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Aerospace - Flight Control Systems - Design, Installation and Test of Piloted Military Aircraft, General Specification For

RATIONALE

This document provides a comprehensive definition of the general performance, design, test, development and quality assurance requirements for military aircraft Flight Control Systems. Specific focus areas are flight safety and integration of the Flight Control System with other aircraft systems and subsystems, such as the electrical and hydraulic systems. It includes the applicable legacy requirements from U.S. Military Specifications MIL-H-9490D, and the inactive MIL-F-18372.

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1. SCOPE

This specification establishes general performance, design, test, development and quality assurance requirements for the Flight Control Systems of military piloted aircraft. Flight Control Systems (FCS) include all components used to transmit flight control commands from the pilot or other sources to appropriate force and moment producers. Flight control commands normally result in control of aircraft altitude, airspeed, flight path, attitude, aerodynamic or geometric configuration, ride quality, and structural modes. Among components included are the pilot's controls, dedicated displays and logic switching, system inertial and air data sensors, signal computation, test devices, mechanical transmission devices, actuators, power sources, and signal transmission lines dedicated to flight control. Excluded are aerodynamic surfaces, engines and engine control systems, rotorcraft rotors, fire control devices, crew displays and electronics not dedicated to flight control. In the event of conflict between this specification and other referenced documents, this specification shall govern. The detail requirements for a particular system shall be specified in the FCS Specification, 4.6.2, the Aircraft Detail Specification, the contract, or purchase order for that system.

Most of the technical concepts and approaches covered by the document represent industry "best practice". They are based on sound and proven engineering practices and have demonstrated successful production experience. Others require specific approval from the procuring activity before use. This requirement for approval is not intended to prohibit their use; but rather to ensure that the prime contractor has fully investigated their capability to perform reliably and to be sufficiently durable under the required conditions and that the prime contractor can present substantiating evidence for approval before the design is committed to.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. Unless otherwise specified the latest issue of SAE publications shall apply and the applicable issue of other publications shall be the issue in effect on the date of invitation for bids or request for proposal. In the event of conflict between the text of this document and the references cited herein, the text of this document takes preference. 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 International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

ARP490 Electrohydraulic Servovalves

ARP988 Electrohydraulic Mechanical Feedback Servovalves

ARP1083 Airborne Hydraulic and Control System Survivability for Military Aircraft

ARP1281 Actuators, Aircraft Flight Controls, Power Operated, Hydraulic, General Specification for

ARP4058 Actuators: Mechanical Geared Rotary, General Specification for

ARP4386 Terminology and Definitions for Aerospace Fluid Power, Actuation and Control Technologies

ARP4493 Aerospace - Direct Drive Servovalves

ARP4754 Certification Considerations for Highly-Integrated or Complex Aircraft Systems

ARP4761 Guidelines and Methods for Conducting the Safety Assessment Process on Civil Airborne Systems and Equipment

ARP4895	Aerospace - Flight Control Actuator Displacement - Method for Collection of Duty Cycle Data
ARP5384	Power Drive Unit
AS5440	Hydraulic Systems, Aircraft, Design and Installation Requirements For
AS5643	Interface Requirements for Military and Aerospace Vehicle Applications
AS6038	Bearing, Ball, Bellcrank, Antifriction, Airframe
AS6039	Bearing, Double Row, Ball, Sealed, Rod End, Antifriction, Self-Aligning
AS7949	Bearing, Ball, Airframe, Antifriction
AS7997	Motor, Aircraft Hydraulic, Constant Displacement General Specification For
AS8775	Hydraulic System Components, Aircraft and Missiles, General Specification for
AS8976	Bearing, Plain, Self-Aligning, All-Metal
AS15002	Fitting, Lubrication, Hydraulic, Surface Check, Straight Threads, Steel, Type II
AS35411	Fittings, Lubrication
AS50881	Wiring Aerospace Vehicles
AS56761	Splicing; Cable Terminal, Process for, Aircraft
AS81820	Bearing, Plain, Self-Lubricating, Self-Aligning, Low Speed
AMS-STD-2175	Casting, Classification and Inspection of
AMS-A-22771	Aluminum Alloy Forgings, Heat Treated
AMS-F-7190	Forging, Steel, for Aircraft/Aerospace Equipment and Special Ordnance Applications

2.1.2 U.S. Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

Specifications

MIL-A-8860	Airplane Strength and Rigidity, General Specification
MIL-A-8861	Airplane Strength and Rigidity, Flight Loads
MIL-A-8865	Airplane Strength and Rigidity, Miscellaneous Loads
MIL-A-8867	Airplane Strength and Rigidity, Ground Tests
MIL-A-8870	Airplane Strength and Rigidity, Divergence, and Other Aeroelastic Instabilities
MIL-A-87229	Auxillary Power Systems, Airborne
MIL-C-81774	Control Panel, Aircraft, General Requirements for

MIL-DTL-781	Terminal; Wire Rope Swaging, General Specification for
MIL-DTL-6117	Terminal, Wire Rope Assemblies, Swaged Type
MIL-DTL-6193	Joint, Universal, Plain, Light and Heavy Duty General Specification For
MIL-DTL-7034	Pulleys, Groove, Antifriction Bearing, Grease Lubricated, Aircraft, General Specification For
MIL-DTL-8878	Turnbuckles, Positive Safetying
MIL-DTL-18375	Wire Rope, Flexible, Corrosion-Resisting, Nonmagnetic, For Aircraft Control
MIL-DTL-83420	Wire Rope, Flexible, For Aircraft Control
MIL-F-83300	Flying Qualities of Piloted V/STOL Aircraft
MIL-I-8500	Interchangeability and Replacementability of Component Parts
MIL-PRF-5503	Actuators: Aeronautical Linear Utility, Hydraulic, General Specification For
MIL-PRF-7958	Push-Pull Controls, Flexible and Rigid
MIL-S-8512	Support Equipment, Aeronautical, Special, General Specification for the Design of
MIL-STD-130	Identification Marking of US Military Property
MIL-STD-202	Test Method Standard, Electronic and Electrical Component Parts
MIL-STD-203	Aircrew Station Controls and Displays: Location, Arrangement and Actuation for
MIL-STD-461	Electromagnetic Interference Characteristics
MIL-STD-464	Electromagnetic Environmental Effects Requirements for Systems
MIL-STD-704	Aircraft Electric Power Characteristics
MIL-STD-810	Environmental Engineering Considerations and Laboratory Tests
MIL-STD-882	Standard Practice for System Safety
MIL-STD-1472	Human Engineering Design Criteria for Military Systems, Equipment and Facilities
MIL-STD-1530	Aircraft Structural Integrity Program, Airplane Requirements
MIL-STD-1553	Digital Time Division Command/Response Multiplex Date Bus
MIL-STD-1773	Fiber Optics Mechanization of an Aircraft Internal Time Division Command/Response Multiplex Data Bus
MIL-STD-1797	Flying Qualities of Piloted Aircraft
MIL-STD-7080	Selection and Installation of Aircraft Electric Equipment

Standards

MS33736 Turnbuckle Assemblies, Clip Locking of

Military Handbooks

MIL-HDBK-17 Composite Materials Handbook

MIL-HDBK-454 General Guidelines for Electronic Equipment

MIL-HDBK-470 Designing and Developing Maintainable Products And Systems, Volume I and Volume II

MIL-HDBK-516 Airworthiness Certification Criteria

MIL-HDBK-781 Reliability Test Methods, Plans and Environments for Engineering Development, Qualification and Production

MIL-HDBK-838 Lubrication of Military Equipment

2.1.2.1 Inactive Specifications and Standards

The requirements of these specifications apply to re-procurements of in-service equipment or legacy systems/subsystems/components being utilized in new systems or later model aircraft.

MIL-E-5400 Electronic Equipment, Airborne, General Specification for

MIL-M-7969 Motor, AC, 400 Cycle 115/200 Volt System, Aircraft, General Specification for

MIL-M-8609 Motor, DC, 28 Volt System, Aircraft, General Specification for

MIL-H-8890 Hydraulic Components, Type III (-65 Deg to Plus 450 Deg F) General Specification for (ASG)

MIL-H-8891 Hydraulic Systems, Manned Flight Vehicles, Type III Design, Installation and Data Requirements For, General Specification For

MIL-M-38510 Microcircuits, General Specification For

2.1.2.2 Military Guide Specifications

Available from ASC/ENSI, Building 560, 2530 Loop Rd West, Wright-Patterson AFB OH 45433-7101, Tel: 937-255-6296.

JSSG-2001 DOD Joint Service Specification Guide, Air Vehicle

JSSG-2006 Aircraft Structures

JSSG-2008 DOD Joint Service Specification Guide, Vehicle Control and Management System

AFSC DH 1-2 General Design Factors

AFSC DH 1-4 Electromagnetic Compatibility

AFSC DH 1-5 Environmental Engineering

AFSC DH 1-6 System Safety

AFSC DH 2-1 Airframe

AFSC DH 2-2 Crew Stations and Passenger Accommodations

2.1.2.3 Rotorcraft Design Standards

Available from U.S. Army Aeroflightdynamics Directorate (AFDD) Mail Stop 243-11 Moffet Field, CA 94035.

ADS-33E-PRF Aeronautical Design Standard Performance Specification Handling Qualities Requirements for Military Rotorcraft

2.1.2.4 Carrier Based Aircraft Requirements

Available from Naval Air Warfare Center Aircraft Divison, Ship Suitability, Building 2649, 21950 Nickles Road, Patuxent River, MD 20670.

AR-40A Automatic Carrier Landing System Airborne Subsystems, General Requirements for

2.1.3 Other Publications

2.1.3.1 NAS Publications

Available from Aerospace Industries Association, 1000 Wilson Boulevard, Suite 1700, Arlington, VA 22209-3928. Tel: 703-358-1000, www.aia-aerospace.org.

NAS 516 Fitting, Lubrication - 1/8 Inch Drive. Flush Type

NASM15981 Fasteners, Externally Threaded, Self-Locking Design And Usage Limitations For

NASM24665 Pin, Cotter (Split)

NASM33540 Safety Wiring And Cotter Pinning

NASM33588 Nut, Self-Locking, Aircraft, Reliability And Maintainability Usage Requirements For

NASM33602 Bolts, Self-Retaining, Aircraft Reliability and Maintainability, Design and Usage Requirement for

2.1.3.2 ASTM Publications

Available from ASTM International, 100 Barr Harbor Drive, P.O. Box C700, West Conshohocken, PA 19428-2959, Tel: 610-832-9585, www.astm.org.

ASTM B 438/B438M Standard Specification for Sintered Bronze Bearings (Oil-Impregnated)

ASTM B 439 Standard Specification for Iron-Base Sintered Bearings (Oil-Impregnated)

2.1.3.3 ISO Publications

Available electronically from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org or http://webstore.ansi.org/ansidocstore/

ISO 22072 Aerospace - Electrohydrostatic actuator (EHA) - Characteristics to be defined in procurement specifications

2.1.3.4 Institute of Electrical and Electronic Engineers/Electronic Industries Association Standards and Guides

Available from IEEE, 445 Hoes Lane, Piscataway, NJ 08854-1331, Tel: 732-981-0060, www.ieee.org. or http://www.ieee.org/web/publications/home/index.html.

IEEE 1394.3-2003 IEEE Standard for a High Performance Serial Bus Peer-to-Peer Data Transport Protocol (PPDT)

IEEE/EIA 12207.0 "Standard for Information Technology - Software Life Cycle Processes." (S/S MIL-STD-498 and MIL-STD-2167)

IEEE/EIA 12207.1 Guide for ISO/IEC 12207, "Standard for Information Technology - Software Life Cycle Processes - Life Cycle Data

IEEE/EIA 12207.2 Guide for ISO/IEC 12207, "Standard for Information Technology - Software Life Cycle Processes - Implementation Considerations"

2.1.3.5 ARINC Publications

Available from ARINC, 2551 Riva Road, Annapolis, MD 21401, www.arinc.com.

ARINC 429 Mark 33 Digital Information Transfer System Parts 1, 2, 3

ARINC 547 Airborne VHF Navigation Receiver

ARINC 579 Airborne VOR Receiver

2.1.3.6 ASME Publications

Available from ASME International, P.O. Box 2300, Fairfield NJ 07007-2300, Tel: 800-843-2763, infocentral@asmeorg or http://store.asme.org/.

ASME B29.100 Chain, Roller, Power Transmission and Conveyor, Flat Link Plates, Single Pitch, Single and Multiple Strand, Connecting Links and Attachment Links

2.1.3.7 FAA Publications

Available from: Federal Aviation Administration, 800 Independence Avenue, SW, Washington, DC 20591, Tel: 866-835-5322, or http://www.airweb.faa.gov/

Advisory Circular 120-29 Criteria for Approving Category I and Category II Weather Minima for Approach

2.2 Abbreviations, Acronyms, Symbols and Their Definitions

ACLS Automatic Carrier Landing System

A/D Analog-to-Digital

AFCF Autopilot Flight Control Function

AGL Above Ground Level

ALS Automatic Landing System

AOA Angle of Attack

APCS Approach Power Compensator System

ARINC	American Radio Inc
BIT	Built-In-Test
Cmo, Cmα, Cnβ	Aircraft Stability Derivatives
CPCI	Computer Program Configuration Item
Di	Ride Discomfort Index
DDV	Direct Drive Valves
DLC	Direct Lift Control
DME	Distance Measurement Equipment
DSP	Digital Signal Processor
EHA	Electrohydrostatic Actuators
EHSV	Electrohydraulic Servovalves
EMA	Electromechanical Actuators
EMI	Electromagnetic Interferences
EMP	Electromagnetic Pulse
ESS	Environmental Stress Screening
FBW	Fly-By-Wire
ϕc/Ye	Ration Bank Command to Lateral Error
FCS	Flight Control SystemFCTFracture Critical Traceable
f_M	Mode Frequency
FMEA	Failure Modes, Effects, and Analysis
FMECA	Failure Mode Effects and Criticality Analyses
FTA	Fault Tree Analysis
GM	Gain Margin
h/hc	Ratio of Altitude to Altitude Command
Hc/Ze	Ratio Altitude Command to Altitude Error
H-DOT	Vertical Rate
HSTA	Horizontal Stabilizer Trim Actuators
HUD	Heads-Up-Display

IAP	Integrated Actuation Package
ICAO	International Civil Aviation Organization
ICD	Interface Control Document
ILS	Instrument Landing System
INS	Inertial Navigation System
KCAS	Knots Calibrated Airspeed
LRU	Line Replaceable Unit
LVDT	Linear Variable Differential Transformer
N/A	Not Applicable
NDT	Non-Destructive Testing
OFP	Operational Flight Program
PBW	Power-By-Wire
PFCS	Primary FCS
PIO	Pilot Induced Oscillation
PLOC	Probability of Loss of Control
PM	Phase Margin
PDE	Power Drive Electronics
PROM	Programmable Read-Only Memory
$Q_{S(FCS)}$	FCS Quantitative Flight Safety
SAE	Society of Automotive Engineers
SAS	Stability Augmentation System
SDP	Software Development Plan
SFCS	Secondary FCS
SOF	Safety-of-Flight
SRA	Shop Replaceable Assembly
STOL	Short Take-Off and Landing
TACAN	Tactical Air Navigation
VG	Turbulence Penetration Airspeed

VHF	Very High Frequency
VL	Maximum Limit Speed
V_{oMAX}	Maximum Operational Airspeed
V_{oMIN}	Minimum Operational Airspeed
VOR	VHF Omni-directional Range
V/STOL	Vertical/Short Takeoff and Landing
WOW	Weight-On-Wheels
WRA	Weapon Replaceable Assembly
ZOC	Zone Of Confusion

2.3 Definitions

2.3.1 Classifications, Flight Categories, and Envelopes

2.3.1.1 Classification of Aircraft

The procuring activity will assign an aircraft to one of these classes and the requirements for that Class shall apply. When no Class is specified, the requirements shall apply to all Classes. When operational missions dictate, the procuring activity may require an aircraft of one Class to meet selected requirements for aircraft of another Class. For the purpose of this specification, an aircraft shall be placed in one of the following Classes:

Class I Small, light aircraft such as:

- Light utility
- Primary trainer
- Light observation

Class II Medium weight, low-to-medium maneuverability aircrafts such as:

- Heavy utility/search and rescue
- Light or medium transport/cargo/tanker
- Early warning/electronic countermeasures/airborne command and control, or communication relay
- Antisubmarine
- Assault transport
- Reconnaissance
- Tactical bomber
- Heavy attack
- Trainer for Class II

Class III — Large, heavy, low-to-medium maneuverability aircraft such as:

Heavy transport /cargo/tanker

Heavy bomber

Patrol/antisubmarine/early warning/electronic countermeasures/airborne command and control, or communication relay

Trainer for Class III

Class IV — High-maneuverability aircraft such as:

Fighter/interceptor

Attack

Tactical reconnaissance

Observation

Trainer for Class IV

2.3.1.2 Flight Phase Categories

For the purpose of this specification, the aircraft's flight profile is separated into categories A, B, and C as follows. When no flight phase is stated in a requirement, that requirement shall apply to all three categories.

Category A: Those non-terminal Flight Phases that require rapid maneuvering, precision tracking, or precise flight-path control.

Category B: Those non-terminal Flight Phases that are normally accomplished using gradual maneuvers and without precise tracking, although accurate flight-path control may be required.

Category C: Terminal Flight Phases that are normally accomplished using gradual maneuvers and usually require accurate flight-path Control.

2.3.1.3 Levels of Flying Qualities

For the purpose of this specification, three levels of pilot's flying qualities shall be specified. The levels are as follows:

Level I: Flying qualities clearly adequate for the mission flight phase.

Level 2: Flying qualities adequate to accomplish the mission flight phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists.

Level 3: Flying qualities such that the aircraft can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, or both. Category A flight phases can be terminated safely, and Category B and C flight phases can be completed.

Specific flying qualities requirements for each of these levels shall as defined in MIL-STD-1797 for fixed wing aircraft, ADS-33E-PRF for rotorcraft, and MIL-F-83300 for V/STOL aircraft.

2.3.1.4 Flight Envelopes

For the purpose of this specification, the flight envelopes are defined as follows:

Operational Flight Envelopes: The Operational Flight Envelopes define the boundaries in terms of speed, altitude, and normal acceleration within which the aircraft must be capable of operating in order to accomplish the required missions. Envelopes for each applicable Flight Phase shall be defined in the Aircraft Detail Specification.

Service Flight Envelopes: For each Aircraft Normal State, the prime contractor shall define, in the Aircraft Detail Specification, Service Flight Envelopes showing the combinations of speed, altitude, and normal acceleration derived from aircraft limits as distinguished from the mission requirements. For each applicable Flight Phase and Aircraft Normal State, the boundaries of the Service Flight Envelopes can be coincident with or lie outside the corresponding Operational Flight Envelopes, but in no case shall they fall inside those Operational Boundaries.

Permissible Flight Envelope: The prime contractor shall define Permissible Flight Envelopes which encompass all regions in which operation of the aircraft is both allowed and possible. These envelopes define boundaries in terms of speed, altitude, and normal acceleration.

2.3.2 FCS Classifications

The FCS provides the means for aircraft control and maneuvering and may employ means for stability augmentation, load limiting and structural mode control, and for pilot relief and workload reduction through automatic controls. FCSs may employ, singly or in combination, mechanical, electrical or optical transmission of commands from the pilot or other sources to the actuators that drive effectors that produce force or moments. The actuation power source may be hydraulic or electric, or sometimes pneumatic. While the detail hardware and software design requirements for these different FCS configurations differ widely, the performance requirements for all configurations will be defined in terms of the class of aircraft, flight phase, flying qualities, and flight envelopes according to 2.3.1.1, 2.3.1.2, 2.3.1.3, and 2.3.1.4 and for each operational state per 2.3.3.

2.3.2.1 Primary FCS (PFCS)

The PFCS provides direct control of aircraft maneuvering by the pilot through the cockpit primary control inceptors. This function includes stability augmentation provided through closed loop feedback of aircraft states as well as command of aircraft response necessary to meet task-oriented flying qualities requirements. The PFCS may include provisions for load limiting or structural mode control. Single or multi-axes thrust vectoring for maneuver or trim control may be included in this classification. Operation of the PFCS is essential to aircraft flight safety and acceptable flying qualities. A basic longitudinal, lateral, and directional system, which moves elevators, ailerons, spoilers, rudders, and propulsion/reaction control devices with a control stick and pedals, is an example.

2.3.2.2 Secondary FCS (SFCS)

The SFCS utilizes commands to position control effectors that control the flight path, lift and drag characteristics of the aircraft, which are not included in the PFCS. Systems such as flaps, slats, trimmable horizontal stabilizer, speedbrakes or airbrakes, wing sweep, ground-steering and propulsion-reversing devices may be included. The SFCS is essential to satisfactory performance but failures in the SFCS are compensated for by the PFCS or the Autopilot Flight Control Function for flight safety as necessary.

2.3.2.3 Autopilot Flight Control Function (AFCF)

The AFCF provides aircrew relief and workload reduction through automatic or semiautomatic flight path control. These functions may be integrated into the PFCS or implemented by wrapping control functions around the PFCS functions. AFCF may employ control stick steering which allows pilot inputs to update reference state values. This classification includes automatic pilots, stick or wheel steering, auto throttles, and similar control mechanizations. Some AFCF modes may require accompanying changes to the PFCS augmentation functions.

2.3.3 FCS Operational State Classifications

2.3.3.1 Operational State I (Normal Operation)

Operational State I is the normal state of FCS performance, safety and reliability. This state satisfies Level 1 flying qualities requirements within the Operational Flight Envelope, Level 2 within the Service Flight Envelope, and the stated requirements outside of these envelopes.

2.3.3.2 Operational State II (Restricted Operation)

Operational State II is the state of less than normal equipment operation or performance, which involves degradation, or failure of only a non-critical portion of the overall FCS. A moderate increase in crew workload and degradation in mission effectiveness may result from a limited selection of normally operating FCS modes available for use; however, the intended mission may be accomplished including aerial refueling and landing at the destination of original intent. This state satisfies at least Level 2 flying qualities requirements within the Operational Flight Envelope and Level 3 within the Service Flight Envelope.

2.3.3.3 Operational State III (Minimum Safe Operation)

Operational State III is the state of degraded FCS performance, safety or reliability which permits safe termination of precision tracking or maneuvering tasks, and safe cruise, descent, and landing at the destination of original intent or alternate but where pilot workload is excessive or mission effectiveness is inadequate. Phases of the intended mission involving precision tracking or maneuvering cannot be completed satisfactorily. This state satisfies at least Level 3 flying qualities requirements.

2.3.3.4 Operational State IV (Controllable to an Immediate Emergency Landing)

Operational State IV is the state of degraded FCS operation at which continued safe flight is not possible; however, sufficient control remains to allow engine restart attempt(s), a controlled descent and immediate emergency landing.

2.3.3.5 Operational State V (Controllable to an Evacuable Flight Condition)

Operational State V is the state of degraded FCS operation at which the FCS capability is limited to maneuvers required to reach a flight condition at which crew evacuation may be safely accomplished.

2.3.4 FCS Criticality Classifications

2.3.4.1 Essential FCS Functions

A function is Essential if loss of the function results in an unsafe condition or inability to maintain FCS Operational State III.

2.3.4.2 Flight Phase Essential FCS Functions

A function is Flight Phase Essential if loss of the function results in an unsafe condition or inability to maintain FCS Operational State III only during specific flight phases.

2.3.4.3 Noncritical FCS Functions

A function is noncritical if loss of the function does not affect flight safety or result in control capability below that required for FCS Operational State III.

2.3.5 Structural Classifications

2.3.5.1 Fracture Critical Part

A primary structural component that is predominantly designed and limited by fatigue crack initiation and crack growth requirements rather than static requirements, the single failure of which could lead to the loss of the aircraft or aircrew. These parts generally call for special fracture toughness controls, quality control procedures, NDT practices, and analytic requirements.

2.3.5.2 Fracture Critical Traceable (FCT) Part

A single load path part, the single failure of which would cause the immediate loss of the aircraft or aircrew. In addition to the requirements for a Fracture Critical part, an FCT part requires serialization and traceability from starting stock to tail number or major subassembly number and reverse.

2.3.6 Document Definitions

2.3.6.1 Aircraft Detail Specification

The procuring activity detailed specification for the aircraft

3. REQUIREMENTS

3.1 General System Requirements

The FCS shall comply with the requirements contained in this specification such that the aircraft missions described by the procuring activity can be performed satisfactorily. The FCS shall meet all of the environmental requirements of this specification.

3.1.1 Safety and Operability Considerations

3.1.1.1 Definitions

The quantitative flight safety requirements in this standard employ the following terms that require definition:

“Loss of Control” is defined as a failure effect, the result of a single failure or multiple failures, which prevents continued safe flight and landing of the aircraft.

“Probability of Loss of Control (PLOC)” is the probability of all of those single and combined failures that would cause loss of control. Conventionally specified by the procuring activity for the entire aircraft, including all of its systems, the allocation to the FCS is made by the procuring activity or the prime contractor.

