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AIR FORCE GUIDE SPECIFICATION

FLIGHT CONTROL SYSTEM GENERAL SPECIFICATION FOR

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AIR FORCE GUIDE SPECIFICATION

FLIGHT CONTROL SYSTEM

GENERAL SPECIFICATION FOR

This specification is approved for use within the Department of the Air Force
and is available for use by all Departments and Agencies
of the Department of Defense within the distribution limitations noted.

1. SCOPE

1.1 Scope. This specification delineates the operational needs and general parameters for a physical product family identified as Flight Control Systems(FCS) for piloted aerospace vehicles. Flight control systems are described to include all elements used to transmit flight control commands from the pilot and other sources to selected force and moment producers. Flight control commands may result in control of the air vehicle's flight path, flight trajectory, attitude, angle of attack, angle of sideslip airspeed, aerodynamic configuration, and response characteristics. Elements included are the pilots' controls, displays and logic switching, transducers, system dynamic and air data sensors, signal computation, test devices, transmission devices, actuators, uninterruptible power, and signal transmission lines dedicated to the flight control system. Excluded are aerodynamic surfaces; surface attachments, hinges, pins and cranks; engines; fire control devices; crew displays and instrumentation. Interfaces of flight control systems with related air vehicle subsystems are defined. Verification provisions are included.

1.2 Applicability. All paragraphs of this specification shall be used for each flight control system specification. Those numbered paragraphs found to be not applicable in the tailoring process shall be listed by paragraph number and title but shall be marked "N/A" in the tailored FCS specification for the specific air vehicle.

1.3 Use. This specification cannot be used for contractual purposes without rewriting the scope and providing supplemental information which relates to operational requirements for the specific air vehicle. The scope must be generated to reflect the coverage of each specific air vehicle FCS specification. The supplemental information must be derived by assessment to the stated operational needs and by interpretation of the rationale, guidance, and lessons learned provided in the appendix to this specification.

1.3.1 Structure. This specification is structured to require tailoring to specific operational needs. It establishes the paragraph numbering and flight control area for a specific air vehicle. Section 3, Requirements, defines which needs and parameters will be stated but leaves blanks within the statement paragraphs for requirements to be tailored for the specific air vehicle under consideration.

1.3.2 Instructional handbook. The instructional handbook, which is contained in the appendix herein, provides the rationale for specified requirements, guidance for inclusion of supplemental information, and a lessons learned repository.

1.4 Deviations. Deviations from Government or contractor generated air vehicle FCS specifications which can be shown to accrue substantial benefits to the Government shall be brought to the attention of the acquisition activity for consideration of change. Deviations should be numbered sequentially and identified in the numbered paragraphs affected. Addendum paragraphs should be added to the air vehicle FCS specification identifying each change and providing the rationale, justification, and benefits expected.

1.5 Contractor required documentation. Documentation and data shall be generated and updated as necessary during FCS development and test to fulfill requirements contained in the applicable contract data requirements list (CDRL). Where the CDRL shows a requirement only for data accession list/internal data, such data shall be generated to fully and completely document each development effort and task.

1.6 Classification

1.6.1 Flight control system classifications

1.6.1.1 Manual flight control systems (MFCS). Manual flight control systems consist of electrical, electronic, mechanical, hydraulic, optical and pneumatic elements which transmit pilot control commands or generate and convey commands which augment pilot control commands and thereby accomplish flight control functions. This classification includes the longitudinal, lateral, directional, lift, drag, and wing geometry control systems as well as their associated augmentation, performance limiting, and control functions.

1.6.1.2 Automatic flight control systems (AFCS). Automatic flight control systems consist of electrical, electronic, mechanical, hydraulic, optical, and pneumatic elements which generate and transmit control commands to provide pilot assistance through automatic or semiautomatic control of the flight path, attitude, or airframe responses to disturbances by references internal or external to the air vehicle. This classification includes automatic pilots, stick or wheel steering, automatic coupled pilotage, structural mode control, and similar control mechanizations.

1.6.2 FCS operational state classifications

1.6.2.1 Operational State I (normal operation). Operational State I is the normal state of flight control system performance, safety, and reliability. This state satisfies the level 1 flying qualities requirements within the operational flight envelope and level 2 within the service envelope and the stated requirements outside of these envelopes.

1.6.2.2 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 portion of the overall flight control system. A moderate increase in crew workload and degradation in mission effectiveness may result from a limited selection or normally operating FCS modes available for use; however, the intended mission may be accomplished. This state satisfies at least level 2 flying qualities requirements within the operational flight envelope and level 3 within the service envelope.

1.6.2.3 Operational State III (minimum safe operation). Operational State III is the state of degraded flight control system 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 in State III 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.

1.6.2.4 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, level 3 flying qualities necessary to allow engine restart attempt(s), a controlled descent, and immediate emergency landing shall remain.

1.6.2.5 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.

1.6.3 FCS criticality classification

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

1.6.3.2 **Mission critical.** A mission essential function is mission critical if interoperability of that function with the FCS is essential to accomplish the mission and failure or degradation of that function could result in an unsafe flight condition or control capability below Operational State II.

1.6.3.3 **Flight phase essential.** 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.

1.6.3.4 **Noncritical.** 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. APPLICABLE DOCUMENTS

2.1 Government documents

2.1.1 *Specifications, standards, and handbooks.* The following specifications, standards, and handbooks form a part of this document to the extent specified herein. Unless otherwise specified, the issues of these documents are those listed in the issue of the Department of Defense Index of Specifications and Standards (DoDISS) and supplement thereto, cited in the solicitation (see 6.2).

SPECIFICATIONS

STANDARDS

(Unless otherwise indicated, copies of federal and military specifications, standards, and handbooks are available from the Standardization Documents Order Desk, Bldg 4D, 700 Robbins Avenue, Philadelphia PA 19111-5094.)

2.1.2 **Other Government documents, drawings, and publications.** The following other Government documents, drawings, and publications form a part of this specification to the extent specified herein. Unless otherwise specified, the issues are those cited in the solicitation.

(Copies of specifications, standards, handbooks, drawings, publications, and other Government documents required by contractors in connection with specific acquisition functions should be obtained from the contracting activity or as directed by the contracting activity.)

2.2 **Non-Government publications.** The following documents form a part of this document to the extent specified herein. Unless otherwise specified, the issues of the documents which are DoD adopted shall be those listed in the issue of the DoDISS cited in the solicitation. Unless otherwise specified, the issues of documents not listed in the DoDISS are the issues of the documents cited in the solicitation.

(Applications for copies should be addressed to the (name and address of the source.)

(Non-Government standards and other publications are normally available from the organizations that prepare or distribute the documents. These documents also may be available in or through libraries or other informational services.)

2.3 **Order of precedence.** In the event of a conflict between the text of this document and the references cited herein (except for associated detail specifications, specification sheets, or MS standards), the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

3. REQUIREMENTS

3.1 System requirements. The flight control system (FCS), a subsystem of the ____(a)____ vehicle, shall provide manual and automatic control of the vehicle. The system shall provide ____(b)____ to enhance operational utility and flexibility for mission accomplishment.

3.1.1 MFCS performance requirements. The MFCS shall interface with and supplement, as required, the characteristics of both the pilot and the air vehicle to allow the flying qualities, special performance, and mission requirements to be met.

3.1.2 AFCS performance requirements. The AFCS shall interface with and supplement the characteristics of the air vehicle to provide, as selected, flight path and attitude control, airframe response and functional performance as specified in the numbered subparagraphs of this section. A pilot interface shall be provided through an AFCS controller. The controller shall be implemented through the ____(a)____ and shall, for the AFCS mode selected, provide functions, responses, and control as shown below:

Attitude Hold (Pitch)	____(b)____
Attitude Hold (Roll)	____(c)____
Heading Hold	____(d)____
Heading Select	____(e)____
Altitude Hold	____(f)____
____(g)____	____(h)____

The authority of the pilot to maneuver the air vehicle through the AFCS shall be____(i)____.

A damping ratio for non-dominant responses of at least ____(j)____critical shall be provided for nonstructural AFCS controlled responses. The AFCS shall be functionally compatible with any automatic AFCS limiter and its associated warning system and not overpower such limiters at the extremes of the flight envelope resulting in unsafe conditions that would require immediate pilot action.

3.1.2.1 Attitude hold (pitch and roll). Attitudes shall be maintained in smooth air with a static accuracy of ____(a)____ degrees in pitch attitude with wings level and ____(b)____ degrees in roll attitude. The rms attitude deviations shall not exceed ____(c)____ degrees in pitch or ____(d)____ degrees in roll attitude and shall provide at least Operational State ____(e)____ in turbulence at the rms gust intensities corresponding to ____(f)____ probability of exceedance (table I). Accuracy requirements shall be achieved and maintained within ____(g)____ seconds of mode engagement for a 5 degree attitude disturbance. Attitude hold engage limits shall be ____(h)____ degrees in pitch and ____(i)____ degrees in roll.

3.1.2.2 Heading hold. In smooth air, heading shall be maintained within a static accuracy of ____(a)____ degrees. Deviations shall not exceed ____(b)____ degrees in heading and shall provide at least Operational State ____(c)____ in turbulence at the rms gust intensities corresponding to____(d)____ probability of exceedance (table I). When heading hold is engaged, the aircraft shall roll towards wings level at a rate not to exceed ____(e)____ deg/sec and a roll acceleration not to exceed ____(f)____deg/sec/sec. The reference heading shall be that heading which exists when the mode is engaged within a tolerance of ____(g)____ degrees.

3.1.2.3 Heading select. The aircraft shall automatically turn through the smallest angle to any heading selected or preselected by the pilot and maintain that heading. In smooth air, heading shall be maintained within a static accuracy of ____(a)____ degrees. Deviations shall not exceed ____(b)____ degrees in heading and shall provide at least Operational State ____(c)____ in turbulence at the rms gust intensities corresponding to ____(d)____ probability of exceedance (table I). The 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 ____(e)____ degrees, or ____(f)____ degrees in landing configuration. Entry into and exit from the turn shall be smooth and rapid. The roll rate shall not exceed ____(g)____ deg/sec and roll acceleration shall not exceed ____(h)____ deg/sec/sec.

3.1.2.4 Lateral acceleration and sideslip limits. Except when side force control or directed sideslip is deliberately induced, the performance specified in table II shall be provided whenever any lateral-directional AFCS function is engaged. Lateral acceleration refers to apparent (measured, sensed) body axis acceleration at the aircraft center of gravity, unless otherwise noted.

3.1.2.5 Altitude hold. Engagement of the altitude hold function at rates of climb or descent less than (a) fpm shall select the existing indicated altitude and control the aircraft to this altitude as reference. The resulting normal acceleration shall not exceed (b) g incremental. For engagement at rates of climb or descent above (a) fpm, resulting normal acceleration shall not exceed (c) g incremental maneuvers. Within the aircraft thrust-drag and performance capability and at steady bank angles, the mode shall provide control accuracies specified in table III. These accuracy requirements apply for an airspeed range (d). For other airspeeds the accuracy requirements shall be (e). Following engagement or perturbation of this mode at 2000 fpm or less, the specified accuracy shall be achieved within (f) seconds. Any periodic residual oscillation within these limits shall have a period of at least (g) seconds.

TABLE I. Rms gust intensities for selected cumulative exceedance probabilities, ft/sec TAS.

		PROBABILITY OF EXCEEDANCE						
FLIGHT SEGMENT	ALTITUDE (FT)	$2x10^{-1}$	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}
TERRAIN FOLLOWING (AGL)	Up to 1000 (LATERAL)	4.0	5.1	8.0	10.2	12.1	14.0	23.1
	Up to 1000 (VERTICAL)	3.5	4.4	7.0	8.9	10.5	12.1	17.5
NORMAL FLIGHT CLIMB CRUISE AND DESCENT (ASL)	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	26.0	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 80,000	0	0	0	0	2.1	5.1	7.2

3.1.2.6 Altitude select. Engagement of the altitude select function at rates of climb or descent less than __(a)__ fpm shall result in the aircraft automatically climbing or descending to any altitude preselected by the pilot or within an automatic navigation or guidance program. The resulting normal acceleration shall not exceed __(b)__ g incremental, and the resulting climb or descent shall not exceed __(a)__ fpm. For engagement at rates of climb or descent above __(a)__ fpm, resulting normal acceleration shall not exceed __(c)__ g incremental maneuvers. Within the aircraft thrust-drag and performance envelope, and at steady bank angles, the mode shall provide control accuracies specified in table III. These accuracy requirements apply for an airspeed range __(d)__. For other airspeeds, the accuracy requirements shall be __(e)__. Following engagement of this mode, the specified accuracy shall be achieved within __(f)__ seconds after initial crossing of selected altitude. Any periodic oscillation within these limits shall have a period of a least __(g)__ seconds.

TABLE II. AFCS lateral acceleration and sideslip limits.

Flight Condition	Incremental Sideslip - Degrees	Lateral Acceleration 1-g
Coordination in steady banked turns		
Lateral Accelerations		
Rolling at:		
30°/sec		
90°/sec		
over 90°/sec		
Coordination in steady "straight and level" flight		

TABLE III. Control accuracy for altitude hold AFCS function.

Altitude in feet				
	Bank angle in degrees			

3.1.2.7 Automatic hovering. Position shall be maintained relative to the point of reference to an accuracy of __(a)__ feet. This accuracy requirement applies during gust intensities of __(b)__ ft/sec, and wind, or point of reference, velocities up to __(c)__ knots.

3.1.2.8 **Mach hold.** The Mach number existing at the engagement of Mach hold shall be the reference. After engagement and stabilization on Mach hold, the AFCS shall maintain indicated Mach number and the error shall not exceed ___(a)___ Mach or ___(b)___ 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 ___(c)___ seconds. A mode response or maximum time to capture reference suitable for the mission phase shall be ___(d)___ seconds. Adjustment capability of at least ___(e)___ Mach shall be available to allow the pilot to vary the reference Mach number around the engaged Mach number.

3.1.2.9 **Airspeed hold.** The airspeed existing at the engagement of airspeed hold shall be the reference. Indicated airspeed shall be maintained within ___(a)___ knots or ___(b)___ percent of the reference speed, whichever is greater, up to ___(c)___ degrees bank angle. Any periodic oscillation within these limits shall have a period of at least ___(d)___ seconds. The mode response or maximum time to capture reference shall be ___(e)___ seconds in the most demanding mission phase. Adjustment capability of at least ___(f)___ knots shall be available to allow the pilot to vary the reference around the engaged airspeed.

3.1.2.10 **Automatic navigation and guidance.** The AFCS shall provide automatic control to intercept and maintain the track defined by the following equipment/subsystems: ________________________. Maneuvers commanded by the AFCS during any phase of such operation shall not place the air vehicle in hazardous attitudes or result in flight limitations being exceeded. Switching and sequencing, and air vehicle body axis rates and accelerations shall result in smooth, nonoscillatory air vehicle control and rapid reduction of error. There shall be no residual oscillations greater than those allowed in the flying qualities requirements for this air vehicle. Requirements for specific equipment/subsystems are as follows: ________ ________.

3.1.2.11 **Control stick (or wheel) steering.** The control stick (or wheel) steering function, as a selectable operating mode, shall ___(a)___. The maneuver limits of the AFCS and the control force limits established by the flying qualities requirements shall apply during control stick (or wheel) steering operations. The pilot shall retain full authority to maneuver the air vehicle within the applicable force and maneuver limits of the flying qualities by reversion to the ___(b)___ function of the FCS. Any reversion or change of mode shall be adequately annunciated to the pilot.

3.1.2.12 **G loss of consciousness (GLOC) systems.** When a GLOC signal is received, the aircraft shall roll through the shortest route possible to wings level and then execute a dive recovery using the maximum g's available up to ___(a)___ g's. Once the recovery is accomplished, which will be determined by ___(b)___, the aircraft shall hold level altitude flight until ___(c)___. If the throttle setting is not sufficient to maintain altitude, ___(d)___. Warning of autorecovery shall be annunciated to the pilot. The pilot shall have control authority to override any autorecovery. There shall be automatic logic to prevent activation of the GLOC recovery system during the following critical flight phases: ___(e)___.

3.1.2.13 **Ground collision warning system(s) (GCWS).** The minimum acceptable performance of the GCWS shall be as follows: ________________________.

3.1.3 **General FCS design.** The design of the FCS shall be entirely suitable for the purpose, mission, and general requirements of the air vehicle. The FCS shall be as simple, direct, and foolproof as possible with respect to design, installation, operation, inspection, and maintenance. The design shall not include features or details which experience has shown to be hazardous or unreliable. Each control and each control loop shall be designed to operate with the ease, smoothness, and positiveness appropriate to its function.

3.1.3.1 **System arrangement.** Assembled elements, subsystems, and separate channels and control loops of the FCS shall be arranged and located in the air vehicle ________________.

3.1.3.2 **Trim controls.** The FCS shall provide trim control conforming to the following requirements: ____ ____.

3.1.3.3 System operation and interface. Separation and isolation shall be provided between ___(a)___ to make the probability of propagated or common mode failure extremely remote. Operational performance shall be met by the FCS ___(b)___ seconds after power is applied. Positive means of disengagement shall be provided for ___(c)___. Mode selection logic shall enhance operational and mission capability and shall provide ___(d)___. Transients due to failures, disengagements, and changes in operating modes shall not exceed ___(e)___.

3.1.3.4 Failure immunity and safety. Within the permissible flight envelope, no single failure in the FCS, which is not extremely remote, shall result in any of the following effects before a pilot or safety device can take effective corrective action.

a. __________
b. __________
c. __________

3.1.3.5 Redundancy. The redundancy requirements shall be as shown in table IV. Exceptions to this requirement should be identified on a component level in cases where cost/complexity/safety trade-offs may indicate less redundancy is required. Specific approval to implement less redundancy must be received from the Government procuring activity.

3.1.3.5.1 Redundancy management. In FCS which utilize electric or electronic redundant channels, redundancy management shall provide ______________________________.

3.1.3.6 Stability. For all closed loop FCS, the required gain and phase margins about nominal shall be as shown in table V. For gain or phase variations within the indicated frequency bounds, no oscillatory instabilities shall exist with amplitudes greater than those allowed for residual oscillations in 3.1.3.8, and any non-oscillatory divergence of the aircraft shall remain within the applicable limits of the flying qualities requirement.

TABLE IV. Redundancy levels.

	CONTROL LOOP	REDUNDANCY
MFCS PITCH ROLL YAW HI LIFT DRAG		
AFCS ATTITUDE NAV/GUID HOLD		

TABLE V. Gain and phase margin requirements (db, degrees).

Mode Frequency Hz \ Airspeed	Airspeed: Below V_{oMIN}	V_{oMIN} to V_{oMAX}	At Limit Airspeed (V_L)	At 1.15 V_L
$f_m < 0.06$				
$0.06 \leq f_m <$ First Aero Elastic Mode				
$f_m >$ First Aero-Elastic Mode				

Where: V_L = Limit airspeed

V_{oMIN} = Minimum operational airspeed

V_{oMAX} = Maximum operational airspeed

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

GM = Gain Margin = The minimum change in loop gain, at nominal phase, which results in an instability beyond that allowed as a residual oscillation

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 contractor's best estimate or measurement of FCS and aircraft phase and gain characteristics available at the time of requirement verification

During the gain and phase variations, the AFCS loops shall be stable for any amplitudes greater than those allowed for residual oscillations in 3.1.3.8. In multiple loop systems, variations shall be considered with all gain and phase values in the feedback paths held at nominal values except for the path under investigation.

A path is defined to include those elements connecting a sensor to a force or moment producers. For both aerodynamic and non-aerodynamic closed loops, at least 6 db gain margin shall exist at zero airspeed. The margins specified shall apply regardless of system implementation and shall be maintained under flight conditions of most adverse center-of-gravity, mass distribution, and external store configuration throughout the operational envelope and during ground operations.

3.1.3.6.1 Sensitivity analyses. 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 test values or predictions and in-service operation due to such factors as poorly defined nonlinear and higher order dynamics, anticipated manufacturing tolerances, aging, wear, maintenance, and noncritical materiel failures. In addition, these tolerances shall also include normally anticipated uncertainties in predicted aerodynamic characteristics, aeroelastic effects, and structural modes. For digital flight control systems, the tolerances established shall specifically include the effects of sampling rates, digital system delay, input and output filters, digital filter implementation, and integration technique. Gain and phase margins shall be defined, based on these tolerances, which shall assure satisfactory operation in fleet use. These gain and phase tolerances shall be established based on variations in system characteristics either anticipated or allowed by component or subsystem specification. The range of variation to be considered shall be based on a selected probability of exceedance for each type of variation. The exceedance probability shall be based on the criticality of the flight control function being provided. The stability requirements established through this sensitivity analysis shall be entered in table IV.

3.1.3.7 Operation in atmospheric disturbances. During normal operation the FCS shall provide a safe level of operation and maintain mission accomplishment capability while flying in atmospheric disturbances. For essential and flight phase essential FCS functions, at least Operational State __(a)__ shall be provided for gust intensities corresponding to exceedance probabilities __(b)__ and __(c)__, respectively (table I). Noncritical controls shall provide at least Operational State __(d)__ in atmospheric disturbances at the intensities corresponding to __(e)__ probability of exceedance (table I) . 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. __(f)__ means to inactivate the noncritical control for flight in heavy disturbances shall be used when required. The dynamic analysis or other means used to satisfy this requirement shall include the effects of rigid body motion, ____(g)____, and the flight control system. Significant nonlinear effects shall be represented by conservative nonlinear or equivalent linear representations. The analytical form of the atmospheric disturbance models specified in the flying qualities requirements, with the exception of the discrete gust, shall be used for flight control analyses at the intensity levels specified herein. The discrete gust to be used shall be defined as a single full wave of a (1-cos) function with a peak amplitude of 40 ft/sec which may be encountered anywhere within the operational flight envelope. Varying gust amplitudes up to 40 ft/sec shall produce near linear air vehicle response. The gust wave length shall be tuned to produce maximum excitation. The gust intensity levels apply at the turbulence penetration airspeed V_G. At the maximum level flight airspeed, V_H, these intensity levels are reduced to ____(h)____ of the specified levels for atmospheric disturbances.

3.1.3.8 Residual oscillations. For normal operation and during steady flight, FCS induced aircraft residual oscillations at all crew and passenger stations shall not exceed __(a)__ g's vertical or __(b)__ g's lateral peak to peak acceleration. Residual oscillations in pitch attitude angle shall satisfy the longitudinal maneuvering characteristic requirements of the flying qualities specification. Residual oscillations in roll and yaw attitude at the pilot's station shall not exceed __(c)__ degrees peak to peak for flight phases requiring precision control of attitude.

3.1.3.9 System test, display, reporting, and monitoring provisions (TDRM). Test and monitoring incorporated into the essential and flight phase essential FCS shall include: ____.

Table VI defines the applicable tests and the air vehicle functions to the flight phase:

TABLE VI. Applicable tests and the air vehicle functions to the flight phase.

PHASE / TEST	PREFLIGHT	INFLIGHT	POSTFLIGHT
______	______	______	______
______	______	______	______
______	______	______	______
______	______	______	______
PHASE / TEST	**PREFLIGHT**	**INFLIGHT**	**POSTFLIGHT**
______	______	______	______
______	______	______	______
______	______	______	______
______	______	______	______

3.1.3.9.1 Preflight. Preflight BIT shall be __(a)__ and include any test sequence (see table VI) prior to takeoff. Preflight tests shall not rely on ground test equipment for their successful completion. Interlocks shall be provided to prevent in-flight engagement and to terminate preflight BIT when the conditions for engagement no longer exist. It shall be possible to perform preflight tests by manipulation of the following equipment: ______________(b)______________.

Test provisions shall include the capability for determining the integrity of the following by the corresponding test: ______________(c)______________.

The functional capability of the following in their fail operational modes shall also be determined by the corresponding test: ______________(d)______________.

The overall tests performed (BITs, VI, PPM, SPCL) contain the following specific related tests: ______________.

3.1.3.9.2 Inflight. Inflight TDRM of equipment performance and critical flight conditions shall operate during __(a)__ and shall be capable of detecting: ______(b)______.

Inflight TDRM shall be passive and not propagate any failures to the __(c)__ flight controls.

Inflight TDRM shall include, but not be limited to, the following capabilities: ______(d)______.

3.1.3.9.3 Postflight. Postflight shall __(a)__ and include the test sequences shown in table VI. Postflight test, display, and reporting shall be capable of __(b)__. Postflight maintenance tests shall have interlocks to prevent inflight engagement and to terminate these tests when conditions suitable for maintenance testing no longer exist.

3.1.3.9.4 Inflight monitoring. Continuous inflight monitoring of equipment performance and critical flight conditions shall operate during __(a)__ and shall be capable of detecting: ______(b)______.

Inflight monitoring shall be passive and not propagate any failures to the __(c)__ flight controls.

Inflight monitoring shall include, but not be limited to, the following capabilities: ______(d)______.

3.1.4 MFCS design. *This section of the specification deals with overall design philosophy of the flight control system. This section is normally completed by the contractor after conducting a series of trade studies to satisfy that system's safety, mission completion, and system reliability requirements. Care must be taken when completing this section to assure that it is in compliance with the overall acquisition strategy of weapon system being procured (For example, some acquisition strategies may insist that no design guidance* be included in any specification). Where requirements in other sections of this specification are performance related requirements, the intent of this section is to provide protection to both the contractor and the procuring activity to assure that the system design is within safety and reliability requirements, and to further assure the procuring activity that major modifications to that design cannot be accomplished without government concurrence. From the procuring agency standpoint, care must be exercised to assure that over specification does not result in Engineering Change Proposals (ECPs) for minor changes or for routine changes during normal system development.

The MFCS shall be mechanized as a __(a)__ using __(b)__ for pilot control of pitch, roll, and yaw. The system shall provide __(c)__ to enhance operational utility and flexibility for mission accomplishment. It shall be designed to provide a satisfactory physical interface between the pilot and the air vehicle such that every pilot action required to monitor and control the FCS to accomplish every phase of any assigned mission shall be consistent with established flying qualities requirement and pilot training practices.

3.1.4.1 Mechanical MFCS design. Mechanical components shall be designed with paramount consideration given to reliability, maintainability, supportability, strength, and simplicity. The mechanical signal transmission paths between the pilot, sensors, or command generator to the surfaces shall be redundant to the extent required to meet the system safety requirement of ________________.

3.1.4.1.1 Reversion--boosted systems. The mechanical FCS shall provide Operational State ______ capability when boost is unavailable. Means shall be provided to re-engage boost following reversion to the mechanical system. Boosted, mechanical FCS shall provide Operational State _________ capability.

3.1.4.1.2 Use of mechanical linkages. Mechanical linkages and artificial feel devices/systems used for signal conversion shall not have friction/free play that results in operation below Operational State ______. Linkages and feel devices shall be balanced appropriately for the desired axis to meet the structural mode and force requirements for this air vehicle. Residual imbalances shall be consistent with feel requirements.

3.1.4.2 Electrical/electronic MFCS design. Electrical/electronic fly-by-wire flight control systems shall be designed to withstand all induced and natural environments such as lightning, EMI, etc. Redundancy shall be employed to achieve the safety requirements of the air vehicle. Reliability, maintainability, supportability, simplicity, and survivability shall be major design parameters. The design is required to have operational State I capability.

3.1.5 AFCS design. AFCS design shall provide those functions and services which fulfill not only the stated needs for the air vehicle, but also the needs for a satisfactory interface with the pilot operator. AFCS design shall be integrated with and complement the MFCS design such that switching between these systems produces no noticeable air vehicle responses. AFCS design shall have no adverse effect on MFCS operational integrity.

3.1.5.1 System management. The __(a)__ management function shall be responsible for ensuring that the automatic flight control system does not permit failures to place the aircraft in an unrecoverable situation. Transients for normal engagement/disengagement and failures shall not exceed __(b)__ and __(c)__, respectively. Failures of the __(d)__ management function shall __(e)__. Appropriate __(f)__ to the crew with __(g)__ to re-engage __(h)__ shall be provided.

3.1.5.2 Mission flight controls. Mission flight controls are the modes of the automatic flight control system that provide trajectory guidance or trajectory stabilization automatically without pilot input. Mission flight control guidance commands (e.g., flight director, bomb Nav, terrain following, integrated fire and flight controls, autopilot, etc.) shall be managed by __(a)__. The guidance signals shall allow neither transients greater than specified in 3.1.5.1 nor erroneous commands. Interface requirements shall be __(b)__. Failures of the mission flight control system shall not __(c)__. Appropriate methods of interlocks for engagement/disengagement of mission flight controls shall be provided with __(d)__ for flight safety.

3.1.6 Mission accomplishment reliability. The probability of mission failure per flight due to relevant materiel failures in the FCS shall not exceed ____________________.

3.1.7 Quantitative flight safety. The probability of air vehicle loss per flight, defined as extremely remote, due to relevant materiel failures in the FCS shall not exceed ________________________.

3.1.8 Survivability. The FCS shall be designed to withstand and operate in unnatural, induced, hostile environments, which would not otherwise cause loss of the air vehicle, without suffering abortive impairment of its ability to maintain at least Operational State __________.

3.1.8.1 All engines out control. The FCS and its power sources shall be designed such that loss or reduction of rotational speed of all power generating engines below power generation speed shall not result in less than FCS Operational State _____. Transients due to change in operational state shall conform to 3.1.3.3 requirements of this specification. Provisions shall be made for reversions to normal operation when sufficient engine generated power is restored.

3.1.9 Invulnerability. Degradation in flight control system operation due to ________________ shall be within the limits specified in the following subparagraphs.

3.1.9.1 Invulnerability to natural environments. The flight control system shall be designed to withstand the full range of natural environment extremes established for this air vehicle without permanent degradation of performance below FCS Operational State __(a)__, or temporary degradation below FCS Operational State __(b)__. Reductions below State __(a)__ 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 structure 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, __(c)__, and build up of manufacturing tolerances.

Specifically, the FCS shall be able to withstand the following natural environmental conditions: __(d)__.

3.1.9.2 Invulnerability to lightning strike and static atmospheric electricity. Flight control system shall maintain Operational State __(a)__ capability or better when subjected to electric field and lightning discharges except that a temporary, recoverable, or extensive loss of performance to Operational State __(b)__ is allowable in the event of a direct lightning strike.

3.1.9.3 Invulnerability to induced environments. Flight control systems 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 radiation including electromagnetic pulse, projected in missions for the air vehicle, without permanent degradation or loss of capability to maintain FCS Operational State __(a)__. These induced environments within structural and crew survival limits shall not result in temporary degradation during the exposure to the environment below FCS Operational State __(b)__ capability. Specifically, but not exclusively, the FCS shall be designed to withstand the following: ______________(c)______________.

3.1.9.4 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. In addition, the FCS design shall comply with the following:

a. Essential and flight phase essential flight control systems shall retain FCS capability of Operational State __(a)__ or better after sustaining the following failures: ______________(b)______________.

b. Flight control systems, including the associated structure hydraulic, pneumatic, and electrical systems shall be designed so that the probability of losing the capability of maintaining FCS operation to no less than Operational State ___(c)___ as a result of an engine or other rotor burst is extremely remote.

c. ______________________________(d)______________________________.

3.1.9.5 Invulnerability to maintenance error. Flight control systems 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 flight control system on the aircraft, except during initial buildup, major overhaul, software modification, or rigging during major maintenance activities, shall be minimized. All line replaceable units (LRUs) shall be designed to permit making internal adjustments only on the bench. The system shall require only a minimum of rerigging following replacement of LRUs. All control linkages and other flight control mechanisms shall be designed to resist jamming from inadvertent entry of maintenance tools or other materiel. In addition ____________ ____________________.

3.1.9.5.1 Invulnerability to software maintenance error. The following provisions shall be implemented for systems using digital computations to prohibit the implementation of the incorrect version of software: ____.

3.1.9.6 Invulnerability to pilot and flight crew inaction and error. Flight control systems shall be designed to minimize the possibility of any flight crew member controlling or adjusting system equipment to a condition or state which could degrade FCS operation. Included shall be: ____________________.

3.1.9.7 Invulnerability to enemy action. Essential and flight phase essential FCS on combat aircraft, including associated structure and power supplies, shall not be degraded below Operational State ______ because of damages due to ____________________________.

3.1.9.8 Invulnerability to bird strikes. Flight control system shall maintain Operational State ________ capability or better when subjected to one or more bird strikes on a leading edge of the aircraft. This shall be accomplished by: ____________________________.

3.1.10 Maintenance provisions. Design and installation of the FCS shall permit trained FCS maintenance personnel to safely and easily perform required maintenance under all anticipated environmental conditions. Means shall be provided to facilitate the accomplishment of all required maintenance functions including: ____________________________.

3.1.10.1 Operational checkout provisions. The design and installation of the FCS shall provide for ground operation as required to verify FCS functional performance, airworthiness and freedom from failures. Operation of the main propulsion engines shall not be required for this checkout. Power for the checkout shall be supplied by ____________________________.

3.1.10.2 Malfunction detection and fault location provisions. Means of having a high probability for detecting malfunctions and failures, and monitoring critical performance conditions as required to locate faults to the replaceable unit, shall be provided for ______________________.

3.1.10.2.1 Malfunction indication. Indications which show that a malfunction has been detected and where the fault is located shall be provided by ____________________________.

3.1.10.2.2 Provisions for checkout with portable test equipment. Provisions shall be made to check out elements of the installed FCS by using portable test equipment identified as ____________________.

3.1.10.3 Accessibility and serviceability. The FCS and its elements shall be designed, installed, located, and provided with access so that inspection, rigging, removal, repair, replacement, and lubrication can be readily accomplished.

Suitable provisions shall be made to facilitate correct rigging of the FCS. The number of rigging positions shall be kept to a practical minimum. Rigging positions shall be readily accessible and located where adequate space is available for the rigging operation. Powered control surface actuator outputs shall not be rig-pinned.

3.1.10.4 Maintenance personnel safety provisions. The FCS and its elements shall be designed to preclude injury of personnel during the course of all maintenance operations including testing. Where positive protection cannot be provided, precautionary warnings or information shall be affixed in the aircraft and to the equipment to indicate any hazard, and appropriate warnings shall be included in the applicable 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 streamers which are highly visible. All such streamers shall be of a type which cannot be blown out of sight such as up into a cavity in the air vehicle.

3.1.11 Structural integrity. The FCS and its elements shall be designed to meet the load, strength, deformation, damage tolerance, stiffness, and durability requirements of ______________________.

3.1.12 Wear life. Assembled unit elements of the FCS shall remain economically repairable and meet reliability requirements for a wear life equal to ______________________.

3.2 Subsystem and component design requirements. Subsystems, subfunctions, components, elements, and assemblies of the FCS and subsystems interfacing with the FCS shall be designed, fabricated, and installed as indicated in the subparagraphs of this section.

3.2.1 Cockpit controls and displays. The design and location of the FCS cockpit control elements and displays shall be in accordance with ______________. Additional requirements are stated in the following subparagraphs.

3.2.1.1 Cockpit controls. Whenever a FCS control is interfaced with redundant flight control channels, mechanical and electrical separation and isolation shall be provided to make the probability of common mode failures ________________________.

3.2.1.1.1 Removable cockpit flight controls. Removable cockpit flight controls shall be positively retained during all flight conditions.

3.2.1.1.2 Movable rudder or directional pedals. Movable rudder or directional pedals shall be interconnected to insure positive movement of each pedal in both directions.

3.2.1.2 Pilot displays. Wherever any display or annunciator is interfaced with redundant flight control channels, mechanical and electrical separation and isolation shall be provided to assure that common mode failures do not occur.

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

AFCS engaged
mode engaged

3.2.1.2.2 FCS warning annunciation. FCS warning annunciation shall be provided in the cockpit to allow crew to assess the operability of redundant or monitored FCS. Annunciation shall be designed to clearly indicate the associated degree of urgency.

a. First degree - immediate action required (warning may be audible)

b. Second degree - caution, action may be required

c. Third degree - informational; no immediate action required.

Warning annunciation shall include, but not be limited to the following: ______________________.

3.2.1.2.3 Cockpit Indicators. Suitable indications shall be provided in the cockpit to indicate to the pilot(s) ______________________.

3.2.2 Sensors. Sensors used for flight control system functions shall be designed and located such that adequate sensing of the desired aircraft and flight control system parameters can be accomplished. Sensors shall be designed to operate throughout the power range specified for the air vehicle. Locations shall be chosen which minimize exposure to conditions which could produce failures or undesirable output signals. Signal and impedance levels for remote sensors shall be designed to minimize EMI effects and to prevent signal level changes due to transmission path loading effects. Closely spaced, redundant electromagnetic sensors shall be designed to prevent cross coupling of signals among the sensors. If self-test or in-flight monitoring BIT are used, the sensors and flight control system shall be fail safe in design in regard to the operation of the BIT.

3.2.3 Signal transmission. All signal transmission concepts, devices, lines, components, and subsystems dedicated to the FCS shall be covered by requirements in this section.

3.2.3.1 General requirements. All signal transmission elements, components, and subsystems of the FCS shall be designed and suitably protected to resist jamming by objects. Where feasible, advantage shall be taken of shielding afforded by heavy structural members, existing armor, and other equipment for protection of important elements of the FCS. Signal transmission elements shall be protected from usage such as steps and handholds. Clearance between FCS elements and structure or other components shall be provided as necessary to insure that no probable combination of temperature effects, air loads, structural deflections, vibration, buildup of manufacturing tolerances, or wear can cause binding or jamming of any portion of the FCS. In locally congested areas, the minimum clearances which may be allowed after all adverse effects are accounted for shall be ______________________.

3.2.3.1.1 Computer signal transmission. Signal transmission of commands between the flight control computers and devices or modules designed to act on the commands shall be performed by using direct ______________________. When redundant computing paths are provided, they shall be isolated or separated to meet invulnerability and failure immunity requirements.

3.2.3.2 Mechanical signal transmission, general. Elements used for mechanical signal transmission shall meet the structural integrity requirements of this specification. Capability shall also be provided to transmit forces to override interference or jams in the mechanical loop up to a level of at least ______________.

3.2.3.2.1 Control cable installations. Wire rope type cable subsystems used for FCS signal transmission shall meet requirements of this specification with respect to performance, safety, maintainability, reliability, structural integrity, and wear life. Requirements for component design and usage shall be as shown in ______________________.

3.2.3.2.2 Push-pull signal transmission installations. Push-pull type subsystems used for FCS signal transmission shall meet other requirements of this specification with respect to performance, safety, maintainability, reliability, structural integrity, and wear life. Requirements for component design and usage shall be as shown in ______________________.

3.2.3.2.3 Control chain. Roller chain may be used for signal transmission in FCS mechanization. Connecting links shall be retained by cotter pins; spring clips shall not be used. The chain used shall be of standard aircraft quality and conform to requirements of ______________________.

3.2.3.3 Electrical signal transmission. The following requirements apply to all essential and flight phase essential signal paths: ______________________.

3.2.3.3.1 Multiplexing. Signal transmission circuits shall be ___(a)___ type utilizing ___(b)___ as the transmission media for the data bus. The data bus, line, and its interface electronics, multiplier terminal unit shall ___(c)___.

3.2.4 Signal computation. The methods of signal computation used in the FCS shall be fully suitable to mission, environment, and other requirements imposed upon the FCS.

3.2.4.1 Transient power effects. Flight control computers shall not suffer adverse effects, which result in operation below FCS Operational State _____, due to 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.

3.2.4.2 Mechanical signal computation. Mechanical signal computation shall be accomplished by means of ____________ elements. Nonlinearities and parameter variations shall not cause adverse effects which cause degradation in flying qualities or the FCS operational state.

3.2.4.3 Electrical signal computation. At the time that the production configuration baseline is established by the procuring agency, a ______ percent growth capability for computation shall exist within each flight control computer. Scaling, ____________ shall provide satisfactory resolution and sensitivity to ensure continuous safe operation for all possible combination of maneuvering demand and gust or other plausible disturbances, and to prevent unacceptable levels of nonlinear characteristics or instabilities.

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

Support and maintenance provisions shall________________.

3.2.5 Control power. 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 airplane performance shall not be greater than ____ ______________________. Essential and flight phase essential flight controls shall be given priority over noncritical controls and other actuated functions during simultaneous demand operation.

3.2.5.1 Hydraulic power subsystems. All hydraulic power generation and distribution systems normally used for flight control shall be designed in accordance with ______________________.

The FCS shall operate in accordance with this specification when applied with such power.

3.2.5.2 Electrical power subsystems. Electrical power generation and distribution subsystems should comply with requirements of this specification and the following: ______________________. For fly-by-wire air vehicles, electrical systems which provide power to essential or flight phase essential controls shall be designed to ensure uninterruptible, isolated, redundant power of adequate quality to meet FCS requirements after any malfunction not considered extremely remote.

3.2.5.3 Pneumatic power subsystems. Pneumatic power using ram-air, engine bleed air, stored gas, mechanically compressed air, or generated gas may be used for noncritical flight control functions. Pneumatic power systems shall conform to ______________________.

3.2.6 Actuation. The design, installation, and performance of flight control actuation components, subsystems, and interfaces shall comply with this specification. Load capability of actuation components and subsystems shall be in accordance with ______________________.

3.2.6.1 Mechanical force transmitting actuation. Mechanical force transmitting devices shall be designed in accordance with the following requirements: ______________________.

3.2.6.2 Mechanical torque transmitting actuation. Mechanical torque transmitting devices shall be designed in accordance with the following requirements: ______________. Backlash accumulation shall not prevent the system from performing its required function throughout the service life of the airplane.

3.2.6.3 Hydraulic actuation. Hydraulic actuation subsystems and components shall be designed in accordance with the following requirements: ______________. If hydraulic bypass provisions are necessary to prevent fluid lock, excessive friction load or damping, ______________. In actuation systems designed for manual control following hydraulic failure, provisions shall be made to ______________.

3.2.6.4 Electromechanical actuation. Electromechanical actuation subsystems and components shall be designed in accordance with the following requirements: ______________________.

3.2.6.5 Pneumatic actuation. Pneumatic actuation subsystems and components shall be designed in accordance with the following requirements: ______________________.

3.2.6.6 Interfaces between actuation systems, support structure, and control surfaces. The interface between actuation system, support structure, and control surfaces shall comply with ______________.

3.2.7 Component design. Design of components and elements shall be entirely suitable for use in the FCS and shall be such that the other requirements established for the FCS are not infringed by that design.

3.2.8 Component fabrication. The selection and treatment of materiel, and the processes and assembling methods used in fabrication shall ______________________.

3.2.9 Component and element installation. Installation of FCS components shall meet ______________.

3.3 Integrity requirement. The FCS component's hardware and software and integrity subsystems shall meet the integrity requirements of this section.

3.3.1 Structural integrity. Load transmission and elements of the FCS shall meet the load, strength, stiffness, deformation durability, and damage tolerance requirements for each element as follows:

a. ______________.

b. ______________.

3.3.2 Mechanical integrity. FCS mechanical devices such as rudder pedals, stick, inertial sensors, actuators, etc., and integrating subsystems shall meet the requirements for load, strength, function, environment, and durability as follows:

a. ______________.

b. ______________.

3.3.3 Electronic integrity. FCS electronic and electro-mechanical devices such as computers, convertors, power supplies, servo's, etc., and integrating subsystem electronics shall meet the functional, environmental, and durability requirements as follows:

a. ______________.

b. ______________.

3.3.4 Software integrity. Software elements (units, components, and flight programs) of the FCS and integrating subsystems shall meet the requirements as follows:

a. ____________________.

b. ____________________.

4. VERIFICATION

4.1 System verification. Verification of the system requirements shall be performed by analyses (includes simulation), inspection, demonstration, ground test, and flight test.

The approach used for quality assurance shall provide a planned and systematic pattern of all actions, structured and time phased throughout the program, to provide adequate confidence that the FCS, its elements, and software conform to the established technical requirements. Compliance with each applicable requirement in section 3 shall be verified as required by its dedicated section 4 paragraph. The lack of a specific verification requirement for any portion of a design requirement in section 3 does not relieve the contractor of responsibility for full compliance with the requirement. The verification processes shall be thoroughly documented and shall clearly show that methods used are suitable and proper, that the procedures followed are comprehensive and thorough, that requirements have been met, and that high quality is a built-in attribute.

When requirements are verified by analyses and flight test, the flight envelope shall be analyzed to determine worst case combinations of airspeed, altitude, gross weight, center of gravity, and maneuver. Flight tests shall be conducted at, or sufficiently near, these cases to validate the adequacy of analytical results. Analytical results shall not be accepted until such validation is accomplished. Test instrumentation shall include appropriate measurement of attitudes, rates, accelerations, controller position and force levels, surface position, thrust, altitudes, altitude rate, and internal flight control system signals and states as required to verify hardware and, if used, software performance.

Requirement verifications which must be completed to support the release of the air vehicle for first flight shall be ____________________________________.

The processes incident to verification of each requirement shall be documented in engineering detail to the extent necessary to show the quality and flight-worthiness status which is exhibited for each unit of product.

4.1.1 MFCS performance verification. MFCS performance shall be verified by inspection, analysis, and ground and flight test. Test conditions, fixtures and methods are as follows: _________________________.

4.1.2 AFCS performance verification. AFCS performance requirements shall be verified as indicated in the subparagraphs of this section. The specified damping ratio for nonstructural AFCS controlled response shall be verified by ______________________________.

4.1.2.1 Attitude hold (pitch and roll). Attitude hold shall be verified by inspection, analyses, and flight test. Test condition, fixtures, and methods are as follows: __________________________________.

4.1.2.2 Heading hold. Heading hold performance parameters shall be verified by a combination of flight tests and _________________. Flight testing shall be performed ________________________.

4.1.2.3 Heading select. Heading select performance parameters (heading accuracy, overshoot, roll rate and acceleration, bank angle limits, and smallest angle to select heading) shall be verified by flight test and ______________________. Flight testing shall be performed ______________________.

4.1.2.4 Lateral acceleration limits and sideslip limits. Lateral acceleration shall be verified by flight tests and ______________. Flight testing of lateral acceleration limits shall be performed ______________.

4.1.2.5 Altitude hold. Resulting normal acceleration, accuracy, and time to achieve accuracy shall be verified in smooth air by flight test and __________. Flight testing shall be performed ______________. Ability to engage or not engage shall be verified by attempting to engage during a climb or descent of ______ ________ fpm at all fight test points.

4.1.2.6 Altitude select. Resulting normal acceleration, accuracy, and time to achieve accuracy shall be verified in smooth air by flight test and __(a)__. Flight testing shall be performed __(b)__. Ability to engage or not engage shall be verified by attempting to engage during a climb or descent of __(c)__ fpm at all flight test points. Ability to maintain sustained load factor or climb or descent rate shall be verified by engaging __(d)__ feet above and below selected altitude.

4.1.2.7 Automatic hovering. Automatic hovering requirements shall be verified by ______________.

4.1.2.8 Mach hold. The Mach hold requirements shall be met during maneuvering flight incident to cruise and in steady flight including climb and descent. Verification shall be made by flight test and __________. Flight testing shall be performed ________________.

4.1.2.9 Airspeed hold. Time to stabilization and accuracy of airspeed hold shall be verified by a combination of flight test and ________________________. Operation during landing approach shall also be verified. Flight testing shall be performed ________________.

4.1.2.10 Automatic navigation and guidance. Verification of navigation and guidance requirements shall be through qualitative assessment by the pilot during ________________ and by ________________.

4.1.2.11 Control stick (or wheel) steering. Control stick (or wheel) steering flying qualities, accuracy, stick force, and maneuvering limits shall be verified by a combination of flight test and ______________. Flight testing shall ________________.

4.1.2.12 G loss of consciousness (GLOC) systems. The GLOC recovery system shall be tested to verify that nuisance activations will not occur and that the recovery minimum altitude lost or occurs within ______ of the set altitude.

4.1.2.13 Ground collision warning systems. The GCWS performance requirements shall be verified by ________________________________.

4.1.3 General FCS design. The FCS design requirements contained in subparagraphs of 3.1.3 shall be verified by ______________________________ and ______________________________.

4.1.3.1 System arrangement. System arrangement shall be verified by ______________________.

4.1.3.2 Trim controls. Trim control requirements shall be verified by ______________________.

4.1.3.3 System operation and interface. System operation and interface requirements shall be verified by ____________________________.

4.1.3.3.1 Warm-up. The time requirements for warm-up shall be verified by ________________.

4.1.3.3.2 Disengagement. Disengagement requirements shall be verified by ________________.

4.1.3.3.3 Mode compatibility. The mode compatibility requirements shall be verified by ____________.

4.1.3.3.4 Failure transients. Compliance with failure transient requirements shall be verified by ______ ____________________.

4.1.3.4 Failure immunity and safety. Compliance with the failure immunity and safety requirements shall be demonstrated by ________________________.

4.1.3.5 Redundancy. Redundancy shall be verified by ________________ and ________________.

4.1.3.5.1 Redundancy management. Redundancy management requirements shall be verified by ________________________________.

4.1.3.6 Stability. Verification of air vehicle stability shall be performed by analyses, simulation, and ground and flight test. Prior to first flight, ground testing shall ______________________________.

4.1.3.6.1 Sensitivity analysis. Stability margins established under this paragraph shall be verified by analysis. This analysis shall include variations due to tolerances affecting system characteristics and uncertainties in modeling.

4.1.3.7 Operation in atmospheric disturbances. Operation in atmospheric disturbance shall be verified by ______________________.

4.1.3.8 Residual oscillation. Compliance with the requirements for residual oscillation shall be verified by ______________________. Residual oscillations shall be measured at ______________________.

4.1.3.9 System test, display, reporting, and monitoring provisions (TDRM). The test and monitoring methods incorporated in the FCS shall be verified ______________________.

4.1.3.9.1 Preflight built-in test (BIT). The proper operation of preflight BIT shall be verified by ground test and __(a)__. Ground test shall demonstrate __(b)__. Prevention of inflight engagement shall be verified __(c)__.

4.1.3.9.2 Inflight. The proper operation of the inflight TDRM shall be verified by __(a)__. Ground test shall demonstrate __(b)__. Prevention of inflight TDRM failure propagation where the normal activity of the air vehicle may be disturbed shall be verified __(c)__.

4.1.3.9.3 Postflight. The proper operation of postflight tests maintenance BIT shall be verified by ground test and __(a)__. Verification test shall demonstrate __(b)__. Prevention of in-flight engagement shall be verified __(c)__.

4.1.3.9.4 Inflight monitoring. The proper operation of the FCS inflight monitoring shall be verified by __(a)__. Ground test shall demonstrate __(b)__. Prevention of inflight monitor failure propagation where the normal activity of the air vehicle may be disturbed shall be verified __(c)__.

4.1.4 MFCS design. MFCS design requirements of 3.1.4 for satisfactory physical interface shall be verified by __________, those for breakout force and free play by ____________, and those for mechanical element characteristics by ____________________.

4.1.4.1 Mechanical MFCS design. Compliance with this requirement shall be verified by:

a. Engineering tests that show adequate strength to a safety factor of 1.5 for the ratio of limit to ultimate load. Tests shall also show the system's ability to clear a jam.

b. Environmental tests that show the system's ability to resist corrosion, withstand acceleration and vibration, compensate for thermal properties, and function under required load.

c. Endurance tests performed under load for a number of cycles that show the system's ability to last for the service life of the aircraft or the specified MTBF.

d. Maintenance demonstration that shows the system adjustments/calibrations are accessible and can be done on the aircraft.

e. Functional/operational tests that certify the system is operational after maintenance actions or initial assembly and that the redundancy provided is achievable under all failure conditions.

4.1.4.1.1 Reversion--boosted systems. The requirement shall be verified in a system test. The test shall simulate realistic surface loadings and provide a realistic representation of, if not the actual, mechanical-boosted system. The test shall demonstrate the ability of the mechanical system to perform in the boosted and reversion modes and the engage/disengagement of the modes from the cockpit. Limitations, if any, shall be noted for inclusion in the simulation effort.

4.1.4.1.2 Use of mechanical linkage. Mechanical linkages and artificial feel devices shall be tested as described in 4.1.4.1.1. In addition, a maintenance demonstration and an endurance test shall be accomplished.

4.1.4.2 Electrical/electronic MFCS design. The electrical/electronic portion of the mechanical flight control system shall be tested by all the tests described in 4.1.4.1 and 4.1.4.1.1, integration tests and flight tests.

4.1.5 AFCS design. AFCS design requirements shall be verified by ____________ and ___________.

4.1.5.1 System management. This requirement shall be verified by ________________________.

4.1.5.2 Mission flight controls. This requirement shall be verified by ______________________.

4.1.6 Mission accomplishment reliability. Mission accomplishment reliability shall be verified by ______ ____________________________.

4.1.7 Quantitative flight safety. The quantitative flight safety requirement shall be verified by _________ ________________________.

4.1.8 Survivability. The survivability requirement shall be verified by ________________________.

4.1.8.1 All engine out control. The all engine out control requirements shall be verified by ___________.

4.1.9 Invulnerability. Verification to invulnerability requirements shall be made by _______________.

4.1.9.1 Invulnerability to natural environments. Flight control invulnerability to natural requirements shall be demonstrated by ____________________________.

4.1.9.2 Invulnerability to lightning strikes and static atmospheric electricity. Flight control system invulnerability to lightning strike and static atmospheric electricity shall be verified by demonstrating the ability to maintain at least the required operational state capability or better when subjected ____________.

4.1.9.3 Invulnerability to induced environments. Flight control system invulnerability to induced environment requirements shall be verified by ____________________________.

4.1.9.4 Invulnerability to onboard failures of other systems and equipment. Compliance with the invulnerability requirements to onboard failure of other systems and equipment shall be demonstrated by __ ____________________________.

4.1.9.5 Invulnerability to maintenance error. Flight control system invulnerability to maintenance error requirements shall be verified by ____________________________.

4.1.9.5.1 Invulnerability to software maintenance error. Flight control system invulnerability to software maintenance error requirements shall be verified by ______________________.

4.1.9.6 Invulnerability to pilot and crew inaction and error. Compliance with the invulnerability to pilot and flight crew inaction and error requirements shall be demonstrated by ______________________.

4.1.9.7 Invulnerability to enemy action. Flight control system invulnerability to enemy action shall be verified by ______________________.

4.1.9.8 Invulnerability to bird strike. Flight control system involunerability to bird strikes shall be verified by ______________________.

4.1.10 Maintenance provisions. The maintenance provision requirements shall be verified by ______________________.

4.1.10.1 Operational checkout provisions. The operational checkout provisions shall be verified by ______________________.

4.1.10.2 Malfunction detection and fault location provisions. Malfunction detection and fault location provisions shall be verified by ______________________.

4.1.10.2.1 Malfunction indication. Requirements for use of instrumentation in malfunction detection and fault location shall be verified by ______________________.

4.1.10.2.2 Provisions for checkout with portable test equipment. Provisions for checkout with portable test equipment shall be verified by ______________________.

4.1.10.3 Accessibility and serviceability. The requirements for accessibility and serviceability shall be verified by ______________________.

4.1.10.4 Maintenance personnel safety provisions. The required safety provisions for maintenance personnel shall be verified by ______________________.

4.1.11 Structural integrity. Structural integrity requirements shall be verified by ______________________.

4.1.12 Wear life. Wear life requirements shall be verified by ______________________.

4.2 Subsystem and component design requirements. Requirements contained in the subparagraphs of this section shall be verified as indicated in their respective verification subparagraphs.

4.2.1 Cockpit controls and displays. ______________________ shall be used to verify compliance with ______________________.

4.2.1.1 Cockpit controls. The separation and isolation between redundant FCS channels and cockpit controls shall be verified by ___(a)___. The probability that common mode failure is ___(b)___ shall be verified by ___(c)___.

4.2.1.1.1 Removable cockpit controls. Positive retention of removable cockpit flight controls shall be verified by ______________________.

4.2.1.1.2 Movable rudder or directional pedals. Positive interconnection of rudder pedals shall be verified by ______________________.

4.2.1.2 Pilot displays. The separation and isolation of pilot displays shall be verified by ___(a)___. The probability that common mode failures do not occur shall be verified by ___(b)___.

4.2.1.2.1 FCS annunciation. FCS annunciation shall be verified by ________________.

4.2.1.2.2 FCS warning and status annunciation. FCS warning and status annunciation requirements can be verified by ______________________.

4.2.1.2.3 Cockpit indicators. Compliance with indicator requirements shall be verified by____________.

4.2.2 Sensors. Correct sensor location and operation shall be verified by analyses, inspection, and test.

4.2.3 Signal transmission. Signal transmission requirements shall be verified by inspection as having complete coverage of the dedicated concepts, devices, lines, components, and subsystems used in the FCS.

4.2.3.1 General requirements. The general requirements for design of signal transmission elements, components, and subsystems shall be verified by ___________________________.

4.2.3.1.1 Computer signal transmission. The method of signal transmission, isolation and separation of redundant computing paths, and direct signal transmission shall be verified by inspection of _____________. Failure immunity requirements shall be verified __________________________.

4.2.3.2 Mechanical signal transmission, general. The general requirements for mechanical signal transmission shall be verified by ____________________________.

4.2.3.2.1 Control cable installations. The requirements for control cable installations shall be verified by ___________________________________.

4.2.3.2.2 Push-pull signal transmission installations. The requirements for push-pull signal transmission installations shall be verified by ___________________________________.

4.2.3.2.3 Control chain. Control chain requirements shall be verified by ________________________.

4.2.3.3 Electrical signal transmission. FCS essential and flight phase essential electrical signal transmission requirements shall be verified by inspection of ___________, by testing of _____________, and by analysis of all potential failure modes involving electrical signal transmissions.

4.2.3.3.1 Multiplexing. The proper operation of multiplex signal transmission circuits shall be verified by __________________________________.

4.2.4 Signal computation. The methods of signal computation used in the FCS shall be verified by ______ __________________________.

4.2.4.1 Transient power effects. The flight control system operational state capability during power system variations shall be verified by __________________________.

4.2.4.2 Mechanical signal computation. A dynamic and steady state analysis shall be performed on mechanical computation systems to verify that no adverse effects are present due to nonlinearities and parameter variations.

4.2.4.3 Electrical signal computation. Growth capability shall be verified ___________________________. __________________ shall be used to verify the adequacy of signal scaling. Proper operation of computation channel disengagement, if applicable, and other fail-safe provisions shall be verified by _______________.

4.2.5 Control power. Sufficient control power shall be verified by ___________________________.

4.2.5.1 Hydraulic power subsystems. Hydraulic power subsystem requirements shall be verified by _____ __________________________________.

4.2.5.2 Electrical power subsystems. Requirements for electrical power subsystems shall be verified by ______________________________.

4.2.5.3 Pneumatic power subsystems. Verification of pneumatic power systems requirements shall be accomplished by ______________________.

4.2.6 Actuation. Verification of FCS actuation components and subsystems shall be accomplished by ______________________________.

4.2.6.1 Mechanical force transmitting actuation. Verification of requirements for mechanical force transmission shall be by ______________________.

4.2.6.2 Mechanical torque transmitting actuation. Verification of mechanical torque transmission requirements shall by accomplished by ______________________.

4.2.6.3 Hydraulic actuation. Hydraulic actuation component requirements shall be verified by ______________________________.

4.2.6.4 Electromechanical actuation. Electromechanical actuation subsystems and components shall be verified by ______________________________.

4.2.6.5 Pneumatic actuation. Pneumatic actuation subsystems and components requirements shall be verified by ______________________________________.

4.2.6.6 Interfaces between actuation systems, support structure, and control surfaces. Requirements for the interface between actuation systems, support structure, and control surfaces shall be verified by ______________________________.

4.2.7 Component design. Component design requirements shall be verified by ______________________.

4.2.8 Component fabrication. Component fabrication requirements shall be verified by ______________________________.

4.2.9 Component and element installation. Installation of FCS components shall be verified by ______________________________.

4.3 Integrity requirements. The FCS integrity requirements for hardware, software, and integrating subsystems shall be verified by:

a. ______________________.

b. ______________________.

c. ______________________.

d. ______________________.

4.3.1 Structural integrity. The integrity for the FCS and integrating subsystem elements shall be verified by ______________________.

4.3.2 Mechanical integrity. The integrity of the FCS and integrating subsystems mechanical devices shall meet the functional, environmental, usage, and life requirements for the device as follows:

a. ______________________.

b. ______________________.

4.3.3 Electronic integrity. The integrity of the FCS and integrating subsystem electronic and electro-mechanical devices shall meet the functional performance under the environments, usage, and durability requirements as follows:

a. ____________________.

b. ____________________.

4.3.4 Software integrity. Software verification shall follow a build-up approach to evaluate the success of the functional and integrated mechanization. Software verification shall meet the following:

a. ____________________.

b. ____________________.

5. PACKAGING

5.1 All deliverable items shall be prepared for shipment as directed by the acquisition activity.

6. NOTES (This section contains information of a general or explanatory nature that may be helpful, but is not mandatory.)

6.1 Intended use. The flight control systems are intended to be used in piloted air vehicles.

6.2 Acquisition requirements. Acquisition documents must specify the following:

a. Title, number, and date of the specification.

b. Issue of DoDISS to be cited in the solicitation, and if required, the specific issue of individual documents referenced (see 2.1.1.).

6.3 Consideration of data requirements. The following data requirements should be considered when this specification is applied on a contract. The applicable Data Item Descriptions (DID's) should be reviewed in conjunction with the specific acquisition to ensure that only essential data are requested/provided and that the DID's are tailored to reflect the requirements of the specific acquisition. To ensure correct contractual application of the data requirements, a Contract Data Requirements List (DD Form 1423) must be prepared to obtain the data, except where DOD Far Supplement 27.475-1 exempts the requirement for a DD Form 1423.

Paragraph No.	DID Number	DID Title	Suggested Tailoring

The above DID's were those cleared as of the date of this specification. The current issue of DOD 5010.12-L, Acquisition Management Systems and Data Requirements Control List (AMSDL), must be researched to ensure that only current, cleared DID's are cited on the DD Form 1423.

