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A critical review of all sections of MIL-F-8785C applicable to large (Class III) aircraft is performed. Recommendations to change, delete, or leave unchanged these sections are given based on currently available flying qualities data from actual large aircraft and simulated large aircraft. The results are documented in the format of the upcoming MIL-Standard and Handbook but with the numbering scheme from MIL-F-8785C for ease of reference.

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FOREWORD

This report was prepared by Messrs. R. T. Meyer, J. R. Knox and S. A. Tingas of the Lockheed-Georgia Company under Contract F33615-81-C-3607 for the Flight Dynamics Laboratory, Air Force Wright Aeronautical Laboratories. Mr. Thomas A. Gentry was the Project Engineer from AFWAL/FIGC. In addition to the AFWAL report number, the report is listed in the Lockheed-Georgia Engineering Reports as LG81ER0221. The 81 designation is retained since contractual effort began in 1981 and progress reports leading to this final report have been consecutively numbered as -1 through -18 with this report designation.

The authors would like to acknowledge the help received in obtaining information to aid in the development of large aircraft flying qualities criteria. Many individuals and companies showed a sincere willingness to provide data for the purpose of making this report a more useful and complete guide for the military and industry on large aircraft. Those individuals and companies are:

Mr. Jerry Rising	Lockheed-California Company
Mr. Don West	Boeing Aircraft Company
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Mr. Carl Crother	North American Rockwell
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Mr. Tom Gentry	AFWAL/FIGC
Mr. Bob Woodcock	AFWAL/FIGC
Mr. Dave Moorhouse	AFWAL/FIGC
Capt. Charles Hudson	MAC Headquarters - USAF

and all the Operational Pilots at Travis and Dover Air Force Bases who participated in the Pilot Evaluation Survey.

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SECTION I

INTRODUCTION AND PURPOSE

This report provides information to help tailor a detailed flying qualities specification to the particular mission requirements of any advanced large aircraft. MIL-F-8785C, Military Specification - Flying Qualities of Piloted Aircraft, was critically reviewed with respect to its applicability to large - Class III - aircraft. Areas where the authors believe that revision, expansion or deletions should be made have been identified; changes are proposed and discussed.

An attempt was made to locate all available pertinent flying qualities data in the identified areas. In particular, References 1 through 4 were reviewed in detail since they provided a large background of applicable flight test and flight simulation data as well as analyses. The statement of work directing this effort specifically mentioned considering Reference 5, which contains results of a recent FDL sponsored large aircraft in-flight simulation to study handling qualities in the approach and landing phase. In addition to these reports unpublished data from Lockheed-Georgia and Lockheed-California were considered. The bibliography and reference list show the compilation of these and other materials used to develop the suggested revisions.

Through personal contact, several other U.S. aircraft manufacturers furnished valuable information. With the help of the Headquarters Military Airlift Command, we asked MAC pilots of the C-5A to comment on that airplane. The returns, which testify to the airplane's high degree of acceptance by service pilots, are summarized in Appendix A.

Proposed changes to MIL-F-8785C are presented in the new format of the Standard and Handbook. The paragraph numbers refer to those in MIL-F-8785C, and are, therefore, not consecutive in this report.

A suggested change to 8785C can easily be identified throughout the report by a vertical line in the right hand margin at the specific lines of the requirement. The format consists of presenting the following:

REQUIREMENT - Text repeated from the specification or modified to reflect suggested changes for Class III aircraft.

RATIONALE - Text describing the reasons for the requirements and the changes (if appropriate).

GUIDANCE - Information to aid in choosing values for filling in blanks or changing values when developing a new specification for a particular aircraft and its unique mission.

LESSON LEARNED - Information or background based on experience of past successes or failures in applying the requirement. In addition, results from studies and applicable references are provided which may have an influence on future consideration of specification application.

In some instances the requirement was considered sufficient without modification, but additional large aircraft information (rationale, etc.) are provided as an aid to tailoring a new specific document. Paragraphs not specifically addressed in this report were considered to be sufficient as they stand.

SECTION II

PROPOSED REVISIONS TO MIL-F-8785C FOR LARGE AIRCRAFT

This section presents the proposed changes to the specification. It uses the format previously described and changed for the new Standard and Handbook, i.e. requirement, rationale, guidance, and lessons learned. Changes are easily recognized by the vertical lines in the right margin.

Table 1 is an index of all requirements presented. It shows the MIL-F-8785C paragraph number, a brief of the title, whether or not a change is suggested and the report page. The suggested changes begin with paragraph 1.3 on page 5 and continue throughout this section.

TABLE 1

Index of MIL-F-8785C Requirements Addressed in Report

MIL-F-8785C Paragraph	Description	Modification Suggested	Report Page
1.3	Airplane Classification	Distinguish Between Class III Combatant and Non-Combatant	5
1.4	Flight Phase Categories	Add Low Altitude Aerial Delivery Phase to Category A	9
3.1.7	Operational Flight Envelope	Add Low Altitude Aerial Delivery to Category A Flight Envelope Definition	11
3.2.1.1	Longitudinal Static Stability	No Change - Data Provided	13
3.2.1.2	Phugoid Stability	Lower level 1 damping; change level 3 for consistency in specification	35

MIL-F-8785C Paragraph	Description	Modification Suggested	Report Page
3.2.1.3	Flight Path Stability	Alternate criteria suggested	41
3.2.2.1.1	Short Period Frequency	Replacement of lower CAP boundary	53
3.2.2.1.2	Short Period Damping Ratio	Change level 3 limit for consistency	82
3.2.2.1.3	Residual Oscillation	No change suggested. References provided	85
3.2.2.2.2	Control Motions in Maneuvering	Change in side-stick controller requirement	86
3.2.3.2	Longitudinal Control	Level 3 change for adverse trim	89
3.3.1.1	Dutch Roll	Damping ratio change, implementation of requirement, additional data	91
3.3.1.2	Roll Mode	New maximums and additional data	108
3.3.2.2	Roll Rate Oscillation	deleted	126
3.3.2.2.1	Roll Rates for Small Inputs	deleted	126
3.3.3	Bank Angle Oscillations	deleted	126
3.3.2.4	Side Slip Excursions	Reduced bank angle required	129
3.3.2.4.1	Sideslip for Small Inputs	Simplified requirement, added data	130
3.3.4	Roll Control Effectiveness	Eliminated inertia ratio application	136
3.3.4.2	Roll Performance	Total modification of times to bank	137
3.4.3	Cross Axis Coupling in Roll	Reduced Angle of roll specified	143
3.5.3	Dynamic Characteristic	Increased allowable response times	144

1.3 Classification of Airplanes

REQUIREMENT

For the purpose of this specification, an airplane shall be placed in one of the following classes:

Class I Small, light airplanes such as

- Light utility
- Primary trainer
- Light observation

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

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

Class III (A) Large, heavy, low-to-medium maneuverability and usually non-combatant airplanes such as

- Heavy transport/cargo/tanker

Class III (B) Large, heavy, low-to-medium maneuverability airplanes with a more combatant type missions such as

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

Class IV High-maneuverability airplanes such as

- Fighter/interceptor
- Attack
- Tactical reconnaissance
- Observation
- Trainer for Class IV

The procuring activity will assign an airplane to one of these Classes, and the requirements for that Class shall apply. When no Class is specified in a requirement, the requirement shall apply to all Classes. When operational missions so dictate, an airplane of one Class may be required by the procuring activity to meet selected requirements ordinarily specified for airplanes of another Class.

RATIONALE

Although this report does not attempt to redefine all requirements with respect to two levels of Class III requirements, some consideration should be given to recognizing the varying needs of this class. The Class III division of aircraft from Reference 1, as shown in Figure 1, considers large and heavy aircraft as varying in weight from 67,000 pounds to one million and beyond. Maneuverability requirements and design load factors also cover a tremendously wide range due to many varied missions.

