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AFWAL-TR-81-3109

BACKGROUND INFORMATION AND USER GUIDE FOR MIL-F-8785C, MILITARY SPECIFICATION - FLYING QUALITIES OF PILOTED AIRPLANES

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JULY 1982

INTERIM REPORT FOR PERIOD MAY 1977 - MAY 1981

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This document is published in support of Military Specification MIL-F-8785C, "Flying Qualities of Piloted Airplanes". It was compiled after an extensive literature review and meetings and discussions with personnel from concerned civilian and governmental organizations. The primary purpose is to explain the revisions from MIL-F-8785B and present substantiating data,

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FOREWORD

This report was prepared by Mr Moorhouse and Mr Woodcock of the Control Dynamics Branch, Flight Control Division. The effort was conducted under Program Element 62201F, Project 2403, Task 05, Work Unit 32. It is part of a continuing effort to upgrade the military flying qualities specification. This is the interim report for the time period May 1977 to May 1981.

The authors would like to acknowledge the significant contributions of Mr T. P. Sweeney of Aeronautical Systems Division to the final version of MIL-F-8785C. Significant inputs were also made by Mr R. C. A'Harrah of Naval Air Systems Command and Mr C. Mazza of Naval Air Development Center. The authors would like to thank them and the numerous people in industry and government who reviewed the proposed revisions and provided comments and suggestions to improve the product.

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SECTION I

INTRODUCTION

This document is published in support of Military Specification MIL-F-8785C "Flying Qualities of Piloted Airplanes" (Reference 1), as part of the effort to revise and update the previous version of the specification, i.e., MIL-F-8785B (Reference 2). The main result of the current revision effort has been an update - where possible - of the existing requirements rather than a complete revision. A summary of the changes is presented in Table 1. Most of the data and discussion in the existing backup document, Reference 3, is still applicable. The approach taken in the present report is to supplement Reference 3 with justification for, and discussion of, the changes to MIL-F-8785B - including the changes contained in Amendment 2. In all cases the discussion in Reference 3 remains applicable unless it is explicitly stated otherwise. In some instances, discussion is presented for a particular requirement that has not been changed. This has been done to clarify items which have been subject to misinterpretation or to suggest potential future revision.

Section II contains the historical development of the revisions. There is also a brief discussion of related specifications and backup documents, plus some of the validation efforts.

The revisions and supporting discussions are presented in Sections III through XIII. The order in which the material is presented parallels that of MIL-F-8785C. The main subject headings are:

III	1.	Scope and Classification
IV	2.	Applicable Documents
V	3.1	Requirements - General
VI	3.2	Longitudinal Flying Qualities
VII	3.3	Lateral-Directional Flying Qualities
VIII	3.4	Miscellaneous Flying Qualities
IX	3.5	Characteristics of the Primary Flight Control System
X	3.6	Characteristics of Secondary Control Systems
XI	3.7	Atmospheric Disturbances
XII	3.8	Use of Disturbance Models
XIII	4.	Quality Assurance
XIV	6.	Notes

The presentation and discussion of the changed paragraphs is in the same format as Reference 3. There is a general discussion of major topics, where appropriate. Each new or revised paragraph of the specification is discussed in sequence, individually or together with closely related paragraphs, under the following subheadings:

Requirement

Related MIL-F-8785B paragraphs (when different from the revision)

Discussion

TABLE 1. SUMMARY OF REVISIONS

Paragraph	Title	Remarks
1.1	Scope	Clarification
1.2	Application	Guidance on additional requirements, and other specifications
1.4	Flight Phase Categories	Amendment 2, some wording for clarity
2.1	Issues of documents	Substitutes MIL-S-83691 for MIL-S-25015, and adds MIL-A-8861 and MIL-F-83300
3.1.1	Operational missions	Clarification
3.1.3	Moments and products of inertia	Includes cross-products of inertia
3.1.8.4	Service load factors	Wording change, Amendment 2
3.1.9	Permissible Flight Envelope	Requires that the contractor define boundaries of the PFE; specific criteria deleted
3.1.10.3.3	Flight outside the Service Flight Envelope	References to "stall" and "spin" changed to "high angle of attack", reference to dangerous flight conditions modified by Amendment 2
3.1.11	Interpretation of subjective requirements	Designates procuring activity as final authority on compliance with subjective requirements (Amendment 2)
3.1.12	Interpretation of quantitative requirements	Introduces the need to define an equivalent system for application to the modal parameter requirements
3.2.1.1	Longitudinal static stability	Explicitly allows zero control gradient with artificial speed stability. Allows an unstable airframe for Level 3. Amendment 2 changed definition of stable gradient
3.2.2.1	Short-period response	Reference to 3.7 and 3.8
3.2.2.1.1	Short-period frequency and acceleration sensitivity	Equivalent systems parameters are to meet the requirements from MIL-F-8785B

TABLE 1. CONTINUED

Paragraph	Title	Remarks
3.2.2.1.2	Short-period damping	Equivalent system parameters are to meet the requirements from MIL-F-8785B
3.2.2.1.3	Residual oscillations	Applies in calm air; not response to atmospheric disturbances
3.2.2.2	Control feel and stability in maneuvering flight at constant speed	Removes elevator-surface-fixed stability requirement in favor of response requirements. Amendment 2 clarified the meaning of stability
3.2.2.2.1	Control forces in maneuvering flight	Defines the load factor range in which control gradients should be linear; minor changes in values. Recognizes sidestick controllers
3.2.2.2.2	Control motions in maneuvering flight	Applies to "all types of pitch controllers"
3.2.2.3	Longitudinal pilot-induced oscillations	Expands the qualitative requirement of MIL-F-8785B
3.2.2.3.1	Dynamic control forces in maneuvering flight	Revised some values of control force per load factor
3.2.2.3.2	Control feel	Reorganizes MIL-F-8785B requirement
3.2.3.4	Longitudinal control in landing	Clarification that this requirement does not apply in atmospheric disturbances
3.2.3.5	Longitudinal control forces in dives-Service Flight Envelope	One-handed wheel control requires the same forces as a center-stick controller
3.3.1.1	Lateral-directional oscillations (Dutch roll)	Requirement for a stable airframe has been deleted. Some damping values revised
3.3.1.3	Spiral stability	Differences of airplane Class eliminated, and Category C grouped with Category A
3.3.1.4	Coupled roll-spiral oscillation	Coupled mode permitted for Category B & C, with minimum damping specified
3.3.2	Lateral-directional dynamic response characteristics	Clarification of wording
3.3.2.1	Lateral-directional response to atmospheric disturbances	Rewording in light of 3.8.3

TABLE 1. CONTINUED

Paragraph	Title	Remarks
3.3.4	Roll control effectiveness	Disturbance effects deleted (now in 3.8.3). Calls for rolls from both wings level and coordinated turns
3.3.4.1	Roll performance for Class IV airplanes	Different speed ranges defined, requirements relaxed at high and low speeds
3.3.4.1.1	Roll performance in Flight Phase CO	360° rolls initiated at 1g and rolls initiated between $.8n_o(-)$ and $.8n_o(+)$ specified separately
3.3.4.1.2	Roll performance in Flight Phase GA	Expanded requirements, load factors between $.8n_o(-)$ and $.8n_o(+)$
3.3.4.1.3	Roll response	Sensitivity clarified
3.3.4.2	Roll performance for Class III airplanes	Requirements relaxed at high and low speeds
	Rudder-pedal-induced rolls	Deleted; uncoupled response now allowed
3.3.5.1	Directional control with speed changes	Specified wings-level flight (Amendment 1)
3.3.9	Lateral-directional control with asymmetric thrust	Adds crosswind to the requirements on asymmetric loss of thrust
3.4.1	Dangerous flight conditions	Procuring activity approval of prevention devices moved to 3.4.1.2 by Amendment 2
3.4.1.2	Devices for indication, warning, prevention, recovery	Guidance and criteria for use of special devices (Amend. 2)
3.4.2	Flight at high angle of attack	Introduction for stall, post-stall-gyration and spin requirements (Amend. 2)
3.4.2.1	Stalls	Describes stalls and required conditions for meeting stall requirements (Amend. 2)
3.4.2.1.1	Stall approach	Warning characteristics, controllability lack of objectionable uncontrollable oscillations (Amend. 2)
3.4.2.1.1.1	Warning speed for stalls at 1g normal to the flight path	Speed range unchanged. Speed reduced "gradually" (Amendment 2)

TABLE I. CONTINUED

Paragraph	Title	Remarks
3.4.2.1.1.2	Warning range for accelerated stalls	Range in percent of $C_{L_{stall}}$, gradual approach (Amend. 2)
3.4.2.1.2	Stall characteristics	Rolling, yawing, pitching limits (Amend. 2)
3.4.2.1.3	Stall prevention and recovery	Allowable control, altitude loss, speed buildup (Amend. 2)
3.4.2.1.3.1	One-engine-out stalls	Recovery and thrust levels on good engine(s) (Amend. 2)
3.4.2.2	Post-stall gyrations and spins	Entry conditions. Store release not allowed, but auto. SAS disengagement is (Amend. 2)
3.4.2.2.2	Recovery from post-stall gyrations and spins	Affected airplanes, allowable recovery techniques & characteristics (Amend. 2)
3.4.3	Cross-axis coupling in roll maneuvers	Roll-pitch-yaw coupling paragraph retitled. This and subsequent paragraphs in 3.4 renumbered consecutively
3.4.4.1	Control force coordination	Force limits apply to sidesticks
3.4.10	Control margin	New requirement to ensure control authority, rate and hinge moment capability
3.4.11	Direct force controls	3.6.5 of MIL-F-8785B re-numbered and expanded to include direct side-force control
3.5.2.3	Rate of control displacement	Reference to the new requirements in 3.4.10 and 3.8.3
3.5.3	Dynamic characteristics	Combines the old 3.5.3 and 3.5.3.1 as a requirement on response to cockpit control input. MIL-F-8785B values for surface lag are revised and expanded
3.5.4	Augmentation systems	Covers both normal and abnormal operations
(3.5.4.1)	Performance of augmentation systems	Deleted
(3.5.4.2)	Saturation of augmentation systems	Deleted; covered by 3.4.10 and 3.8.3

TABLE 1. CONTINUED

Paragraph	Title	Remarks
3.5.5	Failures	Re-worded for emphasis. The phrase "small and gradual" applied to the transient has been deleted
3.5.5.1	Failures transients	Revised values for allowable transients
3.5.5.2	Trim changes due to failures	Wording changes for clarification (Amendment 2)
3.5.6	Transfer to alternate control modes	Again, "small and gradual" deleted
3.5.6.1	Transfer transients	Revised values for allowable transients
3.5.6.2	Trim changes	Wording changes for clarification (Amendment 1)
3.6.1	Trim system	Requirement applies to <u>steady-state</u> untrimmed cockpit control forces
3.6.1.2	Rate of trim operation	Forces for one-handed wheel operations are same as for centerstick controller
3.6.1.4	Trim system irreversibility	Clarification
3.6.2	Speed and flight path control devices	Clarification
3.6.3	Transients and trim changes	Includes any buffeting caused by secondary control devices. Also adds thrust reversers
3.7	Atmospheric disturbance models	All Sections 3.7 reorganized and expanded
3.7.1	Form of the disturbance models	Introduces the equations to be used for turbulence (same as MIL-F-8785B) and gusts
3.7.1.3	Discrete gust model	the "1-cosine" shape of a gust is retained but only half a period is specified to allow more flexibility
3.7.2	Medium high altitude model	Equations for isotropy
3.7.2.1	Turbulence scale lengths	Same scale lengths as MIL-F-8785B above 2000 ft
3.7.2.2	Turbulence intensities	Three RMS intensities are specified consistent with other revisions

TABLE 1. CONTINUED

Paragraph	Title	Remarks
3.7.2.3	Gust lengths	Discrete gusts lengths are same as MIL-F-8785B
3.7.2.4	Gust magnitudes	Light and Moderate gusts calculated as in MIL-F-8785B, Severe gusts taken from MIL-A-008861A
3.7.3	Low-altitude disturbance model	Introduces a separate model for Category C Flight Phases
3.7.3.1	Wind speeds	New requirement, mean (surface) wind vs probability of occurrence
3.7.3.2	Wind shear	New requirement, applies a logarithmic profile to the variation of wind speed wind speed with altitude
3.7.3.3	Vector shear	New requirement, change in wind direction with altitude produces low level wind shears
3.7.3.4	Turbulence	Revised variations in scale length and intensity close to the ground
3.7.3.5	Gusts	Discrete gusts as in MIL-F-8785B
3.7.4	Carrier landing disturbance model	This section contains a ship wake model supplied by NADC
3.7.5	Application of the disturbance models	Reorganized discussion from MIL-F-8785B
3.8	Requirements for use of the disturbance models	Introduces a new section to be used for explicit consideration of the effects of atmospheric disturbances, <u>if required by procuring activity</u>
3.8.1	Use of disturbance models	Modified discussion from 3.7.1 of MIL-F-8785B
3.8.2	Qualitative degrees of suitability	Contains definitions of the effects of increasing disturbance intensity on flying qualities or (indirectly) pilot opinion rating
3.8.3	Effects of atmospheric disturbances	Introduces disturbances as a potential cause of degraded flying qualities
3.8.3.1	Requirements for Airplane Normal States	To be substituted for 3.1.10.1, includes disturbance effects

TABLE 1. CONCLUDED

Paragraph	Title	Remarks
3.8.3.2	Requirements for Airplane Failure States	To be substituted for 3.1.10.2, includes disturbance effects in with Failure State probabilities
4.1	Compliance demonstration	All requirements by analysis, some by flight test or simulation (from Amendment 2). Conditions tabulated for new/modified requirements.
4.1.1	Analytical compliance	Start of an expanded treatment of compliance
4.1.1.1	Effects of Failure States	Renumbered 6.7.1 from MIL-F-8785B
4.1.1.2	Effects of atmospheric disturbances	Added for guidance on satisfying the new disturbance requirements
4.1.1.3	Computational assumptions	Renumbered 6.7.3 from MIL-F-8785B
4.1.2	Simulation	Added for guidance on use of simulation
4.1.3	Flight Test	Exempts atmospheric disturbance requirements from flight test demonstration
4.2	Airplane States	Table updated
4.4	Tests at specialized facilities	Added by Amendment 2
6.1	Intended use	Clarification
6.2.2	Speeds	V_s definition clarified, V_G added
6.2.5	Longitudinal parameters	α_s definition clarified, $C_{L_{stall}}$ defined
6.2.6	Lateral-directional parameters	$\Delta\beta_{max}$ definition clarified
6.2.7	Atmospheric disturbance parameters	New parameters defined, old ones redefined as necessary
6.2.8	Terms used in high-angle-of-attack requirements	Post-stall, post-stall gyration and spin defined (Amendment 2)
6.3	Interpretation of Fs/n limits of Table 5	Conforms to new lower limit
6.5	Engine considerations	Clarification (Amendment 2)
6.8	Related documents	Updated (Amendment 2)

In, addition, references to "elevator, aileron and rudder" have been changed throughout to "pitch, roll and yaw control".

SECTION II

HISTORICAL DEVELOPMENT

A. SPECIFICATIONS

Since publication of MIL-F-8785B in 1969, the Navy and Air Force have conducted and sponsored a number of analyses specifically to validate or recommend revisions to those requirements. The Flight Dynamics Laboratory (FDL) sponsored several comparisons of military airplanes (which had been designed to earlier specifications) to the new requirements:

F-4	AFFDL-TR-70-155, (McDonnell) - Reference 4
F-5/T-38	AFFDL-TR-71-134, (Northrop) - Reference 5
P-3B	AFFDL-TR-72-141, (Pacer Systems) - Reference 6
C-5A	AFFDL-TR-75-3, (Lockheed - Ga.) - Reference 7

As reported in Reference 8, McDonnell's Brulle and Moran compared F-15 developmental and other simulator data to MIL-F-8785B and other requirements. On their own, some manufacturers have made detailed comparisons of the flying qualities of other aircraft - both civil and military - with the MIL-F-8785B requirements. These reports are not generally available.

It has been the practice of the Air Force Systems Command's Aeronautical Systems Division (ASD) to write out detailed specifications for each new aircraft, tailoring the wording of general specifications as appropriate. Thus the F-15 was designed to handle requirements based on a preliminary draft of MIL-F-8785B; perhaps the most notable change to that was the Level 2 floor for the unaugmented airplane. In keeping with the prototype concept, the YF-16/17 flying qualities requirements were just one page long - only slightly more detailed than the 1907 Signal Corps handling requirements for the Wright Flyer, Reference 9. For the production F-16, however, MIL-F-8785B requirements were used with some modification. A noteworthy addition stated requirements in terms of handling qualities during tracking (HQDT - see Twisdale & Franklin's AFFTC-TD-75-1, Reference 10). During YC-14/15 development, both Boeing and Douglas wrote proposed detailed flying qualities requirements for a follow-on production airplane; with the help of these and inputs from NASA and other sources, ASD generated the specification to be used in the development of a production configuration (Reference 11). This document had much in common with MIL-F-8785B, with relatively few modifications for STOL flight conditions.

The FDL has sponsored reviews of MIL-F-8785B with the objectives of recommending revisions. Reference 12 contained recommendations in the areas of equivalent systems, phugoid, short period requirements for Category C, longitudinal pilot induced oscillations, control system lags, turn requirements at high load factor, and failure and engagement/disengagement transients. Reference 13 contained recommended revisions for almost all the main sections of MIL-F-8785B. Reference 14 contained recommendations for heading control, airplane normal and failure states and Category C short period requirements. Reference 15 documents a Naval Air Systems Command - sponsored study of aircraft configurations which could satisfy MIL-F-8785B but have unacceptable flying qualities.

Other military flying qualities specifications have been published since 1969. In 1970, MIL-F-83300 set out requirements for piloted V/STOL aircraft, again with Cornell Aero Lab help in generation (Reference 16) and suggesting improvements (Reference 17). The year 1970 also saw publication of AGARD-R-577 on V/STOL handling to revise AGARD Rep 408A. In Reference 18, Di Franco and Mitchell (also CAL) gave preliminary requirements for lifting re-entry vehicles during terminal flight. An outline for remotely-piloted-vehicle flying qualities design criteria is given in Reference 19. The result of an extensive effort to revise the British military flying qualities requirements of Av. P. 970 is reported in a 1975 RAE Tech. Memo, Reference 20.

Several related Military Specifications have been issued since the appearance of MIL-F-8785B. MIL-A-008861A(USAF) revised the flight loads requirements as part of a general revision of Air Force structural loads requirements in 1971. Coordinated with MIL-F-8785B amendments, MIL-S-83691 (USAF) in 1971 and -83691A in 1972 state Air Force Flight Test Center requirements for demonstrating stall/post-stall/spin characteristics in flight. Also for Air Force use alone, in 1974 MIL-F-9490D set forth completely revised requirements for piloted-aircraft flight control systems, making frequent reference to the generic MIL-F-8785 specification.

Civil requirements have also been developed, although these are generally less detailed than the military specifications. Franco-British authorities published TSS Standard 3-0 (formerly TSS-5) in July 1969 to guide Concorde design. In the United States, the FAA revised a number of times its 1965 tentative requirements for powered-lift transport aircraft; and periodically updated Parts 23, 25, etc. of the Federal Aviation Regulations. The British CAA also issued provisional airworthiness requirements for powered-lift aircraft, in 1972, as well as revising the British Civil Airworthiness Requirements. An exhaustive list of civil specifications is impossible here, but the Society of Automotive Engineers' ARP842B design objectives for flying qualities of civil transport aircraft should be mentioned. This document contains design charts in terms of modal parameters, and is more closely related to the military specifications, although of itself it has no authority.

This summary of related developments of specifications and regulations has stated little about research and development aimed at improving flying qualities requirements. Chalk, Neal and Harris included recommendations for work to improve the requirements in their final report on the MIL-F-8785B revision, Reference 21. The AGARD Flight Mechanics Panel has held a number of meetings on related subjects, and also has had a committee to survey handling qualities specification deficiencies (Reference 22).

NASA, the military services, civil authorities, and individual manufacturers have expended considerable effort. Much of this, however, has been concentrated on vertical or short take-off and landing, where less was known to start with. We want to extend MIL-F-8785 in that direction, but learning continues, and STOL operation is beyond the scope of the present proposed revision. For conventional flight, we seem to have reached a combined state of resources and technical capability that make the needed progress more difficult. Some analytical studies have been made, but progress has been slow, especially in getting validation sufficient for specification use. For lack of resources to do more, much effort has gone into milking a few good but limited sources of flight evaluation data such as Reference 23. We have found the scope of the current revision effort restricted severely by inadequacies both in progress and in substantiation of the advancements achieved.

B. BACKUP DOCUMENTS

Reference 24 represented an unofficial backup document to the then-current flying qualities specifications. The author discussed some of the requirements, presented some substantiating data and then reviewed other proposed requirements. Reference 3 was an official backup document for MIL-F-8785B, being listed in the "related documents" in the amendments to the specification. Substantiation and full discussion of the requirements were presented in this reference. Reference 25 in support of MIL-F-83300 and Reference 26 in support of MIL-F-9490D have followed in the same format. Similarly, the Air Force Flight Test Center issued Reference 27 in support of MIL-S-83691. The current report continues this lead.

A different approach was followed for AGARD-R-577, for which Volume I included discussion with the requirements and Volume II contained substantiation. For the future, we plan to put the flying qualities specification into a new format for such documents. A MIL-STANDARD will be prepared, which will have only the basic form of the requirements. A supporting MIL-HANDBOOK will contain for each item in the Standard, the rationale, suggested quantitative criteria to insert into the basic requirements, verification procedures and leasons learned from past experience. The Standard will thus be the framework for a detail specification; the Handbook will provide the information necessary to tailor the detail specification to the mission requirements under consideration. Reference 29a contains a discussion of the new format.

C. THE REVISION EFFORT

Amendments to MIL-F-8785B in 1971 and 1974 were directed principally at revising the stall/post-stall/spin requirements. Coordinated with AFFTC development of MIL-S-83691, emphasis was placed on departure resistance. A few minor changes were made also to clarify MIL-F-8785B requirements. Interim Amendment-1 was further revised to secure coordination of the Navy and Army, and the result published as Amendment-2.

An effort to revise MIL-F-8785B more fully was started in August 1973. An initial round of meetings was held with other government agencies and with major airframe companies. During the period from September 1973 to mid-1974, input was received, either at personal meetings or by correspondence, from the following organizations:

Air Force: ASD, FTC, TPS, ADWC, TFWC, SAC, MAC, ATC, TAC

Naval Air Systems Command

Army Aviation Systems Command

NASA HQ, Dryden, Ames

Boeing

Calspan

Douglas

General Dynamics/FW

Grumman

Lockheed-Georgia

Lockheed-California

McDonnell

Northrop

Rockwell

Systems Technology, Inc.

After these initial meetings the work of reviewing existing and proposed requirements, and either validating MIL-F-8785B or proposing revisions, was performed by members of the Flying Qualities Group. Working papers containing proposed revisions were submitted by the following people:

J. Callahan, Major USAF (currently assigned Columbus AFB, MS)

J. Lockenour (currently with Northrop Corp.)

D. Mayhew (currently with Draper Labs.)

D. Moorhouse (AFWAL/FIGC)

R. Quaglieri (currently AFWAL/FIGD)

M. Sanders, Major USAF (currently assigned England AFB, LA)

R. Woodcock (AFWAL/FIGC)

These working papers were collected for internal review in early 1976.

From May 1977 through August 1977, Moorhouse and Woodcock (FDL) and T.P. Sweeney (ASD) critically reviewed the collection of working papers. The proposals were revised and correlated into a single Working Paper, dated August 1977. This document was distributed to various government agencies for comment. Following preliminary coordination meetings with the Navy (Naval Air Systems Command, Naval Air Test Center and Naval Air Development Center, in Dec 1977) and ASD (Jan 1978) a revised Working Paper dated February 1978 (Reference 28) was prepared for industry review. This version was distributed to major airframe companies, research concerns and universities with a solicitation for comments.

A symposium was held in September 1978 as a part of the review process, the proceedings are documented as Reference 29. Workshop sessions plus other comments received were used to further refine the items to be revised. A draft of the revised flying qualities specification, MIL-F-8785C, was prepared and comments were obtained in 1979 and 1980, and the final version was issued in Nov. 1980.

The report is intended to supplement Reference 3. Therefore, it seems in order to put a list here of changes and errata to update that reference. It is not surprising that over the years we have found a few typos of consequence in that 689-page report.

Corrections to AFFDL-TR-69-72:

Cover and title page: Delete "OFFICIAL USE ONLY" and replace the distribution notice with "Approved for public release; distribution unlimited."

p.114, Fig. 25 (3.2.2.1.1): Caption should read "...n/α=5.5..."

p.116, 3.2.2.1.2 DISCUSSION: The first four lines should read: The discussion of 3.2.2.1.1 pertains to what is important to the pilot when the short-period damping is satisfactory. However, when the damping is too low, the airplane short-period response overshoots and oscillates. When...

p.119, 3.2.2.2 DISCUSSION, line 3: Insert "stable" before "stick-fixed."

p.122, 3.2.2.2.1 DISCUSSION, Center - Stick Controllers, 2nd para, line 4 should read "...values of $18/(n_L-1)$ and $85/(n_L-1)$ were chosen"

p.139, 3.2.2.3 DISCUSSION, Historical Development..., 3rd page, 3rd equation below the sketch: Within the first parentheses, the second term should be:

$$M_{\delta_e} \frac{1}{T_{\theta_2}} \frac{\alpha_e}{q}$$

p.146, 3.2.2.3 DISCUSSION, Design Options (Fully Powered Control Systems), polynomial: The numerator of the coefficient of s needs another set of parentheses:

$$K_{\ddot{\theta}} \, (M_{\delta_e} \, 1/T_{\theta_2}) - K_n \frac{Z_{\delta_e}}{g} \left(\frac{1}{T_{n_1}} + \frac{1}{T_{n_2}} \right)$$

p.147, 3.2.2.3 DISCUSSION, Design Options (Fully Powered Control Systems), 2nd page: Change "l_{CP}" to "l_{CR}" in typed lines 1 & 7, the two equations following the latter, the next typed line and the last equation on page 147

(2 places). Change "percussion" to "rotation" in typed lines 2 (2 places) and 6.

p.148, Change "l_{CP}" to "l_{CR}" in the sketch's feedback box (2 places) and the first and last equations on p.148.

p.149, Underlined caption of sketches: Change "l_{CR}" to "l_{CP}" and "percussion" to "rotation." At bottom of sketch (2 places) and in last 2 equations, change "l_{CR}" to "l_{CP};" also in next to last line of text (2 places)

p.150, as on p.149, (2 sketches, lines 1 & 2, line below sketch, lines 7 & 11 of the full paragraph).

p.151, as on p.149 (2 sketches)

p.152, as on p. 149 (1 sketch, equation, 3rd line below sketch).

p.153, 1st three and 5th equations, change "l_{CP}" to "l_{CR}".

p.154 Work diagram in feedback box change "l_{CP}" to "l_{CR}" 3 places; also once in text 3 lines below.

p. 155, 1st polynomial: the numerator of the coefficient of s should be:

$$M_{\delta_e}\frac{\alpha_e}{q}+\frac{Z_{\delta_e}}{V}\,\frac{1}{T_\alpha}\,\frac{\alpha_e}{\dot{\alpha}}+\frac{Z_{\delta_e}}{V}\,\frac{\alpha_e}{\alpha}$$

2nd polynomial: the last term should be:

$$V\,\frac{M_{\delta_e}}{Z_{\delta_e}}\left(\frac{\frac{\alpha_e}{\alpha}+\frac{1}{T_{\Theta_2}}\,\frac{\alpha_e}{q}}{\alpha e/\dot{\alpha}}\right)$$

Last equation: should be:

$$\frac{1}{T_{f_2}}=\frac{\frac{\alpha_e}{\alpha}+\frac{1}{T_{\Theta_2}}\,\frac{\alpha_e}{q}}{\frac{1}{V}\,\frac{Z_{\delta_e}}{M_{\delta_e}}\,\frac{\alpha_e}{\alpha}+\frac{\alpha_e}{q}+\frac{\alpha_e}{\dot{\alpha}}}$$

p.156, 1st line of text: the parenthetical expression should be ($H_{\alpha_e}=0$, $K_{\alpha_e}=0$)

p.295, 3.3.4 DISCUSSION, Bank Angle in a Specified Time, ϕ_t, 4th line below table: "ϕ_t" should be "t_ϕ".

p.420, 3.7.2 DISCUSSION, 2nd page, lines 5, 11, 36, 40, 41, 44, 47: spell it "homogeneity."

p.512, Bibliography: In entry B67, delete "(Title Unclassified)" and "CONFIDENTIAL."

p.513, Change entry B76 to read, Cooper, G.E.: "Understanding and Interpreting Pilot Opinion." Aeronautical Engineering Review. Vol. 16, No. 3, p. 47, March 1957.

p.519, Bibliography, entry C9: Delete everything after the underlined title and replace with "NASA Langley LWP-269, 1966."

p.523, In entry C46, delete "(Title Unclassified)" and "CONFIDENTIAL."

p.536, In entries E32 and E33, delete "(Title Unclassified)" and "CONFIDENTIAL." For E32, add at end "(ARC R&M 2983, published in the ARC TR for the year 1953, in 1964)".

p.554, In entry J33, delete "(Title Unclassified)" and "CONFIDENTIAL".

p.583, In entries P43, and P48, delete "CONFIDENTIAL". In entry P47, delete "SECRET".

p.640, Appendix V, 2nd page, 1st line above sketch: add at end of sentence, "(assuming that the vane axis is normal to the flight path)".

p.641, Appendix V, 3rd page, 2nd full paragraph, line 3 should read, "...Dutch roll frequency squared, $\omega_{n_d}^2$ ...". Last line should read, "...L'_β and $L'_r N'_\beta$ ..."

p.666, Appendix V, VB-3, Theory, 4th page, equation at bottom should be:

$$\psi_p = \psi_{z_1} + \psi_{z_2} - \psi_{p_1} - \psi_{p_2} - \psi_{p_3}$$

p.658, Appendix V, VC, 1st page: In equation 1, a minus sign should precede L'_{δ_a}. In equation 2, "K_p" should be "K_ϕ" and "N_p" should be "N_ϕ".

p.669, Equations 6 & 7 for ψ_p and ψ_β should read:

$$\psi_p = \{ \lambda \cdots$$
$$\psi_\beta = \{ \lambda \cdots$$

p.670, equations with sketch: Each of the three paired quantities in the denominators of K_S and K_R should have a bar over them, as is done in the numerators.

p.671, equation 10: In the first bracket in the denominator, the square root should be:

$$\sqrt{1 + \frac{4g}{V} \frac{L'_r}{{L'_p}^2}}$$

as in the second bracket.

SECTION III

STATEMENT AND DISCUSSION OF REQUIREMENTS ON SCOPE (1.)

1. SCOPE

A. 1.1 SCOPE

REQUIREMENT

1.1 Scope: This specification contains the requirements for the flying and handling qualities, in flight and on the ground, of U.S. Military, manned, piloted airplanes except for flight at airspeeds below V_{con} (MIL-F-83300). It is intended to assure flying qualities that provide adequate mission performance and flight safety regardless of design implementation or flight control system mechanization. The structure of the specification allows its use to guide these aspects in design tradeoffs, analyses and tests.

1.2 Application: The flying qualities of all airplanes proposed or contracted for shall be in accordance with the provisions of this specification. The requirements apply as stated to the combination of airframe and related subsystems. Stability augmentation and control augmentation are specifically to be included when provided in the airplane. The automatic flight control system is also to be considered to the extent stated in MIL-F-9490 or MIL-C-18244, whichever applies. The requirements are written in terms of cockpit flight controls that produce essentially pitching, yawing and rolling moments. This approach is not meant to preclude other modes of control for special purposes. Additional or alternative requirements may be imposed by the procuring activity in order to fit better the intended use or the particular design.

DISCUSSION

The scope has been defined in terms of the type of vehicle for which this specification applies. Also, ground handling is mentioned explicitly. Our intent is given more pominence by incorporating in the opening paragraph material from 1.2 and 6.1. As suggested in Reference 5, mention of deviation has been deleted from 1.2; of course, the possibility remains implicit.

Applicability to stability and control augmentation systems (SCAS) is stated in order to remove any possibility of misunderstanding. It has never been our intent to restrict application to the "bare airframe". A new paragraph, 3.1.12, gives guidance for application to configurations in which a SCAS introduces new modes or characteristics. As always, the procuring activity may introduce new or different requirements for a particular case. Also, it should be noted that the Air Force's current flight control system specification MIL-F-9490D, makes frequent reference to MIL-F-8785.

Factors affecting V/STOL conversion speed, V_{con}, are discussed in Reference 25.

B. 1.4 FLIGHT PHASE CATEGORIES

REQUIREMENT

1.4 Flight Phase Categories: The Flight Phases have been combined into three Categories which are referred to in the requirement statements. These Flight Phases shall be considered in the context of total missions so that there will be no gap between successive Phases of any flight and so that transition will be smooth. In certain cases, requirements are directed at specific Flight Phases indentified in the requirement. When no Flight Phase or Category is stated in a requirement, that requirement shall apply to all three Categories. Flight Phases descriptive of most military airplane missions are:

Nonterminal Flight Phases:

Category A - Those nonterminal Flight Phases that require rapid maneuvering, precision tracking, or precise flight-path control. Included in this Category are:

a. Air-to-air combat (CO)
b. Ground attack (GA)
c. Weapon delivery/launch (WD)
d. Aerial recovery (AR)
e. Reconnaissance (RC)
f. In-flight refueling (receiver) (RR)
g. Terrain following (TF)
h. Antisubmarine search (AS)
i. Close formation flying (FF)

Category B - Those nonterminal Flight Phases that are normally accomplished using gradual maneuvers and without precision tracking, although accurate flight-path control may be required. Included in this Category are:

a. Climb (CL)
b. Cruise (CR)
c. Loiter (LO)
d. In-flight refueling (tanker) (RT)
e. Descent (D)
f. Emergency descent (ED)
g. Emergency deceleration (DE)
h. Aerial delivery (AD)

Terminal Flight Phases:

Category C - Terminal Flight Phases are normally accomplished during gradual maneuvers and usually require accurate flight-path control. Included in this Category are:

a. Takeoff (TO)
b. Catapult takeoff (CT)
c. Approach (PA)
d. Wave-off/go-around (WO)
e. Landing (L)

When necessary, recategorization or addition of Flight Phases or delineation of requirements for special situations, e.g., zoom climbs, will be accomplished by the procuring activity.

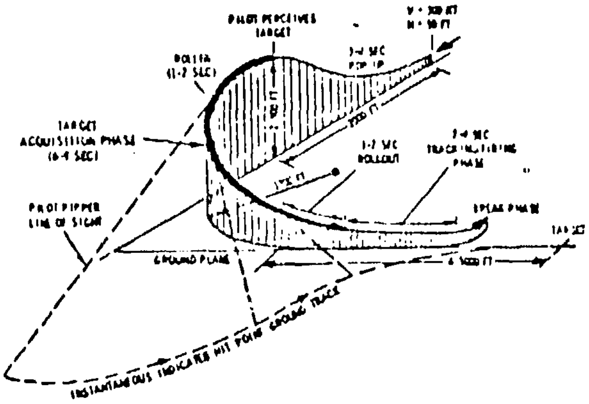
DISCUSSION

Reversal of the order of the third and fourth sentences, as presented in

Amendment-2, was incorporated in order to improve the flow of thought.

The Flight Phase Categories have not been revised. Reference 3 discusses the rationale for putting Flight Phases with similar flying qualities requirements into the three Categories. There was, however, the caveat at the end of 1.4 which suggested that additional requirements could (or should) be specified by the procuring activity. Some aspects–e.g., attitude regulation – are common to many tasks. Still, as airplane missions and tactics evolve, it becomes more probable that a specific Flight Phase may not be adequately represented by the 'average' characteristics of the appropriate Category. Reference 29b documents experience with the A-10. That airplane appeared to meet MIL-F-8785B requirements for Category A (which includes ground attack) and it was rated Level 1 during flight tests using a straight-in approach. Its flying qualities were unsatisfactory, however, when evaluated in an operationally realistic ground attack task. In addition, advancing flight control technology has greatly increased the potential for tailoring the flying qualities for specific tasks within a Flight Phase Category without compromising other tasks. Truly task-oriented flying qualities would receive an impetus from the inclusion of requirements related to actual operational tasks into the specification for a particular airplane.

In close air support, a wide variety of attack maneuvers may be characterized by three general phases, as sketched:



Ground Attack Maneuver Scenario

Target acquisition – rapid rolling toward target while developing 4 to 5g's; bank and g's held until rollout onto target (return to zero bank and 1g)

Weapon delivery or tracking/firing – errors eliminated and pipper maintained on target

Break – a gross maneuver to reposition for another attack while maintaining aircraft survival.

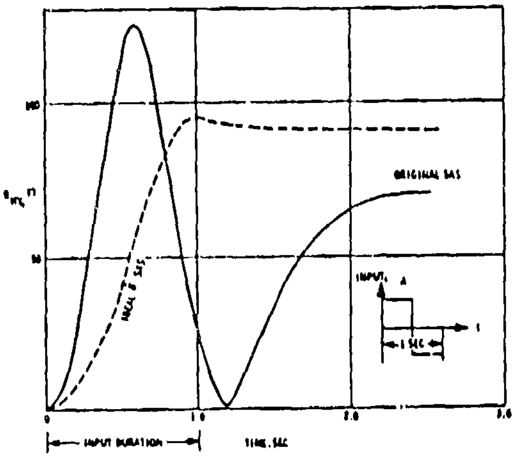
For the gross target acquisition maneuvers, highly predictable terminal orientation of the velocity vector is vital to minimizing the duration of the relatively vulnerable weapon delivery phase. Excellent roll response is required, in terms of both quickness and maintaining turn coordination. Weapon delivery requires rapid, precise control of the velocity vector for dropping unguided bombs, or the pipper line of sight (and thus aircraft attitude) for gunnery. (Material extracted from Reference 29b)

While the original stability augmentation of A-10 apparently met MIL-F-8785B requirements on lateral-directional dynamics, and pilots rated it satisfactory in "the originally planned tactical maneuvers... It was only as the maneuvers became very aggressive that the problem surfaced." For these aggressive maneuvers, the average maxima quoted are:

normal acceleration	4.5g
roll rate	93 deg/sec
bank angle	93 deg
tracking time	2.33 sec

In the development of the A-10 to satisfy the requirements of the task outlined above, the aerodynamic configuration remained unchanged and the flight control system modifications were relatively minor. This will not necessarily be so in more sophisticated designs. The cost of fixing such deficiencies could be very high after a new airplane has flown, and so it would obviously be beneficial to consider operational maneuvers as early as possible in the design phase. In the example cited, little more than the sketch would be required as an additional Flight Phase in the specification.

For this more severe Flight Phase, more stringent requirements might be placed on Dutch roll damping and roll-yaw coupling - see the sketched responses of lateral tracking error to a roll-control doublet. Although no A-10 deficiency was indicated at high g's, certainly for such a severe Flight Phase the lateral-directional characteristics must be investigated in pullups and turns - and possibly during rapid rolls - as well as in straight flight. (While the requirements of MIL-F-8785B apply throughout the V-h-n Flight Envelopes, often the lateral-directional behavior has been evaluated primarily in 1-g flight). Commonly it is observed that the amount of aileron-to-rudder crossfeed needed to coordinate turn entries varies considerably with angle of attack. Thus, one might find no single crossfeed gain suitable for all phases of the ground attack described.



Response to a 1-Second, Half-Stick Aileron Doublet For Tracking Scenario

SECTION IV

STATEMENT AND DISCUSSION OF APPLICABLE DOCUMENTS (2.)

2. APPLICABLE DOCUMENTS

A. 2.1 ISSUES OF DOCUMENTS

REQUIREMENTS

2.1 Issues of Documents: The following documents, of the issue in effect on the date of invitation for bids or request for proposal, form a part of this specification to the extent specified herein:

SPECIFICATIONS
MILITARY

MIL-D-8708	Demonstration Requirements for Airplanes
MIL-A-8861	Airplane Strength and Rigidity Flight Loads
MIL-F-9490	Flight Control Systems - Design, Installation and Test of, Piloted Aircraft, General Specification for
MIL-C-18244	Control and Stabilization Systems, Automatic, Piloted Aircraft, General Specification for
MIL-F-18372	Flight Control Systems, Design, Installation and Test of, Aircraft (General Specification for)
MIL-W-25140	Weight and Balance Control Data (for Airplanes and Rotorcraft)
MIL-F-83300	Flying Qualities of Piloted V/STOL Aircraft
MIL-S-83691	Stall/Post-Stall/Spin Flight Test Demonstration Requirements for Airplanes

STANDARDS

MIL-STD-756	Reliability Prediction

(Copies of specifications and standards required by contractors in connection with specific procurement functions should be obtained from the procuring activity or as directed by the contracting officer).

DISCUSSION

MIL-S-83691 was substituted for MIL-S-25015 in Amendment-2. MIL-A-8861 and MIL-F-83300 were added to the list. All the listed documents, and no others, are called out in one or more requirements of MIL-F-8785C.

As of the publication of this Technical Report, the latest versions of these documents are:

MIL-D-8708B(AS), 31 January 1969
MIL-D-8861(ASG), 18 May 1960;
MIL-C-18244A(WEP), 1 December 1962
MIL-W-25140A, 15 April 1973
MIL-S-83691A(USAF), 15 April 1972
MIL-F-9490D(USAF), 6 June 1975
MIL-D-008861A(USAF), 31 March 1971
MIL-F-18372(Aer), 31 March 1955
MIL-F-83300, 31 December 1970
MIL-STD-756A, 15 May 1963

SECTION V

STATEMENT AND DISCUSSION OF GENERAL REQUIREMENTS (3.1)

3.1 GENERAL REQUIREMENTS

Experience in recent aircraft procurements and at the Air Force Flight Test Center has emphasized the importance of precision tracking as a means of evaluating flying qualities and identifying and correcting flying quality deficiencies. Although this discussion tends to emphasize longitudinal flying qualities, it was found that precision tracking is important to flying qualities in all axes.

Reference 10 documents a study in which flight tests were conducted and techniques developed for evaluating handling qualities in combat-oriented air-to-air tracking maneuvers. The TWeaD II F-4C, incorporating a variable gain augmentation system, was the tracking aircraft. It was found that handling qualities levels, as defined by pilot ratings, correlated well with pipper motion, tracking error, and pilot comments. Pilots were able to detect even small degradations in handling qualities, and could rapidly select values of gains and gradients which resulted in an optimum flight control system. Such subtle anomalies as uncommanded pitch excursions were readily identified during tracking tests. It was felt that these "pitch glitches" would not have been discovered by the pilot or engineers in a conventional stability and control program, and might not even have been detected until after the aircraft had been accepted into the operational inventory and perhaps been introduced into combat. Reference 10 presents detailed procedural information on air-to-air tracking techniques, which is intended to be incorporated into a future edition of *AFFTC Stability and Control Manual*.

The flying qualities specification on the F-15 was originally written such that the Level 1 short-period response requirements were to be in accord with MIL-F-8785B. It was found that, whereas those requirements on $_{sp}$ vs n_z/α help define an adequate *baseline* airframe/flight control system, the requirements were inadequate as a requirement on *precision* tracking. The tracking maneuver itself was found to be a valuable tool for handling qualities investigations, and aft c.g. limits were defined from precision tracking tasks. This experience suggested that a flying qualities criterion be evolved which stipulates that, for longitudinal tracking, a pilot should be able to keep the pipper on target within a given mil tolerance for a minimum number of seconds. The tracking maneuvers could typically commence with the pipper displaced 10 mils down or up from the target.

Tracking experiments were used extensively during the YF-16 flight test program. Reference 35 documents the technique used and the results obtained. The tracking technique is referred to as Handling Qualities During Tracking (HQDT). A distinction needs to be made between HQDT and operational tracking. HQDT is not oriented toward probability of hits/probability of kill predictions, nor is it used to evolve or evaluate operational tactics. Typically, a HQDT maneuver involves about forty seconds of precision tracking of a specific aim point on a target aircraft during a constant-g or slow windup turn. Gun camera film is scored and computer processed to display a qualitative and quantitative summary of the run. Pilot ratings and comments, supported by analysis of the general trend of the pitch and azimuth tracking characteristics, may then reveal flying quality deficiencies which impact the capability of the fighter to accomplish its mission. In AFFTC experience the tracking performance has been too variable for valid comparisons - the useful data being the pilot ratings and comments.

References 10 and 35 both point out that a fixed, depressed - reticle gunsight is essential for the evaluation of flying qualities during tracking. The use of an automated fire control system computing sight tends to mask the true tracking characteristics of the closed-loop system consisting of the pilot, aircraft aerodynamics and flight control system. The computing sight dynamics involved computation and presentation delays which were long relative to motions seen when tracking with a fixed pipper. In the YF-16 program, the fixed sight was used for precision tracking during the development phase, whereas the computing sight was used at a later stage for an overall evaluation of the integration of the fire control system with the airframe/flight control system.

Current and projected research on flight/fire control system integration is expected to generate the principles needed to perform the trade-offs between aircraft and sight dynamics. Until these guidelines are developed and accepted, however, there is no assurance that a fire control system can compensate for any flying qualities problems. On the contrary, poor aircraft dynamics may compound sight or fire control problems. For the present, therefore, continued evaluation with a fixed sight is warranted.

The importance of precision tracking to the development and evaluation of flying qualities suggests that MIL-F-8785B could be rewritten in terms of performance standards during prescribed tracking tests. This approach, however, raises a long-standing controversy: should the specification parameters be oriented more toward aircraft design or toward operational use? And what requirements can we have sufficient confidence in? Currently, our flying qualities requirements are primarily on airplane characteristics rather than on what a pilot can do with the airplane. We see increasing emphasis, however, on relating requirements of all kinds directly to mission performance. For specification purposes we would need to find tasks for which pilots can obtain consistent performance with the vehicle, then seek a broader acceptance of pilot-in-the-loop flying qualities requirements (see George's summary in Ref. 29d).

It is recognized that expertise in the conduct of flight tests and the extraction of flying qualities data therefrom is properly vested in such flight test agencies as Naval Air Test Center and Air Force Flight Test Center. Historically, an attempt has been made to avoid specifying requirements on the pilot-vehicle combination in MIL-F-8785B, because of the reliance of such requirements on pilot skill, experience, and background. These variables could lead to inconsistencies in evaluating the degree of compliance with such requirements. It is further felt that specifying flight test objectives would leave unanswered the question of what characteristics make a system capable of meeting those objectives. The approach taken in revising MIL-F-8785B, therfore, is based on the premise that if aircraft flying qualities are going to be judged in closed-loop tracking, then the specification should provide guidance and requirements oriented toward developing an aircraft which will exhibit good flying qualities during tracking. For the future, we hope to make the mission orientation more explicit.

MIL-F-8785 itself was a significant departure from its predecessors in formalizing a framework for considering flying qualities. New requirements called for definition of Normal and Failure State; establishment of Operational, Service and Permissible Flight Envelopes; statement of three Levels of flying qualities; and application of these Levels according to the probability of encountering failures which degraded flying qualities in the Operational and Service Flight Envelopes. We saw this framework as necessary for a rational approach to flying qualities specification; but a number of users feared that the cost and effort of designing to and showing compliance with the MIL-F-8785B requirements would be increased manyfold. While we cannot claim to have overcome all objections, the following excerpt from the AFFDL/FGC 21-25 June 1971 Weekly Activity Report indicates that things are not all that bad.

> 12. visited the Handling Qualities Group to discuss experience in applying Military Specification, MIL-F-8785B in a recent study effort. The purpose of the effort was to establish a set of flying qualities requirements based on MIL-F-8785B to be applied in a weapon system development program and to take a preliminary look at the ability of the configuration to meet these requirements. The airplane in question was intended solely to conduct weapon delivery missions against ground targets. It was a relatively unsophisticated, subsonic airplane required to carry several external store complements, and to follow four mission profiles in the conduct of its basic air-to-ground weapon delivery operations. Applying the portions of the specification concerned with defining airplane normal and failure states and establishing flight envelopes at first appeared to be a task of monumental proportions, but, as it was necessary in order to identify the applicable MIL-F-8785B requirements, there was no way to avoid it. They found that defining the normal states for each flight phase was more of a bookkeeping problem than anything else. It was, however, the only approach to insuring that the combination of configuration, loading, etc., that were critical with respect to each of the MIL-F-8785B requirements were identified. Because of this, and because of the improved understanding of all aspects of the total system that resulted, felt that the effort involved was worthwhile. All that was required in this documentation effort with respect to flight envelopes was that the operational flight envelopes be constructed. Since these represent the speed, altitude and load factor capability necessary to complete the mission, consideration of the effect of external stores, etc., on airplane limitations was not necessary, which simplified the task a great deal. There was considerable overlap of the envelopes constructed by , which led to a manageable number of envelopes to be considered. was very liberal in sizing these envelopes, realizing that larger envelopes enhanced the competitiveness of their design. They had not come to grips with the problem of providing Level 1 flying qualities within these large envelopes, and the impact on such things as system weight, cost, complexity, reliability, etc. They acknowledged that they might have had to reduce these envelopes because of these considerations, in order to be responsive to the need for a relatively simple system. The identification of system failures that would have an affect on flying qualities, and the assessment of the failure consequences in terms of degraded flying qualities were found to be straightforward.

The process of establishing the per flights probability of these failures presented no particular problem. identified some failure modes through this evaluation which would not otherwise have been recognized. They did not have confidence in the accuracy of their failure probability analysis because of the inaccuracy in the system component failure rate data available in the open literature. Looking back on the application of MIL-F-8785B in this particular study, concludes that it was by no means as big a problem as had been anticipated, and that the benefits throughout the service life of the airplane would have more then compensated for the additional design effort required. They would recommend no changes to MIL-F-8785B based on their experience in this application of the specification. (Wilson)

A. 3.1.1 OPERATIONAL MISSIONS

REQUIREMENT

3.1.1 Operational missions. The procuring activity will specify the operational missions to be considered by the contractor in designing the airplane to meet the flying qualities requirements of this specification. These missions will include all associated Flight Phases and tasks, such as takeoff, takeoff abort, landing and missed approach. Operational missions include aircrew upgrade and training.

DISCUSSION

This change is an attempt to clarify the meaning of the paragraph and the detail to which the mission should be defined.

B. 3.1.3 MOMENTS AND PRODUCTS OF INERTIA

REQUIREMENT

3.1.3 Moments and products of inertia. The contractor shall define the moments and products of inertia of the airplane associated with all loadings of 3.1.2. The requirement of this specification shall apply for all moments and products of inertia so defined.

DISCUSSION

This is a semantic change to include cross-products of inertia explicitly. The axis system in which values are given must be identified, of course.

C. 3.1.4 EXTERNAL STORES

DISCUSSION

This paragraph is unchanged. However, it takes on increased significance because of changes elsewhere. Static longitudinal stability is no longer required for Level 3 and the requirements for control-surface-fixed short-period and dutch-roll stability have been deleted. Thus, granted Special Failure States, the basic airframe may be quite unstable. Stability then will be provided through the flight control system at least for normal operation.

The tolerable amount of basic-airframe instability is a flight safety consideration; an excess of control authority over that needed to trim must be available for recovery from high angle of attack, maneuvers, upsets, etc. External stores, being generally destablizing, will tend to aggravate the recovery problem by decreasing the amount of control available for recovery. Thus, especially in these cases particular attention must be given to anticipating the full operational complement of external stores - possibly allowing growth margins. It just may not be possible to carry a store that is more destabilizing than has been designed for.

D. 3.1.6.2.1 AIRPLANE SPECIAL FAILURE STATES

DISCUSSION

This paragraph has not been changed. With the emergence of "relaxed static stability" and other "control-configured vehicle" designs it takes on increased significance.

In the last analysis the procuring activity is responsible for approving design tradeoffs that bear upon safety. Rather than inhibiting imaginative design, then, this paragraph should be construed as forcing examination of failure possiblities as they affect flight safety through deterioration of flying qualities. The present state of the art can support some properly implemented reliance on stability augmentation to maintain Level 3 flying qualities, but it must be done carefully and for good reason.

Concerning the admissibility of a Special Failure State on the basis of its remoteness of possibility, the combined probability of having any flying qualities worse than Level 3 - not just the individual Failure State probability - must be kept extremely remote.

E. 3.1.7 OPERATIONAL FLIGHT ENVELOPES AND 3.1.8 SERVICE FLIGHT ENVELOPES

DISCUSSION

Paragraphs 3.1.7 and 3.1.8 have not been changed. Some Air Force fighter pilots have expressed dissatisfaction with the terminology, which might be taken to imply no operational need for flight outside the Operational Flight Envelope. Considering the Service Flight Envelope boundaries which must encompass the Operational, these pilots saw no way to extend the Operational Flight Envelope to higher angles of attack or lower speeds which they have found useful in air combat operations. We have never intended to preclude such use where it is safe, so we looked-unsuccessfully-for a name to replace "Operational" which would not have that restrictive connotation. It seems worth noting, nevertheless, that an "Operational Flight Envelope" defines the region in which Level 1 flying qualities are normally required - but this region will not always encompass the entire combat flight envelope.

Similarly, Level 2 flying qualities are required in the Service Flight Envelope. Note, however, that the minimum service speed is a function of stall speed, V_s, and the first item in the definition is based on lift plus thrust component. For STOL or high-thrust-to-weight configurations, V_s by this definition can be significantly lower than the aerodynamic or power-off stall speed. Other items in the definition of V_s and minimum service speed give a minimum usable speed which could be higher or lower than the aerodynamic stall speed. This applies in level flight and in maneuvers. It is doubtful that this interpretation has in fact been used; however, there are operational benefits to be gained from improving flying qualities at extreme flight conditions. The safe, usable attainment of more extreme flight conditions may be emphasized for missions in which maneuvering at high angle of attack is critical. The procuring activity could accomplish this by tailoring the requirements for determining the Service and Permissible Flight Envelopes. As an example, we could require that the Service Flight Envelope include the aerodynamic stall speed, with the Permissible Flight Envelope defined consistent with operational maneuvers appropriate to the mission (see Section V.G).

In the revised roll performance requirements of para. 3.3.4 we have felt the need to make a further distinction as a function of airspeed within the Operational and Service Flight Envelopes.

F. 3.1.8.4 SERVICE LOAD FACTORS

REQUIREMENT

3.1.8.4 Service load factors. Maximum and minimum service load factors, n(+) [n(-)], shall be established as a function of speed for several significant altitudes. The maximum [minimum] service load factor, when trimmed for lg flight at a particular speed and altitude, is the lowest [highest] algebraically of:

a. The positive [negative] structural limit load factor

b. The steady load factor corresponding to the minimum allowable value of lift coefficient for stall warning (3.4.2.1.1.2)

c. The steady load factor at which the pitch control is in the full airplane-nose-up [nose-down] position

d. A safe margin below [above] the load factor at which intolerable buffet or structural vibration is encountered.

DISCUSSION

Amendment 2 changed the wording of subparagraph b. to conform to the rewritten requirements at high angle of attack (3.4.2). Specifically, stall warning reference was changed from angle of attack to lift coefficient. The paragraph number for stall warning requirements was changed.

G. 3.1.9 PERMISSIBLE FLIGHT ENVELOPES

REQUIREMENT

3.1.9 Permissible Flight Envelopes. The contractor shall define Permissible Flight Envelopes which encompass all regions in which operation of the airplane is both allowable and possible, consistent with 3.1.10.3.3. These Envelopes define boundaries in terms of speed. altitude and load factor.

RELATED MIL-F-8785B PARAGRAPHS 3.1.9, 3.1.9.1, 3.1.9.2, 3.1.9.2.1

DISCUSSION

This revision deletes the restrictions on the Permissible Flight Envelopes (PFE), leaving only the real requirement that it be defined and that it shall be possible for the pilot to return the aircraft to the Service Flight Envelope. The cross-reference of 3.1.9 and 3.1.10.3.3 means that Level 2 flying qualities are not required outside of the Service Flight Envelope up to stall, maximum dives or other similar limits which can be used to define the PFE. The revision is intended to emphasize that the contractor is required to define the PFE appropriate to the airplane type and mission. For a transport mission, the requirement applies primarily to safety of flight items related to stall and maximum dive speed. For a fighter mission, consideration of extreme flight conditions related to combat would also be appropriate. The PFE limits in MIL-F-8785B are still valid for many missions and the discussion in Reference 3 (some of which is repeated here) is still valid.

The maximum permissible speed in dives and level flight can and must be defined for pilots' information. To allow for upsets, phugoid oscillations and other inadvertent excursions beyond placard speed, some margin is often needed between the maximum permissible speed and the high-speed boundaries of the Operational and Service Flight Envelopes. No attempt has been made to quantify such a margin, leaving only the basic requirement of 3.1.10.3.3. The margin may also be set by other requirements, e.g. structural, gust upset, etc. Civil airworthiness requirements will be appropriate for some military airplanes.

The minimum permissible speed must also be defined; however, we feel that minimum usable speed should be emphasized and not just allowed as a deviation from stall speed. In MIL-F-8785B the minimum permissible speed was defined in terms of V_S or controllability limits. As noted in the discussion of minimum service speed (see Section V.E), the literal definition of V_S could produce speeds less than the aerodynamic stall speed. We suggest, therefore, the definition of a minimum usable speed consistent with the mission requirements and the other flight envelopes.

This change, of course, does not relieve the need to meet the requirements on flight at high angle of attack (see paragraphs 3.1.10.3.3) but rather is intended to emphasize consideration of those requirements according to the mission.

H. 3.1.10.3.3 FLIGHT OUTSIDE THE SERVICE FLIGHT ENVELOPE

REQUIREMENT

3.1.10.3.3 Flight outside the Service Flight Envelope. From all points in the Permissible Flight Envelopes, it shall be possible readily and safely to return to the Service Flight Envelope without exceptional pilot skill or technique, regardless of component or system failures. The requirements on flight at high angle of attack, dive characteristics, dive recovery devices and dangerous flight conditions shall also apply.

DISCUSSION

This change was made by Amendment 2. Consistent with other changes in the amendment, references to 'stall' and 'spin' have been replaced by the more general reference to "flight at high angle of attack." The requirements of 3.4.2 in Amendment 2 place more emphasis on resistance to loss of control.

I. 3.1.11 INTERPRETATION OF SUBJECTIVE REQUIREMENTS

REQUIREMENT

3.1.11 Interpretation of subjective requirements. In several instances throughout the specification subjective terms, such as objectionable flight characteristics, realistic time delay, normal pilot technique and excessive loss of altitude or buildup of speed, have been employed to permit latitude where absolute quantitative criteria might be unduly restrictive. Final determination of compliance with requirements so worded will be made by the procuring activity (1.5).

DISCUSSION

This paragraph, moved from section 4 by Amendment 2 for added emphasis, seems self-explanatory. The further changes in the present revision to replace 'qualitative' with the word 'subjective' was made to prevent confusion with the definition of qualitative requirements to account for the effects of atmospheric disturbances (3.8.2).

J. 3.1.12 INTERPRETATION OF QUANTITATIVE REQUIREMENTS

REQUIREMENTS

3.1.12 Interpretation of quantitative requirements. The numerical requirements of this specification generally are stated in terms of a linear mathmatical description of the aircraft. Certain factors, for example flight control system nonlinearities and higher-order characteristics or aerodynamic nonlinearities, can cause the aircraft response to differ significantly from that of the linear model. The contractor shall define equivalent classical systems which have responses most closely matching those of the actual aircraft. Then those numerical requirements of section 3 which are stated in terms of linear system parameters (such as frequency, damping ratio and modal phase angles) apply to the parameters of that equivalent system rather than to any particular modes of the actual higher-order system. The procuring activity shall be the judge of the adequacy of the response match between equivalent and actual aircraft.

DISCUSSION

In the past, both operational experience and flying qualities research were largely limited to aircraft which behaved in the classical manner: response to control and disturbance inputs characterized by transfer functions of familiar form. The effects of additional dynamics introduced through the flight control system were recognized at the time MIL-F-8785B was written, but limited knowledge prevented adequate treatment. Still, aircraft design developments continue to emphasize equalization to "improve" aircraft response. In Reference 15, Stapleford discusses both good and bad possibilities. Certainly one would expect that failure to consider one or more dynamic modes in the frequency range of pilot control would give erroneous results. Prime examples include the F-14[30] and the YF-17[31] designs. The F-14's stability augmentation system was designed to increase the low short-period frequency. At one stage it did that well in landing approach, but it also introduced higher-order dynamics which resulted in an overall "effective short-period frequency" little changed from augmentation-off. In a flight evaluation of predicted YF-17 characteristics using the FDL Calspan NT-33 Variable Stability Airplane, pilots rated the short-period response poor to bad. The equivalent-system approach may not have been used to improve the response. However, it is pertinent that a configuration intended to have good flying qualities got "good" pilot ratings in flight only after the flight control system compensation had been simplified.

Boothe et al [32] suggest several simple mechanizations which augment stability without increasing the order of the system response. However, prefilters, forward-loop compensation, crossfeeds, etc. are legitimate design tools which are being used on many current aircraft and indeed seem to be the norm. These artifacts do increase system order and we need to be able to account for their effects in the requirements. Thus, with modern flight control and stability augmentation systems, there is considerable confusion regarding the "proper" selection of modal parameters such as short-period frequency and damping. Correlation of Level 1 flying qualities with characteristics of the bare airframe is certainly not valid for augmented aircraft in general. Stability and control augmentation frequently introduce additional dynamics in the frequency range of pilot control, thereby invalidating any interpretation of the requirements in terms of particular roots of a transfer function. Although these fallacies have been pointed out many times, misinterpretations continue. The feeling is not uncommon that some requirement just do not apply. To clarify application of the requirements to flying qualities in general this new paragraph, 3.1.12, has been added.

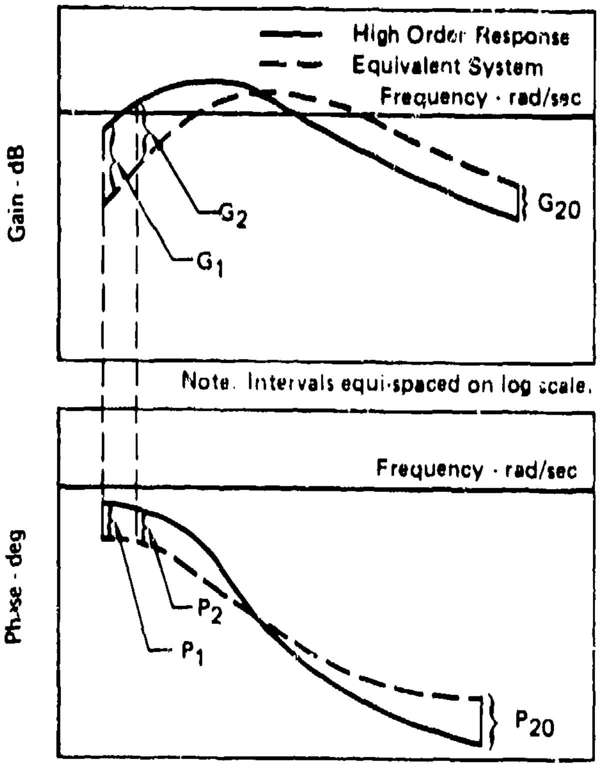
In reality we are only interested in pilots' opinion as to whether the actual airplane dynamics enable the appropriate tasks to be performed well enough with acceptable workload. We now require, therefore, that the actual dynamics be approximated by the responses of transfer functions of classical form. The appropriate parameters of this equivalent transfer function must meet the modal requirements of the specification. This so-called "equivalent system" approach allows continued use of the familiar data base for a broad range of mechanizations. It was proposed first in Reference 12, and more recently has been advocated strongly by Hodgkinson and others (References 29c, 33, and 34).

