SAE Aerospace
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AEROSPACE INFORMATION REPORT

AIR4922

Issued 1996-10
Reaffirmed 2008-07

Primary Flight Control Hydraulic Actuation System Interface Definition

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FOREWORD

This Aerospace Information Report is the direct result of technical contributions by a number of industry experts associated with SAE Committee A-6. It is intended to give an awareness of relevant issues and parameters governing the successful integration of Primary Flight Control Hydraulic Actuation Systems. The document does not exclude commercial applications but presents a heavier emphasis on military vehicles with some references to commercial applications; reflecting technical contributions of committee members.

This document primarily provides an introductory treatment of the more relevant issues regarding system interfaces. The information may be used to support the preparation of an interface specification. Considerations for use in making trades and evaluation of several types of interfaces are included. More detailed information relating to specific interface design is left to other SAE documentation.

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1. SCOPE:

This SAE Aerospace Information Report (AIR) provides a description of the interfaces and their requirements for generic and specific hydraulic actuation systems used in the flight control systems of manned aircraft. Included are the basic control system characteristics and functional requirements, and the essential interfaces (structural, mechanical, hydraulic power, control input, status monitoring, and environment). Major design issues, requirements, and other considerations are presented and discussed.

1.1 Purpose:

The primary purpose of this document is to describe the interfaces to aid in the development of Interface Control Documents (ICDs) for primary flight control servoactuation systems in future applications. Due to the variety of applications, the number of, and type of, ICDs required for a particular application is left up to the user of this document. The lessons learned from previously developed production aircraft are discussed.

1.2 Field of Application:

This document provides a design foundation for (1) hydraulic, electronic, fiber optic, fluidic, aerodynamic, structural and mechanical interface integration with the aircraft primary flight control actuation system, (2) system failure monitoring/management, (3) actuation system electronic loop closures, and (4) hydraulic actuation loop closures.

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2. REFERENCES:

2.1 Applicable Documents:

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications: Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

ARP1383	Impulse Testing of Hydraulic Actuators, Valves, Pressure Containers and Similar Fluid System Components
ARP4386	Terminology and Definitions for Aerospace Fluid Power, Actuation and Control Technologies
AIR4253	Description of Actuation Systems for FBW FCS
AIR1657	Handbook of Hydraulic Metric Calculations
ARP4752	Aerospace Design & Installation of Commercial Transport Aircraft

2.1.2 U.S. Government Publications: Available from DODSSP, Subscription Services Desk, Building 4D, 700 Robbins Avenue, Philadelphia, PA 19111-5094.

Part 25 "Airworthiness Standards: Transport Category Airplanes" Code of Federal Regulations, Aeronautics and Space.

2.1.3 Department of Defense Specifications and Standards: Available from DODSSP-Customer Service, Standardization Document Order Desk, 700 Robbins Avenue, Bldg. 4D, Philadelphia, PA 19111-5094.

MIL-A-8870	Airplane Strength and Rigidity, Vibration, Flutter and Divergence
MIL-H-5440	Hydraulic Systems, Aircraft, Design and Installation Requirements for
MIL-H-83282	Hydraulic Fluid, Fire Resistant, Synthetic Hydrocarbon Base, Aircraft, Metric NATO Code Number H-537
MIL-E-5400	Electronic Equipment, Airborne, General Specification For

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2.1.4 Related Publications: The following publications are provided for information only and are not a required part of this SAE Technical Report.

SAE Format Guidelines for the Electronic Capture of SAE Documents, dated November 21, 1989

Quick Reference Guide for the Preparation of SAE Documents, dated 3/91

SAE Guide for Preparation of Aerospace Documents AS, ARP, AIR, MA, and Map, dated January 1, 1987

AIR4002	8000 psi Hydraulic Actuation Systems: Experience and Test Results
AIR4094	Aircraft Flight Control System Descriptions
ARD50020	Fiber Optic Interconnection Systems for Aerospace Applications
ARD50024	Fiber Optic Coupled Sensors for Aerospace

2.2 Applicable References:

1. HARSCHBURGER, H.E. "Development of Redundant Flight Control Actuation Systems for the F/A18 Strike Fighter", SAE Paper No. 831484, October 1983.

2. HARSCHBURGER H.E., HESS R. K., HOFFMAN J.N., Control Surface Actuation Dynamics, McDonnell Aircraft Company, May 7,1990.

3. STERN H., Fluidics: An Overview of Thirty Years of the Technology, Purdue University.

4. VICK, R.L., Hydraulic Actuator Stiffness, Actuation Stiffness Considerations and Applications Symposium, SAE Subcommittee A6-D, May 10, 1990. Allied-Signal Aerospace.

2.2 (Continued):

5. WILKINSON, K., Aeroelastic Design Requirements for Aircraft Control Surface Control Actuators, Grumman Aircraft Systems Division. Presented at SAE Guidance and Control Meeting, Denver CO., 1991.

6. RAYMOND, E.T., CHENOWETH, C.E. Aircraft Flight Control Actuation System Design, 1993.

2.3 Definitions:

The primary source for terms and definitions has been from ARP4386.

2.3.1 Abbreviations:

BIT	Built-In-Test
CAS	Control Augmentation System
CDR	Critical Design Review
DDV	Direct Drive Valve
DoF	Degree of Freedom
ECD	Envelope Control Drawing
EMI	Electromagnetic Interference
EMP	Electro Magnetic Pulse
EHV	Electro Hydraulic Valve
FBL	Fly-By-Light
FBW	Fly-By-Wire
FCES	Flight Control Electronic Set
FMECA	Failure Modes and Effects Criticality Analysis
GVS	Ground Vibration Survey
HIRF	High Intensity Radio Frequency
ICD	Interface Control Document
IPT	Integrated Product Team
LRA	Line Replaceable Assemblies
LRU	Line Replaceable Unit
LRS	Laminar Rate Sensors
LVDT	Linear Variable Differential Transducer
MCV	Main Control Valve
MTBF	Mean Time Between Failures
PDR	Preliminary Design Review
PCV	Power Control Valve
SAS	Stability Augmentation System
SOV	Solenoid Operated Valve
TRR	Test Readiness Review
VRMS	Volts Root Mean Square

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3. TYPES OF INTERFACES:

A hydraulic, primary flight control, actuation system normally interfaces with the following subsystems:

a. Command Control System (Mechanical, Electronic or Fiber Optic)
b. Hydraulic Power Supply System
c. Control Surface Structure
d. Airframe Structure

A typical system is illustrated in Figure 1. It provides control of surface motion in response to a command initiated by the pilot or automatic control. This is accomplished by amplifying and transducing the signal into hydraulic power at the main control servovalve. The valve's output hydraulic flow/pressure drives the actuator until its loop closure (feedback) signal negates the input signal and reduces the valve output to stop the actuator motion. The actuator interfaces with the hydraulic power supply, the control surface loads, the structural stiffness and inertia of all elements, which affect both the accuracy of the response to the command and the stability of the system.

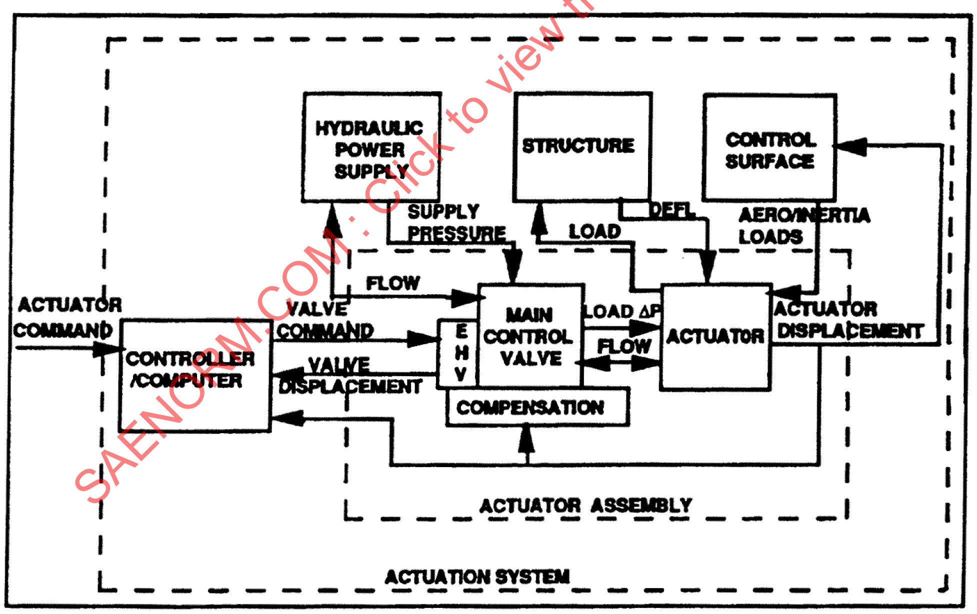

FIGURE 1 - Typical Hydraulic Primary Flight Control Actuation System

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4. REQUIREMENTS FOR INTERFACES:

It is extremely important that all parties involved in the design, development, and testing of primary flight control hydraulic actuation systems understand the physical and functional interface requirements. In order to ensure compliance with requirements, Interface Control Documents (ICD) normally provide a description of these interfaces. Where responsibilities may be split in the system acquisition process, the ICDs play an even bigger role of ensuring compliance with contractual requirements. They also serve as a focal point for all the requirements from all disciplines involved. ICDs are being developed and updated up to the preliminary design review (PDR) phase of a program. At that time, the interfaces must be firmed up to allow the component designs to be finalized. After the interfaces are frozen, the pace of ICD change slows down. However, reviews and negotiations of appropriate changes are an allowable and continuing part of the design development process.

The ICD describes several types of interfaces. For example, it represents an agreement between contractor design teams or groups, the in-house teams of commercial aircraft entrepreneurs, a contractor group and a supplier, or between subsystem and component suppliers. The ICD defines the design characteristics of interfacing subsystems or components. Its purpose is to ensure that the overall system will meet its design requirements.

An equally important feature of the ICD is to maintain configuration control during the life cycle of the system. ICD maintenance is a significant task for whomever assumes the system responsibility. The job of developing and maintaining an ICD is left to a working group, such as an integrated product development team (IPD). The ICD working group addresses the very large and difficult issue of the relationship between an ICD and the Product Specification or Purchase Order. Also, in order to produce a balanced design and resolve conflicts, the group or team that develops and maintains the ICD should be the group that has been given overall responsibility, accountability and authority for the overall system performance.

It is important to understand that an ICD not only controls suppliers but also controls the internal disciplines and associated interfaces of the prime and/or subsystem contracting organizations, military /commercial. Such formalizing of requirements reduces the possibility of misunderstandings or the overlooking of a particular discipline's requirements. The activities to define an ICD generally take place before PDR, but they are almost always after receipt of a contract based on a proposal to meet a specification. The iterative ICD process frequently results in desirable modifications to the architecture, envelope, performance requirements and other contractually agreed upon parameters. The ICD working group cannot readily amend these other documents, and the result may be conflict between the documents. Therefore, the ICD working group needs to define priority or precedence provisions so that they can be referenced in the proposal and purchase orders. Specifications must be revised to the mutually agreed parameters by the end of a Joint Definition Phase and before PDR for the ICD to be effective.

