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AEROSPACE INFORMATION REPORT

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AIRCRAFT FLIGHT CONTROL SYSTEMS DESCRIPTIONS

TABLE OF CONTENTS

1. SCOPE:

This Aerospace Information Report (AIR) supplies information on the flight control systems incorporated on various aircraft. A brief description of the aircraft is followed by a description of the flight control system, some specific components, drawings of the internal arrangement, block diagrams, and schematics. System operation redundancy management is also presented.

2. PURPOSE:

The purpose of this document is to provide system description information on various aircraft flight control systems.

3. GENERAL:

3.1 Fairchild Republic A-10 Thunderbolt II:

The Fairchild Republic A-10 Thunderbolt II (Figure 1) is a twin engine close air support attack aircraft. The surfaces used to effect pitch, roll, and yaw are the traditional elevators, ailerons, and rudders which are controlled by a mechanical primary flight control system (Figure 2).

3.1.1 System Description: The flight control system is a type III irreversible power control which reverts to type I (reversible mechanical control system) with the loss of both hydraulic systems. Loss of either hydraulic system will still retain full powered control response. Loss of both systems automatically engages the manual reversion mode that has performance for moderate maneuvers and safe landings. The linkages consist of push-pull rods, cables and cranks configured for straight parallel paths with low friction and minimum connections (Figure 2). Artificial feel is provided by redundant spring/cam devices located at each surface actuator. Redundant stability augmentation systems (SAS) are provided to enhance tracking and minimize trim transients for speed brake deployment in pitch, and to reduce sideslip in yaw during abrupt roll maneuvers. The roll axis does not employ a SAS. Redundant pilot control capability is provided through separate transmission paths for the pitch, roll, and yaw commands. In addition, the elevators and rudders have dual control surfaces and actuators while the ailerons are equipped with tandem hydraulic actuators.

3.1.2 System Mechanization: The pitch control is effected with two independent elevators. Pitch linkage separates into extreme left and right parallelogram cable and linkage transmission paths (Figure 3). Each system drives independent hydraulic actuators attached to the left and right elevators. A torque shaft cross connection between the two elevators for uniform displacement is provided with prescribed torsional stiffness and 12 blind rivets which fail in the event of a jam of one of the elevators. Electrically operated pitch control disconnectors, which normally function as bellcranks, release if a jam is encountered in either the left or right control run that reaches a magnitude of 40 to 65 lb at the stick grip. A bobweight and balance spring under the cockpit floor provides incremental normal "g" force feel at the stick in addition to the artificial feel provided by the spring/cam devices located by the actuator.

3.1.2 (Continued):

Redundant SAS signals are integrally summed with stick signals at each control surface actuator. The SAS signals are summed from two sources, pitch damping and speed brake cross feed and are dual redundant. Signals to the left and right simplex elevator actuators are fully independent. When the two LVDTs differ beyond specified thresholds, both SAS systems are automatically shut down. Left and right SAS systems can be individually re-engaged at the pilot's discretion.

Roll control is effected by two ailerons each powered by tandem hydraulic servoactuators under the wings in faired armament pylons. Lateral stick signals are transmitted from the armored cockpit area via independent parallelogram cables separated into extreme left and right transmission paths at the aft end of the roll stick output pushrod (see Figure 4). Jam protection similar to that in pitch is afforded for both roll control systems. Fail operative capability with 50% roll rate control is retained subsequent to a jam. The aileron actuators are dual tandem units with the left and right hydraulic circuits fully independent. Loss of one hydraulic power supply has no discernible effect on aileron response. Loss of both hydraulic power supplies automatically engages the manual reversion mode in which pilot control is transferred to operate aileron servo tabs to move the ailerons for roll control. The roll axis is heavily damped and requires no stability augmentation system.

Yaw control is effected through dual rudders with the cable run separating into left and right linkages in the extreme aft fuselage to drive individual simplex rudder actuators (Figure 5). The yaw axis has dual stability augmentation systems similar to the pitch system. Electrical SAS signals to the actuator are summed from roll attitude, rudder trim, yaw rate gyro, and angle of attack times roll rate. These signals are added to the pedal commands to effect total command signals. As in the pitch SAS when two SAS LVDTs differ beyond a specified threshold, both SAS systems automatically shut down. At aircraft speed above 240 knots indicated, a "Q" sensing switch limits rudder travel to $\pm 8°$ to protect fins from excessive air loads.

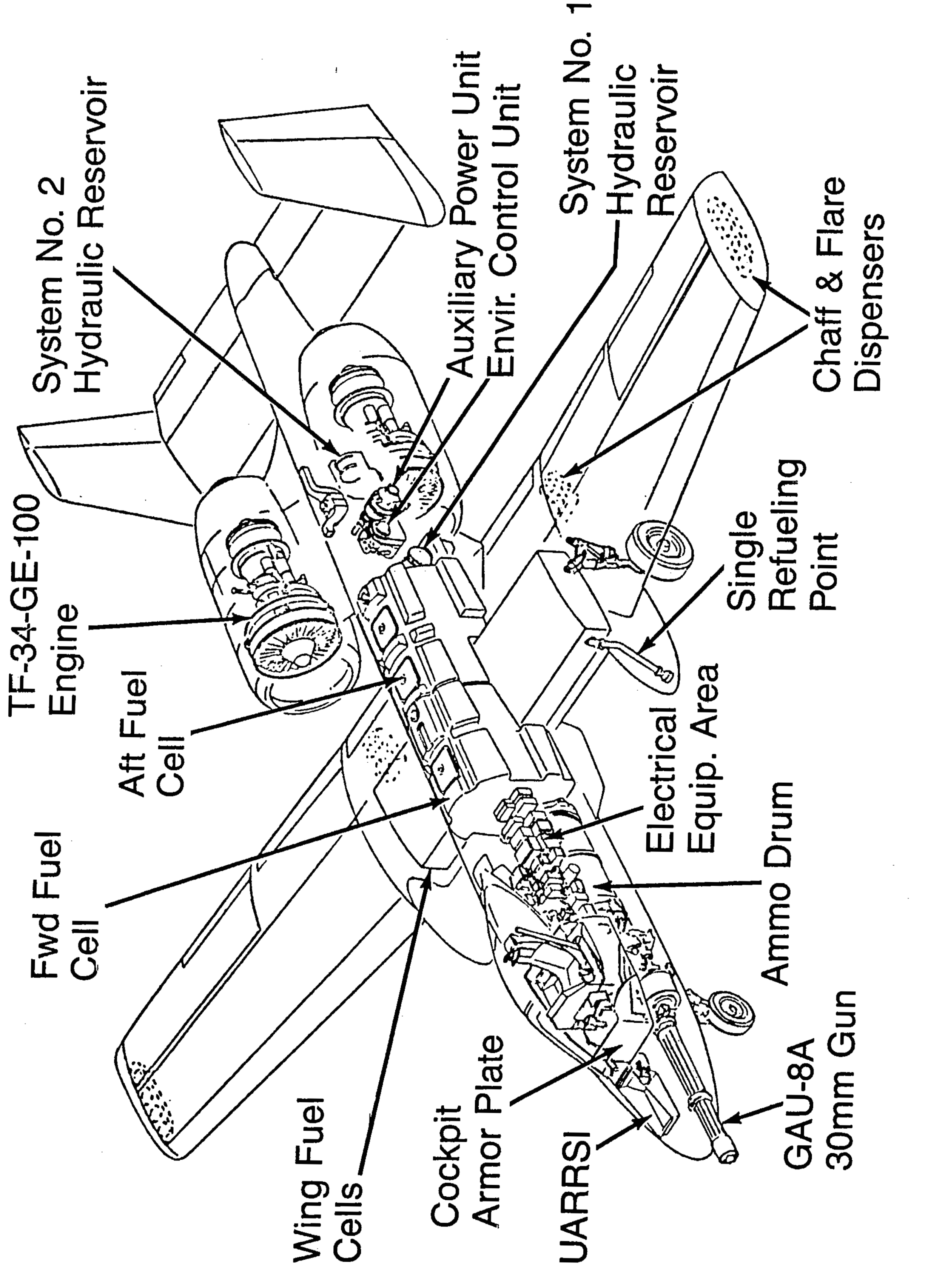


FIGURE 1 - Fairchild Republic A-10 Thunderbolt II, Internal Arrangement

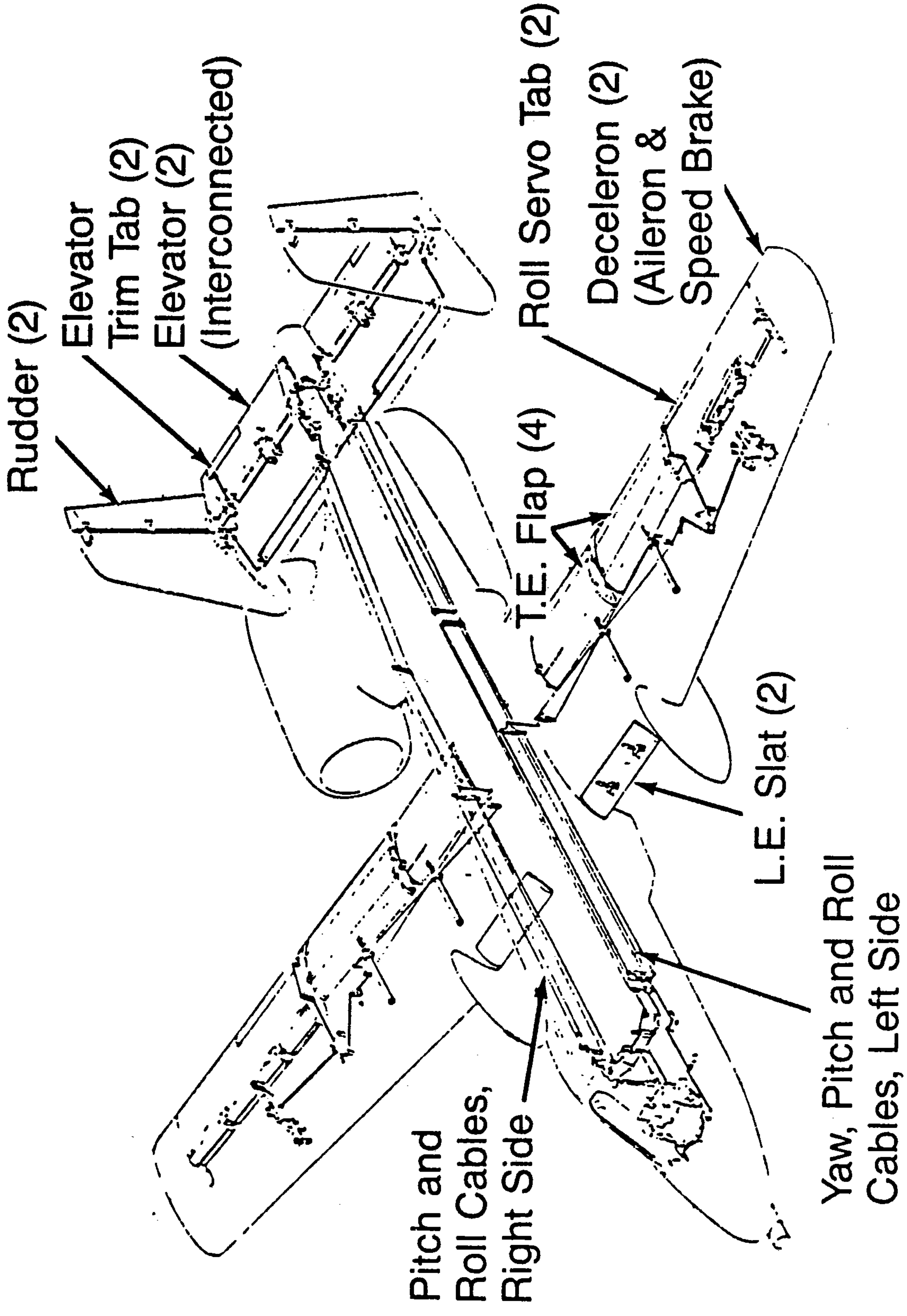


FIGURE 2 - Fairchild Republic A-10 Thunderbolt II, Flight Control Subsystems

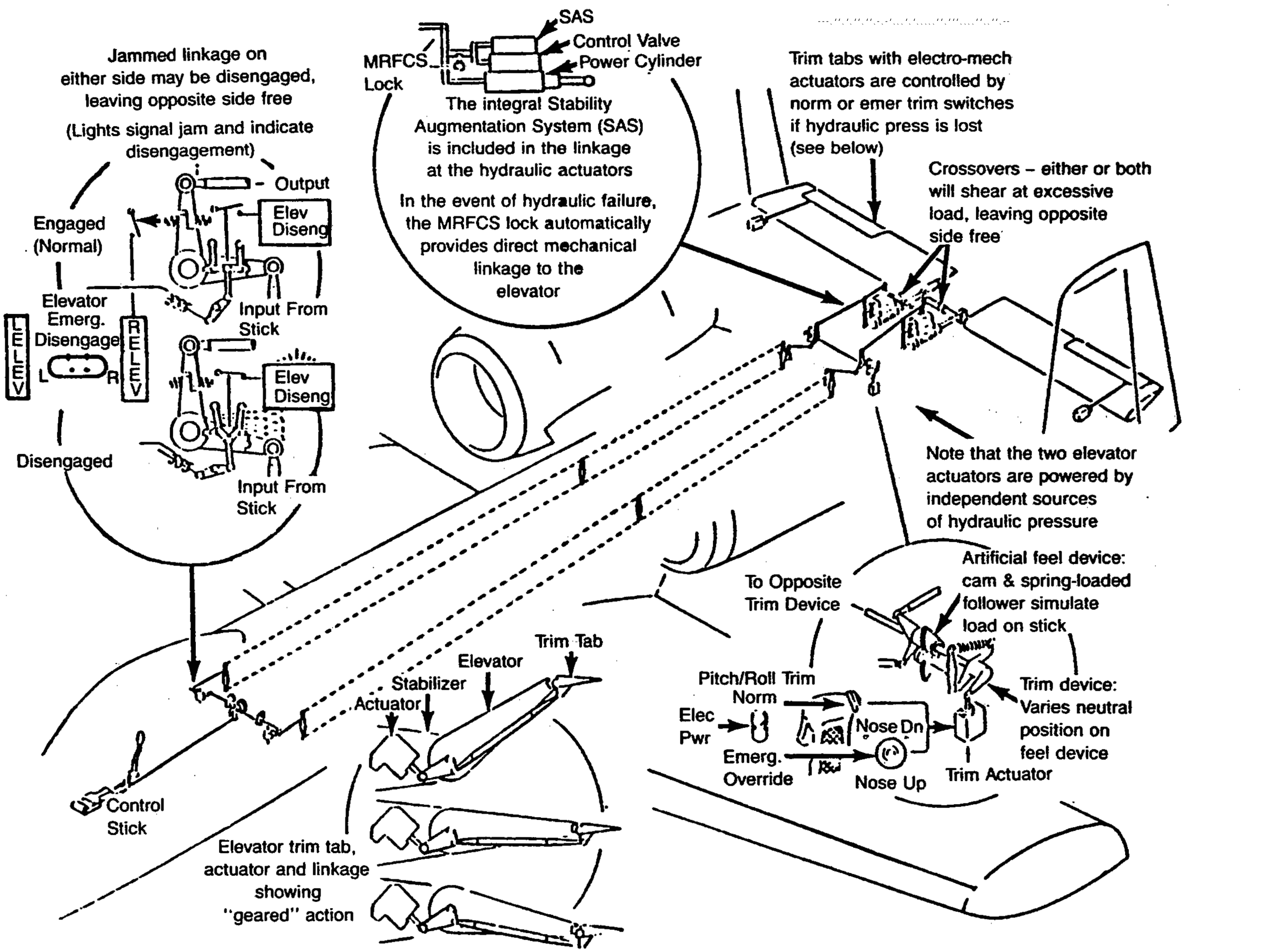


FIGURE 3 - Fairchild Republic A-10 Thunderbolt II, Pitch Control System Schematic

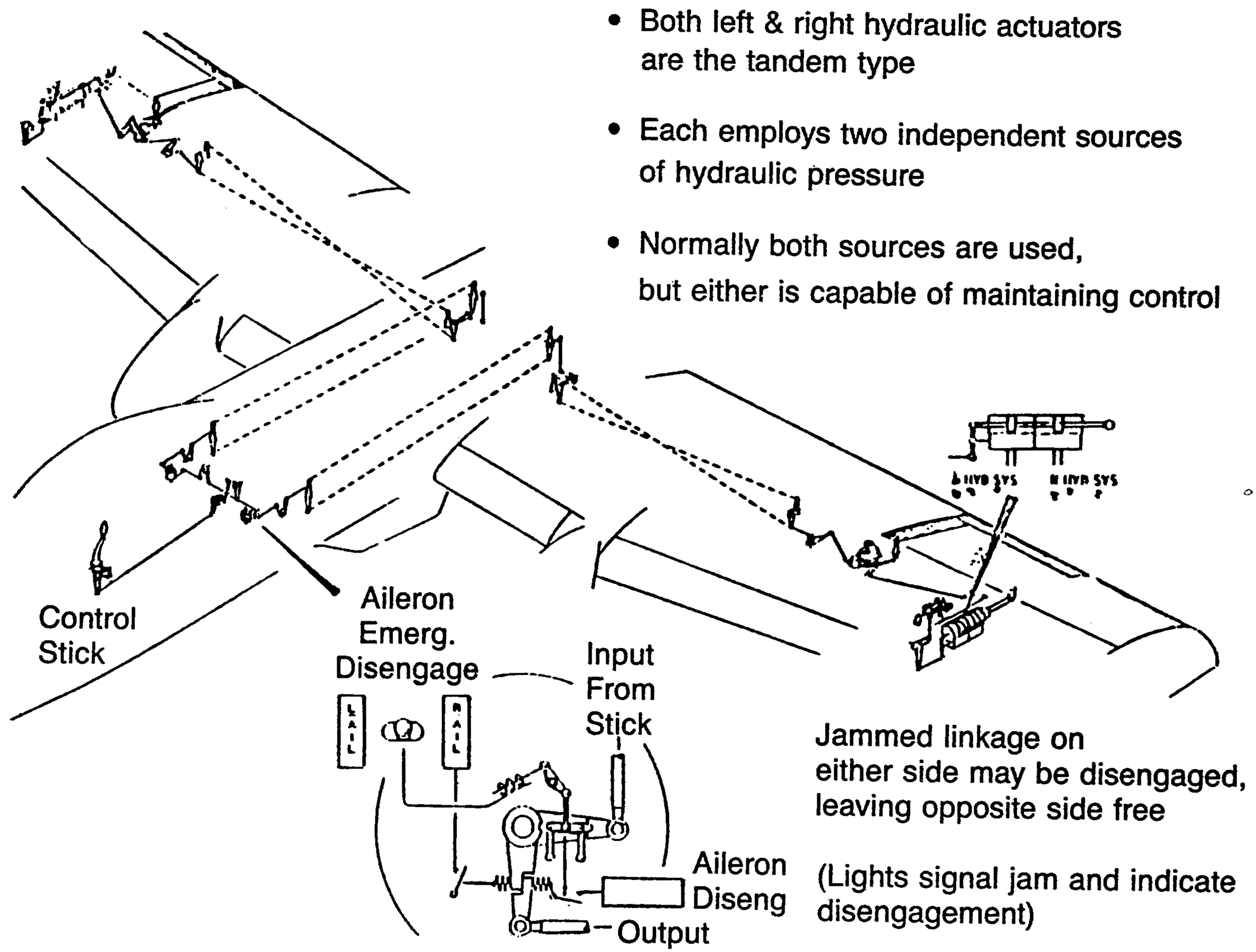


FIGURE 4 - Fairchild Republic A-10 Thunderbolt II, Roll Control System Schematic

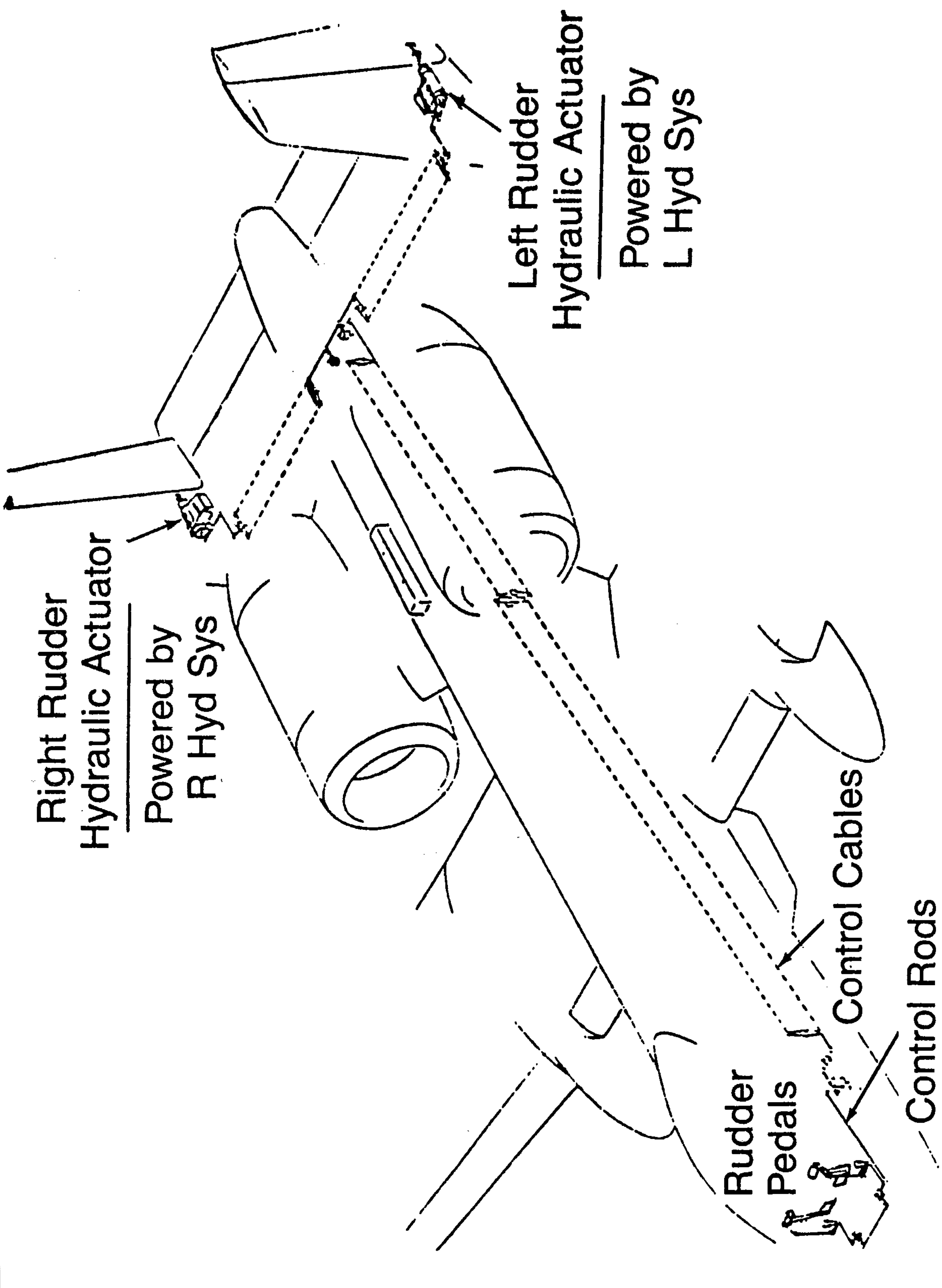


FIGURE 5 - Fairchild Republic A-10 Thunderbolt II, Yaw Control System Schematic

3.2 Fairchild Republic T-46:

The Fairchild Republic T-46 (Figure 6) is a two place twin engine jet trainer. Aircraft control is effected by two elevators, two ailerons, and two rudders. The pitch and roll controls are fully manual while the rudder is serviced by a hydraulic actuator for yaw control.