3.1.1.2 Flight Safety Assessment

The assessment of the quantitative flight safety of an FCS shall include calculation of the PLOC and also an assessment of the consequence of a single failure or multiple failures across the Operational Flight Envelope. The prime contractor shall develop a Consequence of Failure Assessment Plan for approval by the procuring activity to address the failure immunity requirements outlined in 3.1.1.4. The Fault Tree Analysis (FTA), and Failure Modes, Effects and Analysis (FMEA) methods in ARP4761 should be used as a guide.

The quantitative flight safety assessment of the FCS shall include all flight critical components and subsystems. These shall include items such as: mechanical controls, FCS electronic set, air data and aircraft motion sensors, cockpit controls, hydraulically or electrically powered control effectors, trim or cockpit control feel actuators, hydraulic system components, electrical power system components, including constant speed drives for generators and hydraulic system pump drive gear boxes. All moment producers integrally controlled by the engine control system, and the engine itself shall not be included. For a STOL or V/STOL aircraft the approach to be adopted for all of the functions controlled by the engine control system shall be agreed between the procuring activity and the prime contractor.

A representative mission to which this requirement applies, including mission duration, is as defined by the procuring activity and described in more detail by the prime contractor, to allow the component failure rate calculations. The prime contractor must define whether the FTAs will be developed for one hour of flight or be developed for the duration of one flight and the end result divided by the flight length in hours. These two approaches will give differing results when combined failures or dormant failures with long exposure times are significant to the end result.

3.1.1.3 Quantitative Flight Safety

The PLOC due to failures of the FCS shall not exceed the value specified by the procuring activity, or if otherwise specified, the equivalent of the maximum acceptable aircraft loss rate due to relevant FCS failures ($Q_{S(FCS)}$). If the FCS PLOC is not specified by the procuring activity, the numerical requirements of Table 1 apply.

TABLE 1 - FCS QUANTITATIVE FLIGHT SAFETY REQUIREMENTS

Aircraft Description	Aircraft Class	Maximum Aircraft Loss Rate From FCS Failures Per Flight Hour, $Q_{S(FCS)}$
Small, light, medium weight Low to high maneuverability	I, II IV	1.0×10^{-6}
Large, heavy weight Low to medium maneuverability	III	1.0×10^{-8}
Rotary wing	N/A	1.0×10^{-7}

3.1.1.4 Failure Immunity and Safety

A failure immunity and safety assessment shall be made to determine if the system's fault accommodation features provide a safe reaction to, and recovery from, a single failure or a combination of failures. Within the Permissible Flight Envelope, no single failure or failure combination, in the FCS or related subsystems, which is not one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1, shall result in any of the following effects before a pilot or safety device can be expected to take effective corrective action:

a. Flutter, divergence, or other aeroelastic instabilities of the aircraft, or a structural damping coefficient for any critical flutter mode below the fail-safe stability limit of MIL-A-8870.

b. Uncontrollable motions of the aircraft or uncommanded maneuvers, which exceed limit airframe loads.

c. Inability to land the aircraft safely.

d. Any asymmetric, unsynchronized, unusual operation or lack of operation of flight controls that results in worse than FCS Operational State IV.

e. Exceedance of the Permissible Flight Envelope or inability to return to the Service Flight Envelope.

f. FCS failures that could cause total loss of thrust.

g. Erroneous, false, misleading, or missing aircraft information displayed to the aircrew, such as altitude/attitude/angle-of-attack/etc., that could result in either the incorrect or no pilot inputs to the FCS.

3.1.1.4.1 Automatic Terrain Following Failure Immunity

The terrain following system shall detect any potentially critical failure, in the command generation scheme, sensors, (including radar and radar altimeter) or terrain following AFCF, not shown to be one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1, and provide warning to the pilot. Any failure resulting in loss of the automatic terrain following function or unsafe flying condition shall provide safe exit (automatic flyup) from the low altitude, high-speed environment. Take-over or injection of commands by the pilot while the system is operating shall permit a smooth and positive transition without adverse transients. AFCF function accuracy (heading and roll attitude hold) shall be maintained to the degree specified in 3.2.4.2.

3.1.1.5 Transient Electrical Power Effects

Flight control or Vehicle Management computers, or embedded subsystem computers such as microprocessors or Digital Signal Processors (DSPs), shall not suffer adverse effects, which result in operation below FCS Operational State I, due to electrical power source variations within the limits specified for the applicable power system. In the event of power source interruption, no adverse effects shall result which limit operation or performance of flight control computers upon resumption of normal quality power.

3.1.1.6 Priority

Essential and Flight Phase Essential flight controls shall be given priority over noncritical controls and other actuated functions during simultaneous demand operation. However, no specific priority provisions, such as hydraulic priority valves, are required unless there is a likelihood of simultaneous demands which could prevent one or more Essential or Flight Phase Essential actuation systems from meeting their performance requirements. Where provided, priority controls shall be highly resistant to deterioration, binding or failure while dormant under normal aircraft operations so that they will function as required when conditions dictate. If flight safety can be endangered by failure of such controls, ground checkout means for ready determination of their operability shall be provided and procedures specified.

3.1.2 Reliability Considerations

FCS reliability shall be consistent with overall system requirements.

3.1.2.1 Mission Accomplishment Reliability

The probability of mission failure per flight hour, $Q_{M(FCS)}$, due to relevant material failures in the FCS shall be in accordance with the Aircraft Detail Specification. Where overall aircraft mission accomplishment reliability is not specified, $Q_{M(FCS)} < 1x10^{-5}$.

3.1.3 Redundancy Considerations

The prime contractor shall determine the redundancy approaches to be employed by the FCS and shall use the minimum levels required to satisfy the requirements of this standard.

3.1.3.1 Redundancy

In the design of a redundant FCS, the term redundancy refers to a mechanization which will retain functional integrity after failures, and provide the same or similar flying qualities and performance capability. In practice, it can take the form of providing duplicate or alternate components, channels, or subsystems; each capable of performing the given function. The redundancy approach determined by the prime contractor shall be:

a. Based on meeting the flight safety and mission reliability requirements of this specification.

b. Consistent with the use of the system test and monitoring provisions of requirements of 3.3.1 and associated subparagraphs.

c. Based on fault accommodation features that are demonstrated by analysis and simulation to provide a safe reaction to, and recovery from, single failures or failure combinations including those that are more probable than one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1.

d. Addressed in the software requirements definition when applicable.

3.1.3.2 Isolation and Protection of Redundant Subsystems

Redundant subsystems shall employ isolation of the redundant elements to preclude failure of one portion of the system from affecting any other part of the system. Requirements for isolations of electrical signal channels are defined in 3.4.5, hydraulic subsystem requirements are in 3.5.3, and mechanical component requirements are defined in 3.6.2.11.

3.1.3.3 Redundancy Management

The FCS shall perform the redundancy management of the components and subsystems within the FCS itself and, where necessary, of those external to the FCS that are essential to its flight critical functions. Redundancy management shall provide failure detection and suppression of failure transients, efficient and effective system operation for maximum mission reliability and safety. Redundancy management should be employed at various levels within the system or channel to perform such tasks as: signal selection, fault isolation, reconfiguration, and actuator management. Redundancy management shall accomplish the following:

a. Provide failure detection, isolation, and corrective action to meet the requirements of 3.1.1.4 and the transient limits in 3.2.1.10 within 0.15 seconds or time before divergence to double amplitude, whichever is shorter.

b. Prevent propagation of failures among aircraft control redundant elements.

c. Prevent propagation of failures from other systems/subsystems to and from aircraft control redundant elements.

d. Provide physical and electrical isolation between redundant elements.

e. Provide use of voting and comparison on redundant elements to the maximum extent possible.

f. Permit re-admittance of previously failed elements back into the voting plane only when operation within tolerance is evident.

g. Provide maximum transparency to use of inputs and outputs (e.g., sensor, hydraulics, electrical power, commands, etc.).

h. Provide for an automatic in-flight restart of the FCS, which will maintain aircraft control, in the event of an all-channel “generic software error”.

3.1.4 Maintainability Considerations

FCS design and installation shall permit normally assigned maintenance personnel to perform required maintenance safely and easily under all anticipated environmental conditions. Means shall be provided to permit the accomplishment within the allocated maintenance budget and personnel skill level of all required organizational and intermediate level maintenance functions including: operational checkouts, system malfunction detection, fault isolation to the LRU/WRA level, LRU/WRA removal and replacement, inspection, repair, servicing, and testing. In addition the design shall employ provisions to facilitate efficient overhaul and performance testing and evaluation at the depot level.

3.1.4.1 Operational Checkout Provisions

The FCS shall be designed with provisions for operation on the ground, without operating the main engines, to verify system operation and freedom from failure, including verifying system redundancy and the absence of dormant system failures that would not normally detected without intrusive operation of the system, to the maximum extent possible. Electric and electronic components shall be designed to operate with the electric power generators supplied by standard ground carts. Hydraulic components shall be designed to operate with the standard hydraulic ground carts.

3.1.4.2 Malfunction Detection and Fault Isolation Provisions

The FCS shall have means for providing a high probability of detecting failures and monitoring critical performance conditions as required to isolate faults to the LRU/WRA level. These means may include cockpit instrumentation and built-in-test functions.

3.1.4.2.1 Use of Cockpit Instrumentation

Where acceptable procedures are provided, cockpit instrumentation may be used for malfunction detection and fault isolation where it provides a readily understandable condition indication either alone or in coordination with built-in test equipment.

3.1.4.3 Accessibility and Serviceability

The FCS components shall be designed, located, and provided with easy access so that inspection, rigging, removal, repair, and replacement can be readily accomplished. Suitable provisions for rigging pins, or the equivalent, shall be made to facilitate correct rigging of the FCS. In addition, all FCS components shall be designed so their removal and replacement can be accomplished without disturbing the rigging insofar as practical. Special tools required for installation and rigging shall be avoided to the maximum extent possible. If rig or other system setup information is stored in non-volatile memory within a LRU/WRA, provisions shall be made for electronic transfer of this data from redundant LRU/WRAs into an LRU/WRA which has been installed to replace one removed for maintenance.

3.1.4.4 Maintenance Personnel and Safety Provisions

Systems and components shall be designed to preclude injury of personnel during the course of all maintenance operations including testing. All devices which contain any type of stored energy (such as mechanical, electrical, hydraulic, or pneumatic), or which can produce energy capable of causing injury to maintenance personnel, shall be provided with a positive means of disconnecting the energy source, allowing controlled release of the energy, or preventing its inadvertent release. Where positive protection cannot be provided, precautionary warnings or information shall be affixed in the aircraft and to the equipment to indicate the hazard; and appropriate warnings shall be included in the application maintenance instructions. Safety pins, jacks, locks, or other devices intended to prevent actuation shall be readily accessible and shall be highly visible from the ground, or include highly visible streamers. All such streamers shall be of a type which cannot be blown out of sight such as up into a cavity in the aircraft. Streamers shall be in accordance with MIL-S-8512.

3.1.5 Survivability Requirements

The FCS shall withstand and operate in unnatural, induced, hostile environments. The FCS shall provide at least Operational State III performance in all situations where damage sustained by the airframe and other systems would not cause loss of control.

3.1.5.1 All-Engines-Out Control

Engine generated power is required for normal FCS operation. Loss of such power may lead to a change in FCS Operational State and/or FCS functional capability. Supplementary means or power source shall be provided as necessary to supplement the control power available from the engine(s) where engines are unproven, airframe aerodynamics not established in flight, airframe/inlet flow field interactions not adequately verified in flight, or wind milling power is insufficient to maintain Operational State IV control capability anywhere in the aircraft Permissible Flight Envelope. Such supplementary means shall provide control power for a period of time in accordance with the Aircraft Detail Specification. FCS design (including power sources) shall be such that unintentional loss of any or all engine thrust shall not result in less than FCS Operational State IV including any necessary transition to emergency source(s) of power for this specified period of time. Provision shall be made for in-flight return to normal power wherein the transition shall not result in a worse FCS Operational State.

3.1.5.2 Power Capacity

Sufficient electrical, hydraulic, and pneumatic power capacity shall be provided in all flight phases and with all corresponding engine speed settings such that the probability of losing the capability to maintain at least FCS Operational State III aircraft performance shall be at least one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1, when considering the combined probability of system and component failure and the cumulative exceedance probability of turbulence. Analysis and integration studies shall be performed to insure balanced requirements for FCS demands and power capacity. These studies shall include both ground and in-flight power requirements.

3.1.5.3 Invulnerability Considerations for FCS Design

Degradation in FCS operation due to variations in natural environments, adverse events of nature, induced environments, onboard failure of other systems, maintenance error, flight crew error or enemy actions shall be within the limits specified in the following subparagraphs.

3.1.5.3.1 Invulnerability to Natural Environments

FCS shall be designed to withstand the full range of natural environmental extremes established for the particular aircraft or system without permanent degradation of performance below FCS Operational State I, or temporary degradation below FCS Operational State II. Reduction below State I shall be experienced only at adverse environmental extremes not normally encountered and shall be transient in nature only; and, the function shall be recovered as soon as the aircraft has passed through the adverse environment. System components and clearances with structures and other components shall be adequate to preclude binding or jamming, instability, or out-of-specification operation of any portion of the system due to possible combinations of temperature effects, ice formations, loads, deflections, including structural deflections, and buildup of manufacturing tolerances. Specific environmental conditions are defined in 4.4.2.1.

3.1.5.3.2 Invulnerability to Lightning Strike and Static Atmospheric Electricity

The FCS shall maintain Operational State II capability or better when subjected to electric field and lightning discharge except that a temporary, recoverable, more extensive loss of performance to State III is allowable in the event of a direct lightning strike to the aircraft. Structural and FCS bonding shall meet the requirements of MIL-STD-464 and follow the guidance of its referenced documents.

3.1.5.3.3 Invulnerability to Induced Environments

FCS shall withstand the full range of worst-case induced temperatures and temperature shock, acceleration, vibration, noise, and shock, induced pressures, explosive and corrosive atmospheres, electromagnetic Interferences (EMI) and nuclear environment, projected in missions for the particular aircraft, without permanent degradation or loss of capability to maintain FCS Operational State II capability. Specific induced environmental conditions shall be in accordance with the Aircraft Detail Specification. These induced environments, within structural and crew survival limits, shall not result in temporary degradation below FCS Operational State IV capability during the exposure to the environment. Requirements for directed energy and high power microwave weapons, and nuclear radiation including Electromagnetic Pulse (EMP) shall be defined by the procuring activity. The FCS shall meet the applicable requirements of MIL-STD-464 and MIL-STD-461.

3.1.5.3.4 Invulnerability to Enemy Action

The specific enemy threats and operational capability after encountering the threats shall be defined by the procuring activity. If the threats are not defined, the Essential and Flight Phase Essential FCS for combat aircraft, including associated structure and power supplies shall withstand at least one direct encounter from the implied threat inherent to the mission defined in the Aircraft Detail Specification without degradation below Operational State III.

3.1.5.3.5 System Operation and Interface

Whenever a non critical control or other aircraft system is interfaced with Essential or Flight Phase Essential flight control channels, separation and isolation shall be provided to make the probability of propagated or common mode failures to be one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1. Operational performance shall be met by the FCS within 90 seconds after power is applied during initial startup on the ground, except for cold weather startup (<-40 °C) where the allowable startup time shall be set by the prime contractor or procuring activity.

3.1.5.3.6 Signal Path Protection

Where redundant computing paths are provided they shall be isolated or separated to meet the invulnerability requirements of 3.1.5.3. Design options and techniques to enhance the survivability of redundant systems are provided in ARP1083.

3.1.5.3.7 Invulnerability to Onboard Failures of Other Systems and Equipment

The FCS shall meet its failure state/reliability budget, as allocated within the weapon system, for self-generated failure (within the FCS) and for those FCS failures induced by failures of other interfacing systems within the weapons systems (3.1.2.1, 3.1.1). In addition, the FCS design shall comply with the following:

a. Essential and Flight Phase Essential FCSs shall retain FCS capability at Operational State III (minimum safe) or better after sustaining the following failures:

    1. Failure of the critical engine in a two-engine aircraft.

    2. Failure of the two most critical engines in aircraft having three or more propulsive engines.

    3. Failure of any single equipment item or structural member which, in itself, does not cause degradation below State III. This includes any plausible single failure of any onboard electrical or electronic equipment in any subsystem of the aircraft.

b. The FCS for Class III aircraft, including the associated structure and power supplies, shall be designed so that the probability of failing to maintain FCS Operational State IV, as a result of an engine or other rotor burst, shall be one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1.

c. The FCS for Class I, II and IV aircraft, including the associated structure and power supplies, shall be designed so that the probability of failing to maintain FCS Operational State V as a result of an engine or other rotor burst shall be one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1.

d. In the event of a failure that has no immediate effect, such as loss of required cooling for electrical signal computation, or a series of such failures not shown to be one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1, which will unavoidably lead to degraded FCS operation, undegraded operation shall be provided for a period of time determined by the prime contractor and approved by the procuring activity.

3.1.5.3.8 Invulnerability to Pilot and Flight Crew Inaction and Error

The FCS shall be designed to minimize the possibility of any flight crew member controlling or adjusting system equipment to a condition state which could degrade FCS operation. For example:

a. Protection against improper position and sequencing of controls. Wherever practical, cockpit controls, other than stick or wheel and rudder pedals, shall be equipped with positive action gates to prevent inadvertent positioning which can compromise safe operation of the aircraft. Positive interlocks to prevent hazardous operation or sequencing of switches shall be provided.

b. Redundant interlocks shall be used to prevent inadvertent actuation of control systems that would produce structural damage, if actuated.

c. Pilot reaction to failure - The FCS shall be designed so that the normal pilot reaction to cues provided by probable failure conditions is instinctively correct.

d. Warning requirements

   1. Warning information shall be provided to alert the crew to unsafe system operating conditions. Systems, controls, and associated monitoring and warning means shall be designed to preclude crew errors that create additional hazards.

   2. A distinguishable warning shall be provided to the pilot under all expected flight conditions for any failure in a redundant or monitored FCS that could result in an unsafe condition if the pilot were not aware of the failure.

3.1.5.3.9 Invulnerability to Maintenance Error

The FCS shall be designed so that it is physically impossible to install or connect any component item improperly without one or more overt modifications of the equipment or the aircraft. Provisions for adjusting the FCS on the aircraft, except during initial buildup, major overhaul, software modification, or rigging during major maintenance activities, shall be minimized. LRU/WRAs shall be designed to permit making internal adjustments only on the bench. The system shall require only a minimum of re-rigging following replacement of LRU/WRAs. In addition, all control linkages and other flight control mechanisms shall be designed to minimize the probability of jamming from inadvertent entry of maintenance tools or other material.

3.1.5.3.10 Invulnerability to Software Maintenance Error

The following provisions shall be implemented for systems using digital computations, to prevent propagation of software errors from any source:

a. Means for identification of the operational flight program (OFP) shall be provided, and procedures shall be established to prohibit the implementation of unintended versions of software in the FCS.

b. For systems designed for on-aircraft software loading, the system shall have provisions to prevent loading the same version of software already in the flight control computers.

c. Software configuration control and OFP installation requirements shall be documented in the Software Development plan, 4.6.1 (h).

d. Safety requirements shall include the establishment of safety design processes to design safety into the subsystem, as defined in 3.4.6.1.

e. For FCS having redundant channels or software functions distributed over multiple LRUs/WRAs, provisions shall be provided so that the system automatically detects any software version incompatibilities and alerts the flight crew at power-up.

3.1.6 Electromagnetic Interference (EMI) Limits

The FCS shall operate safely within the EMI environment and shall meet the requirements of this specification and any additional requirements dictated by the Aircraft Detail Specification. Special consideration shall be given to protecting the electronic subsystems of the FCS from lightning effects. The FCS shall operate within the limits of MIL-STD-464 and MIL-STD-461 environments, including both the FCS susceptibility to, and generation of, electromagnetic interference. Electromagnetic Interference created by the systems and components during normal operation shall be within the limits of MIL-STD-464 and MIL-STD-461, respectively. Failure modes of all onboard systems and equipment, including flight controls, where these limits may be exceeded shall be identified in addition to sources of conducted EMI that may be detrimental to FCS operation. Additionally, the estimated magnitude of EMI created by these failure modes shall be provided for the assessment of the safety of the FCS.

3.2 System Performance Requirements

3.2.1 General FCS Performance Requirements

The FCS shall comply with the applicable general flying qualities requirements of MIL-STD-1797 for fixed wing aircraft, ADS-33E-PRF for rotorcraft, and MIL-F-83300 for V/STOL aircraft as applicable, and the special performance requirements of the Aircraft Detail Specification. The selected autopilot functions shall provide the performance capabilities specified herein and in the Aircraft Detail Specification.

3.2.1.1 Warm-up

After power is applied to the FCS during initial startup, the warm-up time required to meet this specification shall not be more than 90 seconds. This requirement applies to electronic, hydraulic and other system components. A cold weather hydraulic warm-up mode may be provided to meet this requirement. The specified system performance that shall be provided following this warm-up period shall be documented in the FCS Specification, 4.6.2.

3.2.1.2 Disengagement

Provisions shall be made for positive in-flight disengagement of Flight Phase Essential and noncritical controls under all load conditions. No out of trim condition shall exist at disengagement which cannot be easily controlled by the pilot. The pilot shall be informed of automatic disengagement. Disengagement circuitry shall be designed such that a failure of the circuitry itself does not prevent automatic or manual disengagement.

3.2.1.3 Status of Modes

A means shall be provided so that the flight crew can visually determine the operational status of the FCS.

3.2.1.3.1 Mode Compatibility

Mode compatibility logic shall provide flexibility of FCS operation and ease of mode selection. The mode selection logic shall include the following additional requirements:

a. Make correct mode selection by the crew highly probable.

b. Prevent the engagement of incompatible modes.

c. Disconnect, as appropriate, previously engaged modes upon selection of higher priority modes.

d. Provide arming of appropriate modes while certain modes are engaged.

e. Provide for the emergency disengagement of a higher priority mode, in the event of its failure, and reversion to the basic FCS mode.

f. Provide for mode engagement after mode engagement criteria have been met.

g. Provide appropriate pilot notification of modes as selections and de-selections are made. Mode status, warnings and cautions shall be clear, concise and not ambiguous.

h. Minimize engage and disengage transients, whether the transfer is pilot-selected or an automatic response to a failure, and provide adequate time for pilot response.

i. Alert the pilot when a mode is engaged that is incompatible with a precision manual control task such as landing.

3.2.1.4 Stability

All modes of the FCS must be able to rapidly decrease any transient oscillation, and changes in parameters within the 3 sigma tolerance limits for all of the FCS components must not result in instability.

3.2.1.4.1 Aerodynamic-Closed Loop

An aerodynamic loop is one which relies on aerodynamics and/or thrust vectoring for loop closure such as stability augmentation. Required gain and phase margins are defined in Table 2 for all aerodynamically closed loops. With these gain or phase variations included, no oscillatory instabilities shall exist, and any non-oscillatory divergence of the aircraft shall remain within the applicable limits of MIL-STD-1797, MIL-F-83300, or ADS-33E-PRF. AFCF modes shall be stable with these gain or phase variations included for any amplitudes greater than those allowed for residual oscillations in 3.2.1.7. For the automatic modes, the stability requirement applies only to the airspeed range of operation of these modes. In multiple loop systems, variations shall be made with all feedback paths held at their nominal values except for the path under investigation. A path is defined to include those elements connecting feedback sensors to a force or moment producer. The loop breaks for analysis shall be made at the actuator commands. Where it is appropriate to do so based on symmetry, the loop break can be made at the point where the command feeds a pair of actuators (symmetric stabilator command, for example).

The margins specified by Table 2 shall be maintained under flight conditions of most adverse center-of-gravity, mass distribution, and external store configuration throughout the Operational Flight Envelope and during ground operations. If the control laws or associated gains change significantly with an angle-of-attack or aircraft geometric configuration, the stability analysis shall be made at representative values within the Operational Flight Envelope and not just 1g flight. Where analysis is used to demonstrate compliance with these stability requirements, the effects of major system nonlinearities shall be included when possible. The probability of loss of gain margin or phase margins which results in an unrecoverable condition shall be comparable with the required probability for loss of the aircraft due to FCS failure.

Analysis of the flexible aircraft models shall be verified by ground vibration testing and airframe/FCS "structural coupling" ground testing. "Phase stabilization" shall not be used in determining the stability margins for flexible aircraft modes.

TABLE 2 - GAIN AND PHASE MARGIN REQUIREMENTS

Mode Frequency (Hz)	Airspeed			
	Below V_{OMIN}	V_{OMIN} To V_{OMAX}	At Limit Airspeed (V_L)	At 1.15 V_L
$f_M < 0.06$	GM = 6dB (No Phase Reqmt. Below V_{OMIN})	GM = ±4.5 dB PM = ±30 degrees	GM = ±3.0 dB PM = ±20 degrees	GM = 0 dB PM = 0 degrees (Stable at Nominal Phase and Gain)
$0.06 \le f_M$ First Aeroelastic Mode	GM = 6dB (No Phase Reqmt. Below V_{OMIN})	GM = ±6.0 dB PM = ±45 degrees	GM = ±4.5 dB PM = ±30 degrees	GM = 0 dB PM = 0 degrees (Stable at Nominal Phase and Gain)
f_M > First Aeroelastic Mode	GM = 6dB (No Phase Reqmt. Below V_{OMIN})	GM = ±8.0 dB PM = ±60 degrees	GM = ±6.0 dB PM = ±45 degrees	GM = 0 dB PM = 0 degrees (Stable at Nominal Phase and Gain)

where:

V_L = Limit Airspeed (MIL-A-8860)

V_{OMIN} = Minimum Operational Airspeed (MIL-STD-1797)

V_{OMAX} = Maximum Operational Airspeed (MIL-STD-1797)

Mode = A characteristic aeroelastic response of the aircraft as described by an aeroelastic characteristic root of the coupled aircraft/FCS dynamic equation of motion.

