MIL-H-83282	3000 MIL-H-83282	3000 MIL-H-83282	3000 MIL-H-83282	3000 MIL-H-83282
Redundancy Hydraulic Electrical	Dual Triplex	Dual Triplex	Simplex Dual	Simplex Dual	Simplex 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 deg/s	5.6 80	5.6 80 (Rudder) 100 (Canard)	6.0 50 (Speed Brake) 87 (Thrust Vector)	1.6 30	N/A 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 EHSV's
 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
Servo valve	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
Servo valves	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
Servovalues	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) Fluid	3,000 A	3,000 A	3,000 A	3,000 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 Retract	10,700 10,700	11,000 11,000	4,900 4,900	7,100 5,500
Stroke (in)	3.54	2.50	1.70	2.25
Max. No Load Rate Extend (in/sec) Retract (in/sec)	4.1 4.1	2.09 2.09	1.77 1.77	2.7 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)

Characteristic	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
Servovalues	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)

Characteristic	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
Servo valve	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
Servo valve	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		27.5 (4000) Mil-PRF-5606/83282/87257				
Pressure	MPa (psi)					
Fluid						
Redundancy		Dual Quadruplex				Single
Hydraulic						Single
Electrical						Single
Valve		Direct Drive Valve (Quadruplex Motor)				EHSV
Type						
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)

Characteristic	Aileron		Rudder	Elevator	
Actuators per surface	1 Conventional FBW Actuator	1 EHA	2 EBHA	1 Conventional FBW Actuator	1 EHA
Hydraulics Pressure	3000 psi	3000 psi	3000 psi	3000 psi	3000 psi
Fluid	Phosphate ester type IV / V	Phosphate ester type IV / V	Phosphate ester type IV / V	Phosphate ester type IV / V	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
Servo valves	2 stage single inlet	N / A	2 stage single inlet	2 stage single inlet	N / A
Output force					
Extend	148 kN	120 kN	120 kN	148 kN	82 kN
Retract	148 kN	120 kN	120 kN	148 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)

Characteristic	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
Servo valves	2 stage single inlet	2 stage single inlet	2 stage single inlet
Output force			
Extend	110 kN	96 kN	90 kN
Retract	87 kN	96 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 with 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 with 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 sharing 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 output 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.