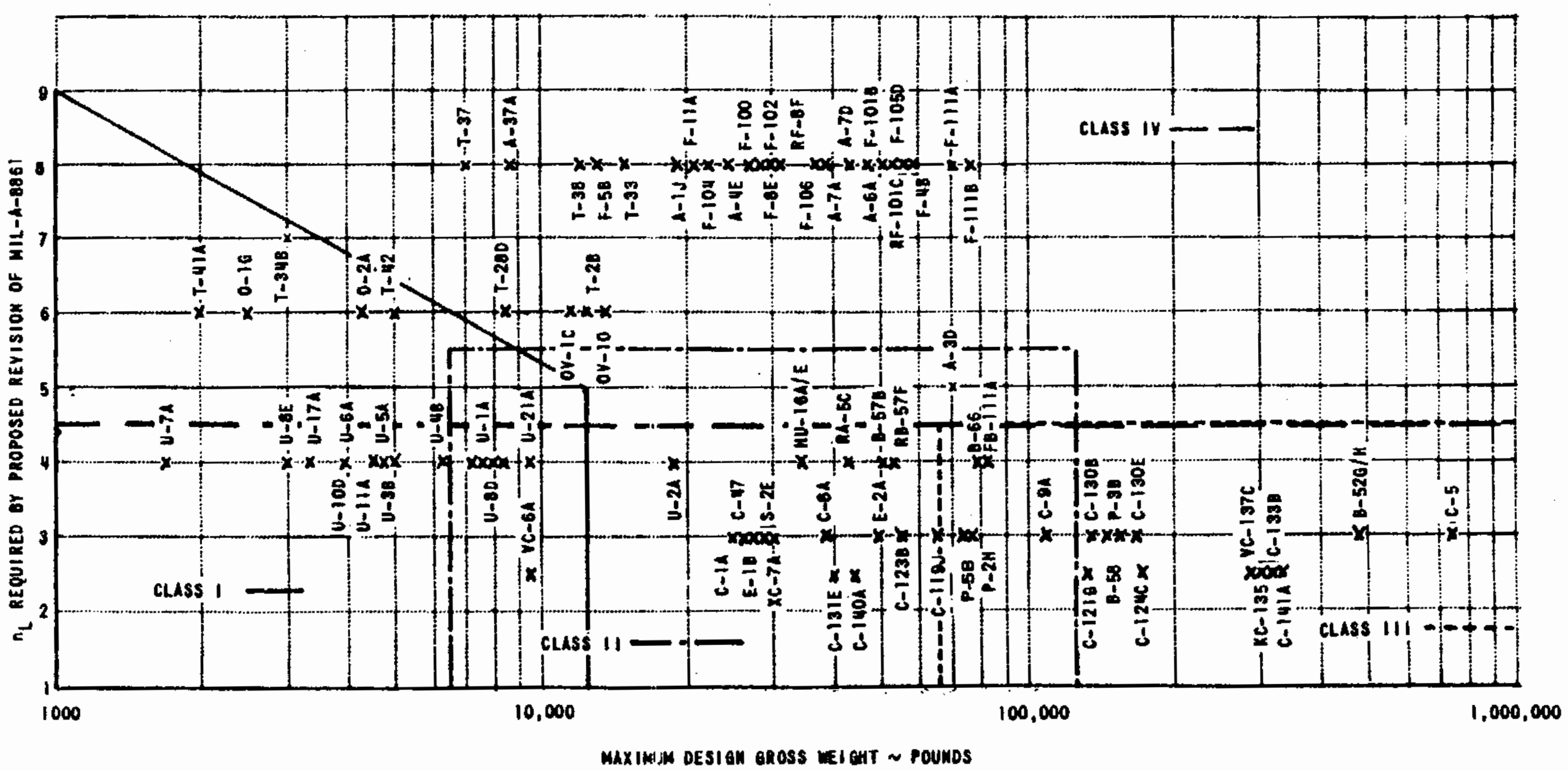


Figure 1 Classification of Aircraft (from Reference 1)

The suggested revision is to break Class III designation into: III(A) - non-combatant type aircraft; and III(B) - combatant aircraft. Missions and therefore maneuverability requirements are vastly different for the two different groups.

Another possible break in the classification could be: III(C) - Very Large Aircraft. This is not suggested, however, since too many classifications would complicate rather than aid in the development of particular specifications. One main reason for a suggested division in the Class III is that the imposition of high maneuverability requirements on very large aircraft with personnel appreciably offset from the rotational axes can produce very undesirable results. A new large aircraft specification should designate the required maneuverability based on mission-peculiar needs. It seems obvious that combatant or non-combatant roles will dictate the requirements in non-terminal flight phases.

1.4 Flight Phase Categories

REQUIREMENT

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 identified in the requirement. When no Flight Phase 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)

.

.

.

i. Close formation flying (FF)
j. Low altitude aerial delivery (LAAD)

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)

.

.

.

h. Aerial delivery (AD)

Terminal Flight Phases:

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

a. Takeoff (TO)

.

.

.

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.

RATIONALE

The last paragraph of 1.4 states that the procuring activity will recategorize, add or delete as necessary. Recent experience (Reference 6) has shown that the aerial delivery flight phase, if conducted at low altitude, becomes more in line with Category A requirements. Rapid maneuverability is obviously required in close proximity to the ground and precise flight path control is a must. The problems of insuring that control sensitivity is sufficient, yet not so high as to cause PIO, are rather unique to the mission. For these reasons, it is suggested that low altitude aerial delivery (LAAD) be added as "j" under Category A.

3.1.7 Operational Flight Envelopes

REQUIREMENT

The operational flight envelopes define the boundaries in terms of speed, altitude and load factor within which the airplane must be capable of operating in order to accomplish the missions of 3.1.1. Envelopes for each applicable Flight Phase shall be established with the guidance and approval of the procuring activity. In the absence of specific guidance, the contractor shall use the representative conditions of Table 2 for the applicable Flight Phases.

Table 2

Operational Flight Envelopes

Flight Phase Category	Flight Phase	Airspeed		Altitude		Load Factor	
		$V_{o_{min}}$ ($M_{o_{min}}$)	$V_{o_{max}}$ ($M_{o_{max}}$)	$h_{o_{min}}$	$h_{o_{max}}$	$n_{o_{min}}$	$n_{o_{max}}$
A	Air-to-Air Combat (CO)	1.4 V_s	V_{MAT}	MSL	Combat Ceiling	-1.0	n_L
	• • • •						
	Close Formation Flying (FF)	1.4 V_s	V_{MAT}	MSL	Combat Ceiling	-1.0	n_L
	Low Altitude Aerial Delivery (LAAD)	1.2 V_s	-	MSL	-	.5	2.0

RATIONALE

In conjunction with the addition of "low altitude aerial delivery" to Flight Phase Category A in paragraph 1.4, it is entered into Table 2 with representative conditions. The uniqueness of this mission is such that the procuring agency will probably provide specific conditions.

Weight of the payload, method of delivery, and nature of the payload will set the airspeed, altitude and load factors. The values shown in Table 2 are considered representative. Reference 6 is an excellent source of information on the "low altitude parachute extraction system" used on the C-130. References 7-9 are additional sources of data for aircraft response, capabilities and problem areas associated with aerial delivery based on flight test of large aircraft.

3.2.1.1 Longitudinal Static Stability

REQUIREMENT

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, and

b. 1g 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 Envelopes). 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.

RATIONALE

The requirement, taken directly from MIL-F-8785C without change, insures positive "static" stability for Levels 1 and 2 and limits the amount of "static" instability for Level 3. Static stability implies that restoring pitching moments are generated when airspeed is disturbed from trim, and a "static" instability implies an aperiodic divergence. The intent of the requirement is to insure that altitude and airspeed will not diverge for unattended pilot operation for Levels 1 and 2, and to limit the divergence for Level 3.

To accommodate the relaxed static stability aircraft concept, the requirement allows relaxation to an instability of no less than six seconds time to double amplitude for Level 3.

GUIDANCE

The Levels 1 and 2 requirements are presented in terms of stick force per velocity gradients because they are a straightforward way to detect - in flight - slightly divergent modes which are otherwise difficult to quantify. This gradient provides a necessary but not sufficient condition for stability of "natural" aircraft. It does appear however to be a good indicator of aperiodic instability.

The requirement allows stability to be provided with Command Stability Augmentation Systems that produce zero gradients of column force and position with respect to speed, yet are stable with respect to external disturbances. These systems are permitted if they meet the intent of the specification, i.e., that attitude and speed will not diverge for unattended pilot operation.

Data presented in Reference 10 refutes the use of "time to double amplitude" as a flying qualities criterion, and provides a well documented set of relaxed static stability criteria for the landing flight phase. Although that study and data presented in Reference 11 indicate that a considerable relaxation or decrease in time to double is allowable for systems with higher damping, the more conservative (T_2 = 6 sec) criterion is suggested for retention due to the lack of operational flight experience in this area, especially with regard to turbulence and wind shear.

The allowance of static instability (T_2 = 6 sec.) for Level 3 in this paragraph leads to recommended changes in other Level 3 boundaries. Specifically, these are the phugoid (3.2.1.2), short period (3.2.2.1.1 and 3.2.2.1.2), and stick force/g (3.2.2.2.1) characteristics. These additional changes are needed to provide a consistency throughout the requirements since they are interrelated.

The following discussion presents three cases where speed changes with relaxed stability have quite different effects on other related characteristic modes.