GM = Gain Margin = The minimum change in loop gain, at nominal phase, which results in an instability.

PM = Phase Margin = The minimum change in phase, at nominal loop gain, which results in an instability.

f_M = Mode frequency in Hz (FCS engaged).

Nominal Phase and Gain = The prime contractor's best estimate or measurement of FCS and aircraft phase and gain characteristics available at the time of requirement verification.

3.2.1.4.2 Non-Aerodynamic-Closed Loop

A non-aerodynamic closed loop is one which does not rely on aerodynamics for loop closure, such as a servoactuator.

3.2.1.4.2.1 Stability Margins

All non-aerodynamic-closed loops shall be stable on-ground or in-air, inertially loaded and installed within the aircraft load loop structure. The stability margins shall meet or exceed the following:

a. In the nominal gain tolerance and operating condition, 8 dB and 60 degrees gain and phase, respectively shall apply to the flexible aircraft modes. Analysis of the servoactuators and flexible aircraft models must be verified by ground vibration testing and airframe/FCS "structural coupling" ground testing.

b. The loops shall be stable with the loop in the worst-case operating condition at a tolerance condition established by a Monte Carlo or equivalent analysis that varies component values up to their 3 sigma level. The prime contractor shall provide the rationale for the worst conditions in the FCS Analysis Report, 4.6.3.1.

3.2.1.4.3 Sensitivity Analysis

The sensitivity analysis shall be performed for frequencies below the first aeroelastic mode. Tolerances on feedback gain and phase shall be established at the system level based on the anticipated range of gain and phase errors which will exist between nominal values or predictions and in-service operation due to such factors as poorly defined nonlinear and higher order dynamics, aerodynamic parameter uncertainty, anticipated manufacturing tolerances, aging, wear, maintenance and noncritical material failures. Gain and phase margins shall be defined, based on these tolerances, which will assure satisfactory operation in fleet usage. These gain and phase tolerances shall be established based on variations in system characteristics either anticipated or allowed by component or subsystem specification. The prime contractor shall establish, with the approval of the procuring activity, the parameters and range of variation to be considered. Assessment of aerodynamic uncertainties shall be performed using 20 percent variations on critical stability derivatives such as Cmo, Cmα, Cnβ, etc. The stability margins established through the sensitivity analysis, of variations in system characteristics, shall not be less than 50 percent of the gain and phase margin requirements of Table 2.

3.2.1.5 Operation in Atmospheric Disturbances and Atmospheric Models

The FCS must be capable of operating while flying in the following applicable random and discrete turbulence environments for all design centers of gravity, mass distributions, and external stores configurations. The dynamic analysis or other means used to satisfy these requirements shall include the effects of rigid body motion, significant flexible degrees of freedom, and the FCS. The effect of the turbulence on the pitot system and on any vanes or other sensors must be considered.

a. In normal operation (Operational State I) and in the turbulence environments of 3.2.1.5.1 and 3.2.1.5.2 the FCS shall provide a safe level of operation and maintain mission accomplishment capability.

b. While operating in the turbulence levels of 3.2.1.5.1 with only the Essential and Flight Phase Essential controls engaged and active, the FCS shall provide at least Operational State I performance.

c. The FCS shall provide at least Operational State III for gust intensities corresponding to exceedance probabilities specified in Table 3.

d. Noncritical controls shall provide at least Operational State II in atmospheric disturbances at the intensities corresponding to 10^{-2} probability of exceedance.

e. Noncritical controls operating in disturbances with gust intensities above those specified shall not degrade flight safety or mission effectiveness below the level that would exist with the control inactive. Automatic or manual means to inactivate the noncritical control for flight in heavy disturbances shall be used when required.

3.2.1.5.1 Random Turbulence

The root-mean-square turbulence intensity to be used for normal flight and for terrain following shall have a cumulative probability of exceedance as listed in Table 3. The relationship among vertical, lateral, and longitudinal root-mean-square intensities and scales shall be investigated and the results used to establish intensities for lateral and longitudinal gusts. The listed turbulence intensity levels apply at the turbulence penetration airspeed, VG. The mathematical forms of continuous random turbulence to be used in conjunction with the specified intensity levels shall meet the applicable requirements of MIL-STD-1797, MIL-F-83300, or ADS-33E-PRF requirements as applicable. Table 4 defines root-mean-square vertical gust amplitudes versus altitude for selected exceedance probabilities.

TABLE 3 - TURBULENCE INTENSITY EXCEEDANCE PROBABILITY

FCS Functional Critically	Aircraft Classes	
	Class III	Class I, II, IV
Essential	10^{-6}	10^{-5}
Flight Phase Essential	$\frac{1}{T}10^{-6}$	$\frac{1}{T}10^{-5}$
Noncritical	10^{-2}	10^{-2}

where:

T = Longest time spent in Essential flight phase segment in any mission divided by the total flight time per mission

TABLE 4 - ROOT-MEAN-SQUARE GUST INTENSITIES FOR SELECTED CUMULATIVE EXCEEDANCE PROBABILITIES (FEET PER SECOND TRUE AIRSPEED)

Flight Segment	Altitude (feet-AGL)	Probability of Exceedance						
		2 x 10^{-1}	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
Terrain Following	Up to 1,000 (Lateral)	4.0	5.1	8.0	10.2	12.1	14.0	23.1
	Up to 1,000 (Vertical)	3.5	4.4	7.0	8.9	10.5	12.1	17.5
Normal Flight Climb Cruise and Descent	500	3.2	4.2	6.6	8.6	11.8	15.6	18.7
	1,750	2.2	3.6	6.9	9.6	13.0	17.6	21.5
	3,750	1.5	3.3	7.4	10.6	16.0	23.0	28.4
	7,500	0	1.6	6.7	10.1	15.1	23.6	30.2
	15,000	0	0	4.6	8.0	11.6	22.1	30.7
	25,000	0	0	2.7	6.6	9.7	20.0	31.0
	35,000	0	0	0.4	5.0	8.1	16.0	25.2
	45,000	0	0	0	4.2	8.2	15.1	23.1
	55,000	0	0	0	2.7	7.9	12.1	17.5
	65,000	0	0	0	0	4.9	7.9	10.7
	75,000	0	0	0	0	3.2	6.2	8.4
	Over 85,000	0	0	0	0	2.1	5.1	7.2

3.2.1.5.2 Discrete Gusts

Discrete gust amplitudes to be used shall be established using the relationship between random and discrete gust amplitudes in accordance with the applicable requirements of MIL-STD-1797, MIL F-83300, or ADS-33E-PRF requirements, and the root-mean-square amplitudes specified in 3.2.1.5.1. The maximum discrete gust to be used shall be defined as a single full wave of a (1-cosine) function with a peak amplitude of 60 feet per second which may be encountered anywhere within the Operational Flight Envelope. The wavelength of the discrete gust shall be tuned to provide maximum excitation.

3.2.1.5.3 Low-Altitude Disturbance Model

MIL-STD-1797 specifies the model of atmospheric disturbances to be used for all Category C operations. The effects of wind shear, turbulence and gusts may be analyzed separately. Some analysis and piloted simulation is required considering a complete environmental representation, demonstrating compliance with the requirements with the cumulative effects of wind shear, turbulence and gusts. A non-Gaussian turbulence representation together with a wind model may also be used to represent the patchy, intermittent nature of actual measured turbulence.

3.2.1.5.4 Carrier Landing Disturbance Model

MIL-STD-1797 specifies the model of atmospheric disturbances to be used for carrier landing operations. The model shall be used in analysis and piloted simulations to determine aircraft control response and path control accuracy during carrier landing. This model supplements but does not replace the low-altitude model of 3.2.1.5.3.

3.2.1.6 Internal Noise

There shall be no noticeable high frequency motion of the control surfaces due to noise signals generated by the FCS.

3.2.1.7 Residual Oscillations

Residual oscillations shall not interfere with the pilot's performance of his required tasks. For normal operation during steady flight in calm air, the FCS induced aircraft residual oscillations at all crew and passenger stations shall not exceed 0.05g's vertical or 0.02g's lateral peak to peak acceleration. Residual oscillations in pitch attitude angle shall satisfy the longitudinal maneuvering characteristic requirements of MIL-STD-1797, MIL-F-83300, or ADS-33E-PRF as applicable. Residual oscillations in roll and yaw attitude at the pilot's station shall not exceed 0.6 degree peak to peak for flight phases requiring precision control of attitude. These limits do not apply to failure states such as FCS Operational States below State I. Residual oscillation that result in measurable actuator motion or cylinder chamber pressure variation shall be considered in defining actuator service life.

3.2.1.8 Acceleration Effects

Acceleration forces acting upon the FCS components shall not cause un-commanded control inputs, cause components to malfunction or become inoperative within the Operational Flight Envelope and during catapult launches.

3.2.1.9 Structural Protection

Within the Operational Flight Envelope, means shall be provided to prevent the pilot or the FCS from applying commands that will cause the aircraft to exceed the limit load factor. Provisions for pilot override under emergency conditions shall be incorporated. Structural protection requirements shall be defined in the Aircraft Detail Specification.

3.2.1.9.1 Flight Load and Fatigue Alleviation

Provisions for flight load and fatigue alleviation shall be defined in the Aircraft Detail Specification. These provisions shall be developed using best system engineering practice to determine the tradeoff with flying qualities and flight control actuator requirements.

3.2.1.9.2 Gust and Maneuver Load Alleviation

Provisions for flight maneuver load and gust alleviation shall be determined by the prime contractor and documented in the FCS Specification, 4.6.2. These provisions shall be developed using best system engineering practice to determine the tradeoff with flying qualities and flight control sensor and actuator requirements.

3.2.1.10 Failure Transients

Aircraft motions following FCS or component failures shall be such that dangerous conditions can be avoided by pilot corrective action. A specified value of time delay between the failure and initiation of pilot corrective action shall be incorporated when determining compliance. The value of time delay shall be determined by the prime contractor and approved by the procuring activity. This time delay includes an interval between the occurrence of the failure and the occurrence of a cue such as acceleration, rate, displacement, or sound that will definitely indicate to the pilot that a failure has occurred, plus an additional interval which represents the time required for the pilot to diagnose the situation and initiate corrective action. During operation at a trimmed flight condition the transients shall not exceed the levels defined in Table 5. A time delay of at least 2 seconds between the failure cue and initiation of pilot corrective action shall be incorporated when determining compliance. During maneuvering flight no single failure within the FCS shall result in: intolerable flying qualities, a dangerous change in flight path, departure from controlled flight, or exceeding the aircraft structural limits

TABLE 5 - FAILURE TRANSIENTS

Operational State I or II (after failure)	±0.5 g max incremental normal acceleration or ±0.5 g lateral acceleration at the pilot's station or ±10 degrees per second roll rate, except that neither stall angle of attack nor structural limits shall be exceeded. For Category A vertical or lateral excursions of 5 feet, ±2 degrees bank angle
Operational State II (after failure and FCS reconfiguration)	±2.0 g max incremental normal or ±0.5 g lateral acceleration at the pilot's station, ±20 degrees per second roll rate, the lesser of 5 degrees sideslip and the structural limit.
Operational State III (after failure)	No dangerous attitude reached or structural limit exceeded and no dangerous alteration of the flight path from which recovery is impossible.

3.2.2 Primary FCS Requirements

The following requirements apply. References to mechanical or electrical flight controls apply only when that mechanization is used.

3.2.2.1 Primary Functional Modes of the PFCS

The primary functional modes control the basic longitudinal, lateral, and directional axes of the aircraft through such control effectors as elevators, ailerons, rudders and canards for fixed wing aircraft and swashplates and tail rotors for rotorcraft. The Aircraft Detail Specification shall determine the applicable modes. The modes may be separated and divided by axis and selectable by the pilot or there may be one primary mode of operation, nonselectable.

3.2.2.2 Operability Following Failures

The performance and capability of any of the Primary Functional Modes after a failure or failures shall be determined by the prime contractor and documented in the FCS Specification, 4.6.2.

3.2.2.3 Augmentation

When used, augmentation systems shall be compatible with all control modes and airframe dynamic considerations. Single failures in a gain scheduling system, more probable than one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1, shall not degrade augmentation system performance below Operational State II. Pilot-operated gain changing devices shall only be used as emergency backup equipment. Specific approval shall be obtained from the procuring activity for this feature. Positive mechanical, electrical, or software/firmware limits shall be provided in gain schedulers to preclude exceeding limiting gain values.

3.2.2.4 Ratio Changing Mechanisms

Where ratio changing mechanisms are used, monitors and emergency positioning means shall be provided if improper positioning can result in a safety of flight hazard. The requirements for rate of ratio changing shall be defined based on the requirements of MIL-STD-1797, ADS-33E-PRF, and MIL-F-83300 for transient response to configuration or control mode change.

3.2.2.5 Control Centering Breakout Forces and Free Play

The corresponding design requirements shall meet the applicable requirements of MIL-STD-1797, MIL-F-83300, or ADS-33E-PRF. Selected sensitivity and breakout forces shall not lead to overcontrol tendencies. The control sensor electrical deadband shall not be less than the mechanical deadband/breakout forces.

3.2.2.6 Control Force Sensitivities

The pitch, roll, and yaw control force sensitivities shall meet the requirements of MIL-STD-1797, MIL-F-83300, or ADS-33E-PRF requirements as applicable.

3.2.2.7 Reversion

If a backup mode is provided for an FCS, at least FCS Operational State III shall be provided following reversion. While the backup mode is disengaged, interaction of backup mode provisions with the normal mode shall not degrade operation below State I. If a single FCS power system is used in an Essential or Flight Phase Essential fully powered system, emergency mechanical reversion or an emergency power source shall be provided. On single-engine aircraft, the emergency power source shall be independent of engine operation. It shall be possible to re-engage the normal power source in flight following operation with manual reversion controls or emergency power. Manual or automatic changeover to or from emergency provisions shall not result in capability worse than FCS Operation State III.

3.2.2.8 Controller Kinematics

Kinematics shall preclude hazardous unintentional inputs (cross-coupling) into one or more axes with normal control motions within the limits of ultimate structural load factor, design maneuver, and turbulence induced accelerations experienced at the crew station. Controller damping and mass balance shall be set to minimize any aircraft-pilot coupling and/or pilot augmented oscillation tendencies.

3.2.2.9 Feedback to Crew Station Controls

The control device motion and force required to accomplish stability and control augmentation shall not be evident at the crew station controls. Vibratory forces or motion acting upon elements downstream of the controller shall not be evident at the crew station controls. Force and motion feedback to crew station controls shall be considered as not evident if the force’s magnitude is less than half the lowest breakout force of the applicable control. There shall be no feedback through a mechanical backup during normal or degraded operation of the PFCS.

3.2.2.10 Control Feedback

Control forces fed back to the pilot’s controls from the stability and the control augmentation systems when the pilot controls the aircraft manually shall be minimized. Force feedback shall be considered as not reflected at the controls if the magnitude is less than half the breakout force of the control with lowest breakout force. Full freedom of operation of cockpit controls shall be possible at all times that stability augmentation is in use. Provisions shall be made in cockpit control motions so that recovery from an augmentation actuation hardover is possible under all flight conditions. The cockpit control position may shift under this condition.

3.2.2.10.1 Active Feel Augmentation

The pilot and copilot shall have the capability of overriding the feel system at all times. Upon failure of the active feel augmentation system, the control feel shall revert to a breakout force and a force gradient versus deflection required by MIL-F-83300, MIL-STD-1797, or ADS-33E-PRF.

3.2.2.11 Surface Rate Capability

The FCS control surface rate capability shall be adequate to satisfy the Flying Quality, Control Margin, and Pilot Induced Oscillation (PIO) requirements specified in MIL-STD-1797.

3.2.2.12 Data Latency

The FCS data latency and computational delay shall be minimized to ensure the aircraft will satisfy the Flying Quality, Control Margin, and Pilot Induced Oscillation (PIO) requirements specified in MIL-STD-1797 and ADS-33E-PRF.

3.2.3 Secondary FCS (SFCS)

The Aircraft Detail Specification shall specify which modes are applicable. Typical secondary modes include but shall not be limited to the following:

a. High Lift Control

b. Speed Brakes

c. Direct Lift Control

d. Variable Wing Sweep Control

e. Stability Altering Systems

f. Trim (manual and automatic)

g. Maneuver Flaps

h. Nose Wheel Steering

i. Wheel Brake Control Anti-Skid

Outputs from the Secondary Functional Mode controllers shall not cause objectionable aircraft response characteristics.

3.2.3.1 High Lift Control

A control system shall be provided for actuating high lift devices. Unless specified in the Aircraft Detail Specification, the time to operate the landing flaps under normal operating conditions shall not be less than 3 seconds, nor more than 8 seconds, at the maximum aircraft speed for which they should be operated. For Class II and III transport aircraft the prime contractor shall define the flap operating time. Typical operating times are in the range of 15 to 20 seconds. High lift devices shall contain provisions for synchronous operation, unless it can be demonstrated that no hazardous flight attitude will result from unsynchronized operation. The demonstration may be conducted using pilot simulation provided the aerodynamic data base has been explicitly developed to include asymmetric flap forces and moments. In the event of a failure in the high lift control system, the high lift device shall maintain synchronization, or remain synchronized without motion. The degree of asymmetry and the flight conditions for demonstration shall generally be the most critical for inducing hazardous flight attitudes. This demonstration shall be approved by the procuring activity and included in the FCS Development Plan, 4.6.1. An emergency means for operating the high lift devices shall be provided on aircraft where safe operational landings cannot be accomplished without use of the high lift devices. The emergency system shall be completely independent of the basic high lift system up to, but not necessarily including, the actuators.

3.2.3.2 Speed Brakes

If the FCS employs a dedicated speed brake surface or surfaces, the actuation control system shall prevent structural damage if opened at VL. Blowback may be used to prevent structural damage. The time to extend the speed brakes over the operating range shall be as specified in the Aircraft Detail Specification. Emergency retraction is required on speedbrakes that will not automatically retract, as a result of airloads, when the control is moved to the retract position. Where asymmetric operation of speed brakes would cause uncontrollable aerodynamic moments on the aircraft, provisions shall be made to prevent this condition. Where these devices perform functions requiring asymmetric operation, provisions shall be made to prevent unintentional operation. If the speed brake function of increased drag is obtained with atypical deployment of the primary control effectors the FCS shall provide aircraft protection equivalent to the requirements above.

3.2.3.3 Direct Lift Control (DLC)

The DLC system shall be designed for the purposes of enhancing required mission performance, as defined in the Aircraft Detail Specification. It shall have the control power to produce the required rate of change in flight path angle with pitch attitude held constant. DLC systems shall be designed to at least the single-failure, fail-safe criterion. Means for the detection and indication of failures shall be provided. Built-in-Test (BIT) logic shall also be provided. Interlocking logic requirements between the DLC system and any other systems or subsystems shall be as determined by the prime contractor and documented in the FCS Specification, 4.6.2. Whenever deflections of trailing edge flaps are used as an aid in direct lift control of the aircraft, no single failure within the DLC system shall prevent lowering of the flaps to their landing position.

3.2.3.4 Variable Wing Sweep Control

The Variable Wing Sweep Control System shall be able to vary the rate of change of wing sweep angle over the entire flight envelope consistent with mission performance and flight safety requirements. The servomechanism controlling wing sweep angle shall be stable and free of limit cycle oscillations for all flight conditions. Variable wing sweep control systems shall be designed as a minimum to the single-failure, fail-safe criterion. The control system shall contain a failure detection system. The provisions shall be made for an emergency back-up system to actuate the wings to the landing position in case of failure of the main control system if such is necessary to permit a safe landing of the aircraft.

3.2.3.5 Nose Wheel Steering

Where fly-by-wire nose wheel steering is used the control functions shall be determined by the prime contractor and documented in the FCS Specification, 4.6.2. The FCS shall provide mode switching logic and failure detection and isolation for the nose wheel steering system, as specified in 3.1.3.3. The nose wheel steering shall have at least fail-safe capability and shall include the following requirements:

a. Mode switching logic

   1. Fail-safe to a shimmy damper function.

   2. Engage/disengage requirements:

      (a) Pilot action

      (b) WOW

      (c) Ground speed (air speed)

      (d) Wheel/pedal position

b. Ground handling control functions

   1. Dual mode steering

      (a) Low gain (small maximum nose wheel angle) for control during takeoff and landing

      (b) High gain (large maximum nose wheel angle) for taxi and maneuvering at low speeds

   2. Use of yaw rate and/or lateral acceleration feedbacks for control augmentation shall be determined by the prime contractor and documented in the FCS Specification, 4.6.2.

3.2.3.6 Trim Controls

Each of the principal control axes shall have trim controls. The FCS trim requirements shall include the following:

a. Wherever worse than Operational State III would result from a power operated trim control failure that is not less probable than one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1, the pilot shall be given override capability for the failed control.

b. For series trim control, no worse than Operational State III shall result from a trim control becoming inoperative in any position, including separation of the trim actuator, except for failures less probable than one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1.

c. Provisions for prevention of runaway trim and override capability.

d. Warnings for trim conditions at or near the limits that allow the aircraft to maintain controlled flight.

e. Engagement of the Automatic Flight Control Function shall automatically initiate any needed pitch trim.

f. The aircrew shall be provided with clear indication of take-off trim position. Aircraft subject to short alerts shall have the capability incorporated to return all trim to the takeoff position automatically or by a single pilot action.

g. All automatically controlled trim shall incorporate positive means to avoid potentially hazardous adverse trim near stall.

h. In multicrew aircraft with electrical trim systems, interlocks or other provisions in the circuitry shall prevent simultaneous commands by two aircrew members from causing any operation in opposing directions at the same time.

3.2.4 Automatic Flight Control Function (AFCF) Performance Requirements

3.2.4.1 AFCF General Requirements

Integration of the AFCF with the PFCS shall not cause the control feel forces to depart from the applicable requirements of MIL-STD-1797, MIL-F-83300, or ADS-33E-PRF. Subsystems that trim control forces to zero shall not introduce control transients that degrade flying qualities. Engage and disengage, selection logic, and functional safety criteria and limits for each AFCF function shall be established and specified in the Aircraft Detail Specification. When the following functions are used, the specified performance shall be provided. Unless otherwise specified, these requirements apply in smooth air and include sensor error. AFCF requirements for rotorcraft shall be the applicable sections of ADS-33E-PRF.

3.2.4.1.1 Damping

Except where otherwise specified, a damping ratio of at least 0.3 critical shall be provided for nonstructural AFCF controlled mode responses. Specified damping requirements apply only to the response characteristics for perturbations an order of magnitude greater than the allowable residual oscillation.

3.2.4.1.2 Control Stick (or Wheel) Steering

The pilot shall retain full capability to maneuver the aircraft within the applicable control force and maneuver limits of MIL-STD-1797, MIL-F-83300, or ADS-33E-PRF as applicable. Automatic disengagement of the AFCF with reversion to manual control is permitted in meeting these requirements. Specific requirements for Control Stick or Control Wheel logic shall be developed by the prime contractor and documented in the FCS Specification, 4.6.2.

3.2.4.1.3 Lateral Acceleration and Sideslip Limits

Except for flight phases using direct side force control or during which sideslip is deliberately induced, e.g., forward slip to a landing, the following performance shall be provided when any lateral-directional AFCF function is engaged. Lateral acceleration refers to apparent (measured, sensed) body axis acceleration at the aircraft center of gravity.

3.2.4.1.3.1 Coordination in Steady Banked Turns

The incremental sideslip angle shall not exceed 2 degrees from the trimmed value, and lateral acceleration shall not exceed 0.03 g, while at steady bank angles up to the maneuver bank angle limit reached in normal maneuvers with the AFCF engaged. For rotorcraft, only the lateral acceleration limit applies.

3.2.4.1.3.2 Lateral Acceleration Limits, Rolling

Body axis lateral acceleration at the cg shall not exceed ±0.1 g for flight condition with aircraft roll rate capability up to 30 degrees per second, or ±0.2 g for flight condition with aircraft roll rate capability of 30 to 90 degrees per second, or ±0.5 g for flight condition with aircraft roll rates over 90 degrees per second. These limits shall be satisfied for aircraft in essentially constant altitude flight while rolling smoothly from one side to the other at bank rates up to the maximum obtainable through AFCF modes.

3.2.4.1.3.3 Coordination in Straight and Level Flight

The accuracy while the aircraft is in straight and level flight shall be maintained with an incremental sideslip angle of ±1 degrees from the trimmed value or a lateral acceleration of ±0.02 g at the c.g., whichever is lower. For rotorcraft, only the lateral acceleration limit applies.

