New MIL-F-9490D Requirements and Implications on Future Flight Control Design

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The current USAF flight controls specification, MIL-F-9490, has been updated to enhance its applicability to modern aircraft. As a part of a 2½ year program, several draft revisions have been presented and submitted to government and industry for review and comment. Extensive changes have been made, both in the manner in which requirements are stated and through adoption of new requirements in areas not previously addressed. MIL-F-9490D attempts to provide maximum designer freedom while retaining required flight safety. New areas addressed include ride smoothing, turbulence design levels, stability margins, reliability, failure immunity, and invulnerability. This paper discusses the rationale behind these revisions and points out areas where future flight control design may be affected.

Nomenclature

A_S(fcs)	= flight safety allocation factor for flight control
D_i	= ride discomfort index, (vertical or lateral)
f	= frequency, Hz
f_M	= mode frequency in Hz (FCS engaged)
Gain Margin	= the minimum change in loop gain at nominal phase which results in an oscillatory instability beyond that allowed as a residual oscillation or which results in a divergence beyond that permitted by MIL-F-8785. When expressed in dB's, positive values of gain margin correspond to the increase in loop gain required for instability and negative values correspond to the decrease in gain that results in an instability.
Mode	= a characteristic aeroelastic response of the aircraft as described by an aeroelastic characteristic root of the coupled aircraft/FCS dynamic equations-of-motion
Phase Margin	= the minimum change in phase which results in an instability beyond the limits stated above at nominal loop gain. Positive values indicate that the amount of phase lead and negative values indicate the amount of phase lag margin.
Q_S(fcs)	= maximum acceptable aircraft loss rate due to relevant FCS material failures per flight
R_S	= overall aircraft loss rate permitted (specified by the procuring activity)
$T(f)$	= transmissibility at crew station g/fps
V_L	= limit airspeed
$V_{o_{min}}$	= minimum operational airspeed
$V_{o_{max}}$	= maximum operational airspeed
$W(f)$	= acceleration weighting function (vertical or lateral), 1/g
$U^{(f)}$	= gust power spectral density

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Introduction

THE USAF, with the contracted aid of Boeing, recently completed a 2½ year effort to update the AF flight controls specification, MIL-F-9490. This specification, which was last updated in 1966, includes general flight control requirements for USAF piloted aircraft. A working knowledge of these requirements will aid the engineering specialist in preliminary design and proposal efforts leading toward future USAF airplane developments.

The task objective was to develop a general purpose, quantitative flight control specification having long-term applicability for all Air Force piloted aircraft. These aircraft span the entire range of fighters, transports, bombers, trainers, STOL, VTOL, helicopters, and utility vehicles. Mechanizations span the gamut of mechanical, electrical (both analog and digital), hydraulic, pneumatic, and optical designs with many combinations of elements.

In preparing the revision, the recommendations of industry were obtained through initial meetings and two formal review cycles. These specific comments varied substantially, but did help identify concepts too narrow for general application. Several industry reviewers implied that the new areas covered by MIL-F-9490D would substantially increase contractor costs and, therefore, should be eliminated or minimzed. However, increased application of flight-critical electronic flight controls makes it inconceivable that thorough analysis such as reliability, failure mode and effects (FMEA), survivability, and simulation tests would not be performed on major weapon systems prior to first flight. While the previous MIL-F-9490C specification was substantially deficient in these areas, weapon system contract statements of work did require compliance with a number of reliability, safety, maintenance, and survivability system requirements. Also, as a matter of good flight control design practice, airframe primes have relied heavily on company performance criteria, extensive simulation, iron-bird tests, etc. Prior to first flight, Air Force safety review boards have routinely required structural tests, frequency response tests, and EMI ground tests be conducted on the air vehicle.