Using the normal static stability indicator, stick force change with speed, some key points will be developed. When both Z_{δ_e} and thrust axis displacement from the center of mass are negligible, the equation for stick force change with speed is

$$\frac{dF_s}{dU} = \left(\frac{d\,\delta_e}{dU}\right)\frac{dF_s}{d\,\delta_e} = \left[\frac{(C_{L_u} + 2C_L)\;C_{m_{C_L}} - C_{m_u}}{U\;C_{m_{\delta_e}} / C_{L_\alpha}}\right]\left(\frac{dF_s}{d\,\delta_e}\right) \qquad (1)$$

$$(-) = (+) \qquad (-) \quad = \qquad [+] \qquad (-)$$

The signs required for stability, a negative gradient, are shown below the equation. The denominator of the term in brackets is negative so the numerator must remain negative. The numerator can be broken down into the following form to relate the more common stability derivative and speed derivative terms. Then for stability

$$\left[C_{m_{C_L}} - \frac{C_{m_u}}{(C_{L_u} + 2\,C_L)} \right] < 0 \qquad (2)$$

The stick force per velocity requirement thus requires the above bracket to be **negative** for Levels 1 and 2 and limits the magnitude of the bracketed quantity for Level 3. The Level 3 requirement allows for a "static" or aperiodic divergence with a minimum time to double amplitude of six seconds. As will be shown in the following paragraphs, for large aircraft, the critical or unstable motion mode resulting from reduced stability may be aperiodic or oscillatory, may be associated with several different pole-zero combinations, and may occur in the phugoid or the short period modes. The present Level 3 phugoid requirement in 8785C is not consistent for an occurrence of this type.

The velocity derivatives in Equations (1) and (2) can have a significant impact on large aircraft design, especially in the case of transports which normally have operational envelopes that require cruise flight in the transonic regime.

In conventional flight with a forward c.g., $C_{m_{C_L}}$ is negative and often much larger than the speed derivative terms. As the c.g. moves aft, $C_{m_{C_L}}$ becomes a smaller negative term, eventually going to zero and then positive. Obviously, the speed derivatives can become predominant. The derivative C_{m_u} may acquire significant positive or negative values, hence augmenting or degrading the stability levels normally set by $C_{m_{C_L}}$.

A traditional indication of longitudinal static stability has been the relationship of angle of attack and pitching moment. The degree of stability has been measured by the shape of the curve of pitching moment coefficient with lift coefficient. Positive stability is indicated by a curve with negative slope, and neutral stability exists when the slope goes to zero. Since the change in the pitching moment with respect to lift varies directly with c.g. movement for linear C_{m_α} and C_{L_α} relationships, the margin of stability with respect to neutral (static margin) is normally quoted in percent mean aerodynamic chord just as c.g. movement. A confusion in terminology can easily exist when speed derivatives become predominant, such as cases with relaxed stability and transonic speeds. Measuring stability by relating control force or position as a function of speed compounds the problem. The neutral point is defined herein as the c.g. for which $C_{m_{C_L}}$ is zero.

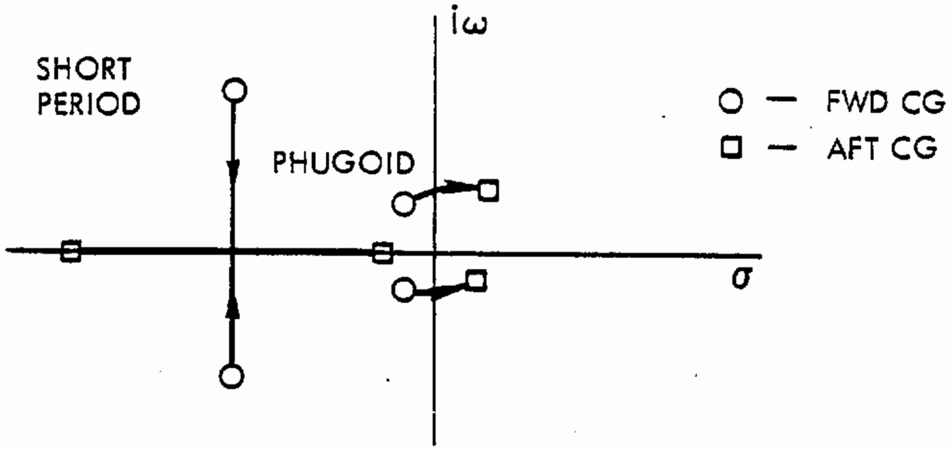
The nonlinearity of C_{m_u} in the transonic region further complicates stability requirements. Analyses and flight verification difficulties can then make a time response criterion more appropriate.

A further look at equation (2) shows that stability may be augmented by control systems that either: decrease the first term, $C_{m_{C_L}}$, (i.e., tend to make it more negative); or increase the second term, $C_{m_u} / (C_{L_u} + 2 C_L)$, now defined as eta, η .

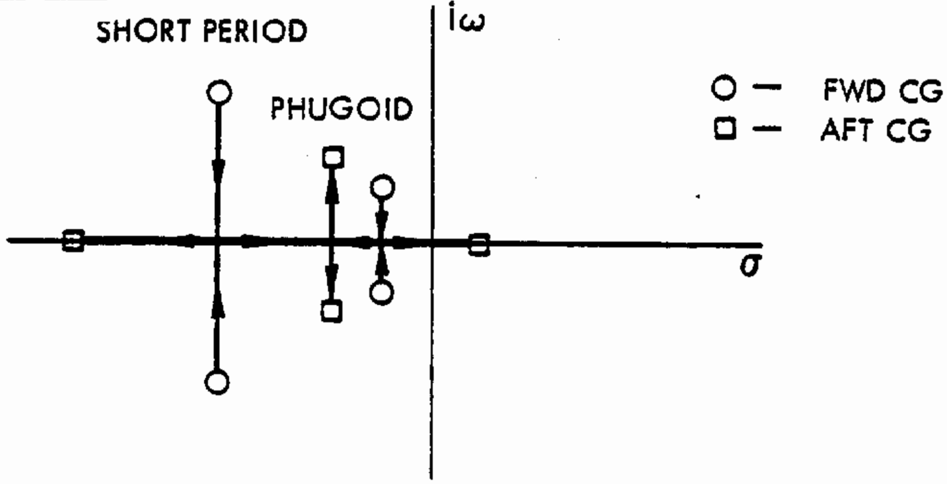
The type of instability, or pattern of the aircraft's characteristic roots, is important with regard to flying qualities and application of this criterion. Types of instability that typically may occur as the c.g. is moved aft for various values of η are shown in Figure 2.

Figure 2a shows the condition where the speed derivative is adding to stability, $\eta > 0$. As the c.g. is moved aft, the phugoid roots migrate to an oscillatory instability with the short period mode becoming an increasingly over-damped root pair on the negative real axis.

A) $\eta > 0$ (TYPE I)



B) $\eta = 0$ (TYPE II)



C) $\eta < 0$ (TYPE III)

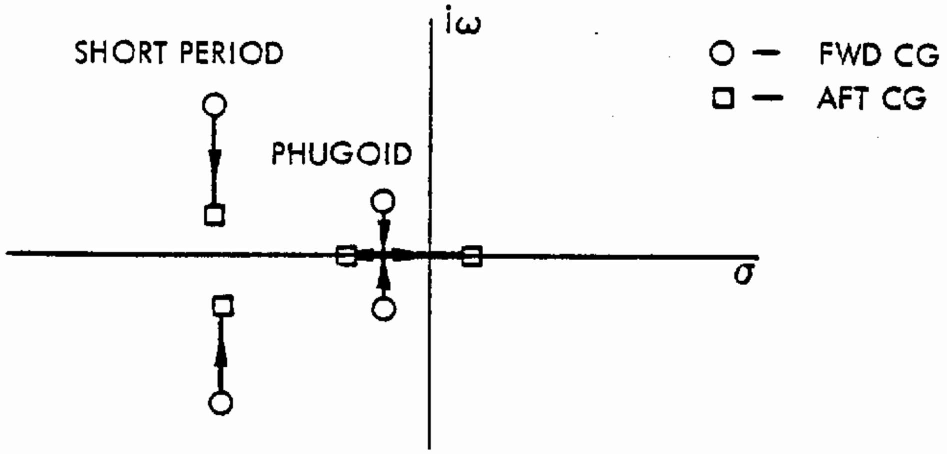


Figure 2 Aircraft Characteristic Root Locations for C.G. Shift and η Variations

The condition where the speed derivative has no stability effect, i.e., $\eta = 0$, is depicted in Figure 2b. The short period and phugoid roots coalesce as the c.g. moves aft to form a new stable, oscillatory mode plus a stable and unstable real root (non-oscillatory) pair. The stable oscillatory mode is an intermediary between the parent phugoid and short period modes. It is different, however, since velocity, angle of attack and attitude are all excited.

Figure 2c shows the condition where the speed derivative degrades stability. As the c.g. moves aft, the phugoid mode breaks down into two real roots, one stable and one unstable, while the short period mode becomes increasingly damped but remains oscillatory.

In order to demonstrate and quantify these effects on large aircraft, cruise and landing configurations of the C-5A ($\eta > 0$ and $\eta = 0$, respectively) and a cruise configuration of a C-141A ($\eta < 0$) were analyzed for extreme aft c.g. locations - outside the allowable c.g. range. The cases are otherwise well inside the flight operational envelopes. In each case, the aircraft are unaugmented. Figures 3 through 5 describe migration of the characteristic roots as a function of c.g. position.