3.2.4.1.3.4 Sideslip Limits

Where sideslip limiting is a system requirement, the static accuracy while the aircraft is in straight and level flight shall be maintained within an incremental side slip angle of ±1 degrees from the trimmed value or a sideslip angle corresponding to a lateral acceleration of ±0.02 g, whichever is the lower.

3.2.4.1.4 Emergency Disengagement

Positive means of emergency disengagement of all AFCF modes shall be provided.

3.2.4.2 Pilot Relief Functions

The pilot relief category shall include those automatic control functions which simplify or ease the control of the flight path of the aircraft. When the following functions are used, the following specified performance shall be provided. Unless otherwise specified, these requirements apply in smooth air and include sensor error.

3.2.4.2.1 Attitude Hold (Pitch and Roll)

Attitudes shall be maintained in smooth air with a static accuracy of ±0.5 degrees pitch attitude with wings level and ±1.0 degrees in roll attitude with respect to the reference attitude. The root-mean-square attitude deviations shall not exceed 5 degrees in pitch and 10 degrees in roll attitude in turbulence at the intensities specified in 3.2.1.5. Accuracy requirements shall be achieved and maintained within 3 seconds of mode engagement for a 5 degrees attitude disturbance for Class IV aircraft, and within 5 seconds for Classes I, II, and III aircraft. Upon completion of a pilot-controlled maneuver, the aircraft attitude maintained by the AFCF shall be the aircraft attitude at the time the commanded forces were removed, if this attitude is within the limits of the attitude hold mode.

3.2.4.2.2 Heading Hold

In smooth air, heading shall be maintained within a static accuracy of ±0.5 degrees with respect to the reference heading. In turbulence, the heading deviation shall not exceed 5.0 degrees, root-mean-square, and at least Operational State II shall be provided at the gust intensities corresponding to a cumulative exceedance probability of 10^{-2}, as defined in 3.2.1.5, Table 4. When Heading Hold is engaged, and the aircraft is rolled to wings level, the aircraft shall capture and hold the heading that exists at the time the aircraft is within approximately 3 degrees of wings level.

3.2.4.2.3 Heading Select

The aircraft shall automatically turn through the smallest angle to any heading selected or preselected by the pilot and maintain that heading to the tolerances specified for Heading Hold. The prime contractor shall determine a bank angle limit which provides a satisfactory turn rate and precludes impending stall. The heading selector shall have 360 degrees control. The aircraft shall not overshoot the selected heading by more than 1.5 degrees with flaps up or 2.5 degrees with flaps down. Entry into and exit from the turn shall be smooth and rapid. The roll rate shall not exceed 10 degrees per second and roll acceleration shall not exceed 5 degrees per second per second.

3.2.4.2.4 Altitude Hold and Altitude Select

Engagement of the Altitude Hold or Altitude Select function at rates of climb or descent less than 2,000 feet per minute shall select the existing indicated barometric altitude or selected altitude, respectively, and control the aircraft to this altitude as reference. The resulting normal acceleration shall not exceed 0.2 g incremental for Classes I, II, and III aircraft, or 0.5 g incremental for Class IV aircraft. For engagement rates above 2,000 feet per minute the AFCF shall not cause any unsafe maneuvers. Within the aircraft thrust drag capability and at steady bank angles, the mode shall provide control accuracies specified in Table 6. These accuracy requirements apply for airspeeds up to Mach 1.0. Double these values are permitted above Mach 1.0 and triple these values apply above Mach 2.0. Following engagement or perturbation of altitude hold or altitude select modes at 2,000 feet per minute or less, the specified accuracy shall be achieved within 30 seconds. Any periodic residual oscillation within these limits shall have a period of at least 20 seconds. Altitude Select allows for the attainment of an altitude preselected by the pilot, or automatically selected by a guidance or navigation program.

TABLE 6 - MINIMUM ACCEPTABLE CONTROL ACCURACY

Altitude (feet)	Bank Angle (degrees)		
	0 - 1	1 - 30	30 - 60
55,000 to 80,000	±0.1 percent at 55,000 varying linearly to ±0.2 percent at 80,000	±60 feet or 0.3 percent whichever is larger	±90 feet or 0.4 percent whichever is larger
30,000 to 55,000	±0.1 percent	±60 feet or 0.3 percent whichever is larger	±90 feet or 0.4 percent whichever is larger
0 to 30,000	±30 feet	±60 feet or 0.3 percent whichever is larger	±90 feet or 0.4 percent whichever is larger

3.2.4.2.5 Mach Hold

The requirements of this paragraph shall be met in straight, steady flight, including climb or descent. The Mach number existing at the engagement of Mach Hold shall be the reference. After engagement and stabilization on Mach Hold, the AFCF shall maintain indicated Mach number and the error shall not exceed ±0.01 Mach or ±2.0 percent of indicated Mach, whichever is larger, with respect to the reference. Any periodic oscillation within these limits shall have a period of at least 20 seconds. A mode response or maximum time to capture reference suitable for the mission phase should be 20 seconds. Adjustment capability of at least ±0.01 Mach shall be available to allow the pilot to vary the reference Mach number around the engaged Mach number.

3.2.4.2.6 Airspeed Hold

The requirements of this paragraph shall be met in straight, steady flight, including climb or descent. The airspeed existing at the engagement of Airspeed Hold shall be the reference. Indicated airspeed shall be maintained within ±10 knots or ±2 percent of the reference airspeed, whichever is greater, up to 60 degrees bank angle. Any periodic oscillation within this limit shall have a period of at least 20 seconds. The prime contractor shall establish a mode response or maximum time to capture requirement which is suitable for the mission phase. Adjustment capability of at least ±10 knots shall be available to allow the pilot to vary the reference airspeed around the engaged airspeed.

3.2.4.2.7 Approach Power Compensator System (APCS)

The APCS is required to control aircraft angle of attack during all phases of the landing approach by automatically adjusting engine thrust. There is normally one APCS configuration used for manually flown approaches and another APCS configuration used in conjunction with the Automatic Carrier Landing System. APCS performance shall be compatible with all FCS modes which may be engaged during approach and landing phases of flight, and shall not result in FCS performance degradation.

3.2.4.2.7.1 Airspeed/AOA Transients

The APCS shall be capable of maintaining an angle of attack such that the approach airspeed shall be within 1.0 percent of the referenced landing speed.

3.2.4.2.7.1.1 Transients Due to Pitch and Roll Maneuvers

The APCS shall respond to a step horizontal wind gust or pilot pitch input like a first order lag with at most a 4 second time constant. The step input used will initially upset the aircraft's angle of attack by ±2 degrees. A single overshoot shall be permitted during the correction. The overshoot shall not exceed 20 percent of the initial error. The APCS shall be able to quickly counteract any airspeed change which may result due to pitch maneuvers. This action may be checked by inputting ±4 degrees incremental pitch step commands. The airspeed change resulting from either pitch command (up or down) shall be ≤1.5 percent of the reference airspeed. In returning to the reference landing speed, only one overshoot in excess of one knot is permitted. In steady state coordinated turns (45 degrees or less), the APCS shall adjust thrust to maintain a relatively constant airspeed in accordance with the inherent error signal generated in measured angle of attack in the turn.

3.2.4.2.7.1.2 Transients In Turbulence

The APCS shall have the capability to correct the airspeed/angle of attack error caused by a step horizontal wind gust or pilot pitch input of a magnitude to upset the aircraft's angle of attack by ±2 degrees. The APCS shall reduce airspeed error to 36.7 percent of the initial error within four seconds after the initial disturbance. A single overshoot shall be permitted during the correction; however, it shall not exceed 20 percent of the initial error.

3.2.4.2.7.1.3 Transients Due to Engage and Disengage

Engagement of the APCS in a 30 degrees banked turn should produce a smooth transition to the reference AOA in 30 seconds. Engagement from 30 knots above nominal approach speed shall produce a smooth transition to On-Speed within 15 to 20 seconds and AOA should reach the reference value within 20 seconds. Engagement from 15 knots below normal approach speed or engagement from an AOA close to the AOA limit shall produce a smooth transition to On-Speed within 15 seconds. AOA should reach the reference value within 20 seconds.

3.2.4.2.7.2 Throttle Movements

3.2.4.2.7.2.1 Throttle Movements Due to Pitch and Roll Maneuvers

During APCS operation, the throttles shall not be retarded beyond a minimum consistent with an engine flight idle RPM or advance beyond the military power setting.

3.2.4.2.7.2.2 Throttle Movements in Turbulence

Throttle activity shall not be excessive in turbulence.

3.2.4.2.7.2.3 Pilot Override Capability

The capability shall be provided for pilot overpower/override of the APCS via application of force to the throttles without degradation of other FCS modes except for Automatic Carrier Landing. No more than 12 pounds-force shall be required to disengage the APCS.

3.2.4.2.7.3 Temperature Compensation

The APCS shall be able to provide proper compensation for a free air temperature range of -53 °C (-63 °F) to 54 °C (130 °F). Three settings shall be used (COLD, NORMAL, HOT) or provisions shall be made to automatically compensate for temperature variations.

3.2.4.2.8 Ride Smoothing

With the FCS in Operational State I, the probability of exceeding the following vertical or lateral axis Ride Discomfort index levels at any crew station during flight turbulence shall be equal to or less than:

TABLE 7 - PROBABILITY OF EXCEEDANCE OF RIDE DISCOMFORT INDICES

Ride Discomfort Index	Probability of Exceedance
0.07	0.20
0.28	0.01

Both requirements apply, separately, to both the vertical and lateral axis. For the lateral axis only lateral gusts and for vertical axis only vertical gusts shall be considered. Effects of attitude hold or other pertinent AFCF modes shall be included, where used.

3.2.4.2.8.1 Ride Discomfort Index

Ride Discomfort Index is defined as:

$$D_i = \left[\int_{0.1}^{f_t} \left| w(f) \right|^2 \left| T_{CS}(f) \right|^2 \Phi_u(f)df \right]^{1/2} \quad \text{(Eq. 1)}$$

where:

D_i = Ride Discomfort Index, (vertical or lateral)

w(f) = Acceleration weighting function (vertical or lateral) l/g

$T_{CS}(f)$ = Transmissibility, at crew station, g per feet per second

$\Phi_u(f)$ = Von Karman gust power spectral density of intensity specified in 3.2.4.2.8 and form specified in MIL-STD-1797

f = Frequency, Hz

f_t = Truncation frequency (frequency beyond which aeroelastic responses are no longer significant in turbulence)

Acceleration weighting functions are defined for vertical and lateral acceleration by Figure 1. Probability of exceedance versus turbulence intensity is specified in 3.2.1.5.1 and 3.2.1.5.2.

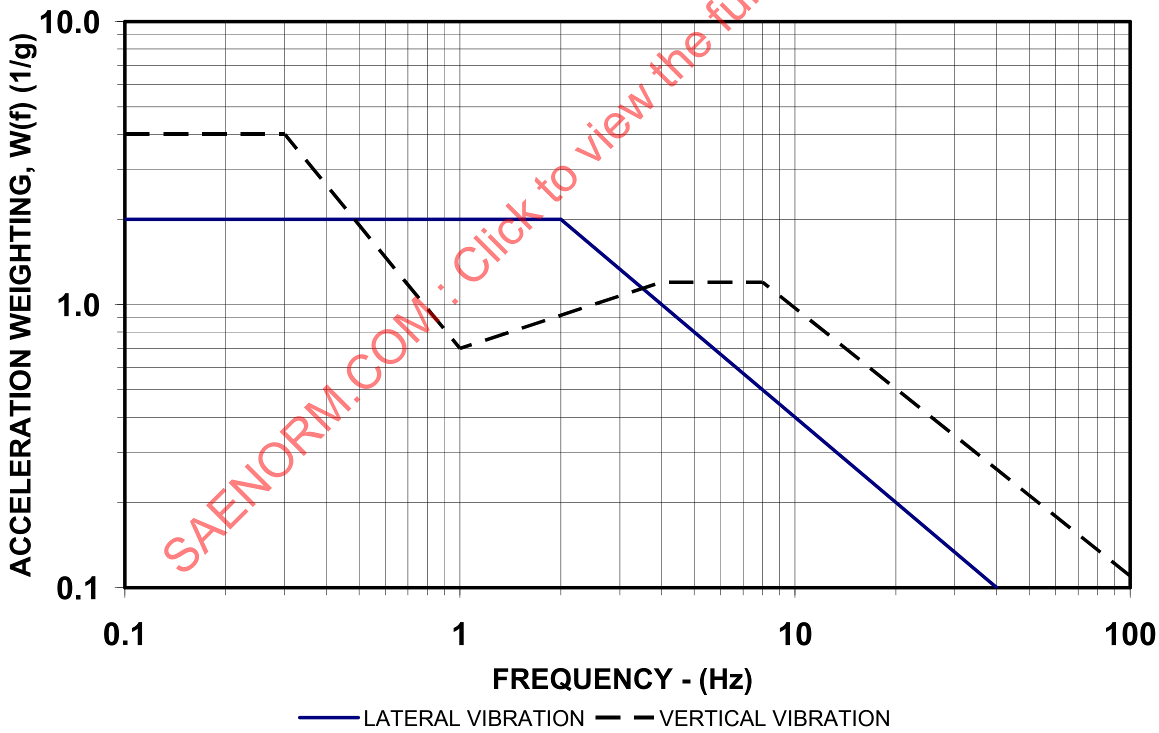

FIGURE 1 - ACCELERATION WEIGHTING FUNCTIONS

3.2.4.3 Automatic Navigation and Guidance Functional Requirements

The guidance category shall include those control functions which provide automatic flight path control in accordance with steering signals generated by guidance and control systems external to the FCS, some of which may not be redundant. During the automatic guidance functions, the AFCF - aircraft combination is an element within the overall guidance loop. The requirements of the guidance loop, the guidance method and the particular guidance computer shall be determined by the prime contractor and documented in the FCS Specification, 4.6.2. Unless specific performance data are established in the applicable system specification, the following requirements shall be met.

3.2.4.3.1 General Tie-In Requirements

Provisions shall be made for the acceptance of external guidance signals from various computers generating the necessary commands in attitude, speed, altitude, flight path rate, acceleration, etc., to control the aircraft's flight path. The FCS hardware and software design shall not assume 100 percent data integrity of externally generated guidance signals, including any externally generated validity flags. The FCS shall incorporate independent reasonability checks and other measures as required to protect against erroneous guidance signals.

3.2.4.3.1.1 AFCF Servo Engage Interlocks

For a mechanically commanded FCS, with autopilot servoactuators, interlocks shall be provided to prevent servo engagement and to provide disengagement in the presence of conditions that render disengagement safer than engagement. Manual override of interlocks shall be provided whenever such override capability will enhance flight safety.

3.2.4.3.1.2 Engage-Disengage Transients

Normal engagement or disengagement of AFCF modes shall not result in transients greater than ±0.1 g normal or lateral acceleration at pilot station, or ±3 degrees per second rate. Normal engagement transient requirements shall be met 2 seconds after completion of any maneuver up to the maneuver limits of the aircraft or the limits of sensor equipment being used.

3.2.4.3.1.3 Manual Override Capability

It shall be possible to manually overpower or countermand the automatic control action of the AFCF using the normal pilot controls. Required pilot forces shall not exceed pilot capability as defined by MIL-STD-1472. The overpower force for V/STOL aircraft and rotorcraft shall not exceed the limit cockpit control forces specified for Level 1 operation in MIL-F-83300. Manual overriding of the AFCF shall not result in an instability due to force fight between the pilot and the AFCF. The pilot shall have the capability to disengage the AFCF through the normal disengagement switches after the initial recovery maneuver.

3.2.4.3.2 Command Signal Limiting

Means shall be provided to limit the command signals from external guidance systems, so that the AFCF system will not cause the aircraft to exceed maneuver limits that are inconsistent with the external guidance function and flight conditions.

3.2.4.3.3 Switching

Switching between guidance modes with zero command signal input from external guidance systems shall not cause transients greater than ±0.05 g normal acceleration at the center of gravity in pitch or ±1 degrees in the roll attitude.

3.2.4.3.4 Noise Compatibility

The AFCF shall be so designed that the noise content in the external guidance signal, as specified in the applicable system specification, shall not saturate any component of the AFCF or limiters in AFCF software, shall not impair the response of the aircraft to the proper guidance signals, and shall not cause objectionable control surface motion or attitude variation. If the specified noise content is too great to achieve this goal, additional noise filtering shall be employed consistent with maintaining stability margins. Since additional noise filters impair the guidance performance, an optimum compromise between performance and noise filtering shall be determined by the procuring activity and the prime contractor.

3.2.4.3.5 Data Link

If the steering information is transmitted to the AFCF via a digital data link, the sampling frequency and number of bits per signal shall be compatible with the accuracy and dynamic performance requirements of the guidance loop. If the steering information is transmitted to the AFCF via an analog data link, the gain variation and the zero shift of the data link shall be compatible with the performance and accuracy requirements of the guidance loop.

3.2.4.3.6 VOR/TACAN Mode

When preconditions for radial capture are satisfied the AFCF shall cause the aircraft to maneuver to acquire a radial beam center. Maximum roll rate and attitude commands shall be limited to provide a smooth capture and subsequent tracking of the radial. The following performance requirements for VOR are stated in terms of crosstrack error (feet) and radial error (degrees) to provide for systems using either ARINC 547 or 579 VOR receivers. For ARINC 547 receivers only the radial error applies. Crosstrack error applied to the ARINC 579 receiver operating in the primary mode (co-located VOR/DME), and radial error applies in the reversionary mode (DME inoperative or not available).

3.2.4.3.6.1 VOR Capture and Tracking

Overshoot shall not exceed 1-1/3 degrees (20 microamperes) beyond the desired VOR radial beam center in a no-wind condition for captures 50 nautical miles or more from the station with intercept angles up to 45 degrees. Following capture at 50 nautical miles or more, the aircraft shall remain within 1-1/3 degrees, root-mean-square, from the VOR radial beam center. The root-mean-square tracking error shall be measured over a 5 minute period between 50 and 10 nautical miles from the station or averaged over the nominal aircraft flight time between the same distance limits, whichever time is shorter.

3.2.4.3.6.2 TACAN Capture and Tracking

Overshoot shall not exceed 0.5 degrees beyond the desired TACAN radial beam center in a no-wind condition for captures 100 nautical miles or more from the station with intercept angles up to 45 degrees. Following capture at 100 nautical miles or more the aircraft shall remain within 0.5 degrees, root-mean-square, from the TACAN radial beam center. The root-mean-square tracking error shall be measured over a 10 minute period between 100 and 10 nautical miles from the station or averaged over the nominal aircraft flight time between the same distance limits, whichever is shorter. The required 0.3 damping ratio shall be exhibited for continuous tracking between 100 and 10 nautical miles from the station.

3.2.4.3.6.3 VOR/TACAN Overstation

The VOR/TACAN mode shall include automatic means for maintaining the aircraft within ±1.0 degree of aircraft heading or ground track existing at the inbound edge of the VOR zone of confusion (ZOC) in a no-wind condition. During overflight of the ZOC, adjustment of the present course heading or its equivalent shall cause the roll AFCF to maneuver the aircraft to capture the appropriate out bound radial upon exiting from the ZOC. The VOR/TACAN capture maneuvering limits may be reinstated during overstation operation.

3.2.4.3.7 Automatic Approach System (ILS)

The approach mode of the AFCF, if installed, shall respond to localizer signals for lateral guidance and glide slope signals for vertical guidance. The system shall be designed to automatically steer the aircraft to a minimum decision height of 100 feet during ICAO Category II weather minimums. The system shall provide timely warning to permit the pilot to complete the landing if runway visual contact is established or to safely execute a go-around following any single failure or combination of failures not shown to be less probable than one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1. The system shall comply with the tracking requirements of 3.2.4.3.7.1 through 3.2.4.3.7.3, for probable combinations of headwind to 25 knots, tailwinds to 10 knots, and crosswinds to 15 knots, with the probability of occurrence of such winds and associated turbulence and wind shears as defined in 3.2.1.5.3 in a no-wind condition.

3.2.4.3.7.1 Localizer Mode

The AFCF shall maintain a constant heading until the aircraft is within ±2 degrees of the beam center, at which point the aircraft will be maneuvered to capture the localizer beam. Heading or roll rate and attitude commands shall be limited to provide a smooth capture and subsequent tracking of the localizer beam. The initial overshoot during capture shall not exceed 1 degree and the system shall exhibit a damping ratio of at least 0.1 with intercept angles of 45 degrees at 8 miles from runway threshold and increasing linearly to 60 degrees at 18 miles from runway threshold in a no-wind condition. For intercept angles less than 45 degrees, the FCS shall always maneuver the aircraft toward the course centerline. There shall be no movement away from the runway threshold during capture. The system shall be considered to be in the tracking mode whenever the following conditions are satisfied: Localizer beam error is 1.0 degree or less, localizer beam rate is 0.025 degrees per second or less. During beam tracking the system shall exhibit a damping ratio of 0.2 or greater. From the outer marker to an altitude of 300 feet above runway elevation on the approach path, the AFCF shall maintain the aircraft 2-sigma position within 0.47 degrees of the localizer beam center. On the approach path from 300 feet above runway elevation to the decision altitude of 100 feet, the AFCF shall maintain the aircraft 2-sigma position within 0.33 degrees. The performance during the tracking mode shall be free of sustained oscillations. These criteria shall be based on a Category II localizer ground installation.

3.2.4.3.7.2 Glideslope Mode

The pitch AFCF shall cause the aircraft to maneuver to acquire the glideslope beam. Neither the position of the aircraft above or below the glideslope nor vertical speed of the aircraft at time of mode selection shall be incorporated as a precondition for mode engagement. When preconditions are satisfied, the first overshoot shall not exceed 0.16 degrees of radial error from glideslope beam center when capturing in a no-wind condition from above or below the beam under normal approach configurations. The system shall exhibit a damping ratio of 0.20 or greater subsequent to the first overshoot and the transient errors encountered during the tracking mode shall not exceed 0.16 degrees of radial error from glideslope beam center. When using a Category II ILS ground facility, the pitch AFCF shall maintain the aircraft glideslope antenna 2-sigma position within 0.16 degrees of beam center or within 12 feet of beam center, whichever is greater, between the altitudes of 700 feet and 100 feet above the glideslope transmitter datum.

3.2.4.3.7.3 Go-Around Mode

The automatic Go-Around mode shall be manually engaged only. The AFCF shall be designed such that no single failure, or combination of failures which are not less probable than one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1, will cause the aircraft to maneuver to increase the rate of descent upon engaging the Go-Around mode. If the Go-Around mode is designed for concurrent operation with other automatic control systems, a single switch location or pilot action shall engage all systems into the appropriate mode for go-around. Should one or any combination of concurrently operating automatic control systems be inoperative at the time of AFCF Go-Around mode engagement, the AFCF shall comply with the performance requirements based on normal go-around procedures including manual management of thrust, flaps, and landing gear.

3.2.4.3.7.3.1 Pitch AFCF Go-Around

The pitch AFCF shall cause the aircraft to smoothly rotate sufficiently to establish a positive rate of climb such that the aircraft will not intersect the obstacle clearance planes defined in FAA Advisory Circular 120-29 more often than 1 in 10^6 events for the wind conditions defined in 3.2.4.3.7, and including high altitude, hot day conditions as defined by the procuring activity. In the event of inadvertent loss of an engine just prior to or during automatic go-around, the system shall not cause the aircraft to approach stall within 30 seconds of mode engagement, based on design approach speed. If operating procedures require the mode to be disengaged upon inadvertent loss of an engine, a timely warning shall be provided for the pilot to initiate the disengage procedure. Disengagement under this condition shall be accomplished manually.

3.2.4.3.7.3.2 Lateral-Heading AFCF Go-Around Performance Standards

The lateral-heading AFCF shall maintain the Aircraft 4 sigma position within the lateral-boundaries of the obstacle clearance planes defined in FAA Advisory Circular 120-29 during wind conditions as specified in 3.2.4.3.7. This capability shall be maintained in the event of the most critical engine failure just prior to or during automatic Go-Around. If normal procedure is to disengage the Go-Around mode after inadvertent loss of one engine, under the wind conditions cited, a pilot of normal skill shall be able to recover aircraft heading such that intersection with the obstacle clearance planes will occur no more than 1 in 10^6 events during recovery.

3.2.4.3.7.3.3 Minimum Go-Around Altitude

A minimum altitude for engaging automatic Go-Around shall be established such that the probability of incurring structural damage to the landing gear, wing tips, or control surface is more than one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1. The minimum altitude shall include normal performance under the wind conditions specified in 3.2.4.3.7 and the probability of inadvertent loss of an engine at any time within 12 seconds preceding mode engagement.

3.2.4.3.8 Automatic Carrier Landing System (ACLS)

The ACLS shall provide for automatic carrier landing and actuate aircraft controls utilizing commands generated externally as described in AR-40A to achieve a safe carrier landing using Link-4A data.