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4. (Continued):

Examples of useful ICDs described in this document are:

a. Electronic (controller) supplier and actuator hardware supplier
b. Contractor structural design group and actuator hardware supplier (envelope control drawing)
c. Contractor hydraulic design group and actuator hardware supplier
d. Contractor Flight Control/ Flight Control Integration Group and all of the above

Figure 2 illustrates how the electronics/software and the equipment hardware development disciplines interact in Fly-By-Wire actuation system development.

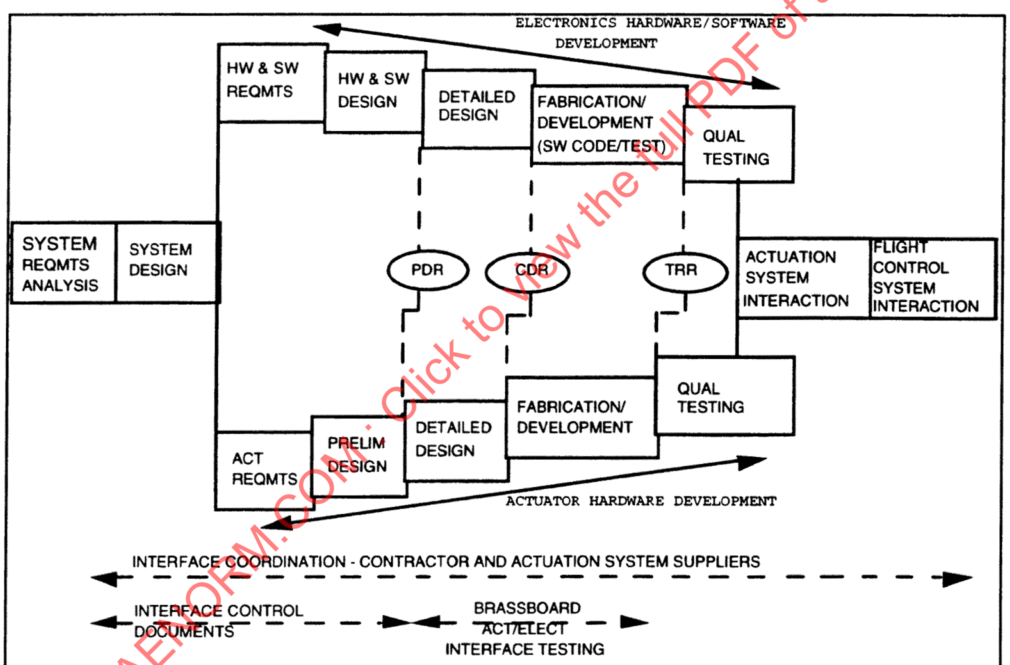

FIGURE 2 - Fly-By-Wire Actuation System Development

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4.1 Interface Design Requirements Methodology:

In general an ICD is comprised of interface control drawings, electrical interface data, envelope drawings, geometry drawings, and master tool drawings that define physical interfaces between major assemblies and line replaceable parts. In addition, specific information such as assembly drawings may be included as reference information to enhance coordination and communication between the supplier and contractor, with the full understanding that component or subsystem specifications are still the controlling documents for the procurement of supplier hardware.

4.1 (Continued):

It is of utmost importance that the methodology to develop a useful Interface Control Document (ICD) be very specific. The development of an effective and worthwhile ICD is an iterative process. The process allows all disciplines to contribute to the successful development of an actuation subsystem without the disciplines encroaching on each other's responsibilities. The iterative process must allow an adequate amount of time for all interfaces to evolve prior to firming up. As such, it is generally found that the period of time from a program go-ahead to PDR is considered adequate for ICD development. Any extension of the approval of ICD issues (especially issues which influence the complexity of the system) into the period of time between PDR and CDR, should be considered to be a risk to the program's schedule.

The ICD should become an associated document to the subsystem specification. Since the Interface Control Document governs all interface parameters of an actuation system, it serves to coordinate activities not only between the airframer and actuator suppliers, but also between the airframer's and supplier's internal disciplines. It follows then that the ICD could also include drawings of master tools, particularly if the masters are to be used by all parties.

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4.2 Structural Interfaces:

The ICD should address critical areas such as envelope and physical interfaces, and particularly structural requirements such as strength, stiffness, fatigue, durability and damage tolerance. Of most importance, it should clearly demarcate the responsibility boundaries of individual documents that make up the ICD by clearly describing the distinction of each. For instance, the ICD should contain Envelope Control Drawings (ECD). The ECDs define envelope borders of individual Line Replaceable Assemblies (LRA), such as actuators, by basic dimensions that are not to be intruded into by any party other than as defined by Interface Control Drawings. As such, ECD's shall not contain any toleranced dimensions. Tolerances for mounting points would be reflected only in the Interface Control Drawings, while the ECD would reflect maximum envelope permitted at such points by the tolerances defined in the Interface Control Drawings. Figure 3 shows relevant Structural/Mechanical Interfaces parameters:

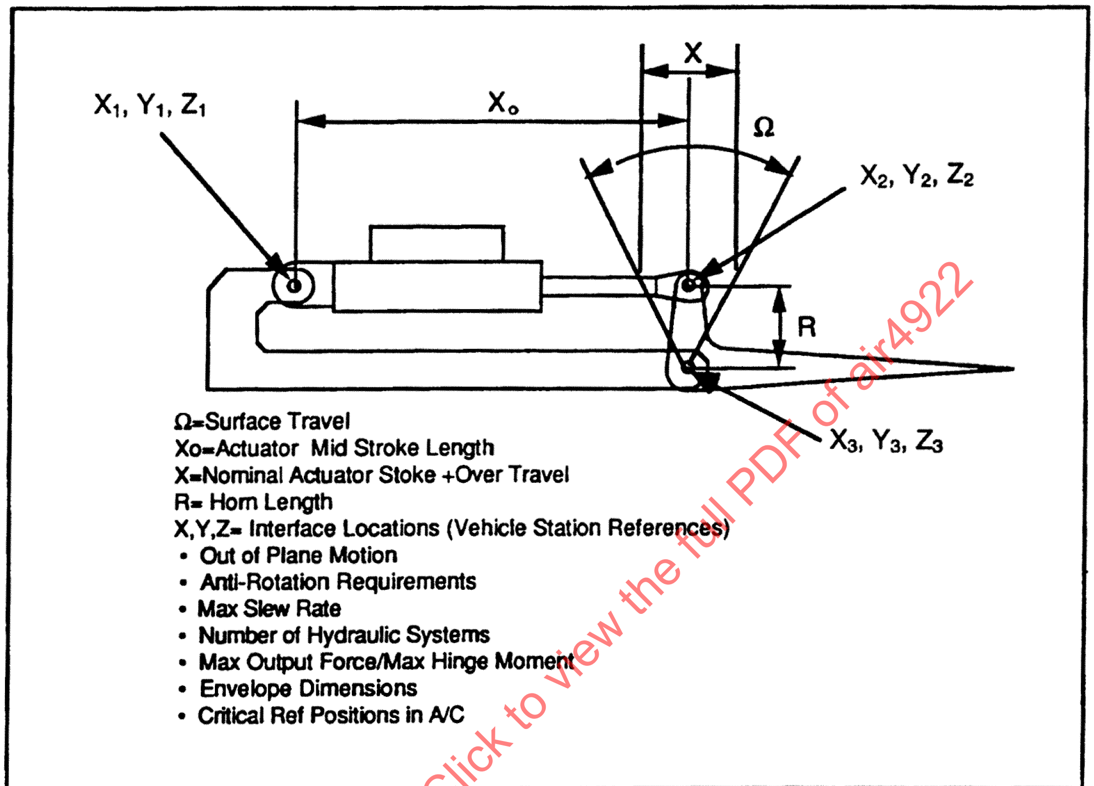

FIGURE 3 - Structural/Mechanical Interfaces

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4.3 Mechanical Interfaces:

The Interface Control Drawings should define all dimensions and associated tolerances governing all parties at interfaces such as mounting locations. It should also contain all interfacing locations and permissible tolerances for hydraulic and electrical connection points, as well as callouts of all interfacing hardware such as electrical connectors. Since electrical ground straps represent interfacing hardware, the Interface Control Drawing should clearly state grounding strap requirements, locations, installation callouts defining the hardware, and installation responsibility. The actuator attachments should be defined in the ICD and should include attachment bolts/bushings and anti-rotation requirements.

The support bearing performance is an important structural/mechanical interface issue. Bearings, particularly if self-lubricating type, could generate significant frictional torque under load and at low temperature, which may significantly affect the design of the interface attachment. Internal spring rates and deflections can be critical when summed with all other structural loop parameters.

4.4 Electrical Interfaces:

From the limited authority series servo used for the aircraft's stability augmentation system to the full authority Fly-By-Wire actuation systems, the electrical interface is critical for most actuator systems. Exceptions, of course, include conventional mechanically signaled actuators which may not have electrical connections or include only stuck valve warning circuits. Wiring schematics should be included in the ICD to define electrical connections, connector pin locations and polarity.

The electrical interface between the servo electronics and the typical actuator consists of (1) Commands to the servomotor (2) Power to position sensors, i.e., power ram and servo/MCV (3) Power to the shut off valve solenoid (4) Return signals from the position sensors.

The most significant interface issue is the level of redundancy of the incoming command signal and the actuator valve configuration in terms of type of valve and the redundancy levels throughout the actuator.

Ground rules regarding reliability and redundancy do change. For example, based on the premise that extremely to infinitely reliable elements do not need to be redundant to provide required levels of flight safety, the DDV has all but eliminated the redundant EHV approach, substituting a higher power electromechanical unit to drive the MCV. For some applications, the MCV can be eliminated, with the DDV providing the required flow and pressure to the main ram of the actuator.

4.4.1 Servovalve/Servomotor/MCV: Until Direct Drive Valves (DDVs) became practical, the typical FBW FCS for high performance aircraft consisted of a 3 or 4 channel computer system interfacing with redundant electrohydraulic valves in the hydraulic actuator. Typically, there were 3 or 4 EHVs driving a dual tandem Main Control Valve (MCV) which in turn provided flow and pressure to the dual tandem power ram. The single power ram piston rod end connected to the control surface horn or crank via a single bolted connection. There are many variations on this theme including: dual concentric MCVs; dual concentric piston rods and rod ends; various innovative bolted connections; and innumerable arrangements of three or four EHVs interfacing with the MCV. One such arrangement consists of four EHVs, arranged in two position summing pairs, each pair force summed on the MCV. When combined with electronic or hydraulic sensors, this arrangement can provide exceptional failure detection and isolation capability.