Figures 3 and 5 are for the C-5 and C-141 high speed cruise configurations where non-zero velocity derivatives occur (Types I and III). The phugoid mode clearly goes unstable with aft c.g. movement for these cases with time to double amplitude of less than six seconds, while the short period mode remains stable. For the $\eta > 0$ case, the unstable roots are oscillatory. The $\eta < 0$ case has an aperiodic divergence. Figure 4 shows a low speed landing case, $C_{m_u} = 0$, where the phugoid and short period modes coalesce to form a pair of oscillatory "phugoid-like" real roots. Evidence indicates that "supercritical" airfoils exhibit characteristics like those of the C-141, i.e., $\eta < 0$.

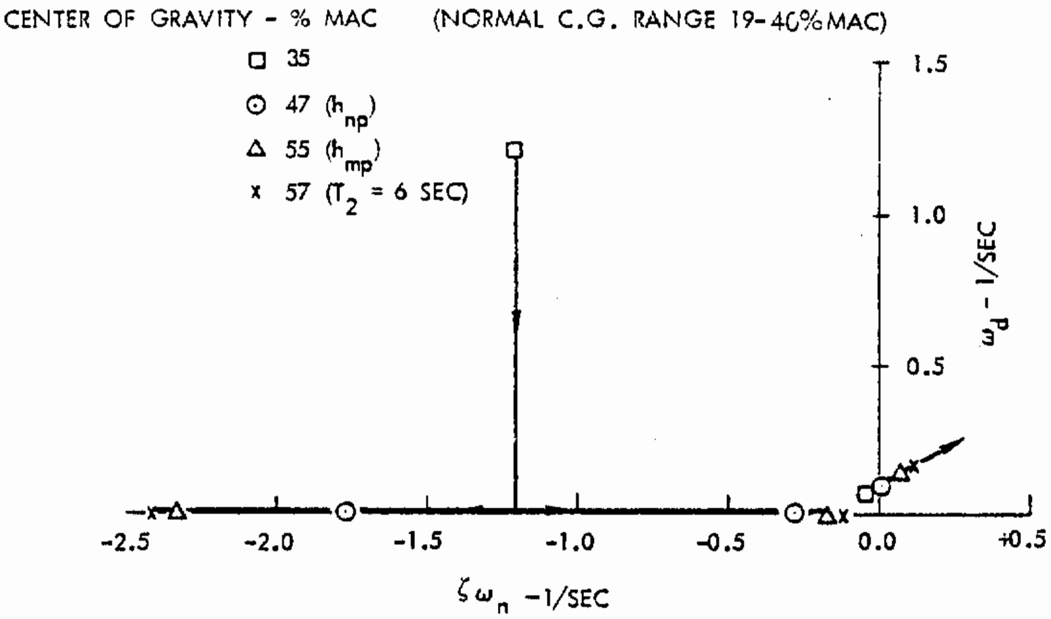


Figure 3 Longitudinal Characteristic Roots for C-5A in Cruise Configuration (Type I, η>0)

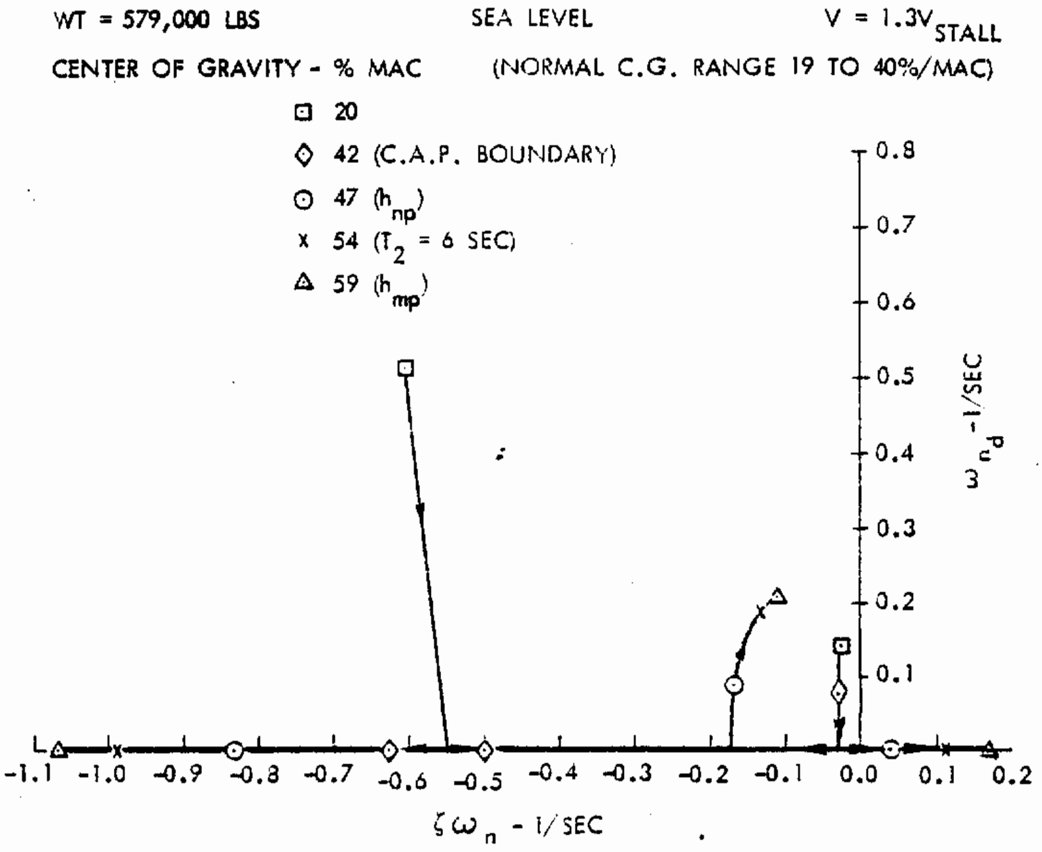


Figure 4 Longitudinal Characteristic Roots for C-5A in Landing Configuration (Type II, η=0)

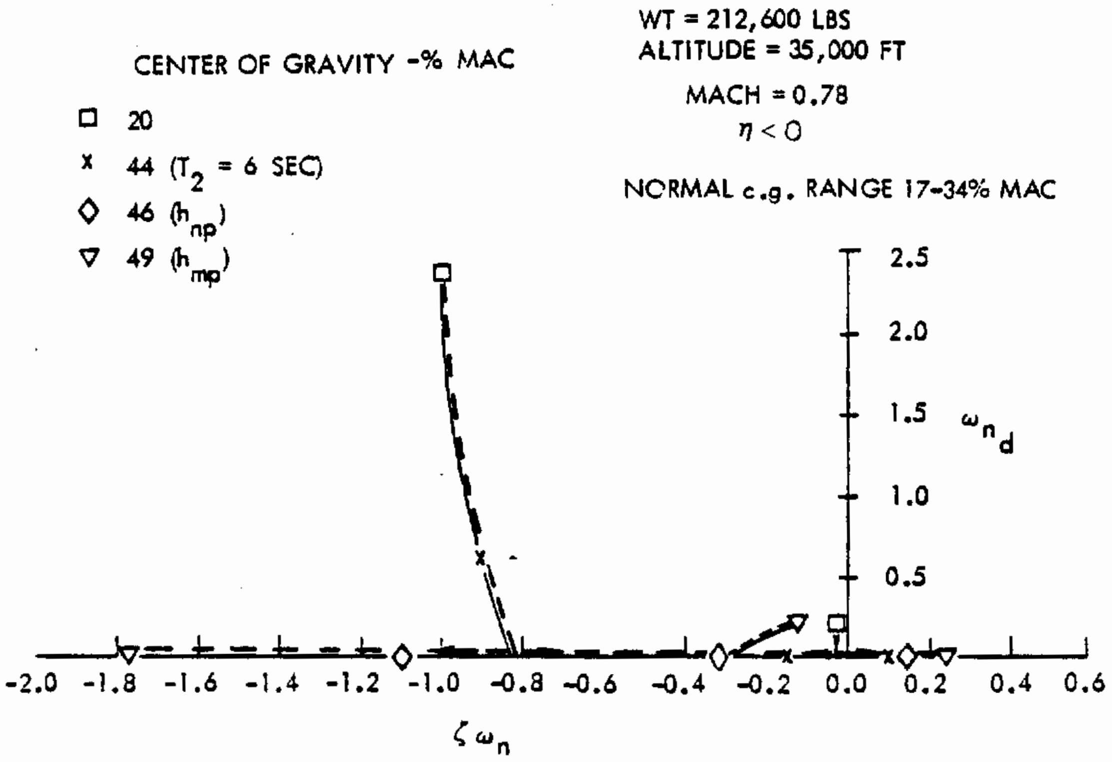


Figure 5 Longitudinal Characteristic Roots for C-141A in Cruise Configuration (Type III, $\eta < 0$)

Table 3 presents information for the c.g. points shown on Figures 3 through 5, as well as additional c.g. locations. Other flying qualities metrics are noted to show how they vary for these three cases as instabilities occur.