3.2.4.3.8.1 ACLS Longitudinal Performance

The performance of the system shall be in accordance with the requirements of AR-40A and the following except that Figure 10A of AR-40A shall be modified as shown in Figure 2. No automatic carrier landing system interlock with the APCS is required.

a. Touchdown dispersion. The one-sigma standard deviations of the lateral and longitudinal touchdown point are ±5 feet and ±24 feet, respectively.

b. Control Responses. The transfer function frequency response at the carrier landing radar tracking point shall meet the requirements of AR-40A, Figure 2. The bank attitude frequency response to bank command gain shall be 0.0 dB ± 2 dB to one radian per second and shall have no more than 50 degrees phase lag at one radian per second.

c. ACLS Vertical (H-DOT) Control. The vertical rate (H-DOT) commands from the data link shall be scaled ±30 feet per second full scale.

The primary aircraft sensor feedbacks shall be pitch rate, INS vertical rate, and INS vertical acceleration. The maximum average effective transport delays from INS vertical rate and vertical acceleration outputs until the commands reach the control surfaces shall be minimized and shall not exceed 205 milliseconds. The recommended maximum signal granularities are 0.12 feet per second for vertical rate and 0.20 feet per second per second for vertical acceleration.

The aircraft response to disturbances shall be as follows:

a. Small H-Dot command steps (±4 feet per second): Initial vertical rate overshoot less than or equal to 20 percent; Initial pitch attitude overshoot less than or equal to 175 percent.

b. Hardover H-Dot command steps (±30 feet per second): Peak Pitch rate less than or equal to 5 degrees per second; Satisfactory pilot takeover characteristics.

c. Simulation vertical step gust (5 feet per second). Vertical error less than or equal to 1.0 foot; Initial pitch attitude overshoot less than or equal to 40 percent.

Simulation longitudinal step gust (15 feet per second): Vertical error less than or equal to 1.5 feet.

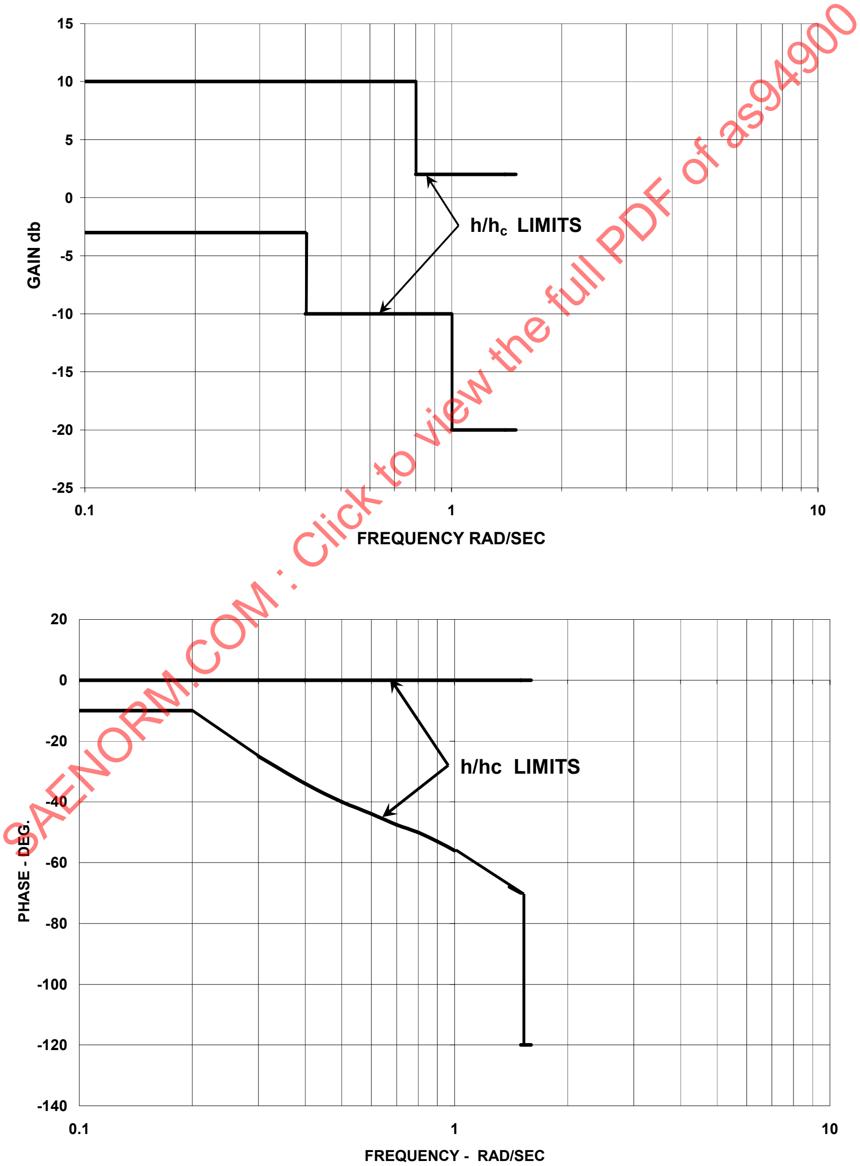

FIGURE 2 - H/H_C FREQUENCY RESPONSE REQUIREMENT

3.2.4.3.8.2 ACLS Lateral (Bank) Control

The bank commands from the data link shall be scaled ±30 degrees full scale.

The aircraft response to bank commands shall be as follows:

a. Small bank command steps (less than or equal to ±10 degrees): bank attitude overshoot less than or equal to 10 percent.

b. Hardover bank command steps (±30 degrees): Maximum roll rate less than or equal to 15 degrees per second.

3.2.4.3.8.3 ACLS Noise Compatibility

Noise which is superimposed on the proper input signal shall not saturate any component of the FCS and shall not cause objectionable motion of the control stick. The performance requirements specified herein shall be met under presence of this noise. The noise content in the input signal to the longitudinal and lateral axes shall be represented by white Gaussian noise which has the following power spectrum density and is passed through a filter with a transfer function $G(j\omega)$.

3.2.4.3.8.3.1 Vertical Rate Command Noise Input

The white noise for the vertical rate command input shall have a magnitude of 1.0 feet per second per second per radian per second at low frequency and remain flat in the frequency range from 0 to at least 30 radians per second. The white noise input shall be passed through the following filter.

$$G(j\omega) = [\ (\ (0.044R/1000)\ /\ (j\omega/50) + 1)\ ]\ x\ (Hc/Ze) \qquad \text{(Eq. 2)}$$

where:

Hc/Ze = Vertical rate command transfer function

R = Radar range in feet

3.2.4.3.8.3.2 Bank Command Noise Input

The white noise for the bank command input shall have a magnitude of 1.0 degree squared per radian per second at low frequency and remain flat in the frequency range from 0 to at least 30 radians per second. The white noise input shall be passed through the following filter.

$$G(j\omega) = [\ (\ (0.044R/1000)\ /\ (j\omega\ /50) + 1)\ ]\ x\ (\phi c/Ye) \qquad \text{(Eq. 3)}$$

where:

$\phi c/Ye$ = Bank command transfer function

The vertical rate command (same as pitch command) and bank command transfer functions are given in AR-40A.

3.2.4.3.9 Automatic Landing System (ALS)

The following automatic land system requirements pertain to the latter stages of the approach; i.e., that portion of the approach below the decision height or the alert height. The ALS shall be designed to be compatible with operations in Category III weather minimums and comply with the following landing accuracies and operational requirements:

a. Longitudinal dispersion of the main landing gear touchdown point shall not exceed 1,500 feet with a 2-sigma probability, with a mean touchdown point beyond the glideslope intersection with the runway. The 1,500 feet dispersion need not be symmetrically located about the nominal touchdown point. The aircraft sink rate at touchdown shall not exceed the structural limit of the landing gear except when the probability of occurrence is shown to be one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1.

b. The lateral dispersion of the aircraft centerline at the main landing gear at touchdown shall not exceed 27 feet on either side of the runway centerline line with a 2-sigma probability. The roll out guidance system shall cause the aircraft to track parallel to or convergent with the centerline of the runway.

c. The systems shall meet these requirements considering reasonable combinations of head winds, as defined in 3.2.4.3.7 according to the probability of encountering these winds and their associated turbulence, as specified in 3.2.1.5.3, along with expected variations in ground facility performance as specified in 3.2.4.3.9.2.

d. Means should be provided to inform the pilot continuously of the mode of operation of the ALS. Indication of system malfunction should be conspicuous and unmistakable. Positive indication should be provided that the flare has been initiated at the minimum normal flare engage heights.

e. The ALS design shall meet the criteria for approval of Category III landing weather minimums in the Aircraft Detail Specification.

f. ALS malfunction shall not cause significant displacement of the aircraft from its approach path, including altitude loss, or cause any action of the FCS that is not readily apparent to the pilot, either by control movement or advisory display. Upon system disconnection, the automatic landing system shall not cause any out-of-trim condition not easily controlled by the pilot.

3.2.4.3.9.1 ALS Performance Standards - Variations of Aircraft and Airborne Equipment Configurations

Automatic landing performance requirements shall be met while including the effects on performance of the following aircraft and airborne equipment variations expected to occur in normal service:

a. Landing weight and center of gravity variations.

b. Landing flap-setting variations.

c. Aircraft approach speed variations.

d. Glide slope and localizer airborne receiver centering errors.

e. FCF automatic landing system sensor, computer and servoactuator tolerances.

f. Performance tolerances of automatic control systems operating concurrently with the AFCF automatic landing system; e.g., stability augmentation systems, load alleviation systems.

3.2.4.3.9.2 ALS Performance Standards-Ground Based Equipment Variations

Proof of compliance with performance requirements for automatic systems shall include the effects of expected variation in type and quality of the ground based equipment.

3.2.4.3.10 Automatic Terrain Following

Performance requirements shall be as specified by the procuring activity.

3.2.4.3.11 Automatic Terrain Avoidance

Performance requirements shall be as specified by the procuring activity.

3.2.4.4 Special AFCF Performance Requirements for Fixed Wing V/STOL

The following requirements are unique for Fixed Wing V/STOL aircraft.

3.2.4.4.1 Attitude Hold

Precise changes to pitch or roll attitude may be made manually by the pilot's control stick motions or through trim controls, without requiring AFCF disengagement.

3.2.4.4.2 Heading Hold

Heading Hold during unaccelerated level flight shall be maintained within ±1.0 degree of the desired heading, for airspeeds below 50 KCAS, and within ±0.5 degree above 50 KCAS. Transient excursions shall be limited to ±5 degree with one overshoot which shall not exceed 20 percent of the initial deviation. Unless otherwise dictated by the procuring activity, Heading Hold shall be provided in the yaw axis for airspeeds below 50 KCAS and in the roll axis for airspeeds above 50 KCAS. Pilot repositioning of the aircraft to a new heading may be accomplished by directional control inputs at airspeeds below 50 KCAS through use of the coordinated turn capability for airspeeds above 50 KCAS or by a Heading Select control at all airspeeds. The aircraft must be within ±3 degree of wings level for heading hold to engage. The AFCF shall not induce transients when switching from heading hold to turning mode.

3.2.4.4.3 Airspeed Hold

The Airspeed Hold function (required only above 50 KCAS) shall hold any desired airspeed to within 3 knots under steady state conditions. Transient airspeed excursions shall be limited to less than 5 knots. After transient response, the aircraft shall return to the reference airspeed with one overshoot that shall not exceed the initial deviation by more than 20 percent.

3.2.4.4.4 Radar and Barometric Altitude Hold

Barometric Altitude or Radar Altitude at engagement shall be used as the reference altitude. Barometric Altitude Hold accuracy shall be within 10 feet for steady state and within 30 feet for transients. Radar Altitude Hold accuracy shall be 4 feet. Aircraft climb/descent responses to abrupt radar altitude changes (flying over a building, etc.) shall be limited to 200 feet per minute. When, radar altimeter failure occurs, the Barometric Altitude Hold function shall automatically engage at the existing altitude and a warning light provided to indicate AFCF is using Barometric inputs for Altitude Hold.

3.2.4.4.5 Coordinated Turn Capability

Unless otherwise dictated by the procuring activity, an automatic, coordinated turn capability shall be provided at airspeeds above 50 KCAS.

3.2.4.4.6 Automatic Approach Capability

An automatic approach to a pilot selected ground speed and radar altitude shall be provided. During the transition from forward flight to hover, the aircraft shall not enter rearward flight (negative ground speed).

3.2.4.4.7 Hover Hold and Hover Trim Control

The hover stability mode shall engage at airspeeds less than 50 KCAS, or as defined by the procuring activity, either by pilot command or automatically at the end of an automatic approach. The hover stability mode shall provide ground speed hold within ±2 knots and shall maintain pitch and roll attitudes within ±0.5 degree and heading within ±1degree. A gust alleviation feature shall be provided to damp longitudinal and lateral excursion. The altitude hold must automatically engage when the altitude is less than or equal to the pilot's preselected altitude. If the aircraft is at an altitude other than that commanded upon hover mode engagement, the AFCF shall provide control inputs necessary for convergence upon the commanded altitude at a safe rate. The radar altitude hold shall then engage.

3.2.4.4.7.1 Special Requirements for V/STOL Aircraft with Rescue Hoist Stations

A hover trim control, located at the rescue hoist station, shall provide a crewman with limited authority (up to ±10 knots) longitudinal and lateral control to position the aircraft during hoist/rescue operations. Control from the rescue hoist station shall be available only in the automatic hover mode.

3.2.4.4.8 Automatic Departure

During transition from hover to forward flight, the aircraft shall not enter into rearward flight or decrease airspeed or altitude, and heading shall be maintained within the tolerances of 3.2.4.4.2.

3.2.4.4.9 Automatic Hovering

Position should be maintained relative to the point of reference to an accuracy of ±4 to ±10 feet, as defined by the procuring activity for the mission requirements of the aircraft. Unless otherwise dictated by the procuring activity, this accuracy requirement applies during gust intensities of 5 feet per second, and wind, or point of reference, velocities up to 45 knots.

3.2.4.5 Special AFCF Performance Requirements for Rotorcraft

The following requirements are unique for rotorcraft.

3.2.4.5.1 Disengagement

Positive, redundant AFCF disengagement capability shall be provided to both the pilot and co-pilot.

3.2.4.5.2 Attitude Hold (Pitch, Rolls and Yaw)

During the Attitude Hold mode, the attitude, in calm air, shall be maintained within ±1 degree of the reference attitude, under conditions of fixed collective pitch control only. Allowable magnitudes and settling times of perturbations induced by variations in collective pitch control shall be as specified by the procuring activity. The dynamic requirements of 3.2.4.2.1 shall be met.

3.2.4.5.3 Heading Hold and Heading Select

The AFCF shall maintain heading within 1 degree of commanded heading in forward flight at speeds above 40 knots indicated. The aircraft shall not overshoot the selected reading by more than 2.5 degree at speeds above 60 knots. The roll rate shall not exceed 5.0 degrees per second and roll acceleration shall not exceed 3.0 degrees per second per second for ADS-33E-PRF Class I and IV aircraft. The Heading Hold accuracies apply under conditions of fixed collective pitch control only. Allowable magnitudes and settling times of perturbations induced by variations in collective pitch control shall be determined by the prime contractor and documented in the FCS Specification, 4.6.2.

3.2.4.5.4 Altitude Hold

3.2.4.5.4.1 Barometric Altitude Stabilization

The requirements of 3.2.4.2.4 shall be met when the rotorcraft is outside the ground effect as defined for the specified rotorcraft.

3.2.4.5.4.2 Stabilization of Altitude Above the Terrain

The operational range of the absolute altitude control mode shall be as specified in the applicable system specification. The system shall maintain altitude, in calm air, within ±7 feet of the altitude indicated by the altitude sensor.

3.2.4.5.5 Hover Hold

For MIL-F-83300 Class II and rotorcraft, position shall be maintained with a drift of less than 20 feet plus sensor error over a 2 minute period. Altitude shall be maintained in ground effect within 5 feet over a 5-minute period. Where special mission requirements dictate, the prime contractor shall establish further requirements, subject to procuring activity approval.

3.2.4.5.6 Vernier Control for Hovering

Vernier control shall be provided for accurate positioning of the aircraft during hovering, unless control commensurate with minimum accuracy requirements can be obtained with the regular controls.

3.2.4.5.7 Ground Speed Hold

Where Ground Speed Hold is a system requirement, provisions shall be made to insert ground speed signals to the pitch and roll controls. After engagement of the Ground Speed Hold mode, the ground speed existing at the time of engagement shall be held in steady flight in calm air within ±3 knots.

3.3 System Testability Requirements

3.3.1 System Test and Monitoring Provisions

Test and monitoring means shall be incorporated into the Essential and Flight Phase Essential FCS as required to meet the following requirements of this specification:

a. Mission Accomplishment Reliability (see 3.1.2.1)

b. Flight Safety and Failure Immunity (see 3.1.1.3 to 3.1.1.4.1)

c. Fault Isolation (see 3.1.3.2 to 3.1.3.3, 3.1.5 to 3.1.5.1)

d. Invulnerability (see 3.1.5.3 to 3.1.5.3.10)

The effect of detected and undetected FCS failures taken with the probability of occurrence of such failures shall comply with the system reliability and safety requirements. This requirement shall address all failures, including mechanical, electrical, hydraulic components and power sources.

3.3.2 Built-In-Test (BIT) Equipment

The total maintenance and testing, including BIT, and in-flight monitoring where used, shall provide an integrated means of fault isolation to the LRU/WRA level with a confidence factor of 90 percent or greater. BIT functions shall have multiple provisions to ensure they cannot be engaged in flight. The test equipment shall not have the capability of imposing signals which exceed operating limits on any part of the system or which reduce the systems' endurance capability or fatigue life. Ground test signals shall not be of sufficient magnitude to drive actuators into hard-stop limits.

3.3.3 Maintenance BIT

Where required, BIT shall also be provided as a postflight maintenance aid for the FCS. BIT shall be designed to avoid duplicating test features included as part of the preflight test or monitoring functions. Maintenance BIT shall operate in various aircraft ground configurations such as with wings folded, swept back, etc., with hydraulic pressure on and off, with the flaps up and down, and shall give meaningful test results. The BIT operation shall not stroke those actuators where the control surfaces do not have proper clearances. The BIT operation shall not exceed a time limit defined in the Aircraft Detail Specification.

3.3.4 Preflight or Pre-engage BIT for Fly-By-Wire (FBW) Systems

Preflight or pre-engage BIT may be automatic or pilot-initiated, and includes any test sequence normally conducted prior to takeoff or prior to engagement of a control to provide assurance of subsequent system safety and operability. It should be demonstrated that redundant electronic channels and hydro-mechanical components are operating normally without any safety-critical latent failures prior to takeoff. This includes all backup or normally disengaged channels, and the ability of normally engaged channels to isolate or disengage elements upon detected failures. The preflight tests shall not rely on special ground test equipment for their successful completion. Any test sequence which could disturb the normal activity of the aircraft in a given mode shall be inhibited when that mode is engaged. Preflight BIT that requires moving control surfaces shall be initiated only by the pilot or maintenance personnel, to avoid the personnel danger inherent in automatic initiation. The preflight BIT shall take less than 90 seconds to complete. Operation of Preflight BIT shall be prevented in flight by methods determined by the prime contractor and documented in the FCS Specification, 4.6.2.

3.3.5 Preflight BIT Status Annunciation

This display shall perform the following functions:

a. Indicate the progress of the preflight test.

b. Instruct the crew to provide required manual input.

c. Indicate lack of system readiness when failure conditions are detected.

3.3.6 Portable Test Equipment

Where the use of BIT equipment would cause excessive penalties and where the use of portable test equipment is compatible with the maintenance support concept, provisions shall be made to permit the use of generally available and commonly used portable test equipment. Components which require peculiar, special, or new items of test equipment shall be avoided unless dictated by aircraft design, mission requirements, or state-of-the-art improvements.

3.3.7 Use of Cockpit Instrumentation

Where acceptable procedures result or are provided, cockpit instrumentation may be used for malfunction detection and fault isolation when it provides readily understandable condition indication either alone or in coordination with built-in test equipment, or with portable test equipment. When available, existing cockpit electronic multifunction displays shall be used to present FCS BIT status and to provide the means for interacting with the FCS for more extensive maintenance diagnostics.

3.3.8 Ground Power Requirements for System Test

Electric and electronic components shall be designed to operate with the electric power generators supplied by standard ground carts. Hydraulic components shall be designed to operate with the standard hydraulic ground carts.

3.3.9 Protection Against Dormant Failures

The use of critical components that can not be readily tested as installed, and therefore could be subject to dormant failure leading to a catastrophic event following a second failure, shall be minimized. Those that remain shall be subject to analysis of failure probability, and the required off-aircraft testing-interval exposure time, to ensure that the safety requirement of 3.1.1.3 is met.

3.4 System Design Requirements

3.4.1 System General Design Requirements

3.4.2 Mechanical FCS Design

In the design of mechanical components, the reliability, strength and simplicity of the system shall be paramount considerations. The signal transmission between the pilot's controls and the control surfaces shall be redundant to the extent required to meet reliability, failure immunity, invulnerability and other requirements of this specification.

3.4.2.1 Structural Integrity

3.4.2.1.1 Single-Point-Failure Points

All flight-critical, single-load-path mechanical components shall be identified as Single-Point-Failure Points and designated Fracture Critical Traceable. They shall be serialized and their manufacturing traceability back to the raw material lot shall be ensured.

3.4.2.1.2 Strength

The overall FCS shall be designed to meet the applicable load, strength, and deformation requirements of MIL-A-8860, MIL-A-8861, MIL-A-8865 and MIL-STD-1530. The components of the systems shall be designed in accordance with the strength requirements of MIL-A-8860, AMS-STD-2175, AMS-F-7190, and AMS-A-22771 as applicable.MIL-HDBK-17 provide guidance on the strength and selection of metallic materials and composites respectively.

3.4.2.1.3 Load Capability

Elements of mechanical signal transmission systems subjected to loads generated by the pilot(s) shall be capable of withstanding the loads due to pilot's input limits specified in MIL-A-8865, Section 3.7, FCS Loads, taken as limit loads, unless higher loads can be imposed such as by a powered actuation system or loads resulting from aerodynamic forces. Where higher loads are thusly imposed, they shall be met with the same margins and circumstances as specified in MIL-A-8865.

3.4.2.1.4 Damage Tolerance

Those structural elements of the FCS that are essential to safety of flight (to control Essential and Flight Phase Essential functions) shall meet the damage tolerance requirements of JSSG-2006.

3.4.2.1.5 Load Capability of Dual-Load-Path Elements

The load path remaining after a single failure in dual-load-path elements shall meet the following requirements.

a. Where the failure is not evident by visual inspection or by obvious changes in control characteristics, the remaining path shall be capable of sustaining a fatigue spectrum loading based on one overhaul period. The time interval corresponding to an overhaul period shall be established by the prime contractor. The remaining path shall also withstand, as ultimate load, loading equal to 1.5 times the limit loads specified in MIL-A-8865, or 1.5 times the load from an alternate source, such as a powered actuation system or loads resulting from aerodynamic or other forces, if such load is greater.

b. Where the single failure is obvious, the remaining load path shall be capable of withstanding, as ultimate load, loading equal to 1.15 times limit loads specified in MIL-A-8865, or 1.15 times the load from an alternate source, such as a powered actuation system or loads resulting from aerodynamic or other forces, if such load is greater.

3.4.2.1.6 Stiffness

The stiffness of the FCS shall be sufficient to provide satisfactory operation and to enable the aircraft to meet the stability, control, and flutter requirements. Normal structural deflections shall not cause undesirable control system inputs or outputs. The applicable design requirements specified in MIL-A-8870 shall be met.

3.4.2.1.7 Durability

Durability of the FCS shall be equal to that of the airframe primary structure considering the total number of ground and flight load cycles expected during the specified design service life and design usage of the aircraft from all commands, e.g., from the PFCS, AFCF, servo feedback and from load inputs. Vibrations and sonic fatigue requirements shall also be considered in the design of the FCS.

3.4.2.1.8 Wear Life

Mechanical elements of the FCS shall be designed to have wear life equal to the wear life specified for the overall aircraft. Parts subject to wear, such as hydraulic seals, bearings, control cables, sensors and hydraulic actuator barrels, may be replaced or their wearing surfaces renewed after they exceed their useful life. The design, analysis and verification of those parts intended to have their wearing surfaces renewed shall take into account any reduction of fatigue life caused by the renewal process. However, all replacements shall be within the FCS wear out-replacement budget established for the overall weapon system. Electronic and other non-mechanical LRUs/WRAs shall remain economically repairable and shall meet reliability requirements throughout the specified airframe lifetime.

3.4.3 Fixed Wing V/STOL Aircraft Requirements

3.4.3.1 Conversion Mechanisms

Conversion mechanisms, if required, shall be powered in such a way that conversion can be accomplished at any time, regardless of any system failure.

3.4.3.2 Transition

The transition from one set of controls to another set shall be smooth and shall not cause undesirable transients.

3.4.3.3 Interface of Powerplant and FCS

Any powerplant controls that are used for direct flight path control or to provide aircraft damping shall be considered as an integral part of the PFCS, and shall be designed to conform to the philosophical and hardware requirements for that system.

3.4.4 Rotorcraft Requirements

3.4.4.1 Jamming of Swashplate Power Actuators

The swashplate power actuators in aircraft subject to combat damage shall be jam proof. The threat shall be specified by the procuring activity.