In order to demonstrate compliance with the model requirements of MIL-F-8785C, equivalent systems must first be defined to approximate the actual airplane dynamics whether predicted analytically or obtained from flight test. Considerations for specific axes are discussed elsewhere following the appropriate requirement. In general, however, it has been necessary to add a term representing a time delay to the 'classical form' of the transfer functions. This term has allowed a closer match of the higher-frequency content of most advanced systems considered to date. The time delay has been correlated with pilot opinion ratings, and has yielded new requirements in 3.5.3.

The preceding discussion should not be taken to imply that there is little problem with applying the specification requirements to equivalent system parameters. For configurations which exhibit conventional-appearing dynamics, application is indeed straightforward. It also appears to be true at present that pilots are most comfortable with response to dynamics that are 'natural', i.e., like the classical modes. Certainly, additional prominent modes result in a more complicated dynamic response. As we consider configurations with dynamics which depart more and more from the classical order or form, then more and more judgement will be required in defining the appropriate equivalent system parameters and assessing compliance with the requirements. Hodgkinson has suggested that flying qualities will be poor if no equivalent system can be found to give a 'good' fit to the actual response. Success of the equivalent system approach in applying or defining the Level 2 and 3 boundaries is not definite at this time. There are also questions which remain to be answered: Is the equivalent system solution unique? (Not universally, it seems). Can the equivalent system parameters be juggled until compliance is indicated? (In limited observations, some tendency toward equivalent results from different techniques has been noted). Are requirements necessary for either the amount or the quality of the mismatch? (To date this has not been a major problem). In spite of the qualifying remarks and the above questions, this approach is a way to apply known requirements to advanced configurations with high-order dynamic responses. We preserve the validated data base of MIL-F-8785B and the experience in its use. At the same time the equivalent systems are to be defined by matching an appropriate airplane response to pilot control input. We, therefore, focus attention on the quality of the actual overall response perceived by the pilot, rather than imply consideration of a dominant mode as may be inferred (however incorrectly) for MIL-F-8785B. We also believe that the use of the equivalent system approach is responsive to the needs of designers. Failure of an equivalent system parameter to meet the requirement then indicates the characteristics of the system (e.g., damping, delay or lag, etc.) that must be improved. We acknowledge that the use of equivalent systems is not a magic solution to good flying qualities; however, properly used it is a good tool for designing or evaluating advanced configurations which are becoming indiscriminately complex.

Determining Parameters of the Equivalent System

To facilitate the reduction of higher-order systems to equivalent systems, a computer program is required. At this stage, judging the adequacy of a match remains something of an art - no method should be used blindly, without exercise of engineering judgment. One such program utilizes a first-order maximum-likelihood least-squares fit to find an optimum set of equivalent-system parameters, given an initial estimate of this set, which minimizes a cost function. The cost function is a measure of the area contained between the two amplitude and phase curves in the sketch. One possible choice is, for frequencies at



Minimize Cost Functional, i.e., Mismatch $= \sum_{i=1}^{20} (G_i^2 + WP_i^2)$; $W = 0.02$

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SKETCH OF EQUIVALENT SYSTEM DETERMINATION equally spaced logarithmic increments, the sum of squares of the gain errors (in decibels) and, with a weighting factor, the phase errors. It is not clear, however, that each frequency should be given equal weight. One might want to force a good fit in the region around "crossover," which is a measure of the bandwidth expected for piloted closed-loop control. That choice generally would require some consideration of pilot adaptation: whether, what form, how much.

The match may be over a specified frequency range, or an open-loop phase angle value may be substituted for the upper frequency limit. As we shall see, the phase-angle cutoff option is especially important. Options could allow the user to match either the amplitude or phase portion of the Bode plot, or both portions, weighting the importance of each. Any or all of the equivalent system parameters may be "turned loose" simultaneously to undergo optimization, with the rest of them remaining inactive at stipulated values, possibly being freed in a later iteration. The kinematic relationships among the motion variables must be kept in mind; this point is discussed in some detail where appropriate to specific requirements.

The initial set of equivalent system parameters can be determined by a variety of standard techniques, such as an "eyeball" fit of the Bode plot, analog matching techniques in the time domain (as in reference 23), pole-zero cancellation on a root plot, etc. In general it has been found sufficient to initialize the numerator time constant, T_{θ}, at the bare-air-frame value, T_{θ_2}. The initial value of static gain is not critical, and can be nominally set to 1.

To some extent, experience has shown that handling qualities predicted by equivalent system parameters are fairly insensitive to the frequency range over which the parameters were determined. The following general guidelines are offered for short-term response:

1. Low-frequency cutoff: approximately .1 to .3 rad/sec - but at least 3 times the undamped natural frequency or time constant of any lightly-damped (e.g., phugoid) mode.

2. High-frequency cutoff: a frequency, ω (rad/sec) 2 to 4 times (one or two octaves above) the frequency at which phase angle contribution, ϕ (rad), of the aircraft and flight control system is given by

$$\phi = -4.7 + 0.3\omega$$

The cutoff frequency usually need not exceed 10 rad/sec. One or two octaves generally should be sufficient margin from the peak-response frequency, in the absence of aliasing phenomena or nearby large structural resonances.

A one-minute period corresponds to a frequency of 0.1 rad/sec. Phugoid frequency usually is more or less of that order of magnitude. Spiral divergence requirements limit divergent inverse time constant to be smaller than 0.086 for Level 2, 0.173 for Level 3. The highest frequency observed for pilot control in tight tracking is 8 to 10 rad/sec. The phase cutoff is based on the Neal-Smith analysis of longitudinal dynamics: their pilot model, with a 0.3 sec. time delay, can contribute no more than 90° lead compensation:

a maximum phase lead of $\pi/2 - 0.3\omega$ to help meet the $-\pi$ phase-angle stability criterion. Certainly that much or more high-frequency lead would greatly downgrade pilot opinion.

Deciding whether a fit is good enough remains a matter of judgment. We have no experience with trying to outsmart this requirement; but for the higher-order systems which have been examined, most of the time a decent fit could be found when looking for the best fit. The frequency range in which the fit is poorest, and the nature of the deviations, should be considered if the fit is not uniformly good.

Transfer functions are inherently linear representations. Various requirements state specifically that they apply to all amplitudes of motion to each cycle of oscillation. Generally, the intent in this specification is to establish bounds on parameters of a rational quasilinear representation of the system for all reasonable amplitudes of control imputs and airplane motions. The control saturation attendant to very high feedback gain can result in poor flying qualities at moderate to large amplitudes if saturation of control-surface amplitude or rate alters the motion parameters too severly from their values at small amplitude.

It is, of course, possible to find higher-order systems for which a good fit could not be attained with an equivalent system. The problem might arise with two or more lightly damped second-order roots in the frequency range of interest, or an uncommon closed-loop resonance near or beyond 10 rad/sec. The question has to be posed whether we could realistically expect to encounter these systems in practice. Examining several actual higher-order systems, having both good and bad flying qualities, such configurations seem to be rare. In the experience of Hodgkinson and others (Reference 33) inability to match with an equivalent system may in itself be an indication of very poor flying qualities.

One often encounters more than one equivalent system giving a good fit. Slight differences in the frequency range used, differences in initial parameter values, or differences in optimization procedure can lead to a multitude of "equivalent" systems. The situation is analogous to the non-uniqueness problem encountered by past researchers in analog matching. Although this may present a dilemma for purposes of identifying a plant, in our experience it has not been a problem for purposes of predicting handling qualities Levels; each "good fit" equivalent system for a given higher-order system has generally led to the same prediction of pitch tracking flying qualities.

SECTION VI

STATEMENT AND DISCUSSION OF LONGITUDINAL REQUIREMENTS (3.2)

3.2 LONGITUDINAL FLYING QUALITIES

In the time since MIL-F-8785B and Reference 3 were published, various attempts have been made to develop new requirements. There is much discussion on relative merits of the frequency domain vs the time domain, and on open-loop vs closed-loop requirements. We have kept the form of the requirements as in MIL-F-8785B for the present revision. In the future Standard and Handbook, the intent is to present alternative requirements and discuss the applicability of each, concentrating on how the different criteria are similar rather than highlighting differences to choose a "best".

A. 3.2.1.1 LONGITUDINAL STATIC STABILITY

REQUIREMENTS

3.2.1.1 Longitudinal static stability. For Levels 1 and 2 there shall be no tendency for airspeed to diverge aperiodically when the airplane is disturbed from trim with the cockpit controls fixed and with them free. This requirement will be considered satisfied if the variations of pitch control force and pitch control position with airspeed are smooth and the local gradients stable, with:

a. Trimmer and throttle controls not moved from the trim settings by the crew,

b. 1-g acceleration normal to the flight path, and,

c. Constant altitude

over a range about the trim speed of ± 15 percent or ± 50 knots equivalent airspeed, whichever is less (except where limited by the boundaries of the Service Flight Envelope). Alternatively, this requirement will be considered satisfied if stability with respect to speed is provided through the flight control system, even though the resulting pitch control force and deflection gradients may be zero. For Level 3 the requirements may be relaxed, subject to approval by the procuring activity of the maximum instability to be allowed for the particular case. In no event shall its time to double amplitude be less than 6 seconds. In the presence of one or more other Level 3 flying qualities, no static longitudinal instability will be permitted unless the flight safety of that combination of characteristics has been demonstrated to the satisfaction of the procuring activity. Stable gradients mean that the pitch controller deflection and force increments required to maintain straight, steady flight at a different speed are in the same sense as those required to initiate the speed change; that is, airplane-nose-down control to fly at a faster speed, airplane-nose-up control to fly at a slower speed. The term gradient does not include that portion of the control force or control position versus airspeed curve within the breakout force range.

DISCUSSION

Explicit sanction is given to zero control gradients if stability with respect to disturbances is provided through stability or control augmentation. This was not intended to be excluded by MIL-F-8785B, as can be illustrated by quoting directly from Reference 3: "The primary purpose of the static stability paragraphs of MIL-F-8785B is to prevent divergences in airspeed and angle of attack which might remain undetected by a busy pilot so that, at the worst, the airplane would end up in an unsafe flight condition or run out of control available for recovery. A statement banning such divergences was therefore made the primary requirement of 3.2.1.1. Airplanes having certain types of SAS, such as maneuver-command systems, have zero gradients of control force and position with speed yet can be quite stable with respect to external disturbances. If such systems meet the primary intent of 3.2.1.1, i.e., positive stability with respect to speed, paragraph 3.2.1.1 should not be interpreted as disallowing these systems." Thus, although artificial stability was "allowed" by the discussion of Reference 3, the increasing use of control modes such as attitude hold/rate command makes it more desirable to add this clarification to the specification itself. For design guidance it should be noted that zero speed stability removes an airspeed cue that pilots sometimes find valuable, particularly at low speed; and that automatic trimming has been known to lead to an insidious slowdown of some aircraft to stall when the pilot holds a small back force.

A second effect of the revision is to limit the requirement for stability to Levels 1 and 2. MIL-F-8785B allowed no static instability, even for Level 3, giving a designer only the choice between making the basic airframe stable or requesting approval of a Special Failure State. This conservative requirement was self-defeating, because once the boundary was violated, there was no explicit limit or even guidance on the tolerable amount of instability. Reference 3, p. 56, does provide a brief qualitative discussion on control-surface-fixed instability for consideration of possible Special Failure States. Again, it was decided to put this allowance into the specification itself with an explicit limit on the instability allowed and with additional guidance, such as 3.4.10, Control Margin.

Excesses of either stability or instability increase the control power required. Conceivably, supersonic performance optimization may give an uncontrollably rapid divergence subsonically. In that case, simple pitch rate augmentation might be used to restore control with high reliability (e.g., the SST "hard SAS"). In Reference 36, Wasserman and Mitchell report that "with increased pitch damping (T_2 held constant),... the associated delay in the appearance of the instability in attitude response was considered 'insidious'".

The original backup document, Reference 3 p. 60 and 61, in discussing data interpretation allows that "A certain amount of static instability might have been allowable for Level 3, as shown in several references. After studying the available data, it is obvious that many factors influence the amount of instability which can be handled. Because even a small instability can be quite dangerous under some circumstances (e.g., low total damping), it was decided to require the airplane to be statically stable, even for Level 3. Aside from the data, there is great reluctance to allow airplanes to be designed with any instabilities, because of design and requirement uncertainties, and because of the possibility of experiencing several Level 3 flying qualities simultaneously..." That report shows data that indicate a Level 3 limit for phugoid-mode time to double amplitude of 8 to 10 seconds (pp. 70, 71).

Since publication of MIL-F-8785, ground-based and in-flight simulation studies related to the Boeing SST, the B-1 and other configurations have shown the apparent feasibility even of instrument landing with static instability as great as 6 seconds to double amplitude. The Concorde now in commercial service becomes statically unstable as the angle of attack for stick shaker operation is approached. The F-16 with a degree of relaxed static stability appears to be a very successful design. Still the possible cases are so diverse that it seems better not to allow any instability without substantiation that the airplane does indeed remain flyable. Therefore, the requirement provides for review of the actual Level 3 boundary by the procuring activity. For cases similar to those which have been previously investigated in some detail, perhaps analysis would be an adequate basis for approval. In other cases, ground-based or in-flight simulation might be necessary to establish an appropriate quantitative Level 3 boundary.

An unstable airframe (even though stabilized through the flight control system) runs the risk of uncontrollable divergence if control authority or rate is insufficient; see 3.4.10, Control Margin.

Level 3 applies to Airplane Failure States of greater or lesser probability in the Service or Operational Flight Envelopes respectively. It is rational to ask how to consider combinations of adverse conditions: Flight Envelope, maneuvering, turbulence level, wind shear, visibility, etc. Worst-case combinations of everything are possible, but with slight probability.

In view of Air Force missions, IFR must be considered common; therefore, one would seem remiss not to consider both VFR and IFR for Level 3. The Level 3 definition is perhaps as explicit as necessary about maneuver capability: somehow or other get through the remaining Flight Phases and make a safe landing, without particular danger of damage. Other factors might also be considered to compound the difficulty to the extent that they are commonly encountered: light to moderate turbulence and winds, with the expected exponential shear near the ground; loose formation flight, perhaps including in-flight refueling with difficulty but not danger.

The 6-second limit on instability was derived from in-flight and ground-based simulator studies which have shown that unstable configurations are safely flyable. Reference 36, for example, indicated a Level 2 boundary at 2.5 seconds in 'light' turbulence and 4.25 seconds in 'moderate' turbulence. Pilot ratings were fairly constant at 5 to 6 until the time to double amplitude was reduced below 6 seconds, when significant deterioration began. A seemingly conservative value was chosen for the absolute limit on allowable pitch instability. These experiments were conducted in a research atmosphere, however, not in a real operational environment. There is also the matter of design uncertainties "cliffs", where small differences in configuration or flight condition can have a large effect on flying qualities. This degree of instability allows little margin for later addition of more - destabilizing external stores.

Little is yet known about the cumulative effects of several poor flying qualities together, except that an aircraft that is safe with any one "unacceptable" quality can become unflyable with some combinations of these characteristics. Further, a number of plausible single and multiple failures can degrade several handling qualities at once. Loss of just the pitch axis of augmentation, for example, could degrade damping, frequency, maneuvering force gradients, friction and backlash. A pilot-induced oscillation could not be stopped by clamping the control stick if $d\delta_e/dn_z$ is unstable. Consideration must also be taken of the pilot controller characteristics and other modes, to ensure that there will not be any unsafe combinations of Level 3 qualities.

Control of an unstable vehicle requires a high degree of pilot attention. In approach and landing pilots do concentrate on flying to the extent that a rather large amount of instability may not even be noticed; the pilot may unconsciously compensate if feasible, to retain precision and closed-loop stability. World War I experience with unstable fighters showed high effectiveness to be possible, but with significant aircraft loss rates due to loss of control. At this date it is not possible to sort out the exact degree of instability or the contributions of inadequate pilot training, lack of a known spin recovery technique, and other airplane idiosyncracies. In cruise, pilots tend to be less atentive to the controls. Several flight investigations, however, have documented the adequacy of the new Level 3 instability limit for safe flight in general.

Note that the revision allows an unstable airframe with artificial stability, does not require it. A designer can consider this option in design trade-offs, but for some missions the best solution may not be an unstable airframe.

The new revision keeps the Amendment 2 clarification of the definition of stable gradients. Specification of constant altitude in these requirements is definitive at some sacrifice of relevance. Reference 3, Appendix IVA, pages 679 and 630, discusses flight test techniques.

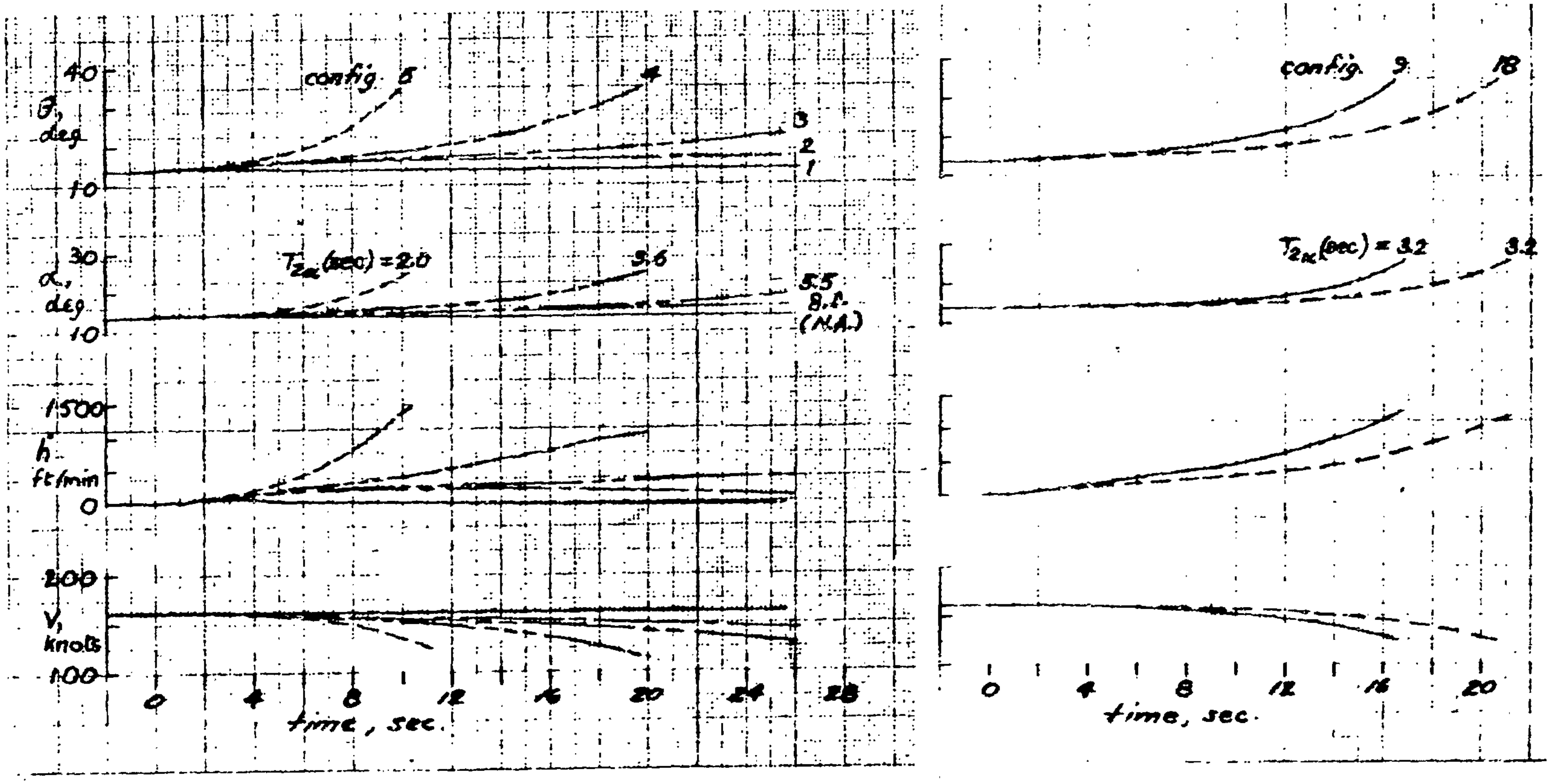
Substantiation

In response to a step control input, stable aircraft reach new steady values of θ, α, $\dot{h}$ and V; unstable aircraft have the same initial response, then diverge, as illustrated by the following figure 1 (from Reference 37). For a supersonic transport design, impulse responses are shown for various degrees of static instability as C_{m_α} varied. Also shown is the response of a configurations having much more static instability, with time to double amplitude increased by a pitch damper. Evaluation pilots rated both of these configurations unacceptable, but termed the latter's characteristics insidious. From Reference 38, commenting on an F9F-2 airplane with static instability ameliorated by a pitch damper to give about 6 seconds to double amplitude:

> "The rate of divergence of the airspeed was scarcely noticable to the pilots in normal flying. However, this degree of instability might be objectionable for flight operations where accurate control of airspeed is required."

From Reference 39, pilot tolerance of aperiodic instability is much greater than of oscillatory instability (Figures 2 and 3); nevertheless, the 2/3 sec T_2 boundary of that variable-stability YF-86D evaluation for aperiodic divergence is not considered safe. With less than 1 second to double amplitude, "there was a dangerous situation in that a short distraction of the pilot's attention could allow the unstable vehicle to diverge to the point that it was difficult to recover". For statically stable configurations "the unacceptable boundary is close to the zero damping boundary over most of the frequency range... in the very low-frequency and very high - frequency ranges a small amount of positive damping is required to remain within the acceptable region". Commenting on this different tolerance, Taylor and Day (reference 40) state:

> "at the higher frequencies, the technique for controlling the motion was not learned as quickly... Controlling the pure divergence in the region of a static instability was more natural and less tiring than controlling the oscillatory airplane motions, inasmuch as the pilot need only to counteract the angle-of-attack divergence without leading the motion to stabilize the aircraft."



(a.) Comparison of linear $C_m(\alpha)$ configurations 1 - 5

(b.) Effect of increased pitch damping with same T_2 . ($C_{m_q} + C_{m_{\dot{\alpha}}}$) for config 18 was 5 times that of config 9.

Figure 1. - Comparison of effects of various stability characteristics on airplane response to elevator pulse (-5 deg for 0.2 sec at t = 0)

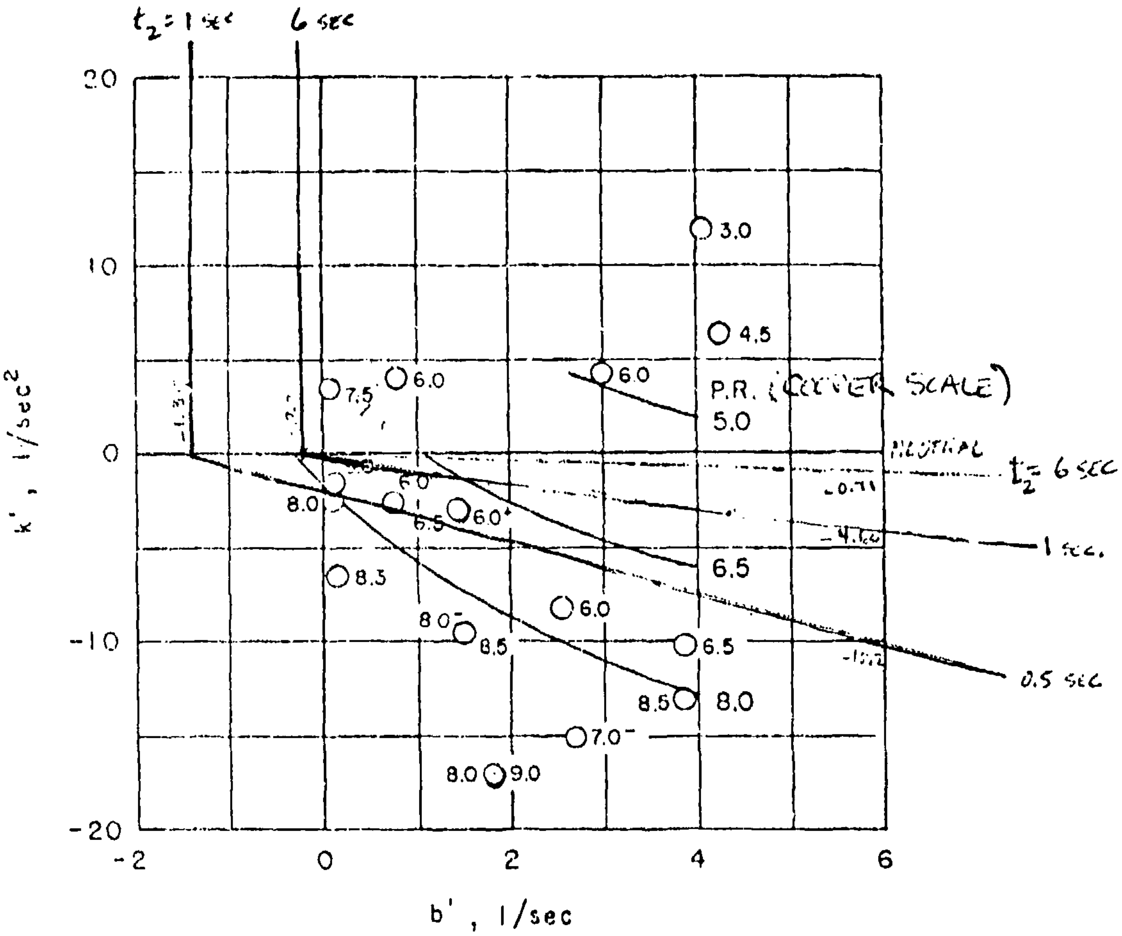
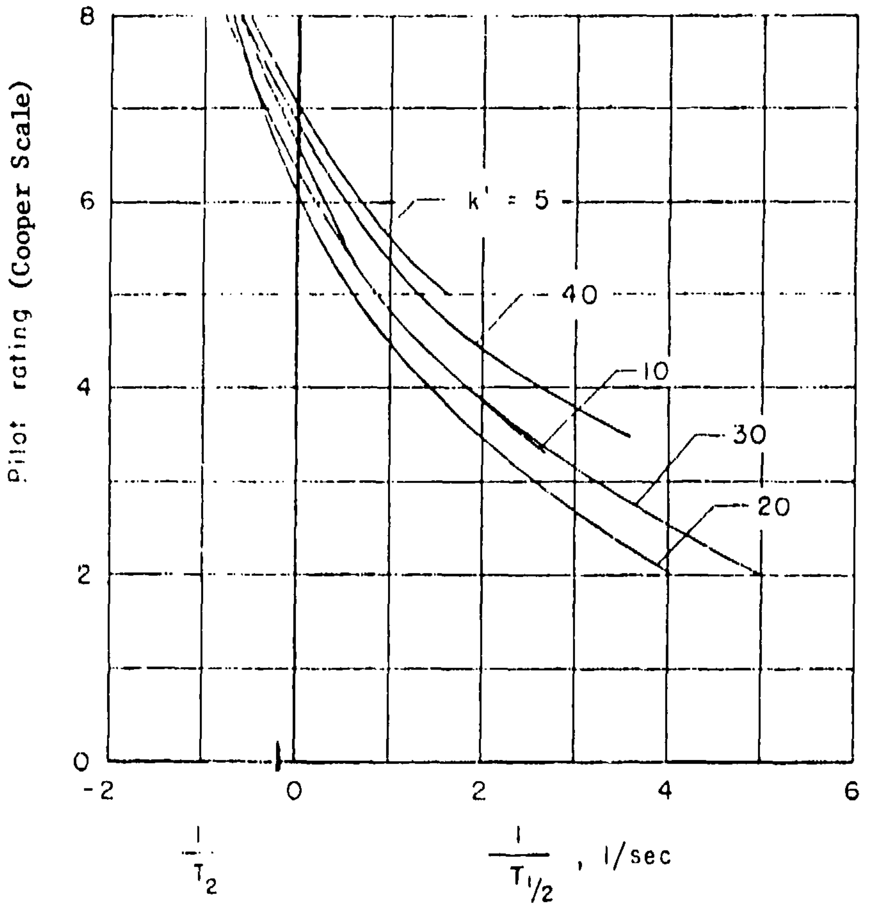


Figure 2. - Contours of constant pilot opinion in statically unstable region; constant stick-to-stabilizer gearing (Ref. 39)



(a) τ = 0.15 sec.

Figure 3. Pilot rating as a function of $1/T_2$ and $1/T_{1/2}$ for constant positive values of k' (Ref. 39).

Neglecting the 0.15-second control-system time constant τ,

$$\frac{q}{\delta_c} = \frac{C_{o_q} + C_{1_q}s}{s^2 + b's + k'}; \quad \frac{\alpha}{\delta_c} = \frac{C_{o_\alpha}}{s^2 + b's + k'}$$

$$b' = b - K_q C_{1_q}; \qquad k' = k - K_q C_{o_q} - K_\alpha C_{o_\alpha}$$

The unchanged phugoid requirement, $T_2 \geq 55$ seconds for Level 3, still limits the tolerable oscillatory instability at low frequency (the α, q and n_z feedbacks used in these variable - stability airplanes would not suppress the phugoid mode in the region of low short-period frequency and damping). Higher-frequency instabilities are unlikely, requiring considerable negative aerodynamic damping; the limit of 6 seconds to double amplitude would fit the Level 3 boundary of Ref. 39 for $0 \leq \omega_n \leq 6$ rad/sec.

For aperiodic instability, reference 41 shows that the boundary of acceptability "for emergency condition" (Cooper 6.5) was insensitive to the value of lift-curve slope, or $1/T_{\theta_2}$ or n_z/α, for positive lift-curve slopes. This boundary value was 2 seconds to double amplitude.

Reference 36 demonstrates that at least at low speeds, the "short-period" approximation can give a grossly different value of T_2; further, configurations with unstable values thus calculated are rated bad. The T_2 obtained from the angle-of-attack trace matched the theoretical value well when C_{m_α} was actually linear. References 36 and 37 both elaborate on the range of values for time to double amplitude obtained by different means: calculation from three-degree-of-freedom equations and various simplifications, measurement from α, θ or V responses. M_α nonlinearities gave different results for nose-up and nose-down perturbations; of course the worst direction would govern, for all reasonable magnitudes. Most of the evaluations gave some consideration to turbulence. Reference 36's baseline configuration had a Level 2 value of $d\gamma/dV$, but zero values were included in the evaluation - with a little improvement in rating, less noticeable in turbulence. The evaluations considered both visual and instrument flight.

On the basis of all these considerations, 6 seconds to double amplitude seems a reasonable, safe limit. Operators may be well advised to give pilots of potentially unstable airplanes some flight simulator experience with such instability. The provision for demonstration "to the satisfaction of the procuring activity" implements reference 3's caveat that two or more Level 3 characteristics together may be unflyable.

B. 3.2.1.2 PHUGOID STABILITY

DISCUSSION

The phugoid requirements have not been changed. An attitude hold/rate command system used as the normal means of piloted control will tend to suppress the phugoid mode. If the mode is not evident, then certainly the damping requirement of 3.2.1.2 has been met. Of course an attitude command is not suitable for unrestricted maneuvering. However, attitude command may be found acceptable - possibly even desirable - for small corrections to an essentially straight flight path as on landing approach; and rate plus integral signal in the forward loop with pitch-rate feedback, can provide attitude hold hands-off while retaining rate command for maneuvering. As discussed under 3.1.2.2, the resulting zero gradient of control force with airspeed is permitted (See also the discussion on side effects of stabiltiy and control augmentation under 3.5.4).

Reference 12 proposed that increased phugoid damping should be required at all Levels when the frequency was greater than about 0.1 rad/sec. Conversely, Reference 7 recommended that the requirements be relaxed if the period of the phugoid oscillation was greater than 30 secs. Considering data scatter plus the interaction of the requirement with gust response due to M_u and with separation from the short-period frequency, we have not changed the MIL-F-8785B requirements.

Reference 33 discusses two different approaches to deriving equivalent system parameters for the phugoid mode. The actual pitch dynamics can be matched by an equivalent 'full' longitudinal transfer function of the form:

$$\frac{\theta}{F_s} = \frac{K\ (s + 1/T_{E1})(s + 1/T_{E2})\ \bar{e}^{AES}}{(s^2 + 2\zeta_{PE}\omega_{np_E}s + \omega^2_{np_E})(s^2 + 2\zeta_{SPE}\omega_{nSPE}s + \omega^2_{nSPE})}$$

The matching would obviously be done over a frequency range that spans the range of control inputs (typically 0.01 to 10. rad/sec.). If the (equivalent) short period and phugoid modes are separated so that there is no significant interaction, then it is accurate to match the phugoid mode separately, i.e.,

$$\frac{\theta}{F_s} = \frac{K_p(s + 1/T_{E1})}{(s^2 + 2\zeta_{p_E}\omega_{np_E}s + \omega^2_{np_E})}$$

over a restricted frequency range appropriate to the mode. A lower frequency bound of 0.01 rad/sec. is probably appropriate, but the upper bound is a function of the response characteristics. At this time we suggest using the frequency corresponding to the minimum gain between the resonant peaks of the pitch rate response to pilot input.

C. 3.2.1.3 FLIGHT-PATH STABILITY

DISCUSSION

No change is made at this time. It should be noted, however, that engine response must also be considered in determining the adequacy of speed and flight-path control. For example, Reference 29e discusses the piloting difficulties created by changing to slower-responding engines in the F-4. Engine manufacturers are little aware of flying qualities, so people concerned with the airframe must take special pains. As shown by the F-100 engine, often things can be done in the design of a new engine to improve its response. Integration of flight and propulsion control systems offers further possibilities (Reference 42 is an example of work being done in this area).

For STOL operation on the normal approach glide path, Gerken (Reference 11) with C-14 and C-15 type aircraft in mind specifies the MIL-F-8785B values of $d\gamma/dV$ "when the longitudinal column is used chiefly for rapid flight path control" (conventional technique). On the other hand, for "backside technique", "when a primary controller other than the longitudinal column is used to effect a rapid change in flight path", he specifies $d\gamma/dV$ no more than:

Level 1	0.20 degrees/knot at Vo_{min}
Levels 2 and 3	0.35 degrees/knot at Vo_{min}

and no more than 0.05 deg/kt more positive 5 knots slower. When a speed hold mode is functioning, the requirement does not apply. The new part of the requirement accounts for the "back-side technique", which can be learned: control flight path with throttle, and airspeed through pitch attitude commanded by column or stick.

Reference 11 states other pertinent requirements as well. For Level 1, hands-off flight path stability is called out - reinforcement of short-period and phugoid requirements. Also, the ratio of steady pitch attitude to flight-path angle "at constant airspeed for column inputs, for airplanes that use the longitudinal column for rapid flight-path control, shall be $0.75 \leq \Delta\theta/\Delta\gamma \leq 1.5$ for Level 1, $0.5 \leq \Delta\theta/\Delta\gamma \leq 1.5$ for Levels 2 and 3." The requirement implies a functioning airspeed hold mode while the pilot commands flight path in the "conventional" manner with pitch control, rather than in the "backside" manner with throttle. It is intended to assure conventional response in STOL operation where bare-airframe characteristics may be masked by augmentation.

The numerical requirements of MIL-F-8785B were chosen with some consideration of turbulence, and Reference 20 specifically comments that "the values specified make sufficient allowance for the effects of at least moderate turbulence". In Reference 28 we suggested a possible form for flight-path stability requirements as explicit functions of atmospheric disturbances. Recognizing that flight path/airspeed control becomes more difficult as disturbance intensity increases, the following form is suggested for the maximum value of rate of change of flight path angle with airspeed:

FLYING QUALITIES	ATMOSPHERIC DISTURBANCES		
	LIGHT	MODERATE	SEVERE
LEVEL 1	0.06	-0.03	-0.12
LEVEL 2	0.15	0.06	-0.03
LEVEL 3	0.24	0.15	0.0

The numbers suggested for moderate and severe atmospheric disturbances are arbitrary, at present. It should be pointed out, however, that the sense of these requirements can be satisfied by increasing airspeed which is commonly done in adverse conditions. In application, therefore, this requirement would probably mean defining the approach speeds to be used in adverse conditions, rather than a "rule of thumb" of adding 50% of the wind or 50% of the reported gusts to the approach speed.

Lack of data precluded any attempt to include such a requirement in the specification. If desired by the procuring activity subjective requirements would be applied through the new section 3.8.3.

Ralph Smith, Ref. 43, proposes an alternative to the $d\gamma/dV$ requirement to apply when the "backside technique" is used, an upper bound on time to arrest rate of sink $\Delta\gamma = 3$ deg. by throttle control:

Level 1	$t_s \leq 3.0$ sec.
Level 2	$3.0 < t_s \leq 5.0$ sec.
Level 3	$5.0 < t_s$

based on reported experience with 14 Class II, III and IV airplanes. His calculations included incremental elevator deflection for a 5 deg. increase in angle of attack. For front-side operation he believes his proposed short-period requirements (discussed in the next subsection) to be sufficient. "More research is clearly needed if more definitive power approach requirements are to be developed".

D. 3.2.2.1 SHORT-PERIOD RESPONSE

REQUIREMENT

3.2.2.1 Short-period response. The short-period response of angle of attack which occurs at approximately constant speed, and which may be produced by abrupt pitch control inputs, shall meet the requirements of 3.2.2.1.1 and 3.2.2.1.2. These requirements apply, with the cockpit control free and with it fixed, for responses of any magnitude that might be experienced in service use. If oscillations are nonlinear with amplitude, the requirements shall apply to each cycle of the oscillation. In addition to meeting the numerical requirements of 3.2.2.1.1 and 3.2.2.1.2, the contractor shall show that the airplane has suitable response characteristics in atmospheric disturbances (3.7 and 3.8).

3.2.2.1.1 Short-period frequency and acceleration sensitivity. The equivalent short-period undamped natural frequency, $\omega_{n_{sp}}$, shall be within the limits shown on figures 1, 2 and 3. If suitable means of directly controlling normal force are provided, the lower bounds on $\omega_{n_{sp}}$ and n/α of figure 3 may be relaxed if approved by the procuring activity.

3.2.2.1.2 Short-period damping. The equivalent short-period damping ratio, ζ_{sp}, shall be within the limits of table IV.

TABLE IV. Short-period damping ratio limits.

Level	Category A and C Flight Phases		Category B Flight Phases	
	Minimum	Maximum	Minimum	Maximum
1	0.35	1.30	0.30	2.00
2	0.25	2.00	0.20	2.00
3	0.15*	-	0.15	-

*May be reduced at altitudes above 20,000 feet if approved by the procuring activity.

DISCUSSION

The first change is to add the reference to Sections 3.7 and 3.8 to the MIL-F-8785B requirement for "suitable response characteristics in atmospheric disturbances" in 3.2.2.1, rather than delete that sentence as proposed earlier.

The other change is to call out explicitly equivalent frequency in 3.2.2.1.1 and equivalent damping ratio in 3.2.2.1.2 even though it would be covered by 3.1.12. The equivalent parameters are to be determined by approximating the actual frequency response by an equivalent transfer function

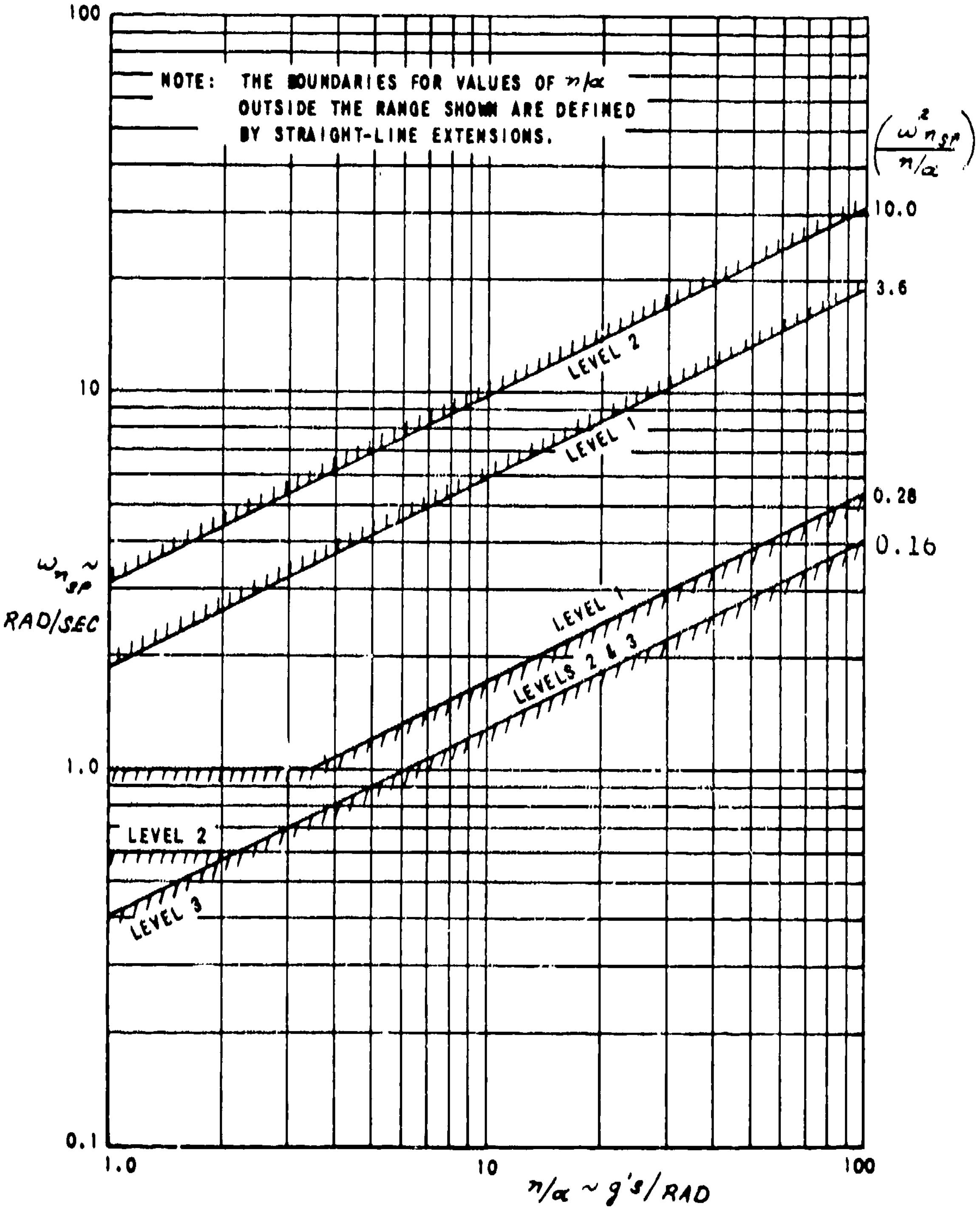


Figure 4. (MIL-F-8785C Figure 1) Short-Period Frequency Requirements - Category A Flight Phases.

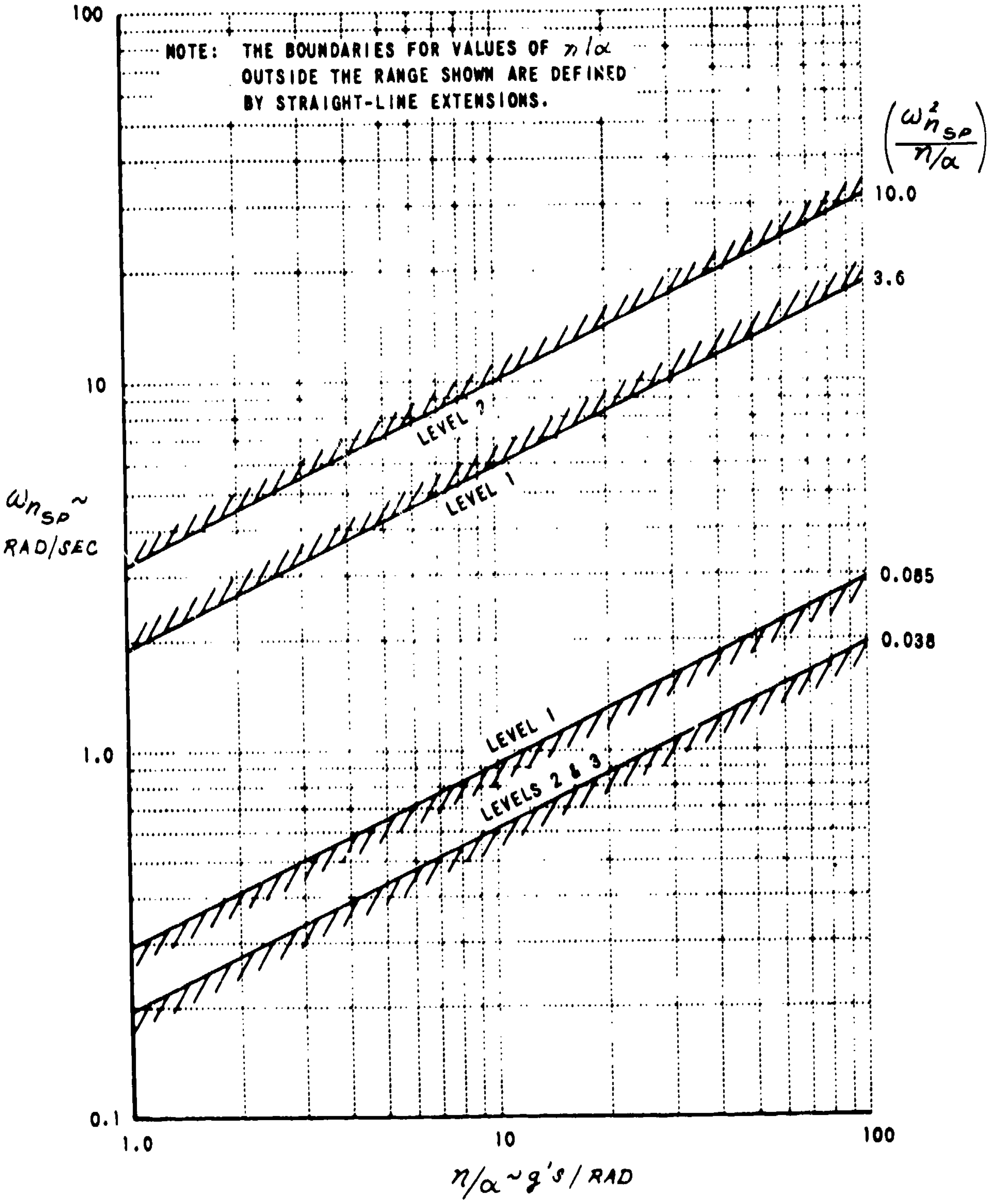


Figure 5. (MIL-F-8785C Figure 2) Short-Period Frequency Requirements - Category B Flight Phases.

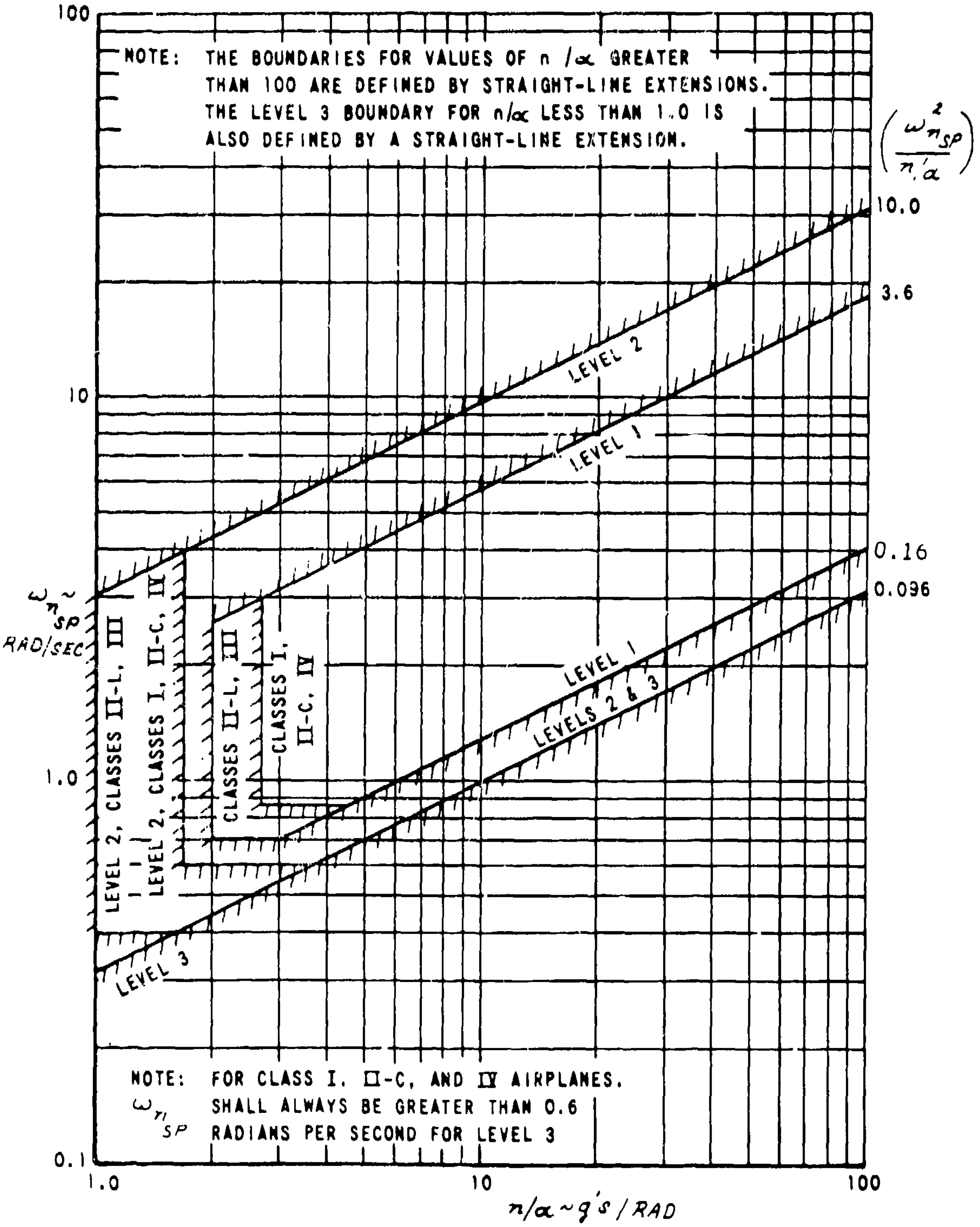


Figure 6. (MIL-F-8785C Figure 3) Short-Period Frequency Requirements - Category C Flight Phases.

of the form:

$$\frac{\dot{\theta}(s)}{F_s(s)} = \frac{Ke^{-A_E s}\,(s + 1/T_E)}{s^2 + 2\zeta_E \omega_E s + \omega_E^2}$$

Note that it is required to match the overall airplane response to pilot-applied control force so as to include all the contributions from the flight control system, feel system, etc. In an ideal 'classical' system which is truly represented by the short-period mode, the equivalent time delay would be too small to be of concern, the equivalent frequency and damping ratio would be the values determined from the short-period roots, and

$$\frac{1}{T_E} = \frac{1}{T_{\theta_2}} \approx \frac{g}{V} n_\alpha \approx \frac{\rho VS}{2m} C_{L_\alpha}$$

For some configurations, this may still be a valid representation. For an augmented system in general, however, the time delay is liable to be significant and the other parameters assume equivalent values which may differ from their classical approximation. A_E is the total effective time delay contributed by all sources including high-frequency flight control system modes (actuators, compensation, etc.), digital sampling and computation delays, etc., etc. The requirements on allowable time delay, both actual and equivalent, are presented in Section 3.5.3.

The interpretation of equivalent numerator time constant has also been questioned, because of its relation to the airframe parameter n_α. In practice we suggest that if a 'good response match' can be obtained using $1/T_E$ fixed at the value calculated from the airframe n_α, then this would be the preferred approach. Reference 34, however, presents data to support using an optimized-fit "equivalent n_α" for comparison with the ωn_{SP} vs n/α requirements in MIL-F-8785C. This equivalent n_α $(= \frac{V}{g}\frac{1}{T_E})$ is to be interpreted as a parameter influencing the acceptability of the short-term response to pitch control input; it is not the steady-state "normal acceleration sensitivity, n/α ". This approach will be required for many augmented systems, especially when the relationship between pitch acceleration and steady state normal acceleration is modified by the flight control system. In that case, we would also recommend matching both normal acceleration and pitch rate response simultaneously. As discussed under "Alternative Criteria" it may be desired to specify both $\omega^2/[(V/g)(1/T_E)]$ and $\omega^2/(n/\alpha)$.

Figure 7 (from Reference 34) indicates the possible interpretations of results with $1/T_E$ free in obtaining the equivalent system parameters. For the point plotted at the high value of n_α, the proximity to the lower frequency boundary is consistent with pilot comments of sluggishness. Data from References 23 and 48 were compared with the MIL-F-8785C boundaries using this interpretation of equivalent n_α. The results are given in Figures 8 and 9 (also form Reference 34), showing reasonable correlation. Rather than specify

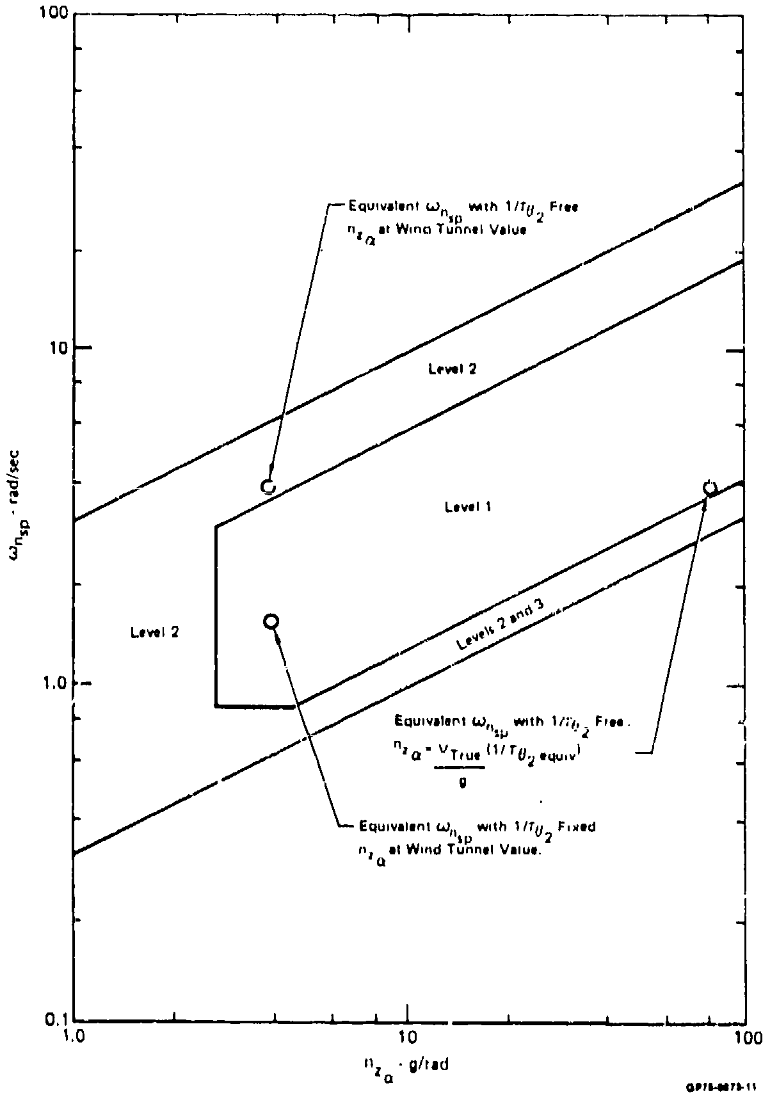


Figure 7. Alternative Correlations of "Sluggish" Dynamics with MIL-F-8785B Cat. C Requirement

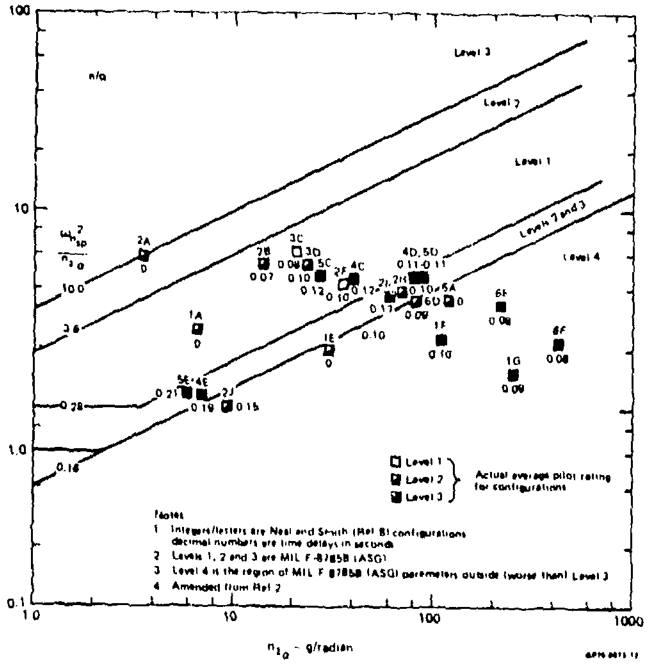


Figure 8. Comparison of $1/T_{\theta_2}$ freed cases with MIL-F-8785B Cat. A Requirements Neal and Smith's Data, Frequency Matched Equivalents

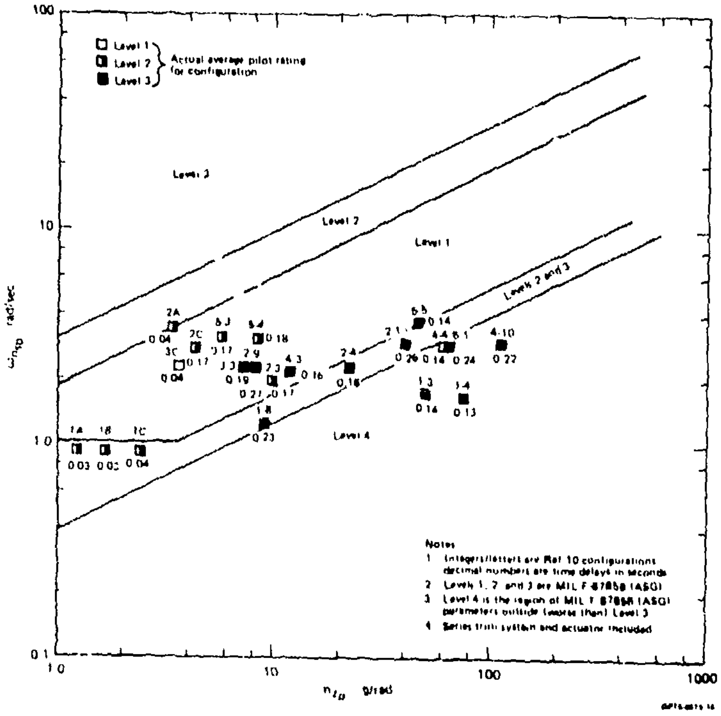


Figure 9. Comparison of $1/T_{\theta_2}$ freed cases with MIL-F-8785B Cat. A Requirements Smith's Flare Maneuver Data

this approach at this time, we recommend that any configuration which shows a significant change in equivalent system values from n_α fixed to n_α free be considered a potential flying qualities problem. In particular, it may be appropriate to consider alternative criteria as discussed in the following subsections.

The Level 3 floor on $\omega_{n_{SP}}/(n/\alpha)$ was adopted in MIL-F-8785, according to Ref. 3, to account for uncertainties in the data and concern for safety when the pilot is not concentrating intently the piloting task. To keep this floor is not exactly consistent with allowing 6 seconds to double amplitude in 3.2.1.1, longitudinal static stability. Although it was not possible to reach agreement to delete the Level 3 boundary of 3.2.2.1.1, the specification does allow the Procuring Activity to grant a Special Failure State upon review. Of course, the specification can - should - be tailored for each procurement. Expressed willingness to consider relaxed static stability would be a prior evidence that, given enough justification, reliability, etc., this Level 3 floor would be waived.

ALTERNATIVE CRITERIA

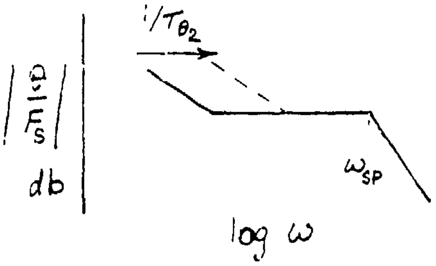
Numerator Time Constant

All along, there has been considerable discussion as to whether T_{θ_2} or n_α is the more appropriate parameter to characterize pitch response. References 44 and 45, for example, both discuss the importance of the numerator time constant, while Reference 46 suggests that it is the important parameter in landing approach. The British flying qualities specification (Ref. 20) uses the ω_n^2/n_α requirement of MIL-F-8785B/C, except that the Category C requirements are modified by the addition of the following:

Minimum values of n_α	V < 100 kn	V > 100Kn
Level 1 boundary	1.67	V(Kn)/60
Levels 2 and 3 boundary	1.0	V(Kn)/100

With the classical approximate relationship between n_α and $T\theta_2$, this is equivalent to specifying maximum values for $T\theta_2$ of 3.1 secs. for Level 1 and 5.2 secs. for Levels 2 and 3. There is also a note that these lower bounds of n_α may apply to Category A as well as Category C.

The requirements of MIL-F-8785B were in terms of n_α and did not consider numerator time constant per se.. It is possible for two classical aircraft to have the same values of short-period frequency and damping and n_α but different numerator time constants, just by virtue of having different airspeeds. The specification would not discriminate between these two configurations in terms of flying qualities, although there is a change in pitch dynamics, as sketched. The effect of that change on pilot opinion rating is going to be influenced by the



proximity of $1/T\theta_2$ to the short-period frequency (and possibly by the phugoid dynamics also). To support using n_α instead of $1/T\theta_2$ for the final version of MIL-F-8785B, Reference 3 cited:

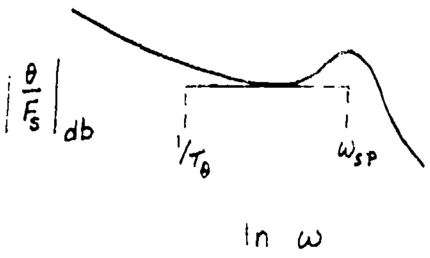
> $\omega^2_{n_{SP}}/(n/\alpha)$ and ζ_{SP} boundaries fit the available flight data, over an n/α range of 12.3 to 61.5 for Category A Flight Phases, roughly 2 to 20 for B-70 Category B, and 2+ to 11 for Category C.
>
> $\omega^2_{n_{SP}}/(n/\alpha)$ corresponds to $(F_s/n)M_{F_s}$ and to Bihrle's Control Anticipation Parameter, Reference 47, the ratio of initial pitching acceleration to steady-state load factor, for pitch control. This correspondence holds for any forms of stability and control augmentation involving only the pitch control, as well as for the basic airframe.

Also $\omega^2_{n_{SP}}/(n/\alpha)$ tends to be invariant with speed, so that over a wide speed range an airplane can stay within the boundaries. That is a nice practical convenience.

The use of an equivalent n_α based on a numerator time constant should bridge the two opposing factions. Preliminary studies at Naval Air Development Center indicate the following tendencies for several current airplanes:

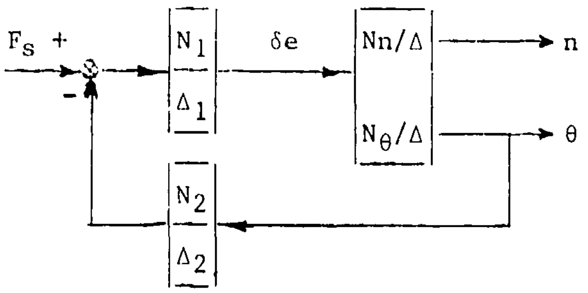
> The actual short-period roots can be misleading indicators of flying qualities.
>
> With $1/T\theta_2$ fixed at $-Z_w$, large T_E would indicate poor flying qualities.
>
> With free $1/T\theta_2$, small $\omega^2_E/(n/\alpha)_E$ would indicate poor flying qualities.
>
> Simultaneously matching $\dot{\theta}/F_s$ and n/F_s reduced the T_E and $(n/\alpha)_E$ excursions somewhat.