Locations of the neutral and maneuver points are critical in aircraft design. The c.g. positions for these points are noted in the table and can be verified as follows. The stability point is defined as the c.g. location at which a speed change does not require a change in trim elevator position. The neutral point refers to the c.g. location where the slope of pitching moment coefficient to lift coefficient is zero for that speed. Static margin refers to the distance that the c.g. is forward of the neutral point. A negative static margin means the c.g. is aft of the neutral point. The maneuver point (h_{mp}) is defined as the c.g. at which "elevator per g" goes to zero, i.e., a change in steady elevator deflection is not required for a corresponding change in load factor at constant speed.

At low speed and altitude the neutral point is usually more important to the pilot, in part due to the requirement for precise airspeed control and the otherwise demanding nature of the landing approach task. The maneuver point is well aft of the c.g. range at low altitude but tends to move forward as altitude increases. At high altitude and speed, maneuvers involving appreciable change in load factor become more important and critical than static stability. Maneuver margin and dynamic response are then the critical longitudinal stability parameters at those conditions.

The time to double amplitude of six seconds can be examined in detail for these three cases. The effect of the velocity derivatives on the Level 3 (T_2 = 6 sec.) requirement in conjunction with other pertinent flying quality metrics may be obtained from Table 3. These results are also summarized pictorially in Figure 6.

TABLE 3

Parameter Variations for Cases of Types I-III

CASE	C.G.		δ_e/n	$d\delta_e/dv$	T_2	$\omega^2/_{n/\alpha}$	$\frac{1}{T_{SP_1}}$ or (ζ_{sp})	$\frac{1}{T_{SP_2}}$ or (ω_{sp})	$\frac{1}{T_{P_1}}$ or (ζ_p)	$\frac{1}{T_{P_2}}$ or (ω_p)
	~ % $\bar{c}$		DEG/g	DEG/KT	SEC	$^1/\text{SEC}^2$				
CASE 1	20.0		-4.0	0.027		0.173	(0.56)	(2.26)	(0.12)	(0.07)
LAC C-5A	30.0		-2.9	0.022		0.128	(0.65)	(1.92)	(0.12)	(0.08)
WT = 450,000 LBS	40.0		-2.3	0.020		0.101	(0.81)	(1.50)	(0.07)	(0.09)
ALTITUDE = 20,000 FT	41.5	5% SM	-1.6	0.017		0.068	(0.83)	(1.42)	(0.09)	(0.09)
MACH = 0.78	43.5	3% SM	-1.4	0.016		0.059	(0.92)	(1.32)	(0.10)	(0.10)
n/α = 29.5	46.5	NP	-0.9	0.014	2475.0	-	0.71	1.68	(-0.00)	(0.11)
η = 0.44	55.0	MP	0.0	0.011	9.4	-	0.14	2.32	(-0.46)	(0.16)
(TYPE I)	57.0	T_2=6"	0.2	0.010	6.0	-	0.12	2.42	(-0.66)	(0.17)
	60.0		0.6	0.008	3.9	-	0.10	2.56	(-1.00)	(0.18)
CASE 2	20.0		-32.4	0.310		0.221	(0.73)	(0.86)	(0.07)	(0.16)
LAC C-5A	30.0		-24.9	0.183		0.165	(0.82)	(0.74)	(0.12)	(0.14)
WT = 579,000 LBS	40.0		-16.1	0.062		0.105	(0.95)	(0.60)	(0.26)	(0.10)
ALTITUDE = SL	42.3	5% SM	-14.2	0.038		-	0.66	0.46	(0.41)	(0.08)
V = 1.3 V_{STALL}	44.3	3% SM	-12.6	0.010		-	0.78	0.32	0.06	0.04
n/α = 3.35	47.3	NP	-10.7	-0.017	22.0	-	-0.03	0.84	(0.89)	(0.20)
η = 0	54.0	T_2=6"	- 4.6	-0.108	6.0	-	-0.12	0.99	(0.57)	(0.24)
(TYPE II)	59.0	MP	0.0	-0.174	4.1	-	-0.17	1.07	(0.46)	(0.24)
	65.0		4.6	-0.242	3.0	-	-0.23	1.14	(0.38)	(0.24)
CASE 3	20.0		- 6.1	-0.005		0.460	(0.38)	(2.64)	(0.12)	(0.03)
LAC C-141A	28.0		- 5.3	-0.003	18.9	0.320	(0.47)	(2.03)	-0.04	0.04
WT = 212,600 LBS	36.0		- 1.7	-0.011	13.0	0.260	(0.53)	(1.78)	-0.05	0.06
ALTITUDE = 34,900 FT	41.0	5% SM	- 1.7	-0.016	8.6	0.126	(0.65)	(1.40)	-0.09	0.08
MACH = 0.75	43.0	3% SM	- 1.3	-0.017	7.1	0.094	(0.74)	(1.21)	-0.12	0.10
n/α = 15.5	44.0	T_2=6"	- 1.1	-0.018	6.0	0.077	(0.81)	(1.11)	-0.11	0.13
η = -0.21	46.0	NP	- 0.6	-0.021	5.1	-	-0.15	1.29	(1.00)	(0.33)
(TYPE III)	49.0	MP	0.0	-0.024	3.1	-	-0.23	1.79	(0.48)	(0.24)
	52.0		0.6	-0.026	1.7	-	-0.40	2.08	(0.22)	(0.17)

SM = STATIC MARGIN

NP = NEUTRAL POINT

MP = MANEUVER POINT

$$\eta = \frac{C_{m_u}}{\left(C_{L_u} + 2\ C_L\right)}$$

NOTE: ALL CASES ARE UNAUGMENTED

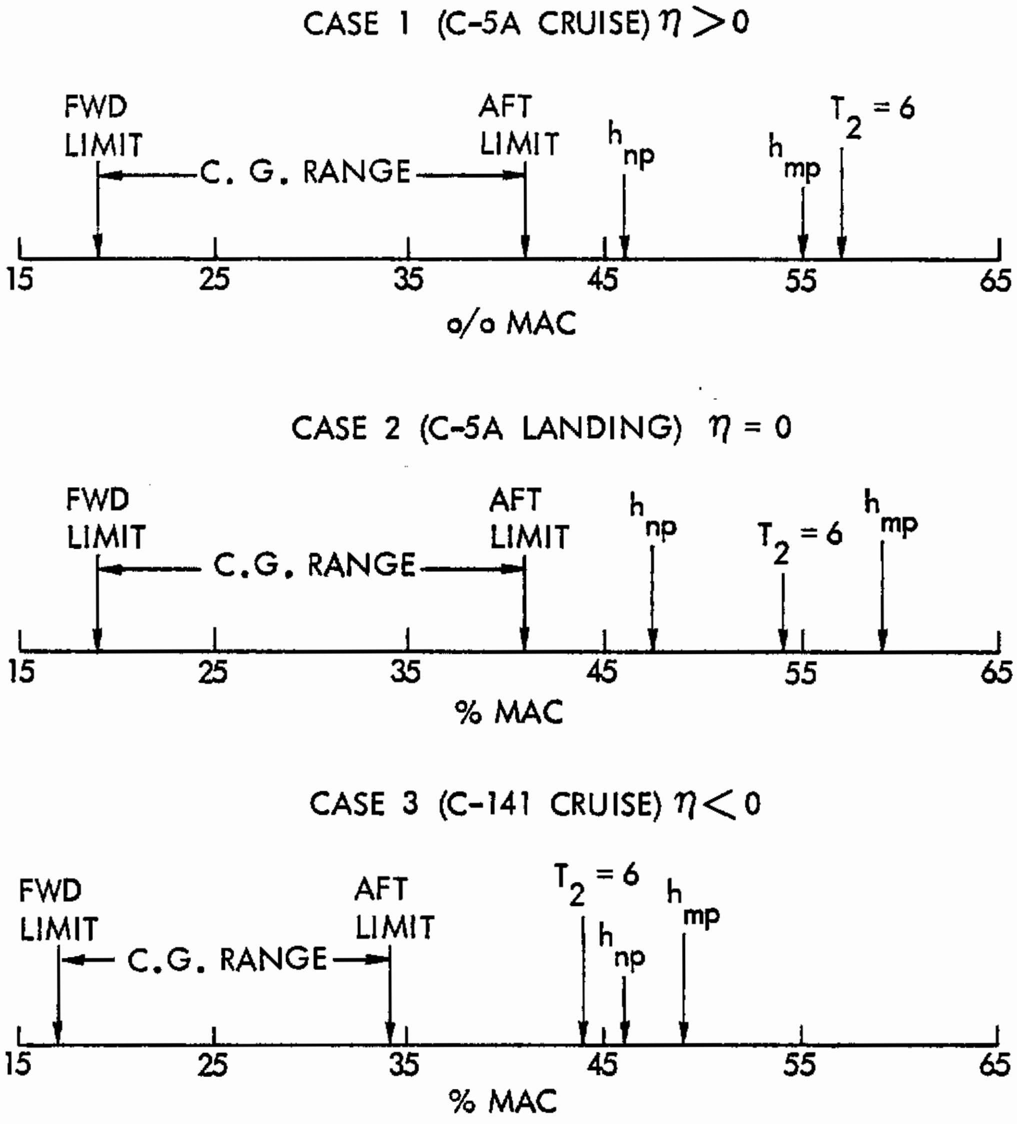


Figure 6 Summary of Level 3 C.G. Location with Respect to Other Pertinent Parameters for Three Speed Derivative Conditions