3.2.1 System Description: The flight control system is a type I for pitch and roll and a type III for yaw which supports stability augmentation and a fully manual reversion capability. The control runs have no mechanical redundancy while the hydraulic rudder actuator has the capability to retain 50% yaw control after any jam in the cable system or rudder surface downstream of the rudder actuator. The actuator can override cable force limiting springs in the cable system leading to the jammed side and transmit pilot's command to the operable rudder surface.

3.2.2 System Mechanization: Control stick pitch motion is manually transmitted through a series of cable and pushrods (Figure 7) to two independently mounted elevators interconnected with a torque shaft. A spring balanced bobweight is incorporated to provide a stick force per G characteristic, the elevators are 70% mass balanced and have aerodynamic balance. The elevators travel 32° TEU and 10° TED. A trim tab is mounted on the inboard edge of the right elevator.

Roll control is effected through spring tabs on the ailerons. A manual cable and pushrod system transmits control stick motion to aileron displacement (Figure 8). A pivoted conical mechanism generates 24° TEU and 16° TED aileron displacement for equal input cable travels. The unequal aileron travels benefit proverse yaw. The ailerons are 70% mass balanced while the aileron tabs are 100% mass balanced.

The yaw control system is a type III, in which a single cable transmission path sends pedal commands to an irreversible hydraulic linear actuator (Figure 9). The actuator positions two rudder surfaces through independent sets of control cables. Spring force limiters limit rudder torques and travels to operational requirements regardless of full pedal deflections. A spring/cam centering device in the actuator assembly provides a pedal force gradient peaking at 45 lb.

The yaw controls incorporate a SAS to augment dutch roll damping and minimize aircraft heading oscillations. Rate gyros sense rotational rates about yaw and output electrical signals to the actuator while a LVDT provides position feedback information to the hydraulic actuator.

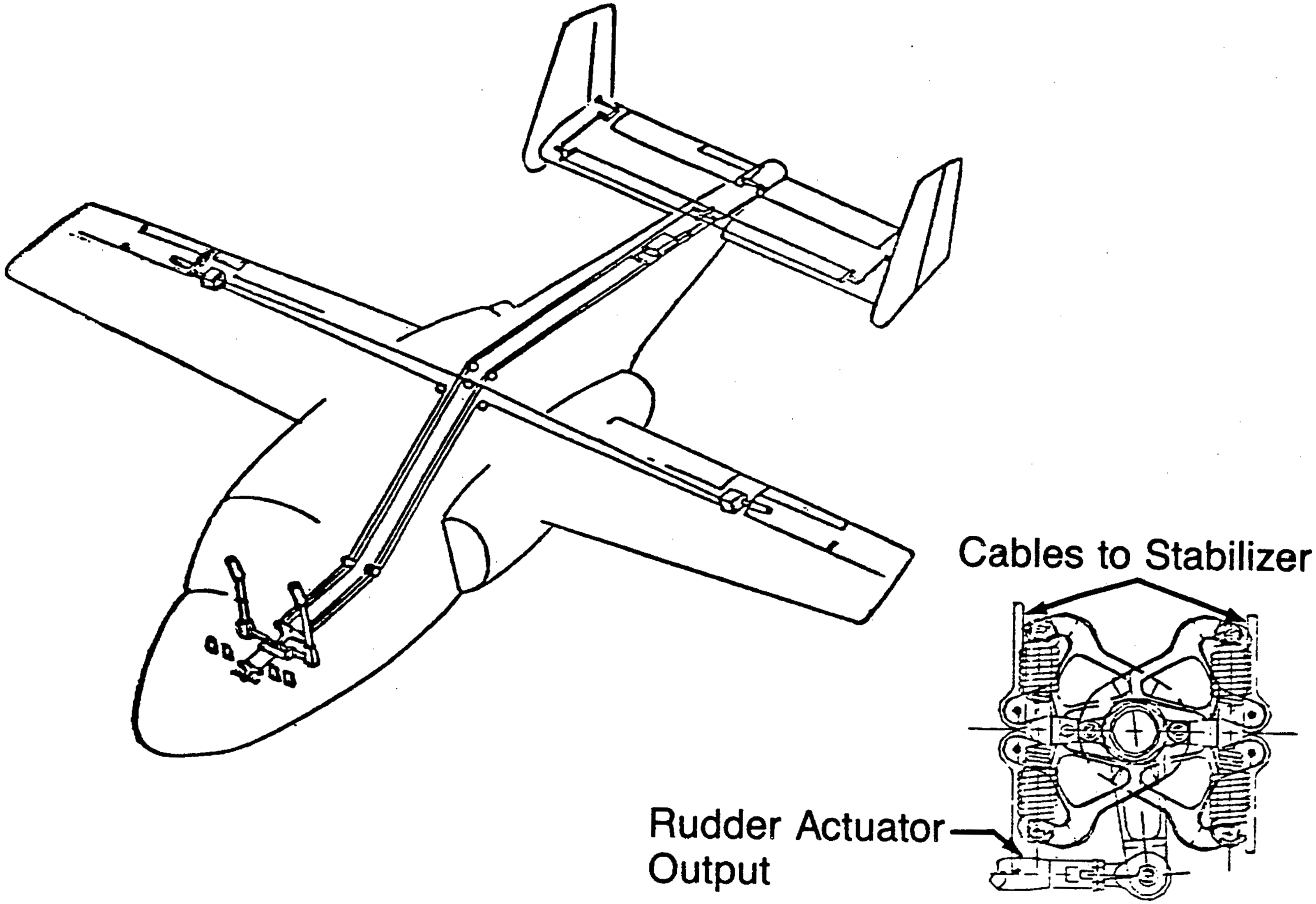


FIGURE 6 - Fairchild Republic T-46, Primary Flight Controls (Fuselage)

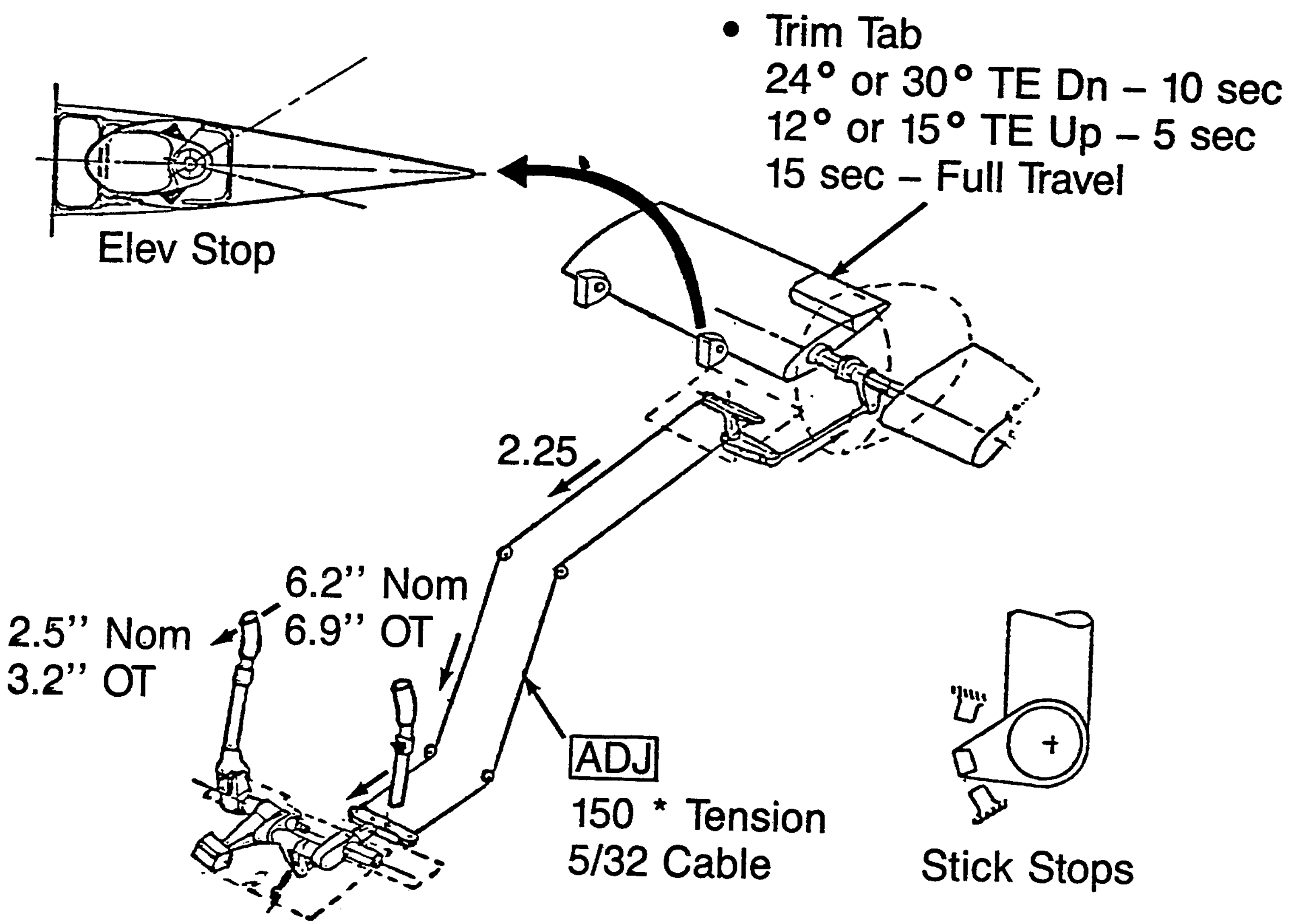


FIGURE 7 - Fairchild Republic T-46, Pitch Control Schematic

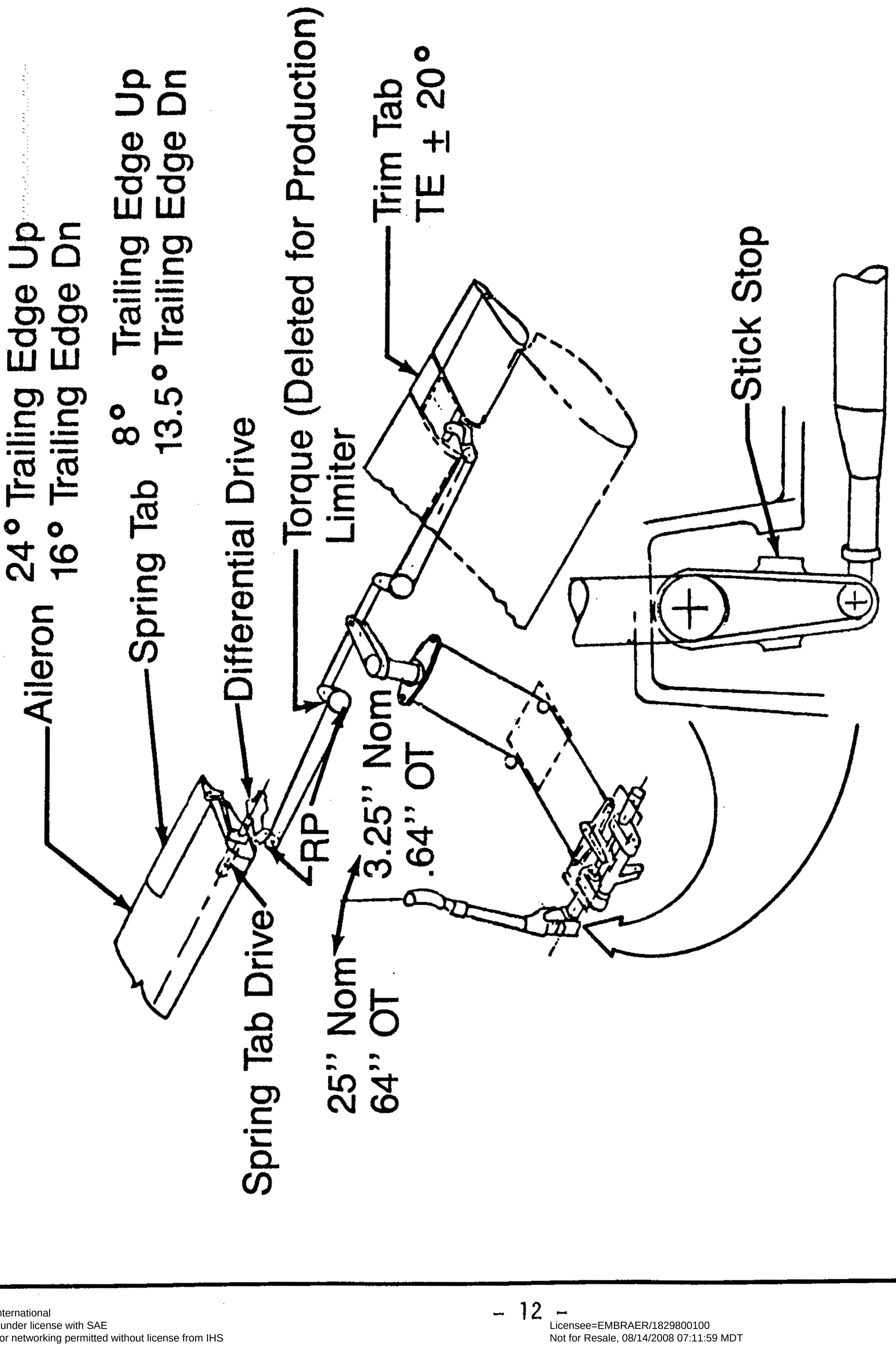


FIGURE 8 - Fairchild Republic T-46, Roll Control Schematic

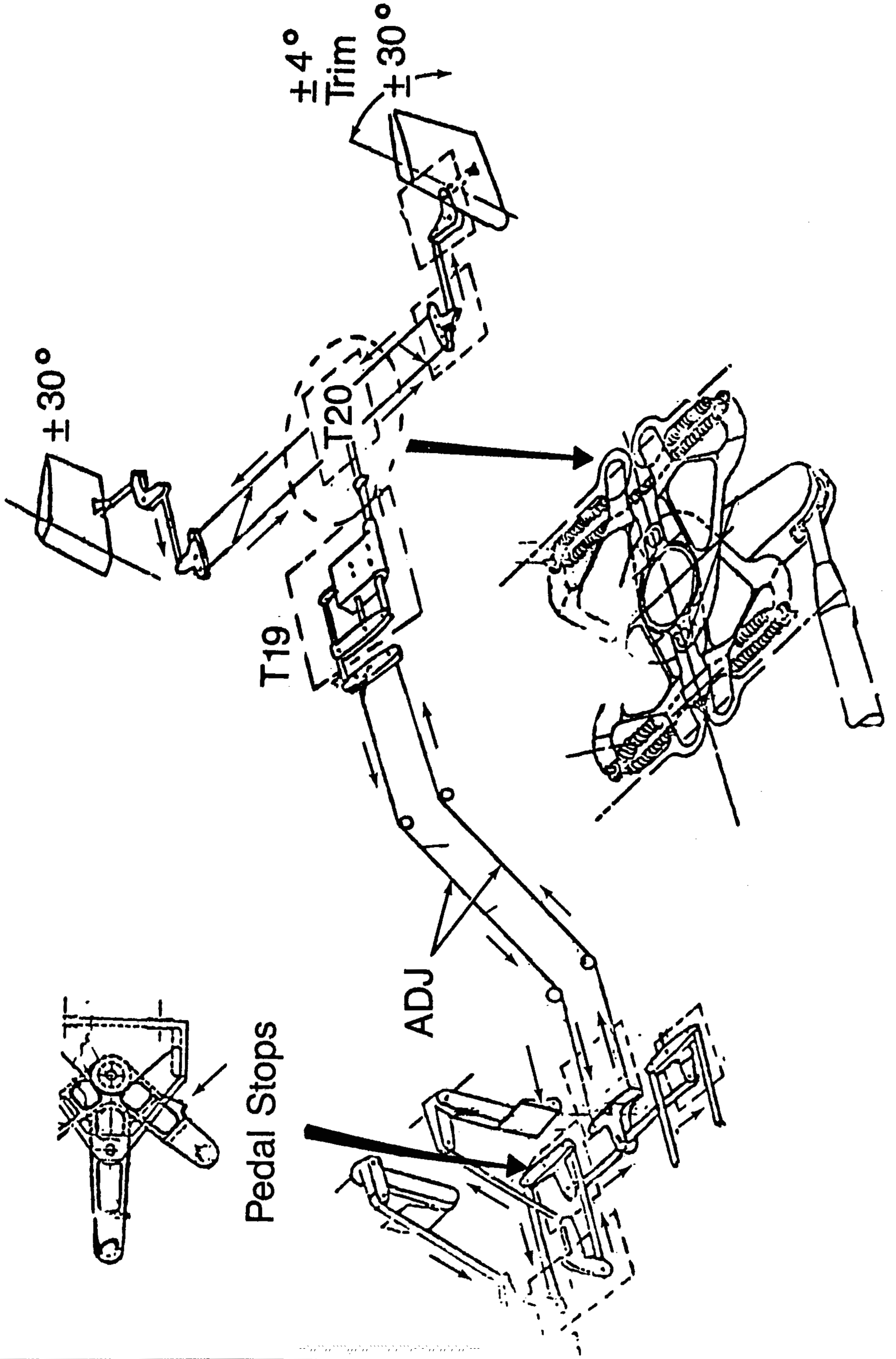


FIGURE 9 - Fairchild Republic T-46, Yaw Control Schematic

3.3 General Dynamics F-111:

3.3.1 F-111 Flight Control System Description: The primary flight control system provides control of the aircraft by movement of a rudder, a pair of spoilers on each wing and a pair of movable horizontal stabilizers. Pitch attitude of the aircraft is controlled by symmetrical deflection of the horizontal stabilizer surfaces. Roll attitude is controlled by asymmetrical deflection of the horizontal stabilizer surfaces; and when the wing sweep angle is less than 45°, roll control is aided by action of two spoilers on top of each wing. Yaw control is accomplished by deflection of a rudder surface located on the trailing edge of the vertical stabilizer. Hydraulic servoactuators are used to produce control surface movement.

A system of push-pull tubes, bellcranks, cables, and pulleys are used to connect the cockpit controls with the rudder and horizontal stabilizer hydraulic actuators. The linkage connections are secured with self-retaining bolts, which use self-locking cotter keyed nuts.

The stability augmentation system employs redundant sensors, electronic circuitry and electrohydraulic dampers. The three damper actuators, the horizontal stabilizer actuators, and the rudder actuator are supplied by both primary and utility hydraulic systems and can operate on either system should one system fail.