6.4 Abbreviations

A_S(FCS)	flight safety allocation factor for FCS
AC, ac	alternating current
A/D	analog-to-digital
AFCS	automatic flight control system
AFLC	Air Force Logistics Command
AFTEC	Air Force Test and Evaluation Center
AGE	Aerospace Ground Equipment
APU	Auxiliary Power Unit
ARINC	Aeronautical Radio, Incorporated
ARP	Aerospace Recommended Practices (Society of Automotive Engineers)
ASD/ENFTC	Aeronautical Systems Division/Flight Stability & Control Branch, Flight Technology Division, Directorate of Flight Systems Engineering
BIT	built-in test
CAS	command/control augmentation system
CCV	Control Configured Vehicle
CFIT	Controlled Flight Into Terrain
C_{l_β}	change in rolling moment due to change in sideslip angle
$C_{M_{\dot\alpha}}$	change in pitching moment due to change in angle of attack
CDR	critical design review
CPU	Central Processing Unit
CDRL	contract data requirements list
CTOL	Conventional Takeoff and Landing
c.g., cg	center of gravity
D/A	digital-to-analog
db	decibels, 20 log output/input
DC, dc	direct current
deg/sec	degrees per second
DFBW	Digital Fly-by-Wire

DH	Decision Height
deg/sec/sec	degrees per second per second
DFO	dual fail-operational
DME	distance measuring equipment
DT&E	development test and evaluation
EBU	Emergency Backup Unit
EFCS	electric flight control system
EMI	electromagnetic interference
EMP	electromagnetic pulse
EPROM	erasable programmable read only memory
FBW	Fly-by-Wire
FCS	Flight Control System
f_m	mode frequency in Hz
FAA	Federal Aviation Administration
FCA	functional configuration audit
FMEA	failure modes and effects analysis
fpm	feet per minute
ft/sec	feet per second
g	gravitational unit of 32.2 ft/sec^2
GLA	Gust Load Alleviation
GM	gain margin
GCWS	Ground Collision Warning System
GLOC	G Loss of Consciousness
HOL	Higher Order Language
Hz	hertz--oscillatory frequency in cycles per second
ICAO	International Civil Aviation Organization
IFIM	Inflight Integrity Management
IFM	Inflight Monitor
in/sec^2	inches per second per second

ILS	instrument landing system
I/O	Input/Output
KCAS	knots, calibrated airspeed
lbs/in	pounds per inch
LRU	line replaceable unit
MFCS	manual flight control system
MLC	Maneuver Load Control
MPS	Motor-Pump-Servoactuator Package
MLS	microwave landing system
MTBF	mean time between failure/fault
MTBA	Meantime Between Actions
MTR	Meantime to Repair
OFP	operational flight program
PAR	Precision Approach Radar
PCA	physical configuration audit
PIO	pilot induced oscillation
PM	phase margin
PPM	physical parameter measurement
PROM	programmable read only memory
psi	pounds per square inch
$Q_{S(FCS)}$	maximum acceptable air vehicle loss not due to FCS
QPL	qualified products list
RAM	Random Access Memory
RDMS	Redundancy Data Management System
RSS	Relaxed Static Stability
RVR	Runway Visual Range
R_S	overall air vehicle flight safety requirement
rad/sec	radians per second
REO	responsible engineering office

RFP	request for proposal
rms	root mean square
ROM	read only memory
SAS	stability augmentation system
SCAS	stability and control augmentation system
SFO	single fail-operational
TACAN	tactical air navigation
TAS	true airspeed
TBD	to be determined
TF/TA	terrain following/terrain avoidance
$V_{o\ MAX}$	maximum operational airspeed (MIL-F-8785)
$V_{o\ MIN}$	minimum operational airspeed (MIL-F-8785)
V_G	turbulence penetration airspeed
V_H	maximum level flight speed
V_L	limit airspeed (MIL-A-8860)
VAP	vunerability analysis plan
VHF	very high frequency
VOR	VHF omni-directional range
V/STOL	Vertical/Short Takeoff and Landing
WRA	Weapon Replaceable Assembly
ZOC	zone of confusion

6.5 Definitions

6.5.1 Abort. An abort is mission dependent and implies degraded handling qualities.

6.5.2 Acceptance. The determination by the user/customer that the product meets his requirements.

6.5.3 Active control system. A system which actively commands the movement of control surfaces on the basis of sensor inputs to provide some function or characteristic not available in the aircraft passively.

6.5.4 Aerodynamic closed loop. A loop which relies on aerodynamics for loop closure such as stability augmentation. A nonaerodynamic closed loop does not rely on aerodynamics for loop closures. An example is a servo-actuator loop.

6.5.5 Airspeeds. MIL-F-8785 defines airspeeds associated with flying qualities and MIL-A-8860 defines airspeeds related to landing and flutter.

6.5.6 Assembler. A program which translates pneumonic assembly language instructions into the binary instructions used by the processor, assigns values to named addresses, and performs other functions as an aid to the programmer in writing a software program.

6.5.7 Alert height. A height (100 feet or less above the highest elevation in the touchdown zone), base upon the characteristics of the aircraft and the particular airborne Category III system above which a Category III approach would be discontinued and a missed approach executed if a failure occurred in one of the required redundant operational systems in the aircraft or in the ground equipment.

6.5.8 All weather landing system. An all weather landing system includes specifically all the elements of airborne equipment and more generally includes the ground-based equipment necessary for completion of the all weather landing. All weather landings comprise the operations and procedures required to conduct approaches and landings during Categories II and III visibility conditions defined by the International Civil Aviation Organization.

6.5.9 Automatic landing system. A landing system which provides automatic flight control to touchdown or to touchdown and beyond.

6.5.10 Category I operations. An instrument approach procedure which provides for approaches to a decision height (DH) of not less than 200 feet and visibility of not less than 1/2 mile or RVR (Runway Visual Range) 2,500 feet (RVR 1,800 feet with operative touchdown zone and runway centerline lights).

6.5.11 Category II operations. An instrument approach procedure which provides approaches to minima of less than DH 200 feet/RVR 2,400 feet to as low as DH 100 feet/RVR 1,200 feet.

6.5.12 Category IIIa operations. Operations with no decision height limitation, to and along the surface of the runway with external visual reference during the final phase of the landing and with runway visual range not less than 700 feet.

6.5.13 Category IIIb operations. Operations with no decision height, to and along the surface of the runway with runway visual range not less than 150 feet and with reliance on the system for part or all of the rollout along the runway and with external visual reference for guidance along the taxiway.

6.5.14 Category IIIc operations. Operations with no decision height, to and along the surface of the runway and taxiways without reliance on external visual reference.

6.5.15 Channel. The term describing a single signal or control path within a device or system that may contain many paths. A channel is an entity within itself and contains elements individual to that channel. A model may be used as a reference channel in a detection/correction system.

6.5.16 Classes. Airplane classes are defined using the MIL-STD-1797 definitions for the following classes:

6.5.16.1 Class I. Small, light airplanes such as:

Light utility
Primary trainer
Light observation

6.5.16.2 Class II. Medium weight, low-to-medium maneuverability airplanes such as:

Heavy utility/search and rescue
Light or medium transport/cargo/tanker
Early warning/electronic counter-measures/airborne command, control or communications

relay
Antisubmarine
Assault transport
Reconnaissance
Tactical bomber
Heavy attack
Trainer for Class II

6.5.16.3 Class III. Large, heavy, low-to-medium maneuverability airplanes such as:

Heavy transport/cargo/tanker
Heavy bomber
Patrol/early warning/electronic countermeasures/airborne command, control, or communications relay
Trainer for Class III

6.5.16.4 Class IV. High-maneuverability airplanes such as:

Fighter/interceptor
Attack
Tactical reconnaissance
Observation
Trainer for Class IV

Where MIL-F-83300 applies, the corresponding MIL-F-83300, Class I, II, III or IV applies.

6.5.17 Compiler. A program which translates a higher order language into the language of a particular computer and performs the assembler functions.

6.5.18 Comparison monitor. A device which compares signals and/or warning outputs from two or more sources and provides its own signal to indicate that the two or more outputs are within or outside specified tolerances.

6.5.19 Computer. A system containing a processor, variable storage memory, program storage memory, and input and output interface circuits including control, timing, power supplies, etc. The computer can perform a large variety of functions by the sequential execution of a set of basic operations in the processor. The commands for the set of operations is called the software program and is stored in the program memory. (The hardware necessary to convert input signals to the proper digital form and also the hardware necessary to convert the output signals to the proper form are usually included within the definition of a computer.)

6.5.20 Control Configured Vehicle (CCV). An aircraft whose basic aerodynamic and/or structural design includes the use of an active control system.

6.5.21 Control law. An algorithm which defines the relationship between the input and output of a flight control system.

6.5.22 Control wheel (stick) steering. An AFCS mode which permits pilot manual control inputs to be introduced into the system through the wheel or stick when the AFCS is engaged and controlling the airplane.

6.5.23 Damping ratio. In actuality, most engineering systems during their vibratory motion encounter friction or resistance in the form of damping. Damping, in its various forms such as air damping, fluid friction, Coulomb dry friction, magnetic damping, internal damping, etc., will always slow down the motion, and cause the eventual dying out of the oscillation. If the damping is heavy, oscillation will not occur; the system is said to be overdamped. If the damping is light, oscillation is possible; the system is said to be underdamped. A critically-damped system is one in which the amount of damping is such that the resultant motion is on the borderline between the two previous ones. An overdamped system has a damping ratio greater than one. An underdamped system has a damping ratio less than one, and a critically damped system has a ration equal to one.

6.5.24 Decision height. Decision height, with respect to operation of aircraft means the height at which a decision must be made during an ILS (Instrument Landing System) or PAR (Precision Approach Radar) instrument approach to either continue the approach or to execute a missed approach. This height is expressed in feet above runway datum altitude and for Category II ILS operations, the height is additionally expressed as a radio altimeter reading.

6.5.25 Direct Lift Control (DLC). A system that will enable the pilot to give vertical translation to the aircraft without a rotational moment.

6.5.26 Dual load path. A type of passive paralleling wherein two separate load carrying paths exist. Each load path is capable of carrying sufficient load such that failure of either member will not jeopardize system performance.

6.5.27 Elastic Mode Suppression. Active control to increase the damping of lightly damped structural bending modes excited by gusts.

6.5.28 Electrical Flight Control System (EFCS). A flight control system wherein one or more axes of vehicle control is, at one point or another, completely electrical. Non-electrical backup or other reversion means may exist. Electrical flight control is commonly referred to as fly-by-wire, especially where the application is either manual or essential.

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

6.5.30 Extremely remote. The probability of an event occurring which, although theoretically possible, is not expected in the life of an individual aircraft. For the purpose of this specification, the extremely remote probability for a specific aircraft is defined as numerically equal to the maximum aircraft loss rate due to relevant FCS material failures specified in 3.2.3.1.

6.5.31 Fail operational. The capability of the FCS for continued operation without degradation following a single failure and to fail passive in the event of a related subsequent failure.

6.5.32 Dual fail operational. A system that will continue to operate with no degradation in performance with 100 percent probability after the first failure and operate with no degradation in performance with a 95 percent probability after the second failure.

6.5.33 Fail passive. The capability of the FCS to automatically disconnect and to revert to a passive state following a failure. Allowable failure transient or out of trim condition shall result in no significant steady state deviation from the vehicle flight path which could impair safe flight.

6.5.34 Fail safe. The capability of the FCS in a single channel mode of operation to revert to a safe state following an automatic disconnect in the event of failure or pilot initiated disconnect. Safe state may be achieved by authority limiting and positive removal of actuation motive power. The allowable authority limits need to be established to provide the desired performance objectives and in consideration of structural design limits and safe recovery characteristics.

6.5.35 Failure. The inability of an item to perform within previously specified limits, usually considered permanent.

6.5.36 Failure, latent. A failure that has the potential of being detected under specific conditions. When this condition occurs, the failure is then detectable through the system response or a display annunciation to the pilot.

6.5.37 Failure rate. The number of failures of an item per unit measure of life (flights, time, cycles, events, miles, etc.) as applicable for the item.

6.5.38 Fault. An anomaly in the performance of a system.

6.5.39 Fault tolerance. A system which is able to continue to provide critical functions after the occurrence of a fault.

6.5.40 Firmware. A set of binary machine language instructions stored in read-only memory in a computer for the purpose of providing a step-by-step control of the processor.

6.5.41 Flight control systems. 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 may result in control of aircraft flight path, attitude, airspeed, aerodynamic configuration, ride, and structural modes. Among components included are the pilot's controls, dedicated displays, and logic switching, transducers, system dynamic and air data sensors, signal computation, test devices, transmission devices, actuators, and signal transmission lines dedicated to flight control. The interfaces of flight control systems with related subsystems are defined.

6.5.42 Flight director subsystem. A subsystem which provides the pilot a display of actual and desired flight parameters. When operating in a flight director mode, the pilot's task is to minimize the difference between the displayed actual and desired values through control actions. Many modern flight control systems have integrated many of the automatic flight controls and flight director functions.

6.5.43 Flight envelope. Altitude and Mach range of an aircraft.

6.5.44 Flutter suppression. Active control to suppress aeroelastic modes.

6.5.45 Fly-by-wire (FBW). The use of electrical signals to connect the pilot's control devices with the control surfaces.

6.5.46 Fully-powered control system. See power-operated control.

6.5.47 Gust-Load Alleviation (GLA). Active control to reduce loads due to gusts.

6.5.48 High Order Language (HOL). An HOL is "independent of" the particular computer rather than "dependent on" the particular computer. HOLs such as FORTRAN, JOVIAL, PASCAL, etc., are completely machine independent and require a compiler to convert them to the language of the particular machine.

6.5.49 Inflight monitoring. Continuous automatic monitoring of system performance normally performed inflight as a safety check.

6.5.50 Integrated Actuator Package (IAP). An actuator design wherein the driving hydraulic source is contained within the package.

6.5.51 Integrated circuits. An entire functional electronic circuit, fabricated on one tiny monolithic silicone chip. It may contain anywhere from a few to thousands of transistors, resistors, diodes, capacitors, etc.

6.5.52 Large Scale Integration (LSI). An integrated circuit on a single small silicone chip, upon which more than 1000 digital gates have been fabricated.

6.5.53 **Maneuver-Load Control (MLC).** Active redistribution of the increased loads due to maneuvers in order to reduce structural loads.

6.5.54 **Microelectronics.** Synonymous with integrated circuits.

6.5.55 **Microprocessor.** A digital CPU fabricated on one or more LSI chips. All contain an Arithmetic/Logic Unit, several registers, and the necessary control. When data storage, a clock, some input/output interface circuits, and a power supply are added, the microprocessor becomes a microcomputer. It may mean just a CPU or an entire microcomputer.

6.5.56 **Processor.**

a. Short for microprocessor.

b. A software program which includes the compiling of a given program language, e.g., BASIC processor, COBOL processor.

6.5.57 **Multimode FCS.** Multimode flight control systems encompass those modes automatically selected for the mission segments and are optimized for those segments.

6.5.58 **Nonaerodynamic loops.** Inner feedback loops within an FCS which do not rely on aerodynamics for loop closure. Examples include AFCS servo loops and actuator feedback loops.

6.5.59 **Noncritical FCS.** 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.

6.5.60 **Parallel trim.** Allows the pilot to reduce the steady state control forces to zero by changing the cockpit controller force neutral point with no change in the cockpit controller to control surface(s) relationship.

6.5.61 **Power-boosted control.** A reversible control wherein pilot effort is exerted through mechanical linkages and is boosted, directly in proportion to the force of the input, by a power source.

6.5.62 **Power-operated control.** An irreversible control wherein the pilot, through mechanical linkages or other means, actuates a power control package to control an aerodynamic surface or other device.

6.5.63 **Random failure.** Any failure whose occurrence is unpredictable in an absolute sense which is predictable only in a probabilistic or statistical sense. Random failures are those which cannot be attributed to wearout, defective design, or abnormal stress, and can occur at any time within the equipment's useful life.

6.5.64 **Redundancy.** A design approach such that two or more independent failures, rather than a single failure, are required to produce a given undesirable condition. Redundancy may take the form:

a. Providing two or more components, subsystems, or channels, each capable of performing the given function.

b. Monitoring devices to detect failures and accomplish annunciation and automatic disconnect or automatic switching.

c. Combination of the two above features.

6.5.65 **Redundancy Management.** The process of managing redundant elements in order to identify a failure and then reconfiguring the system to remove the effects of the failed element and continue operation with unfailed elements.

6.5.66 Relaxed Static Stability (RSS). The use of active control to allow the static stability of the basic unaugmented airframe to be relaxed. The aircraft with the active system operating will have the normal stability margins.

6.5.67 Relevant failure. Any random or normal wearout failure occurring in service prior to end of specified service life when the equipment is properly operated within design load and environment limits. A normal wearout failure is relatively improbable on a new part, but undergoes a relatively rapid rise in probability of occurrence after an extended period of service (operating hours or calendar time). Wearout is typical of seals, bearings, motor brushes, fatigue-critical structure, etc. A realistic system reliability computation must include proper allowance for such failures wherever they are not avoided by scheduled replacement/overhaul procedure in service.

6.5.68 Reversion. The capability to revert to a backup or alternate control from normal control means. The alternate control may use mechanical or electrical signal transmission and powered actuation.

6.5.69 Ride-Control System. Active control to improve the quality of the ride for the crew and passengers.

6.5.70 Series Trim. Allows the pilot to reduce the steady state control forces to zero by moving the control surface(s) to a different position in relation to the cockpit controller fixed neutral point.

6.5.71 Software. A set of instructions intended to be stored in programmable memory of a computer is for the purpose of providing step-by-step control to the processor. This includes source program instructions requiring assembly or compilation as well as binary machine language instructions.

6.5.72 Stability Augmentation System (SAS). An active control system which augments the natural stability of an aircraft.

6.5.73 Transient Fault. A temporary anomaly in the performance of a system.

6.5.74 Turbulence cumulative exceedance probability. The cumulative probability of experiencing turbulence at an intensity equal to or exceeding a given level. This probability accounts for both the probability of encountering turbulence and the distribution of the RMS intensity of the turbulence, if encountered.

6.5.75 Validation. The determination that a resulting product meets the objectives that led to the specification for the product. This determination usually includes operation in a real environment.

6.5.76 Variable geometry control system. Those components and subsystems which transmit control commands from the pilot(s) and which produce forces and moments to change the aerodynamic configuration of the aircraft. Variable geometry controls include those for changing wing sweep angle and wing incidence angle, folding wing tips, deploying canard surfaces, and varying the angle of the nose of the aircraft with the body.

6.6 Subject term (key word) listing

actuators
analog controls
computers
digital controls
electrical power
flight controls
flight test

guidance and control
hydraulics
mechanical controls
navigation
sensors
stability and control

6.7 **International standardization agreements.** Certain provisions of this specification (Requirement Guidance for 3.1.3.9) are the subject of international standardization agreement (STANAG 3221). When amendment, revision, or cancellation of this specification is proposed that will modify the international agreement concerned, the preparing activity will take appropriate action through international standardization channels, including departmental standardization offices, to change the agreement or make other appropriate accommodations.

6.8 **Responsible engineering office.** The office responsible for development and technical maintenance of this specification is ASD/ENFTC, Wright-Patterson AFB, OH 45433-6503. Requests for additional information or assistance on this specification can be obtained from ASD/ENFTC: DSN 785-5730, Commercial (513) 255-5730. Any information obtained relating to Government contracts must be obtained through contracting officers.

6.9 **Changes from previous issue.** Marginal notations are not used in this revision to identify changes with respect to the previous issue due to the extensiveness of the changes.

Custodian:
Air Force - 11

Preparing activity: Air Force - 11

Project No. 6610-F353

FLIGHT CONTROL SYSTEM

HANDBOOK FOR

10. SCOPE

10.1 Scope. This appendix provides rationale, guidance, lessons learned, and instructions to assist the procuring activity in tailoring sections 3 and 4 of AFGS-87242A for flight control systems to a specific piloted air vehicle.

10.2 Format

10.2.1 Requirement/verification identity. Section 30 of this appendix parallels sections 3 and 4 of the basic specification; paragraph titles and numbering are in the same sequence. Section 30 provides each requirement (section 3) and associated verification (section 4) as stated in the basic specification. Both the requirement and verification have sections for rationale, guidance, and lessons learned.

10.2.2 Requirement/verification package. Section 30 of this appendix has been arranged so that the requirement and associated verification is a complete package to permit addition to or deletion from the criteria as a single requirement. A requirement is not specified without an associated verification.

10.3 Responsible engineering office. The responsible engineering office (REO) for this appendix is ASD/ENFTC, Wright-Patterson AFB OH 45433-6503, DSN 785-3433, Commercial (513) 255-3433.

10.4 Classification

10.4.1 Flight control system classifications

10.4.1.1 Manual flight control systems (MFCS). Manual flight control systems consist of electrical, electronic, mechanical, hydraulic, optical, and pneumatic elements which transmit pilot control commands or generate and convey commands which augment pilot control commands and thereby accomplish flight control functions.

10.4.1.2 Automatic flight control systems (AFCS). Automatic flight control systems consist of electrical, electronic, mechanical, hydraulic, optical, and pneumatic elements which generate and transmit control commands to provide automatic or semiautomatic control of the flight path, attitude, or airframe responses to disturbances by references internal or external to the air vehicle. This classification includes automatic pilots, stick or wheel steering, automatic coupled pilotage, structural mode control, and similar control mechanizations.

10.4.2 FCS operational state classifications

10.4.2.1 Operational State I (normal operation). Operational State I is the normal state of flight control system performance, safety, and reliability. This state satisfies level 1 flying qualities requirements within the operational flight envelope and level 2 within the service envelope and the stated requirements outside of these envelopes.

10.4.2.2 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 portion of the overall flight control system. A moderate increase in crew workload and degradation in mission effectiveness may result from a limited selection or normally operating FCS modes available for use; however, the intended mission may be accomplished. This state satisfies at least level 2 flying qualities requirements within the operational flight envelope and level 3 within the service envelope.

10.4.2.3 Operational State III (minimum safe operation). Operational State III is the state of degraded flight control system 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 in State III 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.

10.4.2.4 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.

10.4.2.5 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.

10.4.3 FCS criticality classification

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

10.4.3.2 Flight phase essential. 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.

10.4.3.3 Noncritical. 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.

20. APPLICABLE DOCUMENTS

20.1 References. The documents referenced in this appendix are not intended to be applied contractually. Their primary purpose is to provide background information for the Government engineers responsible for developing the most appropriate performance values (filling in the blanks) for the requirements contained in the specification proper.

20.2 Avoidance of tiering. Should it be determined that the references contained in this appendix are necessary in writing an RFP or building a contract, excessive tiering shall be avoided by calling out only those portions of the reference which have direct applicability. It is a goal of the Department of Defense that the practice of referencing documents in their entirety be eliminated in order to reduce the tiering effect.

20.3 Government documents

SPECIFICATIONS

Military

MIL-U-3963	Universal Joint, Antifriction Bearings
MIL-B-5087	Bonding, Electrical, and Lightning Protection, for Aerospace Systems
MIL-W-5088	Wiring, Aerospace Vehicle
MIL-E-5400	Electronic Equipment, Aerospace, General Specification for
MIL-H-5440	Hydraulic Systems, Aircraft Types I and II, Design and Installation Requirements for
MIL-A-5503	Actuators; Aeronautical, Linear Utility, Hydraulic, General Specification for
MIL-P-5518	Pneumatic Systems, Aircraft; Design, Installation, and Data Requirements for
MIL-C-6021	Castings, Classification and Inspection of
MIL-E-6051	Electromagnetic Compatibility Requirements, Systems
MIL-J-6193	Joints, Universal, Plain, Light and Heavy Duty
MIL-G-6641	Gearbox, Aircraft Accessory Drive, General Specification for
MIL-I-7064	Indicator, Position, Elevator Trim Tab
MIL-E-7080	Electric Equipment, Aircraft, Selection and Installation of
MIL-F-7190	Forgings, Steel, for Aircraft/Aerospace Equipment and Special Ordnance Applications

MIL-D-7602	Drive, Turbine, Air, Aircraft Accessory, General Specification for
MIL-C-7958	Controls, Push-Pull, Flexible and Rigid
MIL-M-7969	Motors, Alternating Current, 400-Cycle, 115/200 Volt System, Aircraft, General Specification for
MIL-M-7997	Motors, Aircraft Hydraulic, Constant Displacement General Specification for
MIL-P-8564	Pneumatic System Components, Aeronautical, General Specification for
MIL-M-8609	Motors, Direct Current, 28-Volt System, Aircraft, General Specification for
MIL-S-8698	Structural Design Requirements, Helicopters
MIL-H-8775	Hydraulic System Components, Aircraft and Missiles, General Specifications for
MIL-F-8785	Flying Qualities of Piloted Airplanes
MIL-A-8860	Airplane Strength and Rigidity, General Specification for
MIL-A-8861	Airplane Strength and Rigidity, Flight Loads
MIL-A-8865	Airplane Strength and Rigidity, Miscellaneous Loads
MIL-A-8866	Airplane Strength and Rigidity Reliability Requirements, Repeated Loads, Fatigue and Damage Tolerance
MIL-A-8867	Airplane Strength and Rigidity Ground Tests
MIL-A-8870	Airplane Strength and Rigidity Vibration, Flutter and Divergence
MIL-A-8871	Airplane Strength and Rigidity Flight and Ground Operations Tests
MIL-P-8875	Pump, Rotary, Power-Driven, Fuel, Aircraft, 400 GPH (Taper Threaded Ports)
MIL-S-8879	Screw Threads, Controlled Radius Root with Increased Minor Diameter; General Specification for
MIL-H-8890	Hydraulic Components, Type III, (-65° to +450°F), General Specification for
MIL-H-8891	Hydraulic Systems, Manned Flight Vehicles, Type III Design, Installation and Data Requirements for, General Specification for
MIL-A-8892	Airplane Strength and Rigidity, Vibration
MIL-A-8893	Airplane Strength and Rigidity, Sonic Fatigue
MIL-S-9419	Switch, Toggle, Momentary, Four-Position On, Center Off, General Specification for
MIL-F-9490	Flight Control Systems—Design, Installation and Test of, Piloted Aircraft, General Specification for
MIL-A-21180	Aluminum-Alloy Castings, High Strength
MIL-A-22771	Aluminum Alloy Forgings, Heat Treated
MIL-C-27500	Cable, Power, Electrical and Cable Special Purpose, Electrical Shielded and Unshielded, General Specification for

MIL-V-27162	Valves, Servo Control, Electrohydraulic, General Specification for
MIL-E-38453	Environmental Control, Environmental Protection, and Engine Bleed Air Systems, Aircraft, General Specification for
MIL-M-38510	Microcircuit, General Specification for
MIL-S-52779	Software Quality Assurance Program Requirements
MIL-F-83142	Forging, Titanium Alloys, Premium Quality
MIL-F-83300	Flying Qualities of Piloted V/STOL Aircraft
MIL-A-83444	Airplane Damage Tolerance Requirements
AFGS-87221	Aircraft Structures, General Specification for
MIL-H-87227	Hydraulic Power Systems
MIL-A-87244	Avionic/Electronic Integrity Program Requirements (AVIP)
AFGS-87249	Mechanical Equipment & Subsystems Integrity Program (MECSIP)

STANDARDS

Military

MIL-STD-130	Identification Marking of U.S. Military Property
MIL-STD-203	Aircrew Station Controls and Displays: Assignment, Location, and Actuation of, for Fixed Wing Aircraft
MIL-STD-250	Aircrew Station Controls and Displays for Rotary Wing Aircraft
MIL-STD-454	Standard General Requirements for Electronic Equipment
MIL-STD-461	Electromagnetic Emission and Susceptibility Requirements for the Control of Electromagnetic Interference
MIL-STD-462	Electromagnetic Interference Characteristics, Measurement of
MIL-STD-810	Environmental Test Methods and Engineering Guidelines
MIL-STD-882	System Safety Program Requirement
MIL-STD-883	Test Methods and Procedures for Microelectronics
MIL-STD-1472	Human Engineering Design Criteria for Military Systems, Equipment and Facilities
MIL-STD-1521	Technical Reviews and Audits for Systems, Equipments, and Computer Software
MIL-STD-1530	Aircraft Structural Integrity Program, Airplane Requirements
MIL-STD-1553	Digital Time Division Command/Response Multiplex Data Bus
MIL-STD-1599	Bearings, Control System Components, and Associated Hardware Used in the Design and Construction of Aerospace Mechanical Systems and Subsystems
MIL-STD-1797	Flying Qualities of Piloted Aircraft
MIL-STD-1798	Mechanical Equipment & Subsystems Integrity Program (MECSIP)
MIL-STD-1803	Software Development Integrity Program (SDIP)
DOD-STD-2167	Defense System Software Development

DOD-STD-2168 Defense System Software Quality Program

MS-15981 Fasteners, Externally Threaded, Self-Locking, Design and Usage Limitations for

MS-24665 Pin, Cotter (Split)

MS-33540 Safety Wiring and Cotter Pinning, General Practices for

MS-33588 Nuts, Self-Locking, Aircraft Reliability and Maintainability Usage Requirements for

MS-33602 Bolts, Self-Retaining, Aircraft Reliability and Maintainability Design and Usage, Requirements for

HANDBOOKS

Military

MIL-HDBK-5 Metallic Materials and Elements for Aerospace Vehicle Structures

MIL-HDBK-17 Plastics for Aerospace Vehicles Transparent Glazing Materials

(Copies of federal and military specifications, standards, and handbooks are available from the Standardization Documents Order Desk, Bldg 4D, 700 Robbins Ave, Philadelphia PA 19111-5094.)

Air Force Systems Command

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

(Copies of AFSC DHs are available from ASD/ENES, Wright-Patterson AFB OH 45433-6503.)

20.4 Other documents

AFFDL-TR-70-121 Liquid Metal Actuator Package Design Study for a Fly-by-wire FCS, February 1971

AFFDL-TR-71-78 Design Criteria for High Authority Closed-Loop Primary Flight Control System, August 1972

AFFDL-TR-73-83 Control Configured Vehicle Ride Control System (CCV-RCS), July 1973

AFFDL-TR-73-105 Survivable Flight Control System Final Report, December 1973

AFFDL-TR-74-116 Background Information and User Guide for MIL-F-9490D

AFFTC-TR-76-15 Flight Test and Evaluation of a Multi-Mode Digital Flight Control System Implemented in an A-7D (Digitac) Vol I, June 1976

AFFDL-TR-76-116 The Development and Solution of Boundary Integral Equations for Crack Problems in Fracture Mechanics

AFFDL-TR-77-7 Validation of MIL-F-9490D—General Specification for Flight Control Systems for Piloted Military Aircraft Validation, Vol II: YF-17 Lightweight Fighter; Vol III: C-5A Heavy Logistics Transport Validation, April 1977

AFWAL-TR-81-3113 Digitac II - Digital Flight Control System Advanced Techniques Evaluation, September 1981

AFWAL-TR-82-3081 Flying Qualities of Air Vehicles (Proposed Mil Standard)

ASD-TR-88-5034 Ground Collision Warning System Performance Criteria for High Maneuverability Aircraft, December 1988

AFSCR 800-37 Joint AFLC/AFSC Lessons Learned Program

FAA-SS-73-1 SST Longitudinal Control System Design and Design Processes--Hardened Stability Augmentation System, June 1973

FAA Adv Cir 120-29 Criteria for Approving CAT I and II Landing Minima for FAR 121 Operators, September 1970

FAA Adv Cir 20-57A Automatic Landing Systems (ALS), January 1971

FAA Adv Cir 120-28A Criteria for Approval Category III Landing Weather Minima, March 1984

NASA TN-D-6867 Ground and Flight Test Methods for Determining Limit Cycles and Structural Resonance Characteristics of Aircraft Stability Augmentation Systems, June 1972

NASA CR-124834 A Proposed Criterion for Aircraft Flight in Turbulence, 1971

TO 1-1A-14 Installation Practices, Aircraft Electrical and Electronic Wiring

ANSI B29.1-75 Precision Power Transmission Roller Chains, Attachments and Sprockets, Connecting Link, Cotter Pin Type

ARP 988 Electrohydraulic Mechanical Feedback Servoactuators

ARP 1281 Servoactuators: Aircraft Flight Controls, Power Operated, Hydraulic, General Specification for

Draper Lab Digital Fly-by-Wire Flight Control Validation R-1164 Experience, June 1978

STANAG 3221 Automatic Flight Control System (AFCS) - Design Standards and Location of Controls

30. REQUIREMENTS AND VERIFICATIONS

3.1 System requirements. The flight control system (FCS), a subsystem of the ___(a)___ vehicle, shall provide manual and automatic control of the vehicle. The system shall provide ___(b)___ to enhance operational utility and flexibility for mission accomplishment.

REQUIREMENT RATIONALE (3.1)

A system approach is an overriding principle in the synthesis of new control systems. This requirement forces identification of, and tailoring to, a set of basic parameters needed to fulfill the function of, and operational needs which have been identified for the vehicle and its mission.

REQUIREMENT GUIDANCE

Blank (a) would be the name/number of the vehicle; (b) would be phases such as automatic control of path following, control of ground roll and maneuvering, automatic missile evasion maneuvers, integration of vehicle management and mission management functions. Limiting functions implemented through the FCS should be considered.

REQUIREMENT LESSONS LEARNED

MIL-F-9490 (4 February 1955) and revisions through MIL-F-9490B (7 August 1957) contained only system requirements. As flight control systems became more complex, the need was realized for incorporation of lessons learned in the specification. Consequently, MIL-F-9490C (13 March 1964) included lessons learned. It placed constraints on the choice of design solutions to allow only those which had proven feasible during service use. The specification contained requirements for system performance as well as for system installation and component design. MIL-F-9490D (6 June 1975) expanded the coverage of lessons learned; it contains, as general requirements, all lessons learned to date. Unless otherwise specified, all references to MIL-F-9490 in the following Guidance paragraphs are to the D revision. The background guide for the requirements of MIL-F-9490D is in AFFDL-TR-74-116.

4.1 System verification. Verification of the system requirements shall be performed by analyses (includes simulation), inspection, demonstration, ground test and flight test.

The approach used for quality assurance shall provide a planned and systematic pattern of all actions, structured and time phased throughout the program, to provide adequate confidence that the FCS, its elements, and software conform to the established technical requirements. Compliance with each applicable requirement in section 3 shall be verified as required by its dedicated section 4 paragraph. The lack of a specific verification requirement for any portion of a design requirement in section 3 does not relieve the contractor of responsibility for full compliance with the requirement. The verification processes shall be thoroughly documented and shall clearly show that methods used are suitable and proper, that the procedures followed are comprehensive and thorough, that requirements have been met, and that high quality is a built-in attribute.

When requirements are verified by analyses and flight test, the flight envelope shall be analyzed to determine worst case combinations of airspeed, altitude, gross weight, center of gravity, and maneuver. Flight tests shall be conducted at, or sufficiently near, these cases to validate the adequacy of analytical results. Analytical results shall not be accepted until such validation is accomplished. Test instrumentation shall include appropriate measurement of attitudes, rates, accelerations, controller position and force levels, surface position, thrust, altitudes, altitude rate, and internal flight control system signals and states as required to verify hardware and, if used, software performance.

Requirement verifications which must be completed to support the release of the air vehicle for first flight shall be ______________________.

The processes incident to verification of each requirement shall be documented in engineering detail to the extent necessary to show the quality and flight-worthiness status which is exhibited for each unit of product.

VERIFICATION RATIONALE (4.1)

It has long been recognized that good quality is not inspected into a product at the end of the development/production processes. This verification requirement provides the means for assuring that quality is an attribute which is built into the FCS, its elements and its software. It also establishes the need for verifying conformance with each technical requirement, and for providing documentation for this conformance and the processes used in arriving at that end.

Flight-worthiness certification of the air vehicle is required before it can be released for first flight. This verification requirement provides the means for listing in advance those verifications, either complete or partial, which must be completed to show that the FCS is airworthy and that the air vehicle may be released for first flight.

The final paragraph of the verification requirement establishes the need for setting down in record form the significant points of the verification process such that an engineering assessment can be made of the quality and flight-worthiness of the unit of product after the process has been completed.

VERIFICATION GUIDANCE

Methods of verification are tailored to requirements as indicated in the dedicated verification paragraph for each requirement paragraph in section 3. The methods which may be used include analysis, inspection, test, and others as discussed below.

Software/computer programs. MIL-S-52779 and MIL-STD-1521 are DoD documents approved for use by all departments and agencies of the Air Force, and may therefore, be used with this specification. The standardization of software procedures and documentation, and the goal of a common DoD software language, provide great opportunity for increased efficiency in system acquisition.

Analysis. Compliance with requirements in cases where testing or inspection would be hazardous, or otherwise impractical, may be verified through analyses. These analyses may be linear or nonlinear, deterministic or probabilistic in nature, and may include piloted and nonpiloted simulations, as best suited and adequate for the application. Where test verification is limited by test sample considerations, or is clearly inadequate, compliance should be verified by the appropriate analytical techniques. Analyses required for design of FCS today go beyond the methods normally associated with linear and nonlinear analyses.

In order to imply the wider range of analytical techniques that may be required, the words deterministic and probabilistic have been used. The intent is to encompass not only the usual linear and nonlinear analytical control techniques, which may or may not be stochastic in nature, but also to include areas of analysis which may fall partially or completely outside the realm of mathematics, such as failure mode effect analysis and software verification and validation.

It is the intent to point out that the analytical methods to be used should be appropriate for the problems to which they are to be applied.

Several of the requirements included in section 3 can only be verified by analysis. Preliminary compliance demonstration for many more of the requirements of section 3 may also be provided through analysis.

Requirements which will likely be demonstrated through analysis include:

- Reliability and failure immunity
- Invulnerability
- Maintainability
- Operation in turbulence
- Gain margins at high frequencies and phase margins at all frequencies.

Technical areas which interface with that of flight controls often require analyses which include the FCS. Some of these analyses which may be useful in FCS validation are:

- Reliability and maintainability analysis
- Failure mode effects and criticality analysis

- Vulnerability analysis

- System hazard analysis

- Subsystem hazard analysis

- Operating and support hazard analysis

Where compliance with specification requirements through analytical predictions is used, the documentation should define the major assumptions and approximations used and verify that the modeling and analysis procedures used are conservative. Verification should normally require prior use and validation through comparison with flight, wind tunnel, or ground testing data. In cases of digital flight control applications, validation should require comparison to simulation or emulation results obtained through the use of a general purpose machine. Where digital mechanization is involved in the flight control system, pre-analysis of the simulation mechanization is required to assess its validity. The artifacts introduced by the simulation mechanization used should be investigated to assess and minimize their effects on the simulation results. In all cases the tolerances should be established on analytical predictions used to demonstrate compliance with specification requirements. These tolerances should reflect anticipated variations in system or component characteristics, such as:

a. Parameters that change with temperature, atmospheric pressure and other environmental factors.

b. Parameters that change with failures or manufacturing tolerances.

c. Parameters that critically affect system performance or stability.

d. Parameters that are not accurately known (if they are significant).

e. Parameters that change as a result of aging or wear.

In an operational flight program for a digital flight control system, simulation will be required to evaluate such areas as integration techniques, filter implementations, iteration intervals, and failure isolation and switching. Emulation can serve in the early stages of design to evaluate the effect of interrupts and the implementation of background tasks.

Piloted simulations should be performed during FCS development to define and verify required functional characteristics and to evaluate degraded mode effects. As a minimum, the following simulations should be accomplished:

a. Piloted simulations using computer simulation of the FCS prior to hardware availability.

b. Piloted simulations using actual FCS hardware prior to first flight.

c. Piloted simulations for digital FCS prior to each flight that is preceded by major software modifications.

The requirement for piloted simulations following major software modifications places the same emphasis on major software modifications as on FCS hardware before its first inflight operation.

Software modifications in general will introduce some unknowns into the computer structure. Modules of code which are modified and the flow-through to other modules should be reverified. Rather than proceed through a complete reverification of the complete flight following software modifications, piloted simulations can be performed to find any major or critical problems before beginning flight tests.

In the application of piloted simulation to the evaluation of the FCS development, it is paramount, particularly for fighter aircraft, that the simulation go beyond 1 g flight. The simulation must address critical areas such as high angle of attack, PIO, and landing tasks. Sensitivity studies should be performed to determine the range of uncertainty in aerodynamic characteristics, sensed parameters, or other characteristics for which the flight control system can compensate, and provide level 3 flying qualities.

In view of the potential importance of motion cues in evaluating handling characteristics and failure effects in these critical areas, a portion of the piloted simulation for highly maneuverable aircraft may need to be conducted on a motion-based simulator.

Inspection. Compliance with requirements by measuring, examining, testing or otherwise comparing a unit of product with the specific requirements may be verified by inspection of documentation or inspection of the physical unit.

Compliance with requirements associated with the physical arrangement of parts, or the physical relationship of parts should be verified by inspection of documentation and inspection of the physical installation. Documentation may include documents showing the qualification status of components which have been qualified to the requirements specifications, or drawings showing clearances or other physical relationships. Where applicable, flight control system software specifications, documentation, and analyses should be inspected or reviewed as part of the verification process. Unless otherwise specified, the supplier may use his own or any other facilities suitable for the performance of the inspection requirements specified herein. The government reserves the right to perform any of the inspections set forth in specifications where such inspections are deemed necessary to ensure supplies and services conform to prescribed requirements.

Many of the paragraphs in section 3 cover elements or subsystems, etc., which require compliance with military specifications or contractor prepared specifications. Requirements may be stated in terms of physical arrangement of physical clearances.

In the case of demonstration of compliance with such specifications, tests may be conducted on the element or subsystem specifically for this purpose. However, these tests are requirements of the component or subsystem specification but compliance with section 3 requirements can often be verified by inspection of the qualification status of the element or subsystem which is maintained incident to more specification requirements.

In the case of requirements involving physical relationships, physical inspection will provide the desired proof of hardware and software.

Where digital implementation is employed, visual inspections and walk-throughs need to be performed at appropriate points during the development cycle. Various types of documentation, in addition to the actual flight code of the operational program, can benefit from these walk-throughs, which are usually done by multidisciplinary teams which can bring varied perspectives to assess the emerging software. Such inspections have proven to be effective in the timely elimination of many types of software problems.

Test. To the extent feasible, compliance with quantitative requirements should be verified by tests. Tests should include hardware tests and software tests and may be conducted in the laboratory, on the ground, or during flight.

Verification by test is the preferred method for demonstrating compliance with requirements. Due to safety or cost considerations, many requirements cannot be demonstrated during flight testing. In some cases analytically predicted trends are validated during flight at a critical or representative set of flight conditions and analysis trends are used to extrapolate these validated analysis trends to show compliance at all flight conditions not specifically tested.

Verification by ground or operational mockup testing is generally preferred where flight testing is not feasible.

Instrumentation used in conducting verification tests should:

a. Conform to laboratory standards whose calibration is traceable to the prime standards at the U.S. Bureau of Standards.

b. Be accurate to within one-third the tolerance for the variable to be measured.

c. Be suitable for measuring the test parameter(s).

d. Be verified no less frequently than every 12 months.

Test conditions should be established for operation which accurately represent in-service usage during both ground and in-flight operations. Flight phases and flight envelopes are usually defined incident to flying qualities requirements. Load, and load cycle spectra for use in wear life tests are usually developed incident to structural analyses and tests. Environmental test methods and procedures should be based on MIL-STD-461 or MIL-STD-810. Among the tests usually performed are:

a. Pulse tests for lightning. Flight control electronics should be tested for indirect effects of lightning. The criteria used to harden electronics in prior air vehicles was to apply a 500-volt square wave pulse or a damped sinusoid. The duration of the pulse was 5 microseconds with a frequency of 1 MHz for the damped sinusoid.

b. Dielectric strength tests. Each circuit of electrical and electronic components should be subjected to a test equivalent to the application of a root mean square test voltage of three times the maximum (but not less than 500 volts) surge DC or three times the maximum surge peak AC voltage to which the circuit will be subjected under service conditions. The test voltage should be of commercial frequency and should be applied between ungrounded terminals and ground, and between terminals insulated from each other, for a period of one minute. Tests should be accomplished at normal ground barometric pressure and no breakdown of insulation or air gap should occur. Circuits containing capacitors or other similar electronic parts which may be subject to damage by application of above voltages should be subjected to twice the surge peak operating voltage for the specified period. If the maximum peak operating voltage is greater than 700 V, the rms value of the test voltage should be 1.5 times greater than the maximum peak operating voltage. Electrical and electronic components should also be tested for resistance to air gap breakdown at the maximum altitude specified in the altitude test.

c. Electromagnetic interference limits. The flight control system and components should be assembled and arranged in a manner as specified in the system or component specification, with interconnecting cables and supporting brackets representative of an actual installation. Provisions should also be made for inverting all components with respect to the ground plane, or positioning in such a manner as to permit measurements from the bottom of all components. Measurement of radiated and conducted interference limits should be made in accordance with MIL-STD-461 with the system switches, controls and components operated as in actual service.

d. Sand and dust. Each component with simulated external connections attached should be subjected to individual tests before and after exposure. Any dust film or dust penetration should not result in a deterioration of the performance of the component.

e. Fungus. Equipment which has parts of organic material or other materials which may grow fungus should be subjected to a fungus resistance test. The component should be subjected to individual tests before and after exposure. Any fungus present should not result in a deterioration of the performance or service life of the component.

f. Extreme temperature tests. Dynamic operation using expected high and low temperature and temperature shock should be verified on all components subject to binding or malfunction resulting from:

(1) Differential expansion or contraction of mating parts.

(2) Deterioration of lubricant.

(3) Deterioration of hydraulic fluid.

(4) Deterioration of any type seal device.

(5) Deterioration of electrical part.

(6) Altered hydraulic or electrical characteristics.

The component should be subjected to individual tests before, during, and after exposure. From these tests and a visual examination there should be no evidence of damage or deterioration which would prevent the component from meeting its operational requirements.

Individual component high and low temperature extremes selected for each test should be determined by careful analysis of the environmental conditions to which the component will be exposed during dynamic operation. For these temperature extremes, the items above should be checked against their specifications to see if they will deteriorate under the same conditions. If they do, a different lubricant, fluid, seal, or electrical part should be specified.

g. Humidity and corrosion and icing. Components subject to failure due to corrosion, entrance of moisture, or formation of ice should be given humidity tests and salt spray tests. In addition, if ice formation might be detrimental to the equipment, an icing test should be conducted as follows:

(1) Cool test items to -12°C (10.4°F) or lower.

(2) Reduce ambient air pressure to simulate 40,000 feet pressure altitude and maintain for at least 15 minutes.

(3) Increase ambient air pressure to ground level by introducing warm moist air at a temperature of at least 49°C (120°F) and a relative humidity of 95±5 percent. Continue circulating warm moist air until the test item temperature is at least 5°C (41°F). Items 1, 2, and 3 constitute one cycle of testing.

Twenty-five cycles should be performed to determine acceptability. Following each five cycles, the test item should be functionally checked while at a -12°C (10.4°F) temperature. At the conclusion of the 25 cycles, and following the functional check, the equipment should be examined for evidence of internal moisture, corrosion, or other defects.

h. Altitude. Electrical equipment and other flight control system items which may be adversely affected by high-altitude operation should be tested. A percentage of the total life test cycles, consistent with service requirements of the component, but not less than 25 percent, should be conducted at the high-altitude condition.

i. Vibration, shock and acceleration. All equipment subject to failure or malfunction due to vibration, shock, or high accelerations should be tested.

j. Combined temperature-altitude tests. Components and systems subject to leakage, or which may experience cooling problems, should be subjected to combined temperature-altitude tests.

k. Component life testing. Components which are subject to wear, fatigue, or other deterioration due to usage, should be life tested under realistic environmental conditions for a number of cycles representative of the desired life expectancy of the component. In most cases, life test requirements are defined in government specifications, but should be revised to reflect actual expected usage. Hydraulic components should be tested while using hydraulic fluid at a typical fleet environment fluid cleanliness level.

l. System life testing. The mechanical portions of the complete FCS, such as pulleys, cable rods, torque tubes, control sticks or wheels, etc., should be tested as a complete system mockup in which loads, relative distances and locations, and other characteristics are realistic.

m. Miscellaneous tests. Equipment which is located so that it is subjected to rain, sunshine, sand, and dust should be tested accordingly. Components failing a service condition test should not be resubmitted for test without furnishing complete information on the corrective action taken subsequent to the failure. This information should be furnished to the procuring activity or in the test report, depending upon location of testing. Depending upon the nature of the failure encountered and corrective action required and at the option of the procuring activity, the rework or modifications accomplished should also be incorporated into the other test samples. Where rework or modifications may be considered as sufficient to affect performance under the other service condition tests already completed, at the option of the procuring activity, these tests should be repeated in the specified order.

Components to be used under a particular category of service application, which have previously been subjected to and accepted under the requirements of a lower, or less severe category application, either as an individual component or as a component of the same or a different system, should be subjected to a rerun of those service condition tests which vary with category of service application.

n. Functional mockup and simulator tests. Where one of the first air vehicles in a new series of aircraft will not be available for extensive testing of the FCS prior to flight of that model, an operational mockup which functionally, statically, and dynamically duplicates the flight control system should be constructed. For essential and flight phase essential flight controls, an accurate electrical representation should be provided. Production configuration components should be used for all flight control system parts, and the hydraulic system should be compatible with air vehicle hydraulic system requirements. Primary aircraft structure need not be duplicated; however, production configuration mounting brackets should be used and should be attached to the structure which simulates actual mounting compliance. Mechanical components of the FCS should be duplicated dimensionally. Inertia and compliance of flight control surfaces should be duplicated or accurately simulated. The operational mockup should be coupled with a computer simulation of aircraft characteristics and external inputs to the flight control system. The following minimum testing should be conducted on the operational mockup, or other appropriate test facility:

(1) Power supply variation tests to demonstrate satisfactory operation over the range of allowable variations specified in the applicable control power specifications.

(2) System fatigue tests (where system installation geometry or dynamic characteristics are critical to fatigue life) to demonstrate compliance with the requirements. The duty cycle required shall be established as representative of flight and ground usage.

(3) Stability margin tests to verify those requirements which can be verified by test using an aircraft simulation or the operational mockup, but which cannot be economically or safely demonstrated in flight.

(4) Tests to determine the effects of single and multiple failure on performance, safety, and mission completion reliability; and the development of emergency procedures to counteract the effects of failures.

(5) Miscellaneous tests to demonstrate FCS performance, and compatibility among FCS and with interfacing systems.

(6) System wear life where component wear life is interactive.

(7) Temperature variation tests duplicating normal operation or failure of temperature regulating elements shall be performed on components whose performance is determined to be sensitive to variations in temperature.

The operational mockup is a tool used for validation of the flight control system design prior to first flight and is also a useful tool in flight control development. The more nearly this tool functionally resembles the flight vehicle installation, the greater the confidence level in the test results. Ideally, an airframe with a flight control system installed and with aircraft flight dynamics simulated would be the mockup. Use of an airframe for the operational mockup is becoming more popular—especially where the FCS airframe interaction is expected to be complex.

Inclusion or exclusion of means for simulation of control surface aerodynamic hinge moments is dependent upon specific usage and should be justified. Where aircraft structural compliance is simulated in lieu of airframe parts, verification should be established through a detailed analysis of compliance.

The specified tests may be performed individually or, where feasible, a single test may satisfy multiple requirements. For example, structural strength and rigidity may be verified during performance (response) test, and fatigue requirements may be verified as a part of endurance testing. Note that the specified minimum tests may be performed on alternate test facilities. Separate component life/loading testing, for example, may be justifiable in some cases.

When performing power supply variation tests, each component should be tested individually or assembled, or both, into a system in a manner as specified in the component or system specification. Rated electrical, hydraulics and other required power sources should be applied and all calibration settings placed at maximum rated positions. After completion of the warmup period, the power sources should be varied and modulated, throughout their specified and possible limits. No steady state or transient modulation changes in the power source, within possible limits, should cause a variation or modulation in the system's performance which may result in undesirable or unsatisfactory operation. With rated power applied, the system's switches, controls and components should be operated as in actual service. Observation of the rated power source should note no variation or modulation of the power source beyond permissible operational limits when the system is operated against load conditions varying from no load to full load conditions.

Fatigue tests may be accomplished by cycling loads on components fixed in one or both hardover positions or in an intermediate position such as by hydraulic pressure impulse testing. It should also be noted that for fatigue testing, the "appropriate alternate test facility" could be the aircraft fatigue test rig. See MIL-A-8866 for discussion of fatigue scatter factors and MIL-A-8867 for fatigue test requirements. Note that required fatigue tests include all linkages, controls, etc.

Subsystem math models used to analytically predict stability margins for feedback systems should be verified on the operational mockup to the extent practical. This practice is encouraged since the FCS hardware such as sensors, electronics and actuators included on the operational mockup eliminate error included in the analytical predictions due to nonlinearities and other math modeling problems associated with these components. Where significant differences between the analytical predictions and the operational mockup margins are observed, further frequency response or other tests should be performed to identify the components which are improperly modeled. Once these components are identified, the corresponding math models can be corrected and analytical margin predictions refined.

One of the major uses of an operational mockup is evaluation of failure effects within the FCS. The program should also include performance oriented tests or simulations to verify predicted performance and to evaluate system compatibility.

For essential and flight phase essential controls, the following mockup tests of AFCS BIT and failure reversion capability should be considered:

a. Overtemperature test of AFCS computers, panels, and sensors to evaluate the BIT capability of detecting failures induced by progressive overheating.

b. Wire hardness failures (shorts between wires and ground and open circuits) to evaluate BIT capability to detect wiring damage/failures.

The main objective of these tests is not necessarily to make individual components less vulnerable to hazards or enemy action. Rather, the primary objective is to ensure that true redundancy exists by verifying that individual failures in each channel (1) are detected, (2) are remedied, and (3) are not the cause of multichannel failures.

While the application of the temperature variation test is relevant to the overall flight control system, it is a consequence of the potential thermal effects on electrical signal computation.

As the aircraft designs continue to place more capability, power, and performance into smaller integrated packages with space at a premium, the thermal environments within these packages become ever more hostile for electrical flight control components. It is essential that the effect of these environments on the flight control system be known, particularly as they affect the reliability and performance of digital flight control systems, and redundant systems in general.

For the flight worthiness certification, each element, subsystem, etc. of the FCS should demonstrate conformance with its approved and released engineering control documentation.

Testing which should be completed before first flight and support flight worthiness certification includes:

a. Gain margin tests to demonstrate the zero airspeed stability margin requirements for feedback systems depending on aerodynamics for loop closure and to demonstrate stability margins for nonaerodynamic loops. Primary and secondary structure should be excited, with special attention given to areas where feedback sensors are located with loop gains increased to verify the zero airspeed requirement. For redundant and multiple-loop systems, the stability requirement in degraded configurations should also be demonstrated. (These tests are performed in conjunction with structural testing. They are designed to determine if structural mode frequencies are propagating into the FCS and, if so, if there is proper compensation.)

b. Functional, dynamic, and static tests to demonstrate that all FCS equipment items are properly installed and that steady state responses meet FCS specification requirements. These tests should include integrated FCS and test instrumentation as installed on the prototype air vehicle. Compliance with the applicable residual oscillation requirements should be demonstrated.

c. Electromagnetic interference (EMI) tests to demonstrate compliance with requirements. Measurement of interference limits should be made in accordance with MIL-STD-461 and MIL-E-6051.

d. An integrity test to ensure strength and soundness of components and connections, adequate clearances, and proper operation.

e. Ground vibration tests with active controls using soft suspension system to simulate free-free condition. Flight control sensor outputs and open loop frequency response data should be recorded for correlation with analytical results used in predicting servoelastic and aeroservoelastic stability.

f. Taxi tests with increasing speed and all feedback loops closed to examine servoelastic stability above zero airspeed. Flight control sensor outputs and control surface deflections should be recorded.

g. Testing to verify that installed flight control lightning hardeners conform to the developed criteria.

The complete FCS should pass all of the operational mockup tests prior to first flight except that only 20 percent of the required fatigue life demonstration need be completed.

Certification that a component is safe for flight because of prior qualification and use on other aircraft may be allowed provided that the component design is identical to the previously qualified part in all significant respects and that its capability to operate under all conditions specified for its new application has been proven.

The documentation process should include a written summary, describing the work done to satisfy requirement verification, the results obtained and pertinent supporting facts. Significant points should include:

a. Reference to the requirement being validated.

b. Identification of the documents used for engineering control of the unit of product.

c. Identification of the method, equipment, instrumentation, and procedures used.

d. Identification of the unit of product used.

e. Results obtained.

f. Criteria which applies to the results.

The method, format, arrangement, etc. used for presenting the information should be chosen such that it offers an organized, complete, clear, and concise written record of the facts relevant to the verification.

VERIFICATION LESSONS LEARNED

In specifying testing as the means by which requirements are to be verified the following lessons learned should be considered.

a. There is a need to consider program objectives in deciding the level of testing required. Because of the differences in prototype development, full-scale development, and pilot production programs, the extent of testing feasibility may be beyond the scope of testing required.

b. Following some system modifications, the retesting required can be significantly less than the retesting feasible.

c. A test may be feasible, but not necessarily desirable when taken to the maximum extent. For example, the practical limitations of cost and time on the realizability of thorough or exhaustive testing of software must be taken into account when deciding on the extent of testing required. When such a case arises, an effective application of analysis is required for the interpretation of test results so that a required confidence level of performance is achieved.

d. Software verification and validation is a test, and a requirement is needed to address the issues of software.

e. Appropriate FCS acceptance tests should be defined by the detailed specification. Where interfacing components of the FCS are procured from various sources, sufficient acceptance testing should be performed to ensure overall system performance repeatability.

With the advent of comprehensive built-in test and inflight monitoring in modern aircraft, the potential for interface problems between FCS components exists as a result of the levels of sensitivity within the components. This lesson serves to ensure proper integration during the development phase and to establish the allowable tolerances of interfacing components.

This interface problem is typified for fly-by-wire flight control systems by the need of the flight control computer vendor to have integrated servoactuator packages or sensors on the premises during development to verify that acceptable interfacing is achieved.

Verification testing often leads to anomalies which are explained by statements such as those shown below. The verification documentation recording the facts should contain statements which address the factors which underlie each of these statements, thus leaving the recorded results free from doubt that any such factors influenced those results.

a. Manufacturing defect/error--quality control oversight.

b. Contaminated during assembly/manufacturing/handling.

c. Power source not per design conditions/ power cables faulty.

d. Test fixture improperly designed. Breaks/ damages/overloads unit.

e. Test fixture/rig not properly calibrated--loads too high.

f. Test instrumentation out of calibration--unit operated out of envelope.

g. Materials/heat treatment/finish not per specification.

h. Operator error--procedures not followed.

3.1.1 MFCS performance requirements. The MFCS shall interface with and supplement, as required, the characteristics of both the pilot and the air vehicle to allow the flying qualities, special performance and mission requirements to be met.

REQUIREMENT RATIONALE (3.1.1)

In those air vehicles covered by this specification the pilot is responsible for mission accomplishment. The MFCS provides the means by which the pilot controls the air vehicle for that purpose since one of the primary characteristics of the MFCS is that it is mechanized so that the pilot is a highly active element in the control loop. It is not intended that the FCS alone insure that the established flying qualities and performance requirements are met; however, the FCS shall not prevent those requirements from being met. The flying qualities, special performance and mission requirements are the performance parameters which insure that the capability exists to accomplish the mission.

REQUIREMENT GUIDANCE

When using the MFCS, the pilot must be able to consistently maneuver and control the air vehicle with accuracy, ease, and safety to meet mission requirements under all required flight conditions, operating environments, and vehicle configurations. As an active element in the MFCS, pilot action, in the general case, may range from direct manual control of surfaces to a supervisory or voting role in the generation of controlling moments. Mechanizations used range from direct mechanical manual systems through boosted and fully powered mechanical systems to the fully fly-by-wire systems. The MFCS includes those systems which enhance lift and drag, and provide stability and control augmentation system (SCAS), command/control augmentation system (CAS), stability augmentation system (SAS), etc.

REQUIREMENT LESSONS LEARNED

Experience has shown that design practices may have a strong influence on MFCS performance. A few of the lessons learned with respect to design practices are outlined below.

a. Selectable command modes. Pilots will select and adapt to special augmentation modes during weapons delivery and other special flight phases where special mission task requirements conflict with normal flying qualities. Consider selectable command modes, where pertinent; but inconsistencies in display indications or the results of cockpit control motions can be confusing to the pilot. For example, reversals of sense must be avoided.

b. Stabilization axis. In control system designs in which the pilot's lateral controller operates both ailerons and rudder or their equivalent, consideration should be given to the resultant effective axis of rotation. The optimum resultant effective axis of rotation is a function of the task, e.g., air to air gunnery, air to ground gunnery, and weapon delivery.

c. Gust and external disturbance response. Designs where specific measures are taken to improve the gust and external disturbance response of the aircraft are recommended.

d. Limit cycles during weapons delivery. FCS should be designed paying particular attention to the avoidance of the limit cycle during flight conditions at which weapons will be delivered. The limit cycle should be undetectable to the pilot. Similarly, if system gain changing takes place during weapon delivery, while the servos are moving, no thumping sensations should be experienced by the pilot and flying qualities must remain satisfactory throughout, despite the gain changes.

e. Trim changes. Apparent trim changes originating in the augmentation or control systems should be avoided whether due to extended low frequency response in the systems or to a normal accelerometer sensing less than 1 g in a climb or dive. An automatic trim system reducing these apparent trim changes to below pilot threshold will normally be acceptable. Where there are directional trim changes with speed change during a weapon delivery run, systems designed to minimize the trim change are desirable.

f. Constant stick forces. Systems incorporating washout filters on sensor outputs or elsewhere in the system should be designed to avoid changes in stick force with time during sustained constant normal acceleration turns.

g. Symmetrical stick forces. Control systems incorporating models should be designed to provide identical sensitivity for nose-down and nose-up commands. Whatever the system design, the stick forces for a given magnitude response should be the same irrespective of the sign of the command. This applies both laterally and longitudinally.

h. Aircraft flexibility. There can be effects beyond the impact of aeroelasticity on aircraft handling and flight control systems. For example, the design of a control-augmentation system to be used in part for weapon delivery must address itself to the effects of aircraft flexibility on weapon delivery accuracy. A reduction in amplitude of flexible body oscillation may be necessary to reduce oscillatory boresight errors. Static boresight errors due to loading in high-g maneuvers should also be considered in estimating delivery accuracy degradation due to flexibility.

i. Hysteresis. Hysteresis or backlash at any point in the control-augmentation system should be controlled either by antibacklash springs or by other means, at least to the point that limit cycles existing anywhere are imperceptible to the pilot at any flight condition at which weapons may be delivered.

j. Gun moments. The effect of firing high repetition rate small caliber weapons or large projectiles from the aircraft may cause perturbations of the vehicle. These should be evaluated and compensated for in the control system design.

k. Growth capability. A candidate system concept should be carefully examined for growth capability before selection for design and development. The complexity of a system can escalate as knowledge of aircraft dynamic characteristics are refined and the detail problems of designing flight-critical controls become known.

4.1.1 MFCS performance verification. MFCS performance shall be verified by inspection, analysis, and ground and flight test. Test conditions, fixtures, and methods are as follows: ______________

______________________________________.

VERIFICATION RATIONALE (4.1.1)

Flight test is the only means for including all the variables which influence assessment of MFCS performance. Factors such as affordability, feasibility, risk, etc., may limit the scope of flight testing. For such programs, the use of analysis or simulation or both may provide the means for the necessary verification.

VERIFICATION GUIDANCE

Determine the feasibility and cost effectiveness of using analysis and simulation in the process of verifying MFCS performance. Select the method or methods which provide an acceptable assessment. If a mix is chosen, consider the scope of the data base required from the flight test to make the analysis, simulation or both, credible and sufficient.

VERIFICATION LESSONS LEARNED

Care must be taken when procuring an 'off-the-shelf' aircraft to ensure that certification requirements match the mission for which it will be procured. In this case methods of verification must be carefully reviewed.