3.4.4.2 Actuation Stiffness

The stiffness of the swashplate support, in conjunction with rotor blade torsional stiffness shall be adequate to minimize control loads and shaking forces generated by the rotor.

3.4.4.3 Frequency Response

The swashplate power actuator frequency response shall be adequate to meet the ADS-33E-PRF and other applicable rotorcraft flying qualities requirements when operated in series with the direct linkage and rotating controls.

3.4.4.4 Blade Flapping

Suitable provisions shall be made to control the blade flapping when starting or stopping the rotor It shall be possible to start and stop the rotor in wind velocities up to 45 knots, from the most critical direction, without physical contact of the rotor blades with any part of the airframe, excluding the rotor stops, and without causing damage to the rotor system.

3.4.4.5 Fatigue Life Design

Components shall be designed to minimum safe-life of 3,600 hours except for seals. Seals shall be designed for a minimum life of 1,200 hours. Fatigue lives shall be substantiated by component bench testing and flight strain survey. Fatigue lives shall be determined using actual bench test strengths and measured flight loads.

3.4.4.6 Engine-Out Requirement

One Engine Out (OEI) and All Engine Out (AEI) requirements for rotorcraft shall be in accordance with the applicable sections of ADS-33E-PRF.

3.4.5 Electrical FCS Design

3.4.5.1 Electrical Signal Transmission

The following requirements apply to all Essential and Flight Phase Essential signal paths. Except for power sources, such systems shall be independent of failure modes associated with any other electrical system. Cross connections between redundant electrical signal paths shall be eliminated, or minimized and electrically isolated. Wire runs and components in redundant control paths shall be physically separated and electrical shielding shall be installed, as necessary, to meet failure immunity and invulnerability requirements. All interconnecting wiring shall be prefabricated, jacketed cable assemblies. The outer jackets shall be identifiable by a unique color or other means. Wiring installation shall be in accordance with AS50881.

3.4.5.2 Isolation and Protection of Redundant Electrical Circuits

FCS wiring in individual channels shall be routed, isolated and protected to minimize the applicable threats to redundancy. Channel loss due to any foreseeable hazard, the probability of which is not less than one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1, shall be limited to a maximum of a single channel. The adequacy of the separation, isolation and protection attainable in any given location for any given hazard shall be evaluated for each aircraft design.

a. Redundant channels for the same control axis and electronic comparison model signals shall not utilize the same connectors or adjacent pins within connectors, cables or cable runways, or circuit cards unless the design can be shown by demonstration or analysis to meet the appropriate isolation/separation requirements. If space constraints require redundant signals to run through the same connector, the connector shall have a cable continuity signal (short pin) and be safety wired.

b. Cross connections between redundant electrical signal channels shall be minimized, and failure detection/isolation provisions shall be mechanized in such a way that no single electrical failure can disable more than one channel. Isolation shall prevent any failure in one signal channel from initiating a failure or a cascade of failures in any other signal channels.

c. Each redundant electrical signal channel shall be associated with an electrical power source that is not connected to any other signal channel. The loss of a single electrical power source shall not result in the loss of more than one signal channel in a redundant system.

d. The wiring of the redundant electrical channels for a given control effectors shall be separated to the maximum extent possible. If adequate separation is not possible, physical and thermal barriers shall be provided between the channels.

e. FCS wiring shall be separated from the wiring of other systems to the maximum extent possible so that a failure in other systems cannot introduce failures in the FCS.

f. Wiring shall be supported to minimize chafing, stress, vibration, and shock.

g. Wiring in areas subject to maintenance action and possible abuse by maintenance personnel shall be protected to the maximum extent possible with over-braiding or conduits.

Additional protection shall be provided for the wiring where analysis shows that any single hazardous event, the probability of which is not less than one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1, could cause the loss of more than one FCS channel. Primary structural components shall be used to afford this protection where possible. Where it is necessary to route the wiring through wheel wells or other areas subjected, during flight, to the slipstream or impingement of runway fluids, gravel, etc., the wiring shall be protected by enclosures and routed directly through without unnecessary termination or junctions. Where terminations or junctions to equipment in these areas are required, they shall be protected from such impingements. This shall also be done in areas where a high level of maintenance is likely to be required on other systems and equipment.

3.4.5.3 Cable Assembly Design and Construction

During design of the cable assemblies, particular attention shall be paid to the requirements of the circuits within the cable

a. The outer jacketing for FCS wiring shall not create stresses on the wire and connector terminations and shall not stress the wires in a manner which opens the connector grommet seals.

b. Cable construction near LRU/WRA terminals shall be ruggedized to prevent damage due to repeated replacement of the LRU/WRA.

c. Cable construction near LRU/WRA terminals shall provide provisions for repairs of damaged connectors/pins over the life of the aircraft.

d. Wire gages shall be selected based on peak current and wire length. For FBW signal applications within aircraft wiring harnesses interconnecting LRU/WRAs wires smaller than 24 gauge shall not be used without approval of the procuring activity.

e. Adequate EMI and EMP control methods, e.g. shielding, twisting, etc., shall be incorporated into the design.

f. Where shielded wires are used, provisions shall be made for carrying the shields through the connectors where single point grounding is necessary.

g. A signal return wire shall be provided for each signal level circuit in the cables.

h. Terminal boards shall not be used in FCS wiring. Splices shall be qualified, permanent-type splices.

i. For wire harnesses which are considered part of an LRU/WRA, including actuators, the design shall not allow potting material to escape into the wire crimp areas during fabrication.

3.4.5.3.1 Cable Assembly Construction

All cable assemblies shall be constructed in an area with temperature and humidity controls and positive pressure ventilation and shall be cleaned (all wire cuttings, etc., removed) and inspected after layup and prior to jacketing to assure that no potentially damaging particles have been included, particularly at the entrance to the grommet seal. All cable assemblies shall be constructed, tested and inspected by specially trained and certified personnel.

3.4.5.4 Wire Terminations

Crimp type wire terminations (spade, lug, or connector) shall be used on all FCS cables. Soldered and potted connections shall not be used. With the terminal installed on the wire, the wire shall be visible for inspection at both ends of the crimp barrel. The length of wire visible between the insulation and barrel shall not exceed 1/16 inch.

3.4.5.5 Inspection and Replacement of FCS Electrical Wiring

The FCS electrical wiring (or conduit containing the wiring) shall be installed so as to satisfy the requirements of 3.1.3.2 and so that it can be inspected for damage and replaced as necessary. The installation shall provide for visual inspection in critical areas such as hazardous environment areas or areas where a high level of maintenance is required on systems or equipment in close proximity.

3.4.5.6 Water Intrusion

LRUs/WRAs of the FCS that are installed in the aircraft with electrical connectors located on the top or on the side, shall be designed so that moisture traveling along the cables shall have no deleterious effect. Electrical connectors pertaining to the FCS shall not be installed in a position to trap moisture. For all designs, discrete inputs that utilize open/ground logic shall be designed to prevent false triggering due to moisture intrusion into connectors or external wiring.

3.4.5.7 Electrical Power

The electrical power sources of the FCS shall be designed consistent with the FCS reliability, operation, and safety requirements. Each redundant electrical signal channel shall be associated with an electrical power source that is not connected to any other signal channel. The loss of a single electrical power source shall not result in the loss of more than one signal channel in a redundant system.

3.4.5.7.1 Transient Power Effects

Flight control computers or Vehicle Management computers, or embedded subsystem computers such as microprocessors or DSPs, shall not suffer adverse effects due to power source variations within the limits specified for the applicable power system. The performance during these variations shall meet the requirements of 3.1.1.5. In the event of power source interruption, no adverse effects shall result which limit operation or performance of flight control computers upon resumption of normal quality power.

3.4.6 Computational Methods and Software

The requirements for the computational systems shall be consistent with the FCS electronics architecture: primarily analog, hybrid analog/digital, or primarily digital. The FCS architecture shall be determined by the prime contractor and documented in the FCS Development Plan, 4.6.1. The computational systems shall provide the following capability:

a. Redundancy and fault tolerance provisions shall include failure detection and accommodation features consistent with 3.1.3 and the performance and safety requirements established for the FCS.

b. Separation of functional elements shall preclude the propagation of failures across boundaries of redundancy or propagation of failures across functional boundaries.

c. The scaling of signals and calculations shall provide satisfactory resolution and sensitivity under all possible combinations of demands and disturbances imposed on the system.

d. Sufficient dynamic response capability shall be provided throughout all aspects of the analog and digital elements to satisfy the overall control system bandwidth requirements.

e. Invulnerability to external influences defined in 3.1.5.3.

3.4.6.1 Analog Computation

The requirements for analog systems and circuits are dependent on FCS architecture. The specific FCS architecture shall be determined by the prime contractor and documented in the FCS Development Plan, 4.6.1. The analog computational systems shall provide the following capability:

a. Redundant electrical signal paths within a computer shall be isolated as required by failure immunity, safety, and invulnerability requirements specified in 3.1.1.4.

b. The circuits and signal path designs shall be consistent with the electromagnetic interference requirements of 3.1.6, and the system testability requirements of 3.3.1.

c. For failures which may cause a hazardous deviation in the aircraft path, the computer shall have provisions for rapidly disabling its command outputs or servos unless other fail-safe provisions exist.

d. Analog signals shall be scaled to provide satisfactory resolution and sensitivity to ensure continuous safe operation for all possible combinations of maneuvering demand and gust or other plausible disturbances, and to prevent unacceptable levels of nonlinear characteristics or instabilities.

e. Anti-Aliasing filters shall be incorporated to the extent required to meet the FCS performance requirements.

f. The analog computation growth capability shall be consistent with the FCS architecture. The growth capability of analog circuits, programmable logic devices, input/output circuits and connectors/pins, and spare card slots shall be determined by the prime contractor and documented in the FCS Development Plan, 4.6.1.

3.4.6.2 Digital Computation

Redundant signal computation shall be implemented as required by the flight safety and failure immunity and invulnerability requirements specified herein and to meet the closed loop flying qualities requirements. At the time of full rate production aircraft acceptance by the procuring activity, the total computation time and workspace storage used in the FCS shall not exceed the following for worst-case conditions:

a. For central flight control or aircraft management computers the real-time-critical computation time shall not exceed 60 percent of the total computation time allocated for flight control use.

b. For embedded subsystem microprocessors or digital signal processors that specialize in hardware-intensive applications which have low functional volatility over their product life, the real-time-critical computation time shall not exceed 80 percent of the processor's total computation time.

c. For designs which use multiple processors, the estimate of available remaining throughput shall account for inter-processor timing and not take credit for processor idle time waiting for required co-processor task completion.

d. For central flight control or aircraft management computers the program and workspace storage shall be sized such that at least 40 percent of the total storage for each type is available for growth.

e. For subsystem computers that specialize in hardware-intensive applications the program and workspace storage shall be sized such that at least 25 percent of the total storage for each type is available for growth.

f. Computation and sample rate shall be established at a level which ensures that the digital computation process will not introduce unacceptable phase shift, round off error, nonlinear characteristics, and frequency fold over or aliasing into the system response.

3.4.6.3 Computational Input/Output Growth Capability

In the implementation of an analog or digital computer for electrical signal computation, the input/out put growth capability shall be consistent with the growth capability of the computer and the computer connector reserve capacity.

3.4.6.4 Software Development and Support

For programmable computers, system software shall be developed and controlled in accordance with a Software Development Plan, 4.6.1 (h), with IEEE/EIA 12207.0, IEEE/EIA 12207.1, IEEE/EIA 12207.2. A Software System Safety Plan shall be prepared by the prime contractor, in accordance with MIL-STD-882.

3.4.6.5 Program Scaling

Parameter scaling, word size, input limiting, and overflow protection shall ensure correct processing and continuous safe operation for all possible combinations of maneuvering demand and gust or other plausible disturbance within the Service Flight Envelope of the system. Any condition capable of producing an overflow in an Essential or Flight Phase Essential function shall be precluded by hardware overflow detection and software or firmware that provides for data recovery and continuous safe operation following an overflow. Scaling shall provide satisfactory resolution to prevent the granularity due to digitizing processes from introducing, into the system response, unacceptable levels of nonlinear characteristics or instabilities.

3.4.6.6 Memory Protection

Memory protection features shall be provided to avoid inadvertent alteration of memory contents. Memory protection shall be such that neither EMI as specified in 3.1.6 nor electrical power source transients shall cause loss of program memory, memory scramble, erroneous commands, or loss of ability for continued operation. The electrical power source transients shall be as specified in MIL-STD-704 for Category C utilization equipment. For applications where system failures could be hazardous to safety of flight, the levels for normal, abnormal, and emergency electric system operation shall apply. For applications which are not critical to safety of flight, the levels for normal operation shall apply. These transient requirements shall apply to cases when all or only one of the redundant power sources is operating. For systems which load and run program instructions from volatile memory after startup, the design shall incorporate features to automatically recover from single event upsets.

3.4.6.7 Software Maintenance and Verifiability

Any modification to system software shall be evaluated prior to implementation on an aircraft in accordance with the appropriate procedures of analysis, inspection, and test defined in the quality assurance section of this specification. To aid in software maintenance, safety, and reliability, each Programmable Read Only Memory (PROM) shall reserve one word (or more) to serve in identification of the software version and Operational Flight Program (OFP) portion contained within the PROM.

3.4.6.8 Multiplexing

The multiplexing signal transmission circuits shall be of a digital time-division-multiplexing type utilizing a twisted shielded pair cable, or fiber optic cable as the transmission media for the multiplex bus, as specified in MIL-STD-1553, MIL-STD-1773, IEEE 1394, or ARINC standards.

3.5 Subsystem Design Requirements

3.5.1 Subsystem General Design Requirements

3.5.1.1 Power Subsystem Capacity

Sufficient electrical, hydraulic, and pneumatic power capacity shall be provided to meet the requirements of 3.1.5.2.

3.5.1.2 Power Subsystem Redundancy

Multiple electrical and hydraulic power systems shall be provided as necessary to meet the safety requirements of 3.1.1, the mission accomplishment reliability requirements of 3.1.2.1 and the survivability requirements of 3.1.5.

3.5.1.3 Priority

Essential and Flight Phase Essential flight controls shall be given priority over noncritical controls and other actuated functions to the degree specified in 3.1.1.6.

3.5.2 Electrical Power Subsystems

All electrical power generation and distribution subsystems used for flight control shall provide electrical power in accordance with MIL-STD-704. The FCS shall operate in accordance with this specification when supplied with power in accordance with MIL-STD-704. The prime contractor shall specify the applicable revision of MIL-STD-704 for each electrical power requirement.

3.5.2.1 Power Availability Protection

Electric systems which provide power to Essential or Flight Phase Essential controls shall, in conjunction with the FCS itself, ensure uninterruptible power to the FCS, of adequate quality to meet FCS requirements, after any malfunction not considered to be less probable than one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1. Uninterruptible power is defined as power that at no time exhibits voltage or current disruptions of a magnitude or duration that would cause upset to, or disruption of, Essential or Flight Phase Essential flight control functions. Redundant sources employed to achieve uninterruptibility shall be isolated and therefore, except for their basic power sources, shall be independent of failure modes associated with any other electrical system. At least one primary source of electrical power shall be a FCS direct source with no other equipment/functions tied to it. An alternate source of power shall be provided for all Essential or Flight Phase Essential control signal transmission paths, sufficient to continuously maintain at least FCS Operational State III performance, in the event of loss of all electrical power supplied from engine-driven generators. For highly augmented aircraft the transfer to this alternate source shall be uninterruptible. The minimum flight time and maneuvering requirements while operating on the alternate source of power shall be defined by the prime contractor and approved by the procuring agency.

3.5.2.1.1 Power Supply Interlocks

Control systems employing both ac and dc power inputs shall incorporate interlocks to disconnect both power inputs should either type of power be lost. Alternatively, the control system may be designed to accommodate a single loss of ac or dc power, either by maintaining FCS Operational State III or better with either power source or by ensuring that loss of either safely disables the control channel.

3.5.2.2 Overload Protection

Overload protection of the primary power wiring to the system or component shall be provided by the aircraft prime contractor. Installation requirements of system or component specification shall specify the value of starting current versus time, surge currents if applicable, normal operating current, regenerative effects and recommended protective provisions. Additional protection as necessary shall be provided within the system or component. Such circuit protection shall be provided in signal circuits or other circuits to ensure that overload conditions from secondary units receiving power from the FCS shall not result in unsafe motion of the aircraft.

3.5.2.3 Phase Separation and Polarity Reversal Protection

In systems affecting flight safety, practical methods to prevent phase reversal and polarity reversal shall be implemented.

3.5.3 Hydraulic Power Subsystems

All hydraulic power generation and distribution systems normally used for flight control shall be designed in accordance with AS5440.

3.5.4 Pneumatic Power Subsystems

The use of pneumatic power systems for FCS applications shall be determined by the prime contractor and documented in the FCS Specification, 4.6.2. Pneumatic systems used for FCS functions shall be designed in accordance with MIL-A-87229.

3.5.5 Actuation Subsystems

3.5.5.1 Actuation Subsystems General Requirements

3.5.5.1.1 Control Surface Flutter and Buzz Protection

All flight control surface actuation systems controlling surfaces which are not dynamically balanced shall provide sufficient dynamic stiffness or damping to prevent flutter, buzz, and all other related dynamic instabilities for all operating modes and meet the requirements of MIL-A-8870, including the over-life requirements for control surface freeplay. Techniques or mechanizations designed to artificially increase effective stiffness, damping, or natural frequency shall not be used without prior approval of the procuring activity. The prime contractor shall determine the stiffness and freeplay requirements to prevent flutter and buzz for each control surface installation. The prime contractor shall allocate these requirements to:

a. Structural stiffness of aircraft control surface installation and actuator backup structure, freeplay in installation hardware, and damping.

b. Actuation subsystem freeplay and, for each mode of operation, its complex impedance in the form of dynamic stiffness or damping or some combination of the two, over the frequency range of interest.

c. Control surface damper characteristics and freeplay.

3.5.5.1.1.1 Actuation Impedance in Failed Modes of Operation

The prime contractor shall specify the impedance required from an actuation subsystem driving a flutter-critical surface following loss of normal operation. The type of fail-safe operation required, such as fail-to-a-fixed position or damped-trail shall also be specified. For actuators employing hydraulic fluid, means shall be incorporated within the actuator to supply make-up fluid for a flight time and for a range of actuator temperature to be agreed upon with the procuring activity. If the actuator is unbalanced this means shall also accommodate the area imbalance.

3.5.5.1.2 Control Surface Dampers

Damping requirements for surface dampers shall be based upon the anticipated flutter frequency, but the endurance requirements shall be based upon the same criteria established for the surface control actuators. Detail design of hydraulic dampers shall conform to the applicable requirements of MIL-PRF-5503.

3.5.5.1.3 Reversion and Re-engagement of Powered Actuation Subsystems

This requirement is applicable to mechanical control systems or mechanical portions of an overall system. At reversion to a manual mode, if applicable, and at reengagement of the powered mode, the transients shall be minimized. After reversion to a manual mode at least FCS Operational State III shall be provided. Reversion to manual mode shall not result in objectionably high pilot forces. It shall be possible to re-engage the powered mode following operation with mechanical reversion. The normal, powered control mode shall meet the applicable Operational State of the Aircraft Detail Specification and the control force levels specified in MIL-STD-1797, MIL-F-83300, or ADS-33E-PRF as applicable.

3.5.5.1.4 Synchronization of Redundant Actuation

3.5.5.1.4.1 Force Synchronization of Multiple Connected Servoactuators

In Essential and Flight Phase Essential flight control actuator installations employing multiple connected servoactuators, the actuators shall be synchronized as necessary to ensure the specified actuation subsystem performance and the durability specified in 3.4.2.1.7 for the servoactuators and the structure between them.

3.5.5.1.4.2 Synchronization of Multiple Commands Within an Actuation Subsystem

When multiple, redundant commands to an actuation subsystem are used simultaneously, means shall be adopted to ensure that the commands work in unison in normal operation and during the shutdown and engagement of individual channels to provide the specified performance and durability.

3.5.5.1.5 Load Capability

3.5.5.1.5.1 Load Capability of Elements Subjected to Pilot Loads

Elements of actuation systems subjected to loads generated by the pilot(s) shall be capable of withstanding the pilot input limit loads specified in MIL-A-8865, Section 3.7, FCS Loads, treated as stressing case limit loads. If loading from sources such as a powered actuation system or aerodynamic forces can also be imposed, then the worst-case combination of all sources of load shall be used to determine the stressing cases. Hydromechanical servoactuators shall be provided with control valve command input stops and these shall also be capable of withstanding these design loads. The force output of pilot-assist control-signal servoactuators may be load limited by spring cartridges. Pilot-driven position sensor mechanisms shall not be placed in the load path between the pilot and the control stops. The stressing cases for the sensor mechanisms shall be specified by the prime contractor.

3.5.5.1.5.2 Load Capability of Elements Driven by Power Actuators

Elements subjected to loads generated by a powered actuation system, including all parts of the actuator, shall be capable of withstanding the worst-case combination possible of the maximum output of the actuation system, loads due to bottoming including static and impact ground gust loading to the requirements of MIL-A-8865, jamming, other parallel actuators and the maximum aerodynamic load, as controlled by load limiting provisions, as the limit load. Ultimate load capability shall be 1.5 times limit load or as specified by the prime contractor. In dual load path design, each path shall be capable of sustaining load as specified in 3.4.2.1.4 without failure. Surface position sensor mechanisms shall not be placed in the load path between the actuator and the surface. The stressing cases for the sensor mechanisms shall be specified by the prime contractor.

3.5.5.1.6 Actuation Subsystem Dynamic Performance

The prime contractor shall perform analysis and simulation studies to establish the large amplitude and small amplitude dynamic response requirement for the PFCS servoactuators, together with the amplitudes to be used for specification, analysis and test. The studies shall include considerations such as the aircraft dynamic performance, the flying qualities requirements, and the extent to which excessive phase lag can degrade flying qualities and increase the potential for pilot induced oscillations. The requirements that result from the studies shall be specified at defined tolerance and operating conditions and may include nominal and extreme cases. These requirements shall apply to both hydraulic and electrical actuation subsystems.

The large amplitude studies shall include the effects of actuator rate limiting and/or acceleration limiting. The prime contractor shall define the amplitude to be used, surface by surface, and the dynamic performance to be achieved at that amplitude, including the maximum acceptable total phase lag and time delay between the command and the actuator output. This requirement shall include the effects of all significant non-linearities such as servoactuator rate limiting caused by design characteristics such as servovalve position saturation, servomotor velocity limits or hydraulic supply flow limitations, or servoactuator acceleration limiting caused by control valve spool rate saturation or servomotor acceleration limits. Common practice for these studies is to use an amplitude of 10 percent of full stroke, peak-to-peak.

The small amplitude studies shall include nonlinearities such as control valve and servomotor threshold that can produce distorted waveforms and result in excessive phase lag. The prime contractor shall define the amplitude to be used and the dynamic performance requirements at that amplitude. The allowable phase lags shall be consistent with the aircraft residual oscillations requirements of 3.2.1.7. Common practice for these studies is to use an amplitude of 1 percent of full stroke, peak-to-peak.

3.5.5.1.6.1 Actuation Subsystem Stability Margins

The actuation subsystem stability shall comply with the FCS requirements of 3.2.1.4. In the absence of any other stability margin requirements imposed by the aircraft control concepts, the minimum stability margins for any actuator loop closure, at the worst-case tolerance condition and operating condition, at the end of life, shall be:

Gain margin: 6.0 dB

Phase margin: 45 degrees

3.5.5.1.7 Operational Temperature Range

The prime contractor shall specify the operational temperature range for the actuation subsystem. If preflight warming is used to raise the minimum operational temperature, for functionality or performance reasons, the procuring activity shall approve any consequent operational impact.

3.5.5.1.8 Power Control Actuation Failure and Fail-Safe Provisions

FBW systems shall include provisions to reduce the failure effects and ensure that Operational State IV is met after failure of a control surface actuation system, such as the following:

a. Reconfiguration of the control law to use aerodynamic control power from the remaining operative surfaces to override control moments generated by the failed surface.

b. Detection and isolation of the failures in accordance with the requirements of 3.2.1.10 and reversion to a fail-safe mode such as damped bypass, powered to a neutral position or locked in the failed position.

3.5.5.2 Hydraulic Actuation Subsystems

3.5.5.2.1 Hydraulic Actuation Components

Hydraulic actuation components shall be designed in accordance with AS8775 and program specific component specifications and other documents as applicable.

3.5.5.2.1.1 Wiring Within Hydraulic Components

Electrical wiring within actuation components shall be designed to provide robust protection so as to preclude damage and/or degradation due to the ingress of water, cleaning and other fluids and to the specified environmental requirements including but not limited to, temperature extremes, vibration and EMI. The prime contractor FCS Specification, 4.6.2, shall provide technical justification for wire gauges and installation, which may include prior successful use in applications applying similar environments and similar wiring protection.

3.5.5.2.2 Actuating Cylinders

Actuating cylinders without control valves and feedback provisions in the same LRU/WRA shall be designed in accordance with MIL-PRF-5503, except that the life cycling requirements shall be modified to reflect the specific usage (see 3.4.2.1.7).