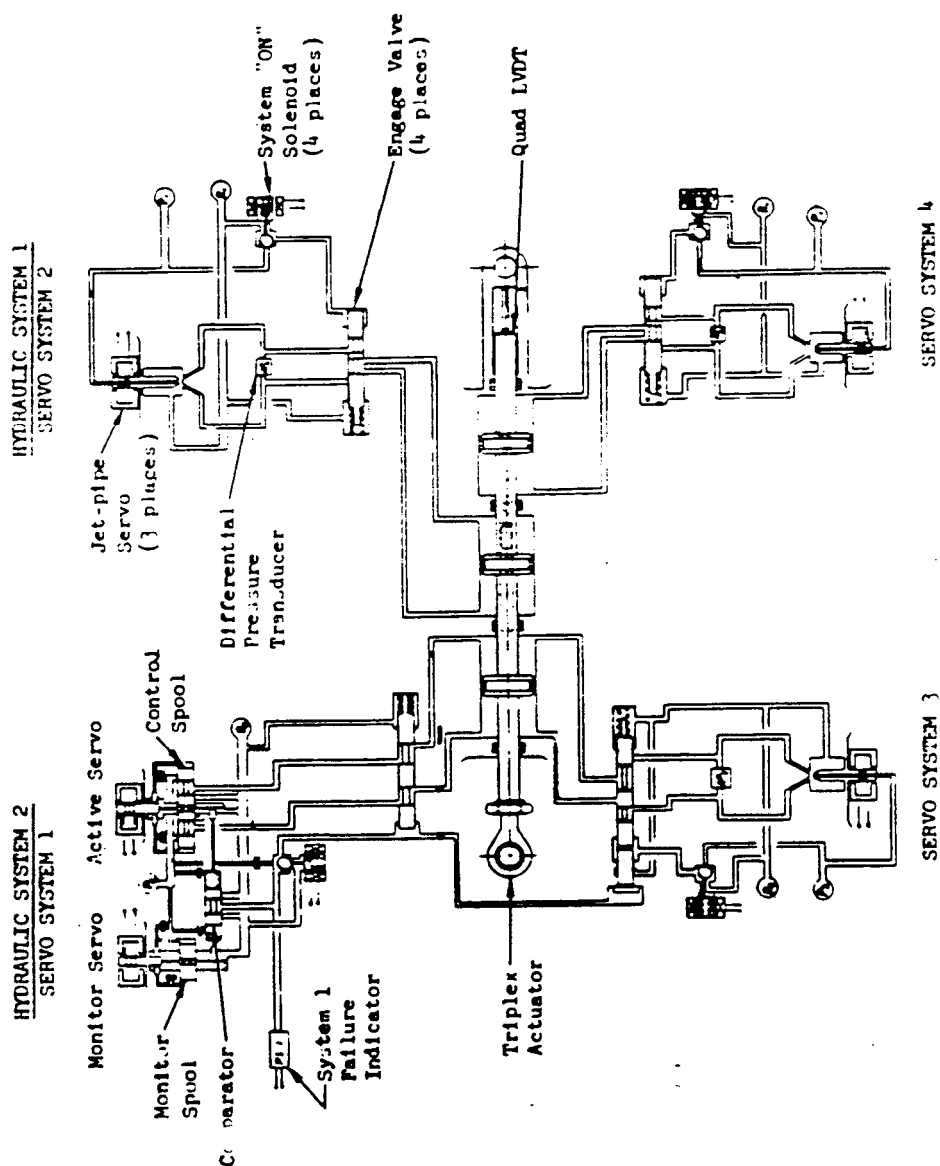


FIGURE 1 - PHASE I HYDRAULIC SCHEMATIC
QUAD REDUNDANT SECONDARY ACTUATOR

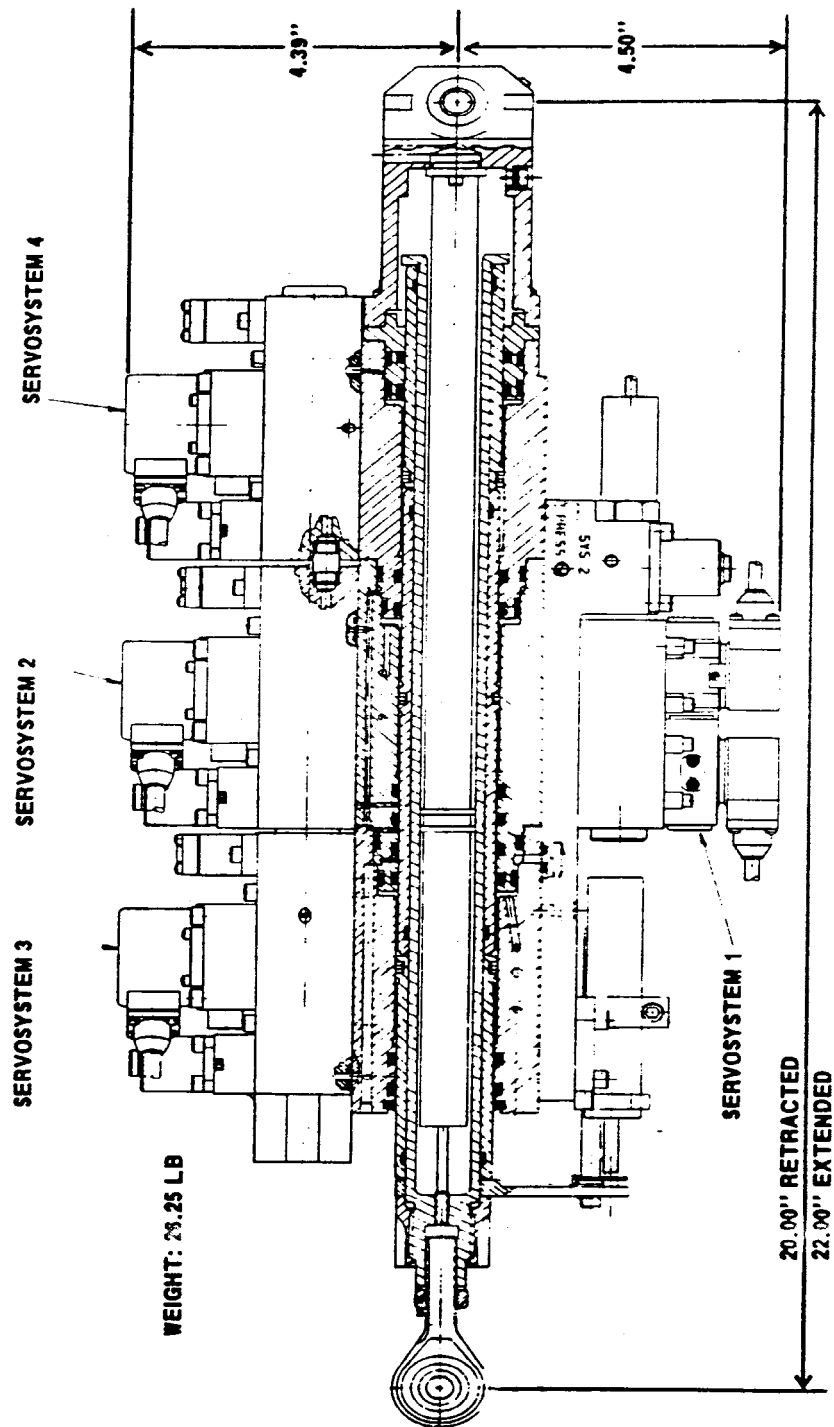


FIGURE 2 - PHASE J SECONDARY SERVOACTUATOR
CROSS-SECTION

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 configuration 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.