Most of the revised MIL-F-9490D requirements merely reflect these accepted industry practices and should not result in significant increase in cost. A classical case in point was the YF-16 and YF-17 Lightweight Fighter prototype flight control developments by General Dynamics and Northrop. While no military specifications were required under the simplified contracting procedures, both companies developed thorough flight control specifications including gain and phase margins; established reliability and performance requirements; conducted extensive pilot-in-the-loop simulation tests with flight control hardware; performed thorough FMEA analysis; and conducted ground testing including frequency response, limit cycle, structural, and EMI tests on the aircraft prior to first flight. In addition, Northrop fabricated and applied a highly-detailed iron-bird with load stands to simulate aerodynamic and inertial loading of control actuators driven by the aircraft electrical and hydraulic power supplies. General Dynamics elected to use the first prototype aircraft for final integration tests in lieu of an iron-bird. MIL-F-9490D attempts to standardize on those practices which are essential for verifying flight control system safety and operation. A User's Guide[1] describing these requirements and the supporting rationale for MIL-F-9490D is also available.

The Approach

Requirements were specified assuming a Logical Development Sequence, similar to that shown in Fig. 1. This will be used in future procurements. The following series of development phases will exist:

1) The contractor initially establishes a detailed Flight Control System Specification including flight control functions, performance, reliability, safety, maintainability, and survivability requirements.

2) A design phase is undertaken to implement the requirements established in the flight control specification. Analysis is performed in conjunction with the design phase to satisfy stability, performance, reliability, safety, maintainability, survivability, and cost requirements. Component designs are established. Pilot-in-the-loop simulations are conducted to evaluate flying qualities under realistic mission tasks. Hardware specifications are prepared.

3) Hardware is fabricated and qualified. Piloted simulation is repeated with flight control hardware interconnected with the simulator to verify equipment operation. An operational mockup (iron-bird) test is conducted to evaluate the total flight control system under proper actuator loading and with actual electrical and hydraulic power supplies. Failure effects are evaluated on the simulator and operational mockup. System wear and life cycle tests are conducted on the operational mockup. Following wear tests, stability margin tests are repeated. Prior to flight test, a series of ground tests are conducted on the installed flight control equipment. As a minimum, ground testing includes frequency response, structural effects, gain margin (limit cycle), and EMI tests.

4) Flight testing throughout the flight envelope is performed for specified mission tasks to complete the development sequence. Documentation is provided for the major phases and is updated periodically.

A basic part of the approach was tailoring requirements to this development sequence. For example, Air Force/contractor interface during the flight control system development process is defined by special documentation recommended for incorporation within the contract through the means of the DD-1423 Contract Data Requirements List. The FCS specification is a key element of the documentation sequence. This document will include specific air vehicle requirements in the contract and applicable requirements from MIL-F-9490D; requirements established by the contractor, as required by MIL-F-9490D, based on specific mission requirements; and applicable requirements from AFSC Design Handbooks. Another key element is the FCS Development Plan. This plan will identify the contractors' plans for flight control system development. An important step is the contractor's verification plan. The contractor will define the manner (analysis, test, inspection, etc.) in which he plans to verify each requirement of the FCS specification.

New Classifications

An underlying thrust of this update of MIL-F-9490 was to specify what was required at the system level. Component and subsystem requirements received less emphasis in an effort to avoid excessive "how to do it" guidance. New system orientated classifications were adopted around which the requirements were organized. Major new classifications include manual and automatic FCS, FCS operational states, and FCS criticality classifications. Flight control requirements are separated into manual and automatic classifications, where Manual FCS are defined to include augmentation functions.

The change from separate Primary/Secondary FCS classifications to a single Manual FCS classification was made

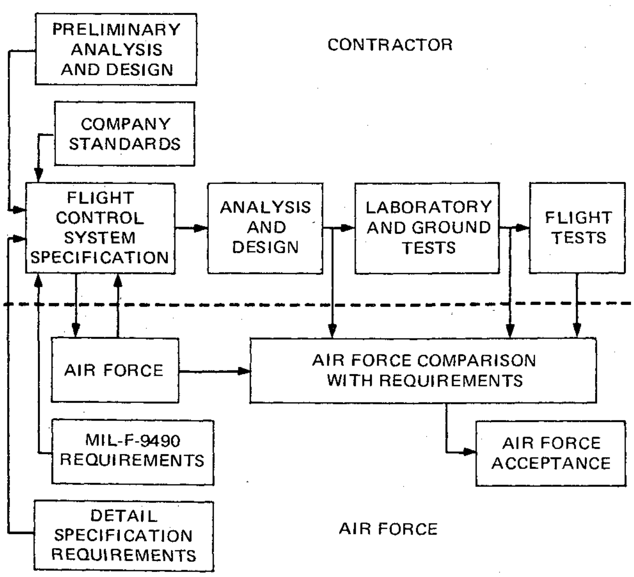

Fig. 1 AF/Contractor interaction during development process.

