MIT Subject 16.885J/ESD.35J
Aircraft Systems Engineering

F/A-18 FLIGHT CONTROL SYSTEM

HENRY HARSCHBURGER
Boeing (Retired)

Flight Control Systems
For Tactical Military Aircraft

- Flight Control System Architecture
  - No Universal FCS Designs
  - Many Different Architectures Will Work
  - Any System Will Have Pros and Cons
- Factors Influencing Architecture
  - Aircraft Mission
  - Aircraft Configuration
  - Procuring Agency
    - Service History With Similar Aircraft
    - Experience
    - Preferences

Flight Control Systems
For Tactical Military Aircraft

- Other Factors Influencing Architecture
  - Flight Control System Team (Government/Contractors/Suppliers)
    - Experience of Team Leaders
    - Lessons Learned
    - Team Members Strongly Held Preferences
    - Organization
      - Total System Vs Subsystem/Component
      - System Integration Responsibility
      - Integration of Interfacing Systems/Subsystems
      - System Testing
      - Development Plan / Integrated Schedules

Brief History of F/A-18A

- 1974 Navy Fighter Study
- DOD Direction HI/LO Mix (F-14/F-15 & Low Cost Fighter)
- USAF and Navy Use Light Weight Fighter YF-16 or YF-17
- Contractor Teams
  - General Dynamics - LTV
  - Northrop - McDonnell Douglas
- Flight Controls
  - YF-16 Fly-By-Wire
  - YF-17 Hydro-Mechanical and CAS
- USAF Selected the YF-16
- Navy Selected Naval Version of YF-17 to Become F/A-18
- F/A-18 Required Changes to YF-17 Flight Control System

Evolution of F/A-18A Flight Control System

F- 4 SFCS (FBW)

F- 4 PACT

F-15

YF-17

F/A-18 Requirements Development

- Customer Requirements
- Experience With F-4 and A-7 Aircraft
- Lessons Learned From Development Programs
- Navy Lessons Learned Database (all aircraft)
- Contractor / Supplier Experience on Recent Programs

Customer Requirements
F/A-18 Weapon System
Detailed Specification

Contractor Design
Requirements F/A-18
Aircraft and Systems

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F/A-18 Flight Control System Requirements

F/A-18 Weapon System Detailed Specification

Significant Specifications and Standards:

- MIL-F-8785 Flying Qualities Piloted Airplanes
- MIL-F-9490 Flight Control Systems - Design, Installation and Testing of Piloted Aircraft, General Specification for
- MIL-H-5440 Hydraulic Systems, Aircraft Types I and II, Design, Installation, and Data Requirements for
- MIL-STD-704 Electrical Power, Aircraft, Characteristics and Utilization of
- DOD-STD-2167 Military Standard, Defense System Software Development

Notes:

1. Specifications Can be Tailored in Weapons System Detailed Specification
2. Military Specifications are Being Replaced by Industry Standards.

Carrier Based Aircraft - Unique Requirements

Navy Experience and Concerns That Drove Requirements

- Reliability History of Their Fleet
  - Electrical Wiring, Connectors and Generators
  - Electronic Systems (Autopilot, Autothrottle, etc.)
- Maintainability History - Needs Major Improvement
- Carrier Operations
  - Approach Speed
  - Catapult/Arresting Gear Loads
  - Spotting Factor (Wing Fold)
  - Environment
    - Corrosion Due to Humidity and Salt Water
    - Electromagnetic Interference
  - “Blue Water Operations” - No Alternate Field in Range
- Survivability
- First Production Digital FBW Flight Control System
  - Electromagnetic Interference
  - Generic Software Failures

F/A-18A FCS REQUIREMENTS

SD-565-1,3.3.1
"3.1.10.2 With mechanical pitch and roll controls only, and with no less than two like failures in the rudder control system, the aircraft shall be capable of returning and performing a field landing. Categories B and C, Level 3 longitudinal short-period and Dutch roll frequencies, time-to-bank, and cross wind requirements shall be met."

SD-565-1, Appendix G.
"4.3.37 The flight control system shall incorporate design features to minimize loss of flight path control due to single hits form a 23 mm HEI-T or specified fragment. Routing and separation of electrical signal wiring and mechanical flight control systems shall be such that maximum protection against 23 mm HEI-T or specified fragment is afforded by masking and/or shielding."

MIL-H-5440F, 3.2
". . . The hydraulic system(s) shall be configured such that any two fluid system failures due to combat or other damage which cause loss of fluid or pressure will not result in complete loss of flight control . . ."

AS1291 (AV), 3.7.68
"b. Ability to withstand one electronic failure and continue to provide Level 1 performance as defined in MIL-F-8785. With two like electronic failures, the flight control system shall provide Level 3 performance.

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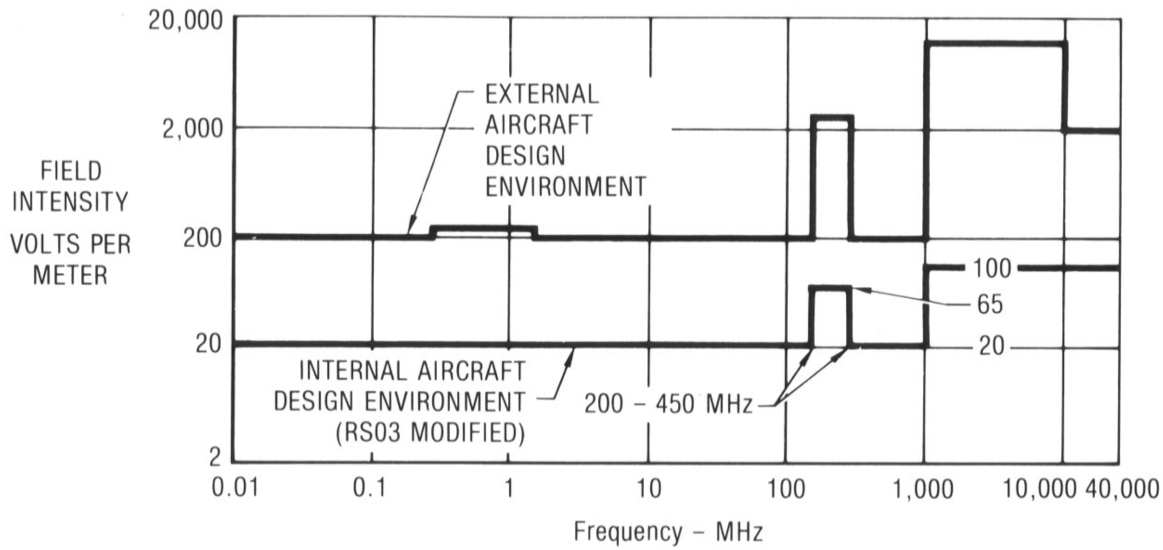
ELECTROMAGNETIC ENVIRONMENT COMPATIBILITY



Design Approach:

- Use Airframe As Electromagnetic Shield (Carbon/epoxy)
- Antenna EM Radiation Control
- Subsystem EM Control: Bonding, Twisted/Shielded Wiring, Filter Pin Connectors
- Ground Plane Interface Requirements

Discussion of Requirements

F/A-18A Hornet

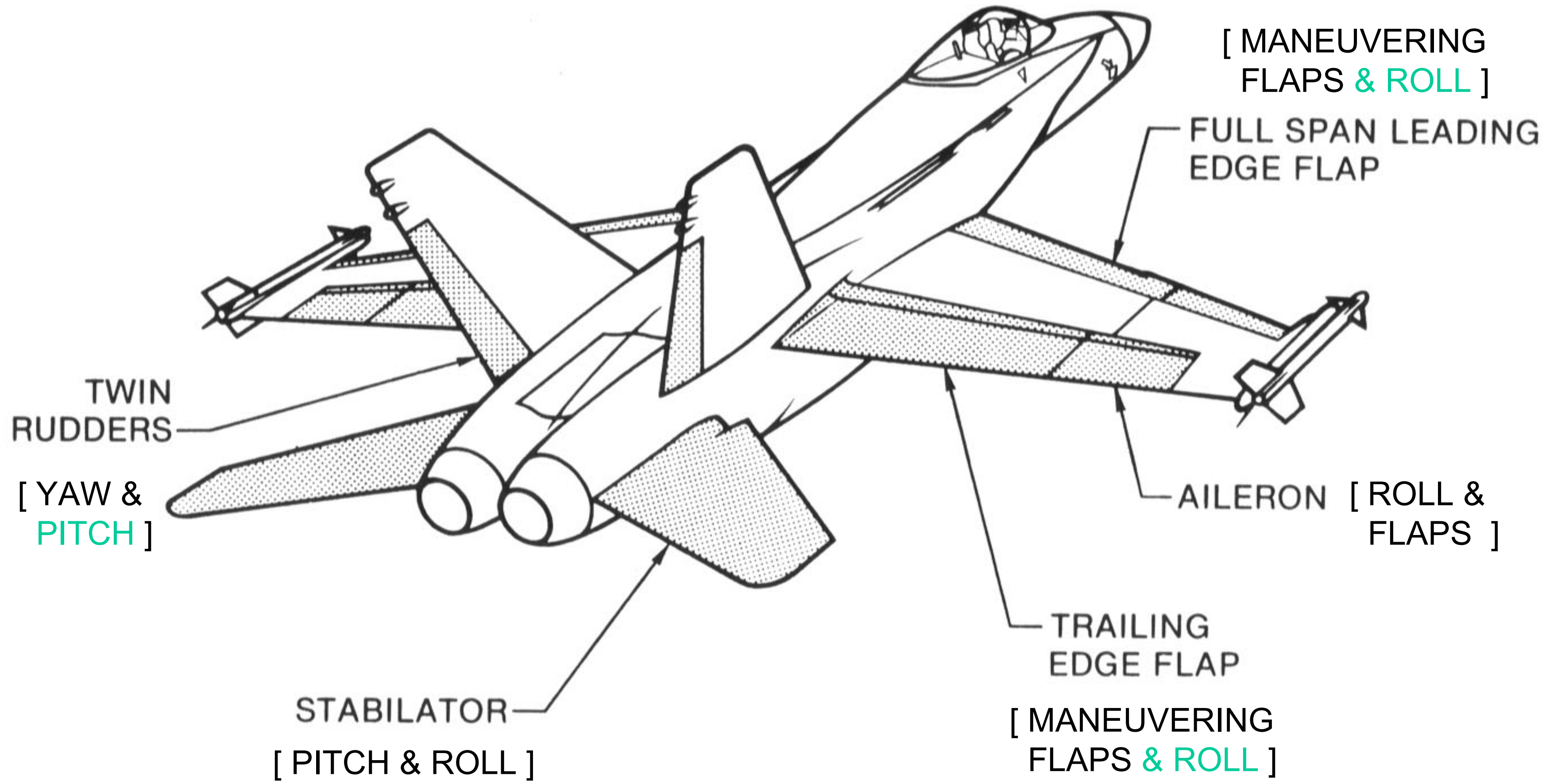
Primary Flight Control System

Quad Digital FBW

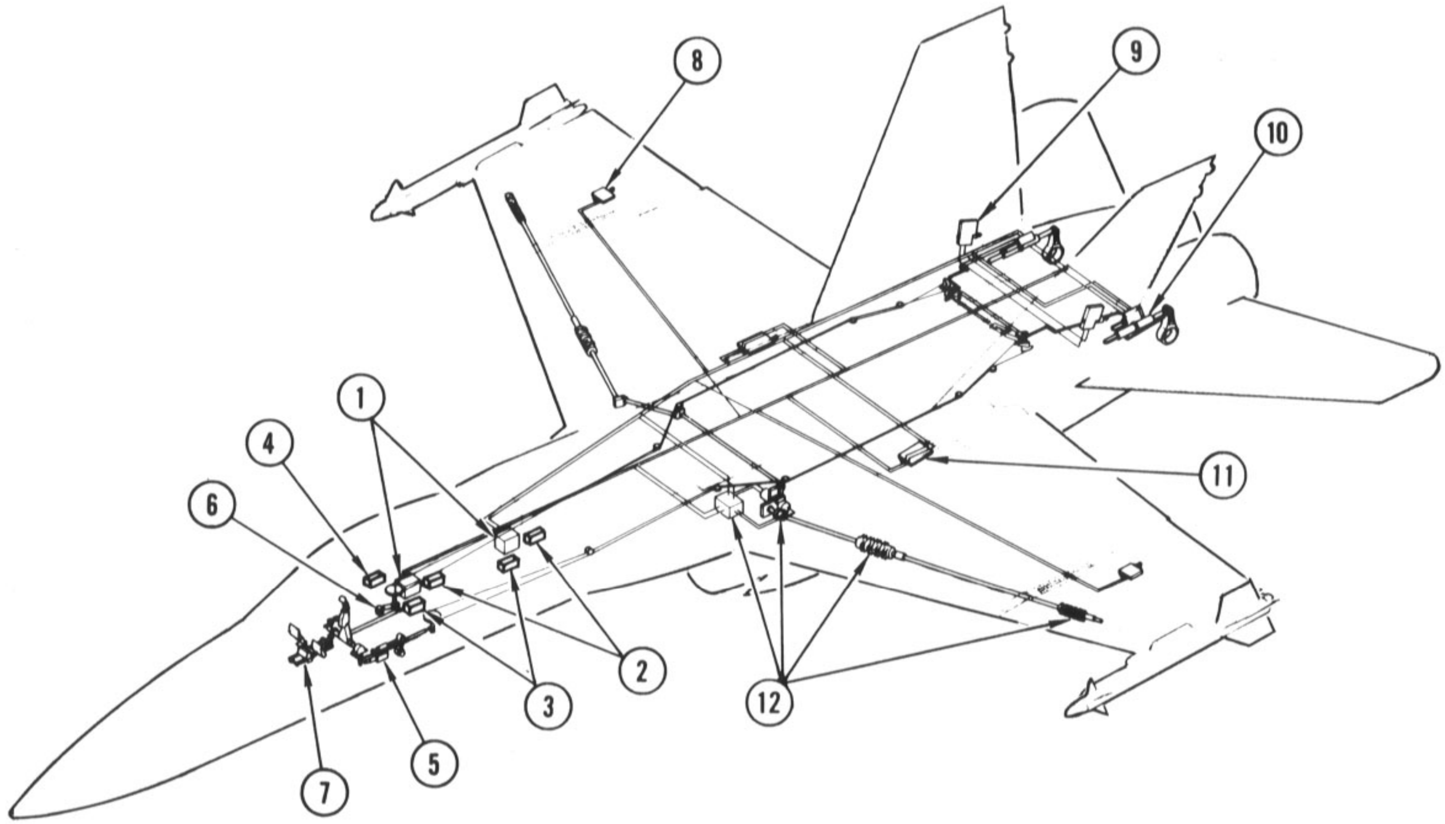
- Ailerons
- Rudders
- Leading Edge Flaps
- Trailing Edge Flaps
- Stabilators - With Mechanical Back-up

WHY DID THEY DO THAT ?