3.1.2 AFCS performance requirements. The AFCS shall interface with and supplement the characteristics of the air vehicle to provide, as selected, flight path and attitude control, airframe response and functional performance as specified in the numbered subparagraphs of this section. A pilot interface shall be provided through an AFCS controller. The controller shall be implemented through the __(a)__ and shall, for the AFCS mode selected, provide functions, responses, and control as shown below:

Attitude Hold (Pitch)	__(b)__
Attitude Hold (Roll)	__(c)__
Heading Hold	__(d)__
Heading Select	__(e)__
Altitude Hold	__(f)__
__(g)__	__(h)__

The authority of the pilot to maneuver the air vehicle through the AFCS shall be __(i)__.

A damping ratio for non-dominant responses of at least __(j)__ critical shall be provided for non-structural AFCS controlled responses. The AFCS shall be functionally compatible with any automatic AFCS limiter and its associated warning system and not overpower such limiters at the extremes of the flight envelope resulting in unsafe conditions that would require immediate pilot action.

REQUIREMENT RATIONALE (3.1.2)

The AFCS flies the aircraft and thus relieves the pilot of the burden of the routine cockpit control manipulation which is required to perform selected functions during various flight phases incident to mission accomplishment. To provide this relief in a manner which is satisfactory to the pilot, the AFCS must duplicate to a great extent the characteristics of the pilot and provide performance within limits satisfactory to the applicable flight phases. A controller should be provided to allow the pilot to adjust the selected references and perform maneuvering which increases the utility of the AFCS and enhances mission accomplishment. The damping ratio is common to all uses of the AFCS; other performance characteristics and limits are specified in the subparagraphs of this section.

REQUIREMENT GUIDANCE

The performance specified in this section is intended to include "not to exceed" values which are felt necessary to satisfy operational requirements. Performance is usually specified with respect to sensor indicated values. Sensor accuracy may be based on the needs of some other function such as display for use in manual control. Where performance is not specified with respect to a FCS sensor reference, sensor error must be included in meeting the required one.

Air Force Manual 11-1 defines AFCS (Automatic Flight Control System as used for the Air Standardization Coordinating Committee) as: "A system which includes all equipment to automatically control the flight of an aircraft or missile to a path or attitude described by references internal or external to the aircraft or missile." The term "autopilot" is an outdated term not now defined but in antiquity was defined in AFM 11-1 as: "That part of an automatic flight control system which provides automatic stabilization with respect to internal references." The requirements contained in the subparagraphs of this section address the most common AFCS functions. The intent of this Appendix, and the corresponding specification, is not to limit the AFCS functions but to provide a guide for the most common and generic functions. The subparagraphs of this section should be extended to provide for configuration peculiar automatic functions, and where feasible, integration of systems to provide functions such as: automatic control of engine thrust, NAV speed, terrain following, terrain avoidance, automatic maneuvering, attack, takeoff, landing, etc.

The performance requirements of the AFCS assume that the pilot will not be in the active control loop. However, during use of the AFCS Controller, the pilot provides supervisory inputs to accomplish the task at hand, establish a new flight phase, provide track guidance commands for which information is not available or is unsuitable for use by the AFCS. The pilot monitors AFCS operational performance and usually makes selection of functions needed to accomplish the desired task. Automatic switching for sequential tasks accomplishment may be included in the AFCS. In any event, the reference established by these actions may require adjustment or change as the mission progresses. STOL ______ and possibly other aircraft may have unique requirements for control (airspeed, heading, attitude, etc) while using pilot inputs for path control or precision maneuvering (air refueling, approach, hovering, etc.) where navigation or guidance commands are not available for AFCS use.

The AFCS Controller functions should be used to provide that facility.

Blank (a) should be filled by the words "control stick" or "control wheel", whichever is appropriate in the tailoring process. If a separate controller is provided as an assembled item of the AFCS, that item should be listed in blank (a).

Blank (b) might be filled by one or more of the following:

(1) Changing to a new pitch attitude.

(2) Maneuvering with pitch attitude stabilization.

(3) Change pitch attitude reference by use of the pitch trim control located on the stick wheel.

(4) Controlling rate of sink with constant seek angle during VTOL/STOL operations.

Blank (c) might be combined with (b) or filled by one or more of the following:

(1) Changing to a new roll attitude.

(2) Maneuvering with roll attitude stabilization.

(3) Change roll attitude reference by use of the roll trim control located on the stick or wheel.

Blank (d) might be filled by the following:

(1) Break and reestablish heading reference lockon through use of roll attitude controller.

(2) Change to roll attitude hold mode through use of roll attitude controller.

Blank (e) might be combined with blank (d) or filled by :

(1) Slew heading reference at a rate proportional to roll attitude controller force/displacement.

(2) Slew heading reference at a constant rate using the roll trim control located on the stick or wheel.

(3) Change to roll attitude hold mode through use of roll attitude controller.

Blank (f) might be filled by:

(1) Change to pitch attitude hold mode through use of the pitch attitude controller.

(2) Change altitude reference through use of the pitch trim control located on the stick or wheel.

Blanks (g) and (h) might be filled by any other function and response which might be required such as:

(1) Mach hold.

Mach number reference change by use of pitch trim control located on the stick or wheel.

(2) Airspeed hold.

Airspeed reference change by use of pitch trim control located on the stick or wheel.

(3) Altitude select.

Altitude reference selected by pilot.

(4) Terrain following

Pilot selectable set clearance and ride setting.

Blank (i) should be filled by showing the pitch and bank attitude limits which will be allowed through the controller. For AFCS which used the generic vertical displacement type gyro, these limits have usually been +25 in roll and +50 in pitch; however, these limits may not be adequate for the planned system. The pilot shall always have full capability to maneuver the Air Vehicle within the applicable force and maneuver limits established by the handling qualities requirements. Reversion to some other FCS mode may be required to fulfill that requirement.

Blank (j)

A damping ratio of 0.3 critical has proven satisfactory as a minimum value in previous AFCSs. This ratio is the equivalent second order viscous damping ratio where the critical ratio is defined as unity. Some aircraft have had autopilot modes, such as altitude hold, that could overpower the authority of automatic angle of attack limiter or stall inhibitor systems to position the pitch control surfaces and result in unsafe flight conditions, especially at low speed extremes of the flight envelope. If this incompatibility does exist, the crew should be alerted to the fact that they are entering the regions through appropriate cockpit display annunciation.

REQUIREMENT LESSONS LEARNED

Specifying performance to include sensor error may lead to deviation requests where sensors are government furnished and can be shown to not provide consistent or adequate performance as needed to meet the requirement.

4.1.2 AFCS performance verification. AFCS performance requirements shall be verified as indicated in the subparagraphs of this section. The specified damping ratio for nonstructural AFCS controlled response shall be verified by __________ __________________________________.

VERIFICATION RATIONALE (4.1.2)

Each requirement in this section will be individually verified by a means specified in its verification subparagraph. The means of verifying the specified damping ratio is left blank to allow the most feasible method to be used.

VERIFICATION GUIDANCE

Analysis, simulation, and bench and flight tests are methods used for verifying AFCS damping ratios. Unless otherwise specified, AFCS performance requirements apply in smooth air and include sensor error. Specified damping requirements apply only to the response characteristics for perturbations an order of magnitude greater than the allowable residual oscillation.

VERIFICATION LESSONS LEARNED

3.1.2.1 **Attitude hold (pitch and roll).** Attitudes shall be maintained in smooth air with a static accuracy of __(a)__ degrees in pitch attitude with wings level and __(b)__ degree in roll attitude. The rms attitude deviations shall not exceed __(c)__ degrees in pitch or __(d)__ degrees in roll attitude and shall provide at least Operational State __(e)__ in turbulence at the rms gust intensities corresponding to __(f)__ probability of exceedance (table I). Accuracy requirements shall be achieved and maintained within __(g)__ seconds of mode engagement for a 5 degree attitude disturbance. Attitude hold engage limits shall be __(h)__ degrees in pitch and __(i)__ degrees in roll.

REQUIREMENT RATIONALE (3.1.2.1)

When attitude hold is desired, this requirement establishes performance criteria based on experience and state-of-the-art capability. Establishing pitch and bank attitude deviation limits in turbulence is intended to provide the pilot with a reasonably stable platform during flight.

REQUIREMENT GUIDANCE

Values previously required were: (a) ±0.5, (b) ±1.0, (c) 5, (d) 10, (e) II, (f) 10^{-2}, (g) 3.5, (h) ±15, (i) ±60.

The accuracy requirement of ±0.5 degrees for attitude hold modes represents a typical air transport requirement, and state-of-the-art capability. The accuracy requirement in turbulence applies only up to the turbulence amplitude limits specified for the chosen probability of exceedance. Attitude hold and other pilot assist functions will normally be classified as noncritical functions and, as such, the turbulence requirement stated will normally apply only in light turbulence. It is important to avoid automatic mode disengagement in light turbulence. Noncritical functions shall provide at least Operational State II in turbulence up to 10^{-2} turbulence intensity exceedance probability and shall not degrade flight safety or mission effectiveness below the level that would exist with the mode inactive.

The 5-degree pitch angle and the 10-degree roll angle limit in turbulence is intended to provide the pilot with a reasonably stable platform during flight in the turbulence environment to which the attitude hold loops will be designed. A system which is easily saturated in turbulence will have trouble meeting these requirements and should be avoided.

For high maneuverability, aircraft accuracy requirements shall be achieved and maintained within 3 seconds of mode engagement. For light, small aircraft and those with low to medium maneuverability, a value of 5 seconds is recommended.

For rotary wing air vehicles, the accuracy requirements should apply only under conditions of fixed, collective pitch.

Attitude hold engage limits should be determined based on the aircraft mission and performance capabilities. The values suggested above are generally accepted for large air vehicles.

REQUIREMENT LESSONS LEARNED

Attitude hold maneuver limits are not included in this general requirement due to the lack of agreement on maneuver limits. MIL-F-9490C set maneuver limits for the attitude hold function ±60 degrees in roll, ±15 degrees in pitch, and ±7 degrees yaw angle for control stick steering applications. Maneuver limits will normally be established for each procurement based on the requirements of that procurement.

4.1.2.1 **Attitude hold (pitch and roll).** Attitude hold shall be verified by inspection, analyses, and flight test. Test condition, fixtures and methods are as follows: ______________________.

VERIFICATION RATIONALE (4.1.2.1)

Although a flight test of all portions of the envelope would be desirable, a combination of flight testing inspection, simulation, and analyses is used for verification because of economic consideration.

VERIFICATION GUIDANCE

In the past, it has been suggested that flight testing be performed at the corners of the design envelope and in the center. Analysis then filled in the other points of the envelope. It may be more meaningful if the flight testing is also performed in the portion of the envelope where the aircraft primary mission is performed. Transports could be checked at cruise, aircraft designed for weapon delivery checked at low altitude along its Mach range, etc.

Piloted simulation iron bird or interpretation of FCS computer generated strip charts are examples of acceptable analysis.

VERIFICATION LESSONS LEARNED

3.1.2.2 Heading hold. In smooth air, heading shall be maintained within a static accuracy of __(a)__ degrees. Deviations shall not exceed __(b)__ degrees in heading and shall provide at least Operational State __(c)__ in turbulence at the rms gust intensities corresponding to __(d)__ probability of exceedance (table I). When heading hold is engaged, the aircraft shall roll towards wings level at a rate not to exceed __(e)__ degrees/sec and a roll acceleration not to exceed __(f)__ degrees/sec/sec. The reference heading shall be that heading which exists when the mode is engaged within a tolerance of __(g)__ degrees.

REQUIREMENT RATIONALE (3.1.2.2)

When heading hold is desired, this requirement establishes performance criteria based on experience and state-of-the-art capability. Establishing heading hold limits in turbulence is intended to provide the pilot with a reasonable navigation accuracy during flight.

REQUIREMENT GUIDANCE

Values previously required: (a) ±0.5, (b) 5.0, (c) II, (d) 10^{-2}.

The heading hold static accuracy requirement of 0.5 degree reflects the current state-of-the-art. Typical air transport heading hold requirements, which may be considered in pertinent applications are as follows: when selection of this mode is made while the aircraft is turning, the airplane should return to wings level at a roll rate not to exceed 6.0 deg/sec, a roll acceleration not to exceed 3.0 deg/sec^2, and should hold the heading that exists at the time the airplane is within approximately 3 degrees of wings level. Desirable rates and acceleration vary with air vehicle mission and should be determined in design.

For rotary wing air vehicles, the values used for blank (a) should be:

1.0 for airspeeds less than 50 knots, and
0.5 for airspeeds greater than 50 knots,

with all other values remaining near those previously used in MIL-F-9490 and in typical air transports.

Selection of the reference heading depends on the dual criteria having been satisfied, e.g., (a) heading hold is selected, (b) the roll attitude is approximately wings level. These criteria ensure that the aircraft will not be forced to make an appreciable turn in the opposite direction in order to capture a heading that existed while the aircraft was in a turn and heading hold was engaged. It is important to avoid automatic mode disengagement in light turbulence. Heading hold is normally classified as a noncritical function which shall provide at least Operational State II capability in atmospheric disturbance designated for 10^{-2} turbulence exceedance probability and shall not degrade flight safety or mission effectiveness below the level that would exist with the mode inactive.

REQUIREMENT LESSONS LEARNED

A 5-degree rms deviation requirement for operation in light turbulence is desirable. This prevents design of an easily saturable mode while not restricting the functional design of the overall AFCS.

4.1.2.2 Heading hold. Heading hold performance parameters shall be verified by a combination of flight tests and ________. Flight testing shall be performed ________________.

VERIFICATION RATIONALE (4.1.2.2)

Although a flight test of all design points would be desirable, a combination of flight testing and analyses is used for verification because of economic considerations.

VERIFICATION GUIDANCE

In the past it has been suggested that flight testing be performed in the center and at the corners of the design envelope. Analysis then filled in the other points of the envelope. It may be more meaningful if the flight testing is performed in the portion of the envelope where the aircraft primary mission is performed. Transports could be checked at cruise, aircraft designed for weapon delivery checked at low altitude along its Mach range, etc.

Piloted simulation or interpretation of FCS computer generated strip charts are examples of acceptable analysis.

If flight test is the only verification required, delete "and _______." from the first sentence of 4.1.2.2, and do not include information on analysis.

VERIFICATION LESSONS LEARNED

3.1.2.3 **Heading select.** The aircraft shall automatically turn through the smallest angle to any heading selected or preselected by the pilot and maintain that heading. In smooth air, heading shall be maintained within a static accuracy of __(a)__ degrees. Deviations shall not exceed __(b)__ degrees in heading and shall provide at least Operational State __(c)__ in turbulence at the rms gust intensities corresponding to __(d)__ probability of exceedance (table I). The 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 __(e)__ degrees, or __(f)__ degrees in landing configuration. Entry into and exit from the turn shall be smooth and rapid. The roll rate shall not exceed __(g)__ deg/sec and roll acceleration shall not exceed __(h)__ deg/sec^2.

REQUIREMENT RATIONALE (3.1.2.3)

The roll rate and acceleration upper limits are specified to preclude an overly rapid response. The requirement for smooth and rapid roll-in and roll-out of the turn is stated to ensure that the response is not unduly sluggish.

REQUIREMENT GUIDANCE

Values previously required: (a) +0.5, (b) 5.0, (c) II, (d) 10, (e) 1.5, (f) 2.5, (g) 10/20, and (h) 5/10.

The imposition of limits on roll rate and roll acceleration when maneuvering to the new heading establishes an upper limit for the rates and accelerations but does not address an acceptable minimum. The requirement for smooth and rapid response assures that minimum rates, as well as maximum rates, will be acceptable. The lower suggested values for roll rate and roll acceleration are for light aircraft and low to medium maneuverability air vehicles. Higher values are suggested for high maneuverability aircraft.

Care must be taken to make sure the overshoot and rate/acceleration requirements are compatible.

REQUIREMENT LESSONS LEARNED

4.1.2.3 **Heading select.** Heading select performance parameters (heading accuracy, overshoot, roll rate and acceleration, bank angle limits, and smallest angle to select heading) shall be verified by flight test and __________. Flight testing shall be performed ____________________.

VERIFICATION RATIONALE (4.1.2.3)

Although a flight test of all design points would be desirable, a combination of flight testing and analyses is used for verification because of economic considerations.

VERIFICATION GUIDANCE

In the past it has been suggested that flight testing be performed with delta heading of 30 degrees, 90 degrees, 150 degrees, and 190 degrees at each of four representative in flight conditions and two landing conditions. Analysis then filled in the other points of the envelope. The flight testing should be performed in the portion of the envelope where the aircraft primary mission is performed.

Piloted simulation or interpretation of FCS computer generated time histories are examples of acceptable analysis.

If the option of using analysis is not desired, then delete "and ____________."

VERIFICATION LESSONS LEARNED

3.1.2.4 Lateral acceleration and sideslip limits. Except when side force control or directed sideslip is deliberately induced, the performance specified in table II shall be provided whenever any lateral-directional AFCS function is engaged. Lateral acceleration refers to apparent (measured, sensed) body axis acceleration at the aircraft center of gravity, unless otherwise noted.

REQUIREMENT RATIONALE (3.1.2.4)

This requirement is necessary to maintain acceptable flight path control, good flying qualities and, in certain applications, to restrict lateral acceleration limits to an acceptable level because of structural limits. The lateral acceleration limits, rolling, are specified to maintain acceptable crew or passenger comfort.

REQUIREMENT GUIDANCE

The mission of the air vehicle will determine the lateral acceleration limits. Transport aircraft may have limits based on passenger comfort. Effects of angle of attack and c.g. position should be evaluated.

AFCS performance requirements include "not to exceed" parameters associated with accurate control of the flight path and are specified at the c.g. These values should not conflict with flying qualities limits which are generally specified at the crew station and are designated for crew comfort and/or fatigue reasons.

The requirement has been changed from absolute to incremental values of sideslip angle and lateral acceleration to account for steady-state trimmed sideslip angles which are required to support the vehicle and the store asymmetries.

Vehicle asymmetries, especially those caused by asymmetric stores, will require a steady-state sideslip angle to balance the unsymmetrical aerodynamic forces. Non-zero bank angles may also be required to support steady-state trim. Under these conditions it is necessary to replace the absolute sideslip angle restriction with incremental sideslip from unaccelerated flight reference sideslip values.

Values previously required are listed in table VII:

TABLE VII. AFCS lateral acceleration and sideslip limit values.

Flight Condition	Incremental Sideslip	Lateral Acceleration
Coordination in Steady Banked Turns	2	0.03 g
Lateral Accelerations Rolling at		
30°/sec		+ 0.1 g
90°/sec		+ 0.2 g
over 90°/sec		+ 0.5 g
Coordination in Steady "Straight Level" Flight	1	+ 0.02 g

REQUIREMENT LESSONS LEARNED

An aircraft's roll rate capability will vary within the aircraft's flight envelope and, as roll rate capability varies, so will the required lateral acceleration limits. For example, if an aircraft with a 90 deg/sec maximum roll rate capability can only roll at 30 deg/sec in some portion of the envelope, then at that condition the tolerance should be +0.1 g, not +0.5 g.

4.1.2.4 Lateral acceleration limits and sideslip limits. Lateral acceleration shall be verified by flight tests and ________________. Flight testing of lateral acceleration limits shall be performed ______ ____________________________.

VERIFICATION RATIONALE (4.1.2.4)

Lateral acceleration limits are imposed because of safety and invulnerability to failure requirements. A combination of flight testing and analyses is used for verification because of economic considerations.

VERIFICATION GUIDANCE

In the past, it has been suggested that flight testing be performed at the corners of the envelope and in the center. Analyses then filled in the other points of the envelope. It may be more meaningful if the flight testing is performed in the portion of the envelope where the aircraft's mission is performed. Transports could be checked at cruise, aircraft designed for weapon delivery checked at low altitude along its Mach range, etc.

Lateral acceleration is usually verified in flight test at zero, 60 deg/sec, and maximum roll rates in smooth air. In the past it was recommended that these maneuvers be performed at the corners of the design envelope and in the center.

In the past it has been required that lateral acceleration, rudder pedal, and stick force would be verified in flight test at +45 degrees of bank in coordination turns performed in smooth air in at least four corners and center of the flight envelope.

Simulator work or interpretation of FCS computer model generated time histories are examples of acceptable analyses.

If analysis is not desired for verification, delete "and ________________."

VERIFICATION LESSONS LEARNED

3.1.2.5 Altitude hold. Engagement of the altitude hold function at rates of climb or descent less than __(a)__ fpm shall select the existing indicated altitude and control the aircraft to this altitude as reference. The resulting normal acceleration shall not exceed __(b)__ g incremental. For engagement at rates of climb or descent above __(a)__ fpm, resulting normal acceleration shall not exceed __(c)__ g incremental maneuvers. Within the aircraft thrust-drag and performance capability and at steady bank angles, the mode shall provide control accuracies specified in table III. These accuracy requirements apply for an airspeed range __(d)__. For other airspeeds the accuracy requirements shall be __(e)__. Following engagement or perturbation of this mode at 2000 fpm or less, the specified accuracy shall be achieved within __(f)__ seconds. Any periodic residual oscillation within these limits shall have a period of at least __(g)__ seconds.

REQUIREMENT RATIONALE (3.1.2.5)

The intent of the altitude hold requirements is to define the normal performance expected for acceptable flight path control, flying qualities and, in some cases, crew/passenger comfort.

REQUIREMENT GUIDANCE

The values previously used for airplanes are: (a) 2000, (b) 0.2/.5, (d) up to MACH 1.0, (e) double the table VIII values above MACH 2.0, (f) 30, and (g) 20.

The value for blank (c) is a compromise between minimum allowable overshoot and maximum desirable g excursion and should be determined by analyses and simulation.

TABLE VIII. Control accuracy for altitude hold AFCS function in airplanes.

	55,000 to 80,000	+0.1% at 55,000 varying linearly to +0.2% at 80,000	±60 ft.	±90 ft.
Altitude in feet	30,000 to 55,000	±0.1%	or ±0.3% whichever is larger	or ±0.4% whichever is larger
	0 to 30,000	±30 ft		
		0 - 1	1 - 30	30 - 60
	Bank angle in degrees			

Altitude hold requirements include acceleration amplitude limits. For reference, commercial transports normally limit normal acceleration for altitude hold engagement of 0.15 g incremental. Residual oscillations are permitted within the amplitude limits specified herein. Response requirements are specified similar to those used in a recent commercial transport AFCS development and in a recent USAF fighter AFCS development.

Altitude hold is usually engaged in some condition other than steady state flight; for example, when climbing to a predetermined cruise altitude or descending to a holding altitude, either straight ahead wings level or in a turn. In a passenger carrying air vehicle engage/disengage transients should not cause undue concern to the passengers or require that seat belts be fastened during autopilot operations. In a non-passenger-carrying air vehicle where the pilot(s) are required to be restrained by seat belts at all times while airborne, a larger transient normal acceleration may be acceptable.

In addition to the altitude hold accuracies specified for steady bank angles, performance in maneuvering flight should also be considered by the designer. Also, the designer should not overlook the need to control altitude excursions during airspeed changes. Altitude hold deviations during normal configuration changes should also be considered.

REQUIREMENT LESSONS LEARNED

Provisions should normally be included to disengage altitude hold at a given angle of attack. Experience has shown that an air vehicle can get in a situation where more thrust is required than is available at the chosen power setting. In this case the altitude hold feature will continue to increase angle of attack until stall. Under certain conditions the stall may be unrecoverable.

Disengagement of altitude hold by momentary application of stick or yoke force with regression to a lower mode, e.g., attitude hold, should be avoided to preclude the possibility of an accidental disengagement and a subsequent undetected loss of altitude. Such an incident for a commercial aircraft, while the crew was preoccupied, resulted in a loss of aircraft. Disengagement of altitude hold should be effected only by deliberate pilot action.

Altitude hold and airspeed hold tolerances increase with airspeed. Experience has shown that tolerances may need to be relaxed for flight near Mach 3.0. Otherwise, the tight loops needed to hold Mach may result in large altitude variations and degraded ride qualities.

4.1.2.5 Altitude hold. Resulting normal acceleration, accuracy, and time to achieve accuracy shall be verified in smooth air by flight test and ________. Flight testing shall be performed ________. Ability to engage or not engage shall be verified by attempting to engage during a climb or descent of ________ fpm at all fight test points.

VERIFICATION RATIONALE (4.1.2.5)

Although a flight test of all design points would be desirable, a combination of flight testing and analysis is used for verification because of economic considerations.

VERIFICATION GUIDANCE

In the past it has been suggested that flight testing be performed at the corners of the design envelope and in the center. Analysis then filled in the other points of the envelope. It is more meaningful if the flight testing is also performed in the portion of the envelope where the aircraft primary mission is performed.

Piloted simulation or interpretation of FCS computer generated time histories are examples of acceptable analyses.

If analysis is not desired for verification, then delete "and ________."

VERIFICATION LESSONS LEARNED

3.1.2.6 Altitude select. Engagement of the altitude select function at rates of climb or descent less than __(a)__ fpm shall result in the aircraft automatically climbing or descending to any altitude preselected by the pilot or within an automatic navigation or guidance program. The resulting normal acceleration shall not exceed __(b)__ g incremental, and the resulting climb or descent shall not exceed __(a)__ fpm. For engagement at rates of climb or descent above __(a)__ fpm, resulting normal acceleration shall not exceed __(c)__ g incremental maneuvers. Within the aircraft thrust-drag and performance envelope, and at steady bank angles, the mode shall provide control accuracies specified in table III. These accuracy requirements apply for an airspeed range __(d)__. For other airspeeds, the accuracy requirements shall be __(e)__. Following engagement of this mode, the specified accuracy shall be achieved within __(f)__ seconds after initial crossing of selected altitude. Any periodic oscillation within these limits shall have a period of at least __(g)__ seconds.

REQUIREMENT RATIONALE (3.1.2.6)

This requirement is similar to 3.1.2.5, Altitude hold, except that it allows for the attainment of an altitude preselected by the pilot, or automatically selected by a guidance or navigation program.

REQUIREMENT GUIDANCE

The values used by this requirement are identical to those given in the guidance for 3.1.2.5, Altitude hold. Refer to that section for additional guidance. Requirements for altitude attainment and capture are based on reasonable g and climb and descent rates. An additional restriction may be necessary to limit aircraft pitch attitude during approach to selected altitude.

REQUIREMENT LESSONS LEARNED

4.1.2.6 Altitude select. Resulting normal acceleration, accuracy, and time to achieve accuracy shall be verified in smooth air by flight test and __(a)__. Flight testing shall be performed __(b)__. Ability to engage or not engage shall be verified by attempting to engage during a climb descent of __(c)__ fpm at all flight test points. Ability to maintain sustained load factor or climb or descent rate shall be verified by engaging __(d)__ feet above and below selected altitude.

VERIFICATION RATIONALE (4.1.2.6)

Consult the rationale provided for 3.2.1.5, Altitude hold, for blanks (a), (b), and (c). Blank (d) provides for the verification of the approach to and capture of the selected altitude.

VERIFICATION GUIDANCE

Verification of 4.1.2.5 provides guidance for this requirement with the exception of ___(d)___. The value of ___(d)___ should be selected with the maximum spread between engagement altitude and selected altitude to assure that load factor or rate of climb or descent is not exceeded.

VERIFICATION LESSONS LEARNED

3.1.2.7 Automatic hovering. Position shall be maintained relative to the point of reference to an accuracy of ___(a)___ feet. This accuracy requirement applies during gust intensities of ___(b)___ feet/sec, and wind, or point of reference, velocities up to ___(c)___ knots.

REQUIREMENT RATIONALE (3.1.2.7)

This requirement provides the means to satisfy, in air vehicles capable of hovering, the need to control, with respect to a reference point external to the air vehicle, both position and velocity along the longitudinal, lateral, and vertical axes. The gust intensities, and wind and reference point velocity requirements allow the operational capability to be tailored for the environmental conditions and sensor systems performance which will be found during field operations.

REQUIREMENT GUIDANCE

Previously used values: (a) ±4 to 10, (b) 5, and (c) 45.

Accuracy requirements should be based on the mission specified for the air vehicle and the capability which it is feasible to provide during the hover mode of operation. Values in the range of +4 to +10 feet may be used for longitudinal, lateral, and vertical positional accuracy. These accuracies should be maintained in gust intensities up to 5 feet per second rms and wind or reference point velocities up to 45 knots.

REQUIREMENT LESSONS LEARNED

4.1.2.7 Automatic hovering. Automatic hovering requirements shall be verified by ______________.

VERIFICATION RATIONALE (4.1.2.7)

Automatic hovering requirements should provide the capability needed in the air vehicle to accomplish a part of the specified mission. The processes used during verification document the extent to which the required capability has been provided and form the basis for planning operational usage of the air vehicle.

VERIFICATION GUIDANCE

Automatic hover requirements may be verified by simulation and flight tests. The most feasible method or combination of methods should be used.

The most feasible method of verification is to use simulation to cover the entire range of required operation, then choose points to be covered by a limited flight test, then use the flight test data to refine the simulation, and then complete the verification.

VERIFICATION LESSONS LEARNED

3.1.2.8 Mach hold. The Mach number existing at the engagement of Mach hold shall be the reference. After engagement and stabilization on Mach hold, the AFCS shall maintain indicated Mach number and the error shall not exceed ___(a)___ Mach or ___(b)___ 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 ___(c)___ seconds. A mode response or maximum time to capture reference suitable for the mission phase shall be ___(d)___ seconds. Adjustment capability of at least ___(e)___ Mach shall be available to allow the pilot to vary the reference Mach number around the engaged Mach number.

REQUIREMENT RATIONALE (3.1.2.8)

The Mach hold mode provides the Mach hold capability in cruise flight where optimum range or time will result, or in climb out where the best rate or angle of climb Mach will be maintained.

REQUIREMENT GUIDANCE

Values previously required: (a) ±0.01, (b) ±2.0, (c) 20, (d) 20, and (e) ±0.01.

The requirement is applicable to a Mach hold mode using either the autopilot pitch axis or an automatic throttle system. This makes possible two-degrees-of-freedom control simultaneously selecting two control modes, e.g., altitude control through pitch and Mach through autothrottle. This enables Mach hold to be engaged during maneuvering flight where the system is unable to control Mach within the requirements, or under conditions where the system is able to control Mach but at the expense of altitude. For example, for a system which controls Mach by pitch, if a Mach upset requires a descent in order to maintain Mach, an ever increasing rate of descent will occur as the aircraft descends to lower altitude. The pilot is responsible for maintaining safe flight under these or similar conditions.

Minimum damping is specified in 3.1.2 for transient response following a disturbance; however, there is no damping requirement for small oscillations within the performance tolerance bands. Establish a maximum time for recapture of the commanded Mach following a disturbance which is suitable for the mission phase. This value will be based on the control characteristics of the individual aircraft being developed and should be included in the FCS specification.

REQUIREMENT LESSONS LEARNED

Mach hold tolerance increases with airspeed. Limited experience has shown tolerances need to be relaxed for flight near Mach 3.0. Otherwise, the tight loops needed to hold Mach may result in large altitude variations and degraded ride qualities.

It is very difficult to engage the mode at the control airspeed required in adverse weather. ARINC Characteristic No. 558 (Air Transport Automatic Throttle System) indicates a full range of adjustment for their system.

This requirement is applicable to a Mach hold mode using either the autopilot pitch axis or an automatic throttle system. The RFP and the FCS specification should define which is to be used. Experience on installing automatic throttle systems has shown that some adjustment capability must be made available for the pilot.

4.1.2.8 Mach hold. The Mach hold requirements shall be met during maneuvering flight incident to cruise and in steady flight including climb and descent. Verification shall be made by flight test and ____________. Flight testing shall be performed ______________________________.

VERIFICATION RATIONALE (4.1.2.8)

A combination of flight test and analysis is used to verify Mach hold for economic reasons.

VERIFICATION GUIDANCE

It is recommended that flight tests be performed at the extremes of the design envelope and in the center. It may be more meaningful if the flight testing were concentrated in the position of the envelope where the aircraft primary mission is performed.

Piloted simulation and interpretation of FCS computer generated strip charts are examples of acceptable analyses.

If analysis is not desired for verification, then delete "and ____________."

VERIFICATION LESSONS LEARNED

3.1.2.9 Airspeed hold. The airspeed existing at the engagement of airspeed hold shall be the reference. Indicated airspeed shall be maintained within __(a)__ knots or __(b)__ percent of the reference speed, whichever is greater, up to __(c)__ degrees bank angle. Any periodic oscillation within these limits shall have a period of at least __(d)__ seconds. The mode response or maximum time to capture reference shall be __(e)__ seconds in the most demanding mission phase. Adjustment capability of at least __(f)__ knots shall be available to allow the pilot to vary the reference around the engaged airspeed.

REQUIREMENT RATIONALE (3.1.2.9)

Airspeed hold mode provides the capability to maintain airspeed in cruise flight where optimum range or time will result.

REQUIREMENT GUIDANCE

Values previously required: (a) ±5, (b) ±2, (c) ±60, (d) ±20, and (f) ±10.

The value inserted in blank (e) should reflect the maximum time to capture reference based on the most demanding mission requirement.

Airspeed hold requirements are specified which are similar to those used in commercial applications. Minimum damping follows the general requirements in this specification for the transient response following a disturbance; however, there is no damping requirement for small oscillations within the performance tolerance bands.

This requirement is applicable to an airspeed hold mode using either the autopilot pitch axis or an automatic throttle system. The RFP and the FCS specification should define which is to be used.

REQUIREMENT LESSONS LEARNED

Airspeed hold tolerance increases with airspeed. Experience has shown tolerances may need to be relaxed for flight near Mach 3.0. Otherwise, the tight loops needed to hold airspeed may result in large altitude variations and degraded ride qualities.

Experience in installing automatic throttle systems has shown that some adjustment capability must be made available for the pilot. It is very difficult to engage the mode at the control airspeed required in adverse weather.

4.1.2.9 Airspeed hold. Time to stabilization and accuracy of airspeed hold shall be verified by a combination of flight test and _______. Operation during landing approach shall also be verified. Flight testing shall be performed __________.

VERIFICATION RATIONALE (4.1.2.9)

Although an extensive flight test would be desirable, a combination of flight test and analyses is used to verify airspeed hold for economic reasons.

VERIFICATION GUIDANCE

In the past it was recommended that flight tests be performed at the corners of the design envelope and in the center. It is more meaningful if the flight testing were concentrated in the portion of the envelope where the aircraft primary mission is performed.

Piloted simulation and interpretation of FCS computer generated time histories are examples of acceptable analyses.

If analysis is not desired for verification, delete "and ____________________."

VERIFICATION LESSONS LEARNED

3.1.2.10 Automatic navigation and guidance. The AFCS shall provide automatic control to intercept and maintain the track defined by the following equipment/subsystems:

____

____

____

Maneuvers commanded by the AFCS during any phase of such operation shall not place the air vehicle in hazardous attitudes or result in flight limitations being exceeded. Switching and sequencing, and air vehicle body axis rates and accelerations shall result in smooth, nonoscillatory air vehicle control and rapid reduction of error. There shall be no residual oscillations greater than those allowed in the flying qualities requirements for this air vehicle. Requirements for specific equipment/subsystems are as follows:

____

____

____

REQUIREMENT RATIONALE (3.1.2.10)

Dynamic progress in the avionics field and changes now occurring in the available navigation and guidance equipment and systems, together with the increasing use of digital computational capability, provide great and varying choices in the use of the AFCS to provide high quality automatic navigation and guidance during various phases of flight for pilot relief and mission accomplishment. The dynamic progress made in AFCS mechanization and performance allows great latitude in maneuvering the air vehicle while maintaining a high level of pilot confidence and flight safety.

REQUIREMENT GUIDANCE

The avionics suite which is installed in the air vehicle drives displays for the operating crew and can provide commands to the AFCS which may be used to implement automatic navigation and guidance. Some of the choices which may be available are listed below:

- VOR
- TACAN
- ILS
- MLS
- Ground Positioning
- Surface Following
- Obstacle Avoidance
- Weapon Delivery
- Fire Control

Detailed requirements have been developed for VOR, TACAN, and ILS. These performance requirements established for VOR/TACAN operation were based on the aviation industry practices of the early 1970s and are now considered international standards, thus much of the detail may be superfluous. However, for MLS, ground positioning and other navigation and guidance systems which may be used in the near future, there is as yet no detailed generalized requirements. In lieu of detailed generalized requirements, it is suggested that accuracy in terms of percentage of steady state path error be required until the detail procurement specification is developed.

The following detailed requirements were published in AFFDL-TR-74-116

a. VOR/TACAN. When preconditions for radial capture are satisfied, the AFCS shall cause the aircraft to maneuver to acquire the 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 a VOR are stated in terms of crosstrack error (feet) and radial error (expressed in microamps; 1 degree = 15 microamps) 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 (collocated VOR/DME), and radial error applies in the reversionary mode (DME inoperative or not available).

b. VOR capture and tracking. Overshoot shall not exceed 5,800 ft (20 microamps) 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 a root-mean-square (rms) average of 5,800 feet (20 microamps) from the VOR radial beam center. Average 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.

c. TACAN capture and tracking. Overshoot shall not exceed 6,300 ft beyond the desired ground track line in a no-wind condition for capture 120 miles or more from the station with intercept angles up to 30 degrees. The required 0.3 damping ratio shall be exhibited for continuous tracking between 120 miles and 20 miles from station.

d. Overstation. The VOR/TACAN mode shall include automatic means for maintaining the aircraft within ±1 degree of aircraft heading or ground track existing at the inbound edge of the VOR ZOC. During overflight of the ZOC, adjustment of the present course heading or its equivalent shall cause the roll AFCS to maneuver the aircraft to capture the appropriate outbound radial upon existing from the ZOC. The VOR/TACAN capture maneuvering limits may be reinstated during overstation operation in a no-wind condition.

e. Automatic instrument low approach system. The approach mode of the AFCS 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 ft 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 combination of failures not shown to be extremely remote. The system shall comply with the tracking requirements for probable combinations of headwinds to 25 knots, tailwinds to 10 knots, and crosswinds to 15 knots, with the probability of occurrence of such winds as shown in table I.

(1) Localizer mode. The AFCS shall cause the aircraft to maneuver to acquire the localizer beam. Heading or roll rate and/or attitude commands shall be limited to provide a smooth capture and subsequent tracking of the localizer beam. Overshoot shall not exceed 0.5 (37.5 microamps) radial error from localizer beam center for captures with initial 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. During localizer capture the system shall exhibit a damping ratio of at least 0.1 within the noted capture ranges, including the effects of system nonlinearities. The system shall be considered to be tracking whenever the following conditions are satisfied; localizer beam error is 1 degree (75 microamps) or less, localizer beam rate is 0.025 degrees/second (2 microamps 1 second) or less, and roll attitude is 5 degrees or less. During beam tracking the system shall exhibit a damping ratio of 0.2 or greater at a distance of 40,000 feet from the localizer transmitter. The AFCS shall maintain the aircraft 2-sigma position within 0.33 degree (25 microamps) of localizer beam center whenever the aircraft is between (1) 40,000 feet horizontal distance from the localizer transmitter, and (2) the point where 100 feet above the ground is reached; these criteria shall be based on a Category II localizer ground installation and 10,000 foot runway is defined by ICAO Annex 10.

(2) Glide slope mode. The pitch AFCS shall cause the aircraft to maneuver to acquire the glide slope beam. Neither the position of the aircraft above or below the glide slope nor vertical speed of the aircraft at time of mode selection shall be incorporated as a precondition for mode engagement. When preconditions are satisfied, overshoot shall not exceed 0.16 degree (35 microamps) of radial error from glide slope beam center when capturing from below the beam in level flight at an altitude greater than 800 ft above the glide slope transmitter datum altitude in a no-wind condition. The system shall exhibit a damping ratio of 0.085 or greater subsequent to the first overshoot for the conditions defined. On a Category II ILS ground facility (including 10,000 foot runway) as defined in ICAO Annex 10, the pitch AFCS shall maintain the aircraft glide slope antenna 2-sigma opposition within 0.16 degree (35 microamps) of beam center or within 12 ft of beam center, whichever is greater, between the altitudes of 700 feet and 100 ft above the glide slope transmitter datum.

(3) Go-around mode. The automatic go-around mode shall be manually engaged only. The AFCS shall be designed such that no single failure or combination of failures not extremely remote 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 AFCS go-around mode engagement, the AFCS shall comply with the performance requirements based on normal go-around procedures including manual management of thrust, flaps, and landing gear.

(4) Pitch AFCS go-around. The pitch AFCS 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 106 events for the wind conditions defined under Automatic Instrument Low-Approach System, 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.

(5) Lateral-heading AFCS go-around performance standards. The lateral-heading AFCS shall maintain the aircraft 4-sigma position within the lateral boundaries of the obstacle clearance planes during wind conditions as specified above. 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 airplane heading such that intersection with the obstacle clearance planes will occur no more than 1 in 106 events during recovery.

(6) 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 extremely remote. The minimum altitude shall include normal performance under the wind conditions specified above and the probability of inadvertent loss of an engine at any time within 12 seconds preceding mode engagement.

f. All weather landing system. The following all weather landing 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. All weather landing system shall comply with the following landing accuracies:

(1) Longitudinal dispersion of the main landing gear touchdown point shall not exceed 1500 feet with a 2-sigma probability, with a mean touchdown point beyond the glideslope intersection with the runway. The 1500 ft dispersion need not be symmetrically located above the nominal touchdown point. The aircraft sink rate at touchdown shall not exceed the structural limit of the landing gear except as an extremely remote occurrence.

(2) 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 with a 2-sigma probability. The roll out guidance system (normally used during ICAO Category IIIb or IIIc visibility conditions) shall cause the aircraft to track parallel to or convergent with the centerline of the runway.

(3) The systems shall meet these requirements considering reasonable combinations of head winds to 25 knots, tail winds to 10 knots, and crosswinds to 15 knots, according to the probability of encountering these winds and their associated turbulence, along with expected variations in aircraft configurations and expected variations in ground facility performance.

(a) All weather landing performance standards--variations of aircraft and airborne equipment configurations. All weather 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.

- Landing weight and center of gravity variations.
- Landing flap setting variations.
- Aircraft approach speed variations.
- Glide slope and localizer airborne receiver centering errors.

– AFCS all weather landing system sensor, computer and servoactuator tolerances.

– Performance tolerances of automatic control systems operating concurrently with the AFCS all weather landing system; e.g., stability augmentation systems, load alleviation systems.

(b) Performance standards--ground based equipment variations. Proof of compliance with performance requirements for all weather landing systems shall include the effects of expected variation in type and quality of the ground based equipment. ILS beam structure, associated tolerances and alignment errors, monitoring, touchdown zone lighting, terrain clearances, and controlled or critical taxi zones shall be considered to meet the requirements for Categories II or III operations as defined by ICAO Annex 10.

REQUIREMENT LESSONS LEARNED

One of the more common complaints from military and commercial pilots relates to limited capture performance for the outbound radial. Generally these complaints have occurred because the AFCS remains in a tracking mode during station overflight. Consequently, outbound captures are hampered by extremely limited bank angles, etc., designed to ensure good tracking performance. Future configurations should provide for more favorable outbound capture performance by development of more comprehensive control laws or providing capture logic reset as a function of station overflight. Because of the limitations of pilot perception and aircraft maneuverability under the combined influence of limited visibility and operations at extremely low altitudes, the primary emphasis of design for all weather landing systems is in terms of assuring safety of operation of the system. Although all weather landing state-of-the-art has been generally established through government and military programs, codification of all weather landing requirements has occurred to a greater degree in civil programs because of their relationship with and obligations to various regulatory agencies around the world. Thus, it was rational for MIL-F-9490 to draw upon the civil codifying experience for not only that which is presently existing, but to include trends which are obvious to the industry as additional experience with various all weather landing systems' configurations is accrued. For this reason, the requirements given herein are based on the performance accuracies, reliability requirements, and methods of showing compliance with the requirements as defined in FAA advisory circulars 20-57A, 120-28A, and 120-29.

4.1.2.10 Automatic navigation and guidance. Verification of navigation and guidance requirements shall be through qualitative assessment by the pilot during ____________________ and by ____________________.

VERIFICATION RATIONALE (4.1.2.10)

The qualitative requirements are best verified by pilot opinion since the basis for providing automatic navigation and guidance is to perform the selected flight phase function to the satisfaction of the pilot while accomplishing, under any condition, the mission for which he is responsible. Optional methods are available for obtaining pilot opinion and for verification of the quantitative requirements on path error.

VERIFICATION GUIDANCE

Pilot opinion should be obtained during flight testing when feasible. Pilot opinion obtained during flight simulation may be a more cost effective and an equally satisfactory method when a flight simulation, based on flight test performance, is available. The quantitative requirements may be verified by flight test, analysis, simulation, or combinations of these methods.

VERIFICATION LESSONS LEARNED

3.1.2.11 *Control stick (or wheel) steering.* The control stick (or wheel) steering function, as a selectable operating mode, shall ___(a)___. The maneuver limits of the AFCS and the control force limits established by the flying qualities requirements shall apply during control stick (or wheel) steering operations. The pilot shall retain full authority to maneuver the air vehicle within the applicable force and maneuver limits of the flying qualities by reversion to the ___(b)___ function of the FCS. Any reversion or change of mode shall be adequately annunciated to the pilot.

REQUIREMENT RATIONALE (3.1.2.11)

Control stick (or wheel) steering (CSS or CWS) is a separate operating mode in some auto pilots and allows the pilot to enter the AFCS control loop to provide an attitude hold/rate command or attitude hold/attitude command control function. Responses and forces unnatural to the pilot, and unintentional interruption or disengagement of the AFCS during this operating mode, is undesirable due to safety-of-flight and flying qualities considerations. The capability to revert to FCS operation which allows full capability to maneuver the air vehicle is a fundamental requirement for any AFCS operation.

REQUIREMENT GUIDANCE (3.1.2.11)

Blank (a) should specify the required operation of the CSS (CWS) mode such as rate command/attitude hold or attitude command/attitude hold. It may be possible to maneuver outside the attitude hold limits while in this mode and then the new attitude held when force is released within the limits. A violation of the limits should be annunciated to the pilot. However, if the force is released outside the attitude limits, the pilot should be warned that the system is not holding the attitude or the aircraft should be automatically returned to the limit attitude. The trim controls located on the stick (or wheel) may be used to change the primary AFCS reference in this mode (such as attitude or heading) or perform some type of integration in order to eliminate stand-off or other errors which may persist during tracking or positioning. In those vehicles having an automatic hover mode of operation, stick steering should provide the capability for vernier control needed during hovering. Blank (b) should indicate a system or function of the FCS provides the required maneuverability and force levels, such as MFCS, CAS, AFCS controller function, etc. Positive, conspicuous, unmistakable, indication should be given to the pilot that a reversion has actually taken place at the operating level of the FCS. The pilot display requirements of this specification should cover this facet of the CSS/CWS implementation as tailored for the air vehicle.

REQUIREMENT LESSONS LEARNED

4.1.2.11 Control stick (or wheel) steering. Control stick (or wheel) steering flying qualities, accuracy, stick force, and maneuvering limits shall be verified by a combination of flight test and ______. Flight testing shall ________________.

VERIFICATION RATIONALE (4.1.2.11)

The performance of the control stick (wheel) steering impacts flight safety. A combination of flight testing and analyses is used for verification because of economic considerations.

VERIFICATION GUIDANCE

The ability to maneuver the air vehicle through control stick steering shall be verified by test during other autopilot tests. Verify also the following flying qualities: rates, stick forces, etc. Demonstrate the compatibility of control steering with the normal and single channel performance of the flight director in at least four corners and center of the flight envelope. The asymmetric roll gradient should be evaluated as a result of pilot comments and anthropometric considerations. Due to the location of the controller, right roll forces are harder and more awkward to apply than left roll forces. For example, windup turn maneuvers to the right are considered by some pilots to be much harder to accomplish as precisely as windup turns to the left. Thus, the right roll force gradient may be reduced from the 80 percent force level.

VERIFICATION LESSONS LEARNED

Four variations of the command—deflection relationships of the side-stick controller were evaluated.

3.1.2.12 G loss of consciousness (GLOC) systems. When a GLOC signal is received, the aircraft shall roll through the shortest route possible to wings level and then execute a dive recovery using the maximum g's available up to __(a)__ g's. Once the recovery is accomplished, which will be determined by ____(b)____, the aircraft shall hold level altitude flight until __(c)__. If the throttle setting is not sufficient to maintain altitude, ____(d)____. Warning of autorecovery shall be annunciated to the pilot. The pilot shall have control authority to override any autorecovery. There shall be automatic logic to prevent activation of the GLOC recovery system during the following critical flight phases: ____(e)____.

REQUIREMENT RATIONALE (3.1.2.12)

Some class A mishaps have been attributed to GLOC. In order to improve flight safety, GLOC systems have been proposed. GLOC systems provide automatic dive recovery and maintain level altitude flight through automatic inputs into the aircraft's flight control system.

REQUIREMENT GUIDANCE

It is suggested that the blanks be filled in as follows:

a. Blank (a). This value is determined by the aircraft's structural limitations. Stores loading should be taken into consideration.

b. Blank (b). This may be clearance of a set altitude, accomplishment of level flight, etc.

c. Blank (c). This value may be a specific time or until the pilot regains control of the aircraft.

d. Blank (d). The system shall maintain constant altitude until the AOA limit is reached, then descend on that limit or maintain constant altitude until a minimum Mach limit is reached, then descend on that Mach number.

e. Blank (e). These may be takeoff, landing, automatic terrain following, etc.

REQUIREMENT LESSONS LEARNED

4.1.2.12 G loss of consciousness (GLOC) systems. The GLOC recovery system shall be tested to verify that nuisance activations will not occur and that the recovery minimum altitude lost or occurs within ________ of the set altitude.

VERIFICATION RATIONALE (4.1.2.12)

The performance of the GLOC system impacts flight safety. A combination of flight testing and analysis is used for verification because of economic considerations.

VERIFICATION GUIDANCE

It is suggested that the blank may be a TBD percentage of the set altitude.

VERIFICATION LESSONS LEARNED

3.1.2.13 Ground collision warning system(s) (GCWS). The minimum acceptable performance of the GCWS shall be as follows: ______________.

REQUIREMENT RATIONALE (3.1.2.13)

Some class A mishaps have been attributed to controlled flight into terrain (CFIT). In order to prevent CFIT mishaps, GCWS have been devised which use radar altitude and aircraft trajectory to warn of impending CFIT. The algorithms used in the GCWS must take into consideration the aircraft's control system and flight characteristics. The GCWS may display warnings via a Head Up Display or Electronic Attitude Direction Indicator, similarly to an autopilot flight director mode. Future systems may initiate an automatic dive recovery, making the GCWS an AFCS mode. Therefore, GCWS have been included as an additional AFCS mode.

REQUIREMENT GUIDANCE

It is suggested that the blank be filled in with requirements from ASD-TR-88-5034.

REQUIREMENT LESSONS LEARNED

4.1.2.13 Ground collision warning system. The GCWS performance requirements shall be verified by ______________________.

VERIFICATION RATIONALE (4.1.2.13)

The performance of the GCWS impacts flight safety. A combination of flight testing and analysis is used for verification because of safety and economic considerations.

VERIFICATION GUIDANCE

It is suggested that the blank be filled in with verification procedures from ASD-TR-88-5034.

VERIFICATION LESSONS LEARNED

3.1.3 General FCS design. The design of the FCS shall be entirely suitable for the purpose, mission, and general requirements of the air vehicle. The FCS shall be as simple, direct, and foolproof as possible with respect to design, installation, operation, inspection, and maintenance. The design shall not include features or details which experience has shown to be hazardous or unreliable. Each control and each control loop shall be designed to operate with the ease, smoothness and positiveness appropriate to its function.

REQUIREMENT RATIONALE (3.1.3)

The opening statement for this section introduces the need for suitability, minimum complexity, avoiding past mistakes, and accommodating the pilot in the FCS design. The qualitative performance statements alert the designer to his obligation to understand the needs which the air vehicle is to satisfy, the mechanizations which have had major deficiencies in the past, and the importance of providing a satisfactory interface with the pilot.

REQUIREMENT GUIDANCE

Other requirements such as flight safety, mission reliability, flying qualities etc., as well as anticipated future usage have led to more complex mechanizations of the FCS than was required to meet the purpose and stated needs. Great effort is required to get such designs simplified since each design specialty is usually unwilling to allow trades downward in their assigned area.

REQUIREMENT LESSONS LEARNED

4.1.3 General FCS design. The FCS design requirements contained in subparagraphs of 3.1.3 shall be verified by ______________________ and ______________________.

VERIFICATION RATIONALE (4.1.3)

Requirements in this paragraph may be verified by inspection, analyses, simulation or flight test, or combinations of these methods. The blanks are provided to allow the most feasible methods to be specified.

VERIFICATION GUIDANCE

The pilot's opinion from piloted simulation and flight test should be used to verify suitability and operating characteristics of the design. Use engineering analyses and inspection to verify simplicity, directness, foolproofness, and hazardous or unreliable features and design details.

VERIFICATION LESSONS LEARNED

3.1.3.1 System arrangement. Assembled elements, subsystems, and separate channels and control loops of the FCS shall be arranged and located in the air vehicle ______________________.

REQUIREMENT RATIONALE (3.1.3.1)

The arrangement of the FCS must enhance performance and promote safety, maintainability, reliability, invulnerability, failure immunity and other general requirements of the specification tailored per this guide. Integration and common usage of functional hardware, and the sensitivity of FCS hardware to locations and environments within the Air Vehicle, makes it necessary to specify the arrangement which will be used for at least the major, critical, portions of the FCS. The blank allows the arrangement to be specified, thus providing a fixed baseline configuration arrangement for design and analysis of the FCS.

REQUIREMENT GUIDANCE

System arrangement should be determined by the general requirements of the FCS specification such as reliability, flight safety, maintainability, etc. Invulnerability requirements may require distribution of system elements. Requirements for locating components of the FCS are contained in 3.2.9 of this Guide Specification and has an influence on how the subsystems, control loops and major assemblies of the FCS will be arranged. One factor which is not specifically called out in the requirements statement references is that of FIRE in the air vehicle. The arrangement chosen should show that fire zones have been considered as serious threat areas and that requirements for containing fires in fighter aircraft may not satisfy the requirements for invulnerability of the FCS. AFSC DH 1-6, DN3J1 and DN3N1 contain some guidance for use in establishing configurations and arrangements which consider FIRE as one of the important design factors.

In addition to traditional FCS hardware arrangement and an arrangement to satisfy specified requirements, sensors and electronic assemblies for the FCS are items which also need to be considered under this title since arrangement and rearrangement of these items can have far reaching effects on FCS performance in the operational environments. Integrated sensor assemblies, remotely located from center of gravity positions, are planned for future aircraft and multi-channel electronics for redundant control are often packaged as one assembly. The blank should be filled to reflect the FCS needs for arrangement of these, and other, items to meet the various requirements for FCS and to help identify and keep constant some of the parameters which influence, and are used to predict, FCS performance.

REQUIREMENT LESSONS LEARNED

Auto ignition temperature, in standard atmosphere, can occur at 4685F for JP-4 jet fuel and 8245F for 100/130 grade aviation gasoline.

Flame temperatures in such fires run from 1650°F to over 2000°F.

Pilots in Southeast Asia, 1970 time frame, found that:

a. Fires in flight burn as long as fluid is available.

b. Thirty seconds is available after wing fire flame becomes visible before an explosion may occur.

Selected components/assemblies used in FCS fail after the elapsed time, in seconds and in the mode shown below:

Component/Assembly	2000°F Flame	1000°F Flame	Failure Mode
Hydraulic Hoses	15-20 sec	90 sec	Melts
Hydraulic Swivel units	90 sec		
Hydraulic Tubes (Return)	90 sec if actuator is hardover - 300 sec otherwise		
Push Pull Tubes - 2024 AL - 1.00"OD - .035" wall	10 sec	600 sec	Melts
Servoactuators	30 sec	420 sec	Seals fail
Brackets - cranks	60 sec	300 sec	Melts
Feel Springs	100 sec	300 sec	Binds
Transducers	100 sec	300 sec	Binds
Trim Actuators	300 sec		
Electric Wiring	11 sec	11 sec	

4.1.3.1 System arrangement. System arrangement shall be verified by ____________________.

VERIFICATION RATIONALE (4.1.3.1)

The stated requirements for arrangement accommodate the operational needs and mission requirements of the air vehicle. Verification that the design does accommodate those needs and requirements is a fundamental step in determining that the vehicle can fulfill its operational role.

VERIFICATION GUIDANCE

Inspection is a feasible method of verification of this requirement. During the design and assembly process the system arrangement should be verified. Inspection of drawings covering the general arrangement of the air vehicle and the layouts in the airframe could be one verification step. The final event in this process could be the physical configuration audit (PCA) for the air vehicle configuration item.

VERIFICATION LESSONS LEARNED

3.1.3.2 Trim controls. The FCS shall provide trim control conforming to the following requirements:____________________.

REQUIREMENT RATIONALE (3.1.3.2)

Trim allows the pilot to adjust the force levels which he must apply at the cockpit controls to control the air vehicle. The trim force levels, range and rate capabilities, which must be provided are established by the flying qualities requirements for the air vehicle. The range of both the forces and rates are such that hazards may develop as a result of improper design, inoperative or malfunctioning trim. The requirements in this paragraph must control trim associated hazards to an acceptable level while accommodating the needs of the pilot. The blank allows tailoring the requirements for the FCS mechanization.

REQUIREMENT GUIDANCE

Flying qualities for the air vehicle contain requirements for trim force levels, ranges and rates of operation, characteristics, etc., in terms applicable to the pilot and aerodynamic performance of the air vehicle. The requirements provide values which must be translated into design requirements for the trim controls for the FCS. Air vehicle configuration and its aerodynamic characteristics, FCS mechanization and function, etc., may lead to requirements for trim controls. These may include:

a. *Series trim* - When series trim is used, no worse than Operational State III should result from the control becoming inoperative in any position, except for cases where such nonoperation can be shown to be extremely remote.

b. AFCS operated trim - Engagement of the pitch channel of the AFCS should automatically initiate needed pitch trim. Manually operated trim should be inhibited or cause AFCS disengagement. Methods for detection or prevention of runaway trim while in an AFCS mode should be incorporated.

c. Automatically commanded trim - Automatically controlled trim should incorporate positive means to avoid hazardous adverse trim near stall angle of attack.

d. Automatic interconnect or augmentation - Designs which use this feature should have provisions which hold or return trim to an appropriate position when the interconnect or augmentation command is removed.

e. Multicrew air vehicle using electric trim - Interlocks in the circuitry should be provided to prevent simultaneous trim commands for operation in opposite directions.

f. Automatic takeoff position - Means should be provided to set all trim to the takeoff positions by a single command from the pilot.

g. FCS with reversion modes of operation - Trim capability should be provided as necessary to meet the flying qualities requirements while operating in FCS reversion modes.

In addition to unique requirements, above, these are some general requirements which should be considered for every FCS. These include: Each of the principal axes of the FCS should have the capability which allows the operating crew to change any steady state forces required at the cockpit to trim the air vehicle. The selected trim position should be maintained indefinitely unless changed by a trim command. Whenever a condition worse than Operational State III would result from a power operated trim failure, that is not extremely remote, the pilot should be provided with a means to easily and quickly disconnect the primary trim function and an alternate capability for trimming the force levels. Each cockpit control for trim should operate in the plane and sense of the forces affected. Design of the trim controls should preclude inadvertent or abrupt operation. Stalling of trimming devices due to actuator loading should not result in a hazard.

REQUIREMENT LESSONS LEARNED

When hydraulic power is used to drive the trim actuator, the control valves must open and close rapidly to achieve high response and small trim increments. Such valve action can produce very large pressure surges in the hydraulic system, leading to component failures. Design should prevent such effects in interfacing systems.

Caution must be used in establishing the maximum total trim position limits such that the available authority of the pilot's direct longitudinal control or the pilot's longitudinal force (strength) capability is not exceeded for any flight condition.

The design should consider the need to trim longitudinal forces to zero for all conditions expected for takeoff and initial climb in order to enhance survivability when ejection is required during that period of flight operation.

4.1.3.2 Trim controls. Trim control requirements shall be verified by ____________________.

VERIFICATION RATIONALE (4.1.3.2)

Trim control requirements are basically a means of enhancing flight safety by specifying design approaches which control the hazards associated with misuse, failure, malfunction, etc., of such controls. Verification of the requirements specified establishes the suitability of the control and the extent and level of the hazard which remains. Analysis, simulation, inspection, and ground and flight tests may be used in the verification process. The blank allows tailoring for each program.

VERIFICATION GUIDANCE

Ground tests and inspection should be used to verify most of the stated requirements. When those requirements have additions from the identified listings, analysis and simulation may be required for some of the verifications. In every instance flight testing should be conducted incident to the flying qualities testing to verify that all design requirements are met.

VERIFICATION LESSONS LEARNED

The effects of trim operation on interfacing systems should be considered during verification testing on the air vehicle. Measurements should be made on interfacing power systems to ensure that surges, noise, spikes, etc., which may be generated by trim operations do not exceed authorized limits.

Flight tests should be conducted to verify that, under the most adverse conditions, positioning trim to its limits of travel does not create a hazard in control of the flight path.

Flight tests should verify that control forces can be reduced to zero at the most adverse takeoff conditions in those air vehicles having pilot ejection escape systems.

3.1.3.3 System operation and interface. Separation and isolation shall be provided between __(a)__ to make the probability of propagated or common mode failure extremely remote. Operational performance shall be met by the FCS __(b)__ seconds after power is applied. Positive means of disengagement shall be provided for __(c)__. Mode selection logic shall enhance operational and mission capability and shall provide __(d)__. Transients due to failures, disengagements and changes in operating modes shall not exceed __(e)__.

REQUIREMENT RATIONALE (3.1.3.3)

Flight safety and mission accomplishment reliability are the basis for this requirement. Air vehicle elements which interface with essential flight controls, and which suffer malfunction or failure, must not be allowed to cause failure in these flight controls.

The time required to bring the FCS from its shut down state to operational status should be a design consideration and under engineering control. Operating efficiency and crew effectiveness are improved by short, controlled, warmup time periods whether it be incident to flight or maintenance activity. Any hazard associated with an unknown FCS status due to warmup can be controlled with confidence when the time required is known to be controlled by design.

Safety considerations require that provisions be made to free essential flight controls from malfunctioning, failed or otherwise distressed elements which are not essential and which might degrade FCS performance or otherwise create a hazard. Disengagement provides one means by which the pilot or safety device may take effective action following single failure or failures combinations, a condition brought out in the requirement for failure immunity and safety.

When a choice of FCS mode selections is made available, it is necessary to specify a mode hierarchy and to ensure that the mode selection logic can handle all possible combinations of desirable and inadvertent selection. Logic is needed to prevent the selection of incompatible modes.

Establishing limits on transients due to failures in the FCS is fundamental to flight safety and acceptance of the air vehicle. Establishing those limits in terms of aerodynamic performance of the air vehicle provides a means for correlating the requirements for flying qualities, human engineering, and flight control. Expressing the limits in terms of aerodynamic performance also allows direct measurement during flight using available flight test instrumentation.

REQUIREMENT GUIDANCE

These requirements apply to FCS design. The FCS design must include features which implement these requirements. The FCS specification should not attempt to levy requirements on other Air Vehicle Subsystems/loops/services.