Now, T_E is to represent the numerator time constant T_θ in the short-period response to pitch commands, according to the classical frequency response sketched. To determine airplane characteristics pertinent to attitude control, then, T_E should be freed so that the best fit to the prescribed θ/F_s transfer function may be found. But in the short term, normal acceleration is related to pitch attitude by the ratio of the two transfer functions. Using the short-period approximation,



$$\frac{n}{\theta} = \frac{(V/g)\,s}{s/(-Z_w) + 1}$$

(As noted earlier, strictly this n is near the instantaneous center of rotation, so that the n/δ zeros are very large). For control and stabilization with a single control surface, feedback cannot change the numerators of any of the transfer functions; while forward-loop and feedback zeros cascade the same additional dynamics on all the responses - for example:



$$\frac{n(s)}{F_s(s)} = \frac{N_1 N_n \Delta_2}{\Delta\Delta_1\Delta_2 + N_\theta N_1 N_2}$$

$$\frac{\theta(s)}{F_s(s)} = \frac{N_1 N_\theta \Delta_2}{\Delta\Delta_1\Delta_2 + N_\theta N_1 N_2}$$

$$\frac{n(s)}{\theta(s)} = \frac{N_n}{N_\theta}$$

Thus the time constant of the n/θ response ratio is independent of the flight control system:

$$1/T_\theta \approx -Z_w$$

Z_w is a fairly accurately known stability derivative of the controls - fixed aircraft. Also, recall that Bihrle's Control Anticipation Parameter (CAP, Ref. 3) is:

$$\mathrm{CAP} = \frac{\dot{q}_o}{n_\infty} = \frac{s^2 N_\theta\big|_{s\to\infty}}{N_n\big|_{s\to o}} \approx \frac{\omega_{SP}{}^2}{n/\alpha} \approx \frac{g}{V}\omega_{SP}^2\, T_\theta$$

The equivalence of CAP and $\omega_{SP}^2/(n/\alpha)$ holds fairly generally unless stability augmentation employs an additional control surface (e.g., wing flap. Since q_o/n_∞ is found from $n(s)/\theta(s)$, the T_θ in CAP should correspond to $-Z_w$, which is not necessarily $1/T_E$. For consonance between pitching and normal-acceleration response to control inputs, then, T_E should remain fixed at its known value instead of being freed to optimize the fit. (Fortunately, in a number of cases we have found that it makes no difference, the optimized T_E value is close to the basic - airframe value).

An alternative "CAP" uses initial cockpit normal acceleration instead of $\dot{q}_o$, since at the pilot location:

$$n_{p_o} = n_o + x_p\dot{q}_o$$

This interpretation seems to fit some large aircraft, but how then would one explain past successful combat aircraft with zero or negative x_p?

These dilemmas cannot always be resolved conclusively. If a good match can be obtained with fixed T_E, that would seem to be the thing to do.

From the frequency - response sketch of $|\theta/F_s|$ it is the frequency separation of ω_E and $1/T_E$ that determines the degree of departure from "ideal" K/s - like response at frequencies below ω_{SP}:

$$\log \omega_E - \log 1/T_E = \log (\omega_E T_E)$$

so that from consideration of the pitch response alone, the proper parameter would be $\omega_E T_E$. Nevertheless, Ref. 3 shows that the similar parameter $\omega_E^2\, T_E g/V$ correlates the available data; Ref. 34 shows further correlation.

Bandwidth and Phase Sensitivity

For Category C Flight Phases Ashkenas, Hoh and Craig (Ref. 14) propose Level1 and 3 requirements (Fig. 10) to assure adequate pitch attitude bandwidth and preclude excessive response sensitivity to pilot gain and compensation. To the phase angles and slopes of θ/F_s and θ/δ_s are added the contribution of an 0.3 - second (pilot's) time delay. Phase Φ is measured at a frequency of 1 rad/sec. Slope is taken as the average over a 1-octave spread ($\omega/\sqrt{2} \leq \omega \leq \sqrt{2}$). For a minimum-phase system (stable, with $1/T_\theta$, and $1/T_{\theta_2}$ positive) $\Delta\Phi/\Delta\omega$ is measured at the higher of the frequency for peak Φ or 1 rad/sec.

This requirement gets directly at "The basic inner attitude response features which are necessary regardless of outer-loop control problems or auxiliary (e.g., direct lift) control". It applies to "The complete airplane attitude response including both the phugoid and short-period modes, ...flight control system characteristics [and] the various controlled element forms resulting from current flight control augmentation concepts". However, we saw sufficient drawbacks not to use it. There is no Level 2 boundary, and the data points shown with pilot rating ≤ 6.5 were scattered on both sides of the "Level 3" boundary. In addition, recent experience (e.g., Ref. 48) indicates that a 1 rad/sec. bandwidth is often insufficient for the flare and touchdown phase of a precision landing. Also, there is a natural reluctance to have such different forms of requirement for terminal and up-and-away flight.

Ralph Smith's Criteria

Ralph Smith (Ref. 43) proposes a set of requirements for short-term longitudinal response based on a "no-tracking hypothesis": "Optimum handling qualities demands minimum closed-loop control by the pilot". His parameters include:

t_q	time to first peak of the q(t) response to a step input in stick force.
$\phi(j\omega_c)$	$\angle \dfrac{a_{z_p}}{F_s}(j\omega_c) - 14.3\omega_c$; a_{z_p} is normal acceleration at pilot station.
ω_c	criterion frequency, rad/sec. approximately the crossover frequency of the pilot - aircraft system dynamics for pitch attitude tracking; a function of aircraft dynamics and disturbance bandwidth (Fig. 11).

His proposed requirements are:

$0.2 \leq t_q \leq 0.9$ for Level 1

$S < -2$db/octave for Level 1

$\angle \dfrac{\theta}{F_s}(j\omega_c) \geq -123^\circ$ for Level 1, -165° for Level 2

$\phi \geq -160^\circ$ when $-122^\circ \geq \angle \dfrac{\theta}{F_s}(j\omega_c) \geq -130^\circ$, for Level 1

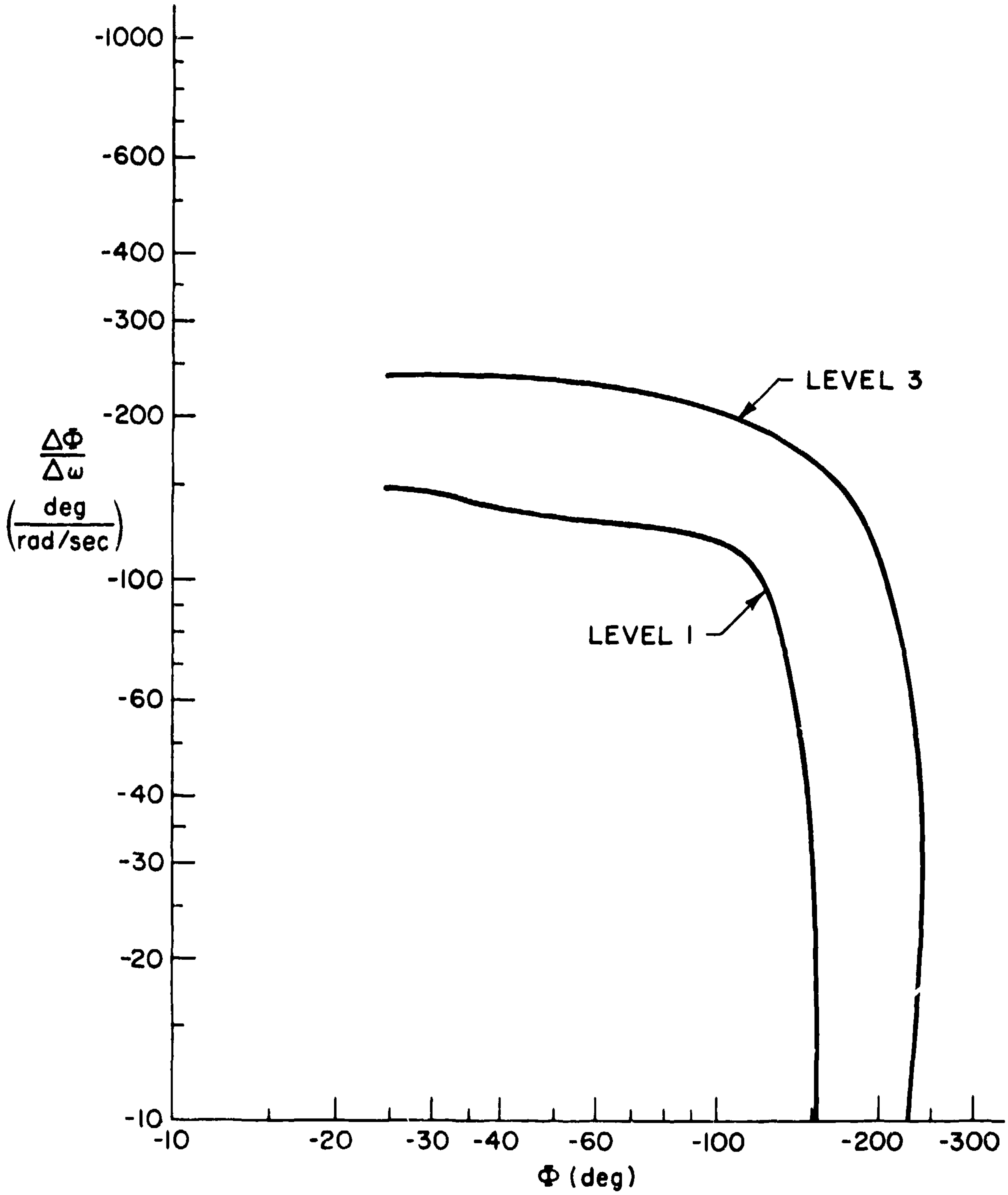


Figure 10. Longitudinal Attitude Control — Category C Requirements

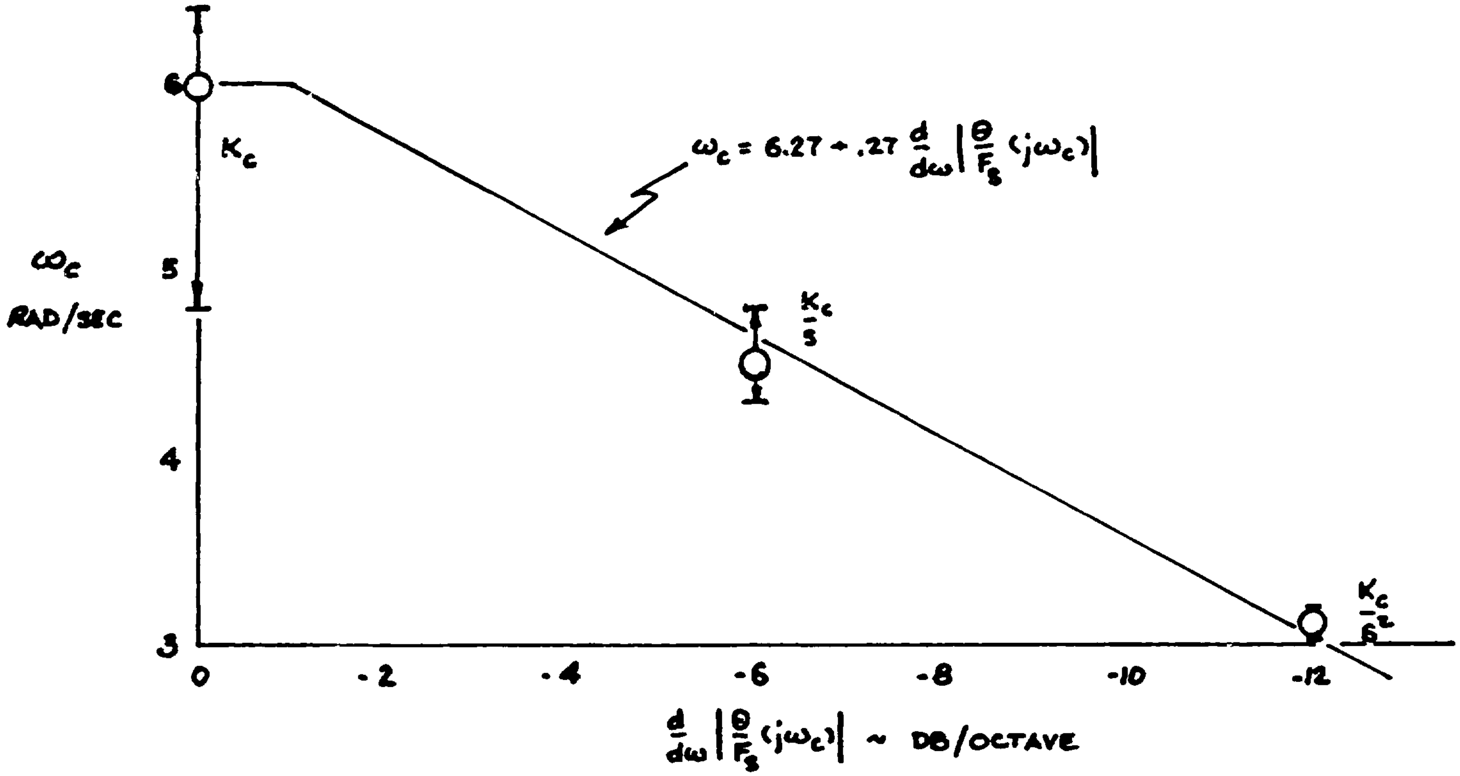


Figure 11. Specification of the Criterion Frequency

$$\phi \geq 220^{\circ} \text{ when } -148^{\circ} \geq \angle \frac{\theta}{F_s}(j\omega_c) \geq -165^{\circ}, \text{ for Level 2}$$

Level 3 floors exist, but data to establish them is lacking. This set of requirements was proposed tentatively, subject to further validation. Smith proposes similar requirements for direct-lift control modes and for tasks in which relative position is important, such as aerial refueling and formation flight. Time did not permit full consideration of Smith's suggestions for MIL-F-8785C.

Time-Domain Criteria

With the thought that pilots are relatively more interested in pitch rate at low speed but normal acceleration at high speed, Malcolm and Tobie (Ref. 49) proposed a criterion in terms of the parameter:

$$C^* = K\left(n_z + \frac{V_{co}}{g} q + 1_p \dot{q}\right)$$

where $n_z + 1_p \dot{q}$ is the normal load factor at the pilot station and V_{co}, often taken to be 400 ft/sec., is the airspeed at which the n_z and q signals are equal. Malcolm and Tobie derived C* time-history boundaries from Cornell Aero Lab "bullseyes" (see Ref. 3, p. 63). Later, Kisslinger and Wendl proposed modified C* boundaries (Ref. 50) derived from their ground-based simulator studies. Time-history bounds are an appealing form of criteria, useful to the flight control designer. However, several investigators (e.g., Neal and Smith [23], and Brulle in a McDonnell internal memo dated 31 December 1974) have found the C* criterion lacking in good correlation with pilot ratings of flying qualities.

While pilots do not characteristically make the step control inputs used in this and a number of other time-response criteria, a step does have a broad-band frequency content although amplitude varies with frequency. Malcolm and Tobie also devised a frequency response version of their C* criterion.

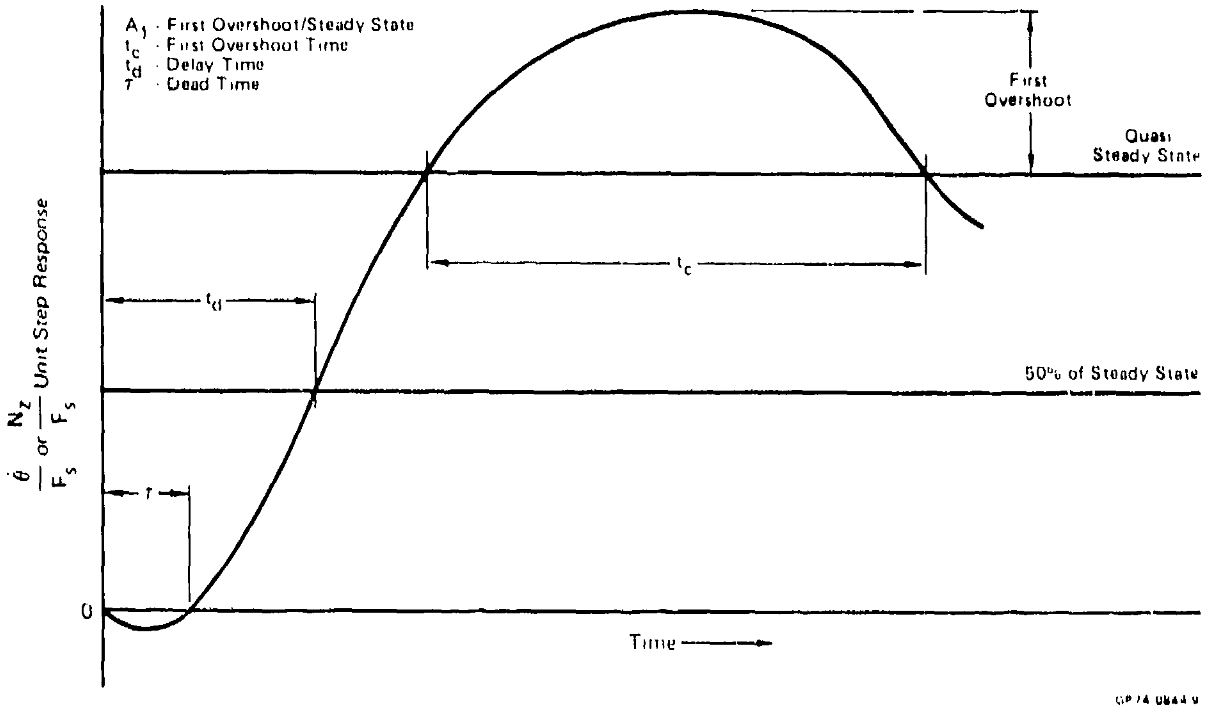
Time Response Parameter (TRP)

Abrams' TRP (Ref. 51) is based on dead time, τ; delay time, t_d; cyclic time, t_c; and ratio of overshoot to steady state, A_1, for the pitch-rate and normal-acceleration responses to a step stick force (Figure 12):

$$\text{TRP} = (\text{TRP})_{\dot{\theta}} + (\text{TRP})_{n_z} + 0.2\,(\tau_{n_z} - 0.2)$$

$$(\text{TRP})_{\dot{\theta}} = (t_d/t_c)_{\dot{\theta}} + 0.08\,(A_{1_{\theta}} - 1.0)$$

$$(\text{TRP})_{n_z} = 0.5\,(t_{d_{n_z}} - 0.7) + 0.3\,(A_{1_{n_z}} - 0.3)$$



TIME RESPONSE PARAMETER (TRP) DEFINITIONS

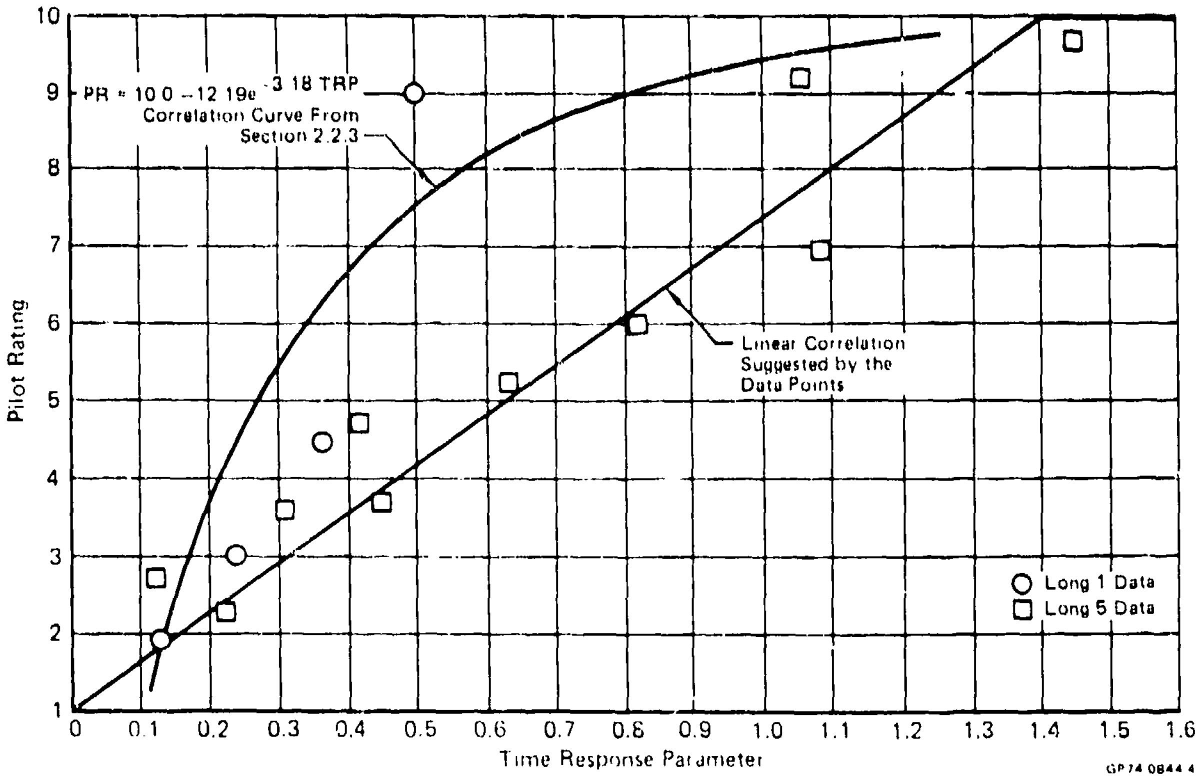


Figure 12. Cooper-Harper Pilot Rating Variation with Time Response Parameter

where the constants were determined empirically. The 0.2 (τ_{n_z} -0.2) term is used only when TRP is small, less than .23. All terms must be positive if any should be negative they are set to zero.

Brulle and Moran (Ref. 8) plot this criterion using the data of Ref. 52 to show good correlation with Cooper-Harper pilot rating:

$$PR = 10 - 12.19 \exp(-3.18\ TRP)$$

with ±1 rating encompassing almost all the data. Using fixed-based simulator evaluations, Brulle again gets excellent correlation of TRP with pilot rating. However, Figure 12 shows this trend to be rather different from that of the Di Franco data. Some moving-base simulator results were intermediate, as were some cases which had deadbeat response with and without direct lift. For these Abrams has suggested a modified TRP with an additional term,

$$TRP_{DB} = 1.4\tau_{n_z} + .16$$

Thus TRP appears to be a useful indicator of flying quality trends, though it does not yet seem definitive enough to use as a requirement.

Chalk's Pitch Rate Response Criteria

In Reference 53, Chalk proposed requirements on pitch rate response as shown in Figure 13. Maximum values for effective time delay, t_1, were also specified but since they are similar to the requirements in 3.5.3 of MIL-F-8785C they are not discussed here. For a classical second-order system the parameters used, transient peak ratio and rise time parameter, are directly related to the parameters used in MIL-F-8785C, viz damping ratio and Control Anticipation Parameter. Once formulated as shown, however, the requirements are independent of system order and apply directly to the actual response - thus avoiding problems of interpretation. The actual numbers themselves are also revised from the corresponding ones in MIL-F-8785B.

CLOSED-LOOP AND PSEUDO CLOSED-LOOP CRITERIA

Neal-Smith Criteria

A criterion for good closed-loop pitch tracking was proposed by Neal and Smith in Reference 23. The gain and phase characteristics of the open-loop transfer function of pitch attitude to pitch attitude error, including a specified pilot model is overlaid on a Nichols chart. The pilot model has a 0.3 second time delay, plus lead/lag compensation as illustrated in Fig. 14. Pilot gain and equalization are adjusted as necessary to meet the closed-loop bandwidth and droop standards shown in Figure 15. Figures 16-20 illustrate use of the Nichols chart. The resulting closed-loop resonance and pilot compensation are then compared to the boundaries indicated in Figure 21, which also contains flying qualities interpretations of the various regions of the figure. Bandwidths were found which resulted in quite good correlation of these boundaries with pilot comments. Examples of further validation of the Neal-Smith criteria are contained in Reference 54 for the B-1 bomber and Reference 55 for an F-4C with a highly augmented

Transient Peak Ratio

The transient peak ratio $\Delta q_2/\Delta q_1$ shall be equal to or less than the following:

Level	$\Delta q_2/\Delta q_1$
1	.30
2	.60
3	.85

Rise Time Parameter

The parameter $\Delta t = t_2 - t_1$ shall have a value between the following limits:

	Nonterminal Flight Phases			Terminal Flight Phases	
Level	Min Δt Max		Level	Min Δt Max	
1	$\underset{(9)}{}\frac{2.74}{V_T} \leq \Delta t \leq \frac{152.4}{V_T}$ (500)		1	(9) $\frac{2.74}{V_T} \leq \Delta t \leq \frac{61}{V_T}$ (200)	
2	(3.2) $\frac{.975}{V_T} \leq t \leq \frac{487.7}{V_T}$ (1600)		2	(3.2) $\frac{.975}{V_T} \leq \Delta t \leq \frac{196.6}{V_T}$ (645)	

where: $V_T \sim ms^{-1}$ true airspeed.
Constant in parenthesis is used for $V_T \sim ft/sec$.

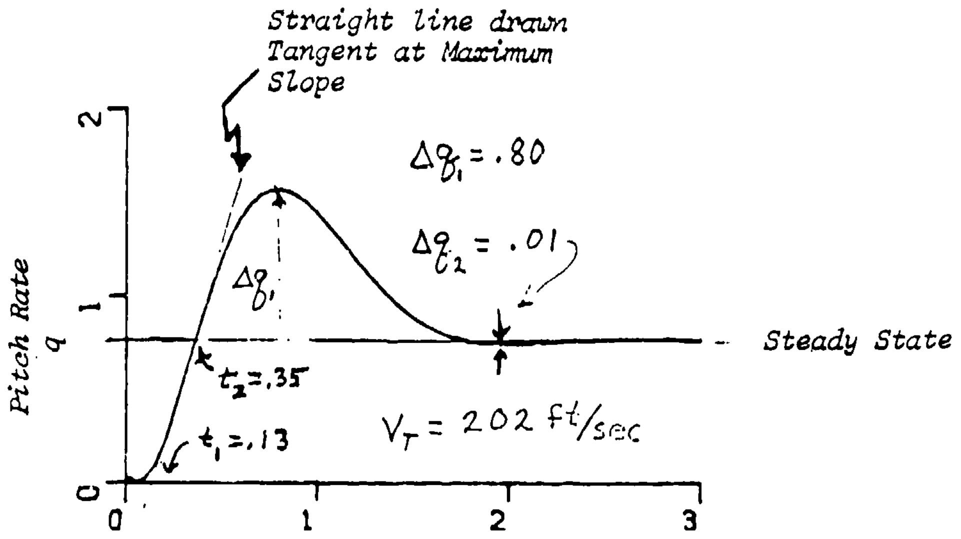


Figure 13. Requirements for Pitch Rate Response to Step Input of Pitch Controller Force

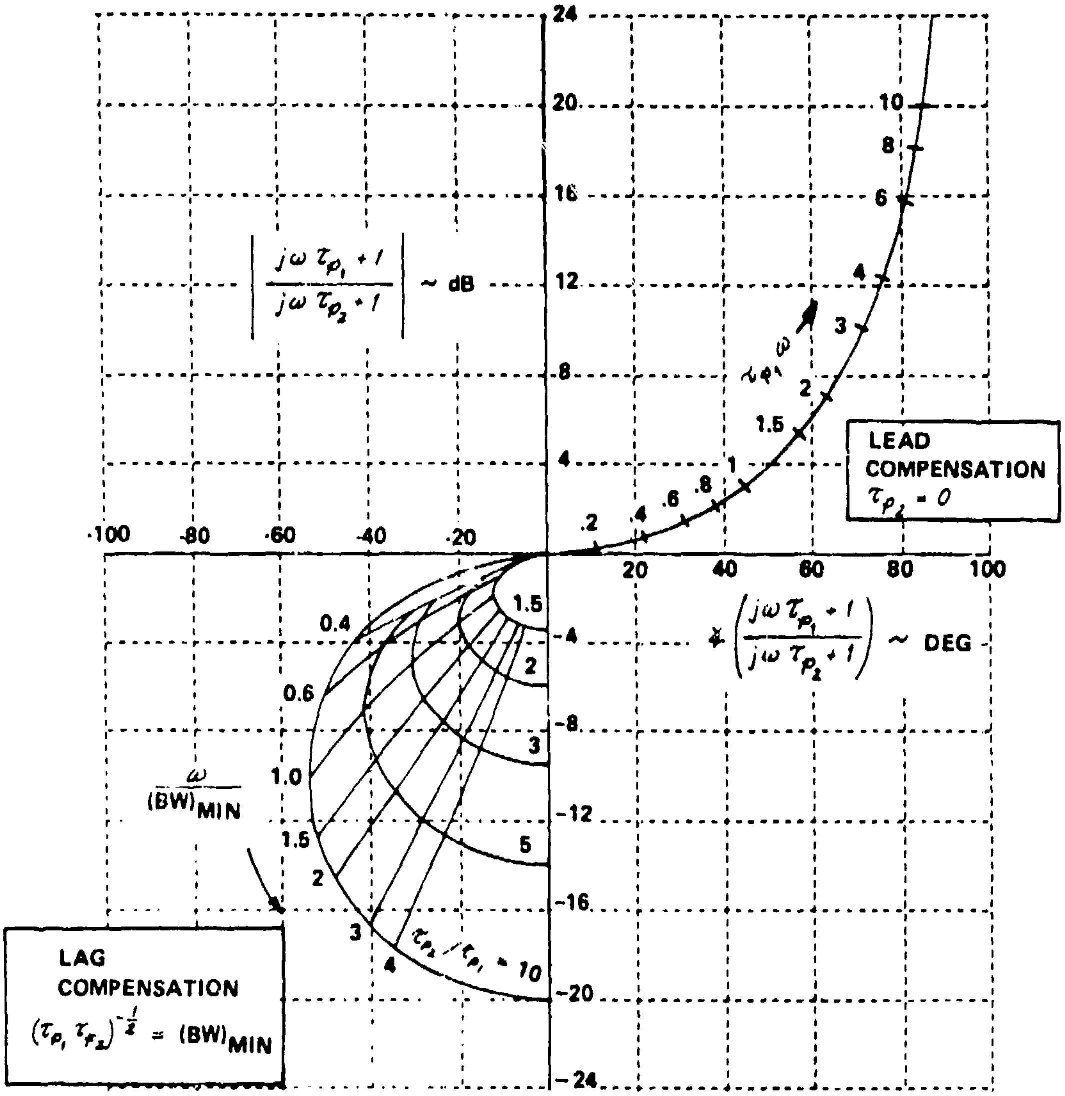


Figure 14. Amplitude-Phase Curves for "Optimum" Pilot Compensation

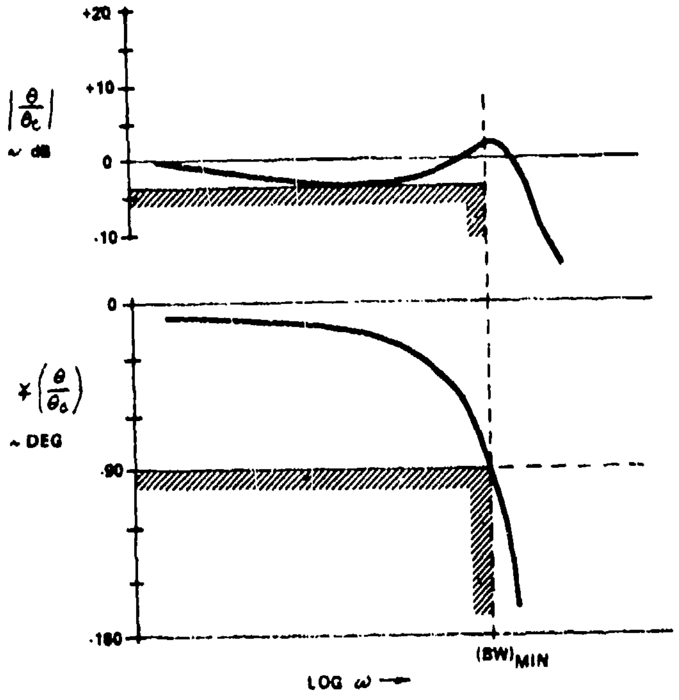


Figure 15. Tracking Performance Standards Used in the Analysis.

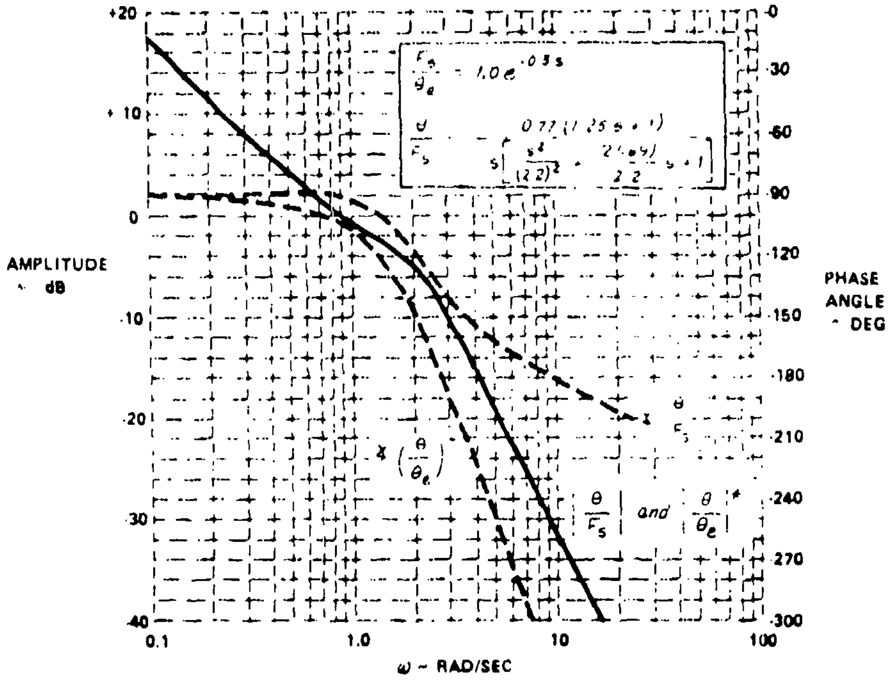


Figure 16. Open-Loop Bode Characteristics for a Configuration Having Low ω_{sp}

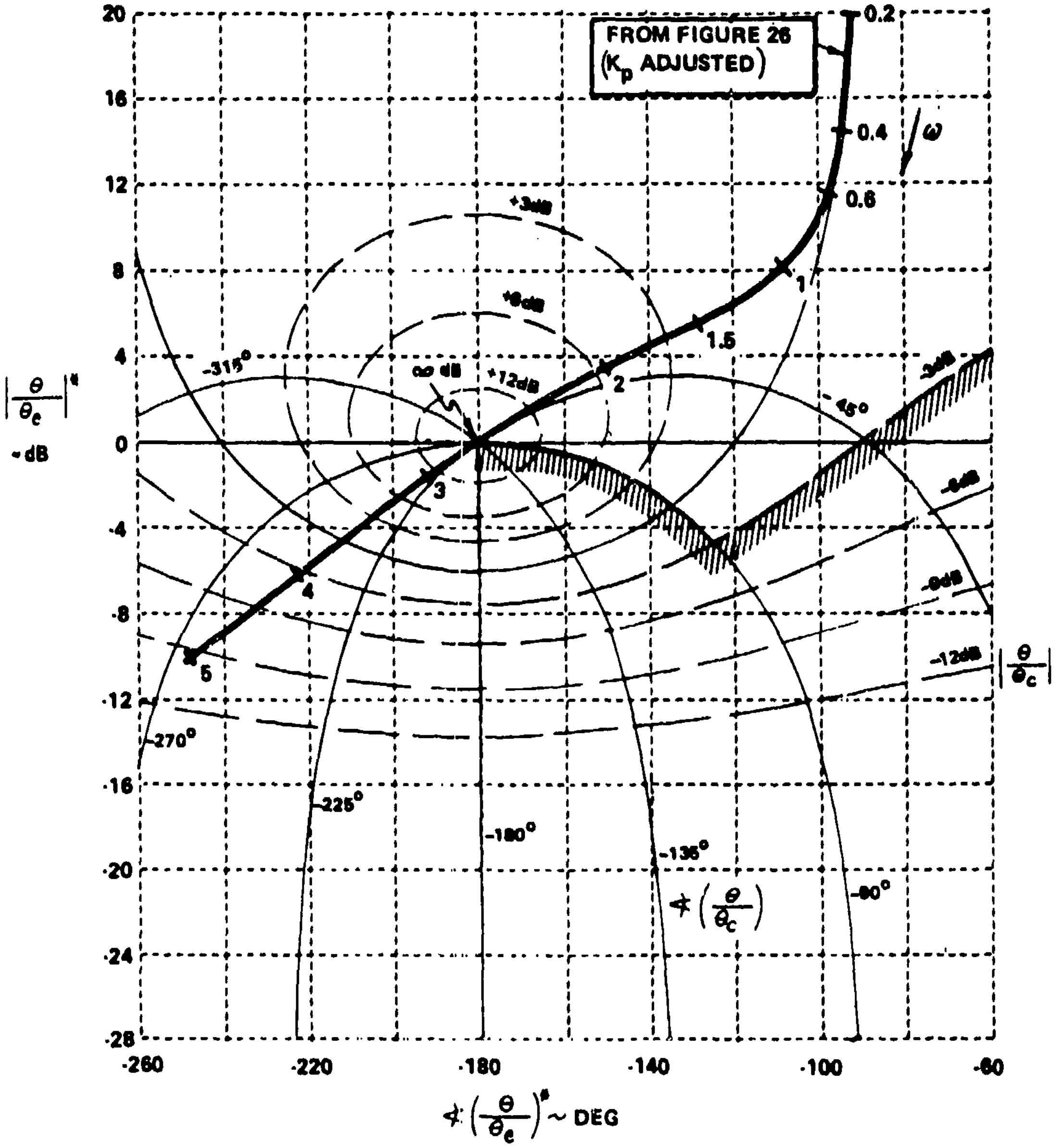


Figure 17. Overlay of $|\theta/\theta_e|^*$ Versus $\measuredangle(\theta/\theta_e)^*$ on a Nichols Chart (Configuration with Low ω_{sp})

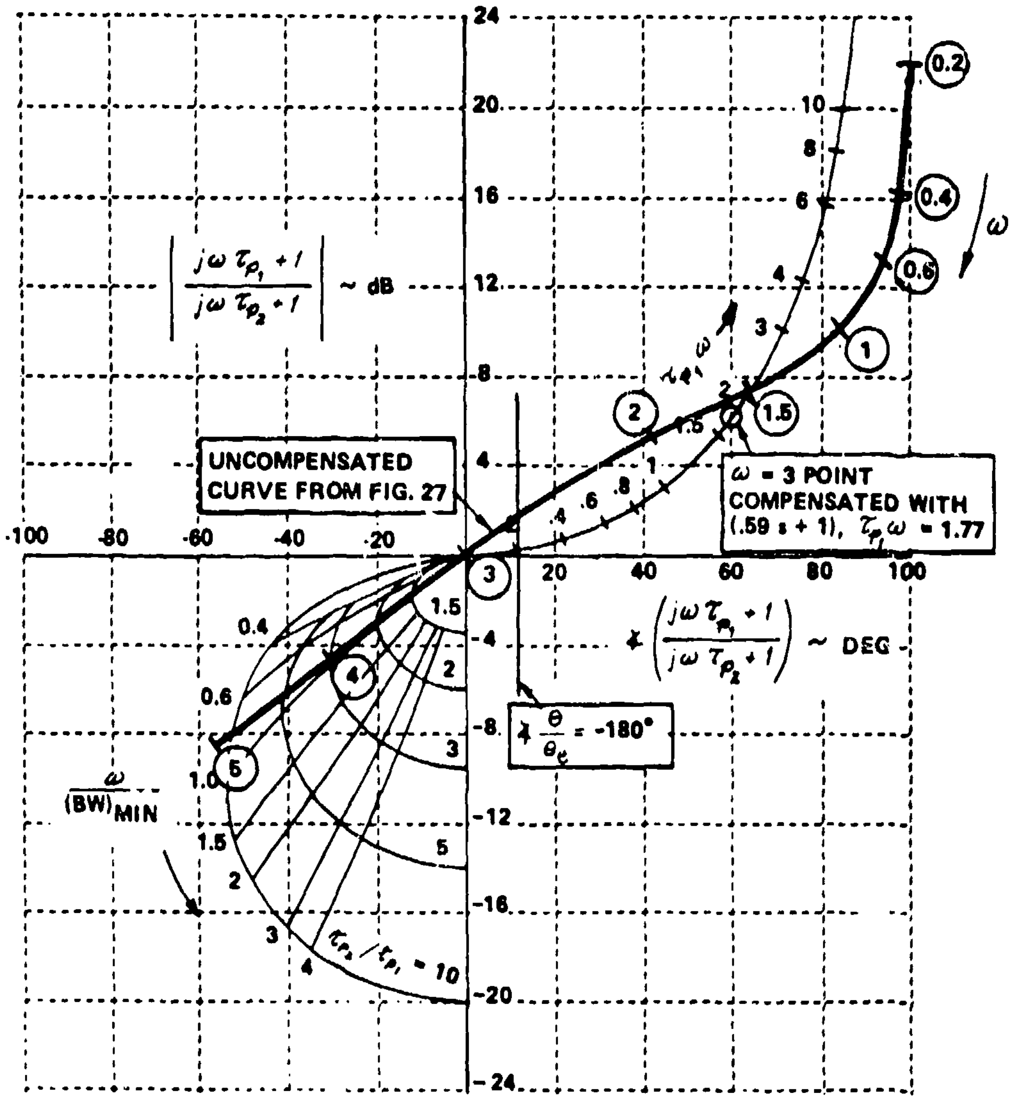


Figure 18. Effects of Pilot Lead Compensation on the Uncompensated Amplitude-Phase Curve (Configuration with Low ω_{SP})

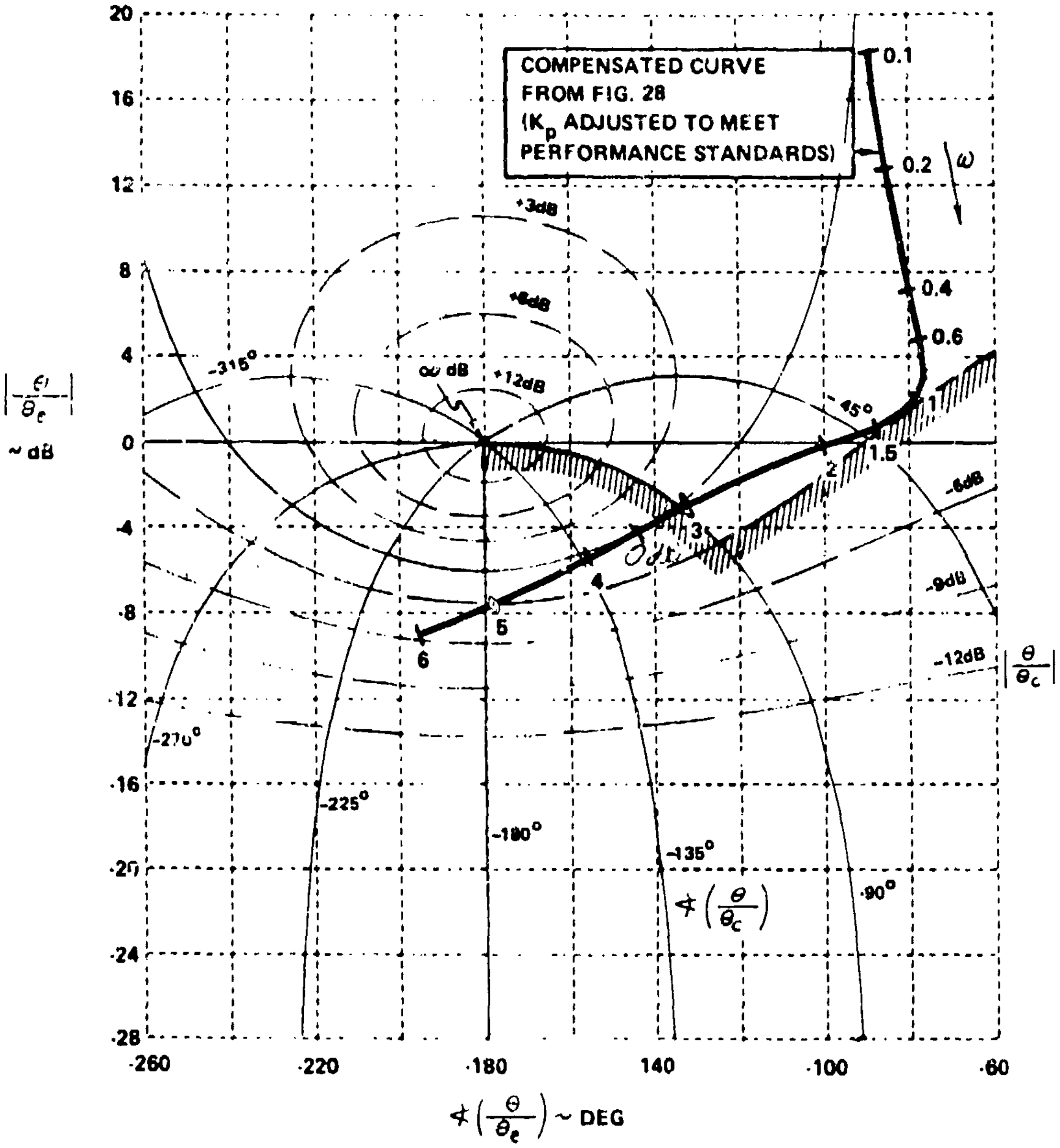


Figure 19. Lead-Compensated Amplitude-Phase Curve Overlayed on a Nichols Chart (Configuration with Low ω_{sp})

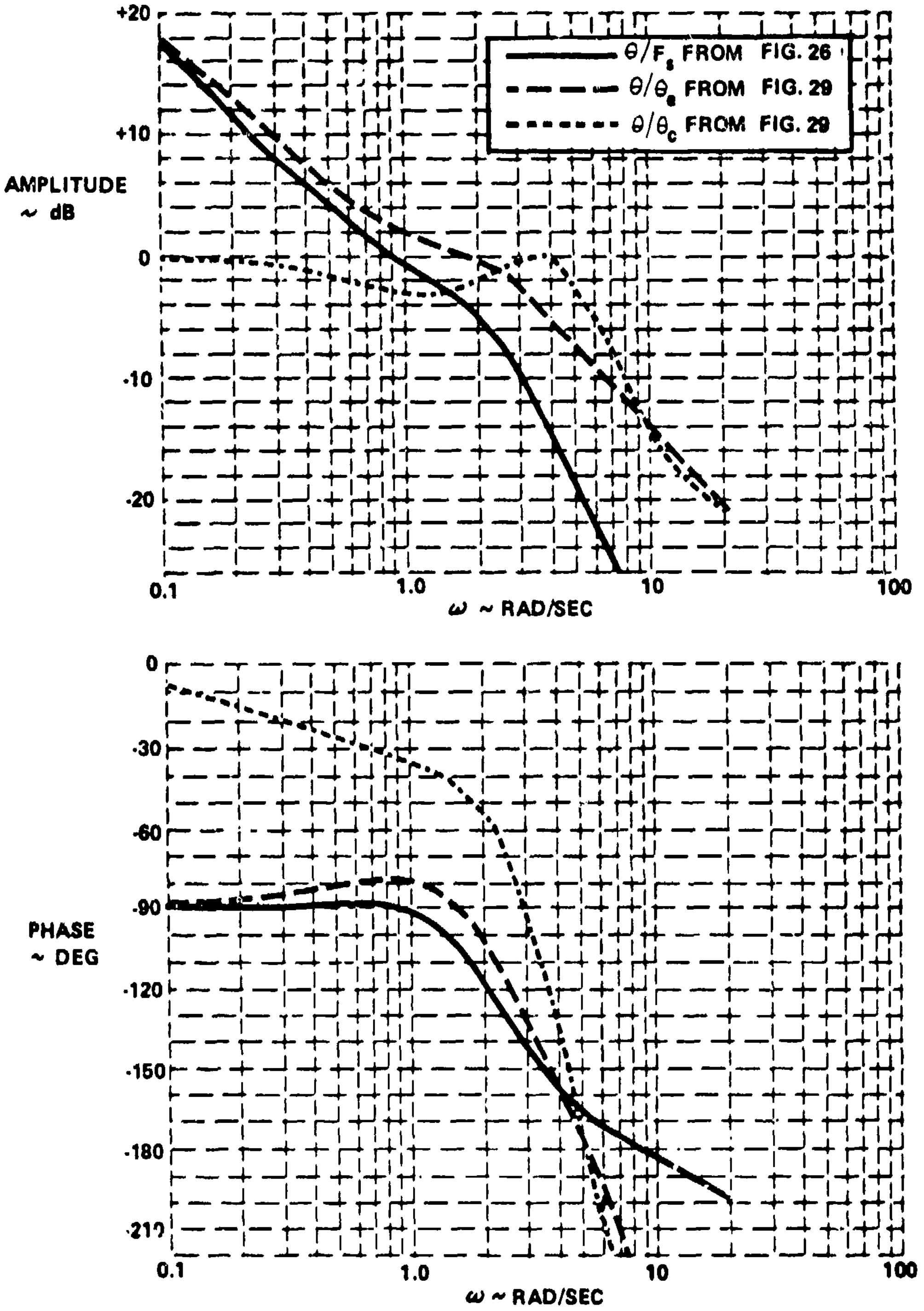


Figure 20. Open-Loop and Closed-Loop Bode Plots for Configuration with Low ω_{sp}

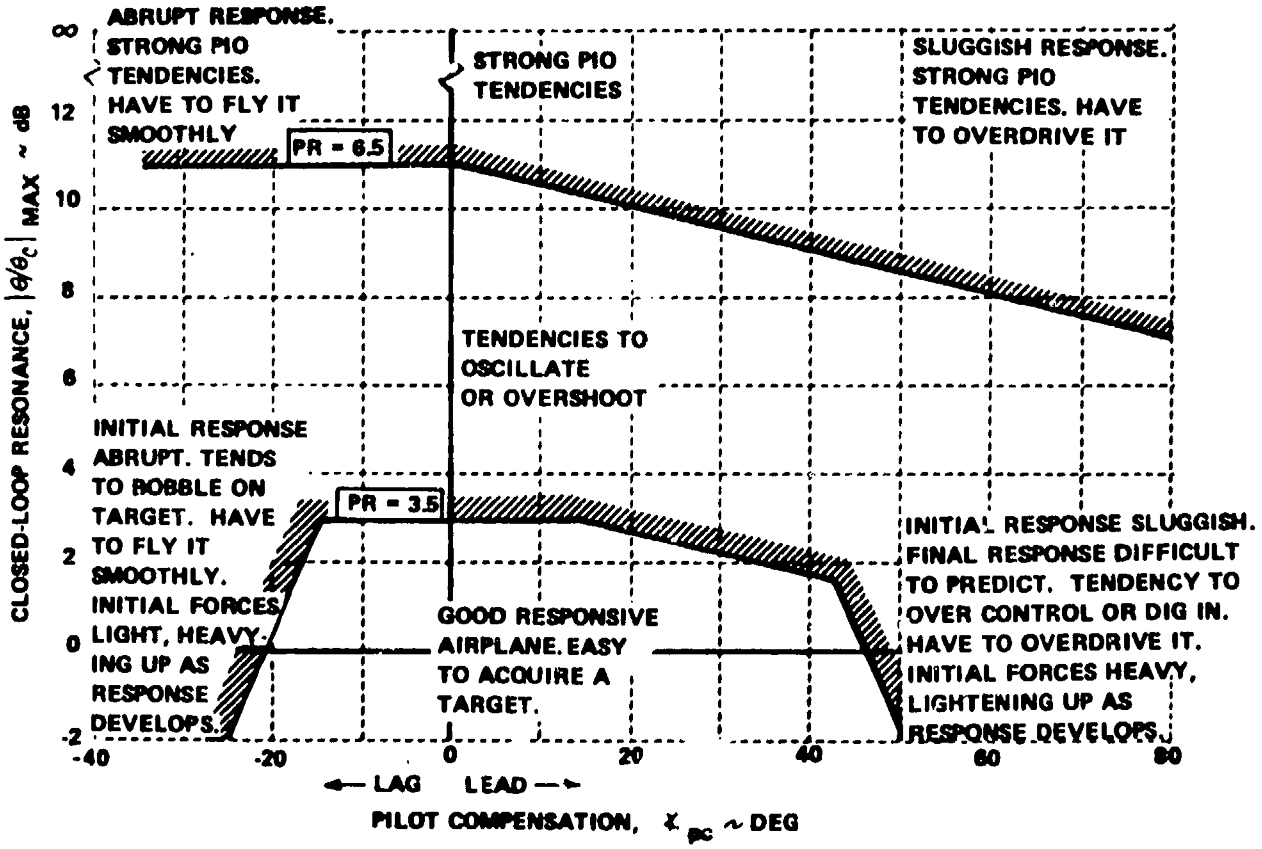


Figure 21. Proposed Criterion for Fighter Maneuvering Dynamics

command augmentation system. Radford and Rogers Smith (Reference 56a) compared the Neal-Smith and other criteria with the data of Reference 43 (LAHOS data). In making the comparison they also modified the orginal rules to achieve a better correlation. Specifically, they (a) note that landing is a high-bandwidth task, (b) proposed not forcing 3 db of droop but using that value as a limit on droop, (c) found that a reduced pilot time delay was necessary, and (d) suggest the need for an additional "adaptability" parameter relating variations in required pilot lead, peak amplitude ratio and bandwidth. Hodgkinson, on the other hand, used the LAHOS data to compare application of the Neal-Smith criterion with the equivalent system approach (Reference 56b), concluding that the Neal-Smith approach offered no better correlation. We felt that we would need a better definition of the required bandwidth for each task before this criterion could be used in the general format of MIL-F-8785C. It can certainly be a help in the design process.

Reference 23 also discussed a way to simplify or approximate the criterion, which was developed into a proposed revision in Reference 14. This proposed requirement is a function of only open-loop characteristics of the pitch response, as shown in Figure 22, from Ref. 13.

Step Target Tracking

In Reference 57, Onstott proposes a two-stage model of tracking a step change in aim error during target tracking. Both models incorporate a 0.3-second time delay and adjustable lead, and the second model also has an integral term. The model parameters and the switching time are selected to maximize the time on target (with a pipper diameter of 5 milliradians). Onstott used the Neal-Smith data to divide the rms error vs time-on-target plane into regions of flying quality Levels, (Figure 23). His finding that both quickness of acquisition (small rms pitch error) and time on target determine flying qualities acceptability is obviously correct in general. This is another approach that we feel would be an aid in the design process but is not defined sufficiently to be used at the basis for a specification.

Reference 56a also compared this approach with the LAHOS data. They found reasonable correlation overall, with some anomalies.

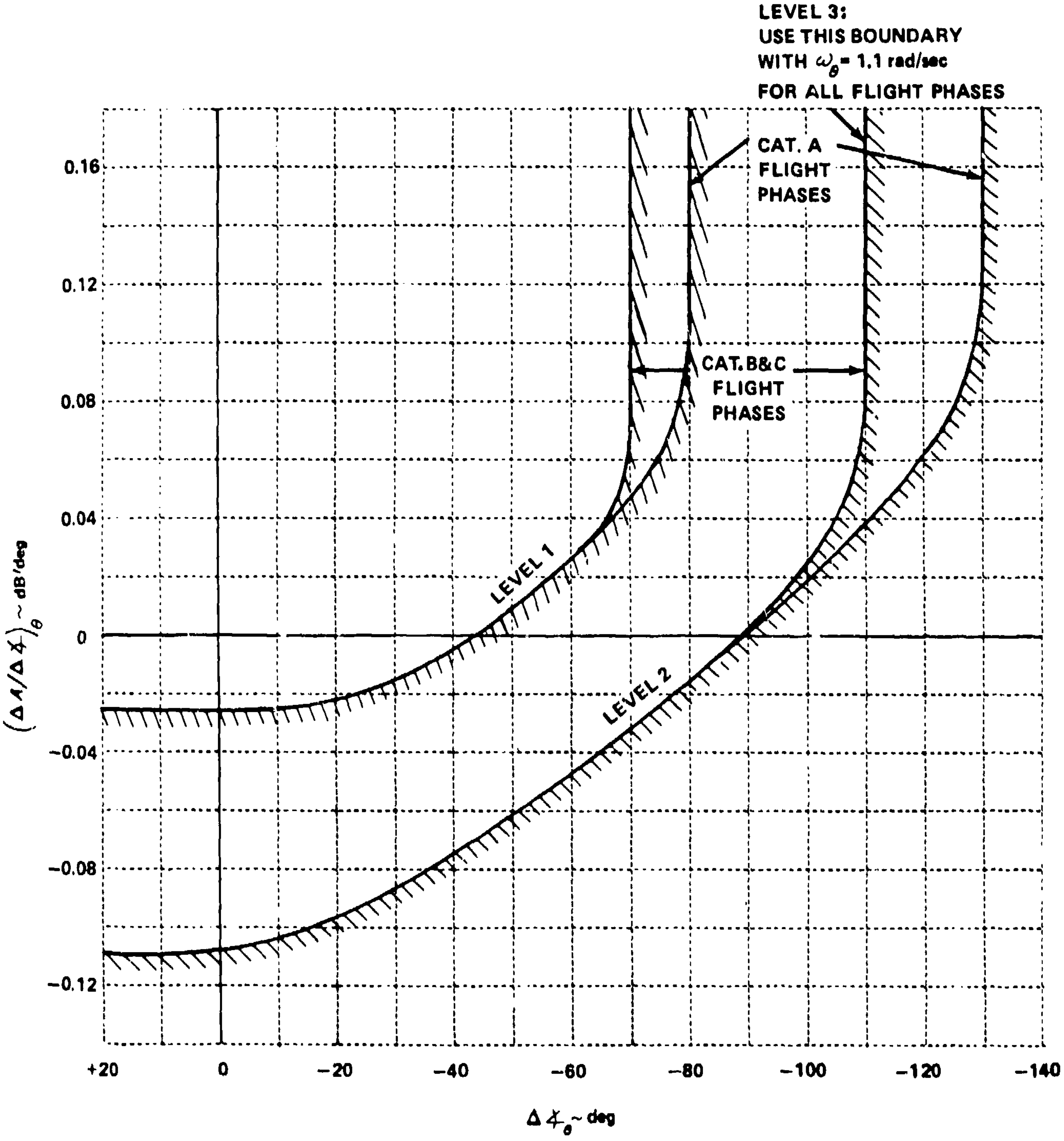


FIGURE 22. **PITCH MANEUVER RESPONSE REQUIREMENTS**

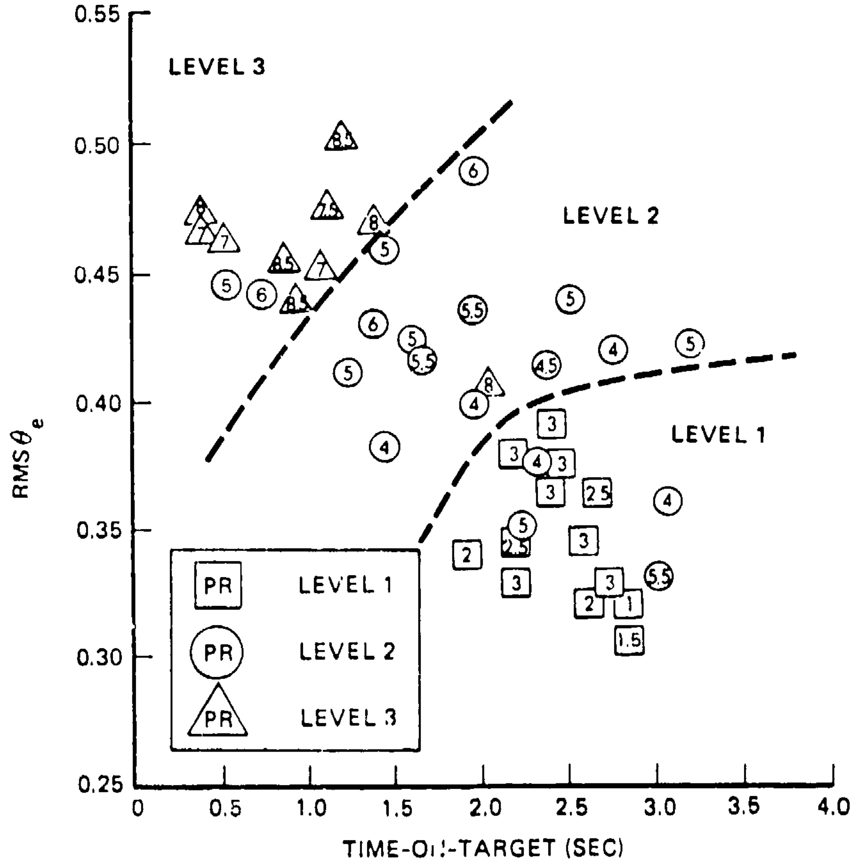


Figure 23. Pilot Ratings as Functions of rms θ_e and Time-On-Target

Paper Pilot and Similar Optimal Pilot Models

"Paper Pilot" is now an adult. Anderson proposed this closed-loop flying qualities prediction technique in 1969 (Ref. 58) as a unified way to specify hover dynamics for both rate and attitude control systems. Paper Pilot adjusts parameters of a pilot model,

$$Y_{p\theta} = -K_p(T_{L_\theta} s + 1)(s - 2/\tau)/(s + 2/\tau)$$

$$Y_{px} = K_{px}(T_{L_x} + 1)$$

to minimize a rating function,

$$R = R_1 + R_2 + R_3 + 1.0$$

$$R_1 = \frac{\sigma_x + 10\sigma_\theta - \sigma_m}{\sigma_m} \qquad 0 \leq R_1 \leq 2.5$$

σ_m required performance, determined empirically to be 0.8ft

$R_2 = 2.5T_{L\theta} \leq 3.25$ sec.

$R_3 = T_{L_x} \leq 1.20$ sec.

T_q in radians/second

for compensating in the presence of atmospheric turbulence. Several theses extended the model to other piloting tasks. Dillow and Picha (Ref. 59) used a pilot model with a "smarty-pants Kalman filter" in single - and dual-axis tracking tasks with thresholds. They were able to find weighting functions which gave good to excellent correlation between analysis and experiment in hover, pitch tracking and roll tracking. Using these cost functions they obtained good correlation of trends, if not ratings and performance, with other experimental data. Dillow and Picha's pilot model uses perceived control variables and their rates. Rms control rate (adjusted to correspond to a 0.1 sec. neuromuscular lag) is a measure of pilot workload, although incomplete understanding of the parameter is professed.

More recent closed-loop analyses utilizing optimal pilot models include the work of Hess (Ref. 60) and Levison (Ref. 56c). Although various investigators have claimed success particularly with single-axis tracking, much of the flying qualities community remains reluctant to use closed-loop parameters directly in a specification (Ref. 29d). For the present, pilot-vehicle analysis has achieved wider acceptance as a design tool, e.g., Ref. 61, than as a form of design requirement.

Summary

As the preceding discussion should indicate, many different criteria have been proposed for the short-term pitch control task. Studies which have compared various criteria, such as Ref. 8, have typically been unable to find one that is better than the rest. We have chosen the equivalent systems approach for MIL-F-8785C for reasons already discussed, not the least of which is continuity with MIL-F-8785B. This does not imply rejection of other approaches. For the future MIL-Standard and Handbook we plan to include alternative criteria with guidance on the similarities rather than the differences.