CONTROL SURFACES



F/A-18A Flight Control System



1. Flight Control Computers
2. Rate Gyros
3. Accelerometers
4. Backup Air Data Sensor Assembly
5. Pitch Stick Position Sensor/Feel Spring
6. Roll Stick Position Sensor/Feel Spring
7. Rudder Pedal Force Sensor
8. Aileron Actuator
9. Rudder Actuator
10. Stabilator Actuator
11. Trailing Edge Flap Actuator
12. Leading Edge Flap Actuation System
    - Hydraulic Drive Unit
    - Servovalve Assembly
    - Asymmetry Sensor

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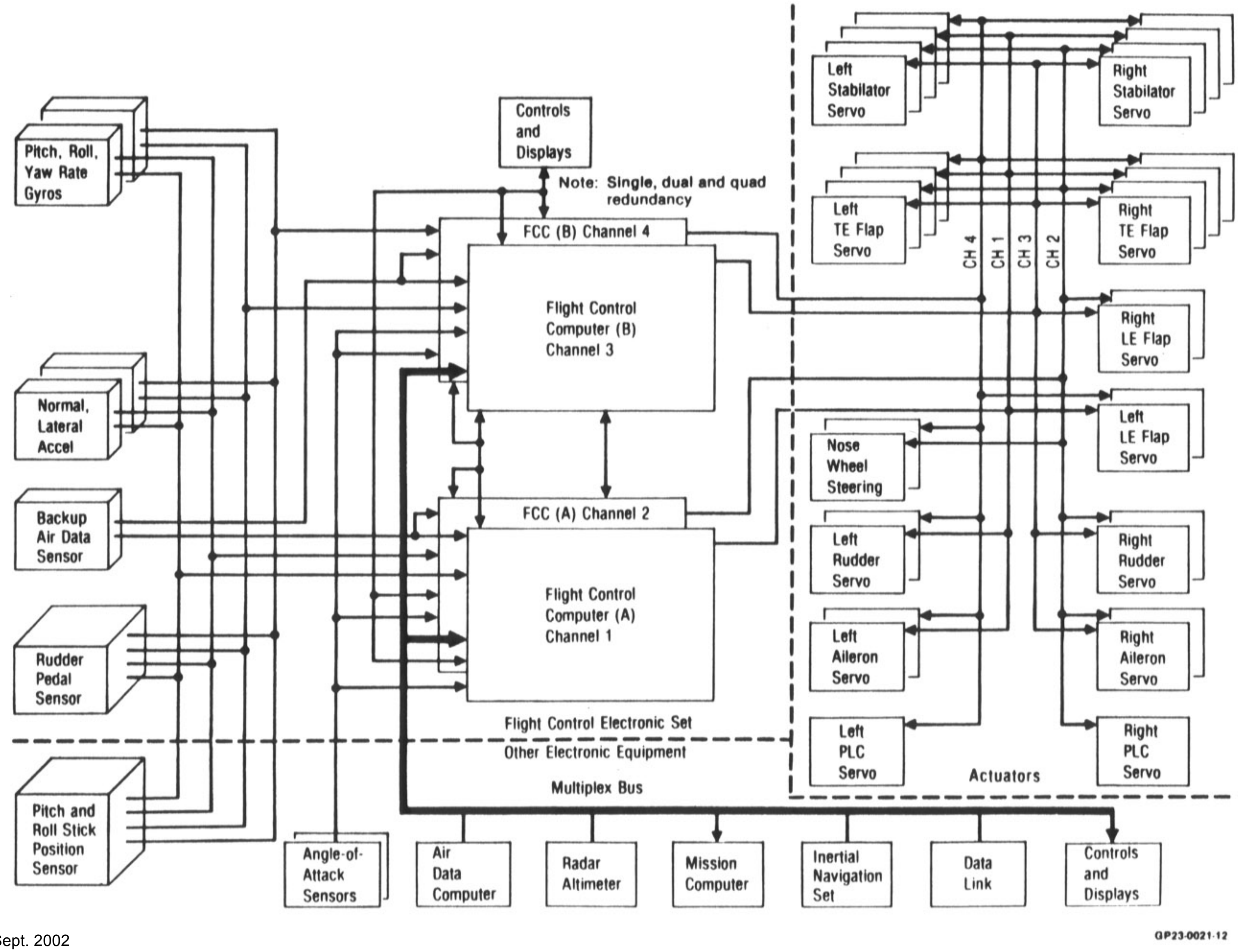
F/A-18A Flight Control System Redundancy Levels

- Redundancy Levels Driven By Reliability and Survivability
- Control Functions Critical to Flying Qualities and/or Safety Must Have Two-Fail-Operate/Fail-Safe Capability
  - Primary Control Commands
  - Motion Sensors
  - Stabilator Actuators
  - Trailing Edge Flap Actuators (Needed for Carrier Landing)
- Control Surfaces with Aerodynamic Redundancy and Less Critical Functions Must Have Fail-Operate/Fail-Safe Capability
- Survivability Protection Dictated Separation of Control Functions
  - Flight Control Computers
  - Motion Sensors
  - Interconnecting Wiring

FLIGHT CONTROL ELECTRONIC SET INTERFACE



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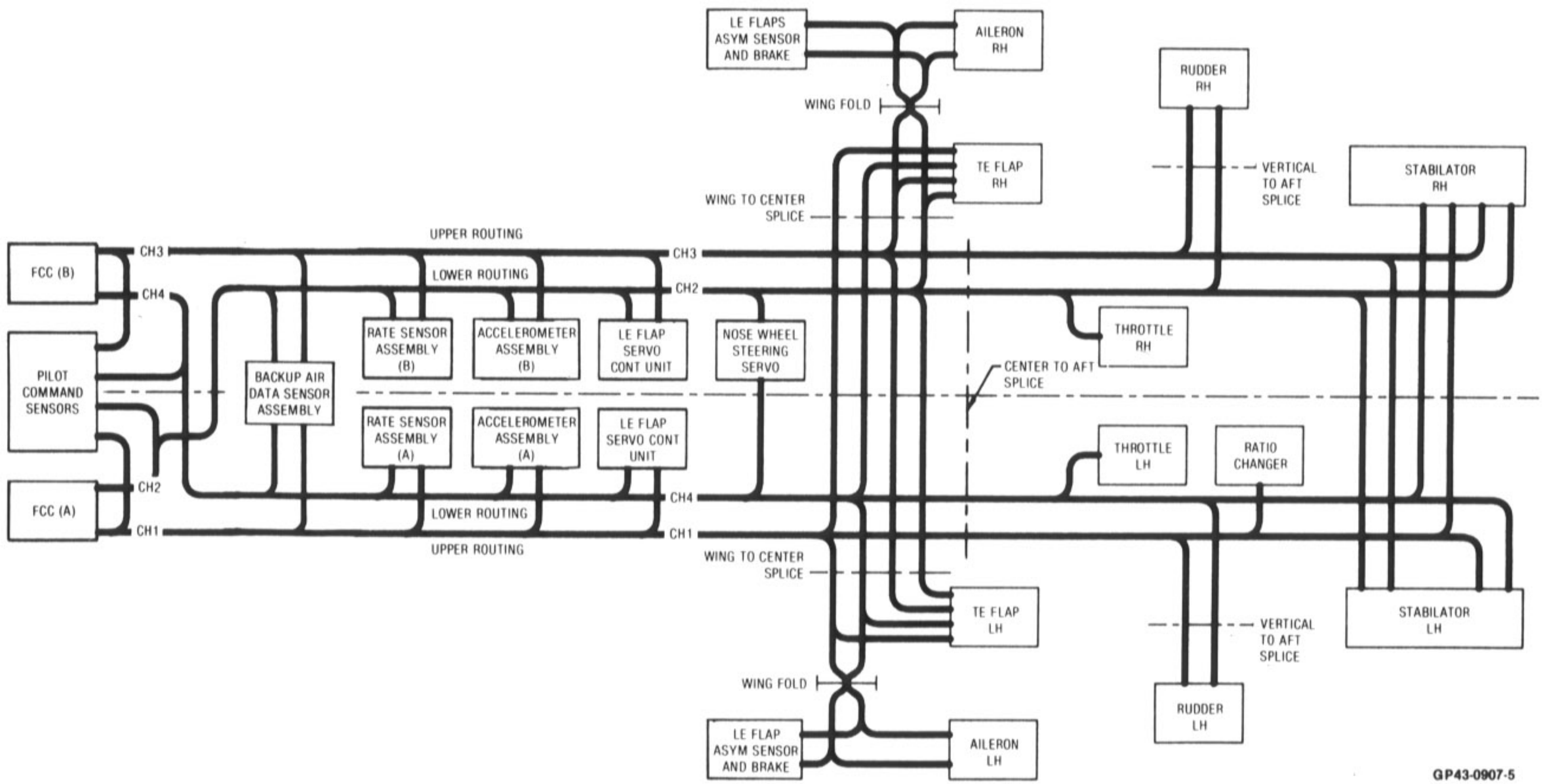
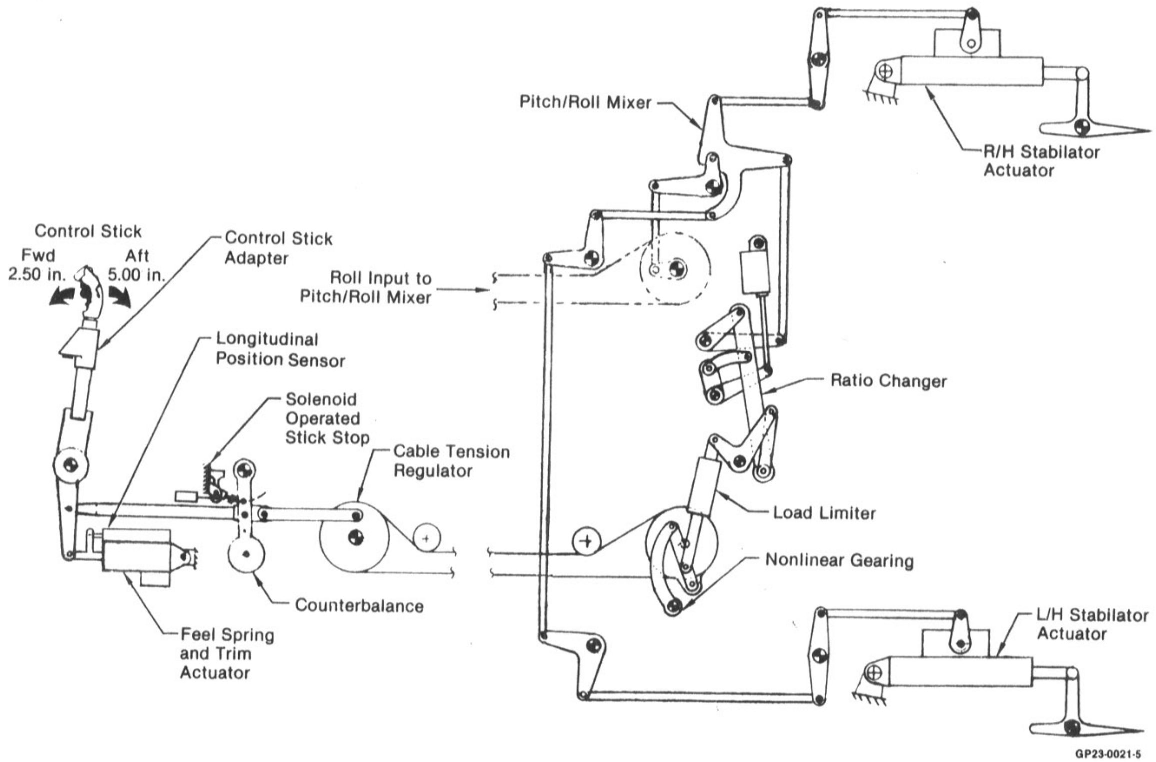
FLIGHT CONTROL CHANNEL ARRANGEMENT



Longitudinal Control System Schematic

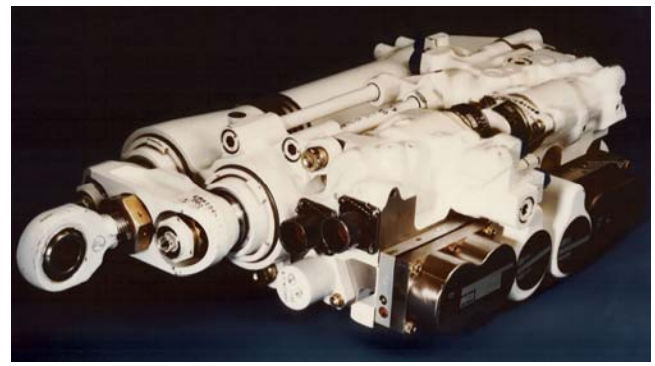


REVERSION TO BACKUP MODES

BACKUP MODES	FAILURES CAUSING REVERSION	PROBABILITY OF REVERSION
MECHANICAL	THIRD PITCH OR ROLL CONTROL STICK SENSOR	3.2×10^{-14} PER 2 HR FLIGHT
	THIRD DIGITAL PROCESSOR	9.7×10^{-10} PER 2 HR FLIGHT
	THIRD COMPUTER POWER SUPPLY	1.6×10^{-9} PER 2 HR FLIGHT
	THIRD STABILATOR ACTUATOR SERVO LOOP	7.7×10^{-7} PER 2 HR FLIGHT
ANALOG DEL	THIRD DIGITAL PROCESSOR	9.7×10^{-10} PER 2 HR FLIGHT