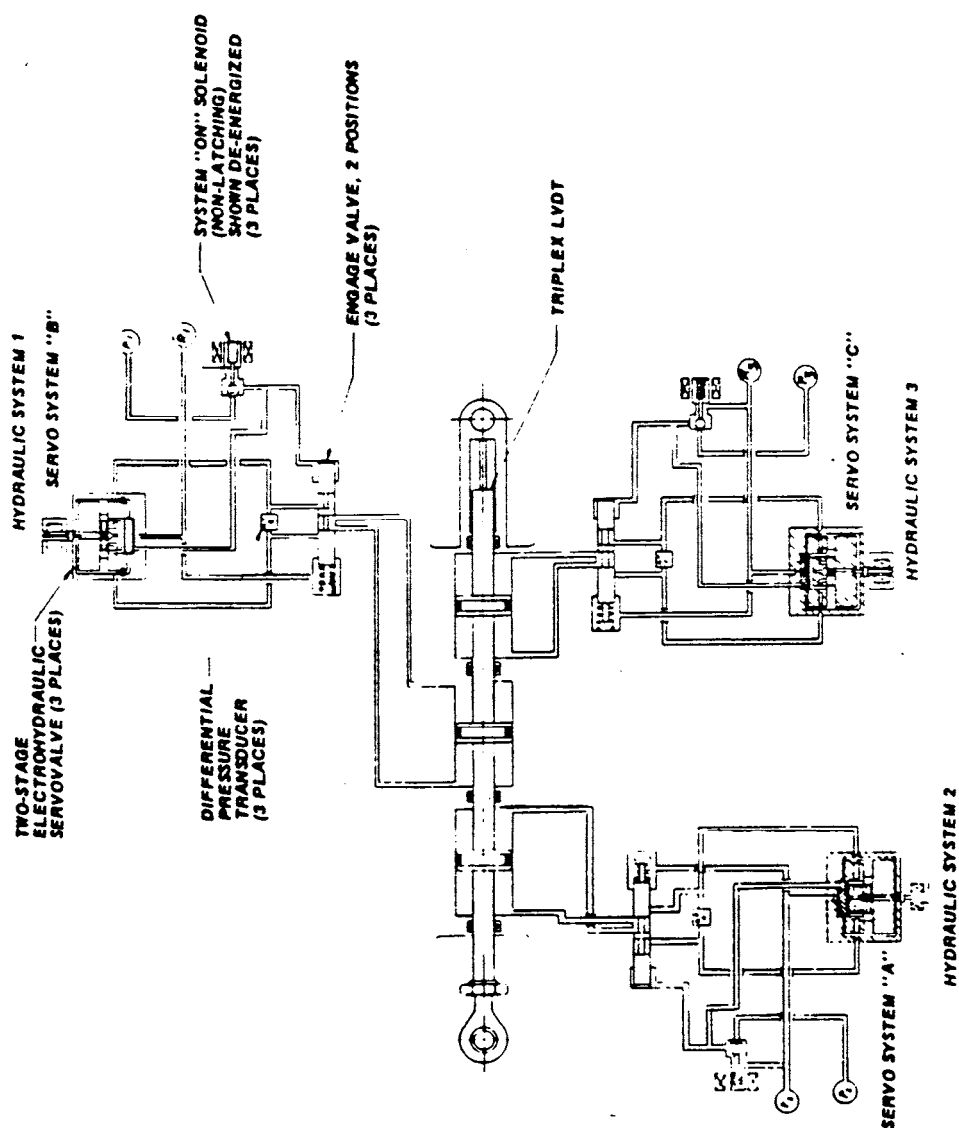


FIGURE 3 - PHASE II HYDRAULIC SCHEMATIC
TRIPLEX REDUNDANT SECONDARY SERVOACTUATOR

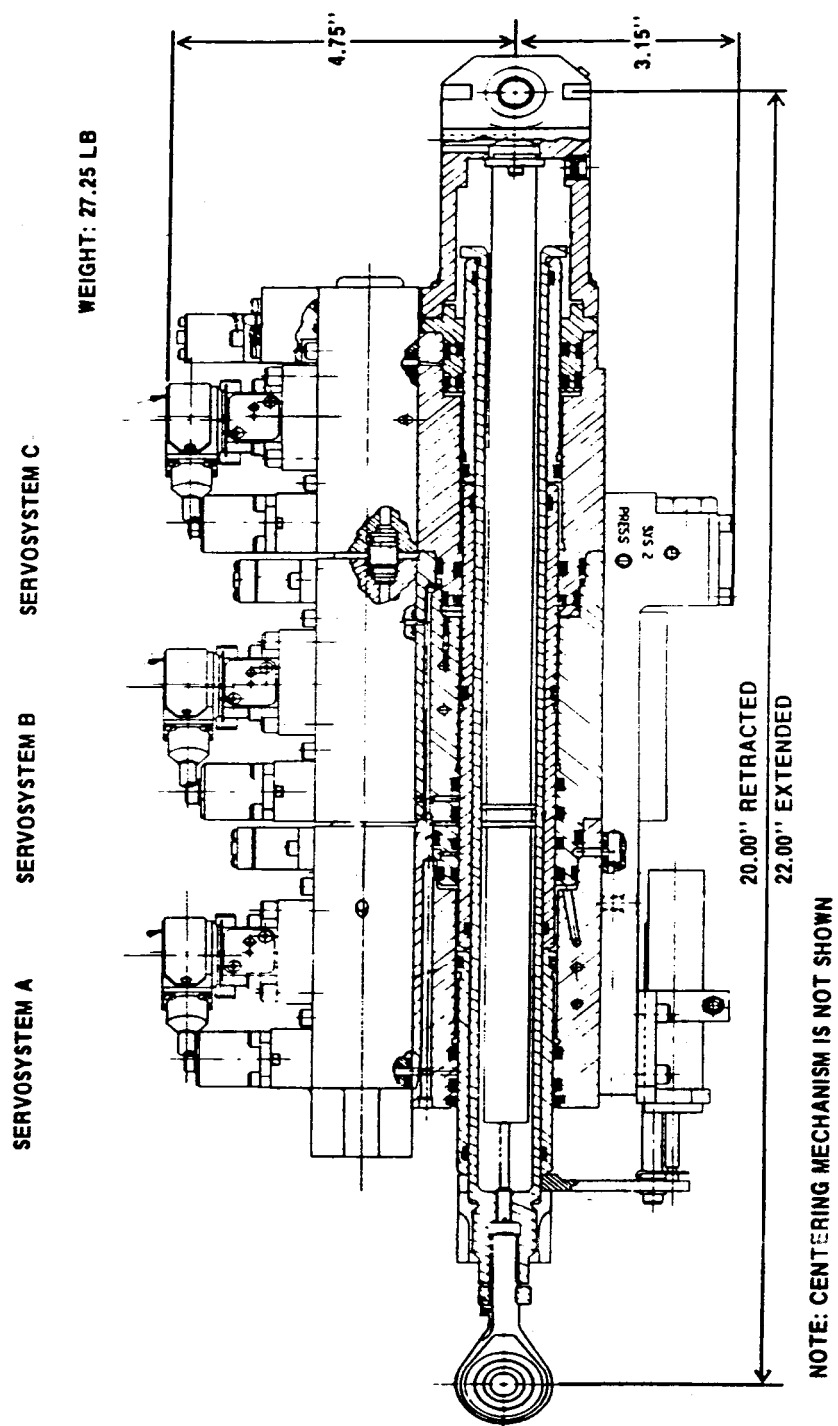


FIGURE 4 - PHASE II SECONDARY SERVOACTUATOR
CROSS-SECTION

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 secondary actuator element. Each element is driven by a single-stage jet pipe servovalve. 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.