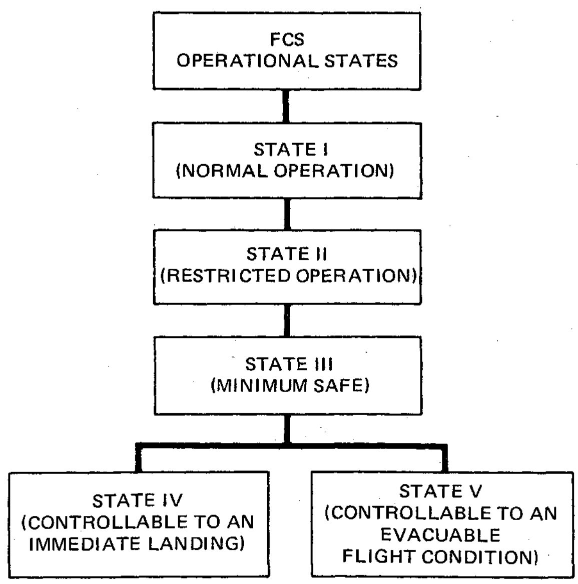

Fig. 2 FCS operational states.

as a result of a serious concern with the high percentage (up to 50 percent) of recent Air Force incident/accident reports due to secondary flight control problems.

FCS Operational States I, II, and III, illustrated in Fig. 2, are defined to reflect normal, restricted, and minimum safe operation. FCS Operational States IV and V define degraded operational states where continued safe flight is not possible, but either a controlled descent to an immediate emergency landing or safe crew evacuation is possible.

These states parallel the MIL-F-8785B flying qualities Levels 1, 2, and 3. For example, FCS Operational State I may be equated with Level 1 flying qualities within the normal flight envelope. However, the FCS Operational State II may correspond to either Level 1 or Level 2 flying qualities. FCS Operational State II may result due to loss of an automatic guidance or ride smoothing function, or a weapons delivery mode, for example, while Level 1 flying qualities are maintained.

A State III FCS operational level may be reached through degradation of any flight control function to a state which requires landing at the nearest friendly base. An FCS failure mode leading to Level 3 flying qualities will result in an Operational State III designation. In addition, single or multiple channel failures resulting in a minimum safe configuration in a redundant FCS required for safety-of-flight, may also result in FCS Operational State III even though the remaining FCS channel(s) may still provide Level 1 flying qualities.

Figure 3 illustrates three criticality classifications adopted to organize requirements. Essential, flight phase essential and noncritical FCS functions are defined. The key separation is whether the function is needed to insure flight safety either full time, only during certain flight phases, or not at all.

New Flight Control Requirements

A multitude of new requirements appear in MIL-F-9490D. Most of these will not affect future FCS developments since they represent merely accepted practices of the industry. Among new requirements most likely to impact future design are ride smoothing system performance, operation in turbulence, stability margin, reiiability/failure immunity, and invulnerability to enemy action. The following paragraphs summarize the intent of these five requirements and outline the rationale behind their adoption.

Ride Smoothing Criteria

Ride Control System performance is specified in terms of a Ride Discomfort Index and associated turbulence levels. When ride control is a contract requirement, ride discomfort cannot exceed the following values at any crew station while flying in the specified turbulence intensities: ride discomfort index (RDI) = 0.10, turbulent intensity (probability of exceedance)‡ = 0.20; RDI = 0.28, turbulent intensity = 0.01. These ride discomfort index limits must not be exceeded at the associated turbulence levels, either in the vertical or lateral axes. Effects of attitude hold or other pertinent AFCS modes are included where used.