Electronic Set

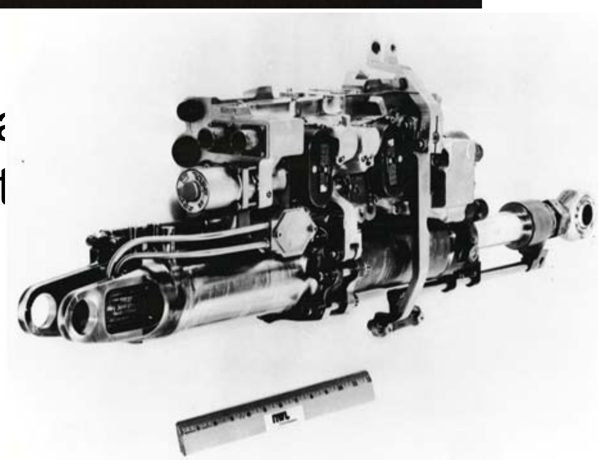
T.E. Flap Actuator

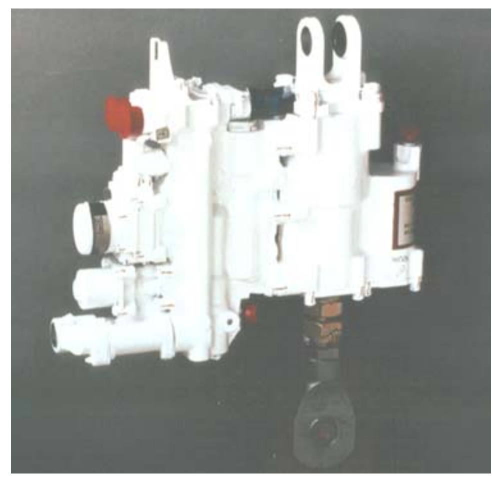


Aileron Actuator

F/A-18A Flight Control Hardware

Stabil
Actuat





Rudder
Actuator

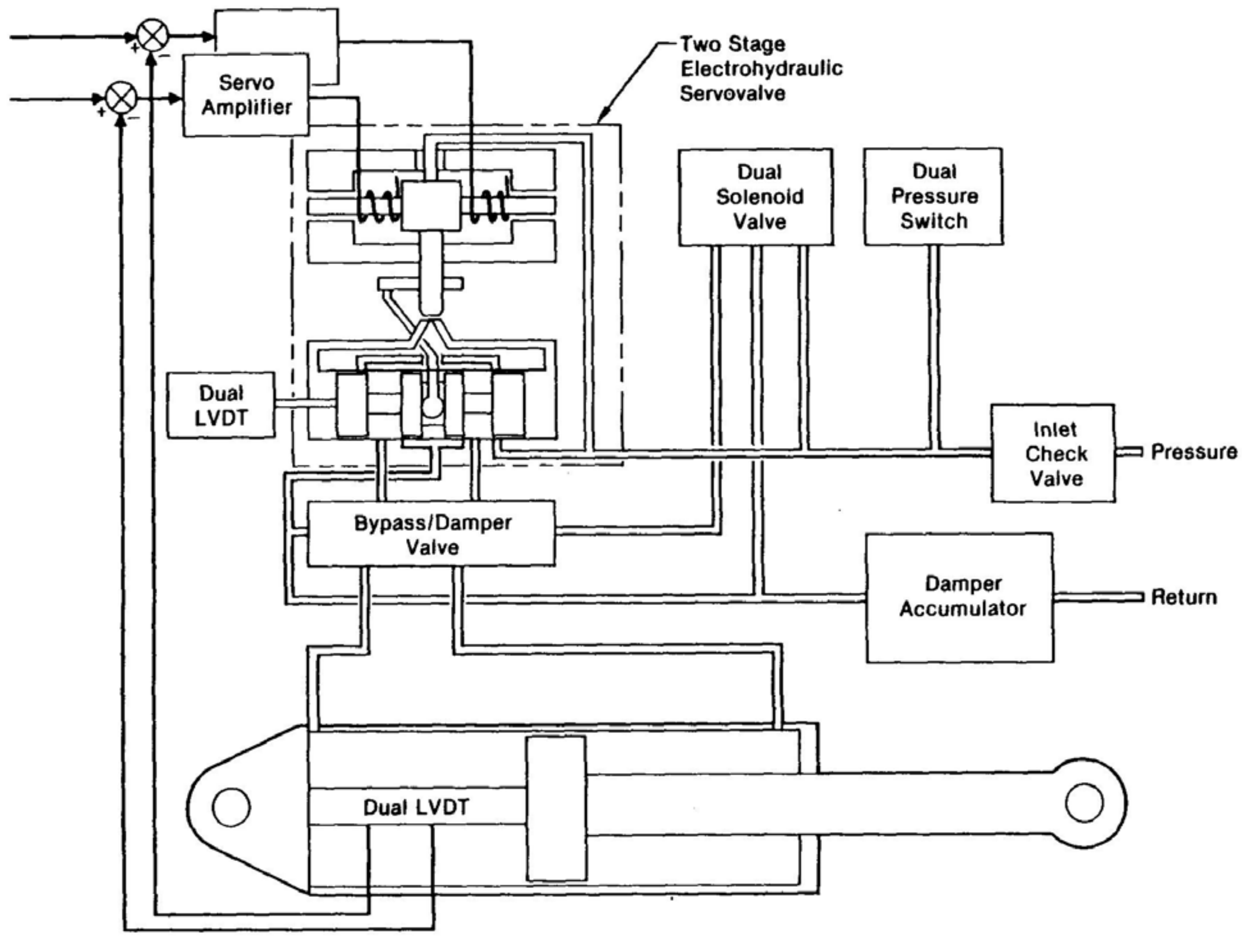
General Approach to FCS Actuation System

- Utilize Experience From F-4 SFCS Program and F15
  - Force Summing Single-Stage EHSV
  - Failure Monitoring
- Thin Wing and Vertical Tail Limit Envelope for Aileron and Rudder Actuators
- Analysis and Simulation Indicated No Carrier Landing Problems With One Aileron or Rudder Inoperative

Aileron and Rudder Actuator Design Rationale

- Redundancy Requirement Fail-Operate/Fail-Safe
- Fail-Safe Defined as Actuator in Flutter Damper Mode
- Envelope and Weight Penalty Precluded Dual Piston Actuator
- Study Select Actuator Configuration
  - Single Piston/Cylinder
  - Single Electrohydraulic Servovalve (EHSV)
  - Dual Servo Electronics
  - Electronic Channel Force Summing in Coils of EHSV Torque Motor
  - Dual Hydraulic Supply via Upstream Switching Valve

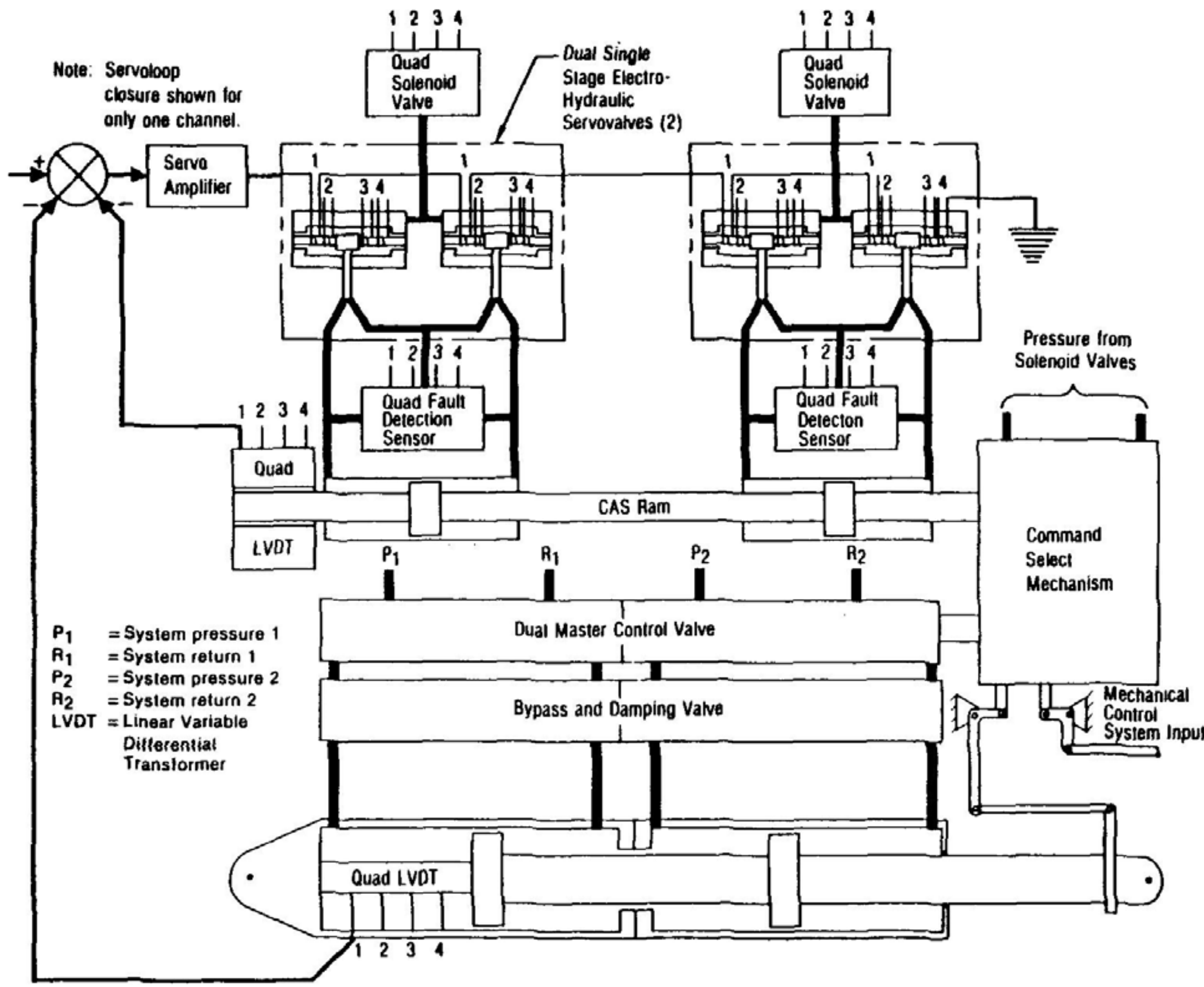
F/A-18A Aileron Actuator



F/A18A Stabilator and Trailing Edge Flap Actuator Design Rationale

- Redundancy for Both Actuators is Two-Fail-Operate/Fail-Safe
- Fail-Safe for T.E. Flap is Retract to Neutral
- Fail-Safe for Stabilator is Switch to Mechanical Mode
- Design Issue - Interface of Quad Electronics With Dual Hydraulics
- Electronic Channel Force Summing in Coils of EHSV Torque Motors
- Normal Dual EHSV Coils Separate to Produce 4 Independent Coils
- Force Fight of EHSV Pressures Needed to Minimize Failure Transients
- Servo is Driven by Two Pair of Quad Coil Single-Stage EHSVs
- EHSVs Arranged as “Siamese Pairs” With One Port of Each Valve Connected the Servo Ram and the Other to a Differential Pressure Sensor for Failure Monitoring

F/A-18A Stabilator Actuator



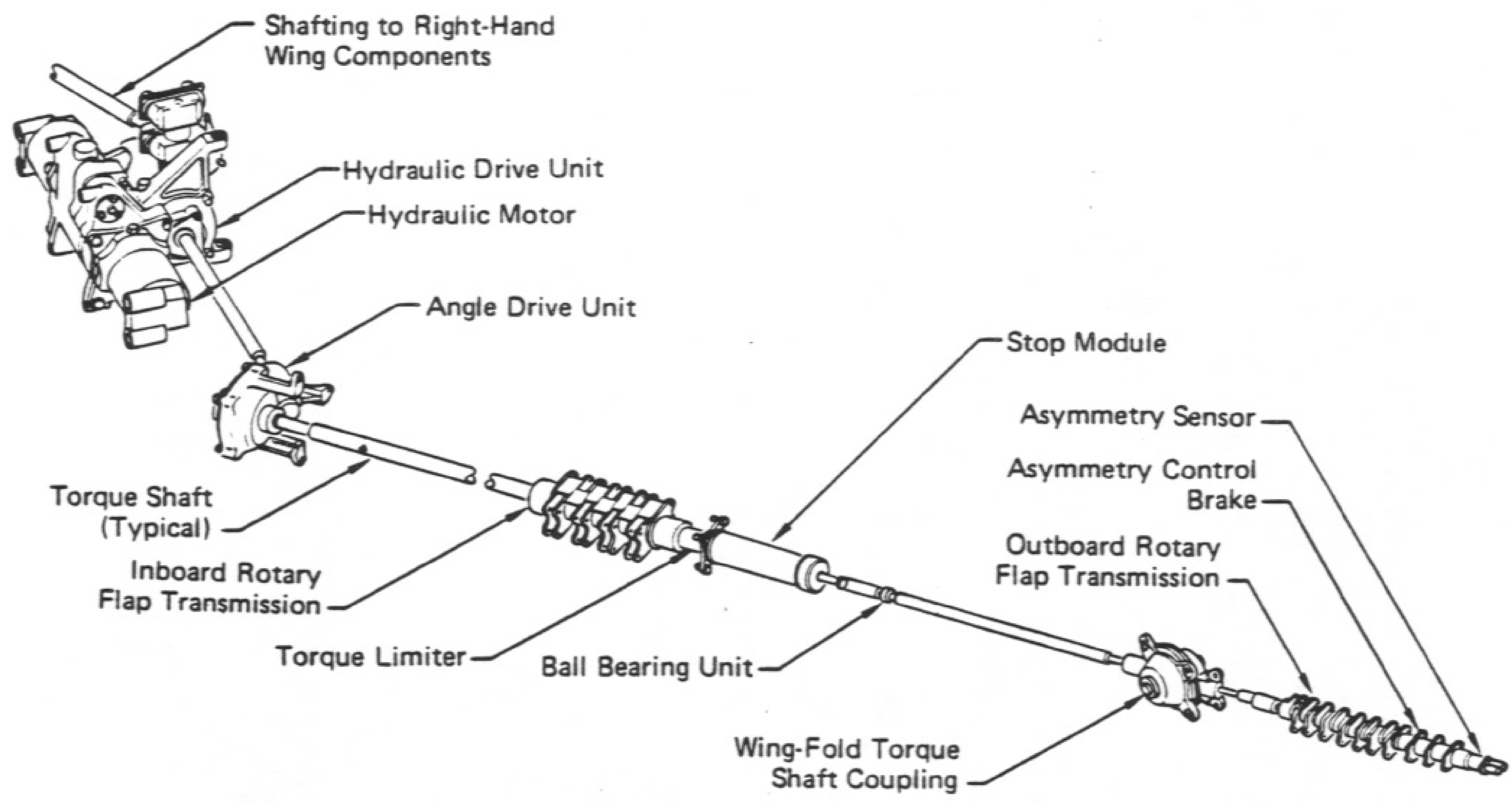
F/A-18 Leading Edge Flap System Design Rationale