Blank (a) should be used to identify the controls/subsystem/services which will be interfaced with essential or flight phase essential flight controls and to which the tailored requirements apply. Two classes of interfacing should be considered:

Intra-FCS Interfaces: These are noncritical FCS subsystems/loops which interface with FCS subsystems/loops which are classified as essential or flight phase essential. An example might be the autopilot loop in a fully fly-by-wire FCS or the AFCS in a fully capable mechanical FCS.

Inter-FCS Interfaces: These are subsystems, services, etc., such as structures, power, navigation, guidance, fire control, propulsion which interface with essential or flight phase essential flight control subsystems/loops. An example might be the electric power generation and distribution subsystem, compass heading service of the navigation/guidance subsystem, the terrain following subsystem, hydraulic subsystem, etc.

Blank (b) should be filled by a number representing the clock time allowed for the FCS to warm-up after power is applied.

The requirement applies to electronic, electrical, mechanical, hydraulic, pneumatic and other powered system elements. Specified system performance must be achievable following the warm-up period. Typical values are 90 seconds for air vehicles requiring quick reaction (from alert status to takeoff readiness) and 3 minutes for those having no special requirement for quickly reaching readiness for takeoff. Class IV air vehicles (fighter types) are usually placed in the quick reaction category and large cargo air vehicles in the category which has no special requirement for quick reaction. The user's requirements and temperature ranges encountered in operational use should be reviewed as part of the tailoring process. The word "warm-up" relates to a period of nonoperation between the time power is applied and the time that full functional capability is reached. This should not be confused with the vulnerability requirements for withstanding specified conditions. Withstanding requirements apply to time periods prior to the application of power as well as time periods extending after warm-up and after reaching operational status. The two requirements are not related and should be stated and verified as separate requirements.

Blank (c) should be filled by identifying (listing) the subsystems/loops/services which shall have a positive means of disengagement.

For this requirement, disengagement means disablement and/or disconnection of selected or otherwise operating functional elements from the operating FCS. Provisions for disengagement of electric controls from the essential controls should be required in those systems which have fully capable backup mechanical controls or which have electric controls with functions and elements not classed as essential. Disengagements must be positive under all loads and conditions. Disengage transients are on the order of ±.5g normal or lateral acceleration at pilots station, or ±3deg/sec rate. The pilot must be informed of each disengagement. This requirement is separate and distinct from any requirement for a means of selecting, changing or otherwise choosing functions and operating modes for the FCS. Disengagement shall not preclude re-engagement of the controls except in those cases where interlocks within the system are not satisfied due to malfunction and/or inaction on the part of the crew.

Blank (d) should be filled by requirements which insure flexibility of FCS operation, ease of mode selection and a design of mode selection logic which:

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

b. Prevents the engagement of incompatible modes (table IX) that could create an immediate undesirable situation or hazard.

c. Disconnects appropriate previously engaged modes upon selection of higher priority modes.

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

e. Provides for the engagement of a more basic FCS mode in the event of a failure of a higher priority mode.

Blank (e) should show the limits on incremental g, roll rate, bank angle, and spatial excursion of the air vehicle. These limits should be such that pilot action can prevent a hazard following transients of this magnitude.

One part of the flying qualities document for piloted airplanes contains requirements limiting airplane motions following system or component failure. Another part of that document contains requirements covering characteristics of flight control systems under failure conditions. These requirements are established primarily to prevent dangerous or intolerable conditions from developing in flight path, body axis attitudes or rates, load factor, etc., after failures develop and before the pilot can begin corrective action with the cockpit controls. The aerodynamic response of the air vehicle to changes in FCS output after failure is evaluated in terms of flying qualities and hazard levels to establish the limits. These limits, as specified in the flying qualities requirements for the air vehicle, are those quantitative values which should be used for completing the blank in this FCS requirement.

In general, the transients associated with one part of the flying qualities document for piloted airplanes contains requirements limiting airplane motions following system or component failure. Another part of that document contains requirements covering characteristics of flight control systems under failure conditions. These requirements are established primarily to prevent dangerous or intolerable conditions from developing in flight path, body axis attitudes or rates, load factor, etc., after failures develop and before the pilot can begin corrective action with the cockpit controls. The aerodynamic response of the air vehicle to changes in FCS output after failure is evaluated in terms of flying qualities and hazard levels to establish the limits.

FCS design must then limit FCS outputs after failures such that these aerodynamic bounds and flight path deviations are not exceeded due to any failure which can be shown not to be extremely remote.

REQUIREMENT LESSONS LEARNED

No attempt should be made to include in this paragraph of the tailored FCS specification requirements for design performance, or features, of interfacing subsystems or services which are not dedicated to the FCS.

TABLE IX. FCS engage and disengage selection logic.

	NORMAL MANUAL	MANUAL WEAPON DELIVERY	EMERGENCY MANUAL	PITCH ATTITUDE HOLD	ROLL ATTITUDE HOLD	HEADING HOLD	HEADING SELECT	ALTITUDE HOLD	MACH HOLD	AIRSPEED HOLD	VOR	TACAN	LOCALIZER	GLIDE PATH	LOAD ALLEVIATION	RIDE SMOOTHING	FLUTTER SUPPRESSION	TERRAIN FOLLOWING	STICK STEERING	STRUCTURAL LOAD CONTROL	AUTOMATIC THROTTLES
NORMAL MANUAL	X																X			X	X
MANUAL WEAPON DELIVERY		X															X			X	X
EMERGENCY MANUAL			X														X			X	X
PITCH ATTITUDE HOLD				X	X	X	X				X	X	X		X		X			X	X
ROLL ATTITUDE HOLD				X	X			X	X	X					X	X	X	X		X	X
HEADING HOLD				X		X		X	X	X					X	X	X	X		X	X
HEADING SELECT				X			X	X	X	X					X	X	X	X		X	X
ALTITUDE HOLD					X	X	X	X			X	X	X		X		X			X	X
MACH HOLD					X	X	X		X		X	X	X		X	X	X			X	
AIRSPEED HOLD					X	X	X			X	X	X	X		X	X	X			X	
VOR				X				X	X	X	X				X	X	X	X		X	X
TACAN				X				X	X	X		X			X	X	X	X		X	X
LOCALIZER				X				X	X	X			X	X	X	X	X	X		X	X
GLIDE PATH													X	X	X		X			X	X
LOAD ALLEVIATION				X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
RIDE SMOOTHING					X	X	X		X	X	X	X	X		X	X	X	X	X	X	X
FLUTTER SUPPRESSION	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
TERRAIN FOLLOWING					X	X	X				X	X	X		X	X	X	X		X	X
STICK STEERING															X	X	X		X	X	X
STRUCTURAL LOAD CONTROL	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
AUTOMATIC THROTTLES	X	X	X	X	X	X	X	X	X			X	X	X	X	X	X	X	X	X	X

The effects of FCS failure transients seem best specified as requirements which relate to man-machine responses to sudden changes in FCS outputs. The burden of translating these requirements is placed on the FCS designer who must determine what failures may occur and what changes in surface (or other moment producer) position, etc., may result from FCS output changes due to such failures.

4.1.3.3 System operation and interface. System operation and interface requirements shall be verified by ____________________.

4.1.3.3.1 Warm-up. The time requirements for warm-up shall be verified by ________________.

4.1.3.3.2 Disengagement. Disengagement requirements shall be verified by ________________.

4.1.3.3.3 Mode compatibility. The mode compatibility requirements shall be verified by ______ ______________.

4.1.3.3.4 Failure transients. Compliance with failure transient requirements shall be verified by _ ________________.

VERIFICATION RATIONALE (4.1.3.3 - 4.1.3.3.4)

Verification of these requirements ensures that the FCS does include the identified design features which enhance safety and operational utility of the air vehicle. Verification allows accurate planning for use of the system in the field and the proper training of the operating crew.

VERIFICATION GUIDANCE

Verify through ground test that each of these requirements has been met. In addition, verify through flight tests that the requirements for disengage/reengage, mode selection logic, and transient effects have been met. An operating mockup may offer a feasible method of ground testing for verification of several of these requirements, provided it reflects the true configuration/performance of the installed FCS. In many cases, propagation effects verification is only feasible at the assembly level by use of a specially designed engineering test stand. Ground testing for verification of these requirements should be completed as part of the flight worthiness testing for the air vehicle.

VERIFICATION LESSONS LEARNED

Verification of most of these requirements has been shown to be best accomplished through exhaustive ground testing; however, a few of the requirements, selected for criticality, should also be verified during flight tests. In conducting verification tests for transient effects during flight, it has been found that a time delay of about two seconds should be allowed between a failure annunciation in the cockpit and the initiation of pilot corrective action to realistically evaluate the hazard potential produced by the transient.

3.1.3.4 Failure immunity and safety. Within the permissible flight envelope, no single failure in the FCS, which is not extremely remote, shall result in any of the following effects before a pilot or safety device can take effective corrective action.

a. ________________

b. ________________

c. ________________

REQUIREMENT RATIONALE (3.1.3.4)

The intent of this requirement is to control inflight hazards which may result from single failures in the FCS. For noncritical controls the pilot may be required to detect and compensate for failures.

REQUIREMENT GUIDANCE

The blank should be filled by listing failure effects which may create significant inflight hazards. These include:

a. Flutter, divergence, or other aeroelastic instabilities within the permissible flight envelope of the aircraft, or a structural damping coefficient for any critical flutter mode below the fail-safe stability limit specified for structural design of the air vehicle.

b. Uncontrollable motions of the aircraft or maneuvers which exceed limit airframe loads or cause severe physical stress on the aircrew.

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 III.

e. Exceedance of the permissible flight envelope or inability to return to the service flight envelope.

For this requirement, extremely remote is defined as numerically equal to the maximum aircraft loss rate due to relevant FCS materiel failures shown in 3.1.7 of the tailored FCS specification.

When the pilot is required to detect and compensate for a failure, neither extreme alertness nor exceptional skill nor strength shall be required on the part of the pilot.

REQUIREMENT LESSONS LEARNED

4.1.3.4 Failure immunity and safety. Compliance with the failure immunity and safety requirements shall be demonstrated by ______________________________.

VERIFICATION RATIONALE (4.1.3.4)

In complex systems, verification of the requirements in this paragraph should follow a well structured and comprehensive outline and cover the entire scope of the FCS. Analyses, simulation, inspection, and ground and flight testing may be required. The blank may require a listing or matrix of methods, by item, based on the design approach, implementation and mechanization methods chosen and configurations available in the FCS for the specific air vehicle. A structured, time phased effort distributed over the design and development time schedule may be required.

VERIFICATION GUIDANCE

Verifications for failure immunity and safety extend beyond the listings of this requirement. The process can begin with the failure modes, effects and criticality analysis for the FCS, extend through the hazard analysis for the air vehicle, and continue to fault tree and any other such analyses. These analyses should identify those failures and failure combinations which are not classed as extremely remote. Analyses, simulation, and ground and flight tests should then be used, as appropriate, to show that none of the failures, not extremely remote, can result in any of the conditions listed. Software development and the verification and validation methods used should be responsive to these requirements and should insure that each is addressed in sufficient detail to show compliance.

VERIFICATION LESSONS LEARNED

3.1.3.5 Redundancy. The redundancy requirements shall be as shown in table IV. Exceptions to this requirement should be identified on a component level in cases where cost/complexity/safety trade-offs may indicate less redundancy is required. Specific approval to implement less redundancy must be received from the Government procuring activity.

REQUIREMENT RATIONALE (3.1.3.5)

Redundancy may be needed to satisfy the reliability, invulnerability, failure immunity or other requirements for the air vehicle. The redundancy required may not be the same for MFCS and the AFCS or for the various control loops or control functions. Table IV, with blanks, provides the flexibility needed to tailor the requirements to the specific air vehicle.

REQUIREMENT GUIDANCE

Redundancy has been defined as a design approach such that two or more independent failures, rather than a single failure, are required to produce a given undesirable condition. More specifically for FCS it means a mechanization which will retain functional integrity after failures, and provide the same or similar performance capability. In practice, it takes the form of providing duplicate or alternate components, channels, or subsystems, each capable of performing the given function. The structural configuration, aerodynamic characteristics and mission flight phase requirements of the air vehicle have a strong influence on the redundancy required to meet the reliability, invulnerability, failure immunity and other requirements of the air vehicle. Analyses, simulation and trade studies will be needed to determine the redundancy for the selected approach for FCS mechanization to fulfill overall system requirements. The blanks should be filled by using terms such as those shown below or combinations of these terms.

Redundancy terms

a. None - No redundancy is required.

b. Fail-Safe - A condition or requirement wherein the control device or system ceases to function but the conditions or consequences resulting from the failure are not hazardous and do not preclude continued safe flight. The condition following failure may be completely passive, or it may involve driving to a predetermined nonactive condition. In FCS it is the capability in a single channel mode of operation to revert to a safe state following an automatic disconnect in the event of a failure or pilot initiated disconnect. Safe state may be achieved by authority limiting and positive removal of actuation motive power. The allowable authority limits need to be established to provide the desired performance objectives and in consideration of structural design limits and safe recovery characteristics.

c. Fail-Passive - A condition or requirement wherein the failed device or system ceases to create any active output. In the purest sense a device that fails passively would simply remove its presence from the control system. However, a device is still considered a fail-passive type if it remains in the system but acts only as an additional load. Sometimes referred to as Fail-Soft. In FCS it is the capability to automatically disconnect and to revert to a passive state following a failure. Allowable failure transient or out of trim condition is to be within the limits as established for the particular air vehicle.

d. Fail-Functional - The capability of the FCS for continued operation with degradation following noncritical failure(s).

e. Fail-Operational - The capability of the FCS for continued operation without degradation following failure(s). This general term describes a condition or system wherein operation continues after a failure. A more explicit description is given by Single Fail-Operational and Dual Fail-Operational. In a true fail-operative situation, a failure will cause no nominal loss of performance.

f. Single Fail-Operational (SFO) - A condition or requirement wherein an active control device or system can sustain any single failure and remain operative. Unless specifically stated, it is understood that no nominal loss of performance occurs after the failure.

g. Dual Fail-Operational (DFO) - A condition or requirement wherein an active control device or system can sustain any two failures within the system and remain operative. It is implicit with DFO that the system be able to accept identical failures in two of its channels. Unless specifically stated, it is understood that no nominal loss of performance occurs after one or two failures.

REQUIREMENT LESSONS LEARNED

Fleet histories have shown that single thread mechanical FCS can provide adequate reliability, failure immunity, etc., such that redundancy in mechanization is not required. In electric flight controls, redundancy is easily obtained and is commonly used in single and dual fail-operate systems. Electrical FCS using the fully control-by-wire mechanization approach for an aerodynamically unstable fighter has used quadruple redundancy to provide two-fail operational, fail-safe redundancy. In practice, the minimum redundancy replication is usually exceeded by one level for flight phase essential and critical controls.

The need for greater redundancy in the flight control function is currently reflected in the effort to develop reconfigurable, self-healing systems. In these systems, redundant control surfaces with redundant control loops are among the approaches being investigated.

4.1.3.5 Redundancy. Redundancy shall be verified by ______________ and ______________.

VERIFICATION RATIONALE (4.1.3.5)

Verification of the redundancy which has been provided is essential if confidence is to be had in the functional reliability, invulnerability, failure immunity, etc., of the FCS for operational missions and general flight safety. The functional levels which have been provided in the design may be verified by methods such as inspection, analysis, simulation and test. The blanks are provided to allow flexibility in choosing the most feasible methods.

VERIFICATION GUIDANCE

Select the most feasible method for verifying the redundancy levels specified. In most cases, analysis and simulation will be the most feasible. An Iron Bird type test stand can provide one of the best simulations for verification, especially for redundant mechanical loops and combinations of mechanical and electric loops. Ground tests using an aircraft may prove feasible but not to the same extent as an Iron Bird test stand. Flight testing may be used to some extent if necessary but safety is an overriding consideration as the hazard level increases with reduction in functional redundancy below the design level.

VERIFICATION LESSONS LEARNED

3.1.3.5.1 Redundancy management. In FCS which utilize ____________ redundant channels, redundancy management shall provide ________.

REQUIREMENT RATIONALE (3.1.3.5.1)

Redundancy management has become a major design area in the implementation of electric and control-by-wire FCS. Thus, a requirement is needed to define the capability and services which are to be provided through management of the various features redundant within a control channel or control system.

REQUIREMENT GUIDANCE

The blank should be filled in using inner loop (basic control of the aircraft) as the *primary consideration*. For example: "fault detection, fault isolation within the manual FCS to prevent and protect the air vehicle from unacceptable transients or loss of control. Table X outlines the redundancy management technique(s) used:"

The redundancy management approach should 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 this specification;

c. Addressed in the software requirements definition when applicable;

d. Fully responsive to the need for the preflight BIT to insure that the designed redundancy is present before flight.

The design should address not only what is required in the FCS itself, but also what is required in supporting and interfacing systems which are considered flight safety critical or flight phase essential.

Voting planes and in-line monitoring (self-test) may be used to isolate certain first failures and a majority of the second like-failures. Hardware self-test features (e.g., the watchdog timer, word count, parity checks on MUX bus receipts, memory parity, and wraparounds) may be used for failure isolation. Software driven self-tests include memory sum checks, which are accomplished in background, and event driven tests which are activated when failures are discovered. Two important rules for redundancy management are:

a. For electrical signal computation, no computer shall interfere with the operation of another.

b. *Pilot intervention shall not be required for* system reconfiguration in the event of a failure.

One important factor in the implementation of redundancy management is the coverage it provides. Coverage has been defined as the conditional probability that, given a failure, the system continues to perform its function. Coverage as high as 1.0 can be obtained for a first failure and a probability of 0.94 or better for the second failure. Flight safety and mission reliability requirements impact the *probability values (redundancy management coverage)* which should be specified. Attempts should be made to achieve the required flight safety goals, etc., while utilizing the lowest failure coverage.

TABLE X. Outline of redundancy management techniques (example only).

Item	Technique
Sensors	
rate gyros,	input voting - select average value
angle of attack,	- select middle value
e.g.	- select smallest value
Command Paths	
Processing	channelized
cross channel data links	output commands only
command selection	output voting - select average value
	- select middle value
	- select smallest value
	- only channel which uses information can select value.
Actuation	
Horizontal tails	single servo/command hydraulic average
Aileron	
Rudder	
Flaps	
Speedbrakes	
e.g.	

Redundancy management should provide protection/suppression of failure transients, and efficient 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
- Recovery from fault
- Cross channel data transmission
- Cross channel synchronization
- Actuator management

REQUIREMENT LESSONS LEARNED

It has been shown that for long missions, a redundancy management method which uses inter-unit selection at the LRU level can provide a more reliable system than one employing a one higher level of redundancy and using mid-value signal voting as the only means of redundancy management, fault detection, and isolation. System architectural studies have indicated that optimum failure survivability and failure isolation, to the LRU level, requires that systems have three voting/monitoring planes. Two of these planes should be in software. One should be at the sensor/controller interface and the other at the output surface command interface. Interactions due to redundancy management methods must be studied carefully during development to prevent such things as interactions between self-test routines, unforeseen timing situations in self-test of cross-computer data links, generation of sneak circuits which defeat the basic redundancy provided in the design, etc.

4.1.3.5.1 Redundancy management. Redundancy management requirements shall be verified by ______________________.

VERIFICATION RATIONALE (4.1.3.5.1)

The coverage provided by the methods selected for redundancy management need to be verified. Since coverage is usually defined as a conditional probability that, given a failure, the system will continue to perform its function; analysis, simulation, and flight test may be used in the verification process. The blank provides the means by which the verification methods which are most feasible can be used, thus tailoring the requirement to the specific air vehicle and the conditions under which it is developed.

VERIFICATION GUIDANCE

One part of the criteria for determining acceptable probability of coverage values for first and second failures is the mission reliability and flight safety requirements stated in this specification. A second part of the criteria is the redundancy management generated transients which should not exceed the failure transient values stated in this specification, and in the flying qualities requirements, for all environments specified for the air vehicle. In general, analysis and simulation are the most flexible and cost effective methods of verification. Where an Iron Bird type flight control system test facility is not available, simulation may not prove to be a suitable method. Flight testing is always a desirable method and should be used when possible to verify analyses and simulations. Pilot evaluation during flight in various intensities of atmospheric disturbance is essential if redundancy management capability and suitability is to be fully verified.

VERIFICATION LESSONS LEARNED

3.1.3.6 Stability. For all closed loop FCS, the required gain and phase margins about nominal shall be as shown in table V. For gain or phase variations within the indicated frequency bounds, no oscillatory instabilities shall exist with amplitudes greater than those allowed for residual oscillations in 3.1.3.8, and any non-oscillatory divergence of the aircraft shall remain within the applicable limits of the flying qualities requirement.

During the gain and phase variations, the AFCS loops shall be stable for any amplitudes greater than those allowed for residual oscillations in 3.1.3.8. In multiple loop systems, variations shall be considered with all gain and phase values in the feedback paths held at nominal values except for the path under investigation.

A path is defined to include those elements connecting a sensor to a force or moment producers. For both aerodynamic and non-aerodynamic closed loops, at least 6 db gain margin shall exist at zero airspeed. The margins specified shall apply regardless of system implementation, and shall be maintained under flight conditions of most adverse center-of-gravity, mass distribution, and external store configuration throughout the operational envelope and during ground operations.

REQUIREMENT RATIONALE (3.1.3.6)

Stability margins are required for FCSs to allow for variations in system dynamics. Three basic types of variations exist:

a. Math modeling and data errors in defining the nominal system and plant.

b. Variations in dynamic characteristic caused by changes in environmental conditions, manufacturing tolerances, aging, wear, noncritical materiel failures, and off-nominal power supplies.

c. Maintenance induced errors in calibration, installation, and adjustment.

REQUIREMENT GUIDANCE

The blanks in table V should be filled by requirements as shown in table XI or by requirements which have been determined through sensitivity analysis, in which case they should not be less than 50 percent of those in table XI. If the latter is chosen, then requirement 3.1.3.6.1 must be included in the specification, otherwise 3.1.3.6.1 should be omitted.

The gain and phase margin definitions listed are commonly used within flight control technology, and are not the classical definitions found in most textbooks. These margins are both positive and negative. A negative gain variation (reduction) can lead to instability on a basically unstable airframe which relies on the feedback system for dynamic stability. Positive and negative phase margins denote the amount of lag and lead that may be added, respectively, before instability occurs.

The math models to be used for these stability analyses will vary with each procurement. The contractor will determine what math model complexity is required for each procurement and should include this model description in the FCS Development Plan.

The gain and phase margins shown in table XI are in the range of values used in previous successful procurements, and are considered the minimums which will provide largely trouble-free service during fleet usage. NASA TN-D-6867 recommends the 6 db zero airspeed requirement and provides a discussion of NASA ground and flight testing of stability augmentation systems. AFFDL-TR-73-105 recommends a 12 db requirement.

TABLE XI. Recommended gain and phase margin requirements (db, degrees).

Mode Frequency Hz \ Airspeed	Airspeed: Below V_{OMIN}	V_{OMIN} to V_{OMAX}	At Limit Airspeed (V_L)	At 1.15 V_L
$f_m < 0.06$	GM = 6 db (No Phase Requirement Below V_{OMIN})	GM = ±4.5 db PM = ± 30°	GM = ±3.0 db PM = ± 20°	GM = 0 PM = 0 (Stable at Nominal Phase and Gain)
$0.06 \leq f_m <$ First Aero-Elastic Mode		GM = ±6.0 db PM = ± 45°	GM = ±4.5 db PM = ± 30°	
$f_m >$ First Aero-Elastic Mode		GM = ±8.0 db PM = ± 60°	GM = ±6.0 db PM = ± 45°	

Where:

V_L	=	Limit airspeed
V_{OMIN}	=	Minimum operational airspeed
V_{OMAX}	=	Maximum operational airspeed
Mode	=	A characteristic aeroelastic response of the aircraft as described by an aeroelastic characteristic root of the coupled aircraft/FCS dynamic equations-of-motion
GM = Gain Margin	=	The minimum change in loop gain, at nominal phase, which results in an instability beyond that allowed as a residual oscillation
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 contractor's best estimate or measurement of FCS and aircraft phase and gain characteristics available at the time of requirement verification

Margins are specified for aerodynamically closed loops and nonaerodynamic loops. An aerodynamic loop is one which relies on aerodynamics for loop closure such as a stability augmentation or AFCS loop. Nonaerodynamic loops do not rely on aerodynamics for loop closure. An example is a servo-actuator loop.

A recommended practice for higher frequency modes is to gain stabilize all modes (±180° phase margin). A feedback signal attenuation of at least 20 db/decade beyond the actuator cutoff frequency is also commonly used. AFFDL-TR-73-83, for example used a 180° phase margin criterion beyond 5 Hz.

These margins can be determined using classical linear analysis techniques, adjusted for known nonlinearities. Normally in test, a lower frequency mode will set the test margins and gain margins at higher frequencies will be unobservable. Consequently, compliance with these gain and phase margin requirements will likely be demonstrated through analysis of open loop frequency response characteristics.

The stability margins specified vary in size with mode frequency and airspeed. The reduction in margin at V_L, reflects a willingness to accept reduced stability and/or performance while flying outside the operational envelope. The increased margins at higher frequencies reflect needs based upon the decreasing accuracy of state-of-the-art modeling and testing techniques at higher frequencies.

The modification to the stability requirement paragraphs reflects the experience gained in recent aircraft development programs in the areas of flight control structural dynamics interaction and digital flight control implementation. This experience highlighted the need for a comprehensive analytical approach, complementing the test verification process, to provide the required stability margins.

Inherent to the success of the analytical approach is the comprehensiveness of the model used in the analysis. Overly simplistic models, although valuable in visualizing trends, may lead to optimistic predictions as pointed out in the related discussion in AFFDL-TR-77-7. The analysis model must provide a valid representation of the airframe structural dynamics and control system characteristics. To this end, it must account for all anticipated nonlinearities, prediction uncertainties and, in the case of digital flight controls, sampling effects.

Aeroservoelastic instability is one manifestation of flight control-structural dynamics interaction that defies detection by traditional ground tests. Working this area has shown that a fully integrated analytical approach, involving the disciplines of aerodynamics, structural dynamics and flight controls, is required to insure the required stability.

The analytical model of the aircraft aerodynamic characteristics used to evaluate limit cycle margins may use rigid body representations, adjusted for flexibility effects, with sufficient allowance for uncertainties in predicting aerodynamic damping and flexible-to-rigid ratios. To evaluate stability margins relative to zero airspeed servoelastic instability and in-flight aeroservoelastic instability, the analytical model must account for the effects of aerodynamic and inertial coupling between axes, airframe structural modes, and the frequency dependent nature of the aerodynamic derivatives.

When digital flight control computers are used, characteristics peculiar to digital implementation need to be considered and appropriately modeled. For example, sampling effects may introduce significant phase shift in the flight control loop closure with an attendant reduction in stability margins, as described in AFFTC-TR-76-15. As the stability margins need to be satisfied regardless of system implementation, the analysis model or a digital system must be sufficiently representative of the real time characteristics.

Figure 1 illustrates a typical FCS block diagram. Several feedback loops are shown; however, only one feedback path is shown, since only one sensor and one moment producer are involved. Thus, only one control path exists and only one stability requirement applies.

REQUIREMENT LESSONS LEARNED

An example of problems encountered in the past with nonaerodynamic loop stability is the B-52 stick steering AFCS. During ground testing of the A/A 42G-11 AFCS, a 4.2 Hz instability was encountered in the pitch control system. This problem occurred the first time the equipment was installed in B-52 60-002 and resulted in a 4.2 Hz unstable oscillation of the control column which would build up until an automatic disconnect occurred through the overpower circuit. This problem was eliminated by attenuating the loop gain near 4.2 Hz through filter modification and relocation of the pitch force transducer. To avoid such problems, a stability analysis of the nonaerodynamic loops should be accomplished with column inertia, feel system characteristics, and other MFCS parameters properly modeled. In some applications the pilot may couple with the system and pilot mass or inertia may have to be included in the analysis. The full range of excursions expected in service should be simulated or otherwise analyzed, especially where breakout dead zones, hysteresis, and rate limiting result in significant nonlinear system characteristics.

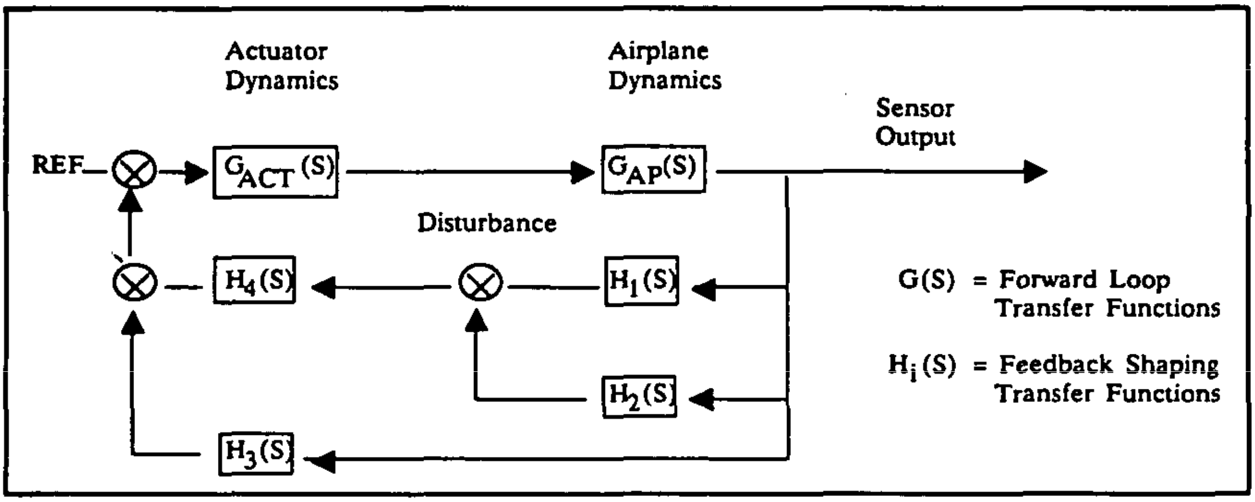


FIGURE 1. Typical FCS block diagram.

As pointed out in AFFDL-TR-77-7, the variations in gain and phase margins as a function of relative mode frequencies (see table XII) are somewhat cumbersome to apply. However, existing data do not provide sufficient basis to revise these requirements. It is generally agreed that 6 db gain and 45 degrees phase margin are adequate, and may even be conservative, once all aerodynamic and aeroelastic characteristics are well known and other concerns, such as residual oscillations and hardware wear effects are satisfied. For initial flights of an aircraft type, larger margins are desirable. This recommendation is largely based on actual test experience revealing lower than predicted stability margins due to prediction inaccuracies in aerodynamic or aeroelastic characteristics, sampling effects in digital implementation, and jump resonance type non-linearity attributed to actuator rate saturation.

4.1.3.6 Stability. Verification of air vehicle stability shall be performed by analyses, simulation, ground and flight test. Prior to first flight, ground testing shall ____________________________.

VERIFICATION RATIONALE (4.1.3.6)

A combination of ground testing, inflight measurement, and analysis is used for verification to most efficiently verify stability margins. Inclusion of major nonlinearities in analyses used to demonstrate compliance is to ensure that adequate margins are retained with the systems operating both in the linear and nonlinear range.

VERIFICATION GUIDANCE

Prior to first flight, aircraft ground testing shall include gain margin tests to demonstrate the zero airspeed stability margin for feedback systems depending on aerodynamics for loop closure and to demonstrate stability margins for nonaerodynamic loops. Primary and secondary structure shall be excited with special attention given to areas where feedback sensors are located with gains increased to verify the zero airspeed requirement. Residual oscillations shall be measured and evaluated inflight at critical flight conditions.

Aerodynamic and adverse condition margins shall be verified by analyses. These analyses shall include the effects of major system nonlinearities. Stability requirements during gain and phase variations shall be verified by analyses. In multiple loop systems stability shall be verified by varying gain and phase values in the path under investigation while holding gain and phase value at nominal in all other feedback paths.

Demonstration of stability margins for nonaerodynamic loops should include frequency response, the effects of vibration and, if practical, doubling the feedback gains in electronic systems. Most FCS, exhibit rate limiting nonlinearities with large control surface amplitudes at higher frequencies. Deadband or hysteresis is also usually present. Where linear analysis techniques such as root locus are used, phase and gain characteristics for the feedback elements operating at small perturbations should be considered to evaluate nonlinearities such as breakout deadzones or hysteresis, and separately, phase and gain characteristics for feedback elements operating at medium and large control surface amplitudes should be considered to evaluate the near linear case and the rate limiting case. Where simulation is used, these nonlinearities can be included directly and evaluated by measuring frequency responses at different control surface amplitudes.

VERIFICATION LESSONS LEARNED

3.1.3.6.1 *Sensitivity analyses.* 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 test values or predictions and in-service operation due to such factors as poorly defined nonlinear and higher order dynamics, anticipated manufacturing tolerances, aging, wear, maintenance and noncritical materiel failures. In addition, these tolerances shall also include normally anticipated uncertainties in predicted aerodynamic characteristics, aeroelastic effects, and structural modes. For digital flight control systems, the tolerances established shall specifically include the effects of sampling rates, digital system delay, input and output filters, digital filter implementation, and integration technique. Gain and phase margins shall be defined, based on these tolerances, which shall assure satisfactory operation in fleet use. These gain and phase tolerances shall be established based on variations in system characteristics either anticipated or allowed by component or subsystem specification. The range of variation to be considered shall be based on a selected probability of exceedance for each type of variation. The exceedance probability shall be based on the criticality of the flight control function being provided. The stability requirements established through this sensitivity analysis shall be entered in table V.

REQUIREMENT RATIONALE (3.1.3.6.1)

This requirement is included to assure that a sufficient number of factors which cause variations in system dynamics are adequately quantified and included in the system analyses when analysis is used, in lieu of the table XI values, to establish the stability requirements for the air vehicles under consideration.

REQUIREMENT GUIDANCE

This requirement is not included when phase and gain margins are those defined by table XI. AFFDL-TR-71-78 documents a sensitivity analysis performed to establish gain and phase margin criteria required to accommodate tolerances in the structural frequencies. Similar analyses can be used to determine stability margins at all frequencies for a given procurement based on the inaccuracies anticipated in the parameters and modeling techniques used and based on the depth of analyses planned to investigate off-nominal conditions and the effects of wear and aging.

REQUIREMENT LESSONS LEARNED

4.1.3.6.1 **Sensitivity analysis.** Stability margins established under this paragraph shall be verified by analysis. This analysis shall include variations due to tolerances affecting system characteristics and uncertainties in modeling.

VERIFICATION RATIONALE (4.1.3.6.1)

Inspection of the sensitivity analyses is used to verify the assumptions made in establishing the desired stability margins.

VERIFICATION GUIDANCE

Prediction of aerodynamic characteristics, aeroelastic effects and structural modes are type of uncertainties found in modeling the air vehicle and its characteristics. In a sensitivity analysis these values are typically varied by a percentage around the nominal value. The percentage may vary for different parameters based on experience {i.e., C_{M_α} may be more accurately defined than C_{l_β}. Therefore, percent variation of C_{M_α} would be less than C_{l_β}.

VERIFICATION LESSONS LEARNED

3.1.3.7 Operation in atmospheric disturbances. During normal operation the FCS shall provide a safe level of operation and maintain mission accomplishment capability while flying in atmospheric disturbances. For essential and flight phase essential FCS functions, at least Operational State __(a)__ shall be provided for gust intensities corresponding to exceedance probabilities __(b)__ and __(c)__, respectively (table I). Noncritical controls shall provide at least Operational State __(d)__ in atmospheric disturbances at the intensities corresponding to __(e)__ probability of exceedance (table I). 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. __(f)__ means to inactivate the noncritical control for flight in heavy disturbances shall be used when required. The dynamic analysis or other means used to satisfy this requirement shall include the effects of rigid body motion, __(g)__, and the flight control system. Significant nonlinear effects shall be represented by conservative nonlinear or equivalent linear representations. The analytical form of the atmospheric disturbance models specified in the flying qualities requirements, with the exception of the discrete gust, shall be used for flight control analyses at the intensity levels specified herein. The discrete gust to be used shall be defined as a single full wave of a (1-cos) function with a peak amplitude of 40 ft/sec which may be encountered anywhere within the operational flight envelope. Varying gust amplitudes up to 40 ft/sec shall produce near linear air vehicle response. The gust wave length shall be tuned to produce maximum excitation. The gust intensity levels apply at the turbulence penetration airspeed, V_G. At the maximum level flight airspeed, V_H, these intensity levels are reduced to __(h)__ of the specified levels for atmospheric disturbances.

REQUIREMENT RATIONALE (3.1.3.7)

The vertical rms gust intensity requirements specified herein for essential and flight phase essential systems are based on safety considerations with a prime objective to retain at least minimum safe operation in any environment the air vehicle structure may be expected to penetrate.

REQUIREMENT GUIDANCE

Values previously required: (a) III, (b) $10^{-6}/T$, $10^{-5}/T$* where T = longest time in essential flight phase segment in any mission/total flight time per mission, (c) 10^{-6}, 10^{-5}*, (d) II, (e) 10^{-2}, (f) automatic or manual, (g) significant flexible degrees of freedom, and (h) 38 percent.

* first value is used for large, heavy, low to medium maneuverability aircraft

The rms vertical gust amplitudes are specified in terms of exceedance probabilities and FCS function criticality. Table I defines rms vertical gust amplitude versus altitude for selected exceedance probabilities. The relationship among vertical, lateral and longitudinal rms intensities and scales defined in the flying qualities requirements shall be used to establish intensities for lateral and longitudinal gusts. For essential controls, the aircraft disturbance penetration capability may be set by the structural strength of the airframe, the augmentation capability of the control system or a combination of the two. Most noncritical controls do not affect disturbance penetration capability and the noncritical controls designer is primarily concerned with maintaining acceptable performance of pilot relief or ride quality during atmospheric disturbances.

Noncritical systems such as ride smoothing systems may be designed to permit saturation in moderate disturbances while maintaining a reduced level of ride improvement. Many pilot relief AFCS modes are commonly disengaged when a disturbance is encountered. It is important to avoid inadvertent automatic mode disengagement in light atmospheric disturbances.

The specification of rms gust intensities for essential and flight phase essential controls is intended to result in control systems capable of operating at least minimum safe (Operational State III) condition in the maximum atmospheric disturbance intensity which the structure can penetrate without exceeding limit load. The intensities specified for noncritical controls are much lower than those defined for essential controls and are correlated with the mission accomplishment probability specified for the particular air vehicle.

Control system rate limiting must be emphasized for FCS controlling an unstable airframe, since rate limiting as well as displacement can cause loss of stability. The procedure used for the American SST design (see FAA-SS-73-1) was to rely on simulation studies to establish the allowable actuator minimum rate requirements. The design condition was piloted flight in heavy turbulence at landing approach. The minimum rate requirements were less than the common criterion of providing stop-to-stop surface travel in one second. After the minimum rate requirements were established, it was verified that the system could provide these minimum rates under any combination of failures which would still allow at least minimum safe control.

The analytical form for atmospheric disturbance models specified in the flying qualities requirements is used for flight control analyses. The major differences between the atmospheric disturbance requirements for the FCS and flying qualities are the intensity levels and discrete components. The flying qualities requirements for intensity levels are generally more lenient than those required in this specification. Discrete impulse gusts produce larger aircraft motion and are felt to be more representative of real world turbulence than the step function usually specified in the flying qualities requirements.

The specified gust intensity levels are reduced in magnitude as airspeed is increased beyond the atmospheric disturbance penetration airspeed. This procedure is based on the precedent of the MIL-A-8861 gust load requirement and similar FAA requirements which allow similar reductions at speeds above the gust penetration airspeed.

REQUIREMENT LESSONS LEARNED

NASA CR-124834 includes an excellent discussion of the current state of the art in understanding the problem of flight safety in turbulence. The author points out that control has been an important, and perhaps critical, factor in recent turbulence related aircraft losses. It was noted that commercial transports have been estimated to spend between 0.01 and 0.1 percent of their flight time in thunderstorms, despite the high priority given to storm avoidance. Mountain waves are also a serious flight safety problem and have resulted in aircraft loss. Clear air turbulence, although quite common, is not generally considered a flight safety problem.

The NASA study, above, emphasized that turbulence normally occurs in patches and recommends a five-mile wide patch for simulation. Other studies indicate an average patch duration of approximately one minute for moderate to severe turbulence for world-wide civil aircraft operation. The turbulence requirements of this specification should be evaluated using the turbulence patch approach, although the length of the patch may be selected as either less or greater than five miles, depending on the mission requirements for the air vehicle.

4.1.3.7 Operation in atmospheric disturbances. Operation in atmospheric disturbance shall be verified by ____________________.

VERIFICATION RATIONALE (4.1.3.7)

The ability of the FCS to provide a safe level of operation in atmospheric disturbances can only be verified by flight test and/or analysis.

VERIFICATION GUIDANCE

FCS operation in atmospheric disturbance should be tested and/or analyzed in conjunction with verification of handling qualities during atmospheric disturbance. See the flying qualities handbook for a discussion of atmospheric disturbance models used for analysis.

VERIFICATION LESSONS LEARNED

3.1.3.8 Residual oscillations. For normal operation and during steady flight, FCS induced aircraft residual oscillations at all crew and passenger stations shall not exceed __(a)__ g's vertical or __(b)__ g's lateral peak to peak acceleration. Residual oscillations in pitch attitude angle shall satisfy the longitudinal maneuvering characteristic requirements of the flying qualities specification. Residual oscillations in roll and yaw attitude at the pilot's station shall not exceed __(c)__ degrees peak to peak for flight phases requiring precision control of attitude.

REQUIREMENT RATIONALE (3.1.3.8)

This requirement is imposed to prevent limit cycles in the control system or structural oscillations that might compromise tactical effectiveness, or cause crew or passenger discomfort.

REQUIREMENT GUIDANCE

Values previously required: (a) 0.04, (b) 0.02, and (c) 0.6.

These residual oscillation requirements apply to both manual and automatic FCSs under normal conditions, and do not apply below FCS Operational State I. The amplitude specified corresponds roughly to the perceptible level.

Residual oscillations of 1 degree peak-to-peak for roll and 0.5 degree peak-to-peak for pitch attitude and heading have been suggested as limits for commercial transports. These higher values may be acceptable for flight phases not requiring precision control of attitudes. In procurements having stringent tracking accuracy requirements, residual oscillations below those previously required may be necessary to obtain desired performance.

REQUIREMENTS LESSONS LEARNED

Roll residual oscillations of 0.7 degree have been reported for large low to medium maneuverability aircraft without complaint from either flight crew or crew members engaged in monitoring equipment in areas without outside visual reference.

4.1.3.8 Residual oscillation. Compliance with the requirements for residual oscillation shall be verified by ______________. Residual oscillations shall be measured at ______________.

VERIFICATION RATIONALE (4.1.3.8)

Ground tests and inflight tests of the actual air vehicles are the only reliable means of verifying the actual residual oscillations.

VERIFICATION GUIDANCE

The flying qualities specification requires the measuring of residual pitch oscillation at pilot's station. Depending on the air vehicle's mission, additional measurement locations may be required depending on crew tasks, passenger comfort, sensitive equipment, locations, etc.

VERIFICATION LESSONS LEARNED

AFWAL-TR-82-3081, Vol II, references an air vehicle design where .049 g peak-to-peak normal acceleration oscillations were undesirable.

3.1.3.9 System Test, Display, Reporting, and Monitoring Provisions (TDRM). Test display, reporting, and monitoring incorporated into the critical and flight phase essential FCS should include:

____

____

Table VI defines the applicable tests and the air vehicle functions to the flight phase:

REQUIREMENT RATIONALE (3.1.3.9)

System test display and monitoring are necessary in order to most effectively and efficiently integrate FCS requirements including flight safety, mission reliability, fault isolation, failure immunity, survivability, invulnerability, operational utility, and maintainability with other systems/subsystems and the aircraft.

REQUIREMENT GUIDANCE

The blanks allow tailoring of the requirements. The testing display and monitoring provided under this requirement should deal only with system testing and monitoring allocated to influence system design and performance. The total test, display reporting, and monitoring capability necessary for critical and flight phase essential FCS should be defined for systems phases of flight (preflight, inflight, and postflight) according to the following tables and definitions:

a. Definitions:

(1) Phases of Flight:

Preflight: Time from identification of an aircraft for a mission to start of takeoff on runway.

Inflight: Time from start of runway to end of landing roll.

Postflight: Time from end of landing roll to certification of aircraft operational utility for another mission.

(2) Built-In-Test (BIT): Integral testing which enables rapid isolation of faulty system components. A BIT may be initiated either automatically or manually to meet a system's peculiar needs.

(a) Coordinated System BIT (CSBIT): A BIT automatically instituted on ground power up that checks the FCS and all integrating subsystems. This BIT is made of several other types of BITs plus unique features.

(b) Power Up BIT (PUBIT): A BIT automatically initiated on power on to test a defined functional system or piece of equipment. A little less extensive than CSBIT, but more extensive than other BITs.

(c) Short Power Up BIT (SPUBIT): A BIT automatically initiated when power is applied/selected by external conditions known apriori. A fast response PUBIT.

(d) Initiated BIT (IBIT): A BIT initiated by personnel action designed to test a defined functional system. Less extensive than PUBIT, but more extensive than other BITs.

(e) Continuous BIT (CBIT): A BIT that automatically runs in background to check a limited number of critical parameters during each defined computer frame (major or minor).

(f) Periodic BIT (PBIT): A BIT that automatically runs every so many computer frames to check parameters which need to be tested less frequently and may or may not be critical.

(g) Off-Line BIT (OLBIT): A BIT automatically or manually initiated to determine which part or parts of a computing entity, function, or components are capable to continue operation once the function, component, or computing entity has been removed from active participation.

(h) Performance Monitoring BIT (PMBIT): A BIT automatically monitoring health of a function capable of detecting and isolating a fault through mostly passive detection techniques and active isolation.

(i) Preflight BIT (PFBIT): A BIT automatically or manually engaged to perform a limited CSBIT of flight critical functions/parameters under time critical conditions.

(j) Pre-Engage BIT (PEBIT): A BIT selected automatically or manually initiated to check a mode or function prior to its engagement/coupling with a flight critical function such as FCS.

(k) Maintenance BIT (MBIT): The most exhaustive of all BITs. It is manually engaged to find a fault down to the component level.

The above is not all inclusive, but covers most types of BIT associated with an end item, function, and system.

(3) Other Test Methods:

(a) Visual Inspections (VI): Used to determine proper movements, serviceability, fluid levels, and general appearance.

(b) Physical Parameter Measurement (PPM): Used to determine proper alignments, clearances, deflections, strains, and elongations.

(c) Special (SPCL): Tests which may require specialized tools, ground support equipment, diagnostic hook-ups, or nondestructive inspections (dye, x-ray, etc.).

(4) "A NATO Standardization Agreement exists in the form of STANAG 3221, which implies that aircraft with AFCS shall be provided with a means by which the pilot can check serviceability prior to takeoff and a means to detect and display inflight malfunctions. The term 'Self Test' and 'Built-in-Test (BIT)' are terms used frequently in the past to describe a means of T&M. The following is a list of specific tests which may be applicable to a BIT. The list is not exhaustive, and tests must be chosen for applicability to the function and level of coverage desired."

(a) Instruction Test Sequence: Test for endless loops, time deadline to exercise all instructions.

(b) Scratch-Pad Read-Write Test: A number of locations in the scratch pad are dedicated to self-testing. On successive test iterations, random patterns are written into these dedicated locations and then checked. This tests the memory integrity and addressing structure of the scratch pad.

(c) Wrap Around Loop Tests: To verify the computer I/O and communication sections for both analog and discrete data.

(d) Use of hardware circuitry to monitor the computer power supplies. Power supply status signals will be exchanged between computers.

(e) Incorporation of a high-priority power failure interrupt to effect an orderly computer shut-down in the event of a power drop-out. Power-off and power-on status signals will be exchanged between computers.

(f) Incorporation of a deadman timer (redundant if necessary to achieve required reliability) to detect computer stoppages. Failure of the software to reset the timer indicates a computer failure.

(g) Use of an internal timer to monitor the time required to complete various portions of the self-test program.

(h) Use of parity to continuously monitor the memory storage locations.

(i) Check data, address, and control lines by reading out of memory data patterns of zeros and ones, stored in predetermined locations.

(j) Memory-sum checks for those portions of memory containing constants and instructions. The sum check requires more execution time than can be used immediately following computer start-up.

(k) Sample Problems to Check the CPU: Designed to exercise the instructions used to solve the control laws.

(l) An arithmetic faults interrupt to sense overflows.

(m) Parity: To monitor continuously the transmission of data over the I/O channels. When bad parity is detected, an interrupt will be initiated.

This list (table XII) is supplied for information only; it is not intended for the FCS engineer to specify the design techniques used to provide BIT.

TABLE XII. Suggested uses of BIT and other tests.

b. Test table:

TEST \ PHASE	PREFLIGHT	INFLIGHT	POSTFLIGHT
CSBIT	X		X
PUBIT	X		X
SPUBIT	X	X	
CBIT	X	X	X
PBIT	X	X	X
OLBIT	X	X	X
PMBIT	X	X	X
PFBIT	X		
PEBIT		X	
MBIT		X	
VI	X		X
PM	X		X
SPCL	X		X
IBIT	X		X

c. Function table:

TEST \ PHASE	PREFLIGHT	INFLIGHT	POSTFLIGHT
FCS	X	X	X
INS	X	X	X
AIR DATA	X	X	X
ELEC POWER	X	X	X
HYDRAULICS	X	X	X
STRUCTURE	X	X	X
AUTOPILOT		X	X
DISPLAYS	X	X	X
AUTO TERRAIN FOLLOWING AVOIDANCE	X	X	X
AUTO BATTLE MANAGEMENT		X	
THREAT AVOIDANCE		X	
COLLISION AVOIDANCE	X	X	
LOSS OF CONSCIOUSNESS	X	X	
ACTUATION	X	X	X
UNIQUE SENSORS	X	X	X
PILOT COMMAND SENSORS	X	X	X
AUTO NAV	X	X	
AUTO RECOVERY	X	X	
AUTO WEAPON DELIVERY		X	
FUEL MGMT	X	X	X
LANDING GEAR SYSTEM	X	X	X
ENVIRONMENTAL CONTROL SYSTEM	X	X	X
MISSION AVIONICS PLANNING	X	X	X

d. Displays: Displays for critical and flight phase essential will have readable, readily identifiable symbology. At least two displays shall be dedicated to critical and flight phase essential information.

e. Reporting: Information for critical and flight phase essential systems taken from any test and displayed to the pilot or crew shall be clear, unambiguous, and result in a single, if any, corrective action.

REQUIREMENT LESSONS LEARNED

The effect of detected and undetected failures taken with the probability of occurrence of such failures must comply with the system reliability and safety requirements. This requirement must address all failures, including but not limited to software, electronic, mechanical, electrical, hydraulic, power sources, actuators, sensors, structure, and displays.

4.1.3.9 System Test, Display, Reporting, and Monitoring Provisions (TDRM). The test and monitoring methods incorporated in the FCS shall be verified by ______________________.

VERIFICATION RATIONALE (4.1.3.9)

The methods used for system test, display, reporting, and monitoring can best be assessed by interface with the contractor, either formal or informal, through briefings/reviews or documentation. This requirement documents the types of tests and monitoring to be done inter and intra FCS.

VERIFICATION GUIDANCE

The following are suggested entries for tailoring this requirement: during PDR, during CDR, and/or informal documentation (list CDRL number).

Verification should be a sequential, time-phased series of events which begin in the design phase and extend through development to provide proof that the TDRM requirements have been met. The blank should be filled by words such as:

Review of documentation incident to design, development and test display reporting and monitoring (TDRM) by:

a. Analysis - (types of analysis)

b. Laboratory tests - (types of tests)

c. Ground tests on the aircraft - (types of tests)

d. Flight test - (certification tests)

The detail design features and performance, which is to be provided, should be established in an engineering document. That document should cover each feature which is necessary to fill the needs of the system. Test procedures should be developed from that document and should include not only the tests for parameters, which ensure proper performance, but also tests which show that features provided for control of hazards, and for ensuring safety of operation, do function properly.

When digital FCS are used, it is essential that an Engineering Test Stand (ETS) be used to verify the TDRM function in both software and hardware. The ETS should include hardware elements of the FCS which have been modified to allow simulation of malfunction and failure in the T&M and FCS. The ETS should include all elements necessary for TDRM to be evaluated, especially elements which are not Flight Control such as those for communication, fault storage, etc. When TDRM is part of an integrated diagnostic system, the TDRM tests should be specifically tailored to cover all the parameters/features necessary for the TDRM functions to be completely verified. In these tests, the failure modes and propagation results of the integrated system should be shown to not degrade FCS performance.

VERIFICATION LESSONS LEARNED

Poorly integrated testing, display, and reporting have led to an enormous cost in lost aircraft, pilots/crew, maintenance troubleshooting, and logistics. Features of TDRM which are most critical and should receive an extremely thorough verification are those which provide:

- Detection of all active and passive failures.
- Comparator limits and trip times (great enough to prevent nuisance annunciation).
- Switching transients (low enough not to create hazard).
- Reliability levels (high enough to make the probability of two similar passive failures virtually nil in one flight).
- Redundancy management (signal selection, fault detection, fault isolation, reconfiguration).

The effect of detected and undetected failures, combined with the probability of occurrence of such failures, should be a factor in TDRM analytical verification.

A thorough verification/validation of BIT, prior to aircraft installation, has resulted in considerable time savings during aircraft debugging procedures. Verification of TDRM software must be in accordance with procedures outlined in the Computer Program Configuration Item Test Plan.

3.1.3.9.1 **Preflight.** Preflight BIT shall be __(a)__ and include any test sequence (see in table VI) prior to takeoff. Preflight tests shall not rely on ground test equipment for their successful completion. Interlocks shall be provided to prevent inflight engagement and to terminate preflight BIT when the conditions for engagement no longer exist. It shall be possible to perform preflight tests by manipulation of the following equipment:

________________(b)________________

Test provisions shall include the capability for determining the integrity of the following by the corresponding test:

________________(c)________________

The functional capability of the following in their fail operational modes shall also be determined by the corresponding test:

________________(d)________________

The overall tests performed (BITS, VI, PPM, SPCL) contain the following specific related tests:

________________(e)________________

REQUIREMENT RATIONALE (3.1.3.9.1)

Preflight tests are required to provide assurance of subsequent system safety and operability.

REQUIREMENT GUIDANCE

Preflight is a means of determining the status of the FCS and integrated systems prior to flight. This can only be determined if each and every critical path is checked.

Additional test capability for checking the command limiting and structural protection systems may be provided. The test provisions should be mechanized to enable the pilot to complete all preflight tests in less than five minutes after warm-up time. PFBIT should complete all tests in less than two minutes. If preflight is not completed prior to takeoff, provision must be provided to safely terminate BIT (e.g. terminates with weigh off wheels). Test equipment should not have the capability of inserting signals which exceed operating limits on any part of the system or which reduces its wear capability or fatigue life.

Preflight tests for essential and flight phase essential FCS should be provided to enable the pilot to determine whether or not the FCS is functioning properly. It should be demonstrated that redundant MFCS electronic channels are operating normally without any safety-critical latent failures prior to takeoff. Depending on the operating rules, the pilot may need to know the operational/failure state channel-by-channel and axis-by-axis. This includes all backup or normally disengaged channels. Pilot-operated preflight check requirements should be integrated into the FCS and should not require use of ground test equipment.

The requirement is designed to allow the flight control engineer to determine (blank a) if the preflight should be automatically initiated, possibly as part of other preflight procedures or if the pilot should be required to initiate the BIT(s). It may be desirable to allow the combination of automatic and pilot initiated preflight BITs. In either case, the subsequent process should be automatic, and this should be stated in the tailoring if pilot initiated BITs are allowed.

Blank (b) is provided to tailor the list of equipment with which it should be possible to perform preflight tests. Suggested equipment which may be manipulated for preflight tests are:

- FCS preflight test means of activation
- Aircraft control stick or wheel
- Aircraft control pedals
- Controls on the FCS control console
- Flaps and speedbrake controls, etc.

Results of the preflight tests should indicate to the pilot the proper functioning of the FCS and integrated systems/subsystems. The test provisions (blank c) should include the capability for determining the integrity of the following:

a. Control paths between pilot's control input and the aircraft power control units. (CSBIT, CBIT, PBIT, PMBIT).

b. MFCS and AFCS sensors and control paths. (CSBIT, PFBIT, PUBIT).

c. MFCS and AFCS fault monitoring and failure isolation systems for sensors, electronics, and servo-systems. (CBIT, PBIT, PMBIT, IBIT, MBIT).

d. Manual and automatic trim systems. (CBIT, PBIT, PMBIT, IBIT, MBIT, VI, PPM, SPCL)

Preflight should also be able to determine the functional capability of the following in their fail operational modes (blank d):

a. Electronic computation and control paths to FCS secondary actuator, excluding sensors. (CBIT, PBIT, PMBIT, MBIT, IBIT)

b. Fault monitoring and failure isolation system for sensors, electronics, and servo-systems. (PMBIT, MBIT, IBIT, VI, PPM, SPCL)

The overall test element with the specific tests contained in the element should be defined in blank (e). Suggested tests from 3.1.3.9 may be used. It is expected that the more complicated the overall test element is, the more lengthy and specific the tests will be. For example, CSBIT may pinpoint it to a faulty system or major item such as a line replaceable unit, module, or area within. Each specific test should be identified against what it is testing for. The exact details of how the test accomplishes its purpose may be specified in another document.

REQUIREMENT LESSONS LEARNED

Experience indicates that the drive tests of the actuators are the most time consuming so that the test times are determined by hardware action times, not software computation. Fault isolation can usually be accomplished while waiting for hardware responses. At low temperatures it may be necessary to integrate warm-up and preflight BIT to achieve desired operational performance.

Electrical signals injected by TDRM should not exceed the operating limits on any part and should not reduce the endurance capability or fatigue life of the elements.

Ground test signals for TDRM should not drive actuators into hard stops; however, they should ensure maximum deflection of cables, hoses, tubing, etc., that connect to the actuators.

The time required to complete the preflight test should be the time required to show a GO/NO-GO condition and should not include the time for fault isolation, system management, etc.

4.1.3.9.1 Preflight. The proper operation of preflight BIT shall be verified by ground test and __(a)__. Ground test shall demonstrate __(b)__. Prevention of inflight engagement shall be verified __(c)__.

VERIFICATION RATIONALE (4.1.3.9.1)

In the past ground on-aircraft tests, analysis, and laboratory tests have been used successfully to demonstrate compliance.

VERIFICATION GUIDANCE

Blank (a) is provided so that other methods besides ground test may be included for verification. The methods usually chosen are laboratory tests and/or analysis. Blank (b) is provided to tailor the requirements of the verification procedure to include specific demonstrations. A suggested input for blank (b) is: "detection of simulated safety critical latent failures and verify annunciation requirements".

Prevention of inflight engagement (blank c) should state that the test not be done in flight and should be verified by on-aircraft ground demonstration that the inhibit logic does prevent unwanted inflight BIT engagement. Additionally, analysis should be used to substantiate the number of interlocks to prevent inflight engagement and acceptable levels for ground test signals.

Laboratory tests and analysis shall be used for verification of BIT software. If BITs are used, the preceding sentence should be appended to the 4.1.3.9.1 requirement.

VERIFICATION LESSONS LEARNED

Verification should show that single and undetected failures in TDRM ground test interlock cannot result in inadvertent engagement of this mode in flight.

3.1.3.9.2 Inflight. Inflight TDRM of equipment performance and critical flight conditions shall operate during ___(a)___ and shall be capable of detecting:

______________(b)______________

Inflight TDRM shall be passive and not propagate any failures to the___(c)___ flight controls.

Inflight TDRM shall include, but not be limited to, the following capabilities:

______________(d)______________

REQUIREMENT RATIONALE (3.1.3.9.2)

As flight control systems become more complex and aircraft more integrated, inflight test monitoring becomes necessary to meet the reliability, survivability, failure immunity, invulnerability, and flight safety requirements, and provide assurance of subsequent system operability for mission completion.

REQUIREMENT GUIDANCE

Inflight TDRM shall operate, as a minimum, during critical and flight phase essential functions (blank a). Inflight TDRM is made up of tests from table XII to perform continuous evaluation of critical functions, such as supplying stability to an unstable airframe. Inflight TDRM, as a minimum, should be capable of detecting (blank b):

a. Any single and/or multiple failure which degrades performance below the system specification requirements.

b. Monitoring circuitry failures which could mask failures of functional circuitry.

c. Single failures which could cause loss of aircraft control.

Failures occurring in the inflight TDRM should not be allowed to disturb the normal operation of the FCS. Blank (c) is provided to list the specific FCS classes. Whereas in this document only two classifications are defined, MFCS and AFCS, modifications to previously produced air vehicles, for which the specification may be used, may include such classifications as primary, secondary, and mission flight control systems.

Inflight monitoring that controls redundancy and integration management logic should be designed to minimize nuisance failure indications. This is particularly important for fly-by-wire and/or unstable vehicle control systems where excessive noise susceptibility and tight monitoring thresholds could erroneously shut down the last channel of a redundant FCS and cause loss of control due to a transient signal.

Blank (d) is provided so that specific capabilities of the monitoring system may be specified (reference table XII). These desired capabilities will probably be generated by lessons learned in the design of a specific air vehicle or class of air vehicles.

Some techniques which might be used in inflight TDRM are:

a. Continuous In-Line Monitoring - Concerns monitoring techniques incorporated in digital computer software to verify the integrity of that computer.

b. Watch-Dog Timer - A check on the system clock and/or system control (for runaway control).

c. Tracer Monitor - Used in analog computers to verify that an amplifier or similar circuit will pass a particular test. It can also be used to verify the presence of an AC excitation voltage.

d. Sign Post Counter - A check on software runaway, a sequence check on software.

e. Status Monitor - Monitors the status signal from another channel or other source.

f. Memory check sum – Checks the integrity of memory.

g. Comparison Monitor – Commonly called a comparator. Can compare across channels or subsystem to a model.

h. Standard Comparator – A stimulus of known value inserted into a unit under test and the response compared against a standard.

i. Wrap-Around – Signals feedback into the system for a validity check of the command.

j. Logic Test – An interrogation or comparison of logic devices to determine the actual state.

k. Signal Management – Signal selection techniques for a redundant system.

l. Preengage BIT – PEBIT tests any automatic performance or mode using any test sequence required prior to engagement of a control or mode. Any test sequence which could disturb the normal activity of the air vehicle in a given mode should be inhibited when that mode is engaged.

This list is not intended to be exhaustive, nor is it to be implied that a properly designed TDRM system needs to include all techniques. Rather, different techniques should be chosen and used in combinations which provide the optimum coverage necessary to meet the various requirements of mission reliability, survivability of safety, etc.