F. 3.2.2.1.3 RESIDUAL OSCILLATIONS

REQUIREMENTS

3.2.2.1.3 Residual oscillations. Any sustained residual oscillations in calm air shall not interfere with the pilot's ability to perform the tasks required in service use of the airplane. For Levels 1 and 2, oscillations in normal acceleration at the pilot's station greater than ±0.05g will be considered excessive for any Flight Phase, as will pitch altitude oscillations greater than ±3 mils for Category A Flight Phases requiring precise control of altitude. These requirements shall apply with the pitch control fixed and with it free.

DISCUSSION

This paragraph is directly from MIL-F-8785B. The phrase "in calm air" was inserted in order to distinguish the requirement from response to atmospheric disturbances (formal consideration of the effects of atmospheric disturbances is contained in the new section 3.8).

F. 3.2.2.2 CONTROL FEEL AND STABILITY IN MANEUVERING FLIGHT AT CONSTANT SPEED

REQUIREMENT

3.2.2.2 Control feel and stability in maneuvering flight at constant speed. In steady turning flight and in pullups at constant speed, there shall be no tendency for the airplane pitch attitude or angle of attack to diverge aperiodically with controls fixed or with controls free. For the above conditions, the incremental control force and control deflection required to maintain a change in normal load factor and pitch rate shall be in the same sense (aft - more positive, forward - more negative) as those required to initiate the change. These requirements apply for all local gradients throughout the range of service load factors defined in 3.1.8.4.

3.2.2.2.1 Control forces in maneuvering flight. At constant speed in steady turning flight, pullups and pushovers, the variation in pitch controller force with steady-state normal acceleration shall have no objectionable nonlinearities within the following load factor ranges:

CLASS	MIN	MAX
I, II & III	0.5	$.5 [n_o(+) + 1]$ or 3 whichever is less
IV	0	

Outside this range, a departure from linearity resulting in a local gradient which differs from the average gradient for the maneuver by more than 50 percent is considered excessive, except that larger increases in force gradient are permissible at load factors greater than $0.85n_L$. All local force gradients shall be within the limits of table V. In addition, F_s/n_z should be near the Level 1 upper boundaries of table V for combinations of high frequency and low damping. The term gradient does not include that portion of the force versus n_z curve within the breadout force.

Since the range of acceptable force gradients for side stick controllers varies with the control deflection gradient and the task to be performed, the contractor shall show that the control force gradients will produce suitable flying qualities.

3.2.2.2.2 Control motions in maneuvering flight. For all types of pitch controllers, the control motions in maneuvering flight shall not be so large or so small as to be objectionable. For Category A Flight Phases, the average gradient of pitch-control force per unit of pitch-control deflection at constant speeds shall not be less than 5 pounds per inch for wheel and center stick constollers or 2 pounds per degree for sidestick controllers for Levels 1 and 2.

DISCUSSION

In line with other revisions, the requirements from MIL-F-8785B have been rewritten in terms of airplane response and pilot controller inputs

TABLE V. Pitch maneuvering force gradient limits.

Center Stick Controllers

Level	Maximum Gradient, $(F_s/n)_{max}$, pounds per g	Minimum Gradient $(F_s/n)_{min}$, pounds per g
1	$\frac{240}{n/\alpha}$ but not more than 28.0 nor less than $\frac{56}{n_L-1}$ *	The higher of $\frac{21}{n_L-1}$ and 3.0
2	$\frac{360}{n/\alpha}$ but not more than 42.5 nor less than $\frac{85}{n_L-1}$	The higher of $\frac{18}{n_L-1}$ and 3.0
3	56.0	The higher of $\frac{12}{n_L-1}$ and 2.0

*For $n_L<3$, $(F_s/n)_{max}$ is 28.0 for Level 1, 42.5 for Level 2.

Wheel Controllers

Level	Maximum Gradient, $(F_s/n)_{max}$, pounds per g	Minimum Gradient, $(F_s/n)_{min}$, pounds per g
1	$\frac{500}{n/\alpha}$ but not more than 120.0 nor less than $\frac{120}{n_L-1}$	The higher of $\frac{35}{n_L-1}$ and 5.0
2	$\frac{775}{n/\alpha}$ but not more than 182.0 nor less than $\frac{182}{n_L-1}$	The higher of $\frac{30}{n_L-1}$ and 6.0
3	240.0	5.0

to achieve the basic result desired. There is now no requirement on the variations of control surface deflection so artificial stability would meet this requirement.

In revising the steady-state control force requirements the following additional changes were made:

a. allowance for gradient changes in moderate maneuvers outside the fine tracking range

b. defined the range over which the gradients are required to be linear

c. low-damping correction to force gradient ranges was inserted

d. some notes were added to cover sidestick controllers

e. some refinements were made to the limits of Table V

f. simplified the definition of stable gradients

g. mention of pitch rate as well as normal acceleration; additional control modes become possible if direct force control is employed

Recent experience in aircraft design has shown that it can be desirable to have multiple stick gains (Ref. 35). These gain changes can be transparent to the pilot if not located within the range of fine tracking force inputs. In general 1g is sufficient clearance for level maneuvering. For high-g tracking, the pilots do not usually trim to within 1g of their task. This leaves a preload on their stick, resulting in better control. If the gradient were linear from 1g trim, the total force would be too high and the gradient would be too heavy (F_s/n_z too high) for good tracking, or too light for trimmed flight. Problems of overstressing the aircraft due to a light gradient can be handled with another gradient change, usually abrupt and quite heavy to indicate a near stall/n_L condition, i.e., a "soft stop" on the stick.

Longitudinal flying qualities depend in a correlated way on several key parameters. Primary among them are stick gain (F_s/n_z), short-period frequency ($\omega_{n_{sp}}$), short-period damping (ζ_{sp}), and the θ to n_z coupling response term (T_{θ_2}). MIL-F-8785C currently attempts to handle these in a minimum coupled way. As a result, an unfortunate choice of parameters, all within the Level 1 boundaries, may not produce a Level 1 rating. Destabilizing combinations such as high $\omega_{n_{sp}}$, low ζ_{sp}, and high gain (low F_s/n_z) should be avoided to prevent PIO tendencies. With these considerations, low damping was added as a potential cause of making higher force gradients desirable.

In Reference 62, it is concluded that insufficient data currently exists to substantiate adequate specifications on sidestick controller characteristics although it is possible to derive design guidance. An earlier study (Reference 63) found that pilots can tolerate a wider range of values of F_s/n_z with a small amount of stick motion. The trends also indicate a better optimum, i.e., a lower pilot rating, is possible with a small amount of deflection. The problem now is to find out if there is an optimum value, or range of values, of deflection. Graves et al

(Reference 64) report the results of a study in which pilots preferred the no-motion stick in a fixed-base simulation, but then universally chose a motion stick in flight tests. The possibility remains, however, that filtering or nonlinear gains may be an adequate substitute for motion in some applications. A major factor in the difficulty of side stick controller specifications is the lack of standardization in construction and design formats (i.e., pivot locations, rotation axes, slide motion inputs and force versus torque activation). Until such formats are settled and/or specified in documents such as MIL-F-9490, only cautions can be included in the flying qualities specification. Experience with a YF-16 proposed slidemotion stick indicates that such motion is not desirable for side sticks (Ref. 35). Some data on sidestick conttollers is available (a section is contained in References 35 and 62 through 72). Reference 62 summarizes available data, and also presents results from an additional data gathering program using inflight simulation conducted by the AF Test Pilot School, sponsored by AFFDL. The addi tion of the 2-lb/deg requirements to the specification was based on results from Reference 63, but Reference 62 would give 1 lb/deg. More specific criteria for sidestick controllers will be formulated as soon as feasible.

References 46 and 47 indicate a consensus that the minimum force gradient for both stick and wheel controllers are too high, especially Level 2 and 3 limits. Data from reference 4 shows that a local gradient of $F_s/n_z=0$ was rated Level 3. Other sources recommend that for high load factor conditions 2 lb/g minimum gradient is desirable with a center stick. Caution should be exercised when considering the zero force gradient; such gradients were obtained with a nondegraded F-4 at aft CG in a condition of high α and n_z. Most important is that the aircraft was trimmed for 1g, leaving a positive, hence recovering force on the stick if released and the initial load factor change response was still in the correct direction. Thus, the pilot comments reflected Level 3 ratings, but the environment was not hostile. The recommendation in Reference 4 was only to lower the Level 1 and 3 minimum local gradients to 2 lb/g. Wheel controlled aircraft are normally flown one-handed (References 6 and 7); thus high minimum gradients cause undue fatigue. As with the centerstick case, no data can be found to establish a limit directly. Upon reflection, considering possible onehanded operation and the nature of Level 3, 5 lb/g seems reasonable. Material in Reference 33, on the other hand, tends to support the present Level 1 and 2 requirements. B-1 (stick) and YC-14/YC-15 (wheel) experience shows that lower minimum force gradients are acceptable in those aircraft.

The "average gradient" is the steady control force less breakout force divided by (n-1), in steady turns, pullups and pushovers from trimmed straight and level flight.

We have not relaxed the maneuvering stability requirement to allow a divergence for Level 3, as we did for static stability in 3.2.1.1. Maneuvering instability thus will be tolerated only as an approved Special Failure State. We will continue to review this conservative approach.

G. 3.2.2.3 LONGITUDINAL PILOT-INDUCED OSCILLATIONS

REQUIREMENT

3.2.2.3 Longitudinal pilot-induced oscillations. There shall be no tendency for pilot-induced oscillations, that is, sustained or uncontrollable oscillations resulting from the efforts of the pilot to control the airplane. The pitch attitude response dynamics of the airframe plus control system shall not change abruptly with the motion amplitudes of pitch, pitch rate or normal acceleration unless it can be shown that this will not result in a pilot-induced oscillation. The requirements in 3.2.2.3.1 through 3.2.2.3.2 shall be met for all expected airplane motion amplitudes and frequencies, starting at any service load factor.

DISCUSSION

The qualititative requirement of MIL-F-8785B is retained in view of uncertainties in the state of the art of flight control system design. This paragraph is a tacit recognition of the complexity of the PIO problem and an admission that no detailed specification is, at this time, a guarantee against building a PIO-prone airframe/flight control system combination. The requirement has been expanded to preclude PIO, PIO tendencies or general handling qualities deficiencies resulting from amplitude-dependent changes in airplane dynamic response to pilot control inputs. These effects can be of mechanical origin, e.g., bobweight coupled with static friction, or due to saturation of elements within the automatic control system. PIO has occurred in the T-38A, A-4D and YF-12 due to such abrupt changes.

The revision stresses inclusion of large-amplitude motions and starting from maneuvering flight. There is, of course, no intent to subject an airplane to loads beyond structural limits.

H. 3.2.2.3.1 DYNAMIC CONTROL FORCES IN MANEUVERING FLIGHT

REQUIREMENT

3.2.2.3.1 *Dynamic control forces in maneuvering flight*. The frequency response of normal acceleration at the pilot to pitch control force shall be such that the inverse amplitude is greater than the following for all frequencies greater than 1.0 rad/sec. Units are pounds per g.

	Level 1	Level 2	Level 3
One-handed Controllers	$\frac{14}{n_L-1}$	$\frac{12}{n_L-1}$	$\frac{8}{n_L-1}$
Two-handed Controllers	$\frac{30}{n_L-1}$	$\frac{25}{n_L-1}$	$\frac{17}{n_L-1}$

3.2.2.3.2 *Control feel*. The deflection of the pilot's control must not lead the control force throughout the frequency range of pilot control inputs. In addition, the peak pitch control forces developed during abrupt maneuvers shall not be objectionably light, and the buildup of control force during the maneuver entry shall lead the buildup of normal acceleration.

RELATED MIL-F-8785B PARAGRAPH

3.2.2.3.1

DISCUSSION

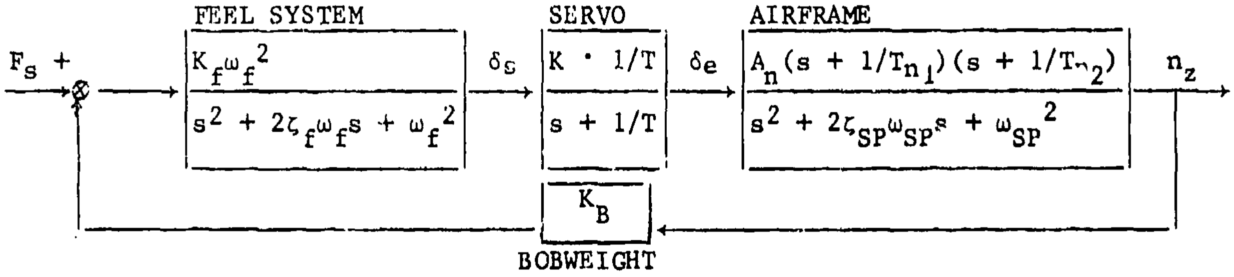
The title and wording of MIL-F-8785B paragraph 3.2.2.3.1 have been changed and expanded for clarity, based largely on the proposals of Reference 13. The numerical values are from that reference although we have used the designations one-handed or two-handed controllers. That is the basic difference between the two sets of numbers, so that sidesticks are now included. From Reference 13: The word dynamic has been substituted for transient in the title to avoid any connotation of the direct ratio of force to normal acceleration in a transient response to a step or pulse force input. The requirement is made applicable to frequencies greater than 1.0 rad/sec to avoid confusion with the phugoid mode.

The MIL-F-8785B requirement did not specify different values for different Levels. The requirement thus applied for all conditions of system failure except approved Airplane Special Failure States, according to 3.1.10.3.2. That made the requirement too severe, so that separate values of dynamic control force per g have been specified for Levels 1, 2 and 3. It is presumed that satisfaction of the requirements will be certified by the Program Office or Flight Test Center in any manner that is convenient to them. In fact, sinusoidal control need not - and probably would not - be used; a more sophisticated test procedure could easily be devised using modern signal analysis concepts and methods. However, the *intent* of the requirement is made clear by issuing the specifications in the form shown; it is unambiguous.

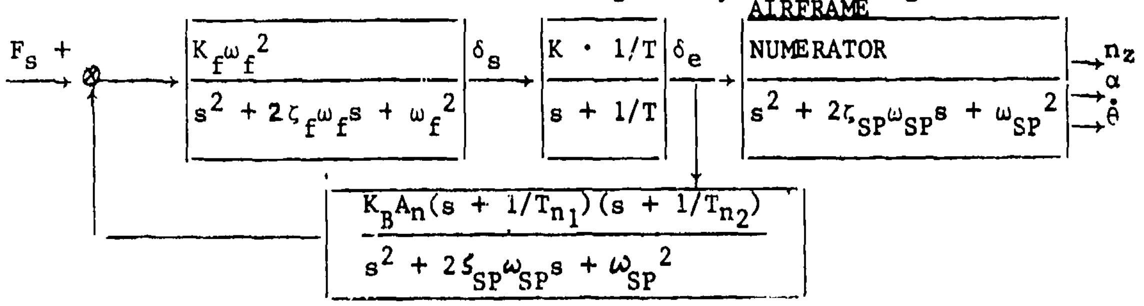
Paragraph 3.2.2.3.1 is very nearly the same as the MIL-F-8785B requirement on transient control forces (para. 3.2.2.3.1). It differs in that the load factor is now referenced to the pilot's location rather than the center of gravity. It thus lends explicit recognition to the importance of pilot-centered motion cues to handling qualities. For some combinations of short-period frequency, control moment arm and distance of the pilot from the c.g. the effect is significant. In general, it appears that the formulation of the PIO requirements in terms of normal acceleration at the pilot tends to provide a small additional margin of latitude to the control system designer. The numerical values in the revised paragraph were proposed in reference 13. The MIL-F-8785B 3 or 6 lb/g values for all Levels are thought too severe. The new 1.5 ratio of static to dynamic F_s/n minima corresponds to a ζ_E boundary of 0.35 or less, whereas the MIL-F-8785B requirement could correspond to a required ζ_E as great as 0.7 for low but adequate steady force gradients. "The trends and values of stick force per g and damping ratio are quite consistent with the data for center sticks in Figures 2 through 5 (3.2.2.3.1) in Reference 3 ..." . Again, it is felt that this requirement will usually be satisfied if the requirements of 3.2.2.1, 3.2.2.2, and 3.2.2.3 are met, at least for aircraft not employing direct lift control (DLC).

The requirement in paragraph 3.2.2.3.2 that the pilot's control deflection not lead the control force is repeated from section 3.5 (para. 3.5.3.1 of MIL-F-8785B, para. 3.5 of MIL-F-8785C) for emphasis.

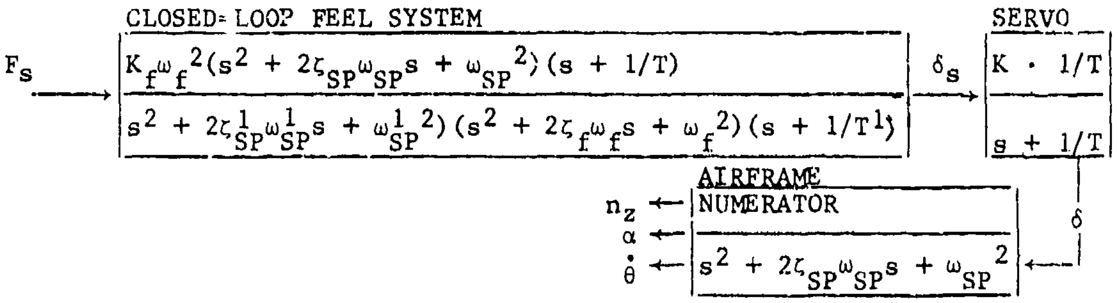
In the manner of reference 3's discussion (pp. 137 et seq.) of bobweight effects, consider an airplane with spring and bobweight feel and a first-order servo:



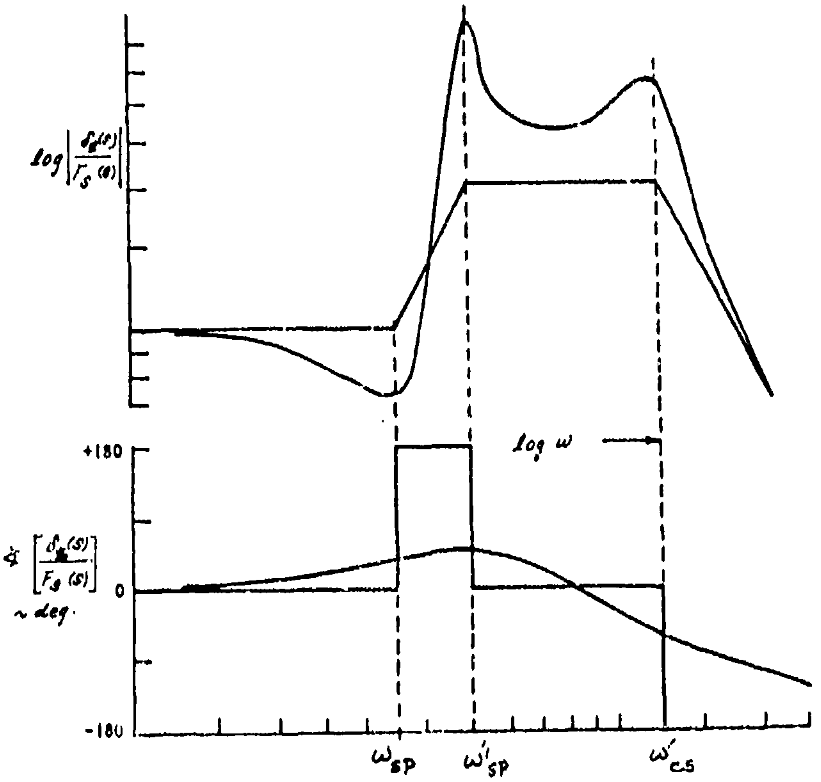
with n_z measured at the bobweight location. The airframe and servo characteristics can be taken as including the effects of any series stability augmentation, which by definition does not feed any signal to the pilot's control stick or column. The block diagram may be rearranged:



which can be simplified to:



where the primes denote control-free characteristics, with the bobweight loop closed. The following sketch, from reference 3, illustrates the frequency response of such a closed-loop feel system when the controls - free short-period natural frequency, ω_{SP}, is higher than controls - fixed.



As can be seen, $\omega_{SP}^1 > \omega_{SP}$ tends to make δ_s lead F_s, as well as to increase the maximum amplitude of δ_s/F_s. References 3, 13 and 73 relate such characteristics to pilot-induced oscillations. This phase requirement, alone, might have eliminated the longitudinal PIO experienced with the A4D-2 and the T-38A. Calspan (ref. 13) proposed the same requirement citing these reasons. Although this requirement is partly intuitive, it appears to be consistent with what little is known about interactions between the neuromuscular system, the feel system and human subjective response. There is some evidence (e.g., reference 74) to indicate that decreasing average stick force levels will result in increased pilot phase lag; by the PIO theory of reference 73, this would promote PIO in a pilot-vehicle system that had a tendency to develop pitch loop resonance.

An additional PIO-related requirement was proposed but, in the end, not adopted for this revision. This result of Ralph [illegible]'s Ref. 73 is, nevertheless, thought to provide useful design gu[illegible]:

Control system phase lag. The total phase angle by [illegible] acceleration measured at the pilot's location lags the pilot's [illegible]ce at a criterion frequency ω_R must be less in magnitude than 1[illegible] degrees, where ω_R is in radian/second. The criterion frequency ω_R [illegible]ned to be any frequency within the range $1 \leq \omega_R \leq 10$ radian/se[illegible] at [illegible] lightly damped (resonant) oscillations in pitch attitude can result from turbulence inputs or from piloting control of the airplane when used in the intended operational manner. This requirement may be waived at the discretion of the procuring activity for those flight conditions for which the ratio of normal acceleration measured at the pilot's location to pitch rate, evaluated at the criterion frequency, is less than .012 g/deg/sec.

This statement was proposed as a replacement for paragraph 3.5.3, Dynamic characteristics. However, in Navy experience the latter has proved its merit. Since this proposed addition is somewhat redundant with para. 3.5.3 as revised, it was not incorporated into the specification. The PIO theory of reference 73 postulates that if the pitch loop is resonant at frequency ω_R, then the pilot may at some time (which cannot necessarily be predicted) attempt to control normal acceleration a_{z_p} to the exclusion or near-exclusion of θ. According to Smith, a PIO may occur when the normal-acceleration response $n_z(j\omega)\ /n_{z_e}(j\omega)$(sub. e denoting the error sensed by the pilot) is "subjectively predictable": concentrated about some resonant frequency within the pilot's bandwidth of control, with a magnitude there above a threshold value. This situation may arise during pitch target tracking or as a result of the pitching response to a large, abrupt control input, failure transient or gust. A pilot attempting to control normal acceleration at that frequency will incite a PIO if no phase margin exists there; that is, if the phase angle of the $n_z(j\omega)/n_{z_e}(j\omega)$ transfer function is more negative than -180° at the resonant frequency. Using a pure .25-second time delay plus gain to model the pilot, the stated phase requirement for the airplane is evolved. Violation of the phase criterion of 3.2.2.4.3 implies that if the pilot switches to a_{z_p} control, the acceleration loop will be dynamically unstable and a PIO will be initiated. This paragraph provides the flight control system engineer with a quantitative criterion for minimum required dynamic performance of fuel and control systems. The amplitude criterion of this paragraph is proposed as a quantitative guide for preliminary identification in the design process (airframe or flight control system) of those flight conditions for which longitudinal PIO is probably not a realistic possibility. A combined threshold is postulated of maximum acceptable rms pitch rate in tracking and minimum a_z consciously felt by the pilot. More data should be collected from inflight simulation to establish the validity of this response ratio; the number selected, .012 g/deg/sec, conforms with past cases of longitudinal PIO (ref. 73). The frequency ω_R is, in disguise, a closed-loop, pilot-vehicle parameter. Fortunately it is also a very physical parameter (pitch loop resonant frequency) that is readily understood and accepted. No method is given in the proposed specification for its selection; methods for doing so are contained in reference 73. The frequency ω_R can be readily identified from flight test;

it would probably be an easy matter for SPO engineers to ascertain compliance with 3.2.2.4.3 without relying on pilot-vehicle analysis methods. Analytical estimates can, and should, be made by the airframe manufacturer as part of the design evolution. Smith points out that the fixed-base piloted simulation often used in flight control system design is appropriate for establishing ω_R. This usage is valid even though ground-based simulation is widely regarded as an ineffective way to investigate PIO tendencies - in Smith's theory, the steps beyond determining ω_R.

It should be noted that Smith's proposed requirements as well as those adopted, are equally valid for classical and nonclassical aircraft control system dynamics, and for linear and nonlinear systems.

I. 3.2.3.3 LONGITUDINAL CONTROL IN TAKEOFF

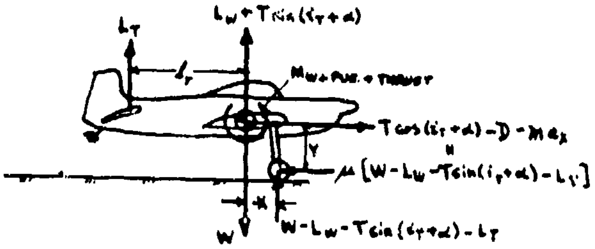
DISCUSSION

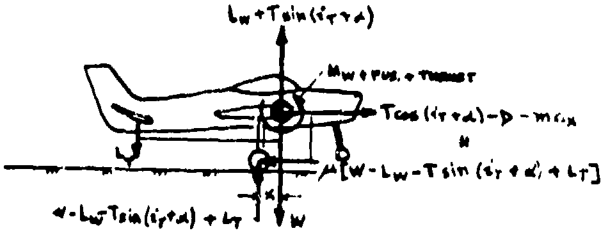
The requirement has not been changed. As noted in reference 13, the diagram in reference 3 is simplified depiction: thrust is shown acting through the center of gravity and parallel to the runway. That is an adequate depiction for the purpose intended, but not to calculate compliance. The thrust may produce significant vertical force and pitching moment about the c.g. For given aircraft attitude, throttle and pitch control settings, the nose-wheel lift-off speed can be calculated by balancing moments about the c.g:

$$\bar{q}S\bar{c}C_m + Tz_t - (W - \bar{q}SC_L - T\sin\xi)(X + \mu Y) = 0$$

where Tz_t is the thrust moment about the c.g. and $\xi = i_t + \alpha$ is thrust inclination to the horizontal. C_m is the aerodynamic pitching moment of the complete airplane, X and Y are horizontal and vertical distances, respectively, between c.g. and main-gear axle, and μ is the main-gear coefficient of rolling friction. Then

$$\frac{1}{2}\rho V_{LO}^2 = \bar{q}_{LO} = \frac{W}{S}\left[\frac{1 - \frac{T}{W}\left(\sin\xi + \frac{z_T/\bar{c}}{X/\bar{c} + \mu Y/\bar{c}}\right)}{C_L + \frac{C_m}{X/\bar{c} + \mu Y/\bar{c}}}\right]$$





J. 3.2.3.3.2 LONGITUDINAL CONTROL FORCE AND TRAVEL IN TAKEOFF

REQUIREMENT

3.2.3.3.3 Longitudinal control force and travel in takeoff. With the trim setting optional but fixed, the elevator-control forces required during all types of takeoffs for which the airplane is designed, including short-field takeoffs and assisted takeoffs such as catapult or rocket-augmented, shall be within the following limits:

Nose-wheel and bicycle-gear airplanes

Classes I, IV-C ---------- 20 pounds pull to 10 pounds push

Classes IV-C, IV-L ------- 30 pounds pull to 10 pounds push

Classes II-L, III -------- 50 pounds pull to 20 pounds push

Tail-wheel airplanes

Classes I, II-C, IV ------ 20 pounds push to 10 pounds pull

Classes II-L, III -------- 35 pounds push to 15 pounds pull

The elevator-control travel during these takeoffs shall not exceed 75 percent of the total travel, stop-to-stop. Here the term takeoff includes the ground run, rotation and lift-off, the ensuing acceleration to V_{max} (TO), and the transient caused by assist cessation. Takeoff power shall be maintained until V_{max} (TO) is reached, with the landing gear and high-lift devices retracted in the normal manner at speeds from $V_{o_{min}}$ (TO) to V_{max} (TO).

DISCUSSION

The editorial, nonsubstantive change of Amendment 2 is retained.

K. 3.2.3.4 LONGITUDINAL CONTROL IN LANDING

REQUIREMENT

3.2.3.4 Longitudinal control in landing. The pitch control shall be sufficiently effective in the landing Flight Phase in close proximity to the ground, that in calm air:

a. The geometry-limited touchdown attitude can be maintained in level flight, or

b. The lower of $V_S(L)$ or the guaranteed landing speed can be obtained.

This requirement shall be met with the airplane trimmed for the approach Flight Phase at the recommended approach speed. The requirements of 3.2.3.4 and 3.2.3.4.1 define Levels 1 and 2, and the requirements of 3.4.10 define Level 3.

DISCUSSION

The addition of "in calm air" is intended to clarify the application of the requirement, in view of other revisions concerning requirements for the effects of atmospheric disturbances (3.8). The requirement to provide sufficient control to achieve either stall speed or attitude limits is applied independently of disturbances. In operations, landing speed would be increased to achieve a safe landing in wind/turbulent/gusting conditions. An editorial change removes a superfluous "the" after a.

Although no specific margin of control is required during flare and landing, the general provisions of the new paragraph 3.4.10 Control Margin apply here. A number that has been used in some civil transport applications is for a nose down pitching acceleration capability in excess of trim than 0.08 rad/sec^2 for Level 1 and 0.05 rad/sec^2 for Levels 2 and 3 (Ref. 53).

L. 3.2.3.5 LONGITUDINAL CONTROL FORCES IN DIVES - SERVICE FLIGHT ENVELOPE

REQUIREMENT

3.2.3.5 Longitudinal control forces in dives - Service Flight Envelope. With the airplane trimmed for level flight at speeds throughout the Service Flight Envelope, the control forces in dives to all attainable speeds within the Service Flight Envelope shall not exceed 50 pounds push or 10 pounds pull for center-stick controllers, nor 75 pounds push or 15 pounds pull for wheel controllers. In similar dives, but with trim optional following the dive entry, it shall be possible with normal piloting techniques to maintain the forces within the limits of 10 pounds push or pull for center-stick controllers, and 20 pounds push or pull for wheel controllers. In event that operation of the trim system requires removal of one hand from wheel control the force limits shall be as for a center-stick. The forces required for recovery from these dives shall be in accordance with the gradients specified in 3.2.2.2.1 although speed may vary during the pullout.

DISCUSSION

One-handed wheel control requires the same forces as for a center-stick controller.

The force limits with fixed trim apply in straight dives at all speeds greater than the trim speed. With trim at a low airspeed, this requirement effectively limits the control force variation with speed.

SECTION VII

STATEMENT AND DISCUSSION OF LATERAL-DIRECTIONAL REQUIREMENTS (3.3)

3.3 LATERAL-DIRECTIONAL FLYING QUALITIES

GENERAL DISCUSSION

In discussing the development of MIL-F-8785B, Reference 3 noted that: "This section was difficult to organize since, primarily, because of coupling between lateral directional motions, each requirement has implications in many areas of flying qualities. Conversely, each flying qualities area is generally a function of many different parameters." These problems have been compounded by potential effects of the flight control system such as higher-order system dynamics, altered mode characteristics, artificial stability, additional modes (six-degree-of-freedom control), etc. Since Reference 3 was published, detail revisions have been proposed by Calspan and STI (References 13 and 14). The proposals are either changes to existing requirements or additional ones. As yet, no one has found a truly simplifying principle for lateral-directional flying qualities requirements.

In treating higher-order systems according to 3.1.12, normally the equivalent lateral-directional system would be taken as the classical three-degree-of-freedom roll response to a stick- or wheel-force input, with the provision for an added time delay. For roll, this is of the form:

$$\frac{\phi(s)}{F_A} = \frac{K_\phi(s^2 + 2\zeta_{\phi_E}\omega_{\phi_E}s + \omega^2_{\phi_E})\, e^{-A_\phi s}}{(s + 1/T_{S_E})(s + 1/T_{R_E})(s^2 + 2\zeta_{D_E}\omega_{D_E}s + \omega_{D_E}{}^2)}$$

and for sideslip:

$$\frac{\beta(s)}{F_R} = \frac{K_\beta(s + 1/T_{\beta_1})(s + 1/T_{\beta_2})(s + 1/T_{\beta_3})\, e^{-A_\beta s}}{(s + 1/T_{S_E})(s + 1/T_{R_E})(s^2 + 2\zeta_{D_E}\omega_{D_E}s + \omega_{D_E}{}^2)}$$

Equivalent system parameter values obtained by matching the responses of such transfer functions to the actual high-order responses would then be used for comparison with modal requirements. The actual high-order responses, however, would be used for comparison with time domain requirements such as ϕ_T, p_{osc}/p_{av} and $\Delta\beta$.

In general, the 'best' match is expected to be obtained by matching both the lateral and directional transfer functions simultaneously (as discussed in Reference 33). It is also obvious that many configurations, modes and flight conditions would be amenable to the use of even lower-order transfer functions, such as the conventional approximations of first order roll subsidence or second order Dutch roll. At present, no rules for application are available. One possible approach, however, would be to use the parameters resulting from the best match to justify further reduction in the order of the equivalent representation. The order reduction may be complicated by the introduction of additional poles and zeros by the flight control system in the relevant frequency range. The 'dominant modes' or simplified representations should not be used until validated by analysis of the transfer function forms above.

A. 3.3.1.1 LATERAL-DIRECTIONAL OSCILLATIONS (DUTCH ROLL)

REQUIREMENT

3.3.1.1 Lateral-directional oscillations (Dutch roll). The frequency, ω_{n_d}, and damping ratio, ζ_d, of the lateral-directional oscillations following a yaw disturbance input shall exceed the minimum values in Table VI. The requirements shall be met in trimmed and in maneuvering flight with cockpit controls fixed and with them free, in oscillations of any magnitude that might be experienced in operational use. If the oscillation is non-linear with amplitude, the requirement shall apply to each cycle of the oscillation. In calm air residual oscillations may be tolerated only if the amplitude is sufficiently small that the motions are not objectionable and do not impair mission performance. For Category A Flight Phases, angular deviations shall be less than ±3 mils.

TABLE VI. Minimum Dutch roll frequency and damping

Level	Flight Phase Category	Class	Min ζ_d*	Min $\zeta_d\omega_{n_d}$,* rad/sec	Min ω_{n_d}, rad/sec
1	A (CO, GA)	IV	0.4	-	1.0
	A	I, IV	0.19	0.35	1.0
		II, III	0.19	0.35	0.4**
	B	All	0.08	0.15	0.4**
	C	I, II-C, IV	0.08	0.15	1.0
		II-L, III	0.08	0.10	0.4**
2	All	All	0.02	0.05	0.4**
3	All	All	0	-	0.4**

* The governing damping requirement is that yielding the larger value of ζ_d, except that a ζ_d of 0.7 is the maximum required for Class III.

** Class III airplanes may be excepted from the minimum ω_{n_d} requirement, subject to approval by the procuring activity, if the requirements of 3.3.2 through 3.3.2.4.1, 3.3.5 and 3.3.9.4 are met.

When $\omega_{n_d}^2 \left|\phi/\beta\right|_d$ is greater than 20 (rad/sec)^2, the minimum $\zeta_d\omega_{n_d}$ shall be increased above the $\zeta_d\omega_{n_d}$ minimum listed above by:

Level 1 $-\Delta\zeta_d\,\omega_{n_d} = .014\ (\omega_{n_d}^2\left|\phi/\beta\right|_d - 20)$

Level 2 $-\Delta\zeta_d\,\omega_{n_d} = .009\ (\omega_{n_d}^2\left|\phi/\beta\right|_d - 20)$

Level 3 $-\Delta\zeta_d\,\omega_{n_d} = .005\ (\omega_{n_d}^2\left|\phi/\beta\right|_d - 20)$

DISCUSSION

Five changes to the Dutch roll frequency and damping requirement of MIL-F-8785B(ASG) have been made:

1. Damping ratio for Category A Flight Phases CO and GA has been increased to $\zeta = .4$
2. The minimum Level 1 $\zeta_d\omega_{n_d}$ requirement for Class II-L and Class III airplanes, Category C Flight Phases has been reduced from 0.15 to 0.10 rad/sec
3. The Level 3 requirement reduced from $\zeta_d = .02$ to $\zeta_d = 0$
4. A maximum required $\zeta_d = 0.7$ has been defined for Class III aircraft which have a low ω_{n_d}
5. The requirement for a stable airframe, control surface fixed, deleted

The first change was incorporated into the A-X specification by ASD and is planned to be retained in future procurements. For this reason the change was included in MIL-F-8785C. The minimum Dutch roll damping ratio and frequency boundaries in MIL-F-8785B(ASG) were not well substantiated in Ref. 3, for frequencies below $\omega_{n_d} = 1.0$ rad/sec. Since publication of Reference 3, the experiment of Reference 76 has been performed. Data from this experiment indicated that when aileron excitation of the Dutch roll mode was small, then configurations with $\omega_{n_d} = 1.0$ rad/sec and $\zeta_d = .1$ or $\zeta_d\omega_{n_d} = 0.10$ were satisfactory for the landing approach Flight Phase. The new data tabulated in Figure 24 show that 23 evaluations all resulted in pilot ratings of 3.5 or better for this Dutch roll value. Also shown in Figure 24 are data from Reference 77, for $\omega_{n_d} = .8$ and $\zeta_d = .1$. These are configurations 207 and 209 of that reference. Configuration 207 had $L'_\beta = 0$, was evaluated 6 times, and received an average rating of 5.5. Configuration 209 had $L'_\beta = -16$, was evaluated 13 times, and received an average rating of 4.5. These new data are considered sufficient justification for reducing the minimum $\zeta_d\omega_{n_d}$ limit for Class II-L and III from 0.15 to 0.10 sec^{-1}.

The requirement for positive damping for Level 3 seems unsupported by any of the available data. In fact, slightly negative or zero ζ_d seems consistent with a large body of data for pilot ratings in the neighborhood of 6.5 to 7. Furthermore, for some designs this requirement, especially if applied to high-altitude flight, could lead to unnecessary configuration compromises or to fail-operational yaw dampers where neither is justified by mission requirements. Thus the Level 3 value of ζ_d has been reduced from $\zeta_d = .02$ to $\zeta_d = 0$. We remain reluctant to allow nagative damping even for Level 3.

Deletion of the requirement for surface-fixed stability allows an aerodynamically/inertially unstable basic airframe provided that the procuring activity judges the benefits, reliability and alternatives sufficient to approve an Airplane Special Failure State (3.1.6.2.1).

REFERENCE 76 HALL-BOOTHE; CLASS II-L; CATEGORY C

GROUP 6 $\omega_d = 1.0$ $\zeta_d = .11$

PR = 2.5, 2.5, 2.0

GROUP 11 $\omega_d = 1.00$ $\zeta_d = .11$

PR = 2.5,3.5, 1.0, 2.0, 2.0, 2.0, 3.0

GROUP 13 $\omega_d = 1.00$ $\zeta_d = .099$

PR = 3.0, 3.0, 3.0, 3.0

GROUP 14 $\omega_d = 1.01$ $\zeta_d = .10$

PR = 2.0, 1.0, 3.0, 3.0, 3.0, 2.0, 2.0, 2.0, 2.5

REFERENCE 77 SECKEL; PU-797, CARRIER LANDING

CONFIGURATION 207 $\omega_d = .8$ $\zeta_d = .1$ $L_\beta = 0$

PR = 5.5 6 EVALUATIONS

CONFIGURATION 209 $\omega_d = .8$ $\zeta_d = .1$ $L_\beta = 16$

PR = 4.5 13 EVALUATIONS

Figure 24 (from Reference 13)- DUTCH ROLL DATA FOR ω_{n_d}

B. 3.3.1.3 SPIRAL STABILITY

REQUIREMENT

3.3.1.3 Spiral stability. The combined effects of spiral stability, flight-control-system characteristics, and rolling moment change with speed shall be such that following a disturbance in bank of up to 20 degrees, the time for the bank angle to double will be greater than the values in Table VIII. This requirement shall be met with the airplane trimmed for wings-level, zero-yaw-rate flight with the cockpit controls free.

TABLE VIII. Spiral Stability - Minimum Time to Double Amplitude

Flight Phase Category	Level 1	Level 2	Level 3
A & C	12 sec	8 sec	4 sec
B	20 sec	8 sec	4 sec

DISCUSSION

The requirements on time to double amplitude of the spiral mode have been simplified by removing the breakdown by airplane Class. Flight Phase Category C has been grouped with Category A rather than B and the Level 2 limit has been reduced from 12 sec to 8 sec. Eliminating the breakdown by Class is a simplification that is more consistent with the available data.

Grouping Category C Flight Phases with Category A Flight Phases is based on the consideration that during Category A and C Flight Phases the pilot is in more continuous control of the airplane than in Category B Flight Phase and is therefore less concerned about long-term attitude characteristics. This point was demonstrated in the TIFS Phase I landing approach experiments reported in Reference 78. Spiral roots with time to double of 9.6 sec were hardly noticed and a case with time to double of 6.4 sec, although noted, was not considered reason for downgrading the rating evaluation. Based on these data together with the extensive data in Ref. 79 and re-examination of the data in Reference 80, it was decided that the Level 2 limits on T_2 be reduced from 12 sec to 8 sec. Even this limit is a conservative interpretation of the data in Reference 79 which could be used to support a value of $T_2 = 6$ sec for Level 2. The gradient of pilot rating with time to double is steep, however, and a conservative interpretation is believed necessary.

Data in Reference 81 for unstable real roots resulting from reduced directional stability also indicate $T_2 = 6$ sec as a reasonable limit for cruise flight. A limit of 2.7 sec for landing approach is also indicated in this report but this value is regarded as too fast and inconsistent with other data to be accepted. The data in this report does lend support for the decision to group Category C with Category A rather than Category B.

In addition, the changes are consistent with the data presented in Reference 3, Figure 2 (3.3.1.3).

C. 3.3.1.4 COUPLED ROLL-SPIRAL OSCILLATION

REQUIREMENT

3.3.1.4 Coupled roll-spiral oscillation. For Flight Phases which involve more than gentle maneuvering, such as CO and GA, the airplane characteristics shall not exhibit a coupled roll-spiral mode in response to the pilot's roll control commands. A coupled roll-spiral mode will be permitted for Category B and C Flight Phases provided the product of frequency and damping ratio exceed the following requirements:

Level	$\zeta_{rs} \omega_{n_{rs}}$
1	0.5
2	0.3
3	0.15

DISCUSSION

The coupled roll-spiral requirement of MIL-F-8785B(ASG) was based primarily on the data in References 82 and 76 and the analysis of Ref. 83. Reference 84 documents additional experience with the M-2 lifting body research vehicle and Reference 85 reports the results of a ground simulator study of the effects of a coupled roll-spiral oscillatory mode on flying qualities for the Cruise and Landing Approach Flight Phases. Also, there are a few points in Reference 86 that were evaluated in the T-33 variable stability airplane used as a ground-based simulator. These points were set up to represent the augmented M2-F2 vehicles before it was flight tested.

The above referenced data have been plotted on Figure 25 [Figure 1 (3.3.1.4) from Reference 3]. Examination of these data together with the comments available in the various reports indicates that a coupled roll-spiral oscillatory mode can be acceptable provided the frequency and damping are above certain minimums. The less than satisfactory ratings obtained for coupled roots in this best area are due primarily to pilot objections to "spiral stability" and lack of roll control effectiveness and high steady forces in turning flight. This is particularly true of the data in Reference 85. In this experimant the roll control gearing and feel system characteristics were set to be compatible with the base configuration for each Flight Phase and were not varied during the experiment as the roll spiral was changed. This constraint is probably the cause of complaints about lack of roll control effectiveness.

The data from Reference 84 do not have pilot ratings associated with each point but the report indicates that control problems were encountered when the angle of attack was near zero or negative for the augmented M2-F2 and that the M2-F3 exhibited improved flying qualities but also had a similar trend of deterioration for negative angles of attack. Data are also shown for the M2-F2 with the SAS turned OFF. This data correlates fairly well with the proposed boundaries considering the fact that the

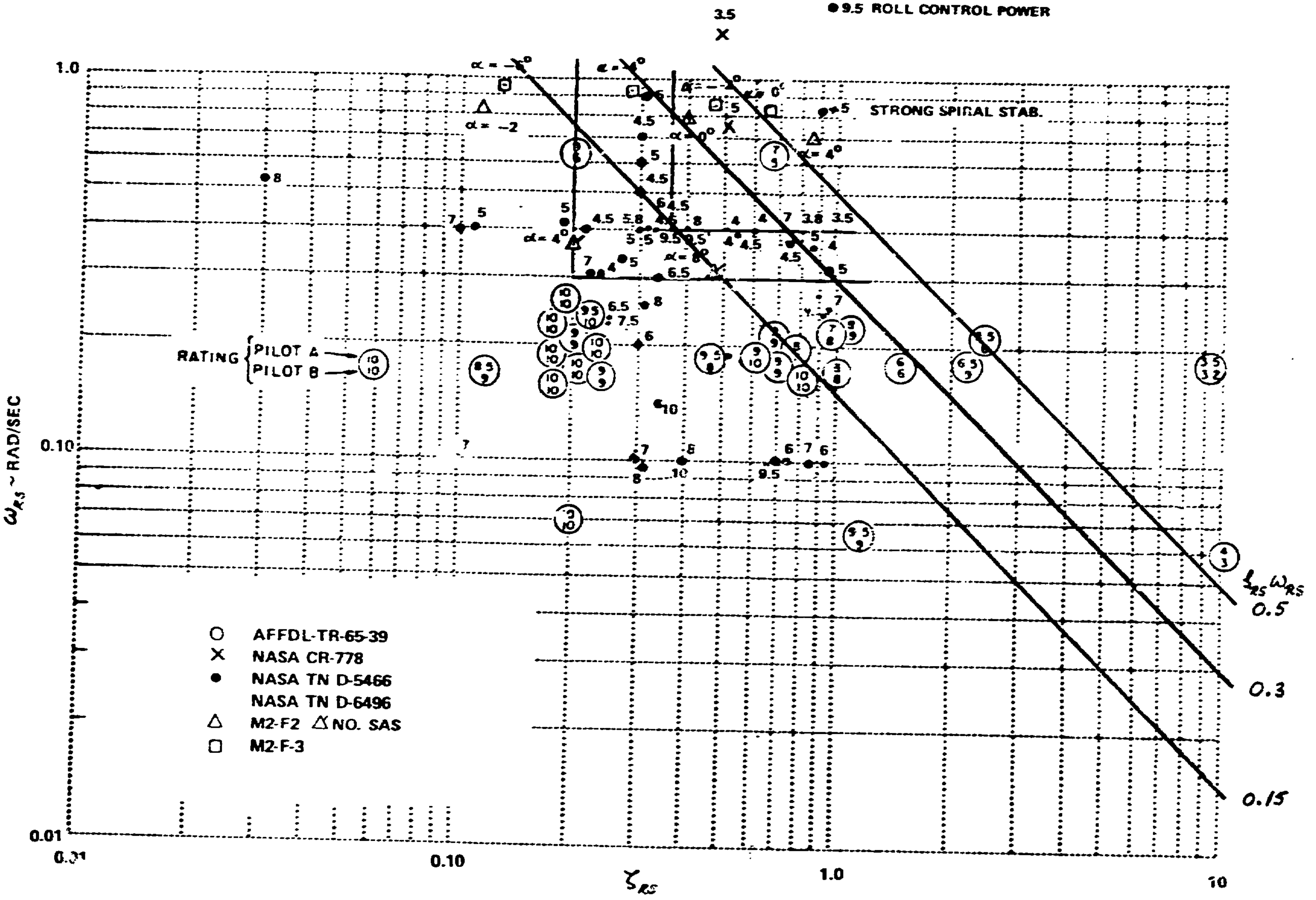


Figure 25. $\omega_{n_{RS}}$ VS ζ_{RS} FOR CONVERGENT DUTCH ROLL (From Reference 14)

Dutch roll mode is also affected by the angle of attack change. Additional cases, evaluated in a fixed-base simulator, are reported in Reference 8.

It should be noted that the coupled roll-spiral cases studied in all of the above experiments were the result of combinations of normal stability derivatives that have taken on rather unusual values. In general, the coupled roll spiral results from fairly large L'_β, large N'_p/L'_p, and large N'_r. If L'_p is low, the coupled roll-spiral will be low frequency and the airplane is likely to be difficult to control.

From Figure 25 it appears that boundary lines of constant $\zeta_{rs}\,\omega_{n_{rs}}$ fit the data better than the boundaries recommended in Reference 13, which are also shown.

It is possible to have a coupled roll-spiral mode as a result of introducing roll attitude stabilization. In this case the roll damping need not be low and L'_β need not be large for the mode to exist, thus the flying qualities may be quite satisfactory for Flight Phases that do not require rapid maneuvering. This should be especially true if proper attention is given to feel system gradients and roll control gain so that they are compatible with the attitude command response that results. Reference 87 reports different reactions from two pilots to two particular mechanizations of direct side force control with "roll stabilization" although the roll stabilization was not documented therein.

We do not expect any problem in the determination of equivalent system parameters for comparison with this requirement. Starting from the complete lateral and directional transfer functions, it should be straight-forward to identify that the roll and spiral modes are coupled. The two first-order terms in the denominator would then be combined into a second-order term to match the actual response. The roll-spiral damping would then be a product of the match.

D. 3.3.2 LATERAL-DIRECTIONAL DYNAMIC RESPONSE CHARACTERISTICS

REQUIREMENT

3.3.2 Lateral-directional dynamic response characteristics. Lateral-directional dynamic response characteristics are stated in terms of response to atmospheric disturbances and in terms of allowable roll rate and bank oscillations, sideslip excursions, roll control forces and yaw control forces that occur during specified rolling and turning maneuvers both to the right and to the left. The requirements of 3.3.2.2, 3.3.2.3 and 3.3.2.4 apply for roll commands of all magnitudes up to the magnitude required to meet the roll performance requirements of 3.3.4 and 3.3.4.1.

3.3.2.1 Lateral-directional response to atmospheric disturbances. The combined effect of ω_{n_d}, ζ_d, T_R, $\not{p}/\beta$, $|\phi/\beta|_d$, gust sensitivity, and flight-control-system nonlinearities on response and controllability characteristics in atmospheric disturbances shall be considered (see 3.8.3). In particular, the roll acceleration, rate and displacement responses to side gusts shall be investigated for airplanes with large rolling moment due to sideslip.

DISCUSSION

The wording of these two paragraphs has been changed slightly to be consistent with other revisions, without any change in intent. Neither the Calspan[13] nor the STI[14] recommended revisions have been adopted. Both Calspan's revised definitions and boundaries and STI's rudder coordination parameter should be useful as design guides, but they still are complicated and seem to be no more adequate than the present requirements.

E. 3.3.4 ROLL CONTROL EFFECTIVENESS

REQUIREMENT

3.3.4 Roll control effectiveness. Roll performance in terms of a bank angle change in a given time, ϕ_t, is specified in Table IXa for Class I and Class II airplanes, in 3.3.4.1 for Class IV airplanes, and 3.3.4.2 for Class III airplanes. For rolls from banked flight, the initial condition shall be coordinated, that is, zero lateral acceleration. The requirements apply to roll commands to the right and to the left, initiated both from steady bank angles and from wings-level flight except as otherwise stated. Inputs shall be abrupt, with time measured from the initiation of control force application. The pitch control shall be fixed throughout the maneuver. Yaw control pedals shall remain free for Class IV airplanes for Level 1, and for all carrier-based airplanes in Category C Flight Phases for Levels 1 and 2; but otherwise, yaw control pedals may be used to reduce sideslip that retards roll rate (not to produce sideslip which augments roll rate) if such control inputs are simple, easily coordinated with roll control inputs and consistent with piloting techniques for the airplane class and mission. For Flight Phase TO, the time required to bank may be increased proportional to the ratio of the rolling moment of inertia at takeoff to the largest rolling moment of inertia at landing, for weights up to the maximum authorized landing weight.

TABLE IXa. Roll performance for Class I and II airplanes

Time to Achieve the Following Bank Angle Change (Seconds)

Class	Level	Category A		Category B		Catetory C	
		60°	45°	60°	45°	30°	25°
I	1	1.3		1.7		1.3	
I	2	1.7		2.5		1.8	
I	3	2.6		3.4		2.6	
II-L	1		1.4		1.9	1.8	
II-L	2		1.9		2.8	2.5	
II-L	3		2.8		3.8	3.6	
II-C	1		1.4		1.9		1.0
II-C	2		1.9		2.8		1.5
II-C	3		2.8		3.8		2.5

DISCUSSION

This paragraph now contains requirements only for Classes I and II, serving as an introduction for other Classes in subparagraphs. The numerical requirements for Classes I and II are unchanged from Reference 2. Although experience seems to suggest that the requirements are too severe, there is insufficient data to formulate new ones.

As an introduction to all the roll control requirements, some of the wording has been changed in order to make the intent clearer. Rolls should be initiated "from steady bank angles and from wings-level flight" instead of "from zero roll rate". The requirements also apply in both left and right rolls.

Conditions for application have been made more explicit. All the requirements of MIL-F-8785B have applied throughout the appropriate V-h-n Flight envelopes; but application of some requirements at other than 1g has sometimes been overlooked. Specification of fixed pitch controller also expresses our continuing intent.

F. 3.3.4.1 ROLL PERFORMANCE FOR CLASS IV AIRPLANES

REQUIREMENT

3.3.4.1 Roll performance for Class IV airplanes. Roll performance in terms of ϕ_t for Class IV airplanes is specified in Table IXb. Additional or alternate roll performance requirements are specified in 3.3.4.1.1 and 3.3.4.1.2; these requirements take precedence over Table IX. Roll performance for Class IV airplanes is specified over the following ranges of airspeeds:

Speed Range Symbol	Equivalent Airspeed Range	
	For Level 1	For Levels 2 & 3
VL	$V_{o_{min}} \leq V < V_{min} + 20$ KTS	$V_{min} \leq V \leq V_{min} + 20$ KTS
L	$V_{min} + 20$ KTS (1) $\leq V < 1.4\ V_{o_{min}}$	$V_{min} + 20$ KTS $\leq V < 1.4\ V_{min}$
M	$1.4\ V_{o_{min}} \leq V < .7\ V_{max}^{(2)}$	$1.4\ V_{min} \leq V < .7\ V_{max}$
H	$.7\ V_{max}^{(2)} \leq V \leq V_{o_{max}}$	$.7\ V_{max} \leq V \leq V_{max}$

(1) Or $V_{o_{min}}$ whichever is greater

(2) Or $V_{o_{min}}$ whichever is less

Table IXb. Roll performance for Class IV airplanes

		Time to Achieve the Following Bank Angle Change (Seconds)				
Level	Speed Range	Category A 30°	50°	90°	Category B 90°	Category C 30°
1	VL	1.1			2.0	1.1
	L	1.1			1.7	1.1
	M			1.3	1.7	1.1
	H		1.1		1.7	1.1
2	VL	1.6			2.8	1.3
	L	1.5			2.5	1.3
	M			1.7	2.5	1.3
	H		1.3		2.5	1.3
3	VL	2.6			3.7	2.0
	L	2.0			3.4	2.0
	M			2.6	3.4	2.0
	H		2.6		3.4	2.0

3.3.4.1.1 Roll performance in Flight Phase CO. Roll performance for Class IV airplanes in Flight Phase CO is specified in Table IXc in terms of ϕ_t for 360° rolls initiated at 1g, and in Table IXd for rolls initiated at load factors between $.8n_o(-)$ and $.8n_o(+)$.

3.3.4.1.2 Roll performance in Flight Phase GA. The roll performance requirements for Class IV airplanes in Flight Phase GA with large complements of external stores may be relaxed from those specified in Table IXb, subject to approval by the procuring activity. For any external loading specified in contract, however, the roll performance shall be not less than that in Table IXe where the roll performance is specified in terms of ϕ_t for rolls initiated at load factors between $.8n_o(-)$ and $.8n_o(+)$. For any asymmetric loading specified in the contract, roll control power shall be sufficient to hold the wings level at the maximum load factors specified in 3.2.3.2 with adequate control margin (3.4.10).

TABLE IXc. Flight Phase CO roll performance in 360° rolls

Level	Speed Range	Time to Achieve the Following Bank Angle Change (Seconds)			
		30°	90°	180°	360°
1	VL	1.0			
	L		1.4	2.3	4.1
	M		1.0	1.6	2.8
	H		1.4	2.3	4.1
2	VL	1.6			
	L	1.3			
	M		1.3	2.0	3.4
	H		1.7	2.6	4.4
3	VL	2.5			
	L	2.0			
	M		1.7	3.0	
	H		2.1		

TABLE IXd. Flight Phase CO roll performance

Level	Speed Range	30°	50°	90°	180°
		Time to Achieve the Following Bank Angle Change (Seconds)			
1	VL	1.0			
	L		1.1		
	M			1.1	2.2
	H		1.0		
2	VL	1.6			
	L	1.3			
	M			1.4	2.8
	H		1.4		
3	VL	2.5			
	L	2.0			
	M			1.7	3.4
	H		1.7		

TABLE IXe. Flight Phase GA roll performance

Level	Speed Range	30°	50°	90°	180°
		Time to Achieve the Following Bank Angle Change (Seconds)			
1	VL	1.5			
	L		1.7		
	M			1.7	3.0
	H		1.5		
2	VL	2.8			
	L	2.2			
	M			2.4	4.2
	H		2.4		
3	VL	4.4			
	L	3.8			
	M			3.4	6.0
	H		3.4		

3.3.4.1.3 Roll response. Stick-controlled Class IV airplanes in Category A Flight Phases shall have a roll response to roll control force not greater than 15 degrees in 1 second per pound for Level 1, and not greater than 25 degrees in 1 second per pound for Level 2. For Category C Flight Phases, the roll sensitivity shall be not greater than 7.5 degrees in 1 second per pound for Level 1, and not greater than 12.5 degrees in 1 second per pound for Level 2. In case of conflict between the requirements of 3.3.4.1.3 and 3.3.4.3, the requirements of 3.3.4.1.3 shall govern. The term sensitivity does not include breakout force.

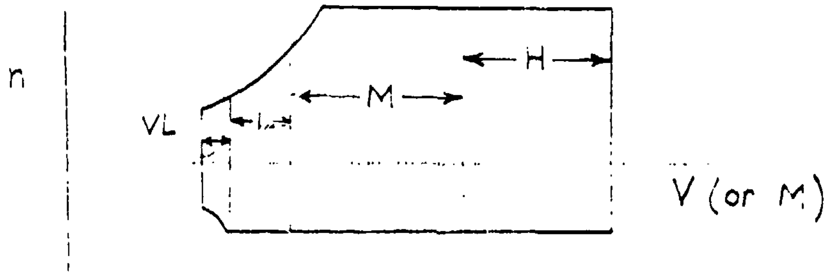
RELATED MIL-F-8785B PARAGRAPHS

3.3.4, 3.3.4.1, 3.3.4.1.1, 3.3.4.1.2, 3.3.4.1.3 and 3.3.4.1.4

DISCUSSION

The roll requirements for Class IV are extensively modified, although the majority of the change is reorganization to allow better definition of the intent of the requirements. The most obvious change is the division of the Operational Flight Envelope into speed ranges with different requirements for the different speeds. This change reflects feedback that the roll requirements were too stringent at the extremes of the envelope, whereas the operational need for the performance was at mid-range speeds. In general, the revision retains the MIL-F-8785B roll requirements in the speed range 'M', with a relaxation in the other speed ranges for the Category A Flight Phases.

The initial proposals for the speed ranges were defined using ASD experience with the F-15 and F-16. At the 1978 Flying Qualities Symposium the authors of MIL-F-8785C presented a modified definition of the speed range (Ref. 29f). The suggested modification - to have the four speed ranges as a function of load factor - was incorrect. The intent is to require a certain roll performance at all load factors in an "operationally useful" speed range, as sketched. The problem then becomes one of defining the required speeds in a general way.



For the final version of MIL-F-8785C, we returned to the definitions proposed in Reference 28. We believe that these do represent the requirement for superior roll performance at combat flight conditions. The procuring activity should retain that philosophy in developing a system specification. Also at the 1978 Symposium, Lockenour presented Northrop's suggested definitions based on the F-5E known performance (Ref. 29g). These recommendations are repeated in Figure 26.

8785B PROPOSED REVISION

SPEED RANGE SYMBOL	EQUIVALENT AIRSPEED RANGE
VL	V_o MIN $\leq V < V_{MIN}$ + 20 KTS
L	V_{MIN} + 20 KTS $\leq V <$ 2VS
M	$2V_S \leq V < 0.7\ V_{MAX}$
H	$0.7\ V_{MAX} \leq V \leq V_o$ MAX

NORTHROP RECOMMENDATION

SPEED RANGE SYMBOL	EQUIVALENT AIRSPEED RANGE
VL	V_o MIN $\leq V < V_o$ MIN + 0.1 ΔV
L	V_o MIN + 0.1 $\Delta V \leq V < V_o$ MIN + 0.4 ΔV
M	V_o MIN + 0.4 $\Delta V \leq V < V_o$ MIN + 0.7 ΔV
H	V_o MIN + 0.7 $\Delta V \leq V \leq V_o$ MAX
WHERE $\Delta V = V_o$ MAX - V_o MIN	

FIGURE 26. RECOMMENDED SPEED RANGE DEFINITIONS FOR THE ROLL PERFORMANCE REQUIREMENTS (Ref 29).

For a configuration with $V_{o_{max}}$ greater than Mach 2 the effect of these proposals would be to move 'M' to supersonic speeds, whereas typical air-to-air combat speeds are high subsonic. The original proposal is still used, although redefined in terms of $V_{o_{min}}$ instead of stall speed. This was done to avoid a potential difficulty with very low vaules of V_S (see discussion of the revision to 6.2.2). It may be that these definitions still do not cover all cases. It is emphasized that the proposed speed ranges should be tailored to the specific application. The intent is to provide sufficient roll maneuverability to do the task at the normal speeds for that task, with a relaxation permitted for speeds at which less maneuverability is normally required. A task requirement such as discussed following 1.4 would then take precedence over the requirements in this section. In line with these speed ranges, the bank angle changes have also been modified to be compatible with the speed at which the roll performance will be demonstrated.

These relaxations at low speed are concessions to the difficulty of doing better without adding excessive structural weight, actuator size, etc. We do this reluctantly, and some misgivings remain. The result of a recent air combat simulation (Ref. 88) show the single outstanding factor influencing convergence and kill was high roll performance. This was a fixed-base simulation, however, and the results must be balanced against feedback that pilots may not be able to use such roll rates at extreme flight conditions.

In another major change, the requirements are now more clearly applied with respect to airplane load factor. Requirements for 360 degree rolls only apply at 1g, which agrees with current requirments in the loads specifications. At elevated load factors, the requirements are stated in terms of bank-to-bank rolls through angles of 180 degrees or less. As stated in the requirements, these rolls are to be initiated at load factors between $.8n_o(+)$ and $.8n_o(-)$. These changes should make the roll performance more amenable to flight test demonstration.

The MIL-F-8785B, paragraph 3.3.4 requirement for roll control effectiveness "to balance the airplane throughout the Service Flight Envelope in the atmospheric disturbances of 3.7.3 and 3.7.4" does not appear in MIL-F-8785C. This change is associated with the revised treatment of atmospheric disturbances in section 3.8, Requirements for use of the disturbance models. Our intent is certainly not to drop this roll effectiveness requirement, but rather to apply it in a broader context.

Roll Axis Orientation

The roll axis is not specified exactly. Its desired orientation varies with the pilot's intent: turns (or straightening out) to modify the flight path, barrel rolls to slow down, aileron rolls to start split S's, ... The most frequent, usually most important use is the first-named, for turn entry or exit. With respect to the direction of flight, a roll axis tilted up corresponds to adverse yaw (nose lagging the turn entry) in stability axes; while a nose-down tilt indicates proverse yaw. Rolling about any axis other than the flight path will generate sideslip, thus exciting Dutch roll motion or even departure from controlled flight at high angle of attack. Other studies have shown that a major contributor to departure is the pα term in the side-force equation;

$$\Sigma Y = mV_o(\dot{\beta} + r - p\alpha)$$

- and $p\alpha_o$ is of course zero in stability axes.