- Thin Wing Cross-Section Was the Design Driver
- Wing Fold Requirement Complicated the Installation Problem
- Needed Actuation Device on Inboard and Outboard Panels
- Rotary Mechanical Drive Was Selected Because It Fit Inside the Wing (also it worked well on the YF-16)
- Planetary Gear Type Transmissions Power Inboard and Outboard Flaps
- Transmissions are Connected to Hydraulic Drive Unit With Torque Shafts
- Mechanical Torque Shaft Coupling/Swivel Solved the Wing Fold Problem

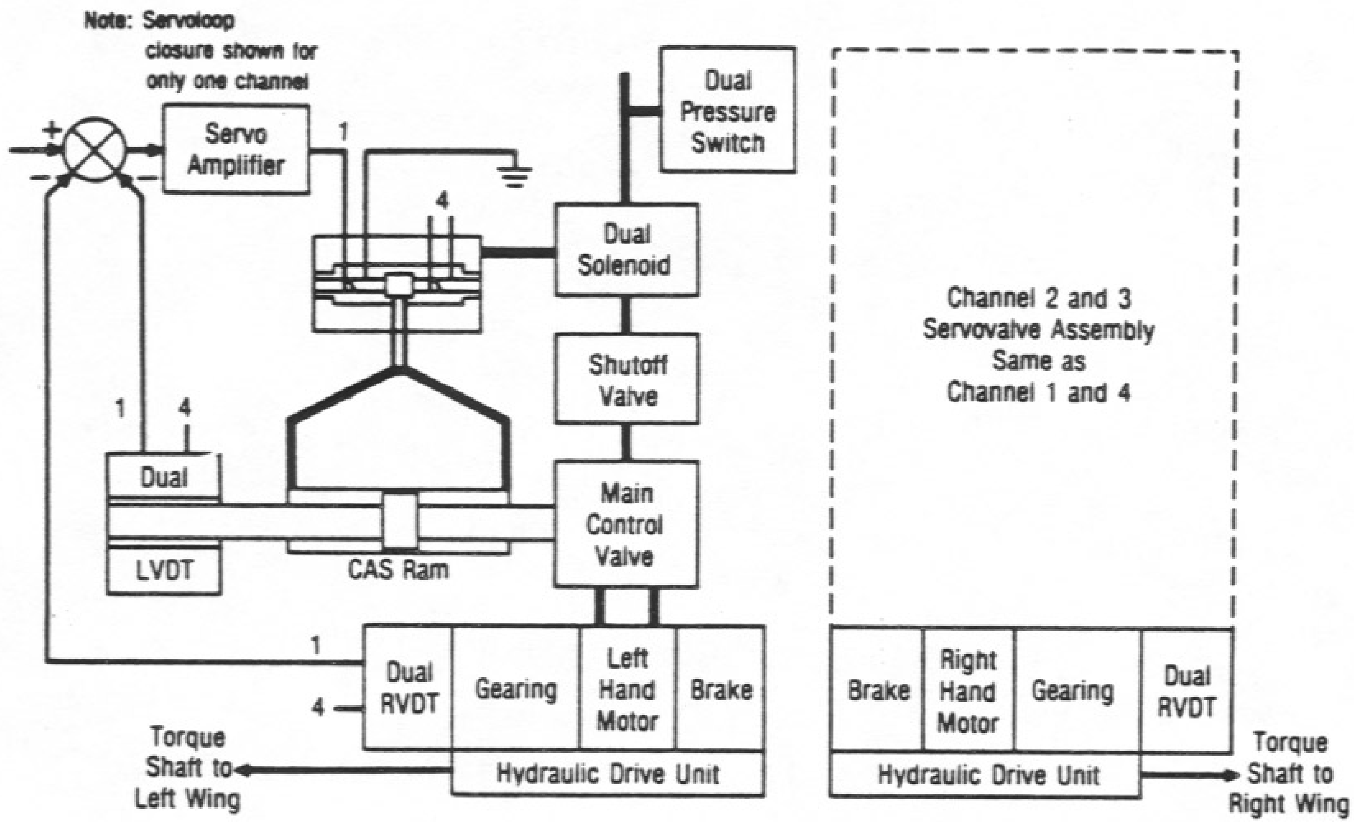
F/A-18 Leading Edge Flap System

- Leading Flap System Redundancy is a Fail-Operate/Fail-Safe
- Fail-Safe is Defined as Locked in Last Position
- A Backup Hydraulic Supply is Provided by a Upstream Switching Valve
- The System Provides Individual Control of the Flaps on Each Wing
- The Servos Which Control Each Flap are Dual Coil Single-Stage EHSV Driving a Servo Ram With Electrical Position Feedback
- The Servo Ram Controls Hydraulic Flow to the Hydraulic Motor that Power the Flap Drive Transmissions
- Asymmetry Control Units are Installed on the OUTBD Transmissions
- Asymmetry Monitor Compares Hydraulic Drive Unit with Asymmetry Control Unit

F/A-18 Leading Edge Flap Drive System



F/A-18 Leading Edge Flap System
Servovalve Assembly



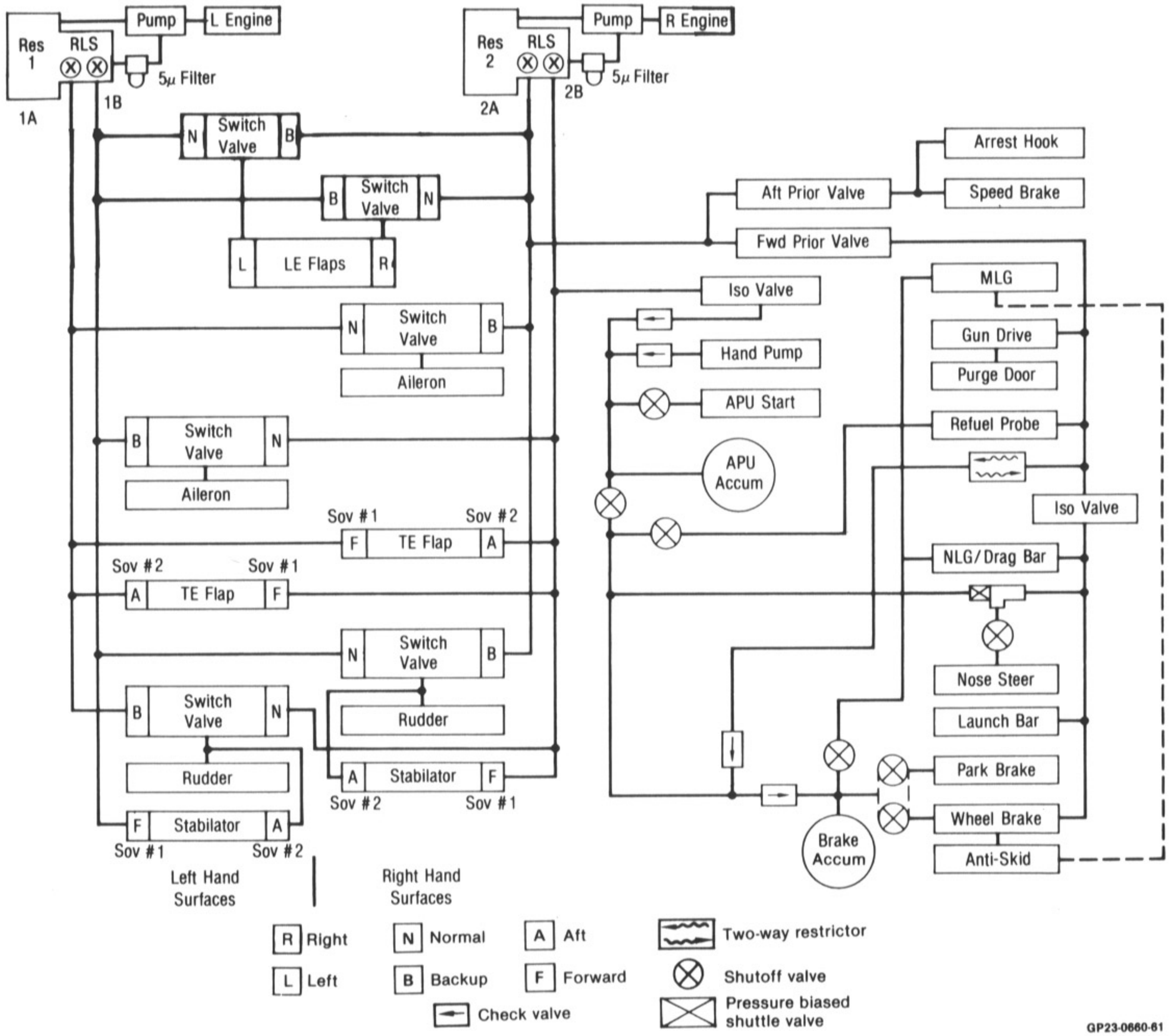
F/A-18A Flight Control System Interfacing Systems

The Design of Interfacing Systems Must Support the Flight Controls Reliability and Survivability Requirements

- The Hydraulic System Has Redundancy and Separation
  - Reservoir Level Sensing - Separate Branches
  - Switching Valve Provide Backup Supplies

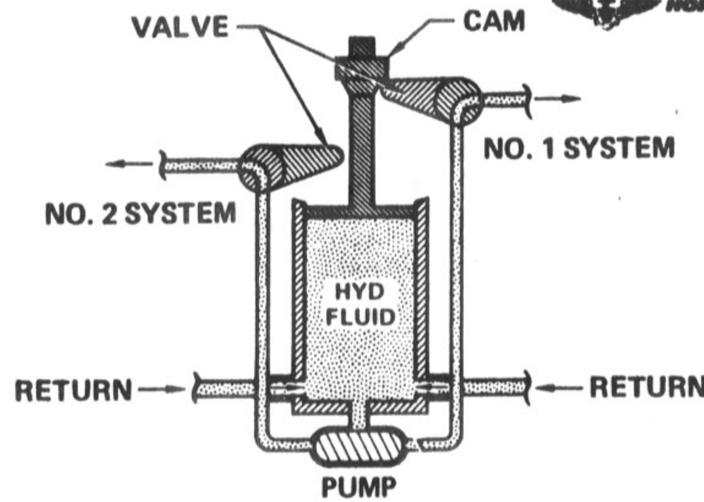
- The Electrical System Has Redundancy and Separation
  - Bus Switching
  - Battery Backup

F/A-18A Hydraulic System Arrangement



HYDRAULIC SYSTEM CIRCUIT BREAKER RESERVOIR LEVEL SENSING (RLS)

BASIC PRINCIPLE SCHEMATIC

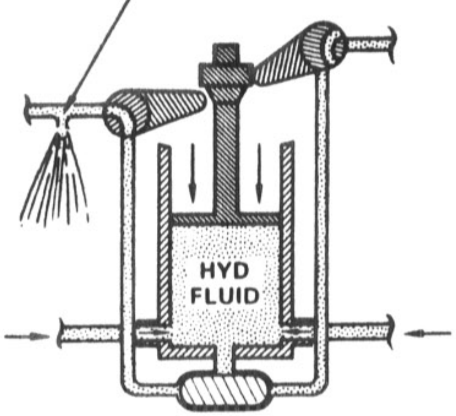


SEARCH

PISTON FOLLOWS LOWERING LEVEL OF RESERVOIR. AUTOMATICALLY SHUTS SYSTEMS SEQUENTIALLY BY CAM OPERATION OF VALVE. RESERVOIR LEVEL DROPS AS LONG AS LEAK IS NOT ISOLATED