3.5.5.2.3 Hydraulic Actuation Mode Control

If hydraulic bypass of hydromechanical actuators is necessary to prevent fluid lock or excessive friction load or damping, bypassing and resetting shall occur automatically when system pressure drops below or returns to the minimum acceptable value for actuation. In actuation systems designed for manual control following hydraulic failure, provisions shall be made to permit bypassing of the hydraulic systems for checkout purposes and permit pilot training with the emergency manual system. For FBW actuators employing solenoid-operated pilot valves driving spool valves to achieve mode control, the change of mode required at loss of system pressure shall occur automatically. The logic applied to control the pilot valve state and govern reset shall be specified by the prime contractor. If mode control is provided by spool valves directly driven by electrical force motors, the logic governing both mode change and reset shall be specified by the prime contractor.

3.5.5.2.4 Hydraulic Motors

Hydraulic motors may be used to actuate relatively low-duty-cycle, noncritical flight control surfaces, such as wing flaps, but specific approval from the procuring activity must be obtained before use in high duty cycle noncritical applications or in any Essential or Flight Phase Essential application. They shall be designed in accordance with AS7997.

3.5.5.2.5 Hydraulic Servoactuators

Hydraulic servoactuators shall be designed in accordance with ARP1281. FBW servoactuators may be controlled by Electrohydraulic Servovalves (EHSVs) designed in accordance with ARP490 or Direct Drive Valves (DDVs), designed in accordance with ARP4493. If electrical-input hydraulic servoactuators having mechanical feedback of actuator position are used, they shall be designed in accordance with ARP988.

3.5.5.2.5.1 Hydraulic Servoactuator Electrical Loop Closure Circuitry

The design of the electrical loop closures for FBW servoactuators, whether centrally, locally or servoactuator located, shall meet the requirements of 3.4.5, 3.6.3, 3.6.5, and 3.6.6. Specific approval of the procuring activity must be obtained for servoactuator mounting of electronics in Essential and Flight Phase Essential applications. For this location the electrical loop closures shall also be designed to meet the thermal, vibration and structural loading environment, the thermal derating and any explicit thermal operating capabilities specified for the servoactuators by the prime contractor. These may include continuous operation over a specified environmental and fluid temperature spectrum and range, cold soak and startup, short term temperature overheat, fluid temperature shock and unpowered storage temperature extremes.

3.5.5.2.5.2 Strength to Clear or Override Jammed Control Valves in Hydromechanical Servoactuators

All mechanical control system elements which transmit input commands to metering valves of hydraulic servoactuators shall have strength to withstand higher loads, above those for normal valve stroking, required to clear foreign material that may occur in projected usage. The use of abnormal force levels shall be apparent to the pilot or shall be obvious at the next aircraft maintenance inspection. Provisions shall be made to permit the pilot(s) to clear or override metering valve jams unless there is sufficient aerodynamic control power from the remaining operative surfaces to override control moments generated by the jammed surface in its most adverse position.

3.5.5.2.5.3 Force to Clear Jammed Control Valves in FBW Servoactuators

All servoactuator control valve components shall be designed for a load capability of 150 percent of the maximum force capability of the EHSV or DDV. The minimum value for this chipshear capability shall be specified by the prime contractor after the consideration of factors that shall include the required functional reliability, the functional criticality, the redundancy within the servoactuator, the detail design of the servoactuator control valve, the surface redundancy and the prior history of similar applications. The chip shear force can be minimized if:

a. The servoactuator controls include jammed valve failure detection, failure isolation and transition to a fail-safe position.

b. Remaining control effectors can provide Operational State IV capability.

c. The maximum aircraft transients during jammed valve detection and isolation meet the requirements of 3.2.1.10 in the Operational Flight Envelope, and do not cause the design structural loads to be exceeded anywhere in the Service Flight Envelope.

3.5.5.2.5.4 Force to Clear Jammed Logic Valves in Servoactuators

All servoactuator bypass valves and other logic valves shall be designed for an adequate chipshear force capability to ensure that the potential for dormant failures that could cause hazard in the event of second failures is minimized. The minimum value for this force shall be specified by the prime contractor after the consideration of factors that shall include the required functional reliability, the functional criticality, the redundancy within the servoactuator, the detail design of the logic valves, the surface redundancy and the prior history of similar applications.

3.5.5.3 Electrical Actuation Subsystems

Electrical actuation is defined as any form of actuation that employs power generated and distributed by an electrical rather than hydraulic or pneumatic power subsystem. These actuation subsystems are often referred to as Power-By-Wire (PBW) subsystems, as defined by ARP4386. Essential or Flight Phase Essential applications require specific approval from the procuring activity.

3.5.5.3.1 Electrohydrostatic Actuators (EHAs)

An EHA is an actuator configuration which uses a variable-speed-reversible electric motor to drive a fixed displacement hydraulic pump coupled to a linear or rotary hydraulic actuator, together with the associated Power Drive Electronics (PDE), as defined by ARP4386. EHAs shall be specified in accordance with the applicable requirements of ISO 22072.

3.5.5.3.1.1 EHA Components

EHA components shall be designed to the requirements of 3.5.5.2.1.

3.5.5.3.1.2 Wiring Within and to EHA Subsystems

Electrical power and signal wiring within actuation components shall be designed to provide robust protection so as to preclude damage and/or degradation due to the ingress of water, cleaning and other fluids and to the specified environmental requirements including but not limited to, temperature extremes, vibration and EMI. The prime-contractor FCS Specification, 4.6.2, shall provide technical justification for wire gages and installation, which may include prior successful use in applications applying similar environments and similar wiring protection. For high power electrical actuation subsystems this justification must also be applied to the power wires to the subsystem.

3.5.5.3.1.3 EHA Actuating Cylinders

EHA actuating cylinders shall be designed in accordance with MIL-PRF-5503, except that the life cycling requirements shall be modified to reflect the specific usage (see 3.4.2.1.7).

3.5.5.3.1.4 EHA Closed Hydraulic System

The EHA closed hydraulic system shall include all of the elements required to prevent cavitation and overpressurization under all operating conditions and storage temperatures, whether the actuator cylinder is balanced or unbalanced, prevent thermal degradation of the fluid, prevent ferromagnetic particle contamination of the motor air gaps, permit mode control to provide fail-safe functionality, enable fluid refilling and allow the specified life between refills. The accumulator fluid level shall be monitored and the status displayed for maintainer and/or aircrew actions.

3.5.5.3.1.5 EHA Servoactuators

EHA flight control servoactuators require a PDE to control and drive the electric motor, and control electronics to provide output position control. The EHA plus the two types of control electronics comprise an EHA subsystem however they are packaged. The electronics may be packaged separately or integrated together and may also be integrated with the EHA WRA/LRU. The packaging arrangement shall be specified by the prime contractor.

3.5.5.3.1.5.1 EHA PDE

The electrical interconnections between the EHA PDE and the EHA electric motor shall allow the servoactuator to meet the EMI requirements of 3.1.6 and shall not negatively impact the servoactuator performance.

3.5.5.3.1.5.2 EHA Loop Closure Circuitry

The EHA loop closure circuitry shall be designed to the requirements of 3.5.5.2.5.1.

3.5.5.3.1.6 EHA Thermal Design

The EHA shall be designed to meet the thermal conditions induced by the duty cycle for the application and the installation environment. The applicable thermal design philosophy and all of its conditions and requirements shall be specified by the prime contractor and approved by the procuring activity.

3.5.5.3.1.6.1 EHA Thermal Design Considerations

All thermal-critical areas of the EHA subsystem, including the PDE, its switching devices, the signal-level electronics, the motor windings and fluid, and of the surrounding structure, shall be considered. The low-temperature exposure and startup effects shall be included and, for high-duty-cycle applications, including PFCS applications, particular attention shall be paid to the high temperature cases. The worst-case conditions shall be evaluated for continued EHA operation and survival and the long-term operational duty cycle shall be evaluated for EHA endurance and reliability. In addition, for protection against ignition of flammable gases, the worst-case-condition surface temperature of EHA subsystems shall not exceed the maximum temperature requirement of 3.6.5.3. The prime contractor shall provide a complete definition of the installation thermal environment and shall specify whether directed cooling is acceptable, the capacity of the cooling and the acceptable consequences of its temporary absence.

3.5.5.3.1.6.2 EHA Thermal Analysis

The worst-case conditions including ground checkout and maintenance and operational duty cycles for the EHA application shall be specified by the prime contractor and employed for the derivation of the local heat generation throughout the EHA and, in conjunction with the specified thermal environment, which shall include all conduction, convection and radiation paths, used to predict the temperature distribution throughout the EHA.

3.5.5.3.2 Integrated Actuation Package (IAP)

An IAP is an actuator configuration which uses a non-reversible electric motor, operating continuously at high RPM, to drive a hydraulic pump that is coupled to a linear or rotary hydraulic actuator. There may also be associated Power Drive Electronics (PDE), see 3.5.5.3.2.4 and 3.5.5.3.2.5 for variant designs.

3.5.5.3.2.1 IAP Components

IAP components shall be designed to the requirements of 3.5.5.2.1.

3.5.5.3.2.2 Wiring Within and to IAP Subsystems

Wiring within IAP components and to IAP subsystems shall be designed to the requirements of 3.5.5.3.1.2.

3.5.5.3.2.3 IAP Actuating Cylinders

IAP actuating cylinders shall be designed in accordance with MIL-PRF-5503, except that the life cycling requirements shall be modified to reflect the specific usage (see 3.4.2.1.7).

3.5.5.3.2.4 IAP Closed Hydraulic System

Variant designs may employ either a variable displacement pump with its displacement controlled with an EHSV, DDV or directly with an electric motor, or a pressure-compensated pump with its flow output controlled with an EHSV or DDV. The IAP closed hydraulic system shall include all of the elements required to prevent cavitation and overpressurization under all operating conditions and storage temperatures, whether the actuator cylinder is balanced or unbalanced, prevent thermal degradation of the fluid, prevent ferromagnetic contamination of the motor air gaps, permit mode control to provide fail-safe functionality, enable fluid refilling and allow the specified life between refills.

3.5.5.3.2.5 IAP Servoactuators

Flight control IAP servoactuators typically employ a fixed-speed electric motor driven by aircraft a.c. bus voltage through motor contactors and therefore do not require motor control PDEs but might require PDEs for power conditioning to be part of the actuation subsystem. Loop closure circuitry provides control valve and output position control.

3.5.5.3.2.5.1 IAP Loop Closure Circuitry

The IAP loop closure circuitry shall be designed to the requirements of 3.5.5.2.5.1.

3.5.5.3.2.6 IAP Thermal Design

The IAP shall be designed to meet the thermal conditions induced by the duty cycle for the application and the installation environment. The applicable thermal design philosophy and all of its conditions and requirements shall be specified by the prime contractor and approved by the procuring activity.

3.5.5.3.2.6.1 IAP Thermal Design Considerations

All thermal-critical areas of the IAP subsystem, including any power electronics and signal-level electronics, the motor windings and fluid, and of the surrounding structure, shall be considered. The low temperature exposure and startup effects shall be included and, for high-duty-cycle applications, including PFCS applications, particular attention shall be paid to the high temperature cases. The worst-case conditions shall be evaluated for continued IAP operation and survival and the long-term operational duty cycle shall be evaluated for IAP endurance and reliability. In addition, for protection against ignition of flammable gases, the worst-case-condition surface temperature of IAP subsystems shall not exceed the maximum temperature requirement of 3.6.5.3. The prime contractor shall provide a complete definition of the installation thermal environment and shall specify whether directed cooling is acceptable, the capacity of the cooling and the acceptable consequences of its temporary absence.

3.5.5.3.2.6.2 IAP Thermal Analysis

The worst-case conditions including ground checkout and maintenance and operational duty cycles for the IAP application shall be specified by the prime contractor and employed for the derivation of the local heat generation throughout the IAP and, in conjunction with the specified thermal environment, which shall include all conduction, convection and radiation paths, used to predict the temperature distribution throughout the IAP.

3.5.5.3.3 Electromechanical Actuators (EMAs)

The EMA is defined as an electrical actuator comprising an electric motor that is coupled to the load positioning element either directly or through a mechanical power train, together, with an associated PDE, as defined by ARP4386. EMAs are frequently used for low power SFCS actuation applications and may also be used for high power SFCS applications and PFCS surface actuation duty, subject to the approval requirements of 3.5.5.3.

3.5.5.3.3.1 EMA Components

EMA Components shall be designed in accordance with MIL-STD-7080, the applicable requirements of 3.5.5.4 and program specific component specifications and other documents as applicable.

3.5.5.3.3.2 Wiring Within and to EMA Subsystems

Wiring within EMA components and to EMA subsystems shall be designed to the requirements of 3.5.5.3.1.2.

3.5.5.3.3.3 EMA Servoactuators

Flight control EMA servoactuators require a PDE to control and drive the variable speed electric motor and EMA loop closure circuitry to provide motor velocity and output position control. The EMA plus the two types of control electronics comprise an EMA subsystem however they are packaged. The electronics may be packaged separately or integrated together and may also be integrated with the EMA WRA/LRU. The packaging arrangement shall be specified by the prime contractor.

3.5.5.3.3.3.1 EMA PDE

The electrical interconnections between the EMA PDE and the EMA electric motor shall allow the servoactuator to meet the EMI requirements of 3.1.6 and shall not negatively impact servoactuator performance.

3.5.5.3.3.3.2 EMA Loop Closure Circuitry

The EMA loop closure circuitry shall be designed to the requirements of 3.5.5.2.5.1.

3.5.5.3.3.4 EMA Thermal Design

The EMA shall be designed to meet the thermal conditions induced by the duty cycle for the application and the installation environment. The thermal design conditions shall include operating requirements for ground checkout and maintenance. The applicable thermal design philosophy and all of its conditions and requirements shall be specified by the prime contractor and approved by the procuring activity.

3.5.5.3.3.4.1 EMA Thermal Design Considerations

All thermal-critical areas of the EMA subsystem, including the PDE, its switching devices, the signal-level electronics and the motor windings, and of the surrounding structure, shall be considered. The low temperature exposure and startup effects shall be included and, for high-duty-cycle applications, including PFCS applications, particular attention shall be paid to the high temperature cases. The worst-case conditions shall be evaluated for continued EMA operation and survival and the long-term operational duty cycle shall be evaluated for EMA endurance and reliability. In addition, for protection against ignition of flammable gases, the worst-case-condition surface temperature of EMA subsystems shall not exceed the maximum temperature requirement of 3.6.5.3. The prime contractor shall provide a complete definition of the installation thermal environment and shall specify whether directed cooling is acceptable, the capacity of the cooling and the acceptable consequences of its temporary absence.

3.5.5.3.3.4.2 EMA Thermal Analysis

The worst-case conditions including ground checkout and maintenance and operational duty cycles for the EMA application shall be specified by the prime contractor and employed for the derivation of the local heat generation throughout the EMA and, in conjunction with the specified thermal environment, which shall include all conduction, convection and radiation paths, used to predict the temperature distribution throughout the EMA.

3.5.5.4 Mechanical Actuation Subsystems

Mechanical actuation subsystems are defined as any form of actuation that employs mechanical components to distribute power from a power source to a surface or set of surfaces. The sub-system may also include safety and sensing devices. Power sources may be manual, electrical, hydraulic or pneumatic. The actuation components may be rotary actuators, linear actuators, or, for manual and manual reversion systems, rods, bellcranks, links and cables. The mechanical power distribution may employ cables, push-pull rods, torque tubes, flexible shafts, angle and other gearboxes. Safety devices may include various forms of brakes, clutches, overspeed protection, symmetry protection, and overload protection, feel devices, gain or ratio changers, and other devices. Sensing devices may include surface position, drivetrain position, speed, temperature, and others. For control cable power distribution and actuation, the requirements specified in 3.6.2.6 and subparagraphs apply. For push-pull rod power distribution and actuation, the requirements specified in 3.6.2.7 and subparagraphs apply. For PFCS applications the prime contractor shall perform an analysis to develop requirement for mechanical actuation for inclusion in the FCS Specification, 4.6.2. This analysis shall include reliability, an FMEA including jams and opens, and a safety assessment. Specific approval from the procuring activity must be obtained before use of such subsystems in Essential and Flight Phase Essential applications.

3.5.5.4.1 Mechanical Force Transmitting Actuation

Mechanical force transmitting actuators are actuators that convert their input power to linearly acting mechanical force at the surface. These actuators include sliding and rolling contact powerscrews. For subsystems that distribute power mechanically to these linear actuators the requirements contained in the subparagraphs of 3.5.5.4.2 apply.

3.5.5.4.1.1 Force Transmitting Powerscrews

Powerscrews with rotary input and linear output motion may be used to actuate relatively low-duty-cycle flight control surfaces, such as wing flaps and trimmable stabilizers, but specific approval from the procuring activity shall be obtained before use in high-duty-cycle applications. Powerscrews shall include non-jamming mechanical stops to prevent disengagement of the nut at each end of its travel. These stops shall be designed to meet the load requirements of 3.5.5.6.1.1. Provisions shall be incorporated into the nut to minimize entry of sand, dust, and other contaminants; to retain its lubricant; and to preclude the entry or retention of water. The nut shall also include provisions for ice breaking. However, positive sealing and ice breakers are not required if the screw is installed such that it is protected from such contamination, or ice, or is inherently resistant to wear and jamming by contamination, or ice.

3.5.5.4.1.1.1 Sliding Contact Powerscrews

Any deviation from the use of standard Acme thread forms shall be approved by the prime contractor. The thread roots shall be rounded as necessary to preclude stress cracking. Lubrication provisions shall be adequate for controlling efficiency, wear, and heating to acceptable values. Where in-service lubrication is necessary, lube fittings in accordance with 3.6.2.4 shall be provided. If the design is dependent on inherent friction to maintain irreversibility, this characteristic must be adequate under all expected operating conditions, including the full range of loads, both steady loads and reversing or variable-magnitude loads which may be encountered due to control surface buffeting or buzz, temperatures, and environmental vibration over the full service life of the unit.

3.5.5.4.1.1.2 Rolling Contact Powerscrews

Rolling contact screws include all screws where the contact between the nut and the screw employs rolling elements to transmit power. Rolling contact powerscrews include roller screws and ballscrews. The use of any rolling contact screw other than ballscrews for any flight control application shall be approved by the procuring authority. Ballscrews shall employ an adequate number of balls and ball circuits to keep individual ball loading within allowable non-brinelling limits. On units used in Essential and Flight Phase Essential applications, at least two separate independent ball circuits shall be incorporated.

3.5.5.4.1.1.3 Horizontal Stabilizer Trim Actuators (HSTAs)

Class II and III aircraft with horizontal stabilizers adjustable in their angle of incidence for pitch trim, may use sliding or rolling contact powerscrews for this function. The requirements of 3.5.5.4.1.1.1 or 3.5.5.4.1.1.2 shall therefore apply to HSTA design. The HSTAs shall employ dual load paths when dictated by the requirements of 3.4.2 and the following additional requirements shall then apply:

a. If a ballscrew is used in the HSTA primary load path, the ballscrew shall have more than a single thread start.

b. If a ballscrew is used in the HSTA primary load path, each thread start and its associated circuits shall be capable of withstanding static limit load after at least one-half an aircraft life of flight cycles.

c. HSTA dual load path structure that is subject to wear shall have a discernable first load-path-open-type failure. A discernable failure is a failure noted by the flight crew within a single flight through obvious changes in handling qualities, a flight deck annunciation or during a pre- or post-flight walk around.

d. The HSTA secondary load path shall be capable of supporting continued safe flight and landing after failure of the primary load path until the primary load path failure is detected and corrected.

e. The secondary load path shall be unloaded during normal operation.

f. Degradation of the HSTA secondary load path shall be detected before its load-carrying capacity falls below limit load.

g. No failure conditions, including common mode and adverse wear, shall be allowed to disable all load paths without detection.

HSTAs shall provide the following failure performance:

1. No single failure within an HSTA system, regardless of probability, shall result in loss of irreversibility.

2. No single failure within an HSTA system, regardless of probability, shall cause stabilizer motion and also inhibit shutdown functions.

3. The probability of the following uncommanded motion and position integrity-type failures shall comply with the flight safety requirements of 3.1.1.3:

    a. The probability of uncommanded stabilizer motion greater than 1.0 degree as a result of loss of irreversibility.

    b. The probability of loss of all HSTA position data.

    c. The probability of erroneous HSTA position data.

4. The probability that HSTA system failures result in total loss of stabilizer trim capability shall comply with the Mission Accomplishment Reliability requirements of 3.1.2.1.

3.5.5.4.2 Mechanical Torque Transmitting Actuators

Mechanical torque transmitting actuators are actuators that convert their input power to mechanical torque at the surface. These actuators include cable and pulley systems, torque tube systems, geared actuators, and self-contained screw-and-arm type actuators. Backlash accumulation shall not prevent the system from performing its required function throughout the service life of the aircraft. The detailed requirements for cable and pulley subsystems are specified in 3.6.2.6 and subparagraphs.

3.5.5.4.2.1 Torque Tube Subsystems

All torque tubes shall be coupled through jackshafts mounted to structure on antifriction bearings spaced at close enough intervals and with sufficient misalignment capability to prevent undesirable bending or whipping of the tubes. In addition, the prevention of spark generation in fuel system areas shall be given careful consideration in the detail design. Torque tubes which are exposed to possible misuse, such as support for maintenance personnel, shall be shielded from such misuse or shall be of adequate stiffness to prevent damage to the installation. Each torque tube in a linked run of tubes shall be removable and reinstallable in the aircraft without disturbing the support, component, or other interfacing system element at either end of the torque tube. Guards which are capable of containing a broken torque tube against thrashing shall be installed in appropriate locations to prevent damage to wiring, tubing, and other equipment. The rated operating speed of a torque tube system shall be not greater than 75 percent of the critical speed.

3.5.5.4.2.1.1 Torque Tubes

Torque tubes shall have a minimum wall thickness of 0.035 inch and shall be seamless, except that steel tubes, seam welded by the electrical resistance method, may be used.

3.5.5.4.2.1.2 Torque Tube End Fitting Attachment Methods

End fittings may be attached by riveting, bolting, swaging, welding or electromagnetic forming.

3.5.5.4.2.1.3 Torque Tube Slip Joints

Adequate engagement shall be provided to insure that disengagement will not occur under all expected operating conditions, or due to buildup of adverse manufacturing and installation tolerances.

3.5.5.4.2.1.4 Universal Joints

Universal joints shall be in accordance with MIL-DTL-6193, as specified in AFSC Design Handbook DH 1-2, General Design Factors, Section 4C, Universal Joints, and shall not be used for angularities greater than specified therein or recommended for the specific component by the manufacturer.

3.5.5.4.2.1.5 Bearing and Gearbox Loading

The antifriction bearing mountings and the gearbox brackets shall have sufficient side load capability to accommodate the worst-case shaft spline sliding force, to prevent secondary damage in the event of a jam elsewhere in the system.

3.5.5.4.2.2 Gearing

All gearboxes used in actuating systems shall be designed in accordance with ARP5384.

3.5.5.4.2.3 Flexible Shafting

Flexible shafting may be used providing that minimum bend radii, rated rotational speed, and rated torque are not exceeded, and that extreme temperatures and other operational variations and environments do not cause binding. It shall be designed to withstand the inertial loads produced by the mechanical system during its maximum acceleration reversals. It shall be sealed to protect against the ingress of water, cleaning and other fluids and against all anticipated environments for the application, shall be installed with the fewest possible bends and shall be securely fastened to supporting structure at close intervals.

3.5.5.4.2.4 Helical Splines

Involute helical splines shall use only the ASA standard tooth forms Numbers 1 through 5. Ballsplines shall meet the requirements specified in 3.4.1.5.5.4 for ballscrews.

3.5.5.4.2.5 Rotary Mechanical Actuators

Rotary mechanical actuators used with a through-shaft which attaches to torque tubes at both ends, thus serving as a portion of the torque distribution system, shall be capable of reacting full system torque in both the forward direction (due to a jam anywhere in the system) or in the backdriving direction (due to overrunning load], unless provided with a torque limiter and no-back brake or other devices which would preclude such loading. All geared rotary mechanical actuators shall be designed in accordance with ARP4058.

3.5.5.4.2.6 Torque Limiters

Where used, torque limiters designed to slip or lock to adjacent structure shall be properly located in the transmission system to prevent drive loads in excess of control surface limit load from being transmitted past the limiter in the event of overload or jamming. The rate of application of the limiter(s) and the spring rate of the transmission system shall be matched so that the stress in any member due to sudden application does not exceed its yield strength.

3.5.5.4.2.7 No-Back Brakes

No-back brakes shall prevent back driving (or feedback) forces imposed on the output of an actuating mechanism from being converted to torques which can cause the input shaft to rotate. In no-back brakes of the heat dissipative type, provisions shall be included to distribute heat generated by the brake so that temperature limitations are not exceeded. No-backs shall be designed to be non-jamming over the full temperature range required by the detailed specification, including the effects of any such local heat generation.

3.5.5.5 Pneumatic Actuation

The use of pneumatic actuation systems for FCS applications shall be recommended by the prime contractor and approved by the procuring activity.