3.3.2 Pitch Channel (Figure 10): The salient features of the pitch channel are summarized below:

- Direct mechanical linkage from the control sticks to the left and right horizontal tail actuators
- Parallel trim actuator for pilot trim
- Series trim actuator provides the elevator required to trim (Auto Trim)
- Pitch Damper System
  - Operates in either the TAKEOFF (T.O.) and LAND mode or NORMAL mode, dependent upon the slat position and the control system switch position
  - Automatically provides the required gain by a self adaptive gain changer system
  - Provides a nearly constant stick force per "g"
  - Has electronic and hydraulic redundancy features

3.3.3 Roll Channel (Figure 11): The following salient features of the roll axis are summarized below:

- Direct mechanical linkage from control sticks to the left and right horizontal tail actuators

- Additional roll control is provided by inboard and outboard spoilers on each wing when wing sweep is equal to or less than 45° (by electrical command signals to the spoiler actuator)

- Roll Damper System

  - Provides stability augmentation using roll rate feedback

  - Accepts stick command signals from a stick position transducer

  - Provides automatic gain control by means of a self-adaptive gain changer system

  - Provides for manual roll trim inputs

  - Provides for pilot assist functions through the navigation system

  - Has electronic and hydraulic redundancy features like those in the pitch channel

3.3.4 Yaw Channel (Figure 12): The yaw channel system features are summarized below:

- Rudder pedals are connected to the rudder actuator by a system of cables, push-pull tubes, and bellcranks

- Pedal authority may be limited, or full

- Yaw trim actuator is provided for pilot trim

- Yaw damper system

  - Uses fixed gains for each of two configurations

    - Provides stability augmentation, using washed out yaw rate and lateral acceleration signals during the normal configuration

    - Provides adverse yaw compensation (AYC) signals when in the T.O. and LAND configuration

- Has electronic and hydraulic redundancy features similar to those in the pitch channel

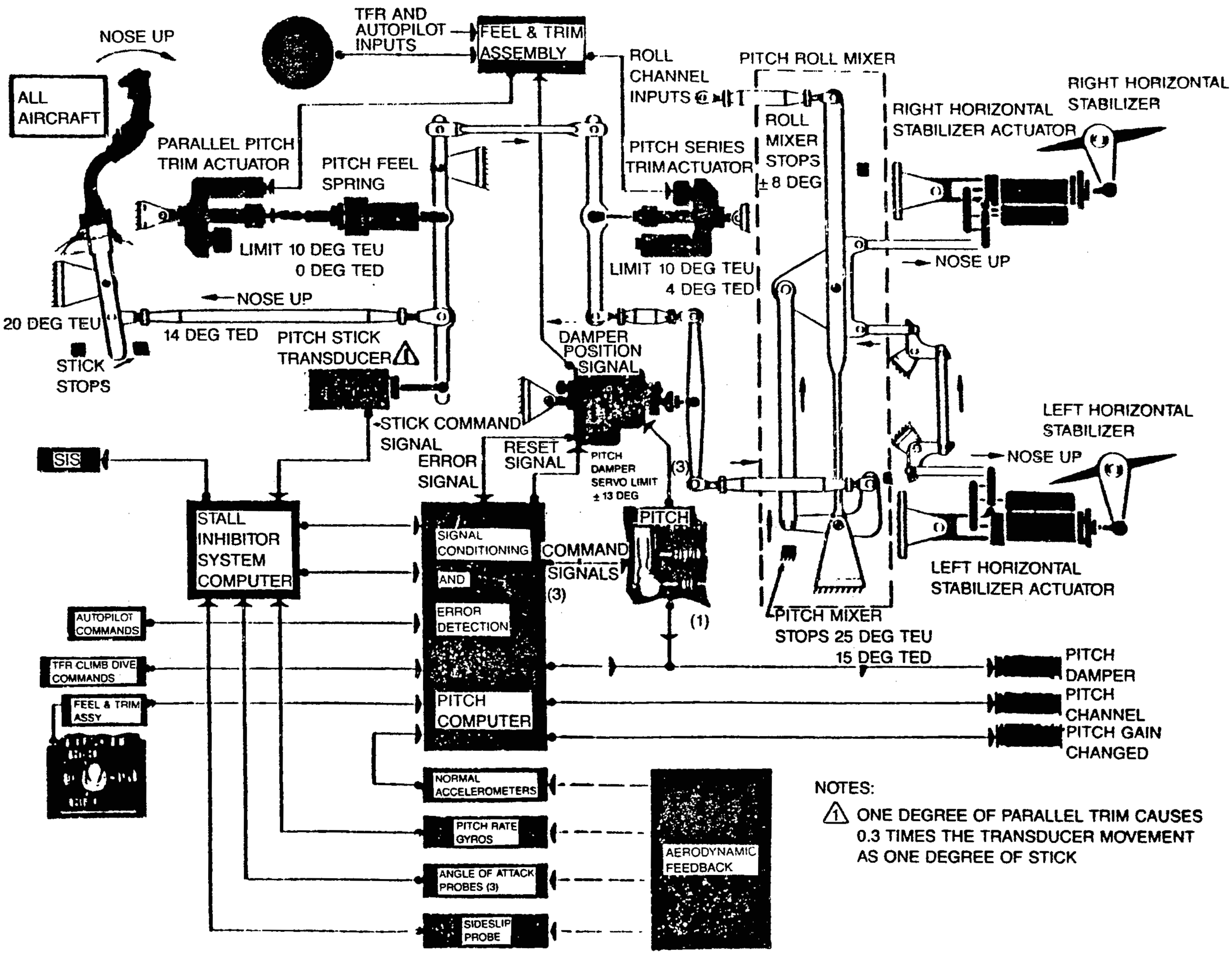


FIGURE 10 - General Dynamics F-111, Pitch Channel Functional Diagram

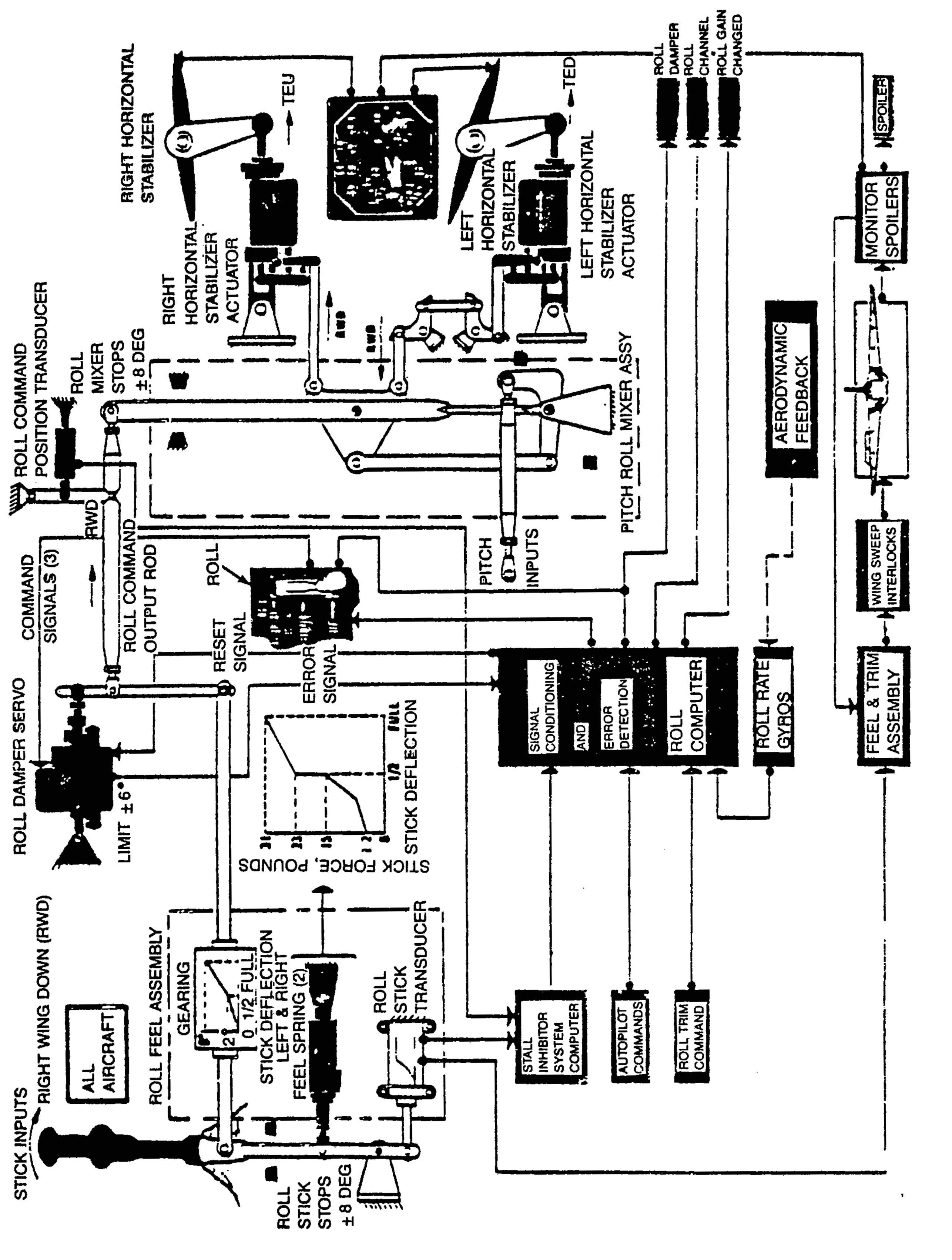


FIGURE 11 - General Dynamics F-111, Roll Channel Functional Diagram

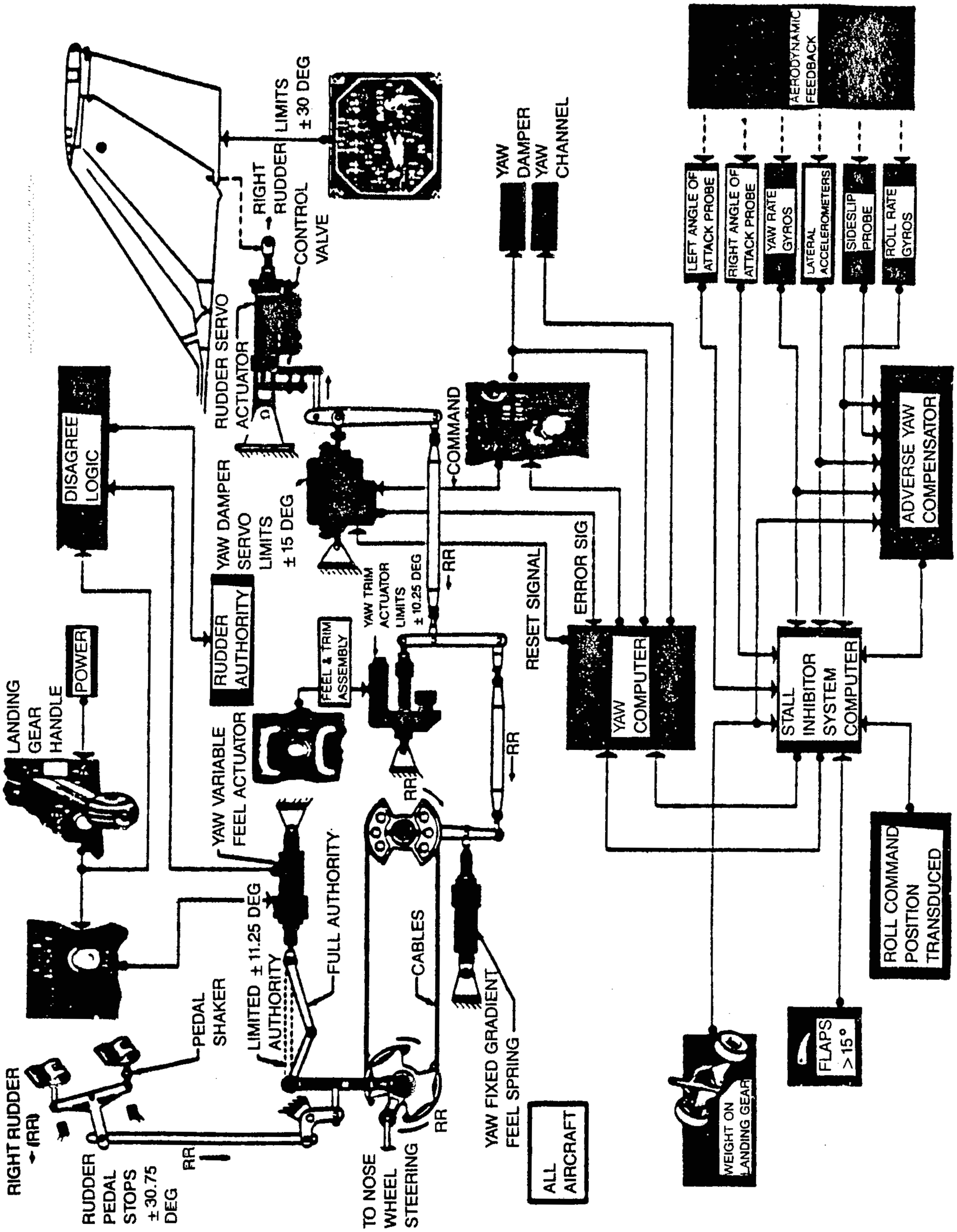


FIGURE 12 - General Dynamics F-111, Yaw Channel Functional Diagram

3.4 General Dynamics F-16 Falcon:

3.4.1 General Description of the F-16 Flight Control System: The F-16 fly-by-wire Flight Control System (FLCS) consists of many interacting components, as illustrated in Figure 13. Pilot commands to the FLCS are generated by a sidestick controller, rudder pedals, and switches in the flight control panels. The electrical commands from these cockpit components are fed to the Flight Control Computer (FLCC), which can be viewed as the "heart" of the FLCS. The FLCC also receives aircraft inertial motion inputs from pitch, roll, and yaw gyros and from normal and lateral accelerometers. Additionally, air data information is transmitted to the FLCC after measurement by total pressure, static pressure, and angle-of-attack (AOA) probes; conversion of pneumatic pressure to electrical signals by the Pneumatic Sensor Assembly (PSA); and signal conditioning by the Electronic Component Assembly (ECA). The FLCC combines these inputs through appropriate control laws to produce control-surface commands that position five primary control surfaces through Integrated Servoactuators (ISAs). Primary control surfaces are defined as two flapereons, two all-moveable horizontal tails, and a rudder. The FLCS provides information back to the pilot through various indicator, caution, and warning lights located in the cockpit.

The F-16 also incorporates several secondary control surfaces - the leading-edge flap and speed brakes. The leading-edge flap is driven by a power drive unit that is programmed by the ECA as a function of AOA, altitude, and Mach number to provide optimum wing contour during maneuvering. The two speed brakes are directly controlled by the pilot.

Protection against failure is achieved by redundancy as shown by Figure 14. Critical functions are replicated up to four times in the FLCS. In the event of consecutive component failures, the system can sense the error by comparison of redundant branches and then provide a valid output command by a selection process.

The F-16 FLCS also employs built-in self test to protect against operation with failure. Inherent in the design of the redundancy management system is the assumption that it is working properly. One of the primary functions of built-in self test is to check the capability of the redundancy management system to detect and correct failures.

Figure 15 is a schematic of the F-16 pitch axis, which shows the system redundancy levels. The pitch axis is the most critical on the F-16 because of the longitudinal static instability of the aircraft. This figure shows two of the most critical parts of the redundancy management system of the F-16 FLCS. The first is the signal "selector". This device selects a good electronic channel even after two consecutive electronic branch failures. The evolution of the selector design was a significant part of the development of the F-16 analog fly-by-wire FLCS. The second critical part of the redundancy management system is the electrical-to-mechanical interface provided by the servoamplifier monitor system and the self-contained hydromechanical failure detection and correction logic in the ISA.

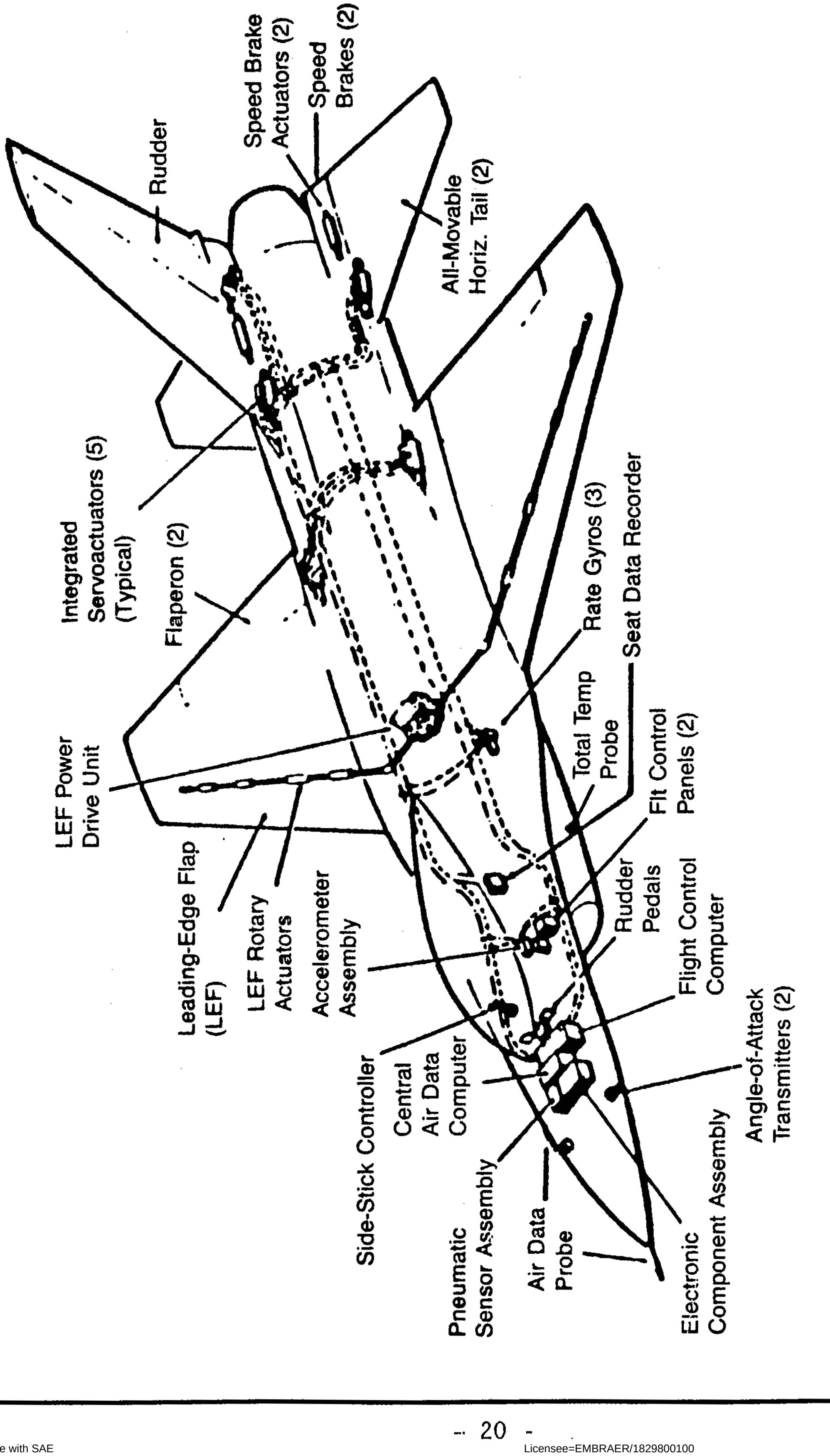


FIGURE 13 - General Dynamics F-16 Falcon, Flight Control System Components

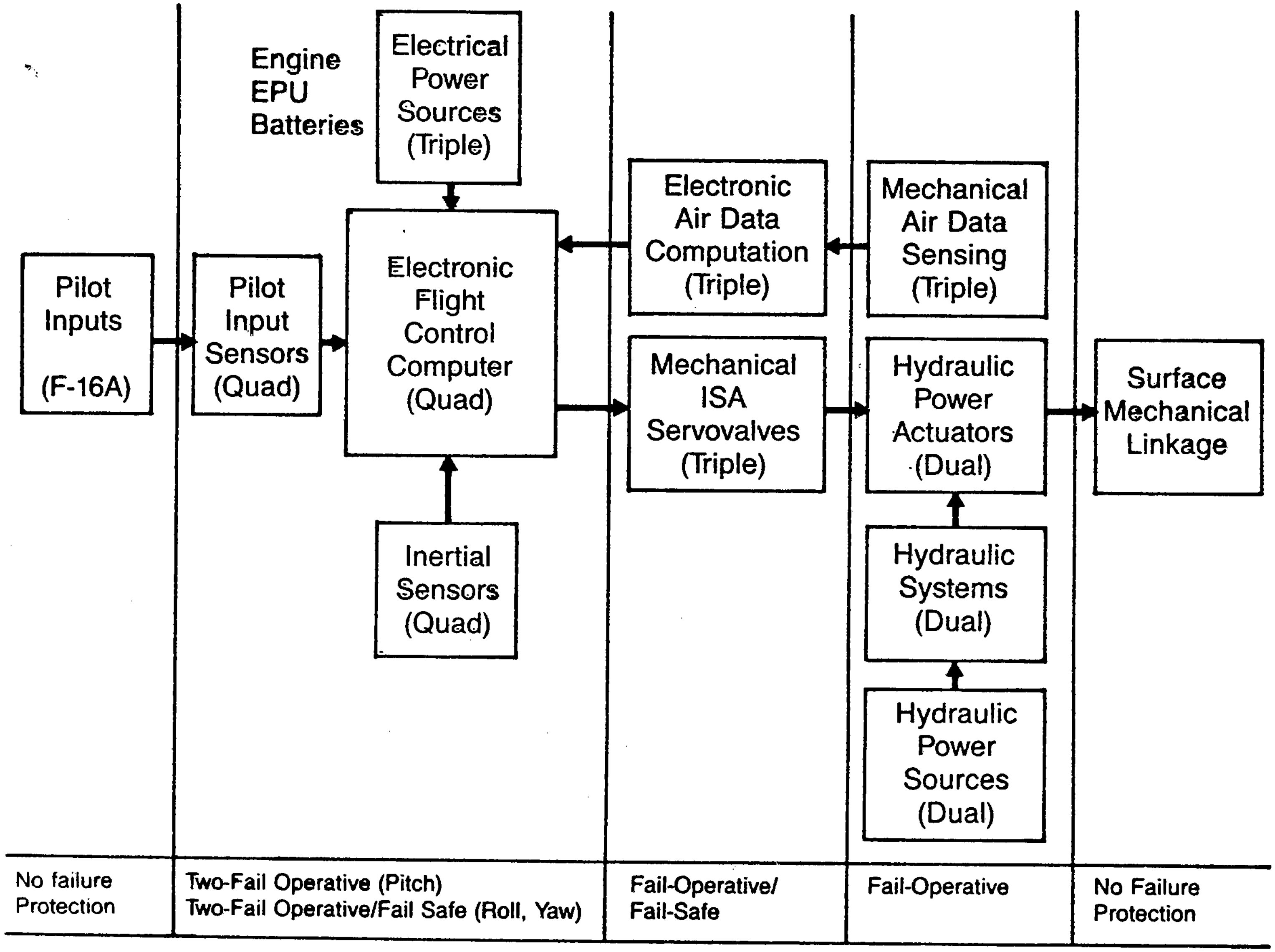


FIGURE 14 - General Dynamics F-16 Falcon, Redundancy & Failure Protection Levels

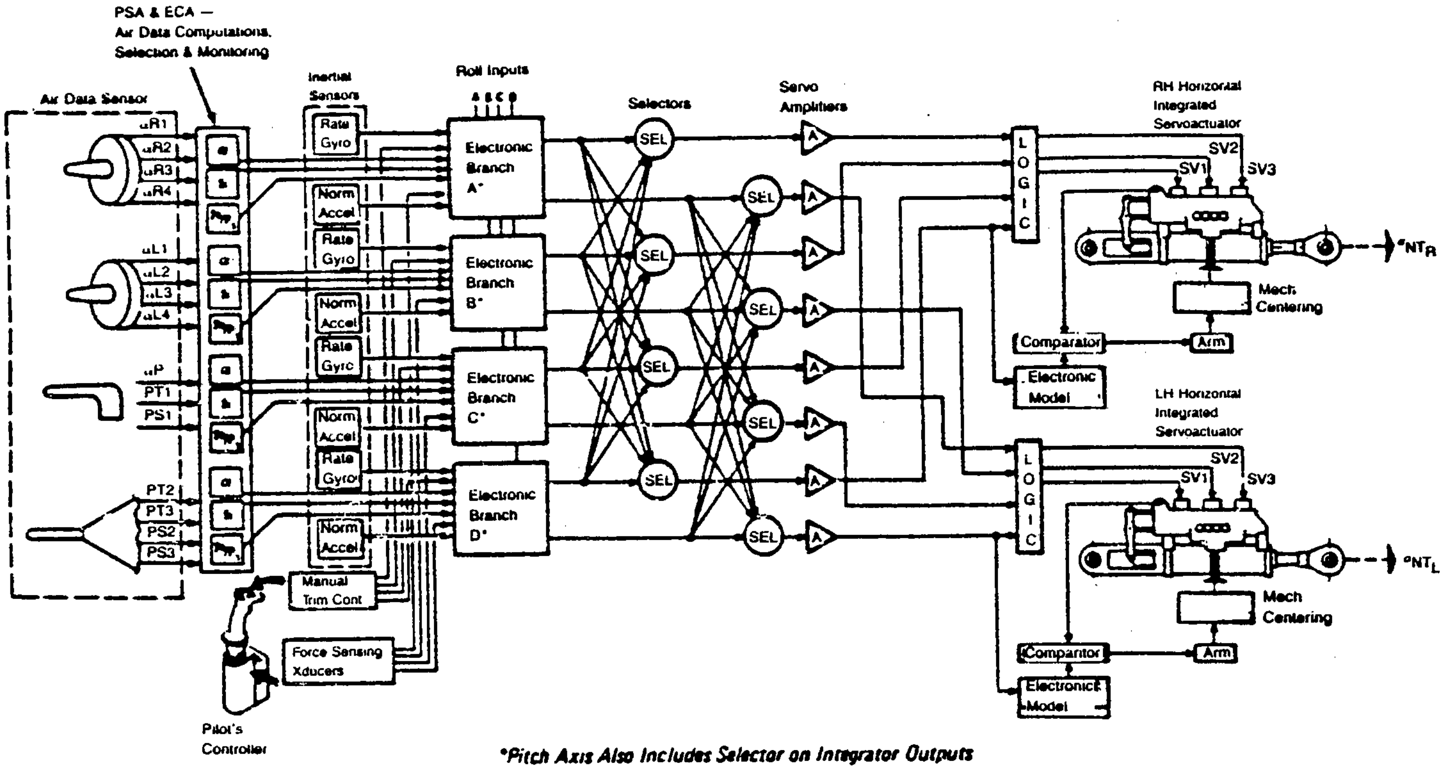


FIGURE 15 - General Dynamics F-16 Falcon, Pitch Axis Electronic Redundancy

3.5 Grumman A-6E Intruder:

The A-6 is a medium-size, all weather, low altitude, two place attack aircraft (Figure 16) capable of high performance and broad mission versatility including tanker capability. The aircraft utilizes a mechanical primary flight control system. An automatic flight control system is integrated with the overall primary control system so as to provide pilot selectable airframe stability augmentation, automatic attitude heading, altitude or mach hold control and automatic carrier landing.