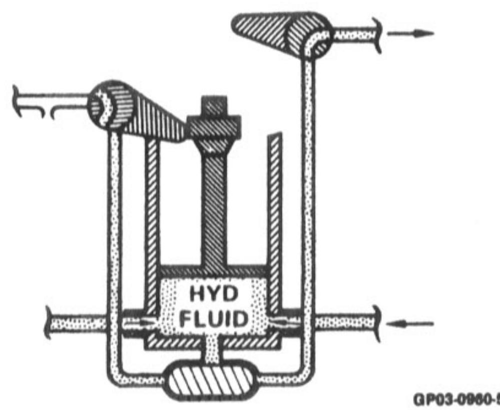
LEAK

RESERVOIR LEVEL BEGINS TO DROP



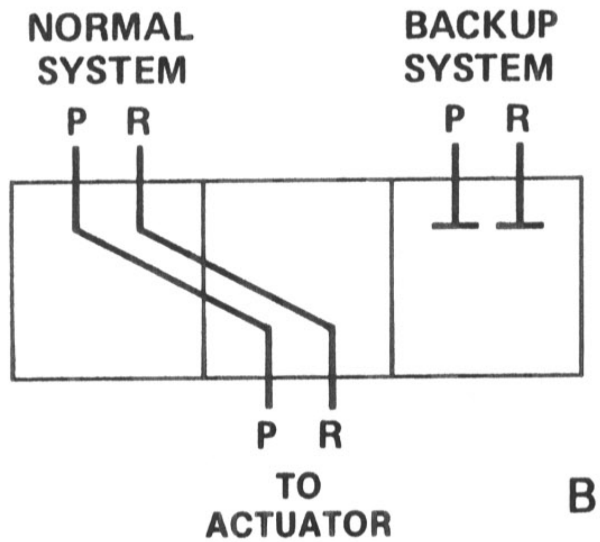
ISOLATE

WHEN LEAKING SYSTEM IS ISOLATED RESERVOIR LEVEL STABILIZES

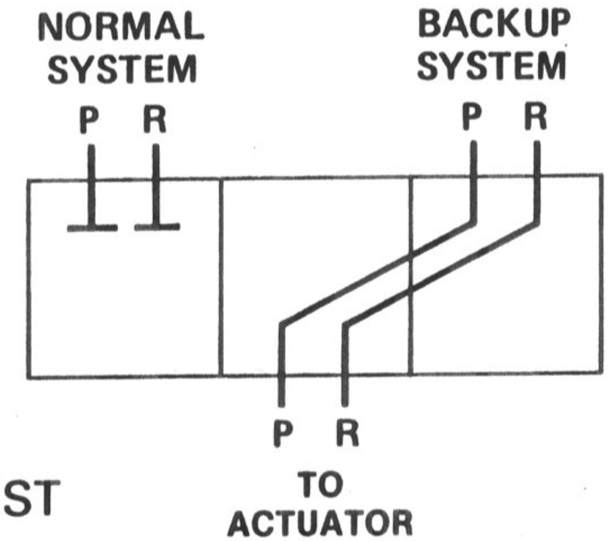


SWITCHING VALVE

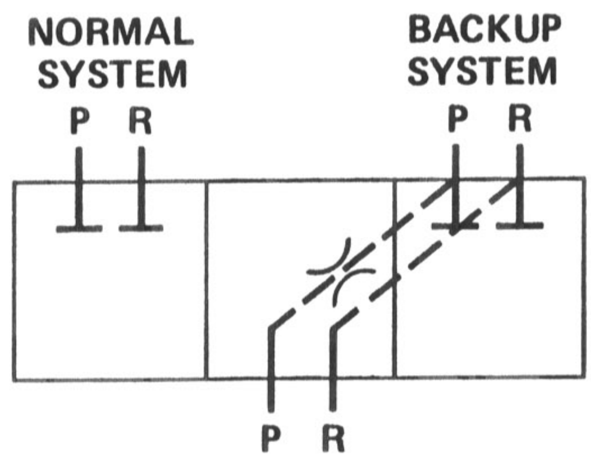
NORMAL



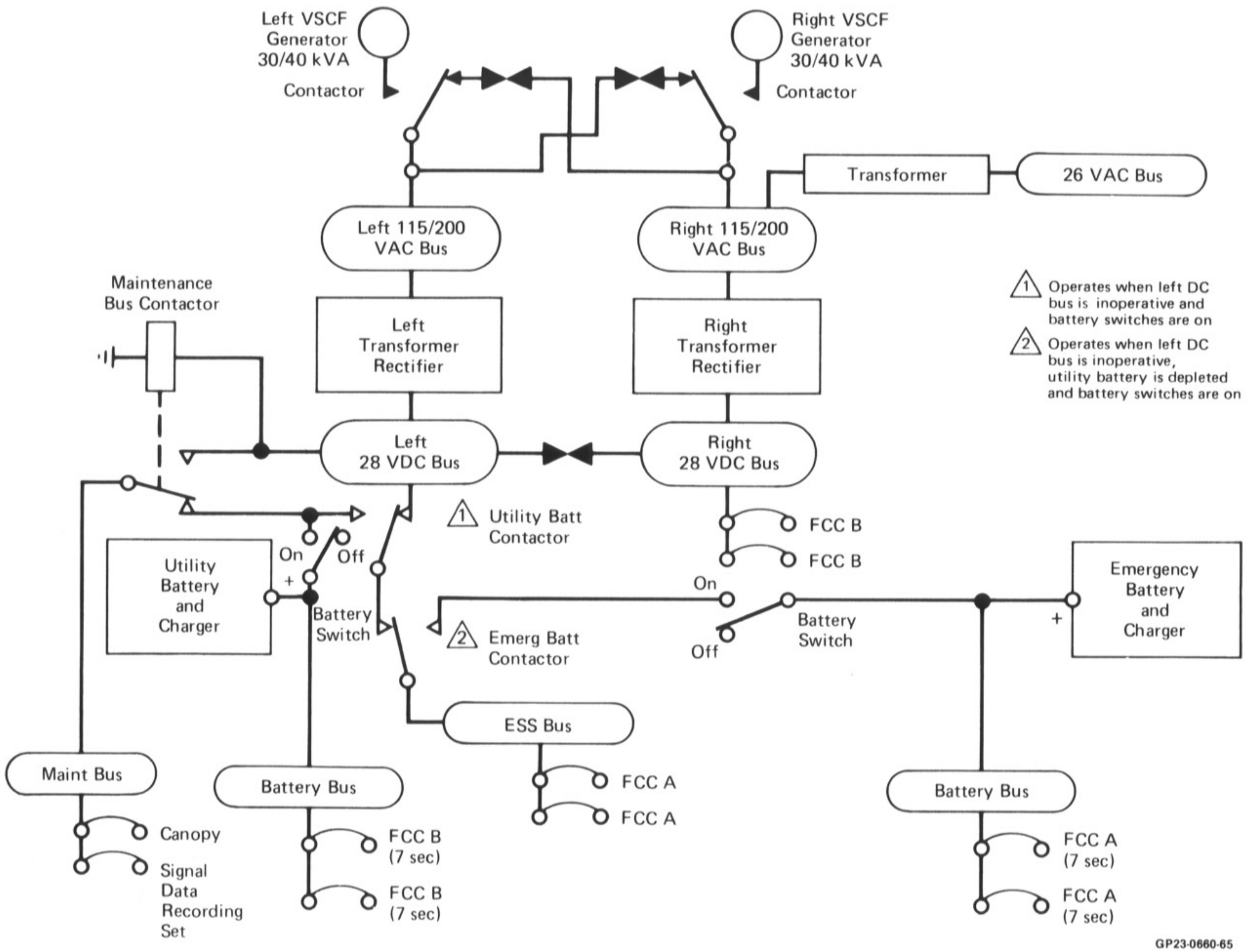
BACKUP



BLOCK AND TEST



F/A-18A Electrical Power System Simplified Schematic



Discussion of F/A-18 Flight Controls

Benefits of Digital Flight Control System Mechanization

- Flight Control System and Avionics System Integration
  - Autopilot and Data Link Modes
  - Built-In-Test
  - Specialized Controls and Displays
  - Flight Test Instrumentation - Flexible and Efficient

- Digital FCS Mechanization - Cost Effective Solutions to Development Problems
  - Multi-Purpose Control Surface Usage
  - Multiple Sensor Inputs
  - Optimal Scheduling of Control Surface

What Were The Lessons Learned ?

F/A-18A Lessons Learned
Design Database

- Limited Aerodynamics, Loads and Dynamics Database
  - Small Scale, Low Fidelity Wind Tunnel Models
  - Modified YF-17 Database
  - No Loads Pressure Instrumentation on Model
- Problem Areas Encountered During Flight Testing
  - LEF Loads
  - Wing Flexibility
  - Aileron Flex - Rigid Ratio
  - Effect of Tip Missiles
  - Approach AOA

• Database - Risk Was Known But Not Quantified
• Risk Management Not Widely Used During This Time

CHANGES DURING FLIGHT TEST DEVELOPMENT

PROBLEM	POTENTIAL CONVENTIONAL SOLUTIONS	F/A-18A FLIGHT CONTROL SYSTEM SOLUTION
NOSE WHEEL LIFTOFF CHARACTERISTICS	— RELOCATE LANDING GEAR — INCREASE STABILATOR AREA	— RUDDER TOE-IN SCHEDULING — SCHEDULED LEADING EDGE FLAP DEFLECTION
ROLL PERFORMANCE	— INCREASE WING STIFFNESS — ADD SPOILERS — INCREASE DIFFERENTIAL STABILATOR HINGE MOMENT AND BENDING MOMENT CAPABILITY	— OPTIMIZE DIFFERENTIAL STABILATOR AND AILERON SCHEDULES — DIFFERENTIAL TRAILING EDGE FLAPS — DIFFERENTIAL LEADING EDGE FLAPS
ROLL COUPLING	— OPERATIONAL LIMITATIONS — MINOR ROLLING SURFACE-TO-RUDDER INTERCONNECT MODIFICATIONS	— OPTIMIZE ROLLING SURFACE-TO-RUDDER INTERCONNECT — INERTIAL COUPLING COMPENSATION FEEDBACKS
STRUCTURAL LOADS	— INCREASE STRUCTURAL WEIGHT	— OPTIMIZE CONTROL SURFACE SCHEDULES — ROLL RATE LIMITER
POWER APPROACH DIRECTIONAL MODE CHARACTERISTICS	— INCREASE VERTICAL STABILATOR AREA	— ESTIMATED SIDESLIP RATE FEEDBACK — RUDDER PEDAL-TO-ROLLING SURFACE INTERCONNECT

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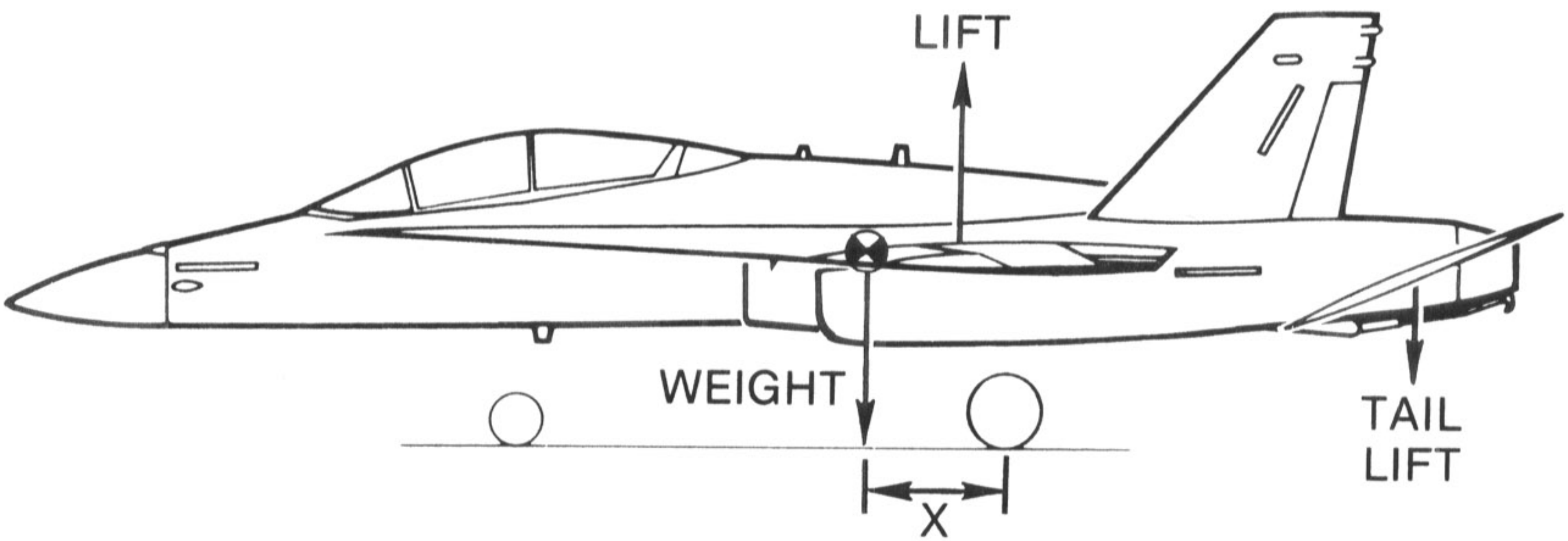
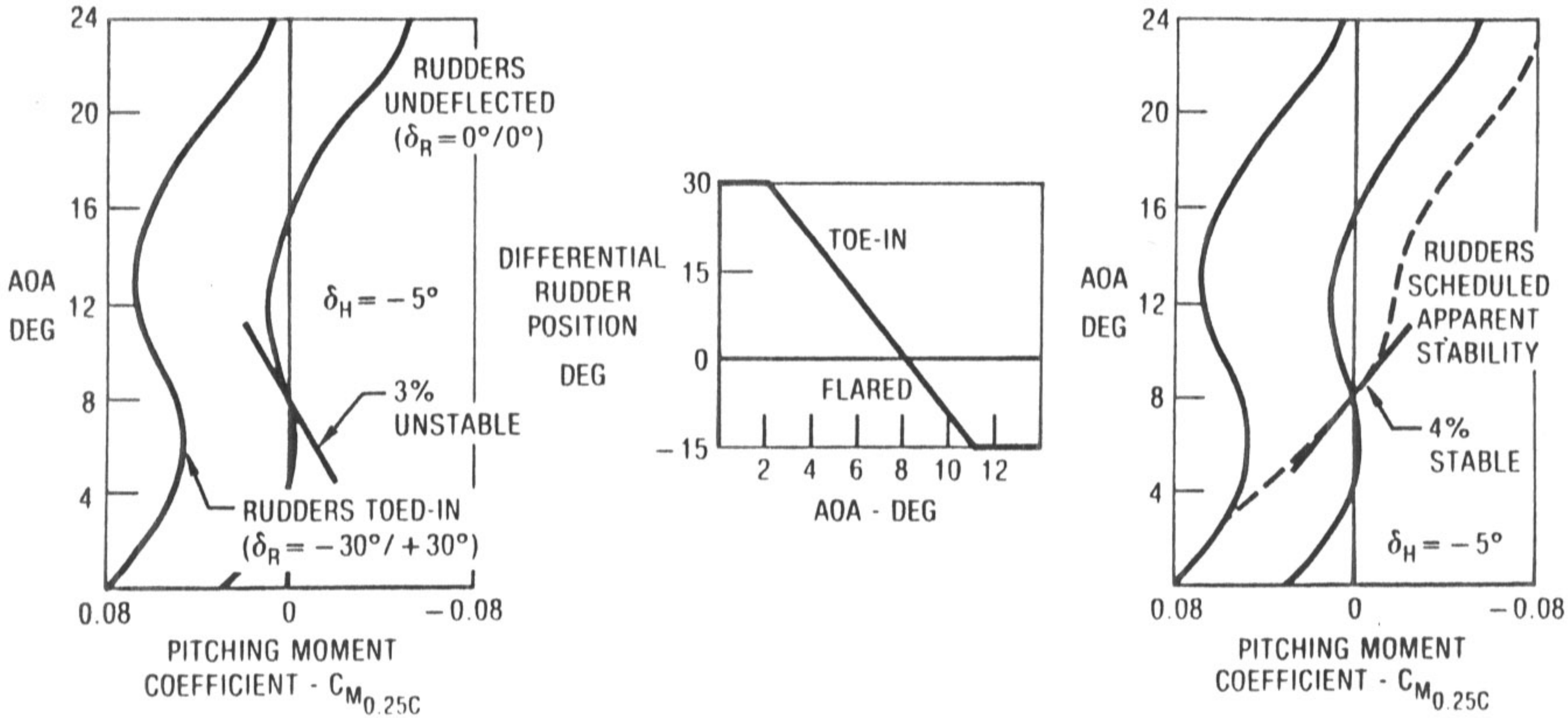
NOSEWHEEL LIFTOFF