REQUIREMENT LESSONS LEARNED

Several inflight monitoring capabilities which have been specifically required in the past are monitoring of hydraulic power, over/under voltage and current levels supplied to the FCS.

The tolerances on command limiting and switching thresholds in high gain/full authority electronic flight controls are critical parameters when TDRM is used for inflight.

Nuisance annunciations should be evaluated in terms of maximum number per operating hour and not as a ratio of nuisance to actual failure annunciations. Factors such as equipment design, cockpit design, mission, pilot workload/opinion may all influence the TDRM chosen and the method of initiation. However, each of these factors must be viewed in light of the reasons for the preengage test.

4.1.3.9.2 Inflight. The proper operation of the inflight TDRM shall be verified by ___(a)___. Ground test shall demonstrate ___(b)___. Prevention of inflight TDRM failure propagation where the normal activity of the air vehicle may be disturbed shall be verified ___(c)___.

VERIFICATION RATIONALE (4.1.3.9.2)

Ground on-aircraft tests, analysis, and laboratory tests have been used successfully to demonstrate compliance.

VERIFICATION GUIDANCE

The methods usually chosen for blank (a) are laboratory tests, ground test, flight test, inspection, and/or analyses. Blank (b) is provided to tailor the requirements of the verification procedure to include specific demonstrations. A suggested input for blank (b) is: "detection of simulation safety critical latent failures and verify annunciation requirements."; for PEBIT words such as "detection of simulated mission critical latent failures and verify annunciation requirements." Prevention of inflight TDRM failure propagation in the FCS should be verified (blank c) by laboratory test and/or on-aircraft ground demonstration of simulated failures. Prevention of preengage BIT initiation during a mode where disturbance to the operation of the air vehicle could occur should also be verified. An iron bird/piloted simulation might be used to verify the FCS immunity to inflight monitor failures. Analysis should be used to verify levels of laboratory and ground test signals.

Laboratory tests and analysis shall be used for verification of monitoring software. If digital TDRM is used, the preceding sentence should be appended to the 4.1.3.9.2 requirement.

VERIFICATION LESSONS LEARNED

3.1.3.9.3 Post flight. Post flight shall ___(a)___ and include the test sequences shown in table VII. Post-flight test, display, and reporting shall be capable of ___(b)___. Post flight maintenance tests shall have interlocks to prevent inflight engagement and to terminate these tests when conditions suitable for maintenance testing no longer exist.

REQUIREMENT RATIONALE (3.1.3.9.3)

Post flight tests, if appropriately designed, will result in more efficient and effective troubleshooting of the FCS; however, care must be taken so that system reliability and safety are not adversely affected. Post flight provides the time when exhaustive testing for maintenance is available and is the most likely time to perform MBIT.

REQUIREMENT GUIDANCE

Maintenance diagnostics may include MBIT, correlation of other BITs, other tests such as VI, PM, and SPCL to perform activities such as complete system checks on the ground and fault isolation to a specified hardware level. MBIT is incorporated as a maintenance aid and comprises two major activities:

a. Maintenance post flight - A ground crew-activated test directed to detection of faults without regard to location, and run on internal APU or battery power to avoid engine operation.

b. Maintenance Fault Isolation - a maintenance activated test directed specifically to maintenance troubleshooting.

The following capabilities are suggested for inclusion in the requirement:

a. Detection of failures and isolation of the failures to a card and preferably component level.

b. Testing comprehensive enough to assure safe mission completion.

c. Initiation by maintenance crew.

d. Correct operation of other tests, BITs, and routine maintenance checks without Aerospace Ground Equipment (AGE) not normally found on the flight line.

e. Operation by assigned ground crew personnel without additional personnel.

f. Safe operation without danger to personnel or equipment.

Blank (a) is provided to specify particular performance features of post flight testing such as "use other tests and aircraft BITs, correlate the stored data, and provide fault isolation to the card/component level."

Blank (b) is provided to specify the display and reporting performance such as "displaying maintenance information on a cockpit ground equipment display, download all or selected information, and provide alpha-numeric to designate faults."

REQUIREMENT LESSONS LEARNED

Special consideration should be given to maintenance BIT requirements since aircraft down time can be drastically reduced if BIT is designed correctly to detect the majority of the failures in the system.

4.1.3.9.3 Post flight. The proper operation of post flight tests maintenance BIT shall be verified by ground test and ___(a)___. Verification test shall demonstrate ___(b)___. Prevention of inflight engagement shall be verified ___(c)___.

VERIFICATION RATIONALE (4.1.3.9.3)

Ground on-aircraft tests, analysis, and laboratory tests have been used successfully to demonstrate compliance.

VERIFICATION GUIDANCE (4.1.3.9.3)

Blank (a) is provided to specify the type of test/analysis used to verify the same. Suggested wording is "analysis using hazard and failure mode and effect to derive a <u>number</u> test cases."

Blank (b) follows with wording such as "post flight and maintenance test to isolate to the card (component) level (through the use of actual inserted or simulated single and multiple faults) to ________ percent accuracy."

Blank (c) provides for specification of the test methods to verify the interlocks suggested wording:

"sequential evaluation of the interlocks through voltage, current, or continuity checks."

The guidance given in 4.1.3.9.1 is also applicable to this requirement.

VERIFICATION LESSONS LEARNED

A thorough verification/validation of BIT prior to aircraft installation has resulted in considerable time savings during aircraft debugging procedures.

3.1.3.9.4 Inflight monitoring. Continuous inflight monitoring of equipment performance and critical flight conditions shall operate during ___(a)___ and shall be capable of detecting: ___(b)___.

Inflight monitoring shall be passive and not propagate any failures to the ___(c)___ flight controls.

Inflight monitoring shall include, but not be limited to, the following capabilities: ___(d)___.

REQUIREMENT RATIONALE (3.1.3.9.4)

As flight control systems become more complex, inflight monitoring becomes necessary to meet the reliability, survivability, failure immunity, invulnerability, and flight safety requirements.

REQUIREMENT GUIDANCE

Inflight monitoring shall operate, as a minimum, during essential and flight phase essential functions (blank a). Inflight monitoring may be a continuous operation, either specified or implied, by the nature of the flight control functions, such as supplying stability to an unstable airframe. An inflight monitoring system, at a minimum, should be capable of detecting (blank b):

a. Any failure which degrades performance below the system specification requirements.

b. Monitoring circuitry failures which could mask failures of functional circuitry.

c. Single failures which could cause loss of aircraft control if combined with another subsequent failure.

Failures occurring in the monitoring system should not be allowed to disturb the normal operating of the FCS. Blank (c) is provided to list the specific FCS classes. Whereas in this document only two classifications are defined, MFCS and AFCS, modifications to previously produced air vehicles, for which the specification may be used, may include such classifications as primary, secondary, and mission flight control systems.

Inflight monitoring that controls redundancy management logic should be designed to minimize nuisance failure indications. This is particularly important for fly-by-wire and/or unstable vehicle control systems where excessive noise susceptibility and tight monitoring thresholds could erroneously shut down the last channel of a redundant FCS and cause loss of control due to a transient signal.

Blank (d) is provided so that specific capabilities of the monitoring system may be specified. These desired capabilities will probably be generated by lessons learned in the design of a specific air vehicle or class of air vehicles. Therefore, in an initial specification of a new air vehicle the last paragraph may be deleted.

Some techniques which might be used in inflight monitoring are:

a. Continuous in-line monitoring - concerns monitoring techniques incorporated in digital computer software to verify the integrity of that computer.

b. Watch-dog timer - a check on the system clock and/or system control (for runaway control).

c. Tracer monitor - used in analog computers to verify that an amplifier or similar circuit will pass a particular test. It can also be used to verify the presence of an AC excitation voltage.

d. Sign post counter - a check on software runaway, a sequence check on software.

e. Status monitor - monitors the status signal from another channel or other source.

f. Memory check sum - checks the integrity of memory.

g. Comparison monitor - commonly called a comparator. Can compare across channels, or subsystem to a model.

h. Standard comparator - a stimulus of known value inserted into a unit under test and the response compared against a standard.

i. Wrap-around - signals feedback into the system for a validity check of the command.

j. Logic test - an interrogation or comparison of logic devices to determine the actual state.

k. Signal management - signal selection techniques for a redundant system.

This list is not intended to be exhaustive, nor is it to be implied that a properly designed monitoring system needs to include all techniques. Rather, different techniques should be chosen and used in combinations which provide the optimum coverage necessary to meet the various requirements of mission reliability, survivability of safety, etc.

REQUIREMENT LESSONS LEARNED

Several inflight monitoring capabilities which have been specifically required in the past are monitoring of hydraulic power, over/under voltage and current levels supplied to the FCS.

4.1.3.9.4 Inflight monitoring. The proper operation of the FCS inflight monitoring shall be verified by ___(a)___. Ground test shall demonstrate ___(b)___. Prevention of inflight monitor failure propagation where the normal activity of the air vehicle may be disturbed shall be verified ___(c)___.

VERIFICATION RATIONALE (4.1.3.9.4)

In the past ground on-aircraft tests, analyses, and laboratory tests have been used successfully to demonstrate compliance.

VERIFICATION GUIDANCE

The methods usually chosen for blank (a) are laboratory tests, ground test, flight test, inspection, and/or analyses. Blank (b) is provided to tailor the requirements of the verification procedure to include specific demonstrations. A suggested input for blank (b) is: "detection of simulated safety critical latent failures and verify annunciation requirements." Prevention of inflight monitor failure propagation in the FCS should be verified (blank c) by laboratory test and/or on-aircraft ground demonstration of simulated failures. An iron bird/piloted simulation might be used to verify the FCS immunity to inflight monitor failures. Analysis should be used to verify levels of laboratory and ground test signals.

Laboratory tests and analyses shall be used for verification of monitoring software. If digital monitoring is used, the preceding sentence should be appended to the 4.1.3.9.4 requirement.

VERIFICATION LESSONS LEARNED

3.1.4 MFCS design. This section of the specification deals with overall design philosophy of the flight control system. This section is normally completed by the contractor after conducting a series of trade studies to satisfy that system's safety, mission completion, and system reliability requirements. Care must be taken when completing this section to assure that it is in compliance with the overall acquisition strategy of weapon system being procured (For example, some acquisition strategies may insist that no design guidance be included in any specification). Where requirements in other sections of this specification are performance related requirements, the intent of this section is to provide protection to both the contractor and the procuring activity to assure that the system design is within safety and reliability requirements, and to further assure the procuring activity that major modifications to that design cannot be accomplished without government concurrence. From the procuring agency standpoint, care must be exercised to assure that over specification does not result in Engineering Change Proposals (ECPs) for minor changes or for routine changes during normal system development.

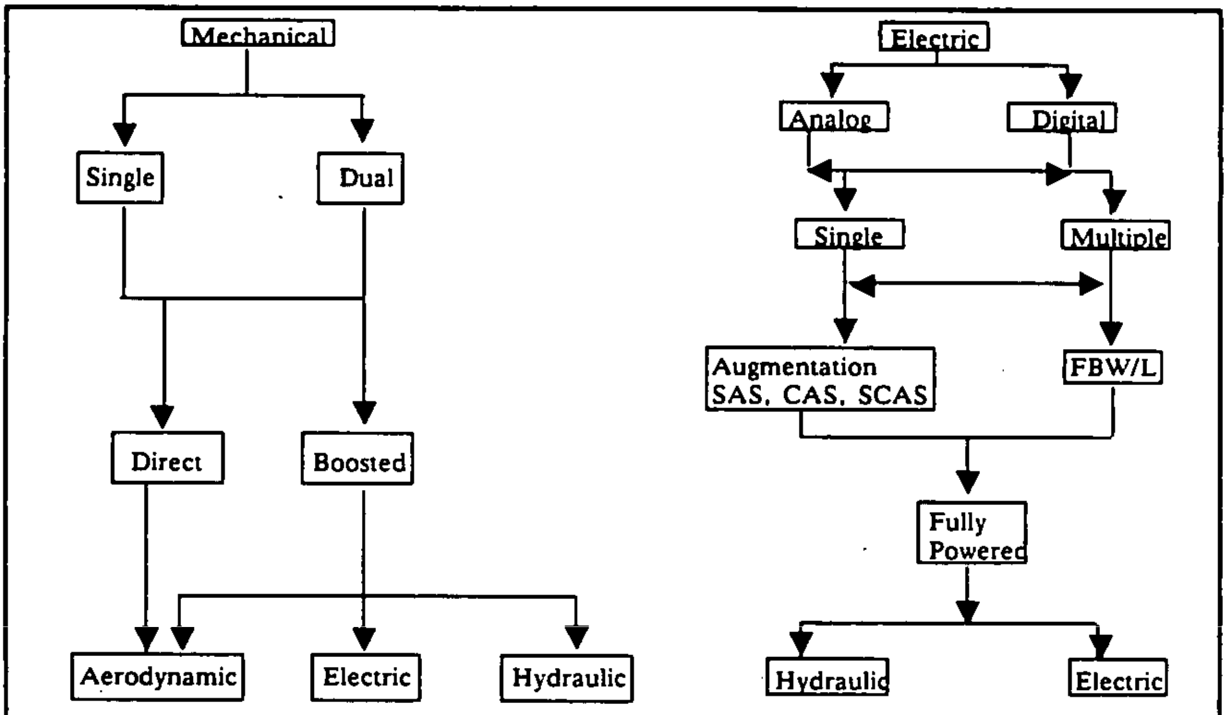
The MFCS shall be mechanized as a ___(a)___ using ___(b)___ for pilot control of pitch, roll, and yaw. The system shall provide ___(c)___ to enhance operational utility and flexibility for mission accomplishment. It shall be designed to provide a satisfactory physical interface between the pilot and the air vehicle such that every pilot action required to monitor and control the FCS to accomplish every phase of any assigned mission shall be consistent with established flying qualities requirement and pilot training practices.

REQUIREMENT RATIONALE (3.1.4)

The use of hydraulic/electric actuation high authority control/stability augmentation fly-by-wire/light command loops and other innovations has made it necessary to establish, and make a matter of record, the features which are fundamental in the FCS design. When the blanks have been filled, some of the important precepts which influence FCS design will have been established.

REQUIREMENT GUIDANCE

Blank (a) should be filled by one or several statements which identify the general type of FCS which will be used for implementing the controls for pitch, roll, yaw, etc. Words should be used such as those shown in figure 2 to describe the mechanization scheme to be used:



For example, words filling the blank might be:

Dual mechanical, direct for pitch using cable assemblies.

Single mechanical, aerodynamic boosted for roll using rod assemblies.

Single mechanical, cable operated, triple redundant, analog SCAS, fully electric powered in pitch.

Quad redundant, digital fly-by-light, hydraulic powered for pitch, roll and yaw.

FIGURE 2. Mechanization scheme.

Blank (b) should be filled by identifying the type of controls which will be provided for the pilot to make inputs for pitch, roll, yaw, etc. The words used might be:

- Force and displacement right side-stick for pitch, roll, and yaw (side-arm controller, right side).

- Force and displacement center stick with rudder pedals.

- Force and displacement column-mounted wheel and floor-mounted rudder pedals.

- Force from left side-arm controller for pitch, roll, yaw with center force and displacement stick and rudder pedals for the right side, copilot.

Blank (c) might be filled by words such as:

- Automatic control of pitch, roll, yaw; mode sequencing, etc.

- Automatic control of high lift devices.

- Automatic control of wing sweep.

- Automatic control of ground spoilers.

- hotas (Hands on throttle and stick) concepts.

The advent of fly-by-wire FCS has opened the way for use of several types of controls to be used, and specified in requirement blank (b) is not clear cut and cuts across the engineering discipline boundaries of flight controls, cockpit design, human factors, flying qualities and possibly others. For programs where several types are feasible, an effort should be made during the conceptual and validation/demonstration phases of acquisition to identify the type of control which should be specified.

REQUIREMENT LESSONS LEARNED

Flying qualities tests on a fighter airplane led to recommendation with respect to the side-stick controller as follows: "The full scale development control stick should be a sidearm force controller. It should allow a very limited displacement in both the longitudinal and lateral axes. The displacement should be in the form of a rotation about a base pivot point, and the movement equivalent to maximum aircraft response should be approximately one-quarter inch from neutral when measured at the top of the controller. The design should incorporate obvious physical stops in both axes which would provide the pilot unmistakable indications that he has commanded the maximum possible aircraft response. (The 'maximum-g command' light was unsatisfactory for this purpose.) Some forward and inboard tilt of the stick should be considered, and its rotation orientation should be optimized. Further development of the pilot controller should make maximum use of a fixed-based flight simulator mated with a detailed cockpit mockup."

Four variations of the command-deflection relationships of the side-stick controller, as shown in figure 3, were evaluated.

The first variation evaluated involved increased sidestick controller displacement. This configuration was referred to as the moveable stick. The objectives of this evaluation were to determine if the moveable stick improved aircraft handling qualities during pilot high gain tasks and if the stick stop cues, provided by the moveable stick, reduced pilot fatigue and improved handling qualities during various tasks when maneuvering near maximum command. The maximum command-deflection relationship for this configuration is shown in figure 3b. Comparing this figure with figure 3a indicates the relative change with respect to the FSD "fixed" stick. This evaluation determined that the handling qualities with a moveable stick were improved over those with the "fixed" stick.

The variations to the side-stick controller mechanization that followed the moveable stick evaluation were:

(1) moveable stick with reduced stick forces (80 percent of the FSD force levels).

(2) item (1) plus electrically skewed (rotated) axes.

(3) item (2) plus asymmetric roll force versus command gradient.

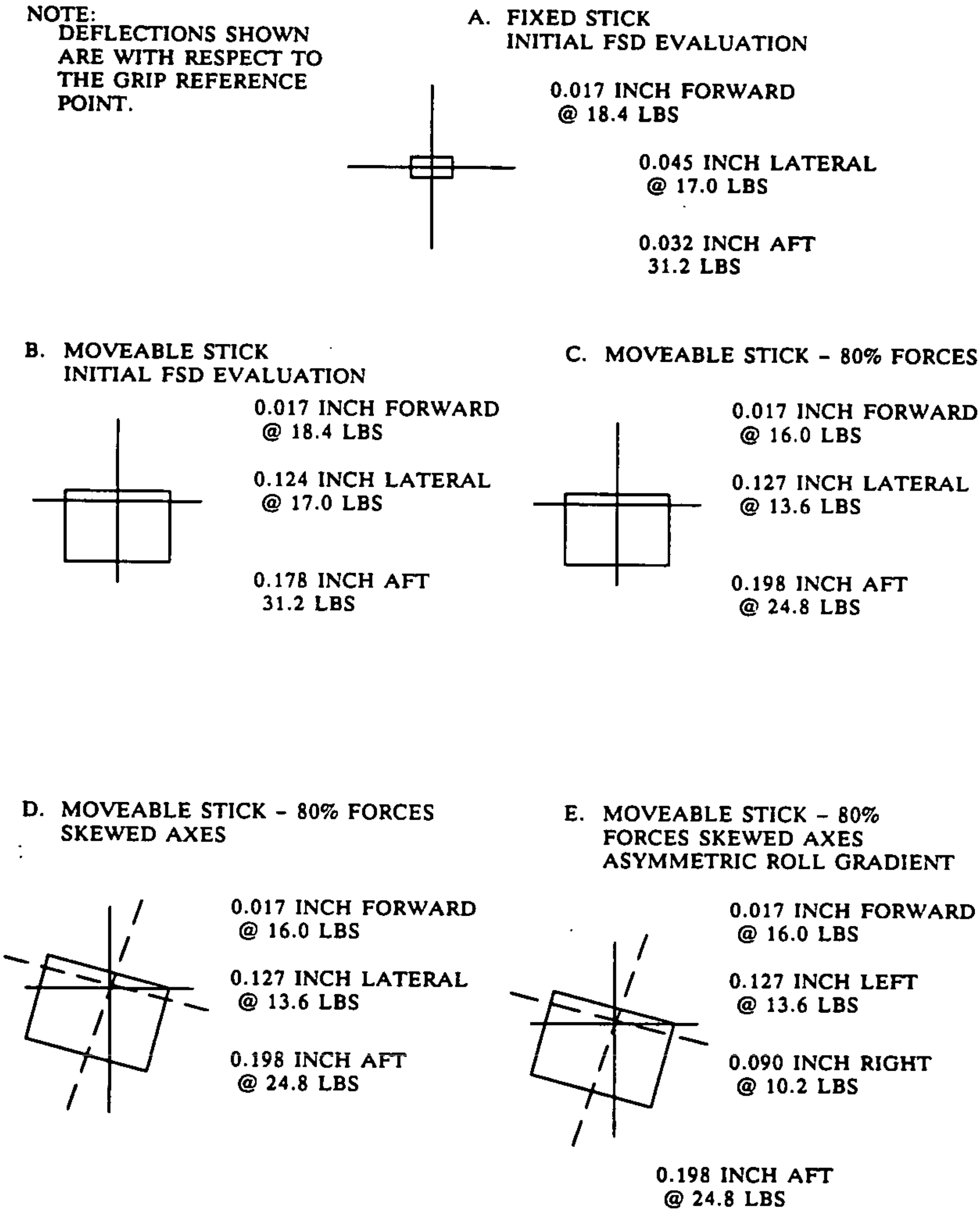


FIGURE 3. Command-deflection relationships of the side-stick controller.

The evaluation in which the FSD force gradients were reduced by 20 percent resulted from the consideration that the FSD force gradients had been selected for the "fixed" stick controller. It was felt that since the moveable stick provided a motion cue to the pilot as a control input "feedback," the force gradients on the moveable sidestick controller could be reduced without increasing the possibility of pilot over control.

The electrically skewed, or rotated, controller axes evaluation was based on previous work accomplished during research in this area. This evaluation involved electrically rotating the longitudinal-lateral axes of the controller 12 degrees clockwise in an attempt to reduce the pitch-roll crosstalk. The level of crosstalk encountered on this airplane varied from pilot to pilot based on flight experience and anthropometric factors. The 12 degrees of rotation was an average value derived from stick force cross plots and simulator studies.

The asymmetric roll gradient was evaluated as a result of pilot comments and anthropometric considerations. Due to the location of the controller, right roll forces were harder and more awkward to apply than left roll forces. For example, windup turn maneuvers to the right were considered by some pilots to be much harder to accomplish as precisely as windup turns to the left. Thus, the right roll force gradient was reduced from the 80 percent force level.

The moveable stick with reduced stick forces was comfortable in takeoff, landing, and formation maneuvers. There was no tendency to over control the aircraft. A noticeable reduction in pilot fatigue while flying with reduced forces was indicated.

The moveable stick with reduced forces and electrically skewed axes significantly improved the overall aircraft handling qualities. Takeoff and landing were considered much more comfortable; an improvement which was attributed specifically to the skewed axes. Crosstalk during takeoff, landing, and formation flying was greatly reduced. This resulted in decreased pilot workload and reduced fatigue.

The resulting comments of the pilots who evaluated the moveable stick with reduced forces, skewed axes, and asymmetric roll gradient indicated that the asymmetric roll gradient degraded the handling qualities of the airplane. There was an objectionable lack of harmony and an unnatural control response. This problem was very evident in the high speed-low altitude regime where intense pilot compensation was required. The asymmetric roll gradient, as tested, was highly undesirable.

The conclusions of these evaluations were that the moveable side-stick controller provided significant improvements over the original "fixed" stick. Reduced forces contributed positively to the handling qualities of the airplane by reducing pilot workload, thereby, reducing pilot fatigue. Skewed axes significantly reduced or eliminated pitch-roll crosstalk, improving the handling qualities, and further reducing pilot workload and fatigue. The asymmetric roll gradient, as tested, was highly objectionable and required intense pilot compensation.

The variation chosen conforms to figure 3d.

The first modern use of a stick on a transport aircraft may have been the Brequet 941, a prototype STOL transport in the 1962 timeframe. That stick received ready acceptance, however that aircraft had left hand throttles for the pilot. The original prototype STOL transport was proposed as a left hand stick with right hand throttles configuration; however, there was enough uncertainty about the stick to warrant replacing it with the wheel/yoke configuration. A control stick development program was later conducted on the Prototype STOL airplane. Seven test pilots flew that configuration and unanimously stated that the control stick was the most suitable control for the AMST aircraft. Benefits which are said to accrue from use of stick vs wheel in large aircraft are: improved instrument visibility, improved turn coordination, improved control of a highly maneuverable large aircraft, and best control for an aircraft that does LAPES, short field landings, etc.

4.1.4 MFCS design. MFCS design requirements of 3.1.4 for satisfactory physical interface shall be verified by ________, those for breakout force and free play by _________, and those for mechanical element characteristics by ________________.

VERIFICATION RATIONALE (4.1.4)

Several methods can be used to verify the different requirements for MFCS design. Blanks are provided to allow flexibility in chosing the verification method for the different requirements.

VERIFICATION GUIDANCE

Choose the most feasible methods for verification of the requirements from analysis, simulation, inspection, ground test, and flight test. Pilot's opinion obtained during piloted simulation or flight test is the best method for verifying a satisfactory physical interface. Ground test is the best method for verification breakout forces and free play. Analysis and flight test are the best methods for verification of mechanical element characteristics.

VERIFICATION LESSON LEARNED

Manual flight controls provide the means by which the pilot-operator controls the air vehicle to accomplish the assigned mission. These controls must be designed and mechanized such that they do not increase the hazard levels for the aircraft, do not have annoying characteristics and do not require excessive skill, alertness, strength, or undue workload on the part of the pilot.

Breakout forces for the controls used for pitch, roll, and yaw should be consistent with the flying qualities requirements for the air vehicle. The human engineering design requirements should contain the values to be used for the breakout forces for controls for flaps, speedbrakes, side force, wing sweep, etc. The values for free play may not be contained in the flying qualities and human engineering requirements. They may only be available after experimentation, usually piloted simulation, using the characteristic of the air vehicle.

Free play, mechanical vibration, and other extraneous movements in the pilot's controls can mask important feel cues and induce physical discomfort when present during long duration missions. Mechanizations which prevent such undesirable characteristics should be chosen for final design. Motions and forces reflected at the pilot's controls have been considered not evident and therefore acceptable if magnitudes are less than half the breakout force of the control (with the lowest breakout force). Stability augmentation service should never prevent full freedom of operation of the pilot's controls.

3.1.4.1 Mechanical MFCS design. Mechanical components shall be designed with paramount consideration given to reliability, maintainability, supportability, strength, and simplicity. The mechanical signal transmission paths between the pilot, sensors, or command generator to the surfaces shall be redundant to the extent required to meet the system safety requirement of ________________.

REQUIREMENT RATIONALE (3.1.4.1)

The mechanical system may be the entire or beginning and ending links of the pilot/command generator to the control surfaces. It is essential for the mechanical components to be designed for safety, reliability, maintainability, and supportability to accommodate their safety-of-flight classification. Simplicity of design is always an objective that leads to good reliability, maintainability, and supportability.

REQUIREMENT GUIDANCE

The system safety classification of the control surface/axis will determine the redundancy required of the connecting mechanical components. Proper consideration must be given to the safety classification. Understating the safety requirement can lead to the use of improper mechanical component selection. Additional design characteristics such as rate required, load carrying capacity, temperature, selection of compatible materials, clearances, lubrication, joint fastening/retention, stability, strength, stress, current fabrication methods, and accepted standard design practices must be considered and tempered to arrive at a chosen design that meets the requirements of this paragraph. The blank should be filled with the appropriate redundancy level (e.g., fail op/fail safe).

REQUIREMENT LESSONS LEARNED

Improper analysis and consideration of this requirement has resulted in costly changes to Air Force aircraft to eliminate corrosion, widen clearances, and perform additional inspections, lubrications, and material changes to accommodate fatigue failures.

4.1.4.1 **Mechanical MFCS design.** Compliance with this requirement shall be verified by:

a. Engineering tests that show adequate strength to a safety factor of 1.5 for the ratio of limit to ultimate load. Tests shall also show the system's ability to clear a jam.

b. Environmental tests that show the system's ability to resist corrosion, withstand acceleration and vibration, compensate for thermal properties, and function under required load.

c. Endurance tests performed under load for a number of cycles that show the system's ability to last for the service life of the aircraft or the specified MTBF.

d. Maintenance demonstration that shows the system adjustments/calibrations are accessible and can be done on the aircraft.

e. Functional/operational tests that certify the system is operational after maintenance actions or initial assembly and that the redundancy provided is achievable under all failure conditions.

VERIFICATION RATIONALE (4.1.4.1)

Due to the safety-of-flight classification of flight control systems, the mechanical system must be rigorously tested to demonstrate its integrity. The above tests will demonstrate the mechanical systems ability to perform for the specified life (usually the service life of the aircraft).

VERIFICATION GUIDANCE

Use of military qualified or standard parts may reduce the amount of testing required by using qualification by similarity. Where testing is required, the test should be as realistic for the application as possible. For example, an endurance test should consider and analyze the relation between the number of cycles to the number of aircraft flight hours by defining percentages of flights and expected maneuvers in those flights. The test should apply loads to the control system that simulate the airloads as estimated by wind tunnel data or measured from flight test. The test should be conducted to allow evaluation of highly stressed, periodically stressed, and cycled parts for fatigue damage. The test should follow the damage tolerance criteria of MIL-A-83444.

VERIFICATION LESSONS LEARNED

Improper testing to the above requirement has resulted in:

a. Corroded parts that require frequent inspection and cleaning.

b. Less than safe clearances for cables, cranks, pulleys, push-pull tubes, and bobweights causing flight control jams.

c. Underdesigned and undetected components for predicted loads and service causing stress corrosion fatigue, fatigue, and breaking of components causing loss of surfaces and aircraft.

d. Underdesigned hydraulic power components inducing hydraulic and control surface stalls.

e. Early wear out of splined joints causing loss of surfaces and aircraft.

f. Under allotted redundancy resulting in loss of surfaces controlling an aircraft axis and loss of aircraft.

3.1.4.1.1 **Reversion--boosted systems.** The mechanical FCS shall provide Operational State ______ capability when boost is unavailable. Means shall be provided to re-engage boost following reversion to the mechanical system. Boosted, mechanical FCS shall provide Operational State ____ capability.

REQUIREMENT RATIONALE (3.1.4.1.1)

Military aircraft with mechanical boosted systems are still being developed and in the inventory. With no reversion mode, the surface controlled and/or other interlocked surfaces would be held at the last position or streamlined. This would render the surface useless and possibly cause loss of aircraft and/or life. The requirement fulfills other requirements of failure immunity and invulnerability.

REQUIREMENT GUIDANCE

It is recommended the reversion mode be required to meet Operational State III capability. The normal mode should be Operational State I. This requirement is applicable to mechanical systems or mechanical portions of an overall system.

REQUIREMENT LESSONS LEARNED

4.1.4.1.1 Reversion--boosted systems. The requirement shall be verified in a system test. The test shall simulate realistic surface loadings and provide a realistic representation of, if not the actual, mechanical-boosted system. The test shall demonstrate the ability of the mechanical system to perform in the boosted and reversion modes and the engage/disengagement of the modes from the cockpit. Limitations, if any, shall be noted for inclusion in the simulation effort.

VERIFICATION RATIONALE (4.1.4.1.1)

The test must fully describe the system and its operations. Limitations, such as force and lag, must be noted to provide a more accurate simulation capability and information for development of the trainer simulator.

VERIFICATION GUIDANCE

The test should be run as a system to include surface loads and positions as estimated by wind tunnel or flight test data. Stick forces, loads, lags, surface positions, limitations, approximations, assumptions, and analyses should be performed prior to, during, and after the test. Modifications to any pertinent issues should be done followed by loads, lags, and stick force information, as a minimum, transferred to the simulator effort for verification of the handling quality/stability characteristics. This test should be redone using the data from the simulator, as required.

VERIFICATION LESSONS LEARNED

3.1.4.1.2 Use of mechanical linkages. Mechanical linkages and artificial feel devices/systems used for signal conversion shall not have friction/free play that results in operation below Operational State ______. Linkages and feel devices shall be balanced appropriately for the desired axis to meet the structural mode and force requirements for this air vehicle. Residual imbalances shall be consistent with feel requirements.

REQUIREMENT RATIONALE (3.1.4.1.2)

Mechanical linkages used for signal conversion and artificial feel devices are critical to the stability and handling characteristics of an aircraft. Improper analysis and implementation can lead to regenerative feedback in the structure or PIO situations with the pilot.

REQUIREMENT GUIDANCE

Operational State I is recommended. The use and length of linkages should be minimized to keep friction and free play at a minimum. Proper selection of parts and material is essential to provide minimum friction and free play. Use of pre-load springs, precision bearings, etc. to reduce free play will increase friction and reflect higher feel forces. This should be accounted for in the analysis of the feel system. The increased lag may result in small amplitude limit cycling which can be corrected for in the electronics.

REQUIREMENT LESSONS LEARNED

Use of mechanical linkages and consideration for their maintainability are critical design parameters. Improper consideration of the aircraft, its flight envelope, and maintenance, produces systems that induce PIO or are damaging to the structure. Other results are the deterioration and eventual disconnection of linkages at fastening points. Aircraft loss has resulted.

4.1.4.1.2 Use of mechanical linkage. Mechanical linkages and artificial feel devices shall be tested as described in 4.1.4.1.1. In addition, a maintenance demonstration and an endurance test shall be accomplished.

VERIFICATION RATIONALE (4.1.4.1.2)

Introduction of mechanical linkages into the flight control system introduces free play and friction re-

sulting in objectionable control system operation and degradation of tracking performance. The resultant degradation in performance, and corrective design actions incorporated into the system must be verified by demonstration and tests.

VERIFICATION GUIDANCE

Verification of all artificial feel system performance usually consists of accurate simulation of the system and testing the system first on a flight simulator, then during flight tests. Testing should verify that the closed loop operation does not result in increased system phase lag or produce small amplitude limit cycling. A maintenance demonstration should be combined with the endurance portion to demonstrate the degradation associated with use and maintenance. The endurance test should follow that described in 4.1.4.1. These tests may be incorporated/combined into an overall test of the system and other testing as applicable.

VERIFICATION LESSONS LEARNED

Inadequate testing of this requirement has led to aircraft loss and costly aircraft changes. Small amplitude oscillations can lead to PIO and regenerative feedback to the structure can cause aircraft flutter and has caused linkage/device disconnection from mounting/fastening points.

3.1.4.2 Electrical/electronic MFCS design. Electrical/electronic fly-by-wire flight control systems shall be designed to withstand all induced and natural environments such as lightning, EMI, etc. Redundancy shall be employed to achieve the safety requirements of the air vehicle. Reliability, maintainability, supportability, simplicity, and survivability shall be major design parameters. The design is required to have operational State I capability.

REQUIREMENT RATIONALE (3.1.4.2)

Electrical/electronics provide the augmentation required to obtain the aircraft stability and good handling characteristics. Failure of this portion of the system can cause objectionable transients and in some cases, departure from controlled flight.

REQUIREMENT GUIDANCE

The redundancy of the augmentation system should be the same as the mechanical system, at a minimum. Analog and digital systems have their own unique sets of concerns. Analog systems may use standard chips. *Floating pins should not be* allowed for unused inputs or circuits. The design should be approached as a synthesis of experience and analysis. Additional consideration to nuclear, chemical, biological, and TEMPEST criteria should influence the design as necessary and should be included in the requirement. The complexity of the circuitry will depend on the mission and aircraft configuration. For complex designs, an independent design review, such as sneak and first failure sneak analyses, is highly recommended. Isolation of redundant channels, both physical and electrical, will aid in achieving a survivable system. Digital equipment is subject to the same guidance as above with extra consideration given to sampling times and increased lags. For both cases, elimination of single-point failures is of primary concern. Operational State I is recommended for this requirement. Current military requirements, standards, specifications, handbooks, and drawings are recommended for consideration for lightning and EMI.

REQUIREMENT LESSONS LEARNED

The use of floating pints, inadequate EMI consideration, single point failures, lack of independent design evaluation, improper phasing, and accounting for lags has resulted in various problems from annoyance to loss of aircraft and life.

4.1.4.2 Electrical/electronic MFCS design. The electrical/electronic portion of the mechanical flight control system shall be tested by all the tests described in 4.1.4.1 and 4.1.4.1.1, integration tests, and *flight tests*.

VERIFICATION RATIONALE (4.1.4.2)

Vulnerability of the electrical/electronic MFCS design is important for survival. Therefore, this requirement needs to be tested under conditions sufficiently representative of the hazard to determine the adequacy of the design.

VERIFICATION GUIDANCE

Although the electrical/electronic portion of these systems may not be flight essential, flight safety is directly dependent upon the design of these systems. The flight safety aspects of the system distinguish it from other mission related avionics in the sense that it must be operative through all phases of flight. Depending on the amount of augmentation, the amount of testing may be reduced. For complex augmentation systems, all the testing should be performed to insure an adequate safe production design. Testing can usually be combined with other planned tests.

VERIFICATION LESSONS LEARNED

Inadequate testing usually leads to objectionable transients, uncommanded motions, and, in complex augmentation, departures from controlled flight/loss of aircraft. Changes to the system are expensive and limitations to the aircraft are usually imposed until the change is in the aircraft. Integration tests, where required, are vital to assure integrity of the flight control system.

3.1.5 AFCS design. AFCS design shall provide those functions and services which fulfill not only the stated needs for the air vehicle but also the needs for a satisfactory interface with the pilot operator. AFCS design shall be integrated with and complement the MFCS design such that switching between these systems produces no noticeable air vehicle responses. AFCS design shall have no adverse effect on MFCS operational integrity.

REQUIREMENT RATIONALE (3.1.5)

AFCS design must accommodate the needs of the air vehicle and the pilot operator. Design efficiency is improved by integration of the AFCS and MFCS. Switching between AFCS and MFCS should be included in the AFCS design. The design of that switching must not result in air vehicle responses which increase the pilot's workload or stress his skill or alertness.

REQUIREMENT GUIDANCE

Using agencies show undue reluctance in stating their needs for AFCS. It is therefore essential that this area become a subject of discussion with the user in order to fully develop that statement of need. Unless this is done, there is risk that the design will be either deficient or excessive with respect to operational need.

REQUIREMENT LESSONS LEARNED

4.1.5 AFCS design. AFCS design requirements shall be verified by __________ and __________.

VERIFICATION RATIONALE (4.1.5)

AFCS design requirements may be verified by analysis, inspection, piloted simulation, ground test, and/or flight test. The blanks allow flexibility in choosing the methods which are most feasible.

VERIFICATION GUIDANCE

Functions and services may be verified by analysis, inspection, simulation, ground test, and/or flight test; interfacing by analysis and flight test; integration and effects on MFCS by analysis, and switching effects by piloted simulation or flight test.

VERIFICATION LESSONS LEARNED

3.1.5.1 System management. The ___(a)___ management function shall be responsible for ensuring that the automatic flight control system does not permit failures to place the aircraft in an unrecoverable situation. Transients for normal engagement/disengagement and failures shall not exceed ___(b)___ and ___(c)___, respectively. Failures of the ___(d)___ management function shall ___(e)___. Appropriate ___(f)___ to the crew with ___(g)___ to re-engage ___(h)___ shall be provided.

REQUIREMENT RATIONALE (3.1.5.1)

As aircraft subsystems are integrated, a redundant means for monitoring the integrating subsystems to prevent departures, uncommanded maneuvers, and loss of aircraft is required.

REQUIREMENT GUIDANCE

The flight control system is recommended to perform the management function. Blank (a) should be filled in with "flight control system integrity." Blanks (b) and (c) should contain 0.1 g, ±3 deg/sec roll rate and 0.5 g, ±10 deg/sec roll rate, respectively (see 3.1.3.3). Blanks (d) and (e) should require the managing function to be limited to the previous failure transients not propagate to the normal (manual) control system, and remove, warn, or limit trajectory command controls provided to the flight control system. The following is appropriate wording for the blanks (d) through (h): (d) "integrity"; (e) "neither cause transients which exceed the specified levels, nor propagate into the manual (normal) flight control system. The failures shall cause the removal of the automatic trajectory guidance commands from the flight control system"; (f) "warnings"; (g) "an override capability"; (h) "any of the trajectory guidance command modes."

REQUIREMENT LESSONS LEARNED

Fleet aircraft have experienced a number of uncommanded maneuvers, departures, and losses when in an automatic mode. Data on any aircraft and corrective action, if any, may be obtained from the safety center at Norton AFB, California. A great percentage of the cases have unknown causes.

4.1.5.1 System management. This requirement shall be verified by ________________.

VERIFICATION RATIONALE (4.1.5.1)

The verification of this requirement is essential to the integrity and safety of the flight control system and the air vehicle. As the complexity level of integration of aircraft subsystems increases, the need for this requirement increases.

VERIFICATION GUIDANCE

Choose the most feasible methods for verification of the requirements from analyses, simulation, inspection, ground test, and flight test. The level of testing will have to be determined by the level of complexity. The best preliminary testing of this function can be achieved in the system integration laboratory tests. The final tests required should be aircraft ground tests and flight tests. Documentation must be complete in order to trace problems discovered. A major factor will be software and its validation/verification.

VERIFICATION LESSONS LEARNED

Poorly tested, integrated, single thread subsystems have led to several thousand incidents where the uncommanded motion of the aircraft has remained unsolved. As a minimum, system integration laboratory test and iron bird testing of the integrated system should be done. All parameters that the management function is using to assess the validity of the integrating subsystem must be inserted, and parameter failure combinations actually performed to verify the management functions performance. One must not forget the actual commands provided, their failure effects, and the failure monitoring system and what it provides. Testing of this function is as critical as testing and verifying the control laws/handling qualities.

3.1.5.2 *Mission flight controls.* Mission flight controls are the modes of the automatic flight control system that provide trajectory guidance or trajectory stabilization automatically without pilot input. Mission flight control guidance commands (e.g., flight director, bomb Nav, terrain following, integrated fire and flight controls, autopilot, etc.) shall be managed by ___(a)___. The guidance signals shall allow neither transients greater than specified in 3.1.5.1 nor erroneous commands. Interface requirements shall be ___(b)___. Failures of the mission flight control system shall not ___(c)___. Appropriate methods of interlocks for engagement/disengagement of mission flight controls shall be provided with ___(d)___ for flight safety.

REQUIREMENT RATIONALE (3.1.5.2)

Part of the automatic flight control system is the outer loop trajectory guidance commands. The automatic modes are generally used for certain phases of flight and/or phases of the mission. To assure safety of flight, these modes and systems must be properly integrated.

REQUIREMENT GUIDANCE

It is suggested that the blanks be filled in as follows:

a. Blank (a) - "the flight control system." This allows the most redundant air vehicle subsystem to be the integrating subsystem/system integrity manager.

b. Blank (b) - "determined by the flight control system implementation requirements." This is based on the selection of the FCS to fill the previous blank. To be consistent the FCS implementation requirements should be the major factor in the selection of the interfaces.

c. Blank (c) - "propagate or induce failures in the manual controls which produce transients in excess of those specified in 3.1.3.3."

Unless appropriate rationale is available to indicate otherwise, failure transients should be held equal to or less than those specified in 3.1.3.3.

d. Blank (d) - "override capability." Appropriate override capability is a necessity to assure that the FCS does not get locked into a mission flight control or other automatic command situation from which it cannot exit.

REQUIREMENT LESSONS LEARNED

Proper integration and interface with the flight control system will preclude uncommanded motions, departures, or unsafe aircraft conditions.

4.1.5.2 Mission flight controls. This requirement shall be verified by ______________________.

VERIFICATION RATIONALE (4.1.5.2)

This requirement must be verified to ensure the system performs as expected both during normal operation and failure conditions.

VERIFICATION GUIDANCE

Choose the most feasible methods for verification of the requirements from analyses, simulation, inspection, ground test, and flight test. The level and detail of the testing will have to be determined by the complexity of the integrations and by the number of integrations.

VERIFICATION LESSONS LEARNED

Poorly tested, integrated, single thread subsystems have led to several thousand incidents where the uncommanded motion of the aircraft has remained unsolved. As a minimum, system integration laboratory test and iron bird testing of the integrated system should be done. All parameters the management function is using to assess the validity of the integrating subsystem must be inserted and parameter failure combinations actually performed to verify the management functions performance. One must not forget the actual commands provided, their failure effects, and the failure monitoring system and what it provides. Testing of this function is as critical as the testing and verifying of the control laws/handling qualities.

3.1.6 Mission accomplishment reliability. The probability of mission failure per flight due to relevant materiel failures in the FCS shall not exceed ______________________.

REQUIREMENT RATIONALE (3.1.6)

Quantitative reliability requirements were developed because of the technological revolution which began early in the twentieth century. In turn, this revolution was significantly accelerated by WW II, the Korean War, and the stress on military preparedness since that time. The wars vividly emphasized the consequences of unreliability, military set-backs and high support costs. The need for reliability requirements was re-enforced by failures in rocket testing. This requirement ensures that the FCS design is responsive to a defined mission accomplishment reliability quantity. Overall system requirements may vary from program to program. Allocation may vary from subsystem to subsystem in the air vehicle. The numerical probability applicable to the FCS is thus a tailorable quantity. The blank forces the requirement to be tailored to each program.

REQUIREMENT GUIDANCE

In this requirement, materiel means assemblies, equipment, parts, etc., used in the FCS. Relevant failures are random or normal wearout failures occurring in service prior to the end of the specified service life when the materiel is properly maintained and operated within the design load and environmental limits. The reliability requirement in this paragraph is a function of mission elapse time. Each mission to which this requirement applies should be defined. When such a mission is not defined elsewhere, a representative mission to which this requirement applies shall be established and defined in the FCS specification. The probabilities specified in this requirement shall not exceed the limits obtained from the following:

a. Where overall aircraft mission accomplishment reliability is specified by the procurement activity, QM(FCS) < (1 - RM)AM(FCS).

b. Where overall aircraft mission accomplishment reliability is not specified,

QM(FCS) ≤ 1×10^{-3}.

where: QM(FCS) = Maximum acceptable mission unreliability due to relevant FCS materiel failures.

RM = Specified overall aircraft mission accomplishment reliability.

AM(FCS) = Mission accomplishment allocation factor for flight control.

These requirements are the same as those found in MIL-F-9490 where reliability and safety requirements for the materiel flight control system (hardware reliability without consideration of pilot errors) are specified on a probabilistic basis for the two operational levels most significant to the aircraft and its weapon system or other function; i.e., flight safety and mission accomplishment. A similar reliability requirement is included in MIL-F-8785.

A single analysis should satisfy both requirements, although different analysis results will apply to each requirement. Basic differences between the two reliability requirements are:

a. MIL-F-8785 takes a worst case approach by assuming a maximum mission length and that all failures occur at the critical point in the flight envelope (with regard to flying qualities). Limits are placed on encountering Level 2 and Level 3 flying qualities. No direct requirement is placed on mission accomplishment.

b. MIL-F-9490 places a requirement on mission accomplishment probability directly. The probability of experiencing a failure is to be considered with the associated probability of being in a flight condition where such a failure is critical.

Due to these basic differences in approach to specifying reliability, the numbered values cited by MIL-F-9490 are at least an order of magnitude more stringent than those found in MIL-F-8785 if one compares mission accomplishment to Level 2 and flight safety to Level 3. However, the intent of both specifications appears to be similar, and the implementations needed to satisfy the flying quality requirement should be similar to those needed to satisfy the flight controls requirements.

The flight safety analysis should consider all failure modes that threaten flight safety, whether single failures or combinations of failures, and whether extremely remote or not. Likewise the mission accomplishment reliability analysis should consider all failure modes that threaten mission accomplishment, whether single failures or combinations and whether extremely remote or not. It should not be inferred that the probability of aircraft loss due to relevant materiel failures in the FCS is identical to the probability of experiencing one or more failure modes that degrade performance below Operational State III. Many of the failure modes that degrade performance below Operational State III will be critical only under certain unfavorable combinations of variables such as:

- Visibility conditions
- Turbulence Levels
- Airspeed or Mach number
- Altitude
- Pilot warning and reaction time
- Gross weight
- Center of gravity location

Thus, if a given failure mode will result in aircraft loss only under combinations of the above variables which can reasonably be expected 10 percent of the time, a failure probability of 10^{-7} per mission will contribute an increment of only 10^{-8} to aircraft loss probability. The designer, however, must beware of over reliance on this philosophy. He still has the responsibility to strive to eliminate as many hazards as practicable, regardless of probability.

Where criticality varies with mission phase, it is generally necessary to construct a suitable mathematical model for each critical failure mode. In some cases it may be necessary to distinguish between failure modes that are hazardous chiefly at the time of occurrence because they introduce an element of surprise and require immediate pilot reaction, and failure modes that are hazardous chiefly because they leave the system in a degraded condition that makes unusual demands on the pilot's skill in some subsequent mission phase.

REQUIREMENT LESSONS LEARNED

To reduce the probability of materiel failures in the flight system, the reliability can be enhanced by careful attention to the following general guidelines:

a. Design the component elements such that they cannot be incorrectly installed, i.e., bell cranks cannot be installed backwards or in the wrong support and connectors cannot be switched.

b. Simplify adjustments. Keep adjustments and adjustment locations to a minimum. Make adjustments positive single action procedures rather than interactive processes. Carefully review the design, especially the nonredundant elements.

c. Identify the weak link. Perform a thorough failure modes and effects analysis on the design. Make certain that the weak link failure symptoms are recognizable, that the failure process is gradual, and that the weak links are installed where they can be easily inspected daily.

d. Isolate as much as possible flight control system elements from other system elements to avoid maintenance induced damage.

e. Assure that the installation areas of flight control elements are unsuitable for storage and transportation of other equipment or materials to prevent control system interference and degradation.

4.1.6 Mission accomplishment reliability. Mission accomplishment reliability shall be verified by ________________________.

VERIFICATION RATIONALE (4.1.6)

Mission accomplishment reliability is a factor in planning for fleet size and operational deployment of the air vehicle. Requirements must be verified if the operational planning is to be based on demonstrated capability. The blank provides the means for tailoring the verification process and use of the most feasible method or combination of methods.

VERIFICATION GUIDANCE

Analysis should be used for verification of the mission accomplishment reliability requirements. There are three stages of verification:

a. During design: to assure compliance with good reliability design practice.

b. During analysis: failure mode, effects and criticality analyses, fault tree analyses, and multiple failure analyses.

c. During aircraft fabrication and test: to assure that the FCS airframe interface provides the desirable reliability characteristics.

The analysis must take into account the failure modes of monitoring and self-test subsystems to whatever extent these modes can impact mission accomplishment reliability. Also to be accounted for are latent failure modes that might go undetected and so uncorrected, even with operative monitoring and test systems.

Probabilities of component failures should include allowances for normal wearout as well as random failure, unless it is assured the assembly involved will be subject to scheduled overhauls at intervals sufficiently short to preclude significant wearout. This consideration applies particularly to hydraulic seals, bearings, and other parts that are typically replaced in scheduled overhaul, and to cooling blowers for electronic equipment, particularly if they contain brushes.

While flight test activity should be closely monitored with a failure data collection, analysis, and corrective action process, the mission and flight safety reliability requirements are too high to be verified in this manner. Certainly any problem observed during the short flight test programs should be corrected, but the mission and flight safety reliability of the FCS can only be verified by thorough analysis using estimated, historical, development and test data, and special supplemental testing, where data is not available.

Strings of components which make up redundant flight control paths will often exhibit high failure rates even though the redundant configuration will satisfy the reliability requirement. These strings should be subjected to reliability development testing using combined environments. The models used to verify meeting the requirement should contain event rates traceable to the development test failure rates through the failure modes and effects analysis.

VERIFICATION LESSONS LEARNED

All failures observed during brief flight tests should have their cause identified, verified, and corrected. Critical, single elements shall be designed with sufficient margin of safety to preclude a flight safety failure. Any FCS element which has an installation that makes it susceptible to maintenance induced failures shall be designed to withstand maintenance induced stresses. FCS designs are revised frequently during flight test. It is important that the analyses and evaluations stay current with the design changes.

3.1.7 Quantitative flight safety. The probability of air vehicle loss per flight, defined as extremely remote, due to relevant materiel failures in the FCS shall not exceed ______________________.

REQUIREMENT RATIONALE (3.1.7)

Flight safety is of paramount importance in the design, development, manufacture, maintenance, and operation of air vehicles. This paragraph insures that every aspect of FCS acquisition is responsive to a defined, quantitative flight safety requirement. The quantitative value used for this requirement may vary between air vehicle designs and is thus a tailorable quantity. The blank provides the means for tailoring the requirement to the specific air vehicle.

REQUIREMENT GUIDANCE

The FCS is a flight-safety critical subsystem of the air vehicle. In aeronautical systems an air vehicle is usually one of the system's major items. During acquisition of an aeronautical system, many technical groups will be working the safety area. The FCS will receive much attention from each of these groups which will include those for system safety, reliability and maintainability, computer resources, and possibly others. The FCS quantitative flight safety requirements should reflect inputs from each of these technical groups.

To provide a means for determining compliance with the requirement, a numerical value must be established. In many cases, a flight safety requirement for the overall air vehicle or weapon system, R_S, will be specified and the maximum allowable probability of air vehicle loss due to materiel failures in the flight control system, Q_S (FCS), can be established based upon the proportion of the maximum allowable probability of air vehicle loss, due to all materiel failures, which is allocated to the flight control system.

A typical division or budgeting of the overall allowable loss rate uses a typical value of A_S (FCS) = 0.10. Assuming a specified flight safety requirement for the overall air vehicle, R_S = 0.9999, then:

> Q_S (FCS) = (1-0.9999) 0.10 = .00001 losses/flight or no more than one air vehicle loss in 100,000 flights due to materiel failures in the flight control system.

In budgeting the overall allowable loss rate into system allocations, the interdependency of systems must be recognized. For instance, powered flight control systems cannot be separated from the hydraulic and electrical power systems. Where dedicated power systems are used, reliability interfaces must be established and such failures included in the FCS flight safety evaluation.

The extremely remote probability of air vehicle loss per flight when caused by relevant materiel failures in the FCS should not exceed:

Q_S (FCS) = (1-Rs)A_S (FCS)

Where: Q_S (FCS) = Maximum acceptable air vehicle loss not due to relevant materiel failures in the FCS.

A_S (FCS) = Flight safety allocation factor for FCS

R_S = Overall air vehicle flight safety requirement as specified in the system requirements.

If overall air vehicle flight safety in terms of RS is not specified in any document, the numerical values in table XIII should be used. Extremely remote is defined as numerically equal to Q_S (FCS), the specified quantitative FCS flight safety loss rate.

TABLE XIII. Q_S (FSC).

Air Vehicle Description	MIL-F-8785 Aircraft Class	Maximum Aircraft Loss Rate Per Flight From FCS Failures
Small, light, medium weight Low to high maneuverability	I, II, IV	Q_S(FCS) - $1x10^{-7}$
Large, heavy weight Low to medium maneuverability	III	Q_S(FCS) - $1x10^{-7}$
Rotary wing	--	Q_S(FCS) - $25x10^{-7}$

Failure in power supplies and other interfacing subsystems that do not otherwise cause air vehicle loss shall be considered. A representative flight to which this requirement applies shall be defined (established) in a contract document.

REQUIREMENT LESSONS LEARNED

For Class III aircraft, field safety experience data for one B-type and two C-type aircraft were examined, and their major Class A accidents in the 1969-1980 time period were reported to occur at rates of 7.628/100,000, 0.249/100,000, and 1.625/100,000 flights, respectively. Of these accidents, 6.103 B-type aircraft were destroyed per 100,000 flights, and 1.870 of one C-type model were destroyed per 100,000 flights, and 0.578 of the other C-type model were destroyed per 100,000 flights. There were two aircraft lost due to materiel failures in the flight control system.

For Classes I, II, and IV aircraft, field safety experience for an F-type was examined, and its class A accidents in the same 10-year period were found to be 9.152/100,000 flights. Of these accidents, aircraft were lost at the rate of 8.210/100,000 flights. Of these, 0.471 and 0.265 were lost per 100,000 flights due to flight controls and hydraulic systems, respectively, for a combined rate of 0.736/100,000 flights which was rounded off and adopted as representative of this class aircraft.

The need for a higher degree of safety for Class III aircraft is self-evident inasmuch as there are often no provisions for evacuating personnel in flight and/or because they are designed to carry nuclear weapons or other stores or equipment which must be recovered if at all possible. At the same time, a higher degree of safety is usually easier to accomplish because such aircraft are generally larger and can more easily accommodate the additional redundancy required. In addition, the design penalties, weights, and cost for ejection seats or escape capsules, usually provided in Class IV aircraft, are not usually required for Class III aircraft.

For rotary-wing air vehicles, field safety experience data for these H-models was examined. A combined major Class A accident rate was found to be 8.773/100,000 flights. Of these accidents, air vehicles were destroyed at the rate of 6.334 per

100,000 flights, with losses due to flight control system and hydraulic power system occurring at rates of 1.402 and 0.00 per 100,000 flights, respectively. These combine for a rate of 1.402 per 100,000 flights.

In calculating the predicted Q_S (FCS) of any given flight control system, it must be recognized that it will not always be possible to determine (on the actual air vehicle) that all subsystems and components are failure-free and operable at the end of pre-flight check. In some designs, it may be feasible to check for complete freedom from failure only at longer maintenance intervals. In those cases it will be necessary to design to a higher reliability to compensate for the fact that daily takeoffs may be made with some components or subsystems already in a failure state.

The reliability of software is presumed to reach 100 percent whenever the system matures to the operational deployment stage. This is attained through trials and tests during development which will ensure that all of the programming errors (coding, logic, hardware interface, and system requirements deficiencies) are eliminated. To attain the near-perfect reliability necessary, requires a very comprehensive technical development procedure, management control, and configuration control.

Air Force publications are available which contain extensive formats of procedures and controls that aid the design, development, and verification of software programs in a manner that enhances the reliability of the software by minimizing the probability of software errors. These documents construct each aspect of the software development program in its most fundamental form and provide for detailed definition of software documentation and development, as well as the organizational structure, assignments, and responsibilities. The software documentation and development definition includes the nature of the schedule, critical milestones, design reviews, and the means of development.

The documentation and verification procedures require thorough documentation of program modification and problems and the implementation of family trees which simplify the methods for software changes by providing an understandable program flow chart. The establishment of preliminary and critical design reviews ensures that the design criteria are being properly implemented.

In literature pertaining to flight control system design and aircraft flight safety and reliability, the term "extremely remote" has been used in reference to the possibility that a system failure, in particular a flight control system failure, could lead to loss of aircraft. The ability of a flight control system to achieve an extremely low probability of catastrophic failure has a significant impact on the levels of redundancy required to meet the FCS quantitative flight safety requirements, i.e., that the probability of loss of aircraft per flight be extremely remote. The following discussion taken from a Charles Draper Laboratory report, R-1164, presents an interpretation and application of the term "extremely improbable."

> The commonly accepted numerical value for "extremely improbable" is 10^{-9}. There is considerable controversy on the role numerical analysis should play in demonstrating this requirement is met. In some situations, it appears that numerical analysis can have real significance and make a valid contribution. For example, numerical analysis can be used to compute the probability of system failure in a redundant system due to random-component failure. Random component failure rates are large enough to be demonstrated in practice. The mathematical techniques for combining these failure rates are also well established. Numerical analysis showing a system failure rate of 10^{-9} per hour can then be believable. The actual value of the number can be significant in this circumstance. A change on this number can change the number of redundant channels required.

4.1.7 Quantitative flight safety. The quantitative flight safety requirement shall be verified by ______________________.

VERIFICATION RATIONALE (4.1.7)

Verification of this requirement offers the opportunity for a critical review of each detail which was considered in establishing the specified numerical value. Verification gives some confidence that safety has been properly emphasized in the program. Analysis and simulation may be used to verify this requirement. The blank provides the means for tailoring the verification method.

VERIFICATION GUIDANCE

The FCS must be a safe subsystem. Safe is defined as freedom from those conditions that can cause injury or death to personnel, damage to or loss of equipment or property. To deliver a safe subsystem, every facet of the design, fabrication, installation and operation of the subsystem must be examined and quantified, including the human element. Analysis is the means by which all these factors can be evaluated.

The flight safety analysis should consider all failure modes that threaten flight safety, whether single failures or combinations of failures, and whether extremely remote or not. It should not be inferred that the probability of aircraft loss due to relevant material failures in the FCS is identical to the probability of experiencing one or more failure modes that degrade performance below Operational State III. Many of the failure modes that degrade performance below Operational State III will be critical only under certain unfavorable combinations of variables such as:

a. Visibility conditions

b. Turbulence levels

c. Airspeed or Mach number

d. Altitude

e. Pilot warning and reaction time

f. Gross weight

g. Center of gravity location

Thus if a given failure mode will result in aircraft loss only under combinations of the above variables which can reasonably be expected 10 percent of the time, a failure probability of 10^{-7} per mission will contribute an increment of only 10^{-8} to aircraft loss probability.

Where criticality varies with mission phase, it is generally necessary to construct a suitable mathematical model for each critical failure mode. In some cases it may be necessary to distinguish between failure modes that are hazardous chiefly at the time of occurrence because they introduce an element of surprise and require immediate pilot reaction, and failure modes that are hazardous chiefly because they leave the system in a degraded condition that makes unusual demands on the pilot's skill in some subsequent mission phase. The fact that a given function is not classed as essential does not necessarily assure that all the failure modes of the associated hardware are non-critical. Such hardware, even if its basic function is not essential, may have dangerous failure modes (hardover, oscillatory, divergent, etc.) that can threaten loss of aircraft. The flight safety analysis must include any such modes, in addition to the various failure modes of hardware performance essential or mission-phase-essential functions.

VERIFICATION LESSONS LEARNED

Not all predicted probability-of-failure statistics can be verified in the laboratory in an absolute sense. However, all verification methods that are reasonable and obtainable within cost restrictions should be considered to detect design errors, common mode errors, generic software errors, and a host of other safety related failures, which affect the reliability of the system.

Critical failure paths, handling qualities, equipment used, failure modes, known and predicted reliability, aircraft environments, and mission requirements should be used to analyze the probability of aircraft loss.

3.1.8 Survivability. The FCS shall be designed to withstand and operate in unnatural, induced, hostile environments, which would not otherwise cause loss of the air vehicle, without suffering abortive impairment of its ability to maintain at least Operational State ______.

REQUIREMENT RATIONALE (3.1.8)

The FCS provides a function critical to mission accomplishment and flight safety. The exposure of the air vehicle to unnatural, induced, hostile environment can vary with planned operational usage and unplanned air vehicle distresses. Thus, the degradation which can be tolerated in FCS operational state due to such an environment can be a tailorable attribute. The blank provides the means for tailoring the requirement to the specific air vehicle.

REQUIREMENT GUIDANCE

The air vehicle specification or the system specification should include requirements for withstanding and/or operating in some unnatural (induced) hostile environments. In addition, other unnatural (induced) hostile environments result from unplanned distresses within the air vehicle. In any event, these unnatural (induced) hostile environments should be defined as the first step in tailoring the requirement for survivability. Survivability requirements should also consider the following factors:

a. Aircraft performance requirements for range, payload, speed, etc., often dictate the need for such lightweight, compact airframes that it is difficult to provide the necessary redundancy and/ or spatial separation to provide the required survivability.

b. Supersonic speeds, size, or other factors introduce aerodynamic surface hinge moments of such magnitude that fully powered systems, without provisions for reversion to mechanical control, are required.

c. For some advanced aircraft, the performance requirements are so stringent that state-of-the-art advancements requiring several years of refinement are needed after introduction of the aircraft into service.

d. Principles of FCS design for survivability are often in conflict with principles for good maintenance because good maintenance design would locate redundant elements close together for ease of service, checkout, and replacement.