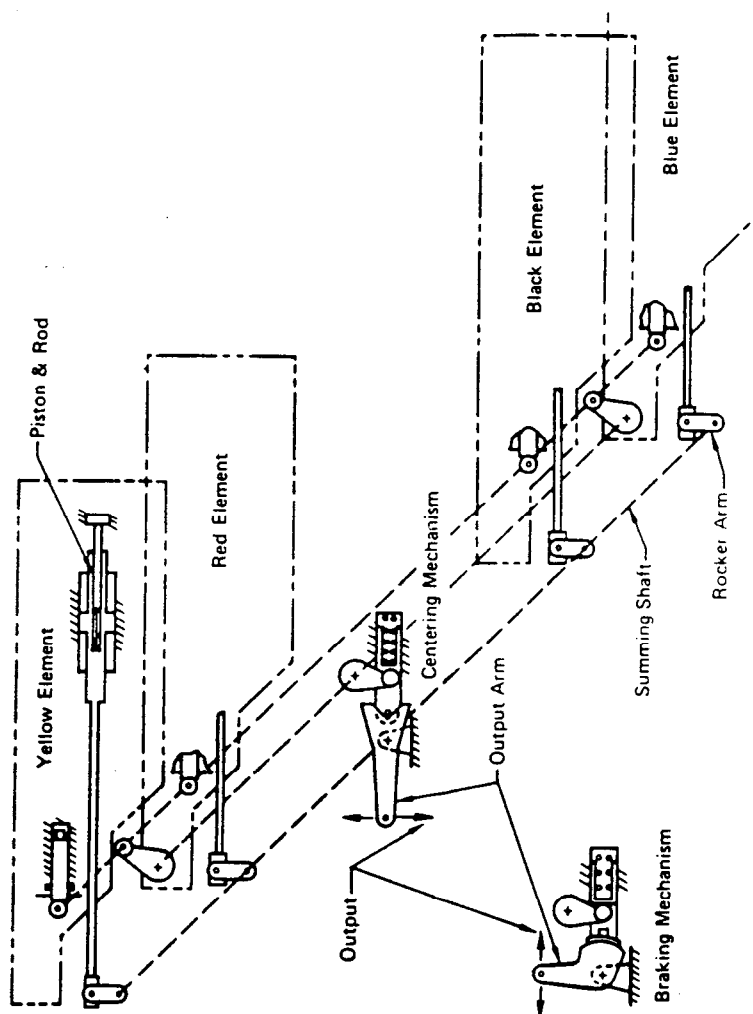


FIGURE 5 - MECHANICAL SCHEMATIC, SECONDARY ACTUATOR

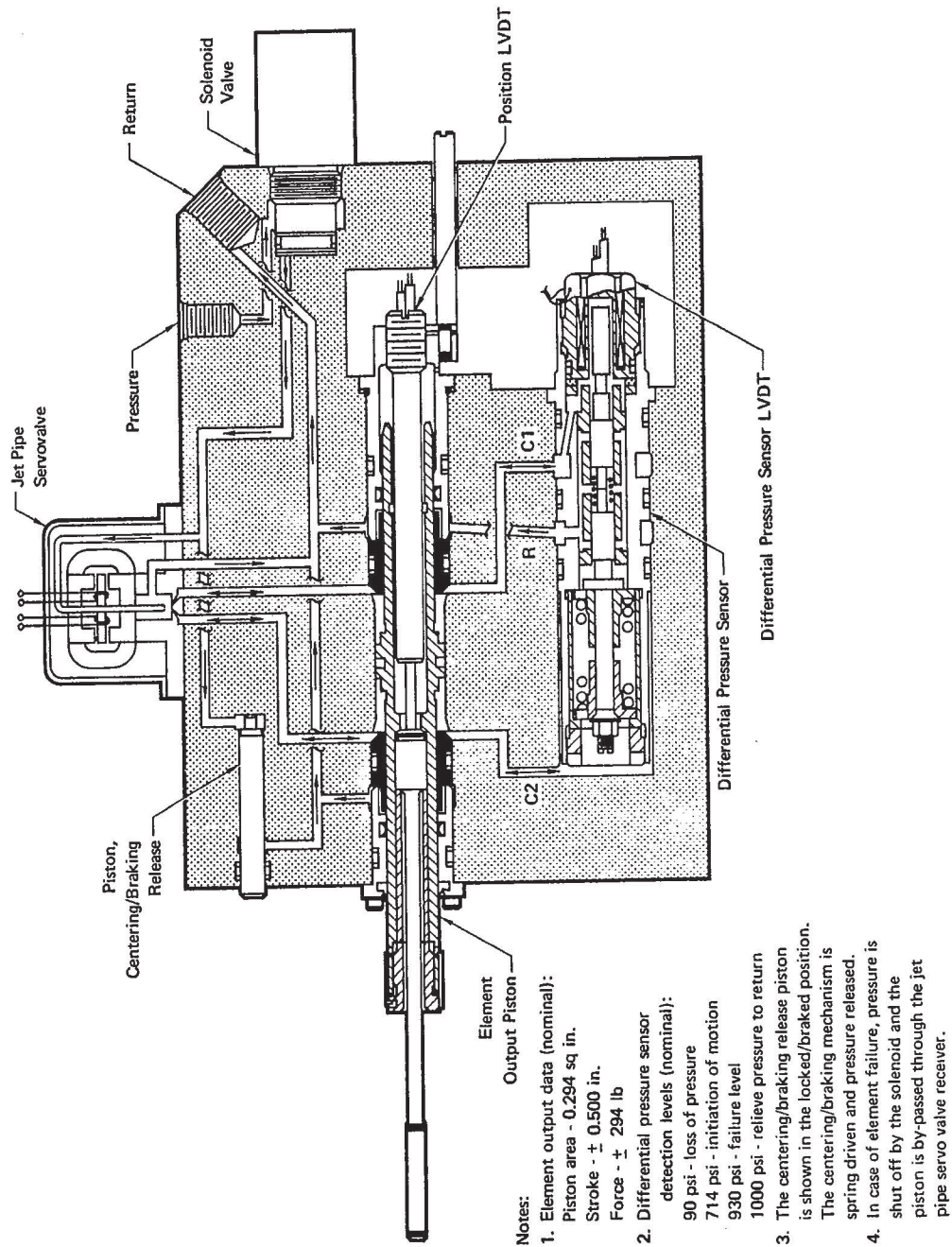


FIGURE 6 - HYDRAULIC SCHEMATIC, SINGLE ACTUATOR ELEMENT

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 with 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.