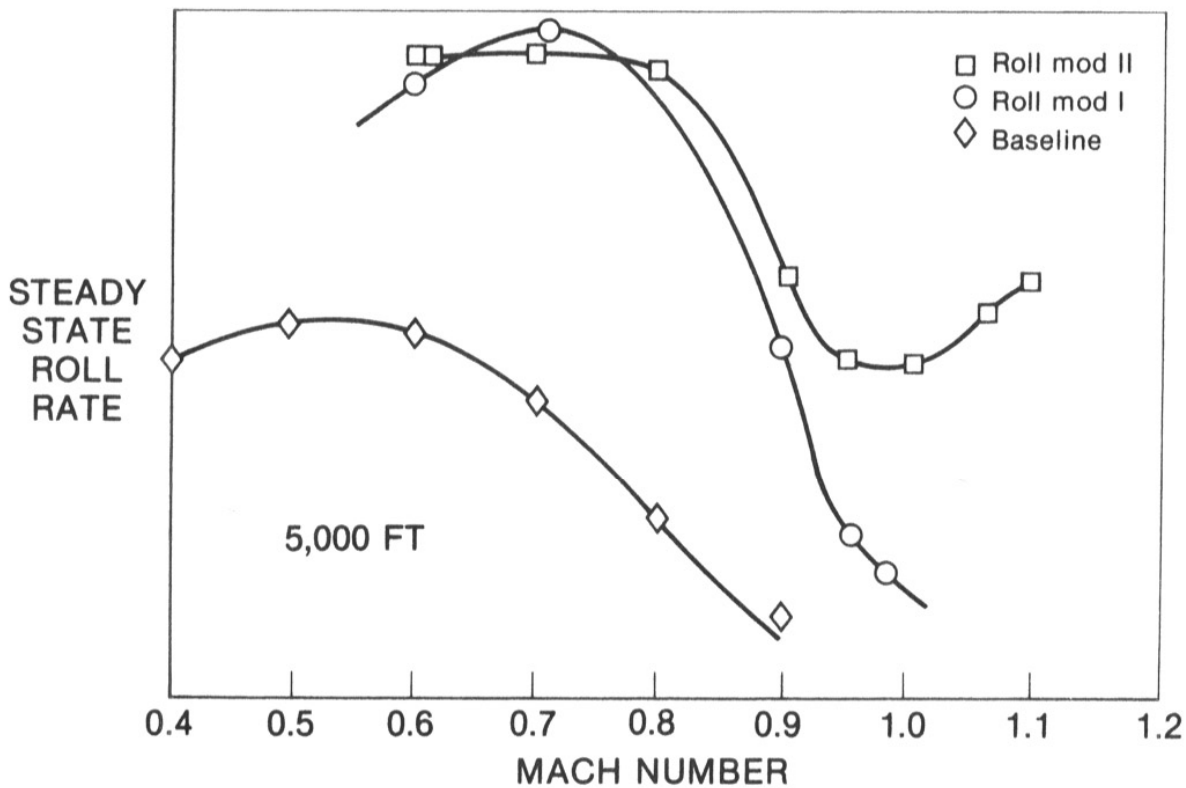


AT NWLO AERODYNAMIC MOMENTS = WEIGHT MOMENT = 36,000 * X

RUDDER SCHEDULE IMPROVES LONGITUDINAL STABILITY



ROLL PERFORMANCE IMPROVEMENTS



BASELINE - AILERONS/DIFFERENTIAL TAILS/RUDDERS

ROLL MOD I - ADDED DIFFERENTIAL FLAPERONS AND MODIFIED AILERON MACH/DYNAMIC PRESSURE SCHEDULES

ROLL MOD II - ADDED DIFFERENTIAL LEADING EDGE FLAPS FOR WING WARPING

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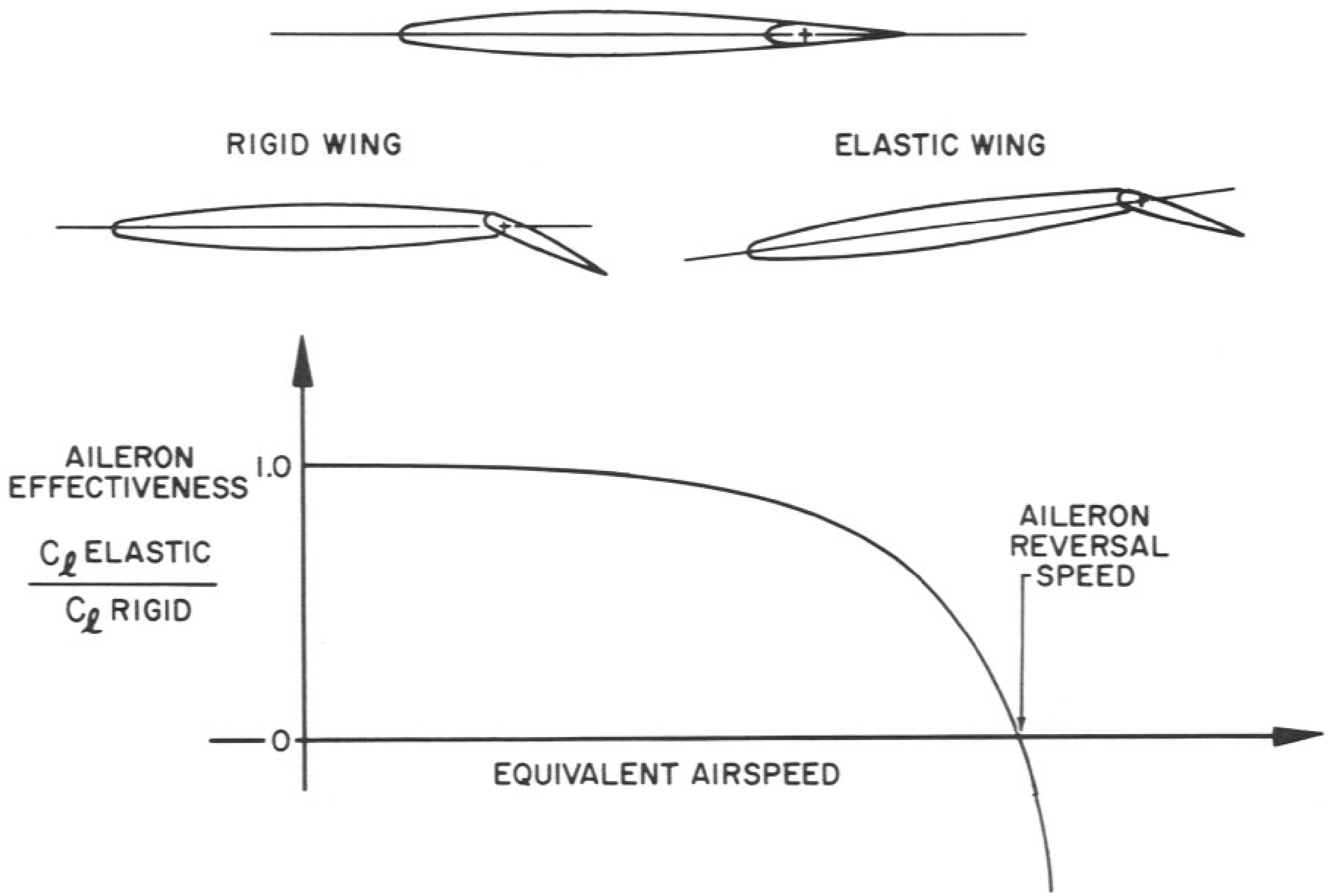
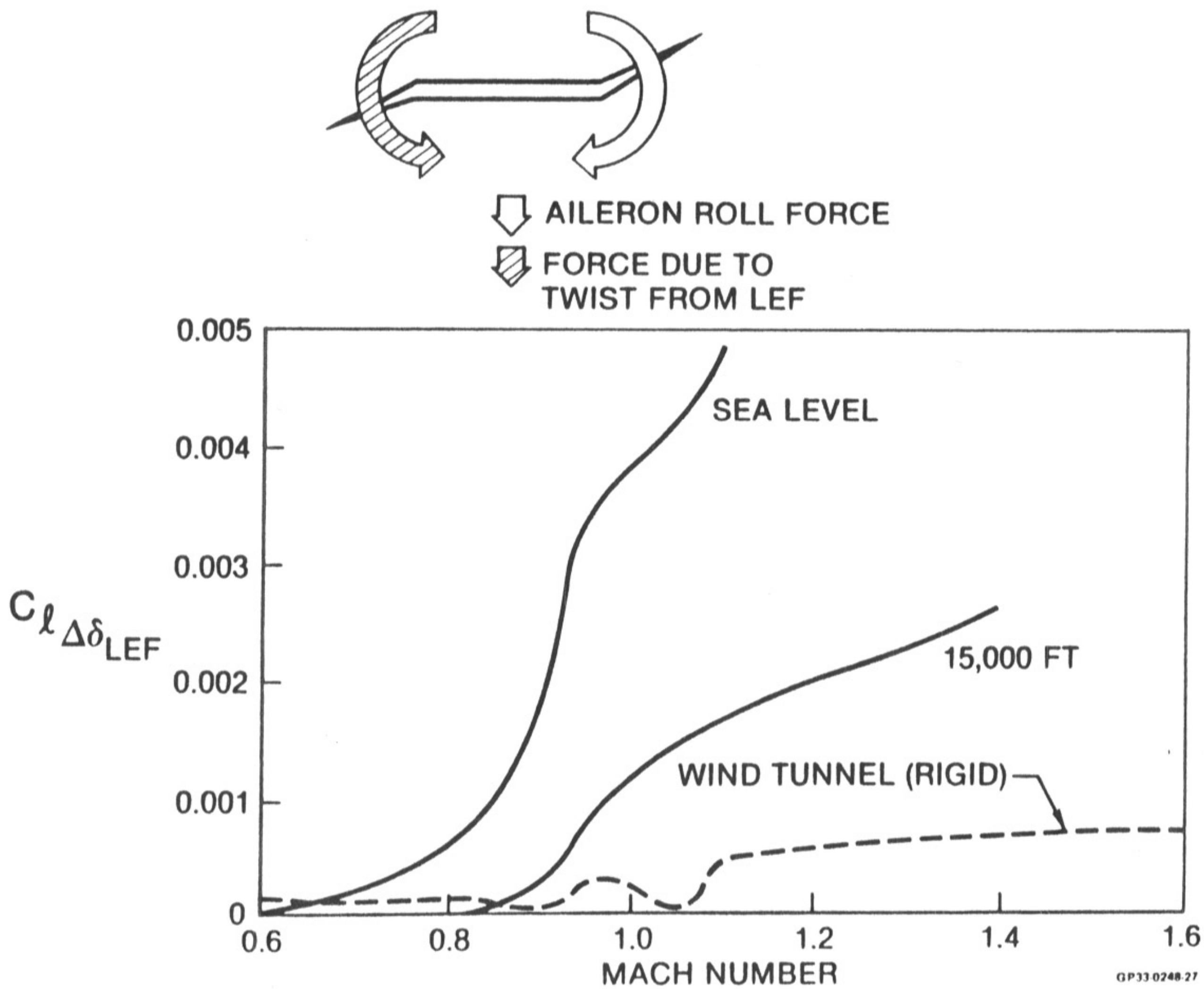
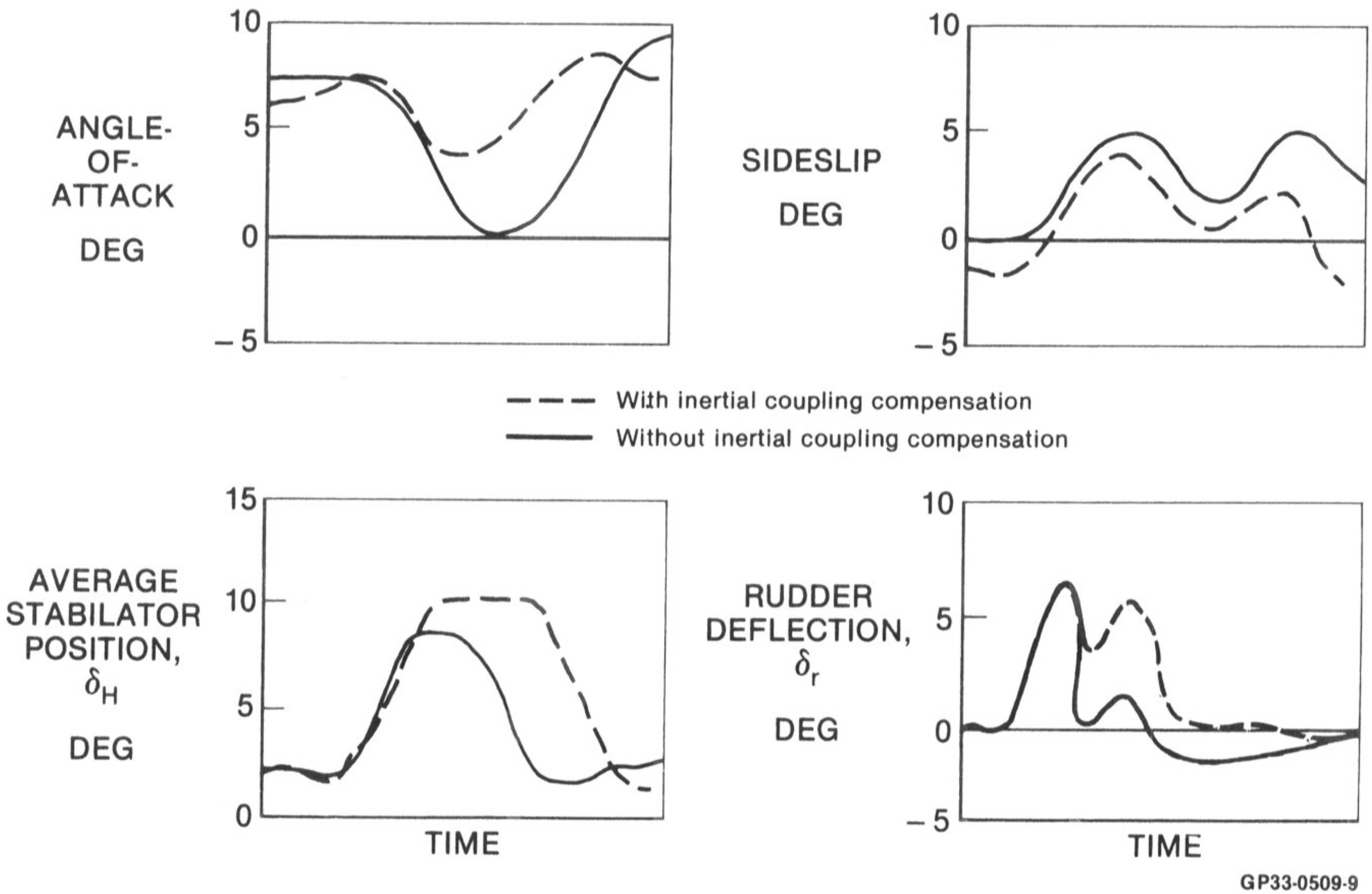
AEROELASTIC CONSIDERATIONS
AILERON REVERSAL / FLEX-TO-RIGID RATIO



