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LEVEL III

2

**APPENDIX TO "BACKGROUND INFORMATION AND
USER GUIDE FOR MIL-F-9490D" AFFDL-TR-74-116**

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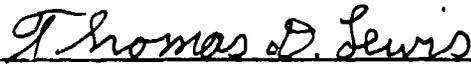
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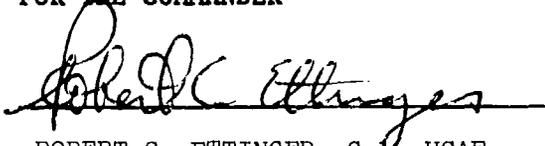


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flight controls, fly-by-wire controls, and self-test and monitoring. These topics are addressed in many requirement areas. Of particular note are the additions of a redundancy management requirement and discussion, which were absent in the D revision, and the integration of software requirements for FCS design and documentation into the specification.

PREFACE

This technical report was prepared by Northrop Corporation, Aircraft Group, Hawthorne, California, for the Flight Dynamics Laboratory under Air Force Contract F33615-79-C-3617. This report covers work performed between July 1979 and January 1980.

The principal investigator and author of this report was John F. Moynes of the Flight Control Development organization. Alex Dobos-Bubno of Flight Control Development served as the lead technical advisor and W. H. Faulkner of Flight Control Research was the chief coordinator. The author would like to acknowledge the contributions of E. E. Schulze, Jr., W. E. Nelson, Jr., and J. L. Lockenour to this program.

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INTRODUCTION

This report is the second of two documents prepared in fulfillment of the Air Force contract for the update of MIL-F-9490D, the general specification for the design, test and installation of flight control systems for piloted aircraft.

The objective of this contract effort was to incorporate, through an amendment to the specification and supporting user information, up-to-date requirements and information necessary for more efficient system acquisition.

This report provides User Guide information and substantiating background material in support of the first document, Amendment 1 to MIL-F-9490D.

MIL-F-9490D is scheduled to be converted into MIL-Prime-SPEC format in 1982. However, results of a validation program conducted under contract by Northrop Corporation with Lockheed-Georgia Company as subcontractor and the release of pertinent new data have indicated that an updated amendment would aid in the preparation of the revision and increase the usefulness of the specification until the new revision is available.

SCOPE

In this program, only existing flight control system data was to be used in the substantiation of new specification requirements. Recommendations and background information were to be based on existing data and require no additional study and analysis programs.

Because of the short duration of the contract, it was necessary to identify and limit the potential areas for revision or discussion early; only areas of significant impact were to be considered. The following is a list of the areas identified in coordination with the Air Force Update Panel.

- a. Digital flight controls requirements relative to redundancy management, data transmission, microprocessor applications, and software verification/validation.
- b. Fly-by-wire controls requirements relative to electrical design, signal transmission, actuation failure management, and immunity to associated subsystem failures.
- c. Self-test capability requirements versus complexity, confidence level, and preflight test duration.
- d. Cockpit controls/displays design requirements to accommodate high-g cockpit geometry constraints and integrated displays.
- e. Actuation requirements to reflect the application of high performance rotary mechanical actuators and electromechanical actuators to essential or flight phase essential functions.
- f. Controls/structure interaction and integration requirements relative to analysis and test verification.
- g. Simulation requirements relative to system development and performance verification as influenced by type of aircraft and flight control system concept.
- h. Compatibility between the update amendment and the new revision of the flying qualities specification, MIL-F-8785C.

Following a literature search and meetings with members of industry, the resulting data were catalogued according to the key areas. Subsequently, the specifications and assimilated data were reviewed and recommended amendments and discussions were prepared.

SUMMARY OF RESULTS

In the preparation of this report it became more apparent than ever that flight control system design requires a multi-disciplinary approach incorporating various aspects of electrical and mechanical engineering and the system, computer, and management sciences. As a result there is a significant amount of overlapping and intertwining of various requirement areas.

The state of the art has advanced rapidly in the last five years, particularly in the area of electronics for digital flight controls. This report attempts to accommodate the current state of the art while providing for the implementation of future advances.

The bulk of this report addresses the interrelated topics of digital flight controls, fly-by-wire controls, and self test and monitoring. These topics are addressed in many requirement areas. In addition to being addressed in the obvious areas of system test and monitoring and electrical signal computation and transmission, they are also referred to in the redundancy, reliability, survivability, invulnerability, and maintenance requirements.

Of particular note are the additions of a redundancy management requirement and discussion, which were absent in the D revision, and the integration of software requirements for FCS design and documentation into the specification. Where the D revision gave little consideration to FCS software, this document attempts to coordinate DOD software requirements and recommended approaches in the specification and User Guide without restricting FCS software design. Both of these modifications have been made with the goal of more efficient system acquisition in mind.

Other subjects covered in this report include updates of the requirements for stability, Automatic Flight Control Systems (AFCS), and cockpit controls/displays, and modification of the quality assurance and actuation requirements. In addition, an effort was made to make MIL-F-9490D compatible with the latest revision of the specification for flying qualities of piloted aircraft, MIL-F-8785C.

In preparing the amendments for the AFCS and the cockpit controls/displays requirements, Volumes II and III of AFFDL-TR-77-7, the Northrop/Lockheed-Georgia

validation of MIL-F-9490D, were the main reference sources, coupled with the current experience of our advisory personnel.

Amendments to the quality assurance requirements provide a thorough and comprehensive documentation of FCS design requirements, in particular software documentation, and test requirements relative to system development and performance verification as influenced by aircraft type and FCS concept.

For some requirements there were no amendments. However, User Guide discussions were expanded in an effort to incorporate recent experiences and current thinking. In some cases, such as stability margins and survivability, the amendment modifies the emphasis of the requirement rather than making a quantitative change. In others, such as reliability and system test and monitoring, amendments were felt to be either undesirable, given the generality of the specification, or out of scope, given the size of the contract effort.

APPENDIX A

Appendix in support of Amendment 1 to MIL-F-9490D and Background
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2. APPLICABLE DOCUMENTS

2.1: Under line 9, "MIL-F-3541", insert "MIL-S-3950 Switches, Toggle, Environmentally Sealed, General Specification for".

Under line 34, "MIL-G-6641", insert "MIL-S-6743 Switches, Sensitive and Push, Snap Action, Actuators and Enclosures, General Specification for".

Under line 91, "MIL-M-38510", insert "MIL-S-52779 Software Quality Assurance Requirements" and "MIL-C-81774 Control Panel, Aircraft, General Requirement for".

Under line 103, "the Selection of", insert "MIL-STD-203 Aircrew Station Controls and Displays for Fixed Wing Aircraft".

Under line 111, "ments for Equipment" insert "MIL-STD-471A Maintainability Verification/Demonstration/Evaluation".

Under line 113, "and Waivers" insert "MIL-STD-483 Configuration Management Practices for Systems, Equipment, Munitions and Computer Programs" and "MIL-STD-490 Specification Practices" and "MIL-STD-499 Engineering Management".

Under line 119, "Equipment and Facilities" insert "MIL-STD-1521 Technical Reviews and Audits for Systems, Equipment, and Computer Programs".

Under line 115, "of", insert "MIL-STD-781 Reliability Design Qualification and Production Acceptance Tests: Exponential Distribution".

Under line 147, "AFSC DH 2-2" insert the following heading and publication title:

"Air Force Regulations Document

AFR-800-14 Vol. I: Management of Computer Resources in Systems
Vol. II: Acquisition and Support Procedures for Computer Resources in Systems".

2.2 Other publications. Line 20: Change the heading to "FAA Advisory Circulars".

Discussion

The applications of the documents which have been added to this section are addressed in the discussions of the appropriate amended requirements of sections 3. and 4. and addition of definitions in Para. 6.6.

3. REQUIREMENTS

3.1.2 AFCS performance requirements. Line 1: Before the first sentence insert "Engage and disengage, selection logic, and functional safety criteria and limits for each AFCS function shall be established and specified in the detail flight control specification."

Discussion

The intent of this amendment is to highlight the need for AFCS requirements to be tailored to each particular procurement activity, thereby allowing flexibility and freedom in AFCS design.

3.1.2.2 Heading hold. Line 4: Delete the last sentence and substitute "When heading hold is engaged, the aircraft shall roll towards wings level. The reference heading shall be that heading that exists when the aircraft passes through a roll attitude that is wings level plus or minus a tolerance."

Discussion

It may be arguable that a heading hold accuracy of ± 0.5 degrees does not appreciably enhance mission effectiveness or aircraft operational efficiency over an accuracy of ± 1.0 degree for the heading hold mode. Since, however, the state-of-the art now allows realization of the more stringent requirement without undue penalty in cost, the requirement is considered valid.

The 5 degree RMS heading 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, reference 1. If a flight controller is used, when the controller is returned to detent, the aircraft shall roll towards wings level; the reference heading shall be that heading that exists when the aircraft passes through a roll attitude that is wings level plus or minus a tolerance.

The requirement states that heading hold shall automatically engage as the controller is returned to the detent. The use of the word "as" makes this confusing. The word "when" is proper in this case. A majority of the aircraft use the detent position as the logic for going to the heading hold mode, reference 1.

For initial engagement of heading hold, or subsequent return to heading hold from control stick (wheel) steering or flight controller commanded bank angle, the selection of the reference heading is not made until two criteria are satisfied:

- 1) heading hold is selected, and
- 2) the roll attitude is approximately wings level.

This dual criterion ensures 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.

3.1.2.3 Heading select. Line 7: After the fourth sentence, insert "Entry into and exit from the turn shall be smooth and rapid."

Discussion

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 a minimum acceptable. The requirement for smooth and rapid assures that minimum rates, as well as maximum, will be acceptable.

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, reference 1.

3.1.2.4 Lateral acceleration and sideslip limits. Line 1: Delete the first sentence and substitute "Except for flight phases using direct side force control or during which sideslip is deliberately induced, e.g., forward slip

to a landing, the following performance shall be provided when any lateral-directional AFCS function is engaged."

Discussion

Deliberately induced sideslip maneuvers, such as those which might be used during coupled autoland modes, are excluded from this requirement.

The acceleration and sideslip limits as previously defined did not account for deliberate sideslip maneuvers. Autoland implementations and the advent of control-configured vehicles require that these limits not be applied during deliberate side-slip or side-force maneuvers.

3.1.2.4.1 Coordination in steady banked turns. Line 1: Delete the first sentence and substitute "The incremental sideslip angle shall not exceed 2 degrees from the trimmed value, and lateral acceleration shall not exceed 0.03g while at steady bank angles up to the maneuver bank angle limit reached during normal maneuvers with the AFCS engaged."

3.1.2.4.2 Lateral acceleration limits, rolling. Line 2: Delete "aircraft with" and substitute "flight condition with aircraft".

line 3: Delete "aircraft with" and substitute "flight condition with aircraft".

line 4: Delete "aircraft with" and substitute "flight condition with aircraft".

Discussion

This change recognizes that 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 +0.1g not +0.5g.

3.1.2.4.3 Coordination in straight and level flight. Line 1: Delete the first sentence and substitute "The accuracy while the aircraft is in straight and level flight shall be maintained with an incremental sideslip angle of +1 degree from the trimmed value or a lateral acceleration of +0.02g at the c.g., whichever is lower."

Discussion

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

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.

3.1.2.6 Mach hold. Line 1: Before the first sentence, insert "The requirements of this paragraph shall be met in straight, steady flight including climb or descent."

Line 7: After the last sentence, add "Adjustment capability of at least +0.01 Mach shall be available to allow the pilot to vary the reference Mach number around the engaged Mach number."

Discussion

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 on the QB-47, C-141, and C-5A 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. ARINC Characteristic No. 558 (Air Transport Automatic Throttle System) indicates a full range of adjustment for their system, reference 1.

The basic purpose of the Mach hold mode is to provide a Mach hold capability in "straight and level" 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. 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.

3.1.2.7 Airspeed hold. Line 1: Before the first sentence, insert "The requirements of this paragraph shall be met in straight, steady flight including climb or descent."

Line 6: After the last sentence, add "Adjustment capability of at least ± 10 knots shall be available to allow the pilot to vary the reference airspeed around the engaged airspeed."