A design objective for survivability in the AFSC Design Handbook is to "design a system to withstand unnatural (induced) hostile environments without suffering abortive impairment of its ability to accomplish its designated mission." This objective equates to FCS Operational State III or better. However, the MIL-F-9490 survivability requirement was for a FCS Operational State IV or V, meaning continued safe flight is not possible. However, the lessons learned stated below implies that at least FCS Operational State III should be the stated requirement and that a short clarifying description of the expected capability should be added to preclude misinterpretation of the FCS operational state classifications as used in the SCOPE section of this document. Thus, the tailoring process requires not only a consideration of the above factors but also a careful evaluation of the needs of the user and the mechanization schemes which are feasible for fulfilling those needs.

REQUIREMENT LESSONS LEARNED

Discussions in the backup information for MIL-F-9490D, and other documents, simply state the real requirement for survivability is for a FCS which will allow continued safe flight to an established base suitable for recovery of the air vehicle. A reasonable probability of a mishap free landing is also expected. This has been the design goal in modifications made in operational fighters in the past even though most such modifications provided capability for only conditional/marginal safe continued flight and high risk for landing.

4.1.8 Survivability. The survivability requirement shall be verified by ________________.

VERIFICATION RATIONALE (4.1.8)

Verification of the survivability requirements document the existence of a FCS capability. That capability can then be the basis for training air crews and for planning operational exercises which use the air vehicle. Verification method must be tailored to the means used to provide the FCS function in the specific environment. The blank allows options in choosing verification method to fit the specific cases.

VERIFICATION GUIDANCE

Analysis, simulation, inspection, and ground and flight tests may be used in the verification of this requirement. The verification should cover the withstanding condition as well as the operating condition for the unnatural (induced) hostile environments. Verification should show that for each applicable environment the required FCS functional capability does exist, meaning that the capability produces FCS output which provides the flying qualities level corresponding to the FCS Operational State specified in the requirement.

VERIFICATION LESSONS LEARNED

3.1.8.1 All engines out control. The FCS and its power sources shall be designed such that loss or reduction of rotational speed of all power generating engines below power generation speed shall not result in less than FCS Operational State ______. Transients due to change in operational state shall conform to 3.1.3.3 requirements of this specification. Provisions shall be made for reversions to normal operation when sufficient engine generated power is restored.

REQUIREMENT RATIONALE (3.1.8.1)

The flight control function is critical to flight safety. Loss of engine generated power can often lead to a change or degradation in FCS functional capability. The intent of this requirement is to limit the degradation in FCS capability due to the loss of engine generated power such that the hazard level is minimized by retaining sufficient control capability during that period of air vehicle distress. The blank allows the limit imposed to be tailored to the requirement of the specific air vehicle.

REQUIREMENT GUIDANCE

When engine generated power is required for FCS operation, loss of such power may lead to a change in FCS Operational State and/or FCS functional capability. It is intended that a suitable minimum control capability be retained after such power loss, that this capability be provided for a period of time sufficient to restore engine rotational speed or arrive at ground level at glide speed, and that reversion to normal FCS Operational State occur when sufficient engine generated power is restored. The operational mission, class, number of power sources, crew evacuation provisions, aerodynamic characteristics and flying qualities of the air vehicle, and the user view of his air operations should be considered in choosing the FCS operational state classification to be specified for this requirement. FCS Operational State IV was the general requirement used in MIL-F-9490.

REQUIREMENT LESSONS LEARNED

In addition to the more common circumstances which result in reduction/loss of engine rotational speed, those associated with very high altitude operation and engine rotor lockup and seizure should be considered.

4.1.8.1 All engines out control. The all engines out control requirements shall be verified by ______________________________.

VERIFICATION RATIONALE (4.1.8.1)

Verification of the requirement documents the minimum capability which the FCS will provide under the all engines out flight condition. This capability would be the basis for training air crews and planning flight operations for the air vehicle. The blank is provided to allow the method of verification to be tailored for the specific air vehicle.

VERIFICATION GUIDANCE

Analysis and simulation should be used in the verification of this requirement. Ground test should be used to substantiate the analysis and simulation. Flight test should be used for verification at selected points in the flight envelope when the risk can be justified.

VERIFICATION LESSONS LEARNED

3.1.9 Invulnerability. Degradation in flight control system operation due to ______ shall be within the limits specified in the following subparagraphs.

REQUIREMENT RATIONALE (3.1.9)

Certain events and conditions can adversely affect the functional and operational integrity of the flight control system. This requirement enumerates those hazards and sets the stage for the limitation of their effects.

REQUIREMENT GUIDANCE

MIL-F-9490 contained requirements to provide invulnerability to the following: natural environments; adverse events of nature, specifically lightning strikes and static atmospheric electricity; induced environments; onboard failures of other (non FCS) systems and equipment; maintenance error; flight crew error; or enemy action. In addition to these hazards, a particular air vehicle mission/operating environment may require the inclusion of unique hazards which will require special protection for the FCS. If this is the case, the hazard should be included in the list and appropriate subparagraphs added to cover the specific invulnerability requirements.

REQUIREMENT LESSONS LEARNED

These invulnerability requirements are specified because experience has shown that failure to ensure that the flight control system be protected from such hazards resulted in loss of life and the air vehicle.

4.1.9 Invulnerability. Verification to invulnerability requirements shall be made by ________.

VERIFICATION RATIONALE (4.1.9)

A variety of methods could be used to verify that the invulnerability requirements have been met. Inspection, environmental tests, and FMEAs are several methods of verifying certain requirements have been met. Other requirements in the subparagraphs, such as direct encounter with enemy action, may only be verifiable by analysis.

VERIFICATION GUIDANCE

It is suggested that the flight control engineer tailor the subparagraphs prior to finishing 4.1.9. In this way all the methods of verification used for the various invulnerability requirements can be included in the introduction of 4.1.9.

VERIFICATION LESSONS LEARNED

3.1.9.1 Invulnerability to natural environments. The flight control system shall be designed to withstand the full range of natural environment extremes established for this air vehicle without permanent degradation of performance below FCS Operational State ___(a)___ or temporary degradation below FCS Operational State ___(b)___. Reductions below Operational State ___(a)___ 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 structure 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, ___(c)___, and build up of manufacturing tolerances.

Specifically, the FCS shall be able to withstand the following natural environmental conditions: ___________(d)___________.

REQUIREMENT RATIONALE (3.1.9.1)

This requirement is an attempt to preclude adverse effects of the natural environment on the FCS, which directly affect the mission performance and flight safety of the air vehicle.

REQUIREMENT GUIDANCE

This requirement encompasses an extremely broad range of adverse environmental possibilities. The requirement is tailorable so that unique operating environments and mission requirements may be taken into account.

Normally, the aircraft specification or contract will define the natural environments or global operational areas in which the aircraft must perform. AFSC DH 1-5 DN 1C1 described methods for establishing environmental criteria for specific systems and vehicles.

Blank (a) will normally be Operational State I and blank (b) Operational State II, the values previously required in MIL-F-9490.

Blank (c) may be used or omitted. It is included so that other environmental conditions might be considered, such as dust (fine sand), condensate, etc.

Blank (d) is provided so that specific conditions and limits may be enumerated. The following are suggestions of environmental conditions which should be considered.

a. Sudden changes in temperature of the surrounding atmosphere, and temperatures encountered during service life either in storage or under service conditions. In the past, DFCS have been designed to operate in the following temperatures: (The ambient temperature within the specified ranges may remain constant for long periods and may vary at a rate as high as 1.7°C per second).

(1) Operating - -54°C to +71°C

(2) Non-operating - -65°C to +71°C

b. Exposure to warm, highly humid atmosphere. The FCS shall withstand the effects of relative humidity up to 100 percent, including conditions wherein condensation takes place in or on the FCS. The FCS shall withstand the above conditions during continuous operation, intermittent operations, and exposure in a non-operating condition.

c. Varying altitude conditions from sea level to 75,000 ft, for both continuous operation and exposure in a non-operating condition. The altitude may remain constant for long periods of time and may vary at a rate as high as 1.0 psi per second.

d. Effects of fungi under conditions favorable for their development; namely high humidity, warm atmosphere, and presence of inorganic salts. The FCS shall also be designed to resist fungi.

e. Effects of a salt atmosphere in both operating and non-operating conditions.

f. Effects of a dry dust (fine sand) laden atmosphere in both operating and non-operating conditions.

REQUIREMENT LESSONS LEARNED

The environmental conditions previously listed have caused operational problems in the past.

4.1.9.1 Invulnerability to natural environments. Flight control invulnerability to natural requirements shall be demonstrated by __________.

VERIFICATION RATIONALE (4.1.9.1)

The invulnerability to the natural environment is usually verified by test and analysis.

VERIFICATION GUIDANCE

Qualification and safety-of-flight testing shall demonstrate equipment performance under environmental extremes. Analysis shall combine these test results and any other design data to demonstrate acceptable design. MIL-STD-810 can provide guidance for specific environmental test.

VERIFICATION LESSONS LEARNED

If tests outlined in MIL-STD-810 had been performed during procurement, environment related problems which developed in the field could have been identified and corrective action taken.

3.1.9.2 Invulnerability to lightning strikes and static atmospheric electricity. Flight control system shall maintain Operational State ___(a)___ capability or better when subjected to electric field and lightning discharges except that a temporary, recoverable, or extensive loss of performance to Operational State __(b)__ is allowable in the event of a direct lightning strike.

REQUIREMENT RATIONALE (3.1.9.2)

Special consideration must be given to lightning protection due to the susceptibility of electronic systems to this type of interference.

This requirement takes on added significance as more reliance is placed on electrical means of control in the flight control systems (such as essential use of fly-by-wire, stability augmentation, load alleviation, and/or ride smoothing features), and the possibility of lightning strikes cannot be ignored.

REQUIREMENT GUIDANCE

Values previously required: (a) II and (b) III.

The problem of providing adequate protection may be compounded by the use of new composite materials and advanced structural concepts in the airframe structure and aerodynamic surfaces which are being developed to save weight and improve life. The use of titanium, stainless steel, bonded structure, and boron/graphite structure introduces new problems in the electrodynamic design areas. Changes in electrical conductivity of the structure can have adverse electrical effects including loss of effectiveness of the structure as a shield against magnetic and electrostatic fields. The structure may no longer be available to provide suitable antenna ground planes, lightning protection, electrical power ground return, and shielding from induced voltages into critical avionics, flight control systems and interior aircraft components. Electrical compatibility may require additional ground return wire, shielding, conductive coatings, and special joining techniques novel to composite and advance structure. New materials and structural concepts should be thoroughly evaluated to determine the most effective method of providing electrical compatibility with a minimum weight penalty.

REQUIREMENT LESSONS LEARNED

Previous ground, on-air vehicle testing of a fly-by-wire air vehicle demonstrated the need for two design efforts to provide adequate lightning strike protection:

a. Keep lightning strike current flowing through the skin.

b. Protect circuitry and components from induced voltage damage.

Potential ways to harden the air vehicle to adequately resist lightning attachment are discussed below.

a. Protection should be provided from lightning-induced transients on electronic flight control interconnect wiring. Large currents resulting from a lightning strike flowing through the aircraft skin can induce significant voltages on adjacent interconnect wiring. To minimize these transient effects, balanced circuits using twisted, shielded wires should be used where possible and the wiring should be physically separated from likely lightning current paths. Redundant channels should be physically separated from each other.

b. Certain air data and aircraft parameters are required as inputs for electrical flight control systems. This information is obtained from probes mounted externally on the aircraft. These probes can be damaged by lightning strikes. To prevent damage, lightning diverters can be used to protect the electrical circuits.

c. Integrity of the electrical power system is required for electrical flight control system operation. Points of entry into the electrical system such as external light wiring and pitot tube heater wiring should be assessed for vulnerability. The wiring can be protected by lightning arrestors located near the point of lightning current entry, if required. Power generation and distribution should also be examined for potential susceptibility to transients. If such susceptibility exists, arrestors should be installed.

Statistics on lightning strikes on various aircraft types indicate substantial differences between the number of lightning strikes reported per flight hour for various aircraft types. These statistics indicate that some aircraft configurations are inherently less vulnerable to lightning strikes or the aircraft configuration is less prone to initiate lightning strikes. Results of future studies of this phenomenon may identify aircraft design features which reduce vulnerability to lightning.

4.1.9.2 Invulnerability to lightning strikes and static atmospheric electricity. Flight control system invulnerability to lightning strike and static atmospheric electricity shall be verified by demonstrating the ability to maintain at least the required operational state capability or better when subjected to ____________________.

VERIFICATION RATIONALE (4.1.9.2)

A current level or specified test is needed to demonstrate the FCS invulnerability to lightning and electric field.

VERIFICATION GUIDANCE

The verification sentence should be completed by specifying a specific current level or by referencing another source. To be consistent with MIL-F-9490 the sentence should end this way: "electric field and lightning discharges as specified in MIL-B-5087 and in AFSC DH 1-5."

Both individual components and the complete system may be tested.

VERIFICATION LESSONS LEARNED

A very successful method to achieve hardness to the indirect effects of lightning was achieved during the development of a fly-by-wire flight control system. The method consisted of testing at an aircraft level to achieve a design criteria of an induced waveform. The design criteria waveform was then used to test each flight control line replacement unit (LRU) and determine what hardening technique was plausible.

The aircraft level test consisted of applying a lightening pulse (at a lower level than real lightning) to attachment points on the aircraft and measuring the induced voltage and current at LRU interfaces. These induced waveforms were then extrapolated to a level of real lightning. The design criteria was developed by adding a GDL safety margin to the extrapolated results.

The design criteria waveform was then used to test each interface device or component of each flight control LRU. The waveform was applied to each input and each output of the device under test for both negative and positive polarity. If the device operated properly after the test, it was deemed lightning hard. If the device failed, a fix was inserted (i.e., parallel resistor or bypass capacitor) and the test repeated until a nonfailed test was achieved.

This aircraft has been struck by lightning many times since production and no flight control failures have been reputed.

3.1.9.3 Invulnerability to induced environments. Flight control systems 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 radiation including electromagnetic pulse, projected in missions for the air vehicle, without permanent degradation or loss of capability to maintain FCS Operational State __(a)__. These induced environments within structural and crew survival limits shall not result in temporary degradation during the exposure to the environment below FCS Operational State __(b)__ capability. Specifically, but not exclusively, the FCS shall be designed to withstand the following: ________ ________(c)________.

REQUIREMENT RATIONALE (3.1.9.3)

Induced environments depend highly upon the design of the particular air vehicle, engines and subsystems. Operation under normal and failure conditions must also be considered. Induced vibrations from aerodynamic and engine acoustic energy and from mechanical vibrations of the engine and other equipment, if at sufficiently severe levels, can induce malfunctions and fatigue failures in flight control components.

REQUIREMENT GUIDANCE

MIL-F-9490 required the FCS to maintain at least Operational State II (blank (a)) with allowable temporary degradation to Operational State IV (blank (b)), however recent procurements have required temporary degradation to Operational State III. Blank (c) is included to allow the flight control engineer the capability to enumerate specific conditions. The following is an example of requirements called out in previous procurements. The FCS shall be designed to withstand:

a. The effects of fluctuating pressure fields associated with turbulent aerodynamic flow and acoustic noise that are characteristic of high performance aircraft.

b. Expected dynamic vibrational stresses and to insure that the performance degradations or malfunctions will not be produced by the service vibration environment. The contractor shall prepare a document for procuring activity approval which specifies induced environments for different zones throughout the air vehicle.

c. Expected dynamic shock stresses produced by the service shock environment anticipated in handling, transportation, and service use. The FCS LRUs shall meet specification requirements after being subjected to 18 impact shocks of 15 g consisting of three shocks in opposite directions along each of three mutually perpendicular axes. Each shock having a time duration of 11 ±1 milliseconds. The "g" value shall be within 10 percent when measured with a 0.2 to 250 Hz filter and maximum "g" shall occur at approximately 5.5 milliseconds.

MIL-F-9490 stated that the structural requirements of MIL-A-8892 and MIL-A-8893 and the applicable EMI requirements of MIL-E-6051 and MIL-STD-461 must be fulfilled. These requirements may or may not be applicable to the air vehicle under consideration but should be investigated.

AFSC DH 1-5, DN-1B1, Natural and Induced Environments, and DN-1C1 Environmental Requirements, give considerable background information.

REQUIREMENT LESSONS LEARNED

With the advent of high speed digital microprocessors in flight control system, standard EMI design techniques no longer prevent spurious emissions from interfering with other on board electronics and RF equipment. The only method known to date to prevent these emissions are filter pins at the connector interface. The problem lies in the fact that these emissions may not be known until after the design of the hardware is complete and an aircraft EMC test is performed. The design of filter pins should be started along with the other hardware and thus prevent the EMI problem from occurring.

An aircraft used fiber optic cables as a Cross Channel Data Link between computers for redundancy management. This was done to isolate the channels from EMI, short circuits, etc. However, the added susceptibility to EMI of the devices used to convert electrical signals to light and back to electrical at the other end negated the benefits of the fiber optic link.

4.1.9.3 Invulnerability to induced environments. Flight control system invulnerability to induced environment requirements shall be verified by ____________________.

VERIFICATION RATIONALE (4.1.9.3)

Environmental tests as part of the equipment formal qualification testing and/or approval based on "similarity" justification are means of demonstrating invulnerability to the induced environment.

VERIFICATION GUIDANCE

MIL-STD-810 provides methods of testing for most natural and induced environments. EMI and nuclear radiation are not covered in MIL-STD-810. EMI testing is covered in MIL-STD-462. In addition, the FCS should be covered under the EMI and nuclear radiation requirements/tests required for the total air vehicle.

To tailor the verification one might cite compliance with MIL-STD-810 testing or, and preferably, the engineer should choose the applicable paragraphs from MIL-STD-810 and include them in this specification.

VERIFICATION LESSONS LEARNED

Recent studies have shown that cycling random vibration and temperature testing rather than performing one, then the other, may be more useful in finding failures in electronic components.

3.1.9.4 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. In addition, the FCS design shall comply with the following:

a. Essential and flight phase essential flight control systems shall retain FCS capability of Operational State __(a)__ or better after sustaining the following failures: ________(b)______.

b. Flight control systems, including the associated structure hydraulic, pneumatic and electrical systems shall be designed so that the probability of losing the capability of maintaining FCS operation to no less than Operational State __(c)__ as a result of an engine or other rotor burst is extremely remote.

c. ______________(d)______________

REQUIREMENT RATIONALE (3.1.9.4)

The requirement is included to ensure that hazards due to failure of other systems and equipment are recognized and that adequate measures are taken in the design to ensure the flight control system is protected.

REQUIREMENT GUIDANCE

Most air vehicles can survive engine failures, including rotor burst, landing gear tire burst, and failure of other systems such as radio-radar transmitter transmission line failures. However, with the use of full-powered flight control system, additional care must be taken to ensure that the air vehicle will not be lost due to failures it could otherwise survive. Protection from the failure of high-energy system components, such as pneumatic cylinders, hydraulic accumulators, and high-force spring cartridges, must be given special attention.

Electrical flight controls are more vulnerable than conventional flight controls to certain hazards; special emphasis should be placed on the design and tests of EFCS equipment. Examples are:

a. Local fires must not be allowed to propagate through areas of more than one channel of AFCS computation or sensor capability. Both separation and measures to prevent flame propagation are needed.

b. Modest temperature increases which would not affect a conventional flight control system can cause electronic components to overheat and malfunction; accordingly, cooling air supply failures must either not affect more than one channel of an AFCS computation or sensor capability, or the flight control system equipment must be able to withstand the loss of cooling air without degradation of performance for a minimum of two hours.

MIL-F-9490 required the FCS retain Operational State III (blank (a)) or better after the following failures (blank (b)):

a. Failure of the critical engine in a two-engine air vehicle.

b. Failure of the two most critical engines in an air vehicle with three or more propulsive engines.

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

In addition MIL-F-9490 required that the probability of transport aircraft losing Operational State IV capability due to engine or other rotor burst be extremely remote. Aircraft in all other classes (i.e., those with crew ejection capability) are allowed to degrade to Operational State V. This should be considered for blank (c).

Blank (d) is provided to allow the FCS engineer to add other requirements which may be unique to the particular configuration under consideration. One area of concern in advanced air vehicle design may be computation of command inputs of the FCS, such as fire control commands which actually steer the air vehicle rather than moving a steering pipper on a display.

REQUIREMENT LESSONS LEARNED

4.1.9.4 Invulnerability to onboard failures of other systems and equipment. Compliance with the invulnerability requirements to onboard failure of other systems and equipment shall be demonstrated by ____________.

VERIFICATION RATIONALE (4.1.9.4)

Analysis, test, and simulation can be used to demonstrate compliance. Analyses will be the most practical method of verifying most failure effects.

VERIFICATION GUIDANCE

FCS engineers should specify appropriate verification for each failure listed in 3.1.9.4. In the past, procuring activities usually requested a Vulnerability Analysis Plan (VAP) as part of the FCS Development Plan. The VAP defines the analytical procedures to be used for the vulnerability analyses. System Safety Program Plan, if required by the procuring activity, and hazard analysis will normally demonstrate, by analysis, that the requirement is satisfied.

VERIFICATION LESSONS LEARNED

3.1.9.5 Invulnerability to maintenance error. Flight control systems 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 flight control system on the aircraft, except during initial buildup, major overhaul, software modification, or rigging during major maintenance activities, shall be minimized. All line replaceable units (LRUs) shall be designed to permit making internal adjustments only on the bench. The system shall require only a minimum of rerigging following replacement of LRUs. All control linkages and other flight control mechanisms shall be designed to resist jamming from inadvertent entry of maintenance tools or other materiel. In addition ____________________.

REQUIREMENT RATIONALE (3.1.9.5)

This requirement is especially important with the increasing complexity of flight control systems and components which tend to increase the potential for serious maladjustment through maintenance error. In general, the first cost due to increased engineering effort and tooling will be somewhat higher than normal to meet this requirement, but the overall costs of maintenance and the probability of failure or loss of performance will be much lower.

REQUIREMENT GUIDANCE

The requirement as stated is the same as was required in MIL-F-9490. It is not required that the blank be filled. The requirement as written will be sufficient in most cases. The blank is included to allow the FCS engineer to call for specific design assurance related to maintenance. Suggestions for inclusion in this requirement are:

a. Irreversible parts shall be used for critical application where reverse assembly or installation would result in change in function or possible interference or jamming.

b. There shall be physical differences in adjacent electrical/hydraulic connections so that interchanging is not possible.

c. Full protection for critical elements which are subject to damage during entry, exits, handling, or other contact incident to maintenance activity, shall be provided.

d. Technical orders and manuals shall contain adequate warning and caution notes when dimensions or procedures are critical or where malpractice can result in damage to equipment or injury to personnel.

REQUIREMENT LESSONS LEARNED

4.1.9.5 Invulnerability to maintenance error. Flight control system invulnerability to maintenance error requirements shall be verified by __________.

VERIFICATION RATIONALE (4.1.9.5)

Hazard analysis should identify areas of potential maintenance error. Inspection of engineering drawings will verify design. Quality assurance program during production and installation should provide verification that the 'as purchased' air vehicles have the designed features incorporated.

VERIFICATION GUIDANCE

It is suggested that the hazard analyses conducted under MIL-STD-882 will identify areas of deficiencies where inspection should be concentrated. Lessons Learned can also prove valuable in determining what should be inspected. Of course it is up to the procuring FCS engineer to make sure that areas of particular concern are addressed.

VERIFICATION LESSONS LEARNED

It is important to inspect design clearances, fasteners, etc., during production to assure that the air vehicle construction has not been modified "on-the-line."

3.1.9.5.1 Invulnerability to software maintenance error. The following provisions shall be implemented for systems using digital computations to prohibit the implementation of the incorrect version of software: __________________________.

REQUIREMENT RATIONALE (3.1.9.5.1)

For systems which utilize digital computation, particular care must be given to software maintenance because of its complexity and importance for proper FCS operation. Means for identification and procedures for implementation need to be mandatory to provide invulnerability to software error.

REQUIREMENT GUIDANCE

Production digital flight control elements should be Criterion II firmware per the AFLC Firmware Policy, Feb 85. Criterion II firmware is that which the government has legal or engineering capability to reproduce/alter/reprogram at the depot or a contractor's facility. For comparison, Criterion I firmware cannot be altered by the government and Criterion III firmware can be altered at the user level. The AFLC Firmware Policy outlines procedures for the control of the software resident is each integrated circuit and provisions for the identification of loaded configurations are contained in this policy.

It is suggested that the flight control engineer become familiar with the AFLC Firmware Policy and the desires/requirements of the program office so that the control system requirements do not conflict with higher level requirements.

In flight test programs, including pre-production programs, it may be desirable to use erasable, programmable, read only memory (EPROM) so that it can be changed easily. This can create a problem in identifying and tracking the software version programmed into a particular computer. In this case, the first step of the preflight test should identify the version which is programmed in the computer.

REQUIREMENT LESSONS LEARNED

The careless reprogramming of the flight computer was the cause of a commercial jet crash in November 1979. The computerized flight route, which was fed into the aircraft's automatic pilot, had been altered shortly before takeoff because of an error in the original data. The pilot, however, was not informed of the change, which sent the aircraft on a direct path over a volcano. When the pilot obtained clearance to descend below the clouds so the passengers could get a better view, he had no idea he was flying straight into the mountain. Although this incident pertains to the reprogramming of a flight (mission) computer, it illustrates the reliance flight crews have on proper programming. The use of firmware is strongly suggested to avoid similar incidents in the flight control system.

4.1.9.5.1 Invulnerability to software maintenance error. Flight control system invulnerability to software maintenance error requirements shall be verified by ____________________________.

VERIFICATION RATIONALE (4.1.9.5.1)

Provisions for the establishment of procedures to prohibit the implementation of unintended versions of software in the FCS are necessary to insure flight safety.

VERIFICATION GUIDANCE

The establishment of proper procedures and, if EPROMs are used, inspection of code are methods of assuring the correct installation of software. The operational flight program (OFP) is not intended to be modified in the field like mission computer software. Therefore, installation of the OFP will be a firmware installation, taking place only in the shop where the LRU has been removed for maintenance. Care must be taken and proper procedures established to assure the correct part has been installed. AFLC Firmware Policy should be reviewed prior to completing the verification paragraph.

VERIFICATION LESSONS LEARNED

3.1.9.6 Invulnerability to pilot and flight crew *inaction and error*. Flight control systems shall be designed to minimize the possibility of any flight crew member controlling or adjusting system equipment to a condition or state which could degrade FCS operation. Included shall be: ___________.

REQUIREMENT RATIONALE (3.1.9.6)

With increasing crew workload and system complexity, measures must be taken to design a crew station and controls which are not easily improperly operated.

REQUIREMENT GUIDANCE

MIL-F-9490 required the following:

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. Protection against inflight engagement of control surface locks.

c. Pilot reaction to failure. Flight control systems 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 controls for any failure in a redundant or monitored flight control system which could result in an unsafe condition if the pilot were not aware of the failure.

In addition AFFDL-TR-74-116 included these recommendations based on lessons learned.

a. Require that a loss-of-control prevention device be incorporated in aircraft that is not highly resistant to departure from controlled flight.

b. Ensure that the flight test program adequately identifies near stall/stall/post-stall characteristics.

c. Require positive stick centering as outlined in MIL-F-8785 after modification as well as during initial design.

d. Require that cockpit instrument illumination level compatibility be demonstrated in a simulator or by other means.

REQUIREMENT LESSONS LEARNED

When selecting switches, the invulnerability to flight crew error requirements must be considered, such as recognizing that the selected positions of pushbutton switches are not apparent.

One example where interlocks may be needed to prevent hazardous operation involves variable geometry controls. Redundant interlocks should be used to prevent inadvertent actuation of control systems that would produce structural damage, if actuated. For instance, flap actuation with wings swept must be prevented.

4.1.9.6 Invulnerability to pilot and crew inaction and error. Compliance with the invulnerability to pilot and flight crew inaction and error requirements shall be demonstrated by ___________.

VERIFICATION RATIONALE (4.1.9.6)

Consideration of system invulnerability to pilot and crew inaction and error should begin early in the design review stages. The final verification will, however, require pilot interaction.

VERIFICATION GUIDANCE

Compliance with this requirement will begin with analyses documented in such CDRLs as the Hazard Analysis Report, Vulnerability Analysis Plan and System Safety Plan, which identify areas of concern and recommend actions. Continued analysis and simulation should verify the acceptability and safety of cockpit controls, interlocks, and warnings. Acceptability of design protection techniques should be demonstrated during the flight test program and, if possible, piloted simulation.

VERIFICATION LESSONS LEARNED

3.1.9.7 Invulnerability to enemy action. Essential and flight phase essential FCS on combat aircraft, including associated structure and power supplies, shall not be degraded below Operational State ________ because of damages due to ____________________.

REQUIREMENT RATIONALE (3.1.9.7)

This requirement establishes the minimum performance required by an air vehicle damaged by direct threat encounter. The intent of the requirement is to enhance the survival of air vehicle and crew.

REQUIREMENT GUIDANCE

MIL-F-9490 required that degradation below Operational State III would not occur due to one direct encounter with a threat defined by the procuring activity. If a threat environment has not been specifically defined, it should be one implied by the intended mission(s) of the system. Adequate redundancy, alternate controls, separation, shrouding, and/or armor protection should be used to prevent degradation below the specified performance level.

REQUIREMENT LESSONS LEARNED

FCS damage caused unacceptably high losses of aircraft in combat during the 1960s. This experience has led to the inclusion of this requirement.

4.1.9.7 Invulnerability to enemy action. Flight control system invulnerability to enemy action shall be verified by ____________________.

VERIFICATION RATIONALE (4.1.9.7)

The analysis of critical flight control functions vulnerability to specified threat damage can verify the resulting operational state of the air vehicle.

VERIFICATION GUIDANCE

Invulnerability to enemy action should be part of the preliminary design considerations since this requirement will dictate the minimum protection required for the air vehicle. The methods of protection should be reviewed for appropriateness early in the design and through continuing survivability/vulnerability analyses.

VERIFICATION LESSONS LEARNED

3.1.9.8 Invulnerability to bird strikes. Flight control system shall maintain Operational State ___ capability or better when subjected to one or more bird strikes on a leading edge of the aircraft. This shall be accomplished by: ____________________
____________________.

REQUIREMENT RATIONALE (3.1.9.8)

Bird strikes are inevitable and measures must be taken to insure flight controls are not damaged or severed in such an accident that may lead to aircraft loss.

REQUIREMENT GUIDANCE

Protection against aircraft losses due to one or more bird strikes can be accomplished by avoiding the grouping of critical lines, such as hydraulic, fuel, and electrical in any one place. Adequate separation, shrouding, and/or armor protection should be used to prevent degradation below the specified performance level.

REQUIREMENT LESSONS LEARNED

FCS damage due to bird strikes has caused aircraft losses. This experience has led to the inclusion of this requirement.

4.1.9.8 Invulnerability to bird strike. Flight control system invulnerability to bird strikes shall be verified by ______________________.

VERIFICATION RATIONALE (4.1.9.8)

See verification rationale for 4.1.9.7, Invulnerability to enemy action.

VERIFICATION GUIDANCE

See verification guidance for 4.1.9.7, Invulnerability to enemy action. Strength strike tests, real or simulated, and analysis of vulnerable areas is needed for verification.

VERIFICATION LESSONS LEARNED

Improper verification can lead to loss of aircraft at some point. In 1987, a B-1B crashed in La Junta, Colorado due to a bird strike, where the nacelle and fuselage came together. While this strike did not immediately affect the FCS, it did strike some fuel lines which caused a fire. This accident prompted thought as to the probability of the same incident impacting flight controls directly. Proper verification must be done in order to lower the probability of future losses.

3.1.10 Maintenance provisions. Design and installation of the FCS shall permit trained FCS maintenance personnel to safely and easily perform required maintenance under all anticipated environmental conditions. Means shall be provided to facilitate the accomplishment of all required maintenance functions including: ________ ______________________.

REQUIREMENT RATIONALE (3.1.10)

Successful operation of an air vehicle and its flight control system is highly dependent upon the ability of the assigned personnel to effectively maintain it in the fully operational condition. The blank allows emphasis to be placed on some of the maintenance functions which are to receive special attention, thus tailoring the requirement to the needs of the specific air vehicle.

REQUIREMENT GUIDANCE

Adequate redundancy, alternate controls, separation, shrouding, and/or armor protection should be used to prevent degradation below the specified performance level. The features which allow effective maintenance must be designed into the system to provide service personnel the means for safe and speedy detection, location, and correction of faults, and for the accessibility necessary for inspection, preventative and corrective maintenance, and parts removal and replacement. This requirement should consider operational checkouts, system malfunction detection, fault isolation to the replaceable unit level, replaceable unit removal and replacement, inspection, servicing, and testing. Structured acquisition programs have maintainability specialists assigned to insure that the maintainability area is fully managed and controlled throughout the acquisition cycle. The specialists, in an air vehicle program, establish maintenance budgets for down time, manhour expenditures, etc. down to at least the major subsystem levels of the FCS. Those budgets are based on the overall air vehicle maintainability requirements. The requirements established under this section of the FCS specification should consider this interface, and the tailored requirements for FCS should support, and conform to the overall maintenance concept which has been established for the air vehicle.

REQUIREMENT LESSONS LEARNED

To facilitate the maintenance function it has been learned that:

a. Designing for built-in-test requirements must be concurrent with the FCS design.

b. A remove and replace requirement affects the installation design and design of the accesses.

c. All built-in-test readouts should be readable without removal of the element or assembly.

d. Designs which permit adjustment of control elements, should provide such adjustment at an easily accessible location.

e. The inspection process should be a hands-off process whenever possible.

f. The concept of throw-away modules is not well accepted in the field because the cost appears to be excessively high.

g. The work involved in replacing a module often exceeds that required to replace a component.

h. Isolation of failure to a component often takes only slightly longer than to a module.

i. Large stock levels of modules are required because ordering modules often requires weeks for delivery to be made; however, normal delivery of electronic piece-parts takes only a few days.

j. Throw-away concept is often not used for all avionics; hence, shops for component replacement capability must be established and maintained with the organization.

4.1.10 Maintenance provisions. The maintenance provision requirements shall be verified by ______________________________.

VERIFICATION RATIONALE (4.1.10)

Verification of these requirements documents the facility with which trained personnel perform designated maintenance on the installed FCS under selected environmental conditions. Analysis and ground test may be used for this verification. The blank provides the means for tailoring the method to the specific air vehicle.

VERIFICATION GUIDANCE

The verification process should demonstrate that Air Force technicians, trained in FCS maintenance, can safely and easily perform all required maintenance on the FCS. This should be demonstrated on an air vehicle for the full range of maintenance actions under a normal ambient type environment. Selected maintenance actions should also be demonstrated under adverse environment and conditions such as high heat and humidity, and very low temperatures when winter clothing is worn. In most major system acquisitions, a group of exercises under the Development, Test and Evaluation (DT&E) program usually include a close look at the maintainability of the air vehicle and its subsystems. These efforts should be used as part of the verification for this requirement.

VERIFICATION LESSONS LEARNED

Maintainability analyses should be part of the design process since designs which fail to meet the maintainability requirements are seldom brought into compliance due to the high cost involved in a redesign.

3.1.10.1 Operational checkout provisions. The design and installation of the FCS shall provide for ground operation as required to verify FCS functional performance, airworthiness, and freedom from failures. Operation of the main propulsion engines shall not be required for this checkout. Power for the checkout shall be supplied by ______ ______________________________.

REQUIREMENT RATIONALE (3.1.10.1)

Flight safety, mission, and maintenance requirements establish the need for provisions to checkout the FCS while the air vehicle is on the ground. Ground safety, environmental standards and operating efficiency establish the need for not using the main propulsion engines for this checkout. The blank allows the means for supplying power for the checkout to be tailored to the specific air vehicle, and the operational and maintenance support concepts developed for its use.

REQUIREMENT GUIDANCE

Ground power carts and on-board power are two options for supplying power for these checkouts. The full range of FCS performance may not be necessary during the checkout process. An in-depth look at the parameters to be verified during checkout should be made to determine what actual FCS performance will be required during this process. Consideration should be given to the possibility that engine driven hydraulic pumps, generators, and other interfacing air vehicle circuitry and elements are not easily checked without operating the main propulsion engines.

REQUIREMENT LESSONS LEARNED

4.1.10.1 **Operational checkout provisions.** The operational checkout provisions shall be verified by ______________________.

VERIFICATION RATIONALE (4.1.10.1)

The ground checkout provisions are one means by which the inflight hazard level due to failures, anomalies, lack of capacity in the FCS can be controlled. The verification process documents the capability which exists in the ground checkout provisions and thus allows evaluation of its role in determining airworthiness, flight safety, and mission capability.

VERIFICATION GUIDANCE

Analysis and ground test should be used for verification. Analysis should be used to determine those parameters and variables which should be used on the ground to check out the FCS. Ground tests should then be used to show that provisions have been made in the design and installation of the FCS to perform checkout using the identified parameters and variables. Testing should show that no anomaly or failure which degrades FCS performance, airworthiness, or mission capability goes undetected during the checkout process.

VERIFICATION LESSONS LEARNED

3.1.10.2 **Malfunction detection and fault location provisions.** Means of having a high probability for detecting malfunctions and failures, and monitoring critical performance conditions as required to locate faults to the replaceable unit, shall be provided for ______________________.

REQUIREMENT RATIONALE (3.1.10.2)

It is essential that the maintainability of the FCS be enhanced whenever possible for support mission and safety requirements. Location of faults in a complex FCS can be very time consuming, involved, and often a self-defeating process unless provisions are made in the design itself for detecting and locating faults down to a replaceable unit level. The blank allows identification of those FCS replaceable units or classes of elements which will be required to have these provisions, thus tailoring the requirement to the specific air vehicle.

REQUIREMENT GUIDANCE

Electrical and electronic FCS elements which provide essential and flight phase essential functions should incorporate on board means to detect and locate faults to the replaceable unit level. In FCSs which use augmentation systems, AFCS, control-by-wire implementation, integrated servoactuators etc., the basic on-board equipment should incorporate the means to detect and locate faults to the replaceable unit level. These means may utilize cockpit instrumentation, built-in-test, or any other maintenance provisions for the air vehicle. For the mechanical and fluid power elements of the FCS, portable test equipment may be used when it conforms to the maintenance support and operational concept for the air vehicle. The provisions for malfunction detection and fault location are not necessarily required during flight. The probability of locating the failure or malfunction to the correct replaceable unit may also be one of the items addressed while tailoring these requirements.

REQUIREMENT LESSONS LEARNED

4.1.10.2 **Malfunction detection and fault location provisions.** Malfunction detection and fault location provisions shall be verified by __________.

VERIFICATION RATIONALE (4.1.10.2)

The capability for malfunction detection and fault location must be verified and documented if those provisions are to be utilized in training and planning for maintenance of the air vehicle in the field. The blank allows the means of verification to be tailored on the basis of the requirements which have been imposed.

VERIFICATION GUIDANCE

A structured program should be devised such that the verification process for these requirements begins early in the development program and continues through the Development, Test, and Evaluation phase. Verification should be accomplished by analysis and ground test. Much of the analysis is incident to reliability, safety, and redundancy management requirements. In addition, testing such as qualification, integration, reliability development, and maintainability demonstration can be useful in the verification process. Failure modes effects and criticality analysis, hazard analysis, redundancy management studies should be applied where possible. Ground tests may be used where failures may be injected or faults introduced to evaluate the detection and location capability which has been provided.

VERIFICATION LESSONS LEARNED

3.1.10.2.1 Malfunction indication. Indications which show that a malfunction has been detected and where the fault is located shall be provided by ______________________.

REQUIREMENT RATIONALE (3.1.10.2.1)

The manner of indicating that a malfunction has been detected, and the location of the fault, is an important consideration in designing for maintainability. The cockpit is the center for control and operation of the air vehicle subsystems and the use of instrumentation at that location for indicating malfunction and fault location can be convenient to the maintenance crew. The blank provides the means for tailoring the requirement to the specific air vehicle.

REQUIREMENT GUIDANCE

Where acceptable procedures and readily understandable condition indications can be provided, either alone or in coordination with built-in or portable test equipment, existing or specialized cockpit instrumentation may be used for indicating that a malfunction has been detected and where the fault is located. The blank should be filled by specifying the instrumentation which will be used and any interfacing requirements which should be imposed.

REQUIREMENT LESSONS LEARNED

4.1.10.2.1 Malfunction indication. Requirements for use of instrumentation in malfunction detection and fault location shall be verified by ______________________.

VERIFICATION RATIONALE (4.1.10.2.1)

The capability of the specified instrumentation to indicate that malfunction has been detected and where the fault is located must be verified and documented as a basis for training and maintenance planning to support operations of the air vehicle in the field. The blank provides the means for tailoring the method to the requirements which have been established.

VERIFICATION GUIDANCE

Analysis and ground test should be used to verify that the identified instrumentation does provide the required indications, and that interfacing between subsystems does not compromise or degrade other functions if the instrumentation has multiple uses. Analysis should show to what extent the specified instrumentation can provide the required indications, under what conditions, what characteristics and limitations the indications will have, and how and when the instrumentation will be activated for this use. Ground tests should be used to verify that instrumentation installed in the air vehicle does provide the required indications for every malfunction and fault location in the FCS which is intended for coverage and that these indications are obtained throughout the range of environmental conditions specified for the air vehicle.

VERIFICATION LESSONS LEARNED

3.1.10.2.2 Provisions for checkout with portable test equipment. Provisions shall be made to check out elements of the installed FCS by using portable test equipment identified as ____________ ____________________.

REQUIREMENT RATIONALE (3.1.10.2.2)

Built-in test equipment may cause excessive penalty if required to check out every essential function of the FCS. In addition, portable test equipment may, in many cases, conform to and be compatible with the maintenance support concept for the air vehicle. Under these circumstances portable test equipment should be identified for use in maintaining the FCS.

REQUIREMENT GUIDANCE

Cost, weight, space, etc. may preclude the use of built-in test for some FCS or checkout procedures. Compatible portable test equipment may exist in inventory which can perform the required test. Mechanical elements of the FCS may require tests using tensiometers, spring seals, graduated quadrants, etc., where electrical elements may require only a multimeter, ammeter, etc., for tests. The FCS, as it will be installed in the air vehicle, should be carefully analyzed to determine what testing will be required during the full range of FCS maintenance activity, and those tests not considered to be candidates for built-in test should be identified with the test equipment which will be needed. The portable test equipment should then be identified in this requirement.

REQUIREMENT LESSONS LEARNED

4.1.10.2.2 Provisions for checkout with portable test equipment. Provisions for checkout with portable test equipment shall be verified by________ ______________________________________.

VERIFICATION RATIONALE (4.1.10.2.2)

The provisions which have been made for checkout of FCS elements by use of portable test equipment must be verified and documented as a basis for training and planning for maintenance support of the air vehicle in the field. The blank provides the means for tailoring the method to the requirements.

VERIFICATION GUIDANCE

Analysis and ground test should be used to verify this requirement. Analysis should show that the provisions made, and test equipment specified, can perform the intended checkout with the required probability of detecting malfunctions, failure, etc. Ground checkout should be used to demonstrate that the specified test equipment is portable and can perform the intended checkout under the full range of environmental conditions specified for the air vehicle.

VERIFICATION LESSONS LEARNED

3.1.10.3 Accessibility and serviceability. The FCS and its elements shall be designed, installed, located, and provided with access so that inspection, rigging, removal, repair, replacement, and lubrication can be readily accomplished.

Suitable provisions shall be made to facilitate correct rigging of the FCS. The number of rigging positions shall be kept to a practical minimum. Rigging positions shall be readily accessible and located where adequate space is available for the rigging operation. Powered control surface actuator outputs shall not be rig-pinned.

REQUIREMENT RATIONALE (3.1.10.3)

Accessibility and serviceability of the FCS and its elements are fundamental to maintenance supportability of the air vehicle in the field. The requirement is basic to safety of flight and to the control of hazards which may develop due to changes or anomalies in FCS elements during operational usage. Tailoring of this requirement is not required since there are no basic options in covering this important area.

REQUIREMENT GUIDANCE

The control of human error, and the ease, speed, and accuracy with which the crew completes maintenance actions under field conditions is a primary concern in the design of the FCS, its elements, and its installation in the air vehicle. The requirements established in this numbered paragraph are the means by which these concerns are addressed.

REQUIREMENT LESSONS LEARNED

In the implementation of these requirements it has been learned that:

a. The elimination of ladders and workstands to reach system elements is a large labor saver. It also allows more people to work on the air vehicle during the same time period.

b. Variations in connectors and mounting hardware may require different work tools and may create logistics problems. Connectors which rotate 30 to 45 degrees and snap into place are preferred over threaded screw-on connectors.

4.1.10.3 Accessibility and serviceability. The requirements for accessibility and serviceability shall be verified by ________________________.

VERIFICATION RATIONALE (4.1.10.3)

Verification of these requirements is simply verification that the installed FCS can be maintained in a flight ready status under all applicable environments. The documentation generated during this process forms the basis for training and planning for maintenance of the installed FCS during operations in the field. The blank allows the methods of verification to be tailored to the specific FCS.

VERIFICATION GUIDANCE

Analysis and ground tests should be used to verify these requirements. Analysis should be used to identify the required crew actions incident to the identified process and what access provisions will be needed. Ground tests, using experienced crew persons, can then be conducted for selected processes to show that the requirements have been met. The maintainability and reliability program will interface closely with this requirement as will the DT&E effort used to demonstrate operational suitability and supportability. These should all be considered during verification of these requirements.

VERIFICATION LESSONS LEARNED

3.1.10.4 Maintenance personnel safety provisions. The FCS and its elements shall be designed to preclude injury of personnel during the course of all maintenance operations including testing. Where positive protection cannot be provided, precautionary warnings or information shall be affixed in the aircraft and to the equipment to indicate any hazard, and appropriate warnings shall be included in the applicable 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 streamers which are highly visible. All such streamers shall be of a type which cannot be blown out of sight such as up into a cavity in the air vehicle.

REQUIREMENT RATIONALE (3.1.10.4)

Successful operation of an air vehicle and its FCS is highly dependent upon the ability of the service personnel to effectively maintain it in the fully operational condition. Requirements in this section emphasize that the features which allow effective maintenance must be designed into the system to provide the servicing crew the means for safe, speedy detection, location and correction of faults, and the accessibility necessary for preventive and corrective maintenance and for part removal and replacement.

REQUIREMENT GUIDANCE

The FCS and its elements should be designed and installed to allow maintenance actions to be completed without significant hazard to the service personnel. Some hazards cannot be avoided or eliminated altogether, and warnings must be attached to or adjacent to the actual components and be included in the maintenance procedures and instructions.

In the flight control system, two of the hazardous areas of concern are:

a. The inadvertent release of stored mechanical, hydraulic, pneumatic, or electrical energy (i.e., from springs, air-oil accumulators, air bottles, charged capacitors, etc.) which can be hazardous even with system power sources turned off.

b. Inadvertent motion or excessive rate of motion of control surfaces or control and power actuators both within the flight control system and in other systems using the same power sources, such as for the actuation of wheel-well, weapon-bay doors, etc.

Streamers shall be highly visible from the ground and shall be clearly identified.

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, should be provided with positive means of disconnecting the energy source, allowing controlled release of the energy, or preventing its inadvertent release.

REQUIREMENT LESSONS LEARNED

4.1.10.4 Maintenance personnel safety provisions. The required safety provisions for maintenance personnel shall be verified by ______________________________.

VERIFICATION RATIONALE (4.1.10.4)

Identification and control of hazards associated with maintenance action is of major concern to field commanders. Verification of these requirements documents the extent to which the hazards incident to FCS maintenance are controlled and the suitability of those controls to the methods used by crew persons while performing maintenance on the air vehicle. The blank allows the verification method to be tailored to the needs of the specific air vehicle.

VERIFICATION GUIDANCE

These requirements should be verified by analysis and ground test. Analysis should be used to identify those FCS maintenance actions which involve hazards to the working crew. Analysis should also establish the level and control which are required and feasible for those hazards. Ground tests should be conducted to show that the hazard levels are properly classified and that the established controls are adequate. This area is also covered by the systems safety specialty and much of the analysis work is performed for that specialty in its hazard analysis. All maintenance personnel who support the air vehicle during its test phases are highly safety conscious and can provide some of the most valuable inputs for this verification. The verification process should be structured to use all of the information which will be available incident to maintaining the air vehicle used in the test programs in a flightworthy condition.

VERIFICATION LESSONS LEARNED

3.1.11 *Structural integrity.* The FCS and its elements shall be designed to meet the load, strength, deformation, damage tolerance, stiffness, and durability requirements of ____________________.

REQUIREMENT RATIONALE (3.1.11)

These are basic structural parameters used in air vehicle design. They apply to the FCS and its elements where safety of flight and control of hazards are primary issues. The blank allows the structural design requirements to be tailored to the specific program and air vehicle.

REQUIREMENT GUIDANCE

Structural design for the FCS and its elements has a strong interface with the structural engineering specialty and that engineering design group which has responsibility for the structural design and testing of the complete air vehicle. The air vehicle specification requirements are tailored by that group, and those requirements apply to the FCS and its elements. Those air vehicle requirements should be carefully reviewed from the FCS viewpoint and any deficiencies corrected by a joint effort between the specialists involved. The blank should be filled by reference to the structural design requirements established for the air vehicle. When no such requirements will be established, the blank may be filled by selection of requirements from such documents as:

MIL-STD-1530 Aircraft Structural Integrity Program, Airplane Requirements.

MIL-A-8860 Airplane Strength and Rigidity, General Specification for

MIL-A-8861 Airplane Strength and Rigidity, Flight Loads

MIL-A-8865 Airplane Strength and Rigidity, Miscellaneous Loads

MIL-A-8866 Airplane Strength and Rigidity, Reliability Requirements Repeated Loads and Fatigue

MIL-A-8867 Airplane Strength and Rigidity, Ground Tests

MIL-A-8870 Airplane Strength and Rigidity Vibration, Flutter and Divergence

MIL-A-8871 Airplane, Strength and Rigidity, Flight and Ground Operation Tests

MIL-A-8892 Airplane Strength and Rigidity, Vibration

MIL-A-8893 Airplane Strength and Rigidity, Sonic Fatigue

MIL-A-83444 Airplane Damage Tolerance Requirements

MIL-S-8698 Structural Design Requirements, Helicopters

MIL-F-7190 Forgings, Steel, for Aircraft and Special Ordnance Applications

MIL-A-21180 Aluminum-Alloy Castings, High Strength

MIL-A-22771 Aluminum Alloy Forgings Heat Treated

MIL-F-83142 Forging, Titanium Alloys, Premium Quality

MIL-HDBK-5 Metallic Materials and Elements for Aerospace Vehicle Structures

MIL-HDBK-17 Plastics for Aerospace Vehicles

MIL-STD-1599 Bearings, Control System Components, and Associated Hardware, Used in the Design and Construction of Aerospace Mechanical Systems and Subsystems

AFSC DH 2-1 DN 2A1 Strength and Rigidity

Requirements contained in MIL-F-9490 covered basic structural parameters for FCS such as:

a. Strength - The overall flight control systems shall be designed to meet the applicable load, strength, and deformation requirements of MIL-A-8860, MIL-A-8861, MIL-A-8865, MIL-S-8698, and MIL-STD-1530. The components of the systems shall be designed in accordance with the strength requirements of MIL-A-8860, MIL-C-6021, MIL-F-7190, MIL-A-21180, MIL-A-22771, MIL-F-83142, MIL-HDBK-5, and MIL-HDBK-17.

b. Damage tolerance - Those structural elements of the flight control system that are essential to safety of flight (to control essential and flight phase essential functions) shall meet the damage tolerance requirements of MIL-A-83444.

c. 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:

(1) 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 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 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.

(2) 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.

d. Stiffness - The stiffness of flight control systems shall be sufficient to provide satisfactory operation and to enable the aircraft to meet the stability, control, and flutter requirements as defined in the applicable portions of MIL-F-8785, MIL-A-8870, MIL-F-83300 and MIL-A-8865. Normal structural deflections shall not cause undesirable control system inputs or outputs.

e. Durability - Flight control systems shall be designed to meet the durability requirements of MIL-A-8866 and 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 MFCS, AFCS, servo feedback, and from load inputs. The requirements of MIL-A-8892 regarding vibrations and MIL-A-8893 regarding sonic fatigue also apply to the FCS.

REQUIREMENT LESSONS LEARNED

It is incumbent upon the design to show due regard for plausible misfeasance in use to insure that no part of the FCS is likely to be subjected to operation, either intermittently or continuously, at loads greater than that for which the part was designed.

4.1.11 Structural integrity. Structural integrity requirements shall be verified by ____________.

VERIFICATION RATIONALE (4.1.11)

The structural integrity of the FCS and its elements must be verified to document the flightworthiness and the control of potential hazards of the installed FCS and its elements.

VERIFICATION GUIDANCE

Structural integrity should be verified by analyses, and ground and flight tests. The engineering design groups responsible for the structural area for the program, or air vehicle, establish the requirements for verification. These requirements should be carefully reviewed from the FCS viewpoint and any deficiencies corrected through a joint effort by the specialists involved. The blank should be filled by reference to the structural verification requirements established for the air vehicle. When no such requirements will be established, those documents used for generating the requirement should be used to generate the verification requirements. Analyses should be performed for each major area. Analyses should be verified at critical points by ground tests. Flight test should be used to verify analysis which can only be verified in flight.

VERIFICATION LESSONS LEARNED

Stress concentration points can lead to fatigue cracking problems which somehow fail to surface during testing. Cracks developed at the base flare of the cockpit control column in a cargo type air vehicle after it had been in field use for several years. This cracking created a hazard because the cracks could lead to complete failure of the column.

The vibration environment defined for various areas inside the air vehicle can be inaccurate, misleading and deficient. The severe vibration environment at the horizontal stabilator servoactuator in a fighter type air vehicle caused fatigue cracking of the input crank to the servoactuator. This cracking was determined to create a hazard because the cracking could cause separation of the input crank.

3.1.12 Wear life. Assembled unit elements of the FCS shall remain economically repairable and meet reliability requirements for a wear life equal to__________________________.

REQUIREMENT RATIONALE (3.1.12)

The cost burden due to wear out and replacement of parts should be one of the issues during design of the FCS. The assembled unit elements of the FCS should be designed and constructed to have a specific wear life capability consistent with the design approach, state-of-the-art, usage, support concept, etc., which is to be used for the specific air vehicle.

REQUIREMENT GUIDANCE

Wear life in MIL-F-9490 was required to be equal to the life of the primary air vehicle structure. The quantity for measure of wear life has usually been expressed in terms of air vehicle operating hours or cycles of operation. Parts subject to wear such as hydraulic packings, rings and seals, bearings, control cables, sensors, hydraulic valves piston, rods and actuator barrels, etc., are allowed to be replaced or their wearing surfaces renewed after they become unserviceable due to wear. Electronic and other nonmechanical assembled unit elements should remain economically repairable and meet the established reliability requirements. The blank should be filled by a single requirement or by a listing of assembled unit elements broken down by individual items, classes, groups, etc. with corresponding wear life requirements. Analysis should be performed to establish the wear life requirements for the specific air vehicle. This requirement may have interfaces with specialities such as reliability, maintainability, supportability, logistics, etc.

REQUIREMENT LESSONS LEARNED

4.1.12 Wear life. Wear life requirements shall be verified by ______________________________.

VERIFICATION RATIONALE (4.1.12)

Wear life requirements must be verified to document the capability of the FCS to support the planned operational usage of the air vehicle.

VERIFICATION GUIDANCE

Analysis and ground test may be used in verifying this requirement. Analysis should be used to establish the quantity which will be used for measuring wear life; any load, stroke, cycle spectrum which applies; any similarities which may be used; which assembled unit elements may be tested separately and which will require system type testing; what replacement or renewal of wearing elements interval should apply, etc. Ground tests should be used for the final verifications. Flight worthiness, prequalification, qualification, reliability, and durability testing may all be used as part of wear life testing.

VERIFICATION LESSONS LEARNED

3.2 Subsystem and component design requirements. Subsystems, subfunctions, components, elements, and assemblies of the FCS and subsystems interfacing with the FCS shall be designed, fabricated, and installed as indicated in the subparagraphs of this section.

REQUIREMENT RATIONALE (3.2)

Technical feedback from experiences with FCS for operational aircraft including design information related to hardware, systems, equipment, components, software, support equipment, and design factors which influence performance, has been in use for many years in refining FCS specification requirements. The requirements in this section reflect much of that feedback. In current vogue is the Lessons Learned program implemented by AFSCR 800-37 which follows this approach for improving requirements and avoiding the pit falls identified by past mistakes. That program requires documentation of lessons learned and use of them as a basis for revising specifications.

REQUIREMENT GUIDANCE

The repository for Lessons Learned should be searched for cases having technical application to FCS. These Lessons Learned cases should be considered during the tailoring process.

REQUIREMENT LESSONS LEARNED

See requirements lessons learned for subparagraphs of this section.

4.2 Subsystem and component design requirements. Requirements contained in the subparagraphs of this section shall be verified as indicated in their respective verification subparagraphs.

VERIFICATION RATIONALE (4.2)

The format requires verification subparagraphs for each requirement.

VERIFICATION GUIDANCE

Each requirement verification subparagraph in this section will provide applicable guidance. The extensive guidance supplied under 4.1 also applies to the following subparagraphs.

VERIFICATION LESSONS LEARNED

Each requirement verification subparagraph in this section will provide lessons learned when a documented file exists.

3.2.1 Cockpit controls and displays. The design and location of the FCS cockpit control elements and displays shall be in accordance with ________ ______. Additional requirements are stated in the following subparagraphs.

REQUIREMENT RATIONALE (3.2.1)

Most of the design requirements for FCS cockpit controls and displays are determined by the crew station and human engineering disciplines. A high degree of commonality between cockpits of aircraft of the same type is desired to minimize problems in pilot transition. In addition, standardized elements and components aid the logistics of acquiring and maintaining spare parts.

REQUIREMENT GUIDANCE

The blank in this requirement should be filled in with the appropriate document(s) or reference to the air crew station section in the particular air vehicle specification being prepared. The other disciplines involved in cockpit controls and displays should be consulted before completing this requirement.

MIL-STD-203 specifies the cockpit controls for conventional takeoff and landing (CTOL) aircraft, while MIL-STD-250 covers rotary wing aircraft. MIL-STD-203 and MIL-F-83300 should be considered when acquiring short takeoff and landing (STOL) aircraft.

REQUIREMENT LESSONS LEARNED

4.2.1 Cockpit controls and displays. ________ ________ shall be used to verify compliance with ______________________________.

VERIFICATION RATIONALE (4.2.1)

Inspection and ground tests are the most applicable methods of verifying the placement and design of controls and displays.

VERIFICATION GUIDANCE

Requirement 3.2.1 is mainly concerned with the appropriate placement of controls and displays, dimensions, movement, etc., and as such, inspection of drawings and mockups can assure the appropriate design during the early phases of the project, while ground tests and inspection prior to first flight assures that the air vehicle cockpit is the same as the mockups and drawings and that the controls operate within specified values.

The second blank in the verification paragraph is to be tailored by specifying controlling document(s). This paragraph should be in accordance with 3.1.4 in what is specified. This blank may be TBD at RFP and left to negotiations with the contractor.

VERIFICATION LESSONS LEARNED

3.2.1.1 Cockpit controls. Whenever a FCS control is interfaced with redundant flight control channels, mechanical and electrical separation, and isolation shall be provided to make the probability of common mode failures ______________.

REQUIREMENT RATIONALE (3.2.1.1)

Separation and isolation of mechanical and electrical elements in redundant systems is necessary for safety of flight considerations. The intent of this requirement is to prevent propagation of a failure from one control channel to another.

REQUIREMENT GUIDANCE

MIL-F-9490 required that the probability of common mode failures be extremely remote. Care must be exercised in implementing any protective features so that it does not introduce a source of possible failure.

REQUIREMENT LESSONS LEARNED

Experience has shown that force sensors which are sensitive to grip torques about a pivot point within the sensor housing can degrade handling qualities. These devices should only respond to forces about the stick pivot point.

4.2.1.1 Cockpit controls. The separation and isolation between redundant FCS channels and cockpit controls shall be verified by ___(a)___. The probability that common mode failure is ___(b)___ shall be verified by ___(c)___.

VERIFICATION RATIONALE (4.2.1.1)

The isolation and separation of mechanical and electrical components between redundant FCS channels and cockpit controls must be physically verified. Hazard analyses must be performed on the control/flight control computer interface to assure the required probability of failure.

VERIFICATION GUIDANCE

Verification of the separation and isolation of the electrical and of the mechanical redundant flight control channels (blank (a)) can best be performed by inspection. The inspection should begin with preliminary drawings and continue through the design and fabrication phases.

Verification that the probability of a common mode failure is that required in 3.2.1.2 (blank (b)) should be performed during the hazard analysis. If the probability is higher than acceptable, then corrective actions should be taken.

VERIFICATION LESSONS LEARNED

3.2.1.1.1 Removable cockpit flight controls. Removable cockpit flight controls shall be positively retained during all flight conditions.

REQUIREMENT RATIONALE (3.2.1.1.1)

Disengagement or loosening of cockpit controls during flight adversely impacts the safe operation of the air vehicle.

REQUIREMENT GUIDANCE

This requirement primarily applies to control sticks, stickgrips, control wheels, and columns. Positive retention can be accomplished by means of a lockwired threaded fastener, self-retaining bolts, and standard threaded nuts or similar devices.

REQUIREMENT LESSONS LEARNED

There have been incidents of cockpit controls becoming unintentionally disengaged in flight because of inadequate retention.

4.2.1.1.1 Removable cockpit controls. Positive retention of removable cockpit flight controls shall be verified by ______________.

VERIFICATION RATIONALE (4.2.1.1.1)

Positive retention of removable flight controls must be verified because of the safety of flight implication.

VERIFICATION GUIDANCE

Inspection and/or test are the most appropriate means of verification. Inspection of the fastening devices to determine that only deliberate, intentional disengagement is possible should be performed. If the fastening device is of a type historically demonstrated to provide positive retention, the inspection may be sufficient verification. However, if the device is unconventional or has a history of losing its retainability, then vibration and life cycle testing may be appropriate.

VERIFICATION LESSONS LEARNED

With repeated use, self-locking nuts lose some of their retainability.

3.2.1.1.2 **Movable rudder or directional pedals.** Movable rudder or directional pedals shall be interconnected to insure positive movement of each pedal in both directions.

REQUIREMENT RATIONALE (3.2.1.1.2)

The force reaction cue from the pedals to the pilot insures that the pilot(s) is (are) aware that yaw control has been commanded.