Assuming that the flight control brain of any vehicle is a digital (software driven) computer, and that the flight path represents an analog quantity directly responsive to the control actuator, there exists an infinite number of choices where the digital to analog (d/a) conversion may take place. Historically, this d/a conversion was made at the milliamp signal level and great pains were taken to generate a "scrupulously clean" analog power actuation output. Or else, in the case of missile flight controls, a full excursion "bang-bang" system, was used, wherein even the flight path was barely smoothed, as long as a reasonable target accuracy was achieved.

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4.4.1 (Continued):

With the advent of more flexible and fast micro-electronic computers and the potential for digital (binary) modulated power actuators the placement of the d/a and electrical/hydraulic interfaces becomes more flexible. The location of these interfaces can have far reaching implications on system power efficiency and performance. Figure 4 illustrates how the d/a interface might segregate components.

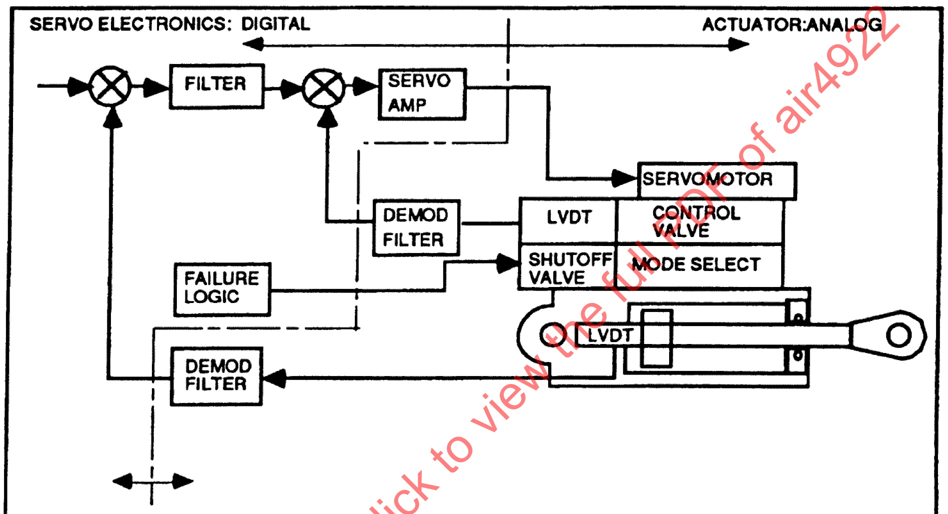

FIGURE 4 - Digital/Analog Electronic Interface:

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4.5 Vehicle Flexibility Characteristics:

Vehicle control can be compromised by flexibility characteristics of the airframe. It is not enough to provide servoactuation with sufficient load capacity and frequency response. If the structure is not sufficiently rigid, it will impact the servoelastic stability of an actuator installed in the vehicle driving a control surface. It is necessary to achieve a complete understanding of the impact vehicle flexibility characteristics have on the response of a flight control actuation system. One way to make certain that aero servoelastic considerations are not overlooked is to make these requirements part of the actuation system ICD. Sufficient structural definition of the vehicle installation must be included to support development of math models to perform servoelastic stability analysis. This should include the structural stiffness (spring rate) of the vehicle actuator installation structure, the control surface horn stiffness, actuator dynamic stiffness requirements and control surface inertia.

4.6 Hydraulic Power Source:

Information necessary to define the actuation system's interface with the hydraulic system can be allocated to three basic areas; installation, structural integrity and performance. Definition of the fitting system, port locations, line hose, coiled tubing or swivel mounting provisions and permissible actuator motion define the elements necessary for installation.

Structural integrity is primarily determined via specification of impulse requirements such as those contained in ARP1383. Generation of those requirements is contingent upon parameters associated with the defined hydraulic system. The significant parameters include: type of fluid, nominal system pressure, flow, return pressure, allowable pressure surges (pressure and return), water hammer characteristics and/or tubing design methods, system isolation requirements, system temperature variations for full and reduced performance, actual or agreed upon fluid bulk modulus at pressure and temperature extremes.

Factors such as relief valve settings and air loads which contribute toward increases in the hydraulic pressures within the actuator must be given consideration in the interface document. These factors may be appropriate to both the structural integrity and performance aspects of the actuation system.

Performance issues related to the hydraulic system interface can drive the design of elements of the actuator. For example; definition of the seal system (static and dynamic) to achieve endurance and reliability goals; specification of redundancy requirements, i.e., rip stop construction, shut off valving and multi-system sources; definition of materials and processes interfacing with the fluid and establishment of specific clearances and fits to achieve desired performance should be considered in the interface control document; hydraulic system line loss characteristics, i.e., differential pressure across the actuator at maximum no load slew rate.

Basic data relative to the hydraulic system such as fluid type, temperature ranges, filtration/contamination level requirements and similar information should be included in the ICD. MIL-H-5440 and ARP4752 may be used for guidance in selecting ICD parameters.

4.6.1 Horsepower: Required hydraulic horsepower should be specified in the ICD. This is typically defined by the combination of actuator slew rate and output force capability. It should also be coordinated with the mission profile. Degraded modes of operation, if applicable, should also be delineated in the ICD and presented against a mission profile for the actuation system operating in a degraded or emergency mode. Pressure versus flow characteristics for the hydraulic system at pressure, return and other ports (as appropriate) should be provided.

In addition to required horsepower, the horsepower rejected to the hydraulic system should be included as a function of the mission segment and the system ports to which it is rejected. This information should also be provided in the ICD for degraded and emergency modes of operation.

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4.6.2 Flow: Required flow rates associated with the pressure levels should be specified in the ICD in addition to the no load flow requirement of the actuation system. Flow rates associated with the loaded system should be defined to characterize the actuation system performance.

4.6.3 Pressure: Interface requirements are not complete without a definition of the pressure levels of importance to the actuation system. These pressures may include but are not limited to the following:

a. Operating pressure (nominal)
b. Max transient pressure
c. Minimum operating pressure
d. Return pressure(min, max, nominal)
e. Design proof and burst pressures (supply and ret)
f. Pressures associated with performance points
g. Pressure losses in the vehicle distribution system
h. Case pressures (i.e., pressures associated with special situations such as motors, which may have unique requirements)

In the event that multi-pressure or variable pressure systems are utilized, the operational parameters affecting pressure determination should be specified in the ICD.

4.6.4 Response: The dynamic characteristics of the pressure supply system should be provided in the ICD to ensure that actuation system dynamics are evaluated with consideration for the hydraulic system capabilities. Dynamics of the return system are also critical for evaluation of both the actuation system and the hydraulic system. Desired return line pressures can be exceeded by actuation system transients.

4.7 Control Interfaces:

Control interfaces are equally as important as physical interfaces to ensure proper and predictable performance of a flight control hydraulic actuation system. Control interfaces can therefore be characterized as functional interfaces.

Important valve and other parameters involved with definition of limit cycling, stiffness and other secondary parameters are pressure gain, valve friction, ram friction (at pressure), torque motor or DDV resonance and damping factors at every stage.

Figure 5 shows an example of an actuation system block diagram.

Table 1 shows a list of some typical parameters that may require definition.

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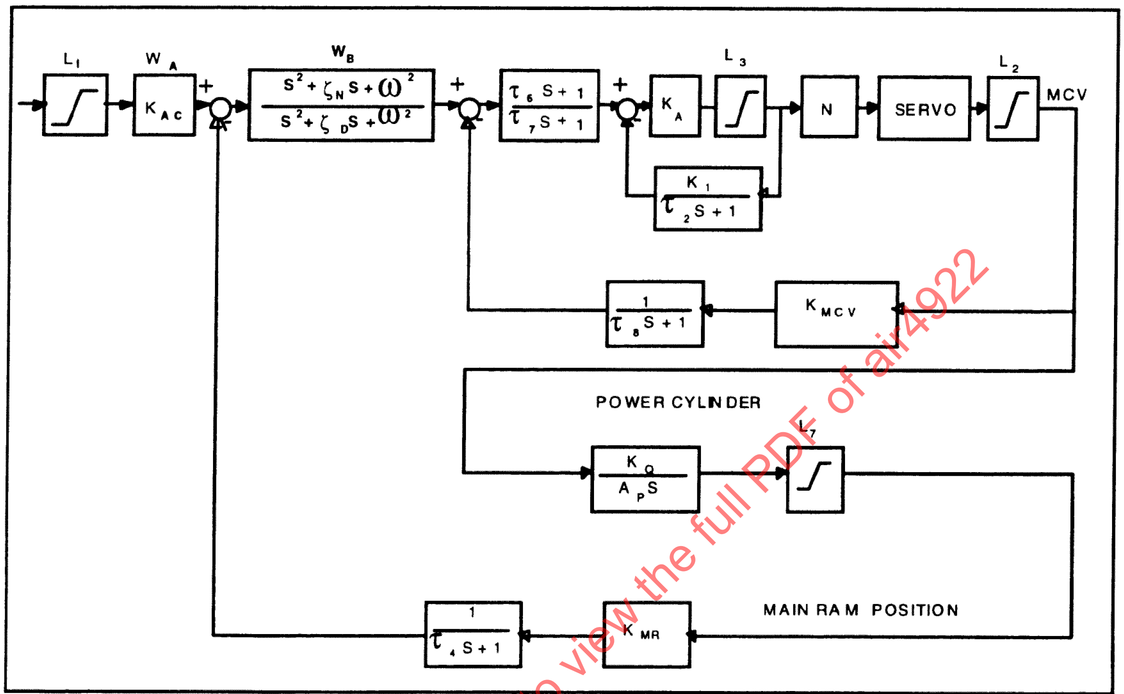

FIGURE 5 - Actuation System Block Diagram

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TABLE 1 - Typical Servoactuator Control Characteristics

Symbol	Title	Units English	Units Metric
A_p	Output RAM Piston Area	IN^2	mm^2
DM	Motor Damping	IN-LB-SEC/RAD	Nms/rad
J	Motor inertia	$IN\text{-}LB\text{-}SEC^2$	$kg\ m^2$
K_A	Amplifier Gain	Volts/Volt	V/V
ωA	Command Filter Lag	RAD/SEC	rad/s
ωB	Notch Filter	RAD/SEC	rad/s
ξn	Notch filter Damping (Numerator)	RAD/SEC	rad/s
ξd	Notch Filter Damping (Denominator)	RAD/SEC	rad/s
K_{AC}	Amplifier Gain	Volts/Volt	V/V
K_C	Servo-cylinder Driver Gain	Volts/Volt	V/V
K_{EQ}	Motor and Valve Flow Force	IN-LB/RAD	Nm/rad
K_I	Current Feedback Gain	Volts/AMP	V/A
K_{MCV}	MC Valve Feedback Gain	Volts/In	V/mm
K_{MR}	Output Ram Feedback Gain	Volts/In	V/mm
K_Q	Flow Gain	$IN^3/SEC/IN$	mL/s/mm
K_T	Torque Constant	IN-LB/AMP	Nm/A
L	Motor Inductance	Henry	H
L_1	D/A Output Limit	Volts	V
L_2	MCV Command Limit	Volts	V
L_3	Current Command Limit	Volts	V
L_7	Output RAM Limit	IN	mm
N	Number of Coils	--	
R	Motor Resistance	OHMS	Ohm
RT	Motor Lever Arm	IN/RAD	mm/rad
τ_2	Current Feedback Time Constant	SEC	s
τ_3	MCV Ripple Filter Time Constant	SEC	s
τ_4	RAM Ripple Filter Time Constant	SEC	s
τ_6	Servoampl Lead Time Constant	SEC	s
τ_7	Servoampl Lag Time Constant	SEC	s

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4.7.1 Control Loops: Today, high performance aircraft are usually inherently unstable. Closed loop "augmentation" systems are required to stabilize the aircraft so that it appears stable to the pilot and handles in a predictable manner. The systems operate by sensing pilot control inputs, aircraft accelerations and/or rates, and position the appropriate control surface to obtain the desired aircraft response.