Discussion

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. Experience on installing automatic throttle systems on the QB-47, C-141, and C-5A has shown that some adjustment capability must be available for the pilot. 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, reference 1.

3.1.2.8 Automatic navigation

Discussion

This paragraph covers only general requirements for VOR and TACAN navigation modes and definition of terms.

Specific requirements for inertial navigation, area navigation, or vertical navigation control are not included in this specification since these requirements will depend on the aircraft mission. Normally these requirements will be included in the procurement detailed specification, when such functions are required.

Requirements for a microwave landing system (MLS) approach mode have not been included at this time because of the lack of definitive information on MLS ground facilities and contingent approach procedures.

3.1.2.8.1 VOR/TACAN

Discussion

The VOR and TACAN overshoot and tracking accuracy requirements are stated in terms of angular error with respect to the selected radial. Thus the allowable error automatically decreases with decreasing distance to the station. The TACAN requirements are more stringent than those for VOR, reflecting the improved performance that should be achieved through use of the TACAN range information. The tracking accuracy requirements are stated in terms of RMS errors over a defined distance from the station that is far enough removed to be out of the geometric sensitive area. All distances are given in terms of nautical miles to be compatible with Air Traffic Control data format. The overstation requirements allow for resetting the capture logic if it is found to be desirable by the contractor.

3.1.2.8.1.1 VOR capture and tracking. Delete the entire paragraph and substitute the following:

"Overshoot shall not exceed 1-1/3 degrees (20 μ a) 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) 1-1/3 degrees (20 μ a) from the VOR radial beam center. RMS 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."

Discussion

The use of the term "average error" is objectionable since large "hunting" errors could occur to right and left of the beam and still result in a small "average" error, reference 1.

3.1.2.8.1.2 TACAN capture and tracking. Delete the entire paragraph and substitute the following:

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

Discussion

The TACAN capture and tracking requirements were translated to angular measure and the required tracking accuracy defined. The requirement, as

compared with VOR tracking accuracy requirements, reflects the improved accuracy that can be achieved through use of the range information.

3.1.2.8.1.3 Overstation. Line 3: At the end of the first sentence, remove the period and insert "in a no-wind condition."

Discussion

The overstation mode requirements for VOR and TACAN defined in this paragraph include provisions for resetting the beam capture logic. 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.

3.1.2.9 Automatic instrument low approach system. Line 1: Change the title to "Automatic approach system (ILS)."

Discussion

This change denotes that the 3.1.2.9 subparagraphs are applicable to only ILS systems.

3.1.2.9.1 Localizer mode. Delete the entire paragraph and substitute the following:

"The AFCS shall maintain a constant heading until the aircraft is within +150 microamperes of the beam center, at which point the aircraft will be maneuvered to capture the localizer beam. Heading or roll rate and attitude commands shall be limited to provide a smooth capture and subsequent tracking of the localizer beam. The initial overshoot during capture shall not

exceed 75 microamperes and the system shall exhibit a damping ratio of at least 0.1 with intercept angles of 45 degrees at 8 miles from runway threshold and increasing linearly to 60 degrees at 18 miles from runway threshold in a no-wind condition. For intercept angles less than 45 degrees, the FCS shall always maneuver the aircraft toward the course centerline. There shall be no movement away from the runway threshold during capture. The system shall be considered to be in the tracking mode whenever the following conditions are satisfied: Localizer beam error is 1 degree ($75\mu\text{a}$) or less, localizer beam rate is 0.025deg/sec ($2\mu\text{a}/\text{sec}$) or less. During beam tracking the system shall exhibit a damping ratio of 0.2 or greater. From the outer marker to an altitude of 300 feet above runway elevation on the approach path, the AFCS shall maintain the aircraft 2-sigma position within 0.47 degrees ($35\mu\text{a}$) of the localizer beam center. On the approach path from 300 feet above runway elevation to the decision altitude of 100 feet, the AFCS shall maintain the aircraft 2 sigma position within 0.33 degrees ($25\mu\text{a}$). The performance during the tracking mode shall be free of sustained oscillations. These criteria shall be based on a Category II localizer ground installation."

Discussion

It is felt that the requirements of this paragraph are too stringent and do not provide maximum designer freedom while retaining required flight safety.

The overshoot requirement of 0.5 degrees (37.5 microamperes) radial error is very tight and could require a special design such as a variable gain system for a requirement that is not critical. The point at which the beam capture is initiated should be specified. It is felt that 150 microamperes is the best point to start beam capture. This requirement states that a damping ratio of 0.2 or greater shall be exhibited during the tracking mode at a distance of 40,000 feet from the transmitter. This does not give the required damping before and after the 40,000 foot point. This damping ratio should be required throughout the tracking mode. The tracking accuracy of the requirement is more stringent than the FAA Category II approach requirement of Advisory Circular AC 120-29. It is felt that the FAA requirements should be used since these requirements are considered applicable to military aircraft, reference 1.

3.1.2.9.2 Glide slope mode. Line 5: After "satisfied" insert "the first".

Line 7: Delete "from below the beam in level flight at an altitude greater than 800 feet above the glide slope transmitter datum altitude in a no-wind condition." and substitute "in a no-wind condition from above or below the beam under normal approach configurations,"

Line 9: Delete "0.085" and substitute "0.20".

Line 10: Delete "for the conditions defined." and substitute "and the transient errors encountered during the tracking mode shall not exceed 0.16 degrees (35 μ a) of radial error from glide slope beam center."

Line 10: Delete "On" and substitute "When using".

Line 11: Delete "(including 10,000 foot runway) as defined in ICAO Annex 10".

Line 13: Delete "opposition" and substitute "position".

Discussion

It is felt that this is a good requirement, but some changes are required. Capture performance requirements are only given for captures from below the beam. At the present time, more and more approaches are being made at a steeper angle due to environmental (noise) considerations; therefore, the performance requirements for capture should be given for above and below the beam. This requirement also limits the capture performance requirements to an altitude greater than 800 feet above the glideslope transmitter datum altitude. The capture requirements should be met at any point of capture.

The damping ratio requirement of 0.085 or greater after the first overshoot is not acceptable. A damping ratio this low would be just as bad as neutral stability and could induce PIO (pilot induced oscillation). The damping ratio after the first overshoot should be similar to the localizer mode.

The transient error that could occur during beam tracking should be covered in this requirement. The transient error should never exceed the error allowed for the first overshoot.

The 2-sigma tracking requirements of 0.16 degrees (35 μ a) or within 12 feet of beam center are felt to be reasonable. This tracking accuracy is the same as that required in Advisory Circular AC 120-29.

3.1.2.9.3 Go-around mode

Discussion

The use of an automatic go-around mode would depend on the aircraft and mission requirements. If such a mode is required then this requirement, with the provision that autopilot steering commands are displayed on the flight director, would be relevant for present and future aircraft.

3.1.2.9.3.2 Lateral-heading AFCS go-around performance standards.

Line 3: After "planes" insert "defined in FAA Advisory Circular 120-29".

Discussion

This requirement is valid for present and future aircraft with a change. The first sentence should be changed to include reference to the FAA Advisory Circular 120-29 which is implied. It should be noted that the performance requirement of the last sentence is completely dependent on pilot reaction and performance and is not an operational performance requirement on the AFCS. It does affect the system design of the automatic go-around mode in the area of failure announcement and affect of failures or disengagement of the mode on the aircraft flight path. No change is suggested in this area.¹

3.1.2.9.3.3 Minimum go-around altitude

Discussion

The requirement is valid for present and future aircraft with the understanding that it assumes that all aircraft will require a minimum altitude for engaging the go-around mode. The C-5A and C-141 flight testing has shown that minimum altitude for these aircraft is the runway altitude.¹

3.1.2.10 All weather landing system. Line 1: Change the title to "Automatic landing system."

Line 1: Delete "all weather" and substitute "automatic".

Line 4: Delete the second sentence and substitute "Automatic landing system shall be designed to be compatible to operations in Category III weather minimums and comply with the following landing accuracies and operational requirements:"

Line 15: Delete "(normally used during ICAO Category IIb or IIIc visibility conditions)".

After line 24, add the following paragraphs:

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

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

f. The automatic landing system design shall meet the criteria for approval of Category III landing weather minimums defined in paragraph 6.6."

Discussion

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

This definition states that an ALS includes all aircraft equipment, ground based equipment, operations, and procedures over some of which the contractor has no authority or control. Since this specification is intended to cover the design, installation, and test of flight control systems by establishing general performance, design, development, and quality assurance requirements for the flight control systems, the requirement for an automatic landing system as defined is believed to be beyond the scope of this specification. The majority of the performance requirements stated in the requirements however are pertinent to an automatic landing mode. It is recognized that the procuring agency has the need to exercise its prerogatives for ground and flight procedures and equipment and for weather minimums for which the aircraft should be cleared. The contractor must satisfy the requirements insofar as he is able within the limitations imposed by requirements and equipment over which he has no control. The contractor should therefore be responsible for installing equipment to meet specific performance requirements which are measurable and for which he has control.

Requirement 3.1.2.10b implies that rollout guidance should be designed to accommodate Category IIIb and IIIc visibility conditions. This requirement could require sophisticated ground equipment to be installed at the landing area. The type of ground guidance used would dictate the equipment to be installed in the aircraft. It is felt that this is not feasible since each government organization, aircraft manufacturer, equipment manufacturer, and related organization would have different approaches on proper ground guidance to achieve Category IIIb and IIIc control. In addition, it is believed that there are no commercial or military airfields that have ground equipment that is capable of guiding an aircraft under the stated weather minima.

This requirement should require equipment installed which could be used in meeting the Category IIIa Landing Weather Minima. Any further requirements beyond Category IIIa should be contained in the RFP with an explanation of the ground equipment to be used.

3.1.2.10.1 All weather landing performance standards - variations of aircraft and airborne equipment configurations. Line 1: Change the title to "Auto-

matic landing performance standards - variations of aircraft and airborne equipment configurations."

Discussion

This requirement is valid for present and future aircraft except for the title "All weather landing system." This should be changed to "Automatic landing system," See the evaluation on requirement 3.1.2.10.¹

3.1.2.10.2 Performance standards - ground based equipment variations. Delete the entire paragraph and substitute the following:

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

Discussion

This requirement includes areas that should not be included in a flight control system specification, such as touchdown zone lighting and taxi zones. Only flight control requirements that the aircraft manufacturer is responsible for should be included in this specification to insure that compliance with requirements can be demonstrated. This same subject is discussed in the evaluation of requirement 3.1.2.10.

This requirement should include the expected variation of the ILS beam that should be considered during design and evaluation.

3.1.3.1 Redundancy

Discussion

In support of the redundancy discussion in the User Guide, formal definitions of the terms fail operate, fail passive and fail safe have been included as an update to the Definitions paragraph 6.6.

In a discussion of the survivability requirements of 3.1.8, the topic of dissimilar back-up systems is reviewed.

3.1.3.1: After this paragraph, insert the following as a new paragraph:

"3.1.3.1.1 Redundancy management. In the design of a redundant flight control system, the redundancy management approach determined by the contractor shall be:

- a. based on meeting the flight safety and mission reliability requirements of this specification.
- b. consistent with the use of the system test and monitoring provisions of requirements 3.1.3.9 and associated subparagraphs.
- c. validated by appropriate analyses.
- d. addressed in the software requirements definition when applicable."

Discussion

With the utilization of redundant channels for the implementation of active control technology in present and future aircraft, redundancy management has become a major flight control system design area, and thus needs to be addressed by this specification. Without this requirement the specification is deficient.

As shown in references 2 through 14, numerous flight control system specifications and studies addressing the implementation of fly-by-wire control systems have major sections addressing redundancy management. Currently the F-18A uses an estimated minimum of 25% of its software for redundancy management.

The purpose of redundancy management is to provide failure transient protection and efficient, effective normal operation, while maximizing mission reliability and flight safety.

To this end, redundancy management must be employed at various levels within the flight control system architecture to perform such tasks as:

- 1) failure detection
- 2) failure isolation
- 3) system reconfiguration
- 4) channel recovery update
- 5) cross channel data transmission
- 6) cross channel synchronization for synchronous computers
- 7) input signal management
- 8) actuator management.