Case 1, $\eta > 0$, data show that the $T_2 = 6$ sec. instability level occurs at a c.g. of 57% MAC which is 11% aft of the neutral point, 2% aft of the maneuver point, and 16% behind the operational aft c.g. limit. The root pattern for this configuration remains that of a classical aircraft with an oscillatory and unstable phugoid and an overdamped short period (damping ratio greater than 2.0). This exceeds the Level 2 maximum allowable damping ratio specified in MIL-F-8785C, which is 2.0. A Level 3 maximum is not given; therefore this damping would not require a modification if the probability of stability augmentation failure is small enough. The natural frequency of the short period mode shows CAP parameter, $\omega_{n_{SP}}^2 / (n/\alpha)$, is below the 8785C Level 3 boundary of 0.038. The stick force per g gradient (indicated by a positive δ_e/n) is unstable, in contradiction to 8785C requirements. Note that the normal indicator of speed stability, $d\delta_e/du$, shows stability for all cases. This is why it was stated as a necessary but not sufficient criterion.

Case 2, $\eta = 0$, data show the Level 3 ($T_2 = 6$ sec) limit to occur at a c.g. of 54% MAC which is 7% aft of the neutral point, 5% forward of the maneuver point, and 13% behind the aft c.g. limit. At this point, the normal short period and phugoid modes have become aperiodic and one root from each mode has coalesced to form a "third mode", which is oscillatory and resembles a well damped phugoid. The remaining mode resembles an unstable short-period motion with an aperiodic divergence. The natural frequency of this mode places the CAP parameter well below the 0.096 MIL-F-8785C Level 3 boundary for Flight Phase C. The stick force or elevator gradient with speed criterion became unstable between the 40 and 47.3% points well before the Level 3 boundary condition and behind the aft c.g. limit.

Case 3, $\eta < 0$, data show the $T_2 = 6$ sec. instability level occurs at a c.g. of 44% MAC which is 2% forward of the neutral point, 5% forward of the maneuver point, and 10% behind the aft c.g. limit. The stability point occurs near the 24% point. These points are for the unaugmented aircraft.

The root pattern for this configuration is characterized by an unstable phugoid with an aperiodic divergence and an oscillatory, but well damped, short period mode at the 44% c.g., where the Level 3 divergence boundary is reached. As the c.g. is moved aft to the 52% point, a well damped oscillatory "phugoid-like third mode" and a "short period like mode" with an unstable aperiodic divergence describe the characteristics. The stick force or elevator gradient becomes unstable well before the Level 3 condition. The C-141 has a full time "Q-Trim" compensator which provides artificial stability by increasing C_{m_u} with velocity or dynamic pressure feedback. This compensation has proved to be very reliable in service. The cruise configuration of the Boeing 757 presented in Reference 12 has a root pattern similar to this case.

In summary, Case 1 shows a condition where δ_e/η will have reversed for the Level 3 condition. This should not be permitted. In all cases the control anticipation parameter, $\omega_n{}^2{}_{SP}/(n/\alpha)$, value needs to be lowered in 3.2.2.1.1 for a consistent Level 3 requirement. At present, it is a more severe limitation than the Level 3 time to double amplitude. The normal stick force or elevator deflection versus speed gradient stability requirement is less restrictive in one case than the δ_e/η or T_2 requirement. The present phugoid stability requirement for Level 3 in 3.2.1.2 is more restrictive in 2 of the 3 cases and is obscure in the third, Type II, case where a new mode exists. The differences shown due to the nature of speed derivatives underscores the fact that total system stability including all modes must be considered in relaxed stability applications. If an instability is allowed in one mode, care must be taken to insure that the other mode is stable.

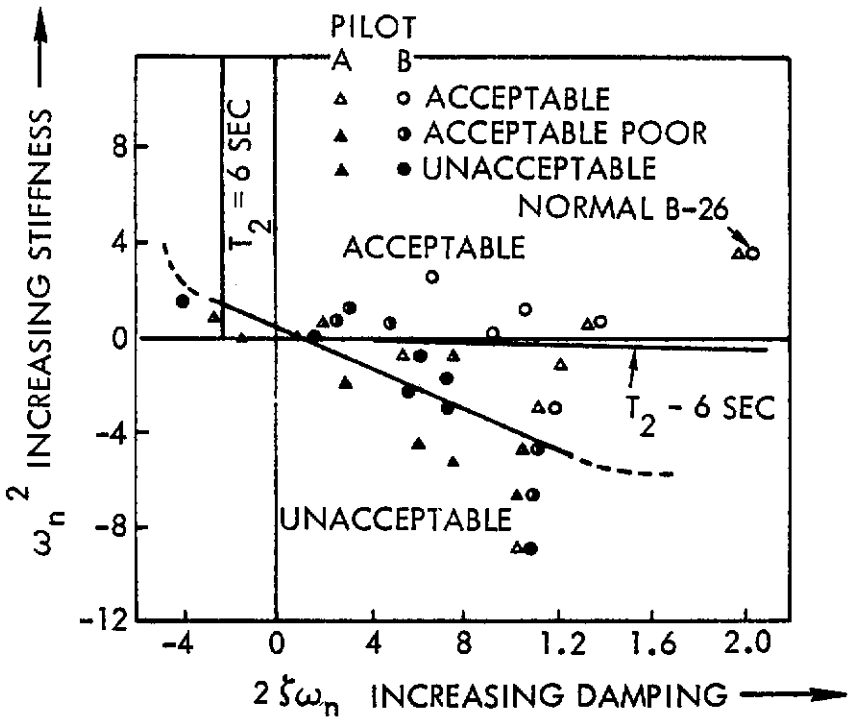
This static stability requirement places two distinct design constraints: stable stick force per velocity gradients for Levels 1 and 2 and a minimum time to double amplitude for Level 3. There is a lack of conclusive data or general consensus of opinion as to what the lower or upper bounds of the stick force per velocity gradient should be. No additional data is presented for this part of the requirement. The need for a stable gradient for Levels 1 and 2 is obvious, however, since the feel of the central forces need to reflect the aircraft stability and provide a suitable reference point.

The second part of the requirement, regarding the Level 3 (T_2 = 6 sec.) boundary, has been investigated on numerous occasions. Several in-flight experiments for the approach and landing task have been reported. Figure 7, taken from Reference 13, summarizes results obtained from a B-26 variable stability experiment. The pilot rating technique is noted. Acceptable and unacceptable regions are shown for both rough and smooth air. These data are shown even though the B-26 is not considered large by today's standards and the rating scales did not conform to the conventional Cooper-Harper nomenclature commonly used. The results are significant and lend credence to this Level 3 boundary. Figure 7 is replotted to a "new" scale, time to double amplitude lines and a CAP boundary in Figure 8 for ease of comparison with following figures. Figure 9 shows results of the T-33 LAHOS study in Reference 14; again based on small aircraft but significant data. Figure 10 shows results in a comparable format for the SST inflight simulator study. These results are representative of large aircraft as shown by a comparison of the flying quality metrics listed below:

	SST (TIFS)	LAC C-5A
$M_{\delta_{ES}}$	0.018 rad/sec/in	0.020 rad/sec/in
$1/T_{\theta_2}$	-0.72 1/sec	-0.84 1/sec
n/α	5.2 g/rad	3.4 g/rad
ω_n^2 (nom)	1.0 rad/sec^2	0.8 rad/sec^2

These plots all show pilot opinion as a function of natural frequency squared and total damping, $2\zeta\omega_n$, of the equivalent short period during Category C flight.