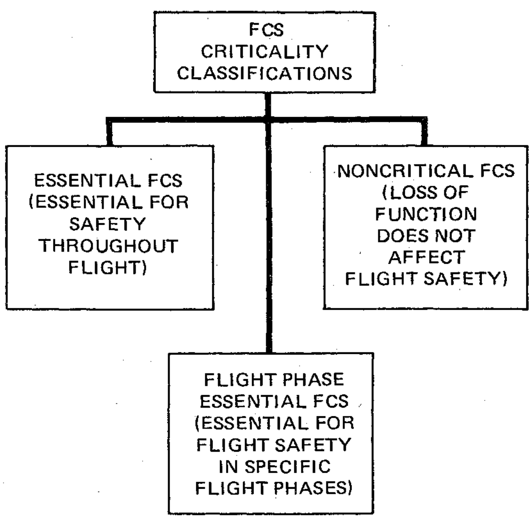

Fig. 3 FCS criticality classifications.

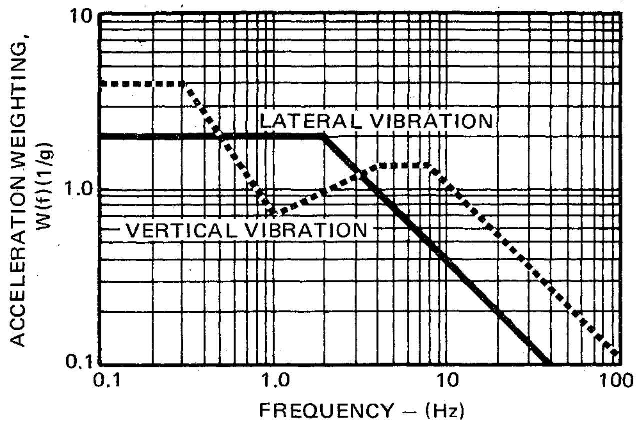

Fig. 4 Acceleration weighting functions.

The ride discomfort index is defined as:

$$D_i = \left[\int_{0.2}^{30} |W(f)|^2 \; |T(F)|^2 \; \phi_u(f) df \right]^{1/2}$$

Acceleration weighting functions are defined for vertical and lateral acceleration by Fig. 4.

These ride requirements are stated in terms of probabilities since the ride discomfort addressed by these requirements is generated by random turbulence. The exceedance probabilities and corresponding Ride Discomfort Index values specified are based on the work of Rustenburg[2,3] and similar Boeing work performed during the American SST development.[4] The acceleration weighting functions defined in Fig. 4 are based on MIL-STD-1472 human sensitivity curves, extrapolated to lower frequencies to reflect U.S. recommendations for ISO standards update.

The two levels of ride discomfort specified are based on short-term and long-term tolerances. Existing data[2,3,4] indicate that below a Ride Discomfort Index of 0.10, little or no degradation in crew performance or passenger comfort is expected. Above a Ride Discomfort Index of 0.28, crew action may be required to reduce the acceleration environment by changing flight path, altitude, and/or airspeed. Figure 5 illustrates unpublished data from a commerical airplane moving base simulator study in terms of incremental pilot ratings (Cooper scale) due to accelerations which also indicate a limit near 0.28 for a delta pilot rating of three.

Both vertical and lateral turbulence and accelerations must be considered separately. The lateral acceleration weighting functions of Fig. 4 reveal that lateral accelerations have been normalized at 2.0 times the vertical weighting at 2.0 Hertz. In effect, the lateral accelerations are magnified to reflect the lower crew tolerance for lateral accelerations. Thus, the same Discomfort Index value is used in both axes.

‡The reader should note that cumulative exceedance probabilities for turbulence are stated in terms of stationary probabilities rather than the nonstationary probabilities used in reliability work. A stationary probability or cumlative probability of exceedance for turbulence encounter means that at a randomly selected time during flight, the probability of being in turbulence at or above the stated intensity is of a given value. This does not define the probability of exceeding a given level of turbulence during a given flight or flight segment. On a fleet lifetime basis, this probability can be interpreted as the portion of total flight time to be spent above the stated intensity.