REQUIREMENT GUIDANCE

Movable rudder pedals operate in such a manner that when one rudder pedal is moved forward a given distance, the other rudder pedal should move aft the same distance with no objectionable dead band or free play.

Independent force command pedals have been used on some fighter aircraft. The intent of this paragraph is not to preclude their use; however, their application may need further investigation. With the advent of fly-by-wire air vehicles, various sensors can be used to sense the pilot force on the pedal. This, however, does not address the reason for this requirement—that is, to provide a positive indication to the pilot that yaw control has been manually commanded and an easily recognizable indication as to what action must be taken to counter the command.

REQUIREMENT LESSONS LEARNED

4.2.1.1.2 **Movable rudder or directional pedals.** Positive interconnection of rudder pedals shall be verified by ______________________.

VERIFICATION RATIONALE (4.2.1.1.2)

The appropriate design and operation of the rudder pedals must be verified to assure safe and adequate operation of the air vehicle.

VERIFICATION GUIDANCE

Inspection of the design and demonstration of the pedal operation prior to and during the flight tests are the suggested methods of verification. Forces should be monitored and be within handling quality specified limits, and operation should be smooth without dead spots or ratching.

VERIFICATION LESSONS LEARNED

3.2.1.2 **Pilot displays.** Wherever any display or annunciator is interfaced with redundant flight control channels, mechanical and electrical separation, and isolation shall be provided to assure that common mode failures do not occur.

REQUIREMENT RATIONALE (3.2.1.2)

Mechanical and electrical separation and isolation are required to prevent any common mode failures from occurring. The intent of this requirement is to prevent loss of display and propagation of a failure from one control channel to another.

REQUIREMENT GUIDANCE

MIL-F-9490 required that the probability of common mode failures be extremely remote. Care must be exercised in implementing any protective features so that it does not introduce a source of possible failure.

MIL-F-9490 also required that pilot displays be designed in accordance with MIL-STD-1472. This has been omitted from this requirement since it is in the purview of the display and human factors engineers to assure compliance with MIL-STD-1472.

REQUIREMENT LESSONS LEARNED

4.2.1.2 **Pilot displays.** The separation and isolation of pilot displays shall be verified by __(a)__.

The probability that common mode failures do not occur shall be verified by ___(b)___.

VERIFICATION RATIONALE (4.2.1.2)

The isolation and separation of mechanical and electrical components between redundant FCS channels and displays must be physically verified. Hazard analyses must be performed on the display/FCS interface to assure the required probability of failure.

VERIFICATION GUIDANCE

Verification of the separation and isolation of the electrical and mechanical redundant flight control channels (blank (a)) can best be performed by inspection. The inspection should begin with preliminary drawings and continue through the design and fabrication phases.

Verification that common mode failures do not occur should be performed during the hazard analysis.

VERIFICATION LESSONS LEARNED

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

AFCS engaged

mode engaged

REQUIREMENT RATIONALE (3.2.1.2.1)

It is important for safety of flight that the pilot(s) be aware of the configuration of the FCS at all times.

REQUIREMENT GUIDANCE

Space is allotted for this requirement to be tailored to the particular FCS under consideration. Other annunciation requirements which should be included if applicable, to the FCS are:

a. Annunciation that automatic mode switching has occurred

b. Preselected values for selectable mode parameters

c. Annunciation of preflight BIT status including:

(1) The progress of the preflight test

(2) Instructions to the crew to provide required manual inputs

(3) Lack of system readiness when failure is encountered.

In addition, if the available manual control authority can be reduced below the level required for maneuvering control by a function such as automatic trim or stability augmentation, pilot displays shall be provided to indicate available control authority for essential and flight phase essential FCS.

REQUIREMENT LESSONS LEARNED

The requirement to annunciate manual control authority when masked by automatic trim is in response to aircraft lost due to loss of pitch control. A fighter aircraft was lost following a failure in the fuel transfer system which caused an aft cg condition to develop. The series autotrim, which is part of the augmentation, maintained the stick in the trimmed position and the stability augmentation masked the degrading pitch stability. As airspeed was reduced and control limits were reached, the aircraft went out of control and was lost.

The probability of the crew mismanaging a safety-critical system should be minimized. Zealous pursuit of this objective can lead to criteria which require that interlock logic be implemented that prevents the crew from isolating a critical channel unless the channel has been annunciated as failed, and which prevents the crew from re-engaging critical channels that have been isolated due to a prior failure indication.

4.2.1.2.1 FCS annunciation. FCS annunciation shall be verified by ________________.

VERIFICATION RATIONALE (4.2.1.2.1)

An adequate design and correct operability need to be verified because of the safety implications.

VERIFICATION GUIDANCE

Inspection of cockpit drawings and layouts should be performed to verify the inclusion and placement of all necessary annunciation. Testing of the FCS during operation must be performed to verify the accurate operation of the annunciator displays.

VERIFICATION LESSONS LEARNED

3.2.1.2.2 FCS warning annunciation. FCS warning annunciation shall be provided in the cockpit to allow crew to assess the operability of redundant or monitored FCS. Annunciation shall be designed to clearly indicate the associated degree of urgency.

a. First degree - immediate action required (warning may be audible)

b. Second degree - caution, action may be required

c. Third degree - informational; no immediate action required.

Warning annunciation shall include, but not be limited to the following: ______________________

____

REQUIREMENT RATIONALE (3.2.1.2.2)

The pilot(s) must be able to quickly and accurately determine the urgency of a warning. This is a safety of flight requirement.

REQUIREMENT GUIDANCE

This requirement interfaces with the crew station, displays, and human factors areas. The FCS engineer may wish to have input in the (visual or audio) type of warning, color of light, and position of displays; however, these design considerations are not within the domain of this specification.

A further explanation of the degrees of urgency follows:

a. First degree - immediate action required (warning may be audible)--loss of system function, hazardous condition imminent. An example of this situation might be taken as total loss of the AFCS at low altitudes during a limited visibility approach.

b. Second degree - caution, action may be required--probable loss of system function. Hazardous condition may be developing. Pilots should make an assessment of system status before responding.

c. Third degree - informational, no immediate action required--possible loss of system function in near future. No impending hazard. An example is pretest of a system identifying a failure. Hazard can be avoided by avoiding use of that system or mode.

Automatic disengagement of an AFCS mode shall be indicated by an appropriate warning display. Whereas manual disengagement by the crew shall not result in warning annunciation. If available manual control authority for flight essential and flight phase essential has been reduced by an automatic function below that which would be required for manual operation, warning annunciation shall occur. Other warnings which may be applicable are the automatic and possible manual disconnect of dampers in each axis, the loss of a channel in a multichannel system, or the disengagement of an augmentation device. It has been suggested that warning and annunciation equipment should be provided with self-test features. If this is desired, a statement to that effect should be added to the requirement.

REQUIREMENT LESSONS LEARNED

The probability of losing the capability to isolate failures and annunciate system status should be minimized. This may require special considerations relative to power source selection. For example, if failures are annunciated by lights, then the design must ensure power to the lights when the channel failure is a power failure.

Runaway trim has caused many accidents in the past. Many of these accidents occurred because the pilot was not aware of the malfunction until it was too late. Low altitude, night, and instrument conditions affect the pilot's capability to detect and react. Commercial transport aircraft provide an aural warning whenever pitch trim is changing.

4.2.1.2.2 FCS warning and status annunciation. FCS warning and status annunciation requirements can be verified by ______________.

VERIFICATION RATIONALE (4.2.1.2.2)

An adequate design of warning annunciation and operability needs to be verified because of the safety implications.

VERIFICATION GUIDANCE

Inspection of cockpit drawing and layout should be performed to verify the inclusion and placement of all necessary warning annunciation. Verification of operability should be accomplished by the introduction of simulated faults or equipment failures during bench tests to determine that the warning on annunciation circuitry is performing as designed.

VERIFICATION LESSONS LEARNED

3.2.1.2.3 Cockpit indicators. Suitable indications shall be provided in the cockpit to indicate to the pilot(s) ____________________________.

REQUIREMENT RATIONALE (3.2.1.2.3)

To meet safety and operability needs the pilot must be provided with accurate information concerning the position of the aerodynamic devices and surfaces.

REQUIREMENT GUIDANCE

Cockpit indicators should be provided for lift and drag devices not automatically controlled, trim devices, and in some air vehicles individual surface position indicators. MIL-F-9490 required that lift and drag devices (such as flaps, slats, speed brakes, etc.) should have indicators which, in addition to showing the current position, are labeled to indicate the correct takeoff, enroute, approach and landing position. MIL-F-9490 also required that if any extension of the lift and drag devices beyond the landing position is possible, the indicators 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. In the past, indicators for lift and drag devices have not met the MIL-F-9490 requirement, especially for speedbrakes. Careful consideration must be given to the mission, aerodynamic configuration, flight control system design, and safety needs before this requirement is excluded or waived for certain devices.

Regarding trim devices MIL-F-9490 required that suitable indications 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 airplane 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 helicopters 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 indicator.)

d. Provide pilot warning of trim failures which could result in exceeding the operational state requirements of 3.1.3.3.

e. Pitch trim indicators should include a motion indicator to alert the pilot of trim motion.

f. Be in a position visible to the pilot.

Aircraft which require takeoff longitudinal trim setting in accordance with cg location shall have suitably calibrated trim position indicators. Where suitable, trim indicators shall be in accordance with MIL-I-7064. 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.

Additionally, MIL-F-9490 required that indicators shall be provided in the cockpit for all control surfaces required for retention of FCS Operational State II, when the cockpit controls do not provide a positive indication of long term or steady state control surface position, or where the effects of control surface positioning is not readily detectable by other means.

REQUIREMENT LESSONS LEARNED

Aircraft which use a trim actuator to move the horizontal stabilizer, and thereby affect pitch trim of the aircraft, have peculiar characteristics. It stems from the fact that small horizontal stabilizer incidence changes have a powerful affect on the pitching moment of the aircraft. For this reason the pilot is typically given a three-second recognition time from the initiation of a pitch trim runaway and the initiation of the pilot's corrective action.

The problem with the typical pitch trim indicator is that the rate of motion of the indicator needle is so slow that the pilot has difficulty recognizing its movement. It is for this reason that a separate barber pole type motion indicator should be included on the face of the indicator to draw the pilot's attention to the indicator the instant pitch trim action is initiated.

4.2.1.2.3 Cockpit indicators. Compliance with indicator requirements shall be verified by ______ ______________________________.

VERIFICATION RATIONALE (4.2.1.2.3)

Accurate operation of cockpit indicators must be verified because of the safety of flight implications. Inspection, analysis, and test can be used to verify the various requirements for cockpit indicators.

VERIFICATION GUIDANCE

Inspection of cockpit layout drawings shall verify the inclusion of the required indicators. Accurate operation of position indicators should be verified by ground operation. Analysis should be used to determine the appropriate settings for those position indicators which are required to be labeled with flight conditions. Unsymmetrical conditions for lift and drag devices from failures and malfunctions of indications should be simulated to verify proper operation of warnings and to demonstrate the pilot's ability to use the indication provided is within the domain of the human factors engineer; however, it is also of concern to the flight controls engineer.

VERIFICATION LESSONS LEARNED

3.2.2 Sensors. Sensors used for flight control system functions shall be designed and located such that adequate sensing of the desired aircraft and flight control system parameters can be accomplished. Sensors shall be designed to operate throughout the power range specified for the air vehicle. Locations shall be chosen which minimize exposure to conditions which could produce failures or undesirable output signals. Signal and impedance levels for remote sensors shall be designed to minimize EMI effects and to prevent signal level changes due to transmission path loading effects. Closely spaced, redundant electromagnetic sensors shall be designed to prevent cross coupling of signals among the sensors. If self-test or in-flight monitoring BIT are used, the sensors and flight control system shall be fail safe in design in regard to the operation of the BIT.

REQUIREMENT RATIONALE (3.2.2)

Attention must be given to the location and design of all sensors to ensure that they provide signals of the quality necessary for the flight control system without distortion inherent in the design due to undesirable structural modes or other effects.

REQUIREMENT GUIDANCE

Displacement, force rate, acceleration, air data, and other sensors used for input into the flight control system are covered by this requirement. Reliability of the sensors should not degrade the overall flight control system reliability.

REQUIREMENT LESSONS LEARNED

4.2.2 **Sensors.** Correct sensor location and operation shall be verified by analyses, inspection, and test.

VERIFICATION RATIONALE (4.2.2)

Analyses, inspections, and tests are used to verify the different aspects of this requirement to assure the correct location and operation of flight critical sensors.

VERIFICATION GUIDANCE

Analyses should be used to determine the correct sensor location. Bending modes, local vibrations, asymmetries, and the characteristics of the parameters being sensed must all be taken into consideration when locating sensors. Inspection should be used to verify the location and correct installation of the sensors. Tests to determine the operability and accuracy of the sensors should also include check of the self-test or inflight monitoring BIT.

It should be verified that faults introduced into the sensor, self-test, and inflight monitoring systems do not propagate into the flight control computers.

VERIFICATION LESSONS LEARNED

3.2.3 Signal transmission. All signal transmission concepts, devices, lines, components, and subsystems dedicated to the FCS shall be covered by requirements in this section.

3.2.3.1 General requirements. All signal transmission elements, components, and subsystems of the FCS shall be designed and suitably protected to resist jamming by objects. Where feasible, advantage shall be taken of shielding afforded by heavy structural members, existing armor, and other equipment for protection of important elements of the FCS. Signal transmission elements shall be protected from usage such as steps and handholds. Clearance between FCS elements and structure or other components shall be provided as necessary to insure that no probable combination of temperature effects, air loads, structural deflections, vibration, buildup of manufacturing tolerances, or wear can cause binding or jamming of any portion of the FCS. In locally congested areas, the minimum clearances which may be allowed after all adverse effects are accounted for shall be ______________ ______________.

REQUIREMENT RATIONALE (3.2.3.1)

Interrupting, impeding, or otherwise interfering with signal generation, propagation or transmission in the FCS may create hazards during air vehicle operation incident to flight. This requirement helps to eliminate or control some of those possible hazards. The blank allows the clearance requirements to be tailored to the needs of the specific air vehicle.

REQUIREMENT GUIDANCE

All portions of the FCS used for signal propagation and transmission such as cables, push-pull rods, torque tubes, light cables, electric wiring, etc. should, where feasible, be routed through the air vehicle in the most direct manner over the shortest practical distance between points being connected.

Where redundant cable, push-pull rod, light cabling, or electric wiring is provided for signal transmission, the separate runs should have sufficient spacing to enhance invulnerability.

Technical order 1-1A-14 recommends 6 inches or more between wiring and plumbing which carries combustible fluids and 3 inches between wiring and control cables. AFSC DH-2-1 indicates that 3 inches is the standard clearance between control cables. A 1/4 inch clearance is considered standard between cables and fairleads. MIL-F-9490 contained allowables for minimum clearances for signal transmission elements as follows.

In locally congested areas only, the following minimum clearances may be used after all adverse effects are accounted for:

a. One-eighth inch between static elements except those within an LRU where closer clearances can be maintained or where contact cannot be detrimental.

b. One-eighth inch between elements which move with respect to each other and which are connected to or are guided by the same structural or equipment element(s) except those within an LRU where closer clearances can be maintained or where contact cannot be detrimental.

c. One-fourth inch between elements which move with respect to each other and which are connected to or are guided by different structural or equipment elements.

d. One-half inch between elements and aircraft structure and equipment to which the elements are not attached. Clearances at the ends of swept paths may not be critical and smaller clearances or zero clearances may be allowed at such extremes of travel unless contact is detrimental.

Every effort should be made to avoid using the minimum clearances and spacings.

REQUIREMENT LESSONS LEARNED

Adverse tolerance buildup and inadequate tooling during manufacturing can result in close clearance situations where nominal clearances are considered adequate.

Signal transmission layout should be determined early in the design of the air vehicle before locations for other equipment can compromise FCS routing.

Aviation history abounds with cases where objects jammed controls creating a class I hazard. Designs which use compact arrangements offer many opportunities for jams to occur. Moving elements located near the lower surface of enclosures and vertically oriented cranks and pulleys, have a higher probability of being jammed. Inverted flight, zero and negative "g", rough and turbulent air effects should be considered when planning protection provisions for signal transmission elements.

4.2.3 **Signal transmission.** Signal transmission requirements shall be verified by inspection as having complete coverage of the dedicated concepts, devices, lines, components, and subsystems used in the FCS.

4.2.3.1 **General requirements.** The general requirements for design of signal transmission elements, components, and subsystems shall be verified by ________________.

VERIFICATION RATIONAL (4.2.3.1)

The design process must be responsive to every detail which can cause any FCS signal transmission function to be interrupted, impeded, or otherwise subjected to interference. Critical evaluation of the results of that process is accomplished and documented during this verification and should show the extent to which hazards have been eliminated or controlled. The blank allows the method of verification to be tailored to the needs of the specific air vehicle.

VERIFICATION GUIDANCE

Use analysis techniques to determine and list the concepts, devices, lines, components, and subsystems which are used for signal transmission and are dedicated to the FCS. Compare, by inspection, those listed items against those covered in the other subparagraphs of this section to determine the completeness of coverage.

Analysis and inspection should be used for evaluation of the design layout for routing, shielding, means of protection, tolerance buildup, and the effects of other factors. Inspection should be used to provide documentation for these requirements based on the installation in vehicle as the flight hours accumulate to document the effects of temperature, structural deflections, vibration, wear, etc.

VERIFICATION LESSONS LEARNED

The flight environment cannot be duplicated on the ground; therefore, evidence of the effects of that environment on clearances (interference) should be sought during inspection.

In long, straight cable runs where sag is normal, even when rigging is proper, the cables may be allowed to rest on fairleads or rub strips.

Water which accumulates on or around FCS elements can freeze in flight and cause interference with FCS function. Inspection should generate documentation covering this point.

3.2.3.1.1 Computer signal transmission. Signal transmission of commands between the flight control computers and devices or modules designed to act on the commands shall be performed by using direct ____________________. When redundant computing paths are provided, they shall be isolated or separated to meet invulnerability and failure immunity requirements.

REQUIREMENT RATIONALE (3.2.3.1.1)

Computer signal transmission elements composed of conventional components such as electrical, electronic, hydraulic, mechanical, or pneumatic devices or nonconventional components such as optical devices, must provide the most direct routing, including necessary separation or isolation and the appropriate levels of redundancy and failure immunity to meet the invulnerability, reliability, and maintainability requirements placed on the FCS.

REQUIREMENT GUIDANCE

The transmission of command signals between flight control computers and the devices or modules designed to act on the commands will usually be by direct means using mechanical, hydraulic, pneumatic, electronic, or electrical components. The direct means, of whatever design, implies that the signal does not pass through any extraneous components or devices on the way to the module or device which ultimately processes the command.

The use of fiber optics or other nonconventional signal paths may be considered in future applications but the FCS engineer must ensure that the contractor has fully investigated their capability to perform the essential functions reliably and can present substantiating evidence for approval before committing designs.

Isolation and separation of redundant paths must be consistent with the overall redundancy concept.

REQUIREMENT LESSONS LEARNED

4.2.3.1.1 Computer signal transmission. The method of signal transmission, isolation, and separation of redundant computing paths, and direct signal transmission shall be verified by inspection of ______________. Failure immunity requirements shall be verified ______________________.

VERIFICATION RATIONALE (4.2.3.1.1)

Signal path transmission methods and design must be verified to assure the integrity of the flight control signals. Invulnerability, reliability, and maintainability must all be considered during the verification of signal path transmission.

VERIFICATION GUIDANCE

Inspection of engineering drawings and other pertinent documentation will verify that the design for computer signal transmission, built-in tests can be verified by failure modes and effects analysis and tests. The validity of the signal should be maintained during transmission and not altered due to variation in the system caused by environmental effects.

VERIFICATION LESSONS LEARNED

3.2.3.2 Mechanical signal transmission, general. Elements used for mechanical signal transmission shall meet the structural integrity requirements of this specification. Capability shall also be provided to transmit forces to override interference or jams in the mechanical loop up to a level of at least ________________________________.

REQUIREMENT RATIONALE (3.2.3.2)

Mechanical signal transmissions are often used in the implementation of critical flight control functions. The forces which may be required to transmit signals in these mechanical loops may vary over a wide range when the normal and abnormal operating states are considered. This requirement provides the means for insuring that the capability exists, within the elements and mechanical loops of these subsystems, to transmit a level of force tailored to the needs of the specific air vehicle.

REQUIREMENT GUIDANCE

The structural integrity requirement in this specification uses MIL-A-8865 as the reference document for guidance. Limit loads for design of the elements used for mechanical signal transmissions generated by the pilot should be taken to be those specified in MIL-A-8865 unless higher loads can be imposed, such as those associated with power actuators or aerodynamic forces. Regardless of load levels used, the same margins and circumstances specified in MIL-A-8865 should be used. Specific values for forces needed to override interference or clear jams depend on the design features of the FCS elements, the installation, and the conditions within the air vehicle. All factors should be considered in determining the value to be used in filling the blank. The force level specified, usually in pounds, would be at the input point most crucial to transmission of the flight control signal.

REQUIREMENT LESSONS LEARNED

Interference and jams are often encountered in the mechanically operated valves of the FCS hydraulic servoactuators. Specific values for the override or clearing forces depend on the specific valve design, materials found in the hydraulic system, and the system approach used in the mechanization. In the past, forces of 300 pounds, taken as limit load, have been used based on a jam clearing load of 200 pounds. However, a value of 1000 pounds has been used in one of the most recent fighters which has a mechanically operated servovalve. In electric fly-by-wire FCS, closure of the servoactuator feedback loop through mechanical signal linkage to the servovalve should be considered in order to provide a suitable force level for overriding interference and clearing jams in the valve.

4.2.3.2 Mechanical signal transmission, general. The general requirements for mechanical signal transmission shall be verified by ____________.

VERIFICATION RATIONALE (4.2.3.2)

Critical flight control functions are often implemented through mechanical signal transmissions. The general requirements in this paragraph provide a means for control of some of the hazards associated with installed mechanical signal transmission control loops. The verification process provides the means for documenting the extent to which the hazards associated with interference and jamming can be controlled in these loops.

VERIFICATION GUIDANCE

Ground testing is the most feasible means of verifying these general requirements. Structural integrity and proof of force transmitting capability of these mechanical signal transmission elements and subsystems should be verified during the System Structural Integrity verification process. These verifications should be conducted on elements, subsystems, and systems installed in an air vehicle. MIL-A-8867 may provide some useful guidance in establishing the procedures and criteria to be used in conducting this verification.

VERIFICATION LESSONS LEARNED

3.2.3.2.1 Control cable installations. Wire rope type cable subsystems used for FCS signal transmission shall meet requirements of this specification with respect to performance, safety, maintainability, reliability, structural integrity, and wear life. Requirements for component design and usage shall be as shown in ________________.

REQUIREMENT RATIONALE (3.2.3.2.1)

Wire rope is used in a large majority of FCS for signal and power transmission. The function provided by the cable system utilizing the wire rope is often critical to flight safety and mission accomplishment. This paragraph provides the means for tailoring requirements for the hardware elements used in the cable systems to the needs of the specific air vehicle and the user. It also allows requirements to be included which control, by proper selection of components, the latent flight hazards which may be created incident to manufacturing, installing, and maintaining cable systems.

REQUIREMENT GUIDANCE

Engineering control of the design and usage of components and elements for flight control cable systems should be exercised and documented in a formal manner. The blank should be filled by reference to the specific engineering documents which will be used for this control. MIL-STD-1599 requirements 206 and 601, or similar vendor documents, should be acceptable as the reference for control of element design and usage.

REQUIREMENT LESSONS LEARNED

The lessons learned with respect to control cable installations are reflected in the requirements in MIL-F-9490 and MIL-STD-1599. Generalized lessons learned relative to sizing, tensioning, locating, actuating, and similar cable control system requirements are grouped under the following headings.

a. Performance:

(1) Cable runs located in aeroelastic structure should be routed to minimize any induced control action caused by structural flexure.

(2) Wire rope size should be chosen with careful consideration for stretch, friction, and other variables which affect performance.

(3) Sheave guards should be supported in a way which precludes binding of the sheave due to structural deflections.

(4) Cable tension rig loads should insure positive cable tension in all control and return legs under all operating conditions and throughout the design temperature range.

(5) Pressure seals for cables which penetrate a pressurized area shall meet compartment sealing requirements within the transmission friction requirements.

(6) Cable system friction levels:

(a) Decrease with larger and fewer pulleys, sectors, etc.

(b) Increase with:

- Larger cable size
- Larger cable travel
- Larger rig loads
- Larger wrap angles up to one cable pitch length
- Larger bearing size in rotating elements
- Larger axial loading on rotating elements

(7) Cable travel has a direct bearing on system flexibility. Larger cable travel results in lower cable loads and thus less deflection and a stiffer system.

b. Safety:

(1) The minimum practical number of interconnections should be a goal in cable loop design.

(2) Provisions should be made in installations to insure that slack return cable assemblies cannot snag on airframe elements when the cable is loaded to limit load under any design condition.

(3) Guards should be installed at all sheaves to prevent cable from coming out of the groove.

(4) Guards should be installed on sectors to insure retention of the cable end in its attachment when the cable is slack.

(5) Pressure seals for cables shall be designed to preclude jamming of the FCS.

c. Maintainability (accessibility and serviceability):

(1) Control cable loops should be designed for easy servicing and rigging and the number of adjustments should be kept to a practical minimum.

(2) Cable assemblies should be installed in parallel runs and be accessible to inspection for their entire length.

(3) Loose spacers should not be used between rotational elements and support brackets.

(4) Fairleads should be designed to permit easy removal and replacement of both the fairlead and the cable assembly.

(5) Cable tension regulators should be used only when positive cable tension cannot be maintained in both legs with reasonable rigging loads.

(6) Cable tension regulators should be provided with integral calibrated dials to show cable tension without the use of separate cable tensiometers or other equipment.

d. Reliability:

(1) Overtravel allowance on cable drums should not be less than five percent of full cable travel in either direction and should allow at least ten degrees of drum overtravel.

(2) When cable wrap varies with cable travel on cable drums, the initial wrap with the sheave in neutral position should be at least 115 percent of the full cable travel in either direction. When overtravel exceeds the minimum requirement, cable wrap should be increased a corresponding amount.

(3) Cable tension regulators should maintain the required tension at all times.

e. Structural integrity:

(1) Wire rope size used in cable assemblies should be chosen so that limit loads do not result in rope loads which exceed 67 percent of its rated breaking strength and does not exceed limit load for the pulleys used.

(2) Design limit load for pulleys should not exceed allowables shown in the pulley design standard.

(3) The diameter and number of grooves on cable drums, and radius and angle sectors should be adequate for the required cable travel.

(4) Installation design for cable assemblies should be such that turnbuckles and fittings are not subject to bending loads which could cause fatigue failures.

f. Wear life:

(1) Wire rope size chosen should meet load requirements with angle safety margin to compensate for wear and deterioration.

(2) Spacing between adjacent cable assemblies should prevent chafing during all operating conditions including vibrations.

(3) Cable assemblies should be provided with drums, sectors, and pulleys of adequate capacity and diameter for the function performed and to meet the endurance and life requirements of the FCS.

(4) Sheaves should be spaced such that no section of the cable ever passes over more than one sheave.

4.2.3.2.1 Control cable installations. The requirements for control cable installations shall be verified by __________________________.

VERIFICATION RATIONALE (4.2.3.2.1)

The functions performed by cable installations used in FCS are often critical to flight safety and mission accomplishment. The requirements levied on cable installations insure that the flight safety hazard and mission reliability levels are controlled by engineering design. The verification process provides the means for documenting the extent to which the requirements have been met and provides a basis for planning for operational use of the air vehicle in the field. Verification may be accomplished by analysis, inspection, and ground and flight testing. The blank allows the verification method to be tailored to the specific air vehicle.

VERIFICATION GUIDANCE

Requirements which apply to control cable installations and which are contained in other paragraphs of this specification as indicated below, should be verified during the verification processes for those paragraphs. Other applicable requirements in this section and those for selection and usage of control cable installation components should be verified by inspection.

Performance 3.1.1

Safety 3.1.7

Maintainability 3.1.10.3

Reliability 3.1.6

Structural integrity 3.1.11

Wear life 3.1.12

VERIFICATION LESSONS LEARNED

3.2.3.2.2 Push-pull signal transmission installations. Push-pull type subsystems used for FCS signal transmission shall meet other requirements of this specification with respect to performance, safety, maintainability, reliability, structural integrity, and wear life. Requirements for component design and usage shall be as shown in ____________.

REQUIREMENT RATIONALE (3.2.3.2.2)

Push-pull rods and push-pull flexible controls are often used in FCS for signal and power transmission. The function provided by such push-pull devices is often critical to safety and mission accomplishment. This paragraph provides the means for tailoring requirements for the hardware elements used in push-pull controls to the needs of the specific air vehicle and the user. It allows requirements to be included which control; by proper selection of components, methods and usage; the latent flight hazards which may be created incident to manufacturing, installing and maintaining push-pull devices.

REQUIREMENT GUIDANCE

Engineering control of the design and usage of components and the methods used for construction of flight control push-pull devices should be exercised and documented in a formal manner. The blank should be filled by reference to the specific engineering documents which will be used for this control. MIL-STD-1599 requirements 207 and 602, or similar vendor documents, should be acceptable as the reference for push-pull rods. A vendor document based on the requirements section of MIL-C-7958 but tailored to FCS usage for the air vehicle should provide an acceptable reference for push-pull flexible controls.

REQUIREMENT LESSONS LEARNED

The lessons learned with respect to push-pull signal transmission devices are reflected in the requirements in MIL-F-9490 and MIL-STD-1599. Generalized lessons learned relative to design, installation, and usage are grouped under the following headings:

a. Performance:

(1) Friction levels in installed FCS using push-pull rods can be minimized by using minimum bearing sizes in cranks, hinges, rod-ends, etc., and by preventing axial preloads on the bearings.

(2) The use of push-pull flexible controls in essential and flight phase essential FCS functions should be carefully evaluated and justified by comprehensive trade studies.

(3) Supports used for push-pull flexible controls should not restrain the push-pull element axially.

(4) Conduits for push-pull flexible controls should be supported at frequent intervals and each bend radius should be made as large as practical.

(5) Levers and bellcranks in push-pull controls should have bearings with adequate self-aligning capability to prevent excessive deflection loading of these elements.

(6) Levers and bellcranks designed with dual load paths which have two sections joined by permanent fasteners should also have the two sections bonded with adhesive.

(7) The lateral vibration natural frequency of each rod section should be determined and synchronization with engine or other vibrations in the air vehicle should be avoided.

4.2.3.2.2 Push-pull signal transmission installations. The requirements for push-pull signal transmission installations shall be verified by ______ ______________________________.

VERIFICATION RATIONALE (4.2.3.2.2)

The functions performed by these push-pull installations in FCSs are often critical to safety and mission accomplishment. These requirements insure that the flight safety hazards and mission unreliability incident to use of push-pull mechanizations in the FCS are controlled by engineering design. The verification process provides the means for documenting the extent to which the requirements have been met and provides a basis for planning for operational use of the air vehicle in the field. Verification may be accomplished by analysis, inspection, and ground and flight testing. The blank allows the verification method to be tailored to the specific air vehicle.

VERIFICATION GUIDANCE

Requirements which apply to these push-pull installations and which are contained in other paragraphs of this specification as indicated below, should be verified during the verification process for those paragraphs. Other applicable requirements in this section and those for selection and usage of push-pull installation components should be verified by inspection.

Performance 3.1.1

Safety 3.1.7

Reliability 3.1.6

Maintainability 3.1.10.3

Structural integrity 3.1.11

Wear life 3.1.12

VERIFICATION LESSONS LEARNED

3.2.3.2.3 Control chain. Roller chain may be used for signal transmission in FCS mechanization. Connecting links shall be retained by cotter pins; spring clips shall not be used. The chain used shall be of standard aircraft quality and conform to requirements of ______________________.

REQUIREMENT RATIONALE (3.2.3.2.3)

Where rotational type signals must be transmitted through areas where a multiplicity of path changes are required, a chain drive may prove to be the most feasible method of mechanization. The function implemented by chain drive may be critical to flight safety and mission accomplishment. This requirement provides the means for engineering control of the type of chain which can be accepted and some of the hazards and unreliability levels which may be created by the design of chain and its elements. The blank provides the means for tailoring the design requirements of the chain to the specific usage.

REQUIREMENT GUIDANCE

American National Standards Institute specification ANSI B29.1-75, "Precision Power Transmission Roller Chain, Attachments and Sprockets, Connecting Link Cotter Pin Type" is the reference which should be used to fill the requirements blank. As an alternative, a contractor-prepared specification might be used, if it provides chain essentially identical to, and interchangeable with, the ANSI B29.1-75 chain. ANSI B29.1-75 is copyrighted by the ASEE, but is adopted by Department of Defense in lieu of a military standard.

REQUIREMENT LESSONS LEARNED

4.2.3.2.3 Control chain. Control chain requirements shall be verified by ________________.

VERIFICATION RATIONALE (4.2.3.2.3)

The function implemented by chain drive may be critical to flight safety and mission accomplishment. The requirements impose some control of the hazards and unreliability levels which may be created by design features of the chain and its associated elements. The verification process documents the extent to which the specified design features are found in the chain used in the FCS. This documentation provides a basis for planning for operational use of the air vehicle in the field.

VERIFICATION GUIDANCE

Verification should be accomplished by inspection and ground test. ANSI B29.1-75 does not contain a quality assurance section but each requirement in that standard should be listed and verified by an appropriate method. Any contractor prepared specification which is used in lieu of ANSI B29.1-75 should contain a quality assurance section. That section might be used in the verification process.

VERIFICATION LESSONS LEARNED

3.2.3.3 Electrical signal transmission. The following requirements apply to all essential and flight phase essential signal paths:

REQUIREMENT RATIONALE (3.2.3.3)

The integrity of the electric signal transmission must be maintained for flight safety. The requirements to be included in this paragraph are those necessary to assure failure immunity and invulnerability of the electric signal and transmission components.

REQUIREMENT GUIDANCE

The design of the signal transmission path and components must be such that it is immune to failures and failure propagation due to the environment, both natural and induced, hostile action, and maintenance errors. Over the years certain minimum requirements for electrical signal transmission have been imposed. The following is a list of previous requirements:

a. Except for power sources, such systems (FCS) shall be independent of failure modes associated with any other electrical system.

b. Cross connections between redundant electrical signal paths shall be eliminated, or minimized and electrically isolated.

c. 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.

d. All interconnecting wiring shall be prefabricated, jacketed cable assemblies.

e. The outer jackets shall be identifiable by a unique color or other means.

f. Wiring installations shall be in accordance with MIL-W-5088.

The scope of MIL-W-5088, published 30 June 1976, covers the selection and installation of wiring and wiring devices used in airplanes, helicopters, and missiles. One would expect that this standard should be imposed for the entire air vehicle and all its subsystems. Whereas it is desirable that the wiring practices in the FCS conform to those in the rest of the air vehicle, there are certain exceptions where the FCS requirements are more stringent for safety reasons. For example, the FCS wiring in flight critical systems must endure high vibration, high/low temperatures, shock, corrosion, and other natural and induced environments. Although MIL-W-5088 allows soldered connectors, it has been shown soldered connectors do not meet the FCS requirements and only crimped connectors provide the desired integrity.

The FCS engineer should review the contents of the current MIL-W-5088 standard if it is being imposed, either on the total system or specifically on the flight control system. MIL-W-5088 sections of particular interest are: Nonmetals; Sealing material; Essential equipment; Essential circuit junctions; and Splices. MIL-F-9490 contained specific design requirements for cable assembly design and construction, wire terminations, inspection, and replacement of wiring.

In the 1975 version of MIL-F-9490, a paragraph on electrical flight control (EFC) interconnections was included to cover the relatively new concept of fly-by-wire flight controls. With the increasing acceptance of flight control computers, a special subparagraph to call attention to the design concerns is probably redundant. That is not to say that the requirements listed there are no longer valid. The requirements listed below are to be considered for inclusion in the electrical signal transmission requirement.

a. Electrical flight control wiring in individual channels shall be routed, isolated, and protected to minimize the applicable threats to redundancy.

b. Channel loss due to any foreseeable hazard, not extremely remote, shall be limited to a maximum of a single channel.

c. Primary structural components shall be used to afford this protection where possible.

d. Where it is approved by the procuring activity to route the flight control system 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 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.

REQUIREMENT LESSONS LEARNED

Wiring associated with redundant systems must be adequately separated and/or protected from hazards such as:

Wire bundle fire,

Equipment or junction box fire,

Connector shorting or decoupling,

Fuel fire,

Engine case burn-through,

Turbine burst fragments (including turbofans and starter turbines),

Battery chemical leakage,

Abrasion from rocks, ice, and mud,

Burst hot-air ducting, and

Lightning currents from plausible failure of lightning protection.

Various systems of bundle routing, raceway selection, or wire protection may be developed. For circuits which are to be separated from one another for reasons other than EMI, adequate separation can normally be achieved by:

a. Physical separation by either routing in separate bundles or raceways, by maintaining a safe clearance from other wires, or by enclosing the critical wire in suitable sleeving or tape,

b. Never routing through the same connector,

c. Not routing through the same junction box, and/or

d. Not routing through areas where excessive environmental conditions or mechanical failures can adversely affect any redundant system wiring; e.g., turbine burst envelopes, hot air from a burst pneumatic duct, etc.

4.2.3.3 Electrical signal transmission. FCS essential and flight phase essential electrical signal transmission requirements shall be verified by inspection of ________, by testing of _________, and by analysis of all potential failure modes involving electrical signal transmissions.

VERIFICATION RATIONALE (4.2.3.3)

Verification of the electrical signal transmission requirements is essential to assure safety of flight. Verification means used in the past have been inspection, bench test, and ground tests.

VERIFICATION GUIDANCE

Inspection of physical and electrical drawings and inspection of first production air vehicle can verify physical separation, shielding, conformance with wiring installation practices, etc. Electrical isolation and redundancy can be verified by inspection and failure mode analysis and test.

VERIFICATION LESSONS LEARNED

3.2.3.3.1 Multiplexing. Signal transmission circuits shall be __(a)__ type utilizing __(b)__ as the transmission media for the data bus. The data bus, line and its interface electronics, multiplier terminal unit shall __(c)__.

REQUIREMENT RATIONALE (3.2.3.3.1)

Multiplexing of data provides the growth and flexibility necessary to meet the demand of digital flight control systems. Reduced weight and the opportunity for increased system reliability and maintainability are other benefits.

REQUIREMENT GUIDANCE

MIL-STD-1553 deals with twisted shielded pair wire cable multiplex bus. It covers the data bus characteristics, the interface between the data bus and the remote terminal, and the interface between the principal parts of the remote terminal. The interface between the remote terminal and the subsystem is not part of the standard. It is strongly recommended that data busses be required to meet this standard especially when interfacing with subsystems in other disciplines. However there may be situations when the data transmission capacity or rate and other system needs can be better met by another industry standard data bus.

Optical data transmission has been used in some prototype applications, primarily internal to the subsystem. If it is desired to allow or require optical data transmission, then this requirement must be appropriately tailored.

Multiplex-signals are usually required to be digital time division multiplexing type (blank (a)). This is required in MIL-STD-1553 and is compatible with optical applications.

If the signals are electrical, the transmission media must be twisted shielded pair wire cables (blank (b)). Omitting the word wire may be sufficient to allow for optical applications. Bundles or ribbons of optical cables may be acceptable for a particular application; however, reliability, maintainability, damage repair, and environment all must be considered. Blank (c) will normally be filled in with "meet MIL-STD-1553", unless it is determined that an industry standard bus or an optical transmission bus is desirable or if a new military standard data bus has been approved.

REQUIREMENT LESSONS LEARNED

AFWAL-TR-81-3113 on DIGITAC II evaluated the use of optical transmission. The optical busses required the majority of the development effort. This effort was expended primarily in the area of the optical receiver design. The optical bus has two characteristics which make detection more difficult than with the electrical bus: (a) The electrical output levels from the photo diode are weak and therefore require more amplification, and (b) The average signal level is dependent on the bus traffic (duty cycle) which complicates detection of bit transitions.

The increased amplification compromises bandwidth (producing distortion of the pulse train), requires lower power supply noise and better dynamic regulation, and aggravates interference problems. A redesign of the basic optical receiver was performed around a now available wide-band (20 megahertz) high-gain amplifier (LH0082). Preservation of the squarewave quality of the signal enabled detection of the transitions by a differentiation process. Circuit isolation and power supply qualities are still important, but the new circuit appears stable and less sensitive to operating anomalies. Initial testing, in January 1981, was completely successful.

As of this writing, optical transmission for aircraft flight control applications has not yet achieved a level of reliability necessary for safety of flight.

4.2.3.3.1 Multiplexing. The proper operation of multiplex signal transmission circuits shall be verified by ______________________.

VERIFICATION RATIONALE (4.2.3.3.1)

The proper operation of multiplexing data transmission circuits depends on correct design and installation. The verification of proper operation includes inspection, test and in the case of a product which is not on the QPL, possible product qualification.

VERIFICATION GUIDANCE

If a MIL-STD-1553 data bus in being used, it should be a product which has been through the government qualification process. If the chosen bus has not been qualified, it should go through the same type of qualification testing as the MIL-STD-1553 bus. The characteristics and tolerances of the interface electronics, terminal unit, and bus need to be verified. The correct installation needs to be verified by inspection of drawings of the first production vehicle. Tests and analysis to determine failure modes and effects also must be performed.

VERIFICATION LESSONS LEARNED

3.2.4 Signal computation. The methods of signal computation used in the FCS shall be fully suitable to mission, environment, and other requirements imposed upon the FCS.

REQUIREMENT RATIONALE (3.2.4)

The methods of signal computation used in the air vehicle must be appropriate to the mission of the air vehicle and must not degrade the reliability of the air vehicle nor impose excessive requirements on other systems.

REQUIREMENT GUIDANCE

There are many options available for use in the designing of the signal computation portion of the FCS. The relative figures of merit of analog and digital computation, trade-offs between central versus dedicated architecture, and interface concerns should be addressed when choosing the FCS computational methods.

Signal computation performed outside of the flight control computers must not be ignored. Geared mechanisms, hydraulic signal blending and even pneumatic summing are all examples of signal computation which could be used in a FCS.

REQUIREMENT LESSONS LEARNED

4.2.4 Signal computation. The methods of signal computation used in the FCS shall be verified by ______________________.

VERIFICATION RATIONALE (4.2.4)

The verification of the methods used for signal computation provides the means of determining the suitability of the chosen designs early in the development.

VERIFICATION GUIDANCE

The applicability of the chosen computer architecture and computational schemes can be verified initially by analysis and inspection of drawings and engineering control documents and ultimately by test of the computational elements.

VERIFICATION LESSONS LEARNED

3.2.4.1 Transient power effects. *Flight control* computers shall not suffer adverse effects, which result in operation below FCS Operational State __, due to 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.

REQUIREMENT RATIONALE (3.2.4.1)

Signal computation elements must provide for the most adverse power source variations and provide the appropriate levels of redundancy and failure immunity to meet the invulnerability, reliability, and maintainability requirements placed on the FCS.

REQUIREMENT GUIDANCE

Power source variations are a common problem in air vehicle power source design. All flight control equipment dependent on electrical power source should be designed with these adverse conditions in mind. Of particular concern are flight control computers in fly-by-wire aircraft, especially those air vehicles which are statically unstable. It is recommended that power source variations should not result in operation below FCS Operational State I.

REQUIREMENT LESSONS LEARNED

The electrical power system should have equivalent redundancy to the flight control system. The electrical power system is normally designed by avionics engineers.

In a quad redundant fly-by-wire airplane, the electrical power system had a problem where a latent failure caused power shut down to critical components of the flight control system. The result was loss of the airplane. Prior to this incident, the power system had been analyzed and found to contain enough failure detection capability to achieve the specified loss of control rate for the airplane. However, the analysis only covered failures occurring in succession; i.e., no latent failures present. For this incident, a latent failure was present prior to the actual failure which shut down the electrical power. The latent failure had also been studied prior to the incident but a wrong assumption was made as to how the failure would manifest itself.

The fix was a two part redesign of the electrical power system. The first was to provide protection for the latent failure and the second was to provide quad independent power to the flight control system.

4.2.4.1 Transient power effects. The flight control system operational state capability during power system variations shall be verified by ____________________.

VERIFICATION RATIONALE (4.2.4.1)

The capability of the flight control system, particularly the flight control computers, to maintain operation in spite of power source variations is necessary to meet reliability and invulnerability requirements.

VERIFICATION GUIDANCE

Analysis and test are the best methods of verifying the flight control computers immunity to power system variations. The flight control computers must be able to function properly for the full range of allowable voltages and currents, since the FCS engineers do not have control over the power system design or operational limits. Power system failure and redundancy needs are covered in other requirements.

VERIFICATION LESSONS LEARNED

3.2.4.2 Mechanical signal computation. Mechanical signal computation shall be accomplished by means of __________ elements. Nonlinearities and parameter variations shall not cause adverse effects which cause degradation in flying qualities or the FCS operational state.

REQUIREMENT RATIONALE (3.2.4.2)

Various means of mechanical signal computation are available, but all may not be desirable for the air vehicle under consideration.

REQUIREMENT GUIDANCE

Mechanical computation equipment includes geared mechanisms, hydraulics, and pneumatic elements for scheduling, comparing, summing, computing, and gain changing as required for input, output, mode control, signal conversion, and signal transmission. MIL-F-9490 required that the mechanical computation elements meet certain other specifications. Geared mechanisms were to meet the requirements of MIL-G-6641. Hydraulic elements were to be designed in accordance with MIL-A-5503, MIL-P-8875, MIL-H-8890, or ARP 1281, as applicable. MIL-V-27162 was cited as a general guide for the design of control valves used in hydraulic computing components. MIL-P-8564 and AFSC DH 1-6, Section 3G, were required, as applicable, for pneumatic computation elements.

Due to the failure immunity requirements for the FCS, mechanical computers must be designed such that the air vehicle is capable of continued normal flight and landing after any single failure in the computer system whose failure probability is greater than extremely remote.

Requirements for mechanical computers that are integrated into the flight control systems must be consistent with the other basic system requirements. The following requirements should be added as applicable.

Hydraulic (and/or pneumatic) computing elements that are integrated into the flight control system shall be consistent with the air vehicle requirements for other hydraulic (and/or pneumatic) elements in the system.

Mechanical computer geared elements shall be designed so that backlash, friction and inertia are minimized to provide adequate sensitivity between the input and output of the computer.

REQUIREMENT LESSONS LEARNED

4.2.4.2 Mechanical signal computation. A dynamic and steady state analysis shall be performed on mechanical computation systems to verify that no adverse effects are present due to nonlinearities and parameter variations.

VERIFICATION RATIONALE (4.2.4.2)

The effect of nonlinearities and parameter variation on stability and/or steady-state performance due to nonlinear characteristics of the elements and parameter variations caused by manufacturing tolerances, wear, and environmental conditions must be considered.

VERIFICATION GUIDANCE

Most real systems are nonlinear to some extent, but the usual region of operation is nearly linear. The purpose of the analysis is to determine the effects of nonlinearities and parameter variations inherent in the system, such as friction, stiction, backlash, saturation, tolerances, wear, and changes due to environment. The system design may need to be modified based on this analysis so that any adverse effects are compensated for or are determined to be insignificant in terms of overall system requirements.

VERIFICATION LESSONS LEARNED

3.2.4.3 Electrical signal computation. At the time that the production configuration baseline is established by the procuring agency, a ____ percent growth capability for computation shall exist within each flight control computer. Scaling, __________ shall provide satisfactory resolution and sensitivity to ensure continuous safe operation for all possible combination of maneuvering demand and gust or other plausible disturbances, and to prevent unacceptable levels of nonlinear characteristics or instabilities.

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

Support and maintenance provisions shall ________
______________.

REQUIREMENT RATIONALE (3.2.4.3)

Provisions for computation growth are necessary to allow for modifications to the flight control system during flight test evaluation and subsequent updates to the fleet. Proper scaling of signals, word size, input limiting, overflow protection, sampling, and computation rates are important to assure not only desirable response, adequate stability margins and acceptable flying qualities, but also safety of flight. Computation failures must not be allowed to propagate to the command processing elements because of the safety of flight implications.

REQUIREMENT GUIDANCE

All electrical signal computation for the flight control system may be categorized as being performed by either analog or digital computation elements. Signal computations include simple summation and amplification as well as the solution of complex automatic flight control equations. Analog computation elements include hardware components required for input/output, mode control, signal processing, control, and signal transmission. Digital computation equipment includes hardware and associated software for data processing, program storage, input/output, control, and signal transmission. This requirement with tailoring is applicable to both analog and digital computation. Growth capability in flight control computers include not only "real estate" such as card slots, I/O ports, connectors, etc., but in digital computers growth capability must also be available in memory, scratchpad allocations, and duty cycles.

Twenty-five percent growth capability is the currently acceptable value and should be available at the time of the Functional Configuration Audit (FCA). This will necessitate judicious planning on the part of the contractor since detailed design solutions offered during the Critical Design Review (CDR) are often modified to account for control law revisions that occur as aerodynamic data and stability analysis are refined.

Scaling in both analog and digital computation is important to provide safe and desirable responses. In digital computation the scaling must provide satisfactory resolution to prevent the granularity due to the D/A and A/D conversions from being apparent to the pilot and from providing the source of additional excitation energy for structural elastic modes.

In addition to scaling the word size, input, limiting, and overflow protection are important in digital computers to provide satisfactory resolution and sensitivity.

If digital computation will be used for flight control computation, overflow, memory protection, sample rates, and computation rates should also be addressed. The blank following the second sentence of the 3.2.4.3 requirement is provided for that purpose. For digital computers the computation rates and sample rates shall be established at a level which ensures that the digital computation process will not introduce unacceptable phase shift, nonlinear characteristics, and frequency fold over or aliasing into the system response. Memory protection features shall be provided to avoid inadvertent alteration or loss of memory contents. Memory protection shall be such that neither electrical power source transients nor EMI shall cause loss of program memory, memory scramble, erroneous commands, or loss of ability for continued operation. Any condition capable of producing an overflow in an essential or flight phase essential function shall be precluded by overflow detection and data recovery and/or continuous safe operation following an overflow.

All possible hazardous failure conditions for the flight control computers need to be identified during the Preliminary Hazard Analysis and fail-safe provisions identified. Inflight monitoring BIT techniques are discussed under 3.1.3.9 and 3.1.3.9.4. Other fail-safe provisions such as output limiting or averaging may be considered.

Support and maintenance provisions for the flight control software, in the form of software support packages are normally part of the responsibility of the logistics personnel and requirements for a particular acquisition should coordinate with the logisticians.

REQUIREMENT LESSONS LEARNED

Occasionally rescaling of computer inputs/outputs is necessary to achieve the desired performance. This need may be discovered during piloted simulation or flight test of the full-scale development air vehicle.

Electronic (digital) use in flight controls has led to more integration with crew systems, propulsion, avionics, and flight equipment. Such integration increases complexity and requires a very rigorous approach to the physical and procedural integration techniques. This takes the software and evaluates it to the level of flight safety. Thus, software requires a very rigorous approach and thorough testing from the unit level on up. Since use of digital lends itself to change, usually many changes in control laws and special features ensue. Every change necessitates complete testing and evaluation. Shortcuts should not be allowed. Thus, the growth of the system, both physical and timing (throughout), needs to be allocated accordingly. Historically, flight systems grow about 50% from a baseline system. In the beginning of a program, at least 75% growth should be allocated. Twenty-five to 35% will be used in development to arrive at a baseline. Flight control history doesn't explicitly show due to eliminating functions, simplifying equations, etc., which is a loss in performance. To get what is really needed, without compromises, 75% is a good value for the beginning, with 35-50% left for production changes.

4.2.4.3 Electrical signal computation. Growth capability shall be verified ____________________. ____________________ shall be used to verify the adequacy of signal scaling. Proper operation of computation channel disengagement, if applicable, and other fail-safe provisions shall be verified by ______________________________.

VERIFICATION RATIONALE (4.2.4.3)

Adequate scaling word size, overflow protection, input limiting, sampling notes, computation rates, and the proper identification and handling of failures must be verified because of the flight safety considerations. Growth capability impacts the 'longevity' of the computer as an element of the FCS and must be verified.

VERIFICATION GUIDANCE

Growth capability should be verified at the FCA by inspection of drawings and analysis reports.

Iron bird tests, piloted simulations, and flight tests can be used to verify proper scaling. Computer characteristics such as overflow protection, input limiting, etc., proper fault isolation and implementation of failsafe provisions should be verified by analysis and the aforementioned tests. These can be performed as part of the invulnerability and failure immunity verification.

VERIFICATION LESSONS LEARNED

Incomplete testing and documentation of the hardware and software has led to unsupportable aircraft for the Air Force. Without "complete" documentation, the making of changes and evaluating the testing is risky. Where safety of flight is concerned, a minimum of compromises and risk are required. Thus, the documentation needs to be complete. Testing, as well, needs to be complete. The change, its impact to the particular function, as well as interfacing functions (both hardware and software) need to be clearly understood. Test cases should cover all possible normal inputs, out of range inputs, abnormal values, and transients both singular and multiple. No other system has as much a catastrophic effect in regards to latent failures as flight controls. Every effort should be made to test at the lowest level. After an accident, it is hard to find the ones or zeros or transients that caused it. Therefore, testing exhaustively is necessary. History has shown that hardware and software design errors exist. Fortunately, the greater percentage have been benign. But, even one that causes loss of your aircraft will have paid for the extra testing involved. Suggested testing methods are a complete set of test cases, an independent peer review, and sneak circuit/software analyses to uncover the latent failures.

3.2.5 Control power. 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 airplane performance shall not be greater than ____________________. Essential and flight phase essential flight controls shall be given priority over noncritical controls and other actuated functions during simultaneous demand operation.

REQUIREMENT RATIONALE (3.2.5)

The trend toward neutral or negative aerodynamic stability has increased the reliance on artificial stabilization in high performance aircraft. This makes sufficient control power capacity and priority essential to safe flight. This paragraph requires that the appropriate preliminary design analysis is done to ensure proper power system sizing and priority provisions of essential flight controls.

REQUIREMENT GUIDANCE

Operational State III is defined in MIL-F-9490 as minimum safe operation and therefore should be tied to the probability of aircraft loss due to FCS failure. This requires that cumulative failure probabilities of FCS and components and the cumulative exceedance probability of turbulence be considered. The probability of aircraft loss due to flight control failures is sometimes referred to as extremely remote.

REQUIREMENT LESSONS LEARNED

The trend toward neutral or negative aerodynamic stability, with increased reliance on artificial stabilization in high performance aircraft, increases surface actuation rate demands. This in turn increases the size, weight, and cost of the power systems. Therefore, it is very important that a careful analysis of requirements be made as early as possible in the aircraft development phase since these requirements impact the procurement of many long lead items such as hydraulic pumps, control valves, reservoirs, tubing, and the prime movers, such as engine power takeoffs and APUs.

In many cases, the power requirements can only be optimized by determining control rate requirements on a realistic flight simulator "flown" by typical service pilots. The simulation should include turbulence intensity levels, as specified in 3.1.3.7 of MIL-F-9490D. To determine control surface rates and power requirements under system partial failure conditions, reduced turbulence intensities (such that the combined probability of turbulence and of each selected failure condition equal the maximum allowable failure rate for the specified flight-safety reliability requirement) should be used.

With the use of fully powered flight control systems powered by hydraulic or electric systems that also supply other loads, care must be taken to ensure that power demands of those other functions do not deprive essential flight control actuation subsystems of sufficient power to perform their functions. In many cases, the power demands for landing gear retraction and extension are greater than required for flight control; and, during landing gear operation by hydraulic systems which also supply utility functions (such as where the dedicated hydraulic system has failed), provisions must be made to prevent disruption of flow to the essential flight controls.

4.2.5 Control power. Sufficient control power shall be verified by ______________________.

VERIFICATION RATIONALE (4.2.5)

Adequate control power is required for safety of flight.

VERIFICATION GUIDANCE

Analysis and simulation is the obvious means of verification, but testing may be feasible and appropriate for some aspects of control power and priority. As with other FCS requirements, verification by test using the iron bird, hybrid simulation, or DT&E aircraft should be done when possible.

VERIFICATION LESSONS LEARNED

3.2.5.1 Hydraulic power subsystems. All hydraulic power generation and distribution systems normally used for flight control shall be designed in accordance with ____________________.

The FCS shall operate in accordance with this specification when applied with such power.

REQUIREMENT RATIONALE (3.2.5.1)

Hydraulics is the most frequently used source of power for essential and flight phase essential FCS functions. Adequate hydraulic power system requirements are necessary for flight safety.

REQUIREMENT GUIDANCE

This is an interface area with the hydraulic systems engineering discipline. Coordination is suggested. Hydraulic power and distribution systems should be designed in accordance with MIL-H-5440 and MIL-H-8891 or similar industry standards as applicable. AFSC DH 1-6, Section 3F, may be helpful in requirement selection.

Hydraulic power subsystem engineering is an engineering area separate from FCS engineering; however, FCS engineering requirements may be the most demanding and most critical requirement which influence the hydraulic power subsystem design. The interfacing of these two areas, therefore, becomes of great importance and close cooperation between the two design engineers is critical. Hydraulic power and distribution systems should be designed in accordance with MIL-H-87227 or similar industry standards as applicable. AFSC DH-1-6, Section 3F, may be helpful in requirement selection. The blank should be filled such as follows: "provide compatible redundancy for the FCS such that loss of any one hydraulic system shall not result in the loss of any control effector or inability to maintain Operational State III. Further, hydraulic failures shall not go below Operational State V for at least two minutes. Hydraulic pressure shall meet the static and dynamic flight control stiffness parameters ___________.

REQUIREMENT LESSONS LEARNED

Hydraulic power for use with fully-powered essential and flight phase essential MFCS, is specified on the basis of proven performance and ability to provide high force outputs with minimum weight. Use of electrical-mechanical actuation or pneumatic power will require justification and specific approval by the procuring activity. Development work directed toward use of liquid metal as hydraulic fluid is described in AFFDL-TR-70-121 and may be further pursued in the future.

Requirements stated herein which may determine hydraulic capacity include: MFCS and AFCS performance (3.1.1 and 3.1.2), failure immunity and safety (3.1.3.4), and operation in turbulence (3.1.3.7).

Redundancy is specified by 3.1.3.1 of MIL-F-9490 at the system level. However, it must be recognized that hydraulic system failures can be a major cause of flight control system failure, and the MIL-H-5440 requirement to keep at least one system free of any noncritical system function has been in effect for many years. There are many aircraft, however, which require two or more power sources for actuation of utility or noncritical flight control functions. In the past, these have often been actuated by an alternate power means, such as a stored-gas-high-pressure pneumatic system for emergency landing gear extension, or an electric motor for emergency flap extension. However, as such loads become higher, such as due to increased aircraft size or speed, there is more incentive to operate hydraulically. Therefore, if it is clearly shown that significant penalties can be avoided by utilizing the "dedicated" hydraulic system as an alternate source of power for the utility or noncritical flight control function, the procuring activity may entertain a request for deviation to the MIL-H-5440 requirement if a reliable isolation shutoff valve can be provided.

Lessons learned are reflected in the requirement found in MIL-H-5440 and MIL-H-8891, the material in AFFDL-TR-76-116 and other such historical documents. The fundamental, or essential part of these lessons is that hydraulic power is a safety critical input to the flight control system in the modern military aircraft. Such status places strict and overriding requirements on the design and installation of that subsystem and on its redundancy, failure modes, reliability, maintainability, vulnerability, etc. The problems associated with the FCS hydraulic power subsystem have been numerous in the past and the current trends to use higher operating pressures and more complex fluids has added to this condition. The FCS engineering specialist should place great emphasis in this area and utilize the hydraulic subsystem engineering specialist to the maximum extent possible to provide the best possible design and a thoroughly tested subsystem for the FCS.

4.2.5.1 Hydraulic power subsystems. Hydraulic power subsystem requirements shall be verified by ______________________.

VERIFICATION RATIONALE (4.2.5.1)

If hydraulic power is required for the operation of essential and flight phase essential FCS components, then the adequacy of the subsystems must be verified because of safety of flight implications.

VERIFICATION GUIDANCE

This requirement paragraph should be verified by test. Coordination with the hydraulics engineering discipline is strongly suggested.

VERIFICATION LESSONS LEARNED

3.2.5.2 Electrical power subsystems. Electrical power generation and distribution subsystems should comply with requirements of this specification and the following: ______________________.
For fly-by-wire air vehicles, electrical systems which provide power to essential or flight phase essential controls shall be designed to ensure uninterruptible, isolated, redundant power of adequate quality to meet FCS requirements after any malfunction not considered extremely remote.

REQUIREMENT RATIONALE (3.2.5.2)

Automatic flight control components and elements of the stability augmentation subsystems require acceptable, uninterrupted electrical power for essential and flight phase essential FCS functions.

REQUIREMENT GUIDANCE

This is an interface area between the FCS and electrical power system engineering disciplines. Coordination is suggested to ensure that the electrical systems which provide power to essential or flight phase essential controls, should ensure uninterruptible, isolated, redundant power of adequate quality to meet FCS requirements after any malfunction not considered extremely remote. Such electrical systems should, except for basic power source, be independent of failure modes associated with any other electrical system. Essential and flight phase essential FCS should be automatically provided alternate sources of power where interruption could result in operation below FCS Operational State III. A protected alternate source of power should 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. Control systems employing both ac and dc power inputs should normally have interlocks incorporated to disconnect both power inputs should either type of power be lost. However, if the loss of either power source can be shown to be equivalent to loss of both or FCS Operational State III or better is maintained with either power source, interlocks may not be required. Further guidance can be obtained from the following documents:

a. MIL–F–9490

b. AFSC Design Handbooks

(1) DH 1–4: Electromagnetic Compatibility

(2) DH 1–6: System Safety

(3) DH 2–1: Airframe

(4) DH 2–2: Crew Stations and Passenger Accommodations

c. MIL–D–6051, MIL–STD–461: Electromagnetic interference limits

REQUIREMENT LESSONS LEARNED

Electrically powered controls which can be considered essential to safe flight include AFCS automatic landing controls, certain command augmentation and stability augmentation systems, and all electrical flight control (fly–by–wire) systems. In order to meet flight–safety requirements, these systems are redundant so that the critical control function will be maintained even when failures occur.

The electrical power sources in the FCS and from the aircraft must be equally dependable and redundant.

The requirement for redundancy has the greatest impact on the design of generating system configurations. A single fault on any part of a paralleled multichannel generating system will result in loss of power to all air vehicle systems until the fault is cleared. During certain extreme cases, this could take up to 3 or 4 seconds and could occur during a critical period such as the final moments of an automatic landing. Electrical isolation of the generating systems would prevent a single fault from affecting more than one channel of flight-critical equipment.

The degree of isolation and the number of isolated channels that may be required will be dependent on the specific requirements for the air vehicle in question. In general, an independent source of electrical power will be required for each redundant channel of essential or flight phase essential control systems.