At high angle of attack, however, the cockpit is higher above a flight-path-aligned roll axis. The result is spurious responses to roll control inputs: lateral acceleration as in the C-5A, F-15, etc; visual slewing of a fixed reference point such as a runway threshold, which was troublesome for the YF-16 at the pilot station. Kinematically;

$$a_{y_p} = V_o\dot{\beta} + x_p\dot{r} + h_p\dot{p}$$

$$v_p = V_o\beta + x_p r + h_p p$$

Also, rolling about the flight path at high angle of attack creates a flywheel effect producing an incremental pitching moment of $I_{XZ}p^2$.

All things considered, generally it appears best to generate and measure the roll motion in stability axes, examining the results carfully at high angle of attack, where the difference between body and stability axes is greatest. In order to achieve the needed roll performance, it may be necessary to accept some uncomfortable lateral acceleration.

G. 3.3.4.2 ROLL PERFORMANCE FOR CLASS III AIRPLANES

REQUIREMENT

3.3.4.2 Roll performance for Class III airplanes. Roll performance in terms of ϕ_t for Class III airplanes is specified in Table IXf over the following ranges of airspeeds:

Speed Range Symbol	Airspeed Range	
	For Level 1	For Levels 2 & 3
L	$V_{o_{min}} \le V < 1.8\ V_{min}$	$V_{min} \le V < 1.8\ V_{min}$
M	$1.8\ V_{min}^{(1)} \le V < .7\ V_{max}^{(2)}$	$1.8\ V_{min} \le V < .7\ V_{max}$
H	$.7\ V_{max}^{(2)} \le V \le V_{o_{max}}$	$.7\ V_{max} \le V \le V_{max}$

(1) Or $V_{o_{min}}$ whichever is greater

(2) Or $V_{o_{max}}$ whichever is less

TABLE IXf. Class III roll performance

Time to Achieve 30° Bank Angle Chang
(Seconds)

Level	Speed Range	Category A	Category B	Category C
1	L	1.8	2.3	2.5
	M	1.5	2.0	2.5
	H	2.0	2.3	2.5
2	L	2.4	3.9	4.0
	M	2.0	3.3	4.0
	H	2.5	3.9	4.0
3	All	3.0	5.0	6.0

RELATED MIL-F-8785B PARAGRAPH

3.3.4

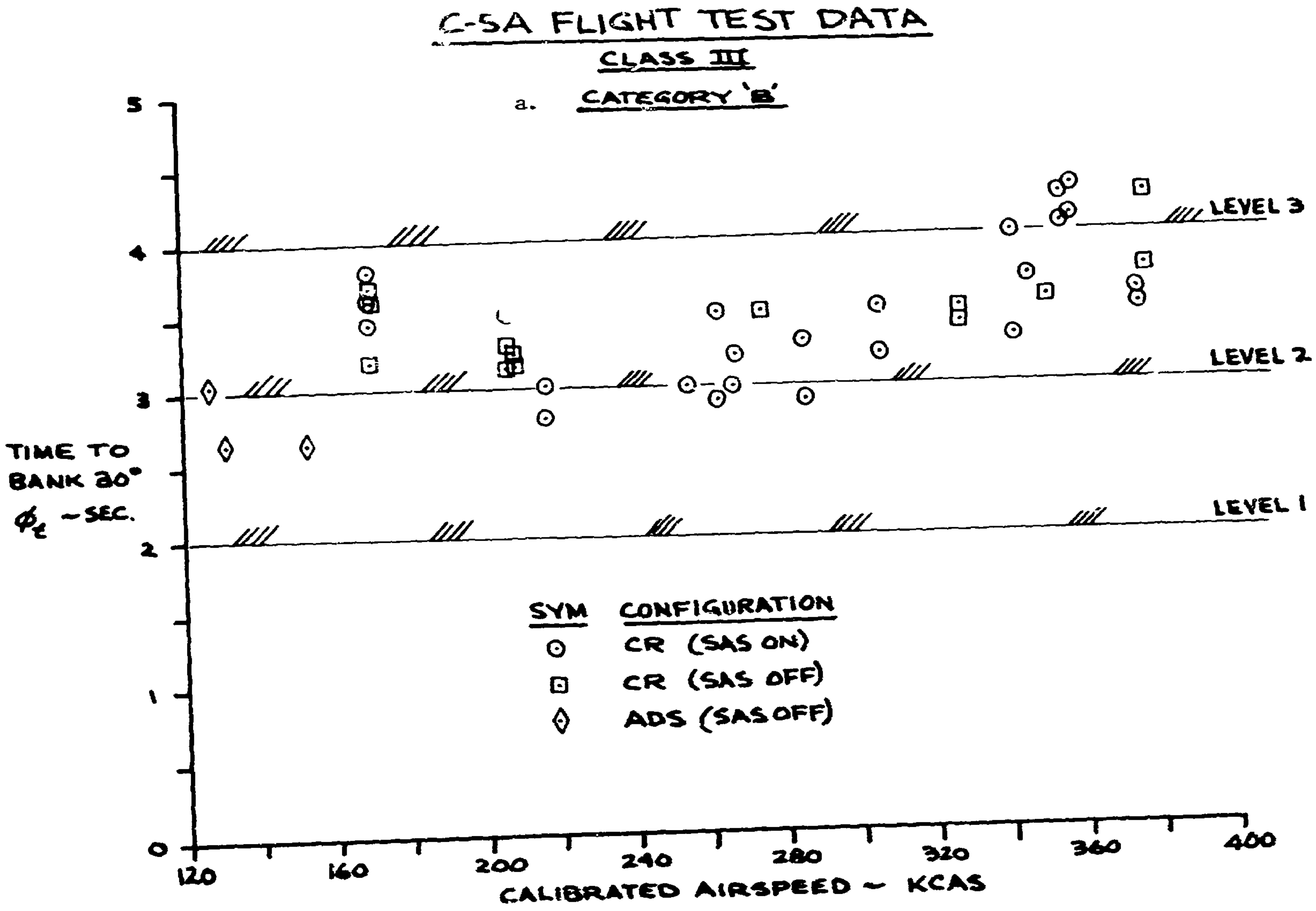
DISCUSSION

Class III roll requirements have also been redefined in terms of three speed ranges. The requirements have been relaxed at the outer speed ranges, except for Category C. The basic requirements for Levels 2 and 3 have also have been relaxed somewhat form MIL-F-8785B:

Category B, Level 2: 30° in 3.3sec instead of 3.0
Category B, Level 3: 30° in 5.0sec instead of 4.0
Category C, Level 2: 30° in 4.0sec instead of 3.2
Category C, Level 3: 30° in 6.0sec instead of 4.0

Reference 13 concluded from a "review of roll control used in various experiments...the roll control authority requirements...for Category C Flight Phases are excessive for airplanes that do not have high sensitivity to crosswind and turbulence. Data clearly indicate that there is an interaction between the roll control authority and the amount of roll damping and roll sensitivity to side velocity". The data was primarily for Class II and III airplanes.

Roll performance of the C-5A is shown in Figures 27a and 27b (from Ref. 7). As can be seen, the airplane does not meet the specification, however, "the roll acceleration available was considered satisfactory by the Joint Test Team on the basis of the offset landing maneuver, which was considered a practical test of lateral-directional maneuver ability". In cruise, also, the airplane was considered acceptable. Reference 11, on the other hand, retained the MIL-F-8785B requirements for application to a production AMST. Thus, although there is some justification for relaxing the Class III roll requirements, it must be done considering the aircraft mission and potential operation.



C-5A FLIGHT TEST DATA

CLASS III

a. CATEGORY 'B'

Figure 27. C-5A Roll Performance

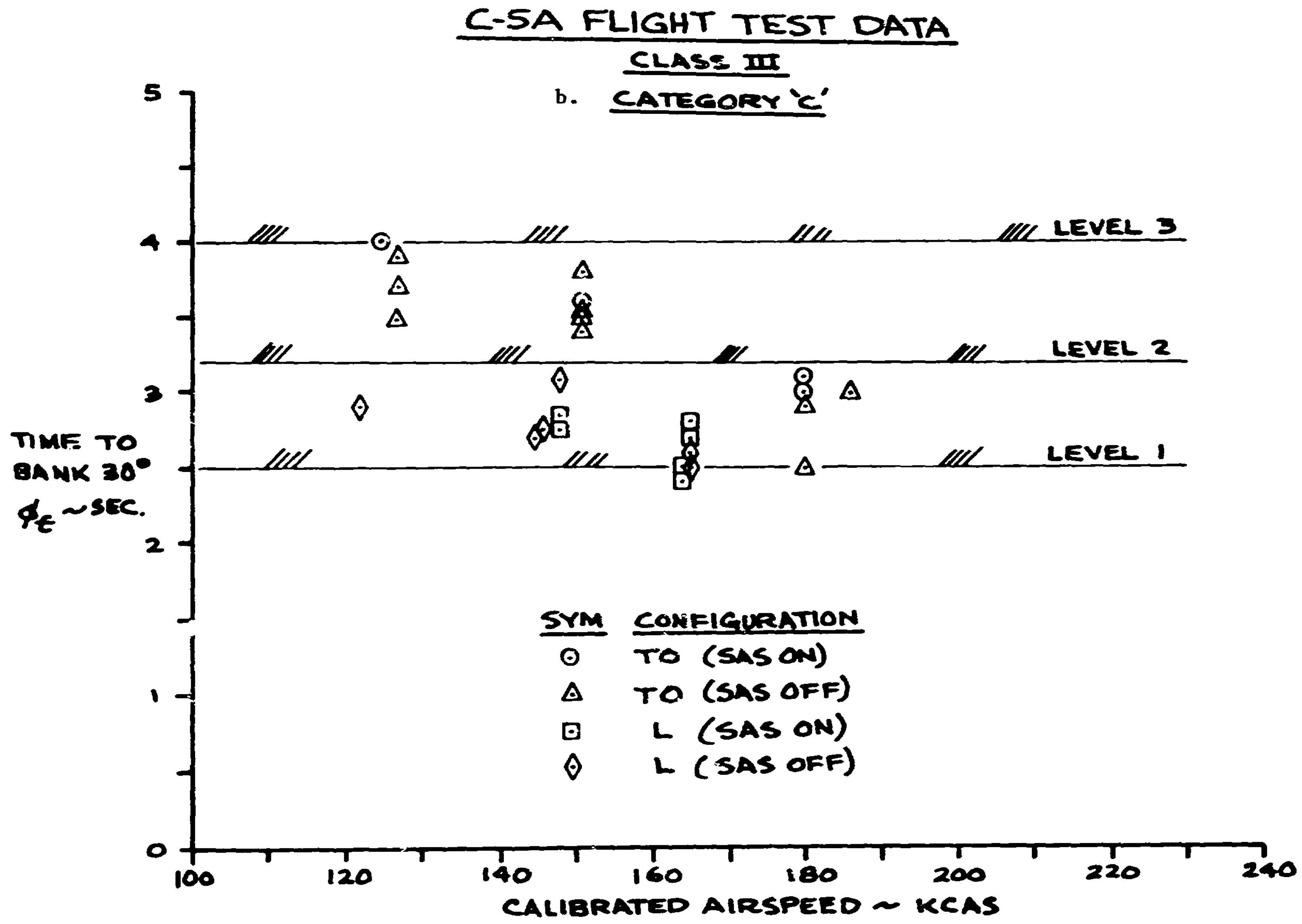


Figure 27. C-5A Roll Performance (concluded)

H. 3.3.4.3 ROLL CONTROL FORCES

REQUIREMENT

3.3.4.3 Roll control forces. The stick or wheel force required to obtain the rolling performance specified in 3.3.4, 3.3.4.1 and 3.3.4.2 shall be neither greater than the maximum in Table X nor less than the breakout force plus:

a. Level 1 -- one-fourth the values in Table X

b. Level 2 -- one-eighth the values in Table X

c. Level 3 -- zero

3.3.4.4 Linearity of roll response. There shall be no objectionable nonlinearities in the variation of rolling response with roll control deflection or force. Sensitivity or sluggishness in response to small control deflections or forces shall be avoided.

3.3.4.5 Wheel control throw. For airplanes with wheel controllers, the wheel throw necessary to meet the roll performance requirements specified in 3.3.4 and 3.3.4.2 shall not exceed 60 degrees in either direction. For completely mechanical systems, the requirement may be relaxed to 80 degrees.

TABLE X. Maximum roll control force

Level	Class	Flight Phase Category	Maximum Stick Force (lb)	Maximum Wheel Force (lb)
1	I, II-C, IV	A,B	20	40
		C	20	20
	II-L, III	A,B	25	50
		C	25	25
2	I, II-C, IV	A,B	30	60
		C	20	20
	II-L, III	A,B	30	60
		C	30	30
3	All	All	35	70

RELATED MIL-F-8785B PARAGRAPHS

3.3.4.2, 3.3.4.3 and 3.3.4.4

DISCUSSION

The requirements are unchanged; the wording has been changed to roll control. We would also add the clarification from Reference 11: The requirement for linearity of roll response from 3.3.4.3 is to apply to the commanded variable. Roll rate should be linear for a rate command system, and attitude should be linear for an attitude command system.

I. 3.3.4.5 RUDDER-PEDAL-INDUCED ROLLS

REQUIREMENT

Deleted

RELATED MIL-F-8785B PARAGRAPH

3.3.4.5 Rudder-pedal-induced rolls. For Levels 1 and 2, it shall be possible to raise a wing by use of rudder pedal alone, with right rudder pedal force required for right rolls and left rudder pedal force required for left rolls. For Level 1, with the aileron control free, it shall be possible to produce a roll rate of 3 degrees per second with an incremental rudder pedal force of 50 pounds or less. The specified roll rate shall be attainable from coordinated turns at up to ± 30 degrees bank angle with the airplane trimmed for wings-level, zero-yaw-rate flight.

DISCUSSION

Qualitatively, there are valid reasons for this requirement, as repeated from Reference 3:

"Rudder pedals are used for many different purposes. Although no list of rudder pedal usage would be complete, some of the more important uses are listed below.

a. To perform a crosswind landing-either employ a steady-rudder-pedal-induced sideslip or else a decrab maneuver.

b. To augment roll rate anywhere within the flight envelope.

c. To raise a wing when the pilot is busy with his hands, such as when taking a clearance.

d. For tracking, for example, in air-to-ground gunnery in a crosswind or when acquiring targets.

e. For wing-overs or other tactical maneuvers to obtain a rapid change in heading or bank angle.

f. For close formation flying.

g. To lose altitude as in a "forward" sideslip or to improve visibility, for example, a pilot landing from the rear seat of a tandem-seat airplane.

h. To counter yawing moments from propeller torque, speed or Mach number change, asymmetric thrust or stores, etc.

i. To coordinate turn entries or steady turns.

j. To taxi".

The requirement in MIL-F-8785B directly addressed many of the above topics. ASD reports feedback ranging from 'three degrees per second is not enough' to 'roll due to rudder is not required', indicating that some other factors need to be taken into account. A tactical fighter requires maneuverability over as wide a range of flight conditions as possible. At high angles of attack, ailerons either become ineffective or produce undesirable coupled motions, and roll due to rudder could be very beneficial. By contrast, although item c above is particularly valid for single-seat airplanes it is not necessary for (multi-crew) transports. Uncoupled pedal response (yaw without rolling) has been found more than satisfactory for transport operation. In response to item d above, CCV experience (Reference 89) has shown that a wings-level-turn mode is beneficial for air-to-ground weapon delivery; and this could be mechanized through the pedals.

The preceding discussion raises some obvious questions: is rudder-pedal-induced roll a valid requirement? is 3°/sec enough or too much? should a maximum value be specified? are the requirements a function of airplane Class or task? Lacking answers to these questions the decision was made to delete the requirement completely. We can probably be certain that 'negative' roll due to rudder is undesirable, but the designer is encouraged to take task and configuration variables into account in establishing and meeting requirements in this area.

J. 3.3.5.1 DIRECTIONAL CONTROL WITH SPEED CHANGE

REQUIREMENT

3.3.5.1 Directional control with speed change. When initially trimmed directionally with symmetric power, the trim change of propeller driven airplanes with speed shall be such that wings-level straight flight can be maintained over a speed range of ±30 percent of the trim speed or ±100 knots equivalent airspeed, whichever is less (except where limited by boundaries of the Service Flight Envelope) with yaw-control-pedal forces not greater than 100 pounds for Levels 1 and 2 and not greater than 180 pounds for Level 3, without trimming. For other airplanes, yaw-control-pedal forces shall not exceed 40 pounds at the specified conditions for Level 1 and 2 or 180 pounds for Level 3.

DISCUSSION

In order to make a meaningful requirement, Amendment 1 specified that wings-level as well as straight flight be maintained.

K. 3.3.9 LATERAL-DIRECTIONAL CONTROL WITH ASYMMETRIC THRUST

REQUIREMENT

3.3.9 Lateral-directional control with asymmetric thrust. Asymmetric loss of thrust may be caused by many factors including engine failure, inlet unstart, propeller failure or propeller-drive failure. Following sudden asymmetric loss of thrust from any factor, the airplane shall be safely controllable in the crosswinds of Table XI from the unfavorable direction. The requirements of 3.3.9.1 through 3.3.9.4 apply for the appropriate Flight Phases when any single failure or malperformance of the propulsive system, including inlet or exhaust, causes loss of thrust on one or more engines or propellers, considering also the effect of the failure or malperformance on all subsystems powered or driven by the failed propulsive system.

DISCUSSION

The change to this requirement is the addition of the phrase "in the crosswinds of Table XI from the unfavorable direction". For all commercial and peace-time military operations, takeoff procedures are planned on the assumption that an engine will fail. The intent, of course, is to ensure safety by having the speeds and speed margins appropriate to the airplane performance capabilities with a failed engine. Extending this to operation in crosswinds, the takeoff is still planned around an engine failure (and according to Murphy's Law it would be the most unfavorable one that failed). The requirement has thus been stated to reflect this practice.

"Safely controllable" means, in addition to having sufficient control effectiveness, that it must not be necessary to sacrifice a required performance capability, such as a climb gradient with one or two engines out, in order to achieve controllability.

Note also that both 3.3.9.1 Thrust loss during takeoff run and 3.3.9.2 Thrust loss after takeoff state: "Automatic devices which normally operate in the event of a thrust failure may be used".

L. 3.3.9.1 THRUST LOSS DURING TAKEOFF RUN

DISCUSSION

This requirement has not been changed. The opportunity is taken to correct a typographical error in Reference 3's statement of the requirement. An inadvertently omitted line has caused some confusion. The last two sentences of the requirement are:

> For the aborted takeoff, the requirement shall be met at all speeds below the maximum takeoff speed; however, additional controls such as nose-wheel steering and differential braking may be used. Automatic devices which normally operate in the event of a thrust failure may be used in either case.

"Either" refers to continued or aborted takeoff.

SECTION VIII

STATEMENT AND DISCUSSION OF MISCELLANEOUS FLYING QUALITIES REQUIREMENTS (3.4)

3.4 MISCELLANEOUS FLYING QUALITIES

A. 3.4.1 Dangerous Flight Conditions

REQUIREMENT

3.4.1 Dangerous flight conditions. Dangerous conditions may exist where the airplane should not be flown. When approaching these flight conditions, it shall be possible by clearly discernible means for the pilot to recognize the impending dangers and take preventive action. Final determination of the adequacy of all warning of impending dangerous flight conditions will be made by the procuring activity, considering functional effectiveness and reliability.

3.4.1.1 Warning and indication. Warning or indication of approach to a dangerous condition shall be clear and unambiguous. For example, a pilot must be able to distinguish readily among stall warning (which requires pitching down or increasing speed), Mach buffet (which may indicate a need to decrease speed), and normal airplane vibration (which indicates no need for pilot action).

3.4.1.2 Devices for indication, warning, prevention, recovery. It is intended that dangerous flight conditions be eliminated and the requirements of this specification met by appropriate aerodynamic design and mass distribution, rather than through incorporation of a special device or devices. Such devices may be used only if the procuring activity approves the need, the design criteria, possible Special Failure States (3.1.6.2.1), and the devices themselves. As a minimum, these devices shall perform their function whenever needed, but shall not limit flight within the Operational Flight Envelope. Neither normal nor inadvertent operation of such devices shall create a hazard to the airplane. For Levels 1 and 2, nuisance operation shall not be possible. Functional failure of the devices shall be indicated to the pilot.

DISCUSSION

In Amendments 1 and 2, these requirements were expanded and rearranged to emphasize that:

> Dangerous flight conditions should be avoided through design of the basic airframe, if possible, rather than through "a special device or devices": stability augmentation, limiters, stick pushers, etc.
>
> Any such devices to be incorporated must be specifically approved by the procuring activity.

MIL-F-8785C makes no further revisions.

Dangerous flight conditions may occur at high angle of attacks, at transonic Mach numbers, as a result of system failures (e.g., flight control, electrical, propulsion). In recognition of design trade-offs, the requirement is less than absolute in reliance on design of the basic aircraft. The procuring activity approval of other means will be based upon considerations such as:

Performance and maneuverability benefits to be gained

Impossibility or great difficulty of design changes or alternatives to fix the basic airframe

Importance of the dangerous conditions to primary, secondary and possible alternative missions

Probability of encounter: a subjective evaluation of pertinent mission requirements and failure probabilities

Consequences of encounter: results of a comprehensive failure mode effects analysis

Operation of the device: its effectiveness, freedom from nuisance operation and other undesirable side effects

Suitability of annunciation to pilot beforehand of inability to perform its function

For stall, warning - rather than just indication of approach - is a universally recognized necessity. On the other hand, an accelerometer or, in low-load-factor airplanes, just bank angle and seat-of-pants give normally adequate indication of approach to limit load factor.

Nuisance operation cannot be allowed to affect mission capability. Without knowing service usage, a designer cannot assign a meaningful probability of nuisance operation.

Regarding high angle of attack, there presently exist two schools of thought for fighter aircraft. All people agree that for air combat a fighter should be able to maneuver with abandon, as unconcerned as possible about exceeding aircraft restrictions. To some this means capability to fly to extreme angles of attack with no fear of departure from controlled flight, while to others it means effective limiters to prevent departure. Characteristics of the airplane one is involved with seem to influence which side one takes - but no limiter should act as a stick pusher, trying to take the stick out of the pilot's hand; pilots object. Inherent capability is encouraged rather than devices which can subtract from the usable flight envelope, be less than totally effective, or fail. Generally test pilots have found ways to defeat limiters - intentionally or inadvertently. Complete safety (given enough altitude) requires means to recover from any attainable flight condition (see 3.4.10 discussion). For the F-16 this meant addition of a special provision for recovery from a locked-in "deep stall", even though an angle-of-attack limiter "normally" would prevent getting into that condition[90].

Transport airplanes can also have high-angle-of-attack problems. Rather than relying on a placard or the flight control system, some transport designs limit the aft center of gravity position to preclude a locked-in deep stall.

As recounted in the discussion of stall requirements, unreliable stall warning is thought to have been a factor in loss of some C-133 airplanes.

Voice warning shows promise, but has yet to be evaluated definitively for stall warning. If sufficiently intelligible and timely, it has the potential advantage of clearly, directly commanding the crew to take the proper action.

B. 3.4.2 FLIGHT AT HIGH ANGLE OF ATTACK

REQUIREMENT

3.4.2 Flight at high angle of attack. The requirements of 3.4.2 through 3.4 2.2.2 concern stall warning, stalls, departure from controlled flight, post-stall gyrations, spins, recoveries and related characteristics. They apply at speeds and angles of attack which in general are outside the Service Flight Envelope. They are intended to assure safety and the absence of mission limitations due to high-angle-of-attack characteristics.

DISCUSSION

Interim Amendment 1 (USAF) completely revised the requirements at high angle of attack, coordinated with the Air Force Flight Test Center's concurrent new stall/post-stall/spin demonstration requirements, MIL-S-83691. Reference 27 is background information and a user guide for that specification. These changes were the result of reawakened interest in the area, occasioned by numerous aircraft losses. A large number of aircraft accidents have been attributed to loss of control at high angle of attack, and it was conjectured that many losses in Vietnam combat (with no evidence to determine a cause) might well be due to the same cause. Whereas previous requirements had concentrated on demonstration of acceptable stall and spin characteristics, the new requirements emphasize prevention of loss of control (departure) as well. All airplanes are covered with flight demonstration maneuvers and control abuse appropriate to the Class and mission. The requirements in this regime of nonlinearities remain largely qualititive.

Amendment 2 changed many of Amendment 1's quantitative requirements related to test and evaluation techniques to qualitative statements, leaving these details of test and evaluation procedures to MIL-S-83691 for the Air Force, MIL-D-8708 for the Navy. MIL-F-8785C makes no further changes.

As discussed in connection with 3.1.7, although stall and post-stall angles of attack are outside the Operational Flight Envelope defined there, nevertheless, these angles may be useful in combat operations. But even if an airplane will never intentionally be flown past stall warning, operators will have a natural concern about inadvertent penetration of this boundary. It is essential both to give adequate design consideration and to demonstrate flight characteristics at high angle of attack.

The means of demonstrating compliance will change with the stage of the design, as for all the flying qualities requirements - progression from rules of thumb through wind-tunnel testing and analysis of various kinds to flight demonstration. Since flight testing at high angle of attack has produced many surprises in the past, the flight program should (a) be planned carefully and (b) push the airplane to the limit allowed by flight safety considerations, searching for any problems before they are found inadvertently in service. Generally it has been observed that during the life of any aircraft type, any motion that can possibly happen will.

These requirements remain largely qualitative, therby furnishing little direct design guidance. This approach reflects both the complexity of this essentially nonlinear problem and the continuing status of high-α design as perhaps more artful than scientific.

C. 3.4.2.1 STALLS

REQUIREMENT

3.4.2.1 Stalls. The stall is defined in terms of airspeed and angle of attack in 6.2.2 and 6.2.5 respectively. It usually is a phenomenon caused by airflow separation induced by high-angle-of-attack but it may instead (3.1.9.2.1) be determined by some limit on usable angle of attack. The stall requirements apply for all Airplane Normal States in straight unaccelerated flight and in turns and pull-ups with attainable normal acceleration up to n_L. Specifically, the Airplane Normal States associated with the configurations, throttle settings, and trim settings of 6.2.2 shall be investigated; also, the requirements apply to Airplane Failure States that affect stall characteristics.

3.4.2.1.1 Stall approach. The stall approach shall be accompanied by an easily perceptible warning. Acceptable stall warning for all types of stalls consists of shaking of the cockpit controls, buffeting or shaking of the airplane, or a combination of both. The onset of this warning shall occur within the ranges specified in 3.4.2.1.1.1 and 3.4.2.1.1.2 but not within the Operational Flight Envelope. The increase in buffeting intensity with further increase in angle of attack shall be sufficiently marked to be noted by the pilot. The warning shall continue until the angle of attack is reduced to a value less than that for warning onset. At all angles of attack up to the stall, the cockpit controls shall remain effective in their normal sense, and small control inputs shall not result in departure from controlled flight. Prior to the stall, uncommanded oscillations shall not be objectionable to the pilot.

3.4.2.1.1.1 Warning speed for stalls at 1g normal to the flight path. Warning onset for stalls at 1g normal to the flight path shall occur between the following limits when the stall is approached gradually:

Flight Phase	Minimum Speed for Onset	Maximum Speed for Onset
Approach	Higher of $1.05V_S$ or V_S + 5 knots	Higher of $1.10V_S$ or V_S + 10 knots
All other	Higher of $1.05V_S$ or V_S + 5 knots	Higher of $1.15V_S$ or V_S + 15 knots

3.4.2.1.1.2 Warning for accelerated stalls. Onset of stall warning shall occur outside the Operational Flight Envelope associated with the Airplane Normal State and within the following range of percentage of lift at stall at that airspeed, in that Airplane State, when the stall is approached gradually:

Flight Phase	Minimum Lift at Onset	Maximum Lift at Onset
Approach	82% $C_{L_{stall}}$	90% $C_{L_{stall}}$
All Other	75% $C_{L_{stall}}$	90% $C_{L_{stall}}$

3.4.2.1.2 Stall characteristics. In the unaccelerated stalls of 3.4.2.1, the airplane shall not exhibit rolling, yawing, or downward pitching at the stall which cannot be controlled to stay within 20 degrees for Classes I, II, and III, or 30 degrees for Class IV airplanes. It is desired that no pitch- up tendencies occur in unaccelerated or accelerated stalls. In unaccelerated stalls, mild nose-up pitch may be acceptable if no pitch control force reversal occurs and if no dangerous, unrecoverable, or objectionable flight conditions result. A mild nose-up tendency may be acceptable in accelerated stalls if the operational effectiveness of the airplane is not compromised and:

a. The airplane has adequate stall warning

b. Pitch effectiveness is such that it is possible to stop the pitchup promptly and reduce the angle of attack, and

c. At no point during the stall, stall approach or recovery does any portion of the airplane exceed structural limit loads.

The requirements apply for all stalls, including stalls entered abruptly.

3.4.2.1.3 Stall prevention and recovery. It shall be possible to prevent the stall by moderate use of the pitch control alone at the onset of the stall warning. It shall be possible to recover from a stall by simple use of the pitch, roll and yaw controls with cockpit control forces not to exceed those of 3.4.5.1, and to regain level flight without excessive loss of altitude or buildup of speed. Throttles shall remain fixed until speed has begun to increase when an angle of attack below the stall has been regained unless compliance would result in exceeding engine operating limitations. In the straight-flight stalls of 3.4.2.1, with airplane trimmed at an airspeed not greater than $1.4V_S$, elevator control power shall be sufficient to recover from any attainable angle of attack.

3.4.2.1.3.1 One-engine-out stalls. On multi-engine airplanes, it shall be possible to recover safely from stalls with the critical engine inoperative. This requirement applies with the remaining engines at up to:

Flight Phase	Thrust
TO	Takeoff
CL	Normal climb
PA	Normal approach
WO	Waveoff

DISCUSSION

It is appropriate to apply these safety-related requirements at all attainable load factors up to n_L; although some manufacturers of very large aircraft have objected that 1.5g is a more reasonable limit for flight test there is no safety reason to so limit analysis or simulation. Amendment 2 also exchanged the arbitrary upper limits on stall entry rate for more general application to include "all stalls, including stalls entered abruptly", throughout these requirements. For stall prevention, Amendment 1 specified "elevator control alone: - a simpler, natural and more universal usage than MIL-F-8785B's " the controls".

Stall classically corresponds to maximum lift coefficient, that is, $C_{L_\alpha}=C$; but other accepted indicators of stall or maximum usable lift are uncommanded motion in pitch, roll or yaw and intolerable buffeting. Consonant with deletion of specific rules for establishing the Permissible Flight Envelope, MIL-F-8785C deletes mention that V_S and α_S may be set by conditions other than aerodynamic flow separation. Although the contractor may set the low-speed bound of the Permissible Flight Envelope arbitrarily, there is no need to state that here. (Regardless of the boundary location, we would expect full stalls to be demonstrated if attainable). Note that according to 3.4.1.1, the contractor must provide adequate warning or indication of approach to any dangerous flight condition.

If a control limit sets minimum permissible speed of a basically stable airplane short of stall warning, no minimum-speed warning may be necessary. But where landing approach speed is restricted because of inability to make altitude corrections, at least some indication - if not warning - should be given. Any such limitation must, of course, be taken into account in setting the airspeed for compliance with performance requirements. While the flying qualities specification puts no requirement on maneuver capability at approach speed, the normal margin from stall speed has been found to be generally adequate, allowing for normal bleedoff of airspeed at $n_z > 1$.

As in MIL-F-8785B, stalls are considered for Airplane Normal States and also for Airplane Failure States that affect stall characteristics. If a stall-warning device fails, 3.4.1.2 requires indication to the pilot, who then can exercise caution.

The unchanged requirement that throttles remain fixed until the airplane has become unstalled and airspeed has begun to increase reflects pilots' concerns. For a sudden, inadvertant stall, the alarm and workload - mental and physical - likely will be proportioned to the danger, so the need for coordinated control action to recover should be minimized, with "first things first".

Interrelation among the various aspects of stalling is illustrated by an investigation into the disappearance of several heavily loaded C-133 airplanes on long over-water flights. Natural stall warning was insufficient, and the artificial warning so unreliable that it was routinely disconnected. Wing drop at stall was severe, becoming worse as throttles were advanced - although during development flight testing, stall tests with power on were limited. For maximum-range cruise, procedure was to climb as close as possible to the absolute ceiling, which put the airplane close to stall. It was, therefore, conjectured that the airplanes lost control at this flight condition and were unable to recover.

In normal operation, a pitch damper (augmenting M_q) may even be destabilizing beyond the stall. This trend may be seen by writing the longitudinal characteristic equation (valid in this nonlinear region as a quasilinear solution for small perturbations) as;

$$\Lambda = s^4 - (Z_w + M_{\dot\alpha} + X_u)s^3 + [-M_\alpha + X_u(Z_w + M_{\dot\alpha}) - X_wZ_u]s^2 + [X_u M_\alpha - M_uX_\alpha +$$

$$g(M_u + Z_uM_{\dot\alpha})]s + g(M_wZ_u - Z_wM_u) - M_qs[s^2 - (Z_w + X_u)s + (X_uZ_w - Z_uX_w)]$$

For sufficiently negative C_{L_α}, Z_w is positive, so that the $M_q Z_w$ terms,

$$M_q Z_w \; s(s - X_u)$$

are negative, therefore destabilizing $[Z_w = -(C_{L_\alpha} + C_D)\rho VS/2m]$. Obviously, normal-acceleration feedback also loses effectiveness and even becomes destabilizing as Z_w diminishes and changes sign. Thus an n_z-command system will actually induce a stall.

In normal operation, a pitch attitude signal to the stability and control augmentation also loses its stabilizing effectiveness at or near the stall. If augmentation completely suppresses the pitching motion, the three-degree-of-freedom longitudinal equations reduce to two:

$$\begin{vmatrix} s-X_u & -X_w \\ -Z_u & s-Z_w \end{vmatrix} \begin{vmatrix} u \\ w \end{vmatrix} = \begin{vmatrix} X_\delta \\ Z_\delta \end{vmatrix} \delta - \begin{vmatrix} X_w \\ Z_w \end{vmatrix} w_g$$

from which the characteristic equation is found to be;

$$s^2 + (1/2\tau)(C_{L_\alpha} + 3C_D + V\frac{\partial C_D}{\partial u})s + (1/2\tau^2)(C_L{}^2 + C_D{}^2 + C_{L_\alpha}C_D - C_{D_{\dot\alpha}}) = 0$$

Ordinarily Z_w is overpowering, with the well-known result that two real roots are given by;

$$1/T_{\theta_1} = -X_w + Z_u X_w/Z_w$$

$$1/T_{\theta_2} = -Z_w$$

But at stall, Z_w is small. There, large C_{D_α} can result in destabilizing the motion: at constant attitude, a decrease in airspeed causes a steeper descent; at the higher angle of attack, drag is increased enough to force a further slowdown.

Another obvious example of possible destabilization through normal operation of the stability augmentation system, mentioned in Ref. 3, is roll rate feedback to ailerons: aileron deflection intended to increase lift on one side may actually cause that wing to stall, and adverse aileron yaw may promote a yawing divergence. Additionally, if aileron deflection into a spin is needed for recovery, a roll damper would fight spin recovery.

These examples show the need for careful consideration of Aircraft Normal States. As discussed under 3.4.1.2 the application to Aircraft Failure States is intended to force careful consideration of failure possibilities and consequences, not necessarily to prohibit compliance by means of the flight control system. Not all significant failures are electronic in nature; Reference 3, for example, mentions the disasterous effect of a stuck slat on one side. In each case the procuring activity will need to weigh tradeoffs in deciding whether or not to grant a Special Failure State. Given the difficulty of accurate early analysis, such problems may not be found until later on, when changing the design of the basic airframe has become exceedingly costly.

Amendment 2 changed the terms of the warning range for accelerated stalls from angle of attack to lift coefficient. According to Ref. 3:

> Angle of attack, rather than load factor, was used as the stall-warning reference...because some airplanes at certain flight conditions exhibit a rather wide range of angle of attack over which the lift coefficient changes relatively little. Stall warning loses its impact and interferes with maneuvering if it occurs at an angle of attack too far below the stall, as has been demonstrated on current operational airplanes.

Nevertheless, objections were raised that linear lift curves up to the stall are the exception rather than the rule, and the requirement should be compatible with the 1g stall warning requirement. Actually, [illegible] much more maneuvering capability remains at these lift coefficients: 1.15 V_s corresponds to 0.32g margin from complete stall, 1.05 V_s to 0.10g margin; these margins would be less if airspeed bleedoff is considered. The increased angle-of-attack margin also provides more timely warning when the stall is approached abruptly, as is common in maneuvering. Although not mentioned in the requirement, a pitch rate signal also could be added to trigger artificial stall warning sooner in abrupt maneuvers (Sensed angle-of-attack rate, since it would include gusts, likely would be too noisy a signal). In any case, occasions will arise when maximum airplane lift capability is needed. Therefore, it is desirable that warning, whether natural buffeting or other, increase in intensity as the stall is approached. Such a variation has been found helpful in gaging proximity to stall. The present wording requires such variation in intensity only for buffet. Another possibility is that buffet at a somewhat higher angle of attack may supplement other warning.

Estimating the onset of natural stall warning is difficult before flight. In judging adequacy, all these factors should be kept in mind.

According to some sources, a 5% margin between warning and stall speed may not be sufficient. The margin needed is a function of the clarity and distinctiveness of warning, the severity of stall and difficulty of recovery, and the expected low-speed maneuvering. The 15% maximum speed margin avoids premature warning which might be disregarded, as well as allowing maneuvering up to 75% of maximum usable lift before the warning. Reduction from 15 to 10% for approach is a concession to carrier and assault-type landings, which utilize a relatively low nominal airspeed; pilots are expected to watch airspeed rather closely on approach.

Amendment 2 clarified that the angular excursion limits at stall apply for piloted control, not just controls-fixed. The 20° or 30° limits are on the amount of attitude change at stall. Reference 91 points out that cases exist in which a pilot's attempts at stabilization do not help, but actually induce instability. For the A-7, aerodynamic coupling between longitudinal and lateral-directional motions while sideslipping is shown to be the cause. While sideslip is not specifically mentioned in these requirements, it probably should be; some sideslip is common, even unavoidable at high angle of attack. Airplanes seldom even have a decent zero-sideslip reference.

Angular excursions in excess of the 20° or 30° limit would be considered to be "departures", and the requirements for departure resistance, characteristics and recovery would then apply.

Control effectiveness generally tends to diminish at extreme angles of attack. Some airplanes in recent times have encountered a stable trim condition in the post-stall region, with too little control effectiveness to break out and recover to unstalled flight. This has occurred with transport (e.g., BAC-111) and executive (e.g., Hansa Jet) aircraft as well as fighters (e.g., F-16). If wind-tunnel tests are extended to such high incidence, the results may be erroneous or they may not be believed. The possibility of such a stable deepstall condition must be precluded by design as much as possible. Reference 92 documents one example of an aerodynamic design solution. For transport and other low-maneuverability aircraft (in general, those not to have a flight spin demonstration) one might expect demonstration of compliance to stop short of post-stall flight test. The discussion of 3.4.10 considers other aspects of this problem.

Interim Amendment 1 limited uncommanded oscillations such as wing rock prior to stall to ± 10 degrees bank, ± 2 degrees in sideslip and pitch attitude. For Amendment 2 it was thought that such limits were too definitive for the state of the design art. Instead, such oscillations are not to "be objectionable to the pilot".

Amendment 1 modified, and Amendment 2 made more specific, the thrust levels for one-engine-out stalls. The intent is to apply the requirement at thrust settings likely in operational use. Throttling back for recovery, in the manner described in 3.4.2.1.3, is allowed.

D. 3.4.2.2 POST-STALL GYRATIONS AND SPINS

REQUIREMENTS

3.4.2.2 Post-stall gyrations and spins. The post-stall gyration and spin requirements apply to all modes of motion that can be entered from upsets, decelerations, and extreme maneuvers appropriate to the Class and Flight Phase Category. Entries from inverted flight shall be included for Classes I and IV airplanes. Entry angles of attack and sideslip up to maximum control capability and under dynamic flight conditions are to be included, except as limited by structural considerations. For all Classes and Flight Phase Categories, thrust settings up to and including MAT shall be included, with and without one critical engine inoperative at entry. The requirements hold for all Airplane Normal States and for all states of stability and control augmentation systems, except approved Special Failure States. Store release shall not be allowed during loss of control, spin or gyration, recovery, or subsequent dive pull-out. Automatic disengagement of augmentation systems, however, is permissible if it is necessary and does not prevent meeting any other requirements; re-engagement shall be possible in flight following recovery.

3.4.2.2.1 Departure from controlled flight. All Classes of airplanes shall be extremely resistent to departure from controlled flight, post-stall gyrations, and spins. The airplane shall exhibit no uncommanded motion which cannot be arrested promptly by simple application of pilot control. In addition, the procuring activity may designate that certain training airplanes shall be capable of a developed spin and consistent recovery.

3.4.2.2.2 Recovery from post-stall gyrations and spins. For airplanes which according to MIL-A-8861 must be structurally designed for spinning, the following requirements apply. The proper recovery technique(s) must be readily ascertainable by the pilot, and simple and easy to apply under the motions encountered. Whatever the motions, safe, consistent recovery and pull-out shall be possible without exceeding the control forces of 3.4.5.1 and without exceeding structural limitations. A single technique shall provide prompt recovery from all post-stall gyrations and incipient spins, without requiring the pilot to determine the direction of motion and without tendency to develop a spin. The same technique used to recover from post-stall gyrations and incipient spins, or at least a compatible one, is also desired for spin recovery. For all modes of spin that can occur, these recoveries shall be attainable within the number of turns, measured from the initiation of recovery action specified as follows:

Class	Flight Phase	Turns for Recovery
I	Category A, B	1-1/2
I	PA	1
Other Classes	PA	1
Other Classes	A & B	2

Avoidance of a spin reversal or an adverse mode change shall not depend upon precise pilot control timing or deflection. It is desired that all airplanes be readily recoverable from all attainable attitudes and motions. The post-stall characteristics of those airplanes not required to comply with this paragraph shall be determined by analysis and model tests.

DISCUSSION

Amendments 1 and 2 incorporated successive refinements to consideration of departure (other than conventional stall, from which immediate recovery has been required all along), post-stall gyrations and spins. A key item is entry attempts from upsets and extreme maneuvers appropriate to the Class and Flight Phase. A complete enumeration of these entry conditions is impossible; but MIL-S-83691A Table 1 gives current guidance, which is amplified by discussion in Ref. 27. MIL-S-83691A's definitions of departure susceptibility and resistance are pertinent here:

> 6.3.13 Extremely susceptible to departure: departure from controlled flight will generally occur with the normal application of pitch control alone or with small roll and yaw control inputs.
>
> 6.3.14 Susceptible to departure: departure from controlled flight will generally occur with the application of brief misapplication of pitch and roll and yaw controls that may be anticipated in operational use.
>
> 6.3.15 Resistant to departure: departure from controlled flight will only occur with a large and reasonably sustained misapplication of pitch and roll and yaw controls.
>
> 6.3.16 Extremely resistant to departure: departure from controlled flight can only occur after an abrupt and inordinately sustained application of gross, abnormal, pro-departure controls.

It is in this context that we require airplanes to be extremely resistant to departure. We note such recent extremes in inducing departure during flight-test as full asymmetric thrust (F-18) and whatever it takes to defeat flight control system departure-prevention measures. But flight testing with a stall limiter turned off is uncommon.

Prior to Amendment 1 there had been no general requirements on post-stall gyrations, as distinguished from spins. MIL-F-8785B had only a reference to the then-current spin demonstration requirements of the Air Force (MIL-S-25015) and the Navy (MIL-D-8708). For airplanes to be spun, MIL-S-25015 required ready recovery form incipient and fully developed (5-turn) spins - except 1-turn spins for landing, 2 turns inverted. MIL-F-8785B Amendment 1 kept the MIL-S-25015 numbers of turns for spin recovery and added more bounds on altitude loss during recovery. The Class I requirements are similar to those of FAR Part 23 for the Aerobatic Category. Amendment 2 deleted all altitude bounds, on the premise that wing loading and drag are set by other consideration, leaving only turns for recovery to determine altitude loss, and that these bounds on turns for recovery could not reasonably be reduced further. Amendment 2 also deleted a number of Amendment 1's "specifics" on departure techniques, as well as an Amendment 1 requirement for the start of recovery to be apparent within 3 seconds or one spin turn. Those specification features indicated desirable tests and characteristics, but added considerable detail in areas where design capability is lacking. That material is felt to be more pertinent to a flight demonstration specification such as MIL-S-83691.

A "panic button" which will always command the right recovery procedure, or display of proper recovery action, can be helpful in confusing situations.

An important addition in Amendment 2 is the requirement to determine by other means the post-stall characteristics of airplanes which will not be flight tested in that regime. For Class II and III airplanes, flight demonstration generally will stop short of all-out attempts to induce departure; control abuse will be scaled appropriately to aircraft missions. Nevertheless, repeated experience has shown the value of "what happens if" information in the Pilot's Handbook and the best possible assurance of the limitation of any catastrophic possibilities. Analyses, wind-tunnel and spin-tunnel testing are warranted even for large transport and bomber aircraft that will never be spun intentionally, even in flight test.

Although store release has at times been a standard part of spin recovery procedure (e.g., F-105) it has also been cautioned against (e.g., F-104). GFE racks may not be stressed for the loads encountered in a spin; conversely the stores may hit the airplane after release. Also, in emergencies the stores might hit friendly people or cause excessive, unwanted damage on the ground, and a lot of stores would be used up in the demonstration. Therefore, Amendment 1 specifically prohibited store release for recovery.

As pointed out in Reference 116 and 117, coupling between longitudinal and lateral-directional motion can precipitate loss of control. Reference 116 discusses the basic phenomenon in controls-fixed flight; Reference 117 gives a simplified analysis method using only static stability derivatives. Reference 91 shows an example application, and as indicated in the stall discussion also points out the possibility of closed-loop instability of the coupled longitudinal and lateral-directional motions when the pilot attempts to maintain control in pitch. These references emphasize the importance of considering nonzero-sideslip initial conditions. A number of references (e.g. Ref. 118) also cite the possibility of large yawing moments at zero sideslip, caused by asymmetric vortex shedding off the nose.

E. 3.4.3 CROSS-AXIS COUPLING IN ROLL MANEUVERS

REQUIREMENTS

3.4.3 Cross-axis coupling in roll maneuvers. For Class I and IV airplanes in yaw-control-free, pitch-control-fixed, maximum-performance rolls through 360 degrees, entered from straight flight or from turns, pushovers, or pullups ranging 0g to 0.8 n_L, the resulting yaw or pitch motions and sideslip or angle of attack changes shall neither exceed structural limits nor cause other dangerous flight conditions such as uncontrollable motions or roll autorotation.

During combat-type maneuvers involving rolls through angles up to 360 degrees and rolls which are checked at a given bank angle, the yawing and pitching shall not be so severe as to impair the tactical effectiveness of the maneuver. These requirements define Level 1 and 2 operation. For Class II and III airplanes, these requirements apply in rolls through 120 degrees and rolls which are checked at a given bank angle.

DISCUSSION

This paragraph has been given a new title, more descriptive than MIL-F-8785B's "Roll-pitch-yaw coupling". Note that from here to the end of section 3.4, MIL-F-8785C renumbers paragraphs that are otherwise unchanged, because of its reorganization of the preceding material.

F. 3.4.4.1 CONTROL FORCE COORDINATION

REQUIREMENT

3.4.4.1 Control force coordination. The cockpit control forces required to perform maneuvers which are normal for the airplane should have magnitudes which are related to the pilot's capabiltiy to produce such forces in combination. The following control force levels are considered to be limiting values compatible with the pilot's capability to apply simultaneous forces:

Type Control	Pitch	Roll	Yaw
Side-stick or Center-stick	50 pounds	25 pounds	
Wheel	75 pounds	40 pounds	
Pedal			175 pounds

DISCUSSION

The only change of substance is to indicate that for side-stick controllers the force needed to perform normal maneuvers has the same numerical limits as for a center stick. That difference in hand position should not greatly affect pilot capability.

G. 3.4.10 CONTROL MARGIN

REQUIREMENT

3.4.10 Control Margin. Control authority, rate and hinge moment capability shall be sufficient to assure safety throughout the combined range of all attainable angles of attack (both positive and negative) and sideslip. This requirement applies to the prevention of loss of control and to recovery from any situation for all maneuvering, including pertinent effects of factors such as regions of control-surface-fixed instability, inertial coupling, fuel slosh, the influence of symmetric and asymmethric stores (3.1.4), stall/post stall/spin characteristics (3.4.2 through 3.4.2.2.2), atmospheric disturbances (3.8) and Airplanes Failure States (3.1.10.1 and 3.1.10.2; maneuvering flight appropriate to the Failure State is to be included). Consideration shall be taken of the degrees of effectiveness and certainty of operation of limiters, e.g. control malfunction or mismanagement, and transients from failures in the propulsion, flight control and other relevant systems.

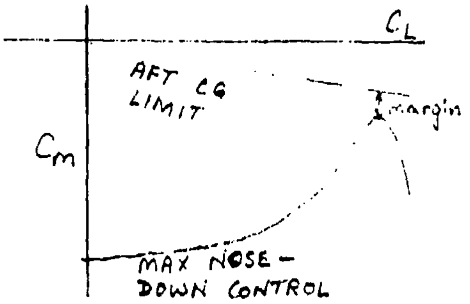
RELATED MIL-F-8785B PARAGRAPH

None.

DISCUSSION

Relaxed static stability, direct force control and other "control configured vehicle" (CCV) or "active control technology" concepts are gaining acceptance. They promise attractive mission performance benefits, while impressive gains continue to be made in reliability of stability augmentation. Therefore, we have allowed for trade-offs involving static instability and alternative control modes. To that end the requirements for control-surface-fixed stability have been deleted from 3.2.2.2 and 3.3.1.1. Also, the role of atmospheric disturbances is explicitly specified by the new requirements included in 3.8.

Whatever the cause, control saturation can be catastrophic in a basically unstable airframe. Then control deflection for recovery, whether commanded by thepilot or automatically, is just not available. This differs from the stable case, in which if the deflection limit is reached for trim full control authority is available for recovery. Control rate limiting can also induce instability if the basic airframe is unstable. Paragraph 3.4.10, together with the related changes mentioned, is intended to require full consideration of all the implications of relaxed static instability and other CCV concepts. It is well known that hinge moments can limit both deflection and rate of control surfaces. When using a surface for control in two axes, as with a horizontal stabilizer deflected symmetrically for pitching and differentially for rolling, priorities or combined limits must be set to assure safety. For the F-16, the full nose-down control put in by stability augmentation has to be overridden in order to rock out of a locked-in deep stall. Also, aerodynamicists sometimes have to remind control analysts that control surfaces themselves stall at an incidence somewhat less than 90°; and if control is supplemented by thrust vectoring, for example, one must consider the control force or moment available in normal operation, the effect on forward thrust, and the possibility of flameout. All the possible interactions of active control must be taken into account.



In considering how much margin or control should be required there is no general quantitative answer, but it is possible to enumerate some cases to consider. Certainly there should be sufficient control authority to pitch the airplane out of any trim point to lower the angle of attack from any attainable value. That is, with full nose-down control the pitching moment should be at least a little negative at the most critical attainable angle of attack, for a center of gravity on the aft limit and nominal trim setting. "Attainable angle of attack" is another issue in itself; but lacking intolerable buffet or a limiter effective in every conceivable situation, angles to at least 90° should be considered. Encountering the wake vortex of another aircraft can be an extremely upsetting experience. These encounters are not uncommon in practice or real air combat, and also may occur in the terminal area and elsewhere; prediction is difficult. Other atmospheric disturbances can be severe too: jet streams, storms, wakes of buildings, etc.

The amount of control capability at extreme angles of attack, positive and negative, must be enough to recover from situations that are not otherwise catastrophic. Avoidance of a locked-in deep stall has been known to limit the allowable relaxation of static stability. Also, control must be sufficient to counter the worst dynamic pitch-up tendency below stall or limit angle of attack. Propulsion and flight control system failure transients must be considered, along with possibly degraded control authority and rate after failure. Fuel system failure or mismanagement must be allowed for.

The flight task will dictate some minimum amount of nose-down control capability. Air combat maneuvering certainly imposes such a requirement, and so do terminal-area operations. Then, there should be some capability to counter atmospheric disturbances while maneuvering and center-of-gravity movement due to fuel slosh while accelerating or climbing, stop rotation at the take-off attitude, etc.

The range of maneuvers considered should account for both the stress of combat and the range of proficiency of service pilots. For example, in 1919 the British traced a number of losses of unstable airplanes to control authority insufficient to complete a loop that had got flattened on top (Ref. 93). Thus nose-up capability at negative angles of attack can also be important. For CCVs as well as conventional airplanes, limiters can help greatly but their effectiveness and certainty of operation need to be considered. Spins attained in the F-15 and F-16 attest to the possibility of defeating limiters. Reference 91 describes the A-7 departure boundary's closing in with increasing sideslip angle; angular rates also affect departure boundaries. Rapid rolling sometimes creates inertial coupling which can put great demands on pitch control. And the transients that propulsion or flight control system failures might cause must be considered as well as gusts and wind shear. Spin/post-stall gyration susceptility and characteristics will be affected.

External stores change both center of gravity and pitching moment (C_{m_0} and C_{m_α}). Experience with past aircraft indicates a firm need to allow some margin to account for unforeseen store loadings. With relaxed static stability this can determine not only the safety, but the possibility of flight with stores not considered in the design process.

Uncertainties exist in the design stage. Nonlinear aerodynamics, particularly hard to predict even from wind-tunnel tests, are almost certain to determine the critical conditions. The center of gravity, too, may not come out as desired. And in service the cg location is only known with limited accuracy. There are also possible malfunctions and mismanagement in fuel usage to consider. We have even seen recent cases (e.g., F-111 and F-16) of misleading wind-tunnel results on basic static stability. Aeroelasticity and dynamic control effectiveness (e.g., F-15) can also reduce control margins.

In addition to conventional control modes, a CCV's direct force controls can offer a number of new possibilities ranging from independent fuselage aiming to constant-attitude landing flares. The additional variables must be accounted for to assure adequate sizing of the control surfaces.

The instabilities and complications resulting from these factors can probably be rectified by stability augmentation if and only if control effectiveness is adequate. The controllability margin conventionally provided by static stability must be traslated for CCVs into margins of control authority and rate.

Paragraph 3.4.9 precludes dangerous single failures. After the first failure it may be advisable to constrict flight envelopes for some assurance of flight safety in case, say, a second hydraulic system should fail. The procuring activity will need to weigh the expected frequency and operational consequences of such measures against predicted benefits.

We do not intend thorough flight demonstration in all cases to show compliance with this requirement. "The combined range of all attainable angles of attack and sideslip" may even extend beyond the Permissible Flight Envelope, except for certain highly maneuverable fighter and trainer airplanes. Flight test bounds will be established according to such requirements as MIL-S-83691. For more extreme flight conditions a combination of model testing - wind-tunnel, free-flight if necessary, and hardware - and analysis will often be adequate.

The requirements of 3.4.10 are largely an emphasis or amplification of other requirements in this specification, among them

3.1.4 External stores

3.1.10.2 Airplane Failure States

3.1.10.2.1 Requirements for specific failure

3.1.10.3.3 Flight outside the Service Flight Envelope

3.2.3.6 Longitudinal control forces in dives - Permissible Flight Envelope

3.2.3.7 Longitudinal control in sideslips

3.3.4.1.2 Roll performance in Flight Phase CA

3.3.8 Lateral-directional control in dives

3.3.9 Lateral-directional control with asymmetric thrust

3.4.2.1.3 Stall prevention and recovery

3.4.2.2.2 Recovery from post-stall gyrations and spins

3.4.3 Cross-axis coupling in roll maneuvers

3.5.5 1 Failure-transients

3.5.6.1 Transfer Transients

3.6.3.1 Pitch trim changes

3.8 Requirements for use of the disturbance models

H. 3.4.11 DIRECT FORCE CONTROLS

REQUIREMENT

3.4.11 Direct force controls. Use of devices for direct normal-force control and direct side-force control shall not produce objectionable changes in attitude for any amount of control up to the maximum available. This requirement shall be met for Levels 1 and 2.

RELATED MIL-F-8785B PARAGRAPH

3.6.5

DISCUSSION

In Reference 2, the related paragraph (3.6.5 Direct normal-force control) was at the end of the section on Secondary Control Systems. Current technology allows the use of direct force controls either as components of the primary flight control system or as trimming systems (Reference 89). The requirement has been moved to the end of the miscellaneous flying qualities section, immediately preceding the section on primary flight control systems. The opportunity has also been taken to generalize the requirement to include side-force control in addition to normal-force control.

Pending the development of more explicit requirements on the use of direct force controls, the wording of 3.4.11 remains purely qualitative - prevent objectionable attitude changes. The assertion of Reference 2 that "This new paragraph requires the designer to minimize pitching moments associated with the use of any direct-lift control device, so that the pilot is provided with an essentially pure lift control" needs to be corrected. Favorable attitude changes should be considered by the designer, and may even be required for some tasks to achieve the potential benefits. For some tasks, a blended normal force and pitching moment (maneuver enhancement) response to control input gives the most beneficial results. Using this approach, it is possible to achieve a conventional-type of attitude response which is better than can be achieved with a single control surface. What is an "objectionable attitude change" needs to be considered within the context of the piloting task.

Reference 94 documents results of a study to develop more explicit criteria. Bandwidth is proposed as the governing parameter:

> The bandwidth of the specified response to a particular control input is defined as the lowest frequency for which the (open-loop) phase margin is at least 45 degrees and the gain margin is at least 6db.

Table 2 lists the response variables, associated with different tasks, which could potentially be subject to the requirements. The required bandwidths proposed in Reference 94 are shown in Table 3. The effects of attitude changes on the 'pure' force modes were also investigated. Small amounts of proverse attitude interference to increase the bandwidth of the mode were acceptable;

TYPICAL AIRCRAFT PARAMETERS SUBJECT TO BANDWIDTH LIMITATION IN MIL STANDARD

TASK	CONTROL VARIABLE
Air-to-air tracking	Pitch or yaw angle if angle of attack or sideslip are not an importance factor for weapon release Path angle if angle of attack or sideslip must be left small for weapon release
Air-to-ground tracking	
Pointing tasks Strafing Photo	Pitch or yaw angle
Flight path tasks Dive bombing	Path angle, normal or lateral velocity
Path deviation tasks and landing	Path angle, normal or lateral velocity

TABLE III.
TENTATIVE BANDWIDTH LIMITATIONS

TASK	REQUIRED BANDWIDTH (rad/sec)	
	LEVEL 1	LEVEL 2
Tracking (CAT A) Air-to-air gunnery Strafing Photo Dive bombing	1.25	0.60
Path deviation (CAT C) Formation Air-to-air refueling Approach	0.30	0.12
Short final and landing path response ("CAT D")	$(\dot{H}_F - 3)/10$* or 1.25	? 0.60

*$\dot{H}_F$ = sink rate in ft/sec on visual or instrument glide slope

however, the pilots did not want the bandwidth increased by large amounts of proverse attitude change. Adverse attitude changes were degrading, of course.

The controller mechanization is also a critical factor in the practical benefits to be realized from the additional theoretical capabilities with additional control surfaces. Reference 94 discusses the data in Reference 89 which shows that the pilot was unwilling or unable to manipulate the two controllers (sidestick and thumb button) used in that mechanization. The theoretical benefits were not achieved in some of the modes. Reference 94 discusses the problem but criteria need to be developed.

SECTION IX

STATEMENT AND DISCUSSION OF PRIMARY FLIGHT CONTROL SYSTEM REQUIREMENTS (3.5)

3.5 CHARACTERISTICS OF THE PRIMARY FLIGHT CONTROL SYSTEM

GENERAL DISCUSSION

One major factor in the need for the current revision (and for even further revisions) is the use of the flight control system (FCS) to modify airplane response. There is the possibility of having a flight control system for which it is difficult to distinguish between primary and secondary FCS, or between manual and automatic FCS. The current MIL-F-9490D combines the primary and secondary designations into a Manual Flight Control System (MFCS) classification. Reference 26 presents as justification: "The change from Primary/Secondary FCS to Manual FCS was made as a result of a serious concern with the high percentage (up to 50 percent) of recent Air Force incident/accident reports which are due to secondary flight control problems. To reduce the number of problems with Secondary Controls, the differentiation between Primary/Secondary control requirements in areas such as failure immunity has been dropped or sharply reduced." A validation study of MIL-F-9490D, Ref. 95, supports the use of the single MFCS designation but there is some discussion of the wording used. In MIL-F-9490D there is still the distinction between Manual and Automatic FCS, which is not addressed directly in MIL-F-8785B. MIL-F-9490D includes "augmentation, performance limiting and control devices" in the MFCS. While it puts "stick or wheel steering" in the AFCS, it just states that "If this mode is required, MIL-F-8785, or if applicable, MIL-F-83300 Flying Qualities of Piloted V/STOL Aircraft , shall be used as the basis for control capability".

In the flying qualities specification the primary item of concern is airplane response, either to pilot control inputs or to external disturbances. The requirements should be independent of the details of the control system mechanization, as far as possible. In simple terms the airplane should do what the pilot wants, when he wants. The current revision incorporates some initial steps towards this goal. More generic terminology has been used for all controls. Requirements on control surface deflection have been deleted in favor of relating the requirements to the controller. An exception to this last change is the requirement on control surface lags retained in 3.5.3. The revisions incorporated in the current version are intended to remove prohibitions (real or implied) on the possible uses of advanced flight control technology.

A. 3.5.2.3 RATE OF CONTROL DISPLACEMENT

REQUIREMENT

3.5.2.3 Rate of control displacement. The ability of the airplane to perform the operational maneuvers required of it shall not be limited in the atmospheric disturbances specified in 3.7 by control surface deflection rates (3.8.3.1, 3.8.3.2 and 3.4.10). For powered or boosted controls, the effect of engine speed and the duty cycle of both primary and secondary controls together with the pilot control techniques shall be included when establishing compliance with this requirement.

DISCUSSION

The revision makes specific reference to new paragraphs 3.8.3 for qualitative requirements on the effects of atmospheric disturbance, and to 3.4.10 for requirements on control margin.

B. 3.5.3 DYNAMIC CHARACTERISTICS

REQUIREMENT

3.5.3 Dynamic characteristics. A linear or smoothly varying airplane response to cockpit-control deflection and to control force shall be provided for all amplitudes of control input. The response of the control surfaces in flight shall not lag the cockpit-control force inputs by more than the angles shown in Table XIII, for frequencies equal to or less than the frequencies shown in Table XIII.

TABLE XIII. Allowable control surface lags

Level	Allowable Lag deg	
	Category A and C Flight Phases	Category B Flight Phases
1	15	30
2	30	45
3	60	60

Control	Upper Frequency rad/sec
pitch	the larger of $\omega_{n\,SP}$ and 2.0
roll & yaw	the largest of ω_{nd}, $1/\tau_R$ and 2.0

In addition, the response of the airplane motion shall not exhibit a time delay longer than the following for a pilot-initiated step control force input.

TABLE XIV Allowable airplane response delay

Level	Allowable Delay Sec
1	0.10
2	0.20
3	0.25

Further, the values of the equivalent time delay derived from equivalent system match of the aircraft response to cockpit controls shall not exceed the values of Table XIV.

3.5.3.1 Damping. All control system oscillations shall be well damped, unless they are of such an amplitude, frequency and phasing that they do not result in objectionable oscillations of the cockpit controls or the airframe during abrupt maneuvers and during flight in atmospheric disturbances.