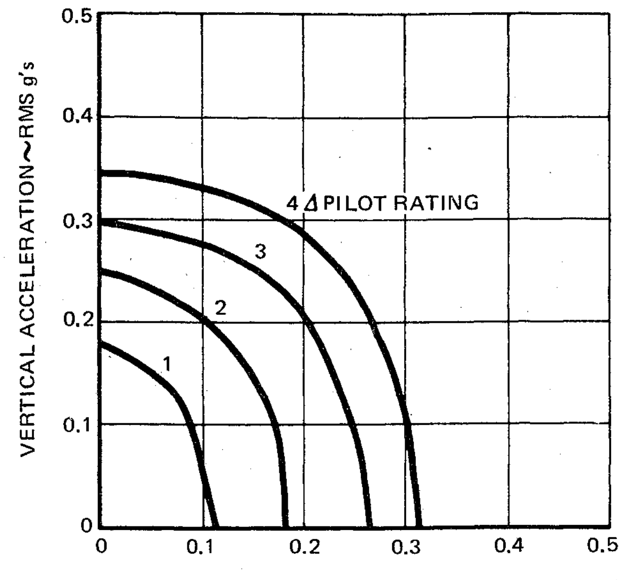

Fig. 5 Effect of cockpit accelerations on flying quality ratings.

The turbulence intensities to be used are determined by the exceedance probabilities specified for Ride Discomfort Index. Generally, the system is required to reduce ride discomfort to the levels specified while flying in turbulence with a cumulative exceedance probability equal to, or less than, the probability specified. For example, at 500 ft AGL 3.2 fps RMS turbulence has a 0.20 probability of exceedance, and 6.6 fps RMS corresponds to a 0.01 exceedance probability. Thus, for an automatic terrain following mission segment using a 500 ft clearance altitude, the 0.10 limit applies in 3.2 fps RMS tubulence, and the 0.28 ride discomfort index limit applies in 6.6 fps turbulence.

These short-term and long-term exposure limits are applied based on mission flight phase duration. The long-term limit, 0.10, applies to any flight phase exceeding 3 hr. The short-term limit, 0.28, applies to all normal mission flight phases.

Combined axis accelerations, as shown in Fig. 5, can be more objectionable to pilots than independent accelerations in either axis. In turbulence, combined axis accelerations are present, and criteria needs to be established for evaluating combined axis accelerations. Several attempts to establish combined axis criteria have been made in recent years,[3,5,6] and analytical methods have been recommended. No consensus currently exists.

Operation in Turbulence

Operation in random and discrete turbulence is specified in terms of turbulence cumulative exceedance probabilities and FCS function criticality. FCS must provide their design function (stability augmentation, pilot relief, etc.) in the following turbulence with an exceedance probability related to the reliability levels designed into the function. Changes in system damping ratios, frequencies, and other characteristics caused by system saturation in turbulence are permitted providing that specified design functions are maintained. Table 1 defines turbulence intensities vs function criticality.

The turbulence intensities for essential controls are intended to result in control systems capable of operating at least at a minimum safe (Operational State III) condition in the maximum turbulence intensity which the structure can penetrate without exceeding limit load. The turbulence intensities specified for noncritical controls are much lower and are correlated with typical mission accomplishment probability levels.

The rationale behind specifying these rather stiff gust requirements is the increasing use of flight phase essential and

Table 1 Turbulence exceedance probabilities

	Turbulence Intensity Exceedance Probability	
FCS Function Criticality	MIL-F-8785 Class III Aircraft	MIL-F-8785 Class I, II, & IV Aircraft
Essential	10^{-6}	10^{-5}
Flight Phase Essential	$\frac{1}{T}\ 10^{-6}$	$\frac{1}{T}\ 10^{-5}$
Noncritical	10^{-2}	10^{-2}

Where T = The longest time spent in essential flight phase segment in any mission/total flight time per mission.

Table 2 Minimum stability margins

Mode Frequency	Below $V_{O_{MIN}}$	$V_{O_{MIN}}$ to $V_{O_{MAX}}$	At V_L
$f_M < 0.06$ Hz	GM = 6 dB	GM = ±4.5 dB PM = ±30°	GM = ±3.0 dB PM = ±20°
$0.06 < f_M <$ First Aero-elastic Mode	GM = 6 dB	GM = ±6.0 dB PM = ±45°	GM = ±4.5 dB PM = ±30°
$f_M >$ First Aero-elastic Mode	GM = 6 dB	GM = ±8.0 dB PM = ±60°	GM = ±6.0 dB PM = ±45°