The control loops can be gain scheduled (Mach, altitude, aircraft configuration, etc.) to provide a more uniform aircraft response to pilot control inputs, such that the aircraft will handle predictably for all conditions throughout the operational flight envelope.

4.7.2 Servo-loop Stability: The stability of a servo-loop is characterized by its response to control inputs. That is, the system is stable if the output becomes steady state for a constant input. In a first order system, the response characteristics are determined by its time constant. The system time constant is defined as the time the system takes to reach approximately 63% of its final value (the actual value is $1-e^{-1}$). In a second order system, the response can be expressed in terms of the systems' damping ratio and natural frequency. The damping ratio is a measure of the system stability.

A lightly damped second order system will oscillate several times before reaching a steady state position, whereas, a highly damped system may likely exhibit a slight overshoot, and no oscillations. The oscillation frequency is referred to as the systems "natural frequency" or "load resonance frequency" when it is associated with the combination of actuator, backup structure and surface inertia.

There are other modes in the system that also have natural frequencies such as servovalve and ram position loop that would yield a different natural frequency if they oscillated.

Flight control servo-loops must interact with the aircraft structural flexibility modes (frequencies at which oscillation amplitudes increase with the same input) such that its stability characteristics do not excite or drive these modes. This can be accomplished through compensation networks that limit the control system response at its natural frequency so that it does not interact with the vehicle predominant structural modes.

It is necessary to distinguish between linear servo instability and limit cycle oscillations which occur due to nonlinearities (e.g., friction, pressure gain). In electrically controlled servoactuators, it is always necessary to define the limits of uncommanded motion which will be acceptable. A small percentage of full stroke (typically 0.1%) at a frequency low enough that it will neither make objectionable noise nor wear out rubbing components such as piston rod seals (typically <2 Hz) may be acceptable.. Failure to define an acceptable limit will penalize the production of components by imposing too stringent a requirement to control friction even though it is generally agreed that the dynamic effects of friction should be eliminated, if possible.

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4.7.3 Performance (Response, Rate, Etc.): FBW rate and acceleration command systems in unstable aircraft require high actuator rates and appropriate time constants. In highly unstable aircraft one of the more critical actuator/control system requirements is to prevent a catastrophic overshoot.

In other more stable conventional military aircraft the augmentation systems often dictate the flight control system actuator rate and time constant requirements. Control surfaces must respond sufficiently to meet the aircraft maneuvering requirements and to correct any undesirable aircraft motions. For example, if the pilot input is in the aircraft nose up direction and this produces an excessively large pitch rate, then the system must compensate by adjusting the control surface in the pitch down direction so that the aircraft pitch rate and change in normal (vertical) acceleration is reasonable and predictable.

4.7.3 (Continued):

In addition, if the aircraft is unstable or marginally stable in a particular axis, the augmentation system must react by positioning the control surface in a way to damp the oscillations. Although we have historically presumed the square law flow/pressure relationship with hydraulic valve controlled systems, and have therefore been comfortable with no-load rate and stall-force type specifications, this kind of specification does not face the real world which demands specific rates at specific loads. No-load rate generally is a ground safety or impact cycling parameter. However, no load rate is also important for landing in turbulence and for achieving low speed combat maneuvers, while loaded rate is a control loop parameter. System trade studies which size tubing, specify water hammer induced impulse cycling, etc. should use loaded rate data for best overall weight and economy.

There is an extensive iterative trade-off between control surface size and its response requirements. The trend toward unstable aircraft causes fly-by-wire actuators to respond much more quickly to damp potential oscillations. Small surfaces which move quicker may require either low or higher power actuators for adequate ride qualities. In the absence of other driving factors such as engine out recovery or gust alleviation, it is worthwhile to reduce system weight by minimizing the control surface size, which then calls for a resizing of the servoactuator and its control surface size. In contrast to the above, low speed/landing configuration requirements usually require large surfaces and long strokes. Therefore, trade-offs of multiple smaller surfaces versus one or two larger surfaces and all the accompanying implications such as fault tolerance, and redundancy must be considered.

In some cases aerodynamic summing/redundant control surface techniques using multiple smaller surfaces can be effective. However, low speed landing requirements usually require some combination of larger surfaces and long strokes. This and the other driving factors noted above result in extensive trade studies of multiple small surfaces versus a large surface versus all the implications of fault tolerance, redundancy, flight safety, etc.

4.7.4 Stability: Aircraft stability is characterized by how the aircraft responds to atmospheric disturbances or to pilot inputs. Performance specifications dictate how well the aircraft must be damped in each axis. The aircraft un-augmented flight characteristics (i.e., degree of instability) and mission requirements determine just how robust the augmentation systems must be to provide the desirable responses. The control system (control surfaces, actuation systems) must be sized accordingly. Also, fault tolerance, graceful degradation after failures, redundancy, redundancy management and other factors enter the picture, including such parameters as stiffness and inertia.

These considerations are particularly applicable to FBW aircraft, particularly those that are highly unstable, in order to provide adequate flying qualities after failures and to meet flight safety requirements.

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4.8 Redundancy Management/Health Monitoring:

The ability of an aircraft to survive failures of flight control system components is dependent on fault tolerance and the redundancy management/health monitoring that is designed into the system architecture. There are a very wide range of redundancy management concepts and it is difficult to discuss this subject in a few paragraphs. AIR4253 provides more insight into the subject. The following are examples of flight safety requirements from AIR4253 that generally drive the system architecture and redundancy management/health monitoring implementation:

a. Probability of Loss of Control (P_{loc}); e.g., uncorrected hardover surface movement or combination of hardovers that could lead to loss of aircraft (could specify different requirements for active failure or jammed surface).

b. Probability of Loss of Function (P_{lof}); e.g., failure isolated and system reverts to a fail safe mode such as damped bypass

To illustrate a capability, Figure 6 shows the F-16A flight control system redundancy management and failure protection levels.

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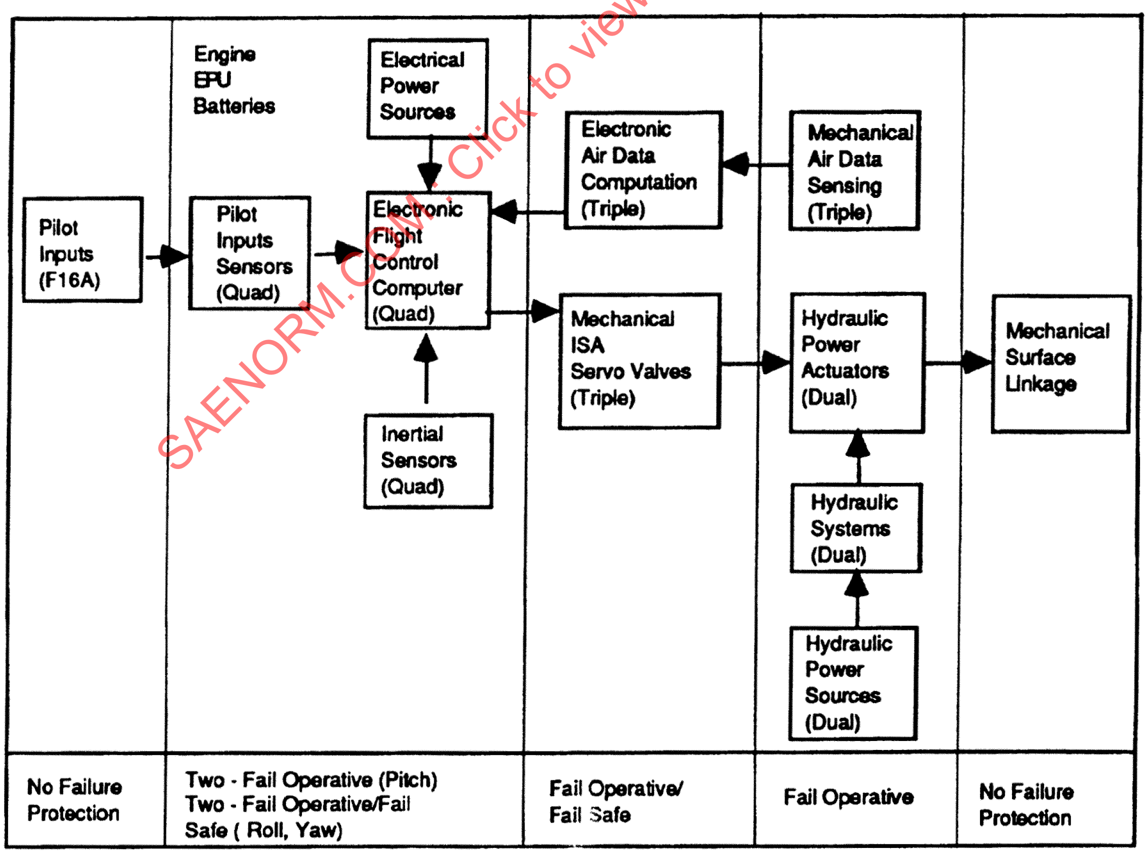

FIGURE 6 - F-16 Redundancy and Failure Protection Levels

4.8 (Continued):

Figure 7 shows the redundancy architecture of the F-18 Stabilator Actuator (Reference 1, paragraph 2.2). The actuator contains a command select mechanism which provides electrical control during normal operation and mechanical control as a backup. Two quadruplex fail detect sensors are used to detect servovalve failures. Two quadruplex solenoids are used for failure isolation.