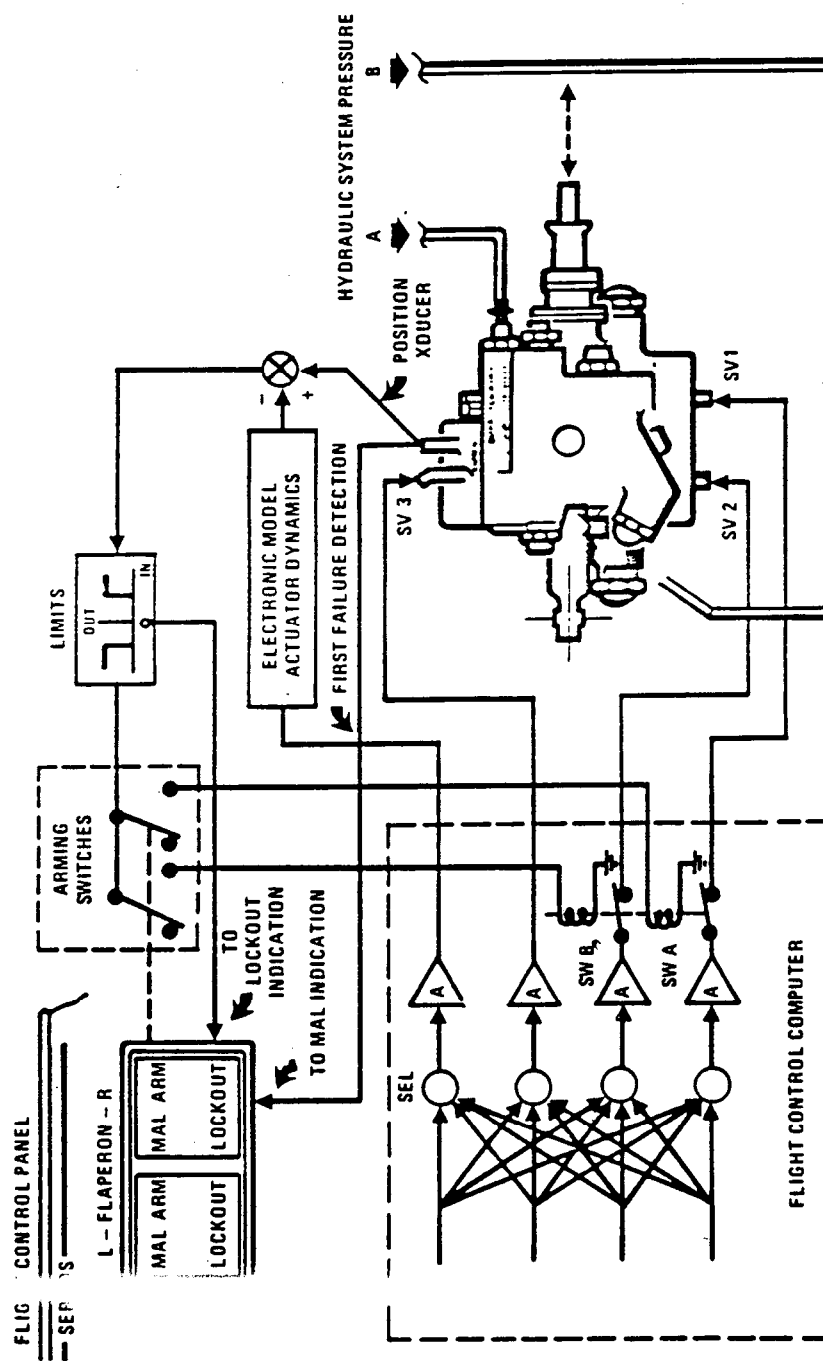


FIGURE 7 - ELECTRICAL INTERFACE WITH YF-16
FLAPERON AND RUDDER SURFACE ACTUATION