3.5.5.6 Interfaces Between Actuation Subsystems, Support Structure, and Control Surfaces

3.5.5.6.1 Control Surface Stops

Surface stops shall be provided at each flight control surface by the associated actuation subsystem to positively limit its range of motion. The stops shall prevent damage to the control surface and the associated structure and provide personnel safety when the aircraft is on the ground. Stops shall be located so that miss-rigging, wear, slackness, or takeup adjustments will not adversely affect the control characteristics of the aircraft because of a change in the range of surface travel. Each stop shall be able to withstand any loads corresponding to the design conditions for the control system. For FBW actuation subsystems, the control laws shall include command position limiters that prevent mechanical bottoming during normal operation. The design of these limiters shall consider the stackup of mechanical and electronics tolerances, as well as the overtravel required to allow electronic rigging.

3.5.5.6.1.1 Stops for Linear Actuation

Where linear actuators, hydraulic, electrical, pneumatic or mechanical, are attached directly to the control surface, stops shall be provided within the actuator. Such actuators shall not only be designed for maximum torsional and axial impact loads, but also for the cumulative fatigue damage due to load cycling predicted during flight and due to bottoming during ground checkout and taxiing.

3.5.5.6.1.2 Stops for Rotary Actuation

For mechanical actuation systems employing rotary actuators, a system stop at the drivetrain level shall be provided. Such actuators and system stops shall not only be designed for maximum impact loads, but also for the cumulative fatigue damage due to load cycling predicted during flight and due to bottoming during ground checkout and taxiing.

3.5.5.6.1.3 Adjustable Stops

All adjustable stops shall be positively locked or safety wired in the adjusted position. Jam nuts (plain or self-locking type) are not considered adequate as locking devices for this application.

3.5.5.6.2 Control Surface Ground Gust Protection

All flight control surfaces shall have provisions to prevent damage from the ground wind loads specified in MIL-A-8865.

3.5.5.6.2.1 Control Surface Locks

Where control surface locks are used, the lock system shall be internal within the aircraft. External locks may be used for rotorcraft rotors. The locks shall either engage the surfaces directly or lock the controls as near to each surface as practicable and shall be spring-loaded to the unlocked position. Control surface locks shall be designed to preclude attempting takeoff with controls locked. The system design shall prevent any control modes from selecting or de-selecting in-flight engagement of any surface locks.

3.5.5.6.2.2 Protection Against In-flight Engagement of Control Surface Locks

Control surface ground gust locks and their controls shall be designed to preclude their becoming engaged during flight.

3.5.6 Trim Subsystem

A suitable trim system shall be provided for each of the primary control axes per requirements in 3.2.3.6. The trim system need not have the authority or rate to be able to perform all desired maneuvers. Manual parallel trim shall maintain a given setting until changed by the pilot. It shall have a deadband in each axis to give the pilot a preciseness of control and its rate shall not be so slow as to be ineffectual or so fast as to create a hazard. The design of trim actuators should consider the possibilities of runaway or inadvertent operation in the high-speed trim mode. The design of the trim actuator shall incorporate features to prevent jams or opens from causing loss of aircraft control.

3.5.7 Artificial Feel Subsystem

Where pilot control forces, adequate to meet the requirements of MIL-STD-1797, MIL-F-83300, or ADS-33E-PRF as applicable, are not provided by aerodynamic means, these forces must be supplied (or the aerodynamic forces augmented) by suitable artificial feel devices. The artificial feel system shall provide a force gradient which meets the Aircraft Detail Specification requirements. Any failure in the systems shall not result in control forces that are either so high or so low as to be hazardous. Artificial feel system design should provide positive control centering to the trim position without overtravel or control oscillation. The pilot and copilot shall have the capability of overriding the artificial feel system at all times. Upon failure of the artificial feel system the control feel shall revert to a breakout force and a force gradient versus deflection as determined by the prime contractor and approved by the procuring activity.

3.5.7.1 Control Stick Dampers

Each damper shall be completely defined by a detail specification. Control stick dampers shall be designed so that they can be overpowered by the pilot in the event of failure or malfunction.

3.5.7.2 Bobweights

Each bobweight shall be completely defined by a detail specification. When the control stick damper is incorporated into the bobweight(s), the damper shall conform to the requirements of 3.5.7.1.

3.5.8 Display and Annunciator Subsystem

3.5.8.1 Pilot Controls and Displays

Wherever an FCS control, display or annunciator is interfaced with redundant flight control channels, mechanical and electrical separation and isolation shall be provided to make the probability of common mode failures at least one order less than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1. FCS controls and displays shall be designed in accordance with the applicable provisions of MIL-C-81774 and MIL-STD-1472.

3.5.8.2 In-flight Monitoring

Continuous in-flight monitoring of equipment performance and critical flight conditions shall be active during all modes of operation. False monitoring warnings, including the automatic or normal pilot response thereto, shall not constitute a specific hazard in excess of the system reliability requirements.

3.5.8.3 FCS Warning and Status Information

Annunciation shall be designed to clearly indicate the associated degree of urgency:

a. WARNING - Immediate action required. Used for operating procedures, practices, conditions, etc., which may result in injury or death if not carefully observed or followed.

b. CAUTION - Action may be required. Used for operating procedures, practices, conditions, etc., which may result in damage to equipment if not carefully observed or followed.

c. ADVISORY - Informational, no immediate action required.

A panel comprising means for displaying WARNING annunciations shall be located within the normal eye scan range of the command pilot. The warnings shall be accompanied by an audible alert. A warning or status indication, which applies only to a particular mode or phase of flight, shall be inhibited or designed to clearly indicate a lesser degree of urgency for all other modes or phases of flight.

3.5.8.4 Failure Status

Failure annunciation shall be displayed to allow the crew to assess the operable status of redundant or monitored FCSs. Automatic disengagement of an AFCF mode shall be indicated by an appropriate status display. Manual disengagement by the crew of systems not necessary for flight safety shall not result in warning annunciation. Loss of valid signals critical to existing modes of operation for AFCF shall result in appropriate status annunciation and/or system deactivation.

3.5.8.5 Control Authority Annunciation

For Essential and Flight Phase Essential FCS, pilot displays shall be provided to indicate available control authority. A warning shall be annunciated if the remaining control authority becomes critical.

3.5.8.6 Lift and Drag Device Position Displays

Displays shall be provided in the cockpit to indicate to the pilot(s) the position of each lift or drag device having a separate control. They shall also indicate the correct takeoff, enroute, approach, and landing position; and, if any extension of the lift and drag devices beyond the landing position is possible, the displays shall be marked to identify the range of extension. In addition, an indication of unsymmetrical operation or other malfunction in the lift or drag device systems shall be provided whenever necessary to enable the pilot(s) to prevent or counteract an unsafe flight or ground condition.

3.5.8.7 Trim Displays

Suitable displays shall be provided to:

a. Indicate the position and the range of travel of each trim device.

b. Indicate the direction of the control movement relative to the aircraft motion.

c. Indicate the position of the trim device with respect to the range of adjustment. Trim devices such as the magnetic brake used in rotorcraft to instantaneously relieve pilot's control forces by changing the feel force reference to zero at the control position held by the pilot at the time the trim switch is activated shall not require separate trim display.

d. Provide pilot caution/warning of trim failures which could result in exceeding the Operational State III requirements of 3.2.1.10.

Aircraft which require takeoff longitudinal trim setting in accordance with cg location shall have suitably calibrated trim position displays. In aircraft requiring quick takeoff capability or certain single pilot aircraft, which use a single trim setting for all takeoff conditions, a "trim-for-takeoff" indication shall be provided.

3.5.8.8 Control Surface Position Indication

Displays shall be provided in the cockpit for all control surfaces when the cockpit controls do not provide a positive indication of long term or steady state control surface position.

3.5.8.9 FCS Annunciation

The FCS control panel, associated panels, or integrated displays shall provide means to display:

a. AFCF engaged.

b. Mode engaged.

c. That automatic mode switching has occurred.

d. Preselected values for selectable mode parameters.

3.5.8.10 Display Data Latency

The prime contractor shall establish display data latency requirements for communication of flight critical data between the FCS and the cockpit display. These shall distinguish between the requirements for data such as FCS modes and monitor status and the more demanding requirements for the data employed for closed loop manual control and displayed by primary flight instruments such as a heads-up-display (HUD), including aircraft rate, acceleration and attitude. The display data latency requirement for primary flight instruments shall allow the aircraft to meet the applicable flying qualities requirements of MIL-STD-1797, ADS-33E-PRF, and MIL-F-83300. The data latency requirements shall be documented in the FCS Specification, 4.6.2.

3.5.9 Sensors

Sensors shall be installed at locations which minimize exposure to conditions which could produce failures or undesired output signals. Careful attention shall be given to the location and installation details of all sensors to ensure that they provide signals of the quality necessary for the FCS without distortion due to undesirable structural modes, cross axis coupling, or environmental effects.

3.5.9.1 Motion Sensor Subsystems

The sensor system shall be designed to be compatible with all applicable paragraphs of 3.1. The use of any unconventional sensor configurations shall be recommended by the prime contractor and approved by the procuring agency. Data transmission from the sensors shall minimize time delays in order to insure compliance with 3.2.

3.6 Component Design and Fabrication Requirements

3.6.1 General Component Requirements

3.6.1.1 Choice of Components

Where practicable, systems, subsystems, or components that are in operational use today shall be used in lieu of design and developing new hardware. This existing hardware must meet the requirements of this specification and the detail equipment specification. The order of preference shall be:

a. In operational use by the Air Force or Navy.

b. In operational use by another branch of service.

c. Certified by a government agency for commercial aircraft.

3.6.1.2 Standardization

Where practical, prime-contractor designed equipment which has been approved for use in some models of aircraft shall also be used in later model aircraft if the installation and requirements are similar. Tolerances shall be such that interchange of any LRU/WRA with any other part bearing the same part number shall not require resetting of parameters or readjustment of other components in order to maintain overall tolerances and performance, with the exception of mechanical system rigging.

3.6.1.3 Interchangeability

Regardless of the manufacturer or supplier, like assemblies, subassemblies, and replaceable parts shall meet the requirements of MIL-I-8500. Items which are not functionally interchangeable shall not be physically interchangeable. Tolerances shall be such that interchange of any computer component, module, or LRU/WRA with any other part bearing the same part number shall require only minimum resetting of parameters or readjustment of other components in order to maintain overall tolerances.

3.6.1.4 Selection of Specifications and Standards

Specifications and standards for necessary commodities and services not specified herein shall be in accordance with the Aircraft Detail Specification.

3.6.1.5 Identification of Product

Equipment components, assemblies, and parts of FCSs shall be identified in accordance with MIL-STD-130.

3.6.1.5.1 Inspection Seals

Corrosion resistant metallic seals shall be provided at all strategic locations to indicate assembly inspection and any unauthorized disassembly.

3.6.1.6 Workmanship

Workmanship of the FCS shall be of sufficiently high grade to insure proper operation and service life of the system and components. The quality of the items being produced shall be uniformly high and shall not depreciate from the qualification test items.

3.6.1.7 Foolproofness

All components of the FCS shall be designed so that incorrect assembly and reversed operation is impossible. Direction of operation and other essential information shall be conspicuously labeled.

3.6.1.8 Ground Operation

Components which, when operated during ground testing, are expected to be subject to high temperatures, shall be designed that such temperatures will not damage or impair the components. This shall include the temperatures that can be generated by operating states encountered during extended maintenance activities. Using externally operated forced cooling or other similar cooling aids shall be considered in the design only upon approval of the procuring activity.

3.6.2 Mechanical Components

Mechanical components not covered by design requirements specified elsewhere within this specification shall be designed in accordance with applicable requirements in: Government and Industry specifications, in the order of precedence specified in; in AFSC Design Handbooks DH 2-1, DN 3B1, Mechanical Flight Controls; and DH 1-2, General Design Factors.

3.6.2.1 Structural Fittings

All structural fittings used in FCSs shall comply with the design requirements specified in AFSC Design Handbook DH 1-2, Design Note DN 4B1, Design Requirements, and where applicable the design considerations specified in Design Note DN 4B2, Forgings and Castings.

3.6.2.1.1 Fail-Safe

Components subject to fatigue loads shall not only be designed to the safe-life requirements specified in the Aircraft Detail Specification, but also shall be designed fail-safe. Fail-safe design shall be achieved through either a redundant load path, a failure warning system, or a damage tolerant/free design.

3.6.2.2 Moisture Pockets

All components shall avoid designs which result in pockets, wells, traps, and the like into which water, condensed moisture, or other liquids can drain or collect. If such designs are unavoidable, provisions for draining shall be incorporated.

3.6.2.3 Temperature Range of Mechanical Components

Mechanical components not covered by design requirements specified elsewhere shall be designed to withstand ambient temperatures in the range of -65 °F (-54 °C) to 203 °F (+95 °C) and operate in a range of -65 °F (-54 °C) to 160 °F (+71 °C).

3.6.2.4 Lubrication

Where applicable, lubrication fittings, in accordance with AS35411, and AS15002, or NAS 516 shall be installed in accordance with MIL-HDBK-838. NAS 516 fittings shall be restricted to non-stressed areas only. Where lubrication fittings are used venting of the lubricated cavity, or other appropriate means, shall be employed to avoid excessive build-up of internal pressure and possible damage to the unit. The prime contractor shall specify the need for periodic lubrication, when appropriate, and the servicing interval.

3.6.2.5 Wear Life

Mechanical elements of the FCS shall be designed to the wear life and the replacement or renewal requirements of 3.4.2.1.8. Also, electronic and other non-mechanical LRUs/WRAs shall also comply with the life requirements of 3.4.2.1.8.

3.6.2.6 Cable and Pulley Subsystem Installations

3.6.2.6.1 Cable Interconnections

The minimum practical number of interconnections shall be used which allow all cable segments to be connected manually. Cable disconnects shall be located and designed so that it is physically impossible to misconnect in any manner, either cables in the same system or the cables of different systems. Cable disconnects and turnbuckles shall be so located that they will not hang up or interfere with adjacent structure or equipment or on each other and will not snag on cables, wires, or tubing.

3.6.2.6.2 Control Element Routing

Within the restrictions and requirements contained elsewhere in this specification, all portions of mechanical signal transmission subsystems, including cables, push-pull rods, and torque tubes shall be routed through the aircraft in the most direct manner over the shortest practical distances between points being connected. Protection from use as steps or handholds shall be provided.

3.6.2.6.3 Control Cable Installations

Control cable installations shall be designed to accommodate easy servicing, and the number of adjustments required shall be kept to the practicable minimum.

3.6.2.6.4 Control Cable

Cable used for the actuation of flight controls shall be the most suitable of the following types for each application. Use of carbon steel or other type cable not listed below requires procuring activity approval.

a. Flexible nylon-coated corrosion-resisting steel wire rope in accordance with MIL-DTL-83420.

b. Preformed flexible corrosion-resisting steel wire rope in accordance with MIL-DTL-83420.

c. Performed flexible corrosion-resisting nonmagnetic steel cable in accordance with MIL-DTL-18375.

3.6.2.6.5 Cable Size

Cable shall be sized to meet the load requirements of the system with ample safety factors to compensate for wear and deterioration where pulleys, fairleads, etc. are encountered. Cable size shall also be adequate in regard to permissible cable stretch, pulley friction values, and other variables which affect system performance. Where substantial loads are carried, cables shall be sized so that limit loads do not exceed 67 percent of the rated breaking strength of the cable and do not exceed the maximum cable limit loads allowed for their pulleys.

3.6.2.6.6 Cable Attachments

Corrosion-resistant steel MS swage-type cable fittings in accordance with MIL-DTL-781, swaged to form cables assemblies in accordance with MIL-DTL-6117, shall be used wherever possible. Thimble ends in accordance with MIL-DTL-6117, attached to cable by splicing and wrapping in accordance with AS56761 may be used in applications where additional joints are needed to prevent bending fatigue failures. Turnbuckles used in flight control cables systems shall be in accordance with MIL-DTL-8878. Turnbuckle and fittings shall be designed so that they are not subject to bending forces which can cause fatigue failures. Turnbuckle terminals shall not have more than three threads exposed at either end. All turnbuckle assemblies shall be properly safetied in accordance with MS33736.

3.6.2.6.7 Cable Routing

Control cables shall be arranged in parallel runs, and be accessible to inspection for their entire length. Cable runs located in aeroelastic structure, such as aircraft wings, shall be routed so as to minimize any induced control action, caused by structural flexure. Spacing between adjacent cables and between cables and adjacent aircraft components, such as electrical wire bundles and hydraulic tubing, shall be adequate to prevent cables, turnbuckles, and fittings from chafing during all operating conditions including vibration. Slack return cables shall not snag on each other or any other equipment or structure when the controlling cables are loaded to design limit loads at the adverse extremes of temperature, structural deflection, and other operating conditions. Cables shall not be subjected to critical bends at the junction with cable terminals or other attaching points such as on drums and sectors.

3.6.2.6.8 Cable Sheaves

Cable drums, sectors, and pulleys of adequate capacity and diameter for their function and to meet aircraft life requirements shall be provided. They shall be large enough in diameter at the groove root, D, relative to the cable diameter, d, and the cable wrap angle employed, that the cable strands are not overstressed. Pulleys with D/d ratios of less than 40:1 shall not be used without the approval of the procuring activity. The diameter and number of grooves on cable drums, and the radius and angle of control cable sectors shall be adequate for the required cable travel. Overtravel allowance at each end of the travel shall not be less than 5 percent of full travel and at least 10 degrees. When cable wrap varies with cable travel, the initial wrap with the sheave in the neutral position shall be at least 115 percent of the full cable unwrap over the total range of travel and overtravel. If overtravel exceeds the minimum required, cable wrap shall be increased a corresponding amount. All cable grooves on drums and sectors, machined or die cast, shall have root radii properly sized for the cable size used thereon. Specific approval shall be obtained before using plain pulleys in Essential applications. Antifriction pulleys used in FCSs shall be MS standards in accordance with MIL-DTL-7034, and the design limit load shall not exceed the allowable limit load specified for the applicable standard.

3.6.2.6.9 Cable and Pulley Alignment

For Essential and Flight-Phase Essential applications fixed-mounted pulleys shall be aligned with their cables within 2 degrees as specified in AFSC Design Handbook DH 2-1, DN 3B1, Subnote 1.1.3(1), Cable Pull. Where a control cable has an angular motion with respect to the plane of the pulleys, the maximum misalignment resulting from this motion must not exceed 2 degrees, and the cable shall not contact the pulley (or quadrant) flange for the total cable travel. For non-critical applications, neither type of misalignment shall exceed 3 degrees.

3.6.2.6.10 Pulley-Bracket Spacers

Loose spacers between pulleys, bearings, and pulley brackets shall not be used.

3.6.2.6.11 Sheave Guards

Guards shall be installed at all sheaves (pulleys, sectors, drums, etc.) as necessary to prevent the cable from jumping out of the groove of the sheave. Guards shall be installed at the approximate point of tangency of the cable to the sheave. Where the cable wrap exceeds 90 degrees, one or more intermediate guards shall be installed. All guards shall be supported in a way which precludes binding of the sheave due to relative deflections in the aircraft structure. Additional guards shall be installed on sectors as necessary to ensure retention of the cable end in its attachment under slack cable conditions. The design of the rubbing edges of the guard and the selection of materials shall be such as to minimize cable wear and prevent jamming even when the cable is slack.

3.6.2.6.12 Sheave Spacing

In any given cable run, no portion of the cable shall ever pass over more than one sheave.

3.6.2.6.13 Cable Tension

Cable rig loads shall insure positive cable tension in control and return legs of closed-loop cable installations under all operating conditions including airframe deflection and differential expansion and contraction between the cable and airframe structure throughout the designed operating temperature range. The cable return leg may be allowed to go slack when the control leg is loaded above the normal operating load at any load up to limit load. The slack shall not result in snagging on any adjacent cables, equipment or structure and there shall be no hazardous loss of system performance. Cable tension regulators shall be provided only if positive cable tension cannot be maintained in both legs, with reasonable rigging loads.

3.6.2.6.14 Cable Tension Regulators

When used, tension regulators shall maintain required tension at all times. Integral calibration shall be provided to show proper cable tension without the use of external tension meters or other equipment.

3.6.2.6.15 Fairleads and Rubbing Strips

Fairleads shall not be used to cause angular change in the direction of a cable in Essential and Flight-Phase-Essential applications if there is space for a pulley or if a straight cable run can be used. When they must be used they shall not cause any angular change greater than 3 degrees in the direction of the cable under all conditions including those due to structural deflections in flight. Fairleads shall be split to permit easy removal unless the size of the hole is sufficient to permit the cable with swage terminals to be threaded through.

3.6.2.6.16 Pressure Seals

Pressure seals shall meet compartment-sealing requirements within cable installation friction requirements. They shall be designed to preclude jamming the control system.

3.6.2.7 Push-Pull Rod Installations

Push-pull rod installations shall be designed to preclude binding or separation from the mating linkage, and shall permit servicing and rigging. Where tubular metallic rods are used, they shall be sealed to prevent the entrance and condensation of vapors.

3.6.2.7.1 Push-Pull Rod Assemblies

Push-pull rod assemblies shall be designed and installed such that inadvertent detachment of adjustable terminals is impossible, and such that any change in length due to loosening of the terminals cannot result in an unsafe condition. On any single rod assembly, adjustment shall be possible at one end only. The fixed end of each rod shall be attached to its mating linkage element in a manner which precludes rotation of the installed assembly. The adjustable end shall be of the clevis type or join a clevis type in such a manner that it also is prevented from rotating. When an unsymmetrical rod is used, such as one with a cutaway portion to allow for relative motion of an attached link, the rod end terminals and mating linkage elements shall positively prevent incorrect installation of the rod. Push-pull rods shall have a minimum wall thickness of 0.035 inches and shall be capable of withstanding loads of 1.5 times limit loads in both tension and compression without failure, buckling, or any other form of permanent deformation. All joints shall be made in a manner which precludes loosening and fatigue failure. All closed cavities in rod assemblies installed in unpressurized spaces shall be provided with drain holes adequate to drain ingested water unless cavities are airtight. All push-pull rod terminals shall incorporate antifriction bearings as specified in 3.6.2.8.1 or self-lubricating spherical bearings as specified in 3.6.2.8.2. All terminal pins shall be retained as specified in 3.5.3.7. Loose washers or other loose spacers shall not be used to maintain terminal spacing in the connecting linkage.

3.6.2.7.2 Levers and Bellcranks

Applicable requirements in AFCS Design Handbook DH 1-6 System Safety, Section 3J; Flight Control Systems, Design Note 3J2; Mechanical Flight Controls; Pulleys, Brackets and Bellcranks, and Design Note 3JX; Safety Design Check List, shall be met. Bearings shall have adequate self-aligning capability if necessary to prevent excessive deflection loads on levers and bellcranks, and, their installations shall be designed for easy replacement so that the parent part may be reused. Levers and bellcranks designed with dual load paths having the two sections positively joined by permanent fasteners, such as rivets, shall be bonded with adhesive.

3.6.2.7.3 Push-Pull Rod Supports

Where long sections of push-pull rods are utilized in applications where the probability of jamming is at least one order lower than the FCS Quantitative Flight Safety Requirements, $Q_{S(FCS)}$ in 3.1.1.3, Table 1, guides shall be installed at intervals to preclude fouling in the event of rod failure.

3.6.2.7.4 Push-Pull Rod Clearance

Clearance between push-pull rods, and between rods and aircraft equipment and structure, shall be as specified in 3.6.2.11 except that it shall also be sufficient to permit removal of adjacent LRUs/WRAs without disconnecting the rods.

3.6.2.7.5 Control Chain

Where used, control chains shall be of standard aircraft quality and conform to ANSI B29.1. Connecting links shall be retained with standard non-hardened cotter pins. Spring clips shall not be used.

3.6.2.7.6 Push-Pull Flexible Controls

Push-pull flexible controls may be used for transmitting control signals in non critical applications, but specific approval from the procuring activity must be obtained before use in Essential and Flight Phase Essential applications. Where used, they shall conform to MIL-PRF-7958. Installations shall avoid an excessive number of bends and shall maximize bend radii to keep friction forces within acceptable values and hence minimize both the induced threshold and the possibility of jamming. They shall be sealed to protect against the ingress of water, cleaning and other fluids and against all anticipated environments for the application. The routing shall preclude damage due to personnel using them as steps and handholds. Conduits shall be supported at frequent intervals, but not so tightly that the control is restrained axially. Push-pull flexible controls should not be used for PFCS functions without approval of the procuring agency.

3.6.2.8 Bearings

FCS bearings shall be selected in accordance with AFSC Design Handbook DH 2-1, Chapter 6, Airframe Bearings, and the following.

3.6.2.8.1 Anti-Friction Bearings

Approved type ball bearings in accordance with AS6038, AS6039 and AS7949 shall be used throughout the FCS, except as indicated in the following paragraphs. Bearing installation shall be arranged in such a manner that failure of the rollers or balls will not result in a complete separation of the control. Where direct axial application of control forces to a bearing cannot be avoided, a fail-safe feature shall be provided.

3.6.2.8.2 Spherical Bearings

Where space or other design limitations preclude the use of antifriction bearings, spherical-type, self-lubricating plain bearings in accordance with AS81820, or spherical or special-type all-metal bearings in accordance with AS8976 with adequate and accessible provisions for lubrication, may be used.