In performing these tasks, in particular failure detection and isolation, the redundancy management approach will influence and be influenced by

the 3.1.3.9 specification requirement and the inflight monitoring techniques discussed in this document and the MIL-F-9490D User Guide. The comprehensiveness of any redundancy management approach will be based on its utilization of voter planes and inline (or self test) monitoring. It has been shown that for long missions, systems employing interunit selection at the LRU level can be more reliable than systems employing one higher level of redundancy and using midvalue signal voting as the only means of fault detection and isolation. Thus application of advanced redundancy management techniques to meet a given reliability requirement can result in significant equipment savings¹¹. Some caveats for redundancy management are: 1) for electrical signal computation no computer shall interfere with the operation of another, and 2) pilot intervention should not be required for system reconfiguration in the event of a failure.

In the implementation of redundancy and redundancy management methods to satisfy flight safety and mission reliability requirements, it is necessary that the design address not only what is required for the flight control system per se, but also what is required for any supporting system (e.g., mission computer and air data system) which is flight safety critical or flight phase essential.

The success criterion by which a redundancy management approach is typically measured is its coverage. Although the term coverage has been given slightly different interpretations in the literature available today, the most encompassing one defines coverage as the conditional probability that, given a failure, the system continues to perform the required function.

While some studies, references 7, 9, and 11, have specified that a probability of coverage as high as 1.0 can be obtained for a first failure and a probability of .94 or better for a second failure in order to achieve an acceptable flight safety value, in practice attempts to achieve the required flight safety goal typically utilize lower failure coverages, references 2, 4, 5, 6, and 15.

The critical criteria for the determination of acceptable probability of coverage values for first and second failures are the mission reliability and flight safety requirements of paragraphs 3.1.6 and 3.1.7. When assured adequate reliability and safety other influencing factors are the tradeoffs between system complexity, weight and cost.

In the development of redundant flight control systems to satisfy the flight safety requirements, there have been as many different approaches as there have been types of aircraft.

The DIGITAC aircraft, a modified A-7D containing dual digital computers, references 5 and 6, is designed to be fail safe for all failures and fail operation/fail safe for failures in the computer and memory units. The fail operation/fail safe capability of the dual computers and memories was achieved by extensive self test; and the fail safe function of the servos and sensors was made possible by comparison monitoring of dual servos and sensors for all flight critical parameters. Through computer monitoring, the interfacing units were fail safe.

Development problems uncovered by this program are contributing to future designs. One example is the problem of interaction between self-test routines. In one instance, a power-supply problem caused one computer to fail. An unforeseen timing situation in the self-test of the cross-computer data link caused the good computer to shut itself off. This problem was corrected. However, its existence shows that these kinds of interactions must be studied very carefully.

The F-8 Digital Fly-by-Wire system has three primary digital channels. There is a back up system which is also electronic. The critical input sensors are triplex, and data from each of the redundant sensors are supplied to all three computers. Identical signal-selection programs are performed in each computer. This signal selection identifies and removes the effects of failed sensors and produces identical input signals for each of the three computers. These identical inputs are used by the computers to produce three control-surface command outputs. The midvalue of the three commands is selected by three different servo-control-electronics channels. These three channels drive the three sections of triplex force-summed secondary actuators which in turn command the primary power actuators. The selection logic in the analog drive channels will identify and eliminate a failed digital channel if its command signals deviate significantly from the other two. The system will continue operating using the two remaining good channels. Many of the faults detected are transient and the system has the capability of restarting the failed channel and returning to full three-channel operation. If the fault is permanent so that only two channels remain and they do not agree, the system

reverts to a triplex direct analog coupling between the pilot commands and the servo drives.

The YC-14 system uses a triple-redundant set of electronics and multiple aerodynamic surfaces to achieve fail operational/fail safe performance.⁶ The system provides automatic signal selection, failure detection, failure isolation, failure warning, and failure isolation confirmation during flight-critical operations. The input signal selection guarantees that all computers will use the same numbers and thus produce identical outputs. The output is selected as the midvalue of the three values. The system continues to operate after the first failure by taking the average of the two remaining systems. When the two remaining systems disagree, they are both disabled and the aircraft is flown manually.

For the quadruplex analog flight control system of the F-16, failure detection and isolation performed by inflight monitoring consist primarily of:

- a) middle-value signal selection following electrical signal computation and FCC servo amplifier failure detection, and
- b) integrated servo actuator (ISA) failure detection.

The ISA failure detection incorporates differential pressure sensing of the servovalves, hydromechanical failure detection, and ISA position versus computer model position.

The F-16 is no less than one fail operate overall and a minimum of two fail operate if one failure is electrical.

The F/A-18A flight control system utilizes quadruplex digital computation, direct electrical links, and a mechanical back-up system in pitch and roll. The leading and trailing edge flaps and horizontal/rolling tail have quadruplex servovalves, and the rudders and aileron surfaces have a dual/dual electrical capability. All actuators have access to two separate hydraulic systems.

The digital flight control computers and the electrical system overall have a two fail operate capability. Hydromechanically the system has at least a fail operate capability.

For the performance of redundancy management the F/A-18 inflight monitoring is very comprehensive. In addition to thorough computer self-test the system has two voting planes. Through a cross channel data link the first evaluates the input signals to the flight control computers, where failed signals are ignored and the remaining good signals are averaged.

The second conceptual voting plane pertains to the actuator quad coil drive current summing concept. To evaluate the status of actuators and actuator signals, the redundancy management employs: differential pressure sensing to evaluate the EHV; cross CAS monitoring to evaluate CAS ram, main ram, and input signals; and a current monitor to check servoamplifiers and EHV coils.

The current redundancy approach for the Advanced Fighter Technology Integration program, i.e., the AFTI-F-16, will be based on a triplex digital flight control system which provides a dual fail operate capability. The following excerpts, taken from reference 2, are an overview of the preliminary AFTI-F-16 redundancy management.

Previous system architectural studies have indicated that optimum failure survivability and failure isolation to the LRU level require that the flight control system have three voting/monitoring planes. Two of these planes are in software and are at the sensor/controller interface and the output surface command interface. The purpose of the input/monitoring plane is to detect and isolate failures associated with the sensors, controllers, and input circuitry from those associated with the processor and its memory. The output voting/ monitoring plane is used to detect and isolate failures associated with the Flight Control Computer CPU and its memory. It is located internally to the ISA's and can be used to isolate failures associated with the computer output circuitry and ISA servovalve coils, as well as internal ISA failures.

In addition to these voting planes there is also processor self-test which is used to isolate certain first failures and majority of second like-failures. Hardware self-test features (e.g., the watchdog timer, word count and parity checks on MUX bus receipts, memory parity and wraparounds) are always active and are 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.

A second like processor failure, if isolated by self-test, will cause control shift to the last remaining good processor. If the failure is not isolated, then for AFTI-F-16 development safety purposes the independent backup unit (IBU) two fail operate capability is engaged. The IBU is also automatically engaged whenever all three processors indicate that they have failed.

In the AFTI program the projected coverage of a flight control computer to isolate its own failure through self test is 0.95^{16} .

3.1.3.3.4 Failure transients. Line 3: Delete the second sentence and substitute "A realistic time delay between the failure and initiation of pilot corrective action shall be incorporated when determining compliance. This time delay should include an interval between the occurrence of the failure and the occurrence of a cue such as acceleration, rate, displacement, or sound that will definitely indicate to the pilot that a failure has occurred, plus an additional interval which represents the time required for the pilot to diagnose the situation and initiate corrective action."

Line 5: Delete the third and fourth sentences and substitute "The following limits apply to transients due to failures within the FCS as a function of the Operational State of the system after the failure:

Operational State I or II (after failure)	+ 0.5g incremental normal or lateral acceleration at the pilot's station and <u>+10</u> degrees per second roll rate, except that neither stall angle of attack nor structural limits shall be exceeded. In addition for Category A, vertical or lateral excursions of 5 feet, <u>+ 2</u> degrees bank angle.
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Operational State III (after failure)	No dangerous attitude or structural limit is reached, and no dangerous alteration of the flight path results from which recovery is impossible."
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Discussion

Both 8785 and 9490 MIL specs cover the transient response following a failure and pilot corrective action. This duplication of coverage is supported because of the essential involvement of these two disciplines in this very important issue. Because of this duplication, however, it is important to correlate the requirements as closely as possible to minimize the analysis and tests necessary to demonstrate compliance.

8785 discusses transients due to failures in two locations. In the "Miscellaneous Flying Qualities" section (paragraph 3.4.8 in 8785C), the considerations by which one determines the pilot reaction time delay are given. Specific numbers are not given, but rather guidance is given for each specific aircraft and its warning system and natural cues. These are the same factors for consideration in 9490. Transients due to failures are also discussed in the "Characteristics of the Primary Flight Control System" section (paragraph 3.5.5.1 of 8785C). This is where load factor, roll rate, etc. response limits are stated.

The objective in both specifications is to assure crew acceptance and flight safety. Therefore the same quantitative limits are used in each specification. 9490D was closely aligned with the Operational State III after failure condition, which required the transients not to exceed 75 percent of limit load factor or 1.5 g's from the initial value, whichever was less. For most aircraft, of course, the 1.5g was the governing requirement, and this was significantly more restrictive than the structural limit allowed by 8785. However, one must consider that even 1.5g's might be excessive, especially at low speed close to the ground. For that reason both specifications require that no flight path deviations be encountered from which recovery is impossible.

3.1.3.6.1 Stability margins. Line 15: Delete the last sentence and substitute the following:

"The margins specified by Table III shall apply regardless of system implementation, analog or digital, 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."

3.1.3.6.2 Sensitivity analysis. Line 6: After the first sentence insert the following:

"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, input and output filters, digital filter implementation, and integration technique."

Discussion

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 of reference 46. 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. These considerations are emphasized by the revision proposed for the stability requirement paragraphs.

Aeroservoelastic instability, the one manifestation of flight control-structural dynamics interaction that defies detection by traditional ground tests, has been addressed in detail in papers authored by Barfield and Felt, reference 21, and Felt et al., reference 22. These papers concluded 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, as pointed out in reference 25.

Reference 25 also provides an example of successfully applying the characteristic diagram technique, with the oscillatory aerodynamic forces calculated by the doublet lattice method, to analyze aeroservoelastic stability. Reference 26 describes a methodology for synthesizing aeroelastic airframe transfer functions that allows the examination of stability by classical stability analysis techniques. The transfer function synthesis method holds the promise of a truly unified and integrated analysis approach to the stability problem.

With digital flight controls coming of age, 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 references 23 and 24. As the stability margins need to be satisfied regardless of system implementation, the analysis model of a digital system must be sufficiently representative of the real time characteristics.

As pointed out in reference 1, the variations in gain and phase margins as a function of relative mode frequencies (e.g., Table III of AFFDL-TR-74-116) 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, as recommended in reference 23. 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. The requirement

allows the necessary latitude to consider each weapon system on an individual basis, thus insuring its applicability to future procurements.

3.1.3.7 Operation in turbulence. Delete the entire paragraph and substitute the following:

"The FCS must be capable of operating while flying in the following applicable random and discrete turbulence environments. The dynamic analysis or other means used to satisfy this requirement shall include the effects of rigid body motion, significant flexible degrees of freedom, and the flight control system. The effect of the turbulence on the pitot system and on any vanes or other sensors must be considered.

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

b. With the essential and flight phase essential controls engaged and active the FCS performance must permit safe termination of precision tracking or maneuver tasks, and safe cruise, descent, and landing at the destination of original intent or alternate. The pilot's workload may be excessive or the mission effectiveness inadequate. The performance must be possible while operating in the turbulence levels of 3.1.3.7.1.

c. The noncritical controls shall provide at least a level of performance which results in a moderate increase in crew workload and degradation in mission effectiveness; however, the intended mission may be accomplished. This performance must be possible while operating in the turbulence levels of 3.1.3.7.1.

d. When operating in turbulence intensities greater than those of 3.1.3.7.1, the operation of the noncritical controls shall not degrade flight safety or mission effectiveness below what exists with the controls inactive. Either manual or automatic means may be used to inactivate the noncritical controls in heavy turbulence when required."