SMOOTH AIR



ROUGH AIR

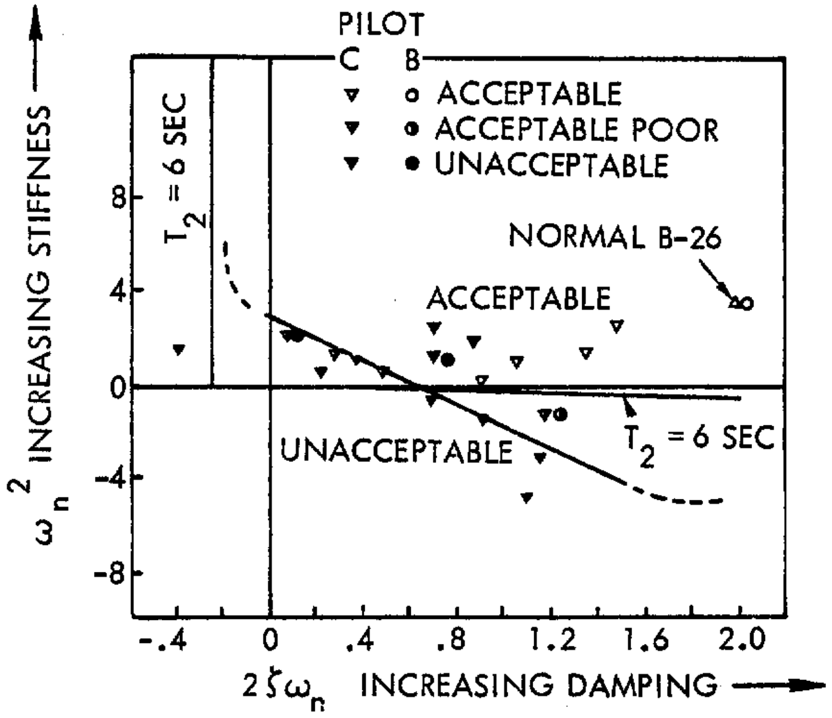


Figure 7 Results of B-26 Variable Stability Longitudinal Handling Qualities Experiment (Reference 13)

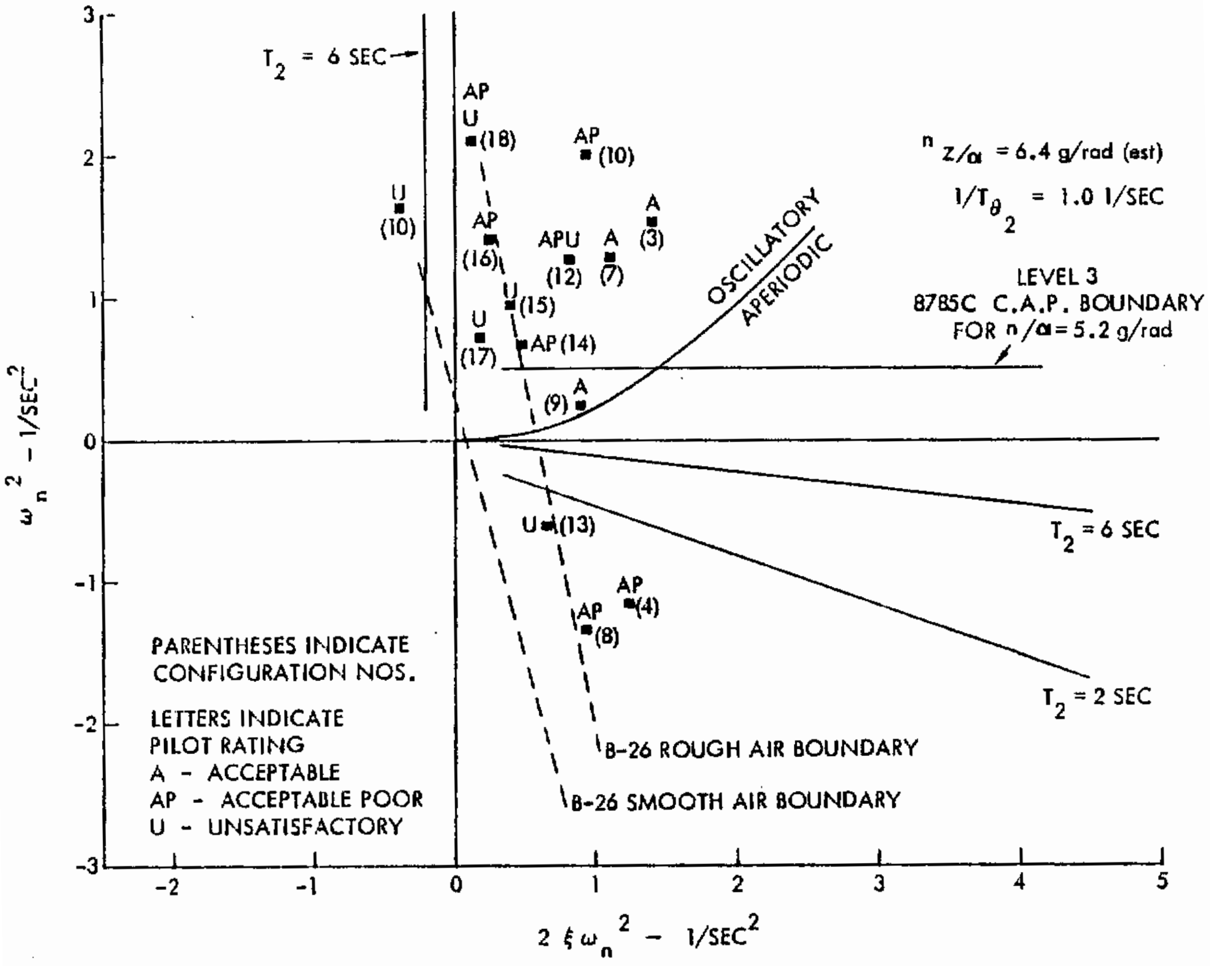


Figure 8 Results of B-26 Minimum Flyable Longitudinal Handling Qualities Study - Rough Air

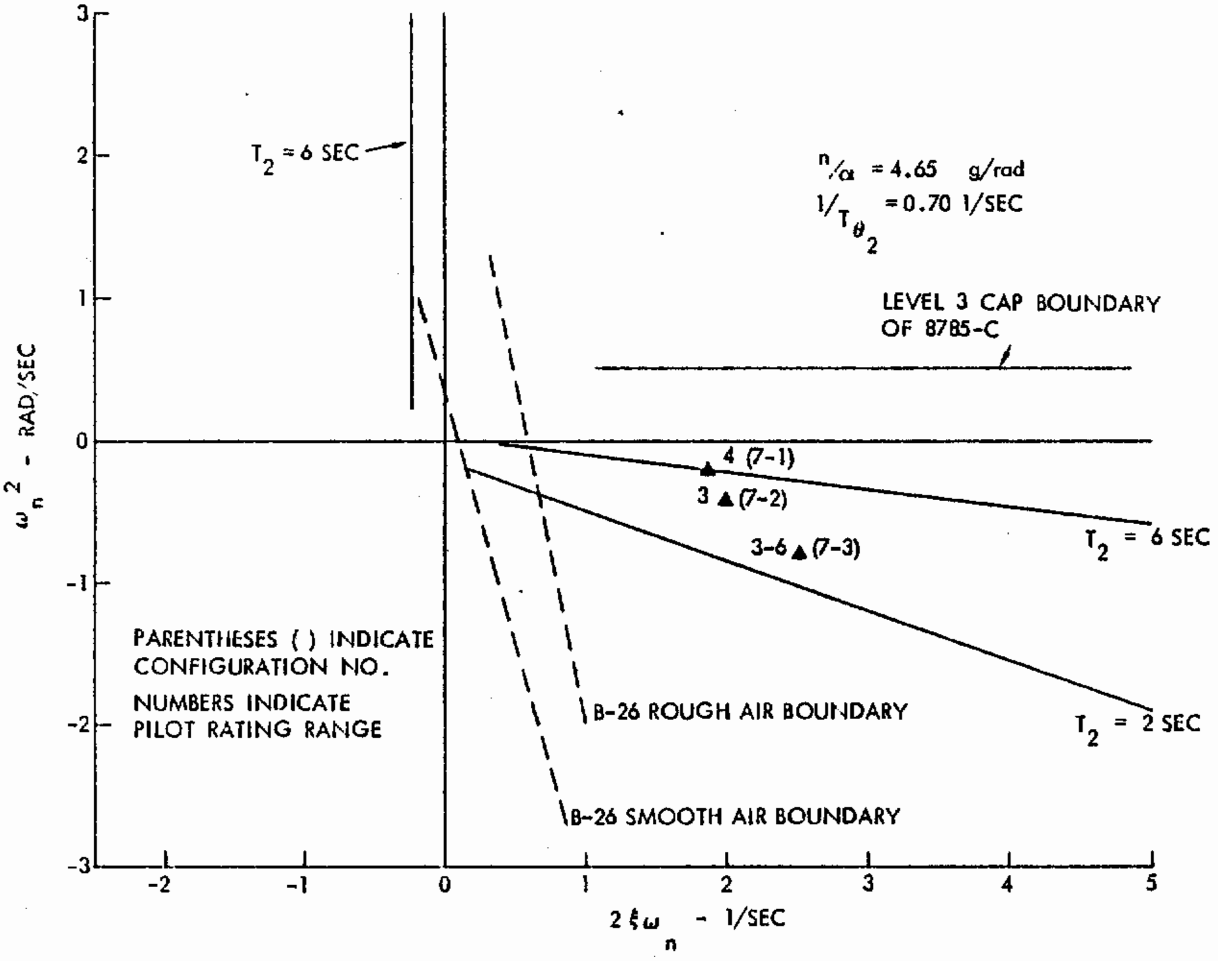


Figure 9 T-33 LAHOS Study Results (Reference 14)