3.5.1 System Description: The primary controls are type III, a power-operated irreversible control system, wherein the pilot through a set of mechanical linkages, provides inputs to actuate power control servoactuators which in turn actuate the main control surfaces of the aircraft. The power control servoactuators are designed for either manual or automatic inputs. Aircraft control is effected by moving flaperons for lateral control, a rudder for directional control and an all moveable stabilizer for longitudinal control.

The actuators are serviced by two separate hydraulic systems, each powered by two pumps. One system, designated the flight hydraulic system, is devoted completely to the primary flight control actuators. The other system, designated the combined system, services everything including the primary flight control actuators. Failure of either system has no effect on the primary flight controls. In the event of a dual engine failure, the windmilling engines will provide sufficient power for the control actuators to effect a safe descent and emergency landing.

3.5.2 System Mechanization: The longitudinal control system (Figure 17) is designed to provide nonlinear stabilizer motions for aircraft up and away flight and powered approach (P/A) configurations with the stabilizer gearing and full throw positions shifted as a function of wing flap deflection. Position signals are conveyed through a mechanical linkage consisting entirely of pushrods and bellcranks. Artificial feel is accomplished through the use of bobweights, a spring bungee, and a sprashpot. The bobweights generate forces proportional to aircraft normal and pitching accelerations, while the spring bungee forces are proportional to control stick displacement. The sprashpot generates damping forces proportional to the mechanical control system velocity to minimize the effects of coupling between control system and airplane natural frequencies. The pitch actuator is a dual tandem arrangement with a manual input and a series electrohydraulic servovalve with mechanical feedback. The actuator is capable of three modes of operation, manual, series, and parallel. In the manual mode, pilot inputs alone control the power valve. In the series mode, upon engagement of the series mode solenoid, electrical signals from the Automatic Flight Control System (AFCS) drive the electrohydraulic servo ram in series with the pilot inputs. Series input signals are limited to $\pm 1.2°$ of surface motion (Figure 18).

3.5.2 (Continued):

The lateral control system (Figure 19) is designed to provide near linear flaperon surface upward motion to an effective surface position of 49.5° for 4.5 in of control stick motion to each side of neutral. Control motions are transmitted through a series of pushrods and bellcranks to secondary electrohydraulic actuator. Control surface motion is effected by a power actuator located in each wing. The secondary actuator may operate in either a manual or series mode. In the manual mode, the actuator acts as a rigid link, directly transmitted control stick motions to the output lever and onto the surface power actuators. In the series mode, the solenoid valve is energized to sum electrical signals with mechanical control stick signals. The output divides into the left and right wing to the flaperon power control actuators which drive both the inboard and outboard flaperon. Artificial feel consists of a spring bungee to provide forces proportional to displacement and an eddy-current damper to minimize coupled aircraft motion and pilot-induced oscillations.

Directional control of the aircraft is effected through a single rudder. Rudder control is effected by a single power actuator located at the rudder surface. Pilot input to the rudder is via mechanical linkages. Rudder displacement is limited as a function of flap position. The power actuator operates in manual and series modes with surface authority limited in series (Figure 20).

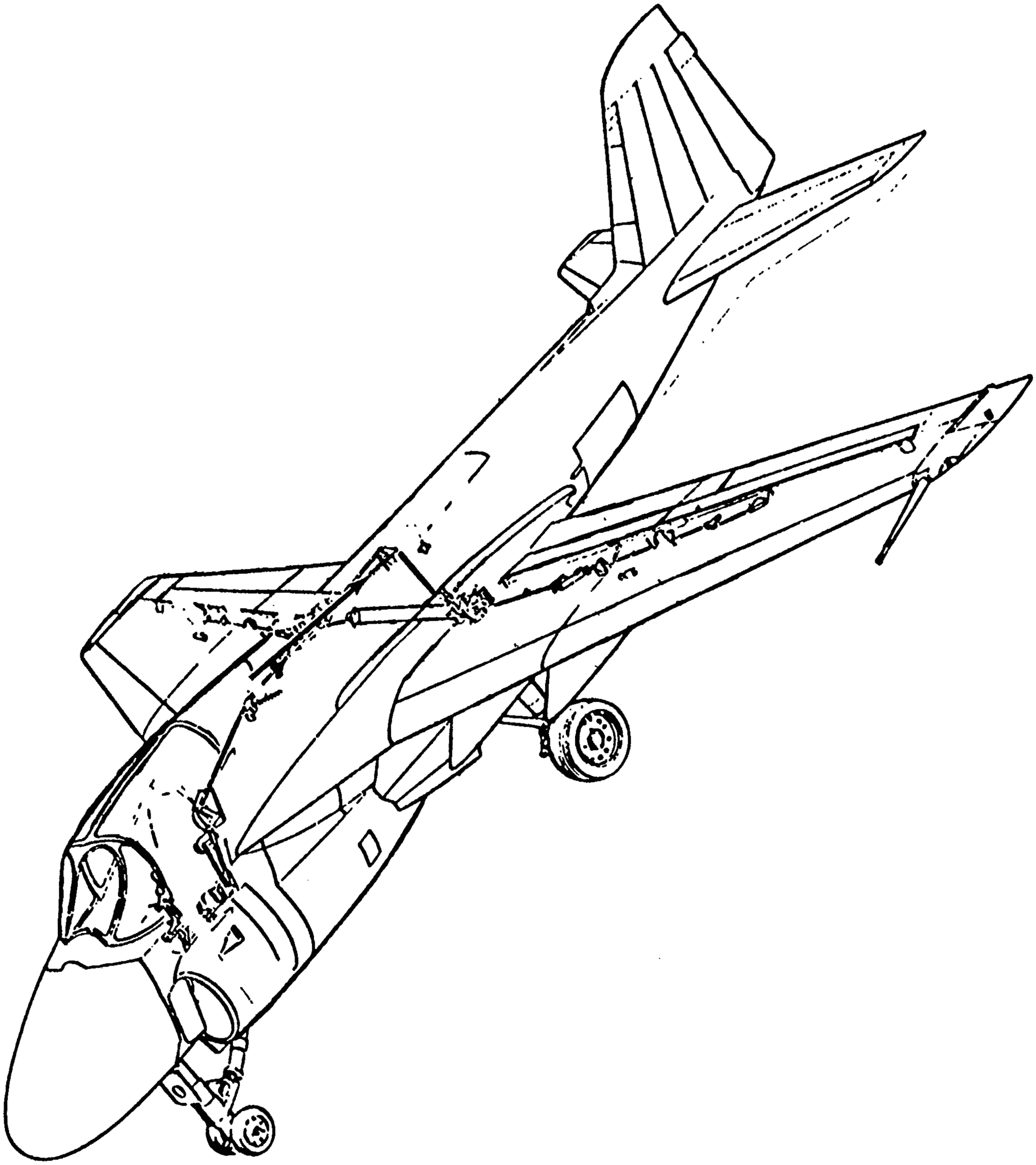


FIGURE 16 - Grumman A-6E Intruder

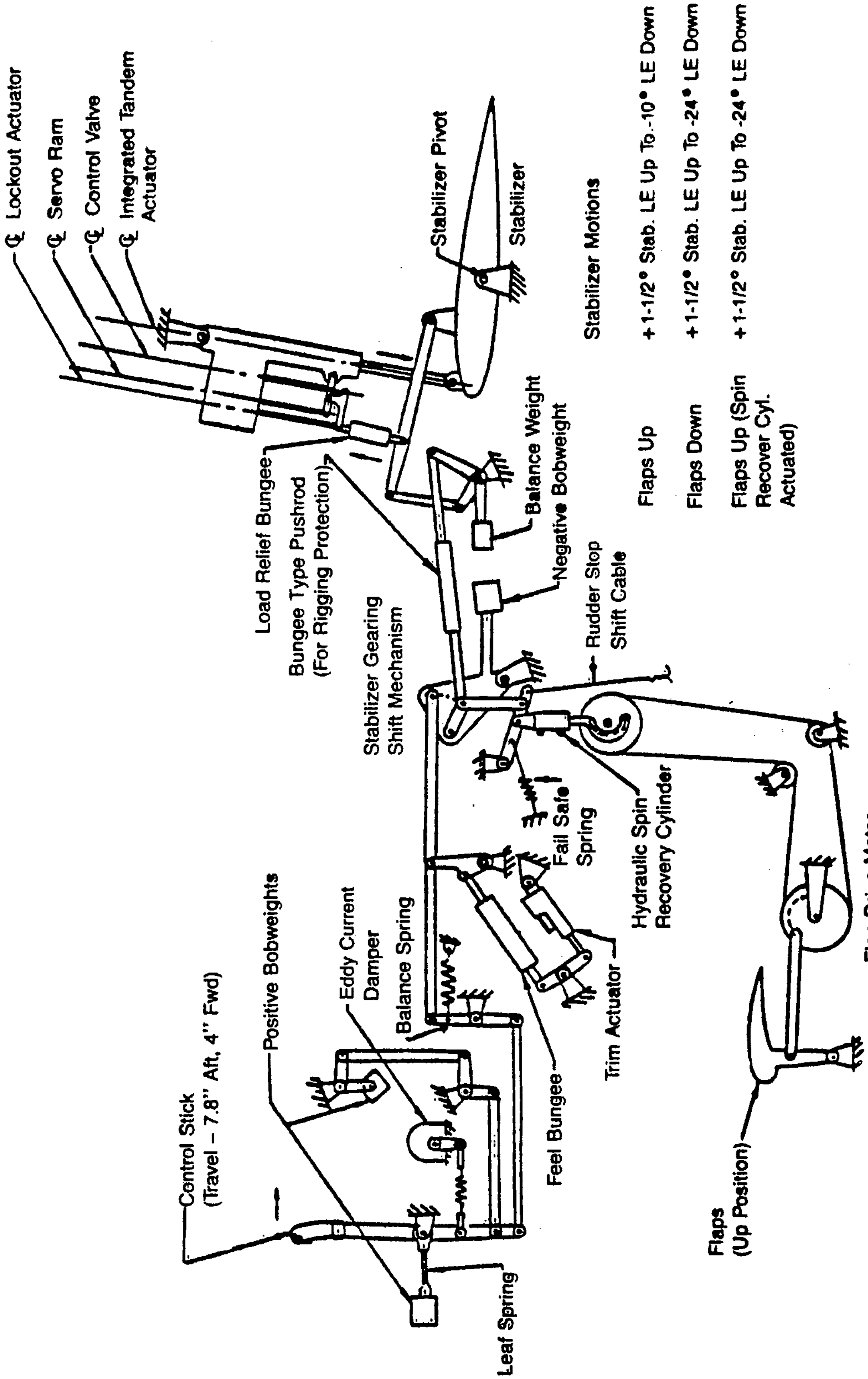


FIGURE 17 - Grumman A-6E Intruder, Primary Control System - Simplified Longitudinal Schematic

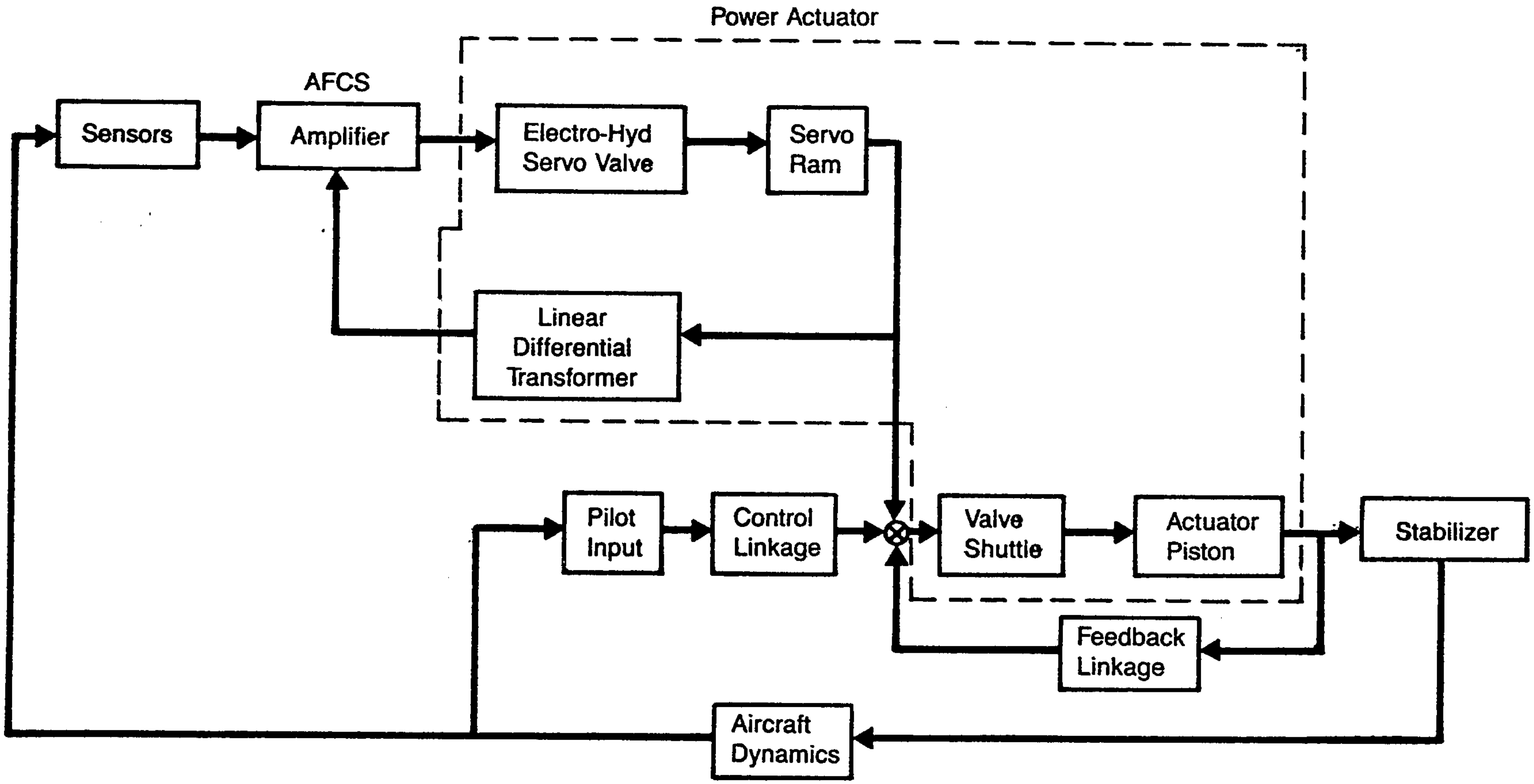


FIGURE 18 - Grumman A-6E Intruder, Longitudinal Control System Series Mode Operation

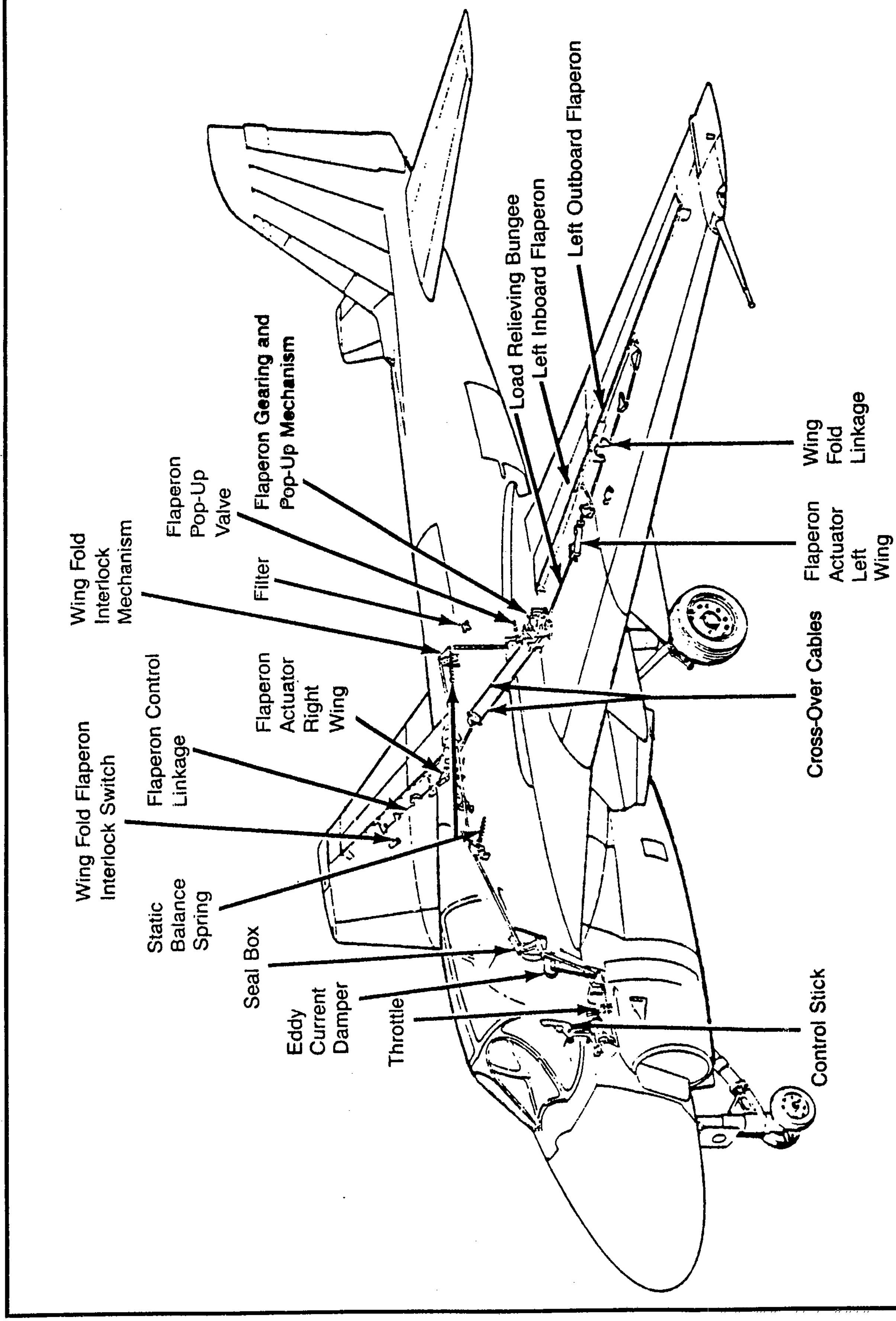
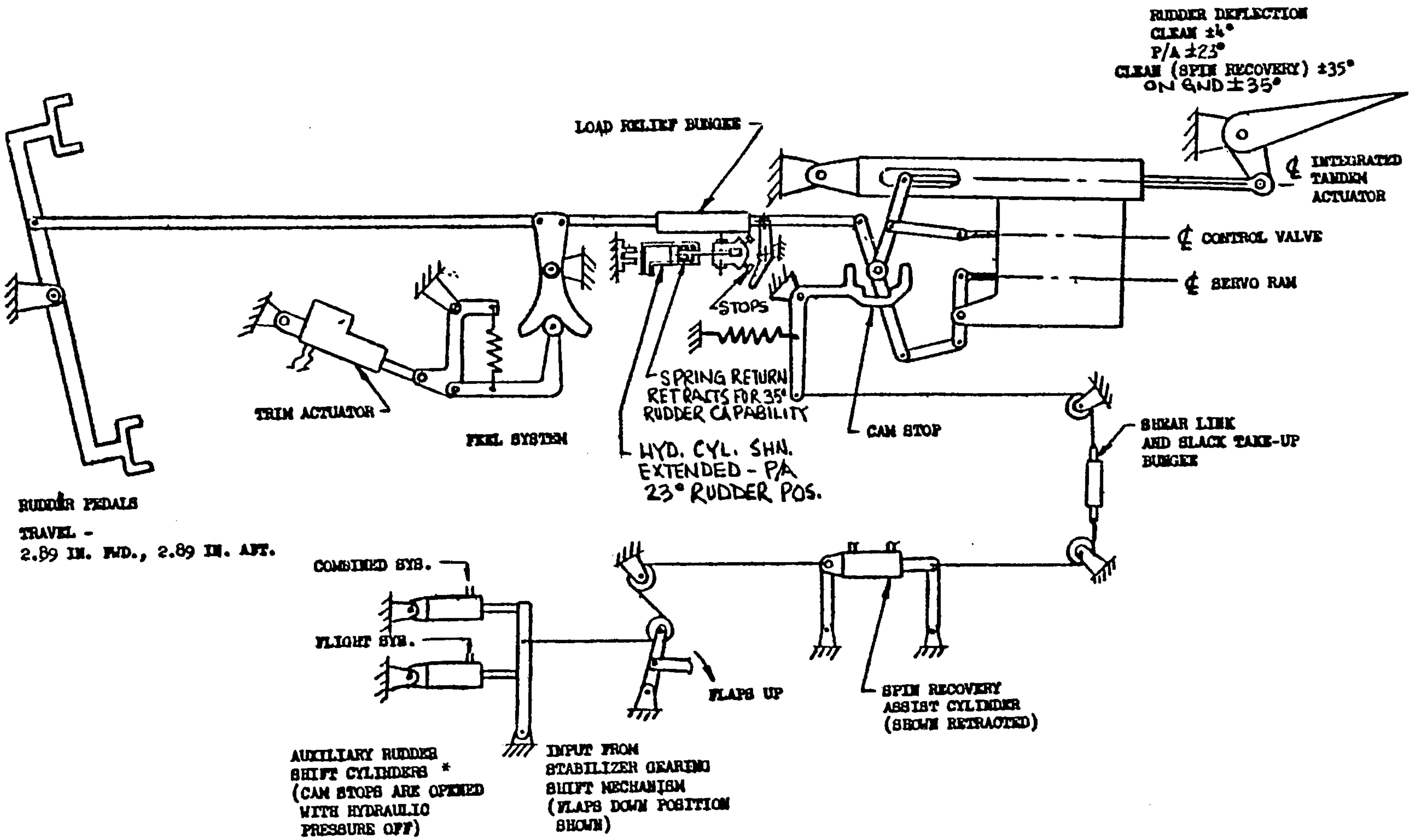