essential controls using feedback loops. Loss of these functions due to saturation in turbulence can lead to aircraft loss. Recent accidents related to severe turbulence are described in the literature.[7,8] The search for the cause of these incidents has centered on possible effects of severe turbulence, such as structural vibration of the pilot's cockpit which limits the pilot's ability to read instruments, or the possibility of pilot disorientation due to apparently conflicting indications from his instruments, combined with unusual motion sensations. It has been concluded[7] that the main hazard is loss of control followed by structural breakup during recovery attempts. The cost of turbulence to DOD operations is difficult to evaluate, but estimated cost for the three year period of 1963-65 has been estimated[8] at $30,000,000 for DOD aircraft loss and damage.

Stability Margins

Stability margins are specified in MIL-F-9490D for the first time in a flight control general specification. Two approaches are open to the contractor. First, specific values of stability margins may be provided, such as 6 dB and 45° at the rigid body mode frequencies. As an alternative, the contractor may elect to perform a sensitivity analysis for one or more systems and analytically justify stability margins of up to 50 percent less than specified values.

Required minimum margins are defined in Table 2. High margins are required at high frequencies, reflecting a progressive lack of faith in existing math modeling techniques at higher frequencies. Reduced margins are allowed above the maximum operational airspeed, reflecting the lower probability of encountering this flight condition.

Reliability, Failure Immunity, and Safety

A major effort in this MIL-F-9490 update was to specify the "ilities" as system level requirements. Reliability, Failure

Table 3 FCS quantitative flight safety requirements

Aircraft Class	Maximum Aircraft Losses Per Flight (Due to FCS Failure)
MIL-F-8785 Class III Aircraft	$Q_{S(fcs)} < 0.5 \times 10^{-6}$
All Rotary Wing Aircraft	$Q_{S(fcs)} < 2.5 \times 10^{-6}$
MIL-F-8785 Class I, II and IV Aircraft	$Q_{S(fcs)} < 10 \times 10^{-6}$

Immunity, and Safety are three elements which are closely related. Reliability and flight safety are quantitatively defined in terms of probabilities. Failure immunity is separately specified in absolute terms. The basic approach to quantitative flight safety and reliability relies on the contractor to budget FCS mission accomplishment and flight safety probabilities within an overall airplane budget. For example, the probability of aircraft loss per flight due to relevant material failures in the flight control system must not exceed:

$$Q_S(fcs) < (1-R_S)A_{S(fcs)}$$

Mission accomplishment reliability is specified in a similar fashion.

Numerical baseline values are also included for use where an overall aircraft loss rate due to material failures was not specified by the procuring activity. Table 3 lists these baseline values.

The baseline values were established using a broad cross section (over ten yr) of pertinent aircraft accident and loss data obtained from the AF Safety and Inspection Center, Norton. Figure 6 illustrates typical in-service fleet data[9] used to establish the baseline values specified. For this example, fighter aircraft losses due to material flight control failures totaled 5.5×10^6 losses/flight. Combined flight control and hydraulic system related losses totaled approximately 10×10^6 losses/flight.

Failure immunity requires that no failure, not extremely remote, can result in any of the following before a pilot or safety device can react: Flutter, divergence, or other aeroelastic instabilities within the permissible flight envelope of the aircraft, or a structural damping coefficient for any critical flutter mode below the fail-safe stability limit of MIL-F-8870; uncontrollable motions of the aircraft within its permissible flight envelope, or maneuvers which generate limit airframe loads; inability to safely land the aircraft; and any asymmetric, unsynchronized, unusual operation or lack of operation of flight controls that produces operation below FCS Operational State III.

Extremely remote is defined as numerically equal to the maximum aircraft loss rate due to relevant FCS material failures allowed by the procurement contract. The intent of this requirement is to insure that no failure(s), not extremely remote, can result in an inflight hazard. For noncritical controls, the pilot may be required to detect and counteract failures by either deactivating the controls or the failed portion there, or by overriding.

Invulnerability to Enemy Action

Future flight controls on combat airplanes designed to MIL-F-9490D will be required to withstand one direct encounter from a specified enemy threat without falling below a minimum safe condition. The type of threat (.50-caliber ground fire, 23 mm explosive shell; missile fragment, etc.) will be specified by the USAF based on mission requirements. This requirement has been adopted largely because of the surprising number of aircraft lost in combat in recent years due to relatively small threats. The percentage of these losses due to flight control failure is considered excessive, especially for aircraft with fully powered controls.