Discussion

The primary point of ambiguity in this requirement as stated in 9490D is the reference to Operational States. The definitions of Operational States in 1.2.2 include three considerations: (1) system operation/failure state, (2) corresponding pilot/mission performance, (3) corresponding 8785 flying

qualities level. In paragraph 3.1.3.7 of 9490D with regard to essential, flight phase essential, and noncritical controls, the Operational States are intended to call out the required pilot/mission performance. However, because of the ambiguity concerning failure states associated with Operational States II and III, 3.1.3.7 becomes unclear. This is avoided by using the pilot/mission performance statement directly.

3.1.3.7.1 Random turbulence. Second paragraph, Line 6, delete the sentence "At the maximum level flight airspeed, V_H these intensity levels are reduced to 38 percent of the specified levels."

Discussion

This change was made due to a lack of justification for its inclusion within the specification.

3.1.3.9 System test and monitoring provisions

Discussion

Since AFFDL-TR-74-116 was issued, there has been a considerable amount of work in system test and monitoring. The F-16 system is now in production, the F/A-18A is in full scale development, and the AFTI-F-16 program is completing its final design phase. With respect to digital flight control systems, the topics of redundancy management, coverage, and self test have received considerable attention. Self test is discussed below and the topics of redundancy management and coverage are addressed in the redundancy management section, 3.1.3.1.1.

In the development of design specifications for the procurement of advanced aircraft (fighter aircraft in particular), the detail that is given to the areas of comprehensive built-in test is intense and far beyond that generality addressed through MIL-F-9490. There was some thought given by advisory personnel on this project, who had been involved with BIT specifications for the F/A-18 and F-5G programs, that the MIL-F-9490 specification should be revamped to address BIT on the design level rather than at the generic level. However, such a task was beyond the scope of the contract and not desired for the 9490 update at this time.

However, comprehensive procedures do need to be established relative to the demonstration and verification of BIT. Two documents which address this area are an addendum to MIL-STD-471A, Demonstration and Evaluation of Equipment/System Built-In Test/External Test/Fault Isolation/Testability Attri-

butes and Requirements, and Report RADC-TR-79-309 BIT External Test Figures of Merit and Demonstration Techniques. The verification and validation of BIT software will have to be in accordance with the overall software procedures as outlined in the Computer Program Configuration Item (CPCI) and defined by the software verification/validation test plan.

Due to the large portion of the FCS Operational Flight Program software that built-in test requires, the BIT software should be modularized in its utilization of the hardware, so that in providing for changes and growth potential, the verification and validation activity required is minimized.

In the design and implementation of electrical signal computation for flight control systems, a key area of concern with respect to flight safety and mission reliability is the systems inflight monitoring capability. This inflight monitoring includes cross channel monitoring, the use of data reasonableness, and computer self test.

The level of self test a computer can competently perform will influence the level of redundancy required to satisfy the system flight safety and mission reliability requirements.

For digital flight control systems, self test is the aspect of inflight monitoring which monitors the integrity of the processor, memory, and input/output interfaces of the digital flight control computer.

For two channel digital flight control system operation, in-line monitoring must be used to resolve any channel differences. When in-line monitoring is used, the computer must first perform self test prior to checking the other elements of the digital flight control system. Self testing will encompass both software and hardware.

The following is a list of recommended self tests from references 8, 9, 14, and 18:

1. Instruction test sequence - test for endless loops, time deadline to exercise all instructions.
2. 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.
3. Wrap around loop tests - to verify the computer I/O sections for both analog and discrete data.

4. Use of hardware circuitry to monitor the computer power supplies. Power supply status signals will be exchanged between computers.

5. 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.

6. 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.

7. Use of an internal timer to monitor the time required to complete various portions of the self-test program.

8. Use of parity to monitor continuously the memory storage locations. When bad parity is indicated, an interrupt will be initiated.

9. Check data, address, and control lines by reading out of memory data patterns of zeroes and ones, stored in predetermined locations.

10. 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.

11. Sample problems to check the CPU - designed to exercise the instructions used to solve the control laws.

12. An arithmetic fault interrupt to sense overflows.

13. Parity - to monitor continuously the transmission of data over the I/O channels. When bad parity is detected, an interrupt will be initiated.

When a choice exists between the implementation of hardware or software to perform monitoring tasks, the use of software is preferred since hardware results in a higher channel failure rate due to additional parts, and consequently results in a higher probability of loss of control.¹⁴

For any flight control system utilizing inflight monitoring, there are two aspects which currently have no requirement in the specification, but which require consideration. The first addresses the allowable frequency of nuisance disconnects and false alarms, and the second is concerned with the recording of failures and transient failures which occur during flight.

During the flight testing of the YF-17 and the DIGITAC programs, numerous nuisance disconnects were encountered in the early phases of each program. The remedy for these nuisance disconnects was typically an opening of the trip monitor levels. This increase in the levels was to account for the

transients associated with the FCS hardware performance and not the actual aircraft dynamics. Some monitor trip levels on the DIGITAC program were increased up to a factor of 10 from their original design values.⁵

While on prototype and experimental projects programs such as the YF-17 and DIGITAC there appears to be little desire or need to specify an acceptable nuisance disconnect level, it may be very desirable in a production type program. The trade-off concern, not unexpectedly, with nuisance disconnects is flight safety. It was a comment of some flight test personnel interviewed, whether some of the trip levels of the DIGITAC (among other aircraft) were even meaningful once an acceptable nuisance disconnect level was attained.

The allowable frequency for nuisance disconnects and false alarms has been addressed in at least two separate ways. In the Advanced Fighter Digital Flight Control Study¹⁴ comes the following recommendation.

Nuisance disconnects of an axis or channel, if specified, should be in terms of a maximum number of occurrences per flight hour, not as a ratio of nuisance to actual failures. Tying nuisance disconnects to actual failures implies that a percentage of disconnects will be actual failures. From the AFTI program¹⁶ comes the requirement for computer self test that the false alarm rate shall not exceed one percent of indicated faults.

With the advent of electrical signal computation, in particular digital computation, there is a potential for a failure to occur in flight which may be impossible to identify on the ground. This is particularly true if the failure results in loss of the aircraft. Consequently there has been a desire to implement a methodology and device to code and record computer states and failure transients as they occur in flight.

In the DIGITAC program there was a feature⁴ which coded and stored any failure in the scratch pad (SPAD) memory. Thus, the SPAD memory could be interrogated on the ground to reveal the causes of inflight or preflight failures. This ability was expanded after the initial flights to allow monitor words set on the ground to be distinguished from those set in flight.

Currently on the F-16 program there is an engineering change proposal that would implement a digital device in the aircraft which in addition to performing some maintenance BIT, self test, and other inflight monitoring, would record in a 1 K, 8-bit nonvolatile memory any failures which might occur in flight so that they could be traced on the ground.

A similar capability exists in the F/A-18.

One of the major contributions to the maintenance of the F-12 flight control system reliability is the mission recording system. Each essential parameter of the various vehicle subsystems is monitored for use in a magnetic tape recorder.¹⁹

For the design of preflight BIT and maintenance BIT, consideration needs to be given to the time desired for the performance of these tasks.

In a definition study for an advanced fighter digital flight control system, the estimated time to perform a built-in test which functioned for both preflight and maintenance was:

BIT (with hydraulics)	= 20 seconds (triplex)
	= 29 seconds (quadruplex)
BIT (without hydraulics)	= 10 seconds

While these times appear to be very desirable and one day attainable, up to this time no aircraft preflight or maintenance BIT has come close.

In the NASA F-8 Digital FBW Program, the F-8 flight time preflight BIT took approximately 40 minutes for all checks, about 5 minutes of which was attributed to digital systems tests. It was felt, however, that the plane was over-tested prior to flight.^{6, 20}

For the F/A-18A, the Navy has set the times of 1 minute for preflight BIT and 2 minutes for maintenance BIT as the desired BIT performance times. Currently the preflight BIT (or as they term it, Initiated BIT) for this aircraft takes 8 minutes to complete and the maintenance BIT takes even longer (it should be noted that these times are expected to be reduced significantly). However, this result should be considered neither unusual nor unexpected in light of the complexity of the system and the level of fault isolation performed by the BIT.

The F-16 performs an automatic preflight BIT in approximately two minutes⁴ and can perform an alert BIT within 45 seconds and a complete maintenance and fault isolation test in less than 5 minutes.

It may well be that the answer to obtaining acceptable preflight BIT times, particularly for complex systems, lies not in a compromise of flight safety and mission reliability, but rather in a reduction of the fault isolation capability of preflight BIT. The argument for this is that if the aim of preflight BIT is to determine a GO or NO GO condition based on any one failure, why isolate the failure with no intent to alleviate the failure at that time. If the GO/NO GO was conditional on the type of failure present, then some level of fault isolation would be required, but not necessarily in depth as is found in current aircraft.

3.1.6 Mission accomplishment reliability

3.1.7 Quantitative flight safety

Discussion

The reliability of software is presumed to reach 100% whenever the system matures to the operational deployment stage. This is attained through trials and tests during development which will insure that all of the programming errors (coding, logic, hardware interface, system requirements deficiencies) are eliminated. To attain the near perfect reliability necessary requires a very comprehensive technical development procedure, management control, and configuration control.

Northrop Document NOR 78-85, Weapon System Computer Software Management²⁷, contains an extensive format 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. The document constructs each aspect of the software development program in its most fundamental form, and provides 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 modifications 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 insures that the design criteria are being properly implemented.

Figures 1 and 2 present typical examples of the software development process and software configuration control. The controls presented in the Northrop document and similarly in references 28 through 32 should be fully implemented in any future flight control development programs.

In literature pertaining to flight control system design and aircraft flight safety and reliability, the term "extremely improbable" is frequently used. This term, which should not be confused with the specification 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 hour be extremely remote.

The following discussion taken from a Draper Laboratory report⁶ on digital fly-by-wire control 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 that 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

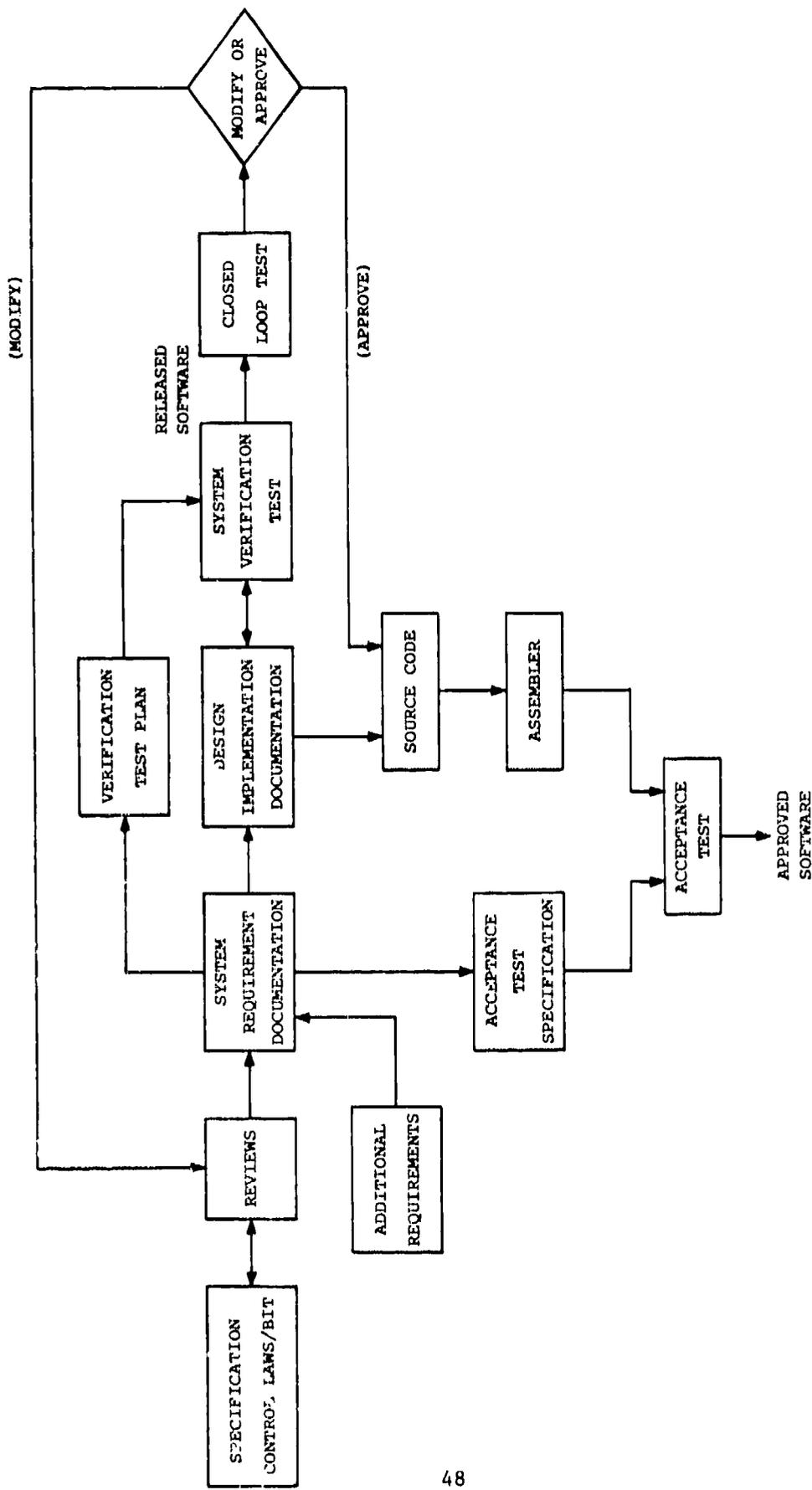


Figure 1. Software development process.