RELATED MIL-F-8785B PARAGRAPHS

3.5.3, 3.5.3.1 and 3.5.3.2

DISCUSSION

Table XIII has been retained in the form of a requirement on control surface motion, in contradiction with the emphasis on airplane response elsewhere in MIL-F-8785C. This was based on Navy desires to use this requirement and to provide continuity with current practice. Reference 3 discusses the requirement and approaches for measuring the lags either on the ground or in flight, and from either time or frequency responses. The phase lag at any given frequency is the product of that frequency times the time delay. The time delay is to be measured from the pilot's initiation of a step control input until the first indication of control surface motion (for Table XIII) or overall airplane response in the commanded motion variable (for Table XIV) for that control input. Generally, one would use the pitch, roll and yaw controls, respectively.

Reference 3 is also very interested in recognizing the problems of lags introduced by filtering the pilots input to cure a sensitive response. The "startling" new (at that time) results of Reference 96 were used to develop the requirements of 3.5.3 in MIL-F-8785B. Since that time, other studies[23, 48] have emphasized the general trend of lags and time delays beyond a certain threshold degrading pilot opinion. Unfortunately the design approach of filtering pilot inputs has progressed along with our knowledge of the problems caused by time delays. This concern has driven the revision to these requirements.

The data used in Reference 3 is reproduced in Figure 28a. As can be seen it is reasonable to interpret those results to develop more stringent requirements. The more recent data of Reference 48 is shown in Figure 28b. The results are taken to support the new requirements of Table XIII.

The results are also expressed as maximum time delays in airplane response in Table XIV. Those requirements also apply to the equivalent time delays determined in the process of obtaining lower-order equivalent systems approximations to the actual responses. The numerical values are supported in Fig. 29 from Reference 29c, and (from recent unpublished data) appear to be applicable to both pitch and roll axes for demanding tasks. The majority of the available data is for Class IV configurations, Reference 56d indicates that higher values may be acceptable for Class III but there is insufficient data to support requirements at this time.

Application of these requirements "for all amplitudes of control input" is an extension of MIL-F-8785B's "for reasonably large force inputs". The purpose is to ensure that effects of amplitude-dependent control or aerodynamic nonlinearities are adequately considered in the assessment and acceptance of handling qualities. In addition to problems at large amplitude, A'Harrah for example recently pointed (AFFTC PIO Workshop, November 1980) to oversensitivity at small amplitudes when a control and stabilization system with high forward-loop gains is adjusted for large-amplitude performance.

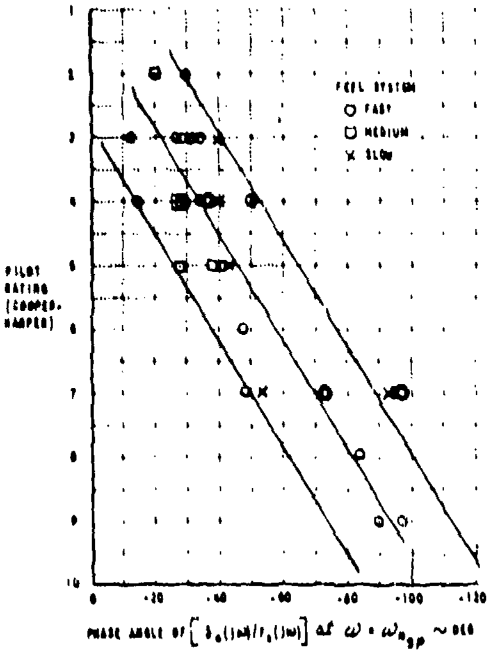


Figure 1 (3.5.3)
CATEGORY A AND C FLIGHT PHASES
(T-33, PILOT B, REFERENCE J59)

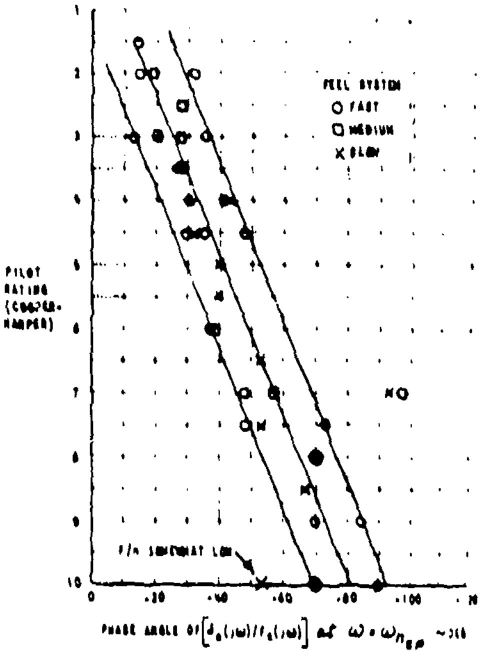
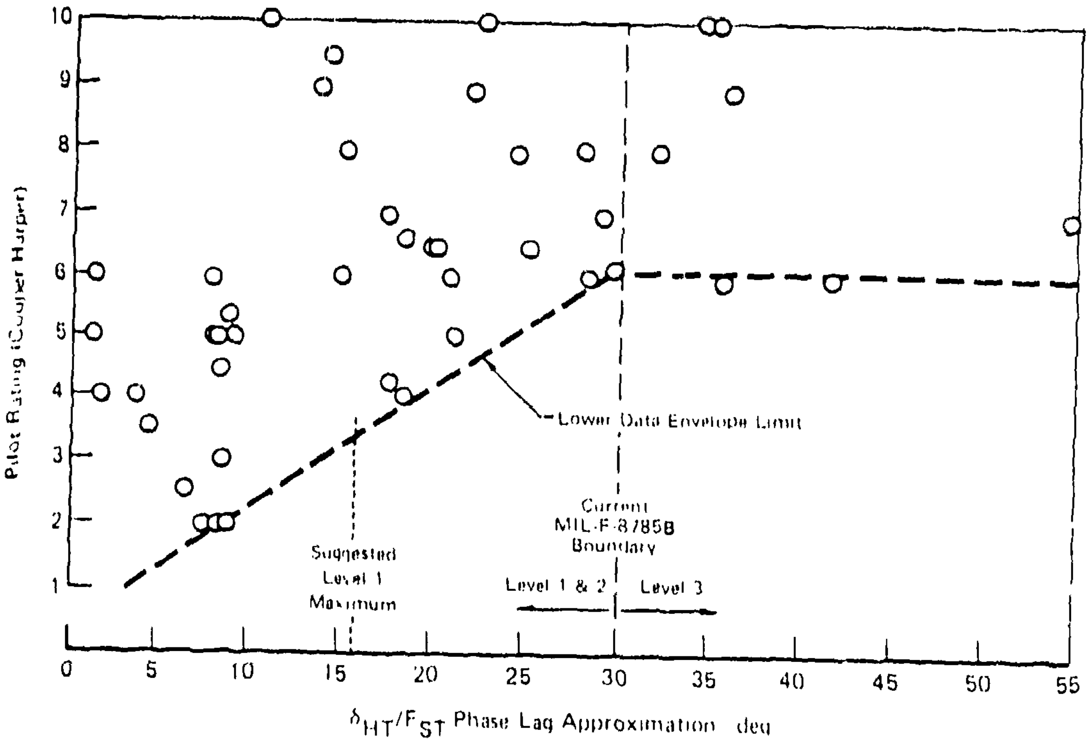


Figure 2 (3.5.3)
CATEGORY A AND C FLIGHT PHASES
(T-33, PILOT H, REFERENCE J59)

a. Data from Reference 3



b. Data from Reference 48

Figure 28. Correlation of pilot-rating with phase lag.

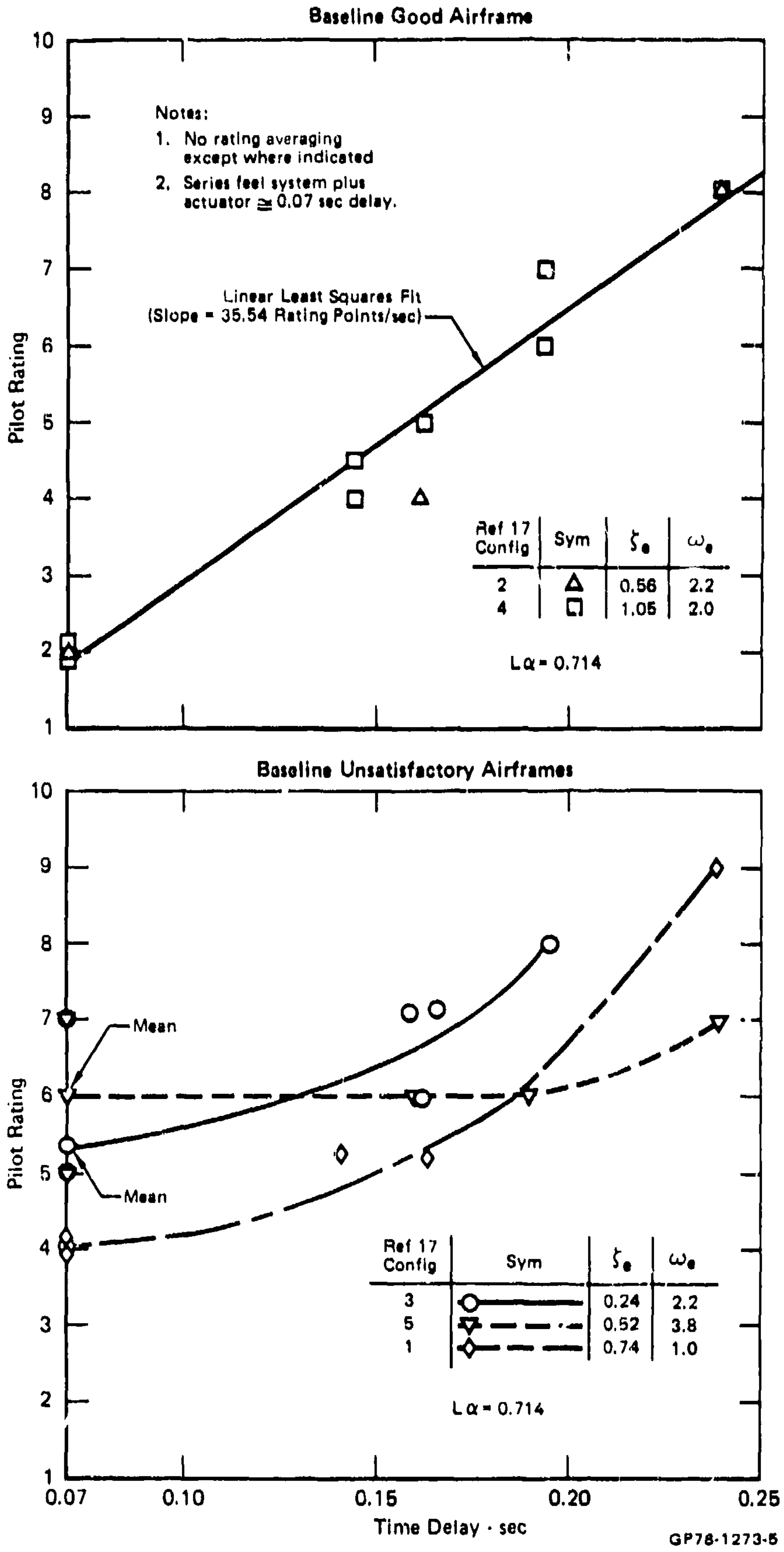


Figure 29.
DEGRADATION OF PILOT OPINION RATING DUE TO EQUIVALENT TIME DELAY
LAHOS Data.

C. 3.5.4 AUGMENTATION SYSTEMS

REQUIREMENT

3.5.4 Augmentation systems. Operation of stability augmentation and control augmentation systems and devices shall not introduce any objectionable flight or ground handling characteristics.

RELATED MIL-F-8785B PARAGRAPHS

3.5.4, 3.5.4.1 and 3.5.4.2

DISCUSSION

In 3.5.4 "Normal operation" has been changed to just "Operation", plus 3.5.4.1 and 3.5.4.2 have been deleted. These changes simplify the requirement so that neither normal nor abnormal operation should cause objectionable characteristics, i.e., only this basic requirement is stated. For abnormal operation, the definition and interpretation of objectionable characteristics must be consistent with any appropriate Failure State or degraded Level of flying qualities. The more detailed requirements of 3.5.4.1 and 3.5.4.2 are believed to be covered by the new paragraphs in 3.4.10 Control margin and 3.8.3 Effects of atmospheric disturbances.

D. 3.5.5 FAILURES

REQUIREMENTS

3.5.5 Failures. The following events shall not cause dangerous or intolerable flying qualities:

a. complete or partial loss of any function of the augmentation system following a single failure

b. failure-induced transient motions and trim changes either immediately after failure or upon subsequent transfer to alternate control modes

c. configuration changes required or recommended following failure

3.5.5.1 Failure transients. With controls free, the airplane motions due to failures described in 3.5.5 shall not exceed the following limits for at least 2 seconds following the failure, as a function of the Level of flying qualities after the failure transient has subsided:

Levels 1 and 2 (after failure)	±.5 g incremental normal or lateral acceleration at the pilots station and ±10 degrees per sec 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 ft and ±2 degrees bank angle.
Level 3 (after failure)	No dangerous attitude or structural limit is reached, and no dangerous alteration of the flight path results from which recovery is impossible.

3.5.5.2 Trim changes due to failures. The change in control forces required to maintain attitude and sideslip for the failures described in 3.5.5 shall not exceed the following limits for at least 5 seconds following the failure:

Pitch -------------------------------------20 pounds
Roll --------------------------------------10 pounds
Yaw ---------------------------------------50 pounds

DISCUSSION

The basic requirements of the MIL-F-8785B paragraph have been restated to achieve the real objective of preventing dangerous conditions as a result of a single failure or related events. The phrase "Failure-induced transient motions .... shall be small and gradual..." that was a part of the MIL-F-8785B requirement has deliberately been deleted. Although the intent was to ensure "that dangerous flying qualities never result", there may be some benefit to a noticeable transient after a failure, or after transfer to an alternate control mode in order to alert the pilot to the change. That possibility is left to the designer without explicit direction to minimize transients.

The acceleration and roll rate limits are now consistent with the requirements in MIL-F-9490D, the back-up document of which (Reference 26) refers to MIL-F-8785B for additional requirements. The revision basically follows the recommendations of Reference 12. In particular, the authors noted that the allowable transient levels of MIL-F-8785B were consistent with failure probability considerations but not with flying qualities considerations. Level 2 has a lower probability of occurrence than Level 1 and was permitted to have larger transient responses, however Level 2 is a poorer handling qualities state and cannot as readily accept the larger responses. It was felt that the values in the current revision were representative of transients which could be handled with Level 1 flying qualities. Conversely, the low allowable transients of MIL-F-8785B were conducive to soft failures which could lead to catastrophic situations if undetected by the pilot. This comment applied to the B-58, in particular, and led General Dynamics/Ft Worth to suggest a minimum allowable transient (according to Reference 12). This has not been incorporated into the current revision, but should be a consideration in the design process.

The 5ft limit on failure transients should preclude collisions in formation flight and also minimize the time span of large but allowable accelerations. If observation by chase plane is not sufficient, accelerometer measurements could be integrated to determine compliance.

Lastly, the revision of 3.5.5.2 was contained in Amendment 2 and makes it clear that the requirement is to apply to incremental forces.

E. 3.5.6 TRANSFER TO ALTERNATE CONTROL MODES

REQUIREMENT

3.5.6 Transfer to alternate control modes. The transient motions and trim changes resulting from the intentional engagement or disengagement of any portion of the primary flight control system by the pilot shall be such that dangerous flying qualities never result.

3.5.6.1 Transfer transients. With controls free, the transients resulting from the situations described in 3.5.6 shall not exceed the following limits for at least 2 seconds following the transfer:

Within the Operational Flight Envelope	±0.1 g normal or lateral acceleration at the pilot's station and 3 degrees per second roll
Within the Service Flight Envelope	±0.5 g at the pilot's station, 5 degrees per second roll, the lesser of 5 degrees sideslip and the structural limits.

These requirements apply only for Airplane Normal States.

3.5.6.2 Trim changes. The change in control forces required to maintain attitude and zero sideslip for the situations described in 3.5.6 shall not exceed the following limits for at least 5 seconds following the transfer:

Pitch --20 pounds
Roll ---10 pounds
Yaw ---50 pounds

These requirements apply only for Airplane Normal States.

DISCUSSION

Again, the phrase "small and gradual enough" has been deleted in favor of a more basic requirement just to prevent dangerous flying qualities. The allowable transients have been increased for reasons similar to those presented in discussion of 3.5.5. Also the addition to 3.5.6.2 from Amendment 2 has been incorporated to indicate that the requirement is on incremental forces.

This requirement applies to intentional actions by the pilot. Again, following the discussion of 3.5.5 there is also a need to consider the results of inadvertent engagement or disengagement of portions of the flight control system. Reference 97 presents the results of an accident investigation in which it is conjectured that inadvertent control input could have been a causal factor: "the DFDR (Digital Flight Data Recorder) readout indicates a vertical acceleration transient of 0.04 g causing a 200-f.p.m. rate of descent. For a pilot to induce such a transient, he would have to intentionally or inadvertently disengage the altitude hold function. It is conceivable that such a transient could have been produced by an inadvertent action on the part of the pilot which caused a force to be applied to the control column. Such a force would have been sufficient to disengage the altitude hold mode". Note that the vertical acceleration transient of 0.04 g was less than the original requirement in MIL-F-8785B, and was also probably less than a pilot's threshold of recognition. There was, however, a significant long-term effect of that unnoticeable transient, namely a rate of descent. The current limit of 0.1 g may allow consideration of the trade-off of the nuisance of a transient upon intentional actions versus the positive annunciation value of a noticable transient following inadvertent inputs. The answer to this implied question is left to the designer. In the above discussion, "dangerous flying qualities" is interpreted rather broadly since an undetected unwanted rate of descent is a problem regardless of the Level of flying qualities.

SECTION X

STATEMENT AND DISCUSSION OF SECONDARY CONTROL SYSTEM REQUIREMENTS (3.6)

3.6 CHARACTERISTICS OF SECONDARY CONTROL SYSTEMS

A. 3.6.1 TRIM SYSTEM

REQUIREMENT

3.6.1 Trim system. In straight flight, throughout the Operational Flight Envelope the trimming devices shall be capable of reducing all the cockpit control forces to zero for Levels 1 and 2. For Level 3 the untrimmed steady-state cockpit control forces shall not exceed 10 pounds pitch, 5 pounds roll and 20 pounds pedal. The failures to be considered in applying the Level 2 and 3 requirements shall include trim sticking and runaway in either direction. It is permissible to meet the Level 2 and 3 requirements by providing the pilot with alternate trim mechanisms or override capability. Additional requirements on trim rate and authority are contained in MIL-F-9490 and MIL-F-18372.

DISCUSSION

Apart from terminology changes, the substantive effect of this revision is to apply the Level 3 requirements to steady-state control forces. This allows transient forces to exceed the limits specified in this paragraph.

B. 3.6.1.2 RATE OF TRIM OPERATION

REQUIREMENT

3.6.1.2 Rate of trim operation. Trim devices shall operate rapidly enough to enable the pilot to maintain low control forces under changing conditions normally encountered in service, yet not so rapidly as to cause over-sensitivity or trim precision difficulties under any conditions. Specifically, it shall be possible to trim the pitch control forces to less than 10 pounds for center-stick airplanes and 20 pounds for wheel-control airplanes throughout (a) dives and ground attack maneuvers required in normal service operation and (b) level-flight accelerations at maximum augmented thrust from 250 knots or V_R/C, whichever is less, to V_{max} at any altitude when the airplane is trimmed for level flight prior to initiation of the maneuver. In the event that operation of the trim system requires removeal of one hand from the wheel-control, Level 1 force limits shall be as for a center-stick.

DISCUSSION

The change applies centerstick force limits when one-handed operation of a wheel controller is necessary to trim.

C. 3.6.1.4 TRIM SYSTEM IRREVERSIBILITY

REQUIREMENT

3.6.1.4 Trim system irreversibility. All trimming devices shall maintain a given setting indefinitely unless changed by the pilot or by a special automatic interconnect (such as to the landing flaps), or by the operation of an augmentation device. If an automatic interconnect or augmentation device is used in conjunction with a trim device, provision shall be made to ensure the accurate return of the device to its initial trim position on removal of each interconnect or augmentation command.

DISCUSSION

The wording of MIL-F-8785B has been rearranged for clarification without any intended change in the requirement.

D. 3.6.2 SPEED AND FLIGHT-PATH CONTROL DEVICES

REQUIREMENT

3.6.2 Speed and flight-path control devices. The effectiveness and response times of the longitudinal control shall be sufficient to provide adequate control of flight path and airspeed at any flight condition within the Operational Flight Envelope. This requirement may be met by use of devices such as throttles, thrust reversers, auxiliary drag devices, and flaps.

DISCUSSION

Consistent with the changes to more generic control terminology throughout Reference 1, this paragraph has been revised to apply to any longitudinal control, i.e., any control with its action in the x-z plane of the aircraft.

E. 3.6.3 TRANSIENTS AND TRIM CHANGES

REQUIREMENT

3.6.3 Transients and trim changes. The transients and steady-state trim changes for normal operation of secondary control devices (such as throttle, thrust reversers, flaps, slats, speed brakes, deceleration devices, dive recovery devices, wing sweep, and landing gear) shall not impose excessive control forces to maintain the desired heading, altitude, rate of climb, speed or load factor without use of the trimmer control. This requirement applies to all in-flight configuration changes and combinations of changes made under service conditions, including the effects of asymmetric operations such as unequal operation of landing gear, speed brakes, slats, or flaps. In no case shall there be any objectionable buffeting or oscillation caused by such devices. More specific requirements on secondary control devices are contained in 3.6.3.1, 3.6.4, and 3.6.5 and in MIL-F-9490 and MIL-F-18372.

DISCUSSION

The phrase "buffeting or oscillation of such devices" has been deleted in favor of "buffeting or oscillation caused by such devices" - a semantic distinction to include airframe buffeting as well as buffeting of the device itself.

SECTION XI

STATEMENT AND DISCUSSION OF ATMOSPHERIC DISTURBANCES (3.7)

3.7 ATMOSPHERIC DISTURBANCES

GENERAL DISCUSSION

For the purpose of the flying qualities specification an engineering model of atmospheric disturbances is required. This engineering model may be considered as the simplest model which is consistent with any related usage in aircraft design, but still correctly identifies the primary parameters of particular interest. This is in contrast to the objectives of basic research into meteorological phenomena or the physics of atmospheric dynamics. It is also noted that terminology has different connotations depending on an individual's background or field of endeavor. To prevent any confusion, certain terms will now be defined for use in interpreting MIL-F-8785C. There is a small change from the nomenclature in MIL-F-8785B, which has been applied to all the following paragraphs, 3.7.1 through 3.7.5.2.

Mean Wind: This is the steady wind, the reference value on which perturbations are superimposed. The mean wind could vary with time and spatial coordinates, but is considered to be only a function of altitude. Since for engineering purposes the mean wind is constant with time, the meteorological concept of "averaging time" does not apply. There is no requirement for the "mean wind" to actually be a mean over any particular time period.

Wind Shear: This is the rate of change of magnitude of the mean wind with altitude.

Vector Shear: This is the rate of change of direction of the mean wind with altitude.

Turbulence: This term is used to denote the continuous, random fluctuations in wind velocity which must be described statistically. Actual atmospheric turbulence has been shown to be non-Gaussian; however, for the current purposes turbulance is assumed to be random with a normal, or Gaussian, distribution.

Gust: This term is used to denote a discrete or deterministic change in the wind velocity. In application gusts may be used independently or superimposed on a mean wind and/or turbulence to represent large disturbances. Used appropriately a gust can actually represent a discrete wind shear such as can occur at a temperature inversion; the large (3σ or 4σ) fluctuations that are not represented in the assumed Gaussian form of turbulence; the fluctuations due to the wake of man-made or topological features; or an independent discrete phenomenon such as the wing-tip vortex of another aircraft.

The above definitions depart from meteorological practice in order to allow some flexibility in defining models of atmospheric disturbances that are tractable for engineering analyses. Although the desirability of tractability should be obvious, flexibility is considered to be equally desirable. During the course of an aircraft development a variety of analyses, computer simulations, piloted simulations, etc. are performed with different objectives and different requirements for atmospheric disturbance inputs. The definitions given earlier identify and separate the primary parameters in atmospheric disturbances which relate to aircraft control and flying qualities. The synoptic effect of any or all of these parameters can also be obtained in a long simulation run. Ultimately, it is suggested that a piloted simulation should be performed which does combine all the above elements and so has the best possible representation of atmospheric disturbances.

The "best possible representation" of atmospheric disturbances is probably not going to be achieved by combining Gaussian turbulence with discrete gusts - better and better approximations would be achieved using more and more complex specifications for the gusts. The non-Gaussian character of actual disturbances which has been alluded to is supported in numerous reports (e.g., References 98-100). In contrast, from Reference 101: "It is the belief of the author that the mjor reasons for failing to achieve realism im many simulator studies are as follows:

1) Use of excessive gust severity values (the use of rms values of around 9 fps nearly always led to "unrealistic" response behavior; the use of the more appropriate values around 3 fps gave a more realistic feel).

2) Use of excessive integral scale values (the use of scale values of around 2500 ft gave unrealistic results, as with the high severity values; the use of scale values of only several hundred feet, as is more appropriate, gave a much better response interpretation).

3) In particular, the appropriate forcing inputs due to the gusts (forces and moments) were not used.

Many feel that the question of intermittency or nonstationarity has a lot to do with achieving realism. It is felt, however, that if the three items, listed had been handled more realistically, then nonstationarity aspects may not be important."

The use of non-Gaussian turbulence in simulations has also yielded mixed results. For the flying qualities study reported in Reference 102 the pilot chose a non-Gaussian turbulence representation as being more realistic than the Dryden form of Gaussian turbulence; however, he said that his ratings were not affected by the turbulence model. Reference 103 showed no conclusive results in an attempt to develop a non-Gaussian model. There are a variety of approaches to developing a non-Gaussian representation. It can safely be stated, therefore, that there is no unanimous opinion with respect to any departure from a Gaussian distribution of disturbances. In fact, the atmosphere itself does not have a uniquely non-Gaussian characteristic. Using the fourth order moment as a measure of "non-Gaussianness" Reference 104 indicates a wide range of values including Gaussian. The most significant point to be made here is that the atmospheric disturbance model to be used, for instance in a piloted ground-based simulation, should be consistent with the objectives of the simulation and the fidelity of the total system representation. The attempt in the current revision has not been to define a universal model but to identify the primary parameters of atmospheric disturbances. Thus non-Gaussian disturbances are suggested but not rigidly defined allowing flexibility in application.

A. 3.7.1 FORM OF THE DISTURBANCE MODELS

REQUIREMENT

3.7.1 Form of the disturbance models. Where feasible, the von Karman form shall be used for the continuous turbulence model, so that the flying qualities analyses will be consistent with the comparable structural analyses. When no comparable structural analysis is performed or when it is not feasible to use the von Karman form, use of the Dryden form will be permissible. In general, both the continuous turbulence model and the discrete gust model shall be used. The scales and intensities used in determining the gust magnitudes for the discrete gust model shall be the same as those in the Dryden turbulence model.

3.7.1.1 Turbulence model (von Karman form). The von Karman form of the spectra for the turbulence velocities is:

$$\Phi_{u_g}(\Omega) = \sigma_u^2 \frac{2L_u}{\pi} \frac{1}{[1 + (1.339L_u\Omega)^2]^{5/6}}$$

$$\Phi_{v_g}(\Omega) = \sigma_v^2 \frac{L_v}{\pi} \frac{1 + (8/3)(1.339L_v\Omega)^2}{[1 + (1.339L_v\Omega)^2]^{11/6}}$$

$$\Phi_{w_g}(\Omega) = \sigma_w^2 \frac{L_w}{\pi} \frac{1 + (8/3)(1.339L_w\Omega)^2}{[1 + (1.339L_w\Omega)^2]^{11/6}}$$

3.7.1.2 Turbulence model (Dryden form). The Dryden form of the spectra for the turbulence velocities is:

$$\Phi_{u_g}(\Omega) = \sigma_u^2 \frac{2L_u}{\pi} \frac{1}{(L_u\Omega)^2 + 1}$$

$$\Phi_{v_g}(\Omega) = \sigma_v^2 \frac{L_v}{\pi} \frac{1 + 3(L_v\Omega)^2}{[1 + (L_v\Omega)^2]^2}$$

$$\Phi_{w_g}(\Omega) = \sigma_w^2 \frac{L_w}{\pi} \frac{1 + 3(L_w\Omega)^2}{[1 + (L_w\Omega)^2]^2}$$

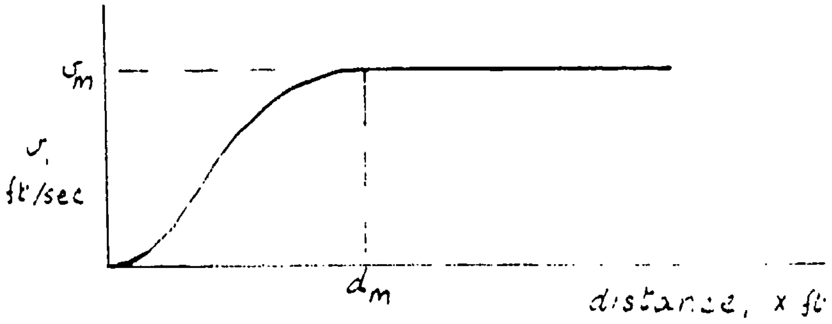
3.7.1.3 Discrete gust model. The discrete gust model may be used for any of the three gust-velocity components and, by derivation, any of the three angular components.

The discrete gust has the "1 - cosine" shape given by:

$v = 0 \quad , x < 0$

$v = \frac{v_m}{2}(1 - \cos\frac{\pi x}{d_m}) \quad , 0 \le x \le d_m$

$v = v_m \quad , x > d_m$



The discrete gust above may be used singly or in multiples in order to assess airplane response to, or pilot control of, large disturbances. Step function or linear ramp gusts may also be used.

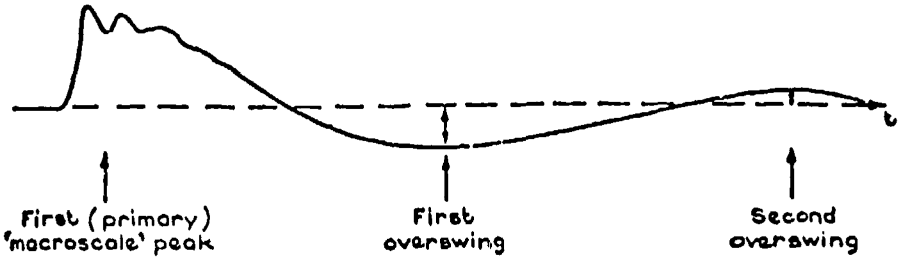
RELATED MIL-F-8785B PARAGRAPHS

3.7.2, 3.7.2.1, 3.7.2.2 and 3.7.2.3

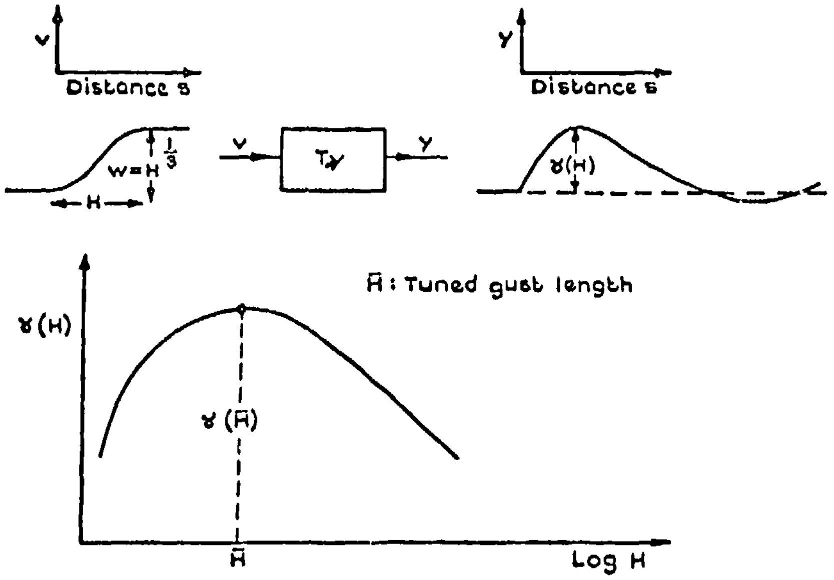
DISCUSSION

In keeping with the overall change making 3.7 just a presentation of the components of an atmospheric disturbance model, the above paragraphs contain the basic form and the equations for the turbulence and gust components. The presentation is little changed from MIL-F-8785B, continuing the implication that the von Karman form be used for analyses and the Dryden form for simulation. The equations for the turbulence spectra are retained as in MIL-F-8785B. As noted in Reference 13: "The spectra and scales as defined in... MIL-F-8785B give the correct answers, but for the wrong reasons". We decided to forego any "correction" at this stage, preferring to retain as much of MIL-F-8785B as possible.

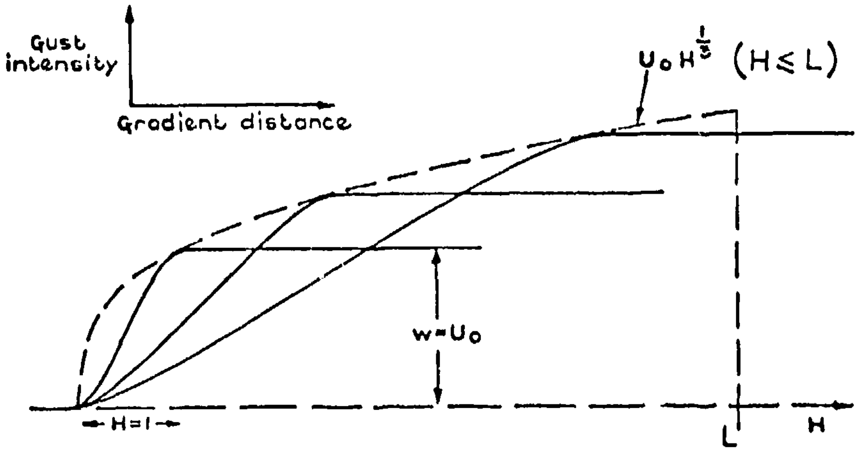
The "1 - cosine" profile for a discrete gust is retained; however, only half a period is specified in order to make the model more flexible. Sequences of two or more half-cycle gusts, appropriately spaced, may be found useful. One obvious application is to use a full period to determine the control authority needed to recover from a large disturbance. In the case of an unstable airframe, with stability provided by the flight control system, the gust recovery can be the critical control sizing criterion. The model and the wording of the requirement leave other options available, such as the requirement in Reference 20. Figure 30 illustrates the equiprobable gust family[100] and the application of the pair of ramp gusts[20]. The requirement states, in part: "The two component ramps have opposite sign and are each members of the same equiprobable family of single ramp gusts. The single ramp components as well as the spacing distance d_s should be varied over all significant distances until the response of maximum amplitude is found. However, to allow for the reduced probability of meeting this gust pattern, the magnitudes of the amplitudes $(v_{g_m})_1$ and $(v_{g_m})_2$ may be reduced from the magnitudes applicable to single ramp gusts by a factor of 0.85". This approach of searching for the worst combination is appropriate to the analysis of single-axis response. Jones' model was derived from consideration of point-to-point velocity differences, i.e., discrete gusts, rather than the distribution of the velocity components. This has been developed into a continuous spectrum of discrete gusts[100]. At this time, we do not know if the complexity of this model is justified for a full piloted simulation.



Typical transient response to discrete-ramp gust illustrating overswings



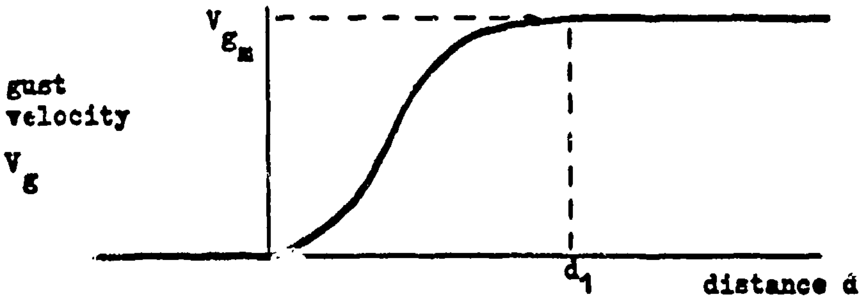
Discrete-gust response function



Family of equiprobable ramp gusts defined for $H < L$ by intensity parameter U_0

Figure 30. Discrete gust application of Jones

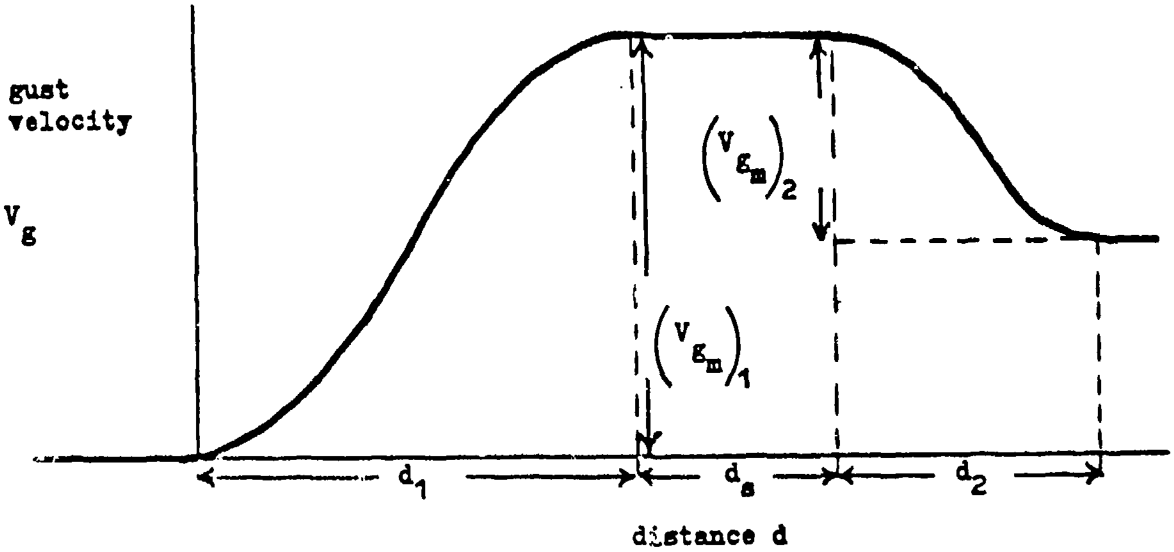
Single Ramp Gust (see para 3.3.3)



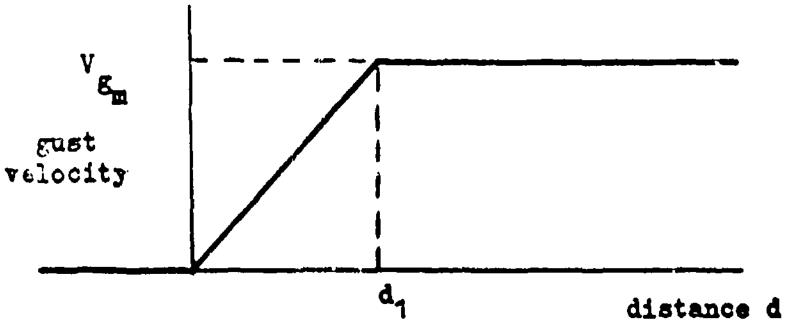
where

$$V_g = \begin{cases} 0 & d_1 < 0 \\ \frac{V_{g_m}}{2}\left(1 - \cos \frac{\pi d}{d_1}\right) & 0 \leq d \leq d_1 \\ V_{g_m} & d > d_1 \end{cases}$$

Pair of Ramp Gusts (see para.3.3.6)



Approximating the Discrete Gust Model (see para.3.3.7)



(Concluded) Figure 30. Discrete Gust Models (Cont)

B. 3.7.2 MEDIUM/HIGH-ALTITUDE MODEL

REQUIREMENT

3.7.2 Medium/high-altitude model. The scales and intensities are based on the assumption that turbulence above 2000ft is isotropic. Then

$$\sigma_u = \sigma_v = \sigma_w$$

and

$$L_u = L_v = L_w$$

3.7.2.1 Turbulence scale lengths. The scales to be used are $L_u = L_v = L_w =$ 2500ft using the von Karman form or $L_u = L_v = L_w =$ 1750ft using the Dryden form.

3.7.2.2 Turbulence intensities. Root-mean-square turbulence intensities are shown on figure 7 as functions of altitude and probability of exceedance. Simplified variations for application to the requirements of this specification are indicated.

3.7.2.3 Gust lengths. Several values of d_m shall be used, each chosen so that the gust is tuned to each of the natural frequencies of the airplane and its flight control system (higher - frequency structural modes may be excepted). For the Severe intensities modes with wavelengths less than the turbulence scale length may be excepted.

3.7.2.4 Gust Magnitudes. The Light and Moderate gust magnitudes u_g, v_g, w_g shall be determined from figure 8 using values of d_x, d_y, d_z determined according to 3.7.2.3, and the appropriate RMS turbulence intensities from figure 7. Severe gust magnitudes shall be:

a. 66ft/sec EAS at V_G, gust penetration speed

b. 50ft/sec EAS at $V_{O_{max}}$

c. 25ft/sec EAS at V_{max}

d. 50ft/sec EAS at speeds up to V_{max}(PA) with the landing gear and other devices which are open or extended in their maximum open or maximum extended positions.

e. For altitudes above 20,000ft the gust magnitudes may be reduced linearly from:

(1) 66ft/sec EAS at 20,000ft to 38ft/sec EAS at 50,000 for the V_G condition

(2) 50ft/sec EAS at 20,000ft to 25ft/sec EAS at 50,000ft for the V_{max} condition

(3) 25ft/sec EAS at 20,000ft to 12.5ft/sec EAS at 50,000ft for the V_{max} condition

f. For altitudes above 50,000ft the equivalent gust velocity specified at 50,000ft shall be multiplied by the factor $\sqrt{\rho/\rho_{50}}$, the square root of the ratio of air density at altitude to standard atmospheric density at 50,000ft.

Medium/high altitude only.

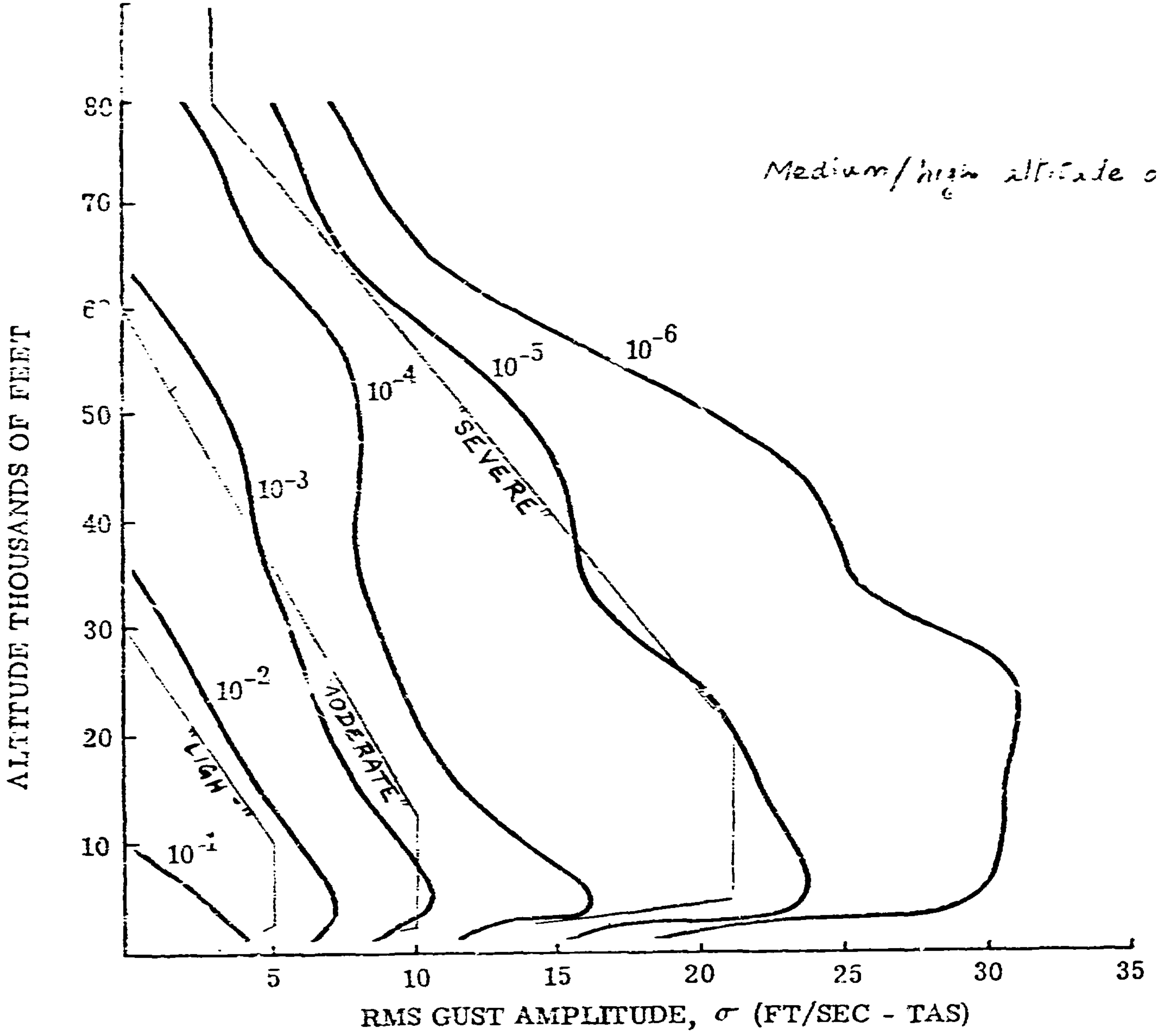


Figure 31. (MIL-F-8785C Fig. 7) Exceedance probability vs. altitude and RMS gust amplitude.

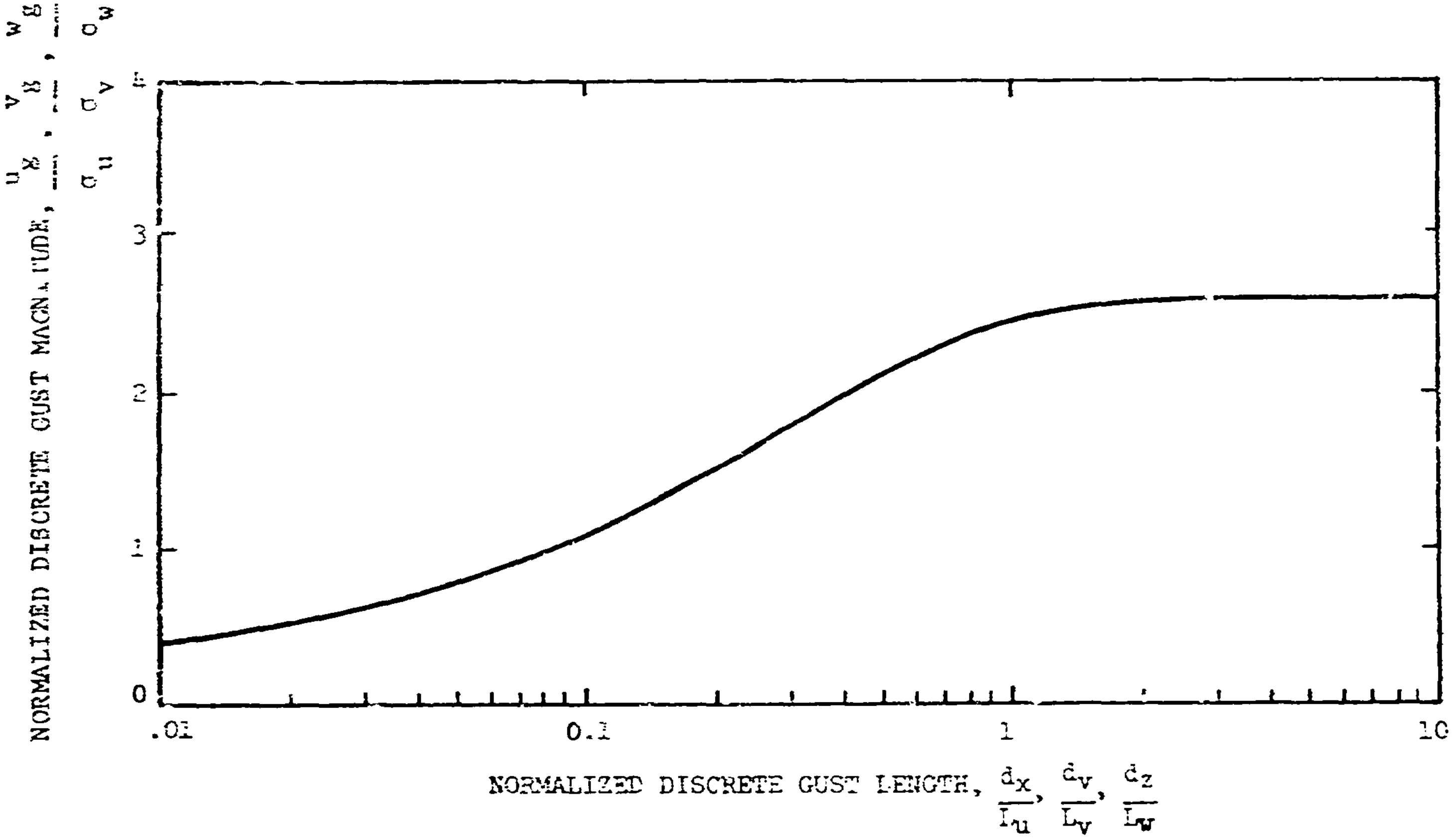


Figure 32. (MIL-F-8785C Fig. 9) Magnitude of discrete gusts.

RELATED MIL-F-8785B PARAGRAPHS

3.7.2 through 3.7.4.2

DISCUSSION

A major advance in Reference 2 was the definition of allowable causes and allowable limits of degraded flying qualities. This was done on a probability basis. Thus, the probability of encountering Level 2 flying qualities after a failure must be less than 10^{-2} per flight within the Operational Flight Envelope (OFE). Flight outside the OFF is also allowed to cause degraded flying qualities. Now, by common observation, atmospheric disturbances tend to degrade flying qualities according to the basic definitions, i.e., 'some increase in pilot workload or degradation in mission effectiveness, or both, exists'. If the pilot does not mentally compensate for his impression of the intensity of the disturbances, the result tends to be a degradation in pilot opinion. These effects occur whether the airframe modal characteristics are influenced or not. The revisions are an attempt to account for the two effects separately, as discussed in section 3.8. The problem in this section was to decide on rational probabilities for the degradation of flying qualities due to atmospheric disturbances per se, and then to define appropriate disturbance intensities.

In order to define the appropriate disturbance intensities we need to consider first the probability of encountering disturbances at all, and then the probable intensity of the disturbance once it has been encountered (as discussed in References 3 and 13). There are two approaches to using the available data, which is in the form of "global" averages. We can use disturbance intensities that correspond to a given probability of exceedance. This is analogous to requiring that the probability that flying qualities will be degraded to a lower Level due to atmospheric disturbances should be less than a specified value. This approach is consistent with other parts of the specification, such as the effects of augmentation failure. The alternative is to assume that disturbances of a given intensity will be encountered, i.e., with a probability of one. In this case, we need the intensities corresponding to a given probability of exceedance under the condition that disturbances have been encountered. These values are relatively insensitive to altitude (since it is mainly the probability of encountering disturbances at all that decreases with increasing altitude). This approach would be consistent with some other requirements in the specification, such as those pertaining to engine failure, which is assumed to happen regardless of probability.

The basic data shown in Figure 31 is taken from Reference 26. The numbers were calculated from the values of proportions of flight time in nonstorm turbulence and in storm turbulence, at a given altitude, and the mean intensity and standard deviation of nonstorm and storm turbulence at the altitude specified in MIL-A-008861A. Belatedly, then, the structures, the flight control system and the flying qualities specifications have consistent turbulence definitions. With all the approximations, assumptions and inaccuracies involved in the measuring, processing and application of the turbulence intensities, it is felt that the complex curves shown in Figure 31 are not justified. Simplified variations are therefore shown for the three intensity levels used in applying 3.7.3.2 to the requirements of the specification.

The most likely RMS turbulence intensity is reasonably invariant with altitude (Reference 3). Therefore a case can be made for something like:

Max. Cooper-Harper Rating

	Normal States		Failure States (P 10^{-4})	
Turbulence	OFE	SFE	OFC	SFE
light (≈2.5 or 3 fps)	3.5	6.5	6.5	9
moderate (≈5 or 6)	6.5	9	9	9
limit (9490D)	9	9	contr	--
thunderstorm (21)	contr	--	-	-

where "contr" should be interpreted to mean that control can be maintained for ejection or landing (MIL-F-9490D Operational State IV or V). This accounts for the <u>most likely</u> value (2.5 to 3 fps) of σ <u>if turbulence is encountered</u>, is coordinated with a related specification, and provides an additional measure of safety in extreme turbulence. "Moderate" turbulence has an order of severity comparable to MIL-F-8785B "clear air turbulence" at altitudes up to about 40,000 ft.

There is also merit in extending the controllability requirements beyond structural limit load. Some airplanes hold together even somewhat beyond design ultimate load, but that might be a suitable final cut-off for flying qualities requirements.

In order to meet mission reliability and flight safety requirements, flight control systems often employ redundant channels (sensors, computers, signal paths, actuation, etc.). Some means such as voting must be used to detect failures, in order to disengage the failed channel. It is important to make the right selection, that is, recognize failures when they occur, disengage the channel, and avoid false failure indications, all with high probability. Atmospheric disturbances, both discrete and random, affect this monitoring. Some small level of disturbance will exercise the system enough to provide good signals for monitoring. Sensor and installation errors etc., on the other hand, will cause the channels to track imperfectly; these differences are accentuated as the disturbance magnitude increases.

Thus we must ask, what are reasonable magnitudes of atmospheric disturbance to consider for flight control design? According to Pritchard (Ref. 3, pp 438), "although [the expected value of gust-intensity variance, E (σg)] is not really constant for nonstorm turbulence it is nearly enough constant so that for simplicity it may be assumed constant". "In MIL-F-8785B, it is assumed that a single value...is valid for clear air turbulence at all altitudes". His Rayleigh cumulative probability distribution P (σ), (Figure 33) has the mode, the most likely value, $\sigma = 2.3$ft/sec. The mean is $\sigma \simeq 2.8$ft/sec, $E(\sigma^2)$ is $(3.25)^2$ ft^2/sec^2.

Added to Fig. 33 are indications of "light", "moderate" and "heavy" turbulence as adopted by the British in their recent Av.P. 970 revision (Ref. 20).

Again quoting, "the discrete probability (P_1) of encountering turbulence at all, which is often called the proportion of time spent in turbulence, is a function of altitude" shown reproduced as Figure 34. At altitudes up to

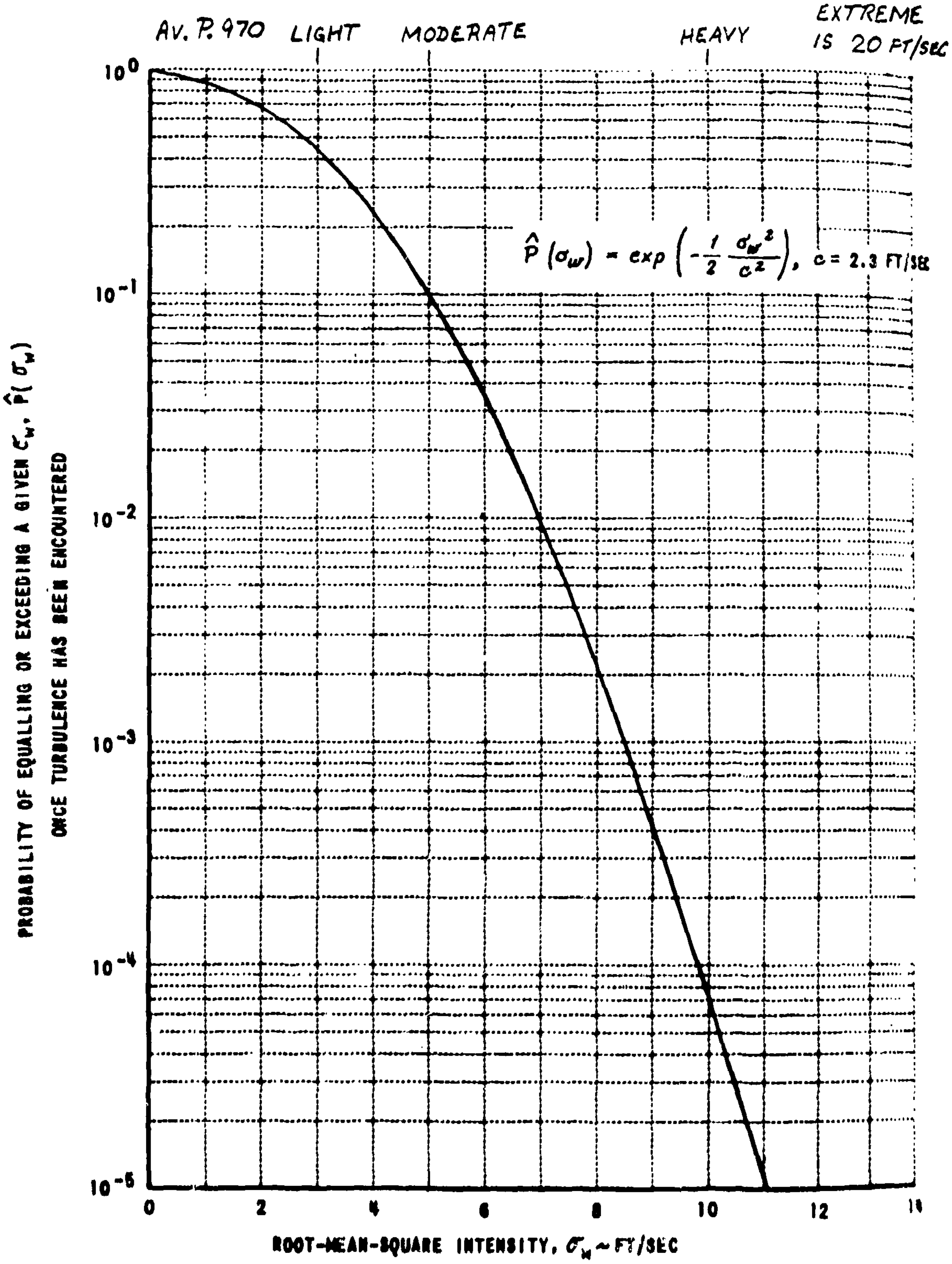


Figure 33. RMS Intensity vs. Exceedance Probability

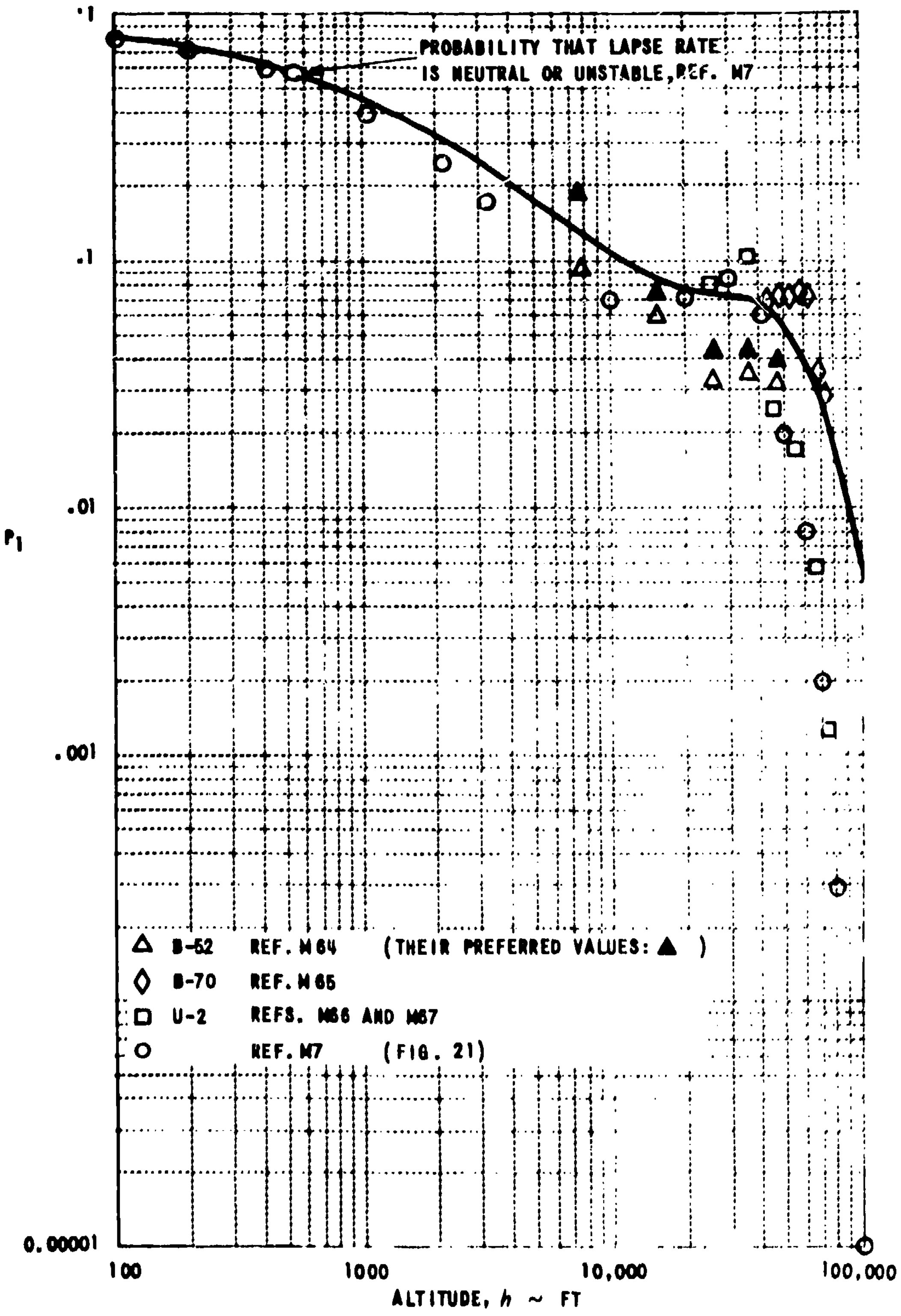


Figure 34. Probability of Encountering Turbulence

90,000ft the proportion is more than 1/100; up to 50,000ft it is more than 1/20; to 10,000ft more than 1/10. None of the proportions are negligible at common or likely airplane flight altitudes.

MIL-F-8785B defines the σ to be considered for clear air turbulence at each altitude as the level that would be exceeded only 1/100 of the time; that is, considering the probability of encounter and the level encountered to be independent, σ(h) is found by taking

$$P_1 \; P\,(\sigma) = .01$$

The result was MIL-F-8785B Fig. 8. In terms of the Av. P. 970 definitions the specified turbulence was more or less "moderate" from sea level to about 40,000ft altitude, than tapering off to "light" at about 75,000ft, going to "calm" at 90,000 feet.

For "essential" functions MIL-F-9490D requires that its specified turbulence reduce Operational State I (normal operation) no further than Operational State III (minimum safe operation, mission may be aborted). The MIL-F-9490D σ corresponds at V_G (gust penetration speed) roughly to MIL-F-8785B's "thunderstorm" turbulence, reducing at V_H to intensities corresponding to 10^{-2} to 10^{-4} probability of exceedance. According to the MIL-F-9490D probabilities the MIL-F-8785B σ corresponds to a 10^{-2} probability, roughly, to about 20,000'; 10^{-3} at 40,000'; 10^{-4} at 80,000'. These comparisons are illustrated in Figure 35, together with the recommended curves. As can be seen, the recommended curves are qualitatively similar to both MIL-F-8785B and MIL-F-9490D, but the simplification shown in this figure is felt to be justified by all the assumptions and implications of using global averages.