Isolated Versus Parallel
Operation of Generators

Parallel operation of multichannel (three or more) generating systems may offer considerable performance and economic advantages over a system composed of isolated channels. However, parallel operation includes the possibility of a single fault causing trips of more than one channel or an overload momentarily affecting and degrading power to all airplane loads. Also, the load division circuitry required for parallel operation adds complexity to the generating system and increases the chances for malfunctions which could cause the temporary loss of one or more generating channels.

Essential and flight phase essential control systems are provided in varying degrees of redundancy, and this imposes the requirement that power sources to these systems be equally reliable. A parallel system, if composed of three or four generating channels, will be a highly reliable source, but it is vulnerable to several single failure modes (failure of current transformer shorting contacts, excitation loss, open current transformer loop, main bus or load circuit faults, synch bus faults), which can transiently interrupt or seriously degrade the quality of power on all main busses simultaneously. Abnormal power quality will be supplied to all loads for a time ranging from 0.020 to 3.0 seconds. This time is dependent on the specific type of failure and the delays associated with the protective circuitry. It should be noted, however, that simultaneous failures will be normally of very short duration and will be automatically cleared from all but the faulted bus. In the unlikely event that multiple failures result in an inability of the system to automatically clear a fault, proper crew action can restore power to the unfaulted busses. Past experience shows that nuisance trips can occur which may result in overloading of the remaining channels and a brief "all power lost" situation.

The required reliability of power sources may be provided most simply by isolating four generating channels with no interconnecting ties between busses. This isolation ensures that a fault on one channel cannot affect the others. However, isolation also means that system overload capabilities are decreased from those of a parallel system of equal rating and isolation may impose weight penalties on the air vehicle design if sufficient generating system capacity with provisions for future growth and overload capability is to be obtained. The degree to which power sources must be isolated is peculiar to each design and application.

Redundant Power Sources

The concept of isolation, as mentioned in the paragraph above, provides redundancy equal to the number of generating channels. The redundancy of power sources, however, is expected to be equal to the number of redundant channels of flight-critical equipment. Autoland systems are being proposed in triple redundant, fail-operative versions. If this system was installed in a two-engine air vehicle (two isolated generating channels), a third power source should be provided. A battery-inverter standby system may be considered as a redundant source, but its capacity severely limits the loads which can be operated from it. A third isolated generating channel, operating continuously, would be required to satisfy the redundancy definition, and its capacity must be adequate for one set of load equipment. Monopropellant emergency power turbine generators are now being installed in several fighter aircraft for an independent backup power source.

A combination of parallel and isolated operation can also be considered (for example, a four channel system operating with channels one and two paralleled and channels three and four paralleled, but one and two are isolated from three and four). These four channels are essentially two isolated sources, and if more redundancy is required, additional isolated sources would be required.

Power Limiting Devices

As mentioned above, the degree of isolation of isolated generating system channels can be compromised by a switchable bus. A transfer bus (to which essential loads are connected) is generally arranged so that loss of power to it would cause it to be transferred to the alternate source of power. This switching capability may well compromise the integrity of both of these power sources in that a fault in the critical load equipment (or on its bus) could be applied to one bus and then the other after switching. For this reason, a transfer bus scheme should not be considered for an air vehicle with essential electrical control systems unless a device is included in series with the transfer bus that eliminates the possibility of a single fault causing unacceptable disturbances to more than one power source.

The development of a practical and reliable power (or current) limiting device for this purpose would simplify power system design for critical loads. Some of the basic requirements of a power limited device are as follows:

a. Sized to coordinate with the largest thermal circuit breaker connected to the priority bus.

b. Sized to carry the maximum startup load connected.

c. Capable of dissipating the electrical losses incurred during maximum load and faulted operation.

d. Self-cooling--no cooling air would be supplied.

e. Reliability must be of exceptionally high order.

f. Failures must be passive, i.e., must not fault the main bus due to component failure of the device.

g. Waveform deterioration during limiting mode must not be severe enough to cause damage to any of the connected loads.

4.2.5.2 Electric power subsystems. Requirements for electrical power subsystems shall be verified by ______________________.

VERIFICATION RATIONALE (4.2.5.2)

Adequate, uninterrupted electrical power to essential and flight phase essential flight control components is required for safe flight.

VERIFICATION GUIDANCE

The means of verification should be coordinated with the electrical power engineering discipline. Verification by test is desired when feasible, but other means, such as analysis, demonstration, or inspection, may be adequate.

VERIFICATION LESSONS LEARNED

3.2.5.3 Pneumatic power subsystems. Pneumatic power using ram-air, engine bleed air, stored gas, mechanically compressed air, or generated gas may be used for noncritical flight control functions. Pneumatic power systems shall conform to ______________________.

REQUIREMENT RATIONALE (3.2.5.3)

Pneumatic power is occasionally used for noncritical flight control functions. This paragraph provides the requirements for the proper design, installation, and performance of these systems.

REQUIREMENT GUIDANCE

Guidance for the development of requirements for pneumatic systems can be obtained from the following documents or similar industry standards:

a. MIL-P-5518: High pressure pneumatic systems.

b. AFSC DH 1-6: System safety, Section 3G; Pressurization and Pneumatic Systems.

c. MIL-E-38453: Engine bleed air systems.

REQUIREMENT LESSONS LEARNED

This requirement was expanded to include ram-air and engine bleed air sources in recognition that low-pressure pneumatic sources are readily available on jet aircraft and have been and will continue to be considered and used for powering noncritical flight control functions. Neither high-pressure nor low-pressure pneumatic sources appear feasible for powering essential or flight phase essential functions, other than hydraulic pumps and electric generators, at this time.

This requirement is not meant to apply to boundary layer control as may be used for short field takeoff and landing applications.

4.2.5.3 Pneumatic power subsystems. Verification of pneumatic power systems requirements shall be accomplished by ______________________.

VERIFICATION RATIONALE (4.2.5.3)

Verification of adequate pneumatic power is required to ensure adequate flight control performance.

VERIFICATION GUIDANCE

Verification should be by analysis or test where feasible.

VERIFICATION LESSONS LEARNED

3.2.6 Actuation. The design, installation, and performance of flight control actuation components, subsystems, and interfaces shall comply with this specification. Load capability of actuation components and subsystems shall be in accordance with ______________.

REQUIREMENT RATIONALE (3.2.6)

This paragraph establishes the system level requirements for FCS actuation systems and specifies load capabilities of elements subjected to pilot loads and elements driven by power actuators.

REQUIREMENT GUIDANCE

This is an area of interface between FCS engineering and the structures discipline. Coordination is required for proper definition of limit and ultimate loads as specified by that discipline. Further guidance may be obtained from MIL-F-9490 and MIL-A-8865.

REQUIREMENT LESSONS LEARNED

4.2.6 Actuation. Verification of FCS actuation components and subsystems shall be accomplished by ______________.

VERIFICATION RATIONALE (4.2.6)

Verification of actuation requirements is necessary to ensure satisfactory performance of these FCS components and subsystems.

VERIFICATION GUIDANCE

Inspection and demonstration may be satisfactory for system level requirements. Load capability is usually verified by test. Individual actuation components and subsystems requirements are verified by the appropriate test and analysis.

VERIFICATION LESSONS LEARNED

3.2.6.1 Mechanical force transmitting actuation. Mechanical force transmitting devices shall be designed in accordance with the following requirements ______________________.

REQUIREMENT RATIONALE (3.2.6.1)

This paragraph provides the requirements for force transmitting devices other than control cables and push-pull rods, which are covered elsewhere. Power-screws are utilized in the actuation of many low duty-cycle flight control surfaces such as wing flaps and trimmable stabilizers.

REQUIREMENT GUIDANCE

Requirements for mechanical force transmitting devices should not include control cable actuation or push-pull rod actuation as these FCS components are covered elsewhere. MIL-F-9490 or other applicable industry specifications and standards may be used as a guide for these requirements.

REQUIREMENT LESSONS LEARNED

Force transmitting powerscrews have been used for a long time for non-critical flight control applications (e.g., landing gear actuation on B-17, B-29, B-50, and B-47 airplanes, and flaps and stabilizer trim on B-52, KC-135, and many commercial airliners), but as yet not for actuation of essential control surfaces. The requirement that specific approval must be obtained before using power-screws for high-duty-cycle applications is not intended to prohibit their use, but rather, to ensure that the contractor has fully investigated their capability to perform reliably under required conditions and can present substantiating evidence for approval before committing the design. Trim actuators including those commanded by AFCS, are usually considered in the low-duty-cycle category. A nonjamming stop is one which does not prevent actuation of the nut by the normal means.

One detail point to note here is that highly loaded threaded powerscrews develop considerable friction, and the design and lubrication provisions must be thoroughly evaluated by analysis and supplemented by rigorous testing under realistic operating conditions. Lubrication provisions must be adequate for controlling efficiency, wear, and heating to acceptable values.

A prime example is the F-111 Acme threaded powerscrew used for variable wingsweep actuation. An extensive trial and error development program, in which a great number of material combinations were evaluated, was required to produce the grease-lubricated teflon and fiberglass cloth lined screw nut design which eventually met the design requirements.

Ballscrews Ref: Product Engineering 5 Feb 1962, Saginaw. Two limiting factors when all balls are to be load carriers:

a. The number of balls in any single circuit should be less than 125.

b. Maximum circuit length should be less than 3-1/2 turns.

The load carrying capacity of ball screws closely parallels that of conventional ball bearings.

Manufacturing limits are about 3/16 inch minimum and 8 inches maximum diameter of all circle pitch diameter.

Leads of about 0.125 time pitch diameter are about minimum--no maximum top limit.

Failure mode is almost always broken balls.

Impact loading of balls determines life. Impacts are the number of balls that pass one point on the nut in one revolution of the screw. It's best to keep the number of impacts to between 5 and 13.6 per revolution.

4.2.6.1 Mechanical force transmitting actuation. Verification of requirements for mechanical force transmission shall be by ______________.

VERIFICATION RATIONALE (4.2.6.1)

This verification provides for the formal documentation of the design and performance of mechanical force transmission devices.

VERIFICATION GUIDANCE

As in other FCS areas, these components should be included in the full scale FCS function mockup and testing. Where testing is not deemed necessary or cost effective, analysis or inspection may be adequate verification.

VERIFICATION LESSONS LEARNED

3.2.6.2 **Mechanical torque transmitting actuation.** Mechanical torque transmitting devices shall be designed in accordance with the following requirements ____________________. Backlash accumulation shall not prevent the system from performing its required function throughout the service life of the airplane.

REQUIREMENT RATIONALE (3.2.6.2)

Torque transmission devices are often used in FCS applications. This paragraph provides for requirements governing the design, installation, and performance of these devices.

REQUIREMENT GUIDANCE

Torque transmission devices include such things as torque tubes, torque limiters, universal joints, slip joints, gear trains, flexible shafts, and helical splines. These devices have not, historically, been used for essential and flight phase essential applications without specific approval. MIL-F-9490 includes requirements for devices of this type and may provide some general guidance. For specific requirements the following documents, or industry equivalents, should be used:

a. MIL-J-6193 or MIL-U-3963 should be used along with AFSC DH 1-2.

b. MIL-G-6641 should be used for the design of gearboxes.

REQUIREMENT LESSONS LEARNED

All torque tubes should be mounted on antifriction bearings with supported couplers (jackshafts mounted to structure on antifriction bearings) spaced at close enough intervals and with sufficient misalignment capability (within the couplers) to prevent undesirable bending or whipping of the tubes. In addition, the prevention of spark generation in fuel system areas should be given careful consideration in the detail design.

A minimum of parts, joints, and related components should be used to accomplish the required purpose; however, it must be possible to remove the torque tube sections from the air vehicle and replace them readily.

Helical splines (also known as Yankee screw drivers) are getting more and more attention as the needs to design mechanisms which can transmit high torque (or translate linear force to torque) in thin airfoil sections increase. When used, lubrication provisions must be adequate for controlling efficiency, wear, and heating to acceptable values. 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, temperatures, and environmental vibration over the full service life of the unit, both steady loads and reversing or variable magnitude loads which may be encountered due to control surface loads, buffeting, or buzz.

Rotary mechanical actuators (often referred to as power hinges) with torque limiters and no-back brakes have been used in some relatively recent applications (e.g., wing tip fold actuation on the RS-70, weapon bay door actuation on the F-111, and leading edge flap actuation on the Boeing 747) but, prior to their selection for actuation of the B-1 rudder, have not been used for actuation of a primary control surface.

As an alternate to a no-back brake, a mechanically irreversible actuator may be used providing it can react rated static limit load applied to the output coupling with the input coupling disconnected, without being back-driven while being subject to any vibration condition within the required vibration envelope or spectrum. Where torque limiters are used, it is desirable that they release upon removal of the downstream jamming load without a requirement for change in the upstream torque value or direction.

No-back brakes, or Sprague clutches, are not suitable for transmitting large power loads or holding heavy loads. When installed in a large transport aircraft for the pitch trim actuator, they were rough in operation, chattered, and failed to hold the overriding loads. These units depend on maintaining precise friction values and wedging angles, and are sensitive to surface finish, environmental conditions, method of operation, etc.

4.2.6.2 Mechanical torque transmitting actuation. Verification of mechanical torque transmission requirements shall by accomplished by ______ ______________________.

VERIFICATION RATIONALE (4.2.6.2)

Performance, installation, and design requirements need to be verified and formally documented for all FCS actuation devices. These elements, while not necessarily flight phase essential, do affect the air vehicle flying qualities and performance.

VERIFICATION GUIDANCE

As in other flight control actuation elements, verification should be by test where feasible. If other means are used, such as inspection or analysis, formal documentation should still be required.

VERIFICATION LESSONS LEARNED

3.2.6.3 Hydraulic actuation. Hydraulic actuation subsystems and components shall be designed in accordance with the following requirements: ___ ____________. If hydraulic bypass provisions are necessary to prevent fluid lock, excessive friction load or damping, __________. In actuation systems designed for manual control following hydraulic failure, provisions shall be made to ____________.

REQUIREMENT RATIONALE (3.2.6.3)

This requirement establishes the guidelines for the design of hydromechanical FCS actuation devices. These devices are critical to flight control performance and flight safety.

REQUIREMENT GUIDANCE

Requirements for hydraulic actuation subsystems and components may be extracted from Military specifications, Design Handbooks, Aerospace Recommended Practice (ARP) documents, and other applicable industry specifications and standards. ARP 1281 provides a good source of general specification requirements and is in the Military format. AFFDL-TR-74-116 contains guidance for the installation, invulnerability, reliability and maintainability of FCS subsystems and components and should be used for coordination with these other disciplines at the system level.

Hydraulic actuation components are classified by the following fluid temperature ranges:

Type I	-65^oF to $+160^oF$
Type II	-65^oF to $+275^oF$
Type III	-65^oF to $+390^oF$

Type I and Type II components should be designed in accordance with MIL-H-8775. Type III components should be designed in accordance with MIL-H-8890.

Other specific component requirements should be applied as follows:

a. MIL-V-27162 and ARP 988 should be applied for electro-hydraulic servo valves with mechanical position feedback.

b. MIL-A-5503 should be applied for actuating cylinders without control valves and feedback provisions (ie., flap actuators, speed brake actuators).

c. MIL-M-7997 should be used to define requirements for hydraulic motors.

For guidance on types of hydraulic actuation devices that may be used for critical flight control functions, AFFDL-TR-74-116 should be used.

Where bypass provisions are necessary, automatic bypass and reset shall be provided as a function of system pressure (Ref. AFFDL-TR-74-116)

In boosted systems, where manual reversion capability is provided, there should be provision for training and checkout.

REQUIREMENT LESSONS LEARNED

Lessons Learned in this area are reflected in the requirements of MIL-F-9490, AFFDL-TR-71-78, AFFDL-TR-74-116, ARP 1281 and other industry specifications and standards.

Rip stop design has been shown to be most effective in preventing propagation of fatigue cracks from areas where more than one hydraulic system input is located. Use of beefed up walls has shown to be ineffective to meet a high lift requirement of 8,000 hours. Many variables, aircraft vibration, thermal, equipment vibration, and hydraulic hammering impact the fatigue life of actuators. Any change in structure, mounting, hydraulic parts, or flight control laws usually do not get evaluated concerning the effect on actuators. Recent failures on a relatively new system, with an average of 1,500 to 2,500 hours, have shown beefed up walls ineffective in the hydraulic power drive units. Cracks have propagated and been very close to causing loss of all hydraulics. Rip stop ideally is mated, bolted parts. Some compromise, such as hollowed out areas in between hydraulic sections, may be acceptable, but testing for as many varied parameters as possible needs to be accomplished to demonstrate the life.

4.2.6.3 Hydraulic actuation. Hydraulic actuation component requirements shall be verified by ____________________________.

VERIFICATION RATIONALE (4.2.6.3)

Hydraulic actuation devices are used in flight control functions critical to flight safety and air vehicle performance. The requirements in this paragraph provide a means for control of some of the hazards associated with installed hydro-mechanical FCS elements. The verification process provides the means for documenting the extent to which the hazards can be minimized or precluded.

VERIFICATION GUIDANCE

Verification of these requirements should be done through ground testing where feasible. Generally, some sort of mock-up or "iron bird" is required as part of the Full Scale Development of these systems. Because of the criticality of these FCS elements, it is best to work out the "bugs" on the ground rather than in flight test or operation. ARP 1281 may provide some useful guidance in establishing the procedures and criteria to be used in conducting this verification.

VERIFICATION LESSONS LEARNED

Experience has shown that impulse pressure cycling tests will reveal weak areas in servo valve bodies and main cylinder design configurations. Impulse testing for 3000 psi units should consist of cycling pressure from 1000 to 4500 psi for 2,000,000 cycles.

For dual system tandem actuator designs, it may be advisable to test the system to ultimate loads with one hydraulic system depressurized. There have been cases of actuator "blow-by" under "g" conditions with a failed hydraulic system.

3.2.6.4 Electromechanical actuation. Electromechanical actuation subsystems and components shall be designed in accordance with the following requirements: ____________________________.

REQUIREMENT RATIONALE (3.2.6.4)

Trade studies are currently being conducted into the feasibility of an all electric air vehicle. This paragraph provides for the requirements for electromechanical actuation devices.

REQUIREMENT GUIDANCE

Electric power may be used to actuate relatively low-duty cycle, noncritical FCS functions, such as trim, but specific approval from the procuring activity should be obtained before use in essential and flight phase essential applications. Electromechanical actuation components should be designed in accordance with MIL-E-7080 or similar specific component specifications.

REQUIREMENT LESSONS LEARNED

Trade studies into the feasibility of electromechanical actuation for primary flight control functions have shown that the technology exists to produce actuation systems with adequate performance (rate, force output, and bandwidth). Problems still exist in the areas of power dissipation, EMI/EMP susceptibility, and package size for adequate force capability. These issues must be adequately resolved before electromechanical devices can be approved for primary FCS functions.

Control functions, such as trim, are not necessarily non-critical for all failure modes. Runaway trim, for example, may create force levels, at some flight conditions, that make it difficult or impossible to recover from such a failure. These kinds of considerations must be addressed in the development of requirements for these or any other FCS subsystems and components.

4.2.6.4 Electromechanical actuation. Electromechanical actuation subsystems and components shall be verified by ____________________.

VERIFICATION RATIONALE (4.2.6.4)

This paragraph provides for the formal documentation of electromechanical FCS performance verification. Even though these devices are not necessarily flight safety critical, they are required for acceptable air vehicle performance and flying qualities.

VERIFICATION GUIDANCE

Verification of these devices, like other FCS actuation devices, should be verified by test.

VERIFICATION LESSONS LEARNED

3.2.6.5 Pneumatic actuation. Pneumatic actuation subsystems and components shall be designed in accordance with the following requirements: ____________________________.

REQUIREMENT RATIONALE (3.2.6.5)

Pneumatic actuation devices have been used for the control of relatively low-duty-cycle, noncritical flight control surfaces. This paragraph provides the requirements for the design of these devices.

REQUIREMENT GUIDANCE

Requirements for pneumatic actuation subsystems and components should be drawn from MIL-P-8564, MIL-D-7602, or similar industry specifications and standards.

Coordination with other system disciplines should be part of the requirement development process to insure that no conflicts are created. MIL-F-9490 provides the guidance for FCS components.

REQUIREMENT LESSONS LEARNED

Pneumatic actuation devices have been used for noncritical flight control functions; however, these pneumatic devices are not considered suitable for the actuation of essential and some flight phase essential flight control surfaces. The A-37 aircraft has a pneumatically actuated yaw damper, but the system is torque limited and easily overridden by pilot inputs.

The dynamic stiffness of pneumatic actuators is reduced by lower bulk modulus values associated with the fluids used in these devices. Reduced dynamic stiffness has a destabilizing effect on the FCS. Due to the compressible nature of the fluids used, pneumatic systems do not provide the force isolation, exhibited by hydraulic actuation systems, resulting in motion feedback to pilot controls. These characteristics have been found to be undesirable in piloted air vehicles (MIL-F-9490D).

4.2.6.5 Pneumatic actuation. Pneumatic actuation subsystems and components requirements shall be verified by ____________________.

VERIFICATION RATIONALE (4.2.6.5)

This paragraph provides for the formal documentation of the performance and functional verification of pneumatic actuation devices.

VERIFICATION GUIDANCE

Verification of performance, stability, installation, and failure immunity should be accomplished by tests where feasible. These FCS components should be included as part of a full scale functional mockup or "iron bird" provided as part of the full scale development of the air vehicle. This type of testing not only verifies the functional characteristics of the individual devices, but provides system integration, installation, and maintenance information necessary to evaluate FCS subsystems and components.

VERIFICATION LESSONS LEARNED

3.2.6.6 Interfaces between actuation systems, support structure, and control surfaces. The interface between actuation system, support structure, and control surfaces shall comply with ______ ______.

REQUIREMENT RATIONALE (3.2.6.6)

The interface between the actuation system, support structure, and control surfaces may be a single failure point in the FCS. Since the loss of or damage to a primary surface may be flight critical, requirements for this interface are necessary to insure flight safety.

REQUIREMENT GUIDANCE

Guidance for requirements in this area should be obtained from MIL-F-9490, MIL-A-8865, MIL-A-8870, and other applicable industry specifications and standards. Areas that should be addressed in these requirements are control surface stops, control surface gust protection, control surface locks, and control surface flutter and buzz prevention.

REQUIREMENT LESSONS LEARNED

Control surface stops are required to prevent exceeding allowable travel limits such as dictated by: aircraft controllability requirements, prevention of damage to the control surface or its primary surface, and/or personnel safety considerations when the air vehicle is on the ground. Where control valve command input stops are provided, the actuator must still withstand bottoming loads in the event of: misrigging, failure of the valve stops or input links, failure or malfunction of feedback provisions, loss of hydraulic pressure where other actuators or aerodynamic forces can bottom the actuator, and when the system is depressurized normally after each flight. Where a power control actuator is located remotely from the surface, the actuator may be used as the primary surface stop, providing the connecting linkage has an extremely remote failure probability.

The control surfaces of any air vehicle which can be nosed over or up by high winds when the control surface is displaced from the neutral position should be locked in the neutral position. Servo tab and spring tab type surfaces need not have locks or snubbers installed if it can be shown that the connecting springs and linkages are sufficient to prevent gust damage to any of the components.

Specific things which can cause inadvertent engagement of gust locks include inadvertent operation of cockpit control lever, relative deflections between the lock control system and the aircraft, component failure and combat damage. Interlocks should be incorporated to prevent takeoff with control surfaces locked or gust lock engaged.

Some of the most pertinent requirements are specified in the stiffness paragraph of MIL-A-8870. When detailed flutter analyses and wind tunnel tests are not yet available, the following general guidelines may be used:

a. For the prevention of flutter, each control surface including its actuation system should have a minimum natural rotational frequency about the control surface hinge line of 1.5 time the natural torsional frequency of the main structure to which it is attached. This should provide sufficient separation of natural frequencies to prevent oscillations of the control surface and main surface or structure from coalescing and causing flutter.

b. For the prevention of transonic buzz instability, experimental data indicates that the system will be sufficiently stiff if its natural rotational frequency.

$$\omega_n \leq \frac{.21a}{b} \text{ rad/sec}$$

where

a = speed of sound in ft/sec

b = semichord of hinged surface at the 3/4 span in feet.

Transonic buzz was first encountered on jet airplanes and has to be considered on all aircraft which fly at high subsonic or transonic speeds. It is still not well understood, but experimental data taken at the Wright Air Development Center in the 1950s led to the development of the equation noted above.

c. Required actuation system stiffness. With the required natural rotational frequency identified, the required actuation subsystem spring rate (Kreq'd) can be determined from the following equation:

$$K_{req'd} \geq \frac{\omega_n^2 \, I}{l^2 g} \text{ lb/in.}$$

where

ω_n = required natural rotational frequency in rad/sec.

I = moment of inertia of the control surface about its hinge line in lb-in.^{2}.

l = minimum actuation lever arm in inches.

g = gravitational constant: 386 in./sec^2.

d. Actuation system stiffness determination. To meet the fail-safe stability requirement, it is usually necessary to provide the required spring rate with only one actuator per control surface operating even though multiple actuators are installed. The actual effective spring rate of a flight control surface actuation subsystem (K_{eff}) is the total spring rate of the supporting structure from the actuator to the hinge line (K_{S1}), the spring rate of the actuator (K_{act}), and the spring rate of the surface structure (K_{S2}) summed in series as shown below:

(1) Frequency relationship. The frequency dependence of the net stiffness of a typical hydraulic flight control servoactuator is shown in figures 4 and 5.

$$\frac{1}{K_{eff(j\omega)}} = \frac{1}{K_{S1}} + \frac{1}{K_{act(j\omega)}} + \frac{1}{K_{S2}}$$

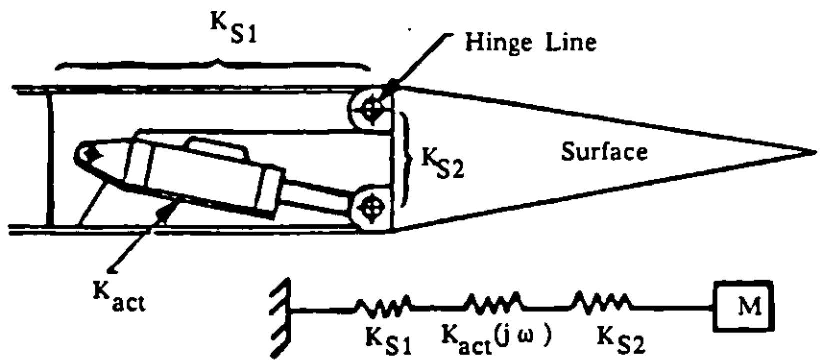


FIGURE 4. Actuator stiffness determination.

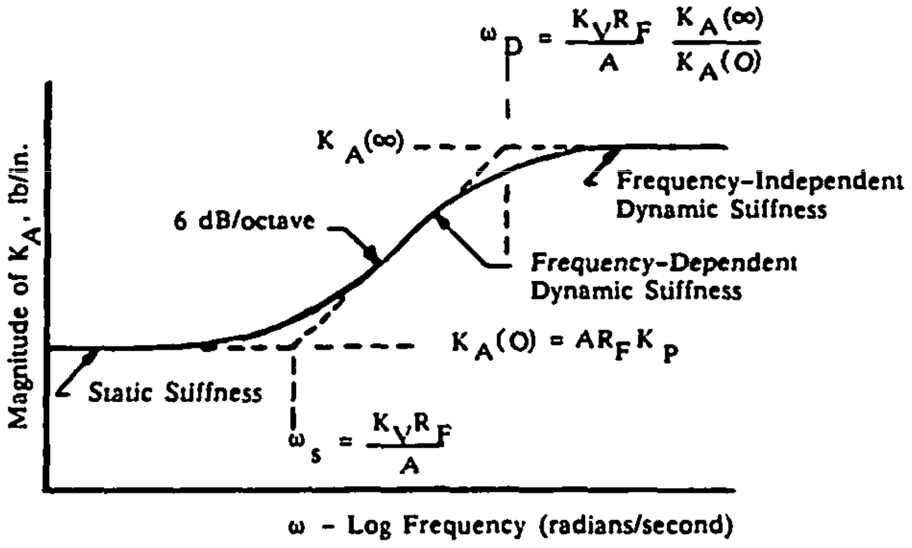


FIGURE 5. Actuator stiffness vs. frequency.

(2) Static stiffness is the actuation system stiffness at zero frequency. The stiffness is essentially constant at all frequencies up to the static stiffness corner frequency, ω_s, which can be calculated as follows:

$$\omega_s = \frac{K_V R_F}{A} \text{ rad/sec}$$

where

K_V = No-load valve gain, in.³/sec/in.

R_F = The feedback ratio, in./in. (ratio of valve displacement to piston rod displacement)

A = Effective area of the actuator piston, in.²

Static stiffness $K_A(0)$ is generally governed by three factors as follows:

$$K_A(0) = A R_F K_P$$

K_P = The effective pressure gain, psi/in., including actuator leakage and structural feedback effects. (Any other pressure gain reducing factors, such as pressure feedback, must also be included).

(3) Dynamic stiffness is determined by the solution of complete transfer functions, and becomes constant at all frequencies above the frequency independent dynamic stiffness lower limit, ω_D, which can be determined as follows:

$$\omega_D = \frac{K_V R_F}{A} \frac{K_A(\infty)}{K_A(0)}$$

The frequency-independent dynamic stiffness, $K_A(\infty)$, of the actuator is made up of a number of incremental springs. For conventional linear actuators, the primary springs are due to the actuator structure ($K_{act\ str}$), i.e.: the cylinder barrel, piston rod, and end caps, the bearings (K_{brg}), and the fluid compliance (K_{fluid}), which are also summed in series as follows:

$$\frac{1}{K_A(\infty)} = \frac{1}{K_{act\ str}} + \frac{1}{K_{brg}} + \frac{1}{K_{fluid}}$$

$$K_{fluid} = \frac{4\beta\eta A}{X_t}$$

where

β = fluid bulk modulus, psi

η = volumetric efficiency

A = effective area, in.^{2}

X_t = total stroke, in.

In calculating the fluid spring, a realistic value for bulk modulus should be used. Most available data represents well-bled fluid with very little entrained air. For normal situations, the value used should be reduced to 80 percent of the ideal, and the tangent modulus (at the normal actuator pressure) rather than the secant modulus should be used. If the moving parts of the actuator(s) are heavy in relation to the surface weight, this must be appropriately taken into account.

(4) Stiffness improvement methods. On stiffness-critical actuating systems, the structural springs may often be more rigid than the fluid spring, and as a result, the fluid compliance may have a great effect on the overall stiffness of the system. However, increasing fluid stiffness by increasing actuator piston area introduces weight penalties in two ways. It increases the size and weight of the actuator, and it increases the flow demand on the hydraulic system which, in turn, can increase the size and weight of hydraulic pumps, fluid lines, reservoirs, and other components, plus weight of all structure which must withstand actuation loads. It may be much more economical (of weight) to stiffen the structural springs once the need is recognized.

In situations where large weight penalties would be incurred to meet the frequency requirements by stiffening existing structure and components, other improvement methods such as the following can be considered:

(5) Utilizing inactive actuators. Where multiple actuators are used to satisfy reliability requirements (which is the normal practice for essential controls), they can be designed to contribute stiffness and damping to the system even though hydraulic supply pressure is lost through hydraulic system failure. This could be accomplished by pressure activated valving. When pressure is lost, a spring loaded valve connects the input and output of the control valve to a compensator at return line pressure. The servo no longer supplies power to the system but does provide stiffness when the metering valve is closed and damping when the valve is open. This concept adds some complexity, but the weight addition could be considerably less than for stiffening existing structure and actuators.

(6) Adding an additional actuator. The concept here is to design an actuation system with one more channel than is required for redundancy. Thus, stiffness may be satisfied with two channels instead of one. For example, in a surface control system that requires three redundant channels, each channel must satisfy the maximum hinge moment and minimum stiffness for the situation when the other two have failed. However, if four channels are used, the maximum hinge moment can be satisfied with two actuators instead of one, and as a result, each actuator will be exactly half the size of those in the three-channel design. With smaller actuators, each channel will be more compliant. However, stiffness now can be satisfied with two parallel actuation channels, and the result is a system that is more rigid than the three-channel system. A scheme of this type to improve stiffness may also have a weight advantage.

(7) Adding an independent damper. Several types can be considered. One is a quasi-servo damper channel similar to the active servoactuators. When the spool valve is closed, this damper provides an additional load path with the stiffness characteristics of the active channels. When the valve is open, in response from the pilot or AFCS, the quasi-servo acts as a viscous damper.

Pure viscous fluid dampers are also used, and there are several linear or rotary types which may be considered. They can be installed parallel to the actuation channels or at any convenient location on a surface such as on the hinge line. They absorb energy from high-frequency, high-amplitude vibrations and dissipate it as heat. If a damped surface experiences considerable activity, throughout a flight, the damper may absorb energy faster than can be radiated and create a high temperature problem.

(8) Adding an actuation stiffness compensation network. The basic actuator stiffness can be modified by introducing hydromechanical or electrical compensating networks within the actuator loop. In the most general case, this can be done by sensing load pressure, passing this signal through a bandpass filter, and feeding this signal as positive or negative feedback to the control valve.

4.2.6.6 Interfaces between actuation systems, support structure, and control surfaces. Requirements for the interface between actuation systems, support structure, and control surfaces shall be verified by ____________________.

VERIFICATION RATIONALE (4.2.6.6)

FCS interfaces may involve flight safety critical control surfaces and/or control paths. Formal documentation of the design and performance of these flight control elements are provided by this verification process.

VERIFICATION GUIDANCE

Verification should be accomplished by test. As in other FCS actuation systems, these elements should be included in the FCS functional mock-up test procedures. The final compliance to these requirements is verified by the Ground Vibration Test.

VERIFICATION LESSONS LEARNED

3.2.7 Component design. *Design of components* and elements shall be entirely suitable for use in the FCS and shall be such that the other requirements established for the FCS are not infringed by that design.

REQUIREMENT RATIONALE (3.2.7)

Many requirements apply to the FCS. Basic requirements are levied on system (MFCS and AFCS) performance and system (MFCS and AFCS) design. Components and elements are assembled and integrated to form these systems. By design, those components and elements must fulfill their role and must not otherwise cause the system requirements not to be met. This paragraph establishes these system requirements as necessary basics to component design.

REQUIREMENT GUIDANCE

In applying this technical requirement to the mechanization used for the FCS, the following information may be useful.

Safety, missions, and economic considerations establish the need for components and elements of the FCS to be controlled by engineering design and for those controls to be in formal technical documentation such as specifications, standards, etc.

Air Force policy promotes standardization of components, elements, etc., as a means of minimizing supply problems and cost, and of increasing reliability by use of proven designs.

Engineering design and documentation should ensure the interchangeability of like assemblies, subassemblies, replacement parts, etc., regardless of manufacturer or supplier. Further, the design and documentation should ensure that items which are not functionally interchangeable are also not physically interchangeable.

Equipment components, elements, assemblies, parts, etc. of the FCS should be masked for proper and easy identification. MIL-STD-130 should be used as a guide in this area.

Inspection seals should be provided to show any unauthorized disassembly, adjustment, etc. when such actions are to be performed only by specially designated activities which are authorized to break these seals and apply new ones.

Two of the important interfaces in component design are between Flight Control Engineering and Human Engineering where design of cockpit controls, levers, handles, knobs, etc. are involved; and between Flight Control Engineering and Structural Engineering where design of forgings, castings, stamping, etc. are involved.

Bearings used in the FCS should be carefully selected. Where possible the bearings should be chosen from approved parts as shown in MIL-STD-1599. AFSC DH 2-1 can also provide some guidance in this area.

For electrical and electronic components and elements, the design should be guided by requirements established in MIL-E-5400, MIL-E-7080, MIL-STD-454, MIL-STD-461, MIL-W-5088, MIL-M-7969, MIL-M-8609. For micro-electronics MIL-M-38510 should be used.

When selecting switches, the invulnerability to flight crew error requirements must be considered, such as recognizing that the selected positions of push button switches are not apparent.

The following recommendations should also be considered:

a. In the design of AFCS components, the minimum feasible number of parts should be used and their size and weight minimized consistent with other requirements specified.

b. Modules or subassemblies should not be smaller than that required to perform a single function (as an example, an amplifier or power supply.)

c. Modules intended for field replacement should be constructed so that electronic parts or connector pins are not exposed outside the frame of the module.

d. Possible requirements for complex test equipment and test procedures should be considered prior to adopting a modular design to ensure that other requirements can be met.

e. Solid state devices are preferred over electron tubes and the latter should be used only when they are the only means to meet the requirements for a specific application.

f. The use of micro electronic technology should be considered on the design of all systems/equipment. An objective appraisal of all factors concerning the system/equipment design should be made with the view of maximizing reliability and minimizing total cost of ownership, weight, and space within the envelope of the other performance parameters of the design.

Thermal design and cooling requirements should emphasize that both the component design and its installation must be considered in achieving resistance to thermal failure. Design techniques which aid in controlling heat vice include:

a. The use of thermal characteristics of finishes, induced draft, and ventilation by means of baffles, internal vents and louvers, and packaging in heat dissipating fluids.

b. Use forced cooling if above means are still insufficient or if a significant reduction in overall size, weight, or failure rate can be realized. Fans or blowers employed should operate from the air vehicle's AC power supply.

REQUIREMENTS LESSON LEARNED

Control stick dampers should be designed so that they can be overpowered by the pilot in the event of failure or malfunction.

All electronic LRUs should receive a minimum of 50 hours burn-in operation and testing (power on) prior to assembly, or after assembly if such is more meaningful, but prior to installation.

Switches can be extremely important elements in the mechanization of FCS, and the design of special electrical/mechanical switches should be subjected to multiple approval processes. The five position trim switch, used in electric trim systems, is one of those and MIL-S-9419 should be consulted for guidance when approving that type switch.

Resistive variable voltage dividers, potentiometers, should not be used in dynamic motion application in FCS such as for sensor or feedback outputs.

Component and element housings should be designed to prevent any accumulation of liquids in pockets, wells, traps, etc., since freezing temperatures might cause the formation of slush or ice which could seriously degrade FCS performance.

Redundant circuiting should not be routed through the same electrical connector.

4.2.7 **Component design.** Component design requirements shall be verified by ____________.

VERIFICATION RATIONALE (4.2.7)

Component design has an impact on flight safety, mission performance, and operating costs. The verification process provides the means for determining the extent to which those factors are impacted by the requirement, and forms a basis for planning for operational use of the air vehicle in the field.

VERIFICATION GUIDANCE

In general, component design requirements should be verified incident to FCS requirement verifications by analyses, inspections, and tests.

When suitability and absence of infringement on system requirements has been established through the verification processes, the quality assurance provisions included in the engineering control documentation should ensure continued suitability of the component or element for use in the FCS.

MIL-STD-883 may offer some guidance in the verification testing of microelectronics. Method 1015 of that standard deals with burn-in tests.

VERIFICATION LESSONS LEARNED

After burn-in, an electronics LRU should be tested to verify that performance remains within specified tolerances.

Tests for control stick dampers should be set up to exercise all joints, connections, bearings, etc., used with the damper since free play which may develop with these elements may seriously impact the pilot's view of flying qualities.

Dielectric strength tests should be conducted on electrical and electronic components and elements. Leakage current should not exceed 10 milliamps when a dielectric stress voltage of 1200 volts, 60 Hz, is applied for 1 minute between insulated circuits and between circuits and case; and there should be no insulation breakdown. When 500 V DC is applied between isolated circuits and the case or connector shell for a period of 10 seconds, the resistance should be at least 50 megohms. When a component or connector has a lower design voltage limitation, the test should be run at an appropriate lower voltage as defined by the component connector specification.

3.2.8 *Component fabrication.* The selection and treatment of materials, and the processes and assembling methods used in fabrication shall ______ ______________________________.

REQUIREMENT RATIONALE (3.2.8)

Materials, processes, and assembly methods used in the fabrication of FCS components and elements impact every requirement applicable to system [FCS] performance. This paragraph provides the means for identifying the manner in which engineering control will be maintained in these technical areas in order to ensure that system requirements are supported in every aspect of component and element fabrication.

REQUIREMENT GUIDANCE

a. The blank may be filled by words such as:

(1) Produce consistently sound and suitable components and elements for the FCS.

(2) Conform to approved industry specifications and practices.

(3) Conform to approved military specifications and practices.

(4) Conform to government specifications and practices.

b. In applying this requirement the following points should be considered.

(1) Government and military specifications, standards, practices, etc., are preferred over those generated by industry and other sources.

(2) MIL-STD-1599 offers guidance in Requirement 104 for selection and treatment of materials; in Requirement 105 for treatments and processes such as coatings, platings and finishes; and in Requirement 204 for safety practices for use during assembly.

AFSC DH 1-2 offers guidance in several aspects of component and element fabrication. Chapter 4 deals with fasteners, fittings, methods, processes, etc., and Chapter 7 deals with materials, treatments and processes.

MIL-STD-454 offers guidance which covers most aspects of fabrication of electronic components and elements.

MIL-C-27500 offers guidance on material selection and construction of electrical cabling for FCS.

Individual parts may be mechanically joined with removable fasteners or by riveted or threaded connections or by qualified methods for permanent joining. Removable fasteners should be selected and used in accordance with requirements which have been specified and which should provide that:

Bolts smaller than one-fourth inch in diameter should not be used to make single-bolt connections or connections essential to proper functioning of the component.

Each removable bolt, screw, nut, pin, or other removable fastener, the loss of which would degrade operation below FCS Operational State III, should incorporate two separate locking or retention devices either of which must be capable of preventing loss of the fastener by itself and retain it in its proper installation with the other locking or retention device missing, failed, or malfunctioning. Where self-retaining bolts are used, their selection and installation should be within the limitations of MS-33602 and only one type should be used in any given system.

No self-locking nut should be used on any bolt subject to rotation in operation unless a nonfriction locking device is used in addition to self-locking device.

Lockbolts listed in AFSC DH 1-2, 4A5, Swaged-Collar-Headed Straight Pins and Collars, may be used for fastening applications not requiring removal on the aircraft.

Rivets for all riveted joints should be selected and used in accordance with the requirements specified.

All threaded joints should be provided with adequate wrenching and holding provisions for assembly and disassembly of the joint before and after service use. Internal screw threads and external rolled threads should be in accordance with the thread form requirements of MIL-S-8879. Pipe threads should not be used.

All adjoining parts should be secured in a manner that will preclude loosening when subjected to internal or external loads or vibration.

All threaded joints which carry critical loads should be positively locked in the assembled position so that load reversal at the threads is prevented. The use of jam locknuts alone is not a positive locking means unless lockwired or otherwise restrained.

Unless restrained from moving by the attachment of adjoining parts, all removable fasteners should be positively locked in place. Self-locking externally threaded fasteners should not be used except within the limitations specified in MS-15981, and self-locking nuts should not be used except within the limitations specified in MS-33588. All other types should incorporate positive locking means or be safetied with cotter pins in accordance with MS-24665, where temperature and strength permit, or be safety wired. Cotter pins and safety wiring should be installed in accordance with MS-33540.

Retainer rings should not be used to retain loaded parts unless the rings are positively confined by a means other than depending on internal pressure or external loads. They should not allow free play which could result in structurally destructive action or fatigue failure of the retained parts or failure of gaskets or packings. Where used, retainer rings should be commercially available types which can be installed and removed with standard tools.

Joints with rolling element bearings should have the inner race securely clamped to prevent rotation of the inner race with respect to the pivot bolt, rivet, shaft, etc.

Electronic parts should be mounted so that ease of producibility and maintainability is assured. Whenever feasible, parts such as resistors, capacitors, etc., should be mounted in an even, regular, row-type arrangement. These parts should be mounted on a base so that the leads do not cross other leads or connections. Heavy electronic parts and assemblies should be solidly mounted so that adverse affects when subjected to vibration and shock will be minimized.

Nonconductive oxides or other nonconductive finishes should be removed from the actual contact area of all surfaces required to act as a path for electric current and from local areas to provide continuity of electrical shielding or bonding. All mating surfaces should be clean and carefully fitted, as necessary, to minimize radio frequency impedance at joints, seams, and mating surfaces. The resultant exposed areas, after assembly at such joints or spots, should be kept to a minimum.

Redundant circuits should be isolated from each other to preclude failure of one portion of the circuit from affecting any other circuit.

The number of electrical connectors should be kept to a minimum within the required limitations for separation of redundant circuits. Connectors should be mounted to preclude nuisance warning indications and intermittent operation when subjected to applicable temperature differentials, vibration, and shock. They should be polarized so that it is impossible to mismate them on a particular piece of equipment.

All electrical assemblies should be thoroughly cleaned of loose, spattered, or excess solder, metal chips, or other foreign material after assembly. Burrs and sharp edges and resin flash should be removed.

REQUIREMENT LESSONS LEARNED

High quality materials and workmanship remain the key to the fabrication of dependable components. Use of proven and controlled processes, such as specified above, are most important in reproducible quality manufacturing. Special processes should be clearly specified on the detail drawings and the fabrication instructions.

It is common practice to secure fasteners (i.e., bolts, screws, nuts, pins, etc.) with a single locking device. Service experience has shown, however, that due to maintenance, manufacturing, or design errors, a single locking device is not adequate for critical applications. Due to a number of instances of loss of fastener integrity, it is considered necessary to require two separate locking devices on all removable fasteners in any installation in which loss of a fastener could jeopardize flight safety.

One acceptable practice is the use of self-retaining bolts with cotterpinned castellated nuts installed as shown on MS-33602. Other fasteners are also acceptable providing they meet the requirements in the referenced AFSC Design Handbook including retention of their locking and/or retention capabilities in all environmental conditions associated with their particular installation.

When impedance type self-retaining bolts are used in bellcrank, rod end, clevis, etc., type joints, entrance and exit chambers not to exceed .015 inches x 45 degrees should be provided at hole faces to aid in the installation and removal of the bolts.

Where lockbolts are used, it should be recognized that they are single locking only, not close tolerance, and can be used only in joints in which clamp-up is allowed.

Jam nuts may be used without lockwire or other retention in applications which serve only to preload threaded joints, wherein inspection intervals are such as to preclude unacceptable fatigue cycles and where backlash is acceptable. Where they are used to prevent joint disconnection, they must be positively retained.

Isolation of redundant circuits is mandatory to obtain the advantages promised by using multiple signal paths. Generally, redundant channels of the same control axis and electronic comparison model signals should not utilize common or adjacent (a) connectors, (b) cables or cable runways, or (c) circuit cards, unless the design can be shown by demonstration or analysis to meet the appropriate isolation/separation requirements.

A high percentage of electronic equipment failures is due to the improper choice and/or assembly of electrical connectors, and special attention to their selection and application is important.

Invulnerability requirements require wiring to be routed with sufficient slack to prevent thermal contraction or expansion, vibration, and flexure from causing damage to the wire terminations and to minimize noise pickup.

Electrical shield should be installed on wire and cable to minimize electrostatic and magnetic coupling.

4.2.8 Component fabrication. Component fabrication requirements shall be verified by ________________________.

VERIFICATION RATIONALE (4.2.8)

The verification process provides the means for determining the quality of materials, processes, and workmanship which has been used in the fabrication of components and elements of the FCS. The information obtained may be useful in planning for operational use of the air vehicle in the field.

VERIFICATION GUIDANCE

Component fabrication requirements may be verified by analysis, inspection, or test. The most feasible method should be chosen and the verifications should be performed in conjunction with other verifications wherever possible. Much of this effort will be part of the Quality and Reliability Assurance programs covered under Air Force regulations in the 74 series.

VERIFICATION LESSONS LEARNED

3.2.9 Component and element installation. Installation of FCS components shall meet ________________________.

REQUIREMENT RATIONALE (3.2.9)

Numerous requirements are placed on the performance and design of the FCS in order to fulfill the mission of the air vehicle. The installation of the components and elements of the FCS must support the accomplishment of these requirements and not cause the FCS, or any other system of the air vehicle, to fall short of meeting those requirements.

REQUIREMENT GUIDANCE

Invulnerability, immunity, survivability, reliability, maintainability, and safety consideration establish the need for engineering control and documentation of the installation of FCS elements and components.

AFSC DH 1-6, Section 3J provides guidance for installation of FCS mechanical elements, including routing, separation, mounting and orientation, and environment. Examples of potential installation problems due to inadequate clearances, incorrect installation, and improper design are also provided.

AFSC DH 1-6, DN 3H1 and DN 3H2, provides guidance for routing, separation, and connection of electrical elements. Safety design consideration for operation in hazardous atmospheres and compatibility of components with respect to the operating environment are also covered.

MIL-F-9490, besides requiring compliance to the aforementioned design handbook sections, specified the following installation requirements:

a. System components shall be located to provide direct routing of the control system signal and power transmission elements in accordance with AFSC DH 1-6 Design Note 3J1, only to the extent that the components and transmission elements are not exposed to undue hazards.

b. All component installations in fuel system areas shall preclude the generation of sparks both during normal operations and possible abnormal and failure conditions.

c. If cooling augmentation is required, the installation of flight control electrical and electronic equipment cooling shall be integrated with the cooling provisions for other electrical and electronic equipment. The requirements specified in AFSC DH 1-6, DN 3H1, shall be met.

REQUIREMENT LESSONS LEARNED

4.2.9 Component and element installation. Installation of FCS components shall be verified by ____________________.

VERIFICATION RATIONALE (4.2.9)

The inspection, test and analysis incident to the verification of the FCS performance and design requirements and quality assurance programs will verify much of the component and element installation against the various engineering and manufacturing control documents employed.

VERIFICATION GUIDANCE

In order for component and element installations to be verified standard practices, adequate design, clearances, and tolerances must all be established.

Contract specifications or applicable government and industry specifications and/or standards should provide the controlling documents. MIL-STD-454 provides graphic examples of acceptable and unacceptable electric/electronic component installations and requirements for acceptable parts, material and installations.

MIL-F-9490 lists other government specifications and standards which may be used as controlling documents.

VERIFICATION LESSONS LEARNED

3.3 Integrity requirements. The FCS component's hardware and software and integrity subsystems shall meet the integrity requirements of this section.

REQUIREMENT RATIONALE (3.3)

The integrity programs are intended to aid in the development to ensure a supportable system(s) and operational suitability.

REQUIREMENT GUIDANCE

Develop a master plan which covers each of the integrity program guidance. Include in each of the specifications planned the appropriate requirements from each of the integrity specification guides.

REQUIREMENT LESSONS LEARNED

Application of engineering principles to establish actual usage spectrums, development, and sound verification methods are essential to ensure equipment and software development, producibility, and life for the weapon system.

4.3 Integrity requirements. The FCS integrity requirements for hardware, software and integrating subsystems shall be verified by

a. ____________________.

b. ____________________.

c. ____________________.

d. ____________________.

VERIFICATION RATIONALE (4.3)

The integrity requirements need to be verified by analysis, test, and demonstration to certified usage spectrums for the intended life.

VERIFICATION GUIDANCE

The verification requirements, for each FCS element/item should reflect the sequence of verification and the type of verification method with a short narrative as to what will be accomplished by each verification. The verification in this section should be broad and general enough to attack the methods by a system approach. For example, the performance life of the rudder pedals, stick, and switches in the cockpit shall be demonstrated by simulating the mission extreme load cycles and applying these to the controllers for twice the controller lives. This example would follow the analysis preparation for the test, the actual design phase, and the initial design phase. This section should consider grouping items to particular types of verification methods to keep the section relatively manageable.

VERIFICATION LESSON LEARNED

Without adequate planning, allocations of resources, identification of verification methods for FCS items, and time schedule constraints with resource constraints, often push one to accept modified testing programs and requirements. While airworthiness is established, item life and support are often not achieved as intended. Application of the integrity approach should aid in precluding these costly compromises.

3.3.1 Structural integrity. Load transmission and elements of the FCS shall meet the load, strength, stiffness, deformation durability and damage tolerance requirements for each element as follows:

a. ________________________.

b. ________________________.

c. ________________________.

REQUIREMENT RATIONALE (3.3.1)

Structural elements of the FCS are often single point potentialities. Structural consideration must be taken into account to demonstrate the FCS elements ability to endure in the specified environment in excess of the proposal life. Design margin must preclude the probability of failure of these elements during the life of the air vehicle.

REQUIREMENT GUIDANCE

The structural design of each FCS element and their build up into a functional item (stick rudder pedals, etc.) need to consider the criticality, usage, and finally demonstrate the life. AFGS-87221 and MIL-STD-1530 should be used to derive the program plan and design requirements.

REQUIREMENT LESSONS LEARNED

Miss analyzed missions, usage spectrum, and tolerance variations have produced structural attack points for control actuation and pilot inputs devices which broke in flight. Some of these instances have caused loss of aircraft.

4.3.1 Structural integrity. The integrity for the FCS and integrating subsystem structural elements shall be verified by ________________________.

VERIFICATION RATIONALE (4.3.1)

Structural attack points are frequently safety critical areas in FCSs. It is vital that verification be performed to establish the safety/integrity of every FCS structural point.

VERIFICATION GUIDANCE

The requirement should cover all FCS structural points, the analysis, and test to be performed. Each point with the analysis and test type to be performed with a short narrative for the type of analyses, test, or demonstration. The test spectrum and/or analysis results should be certified and included in the test requirement.

VERIFICATION LESSONS LEARNED

Inadequate analysis and tests to incorrect spectrums have caused loss of aircraft. Parts which were certified but not subsequently verified through production and support have resulted in defective parts installed. Good tests to actual certified spectrums plus follow up through production are essential for a quality product.

3.3.2 Mechanical integrity. FCS mechanical devices such as rudder pedals, stick, inertial sensors, actuators, etc., and integrating subsystems shall meet the requirements for load, strength, function, environment, and durability as follows:

a. ________________________.

b. ________________________.

REQUIREMENT RATIONALE (3.3.2)

FCS mechanical components, transmission devices and integrating subsystems need to follow a rigorous design process. This will ensure a well designed and producible system of components that will not cause loss of an air vehicle or crew for the air vehicle's life. This requirement provides for rigorous development and operational support of the mechanical device in the FCS and integrity subsystems.

REQUIREMENT GUIDANCE

The mechanical design of each FCS element, integrating subsystem element, and their resulting function need to consider criticality, environment, usage, and operational life. MIL-STD-1798 and AFGS-87249 should be used as guides for determining the program/plan and requirements for this section. Support posturing and equipment for mechanical devices should be included.

REQUIREMENT LESSONS LEARNED

Mechanical devices usually have a few life limited parts such as bearings, seals, and fittings. The operational lives need to be determined with adequate accuracy in order to provide adequate parts stock and spares and determine replacement interval. The full service life of the device needs to be adequately defined for the same preceding reasons. Past inadequate determination life limited parts and devices have led to inadequate support posturing, loss of missions, and on rare occasions, loss of aircraft and crew. The result has been felt through increased support costs, maintenance down time, increased replacement and supply time, and loss of our capability to sustain mission readiness.

4.3.2 Mechanical integrity. The integrity of the FCS and integrating subsystems mechanical devices shall meet the functional, environmental, usage, and life requirements for the device as follows:

a. ____________________.

b. ____________________.

c. ____________________.

VERIFICATION RATIONALE (4.3.2.)

Mechanical devices usually have life limited parts as well as service lives less than the aircraft. These lives must be known prior to production in order to space and support posture adequately. Frequently, these devices are safety critical, making this requirement a must. The device operational usage for all load and environmental spectrums must also be determined in order to determine device life.

VERIFICATION GUIDANCE

Use of the documents referenced in 3.3.2 as a guide is advisable. The verification requirements must reflect the certified loads, environments, and functional usage spectrums in demonstrating by analysis, test, or demonstration of the devices specified life. Flight safety and support absolutely depend on adequate specification of this requirement. The analysis, test, or demonstration should be adequately explained within this requirement.

VERIFICATION LESSONS LEARNED

Mechanical devices, such as switches, bearings, seals, etc., have had catastrophic effects on previous aircraft. The environments and usage spectrums were inadequately applied indicating devices were integrated properly and would perform for the intended life. Past verifications have underestimated the specified life by a factor of 10 and poor integration has led to catastrophic events. Some of these events have been surface hardovers due to under voltage condition on electro-mechanical devices, jamming, friction wearout, and fatigue wear out, allowing improper installation of devices which get by functional tests, misallocation of tolerances, poor prediction of wing bending and torsional effects, poor production (manufacturing) of parts, poor or inadequate capturing techniques (e.g., cotter pins, slip rings) to keep parts/devices in place, inadequate linkage clearances, and improper analysis/measurement of vibration levels/damping characteristics to name a few. Adequate verification to certified test levels that reflect actual usage is essential for flight/safety critical functions performed by mechanical devices.

3.3.3 Electronic integrity. FCS electronic and electro-mechanical devices such as computers, convertors, power supplies, servo's, etc., and integrating subsystem electronics shall meet the functional, environmental, and durability requirements as follows:

a. ____________________.

b. ____________________.

REQUIREMENT RATIONALE (3.3.3)

Electronic devices used in safety/flight critical applications are subject to a variety of adverse environments and manufacturing difficulties. Areas such as solder joints, die makeup, pin attachments, packaging, connections, iteration rates, etc., are variables which must be accounted for in the design and subsequent verification. This requirement sets the functional performance under the operating conditions.

REQUIREMENT GUIDANCE

The electronic design of the FCS and integrating subsystem items should consider the function, environment, usage, storage, and operating life. MIL-A-87244 should be used as a guide for establishing the electronics development program and usage, environmental, and durability requirements. Storage and necessary support items should be included.

REQUIREMENT LESSONS LEARNED

The major problems with electronics have been packaging design, even to the part, and the manufacturing process. Design packaging is improving but still needs a disciplined approach and better analytical tools. Manufacturing needs to be consistent with adequate process control in parts, soldering, grounding, and tolerances.

4.3.3 Electronic integrity. The integrity of the FCS and integrating subsystem electronic and electro-mechanical devices shall meet the functional performance under the environments, usage and durability requirements as follows:

a. ______________________.

b. ______________________.

VERIFICATION RATIONALE (4.3.3)

Electronic devices such as servos, switches, relays, computers, etc., of the FCS and integrating subsystem are a safety critical function. The device life under actual, certified environmental and usage spectrums needs to be verified in order to meet the safety requirement for the air vehicle as well as mission success requirements.

VERIFICATION GUIDANCE

The requirements for each device should be verified by analysis, test, and for demonstration, each type of verification should be explained (e.g., lead flex analysis to establish lead lengths followed by thermal and vibration cycles on powered, installed board). This will identify the types of verification involved, the scope, the interplay, and the success criteria, MIL-A-87244 should be used as guidance.

VERIFICATION LESSONS LEARNED

Past experience is loaded with examples of intermittent shorts, grounding problems, packaging problems, and manufacturing problems. Application of a rigorous design and verification with certified test spectrums coupled with attention to manufacturing should alleviate some of the past problems.

3.3.4 Software integrity. Software elements (units, components, and flight programs) of the FCS and integrating subsystems shall meet the requirements as follows:

a. ______________________.

b. ______________________.

REQUIREMENT RATIONALE (3.3.4)

Performance parameters such as timing, skew, throughput spare, number of inputs and outputs to a unit, sampling time, and data characteristics are some of the critical parameters. For flight critical software and integrating software, it is essential to specify key performance and development parameters to assure a rigorous development.

REQUIREMENT GUIDANCE

Software requirements should consist of the key parameters, data characteristics, languages, and the hardware and software interfaces as well as the process/configuration/security aspects involved in the development. MIL-STD-1803, DOD-STD-2167, and DOD-STD-2168 should be used as guides in establishing the requirements. Hardware elements which provide the data conversions, manage data input/output and do the actual processing should also be addressed. Software development tools and the engineering environment as well as future software support should be considered.

REQUIREMENT LESSONS LEARNED

Past software development has depended on interface documents and company processes to develop and control the software. Key parameters were not addressed. The result has been schedule delays, no growth, and reduction in function capability to stay written throughput and memory constraints and design errors in the mechanization. Although very few aircraft losses have been attributed to software problems, the loss of functional performance and lack of growth have been costly in delays and program updates. It is necessary to provide a well planned and rigorous development to software and cover key parameters to ensure a well integrated functional software system.

4.3.4 Software integrity. Software verification shall follow a build up approach to evaluate the success of the functional and integrated mechanization. Software verification shall meet the following:

a. ____________________.

b. ____________________.

VERIFICATION RATIONALE (4.3.4)

Verification of flight critical software using a rigorous approach is essential to assure the mechanization is adequate and that unwanted logic paths are not inadvertently activated. The FCS and integrating subsystem software must perform as required 100% of the time.

VERIFICATION GUIDANCE

Verification requirements should verify the development tools, the mechanization, the integration, the data characteristics, the support, and the configuration/security aspects. Use of a build up approach requiring different levels of test and test expectations is advised. Each verification method (analysis test and demonstration) should be generally defined, cover the application, and cover specific methods for each function.

VERIFICATION LESSONS LEARNED

Past experience has shown that inadequate build up verification methods have led to severe programmatic delays and cost increases to assure the software is flight worthy. A hap hazard approach to integration has never worked to establish confidence in the software. It is absolutely essential to understand the performance parameters, mechanization build, and verification. Verification is the key to demonstrate that the software performs as intended under varying logic as well as data exceedance characteristics. The few aircraft programs with sound verification methods have been on time and close to cost.

CONTENTS

CONTENTS - Cont'd

CONTENTS - Cont'd

CONTENTS - Cont'd

CONTENTS - Cont'd

CONTENTS - Cont'd

TABLES

FIGURES

STANDARDIZATION DOCUMENT IMPROVEMENT PROPOSAL

INSTRUCTIONS

1. The preparing activity must complete blocks 1, 2, 3, and 8. In block 1, both the document number and revision letter should be given.
2. The submitter of this form must complete blocks 4, 5, 6, and 7.
3. The preparing activity must provide a reply within 30 days from receipt of the form.

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I RECOMMEND A CHANGE:	1. DOCUMENT NUMBER AFGS-87242A	2. DOCUMENT DATE *(YYMMDD)* 910830

3. DOCUMENT TITLE
Flight Control System, Air Force Guide Specification for

4. NATURE OF CHANGE *(Identify paragraph number and include proposed rewrite, if possible. Attach extra sheets as needed.)*

5. REASON FOR RECOMMENDATION

6. SUBMITTER

a. NAME *(Last, First, Middle Initial)*	b. ORGANIZATION	
c. ADDRESS *(Include Zip Code)*	d. TELEPHONE *(Include Area Code)* (1) Commercial (2) AUTOVON *(If applicable)*	7. DATE SUBMITTED *(YYMMDD)*

8. PREPARING ACTIVITY

A. NAME	B. TELEPHONE *(Include Area Code)* (1) Commercial (513) 255-6281 (2) AUTOVON *(If applicable)* 785-6281
C. ADDRESS *(Include Zip Code)* ASD/ENES Wright-Patterson AFB OH 45433-6503	IF YOU DO NOT RECEIVE A REPLY WITHIN 45 DAYS, CONTACT: Defense Quality and Standardization Office 5203 Leesburg Pike, Suite 1403, Falls Church VA 22041-3466 Telephone (703) 756-2340 AUTOVON 289-2340