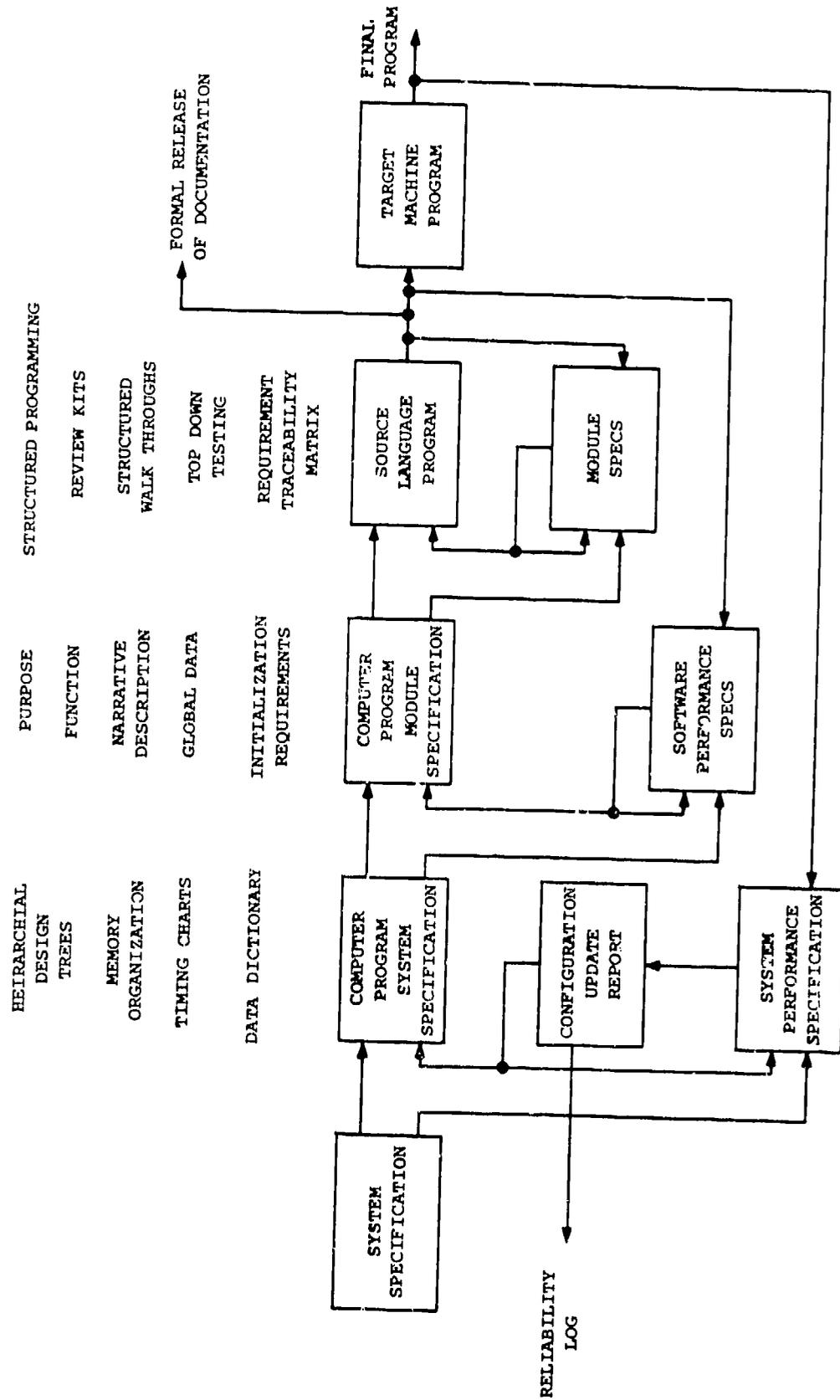


Figure 2. Software configuration control.

hour can then be believable. The actual value of the number can be significant in this circumstance. A change in this number can change the number of redundant channels required.

Numerical analysis may have little or no value in proving that the probability of failure is low due to other failures, such as design errors, common-mode failures, and generic software errors. These classes of faults may be the most likely. A number like 10^{-9} may not be valuable as a legalistic number that must be "proven" with pounds of paper. It may be valuable as a positive goal toward which everyone strives.

For commercial aircraft, the number 10^{-9} seems to be reasonable. It is likely that if advanced electronic flight-control systems can offer even some of the advantages claimed for them, they will be used on virtually all aircraft for at least a generation. If it is assumed that an aircraft generation is at least 15 years, and with at least 6×10^6 commercial aircraft flight hours per year in the U.S. alone, a total of at least 10^8 system operating hours can be assumed. The number 10^{-9} thus means that the probability of a catastrophe due to a system failure is 1 in 10.

3.1.8 Survivability

Discussion

In its survivability discussion, the User Guide predicted "a requirement for a standby flight control capability will also exist in future aircraft equipped with active redundant fly-by-wire control systems".

In light of the F-16, it is apparent that this prediction did not come to pass. However, with qualification it was and still is a good prediction. While the analog F-16 fly-by-wire control system does not have a standby flight control capability or, more to the point, a dissimilar backup system, by being quadruplex it does have one more computational channel than analysis would predict necessary.

While dissimilar backup systems may not be required for analog fly-by-wire control systems, at this time it appears very likely they will be required for all digital fly-by-wire control system applications. The question to be resolved, however, is what constitutes a dissimilar backup system. The concern on this subject is this: What if a glitch in the software leads to a simultaneous, multiple redundant channel drop out?

To provide a dissimilar backup capability both hydromechanical and fluidic signal computation techniques have been studied and employed.

For the F-15 a dual electronic control augmentation system was utilized with an active mechanical control system. In the event of loss of the electronic control augmentation system, a hydromechanical computational device was engaged to provide dissimilar backup insuring level 2 flying qualities. References 33 and 34 discuss studies relative to the implementation of fluidics as a dissimilar backup system.

The approach on the F-18 program was to implement a backup mechanical control system in the pitch and roll axes. The backup system, which is in addition to backup direct electrical links, engages automatically in the event of loss of fly-by-wire control to the horizontal/rolling tail. While the system achieves complete dissimilarity, with no reliance on electrical power, it has not been without penalties. The design implementation of a command select mechanism within an integrated servoactuator which transfers control from electrical to mechanical is very complex, and because of the number of cycles it experiences during preflight BIT, its transition time has a significant impact on the time required for preflight BIT.

Non-production programs such as the AFTI-F-16, the DIGITAC, and the F-8DFBW have implemented analog backup systems for their digital computation channels ^{2,5,6,35,36}. While their backups are dissimilar in terms of electrical signal computation, they are vulnerable in the event of electrical power loss. However, the ability to minimize or eliminate the threat of electrical power loss must be accepted, in view of the success of the F-16 system to date.

With the ability to overcome the problems of electrical power loss comes the potential for the next step in dissimilar backup: the use of dissimilar backup software.

Here the concept of dissimilar software does not imply the approach used on the Concorde SST program, which was very complex and costly. Rather, it involves a simplified, constant gain software program resident in each computer which provides the minimum required control capability of either FCS Operation State IV or State V as required. The potential for this approach has been discussed in reference 6 and demonstrated in work performed on the F-8DFBW program. Although never flown, a dissimilar software program and additional

hardware were implemented on the F-8. When the new hardware detected a simultaneous fault in all computational channels, it was assumed to be a software error and computation reverted to the backup program. This testing was performed by programming some typical software errors into the operational flight program.

In the implementation of dissimilar backup control systems a frequent problem is the synchronization of the two systems. The goal is to minimize the transients in the transfer from one system to the other. As in the F-18, there must be a capability to transfer to and from the backup system. Reference 35 has a thorough discussion of synchronization problems in the F-8FBW program, and reference 37 discusses backup flight control design procedures for increased survivability.

With the increased emphasis on CCV concepts, digital computation, and multiple control surfaces, another area of survivability worthy of attention is control law/control surface reconfiguration. If an aircraft that had a horizontal tail and flaperons, for example, lost control of the horizontal tail, then the control laws would be modified so that the flaperons would provide primary pitch control. This type of approach has been implemented in the HiMAT program and also discussed in reference 38.

A final point relative to survivability in the design of flight control systems in general and fly-by-wire control systems in particular is the potential for batch failures. The possibility exists that each of the redundant flight control computers contains a defective board from the same manufacturing batch, which causes nearly simultaneous failures in all channels as a result of some severe physical or environmental conditions which do not exceed the design requirements. Although an unlikely occurrence, it needs to be addressed and provided for.

3.1.8.1 All engines out control. Line 5: After "flight" insert "airframe/inlet flow-field interactions not adequately verified in flight,".

Line 6: Change "operational envelope" to "permissible flight envelope per MIL-F-8785".

Line 6: After the first sentence, insert "Such supplementary means shall provide control power for a specified duration."

Discussion

The purpose of these amendments is to give the requirement the explicit coverage and definition it is meant to have.

The effect of airframe/inlet flowfield interactions on engine performance is a critical area which should be differentiated from airframe aerodynamics. In support of more efficient systems acquisition, the second amendment establishes the need for a definite time relative to the accomplishment of the survivability requirement.

3.1.9.2 Invulnerability to lightning strikes and static atmospheric electricity.

Discussion

In the User Guide discussion of this requirement, the concluding paragraph states: "Reference 85, 'Final Draft, Aerospace Recommended Practice, Lightning Effects Tests on Aerospace Vehicles and Hardware,' prepared by SAE Committee AE4, Special Task F, 1 May 1974, provides a definitive comprehensive guide to lightning simulation and verification testing of aerospace vehicles. This document has wide general acceptance and is expected to be formalized in 1975."

To date this document has not been formalized and released. Two documents which discuss lightning effects and have been released are references 14 and 18.

There is still much unknown about the impact of lightning strikes on fly-by-wire aircraft. While the HIMAT remotely piloted vehicle has successfully undergone preliminary lightning strike evaluation, and the F-18A has undergone scale model testing to define potentially vulnerable lightning attach points, much remains to be done. At this time there are no published results or recommendations from the F-16 Full-Scale Lightning Strike Test (which was scheduled for June 1979), and no lightning strike evaluation has been performed on a full-scale F-18 to evaluate the effect of lightning strikes on aircraft subsystems.

A nondestructive scaled-down lightning current pulse test conducted on YF-16 No. 1 in 1975 indicated that additional protection would be required for the F-16, reference 3. The direction of the F-16 design effort for lightning strike protection was to: 1) keep lightning strike current flowing through the skin, and 2) protect circuitry and components from induced voltage damage. Protection from damage caused by induced voltage in the circuitry is a function

of the interface circuit characteristics and the input impedance of the components. The length of the circuit, its position with respect to the airframe, and the position of the circuit with respect to known lightning attachment points were considered in determining the general shielding requirements for the FCS.