Av.P. 970 (Reference 20) Leaflet 600/5 notes some fundamental difficulty in estimating an average rate of equalling or exceeding a given σ. Nevertheless, "To assist...in assigning figures to the turbulence intensities in which the requirements of Part 6 are to be met and the intensities where relaxations are acceptable" the Leaflet presents these "typical relationships"

Probability of equalling or exceeding a given σ	Corresponding range of σ	Average (global) rate of equalling or exceeding a given σ
10^{-2}	1+ to 2+ m/s	1 per hour
10^{-4}	2 1/2 to 3 1/2	10^{-2} per hour
10^{-6}	4.6 to 6	10^{-4} per hour

"on the assumption of an average aeroplane speed of 800 km/hr (500 mile/hr or 434 kn)...whilst values...are valid as averages over a large number of flight hours (and over a wide range of environmental conditions) they...do not provide a realistic description...[of] a particular flight". This is also taken as supporting the simplifications recommended.

The discrete gust model is essentially the same as before, except that now there are three intensities or magnitudes specified. The Light and Moderate gust magnitudes are calculated as before. The Severe gust magnitudes are taken directly from MIL-A-008861A. For medium and high altitudes, the discrete gusts may be applied generally as a complete cosine period as specified in MIL-F-8785B.

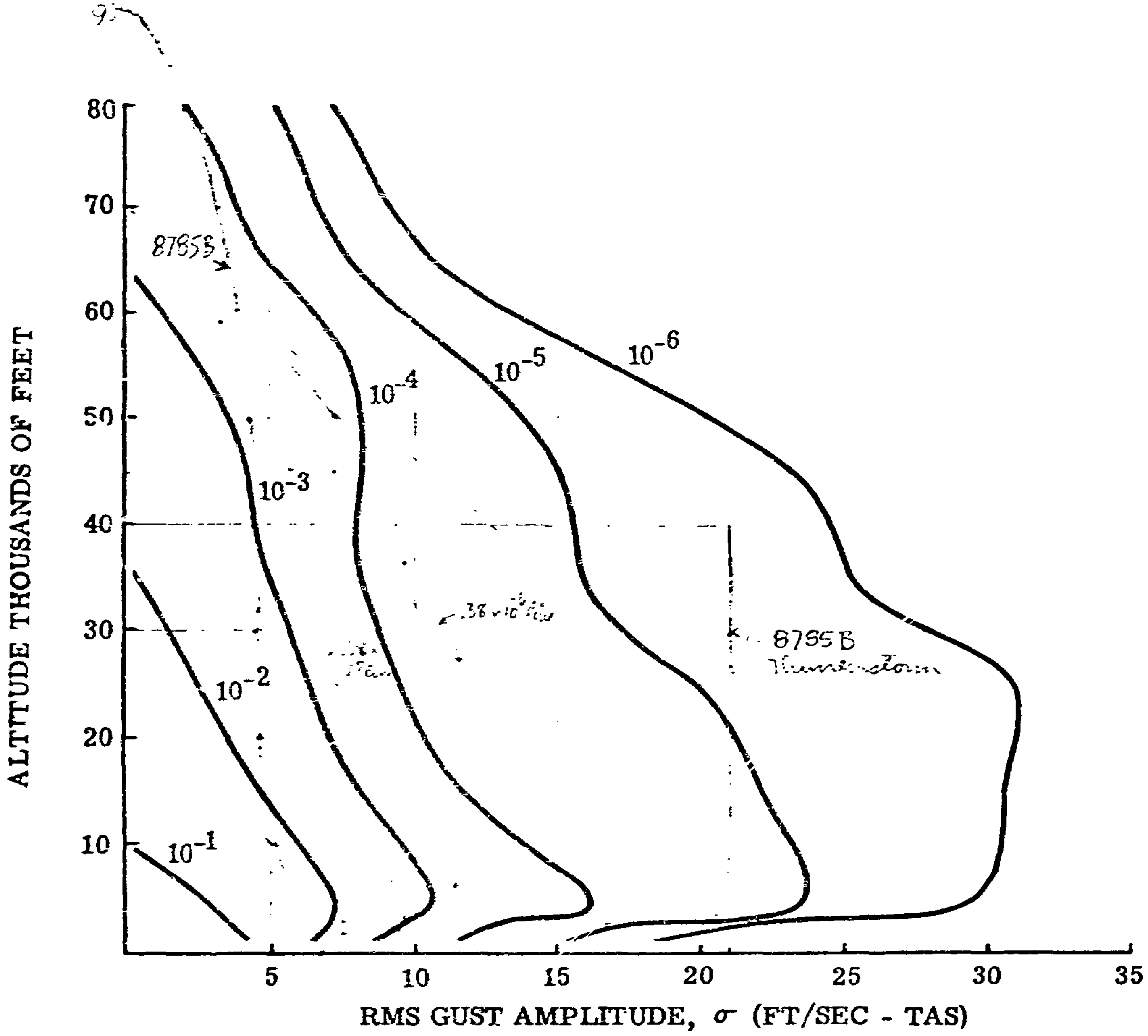


Figure 35. Exceedance probability vs. altitude and RMS gust amplitude.

In Figure 8 of MIL-F-8785C, the ordinate axis was inadvertently mislabeled, retaining the MIL-F-8785B nomenclature for the gust components. As indicated in Figure 32, "v_x/σ_u, v_y/σ_v, v_z/σ_w" should be "u_g/σ_u, v_g/σ_v, w_g/σ_w" in order to conform to the notation of 3.7.2.3.

C. 3.7.3 LOW-ALTITUDE DISTURBANCE MODEL

REQUIREMENT

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

DISCUSSION

The turbulence model in Reference 2 did account for the influence of the ground on the turbulence intensity and scale lengths. Reference 3 acknowledged the model to the "merely a formula that produces reasonable results". Comments from users, however, indicated that the variation close to the ground was not reasonable and that this was the weakest part of the model. Since terminal Flight Phases are critical in airplane design and operations, it was decided to specify a model just for conditions close to the ground.

The wording recognizes (maybe unnecessarily) that different parts of the disturbance model may be critical for different parts of the design; then separate analyses would be appropriate. A simulation of airplane response and controllability in a 'complete' representation of disturbances is required (addressed more fully in the discussion of the revisions to section 4.1).

D. 3.7.3.1 WIND SPEEDS

REQUIREMENT

3.7.3.1 Wind speeds. The wind speed at 20ft above the ground, u_{20}, is given in Figure 9 as a function of probability of occurence. The values to be used for the different levels of atmospheric disturbance are indicated.

3.7.3.2 Wind shear. The magnitude of the wind scalar shear is defined by the use of the following expression for the mean wind profile as a function of altitude:

$$u_W = u_{20} \frac{\ln (h/z_0)}{\ln (20/z_0)}$$

where z_0 = 0.15ft for Category C Flight Phase
2.0ft for other Flight Phases

3.7.3.3 Vector shear. Different orientations of the mean wind relative to the runway for Category C, or relative to the aircraft flight path for other Flight Phases, shall be considered. In addition, changes in direction of the mean wind speed over a given height change shall be considered as follows:

Disturbance Intensity	Change in mean wind heading degrees	Height of vector shear feet
LIGHT	0	--
MODERATE	90	600
SEVERE	90	300

A range of values for the initial wind orientation and the initial altitude for onset of the shear shall be considered. Relative to the runway, values of u_{20} sin ψ_W greater than the crosswind values in 3.3.7 or tailwind component at 20ft greater than 10 knots need not be considered. At any altitude other than 20ft these limits do not apply.

RELATED MIL-F-8785B PARAGRAPH

None

DISCUSSION

The mean wind speed is presented as a curve of probability of exceedance versus a value at 20ft above the ground. The values are consistent with those in MIL-F-9490D and Reference 105. The 20ft reference is used because this is the standard height of wind measuring towers at US airports. This wind speed is the one that a pilot would commonly know before landing. A simple logar-

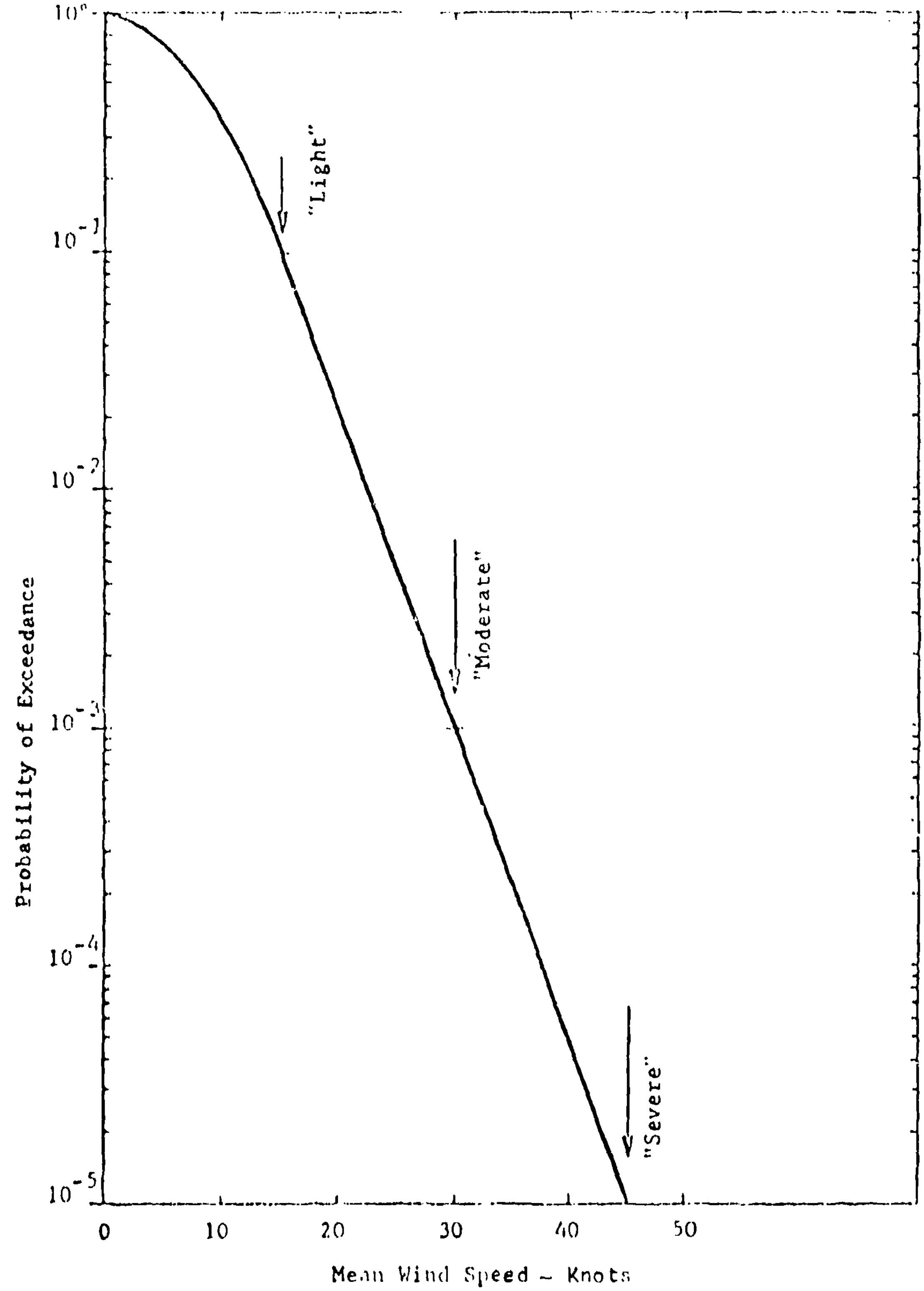


Figure 36. (MIL-F-8785C Figure 9) Probability of exceeding mean wind speed at 20 feet.

ithmic profile is specified in 3.7.3.2 to provide the typical variation of wind speed close to the ground. The value of surface roughness height, z_0, equal to 0.15ft is representative of flat terrain appropriate to most airports, applicable to terminal Flight Phases. The value of 2.0ft for other Flight Phases applies to rougher terrain; the practical effect is to produce more shear away from the ground. If an airplane mission specifically requires landing in rough terrain, an appropriate value for surface roughness height should be used.

Atmospheric stability has significant influences on wind and turbulence characteristics (see, for example, Reference 105 and 106). The mean wind variation produced by the logarithmic wind profile specified in 3.7.3.2 is appropriate for a neutral or slightly unstable atmosphere. The data presented in Figure 37 (Reference 107) indicates that this is consistent with surface wind speeds greater than approximately 10 Kts. Higher wind speeds enhance atmospheric mixing and support the near-neutral stability. Figure 37 also shows that a neutral/slightly unstable atmosphere (i.e., Categories C & D) and hence, by implication, the proposed wind profile occurs with approximately 55% probability. The logarithmic profile is also relatively benign in terms of its effects on aircraft flight path control. It can therefore be considered as a 'normal' wind variation appropriate for routine operation. The remaining categories include those atmospheric conditions which are frequently involved in accidents and, therefore, receive special emphasis.

Unstable conditions caused by the onset of strong surface heating are normally associated with light wind speeds. These conditions often cause significant fluctuations in wind direction, the production of thermals and thunderstorms. Stable atmospheric conditions are often associated with strong temperature inversions. A strong inversion has the ability to make conditions above and below it independent of each other, i.e., there is the potential for significant changes in wind speed and direction across the inversion. The changes in wind speed associated with these conditions (e.g., simple shear, updrafts, downdrafts, etc.) can conveniently be represented by discrete gusts for engineering purposes. Thus, although not directly a part of the 'wind speed' paragraphs, the discrete gusts of 3.7.3.5 adequately represent these effects in each axis separately. The probability of occurrence of changes in wind direction below 1000ft is quite low, in general, but may be associated with particular topographical features in addition to the above conditions. The potential effects on aircraft response and glideslope control can be particularly adverse for the real multi-axis piloting task of landing an aircraft. This was shown in one particular aircraft accident[108, 109]. The calculated winds, from those References and presented in Figure 38, were the result of the passage of a warm front. The data given shows that both the tailwind and crosswind were greater than 20 kts above 500ft altitude, with relatively little variation. Between 500ft and 200ft there was an extreme wind shear, such that the crosswind reduced to less than 5 kts and the tailwind decreased to zero, becoming a small headwind from 250ft to the ground. Thus, the winds by themselves presented a complex piloting task, although the shear in each axis separately was not severe. It can also be seen that the surface winds that would be given by the control tower (equivalent to a 4 kt headwind and a 2 kt crosswind) gave absolutely no indication of potential problems.

The final approach was made with autopilot coupled and autothrottle engaged. Because of conditions peculiar to the airfield the autopilot was

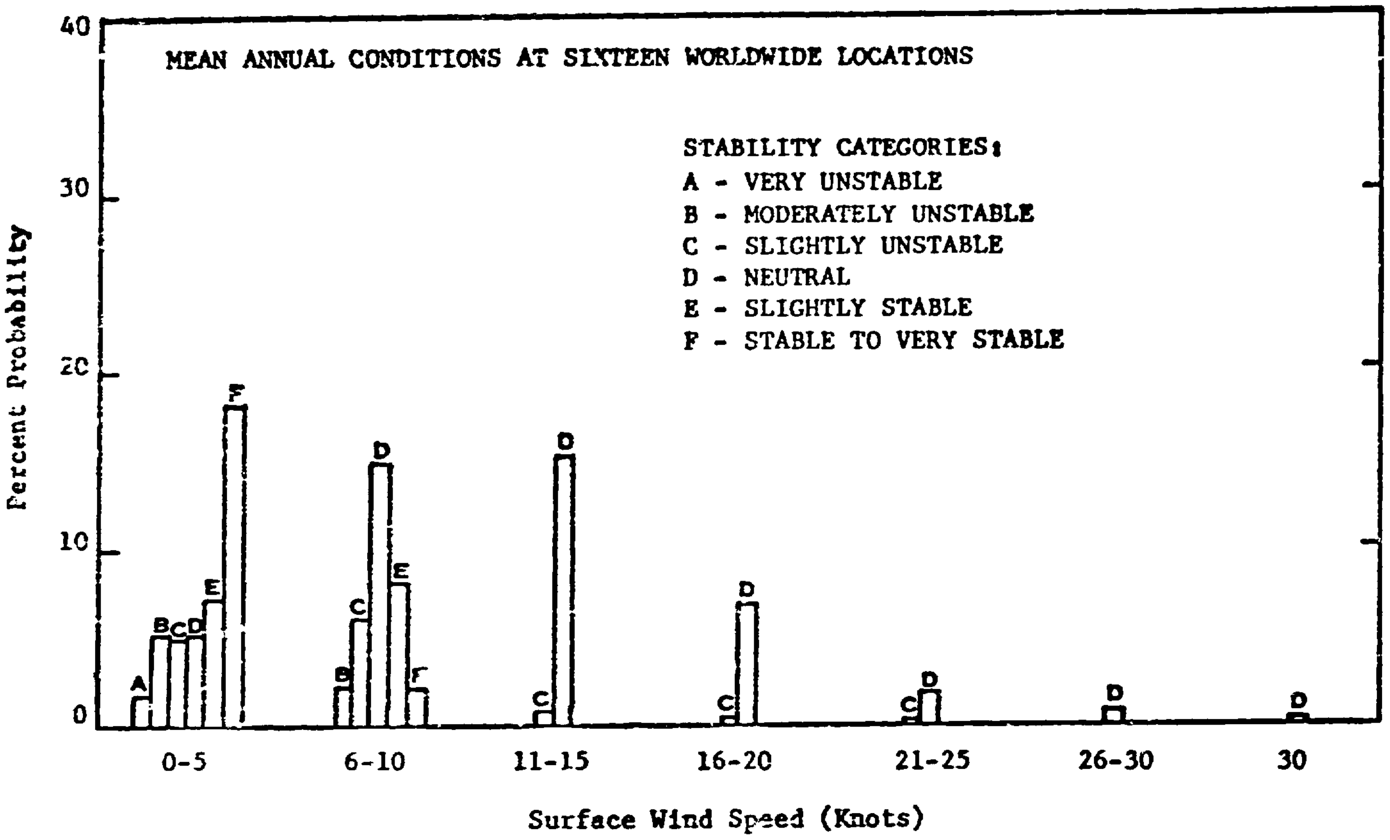


Figure 37. **Joint Percent Probabilities of Surface Wind Speed and Stability Categories**

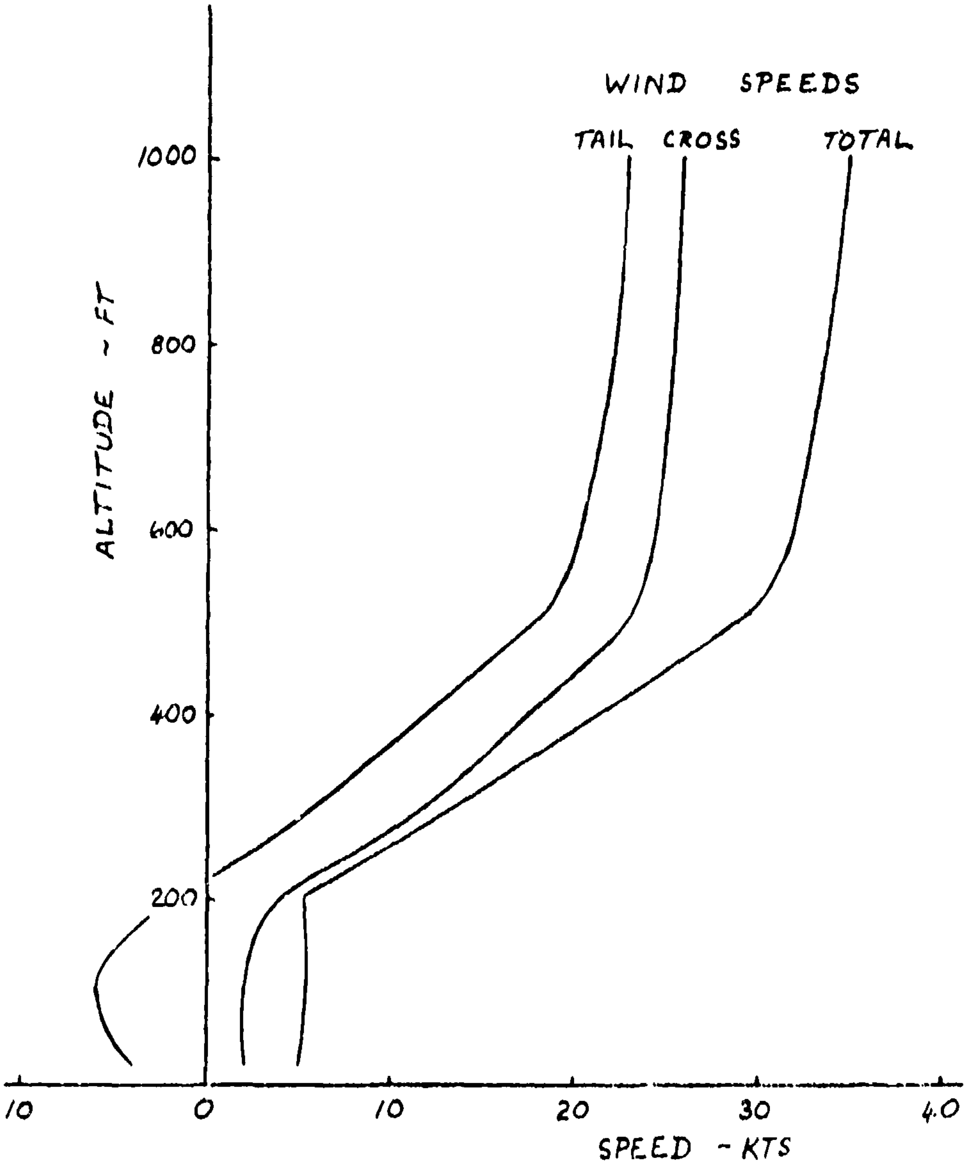
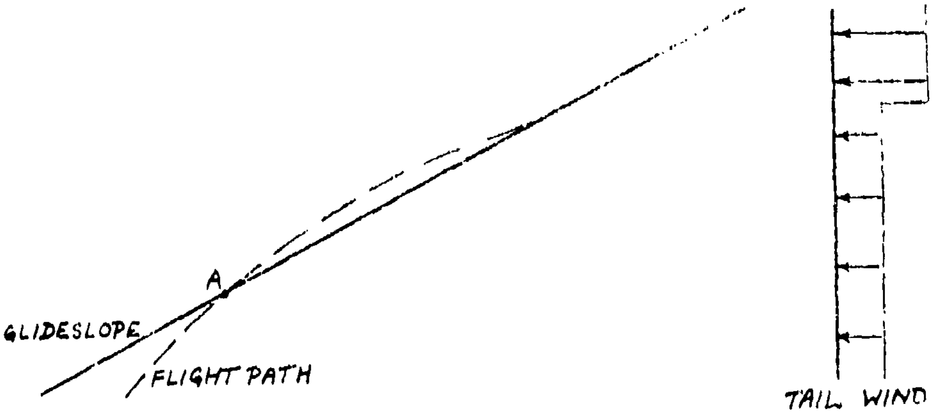


Figure 38. Wind Profile in DC-10 Accident

disengaged at 184ft altitude with the runway partially in sight, and a manual landing was attempted. Above 500ft the automatic flight control system (AFCS established off-nominal trim conditions of higher rate of descent, reduced thrust and reduced pitch attitude in order to maintain the glideslope. As the airplane descended through approximately 500ft the tailwind and crosswind began to decrease. With a decrease in tailwind, the momentum of the aircraft caused an initial increase in airspeed and consequent rise above the initial glideslope. This is discussed in Reference 108, the reference does not point out that without any control input the aircraft would decelerate to approximately the original airspeed and descend below the original glideslope, as sketched. The AFCS responded to the initial perturbation, however, by reducing thrust and decreasing pitch attitude, i.e., the opposite of the long-term corrections required. At point A in the sketch, as the aircraft starts to descend below the nominal glideslope, the AFCS would normally start to reverse the previous inputs and reacquire the glideslope. A further decrease in the tailwind prior to point A, however, would tend to produce another transient increase in airspeed and rise, causing further reduction in thrust and pitch attitude. Since the winds for the accident show a continuous wind shear down to200ft altitude, it is probable that the AFCS was continually correcting the "initial transient" by reducing thrust and pitch attitude until the point at which it was disengaged.



Also starting about 600ft the left cross wind began to decrease, causing the aircraft to move left of the localizer. Although the autopilot put in corrective control inputs, the aircraft was still left of the localizer (but close to the glideslope) when the autopilot was disconnected. With the available visual cues the pilot judged his primary task to be aligning with the runway. At this point, unfortunately, the aircraft was sinking through the glideslope and the pilot was unable to prevent a short landing. The preceding discussion illustrates the insidious nature of a slow vector shear which does not give the pilot an obvious warning of anything unusual.

A 'vector shear' has been included in the model for Moderate and Severe conditions, with primary application to piloted simulation (although it could be used in the design of automatic landing systems). It is felt that this generic disturbance, with the requirement to consider the worst direction and altitude, can be used to represent a variety of adverse environmental conditions. The addition of the vector shear with indeterminate probability means that the low-altitude model is not necessarily consistent; it does, however, form an engineering approach to identifying the primary effects on the landing task of some of the less probable wind shears. The alternate approach of specifying a particular wind profile or family of profiles is believed to be too prone to producing a configuration designed to fly in "the specification shear" at the expense of other real possibilities which are beyond [illegible] present knowledge to specify.

E. 3.7.3.4 TURBULENCE

REQUIREMENT

3.7.3.4 Turbulence. The turbulence models of 3.7.1.1 or 3.7.1.2 shall be used. The appropriate scale lengths are given in figure 10 as functions of altitude. The turbulence intensities to be used are $\sigma_w = 0.1\ U_{20}$, and σ_u and σ_v given by figure 11 as functions of σ_w and altitude.

DISCUSSION

These figures have been taken from Reference 105, where the justification is given.

Briefly, the vertical turbulence intensity has been fixed at a constant value of 10% of the reference wind speed. This is the same as the value specified in MIL-F-9490D. It is a reasonable approximation to the available data, although there is considerable scatter. Also in MIL-F-9490D, the longitudinal and lateral turbulence intensities have been set at double the vertical intensity. This is a simplification which is adequate for automatic landing system requirements. For the manual control requirements of MIL-F-8785C we have specified the more rigorous continuous variation in Figure 40. Also, the continuous variation of scale length with altitude, given in Figure 39, has been specified. This reduction in scale length is seen as a gradual suppression of low frequency disturbances with the power being transferred to higher frequencies as the pilot approaches the runway. This model has been used in a piloted simulation on FDL's LAMARS facility; it received subjective pilot approval.

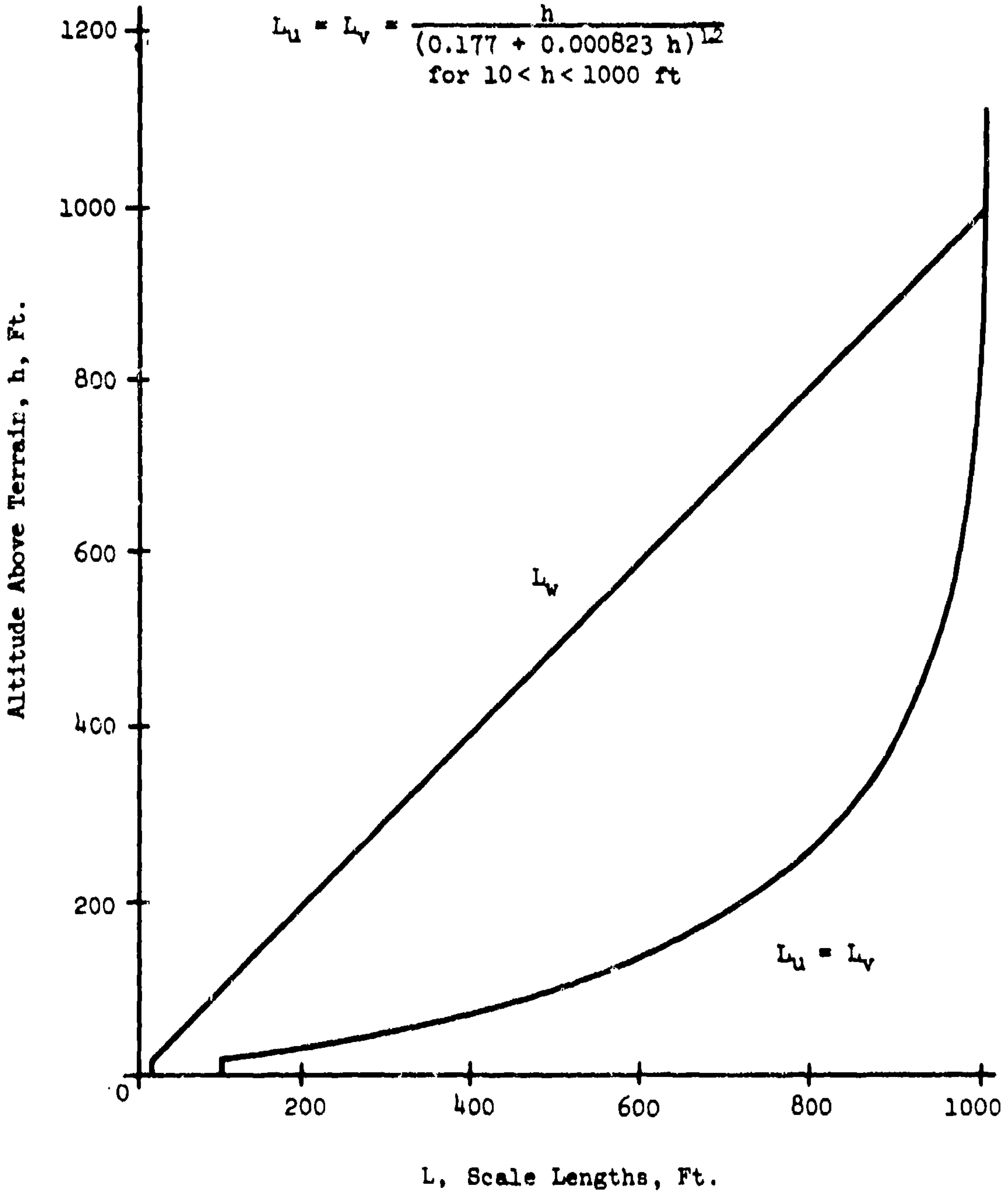
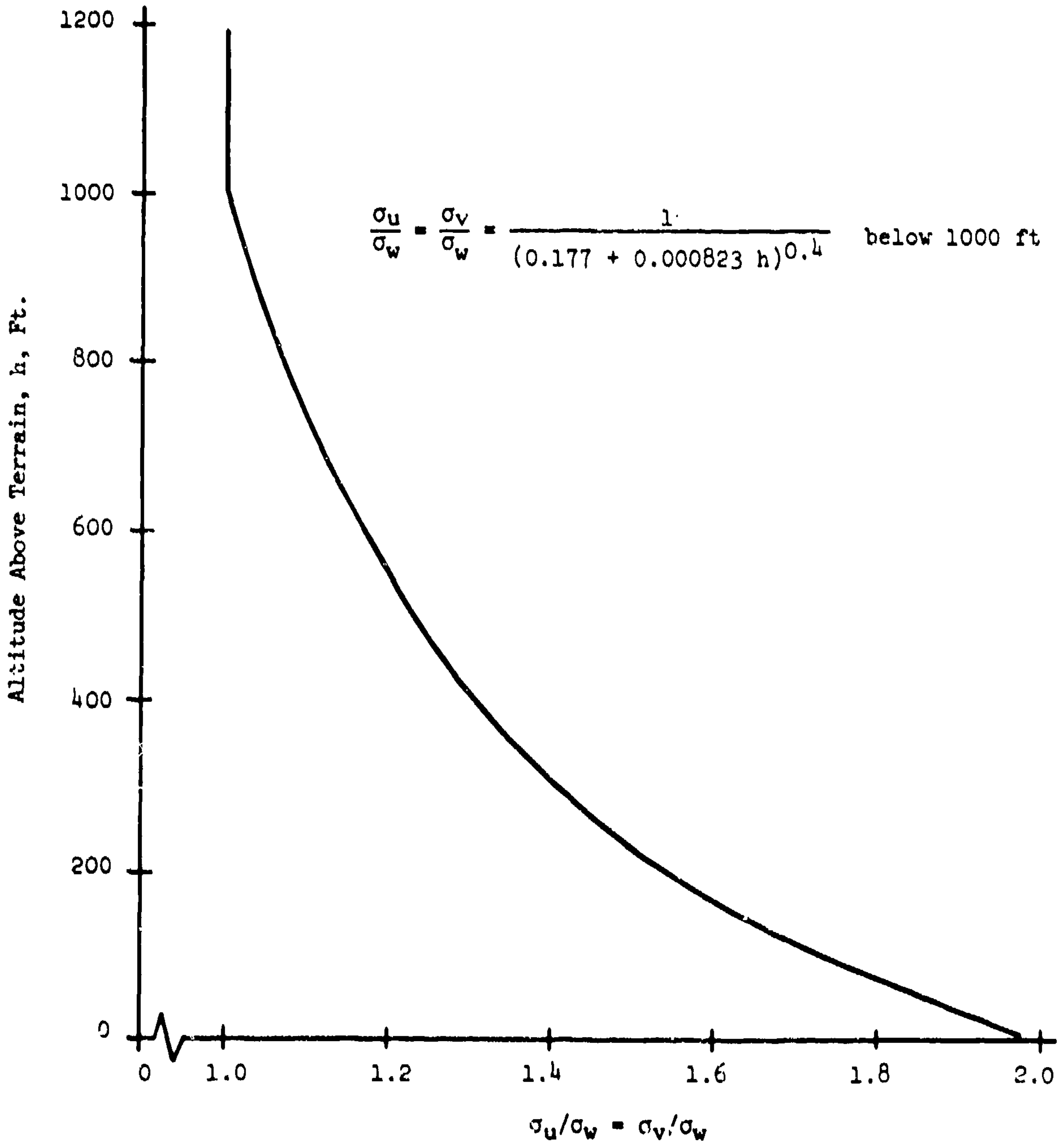


Figure 39. (MIL-F-8785C Figure 10) Low-Altitude Turbulence Integral Scales.



$$\frac{\sigma_u}{\sigma_w} = \frac{\sigma_v}{\sigma_w} = \frac{1}{(0.177 + 0.000823\ h)^{0.4}}$$ below 1000 ft

Figure 40. (MIL-F-8785C Figure 11) Horizontal turbulence RMS intensities.

F. 3.7.3.5 GUSTS

REQUIREMENT

3.7.3.5 Gusts. Discrete gusts of the form given in 3.7.1.3 shall be used, with both single and double ramps to be considered. Several values of d_m shall be used, each chosen so that the gust is tuned to each of the natural frequencies of the airplane and its flight control system. The gust magnitudes shall be determined from figure 8 using the appropriate values from figures 10 and 11. The two halves of a double gust do not have to be the same length or magnitude.

DISCUSSION

As noted in the introductory discussion to Section 3.7, the discrete gust can represent a number of different phenomena including wind shear. The basic model of 3.7.1.3 is also appropriate for representing a shear effect in any axis (horizontal wind shear, downdraft, etc.). In application, these effects can represent the cataclysmic disturbances influencing aircraft performance and controllability margins rather than the insidious piloting task of the vector shear of 3.7.3.3. We then have the problem of determining values of the gusts that ensure a realistic level of flight safety without making impossible design requirements. For medium/high altitudes we have required controllability up to structural limits.

Such extreme gusts are less probable close to the ground. They do happen, however, as evidenced by at least one takeoff accident that occurred due to a downdraft that exceeded the aircraft climb capability[110]. As specified, the model uses the probabilities of exceedance 10^{-1}, 10^{-3} and 10^{-5} giving corresponding mean wind speeds from 3.7.3.1 (Figure 36). Paragraph 3.7.3.4 then gives the three values of the three turbulence intensities, as functions of altitude. For each dynamic mode (natural frequency and gust length), Figure 32 then yields Light, Moderate and Severe gust magnitudes in each axis. It must be stressed that we do not have here a hard and fast requirement for analysis of all modes with three gust magnitudes and all axes. We do suggest this model be used to design for acceptable controllability and performance margins in adverse weather, and beyond that to assist in developing piloting procedures for recovering from upsets. More specific discussion follows 3.8.3.

G. 3.7.4 CARRIER LANDING DISTURBANCE MODEL

REQUIREMENT

3.7.4 Carrier landing disturbance model. This section specifies the model of atmospheric disturbances to be used for carrier landing operations. This model shall be used in analysis and piloted simulation to determine aircraft control response and path control accuracy during carrier landing. This model supplements, but does not replace, the low-altitude model of 3.7.3.

The terminal approach carrier landing disturbance model shall be used during simulation of the last 1/2 mile of the carrier approach. The u velocity component is aligned with the wind over deck. Total disturbance velocities are computed by adding segments caused by random free-air turbulence, u_1, v_1, w_1; steady ship-wake disturbance, u_2, w_2; periodic ship-motion-induced turbulence, u_3, w_3; and random ship-wake disturbance, u_4, v_4, w_4. The total air disturbance components u_g, v_g, and w_g are then computed as:

$$u_g = u_1 + u_2 + u_3 + u_4$$

$$v_g = v_1 + v_4$$

$$w_g = w_1 + w_2 + w_3 + w_4$$

The input to all of the random disturbance filters shall be generated by filtering the wide-band, Gaussian output of zero-mean, unit-variance random-number generators.

3.7.4.1 Free-air turbulence components. The free-air turbulence components which are independent of aircraft relative position are represented by filtering the output of white-noise generators described in 3.7.4 to produce the following spectra:

$$\Phi_{u_1}(\Omega) = \frac{200}{1 + (100\ \Omega)^2} \qquad (\text{ft/sec})^2 \text{ per radian/ft*}$$

$$\Phi_{v_1}(\Omega) = \frac{939[1 + (400\ \Omega)^2]}{[1 + (1000\ \Omega)^2][1 + (400/3\ \Omega)^2]} \qquad (\text{ft/sec})^2 \text{ per radian/ft*}$$

$$\Phi_{w_1}(\Omega) = \frac{71.6}{1 + (100\ \Omega)^2} \qquad (\text{ft/sec})^2 \text{ per radian/ft*}$$

3.7.4.2 Steady component of carrier airwake. The steady components of the carrier airwake consist of a reduction in the steady wind and a predominant upwash aft of the ship which are functions of range. Figure 12 illustrates the steady wind functions $u_2/V_{w/d}$ and $w_2/V_{w/d}$ as functions of position aft of the ship center of pitch.

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* The units, and the constant of Φ_{v_1} are wrong in MIL-F-8785C.

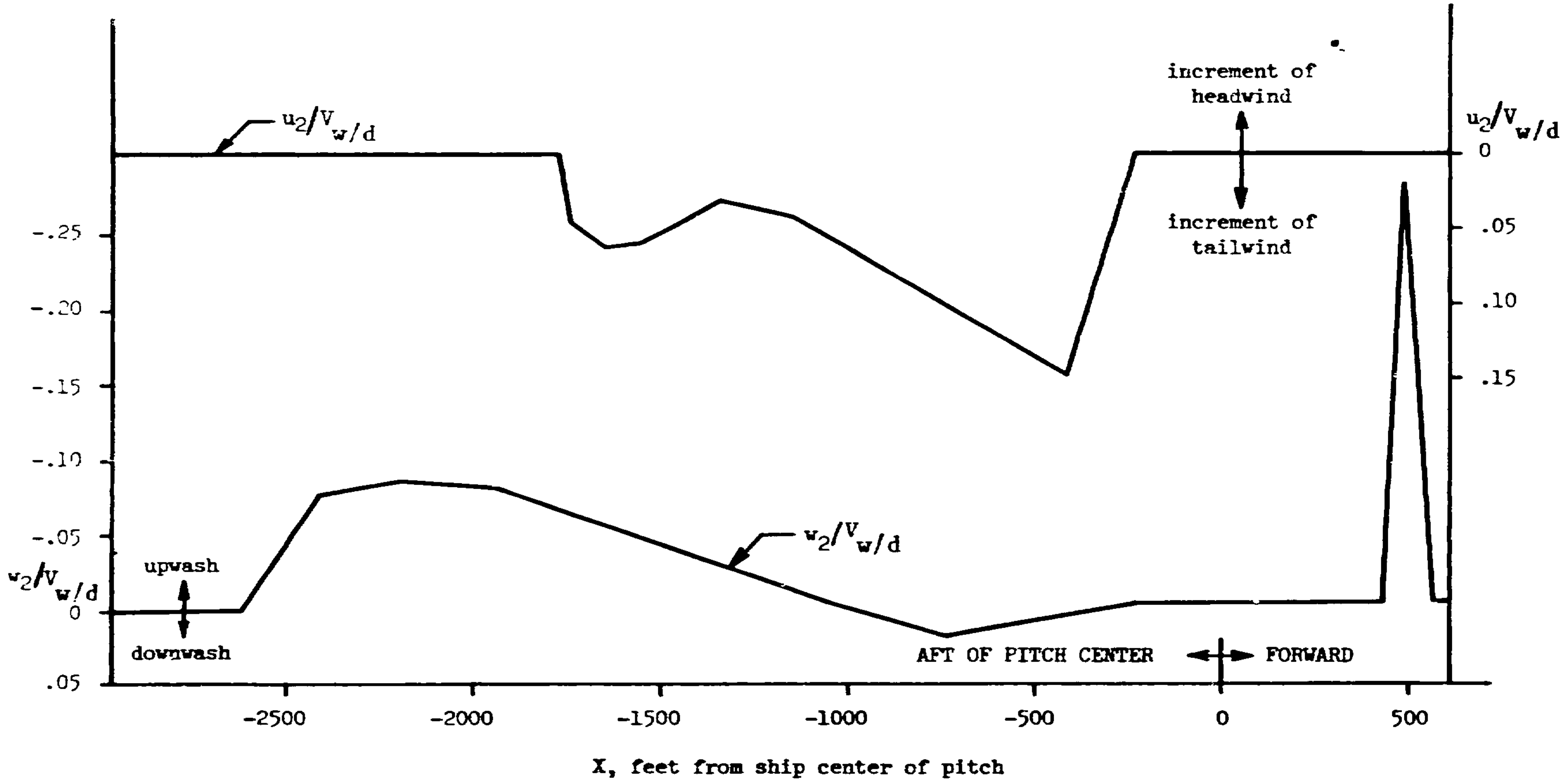

Figure 41. (MIL-F-8785C Figure 12) CVA ship burble steady wind ratios.

3.7.4.3 Periodic component of carrier airwake. The periodic component of the airwake varies with ship pitching frequency, pitch magnitude, wind over deck and aircraft range. These components are computed as follows:

$$u_3 = \theta_s V_{w/d}(2.22 + 0.0009X)C$$

$$w_3 = \theta_s V_{w/d}(4.98 + 0.0018X)C$$

$$C = \text{cosine}\left\{\omega_p\left[t\left(1 + \frac{V - V_{w/d}}{0.85V_{w/d}}\right) + \frac{X}{0.85V_{w/d}}\right] + P\right\}$$

where: ω_p = Ship pitch frequency, radians/second.

θ_s = Ship pitch amplitude, radians.

P = Random phase, radians.

The u component is set to zero for $X < -2236$ feet, and the w component is set to zero for $X < -2536$ feet.

3.7.4.4 Random component of carrier air wake. The ship-related random velocity components are computed by filtering white noise (3.7.4) as follows:

$$u_4 = \frac{\sigma(X)\sqrt{2\tau(X)}\,(\text{Input})}{\tau(X)j\omega + 1}$$

$$w_4 = v_4 = \frac{0.035\ V_{w/d}\sqrt{6.66}\,(\text{Input})}{3.33j\omega + 1}$$

where: $\sigma(X)$ = RMS Amplitude-ft/sec. (Figure 13)

$\tau(X)$ = Time constant-sec. (Figure 13)

$$\text{Input} = \left[\begin{matrix}\text{Random number}\\ \text{output}\end{matrix}\right]\left[\frac{j\omega}{j\omega + 0.1}\right]\sin\,(10\,\pi\,t)$$

RELATED MIL-F-8785B PARAGRAPH

None

DISCUSSION

In developing the form of the requirements for the effects of atmospheric disturbances it became obvious that the Navy had "hidden" flying qualities requirements: Most Navy airplanes are required to make shipboard landings. This is an item to be simulated before flight demonstration, and also presumably, considered in the design. Thus, the requirement to demonstrate a capability for shipboard landing implies a severe environment and there is no need for separate requirements in atmospheric disturbances (at least for the landing Flight Phase). A disturbance model for carrier landing, supplied

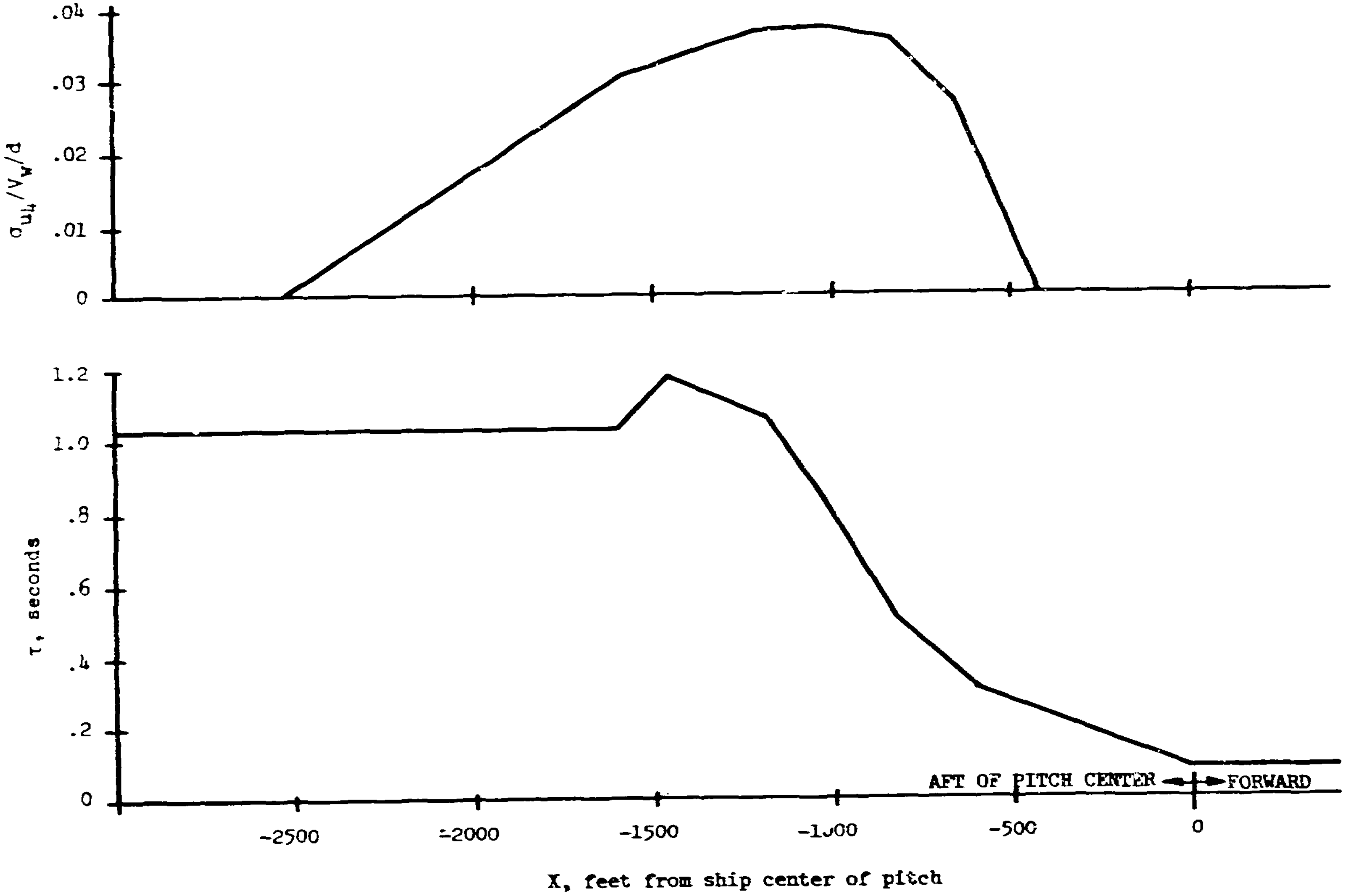

Figure 42. (MIL-F-8785C Fig. 13) U-Component burble time constant and variance.

by the Naval Air Development Center (Reference 111), has been added in this section. Even in calm air, the ship wake provides unavoidable atmospheric disturbances.

It is apparent from informal discussions that some increase in pilot workload, or degradation in pilot rating, is accepted for the task of landing in this environment relative to landing on firm ground in calm air. More work is required to relate the severity of thismodel to the low-altitude model of 3.7.3.

We also need to correct an error in the MIL-F-8785C spectra of the free-air turbulence components for carrier landing, 3.7.4.1. The form of the spectra is correct, although the units should be $(\text{ft/sec})^2$ per radian/ft. The coefficient in the expression for Φ_{v_g} should be 939 instead of 5900 (a factor of 2π). With these changes, the three power spectra can be integrated in closed form:

$$\sigma i = \int_0^\infty \Phi_i(\Omega)\, d\Omega$$

$$\sigma_{u_1} = 1.77 \text{ ft/sec}$$

$$\sigma_{v_1} = 1.69$$

$$\sigma_{w_1} = 1.06$$

H. 3.7.5 APPLICATION OF THE DISTURBANCE MODEL IN ANALYSES

REQUIREMENT

3.7.5 Application of the disturbance model in analyses. The gust and turbulence velocities shall be applied to the airplane equations of motion through the aerodynamic terms only, and the direct effect on the aerodynamic sensors shall be included when such sensors are part of the airplane augmentation system. When using the discrete gust model, all significant aspects of the penetration of the gust by the airplane shall be incorporated in the analyses. Application of the disturbance model depends on the range of frequencies of concern in the analyses of the airframe. When structural modes are significant, the exact distribution of turbulence velocities should be considered. For this purpose, it is acceptable to consider u_g and v_g as being one-dimensional functions only of x, but w_g shall be considered two dimensional, a function of both x and y, for the evaluation of aerodynamic forces and moments.

When structural modes are not significant, airframe rigid-body responses may be evaluated by considering uniform gust or turbulence immersion along with linear gradients of the disturbance velocities. The uniform immersion is accounted for by u_g, v_g and w_g defined at the airplane center of gravity. The angular velocities due to turbulence are equivalent in effect to airplane angular velocities. Approximations for these angular velocities are defined (precisely at very low frequencies only) as follows:

$$p_g = \frac{-\partial w_g}{\partial y}$$

$$-\dot{\alpha}_p = q_g = \frac{\partial w_g}{\partial x}$$

$$r_g = \frac{-\partial v_g}{\partial x}$$

The spectra of the angular velocity disturbances due to turbulence are then given by:

$$\Phi_{p_g}(\Omega) = \frac{\sigma_w^2}{L_w} \frac{0.8\left(\frac{\pi L_w}{4b}\right)^{1/3}}{1 + \left(\frac{4b}{\pi}\Omega\right)^2}$$

$$\Phi_{q_g}(\Omega) = \frac{\Omega^2}{1 + \left(\frac{4b}{\pi}\Omega\right)^2} \Phi_{w_g}(\Omega)$$

$$\Phi_{r_g}(\Omega) = \frac{\Omega^2}{1 + \left(\frac{3b}{\pi}\Omega\right)^2} \Phi_{v_g}(\Omega)$$

where b = wing span. The turbulence components u_g, v_g, w_g, and p_g shall be considered mutually independent (uncorrelated) in a statistical sense. However,

q_g is correlated with w_g and r_g is correlated with v_g. For the discrete gusts the linear gradient gives angular velocity perturbations of the form:

$$p_g = p_m \sin\left(\frac{\pi x}{d_m}\right) \qquad 0 \le x \le d_m$$

For the low-altitude model, the turbulence velocity components u_g, v_g and w_g are to be taken along axes with u_g aligned along the relative mean wind vector and w_g vertical.

DISCUSSION

This paragraph has only minor changes from MIL-F-8785B. mostly changes in the notation not the intent. The one change of significance is to align the low-altitude turbulence perturbations with the relative mean wind vector. The meteorological definition of the turbulence velocities is with u_g longitudinal (i.e., along the actual wind) and v_g and w_g transverse. At medium/high altitudes we have specified isotropic turbulence - the spectra of v_g and w_g are the same in all directions perpendicular to the wind. Also, a mean wind is usually not a factor in flying qualities, and none has been specified. It is, therefore, acceptable to use either body or stability axes.

For the low-altitude model we have specified nonisotropic turbulence spectra to account for the influence of the ground. We have also specified a mean wind, so that the orientation of the turbulence velocities is more critical. The transformation of these velocities to other axes can not be done exactly. Reference 105 addresses this problem and concludes that the use of the mean wind vector relative to the aircraft for u_g is the least inaccurate approximation. This should consider aircraft motion relative to the winds (horizontal) specified in 3.7.3.1-3.7.3.3. The effect of proximity to the ground is reflected in w_g, which should be vertical. v_g then completes the axis system.

OTHER ENVIRONMENTAL FEATURES

This section of MIL-F-8785C now contains a recommended model of disturbances, i.e., wind turbulence and gusts. These factors influence the aircraft flight path directly and increase pilot workload. Other environmental features may be of peripheral importance in a particular application. As we see more reliance on automatic guidance and active displays for task performance, then these also become flying qualities related. Both rain density and visibility are environmental features which have a potential influence, and preliminary models are presented here as guidance.

Rain Model

Reference 19 presents a rain model empirically developed by the USAF Environmental Technical Applications Center. The selected model has been used to estimate the rainfall encountered during manned aircraft approaches and has general acceptance. This model describes a rainstorm consisting of several cells, the rainfall in each being proportional to a ten-minute point rainfall. The discussion is paraphrased as follows.

Microwave frequency energy attenuation is caused by water absorption and is directly related to rainfall rate, raindrop size, radio frequency used, as well as other factors. Since landing systems must operate satisfactorily in any selected climatic regions, the measured point rate rainfall during heavy rain in Southeast Asia was selected as the basis for the recommended precipitation model presented in Figure 43. This rain model, recommended for worldwide applications, will provide 99% weather reliability in the tropical areas and greater reliability in other areas. It is further recommended that this model be used for altitudes to ten thousand feet, since there is little variation over this altitude range. This model does not apply above ten thousand feet; heavier rain rates are possible at the higher altitudes.

The preceding discussion is obviously directed towards the effect on guidance systems. Reference 112 theorizes that heavy rain can affect aircraft performance as much as the winds and wind shears that are normally analyzed in accidents. If that theory is validated, then more emphasis will be placed on the inclusion of a rain model.

Cloud Cover Model

Figure 44 is a table of data presenting the percent of time at a given altitude (on an annual basis) that an aircraft can be expected to be flying in cloud. For the interval 0-200 feet, the data is based on observed occurences of ceiling/visibility less than 200'/0.5 nautical miles. The rationale for this definition is that the top of a fog layer is generally around 200 ft. Thus, an aircraft will be flying "in cloud" for a visibility observation of less than 0.5nm for altitudes less than 200 ft. This data is taken from Reference 113.

Rain Model	Rain Rate, mm/hr.				
	Heavriest Mile	Next 3 Mi	First 10 Mi Average	10-20 Mi Average	0-20 Mi Average
ETAC General Model	1.72R*	0.76R	0.72R	0.53 R	0.62R
Recommended Model	82.6	36.5	34.6	25.4	29.7
RTCA's SC-117 Landing System Model					
1% worst U.S.	19.8	6.86	7.11		5.08
0.1% worst U.S.	104.6	46.2	40.5		29.9
1% worst worldwide	49.3	20.8	20.0		17.4
0.1% worst worldwide	166.1	73.4	69.1		60.4
AN/TPN-19 Instrument Landing System Model	50	50	50		
Worldwide Extreme Rainfall-Point Rate	1872				

* R = measured ten minute point rainfall in the locale under consideration

Figure 43. Comparison of rain models

Annual Percent of Time an Aircraft will be in Clouds Between Indicated Levels
(# denotes less than 0.5% frequency)

	0-200'	200-1500'	1500-3000'	3000-5000'	5000-10000'	10000-15000'	15000-20000'	2000-25000'
Dyess AFB TX	01	05	07	06	06	07	06	03
Sewart AFB TN	01	07	10	14	19	16	08	02
Pope AFB NC	01	08	10	16	21	14	07	03
Langley AFB VA	01	08	10	13	16	11	07	03
Elmendorf AFB AK	01	05	10	27	38	18	11	09
Taitung, Formosa	#	08	23	37	49	28	12	07
Seoul, Korea	01	07	11	14	18	15	09	06
Berlin, Germany	02	13	17	24	31	21	13	06
Prague, Czechoslovakia	04	14	16	17	17	08	06	03
Helsinki, Finland	06	31	13	23	24	16	09	08
Mildenhall AFB, England	04	12	17	33	36	16	08	06
Eskisehir, Turkey	01	04	16	18	27	20	07	02
Leopoldville, Zaire	01	06	26	11	11	11	05	02
Elizabethville, Zaire	01	03	11	04	06	03	04	02
Uelorn, Thailand	01	03	03	07	11	15	08	03
Ubon, Thailand	01	01	13	05	04	08	05	04
Pleikur, Vietnam	02	14	14	19	17	09	05	04
Palat, Vietnam	02	08	22	14	10	12	06	03
Isfahan, Iran	#	#	01	02	02	04	03	01

Figure 44. Annual Cloud Cover

SECTION XII

STATEMENT AND DISCUSSION OF REQUIREMENTS FOR USE OF THE DUSTURBANCE MODELS (3.8)

A. 3.8 REQUIREMENTS FOR USE OF THE DISTURBANCE MODELS

REQUIREMENTS

3.8 Requirements for use of the disturbance models Explicit consideration of the effects of disturbances on flying qualities, if required by the procuring activity, shall be in accordance with requirements in 3.8.2 through 3.8.3.2. In particular, 3.8.3.1 will replace 3.1.10.1 and 3.8.3.2 will replace 3.1.10.2.

DISCUSSION

MIL-F-8785B contained a detailed turbulence model; however, there were few explicit requirements on the use of the mode. The most common use of the model has been for piloted simulation. As stated in Reference 3: "It was to be used in any analysis and simulation of flying qualities and ride qualities that the contractor performs". Specific use of the model was directed for showing compliance with paragraphs 3.3.4 Roll control effectiveness, 3.3.4.1.2 Ground attack with external stores, 3.5.3.2 Damping (i.e., control system oscillations), 3.5.4.1 Performance of augmentation systems and 3.5.4.2 Saturation of augmentation systems. These requirements are basically qualititative, even the first two which require enough roll control power to balance the airplane in turbulence up to thunderstorm intensity. In formulating the present revision, it was apparent that there are still no quantitative requirements. It is also true that disturbances degrade task performance and increase pilot workload, in general. A progressive degradation in flying qualities (in the sense of task performance) with increasing disturbances is both acceptable and natural to the pilot. In formulating this new Section, we have attempted to recognize explicitly the effect of disturbances on flying qualities and to limit the degradation, albeit subjectively.

If the pilot is instructed not to compensate mentally for the effects of disturbances in his rating, then we have the basic use of the Cooper-Harper rating scale (Reference 114): the pilot is rating a given aircraft configuration to do a particular task in a certain atmospheric environment. The pilot's assessment of the influence of a particular disturbance magnitude is certainly going to depend on the task. The allowable degradation in performance of that task is further going to depend on the aircraft mission. Note, however, that the adjectives used to describe the effects of disturbances are the same as those used in 1.5 levels of flying qulaities. This consideration has led heuristically to the form of the requirements given in this new section.

Various options are available for consideration in formulating requirements. Chalk, discussing the use of piloted simulation[13], recommends that a pilot "fly" the aircraft in smooth air, light-to-moderate (i.e., most probable) turbulance and severe turbulence. The pilot would be informed of the expected frequency of encounter of the different turbulence values and would then give a composite or overall rating. This approach would seem to be most useful to the designer in the development of an airplane configuration. It is felt to be an indirect way of specifying and evaluating the effects of disturbances, requiring subjectivepilot judgement which should be minimized. Another approach was proposed in Reference 28 - directly modifying the definitions of Levels of flying qualities to correspond with different disturbance intensities. The reactions to this proposal (see papers in Reference 29) were mainly that it was subject to misinterpretation, although the benefits of more explicit requirements were not questioned. The counter-proposals appeared to be attempting to accomplish the same things in other ways.

Now, let us consider an airplane design which is clearly adequate for its intended mission, i.e., "Level 1", in the landing Flight Phase in the Operational Flight Envelope. In smooth air the task of landing this hypothetical aircraft should yield a Cooper-Harper rating better than 3.5. The rating should remain better than 3.5 in disturbances up to LIGHT.* With greater, MODERATE* disturbances, glideslope tracking might degrade or pilot workload may increase; the pilot rating for Level 1 would be allowed to degrade commensurately, but to no worse than 6.5. Similarly, in SEVERE* disturbances the rating for Level 1 could degrade to worse than 6.5 but not beyond 9. This last statement is equivalent to requiring reasonable confidence that for a "good", Level 1 airplane in something like a thunderstorm, the pilot will not lose control. This progression seems logical and consistent with basic flying qualities definitions. For an Aircraft Normal State, in the Operational Flight Envelope the usual connotation of Level 2 and 3 numerical pilot ratings as requiring improvements would not necessarily apply to such effects of disturbances. A similar progression of the effects of disturbances is shown for airplanes which have less than Level 1 flying qualities in smooth air. In this case we have combinations of probabilities for which the requirement is that, e.g. although a landing may be aborted, control must be maintained to make a go-around, "fly out of the disturbance". For the Landing Flight Phase, "Recoverable" implies that a certain margin of airspace is available.

In acknowledging the degradation in flying qualities due to atmospheric disturbances, we do not need to require that the airplane characteristics remain unchanged. Changes can occur due to basic nonlinearities, augmentation saturation, etc. The point is that MIL-F-8785C limits this degradation - it does not require degradation. This is consistent with the whole philosophy of MIL-F-8785C in presenting minimum acceptable requirements. The revision should not dissuade the use of gust alleviation or ride-smoothing systems - as has been the practice, the advantages and disadvantages of such systems must be weighed for each particular application. The procuring activity always has the option of increasing these minimum requirements, such as requesting all-weather capability. This could be achieved by a modified requirement, such as maintaining basic flying qualities in disturbance intensities corresponding to a probability of 10^{-3}.

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*The terms LIGHT, MODERATE and SEVERE are intended to correspond to specific probabilities; 10^{-1}, 10^{-3}, and 10^{-5} are suggested, as defined in detail in Section 3.7.

A few last comments on this new section - it is intended to be more a clarification than an amplification of requirements, recognizing questions of interpretation. For piloted simulations, the problems of simulating turbulence, especially the higher intensities, are acknowledged. The acceptability of pilot ratings is a function of the intensity of turbulence, wind shear, etc., and the proposed revisions define this trend. Analytical evaluation of flying qualities is unchanged pending the development of quantitative criteria for aircraft response to disturbances. It is suggested that the proposed revisions form a framework for the development of such quantitative criteria. These could take the form of correlating pilot rating either with aircraft responses at the different intensities of disturbances or with calculated pilot compensation to keep the responses within acceptable limits. Lastly, it is believed that evaluation of flying qualities in flight test will be aided, not hampered, by the proposed revisions. The proposal could be used to assess correctly a flight that "finds" turbulence (using weather information for the location). There is no requirement to fly in thunderstorm turbulence to demonstrate compliance with MIL-F-8785C, nor will there be a requirement to demonstrate compliance with all of the proposed 3.1.10 inflight test. Flight test requirements will be determined by the procuring activity, as they are now (see also the revision of 4.1.3). We require (4.1.2) that the analytical gust-response model be validated by flight test, and trust that pilots will evaluate the airplane in whatever turbulence is actually encountered.