FIGURE 19 - Grumman A-6E Intruder, Lateral Control System



* EARLY AIRCRAFT WILL HAVE CABLE GROUNDED AT THIS POINT

FIGURE 20 - Grumman A-6E Intruder, Directional Control System Schematic

3.6 Grumman F-14 Tomcat:

The Grumman F-14 Tomcat is a variable sweep air superiority fighter utilizing a type III mechanical-power augmented flight control system with integral stability and command augmentation (SAS & CAS). A dual-channel, fail-safe stability augmentation system (SAS) is employed in pitch and roll and a three channel fail-operational SAS in yaw. The control system allows for operation at subsonic and supersonic flight while providing performance and agility characteristics necessary for close in air combat superiority.

3.6.1 System Description: The F-14 control system encompasses the use of automatically programmed variable wing sweep along with twin rudders and all moveable horizontal stabilizers for pitch and roll control and wing spoilers for low speed roll performance enhancement. Wing leading and trailing edge flaps are automatically programmed for maneuver enhancement and automatic scheduling of the wing is programmed as a function of speed and altitude. This Mach Sweep Programmer allows utilization of all the inherent advantages of a variable sweep rather than limiting combat operations to a fixed wing sweep position.

Each vertical tail is toed-in 1° and has a 30% chord full span rudder. Rudder deflection is limited thru an infinitely varible device which is controlled as a function of aircraft speed and altitude. The all-moveable horizontal stabilizer can be deflected symmetrically between 10° TED and 33° TEU for pitch control and differentially ±12° for roll control. Maximum deflections are limited to 15° TED and 35° TEU. Additional roll control is provided by four wing spoilers for wing sweep angles less than 57°.

Stability augmentation and other automatic functions to the primary control surfaces are processed through the Automatic Flight Control system (AFCS). These functions are roll command augmentation (CAS), pitch, roll and yaw stability augmentation, automatic rudder interconnect (ARI), pitch/roll autopilot, Mach trim control, spoiler control, roll and yaw authority controls and built-in test (BIT). The system consists of: dual roll and pitch rate gyros, three yaw rate gyros, three lateral accelerometers, three AFCS computers (pitch, yaw, roll), and one AFCS control panel.

3.6.2 F-14 Flight Control Systems Mechanizations: Control stick motion is transmitted to the hydraulic power actuator via a completely mechanical linkage arrangement (see Figure 21) consisting solely of pushrods and bellcranks to the pitch roll/mixer where it branches to the port and starboard stabilizer actuators. The longitudinal control system is designed to provide nonlinear stick to stabilizer relationship so that stick sensitivity levels provide acceptable aircraft handling qualities.

3.6.2 (Continued):

Artificial feel is provided to the pilot through a spring-loaded cam and roller assembly, fore and aft bobweights and a sprashpot. The assembly is designed to provide distinct breakout force plus two force gradients over the range of control stick displacement. The bobweight function provides the pilot with normal acceleration force cues. The sprashpot (eddy current damper) augments control system damping by generating forces proportional to the control stick velocity.

Lateral control (Figure 22) of the aircraft is effected by differential displacement of all the moveable horizontal stabilizer where full stick displacement provides ±7° differential horizontal stabilizer. The SAS/CAS provides an additional ±5° differential via the AFCS. Four sets of spoilers, commanded differentially, assist in roll control for wing sweep positions of less than 57°. During power approach (flaps down), vertical glide path correction (Direct Lift Control) can be made (at pilot option) by proportional symmetric displacement of all the spoilers without changing angle of attack or engine power settings. Pitching moments generated by symmetrical spoiler deflection are compensated by coupled symmetrical horizontal stabilizer deflection.

A mechanical pitch/roll mixer assembly algebraically sums pitch and roll commands, and a lateral authority control device restricts differential commands to the stabilizer as a function of dynamic pressure.

Full rudder pedal corresponds to proportional full deflection of the dual rudders. The artificial feel system mechanized by a spring roller-cam assembly is mechanically similar to the longitudinal feel system. The feel spring force gradient is nonlinear with the force rate decreasing with increasing pedal displacement. A rudder pedal shaker motor emitting high frequency, low amplitude oscillations via a shaker mass imbalance to the left rudder pedal is installed to warn the pilot of excessive angle of attack during approach. Infinitely variable rudder stops restrict the rudder pedal travel as a function of dynamic pressure (Figure 23).

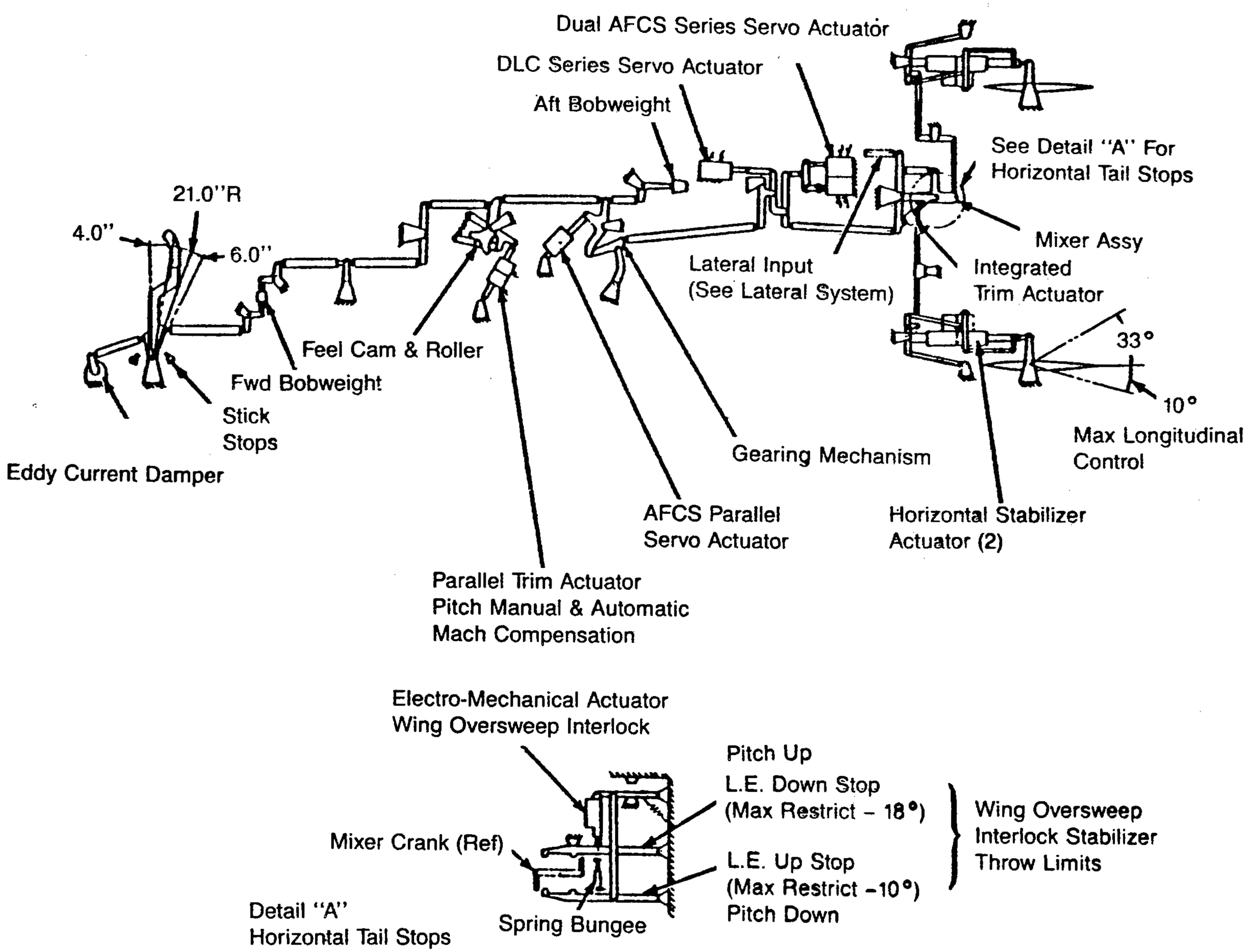


FIGURE 21 - Grumman F-14 Tomcat, Longitudinal Control System Schematic

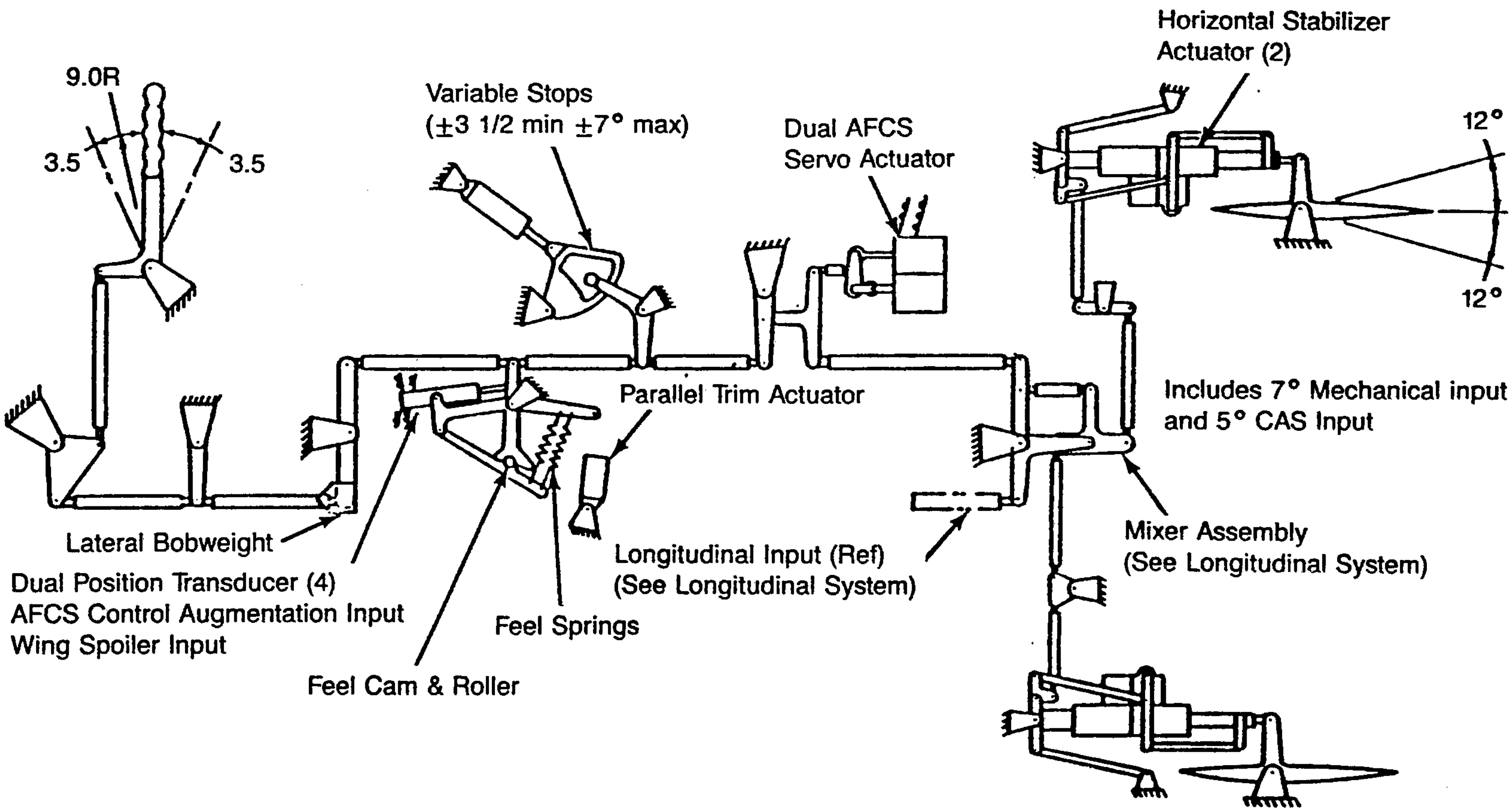


FIGURE 22 - Grumman F-14 Tomcat, Lateral Control System Schematic

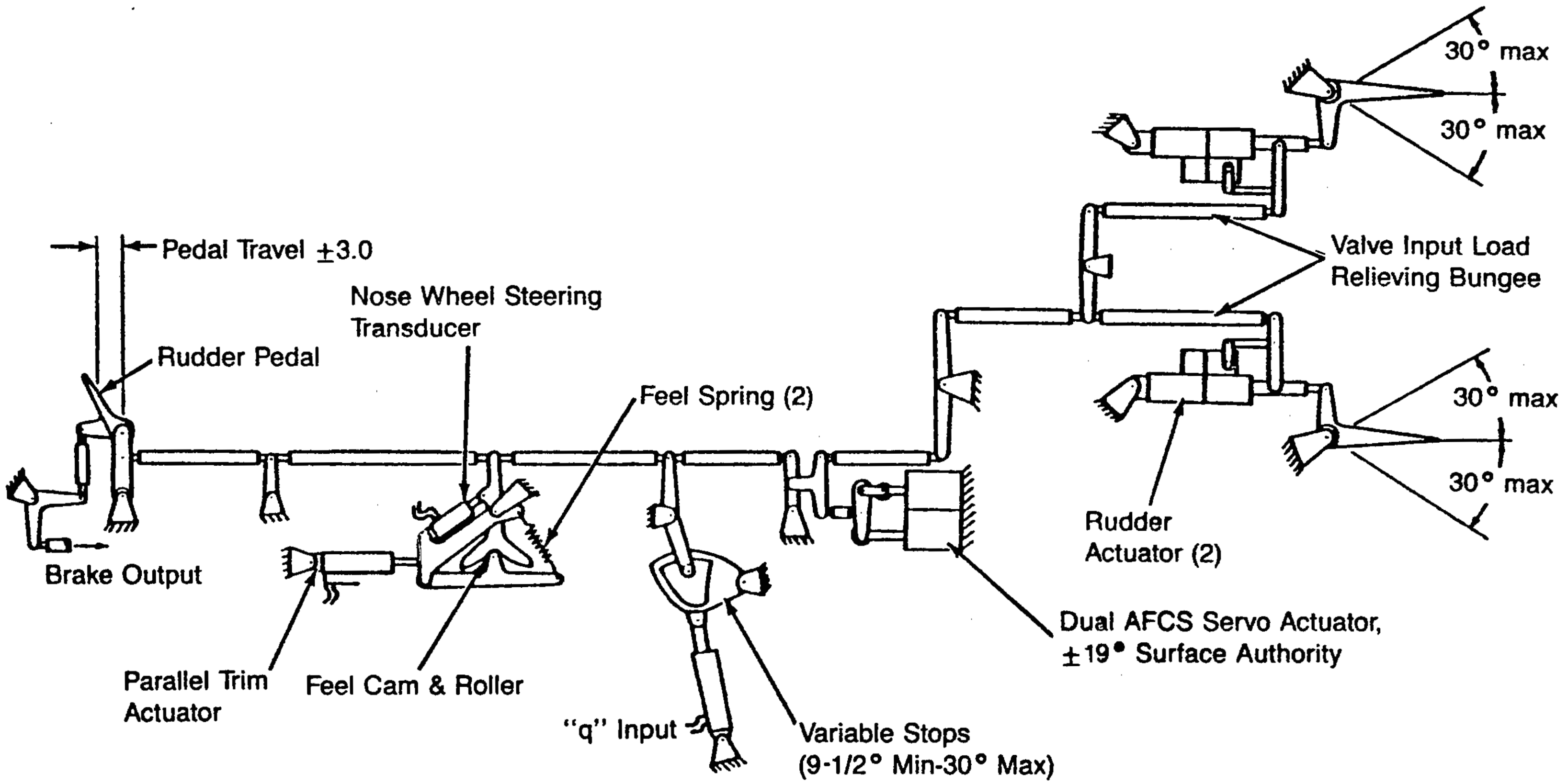


FIGURE 23 - Grumman F-14 Tomcat, Directional Control System Schematic

3.6.2 (Continued):

The Stability Augmentation System (SAS) assists the natural damping of the aircraft. The pitch SAS augments the basic airframe characteristics by providing proportional, closed loop, position control of dual electrohydraulic series servoactuators. The demodulated phase sensitive dc signal of the gyro proportional to pitch rate is fed to a high pass washout filter. The filter prevents the passage of steady state signals representing pitch rate. This permits the pilot to command steady state pitch rates with the SAS damping higher perturbations. Dual channels with cross-channel monitoring and in-line servo monitors are used. In addition to SAS, the roll AFCS provides roll command augmentation (CAS). The command roll rate is compared to the sensed roll rate and their difference is amplified and applied to the roll series servoactuator.

3.7 Grumman X-29A:

The Forward Swept Wing (FSW) X-29A (Figure 24) aircraft is a technology demonstrator incorporating the latest technology in several aspects of its design. The aircraft has been configured by arranging an optimized FSW/all-moveable canard combination on a fuselage that utilizes an F-5A forward module and a new design for the engine ducts and the mid/aft fuselage. This arrangement allows the all-moveable canard to interact with the forward swept wing to minimize trimmed drag over the flight Mach range, and results in a configuration with highly relaxed static stability (35% unstable) for the wing-body-canard configuration at subsonic speeds and positive static stability at supersonic speeds.

3.7.1 System Description: The flight control system (FCS) is required to stabilize, as well as control the X-29A aircraft. The FCS is entirely fly-by-wire (FBW) with all commands processed through a triple redundant digital computer with an additional analog backup (see Figure 25). Analog command functions consist of pitch and roll commands with the center stick and yaw command through two pedals. Sensors for the primary FCS are categorized as either vital or nonvital (see Figure 26). Vital sensors include pitch, roll, and yaw gyros, the stick/pedal input command sensors (LVDTs) and the dynamic pressure sensors, since these sensors are required for the FCS reversion operational mode. Other nonvital sensors include accelerator sensors, attitude heading and reference sensors, air data sensors, throttle control sensors, and control surface position transducers. All sensor data is processed through three identical flight control computers (FCC) interconnected to provide triply redundant flight control system operation. The FCCs provide command signals to the control surface integrated servoactuators; canard, flaperons, rudder, and strake flaps.