For the AFTI-F-16 program preliminary design requirements specify that "each input and output line of the DFCS must survive (not degrade or malfunction) conducted transients greater than those produced within an aircraft by a 200 K Amp lightning strike to the aircraft. Furthermore, the fully operating DFCS must survive (no malfunction beyond safe recovery) a magnetic field spike equivalent to that which produced the conducted transient. At present, the effects of the magnetic field spike on circuit components is unknown."

On the subject of lightning in general, there has been a recent FAA report³⁹ regarding a workshop on grounding and lightning technology.

3.1.9.4 Invulnerability to onboard failures of other systems and equipment.

Under line 25: Add the following:

"d. In the event of a failure such as loss of required cooling for electrical signal computation, or a series of such failures not extremely remote, which will unavoidably lead to degraded FCS operation, undegraded operation shall be provided for a period specified by the procuring agency."

Discussion

The intent of this amendment is to address the very real potential of a failure or series of failures that could lead to degraded FCS operation.

It is simply not feasible in all aircraft configurations to isolate the electrical signal computation channels in such a way that only one channel is lost in the event of a cooling air supply failure, as recommended in the User Guide. Rather than attempt to impose a potentially impractical constraint on the FCS design, a more realistic contingency approach is recommended.

This recommendation is similar to a design requirement for the AFTI-F-16 program which states that in the event of the loss of forced cooling air to the flight control computers "the equipment shall withstand the loss of cooling air without degradation of performance for a minimum of two (2) hours"

Unfortunately, all current fly-by-wire aircraft require forced air cooling of the flight control computers. If this trend is to change, it is apparent that it will be as a result of a design change in the electronic components themselves and not the thermal environment of the aircraft itself.

3.1.9.5 Invulnerability to maintenance error. Line 5: After "major overhaul," insert "software modification,".

Discussion

The potential impact of a software maintenance error warrants its specific inclusion in this requirement, and provides a logical connection to the subparagraph which specifically addresses provisions for software maintenance error.

3.1.9.5: After this paragraph, add the following as a new paragraph:

"3.1.9.5.1 Invulnerability to software maintenance error. For systems utilizing digital computation, means for identification of the operational flight program shall be provided, and procedures shall be established to prohibit the implementation of unintended versions of software in the flight control system."

Discussion

For systems which utilize digital computation, particular care must be given to software maintenance because of its complexity and importance for proper FCS operation. The best expression of the need for the requirement is in the 3.1.9.5 User Guide discussion: "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."

To this end, means for identification and procedures for implementation need to be mandatory to provide invulnerability to software error. Note that requirements addressing software maintenance provisions are specified in paragraph 3.1.10.5.

3.1.10 Maintenance provisions. Line 4: Delete "facilitate the accomplishment of all required" and substitute "permit the accomplishment within the allocated maintenance budget and personnel skill level of all required organizational and intermediate level".

Line 7: Change "overhaul," to "repair,".

Line 7: After the last sentence, add "In addition, the design shall employ provisions to facilitate efficient overhaul and performance verification at the depot level."

Discussion

Ease of maintenance has always been a desired objective, but was usually relegated to secondary importance relative to such prime design considerations as volume, weight, and unit cost. This practice resulted in weapon systems with excessive down time, maintenance hours per flight hour, and spares requirements. With increasingly more complex systems coming into the inventory, this situation has worsened acutely. To reverse this trend, maintainability considerations are now receiving prime emphasis and are expressed as firm, quantitative requirements, with a suitable plan for demonstration of compliance. Such quantitative requirements are Maintenance Man Hour Per Flight Hour (MMH/FH) and Mean Time Between Actions (MTBA) for organizational level and Mean Time to Repair (MTTR) for intermediate level, and are established in consideration of the overall aircraft maintenance budget. Achievement of these numerical objectives and demonstration of compliance involves units/systems dedicated to maintainability development and demonstration.

To reflect this trend, and in recognition of the direct relationship between maintainability and weapon system operational readiness, the requirement is changed from a qualitative consideration to a quantitative goal implied by the reference to the allocated maintenance budget.

3.1.10.2.1 Use of cockpit instrumentation. Line 5: Delete "(for nonelectrical and nonelectronic components)".

Discussion

The last sentence of this requirement references "portable test equipment (for nonelectrical and nonelectronic components)." This statement indicates that portable test equipment can be used only for MFCS, yet requirement 3.1.10.2.2 allows the use of portable test equipment under specific conditions.

3.1.10.2.2: After this paragraph, add the following as new paragraphs:

"3.1.10.2.2.1 Provision for portable test equipment growth. Any special test equipment shall be designed to provide for growth consistent with the FCS growth capability.

3.1.10.2.2.2 Provision for portable test equipment software. Where software is utilized within FCS portable test equipment, its design, verification, validation, and maintenance shall be consistent with the software requirements contained within this specification."

Discussion

The first requirement addresses the possibility that growth in the flight control system may require similar growth in the portable test equipment associated with it. Without this provision for growth, the costly (and potentially untimely) replacement of equipment may be necessary.

The second requirement insures that all software developed relative to the flight control system is addressed through this specification, in order to obtain efficient, consistent, and well documented software implementation.

3.1.10.4 Maintenance personnel safety provisions. After this paragraph, add the following as a new paragraph:

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

Discussion

Similar to other maintenance requirements of 3.1.10, this requirement addresses an area requiring particular attention.

Because of the importance of software maintenance in the development and operational modification of a digital flight control system, there is a need for established service procedures to insure flight safety. In addition, once service has been performed, provisions are necessary for efficient verification that the proper version of software has been implemented. This

need is particularly evident with the advent of multi-role aircraft such as the F-18.

It has been stated⁴⁰ that maintenance can account for more than 50 percent of the life cycle costs of software. These costs include both the correction of software errors and changes necessary for system improvement and adaptation. Because of the significance of software maintenance costs, it is important that the software maintenance procedures be well thought out and not only safe but efficient. Some of the inputs, tasks, and outputs relative to software maintenance are listed in Table 1, from reference 40.

TABLE 1. SOFTWARE MAINTENANCE.

Inputs	Tasks	Outputs
Software documentation	Develop a plan for software maintenance	Revised software documentation
Software code	Review change control procedures for field use	Revised software
Test procedures	Define requalification procedures	Software maintenance plan, change procedures, and retesting plans

During the initial phases of the F-18 full scale development program, software changes were first made in a core memory program and flown on the flight simulator and Iron Bird. Upon satisfactory demonstration, PROM's were burned for incorporation in flight units. Prior to use in flight, these PROM's were then evaluated with the flight simulator and Iron Bird.

3.2.1 Pilot controls and displays. Line 5: After "with" insert "the applicable provisions of MIL-C-81774 and".

Discussion

MIL-C-81774 is the general specification for aircraft control panels and as such is applicable to FCS design. It must therefore be referenced in this requirement.

3.2.1.1 Pilot controls for CTOL aircraft. Line 4: Delete "Strict adherence to the prescribed location and maximum range of motion of these controls is required."

Discussion

The reclining angle of the pilot's seat impacts on the validity of dimensions specified in DH 2-2, SN 1(1) and makes comparisons more academic than practical. The application of control concepts such as force-feel, side arm, primary hand controllers, dual controls, etc., will make it additionally difficult to formalize cockpit arrangement dimensions.

Dimensions applicable to cockpit arrangement of controls should be included in the design specification as exemplary of recommended values to serve as a guide. Locating dimensions and range of travel of flight controls would be established by mockup and a basic dimension control drawing subject to approval by the procuring agency.

3.2.1.1.5 Trim switches. Line 1: Change the title to "Trim controls."

Line 5: Delete "MIL-S-9419" and substitute "MIL-S-9419, MIL-S-3950, or MIL-S-6743".

Line 5: After the last sentence, add "Knob type trim controls may be used for proportional trim subject to approval by the procuring agency."

Discussion

The additions of MIL-S-3950 and MIL-S-6743 provide for coverage of trim switches which are not included in MIL-G-25561 and MIL-S-9419. The reference to trim knobs is added in recognition of their widespread use for proportional trim.

3.2.1.1.8 Normal disengagement means. Delete the entire paragraph and substitute "Means for disengagement of all AFCS and non-critical MFCS modes shall be provided which are compatible with the requirements of 3.1.9.6. Disengagement capability for flight phase essential FCS modes shall require approval by the procuring agency."

Discussion

To assure consistency with the requirements of 3.1.3.2, this requirement should apply not only to AFCS modes, but also to all non-critical and flight phase essential FCS modes. The reference made to compatibility with the requirements of 3.1.9.6 does not provide adequate safeguards relative to disengagement capability for flight phase essential modes, so specific approval by the procuring agency should be required.

For the F-18 flight test aircraft there are means for CAS disengagement of the MFCS in three separate axes, pitch, roll, and yaw. These provisions allow the evaluation of degraded modes. This disengage capability is not included on the production version; however, all F-18 aircraft will have a manual over-ride capability of the flight phase essential leading and trailing edge flaps. The production over-ride switch is a three position device which allows normal automatic operation and two fixed flap settings for take-off and landing.

3.2.1.4.1 FCS annunciation. Line 1: Delete "panel or associated panels" and substitute "panel, associated panels, or integrated displays".

Discussion

The intent of this change is to recognize the trend toward use of integrated displays by including these as acceptable means for display of flight control information.

3.2.1.4.2.2 Failure status. Line 4: After "crew" insert "of systems not necessary for flight safety".

Discussion

The last sentence of the Requirement is too restrictive in that it prohibits warning annunciation of accidental or inadvertent disengagement of systems affecting safety of flight. Future aircraft may require SAS operation to assure at least level III flying qualities.

3.2.1.4.2.3 Control authority annunciation. Line 3: After "augmentation" insert "or manual series trim".

Discussion

The requirement needs to include manual series trim, as a failure of such trim function can also reduce available control authority.

3.2.3.1 General requirements. Line 1: After the title, add the following: "Signal transmission between control system elements or components shall be accomplished by direct mechanical, hydraulic, pneumatic, or electrical connections as appropriate. The use of fiber optic technology or other nonconventional transmission media requires specific approval of the procuring agency."

Discussion

This requirement is equivalent to the requirement of 3.2.4.1.3.1 referring to signal transmission between computer components. The intent of this recommendation is to make the requirement applicable to all flight control signal paths.

As stated in the Background Information and User Guide, the requirement "is not intended to prohibit the use of nonconventional transmission paths, but rather to ensure that the contractor has fully investigated their ability to perform essential functions reliably and can present substantiating evidence for approval before committing designs."

3.2.3.1.4 Rigging provisions. After the second sentence, add "Rigging positions shall have a built-in method of travel measurement such as protractors or scales applied to an external surface, bellcrank, or pulley. Whenever possible, rigging positions shall be independent of each other."

Discussion

Added to provide easy, more rapid and repeatable maintenance method.

3.2.3.2.4.1 Control cable. Change paragraph c. to read "Non-flexible corrosion resisting steel cable in straight runs or Lockclad (aluminum tubing swaged over cable) with corrosion-resisting cable in long straight runs only."

Discussion

Added to allow use of Lockclad.

3.2.3.2.4.12 Fairleads and rubbing strips. Change last sentence to "Fairleads shall have provisions to allow cables with swaged terminals to be threaded through them with a minimum of effort and adjustments."

Discussion

Provides general method rather than single design solution called out previously.

3.2.3.3.1.2 Wire terminations. Line 1: Delete "(spade, lug, or connector)".

Discussion

Words in parenthesis disagree with previous paragraph which forbids use of terminal boards.

3.2.3.3.2 Multiplexing. Delete the entire paragraph and substitute the following:

"Electrical multiplexed signal transmission shall utilize digital time-division-multiplexing techniques and a twisted shielded pair cable as the multiplex bus transmission media. The multiplex bus line, its interface electronics, and all aspects of information transfer via the data bus shall comply with requirements of MIL-STD-1553. The installation of multiplex bus cables shall be according to the requirements for other electrical flight control (EFC) interconnections as specified in 3.2.3.3.1 and subparagraphs. The use of fiber optics or other nonconventional transmission media for the multiplex bus shall require specific approval of the procuring activity."