B. 3.8.1 USE OF DISTURBANCE MODELS

REQUIREMENT

3.8.1 Use of disturbance models. Paragraphs 3.7.1 through 3.7.4.4 specify models of wind shear, continuous random turbulence and discrete gusts that shall be used to assess:

a. The effects of certain environmental conditions on the flying qualities of the airplane.

b. The ability of a pilot to recover from upsets caused by environmental conditions.

c. Flight path control precision during manual and automatic carrier landing.

For the purpose of this specification the atmosphere shall be considered to consist of three regions: low altitude (ground level to approximately 2,000 feet AGL), medium/high altitude (above approximately 2,000 feet) and, for carrier landing only, terminal approach (0-300 feet altitude and 1/2 mile to touchdown). The low altitude model shall apply to Category C and any other Flight Phase (e.g., ground attack, terrain following) designated by the procuring activity. The medium/high-altitude model is intended to apply to those Flight Phases where proximity to the ground is not a factor, generally Categories A and B. In application it will be permissible to use conditions at an average altitude for the medium/high-altitude model only. The carrier landing disturbance model will apply to carrier based aircraft only.

RELATED MIL-F-8785B PARAGRAPH

3.7.1.

DISCUSSION

This paragraph serves only as an introduction to succeeding material, similar to the corresponding paragraph in MIL-F-8785B. The changes reflect the changes in the disturbance model.

C. 3.8.2 QUALITATIVE DEGREES OF SUITABILITY

REQUIREMENT

3.8.2 Qualitative degrees of suitability. In assessing the qualitative suitability of flying qualities three intensities of disturbances shall be considered. These intensities are Light, Moderate and Severe as defined in 3.7. The requirements for the effects of these disturbances are contained in 3.8.3.1 and 3.8.3.2 for the different Flight Envelopes and Airplane States. The qualitative degrees of suitability of flying qualities are categorized as follows:

Satisfactory	Flying qualities clearly adequate for the mission Flight Phase
Acceptable	Flying qualities adequate to accomplish the mission Flight Phase, but some increase in pilot workload or degradation in mission effectiveness, or both, exists
Controllable	Flying qualities such that the airplane can be controlled safely, but pilot workload is excessive or mission effectiveness is inadequate, of both. Category A Flight Phase can be terminated safely, and Category B and C Flight Phase can be completed.
Recoverable	Flying qualities such that control can be maintained long enough to fly out of a disturbance. All Flight Phases can be terminated safely and a wave-off/go-around can be accomplished.

RELATED MIL-F-8785B PARAGRAPH

None

DISCUSSION

Levels of flying qualities are defined in 1.5 to apply to "values of stability and control parameters", i.e., properties of the airframe/flight control system. There is an implicit, unavoidable correspondence with levels of pilot ratings which result from these dynamic characteristics. This association is intentional, as discussed in Reference 3, but it was not stated explicitly in the specification. A problem arises from the use of the specification as a procurement instrument. Pilot rating is subjective and, therefore, not a good "legal" parameter. Good parameters are the measurable quantities such as frequency, damping, etc.

By their nature, the quantitative requirements of MIL-F-8785 apply to the airplane (with its flight control and other subsystems) in any atmospheric environment, at least less than SEVERE. On the other hand, pilot's ratings by their nature[114] are affected by the environment as well. We can expect a less than SEVERE adverse environment to degrade mission effectiveness or pilot workload even if the airplane characteristics remain completely unchanged. Therefore, if the effects of atmospheric disturbances on flying qualities are to be considered adequately, the definitions of flying qualities

Levels cannot be tied in one unique way to the Cooper-Harper pilot rating scale. Section 3.8.2 has been defined to account for these different natures while keeping the proper close tie between qualitative requirements and pilot ratings. The difference between 1.5 and 3.8.2 is thus in the interpretation and application. The concepts set forth in 1.5 are used in 3.1.10.1 (Table II) and 3.1.10.2 (Table III) to relate quantitative requirements to Airplane Normal and Failure States. The concepts in the preceding discussion are used in 3.8.3.1 and 3.8.3.2 to add requirements on the the qualitative effects of atmospheric disturbances. Degrees of suitability will be measured by pilot rating.

The wording of the degrees of suitability Satisfactory, Acceptable and Controllable is intended to correspond to the Levels 1, 2 and 3 of the Cooper-Harper rating scale (Figure 45). The definition of Recoverable is to define better the interface between Level 3 (a rating of 9 or better) and uncontrollable (a rating of 10). This qualitative rating should be interpreted that control will probably be lost if the mission or task is continued, but control can be maintained by aborting the task. One approach would be to assign that specific meaning to rating of 9.5, a number that is not to be used normally.

CONTROLLABLE CAPABLE OF BEING CONTROLLED OR MANAGED IN CONTEXT OF MISSION, WITH AVAILABLE PILOT ATTENTION	ACCEPTABLE MAY HAVE DEFICIENCIES WHICH WARRANT IMPROVEMENT, BUT ADEQUATE FOR MISSION. PILOT COMPENSATION, IF REQUIRED TO ACHIEVE ACCEPTABLE PERFORMANCE, IS FEASIBLE.	SATISFACTORY MEETS ALL REQUIREMENTS AND EXPECTATIONS, GOOD ENOUGH WITHOUT IMPROVEMENT CLEARLY ADEQUATE FOR MISSION.	EXCELLENT, HIGHLY DESIRABLE	1
			GOOD, PLEASANT, WELL BEHAVED	2
			FAIR. SOME MILDLY UNPLEASANT CHARACTERISTICS. GOOD ENOUGH FOR MISSION WITHOUT IMPROVEMENT.	3
		UNSATISFACTORY RELUCTANTLY ACCEPTABLE. DEFICIENCIES WHICH WARRANT IMPROVEMENT. PERFORMANCE ADEQUATE FOR MISSION WITH FEASIBLE PILOT COMPENSATION.	SOME MINOR BUT ANNOYING DEFICIENCIES. IMPROVEMENT IS REQUESTED. EFFECT ON PERFORMANCE IS EASILY COMPENSATED FOR BY PILOT.	4
			MODERATELY OBJECTIONABLE DEFICIENCIES. IMPROVEMENT IS NEEDED. REASONABLE PERFORMANCE REQUIRES CONSIDERABLE PILOT COMPENSATION.	5
			VERY OBJECTIONABLE DEFICIENCIES. MAJOR IMPROVEMENTS ARE NEEDED. REQUIRES BEST AVAILABLE PILOT COMPENSATION TO ACHIEVE ACCEPTABLE PERFORMANCE.	6
	UNACCEPTABLE DEFICIENCIES WHICH REQUIRE MANDATORY IMPROVEMENT. INADEQUATE PERFORMANCE FOR MISSION EVEN WITH MAXIMUM FEASIBLE PILOT COMPENSATION.		MAJOR DEFICIENCIES WHICH REQUIRE MANDATORY IMPROVEMENT FOR ACCEPTANCE. CONTROLLABLE. PERFORMANCE INADEQUATE FOR MISSION, OR PILOT COMPENSATION REQUIRED FOR MINIMUM ACCEPTABLE PERFORMANCE IN MISSION IS TOO HIGH.	7
			CONTROLLABLE WITH DIFFICULTY. REQUIRES SUBSTANTIAL PILOT SKILL AND ATTENTION TO RETAIN CONTROL AND CONTINUE MISSION.	8
			MARGINALLY CONTROLLABLE IN MISSION. REQUIRES MAXIMUM AVAILABLE PILOT SKILL AND ATTENTION TO RETAIN CONTROL.	9
UNCONTROLLABLE CONTROL WILL BE LOST DURING SOME PORTION OF MISSION.			UNCONTROLLABLE IN MISSION.	10

Figure 45. Cooper-Harper Rating Scale

D. 3.8.3 EFFECTS OF ATMOSPHERIC DISTURBANCES

REQUIREMENT

3.8.3 Effects of atmospheric disturbances. Levels of flying qualities as indicated in 1.5 are employed in this specification in realization of the possibility that the airplane may be required to operate under abnormal conditions. Such abnormalities may occur also as a result of extreme atmospheric disturbances, or some combination of conditions. For these factors a degradation of flying qualities is permitted as specified in 3.8.3.1 and 3.1.3.2 (see also 4.1.1).

3.8.3.1 Requirements for airplane normal states. In atmospheric disturbances the minimum required flying qualities for airplane normal states (3.1.6.1) are as specified in Table XVI.

TABLE XVI. Levels for Airplane Normal States

Atmospheric Disturbances	Within Operational Flight Envelope	Within Service Flight Envelope
LIGHT TO CALM	Quantitative requirements Level 1; qualitative requirements Satisfactory	Quantitative requirements Level 2; qualitative requirements Acceptable
MODERATE TO LIGHT	Quantitative requirements Level 1; qualitative requirements Acceptable or better	Quantitative requirements Level 2; qualitative requirements Controllable or better
SEVERE TO MODERATE	Qualitative requirements Controllable or better	Qualitative requirements Recoverable or better

3.8.3.2 Requirements for airplane failure states. When airplane failure states exist (3.1.6.2), a degradation in flying qualities is permitted only if the probability of encountering a lower Level than specified in 3.8.3.1 is sufficiently small. At intervals established by the procuring activity, the contractor shall determine, based on the most accurate available data, the probability of occurence of each Airplane Failure State per flight and the effect of that Failure State on the flying qualities within the Operational and Service Flight Envelopes. These determinations shall be based on MIL-STD-756 except that:

a. All airplane components and systems are assumed to be operating for a time period, per flight, equal to the longest operational mission time to be considered by the contractor in designing the airplane, and,

b. Each specific failure is assumed to be present at whichever point in the Flight Envelope being considered is most critical (in the flying quaiities sense).

From these Failure State probabilities and effects, the contractor shall determine the overall probability, per flight, that one or more flying qualities are degraded to Level 2 because of one or more failures. The contractor shall also determine the probability that one or more flying qualities are degraded to Level 3. Table XVII specifies the requirements as functions of the probability of encountering the degradation in flying qualities.

TABLE XVII. Levels for Airplane Failure States

Atmospheric Disturbances	Failure State I*	Failure State II**
LIGHT TO CALM	Quantitative requirements Level 2 and qualitative requirements Acceptable or better	Quantitative requirements Level 3 and qualitative requirements Controllable or better
MODERATE TO LIGHT	Quantitative requirements Level 2 and qualitative requirements Controllable or better	Quantitative requirements Level 3 and qualitative requirements Recoverable or better
SEVERE TO MODERATE	Qualitative requirements Recoverable or better	

* For flight in the Operational Flight Envelope: Probability of encountering degraded levels of flying qualities due to failure(s) $< 10^{-2}$/flight

** For flight in the Operational Flight Envelope: Probability of encountering degraded levels of flying qualities due to failure(s) $< 10^{-4}$/flight, and for flight in the Service Flight Envelope: Probability of encountering degraded levels of flying qualities due to failure(s) $< 10^{-2}$/flight

DISCUSSION

These changes indicate that atmospheric disturbances are considered among the factors that degrade flying qualities. The quantitative requirements, such as frequency, damping ratio, etc. apply in disturbances up to Moderate. This is consistent with MIL-F-8785B since, in general, the requirements were derived with some consideration of turbulence. This part of the requirement could influence stability augmentation system authority, for instance, to ensure that any saturation would not unduly degrade the modal parameters. The second part of the requirement allows a qualitative degradation in flying qualities (i.e., worsening pilot opinion) with increasing disturbance intensity. This assumes that the pilot maintains the same task performance standards. In calculations, increasing flight path perturbations imply degrading flying qualities; while in piloted simulation, the pilot should attempt to maintain task performance without mentally compensating for the perceived level of disturbance intensity. Note that the wording is "allows" (or, more specifically recognizes) an effect of disturbances, the revision limits but does not require any degradation in flying qualities due to the disturbance.

Specific aircraft may have missions that require prolonged flight in disturbances, e.g., low-altitude penetration. In this case, either the requirements in 3.8.3.1 and 3.8.3.2 can be made more strict or the terms Light, Modertate and Severe can correspond to lower probabilities. Lastly, the intent of the revision is not to add a whole new dimension to the design process. More guidance on applying the requirements is presented in Section 4.1.

SECTION XIII

STATEMENT AND DISCUSSION OF QUALITY ASSURANCE REQUIREMENTS (4.)

4. QUALITY ASSURANCE

GENERAL DISCUSSION

This section contains the conditions and requirements for demonstrating compliance with the numerical flying qualities requirements of section 3. Reference 3 presents some philosophy on the economics of flight testing that is even more appropriate today, as costs continue to inflate. In addition, the flying qualities specification has gradually made a transition from requirements which are entirely demonstratable in flight test into a procurement document with both design and flight test requirements. Thus, recognizing this ambivalence, some parts of the specification should be thought of as design requirements which may not realistically be amenable to demonstration directly in flight test. An example of this is the requirements on the influence of atmospheric disturbances that have been introduced in Section 3.8. It would be prohibitively expensive to attempt a flying qualities evaluation by flight test in a wide range of disturbances, if in fact it were possible. The introduction of more explicit design requirements does not change this fact. By contrast, many other requirements are oriented towards cerification by flight test, especially subjective items which require that certain characteristics shall not be objectionable.

In revising section 4, an attempt has been made in the specification to provide direction as to the analyses, simulations and flight tests that should normally be done. In addition, since it is required to demonstrate compliance with all the requirements analytically at some stage of the design, explicit direction is also given as to which items will not normally apply to flight test. Amplification and additional guidance is contained in the discussion of the appropriate paragraphs in other sections of this report. Finally, as mentioned in the requirements, the methods of determining compliance at various development stages for any particular airplane will be defined by the procuring activity.

A. 4.1 COMPLIANCE DEMONSTRATION

REQUIREMENT

4.1 Compliance demonstration. Compliance with all requirements of Section 3 shall be demonstrated through analysis. In addition, compliance with many of the requirements will be demonstrated by simulation, flight test, or both.

The methods for demonstrating compliance shall be established by agreement between the procuring activity and the contractor. Representative flight conditions, configurations, external store complements, loadings, etc., shall be determined for detailed investigation in order to restrict the number of design and test conditions. The selected design points must be sufficient to allow accurate extrapolation to the other conditions at which the requirements apply. Table XVIII gives general guidelines, but the peculiarities of the specific airplane design may require additional or alternate test conditions. The required failure analyses shall be thorough, excepting only approved Special Failure States (3.1.6.2.1).

DISCUSSION

The change to this paragraph was contained in Amendment 2. In contrast with the wording in MIL-F-8785B, not all the requirements will be demonstrated by simulation or flight test. As indicated in the second paragraph, the actual requirements for demonstrating compliance vary with airplane design configuration. It is only possible to provide general requirements as guidance. This guidance has been added in the following sections; Section 4.1 now serves as an introduction to these new items.

B. 4.1.1 ANALYTICAL COMPLIANCE

DISCUSSION

Paragraph 4.1 indicated three methods of demonstrating compliance: analytical, simulation and flight test. In this revision we have concentrated on adding guidance on each of these. The requirements for demonstrating compliance are unique to the system configuration, mission, etc., and so will continue to be negotiated between the contractor and the procuring activity.

Under 4.1.1 now, we have put related paragraphs from other parts of MIL-F-8785B plus an additional paragraph to convey the intent of the new disturbance requirements. These, plus the effects of failure states, were the areas that we judged to require special emphasis under 4.1.1.

C. 4.1.1.1 EFFECTS OF FAILURE STATES

REQUIREMENT

4.1.1.1 Effects of failure states. To determine theoretical compliance with the requirements of 3.1.10.2, the following steps must be performed:

a. Identify those Airplane Failure States which have a significant effect on flying qualities (3.1.6.2)

b. Define the longest flight duration to be encountered during operational missions (3.1.1)

c. Determine the probability of encountering various Airplane Failure States, per flight, based on the above flight duration (3.1.10.2)

d. Determine the degree of flying qualities degradation associated with each Airplane Failure State in terms of Levels as defined in the specific requirements

e. Determine the most critical Airplane Failure States (assuming the failures are present at whichever point in the Flight Envelope being considered is most critical in a flying qualities sense), and compute the total probability of encountering Level 2 flying qualities in the Operational Flight Envelope due to equipment failures. Likewise, compute the probability of encountering Level 3 qualities in the Operational Flight Envelope, etc.

f. Compare the computed values above with the requirements in 3.1.10.2 and 3.1.10.3. An example which illustrates an approximate estimate of the probabilities of encounter follows: if the failures are all statistically independent, determine the sum of the probabilities of encountering all Airplane Failure States which degrade flying qualities to Level 2 in the Operational Envelope. This sum must be less than 10^{-2} per flight. If the requirements are not met, the designer must consider alternate courses such as:

(1). Improve the airplane flying qualities associated with the more probable Failure States, or

(2). Reduce the probability of encountering the more probable Failure States through equipment redesign, redundancy, etc.

Regardless of the probability of encountering any given Airplane Failure States (with the exception of Special Failure States) the flying qualities shall not degrade below Level 3.

RELATED MIL-F-8785B PARAGRAPH

6.7.1 Theoretical compliance

DISCUSSION

This requirement was contained in Section 6, Notes, in MIL-F-8785B. In that location it is just as binding (contractually or otherwise) as any requirement in the specification. It is more appropriate, however, as a subparagraph of a section concerning compliance demonstration. The wording of the paragraph has not been revised; it is still valid to provide the requirements for the effects of system failures, not considering atmospheric disturbance. Thus, the first step is to determine failure probabilities and whether they satisfy the requirements on Levels of flying qualities - in calm air. Reference 3 did not discuss this paragraph directly, but related discussion occurs under 3.1.10. That discussion presented an approach to failure analyses through the design process. We still believe that probability failure analysis is appropriate and the discussion of Reference 3 is valid for this new paragraph.

Feedback from ASD indicates a trend toward satisfying these requirements by generic failure analysis, i.e., assume a failure will happen if it possibly can. Furthermore, failures are assumed to occur at the most critical flight condition, and in the most critical way. Some failures, e.g., engine failures, are currently accounted for that way in this specification. Reasonably probable failures are assigned a probability of unity, while failures of sufficiently remote probability are labeled as Special Failure States and may receive no further consideration. Selection of failure states is based on preliminary analyses and the associated design considerations are dictated by the SPO. This approach may be extended to attach specific probability limits to Levels 1, 2 and 3, reaching agreement with the reliability and flight safety people along the lines that:

> Satisfactory mission performance demands Level 1 flying qualities in the Operational Flight Envelope. Deterioration to worse than Level 1 flying qualities will be considered to preclude mission accomplishment. (Although some mission capability remains at Level 2 - no abort - that capability is degraded).
>
> Flight safety demands Level 3 or better flying qualities. Any deterioration to worse than Level 3 flying qualities will be included as a contributor to flight safety unreliability. (For landing, consider Level 2).
>
> Effects of failures on flying qualities will be accounted for in this manner for calculation of mission accomplishment reliability and flight safety reliability for comparison to the overall requirements.
>
> Questions arising with regard to mission capability or flight safety in the event of any particular failure or combination of failures will be referred to the procuring activity's flying qualities for resolution.
>
> Additionally, the flying qualities specification may (will) list specific failure cases for which a specified Level of flying qualities is required.

This alternative relieves the flying qualities people of the chore of reliability calculation. With proper interorganizational liaison, it should work where mission accomplishment and flight safety reliability are spearately specified. The probability failure analysis has the appearance of being scientific (even if the numbers used result from art), whereas the generic failure analysis has the appearance of being simple (even if supported by involved analytical efforts). In truth, both approaches require sound engineering judgement backed by whatever data and analysis is available. The critical failure states and flight conditions must be identified, together with their impact on flying qualities. The end product should still be an aircraft in which the effects of failures are consistent with the mission requirements.

D. 4.1.1.2 EFFECTS OF ATMOSPHERIC DISTURBANCES

REQUIREMENT

4.1.1.2 Effects of atmospheric disturbances. Paragraph 4.1.1.1 indicates a procedure for satisfying the requirements on the degrading effects of airplane failure states, without consideration of disturbances. Atmospheric disturbances also may cause a degradation in pilot opinion as specified in 3.8.2. In application, numerical values of control force and deflection, and of steady-state and time-response parameters (for example $n_{o_{max}}$, F_s/n and τ_t) are to be considered as mean values in the presence of atmospheric disturbances. These frequently are equivalent to the values in calm air. Numerical values of frequency-response parameters and of control authority are effective values for the airplane in each particular intensity of atmospheric disturbances. The qualitative requirements of 3.8.3.1 and 3.8.3.2 should then be assessed for both Airplane Normal States and critical Failure States identified in 4.1.1.1.

RELATED MIL-F-8785B PARAGRAPH

None

DISCUSSION

This paragraph has been added in order to provide some guidance on the application of the requirements involving atmospheric disturbances, particularly the requirements in 3.8.3.1 and 3.8.3.2. The intent is not to add a whole new dimension to the matrix of design conditions. Rather, it is to formalize a consideration of turbulence, gusts and winds in designing an aircraft and then assessing its suitability to do the intended mission. The procuring activity should confirm that the probabilities of the proposed disturbances are consistent with the intended missions. It is conceivable that the requirements on the effects of disturbances could be waived or, for an all-weather low-level mission, even made more stringent.

In applying the requirements as in Reference 1 various calculations should be made as the design progresses to aid in choosing the airplane configuration and flight control system parameters. A stability augmentation system should be checked for saturation as the disturbance intensity increases. If the authority is limited in order to bound the effect of a hard-over failure in a single-channel system, severe turbulence might be expected to cause a noticeable degradation in effective damping ratio, etc. If a high-authority augmentation system is chosen, the stability under the influence of external inputs should be checked. Pitch and throttle control authority must be sufficient to counteract the effects of wind shear on the flight path in landing approach. If an aerodynamically-unstable airfame is used, then control authority and rate must be sufficient to recover from discrete-gust upsets. These are examples of the analyses necessary to show compliance with the requirements. In practice, the procedure will not be a consecutive arrangement such as to satisfy paragraph 4.1.1.1, then satisfy 4.1.1.2. Consideration of disturbances is an iterative part of the design process. The degree of consideration will depend on the particular aircraft and mission.

In considering the data sources when drafting the requirements in Reference 1, it seemed appropriate to apply the numerical requirements on individual parameters in moderate, if not more intense, disturbances. This reflects the quantitative requirements in 3.8.3. We do not, however, want to force unnecessary redundancy or complexity on a designer. The revision of 3.8.3 also includes qualitative requirements; for the high-intensity disturbance inputs the requirements are just qualitative. These qualitative requirements are related to pilot opinion; however, it must be admitted that more research is needed to define the variation of pilot rating with either open-loop responses or closed-loop controllability under the influence of disturbances. The new requirements are most amenable to verification by piloted simulation, but the framework will support more explicit quantitative requirements as the data is accumulated.

It is felt that there is currently too little data to support specifications on response criteria. The new British flying qualities specification (Reference 20) does include some response criteria and is, therefore, a starting point. It is also possible to postulate the possible form of other criteria which would require validation before inclusion in the specification, and these are discussed relative to the current paragraph in MIL-F-8785C.

<u>Flight path stability</u> (paragraph 3.2.1.3). If one were to keep pilot ratings in the "Satisfactory" (3.5) range as the intensity of atmospheric disturbances increases, generally it would be necessary to make the Level 1 requirements more stringent. To illustrate how this might be done for all Levels if supporting data were available, consider the parameter $d\gamma/dV$. Both MIL-F-8785C and AvP970 limit the rate of change of flight path angle with airspeed at constant throttle setting (although the numbers are not identical). (Reference 20 also comments that the values specified make sufficient allowance for the effects of at least moderate turbulence). Assuming that flight path/airspeed control becomes more difficult as the intensity of atmospheric disturbances increase, the following <u>form</u> is suggested for the maximum value of rate of change of flight path angle with airspeed:

FLYING QUALITIES	ATMOSPHERIC DISTURBANCES		
	LIGHT	MODERATE	SEVERE
LEVEL 1	0.06	-0.03	-0.12
LEVEL 2	0.15	0.06	-0.03
LEVEL 3	0.24	0.15	0.0

The numbers suggested for moderate and severe atmospheric disturbances are arbitrary. It should be pointed out, however, that the sense of these requirements can be satisfied by increasing airspeed - which is commonly done in adverse conditions. In application, therefore, this requirement would probably mean defining the approach speeds to be used in adverse conditions, rather than using a "rule of thumb" such as adding 50% of the wind or 50% of the reported gusts to the approach speed. The appropriate information should be inserted in the Flight Mannual to guide the pilot in selecting the safest airspeed - a compromise between assuring sufficient flight path control in adverse conditions and preventing a long landing.

Short-period damping (paragraph 3.2.2.1.2). References 1 and 20 have similar requirements for short period damping ratio, which Reference 20 states to be adequate for flight in severe turbulence. Both references allow a reduction in the Level 3 minimum damping ratio above 20,000 ft consistent with the reduction in the probability of encountering turbulence with increasing altitude. Possible revisions could be:

(i) Define the allowable reduction in minimum Level 3 short-period damping ratio with increasing altitude.

(ii) Allow a reduction in minimum Level 3 short-period damping ratio at speeds above the gust penetration speed, V_G, since the aircraft should not fly very long in severe turbulence at those speeds.

Currently it is not felt appropriate to include these changes because of insufficient data.

Pitch attitude deviations (no paragraph). Reference 20 indicates a possible closed-loop criterion based on work reported in Reference 115: the RMS pitch excursion should be less than 1 degree in severe turbulence for Level 1 characteristics of a Class IV aircraft in Flight Phase Category A. It is also possible to postulate that a similar requirement on RMS flight path excursions would exist for Category C flight phase. The work in Reference 115 concerns analytical closed-loop response prediction using a pilot model. Any requirements stated in terms of maximum RMS excursions would be applicable to analytical open - or closed-loop analysis rather than piloted simulation. At present it is believed that available data is insufficient to support this type of requirement. The results of any such analysis would be a useful supplement to data presented to show compliance with the requirements.

Lateral-directional oscillations (Dutch roll) (paragraph 3.3.1.1). The current requirements are presumed to be adequate for moderate turbulence. Reference 20 also increases the minimum allowable Dutch Roll damping for aircraft designed to operate in severe turbulence.

E. 4.1.1.3 COMPUTATIONAL ASSUMPTIONS

REQUIREMENT

4.1.1.3 Computational assumptions. Assumptions a and b of 3.1.10.2 are somewhat conservative, but they simplify the required computations in 3.1.10.2 and provide a set of workable ground rules for theoretical predictions. The reasons for these assumptions are:

a. "...components and systems are...operating for a time period per flight equal to the longest operational mission time...". Since most component failure data are in terms of failures per flight hour, even though continuous operation may not be typical (e.g., yaw damper on during supersonic flight only), failure probabilities must be predicted on a per flight basis using a "typical" total flight time. The "longest operational mission time" as "typical" is a natural result. If acceptance cycles-to-failure reliability data are available (MIL-STD-756), these data may be used for prediction purposes based on maximum cycles per operational mission, subject to procuring activity approval. In any event, compliance with the requirements of 3.1.10.2, as determined in accordance with section 4, is based on the probability of encounter per flight.

b. "...failure is assumed to be present at whichever point...is most critical...". This assumption is in keeping with the requirements of 3.1.6.2 regarding Flight Phases subsequent to the actual failure in question. In cases that are unrealistic from the operational standpoint, the specific Airplane Failure States might fall in the Airplane Special Failure State classification (3.1.6.2.1).

RELATED MIL-F-8785B PARAGRAPH

6.7.3

DISCUSSION

6.7.1 of MIL-F-8785B has been moved to the current location as 4.1.1.1. Similarily, paragraph 6.7.3 of MIL-F-8785B is more appropriate in this location to support the general reorganization of this section. The wording of the paragraph is still valid.

F. 4.1.2 SIMULATION

REQUIREMENT

4.1.2 Simulation. The danger, extent or difficulty of flight testing may dictate simulation rather than flight test to evaluate some conditions and events, such as the influence of Severe disturbances, events close to the ground (except 3.2.3.4 shall be demonstrated in flight), combined Failure States and disturbances etc. In addition, by agreement with the Procuring activity, piloted simulation shall be performed before first flight of a new airplane design in order to demonstrate the suitability of the handling qualities and also to demonstrate compliance with qualitative requirements in atmospheric disturbances and in the critical conditions identified in 4.1.1.1. When simulation is the ultimate method of demonstrating compliance for a requirement, the simulation model shall be validated with flight test data and approved by the procuring activity.

RELATED MIL-F-8785B PARAGRAPH

None

DISCUSSION

This paragraph has been included to provide some guidance on the use of piloted simulation for compliance demonstration rather than engineering development. Specifically, piloted simulation is required before first flight of a new design. Reference 31, for instance, documents the benefits of in-flight simulation before first flight. In addition, it is suggested that piloted simulation of a flight-validated model could be the primary means of demonstrating compliance with certain requirements.

The note that MIL-F-9490D requires "functional mockup and simulator tests" of "an operational mockup which statistically and dynamically duplicates the flight control system", "where one of the first airplanes will not be available for extensive testing of the FCS prior to flight of that model".

G. 4.1.3. FLIGHT TEST DEMONSTRATION

REQUIREMENT

4.1.3. Flight test demonstration. The required flight tests will be defined by operational, technical and safety considerations as decided jointly by the procuring activity, the test agency and the contractor using results from 4.1.1 and 4.1.2. It is not expected that flight test demonstration of the requirements in Moderate or Severe disturbances will be done unless required by the airplane mission. Some flights can be expected to encounter actual disturbances and the qualitative requirements would apply if the disturbance intensity could be categorized.

RELATED MIL-F-8785B PARAGRAPH

None

DISCUSSION

This paragraph completes the requirements on methods of demonstrating compliance. No attempt has been made to expand on the guidance in 4.1 and Table XVII as to what should be flight tested. There is no intent to specify that atmospheric disturbance requirements be flight tested unless the airplane mission demands that capability in operation. The last sentence of the requirement is intended to recognize that in a normal flight test program there will probably be some encounters with real atmospheric disturbances. A chase aircraft, parameter identification or just the available weather information (with some assumptions) would be used to give estimates of probable disturbance intensities. These encounters may then afford the opportunity to check the qualitative requirements informally.

The procuring activity, the test agency and the contractor will jointly agree on which tests are hazardous and what analyses, simulations and buildup maneuvers are needed to assure safety.

In order to call for flight testing in Moderate or Severe disturbances, the procuring activity should specify at the outset of a design what is expected. For example, design for a terrain - following mission might require acceptable ride and flying qualities over specified terrain in specified turbulence. While neither that terrain nor that turbulence may be encountered in flight test, still the actual terrain may be known or measured and the actual turbulence deduced from flight records by parameter identification techniques. That would furnish direct evidence of acceptability, while serving to validate the analysis and simulation which use the specified turbulence.

At the 1978 AFFDL flying qualities workshop (Reference 29), anxiety was expressed over requirements for which flight testing to demonstrate compliance would be extremely difficult or time-consuming. Requirements related to atmospheric disturbances were of particular concern. However, neither past practice, nor present procedures, nor foreseeable future demands show such difficulty. Flight testing has always been a most pragmatic occupation. That certainly holds with flying qualities. The following discussion attempts to show what reasonably can be expected.

Our first military flying qualities specification, Army Air Forces Specification C-1815, was published in 1943. In all the years since, we believe no flight test program has ever thoroughly checked every single requirement. Some factors which always limit testing are: sensor availability and capability, data recording and reduction equipment, engineering manpower limitations, flight safety considerations, funds availability, aircraft availability, configuration or subsystem changes, urgent problems with other parts of the aircraft, emphasis on operational aspects - the list seems endless. The complexity of a contempory flight control system itself may preclude flight evaluation of all failure modes.

Currently flight test costs are up, flying hours are down, and emphasis has shifted from engineering evaluation to investigation of conditions approximating operational use. In this climate we must seek optimized flight test techniques to extract the greatest quantity of most-needed flying qualities data in the available flight test time. There is no hope of a flight handling evaluation of the type and scope of AFFTC's Phase IV evaluations of former years. The change is not all bad.

To a large extent the traditional techniques are being supplanted by parameter identification from dynamic flight records. As AFFTC has shown, using appropriate control inputs data can be accumulated quickly over a large flight envelope for reduction by computer to transfer functions or stability derivatives. Twisdale[10] describes a means of extracting such data from air combat tracking related to the manner in which fighter aircraft are intended to be used. From accurate, well-documented results the aircraft designer's stability and control predictions can be corrected to obtain a validated analytical model. Thoroughness of documentation is as critically essential as accuracy. Where those flight tests do not themselves generate the values of many motion parameters needed to determine MIL-F-8785 compliance, an engineer can then use the validated model to investigate any aspect of specification compliance at will. With this procedure there are now, of course, many more chances for error along the way. For meaningful results a good deal of coordination is necessary among all those involved in design, testing, evaluation and procurement.

Response to turbulence, gusts, etc. is one example of a type of specification requirement which, though necessary, is practically impossible to flight test. Structural flight loads specifications were the first to put design requirements in such terms, MIL-A-8861 (1960, still used by the Navy) and MIL-A-008861A (USAF) continue use of the time honored 1-cosine gust which cannot be found at all in flight (especially when looking for one). Compliance with gust-response requirements has always been shown by analysis and ground testing. That holds equally for the statistical turbulence introduced in 1971 by MIL-A-008861A for mission and design envelope analyses.

As stated in the British flying qualities specification, Av. P. 970 (Reference 20, Leaflet 600/1), "Compliance with some requirements cannot readily be determined by flight testing... In these cases, compliance can be shown by theoretical calculation or simulation, by agreement with the Aeroplane Project Director, provided that the data used is derived as far as possible from flight testing and provided that some back-up qualitative flying is done; for example, some flying must be done in real turbulence". That approach seems about the best that can be done in flight testing for the effects of atmospheric disturbances. It also greatly expands the ability to show compliance with other flying qualities requirements for which direct demonstration would be very demanding of flight time - such as the roll-sideslip coupling requirements of Reference 2.

H. 4.2 AIRPLANE STATES

REQUIREMENT

4.2 Airplane States. The parameters defining Aircraft States shall be tabulated. Table XIX illustrates an acceptable format.

RELATED MIL-F-8785B PARAGRAPH

4.2

DISCUSSION

MIL-F-8785B Table XV has been modified to account for the Amendment 2 and 8785C changes. It is now Table XVIII of MIL-F-8785C. There have been no other changes to the table.

TABLE XVIII. Design and test condition guidelines.

REQ'MT. NO.	TITLE	CRITICAL LOADING (4.2.1, 4.2.2)	LOAD FACTOR	ALTITUDE (4.3.1)	SPEED	FLIGHT PHASE
SECTION 3.2	LONGITUDINAL FLYING QUALITIES					
3.2.1.1	Longitudinal static stability	Most aft c.g	1.0	$h_{o_{min}}$, medium, $h_{o_{max}}$	V_{min} to V_{max} & transonic	CO,CR,LO,RR,FF,RT,PA,L,WO,TO,CT
3.2.1.1.1	Relaxation in transonic flight	↓	↓	↓		
3.2.1.1.2	Elevator control force variations during rapid speed changes	—	As required	↓	$V_{o_{min}}$ to $V_{o_{max}}$ & transonic	CO,GA,DE
3.2.1.2	Phugoid stability	Most forward c.g.†	1.0	↓	V_{min} to V_{max}	CR,LO,PA,RT
3.2.1.3	Flight-path stability	—	↓	↓	$V_{o_{min}}$, $V_{o_{min}}$ - 5 kt	PA
3.2.2.1.1	Short-period frequency and acceleration sensitivity	Most forward c.g.† and most aft c.g.††	↓	↓	V_{min} to V_{max}	*,CR,RT,PA,L,CT
3.2.2.1.2	Short-period damping	Most forward c.g.	↓	↓	V_{min} to V_{max}	*,CR,RT,PA,L CT
3.2.2.1.3	Residual oscillations	—	↓	↓	$V_{o_{min}}$ to $V_{o_{max}}$	*,PA
3.2.2.2	Control feel and stability in maneuvering flight	Most aft c.g.	n(-) to n(+)	↓	V_{min} to V_{max}	*,RT,CR,PA,L,CT
3.2.2.2.1	Control forces in maneuvering flight	Most forward c.g.† and most aft c.g.††	n_o(-) to n(+)	↓	↓	↓
3.2.2.2.2	Control motions in maneuvering flight	Most forward c.g.†	n_o(-) to n(+)	↓	↓	↓
3.2.2.3	Longitudinal pilot-induced oscillations	—	Min. permissible to max. permissible	↓	↓	*,RT,CR,PA,L,CT
3.2.2.3.1	Dynamic control forces in maneuvering flight	Most forward c.g.†	1.0	↓	↓	—
3.2.2.3.2	Control feel	Most aft c.g.††		↓	↓	
3.2.3.1	Longitudinal control in unaccelerated flight	Most forward c.g.	1.0	↓	↓	—
3.2.3.2	Longitudinal control in maneuvering flight	Most forward c.g.†	As required	↓	$V_{o_{min}}$ to $V_{o_{max}}$	CO,GA,AR,TF,CR,PA
3.2.3.3	Longitudinal control in takeoff	Most forward c.g. for nose-wheel airplanes, most aft c.g. for tail-wheel airplanes	1.0	low	As required	TO
3.2.3.3.1	Longitudinal control in catapult takeoff	Most forward c.g. and most aft c.g.	As required	↓	Min. safe launch speed to min. +30	CT
3.2.3.3.2	Longitudinal control force and travel in takeoff	Most forward c.g and most aft c.g	As required	↓	0 to V_{max} (TO)	TO,CT
3.2.3.4	Longitudinal control in landing	Most forward c.g.	1.0	↓	V_s (L) or geometric limit	L
3.2.3.4.1	Longitudinal control forces in landing	Most forward c.g.	1.0			L
3.2.3.5	Longitudinal control forces in dives -Service Flight Envelope	Most forward c.g.† and most aft c.g.††	As required	2000 ft above MSL to h_{max}	V_{min} to V_{max}	D,ED,CO,CR
3.2.3.6	Longitudinal control forces in dives -Permissible Flight Envelope	↓	As required	As required	V_{MAT} to max permissible	D,ED,CO,CR
3.2.3.7	Longitudinal control in sideslips	—	1.0	$h_{o_{min}}$, medium, $h_{o_{max}}$	V_{min} to V_{max}	CO,CR,PA,L

†Combined with heaviest weight

††Combined with lightest weight

TABLE XVIII. Design and test condition guidelines. (Continued)

REQ'MT. NO.	TITLE	CRITICAL LOADING (4.2.1, 4.2.2)	LOAD FACTOR	ALTITUDE (4.3.1)	SPEED	FLIGHT PHASE
SECTION 3.3	LATERAL-DIRECTIONAL FLYING QUALITIES					
3.3.1.1	Lateral-directional oscillations (Dutch roll)	Greatest yawing moment of inertia	1.0 and $n_o(+)$	$h_{o_{min}}$, medium,	V_{min} to V_{max}	*,CR,RT,PA,L
3.3.1.2	Roll mode	Greatest rolling moment of inertia	1.0 and $n_o(+)$	$h_{o_{max}}$	V_{min} to V_{max}	*,CR,PA,L
3.3.1.3	Spiral stability	—	1.0	↓	V_{min} to V_{max}	*,CL,CR,LO,RT DE,PA,L
3.3.1.4	Coupled roll-spiral oscillation	—	1.0 and $n_o(+)$	↓	↓	*,CR,PA,L
3.3.2.1	Lateral-directional response to atmospheric disturbances	—	1.0	↓	↓	—
3.3.2.2	Roll rate oscillations	—	1.0 and $n_o(+)$	↓	↓	*,CR,PA,L
3.3.2.2.1	Additional roll rate requirement for small inputs	—	↓	↓	↓	↓
3.3.2.3	Bank angle oscillations	—	↓	↓	↓	↓
3.3.2.4	Sideslip excursions	Greatest yawing and rolling moment of inertia	1.0	↓	↓	↓
3.3.2.4.1	Additional sideslip requirement for small inputs	↓	1.0	↓	↓	↓
3.3.2.5	Control of sideslip in rolls	Greatest rolling moment of inertia	As required	↓	↓	CO,GA,AR,TF, CR,PA,L
3.3.2.6	Turn coordination	—	↓	↓	$V_{o_{min}}$	CO,CR,LO,PA
3.3.3	Pilot-induced oscillations	—	Min. permissible to max. permissible	MSL to h_{max}	V_{min} to V_{max}	—
3.3.4	Roll control effectiveness	Greatest rolling moment of inertia	As required (not above 0.8 n_L)	$h_{o_{min}}$, medium,	↓	CO,GA,AR,TF, CR,PA,L
3.3.4.1	Roll performance for Class IV airplanes	↓	↓	$h_{o_{max}}$	↓	
3.3.4.1.1	Roll performance in Flight Phase CO	↓	↓	$h_{o_{min}}$	↓	CO
3.3.4.1.2	Roll performance in Flight Phase GA	↓	↓	↓	↓	GA
3.3.4.1.3	Roll response	Smallest rolling moment of inertia	↓	$h_{o_{min}}$, medium	↓	—
3.3.4.2	Roll performance for Class III airplanes	Greatest and smallest rolling moment of inertia	↓	$h_{o_{max}}$	↓	CO,GA,AR,TF, CR,PA,L
3.3.4.3	Roll control forces	↓	↓	↓	↓	—
3.3.4.4	Linearity of roll response	Greatest rolling moment of inertia	↓	↓	↓	CO,GA,AR,TF, CR,PA,L
3.3.4.5	Wheel control throw	↓	↓	↓	↓	CO,GA,AR,TF, CR,PA,L
3.3.5	Directional control characteristics	—	n(-) to n(+)	$h_{o_{min}}$, medium,	↓	*,CR,PA,L
3.3.5.1	Directional control with speed change	—	1.0	$h_{o_{max}}$	↓	CO,GA,CR,D, PA,L
3.3.5.1.1	Directional control with asymmetric loading	—	1.0	↓	$V_{o_{min}}$ to $V_{o_{max}}$	—
3.3.5.2	Directional control in wave-off (go-around)	Lightest weight	1.0	low	V_{min} (PA) or guaranteed landing speed	WO
3.3.6 (3.3.6.1, 3.3.6.2, 3.3.6.3, 3.3.6.3.1, 3.3.6.3.2)	Lateral-directional characteristics in steady sideslips	↓	1.0	$h_{o_{min}}$, medium $h_{o_{max}}$	V_{min} to V_{max}	CO,CR,PA,L

TABLE XVIII. Design and test condition guidelines. (Continued)

REQ'MT. NO.	TITLE	CRITICAL LOADING (4.2.1, 4.2.2)	LOAD FACTOR	ALTITUDE (4.3.1)	SPEED	FLIGHT PHASE
3.3.7	Lateral-directional control in cross winds	——	1.0	low	As required	TO,L
3.3.7.1	Final approach in cross winds	——	1.0	↓	V_{min} to V_{max}	PA
3.3.7.2 (3.3.7.2.1 3.3.7.2.2)	Takeoff run and landing rollout in crosswinds	——	As required	↓	As required	TO,L
3.3.7.3	Taxiing wind speed limits	——	As required	↓	All taxiing speeds	TAXI
3.3.8	Lateral-directional control in dives	·	As required	2000 ft above MSL to h_{max}	V_{MAT} to V_{max}	D,ED
3.3.9.1	Thrust loss during takeoff run	Lightest weight	1.0	$h_{o_{min}}$	0 to max takeoff speed	TO
3.3.9.2	Thrust loss after takeoff	↓	1.0	↓	Down to V_{min}(TO)	TO,CT
3.3.9.3	Transient effects	Lightest weight	1.0	All	V_{min} to V_{max}	CO,GA,TF,CR,CL,TO,CT
3.3.9.4	Asymmetric thrust – rudder pedals free	↓	1.0	$h_{o_{min}}$, medium, $h_{o_{max}}$	1.4 V_{min}	CR
3.3.9.5	Two engines inoperative	↓	1.0	↓	V_{range} (1 & 2 engines out)	——
SECTION 3.4	MISCELLANEOUS FLYING QUALITIES					
3.4.2	Flight at high angle of attack	See MIL-S-83691 or MIL-D-8708, whichever is applicable for flight demonstration. More severe conditions generally will be investigated by analysis and model testing.				
3.4.2.1 (3.4.2.1.1 through 3.4.2.1.3.1)	Stalls					
3.4.2.2 (3.4.2.2.1, 3.4.2.2.2)	Post-stall gyrations and spins					
3.4.3	Cross-axis coupling in roll maneuvers	——	1 to 0.8 n_L	$h_{o_{min}}$, medium, $h_{o_{max}}$	$V_{o_{min}}$ to $V_{o_{max}}$	CO,GA,AR,TF
3.4.4 (3.4.4.1)	Control harmony	——	$n_L(-)$ to $n_L(+)$	↓	↓	——
3.4.5	Buffet	——	↓	↓	↓	*
3.4.6	Release of stores	——	↓	↓	↓	CO,GA,WD,AD
3.4.7	Effects of armament delivery and special equipment	——	↓	↓	↓	*,RT
3.4.8	Transients following failures	——	all	↓	all	——
3.4.10	Control margin	——	↓	↓	↓	——
3.4.11	Direct force control	——	1.0 ± maximum DLC authority	$h_{o_{min}}$, medium, $h_{o_{max}}$	$V_{o_{min}}$ to $V_{o_{max}}$	——

TABLE XVIII. Design and test condition guidelines. (Concluded)

REQ'MT. NO	TITLE	CRITICAL LOADING (4.2.1, 4.2.2)	LOAD FACTOR	ALTITUDE (4.3.1)	SPEED	FLIGHT PHASE
SECTION 3.5	CHARACTERISTICS OF THE PRIMARY FLIGHT CONTROL SYSTEM					
3.5.2 (3.5.2.1, 3.5.2.2, 3.5.2.3)	Mechanical characteristics	—	$n_o(-)$ to $n_o(+)$	$h_{o_{min}}$ and $h_{o_{max}}$	V_{min} to V_{max}	—
3.5.3 (3.5.3.1, 3.5.3.2)	Dynamic characteristics	most forward c.g. & lowest values of rolling and yawing moments of inertia	1.0			—
3.5.5 (3.5.5.1, 3.5.5.2)	Failures	—	all			—
3.5.6 (3.5.6.1, 3.5.6.2)	Transfer to alternate control modes		1.0	$h_{o_{min}}$, medium, $h_{o_{max}}$		—
SECTION 3.6	CHARACTERISTICS OF SECONDARY CONTROL SYSTEMS					
3.6.1	Trim system	most forward c.g. and most aft c.g.	1.0	$h_{o_{min}}$, medium, $h_{o_{max}}$	V_{min} to V_{max}	—
3.6.1.1	Trim for asymmetric thrust	most forward c.g. and most aft c.g.	1.0	$h_{o_{min}}$ and max. attainable	V_{range} to V_{NRT} (with 1 & 2 engines out)	CR
3.6.1.2	Rate of trim operation		1.0	As required	As required	CO,GA,D,FD
3.6.1.3	Stalling of trim systems	most forward c.g. combined with heaviest weight	As required	As required	Start of dive recov. to V_{max}	D,ED,CO,CR
3.6.1.4	Trim system irreversibility		1.0	MSL to h_{max}	V_{min} to V_{max}	—
3.6.2	Speed and flight path control devices		1.0 to $n_o(+)$	$h_{o_{min}}$, medium, $h_{o_{max}}$	$V_{o_{min}}$ to $V_{o_{max}}$	*,RT,FD,DI, PA,MO,GA
3.6.3	Transients and trim changes		$n_o(-)$ to $n_o(+)$	$h_{o_{min}}$, medium, $h_{o_{max}}$	$V_{o_{min}}$ to $V_{o_{max}}$	—
3.6.3.1	Pitch trim changes		As required	As required	As required	CO,CR,PA,FO,CT
3.6.4	Auxiliary dive recovery devices	most aft c.g. combined with lightest weight	As required	MSL to h_{max}	$V_{o_{min}}$ to V_{max}	D,ED
SECTION 3.7	ATMOSPHERIC DISTURBANCES		1.0	MSL to h_{max}	V_{min} to V_{max}	—
SECTION 3.8	REQUIREMENTS FOR USE OF THE DISTURBANCE MODELS	—	All	MSL to h_{max}	V_{min} to V_{max}	—

NOTES

(1) a dash (—) indicates no general guidance can be provided

(2) The phrase "as required" means the flight conditions are specified in the requirement or are determined by the nature of the test maneuver

(3) An asterisk (*) means all applicable Category A Flight Phases

I. 4.4 TESTS AT SPECIALIZED FACILITIES

REQUIREMENT

4.4 Tests at specialized facilities. Certain tests, by their nature, can be conducted only at specialized facilities which are not accessible to either the procuring activity or the contractor except at the option of a third organization. In such cases, when an agreement of test support at the specialized facility is obtained by the procuring activity, an analysis of results obtained in the tests is necessary part of the analytical compliance demonstration.

RELATED MIL-F-8785B PARAGRAPH

None

DISCUSSION

This paragraph was added by Amendment 2. Some unique facilities such as NASA Langley's spin tunnel and free-flight model rig in their large wind tunnel, are frequently used in development but are not under our control. This paragraph is intended to assure the procuring activity access to any data from such sources.

SECTION XIV

STATEMENT AND DISCUSSION OF REQUIREMENTS FOR NOTES (6.)

6. NOTES

A. 6.1 INTENDED USE

REQUIREMENT

6.1 Intended use. This specification contains the flying qualities requirements for piloted airplanes and forms one of the bases for determination by the procuring activity of airplane acceptability. The specification consists of design requirements in terms of criteria for use in stability and control calculations, analysis of wind tunnel test results, simulator evaluations, flight testing, etc. The requirements should be met as far as possible by providing an inherently good basic airframe. Cost, performance, reliability, maintenance, etc. tradeoffs are necessary in determining the proper balance between basic airframe characteristics and augmented dynamic response characteristics. The contractor should advise the procuring activity of any significant design penalties which may result from meeting any particular requirement.

DISCUSSION

According to the manual on specification writing, the "intended use" is of the product rather than of the specification, although that does not quite fit MIL-F-8785. The more significant material of 6.1 has been moved to 1.1 where it is more visible. Recognition of possible tradeoffs is a minimal attempt at realism while still stating a preference for a good basic airframe in accordance with Navy, ASD, etc. wishes. Rather than just mentioning deviations in 1.2, an expanded treatment in 6.1 gives some rationale for considering them in context. Any requirements in section 6 are binding, the specification manual states, but should not be there. It hardly seems necessary to require the contractors to bring discrepancies of this sort to the procuring activities' attention. Av. P. 970 has similar provisions.

Among the published discussions of such tradeoffs from a handling qualities viewpoint is Reference 119. Similarly, Reference 120 gives flight control system considerations.

B. 6.2 DEFINITIONS

REQUIREMENT ADDITIONS OR CHANGES

6.2.2 Speeds

Equivalent airspeed, EAS - true airspeed mutliplied by $\sqrt{\sigma}$, where σ is the ratio of free-stream density at the given altitude to standard sea-level air density

V_S - stall speed (equivalent airspeed), at 1g normal to the flight path, defined as the highest of:

a. speed for steady straight flight at $C_{L_{max}}$, the first local maximum of the curve of lift coefficient (L/gS) vs. angle of attack which occurs as C_L is increased from zero

b. speed at which uncommanded pitching, rolling or yawing occurs (3.4.2.1.2)

c. speed at which intolerable buffet or structural vibration is encountered

Conditions for determining V_S.

The airplane shall be initially trimmed at approximately 1.2 V_S with the following settings, after which the trim and throttle settings shall be held constant:

Flight Phase	Thrust Settings*	Trim Setting
Climb (CL)	Normal climb	For straight flight
Descent (D)	Normal descent	For straight flight
Emergency descent (ED)	Idle	For straight flight
Emergency deceleration (DE)	Idle	For straight flight
Takeoff (TO)	Takeoff	Recommended takeoff setting
Approach (PA)	Normal approach	For normal approach
Wave-off/go-around (WO)	Takeoff	For normal approach
Landing (L)	Idle	For normal approach
All other	TLF 1.2 V_S	For straight flight

* Either on all engines or on remaining engines with critical engine inoperative, whichever yields the higher value of V_S.

In flight test, it is necessary to reduce speed very slowly (Typically 1/2 knot per second or less) to minimize dynamic lift effects. The load factor will generally not be exactly 1g when stall occurs; when this is the case, V_S is defined as follows:

$$V_S = \frac{V}{\sqrt{n_f}}$$

where V and n_f are the measured values at stall, n_f being the load factor normal to the flight path.

$V_S(X)$, $V_{min}(X)$, $V_{max}(X)$ - short-hand notation for the speeds V_S, V_{min}, V_{max} for a given configuration, weight, center-of-gravity position, and external store combination associated with Flight Phase X. For example, the designation $V_{max}(TO)$ is used in 3.2.3.3.2 to emphasize that the speed intended (for the weight, center of gravity, and external store combination under consideration) is V_{max} for the configuration associated with the takeoff Flight Phase. This is necessary to avoid confusion, since the configuration and Flight Phase change from takeoff to climb during the maneuver.

V_G Gust penetration speed

6.2.4 Control parameters

Pitch, roll, yaw controls - the stick or wheel and pedals manipulated by the pilot to produce pitching, rolling and yawing moments respectively; the cockpit controls

Pitch control force, FS - Component of applied force, exerted by the pilot on the cockpit control, in or paralled to the plane of symmetry, acting at the center of the stick grip or wheel in a direction perpendicular to a line between the center of the stick grip and the stick or control column pivot.

Roll control force - for a stick control, the component of control force exerted by the pilot in a plane perpendicular to the plane of symmetry, acting at the center of the stick grip in a direction perpendicular to a line between the center of the stick grip and the stick pivot. For a wheel control, the total moment applied by the pilot about the wheel axis in the plane of the wheel, divided by the average radius from the wheel pivot to the pilot's grip

Yaw-control pedal force - difference of push-force components of forces exerted by the pilot on the yaw-control pedals, lying in planes parallel to the plane of symmetry, measured perpendicular to the pedals at the normal point of application of the pilot's instep on the respective yaw-control pedals

6.2.5 Longitudinal parameters

α_S - the stall angle of attack at constant speed for the configuration, weight, center of gravity position and external-store combination associated with a given Airplane Normal State; defined as the lowest of the following:

a. Angle of attack for the highest steady load factor, normal to the flight path, that can be attained at a given speed or Mach number

b. Angle of attack, for a given speed or Mach number, at which uncommanded pitching, rolling or yawing occurs (3.4.2.1.2)

c. Angle of attack, for a given speed or Mach number, at which intolerable buffeting is encountered.

$C_{L_{stall}}$ - lift coefficient at α_S defined above.

6.2.6 Lateral-directional parameters

$\omega_{n_{RS}}$ - undamped natural frequency of a coupled roll-spiral oscillation

ζ_{RS} - damping ratio of a coupled roll-spiral oscillation

$\Delta\beta$ - maximum change in sideslip occurring within 2 seconds or one-half period of the Dutch roll, whichever is greater, for a step roll-control command (figures 14 and 15).

6.2.7 Atmospheric disturbances parameters

j - $\sqrt{-1}$

t - time

$V_{w/d}$ - magnitude of wind over the aircraft carrier deck (feet per second)

σ, RMS - root-mean-square disturbance intensity, where

$$\sigma^2 = \int_0^\infty \phi(\Omega)\, d\Omega = \int_0^\infty (\omega)\, d\omega$$

u_{20} - wind speed at 20 feet above the ground

x - distance from airplane to ship center of pitch, negative aft of ship (feet)

ψ_w - mean wind direction relative to runway (3.7.3.3)

6.2.8 Terms used in high angle of attack requirements

Post-stall - The flight regime involving angles of attack greater than nominal stall angles of attack. The airplane characteristics in the post-stall regime may consist of three more or less distinct consecutive types of airplane motion following departure from controlled flight; post-stall gyration, incipient spin, and developed spin.

Post-stall gyration (PSG) - Uncontrolled motions about one or more airplane axis following departure from controlled flight. While this type of airplane motion involves angles of attack higher than stall angle, lower angles may be encountered intermittently in the course of the motion.

Spin - The part of the post-stall airplane motion which is characterized by a sustained yaw rotation. The spin may be erect or inverted, flat (high angle of attack) or steep (low but still stalled angle of attack) and rotary motions may have oscillations in pitch, roll and yaw superimposed on them. The incipient spin is the initial, transient phase of the motion during which it isnot possible to identify the spin mode, usually followed by the development spin, the phase during which it is possible to identify the spim mode.

C. 6.3 INTERPRETATION OF F_s/n LIMITS OF TABLE V

REQUIREMENT

6.3 Interpretation of F_s/n limits of table V. Because the limits on F_s/n are a function of both n_L and n/α, table V is rather complex. To illustrate its use, the limits are presented on figure 16 for an airplane having a center-stick controller and n_L = 7.0

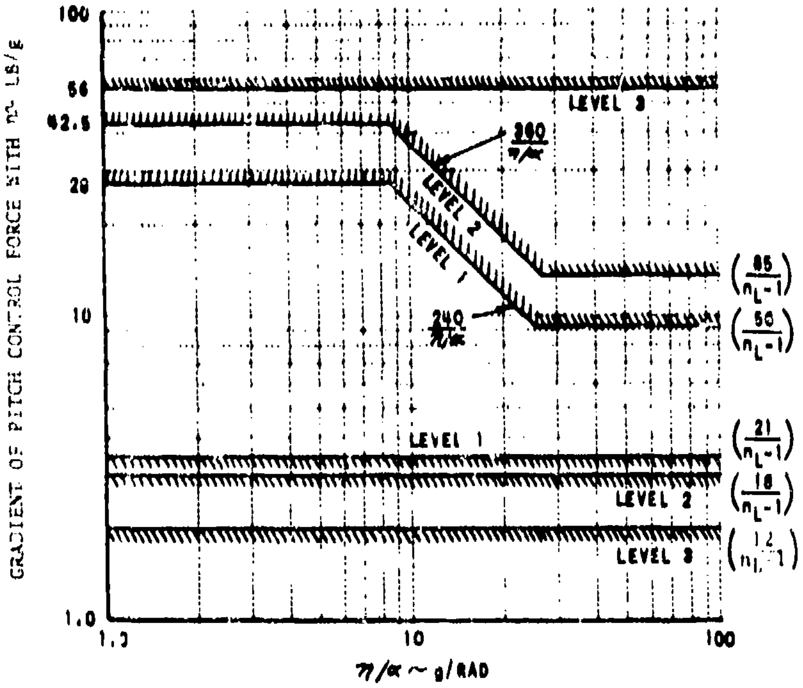

FIGURE 46. (MIL-F-8785C FIGURE 16.) Example of pitch maneuvering force gradient limits: Center-stick controller, n_L = 7.0

DISCUSSION

The Level 3 boundary in the figure has been changed consistent with the revision to 3.2.2.2.1

D. 6.5 ENGINE CONSIDERATION

REQUIREMENT

6.5 Engine consideration. Secondary effects of engine operation may have an important bearing on flying qualities and should not be overlooked in design. These considerations are: the influence of engine gyroscopic moments on airframe dynamic motions; the effects of engine operation (including flameout and intentional shutdown) on charateristcs of flight at high angle of attack (3.4.2); and the reduction at low rpm of engine-derived power for operating the flight control system.

DISCUSSION

These minor wording changes were made in Amendment 2.

E. 6.8 RELATED DOCUMENTS

REQUIREMENTS

6.8 Related documents. The documents listed below, while they do not form a part of this specification, are so closely related to it that their contents should be taken into account in any application of this specification.

SPECIFICATIONS

MILITARY

MIL-C-5011	Charts; standard Aircraft Characteristics and Performances, Piloted Aircraft
MIL-M-7700	Manual, Flight
MIL-A-8860	Airplane Strength and Rigidity - General Specification for
MIL-S-8371	Airplane Strength and Rigidity Flight and Ground Operations Test
MIL-G-38478	General Requirements for Angle-of-Attack-Based Systems

STANDARD

MILITARY

MIL-STD-882	Systems Safety Program for Systems and Associated Subsystems and Equipment: Requirements for

PUBLICATIONS

AFSC Design Handbooks

DH 1-0 General
DH 2-0 Aeronautical Systems

AFFDL Technical Report

TR 69-72	Background Information and User Guide for MIL-F-8785B, Military Specification - Flying Qualities of Piloted Airplanes, August 1969

DISCUSSION

These changes were made in Amendment 2.
In addition, this present report would also be added to the related documents for a detail specification derived from MIL-F-8785C.

REFERENCES

1. "Military Specification, Flying Qualities of Piloted Airplanes", MIL-F-8785C, dated 5 November 1980.

2. "Military Specification, Flying Qualities of Piloted Airplanes", MIL-F-8785B(ASG), dated 7 August 1969.

3. Chalk, C.R. et al., "Background Information and Users Guide for MIL-F-8785B(ASG), 'Military Specification - Flying Qualities of Piloted Airplanes'", AFFDL-TR-69-72, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, August 1969.

4. Brady, C.C., and Hodgkinson, J., "Validation of the Flying Qualities Requirements of MIL-F-8785A(USAF)", AFFDL-TR-70-155, January 1971.

5. Kandalaft, R.N., "Validation of the Flying Qualities Requirements of MIL-F-8785B(ASG)", AFFDL-TR-71-134, September 1971.

6. Richards, R.B., et al., "Validation of the Flying Qualities Requirements of MIL-F-8785B(ASG), Using the P-3B Airplane", AFFDL-TR-72-141, Vol. I, November 1973.

7. Silvers, Charles L., and Withers, Clifton C., "Evaluation of the Flying Qualities Requirements of MIL-F-8785B(ASG) Using the C-5A Airplane", AFFDL-TR-75-3, March 1975.

8. Brulle, R.V., and Moran, W.A., "Dynamic Flying Qualities Investigation", AFFDL-TR-74-142, October 1974.

9. "Advertisement and Specification for a Heavier-Than-Air Flying Machine", Signal Corps Specification No. 486, December 1907.

10. Twisdale, T.R., and Franklin, D.L., Capt., USAF, "Tracking Test Techniques for Handling Qualities Evaluation", FTC-TD-75-1, Air Force Flight Test Center, Edwards AFB, Calif., May 1975.

11. Gerken, G.J., "USAF Flying Qualities Requirements for a STOL Transport", ASD-TR-78-13, May 1979.

12. Craig, S.J., and Ashkenas, I.L., "Background Data and Recommended Revisions for MIL-F-8785B(ASG), Military Specification - Flying Qualities of Piloted Airplanes'", Tech. Report No. 189-1, Systems Technology, Inc., Hawthorne, CA, March 1971.

13. Chalk, C.R., et al., "Revisions to MIL-F-8785B(ASG) Proposed by Cornell Aeronautical Laboratory under Contract F33615-71-C-1254", AFFDL-TR-72-41, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, April 1973.

14. Ashkenas, I.L., et al., "Recommended Revisions to Selected Portions of MIL-F-8785(ASG), and Background Data", AFFDL-TR-73-76, Air Force Flight Dynamics Laboratory, Wright-Patterson AFB, Ohio, August 1973.

15. Stapleford, R.L., et al., "Outsmarting MIL-F-8785B(ASG), the Military Flying Qualities Specification", Systems Technology Inc. Report STI-TR-190-1, August 1971.

16. Key, D.L., "The Generation of a Military Specification for Flying Qualities of Piloted V/STOL Aircraft - MIL-F-83300", AFFDL-TR-71-23, April 1971.

17. Chalk, C.R., Radford, R.C., and Wasserman, R., "Final Report on Program to Improve MIL-F-83300", AFFDL-TR-74-54, June 1974.

18. Di Franco, D.A., and Mitchell, J.F. "Preliminary Handling Qualities Requirements for Lifting Re-Entry Vehicles during Terminal Flight", AFFDL-TR-71-64, August 1971.

19. Prosser, C.F., and Wiler, C.D., "RPV Flying Qualities Design Criteria", AFFDL-TR-76-125, December 1976.

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