DIFFERENTIAL LEADING EDGE FLAPS
ROLL POWER

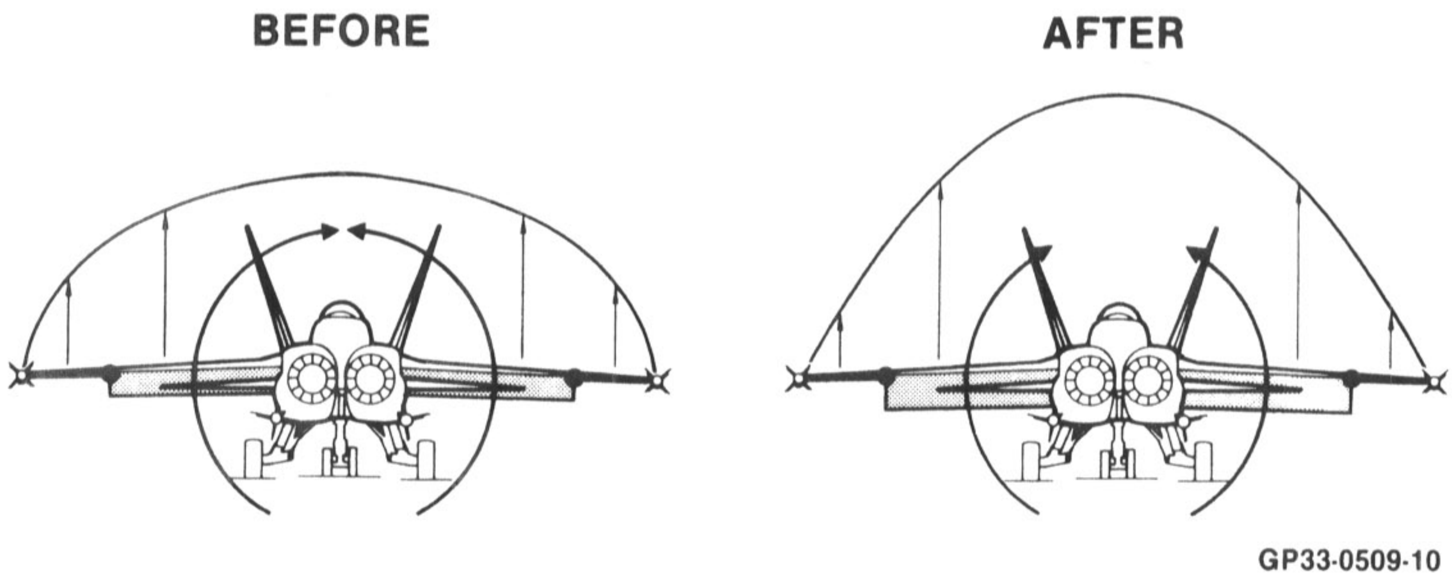


EFFECT OF INERTIAL COUPLING COMPENSATION
360° FULL STICK ROLL



WING-FOLD AND WING-ROOT BENDING MOMENTS

INCREASED TRAILING-EDGE-FLAP DEFLECTIONS
REDUCE WING-FOLD AND WING-ROOT
BENDING MOMENTS



Structural Loads Control

The Digital Flight Control is Very Effective in Controlling Structural Loads

- Control Wing/Pylon Loads With Heavy Stores
- Control Wing-Fold and Wing-Root Bending Loads
- Redistribute Loads by Scheduling Control Surfaces
- Limit Loads by Scheduling Maximum Control Deflection
- Limit Maximum Load Factor - Pilot Over-Ride

INERTIAL COUPLING EQUATIONS AND COMPENSATION

EQUATIONS:

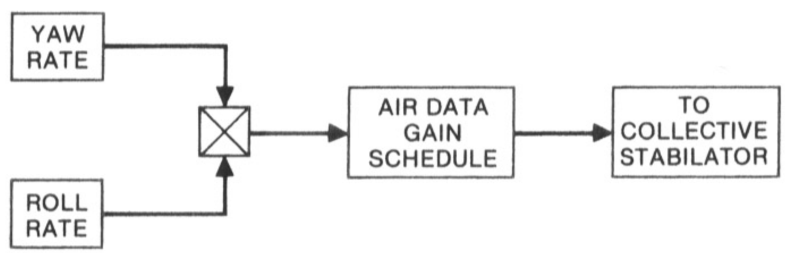
$$\dot{q} = \left(\frac{I_z - I_x}{I_y}\right) p\, r$$

$$\dot{r} = \left(\frac{I_x - I_y}{I_z}\right) p\, q$$

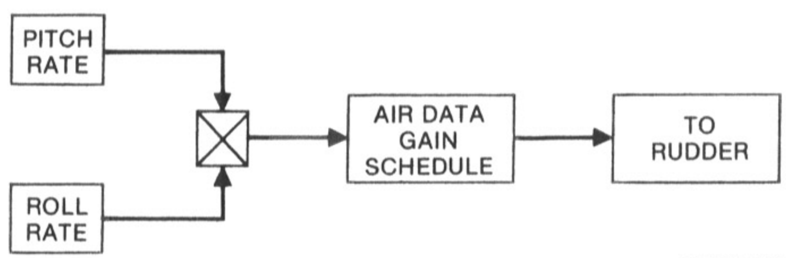
WHERE:

- q = PITCH RATE
- p = ROLL RATE
- r = YAW RATE
- I_x = ROLL MOMENT OF INERTIA
- I_y = PITCH MOMENT OF INERTIA
- I_z = YAW MOMENT OF INERTIA

LONGITUDINAL COMPENSATION FEEDBACK:



DIRECTIONAL COMPENSATION FEEDBACK:



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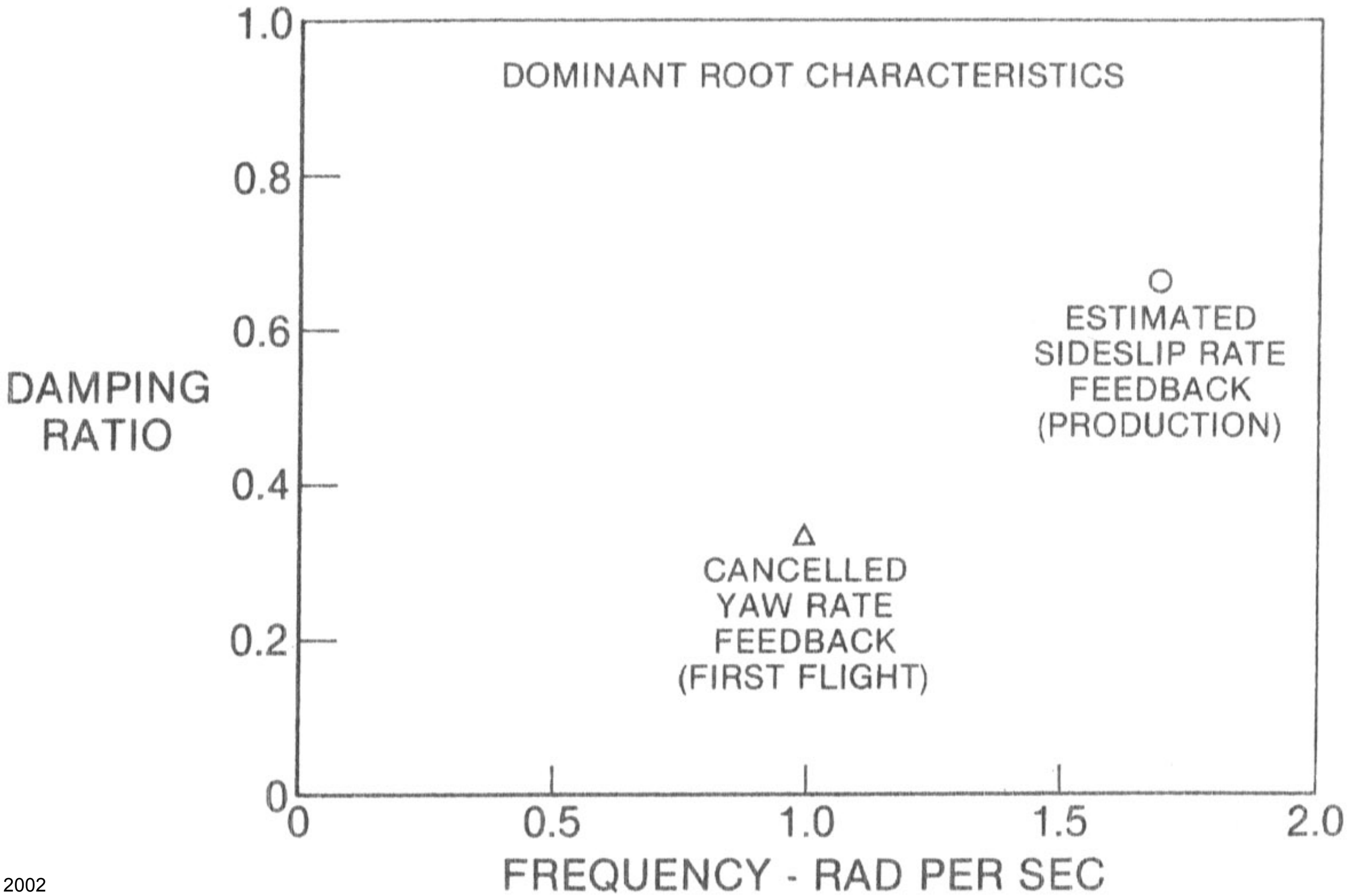
DUTCH ROLL MODE CHARACTERISTICS
POWER APPROACH CONFIGURATION



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Discussion of F/A-18 Flight Control System

Next Topic

- **Systems Engineering**
- **Integrated Product Team**

F/A-18E/F Development

A Brief Discussion on Systems Engineering From the Integrated Product Development Team Perspective

What is Systems Engineering ?

"Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development process that proceeds from concept to production to operation. Systems Engineering considers <u>both the business and the technical needs</u> of all customers with the goal of providing a quality product that meets the user needs".

Reference: International Council On Systems Engineering

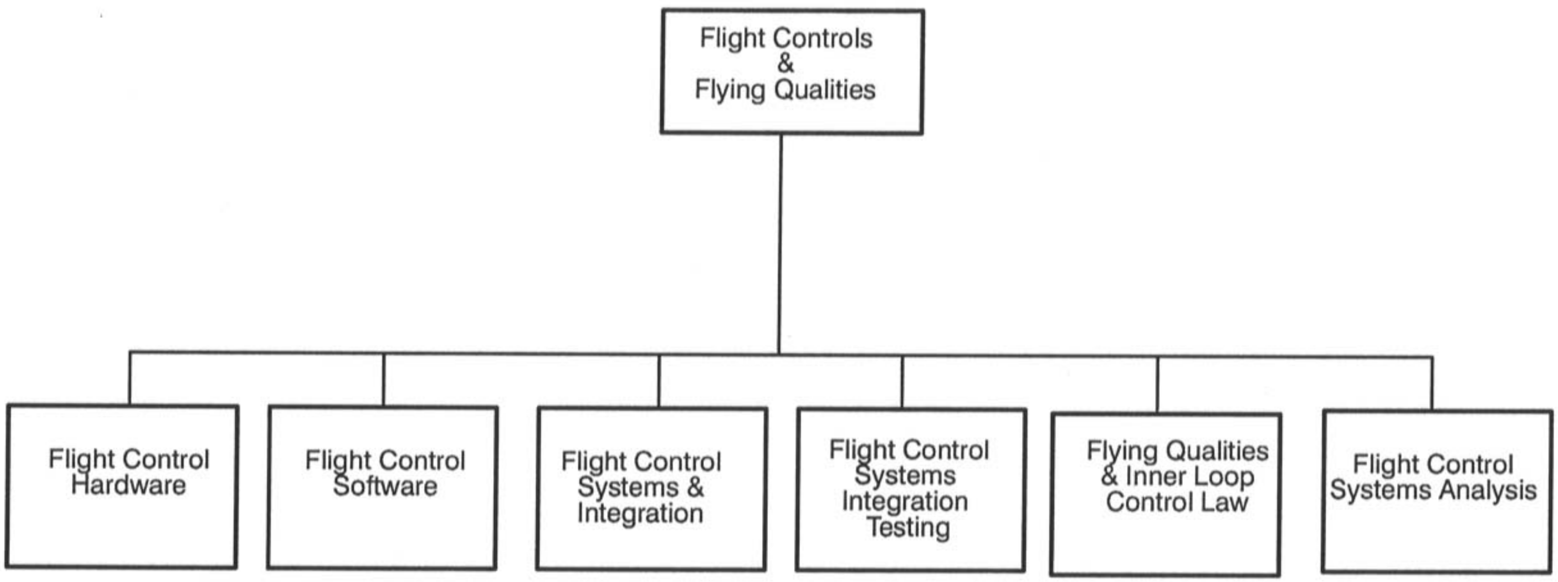
IPT TEAM LEADERS MUST MANAGE:

- **SYSTEM DESIGN AND DEVELOPMENT**
- **COST AND SCHEDULE**

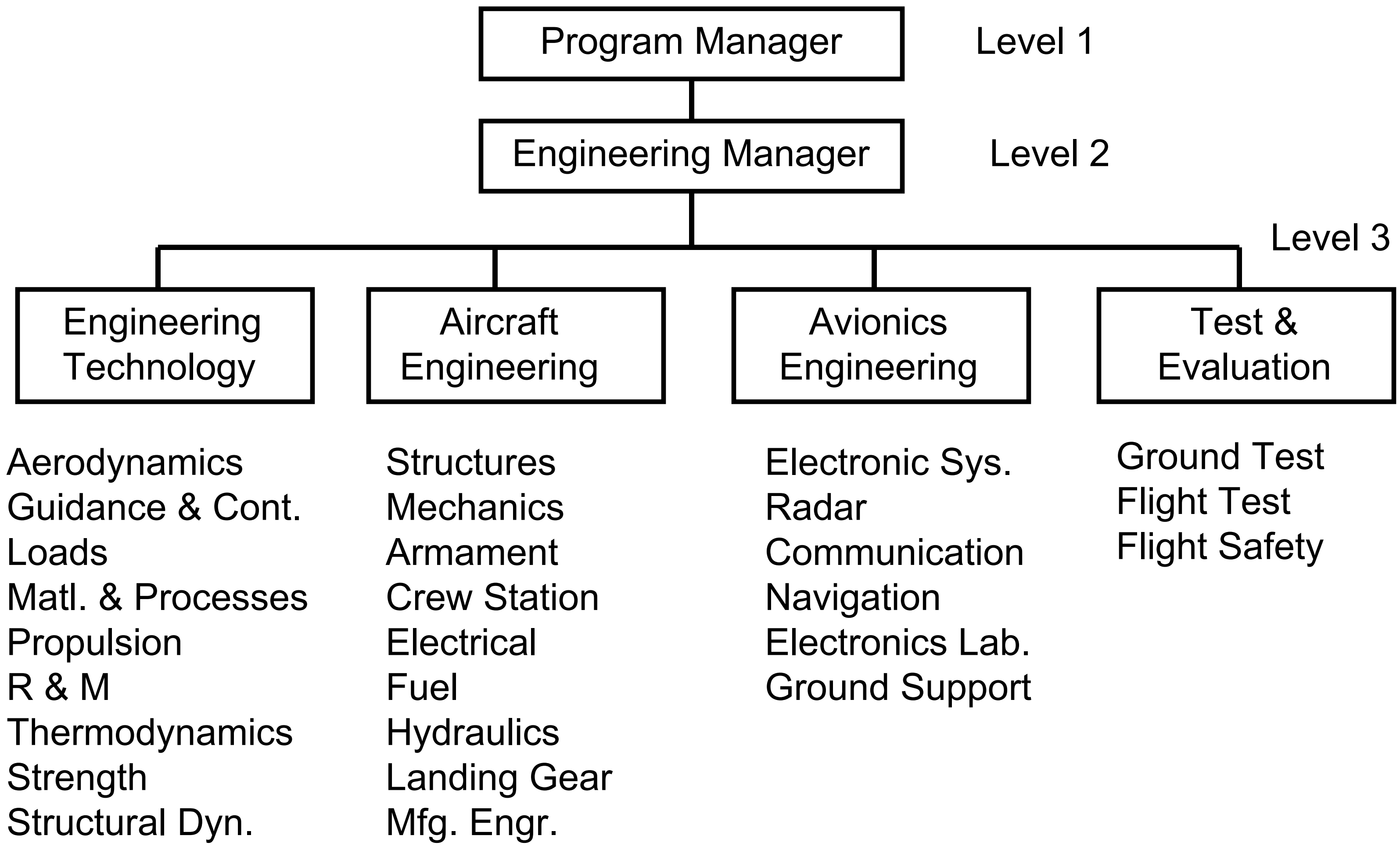
Flight Controls and Flying Qualities Team

Example of Level 4 IPT

Multidiscipline Flight Controls Team



Before IPT - Functional Organizations



Before IPT - Functional Organizations

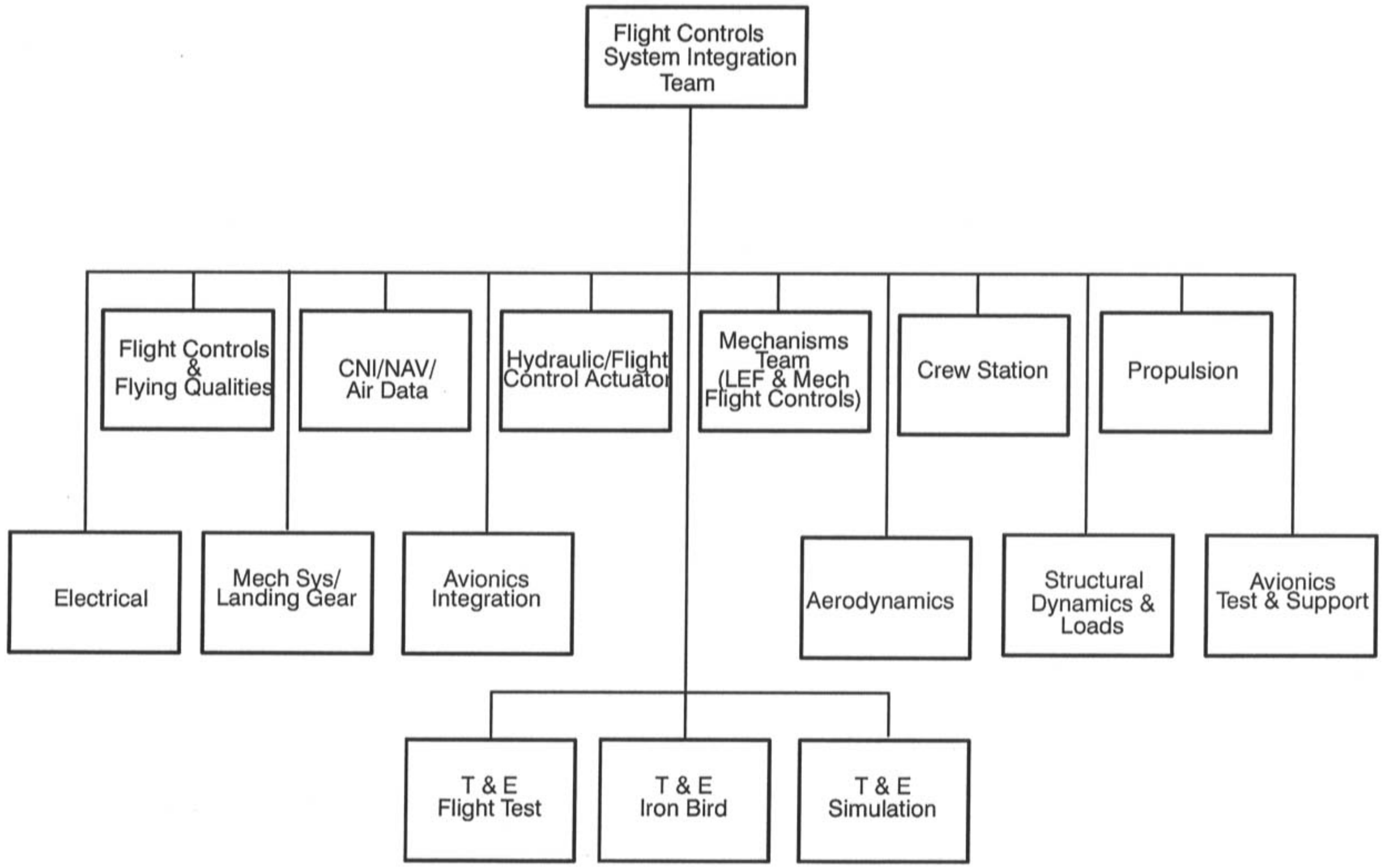
Engineering Technology	Aircraft Engineering	Avionics Engineering	Test & Evaluation
Aerodynamics *	Structures	Electronic Sys. *	Ground Test
Guidance & Cont. *	Mechanics	Radar	Flight Test
Loads	Armament	Communication	Flight Safety *
Matl. & Processes	Crew Station	Navigation *	
Propulsion	Electrical	Electronics Lab.*	
R & M *	Fuel	Ground Support	
Thermodynamics	Hydraulics *		
Strength	Landing Gear		
Structural Dyn.	Mfg. Engr.		

Note:
- Before IPT Cost and Schedule Was Allocated to Functional Groups
- The (*) Indicates Groups Represented in the Flight Controls & Flying Qualities IPT

Flight Controls and Flying Qualities IPT Major Products

- Flying Qualities Requirements
- Flight Control System Requirements
- System Design and Analysis Documents
- System/ Subsystem Interface Documents
- Flight Control Computer and Sensor Hardware
- System Software Design, Code, and Testing
- System Integration Test Requirements and Testing
- Coordination of FCS Integration Team

Flight Control System Integration Team



THIS IS NOT A FORMAL IPT !

Purpose - Horizontal Integration Across Program IPTs

- IPT Charters Included Support of FCS Integration Tasks
- All Teams Concur With FCS Development Plan

Integrated Product Team (IPT)

Responsibility
- Product Delivery
- Customer Supplier Relationship
- Processes
- Trades/Design Decisions

Accountability
- Technical Performance Measurands (TPM)
- Cost
- Schedule
- Risks

Authority
- Management of Multi-Disciplined Team
- Budget
- Performance Appraisals

Program Management Structure Needed to Support Systems Engineering and IPTs

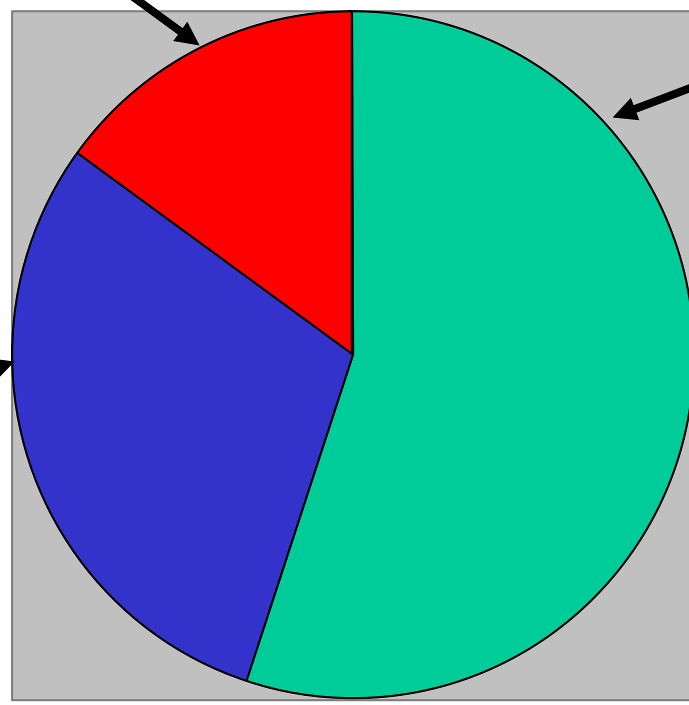
F/A-18E/F
Management Processes to Support IPT

- Requirements Flow Down
- Budget
  - Allocated to IPT
  - Management Reserve - Held at Program Manager Level
- Integrate Schedules
- Weekly Earned Value
  - DOD Cost & Schedule Control Systems Criteria (C/SCSC)
- Weekly Program Managers Meeting
  - Cost
  - Schedule
  - TPM
  - Problems / Issues
  - Risk Management
    - Likelihood / Consequence
    - Mitigation - Plan of Action and Milestones
  - Help Needed

IPT Organization and Management Processes Are
Critical to Completing a Program on Schedule and Cost

IPT Tasks for Development of a New System

What We Don't Know
We Don't Know
- Pop-Up Risks
- Management Reserve



What We Know
- Planned and Scheduled Tasks

What We Know
We Don't Know
- Development Testing
  - Contractor
  - Suppliers
- Risk Reduction Tasks

IPT Budget Should Include Management Reserve Funds

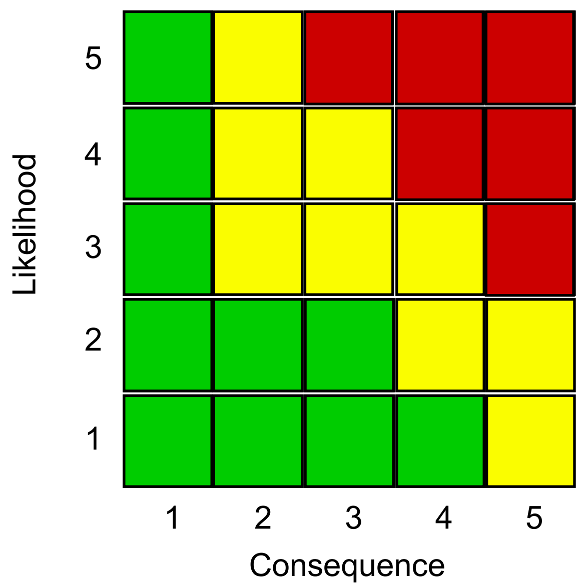
Risk Management Status

- Assess Likelihood That Risk Will Happen (1=not Likely, 5=near Certainty)
- Assess Consequence of Risk Being Realized (1=min. Impact, 5=unacceptable)
- Determine Type of Risk: Schedule, Cost, or Technical

*Place **X** in One Cell*

Risk Type
(Check one)

- ☐ Schedule
- ☐ Cost
- ☐ Technical / Quality

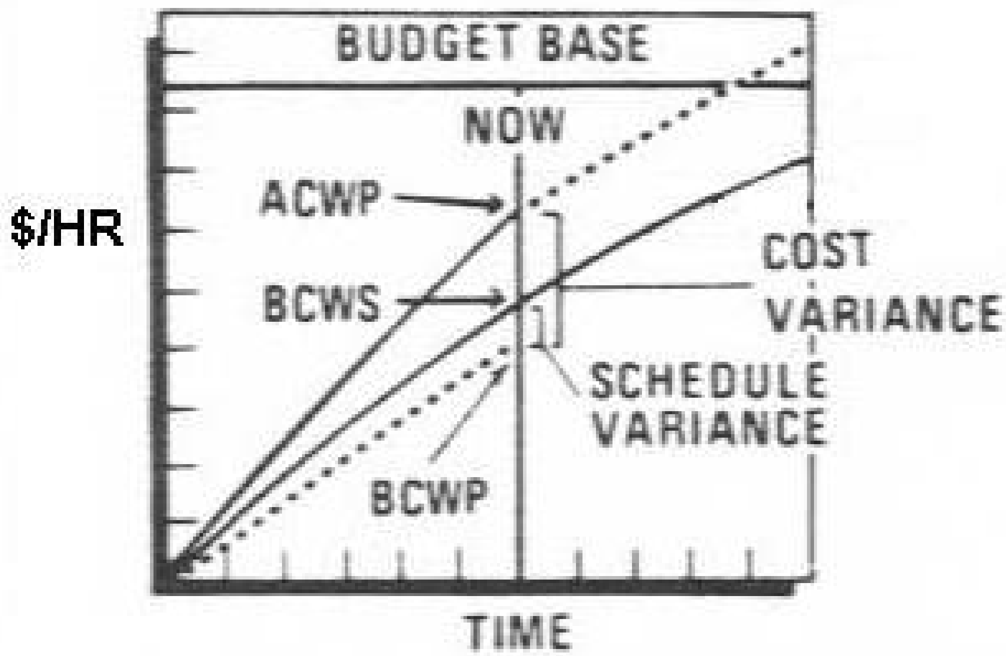


Green = Low Risk
Yellow = Medium Risk
Red = High Risk

Each Risk Must Have a Mitigation Plan

- Statement of Risk
- Plan of Action
- Milestone Schedule

What is Earned Value Management ?



BCWS = Budgeted Cost of Work Scheduled
ACWP = Actual Cost of Work Performed
BCWP = Budgeted Cost of Work Performed

Cost Variance = BCWP - ACWP
Schedule Variance = BCWP - BCWS

Reference:Office of the Under Secretary of Defense
Acquisition Resources & Analysis, www.acq.osd.mil/pm/