Discussion

The recommended changes are intended to emphasize three points concerning the use of multiplexing for flight control signals.

1. A distinction is made between electrical signal multiplexing for which MIL-STD-1553 was designed and other techniques such as optical multiplexing where 1553 would be inappropriate.
2. The statement regarding compliance with MIL-STD-1553 is broadened to ensure full compliance with the military standard. The requirement as stated in 9490D could be narrowly interpreted to apply only to the electrical hardware.
3. The statement regarding installation of multiplex bus cables is added to emphasize the importance of isolating and protecting data buses when used to transmit essential and flight phase essential signals.

3.2.4.1.2 Interchangeability. Line 3: Change "LRU" to "SRU (Shop repairable unit)".

Discussion

This amendment recognizes that an SRU and not an LRU is the appropriate term for this requirement.

Readjustment of the internal parameters following replacement of an SRU is permissible since it is performed in a controlled environment by the appropriate skill level.

Replacement of an LRU should not require any internal resetting of parameters except some adjustment in the aircraft rigging for certain types of LRU such as position sensing devices.

In any case the allowable tolerances on the interchangeable elements shall be such that failure to readjust to overall system tolerances shall not create a hazardous condition.

3.2.4.3 Electrical signal computation

Discussion

Since the MIL-F-9490D User Guide was issued, much literature pertaining to fly-by-wire flight control systems has appeared. References 2, 6, 9, 14, 16, 40, 41, 42, 43, and 44 are some of the sources which were used in the preparation of this report.

An increasingly important aspect of fly-by-wire flight control system technology is microprocessors. Within the past few years microprocessors have grown from four bit controllers to 16 bit mini-computers in performance. The advantage of using microprocessors is that the inexpensive hardware allows high levels of redundancy at reasonable prices. Some are becoming military rated, and where a task can be isolated, a dedicated processor is well suited. The processor can do a reasonable job of self testing without an outside reference.

The basic limitation of microprocessors is the high cost of customizing. While most of the comparisons can be done by software, occasionally there is a need for hardware voting. This must be added or performed with discrete hardware.

A necessary and useful device is a component with built-in voters. We could utilize a hardwired device to create a voter signal and apply that signal to a particular device. However, if that one signal to the device failed, we would consider it a common point failure. If, on the other hand, the "or" and "and" voting logic was built into the device (memory chip) and the voting logic failed, it would be considered a memory failure, not a common point failure. The single device would indeed have higher reliability than the separate devices, but the main point is that the perspective changed to consider the failure to be of a different type.

The critical failure modes can occur in the bus lines. These require bus guardians which then become the critical failure points. For these reasons serial lines become attractive.

The architecture of these systems is in an experimental stage of development. In a few years there will undoubtedly be some established preferences of architecture.

3.2.4.3.1 Analog computation. Line 3: After the first sentence, insert "At the time of aircraft acceptance by the procuring agency, a 25 percent growth capability for computation shall exist within the flight control system."

Line 5: After the last sentence, add "Analog signals shall be scaled to provide satisfactory resolution and sensitivity to ensure continuous safe operation for all possible combinations of maneuvering demand and gust or other plausible disturbances, and to prevent unacceptable levels of nonlinear characteristics or instabilities."

Discussion

The need for adequate growth capability and proper scaling is as real for analog computers as for digital. The inclusion of these amendments makes the requirements for analog computation parallel the existing requirements for digital computation.

One of the improvements of the F-16 aircraft resulting from the YF-16 experience was a rescaling of the roll stick inputs. The benefits of this improvement were more desirable roll response, adequate stability margins, and prevention of pilot induced oscillations during power approach³.

3.2.4.3.2 Digital computation. Line 1: Insert as the first sentence "Redundant signal computation (in particular, redundancy management) shall be implemented as required by the flight safety and failure immunity and invulnerability requirements specified herein to prevent propagation of failures across channels."

Line 4: Delete "Resident and bulk" and substitute "Program and workspace".

Discussion

As discussed in the redundancy management section, it is necessary to prevent the cross channel propagation of failures. One approach has been the use of fiber optics for multiplexed cross channel communication. Employed on the YC-14, fiber optics possess the obvious advantages of electrical isolation, and minimize the risk of external sources of electromagnetic interference corrupting critical cross channel signals⁴⁵.

The use of the words program and workspace provides a more accurate description of the use of storage in digital computation.

Since the D version of this specification was issued, there has been considerable discussion about the required growth capability for digital computation^{1,46}. Apart from the Air Force, the discussion was typically one-sided in favor of eliminating this requirement. Our recommendation is to retain the requirement as it now stands. It is recognized that at the time of aircraft acceptance the need for growth is not only desirable but necessary. It is also realized that at the time of acceptance the percentage growth figures are subject to compromise when traded off against desired aircraft performance.

Therefore the requirement for growth is pertinent and desirable and should be retained. The percent values could be modified, but there appears to be no basis for replacing one somewhat arbitrary value with another.

For the AFTI-F-16 program, the FCS operational flight program is designed to execute within 70 percent allocated memory and 75 percent duty cycles; this is sufficient to permit growth.

In the DIGITAC program, which used approximately 73 percent of the total memory available, a final design aspect of the digital software was modularization to permit partitioning of the original programming task. This allowed the debugging and validation of the software changes to be greatly simplified during the flight test evaluation. It also permitted software changes to be accomplished more easily and in less time. A further discussion of this concept and a description of the modules, identified as computer program components, can be found in reference 5.

In both the space shuttle and F-18 programs the impact of transport lags has been felt. While transport lags are not attributable to digital computation alone, the implementation of digital computation plays a critical role in both the creation and the solution of transport lag problems.

It is of interest to note that in the F-18 flight control system development, the preliminary design was based on a continuous system. For this system the design goal for all control loops was a gain margin of at least 10 db and a phase margin of at least 45 degrees.

3.2.4.3.2.1 Memory protection

3.2.4.3.2.2 Program scaling

Discussion

As discussed in the system test and monitoring section, there is a need for nonvolatile memory which can record in-flight failures, transient failures, and system status. This memory must be protected in a way that insures survivability in the event of loss of the aircraft. For the AFTI-F-16 program nonvolatile memory is required to retain stored data for a minimum of one year under any combination of presence and absence of power.

The application of EPROM's for flight testing is becoming more widespread. They have been used successfully on the YC-14 program and are planned for implementation in the AFTI-F-16 program, in which the memory protection requirements are in complete compliance with this specification. The use of EPROM's is addressed in the discussion of software maintenance.

In the initial phase of flight testing for the F-18, plug-in PROM's were employed in the flight control computers. They were replaced by PROM's hard-wired to the boards when it became apparent that the plug-in PROM's did not provide adequate reliability in an operational environment.

Program scaling is necessary in fixed point computers for protection against overflows in digital computation. Computers are now being developed (e.g., in the AFTI-F-16 program) which have the ability to limit automatically the results of addition, subtraction, multiplication, division, and arithmetic shift operations that would otherwise have overflowed¹⁶.

3.2.4.3.2.3 Software support. Line 1: Change the title to "Software development and support."

Line 1: Delete "For programmable computers a software" and substitute "A software".

Line 1: Insert as the first three sentences "For programmable computers system software shall be developed and controlled in accordance with specifications prepared by the contractor and approved by the AF in accordance with MIL-STD-490 and as supplemented by MIL-STD-483. Definition of the software development plan shall be contained in the computer program development plan (CPDP) outlined in requirement 4.4.1 of this specification. This software will constitute the operational flight program (OFP) portion of the Computer Program Configuration Item (CPCI)."

Line 7: At the end of the last sentence, change the period to a comma and add "and shall encompass the software maintenance requirement 3.1.10.5."

Discussion

The title of this section was modified to reflect the fact that software for digital computation requires both development and support, and that the two are complementary.

The reference to MIL-STD-490 and MIL-STD-483 places this specification in compliance with those specifications as required by AF procedures. The inclusion of this requirement was endorsed in the Digital Flight Control Software Validation Study⁴⁰ and implemented in the AFTI program.

The software development plan establishes the actions and procedures that will be followed during the software development cycle. The plan also describes the phasing of the development activity, the structure and responsibility of

software organization, the engineering development test requirements, the overall software verification and validation process, the documents required and their format, the methods for controlling changes during the development process, and other factors significant in the development effort. The development plan can be organized into several sections that describe the particular aspects of the development cycle, such as those shown in Figure 3, an example of a software system development cycle.

It is necessary for the software support package to address specifically the software maintenance requirement because of the importance of the software support package relative to proper software maintenance.

References 40, 47, 48, 49, 50, and 51 pertain to planning for software quality and software verification, validation, and control procedures.

3.2.4.3.2.3: After this paragraph, add the following as a new paragraph:
"3.2.4.3.3 Computational input/output growth capability. In the implementation of an analog or digital computer for electrical signal computation, the input/output growth capability shall be consistent with the growth capability of the computer and the computer connector reserve capacity."

Discussion

This requirement is consistent with the reserve for growth that is specified for analog and digital computation and the connector reserve capacity. It serves to avoid a bottleneck in signal transmission.

This parallels requirements in the AFTI-F-16 Development and Integration Program¹⁶ in which a 20 percent growth capability is specified for analog and digital input and output signals.

3.2.6 Actuation

Discussion

While the state of the art for actuation has progressed since the specification and User Guide were issued, the actuation requirements appear quite sufficient with little need for amendments.

References 52, 53, 54, 55, 56, and 57 provide a cross-section of some of the work which has been done since that time. The topics include design objectives for improved actuation, direct drive control valves, electrical actuation concepts, and 8000 psi hydraulic control systems. Reference 57 is

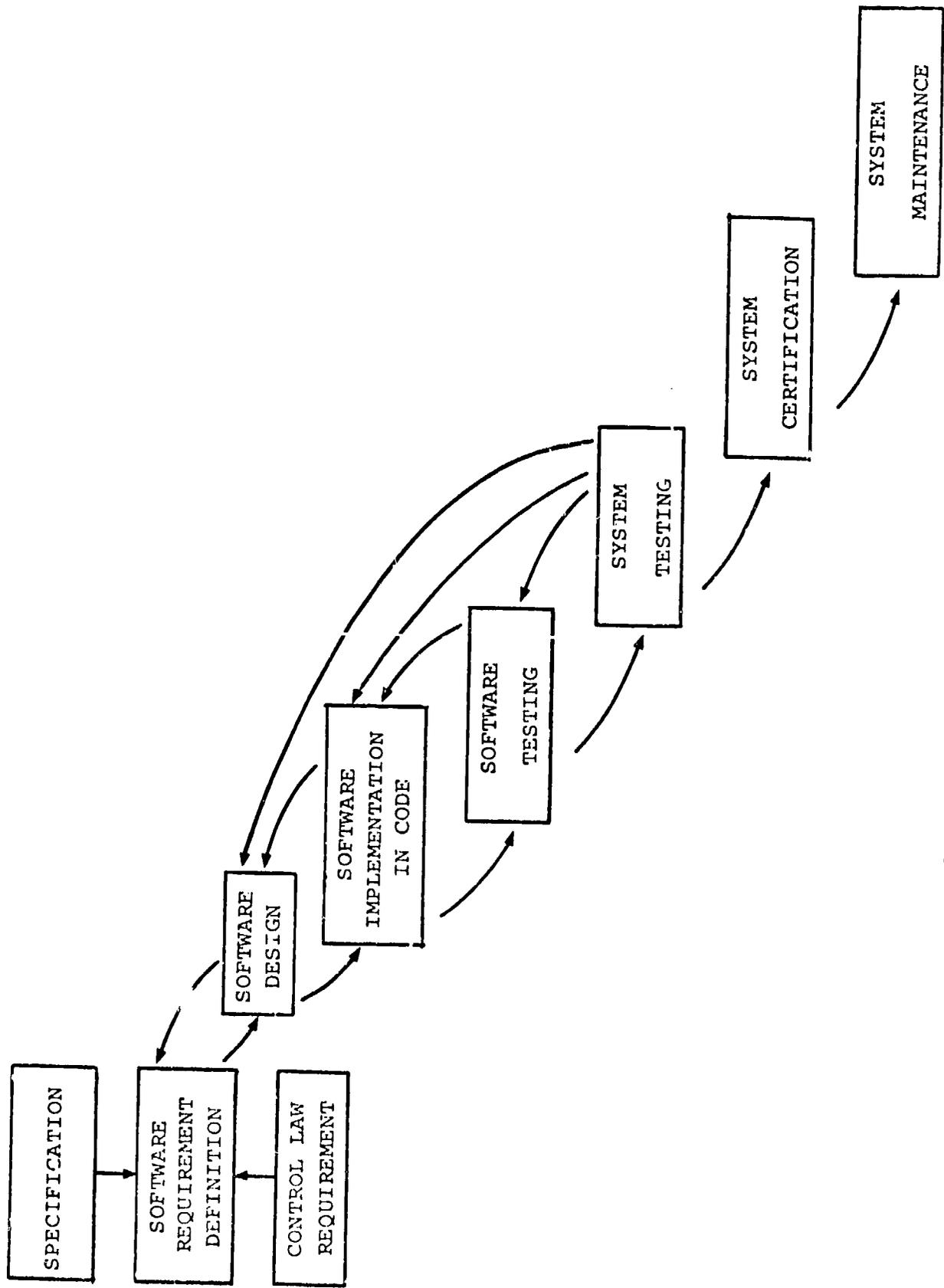


Figure 3. Example of software system development

an Air Force Technical Memorandum which addresses the general design criteria for hydraulic power operated aircraft flight control actuators.