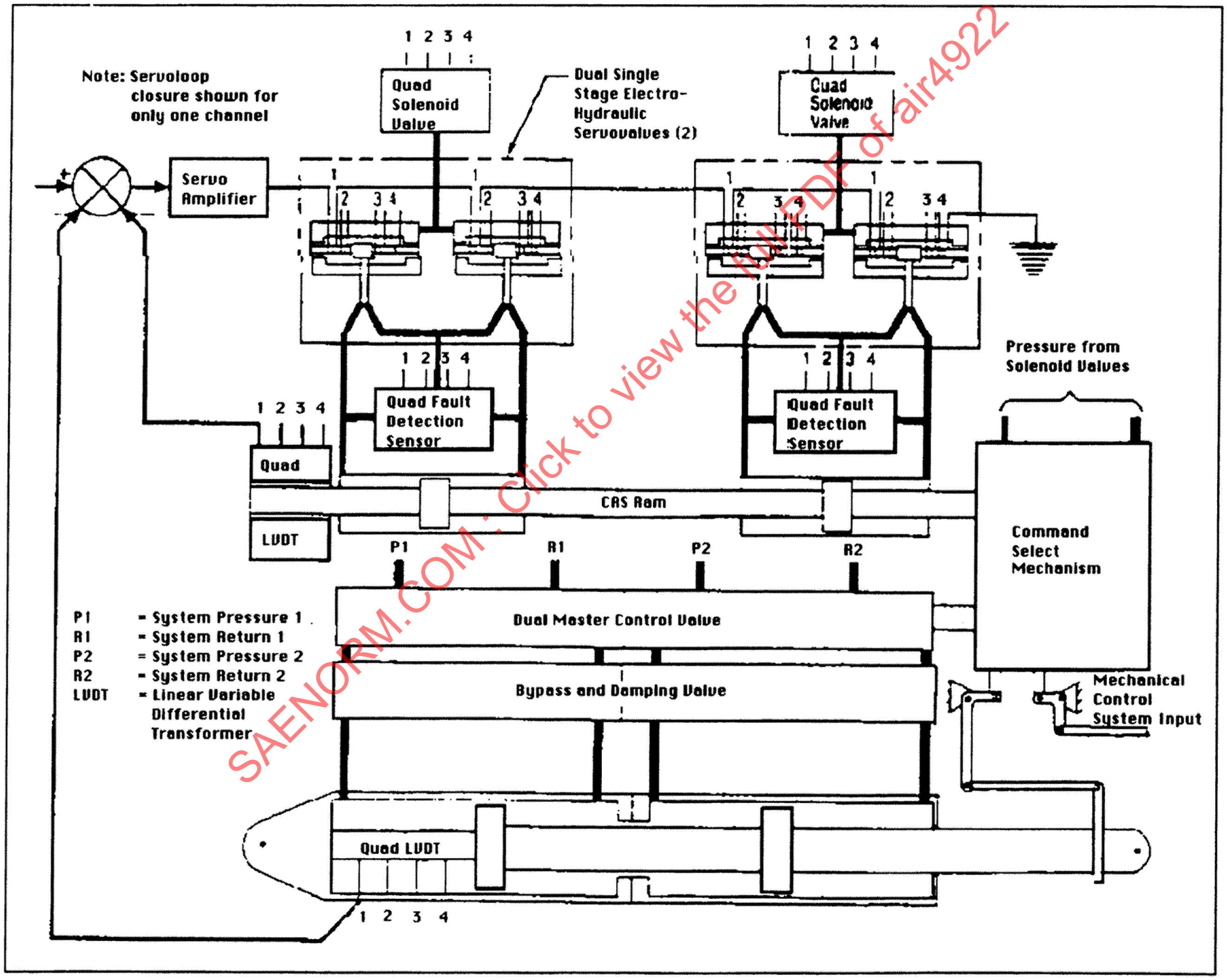

FIGURE 7 - F-18 Stabilator Actuator Schematic (Reference 1, paragraph 2.2)

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4.8.1 Diagnostics: Advances in technology continue to increase the capability and complexity of modern flight control systems. Therefore, maintainability has received significant attention in system designs for the use of diagnostic systems. These diagnostic systems cover three areas: (1) Integrated diagnostics that utilize built-in-test; (2) External diagnostics that comprise automatic test equipment (ATE); and (3) Manual diagnostic testing that use technical manuals and troubleshooting procedures. Utilization of a well designed automatic integrated diagnostic system in modern flight control systems can substantially reduce the need for highly trained field level maintenance personnel and permit less skilled personnel to repair the defective hardware.

4.8.2 Performance Monitoring, Failure Detection, and Fault Isolation: The modern subsystem should have an integrated diagnostic test capability incorporated for verification of acceptable performance, detection of failures, and identification of the fault to the line replaceable unit (LRU). This diagnostic test capability should provide for automatic real-time determination of performance, in all modes of operation, with possible indication to the crew. In no instance should the test capability interrupt normal subsystem operation, cause movement of aircraft flight control surfaces (except for special ground active testing), cause erroneous readings of cockpit indications, or cause any other uncommanded operation of aircraft systems.

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The test capability should typically provide for a minimum of 95% assurance of detecting subsystem failures. The detection percentage should be based on failure rate weighing and provide fault isolation of the detected failures to a single LRU 65% of the time. All failure modes affecting flight safety shall be detected. The test capability should make maximum use of operational parameters at a test rate compatible with system operation and should verify all redundant circuits. The failure mode, effects, and criticality analysis (FMECA) for the system under test is the most important document for development of its diagnostic test capability. The FMECA identifies: (1) LRU failure modes together with their failure rate weighing; (2) identification of the failure effect at the component/functional assembly, system level, and total aircraft; (3) criticality category/level for safety of flight/mission success; (4) when failure is discovered/detected, test system failure detection/ fault isolation method; and (5) corrective action and other information/comments.

Therefore, the FMECA provides for the development of the diagnostic test capability to be integrated into the design of the system under test. Thus, the higher probability failure modes and their criticality to system operation can be identified for developing option detection/isolation requirements. For purposes of the test capability a latent failure is not defined as a failure until that function is commanded and does not perform. In addition, the test capability should only be required to detect single failures and not multiple combinations of failures. Multiple flight control channels and redundant circuits should be validated as required by a special ground active test method that exercises each circuit independently and also does channel comparison for proper tracking. When unique LRU fault isolation is not possible, with automatic diagnostic capability, a technical procedure containing a fault tree, may be required for manual testing to break the LRU isolation ambiguity. The design of modern Fly-By-Wire type systems with micro-processor based controllers provides a good platform for built-in test type diagnostics incorporating proper feed-back information for external LRU's/other subsystem interfaces. The diagnostics would have access to the commands, feedback's, and responses for performance evaluation. Figure 8 shows the F-18 actuator monitors typical in the Fly-By-Wire systems. (Reference 1, paragraph 2.2)

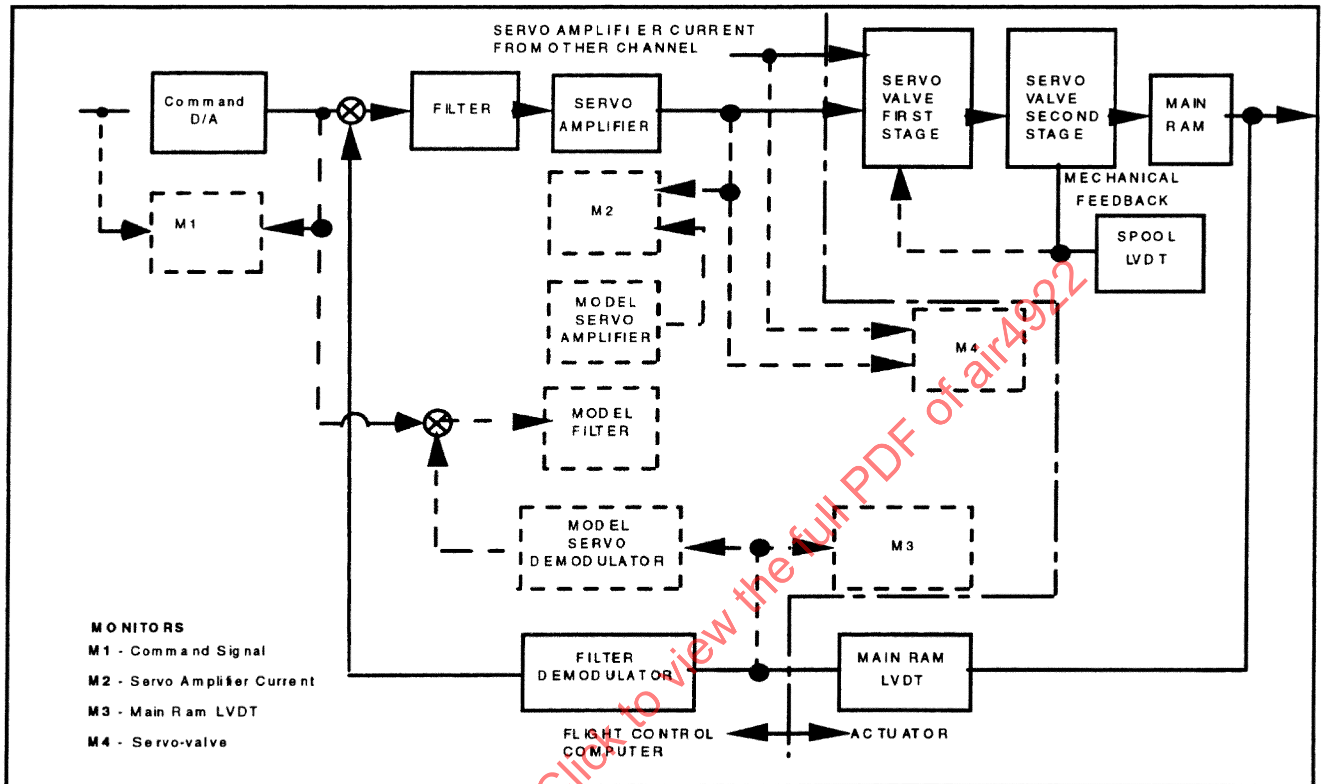

FIGURE 8 - F-18 Aileron Actuator Monitors (Reference 1, paragraph 2.2)

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4.8.3 Typical Actuation System Performance Requirements: The fly-by-wire actuation system will only meet its system performance requirement when operating in conjunction with the servo electronics. Thus, it is essential to define the actuator (servo-cylinder) and electronics interface, which is critical to system performance. The air vehicle flight dynamic requirements are determined by a combination of pilot and vehicle sensor inputs, which result in signal commands, which are transmitted to the electronics. The electronics in turn command actuator position, which results in servo-cylinder ram motion that causes the surface to move.

Typical actuation system performance requirements include:

a. Actuator output force
b. Main output ram travel
c. Main ram velocity
d. Loop gain
e. Frequency response
f. Dynamic stiffness and free play
g. Electrical input threshold

4.8.3 (Continued):

h. Electrical input hysterisis
i. EHV null bias and null shift
j. Chatter and instability
k. Main ram position transducer parameters
l. CAS servo position transducer parameters
m. CAS servo failure transients
n. CAS servo solenoid valve requirements
o. Bypass solenoid valve requirements

4.8.3.1 Technical Interface Parameters: Typical interface parameters between the Flight Control Electronic Set (FCES) and the control surface servo-cylinder are listed below:

1. Command signal characteristics to the servo electronics

   - Voltage range to command full actuator travel; ± volts
   - Any digital to analog conversions which may affect system operation:
     - minimum step size: in (mm) main ram stroke
     - Iteration rate: # per second
   - Polarity (relationship between voltage and actuator motion).