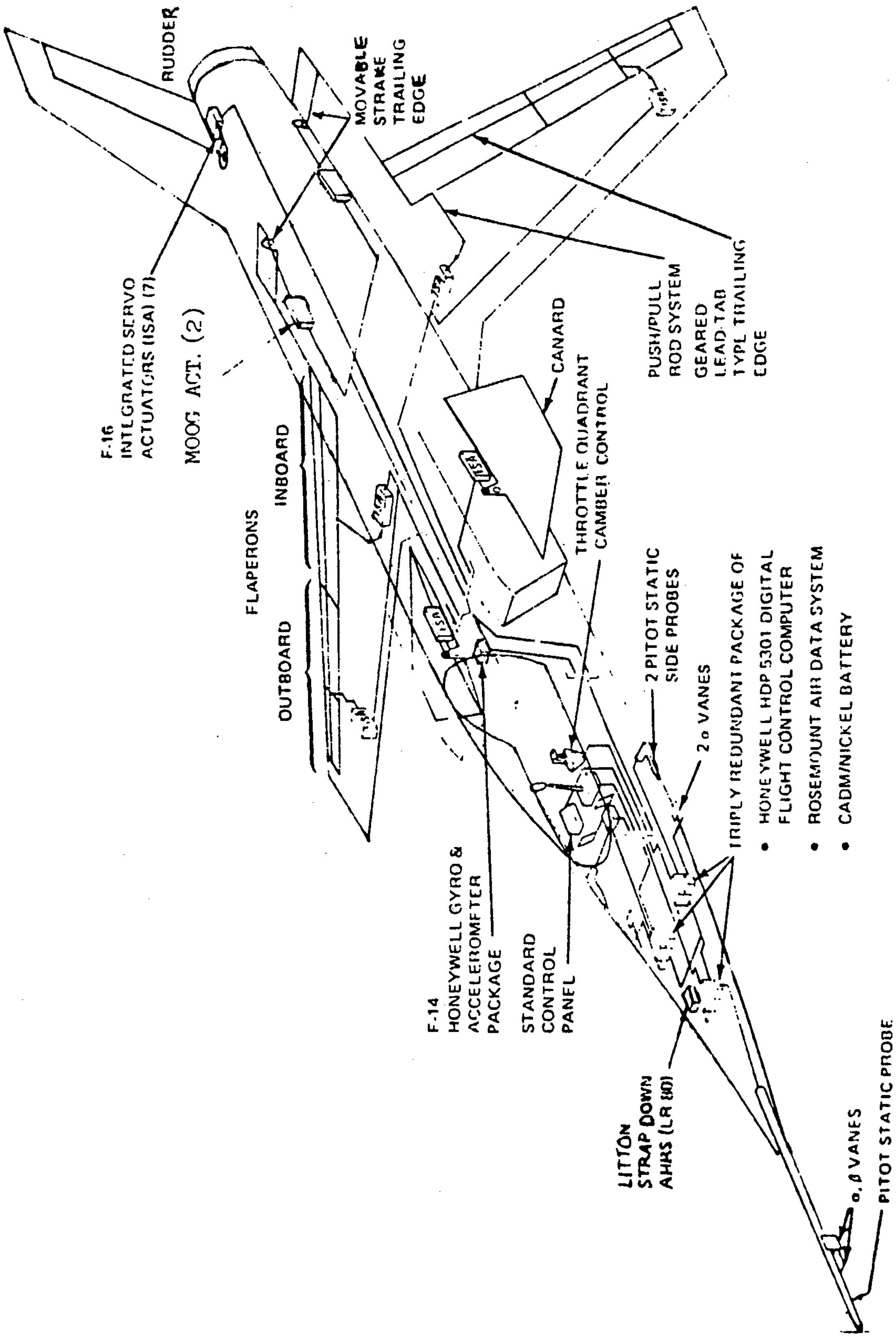


FIGURE 24 - Grumman X-29A

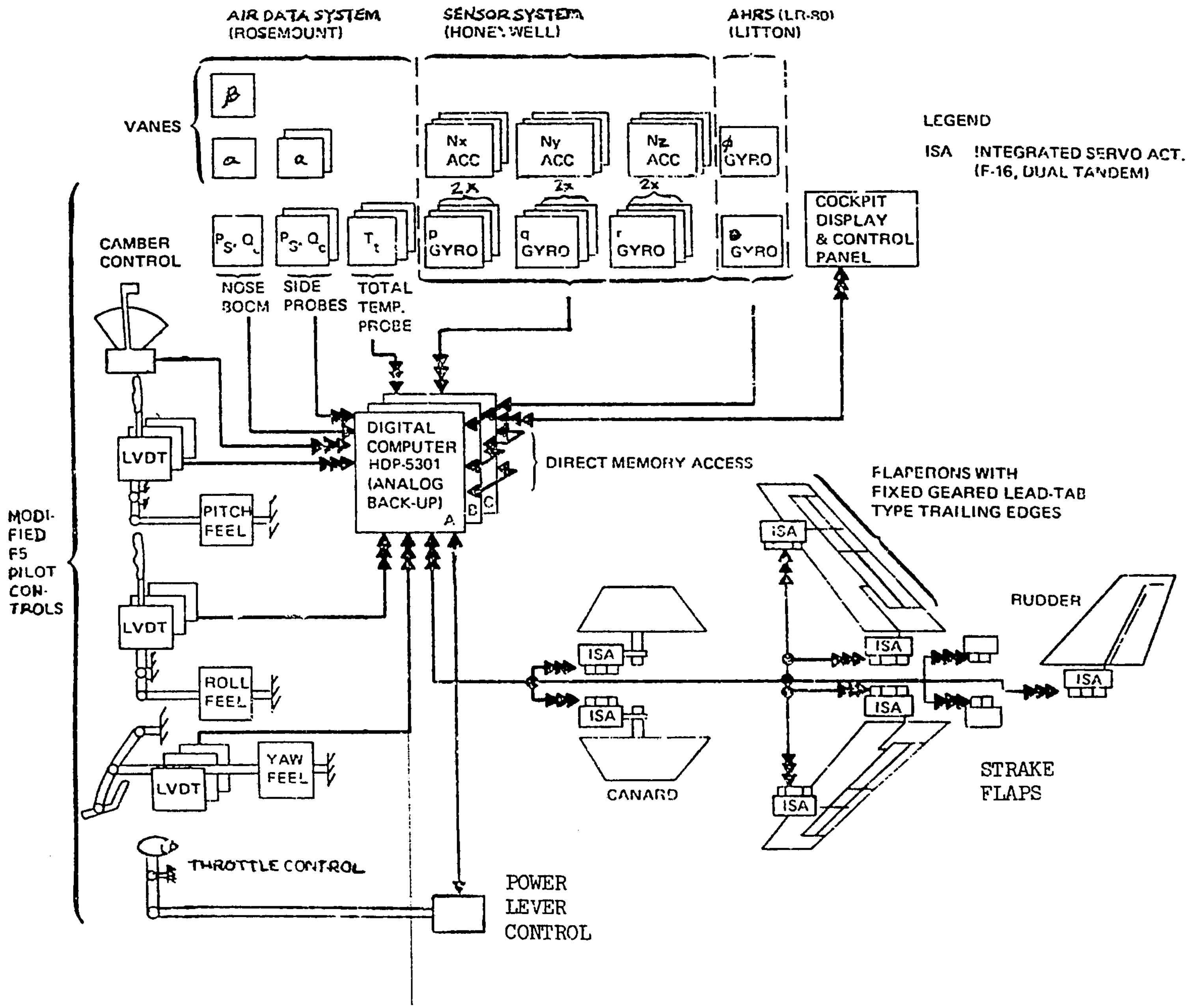


FIGURE 25 - Grumman X-29A Flight Control System

FCC SENSORS

FUNCTION	SENSOR	TYPE	VITAL	NONVITAL	REDUNDANCY
Rates	Pitch Rate Gyro	Rate Gyro	X		Dual Triplex
	Roll Rate Gyro	Rate Gyro	X		Dual Triplex
	Yaw Rate Gyro	Rate Gyro	X		Dual Triplex
Acceleration	Normal Accelerometer	Accel.		X	Triplex
	Lateral Accelerometer	Accel.		X	Triplex
	Longitudinal Accelerometer	Accel.		X	Triplex
Attitude	Pitch Attitude	AHRS		X	Single
	Roll Attitude	AHRS		X	Single
	Heading Attitude	AHRS		X	Single
Stick/Pedal Position	Pitch Position Command	LVDT	X		Triplex
	Roll Position Command	LVDT	X		Triplex
	Yaw Position Command	LVDT	X		Triplex
Air Data	Total Temperature	Transducer		X	Triplex
	Static Pressure (Ps)	Transducer		X	Triplex
	Impact Pressure (qc)	Transducer		X	Triplex
	Angle of Attack	Vane		X	Triplex
	Sideslip	Vane		X	Single
Actuator Position	Canard Actuator Position	LVDT		X	Triplex
	Flaperon Inboard Actuator Position	LVDT		X	Triplex
	Flaperon Outboard Actuator Position	LVDT		X	Triplex
	Rudder Actuator Position	LVDT		X	Triplex
	Strake-Flap Actuator Position	LVDT		X	Triplex
	PLC Actuator Position	RIP		X	Single
Weight on Wheels	Landing Gear Switches	SWITCH	X		Dual Triplex

FIGURE 26

3.7.2 X-29A Flight Control System Mechanization: Longitudinal control stick movement, -4 in forward +6 in aft, is transmitted to a triply redundant LVDT as is lateral and rudder pedal displacement, to produce an electrical signal for the FCC. The pitch stick command varies with altitude and Mach number to be proportional to commanded G's. The artificial feel spring and damper produces a linear force gradient of 4.6 lb/in. Lateral control stick movement of ±3.2 in is nonlinear with roll rate command and a function of several variables including altitude, Mach number, Alpha, and rudder pedal displacement. The artificial feel spring and damper produces a force gradient of 2.5 lb/in. Rudder pedals displace a maximum of ±3.2 in with a linear force gradient of 23.6 lb/in.

Rate and acceleration sensors send electronic signals to the FCCs. Each rate sensor and accelerometer package utilizes three identical sensors to provide triply redundant acceleration and rate sensing. Six rate sensor packages are used, two for each pitch, roll, and yaw. Three accelerometer packages are used. Attitude and heading reference signals produced from inertial sensor mechanisms supply pitch and roll attitude inputs, in synchro format, and heading information to the FCC.

Air data inputs to the FCC supplied from air data sensors include: Static pressure (Ps), Total pressure (Pt), Impact pressure (Qc), Angle of attack (α), Sideslip angle (β), and total temperature (Tt). In addition, triplex-redundant LVDT position transducers supply the FCCs with the positions of the primary flight control surfaces (see Figure 26).

All the data is processed through three identical FCCs and each FCC has the capability to transmit data between the other FCCs. The FCCs provide digital control law computations, air data computations, I/O control, redundancy management, analog reversion circuitry, reversion logic and self test functions. Each control surface and engine power lever is driven by a servoactuator through an FCC interface. The integrated servoactuators (ISA) are a three-stage tandem design that incorporates mechanical feedback. Three, dual-coil electrohydraulic servovalves (EHV) control the main valve operation. The FCCs provide failure monitoring to allow control of the actuator in three operational modes. A differential sensor monitor detects EHV failures, the FCCs provide appropriate signals to a solenoid in each section for ON/OFF control of the EHV pairs. In the event of a primary EHV failure, the second solenoid will activate the standby EHV pair for actuator control in the standby mode. Subsequent EHV failure in the standby section shall de-activate the solenoids control and place the actuator in the safe mode.

3.8 McDonnell Douglas AV-8 Harrier II:

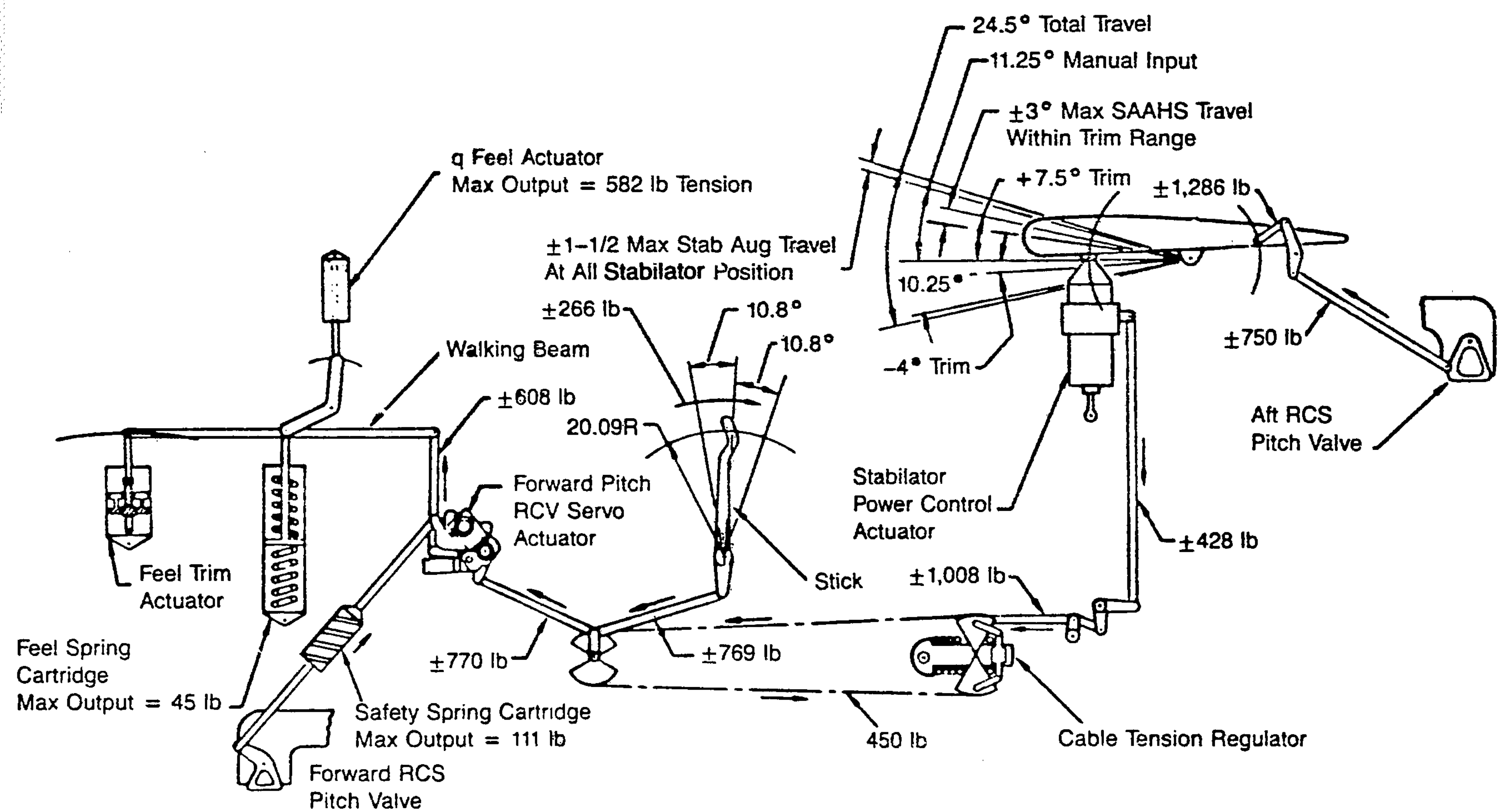
3.8.1 AV-8B Aircraft Flight Control Systems: The AV-8B Harrier II is a V/STOL attack aircraft with a conventional mechanical primary flight control system. An advanced digital electronic flight control system provides the stability augmentation and autopilot functions. The AV-8B digital flight control system is called the Stability Augmentation and Attitude Hold System (SAAHS). This system is a single channel configuration with extensive self-monitoring for fail off operation.

3.8.1.1 System Description: The original approach for the AV-8B automatic flight control system was designed to provide pitch and roll attitude hold along with stability augmentation. This concept provides the SAAHS name for the control system. The design approach was to use the AV-8A and YAV-8B mechanical control system to the maximum extent practicable. The AV-8B has two basic control systems to maintain control of the aircraft throughout the flight regime. The conventional aerodynamic controls consist of an all moveable horizontal stabilator, ailerons and a rudder. These control surfaces are powered by hydraulic power control actuators. The SAAHS stability augmentation series servos are integral with the power control actuators. A V/STOL reaction control system provides control during the jetborne flight phase (hover) and augments the conventional control surfaces during the transition flight phase. The reaction control valves, which emit high pressure air from the engine, are located in the forward and aft fuselage and on each wing tip. The reaction control valves are mechanically linked to the aerodynamic control surfaces.

3.8.2 AV-8B Flight Control System Mechanization: Schematics of the longitudinal, lateral and directional control systems are shown in Figures 27, 28, and 29. The power control actuators are operated either manually by the mechanical control system or by movement of the series servos which are integral with the power control actuators. The reaction control system (RCS) valve shutters are mechanically linked to the control surfaces. The forward longitudinal RCS valve is linked to the pilot's control stick and a forward pitch reaction control valve (RCV) servoactuator provides the SAAHS inputs.

Artificial feel is provided to the pilot throughout the flight regime by double-acting spring cartridges. Dynamic pressure (Q) feel actuators supply additional artificial feel based on signals from the air data computer. Electrically operated trim actuators are provided in the longitudinal and lateral systems.

SAAHS is implemented in a single channel architecture and uses automatic reversion to the mechanical control system upon failure. A block diagram of the SAAHS in Figure 30 depicts the interface with other AV-8B avionics systems, as well as sensors and actuators in the aircraft.



Note: Maximum ult. loads are shown for control rods

FIGURE 27 - McDonnell-Douglas AV-8B Harrier II, Longitudinal Control System Schematic