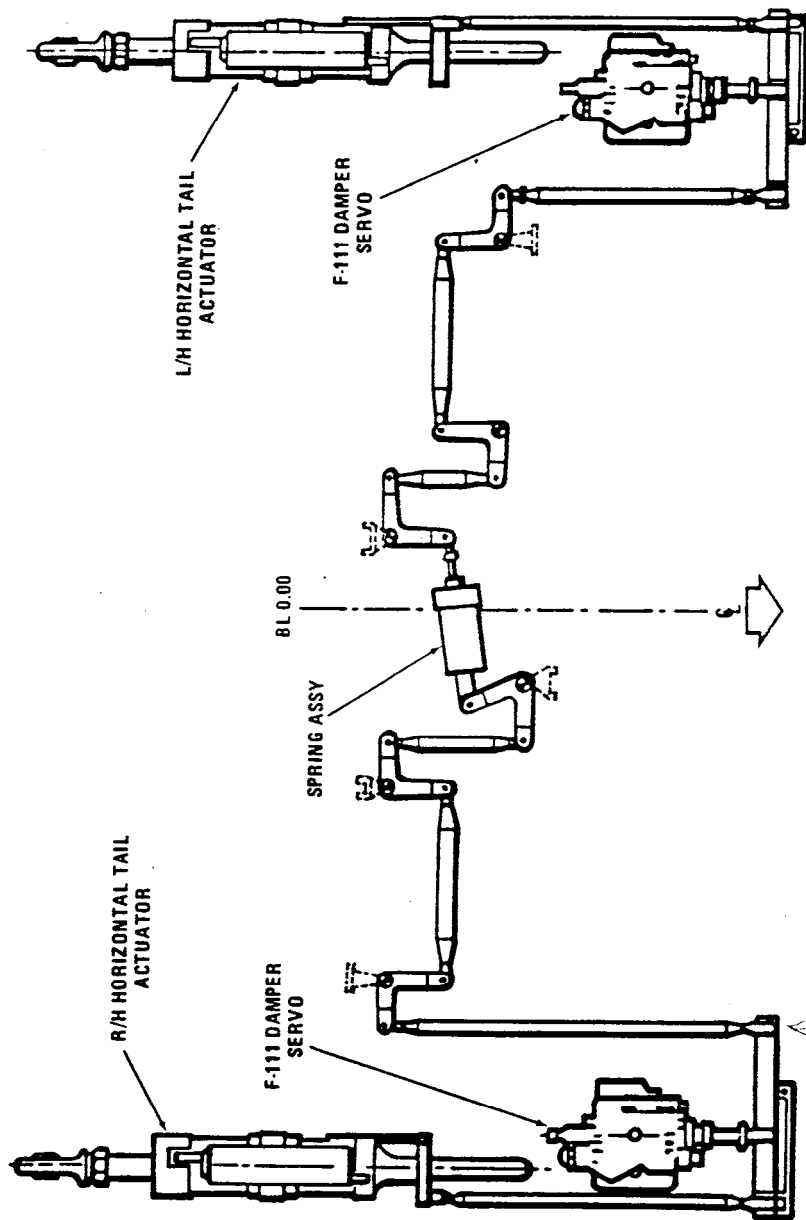


FIGURE 8 - YF-16 HORIZONTAL TAIL SURFACE ACTUATION CROSSOVER LINKAGE