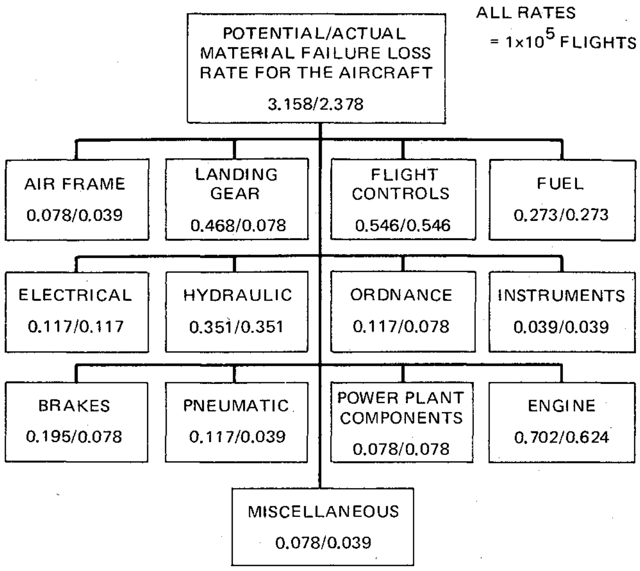

Fig. 6 Potential and actual material failure aircraft loss rates (fighter aircraft).

Implications on Future Design

The concept of emphasizing system level requirements and requiring the contractor to verify each of these requirements may have considerable impact on future flight control design. Verification by analysis, inspection, or test is allowed and except where a specific method is specified, the choice is left to the contractor, subject to USAF concurrence.

The more explicit definition of general system level "ility" requirements may lead to increased emphasis on system trade studies and associated failure effects analysis. For example, many of the requirements are stated in terms of a minimum FCS Operational Level. Simulation and other trade studies may be required to determine existence of a specified Operational Level with a given failure, a given variation of environment, or perhaps in a given turbulence environment.

Specific invulnerability requirements, such as invulnerability to the specified enemy threat, may lead to increased use of redundancy, split surface controls, and a greater degree of separation or armor protection in the future. These invulnerability requirements, which are similar to those being used in a current USAF procurement, require trade-offs with respect to weight increases vs survivability.

Stability margin requirements are expected to result in additional effort during development to demonstrate the margins required, especially at higher frequencies. The intent is to reduce the total effort by reducing the maintenance effort required to chase troublesome intermittent in-service FCS malfunctions which can occur when inadequate margins exist.

Specific requirements for built-in test and inflight monitoring provisions for essential and flight phase essential flight controls will impact the complexity of controls, but should significantly improve flight safety and maintainability.

Increased Air Force/contractor interaction is expected throughout the development process. The Air Force will use the documentation provided by the contractor during development, such as the FCS Specification and FCS Development Plan, to compare analysis predictions, designs, and test results to requirments. Deficiencies or conflicting requirements should be identified early in the development process, and coordinated Air Force/contractor action will be taken to correct such discrepancies. Trade-offs among conflicting requirements will normally be required.

Conclusions

Based on this 2½ year effort, it is clear that the increasing complexity of flight control, as reflected by MIL-F-9490D, is increasing the importance of system level analyses and testing. Accordingly, new and more comprehensive system level requirements have been adopted in MIL-F-9490D.

Future procurements may require increased documentation of these system level analyses and tests, and increased exposure of contractor planning during early design stages will likely be encouraged.

These new requirements will increase the amount of analytical effort required during the design phase, as compared to the effect of MIL-F-9490C. However, when compared to ongoing USAF design efforts, such as the B-1 and F-16, the total flight control design effort should be comparable to that of contemporary designs. The effect on design costs will only be established by application of this specification to an actual procurement. At this time, elements of MIL-F-9490D are currently being applied to the F-16 USAF procurement.

New reliability, maintainability, and invulnerability system requirements have been adopted in response to USAF concern for fleet availability and life cycle costs which may result in not only a more usable aircraft, but in a reduction in fleet life cycle costs.

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