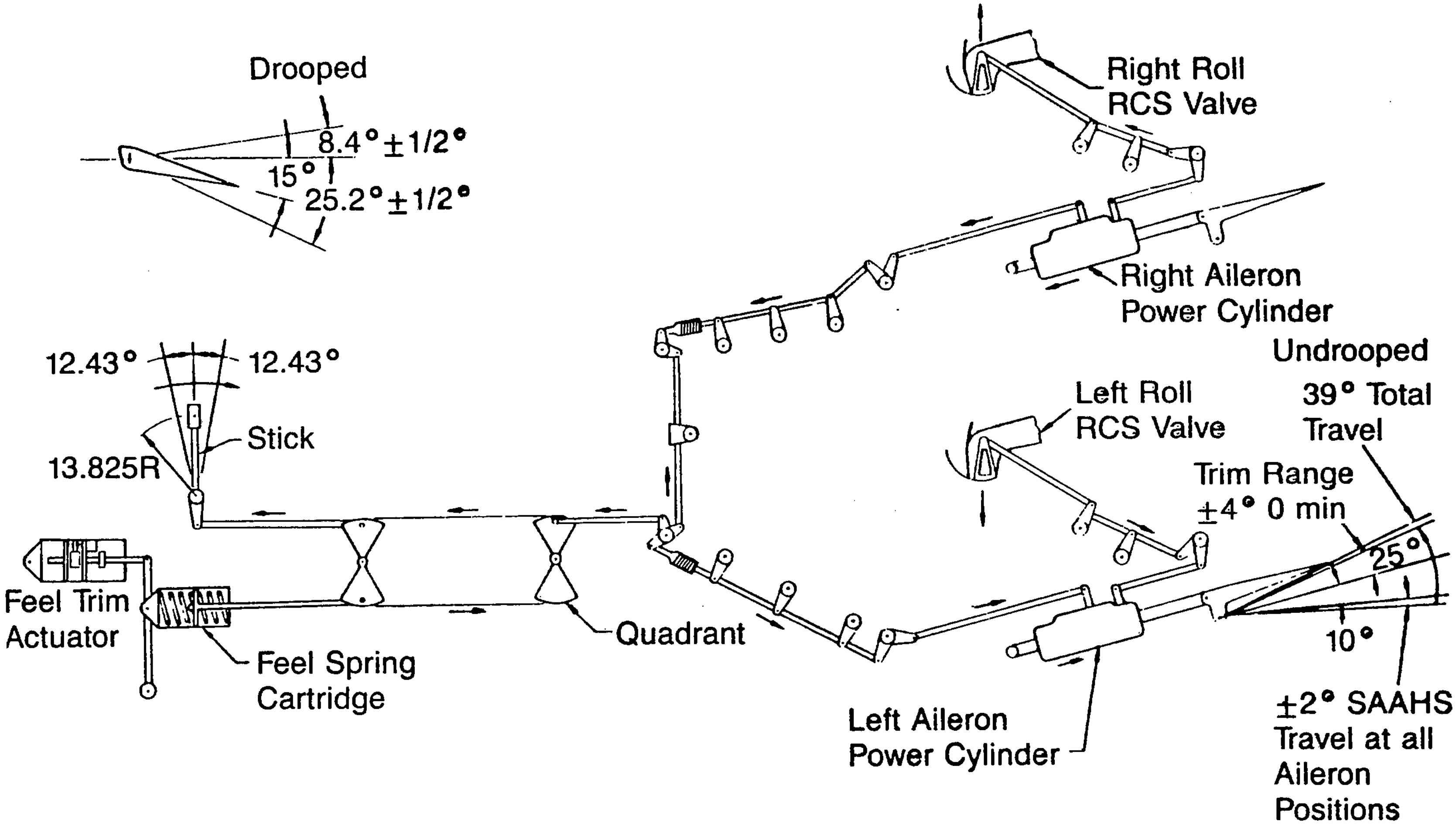


FIGURE 28 - McDonnell-Douglas AV-8B Harrier II, Lateral Control System

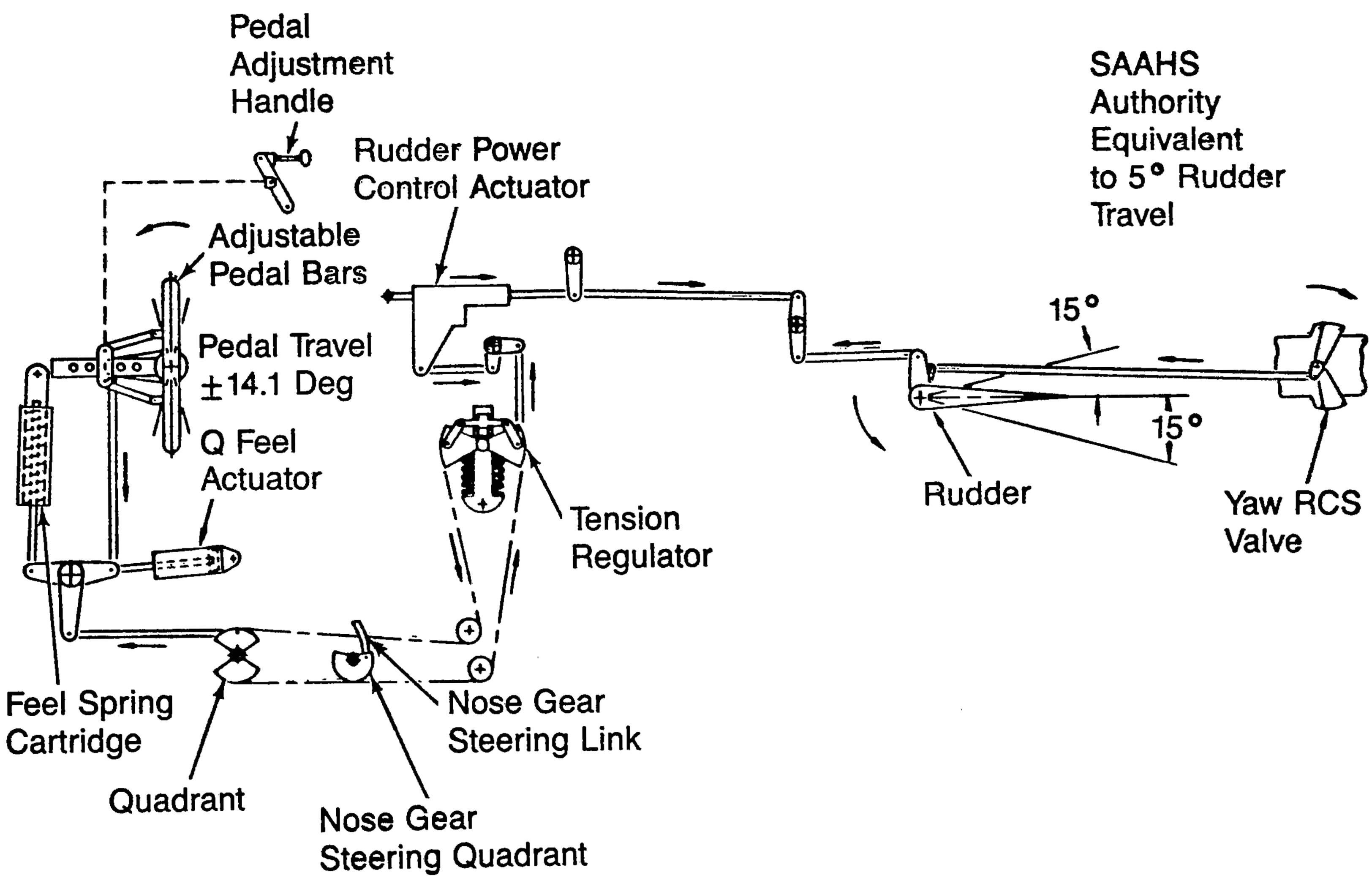


FIGURE 29 - McDonnell Douglas AV-8B Harrier II, Directional Control System

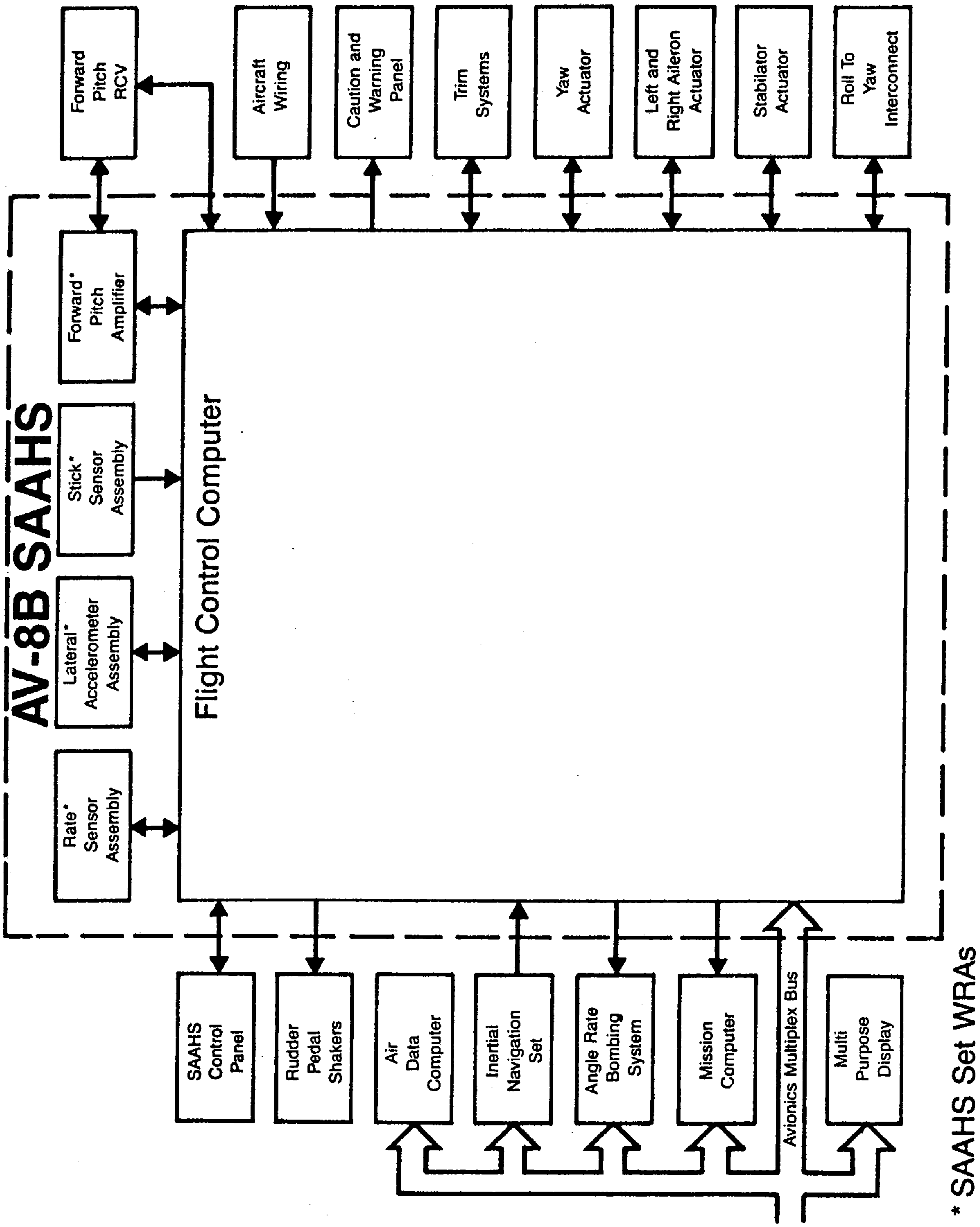


FIGURE 30 - McDonnell-Douglas AV-8B Harrier II, SAAHS Block Diagram

3.8.2 (Continued):

SAAHS operational modes for SAS functions include three-axis rate damping in both vertical and cruise modes and the transition region between these two flight regimes. In addition, SAS functions include rudder/aileron turn coordination enhanced high AOA maneuvering, independent axis engagement, and monitoring. Automatic flight control modes include functions for attitude hold, heading hold, altitude hold, automatic trim, control stick steering, and airspeed scheduled limits. SAAHS control of the AV-8B in all three axes is accomplished through normal aerodynamic surfaces in cruise modes, and by engine bleed air-powered reaction jets in vertical modes. A rudder pedal shaker function warns the pilot of dangerous sideslip in approach and hover.

The heart of the SAAHS system is the digital Flight Control Computer (FCC) which features a 2901 bit slice, 16-bit processor capable of 470 thousand-operations-per-second (kops) with ultraviolet erasable programmable read only memory (UVEPROM). The FCC program consumes 20K words of memory of which 7K words are control law code and 13K words are BIT/IFM. Remaining SAAHS units consist of a three-axis Rate Sensor Assembly (RSA), two Lateral Accelerometer Assemblies (LAA), extended range Roll Rate Gyro Stick Sensor Assembly (SSA), and Forward Pitch Amplifier (FPA).

Due to the weight-sensitive V/STOL application, total SAAHS set weight is approximately 28 lb, with the FCC being only 13.5 lb of this equipment.

3.9 McDonnell-Douglas F-15 Eagle:

3.9.1 F-15A Aircraft Flight Control System: The F-15A Eagle is a high performance air-superiority fighter aircraft. The flight control system is a conventional hydromechanical configuration with an analog dual-channel high-authority Control Augmentation System (CAS). The major factor in the design of the F-15A flight control system was the requirement for the aircraft to meet or exceed Level II flying qualities (MIL-F-8785B) throughout its operational envelope without the aid of electronic augmentation.

3.9.2 System Description: The F-15A flight control system is a hydromechanical configuration with a high-authority control augmentation system. Aircraft primary control is provided by two ailerons, two rudders, and two stabilators. The CAS functions are provided by servos which are integral with the rudder and stabilator actuators.

3.9.3 F-15A Flight Control System Mechanization: Schematics of the longitudinal, lateral and directional control systems are shown in Figures 31, 32, and 33. Meeting Level II flying qualities without electronic augmentation requires a very specialized hydromechanical control system. The heart of this system is the Control Stick Boost and Pitch Compensator (CSBPC). This device contains two major assemblies known as the Pitch/Roll Channel Assembly (PRCA) and the Aileron Rudder Interconnect (ARI). In addition to pilot inputs, these assemblies use information from the pitot and static probes and normal acceleration to adjust the stick to control surface gearing ratios. In the pitch axis, it provides relatively constant stick force per g and pitch trim compensation for disturbances such as speed brake extension, transonic trim change and flap extensions. A roll ratio changer maintains a relatively constant roll response and limits responses which could generate unacceptably high roll accelerations, roll rates, and structural loads. The ARI provides roll coordination at high angles of attack. The CAS, shown in Figure 34, works in conjunction with the hydromechanical control system through series servos in the rudder and stabilator actuators to fine-tune the handling qualities. The CAS accepts inputs from the cockpit controls and motion sensors to compute the commands to the series servos which provide the desired surface deflection and aircraft response. Although CAS does not have full authority over the surface actuators, the actuator mechanical inputs have a detent and the CAS authority is sufficient to fly and land the aircraft in the event of a mechanical failure between the stick and stabilator.

The hydraulic systems incorporate reservoir level sensing and switching valves which result in all actuators having at least two normal sources of hydraulic pressure or a normal source backed up through a switching valve to a second source. The stabilator actuators normally use two hydraulic systems, one of which has an emergency backup. The CAS servos within the stabilator actuators are supplied by the hydraulic system having the backup supply; therefore, two hydraulic failures must occur before the CAS is lost and three failures must occur before total stabilator control is lost.

All of the electrical functions of the primary flight control system can be operated from the primary or emergency electrical busses. If the primary electrical system fails, a hydraulically driven emergency generator is switched into the system using the emergency bus. If all electrical power is lost, the aircraft can be safely flown via the mechanical control system. Electrical power interruptions less than 50 ms have no effect on CAS operation.

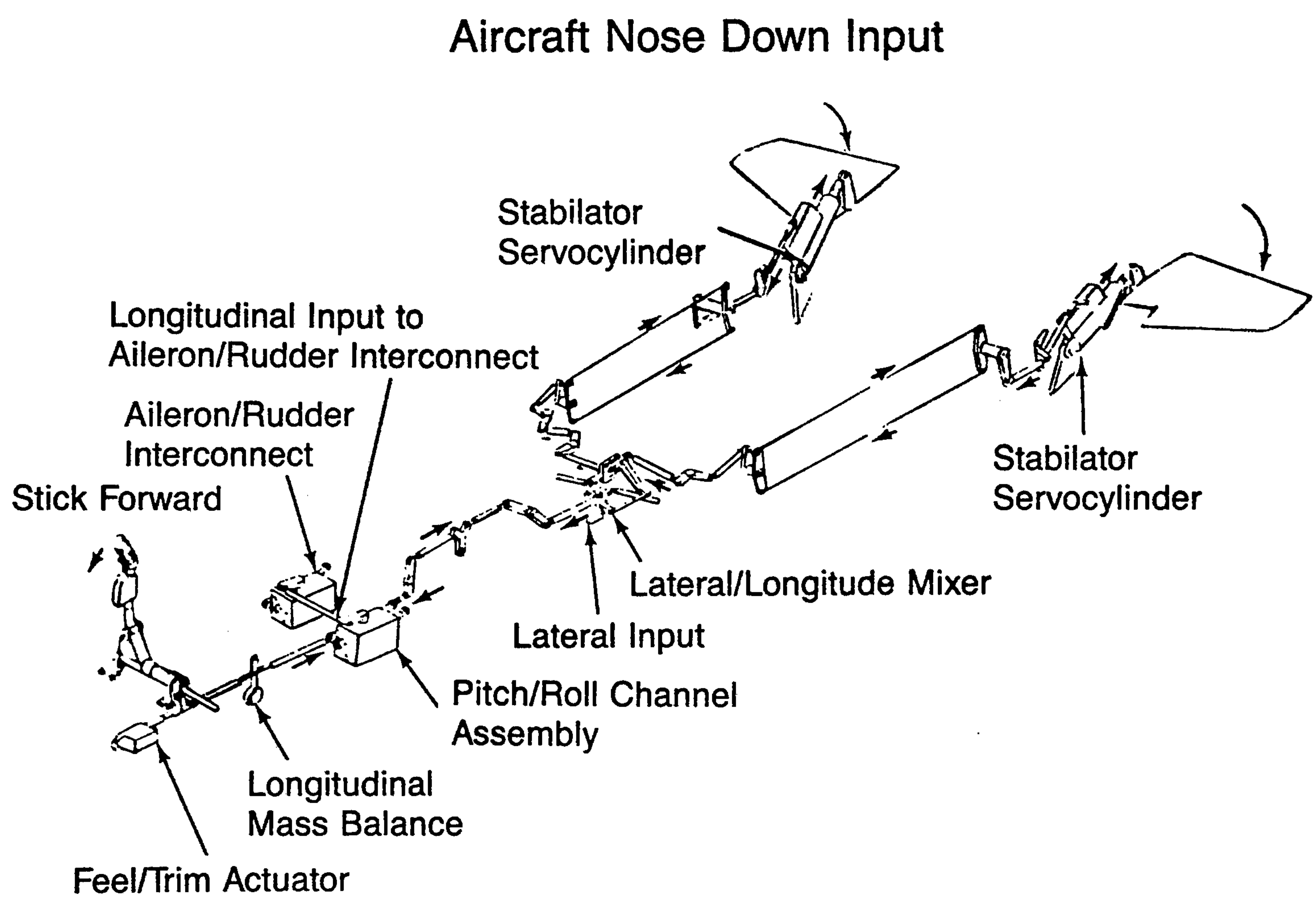


FIGURE 31 - McDonnell-Douglas F-15A Eagle, Flight Control System - Longitudinal Controls

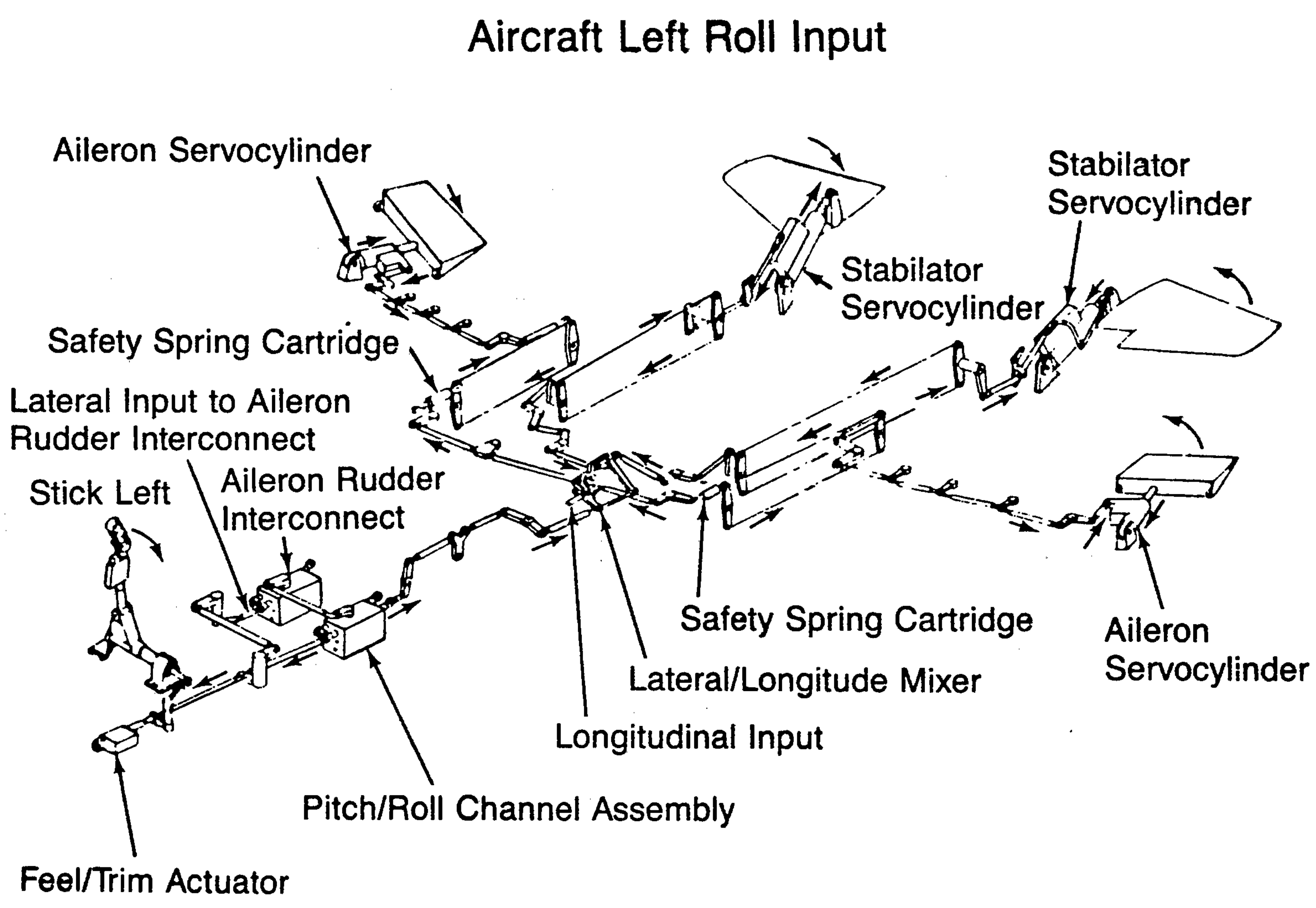


FIGURE 32 - McDonnell-Douglas F-15A Eagle, Flight Control System - Lateral Controls

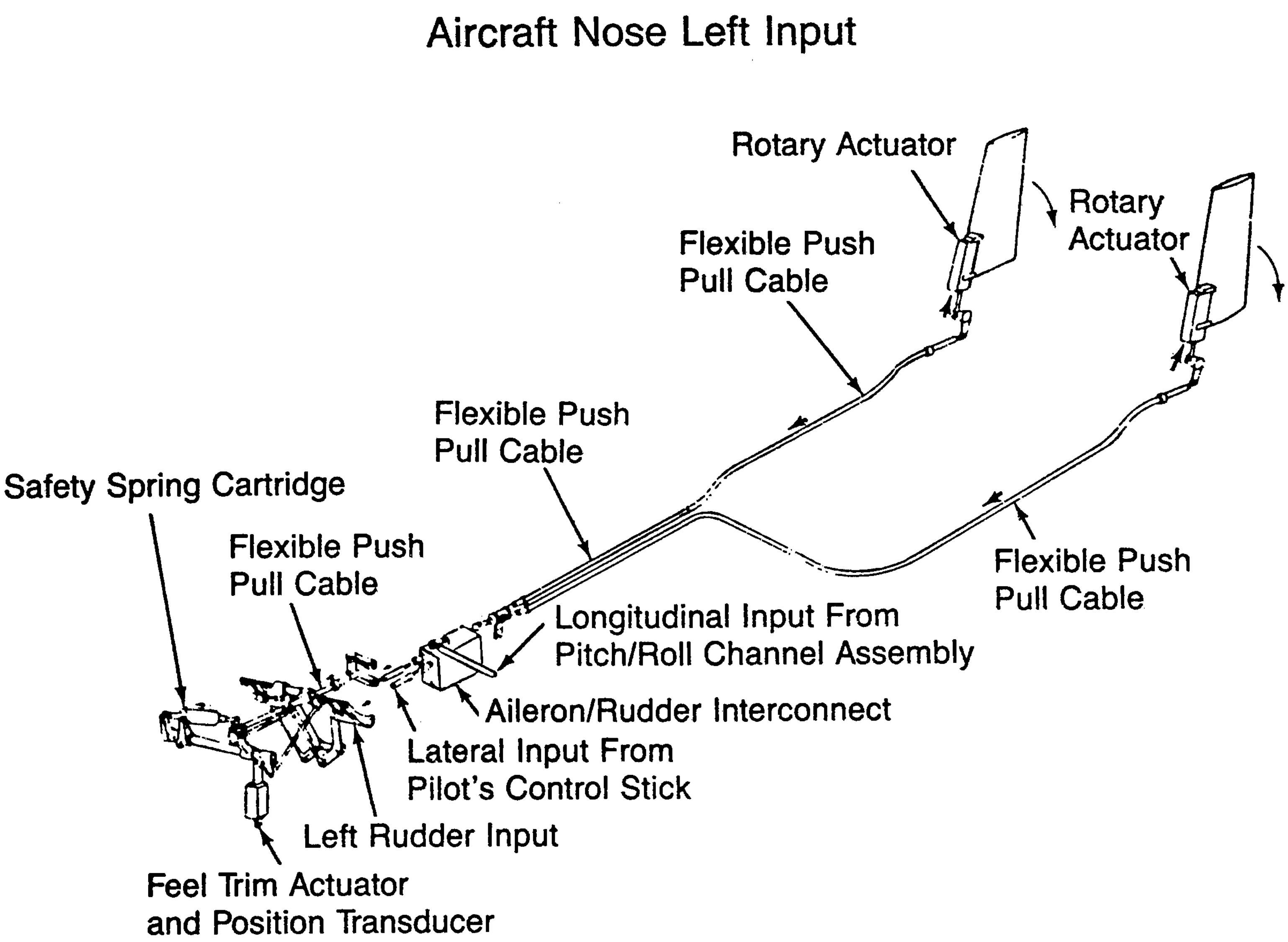


FIGURE 33 - McDonnell-Douglas F-15A Eagle, Flight Control System, Directional Controls