3.2.7.3.2 Microelectronics. Delete the entire paragraph and substitute "Microelectronic devices conforming to the provisions of MIL-M-38510 and available from qualified sources shall be used in preference to other similar devices."

Discussion

The use of specially designed and newly developed microelectronic devices in the YF-17 flight control electronics was necessary to achieve the minimal size, weight, and power design objectives for these electronic assemblies. If the selection of devices had been limited to microcircuits qualified to MIL-M-38510, severe size, weight, and power penalties would have resulted, and possibly some compromises in functional performance. The time span required to qualify a microelectronic device to MIL-M-38510 is so long, and the evolution of microcircuit technology is so rapid that often by the time a particular device is qualified it is obsolete. The unamended requirement limits the Air Force in its application of state-of-the-art technology.

The amended requirement provides an opportunity for flexibility in the implementation of microelectronics for future aircraft procurement, and conforms with the recommendation in the User Guide, which states: "The use of microelectronic technology should be considered in 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."

3.2.7.3.3 Burn-in. Line 1: After "50" insert "power-on".

Discussion

This amendment provides a definitive approach to electronic LRU burn-in to insure reliability and acceptability.

4. QUALITY ASSURANCE

4.1.1 Methods for demonstration of compliance.

Line 6: After the last sentence, add "As applicable, software shall conform to MIL-S-52779 and MIL-STD-1521."

Discussion

MIL-S-52779, Software Quality Assurance Requirements, and MIL-STD-1521, Technical Reviews and Audits for Systems, Equipment, and Computer Programs, are DOD documents approved for use by all departments and agencies of the Air Force, and are therefore referenced in this specification. The standardization of software procedures and documentation, and the goal of a common DOD software language, provide the greatest opportunity for increased efficiency in system acquisition.

4.1.1.1 Analysis. Line 3: After "linear or nonlinear" insert ",deterministic or probabilistic in nature".

Line 4: Delete "as defined by the FCS development plan", and substitute "as best suited and adequate for the application. Where test verification is limited by test sample considerations or is clearly inadequate, compliance shall be verified by the appropriate analytical techniques. The analytical methods to be employed shall be defined in the FCS development plan in accordance with 4.4.1."

Discussion

The analysis required for the design of flight control systems today goes 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 were added. The intent of the change was to encompass not only the usual linear and nonlinear analytical control techniques, which may or may not be stochastic in nature, but also a class 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 of the change in the requirement to point out that the analytical methods to be used, as prescribed by the FCS development plan, should be appropriate for the problems to which they are to be applied.

4.1.1.2 Inspection. Line 7: After the second sentence, insert "Where applicable, flight control system software specifications, documentation, and analyses shall be inspected or reviewed as part of the verification process."

Discussion

Without the amendment the requirement is not up to date in that it addresses inspection only in terms of hardware, with no mention of the very real need for inspection of 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.

4.1.1.3 Test. Line 1: Delete "maximum extent feasible" and substitute "extent required".

Line 3: After "shall include" insert "hardware tests and, where applicable, software verification tests in".

Discussion

The initial phase of this requirement was modified to point out:

a) The 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 feasible 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.

The second modification to the requirement is to recognize the fact that software verification and validation is a test, and that this requirement needs to address specifically the issue of software.

4.2 Analysis requirements. Line 6: After the second sentence, insert "In cases of digital flight control applications, validation shall 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, the simulation, or both, pre-analysis of the simulation mechanization is required to assess its validity. The artifacts introduced by the simulation mechanization used shall be investigated to assess and minimize their effects on the simulation results."

Discussion

The inclusion of digital flight control verification and validation analysis requirements in this section maintains the comprehensive intent of this paragraph.

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.

4.2.1 Piloted simulations. Line 2: Delete the period at the end of the first sentence and insert "to define and verify required functional characteristics and to evaluate degraded mode effects. The piloted simulation plan shall be defined in the FCS development plan."

Under line 5: Add the following:

" c. Piloted simulations for digital flight control systems prior to each flight preceded by major software modifications."

Discussion

For definition and clarity it is necessary for this requirement to discuss the two critical areas of FCS development which utilize piloted simulation. Further, it should be noted that the simulation plan will be defined in the FCS development, as was done in the AFTI-F-16 FCS development plan.

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. Rather than proceed through a complete reverification following software modifications, piloted simulations can be performed to find any major or critical problems before beginning flight tests. To date, this approach has been successfully implemented in the F-18 program.

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; and areas where the aerodynamics are uncertain, such as departure.

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.

4.3.1.2 Acceptance tests. Line 2: After the first sentence, add "Where interfacing components of the FCS are procured from various sources, sufficient acceptance testing shall be performed to ensure overall system performance repeatability."

Discussion

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 requirement serves to insure 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.

4.3.2.1 Component tests. Line 11: After the last sentence, add "Component modifications to the original configuration shall be requalified by using the appropriate verification method from those listed above."

Discussion

The area of requalification of components following modification needs to be addressed within the specification.

4.3.2.2 Functional mockup and simulator tests. Under line 34: Add the following:

"g. 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."

Discussion

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

As 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.

4.3.3 Aircraft ground tests. Line 3: Delete "6 db".

Line 8: After the last sentence of item a., insert "For redundant and multiple-loop systems, the stability requirement in degraded configurations shall also be demonstrated."

Under line 19: Add the following paragraphs:

"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 shall 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 shall be recorded."

Discussion

The requirement for 6 db stability margin at zero airspeed is removed to achieve consistency with the flexibility afforded by the requirements of 3.1.3.6, and in response to the concerns expressed in reference 23. For first flight of an aircraft type, different gain margins may be applied for rigid body limit cycle and ground structural resonance stability, depending on the relative confidence in the predicted aerodynamic, aeroelastic, and structural mode characteristics.

Paragraph e. is added in concert with the recommendations of references 21 and 58. Reference 58 documents the extensive ground vibration testing and analysis correlation effort conducted on the YF-16 under a research contract to improve test methodology on fighter aircraft with active controls. This effort led to the conclusion that the mathematical model used in aeroservo-elastic stability analysis can be, and must be, validated or improved by GVT with active controls.

Paragraph f. is added to reflect the recommendation of reference 21. This requirement does not add to the set of tests already performed prior to first flight, but increases the utility of the taxi test to provide additional confidence relative to servoeelastic stability. The random inputs during taxi provide excitation of the structural modes and evoke control system responses similar to those in the low speed flight environment.

In view of the recent experiences with the YF-16 and YF-17 aircraft, aircraft ground tests, however extensive, can no longer be considered adequate to insure stability in flight for state-of-the-art structures and flight control designs. Analysis, ground tests, and flight test evaluation are mandatory to achieve this end. However, the usefulness of ground tests remains undeniable as a necessary ingredient of the overall process.

Reference 23 provides an excellent synopsis of stability margin tests conducted on a variety of research, prototype, and production aircraft with appropriate conclusions and recommendations added.

With the increasing use of digital flight control systems and redundant system implementations, both analog and digital, several new considerations came into focus and need to be addressed as part of the overall stability problem. Redundant actuation loops with input equalization of multiple feedbacks may lead to non-aerodynamic loop instability due to beat frequencies

resulting from feedback sensor excitation differences and equalization network characteristics. The presence of digitizing in the actuation driver acts as a high frequency excitation in digital flight control implementations and may also result in a buzz or non-aerodynamic loop instability.

Redundant and multiple loop systems, where any control law or computational reconfiguration occurs following specific failures, must be evaluated in the degraded states to insure the required minimum stability.

Finally, the importance of analytical modeling techniques relative to actual flight control system implementation is highlighted in reference 24, the report on the DIGITAC development and evaluation. Significant phase lags, attributed to sampling effects, were found in the actual system relative to earlier linear simulation results, with an attendant degradation in limit cycle stability characteristics. By their nature, digital systems also incorporate numerous linear filter stages, such as aliasing filters, smoothing filters, and sample-hold characteristics, that are not required in analog systems and need to be accounted for in any simulation of digital systems.

In addition to exploring some of the impacts of digital flight control implementation, reference 24 documents one of the most extensive ground test programs ever performed on an aircraft, and provides a valuable guide toward planning a test program for a multi-loop, highly complex control system.

4.4.1. Flight control system development plan. Under line 26: Add the following:

"h. Where applicable, a computer program development plan (CPDP) to define how the flight software is to be developed, documented, controlled, and verified, including specific documentation stages as they relate to computer hardware design and overall flight control system development and verification. AFR-800-14 shall be used for guidance in the development of the CPDP,".

Discussion

The minimum list of elements to be included in the flight control system development plan is quite extensive, but none of these specifically address any of the aspects of digital implementation. This may serve to maintain the generality of the stated provisions; nonetheless, the section seems to be where the overall integrated V&V methodology should be specified.

The FCS development plan needs to address the software verification and validation procedures for digital flight control implementations. These procedures in turn will be detailed further in the computer program development plan. Where flight-critical or flight-phase critical functions are involved, the V&V plans should reflect an integrated methodology. An example of this methodology is described in AFFDL-TR-79-3076³⁹.

Vol. I, Management of Computer Resources in Systems, and Vol. II, Acquisition and Support Procedures for Computer Resources in Systems, of AFR-800-14 specifically address policies required for the development of computer programs and requirements that apply throughout a system's life cycle.

4.4.3.1 FCS analysis report. Line 1: Delete the first sentence and substitute "The contractor shall prepare a report describing FCS analysis."

Under line 43: Add the following:

"j. Where applicable, a comprehensive system-oriented description of the flight software with regard to its design, implementation and analytical evaluation. Representations shall be oriented toward understandability of various types, aspects, or functions of the software."

Discussion

The rationale for the first amendment to this section is covered in the discussion of section 4.4.

With the importance of software for digital flight control applications, it is essential that there be specific provisions which call for particular V&V methodology results in the FCS analysis report. These results would include software analyses, documentation, backup data, etc., along with descriptions of their nature, origins, and significance.

4.4.3.3 FCS test report. Under line 18: Add the following:

"d. Where applicable, a summary of flight software testing over the range of conditions addressed on a system level."

Discussion

Similar to the reasons stated in the discussion of section 4.4.3.1, the FCS test report needs to include the test data related to the verification and validation methodology applied to the flight control software. In the

report the significance and completeness of these data shall be addressed along with test confirmation of prior software analysis.

6. NOTES

6.6: After the definition of "Extremely remote" insert the following:

"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.

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 is to be within the limits as established for the particular procurement.

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 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."

Discussion

Refer to the 3.1.3.1 paragraph discussion in this document.

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