2. Servo-amplifier characteristics: current driver

   - Gain: in milliamperes/volt out of main ram LVDT
   - Maximum output: current in milliamperes
   - Null offset: ± milliamperes
   - Dynamic response: bandpass in Hz

3. Electrohydraulic servovalve characteristics:

   - Coil configuration/polarity
   - Coil impedance
   - Rated current: in milliamperes
   - Flow gain/pressure gain: in psi/ma (kPa/mA); 1 psi = 6.9 kPa
   - Null current: in ma
   - Dynamic response: bandpass in Hz
   - Polarity

4. Servo ram:

   - Area: in^2 (mm^2); 1 in^2 = 654 mm^2
   - Stroke: in (mm); 1 in = 25.4 mm

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4.8.3.1 (Continued):

5. Main control valve:

   - Flow gain: cis/in (mL/s/mm); 1 cis/in = 0.654 mL/s/mm
   - Pressure gain: psi/in (Pa/mm); 1 psi/in = 271 Pa/mm
   - Stroke: in (mm); 1 in = 25.4 mm

6. LVDT excitation (output from servo-electronics)

   - Voltage: VRMS
   - Frequency: Hz
   - Load capability: IAW wiring diagram
   - Primary coil impedance: IAW wiring diagram

7. LVDT characteristics (main ram, servo ram similar parameters):

   - Signal range: ± VRMS
   - Scale factor: VRMS/inch (mVrms/mm); 1 VRMS/inch = 39.4 mVrms/mm
   - Temperature coefficient: % per °F (C); 1 °C = 1.8 °F
   - Load in electronics demodulator: ohms
   - Secondary coil impedance: IAW wiring diagram
   - Accuracy: ± VRMS
   - Tracking accuracy: ± VRMS
   - Null voltage: ± VRMS
   - Null coincidence: ± in (± mm); 1 in = 25.4 mm
   - Polarity: IAW wiring diagram
   - Phase shift: deg
   - Center tap voltage: VRMS (servo only)
   - Cross coupling: VRMS

8. Electrohydraulic servovalve failure detection sensor

   - Sensor hydraulic characteristics: list fail pressure
   - Sensor electrical characteristics (LVDT or switch)
   - Failure detection threshold: list fail voltage

9. Solenoid shutoff valve

   - Coil configuration: see wiring diagram
   - Engage voltage: VDC
   - Dropout voltage: VDC
   - Dropout time: ms
   - Dropout voltage transient suppression: - volts
   - Electronics switch dropout time: ms

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4.8.3.1 (Continued):

10. Servo-electronics filters

- LVDT demodulator ripple voltage: VRMS (Hz)
- EMI filters: IAW wiring diagram

4.9 Aerodynamic/Environment Interfaces:

4.9.1 Hinge Moment Loads: Hinge Moments are derived primarily from aerodynamic loading on the control surface. Loads are derived from wind tunnel aerodynamic model tests and adjusted as flight test data is acquired from the flight test vehicle.

Inertial loads, induced structural loading, friction, etc., can add to these hinge moments; and must be considered. Location of hinges (about which the actuator applies its load) relative to aerodynamic loading and centers of pressure have an important influence on actuator loading and, consequently, sizing of the actuator; and its power requirements.

4.9.2 Surface Rates and Displacements: Surface rates and displacement requirements dictate flow and horsepower output of the hydraulic system. These requirements indirectly influence envelope since the magnitude of the moment arm at the surface influences stiffness and hence, flutter characteristics. Table 2 shows F-15 S/MTD actuation parameters.

TABLE 2 - F-15 S/MTD Flight Control Actuator Requirements

Surface Actuator	Output force Per Actuator	Actuator Stroke	Actuator Velocity	Total Flow Per Actuator
Stab/Canard	42,200 lb (c) (189 kN) 38,600 lb(t) (173 kN)	±3.9 in (±99 mm)	8.4 in/s (213 mm/s)	31.9 gpm (121 L/min)
Ail/Flap	23,100 lb (c) (103 kN) 18,500 lb (t) (82 kN)	±.7 in (±18 mm)	3.3 in/s (84 mm/s)	6.7 gpm (25 L/min)
Rudder	22,000 lb (c) (98 kN)	±30 deg	105 deg/s	3.9 gpm (15 L/min)

(c) = Compression
(t) = Tension

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4.10 Reliability and Maintainability:

Failures in primary flight control systems are generally associated with adverse effects to safety-of-crew/passengers, safety-of-flight. It is for this reason that reliability requirements for primary flight controls strictly govern the configuration of the flight control systems. Reliability considerations are central in decisions stemming from the selection of the number of hydraulic systems providing power to hydraulic servoactuators and the level of redundancy of electronic servo-loops that provide control of servoactuators. It must be understood that there is a distinction between reliability (in terms of MTBF) and system availability. Higher system redundancy improves system availability but decreases reliability in terms of MTBF.

Maintainability issues govern the configuration of servoactuators by dictating to what sub-component level Line Replacement Articles (LRA) are designated. In general, maintenance on the servovalve portion of military aircraft servoactuators is performed at *Depot* level due to the complexity of the actuators and the cleanliness requirements of the maintenance environment. The criticality of the maintenance action also dictates particular retest requirements not available at *Organizational* "O" level. Filtration maintenance is generally performed at "O" level, therefore positioning of the filters is dictated by "as installed" accessibility.

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5. INTERFACE DESIGN ISSUES:

The issues in this section are difficult to cover in a few pages. A more comprehensive treatment can be found in References 2, 4, and 5 of Paragraph 2.2.

5.1 Actuator Stiffness:

Actuator stiffness is a complex expression. Actuator functional stiffness involves the effects of physical stiffness as well as loop gains and control valve performance characteristics.

The linear hydraulic actuator spring rate is the cumulative effect of the various load path spring rates including the oil spring and the effects of cylinder breathing or bulging.

The following contribute to the total actuation system installed spring rate:

a. Linear spring rate of head end bearing
b. Linear spring rate of tailstock
c. Linear spring rate of barrel section
d. Linear spring rate of piston rod
e. Linear spring rate of rod end
f. Linear spring rate of rod end bearing
g. Linear spring rate effect of the change in oil pressure in the left chamber, i.e., cylinder breathing
h. Linear spring rate effect of the change in oil pressure in the right chamber, i.e., cylinder breathing
i. Linear spring rate effect of left hand oil chamber (blocked port)
j. Linear spring rate effect of right hand oil chamber (blocked port)
k. Equivalent linear actuator spring rate

5.1 (Continued):

In the case of an actuated all-moving control surface, the stiffness of the actuator control loop represents a significant proportion of the overall torsional stiffness requirement.

By design, in a conventional position feedback system, functional stiffness is higher than physical stiffness. For a closed-loop position servoactuator, an actuator has a constant static stiffness, measured at zero frequency in terms of resistive force per displaced output motion (e.g., lb/in, mN/mm), where 1 lb/in = 175 mN/mm. At high frequency, beyond the bandpass of the servoactuator, the actuator has a constant infinite frequency stiffness. This high frequency stiffness is dictated not by closed-loop performance, since it is beyond the frequency response capability of the servo-loop, but by spring rate of the actuator mechanical parts and the fluid compressibility within the actuator. There is a transition stiffness between the static stiffness and infinite frequency stiffness. The term dynamic stiffness refers to the stiffness over the complete frequency spectrum. NOTE: See the curve in Reference 2, paragraph 2.2.

The terms static stiffness, dynamic stiffness, infinite frequency stiffness and servo stiffness are frequently used ambiguously and misapplied in the system definition. Hence, it is recommended to use these terms only with definitions attached so that there is no ambiguity. Notably, static stiffness is used by different groups for the lower end of the spectrum: the DC or very low frequency stiffness where all feedback loops are fully satisfied will approach the stiffness of the rod end and tail stock (parts outside the feedback loop); the infinite frequency stiffness where all mechanical parts and the oil compressibility provide the stiffness. Therefore, it is recommended that the terms zero frequency and infinite frequency be used for the ends of the dynamic stiffness curve. These may be displayed on log paper as two horizontal lines for zero and infinite frequency connected by a curve with a dip at an intermediate frequency near the servo bandwidth of the actuator.

5.1.1 Static (Zero Frequency Stiffness): The static stiffness of an actuator is the combined stiffness of two types of elements arranged in series:

1. The stiffness of the actuator structural elements outside the position control loop; for example, for a typical FBW actuator this includes the bearings and the structure containing them at each end of the actuator.

2. The stiffness due to the feedback loop, which is the gain of the closed position loop. This force gain is the product of the pressure gain of the main control valve, the net area of the actuator piston(s) and the gain of the loop closed around the actuator itself.

In the case of a dual tandem actuator, both the dual and single system stiffness must be evaluated to allow for considerations when one chamber has failed. By design, in a conventional position feedback system, system stiffness is higher than the actuator static stiffness.

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5.1.1 (Continued):

In general, for actuators with the same output force requirements, the stiffness decreases with increasing operating pressures (reduced actuator area) and temperatures (reduced bulk modulus). The lower actuator stiffness lowers the system servoelastic resonant frequency. The required actuator stiffness can be determined from the vehicle structural stiffness, control surface inertia and the required rotational frequency of the surface.

5.1.2 Dynamic: Dynamic stiffness of an actuator is determined by the solution of transfer functions for the complete actuator closed loop and is a variable with operating frequency. At frequencies well above the band-width of the actuator, it becomes asymptotic to the "infinite frequency stiffness" since the system can no longer respond fast enough to the commanded inputs.

The infinite frequency stiffness may be calculated as the combination of the stiffness of all of the structural elements of the actuator and the effective stiffness of the column of the fluid. The adiabatic bulk modulus of the fluid and how this modulus changes with temperature and pressure is therefore of importance. With dual tandem actuators both the dual and single system stiffness must be evaluated to cover the case wherein one hydraulic system has failed. This infinite frequency stiffness, in combination with the stiffness of the supporting structure and of the attachment of the actuator to the surface and the inertia of the surface, determines the load resonant frequency. This frequency must be many times the band-width of the actuator for the actuation system to have satisfactory stability. In certain aircraft such as the YF-23A and B-2 there is a separation of approximately two (or less) and these systems are quite stable. However, it must be understood that compensation must be used to guarantee stability.