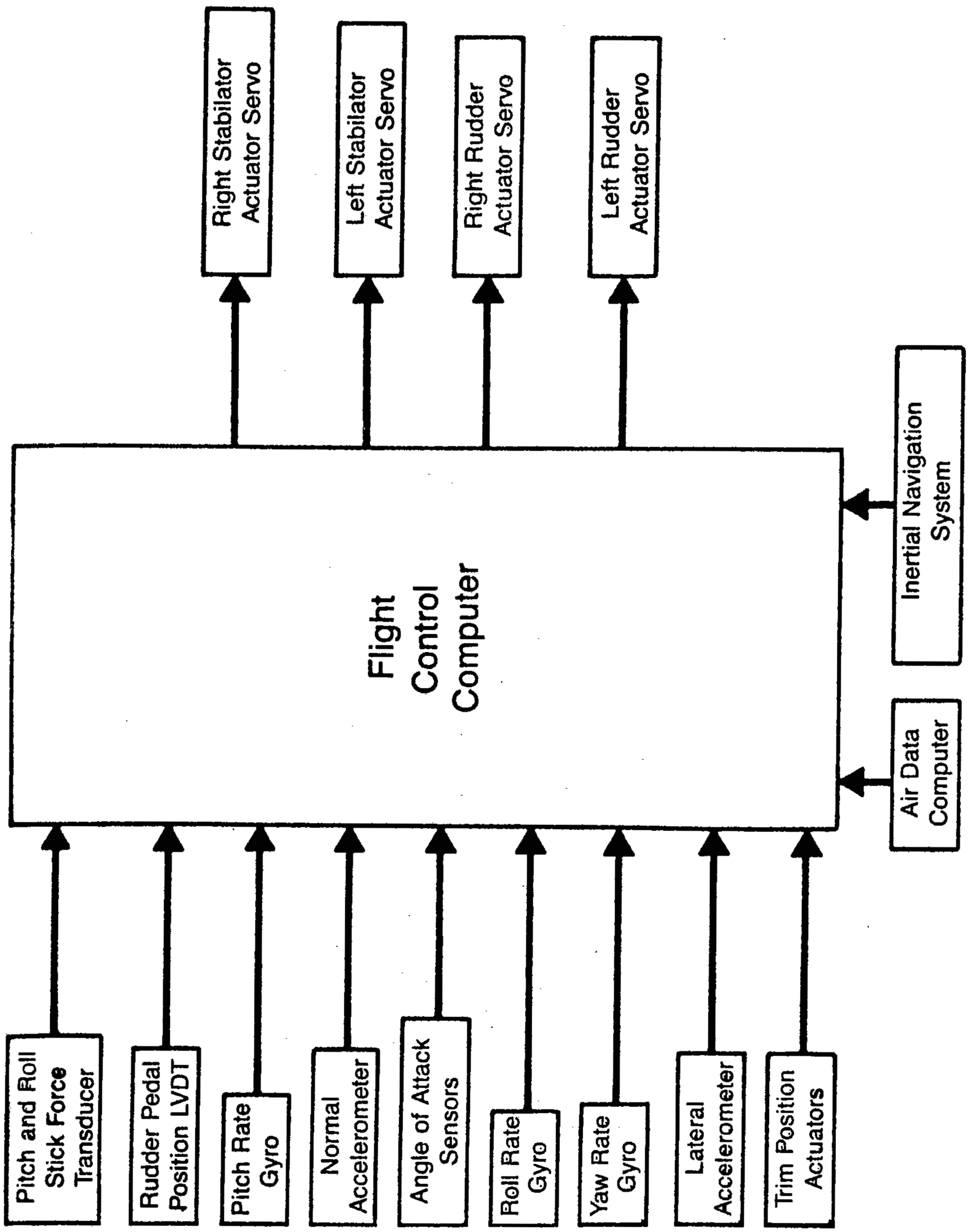


FIGURE 34 - McDonnell-Douglas F-15A Eagle, Control Augmentation System

3.10 McDonnell-Douglas F/A-18 Hornet:

3.10.1 F/A-18 Aircraft Flight Controls Systems: The F/A-18 Hornet is a high performance fighter aircraft with a digital control-by-wire (CBW) primary flight control system. The quadruplex digital flight control system provides all of the conventional stability and control functions as well as autopilot and coupled data link modes. The major factor in the F/A-18 flight control system design philosophy was to provide a highly reliable, survivability, and safe aircraft with minimum system degradation with loss of any component.

3.10.2 System Description: The F/A-18 flight control system is a control augmentation system (CAS) configuration which is implemented using fly-by-wire techniques. A functional diagram of the flight control system is shown in Figure 35. All primary control law computations are performed by the four digital computers working in parallel (quadruplex redundancy). The computers use inputs from analog cockpit controls and motion sensors to compute commands to the redundant electrohydraulic servoactuators which provide the desired surface deflection and aircraft response. Aircraft control is provided by two ailerons, two rudders, two stabilators, two leading-edge flaps, and two trailing-edge flaps. The flight control system redundancy provides two-fail-operate capability for the primary control functions. Backup modes include mechanical control for the two stabilator control surfaces and fly-by-wire analog position control of the aileron and rudder control surfaces.

3.10.3 F/A-18 Flight Control System Mechanization: Reliability and survivability considerations in consonance with the F/A-18 aerodynamic configuration were used to establish the redundancy levels for each control function. Control functions which are critical from a flying qualities or safety standpoints were designed with two-fail-operate/fail-safe capability. These functions include primary control commands, motion sensors, and stabilator and trailing edge flap actuators. Less critical functions or control surfaces with aerodynamic redundancy were designed with fail-operate/fail-safe capability. The redundancy selected for all of the major flight control system components is shown in Figure 36.

A major factor in the F/A-18 design philosophy is to provide maximum system capability with the loss of any control function. The backup modes are analog DEL control of the ailerons and rudder, and mechanical control of the integrated stabilator surface actuators. The aileron and rudder analog DEL mode can only be engaged following three digital processor failures. Reversion to the stabilator servoactuator mechanical backup mode will occur in the event of any one of the following failure conditions:

- Three pitch or roll stick sensor failures
- Three digital processor failures
- Three computer power supply failures
- Two generator and two battery failures
- Three servoactuator electrical failures

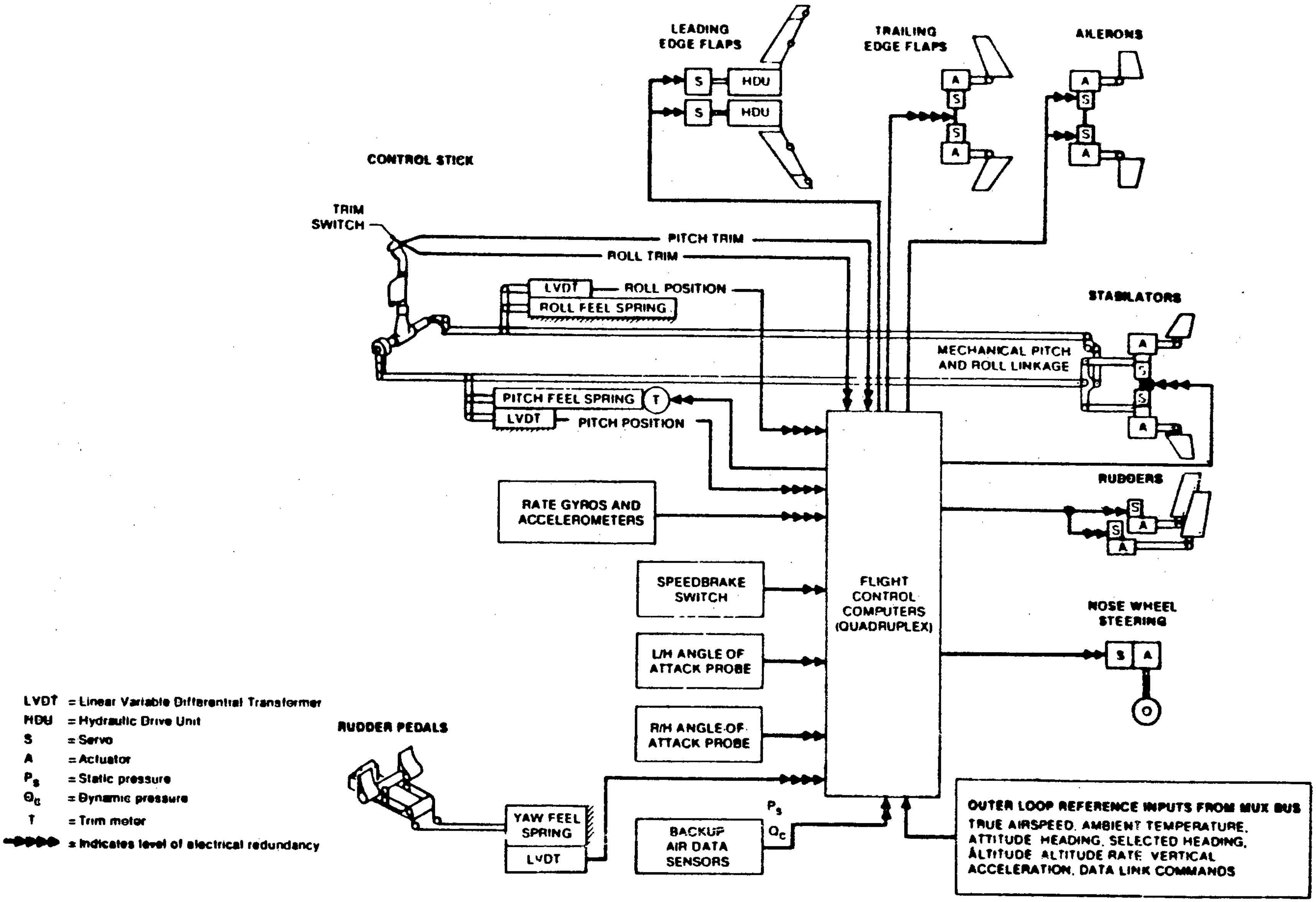


FIGURE 35 - McDonnell-Douglas F/A-18 Hornet, Flight Control System Functional Diagram

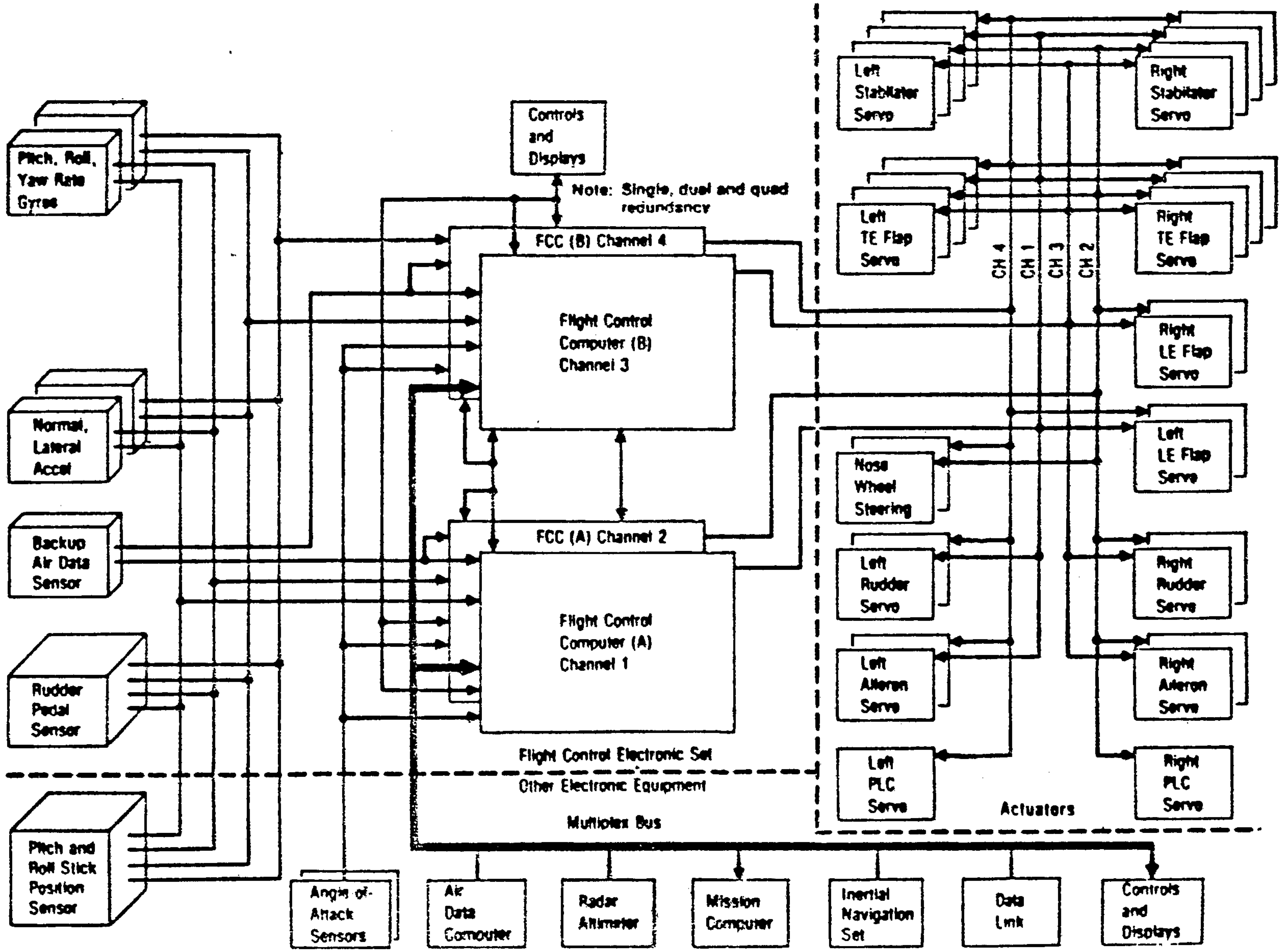


FIGURE 36 - McDonnell-Douglas F/A-18 Hornet, Flight Control Electronic Set Interface

3.10.3 (Continued):

The mechanical control system schematics are shown in Figures 37 and 38.

In the area of aircraft power systems, equal concern was present in the areas of both hydraulic and electrical supplies. Incorporation of reservoir level sensing and switching valves resulted in all actuators having at least two normal sources of hydraulic pressure or a normal source backed up through a switching valve to a second source. The stabilator has one of the two chambers backed up through a switching valve; therefore, three hydraulic supply failures must occur before total stabilator control is lost.

Batteries back up the normal FCS electrical power input. These batteries automatically power the FCS if the primary sources are lost.

The specification for electrical supplies, MIL-STD-704, allows 50 ms interruptions of power. This would not affect most analog systems; however, loss of power for that long could scramble the memory of a digital system. Therefore, a 7-s "hold-up" circuit was put into the computer power supplies to connect them directly to the batteries for 7 s if the voltage to these supplies falls below 16 V for more than 5 μs.

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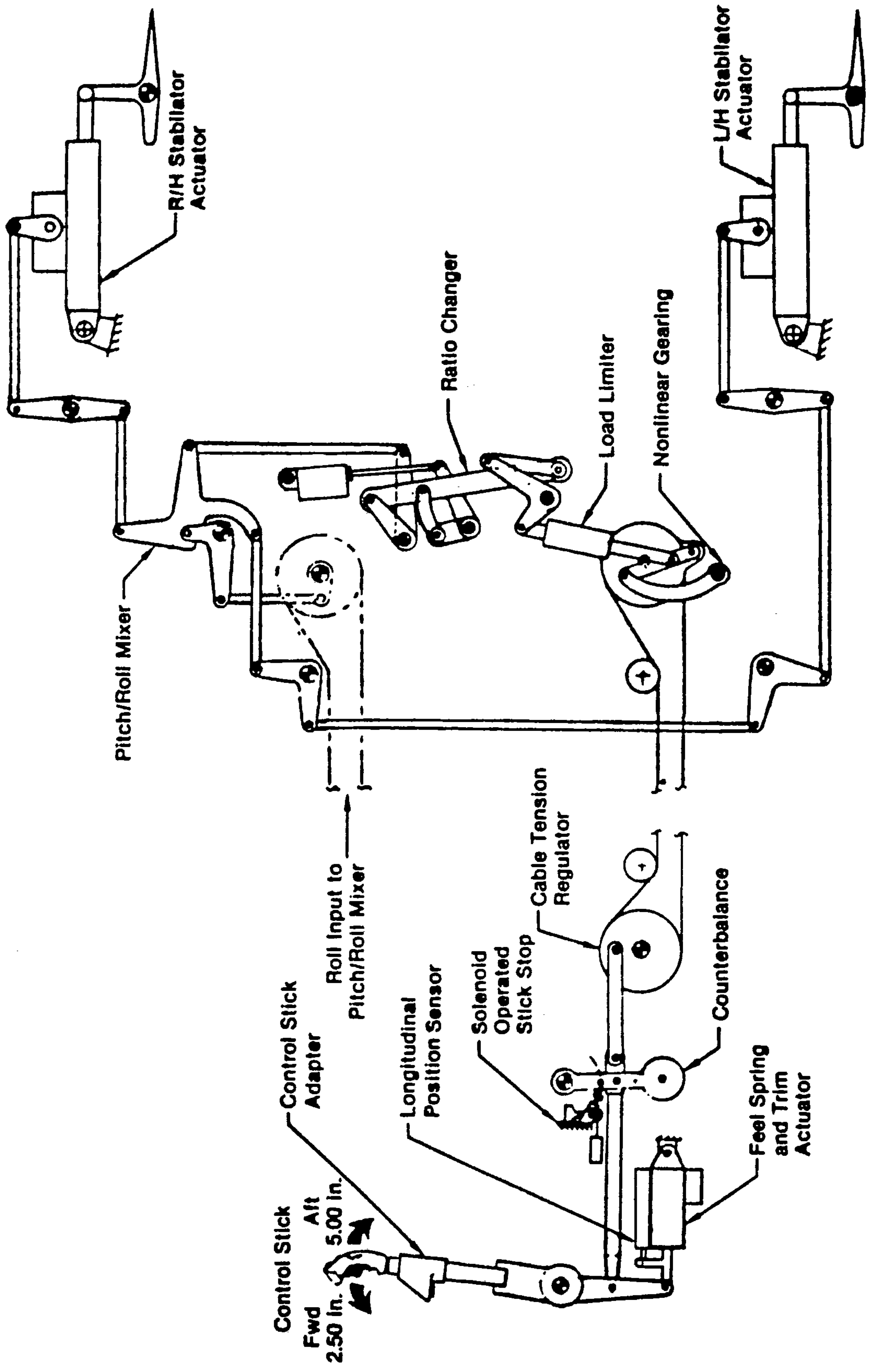

FIGURE 37 - McDonnell-Douglas F/A-18 Hornet, Longitudinal Control System Schematic

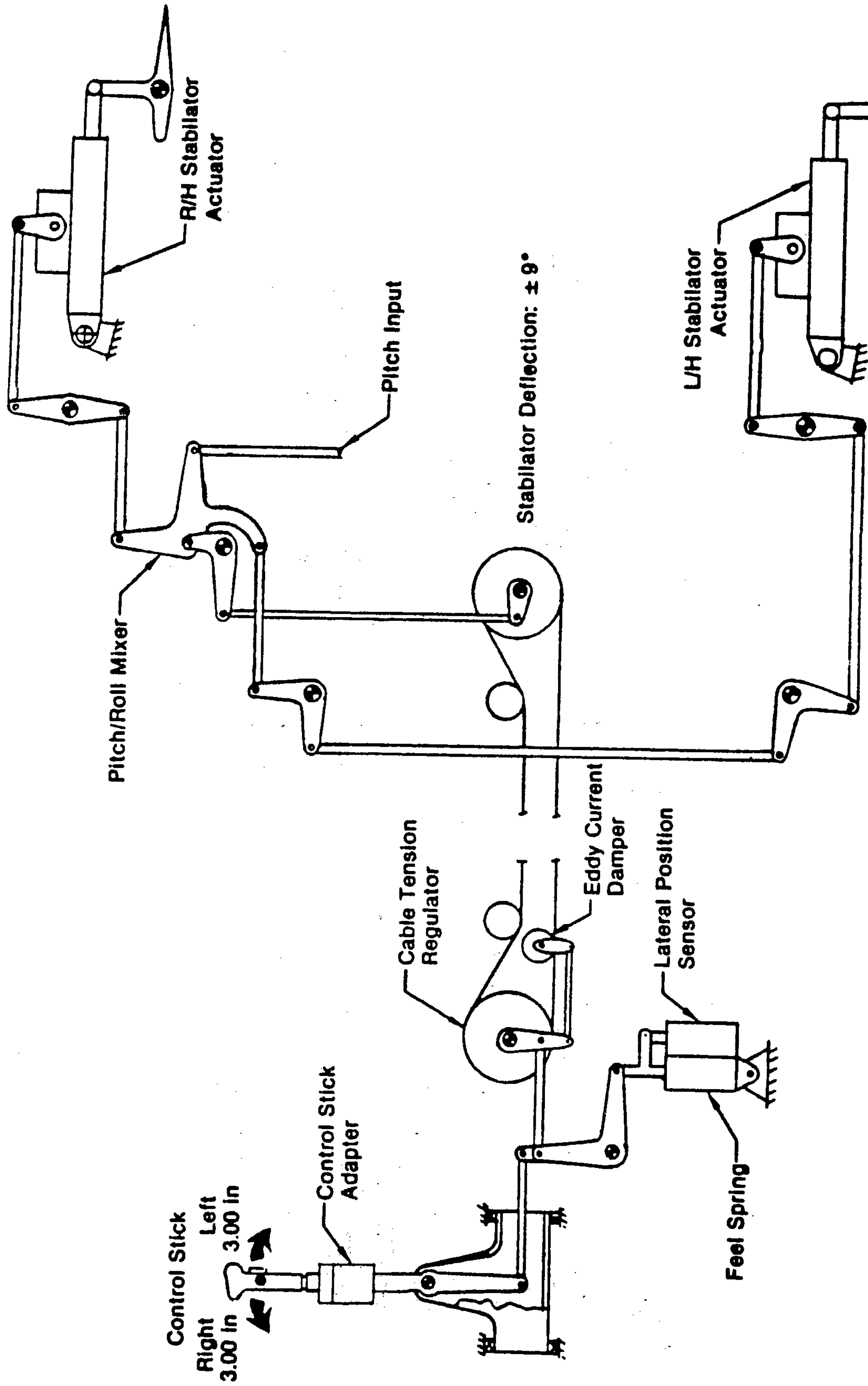

FIGURE 38 - McDonnell-Douglas F/A-18 Hornet, Lateral Control Schematic