5.1.3 Fluid Column Stiffness: For an equal area (balanced) actuator (Figure 9), the minimum oil column stiffness occurs at the mid stroke position and may be calculated as follows: (See Reference 4, paragraph 2.2.)

$$P = \frac{\Delta Vol}{Vol} \cdot \beta \qquad \text{(Eq. 1)}$$

Assume piston displaced by δX. Then,

For Upper Chamber,

$$\Delta Vol = A \cdot \delta x \qquad \text{(Eq. 2)}$$

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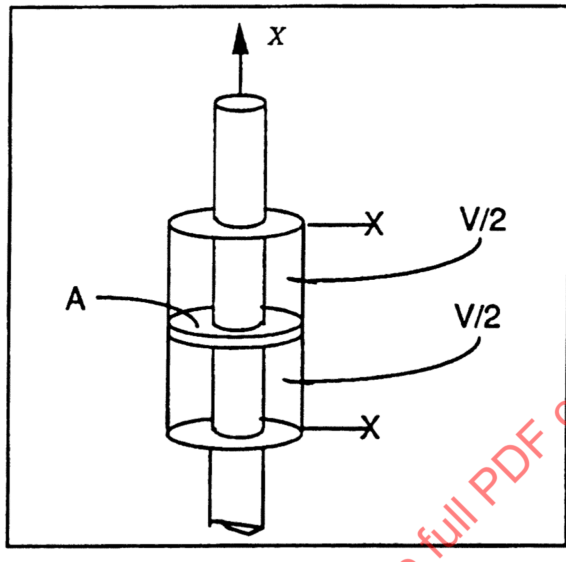

FIGURE 9 - Balanced Cylinder Schematic

5.1.3 (Continued):

$$Vol = \frac{V}{2} \qquad \text{(Eq. 3)}$$

and

$$\delta P_{upper} = \frac{A \cdot \delta x}{\frac{V}{2}} \cdot \beta = \frac{2A\beta}{V} \cdot \delta x \qquad \text{(Eq. 4)}$$

Similarly, for lower chamber

$$\delta P_{lower} = -\frac{2A\beta}{V} \cdot \delta x \qquad \text{(Eq. 5)}$$

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5.1.3 (Continued):

So,

$$\Delta P = \delta P_{upper} - P_{lower} = \frac{4A\beta}{V} \cdot \delta x \qquad \text{(Eq. 6)}$$

Force,

$$F = \Delta P \cdot A = \frac{4A^2\beta}{V} \cdot \delta x \qquad \text{(Eq. 7)}$$

Stiffness,

$$\boxed{K_o = F/\delta x = \frac{4A^2\beta}{V}} \qquad \text{(Eq. 8)}$$

NOTE: This holds for a valve controlled actuator where both chambers are pressurized and blocked by the valve.

where:

- β is the adiabatic bulk modulus of the fluid at the worst case (highest) temperature and (lowest) pressure
- A is the piston area
- V is the combined fluid volume on both sides of the piston head, including both swept and unswept volume

5.1.4 Effective Bulk Modulus: Bulk Modulus of the hydraulic fluid is a parameter that varies significantly with pressure and very significantly with temperature. For example, the modulus of MIL-H-83282 (Reference c, paragraph 2.1.3), which is approximately 213,000 psi (1470 MPa) at 100 °F (38 °C) and 0 psi (0 kPa), is increased by 15% if the test pressure is raised to 3000 psi (21 MPa) but is decreased 40% if the test temperature is increased to 275 °F (135 °C). The bulk modulus is sometimes significantly changed by reformulation. For example, published bulk modulus test data for the "A" version of MIL-H-83282 is about 12% lower than the test data reported for the "NC" fluid. It is, therefore, important for the accuracy of a stiffness analysis to use the bulk modulus applicable to the appropriate analysis condition and fluid version. For the first approximation of the stiffness of an actuator which has been sized, but not designed, the concept of "effective bulk modulus" is sometimes used. That is, the oil column stiffness is used as an approximation for the overall infinite frequency stiffness but calculated with a modulus number degraded by a factor that is typically between 0.85 and 0.5 (there is no agreement on a uniform number) to account for all of the mechanical compliance such as cylinder axial and circumferencial expansion (breathing) and to account for the entrained air in the fluid, as discussed below.

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5.1.4 (Continued):

Bulk modulus is affected by such conditions as the presence of air in solution. Entrained air will change the bulk modulus significantly while dissolved air will not. The residual air in a high pressure aircraft hydraulic system that has been carefully cycled and bled, tends to dissolve into the high pressure fluid. However, systems and components need to be designed to encourage the purging of entrained air by the cycling process because non-dissolved air will certainly cause significant losses of stiffness which cannot be calculated.

5.1.5 System Free Play: System free play is characterized as a summation of running clearances of all the mechanical components that make up the system structural loop when subjected to a small (100 lb) load , i.e., fasteners, bearings, bushings, valve input arms, push-rods, and support lugs. Excessive system free play can have severe adverse effects since it could result in instability of the control loop. Free play also lowers stiffness (sometimes severely) and can be a contributory factor in lowering the flutter speed of the control surface.

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5.1.6 Structural Feedback: Structural feedback is not required or readily available with fly-by-wire actuators. However with simple mechanical feedback actuators (Figure 11) structural feedback is a very useful tool. When this type of actuator is loaded it deflects against it's structural backup spring, creating a valve error. For the system shown in Figure 11, this valve error will be opposite to the error caused by the actuator's own position feedback linkage thereby reducing the effective valve gain. This type of force (equivalent to acceleration) feedback compensation, which is achieved by the reversal linkage shown on the left of the figure, has been used in the past (e.g., the Grumman F-14 horizontal stabilizer actuator) to avoid an actuator limit-cycle instability. Unfortunate by-products of this system are:

a. The valve compensation tends to reduce the stiffness of the actuator at low frequency

b. The actuator backup spring has, in some cases, to be made flexible to achieve the desired level of stability, thereby further reducing the dynamic stiffness of the actuator loop.

5.2 Flutter Considerations:

A significant phenomenon that plays a key role in flight control system design is flutter. Since the onset of flutter has safety-of-flight implications, design considerations on ways to control flutter are given a high priority. Guidance for design requirements may be found in AIR4253 and MIL-A-8870.

5.2.1 Definition of Flutter: Flutter is a dynamic, aeroelastic, divergent oscillation that occurs when energy is extracted from the windstream. It is characterized by a divergent oscillation of an aircraft structure to the point of structural failure. The point where the instability becomes divergent is defined as the flutter speed. There are two types of flutter: classical or structurally interactive multi-mode Multi-DoF flutter and; single DoF "Buzz". Classical flutter occurs when surface oscillation frequency is near structural modes and is generally prevented by: mass balance; dampers; high rotational stiffness; or by geometric arrangements of the control surface hinge line and/or control surface planform. "Buzz" is a transonic/supersonic phenomenon caused by the interplay between surface motion and the resulting changes in shock strength and position.

5.2.2 Flutter Prevention: Flutter is generally controlled by direct damping or system stiffness. Since dampers are generally undesirable, high control system stiffness is the generally preferred primary method of control.

The design trade-offs required to define a near optimum solution to control surface flutter-stability requirements are too complex to cover in this document and is left to the more in-depth reference documents, but some of the techniques utilized are: actuator control loop stiffness, mass balance of the surface, aerodynamic planform of the control surface, location of the control surface hinge line, the use of dampers, augmentation of the actuators' stiffness characteristics in the frequency range of interest and utilization of the actuator inner feedback control loops to control the actuator characteristics in such a way as to affect actuator damping in addition to actuator stiffness. The stiffness of the actuator control loop represents a significant portion of the aircraft torsional stiffness requirement.

The first and most extensive trade-off involves the aerodynamic planform of the control surface, the pressure distributions across the surface, the location of the center of pressure across the flight envelope, the hinge line location, the redundancy of the hydraulic ram (single chamber, dual tandem, etc.), and consideration of failure modes and effects. Generally speaking, positioning the hinge line far forward, as on the F-15, tends to minimize flutter problems but significantly increases the hinge moments. Ideally, there would be an optimum hinge line location where the actuator bore size, based on hinge moment requirements would be the same as the bore size required by flutter/stiffness requirements. The F-14 hinge line location was selected based on hinge moments, actuator stall requirements after failure of one hydraulic system and consideration of situations where the center of aerodynamic pressure was forward of the hinge line. Consequently the flutter/stiffness requirements required a larger bore actuator than was required by hinge moment requirements.

The control surface inertia is a significant parameter that requires careful evaluation to control an aircraft's propensity to flutter. A number of solutions have been applied in order to meet flutter speed requirements and maintain safe flutter speed design margins. Figure 10 shows examples of a few solutions. The F-15 includes a modification, also shown in Figure 10, that removes the apex area at the leading edge of the stabilizer. This is done to reduce the influence of aerodynamic forces that are very powerful at the apex of the horizontal stabilizer control surface.

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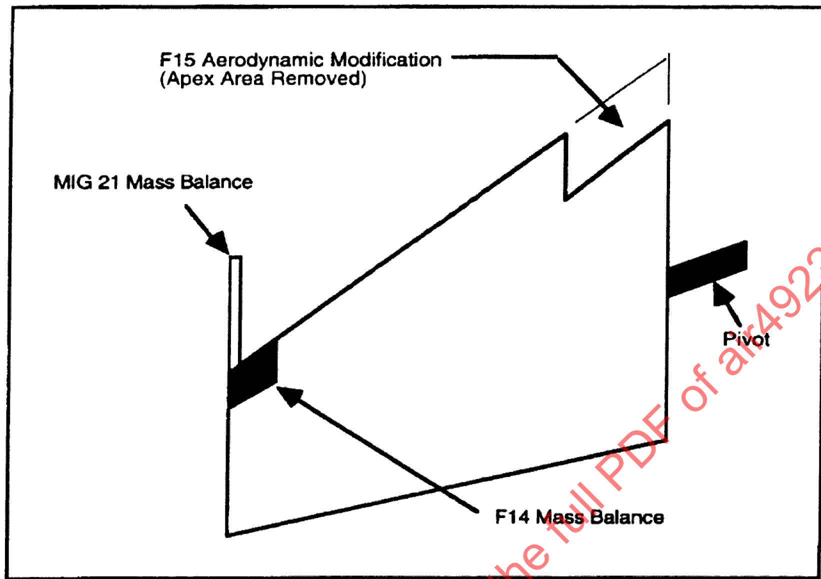

FIGURE 10 - Control Surface Inertia Treatments (Reference 5, paragraph 2.2)

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6. INTERFACE PROBLEMS/SOLUTIONS (Lessons Learned):

Typical problems associated with interfaces differ between mechanical input systems and Fly-By-Wire systems. In the case of mechanical input systems, head-end interface tolerances are critical since excessive free play will create adverse feedback to the valve input. The result could be free-play induced oscillation of the surface. The above condition became apparent during the development phase of the F14 Fighter program. Excessive free play at the head end of the actuator resulted in limit cycle oscillation of the control surface. It was also discovered that if the clearance between the valve input arm and the valve stem grew from a lap fit of .0001 in (2.5 µm) to as little as .001 in (25 µm), the valve became unstable resulting in limit cycle oscillation.

In the case of Fly-By-Wire systems, head-end free-play is generally not as critical for the above reason since feedback is generally internal to the servoactuator. However, free-play of any system results in a reduction of "apparent stiffness" leading to potential reduction in flutter speed margin. Extreme measures are employed in an attempt to reduce joint free play to an absolute minimum. Such devices as tapered bolts and expandable bolts are often used.

6. (Continued):

Dual tandem actuators have been used extensively in military applications. However, for commercial aircraft it is virtually the standard practice to use separate actuators, each supplied by a different hydraulic system for each primary flight control surface. In addition, it is increasingly becoming the practice to use the active/standby system for flight control actuators to overcome problems of force-fighting. This system generally uses an automatic changeover system that, in the event of a hydraulic or flight control signaling failure (for example) selects an alternative flight control actuator to operate the surface.

7. INTERFACE DEVELOPMENT/VALIDATION:

7.1 Test and Evaluation:

7.1.1 Iron Bird / Flight Control System Simulator: The Iron Bird is a full scale mockup of all the components that make up the aircraft flight control system (It may also include landing gear, inlet ramp or any other systems that places large demands on the hydraulic system). The Iron Bird may consist of all the surface actuation systems, all interconnecting linkages, the flight control electronics, augmentation systems and cockpit controls. The simulated control surfaces approximate the actual center of gravity and mass moment of inertia of the aircraft control surface.

The Iron Bird is the first place that the entire flight control system is mated together. Hence, it has been an established practice to construct an Iron Bird to evaluate the performance of flight control components prior to the availability of the vehicle. The Iron Bird provides a tool to integrate all components, from pumps, reservoirs, hydraulic circuit to servoactuators as a complete system. Since the Iron Bird derives its name from the use of heavy structural members in its make up, generally surface flexibilities are simulated by means of spring components. During the flight test phase of a program, the Iron Bird provides a test tool that allows integration of the flight control system without putting a burden on the flight test vehicles' crowded schedules. It allows evaluation of the control system failure modes which may be catastrophic if done on the actual flight aircraft. Control system static and dynamic characteristics are determined as well as the overall compatibility of the various systems. Computer generated signals that approximate aircraft motion may be supplied to the aircraft augmentation system or the flight computer to evaluate closed loop performance. The Iron Bird generally evolves as an element of a man-in-the-loop simulator.

7.1.2 Man-In-Loop (MIL) Simulator: The Man-In-Loop simulator is one of the tools used during flight control development to develop the aircraft control laws and evaluate handling qualities. In addition, it is used to aid in finalizing cockpit instrumentation and controls. It is critical that simulation models of the actuators and hydraulic system be validated using Iron Bird test results.

The simulator is also used extensively to familiarize the flight crews with the aircraft handling characteristics and to develop procedures for both normal and emergency situations. Flight test maneuvers are practiced and data derived from the simulator are compared with that obtained from flight test to update the aerodynamic models used in both the simulator and 6 degree-of-freedom computer models.

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7.1.2 (Continued):

In-flight emergencies encountered during flight test or during normal infield usage can be duplicated on the simulator. Procedures or design changes can be implemented to prevent a recurrence.

7.1.3 Computer 6-DoF: Aerodynamic data derived from wind tunnel tests are used to develop 6 degree-of freedom computer models. Computer models are used in the initial design process to predict handling qualities and static and dynamic stability throughout the expected aircraft flight envelope. Compliance with applicable military specifications and established handling qualities criteria are determined. Augmentation systems are then designed to bring the aircraft in specification compliance where necessary. The 6-DoF models are used to define actuation system requirements early in the design phase.

7.1.4 Ground Vibration: The effects of flutter are a safety-of-flight concern in aircraft development. The actuation system servoelastic characteristics and vehicle structural modes must be verified before flight test. Since the vibration environment for high performance, light weight aircraft is characterized by high frequencies, the adverse effects of high vibration levels on system components must be fully investigated. All components are therefore evaluated prior to first flight by the performance of a Ground Vibration Survey.

7.1.5 In-Flight: It is necessary, in the life of a program, to provide verification of hinge moment and aerodynamic damping to support the analysis. Loads that are generated by the wind tunnel model are confirmed and refined by data obtained when the flight test vehicle becomes available.

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7.2 Analytical:

7.2.1 Linear Dynamic Performance Estimation: Linear dynamic performance estimation in primary flight control actuators is controlled by closing loops that compare the commanded and actual displacements. The high dynamic performance needed by contemporary aircraft requires rapid actuator response. This is achieved by increasing internal "gains". Sometimes, the higher gain results in actuator instabilities; obviously, the design process involves optimization between dynamic response and stability. Actuator velocity and acceleration terms may be required in compensation circuits. In the early phases of actuation system design, the optimization is between dynamic response and stability. This is initiated by developing linear models of the actuators' component parts. Next a stability analysis is executed using one, or more, "control theory" methods such as "root locus", "bode" diagrams, etc. If the response, at the acceptable stability limit, is inadequate then dynamic compensation, usually in the form of a filter or added feedback, is required. The stability analysis is repeated to evaluate the best approach. When the optimization process is complete: (1) frequency response diagrams are made to illustrate the linearized response and stability, (2) the response to square wave commands are used to illustrate transient response, and (3) the response to triangular wave commands are used to determine the "minimum increment of control".

For manufacturing and maintainability considerations, feedback and compensation circuits may be integral with the actuator. However, in today's "software" world, loop closures are more likely to be in separate LRU.

7.2.2 Nonlinear Simulation: Hydraulic system performance often exhibits nonlinear response. The dynamic and distributed nature of the tubing coupled with these non-linearities necessitates simulation to predict compliance with the systems' requirements. Commercially available simulation programs have been developed for large scale systems. There are many programs and new ones emerge often. By example, one was developed to support the F-15 Program. It has also been used for the F-16 and F-18 aircraft. Another was developed to support both the design of the space shuttle hydraulic system and preflight validation.

These programs have been used:

a. To evaluate the effects of hydraulic system transients.

b. For dynamic failure management investigations.

c. As a substitute for destructive tests.

d. To evaluate the effects of environmental changes on dynamic performance.

There are a series of steps that are necessary to facilitate this simulation approach. First, "generic", physical models must be developed for unique components. These models consist of sets of dynamic, physical equations capable of simulating the components' performance. The model is considered generic until the component test data is integrated into the equations. When all of the component models are test validated, they are integrated into a system simulation. Since all of the constituent models are physically accurate, the simulation can be used as a system development tool. It can be used with an Iron Bird or as a stand-alone tool for aerospace vehicle subsystem development.

8. APPLICATIONS OF ACTUATION SYSTEM FEATURES:

Interface characteristics vary widely from conventional to state-of-the-art to advanced state-of-the-art. There are several actuation systems that have special interface considerations. Examples are provided below:

a. Many hydromechanical actuators have used structural feedback as compensation for low servoelastic margins, i.e., provide damping for the control surface rotational mode.

b. Examples of fly-by-wire actuator interface parameters

c. Fly-by-light interface issues

d. Smart actuation interface issues

e. Fluidics interface issues

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8.1 F-14 Horizontal Tail Actuation:

The Grumman F-14 Tomcat is a variable sweep air superiority fighter that makes use of hydromechanical flight control actuators. The flight control system is a power augmented system with integral stability and command augmentation (SAS & CAS). The split horizontal tail provides pitch control through symmetric motion and roll control through asymmetric motion. A single mechanical input to the servoactuator provides integrated commands from the pilot, trim system and the Automatic Flight Control System. The F-14 flight control system design was driven by stiffness requirements rather than hinge moment requirements.

Mechanical feedback is summed with structural feedback to prevent adverse actuator inputs from structural deflections. Figure 11 shows a schematic of the servoactuator configuration.

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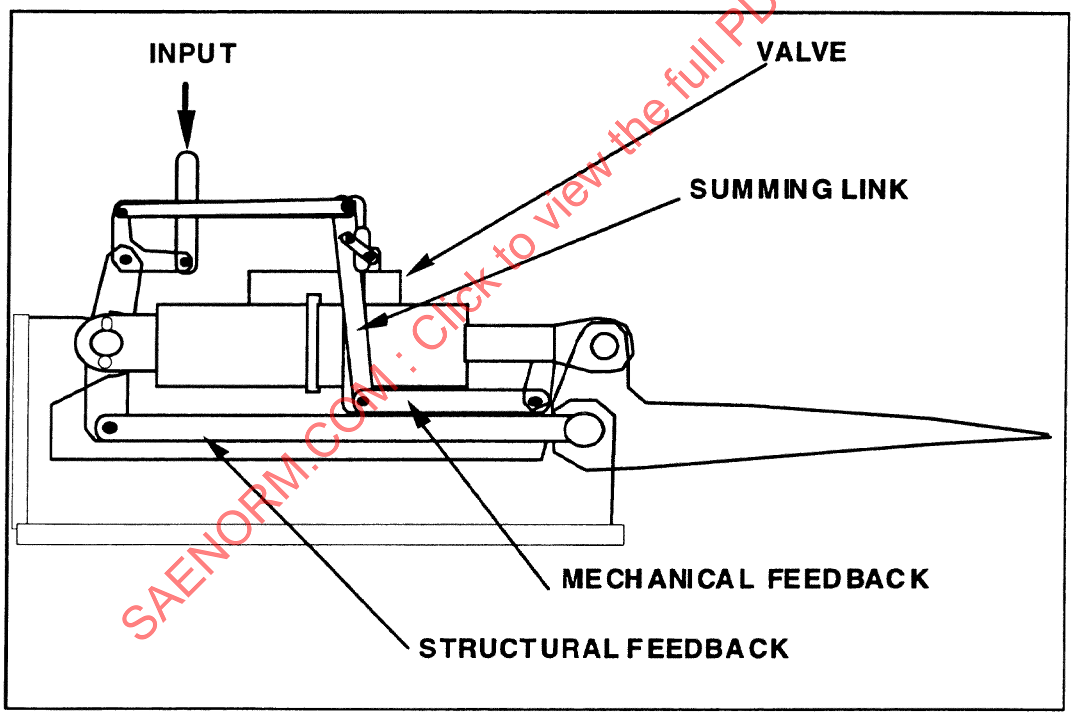

FIGURE 11 - F-14 Horizontal Tail Servoactuator Schematic

8.2 F-15 Actuation:

Table 3 describes the basic functional organization of the F-15 S/MTD

TABLE 3 - F-15 S/MTD Control Surfaces Actuators

S/MTD All Surfaces - Electro-Hydraulic

Surface Actuator	Elect. Inputs	Hyd. Inputs	Hyd. Backup	Single Hyd. Supply Failure	Dual Hyd. Supply Failure	Dual Elect Failure*
Stabilator	4	2	Yes	1/2 Load Capability **	1/2 Load Capability	No Change
Canard	4	2	No	1/2 Load Capability	Trail Neutral Lock	No Change
Aileron	2	2	No	1/2 Load Capability	Trail (Damped)	Trail (Damped)
Flaperon	2	2	No	1/2 Load Capability	Trail (Damped)	Trail (Damped)
Rudder	2	1	Yes	No Change	Trail (Damped)	Trail (Damped)

* Single Electrical Failure - No change for all actuators
All electric off - stabilator / canard goes to neutral lock others to damped trail

** No change if single failure is in backed-up side

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