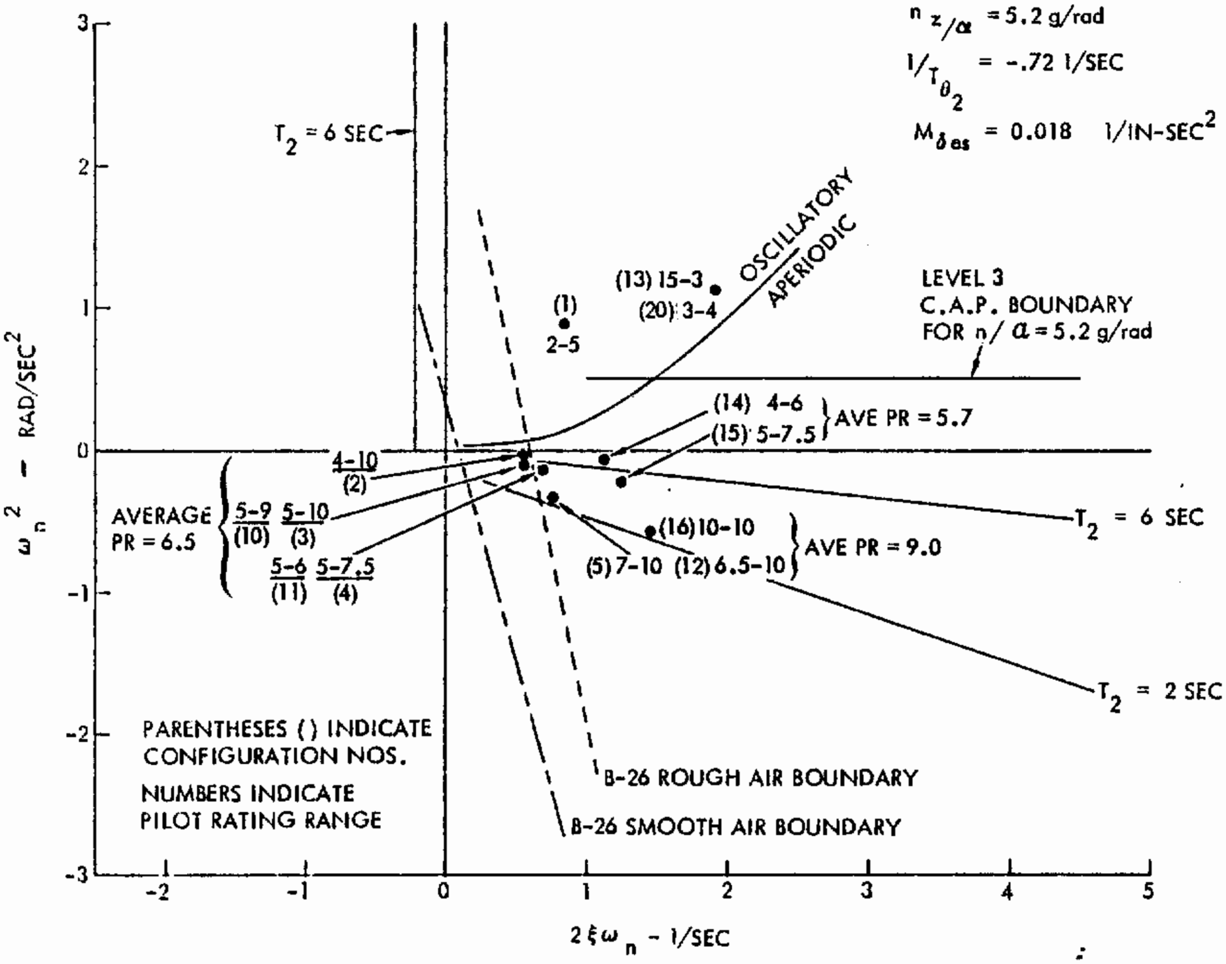


Figure 10 Minimum Longitudinal Stability Flight Data SST (TIFS)

For statically unstable cases the most negative and positive real roots of the aircraft stability quartic are used to form the second order equivalent "short period mode". Statically stable cases use the conventional short period mode. Position of the remaining root pair is important. The aircraft used in these experiments have the remaining pair of roots well separated in frequency, remaining near the origin so that they have a small effect on total system damping. These data should be viewed in this context.

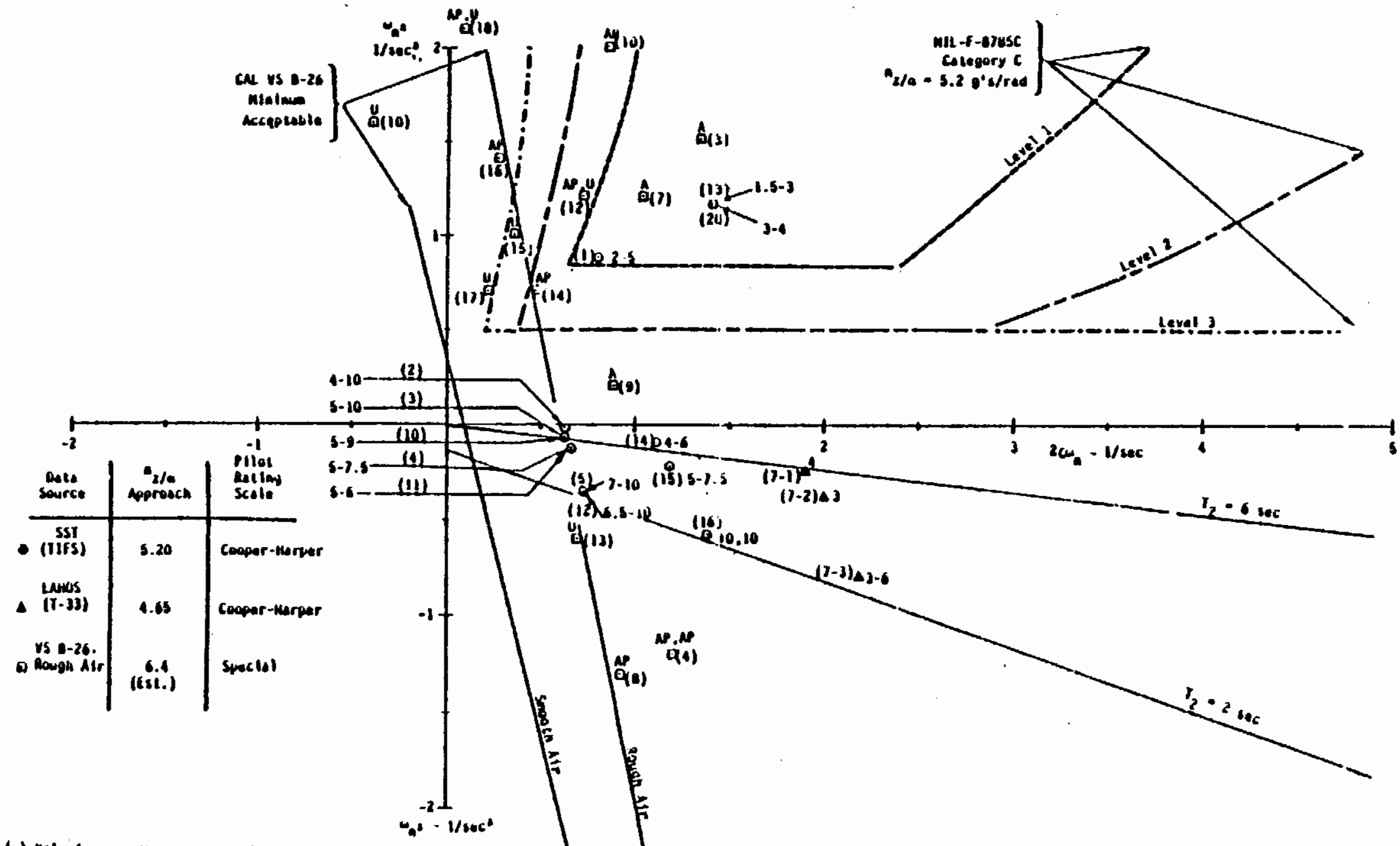
The plots show trends as expected, i.e., ratings usually degrade with low damping and low frequency. A significant factor is that there are many cases where ratings are Level 2 with time to double much less than the Level 3 boundary of 6 seconds.

Reference 10 cautions that flying qualities of aircraft with reduced stability are not only a function of the aircraft's characteristic roots, but are strongly influenced by control sensitivity ($M_{\delta_{ES}}$ ~rad/sec^2/in) and pitch transfer function numerator time constant ($1/T_{\theta_2}$ ~1/sec).

During landing approach the aircraft is also required to be "front side", i.e., $d\gamma/dU$ meets 8785C Level 1 requirements.

After extensive study of the preceeding data, Schuler in Reference 15) a, summarizing Reference 10, presents most of these data with present MIL-F-8785C requirements in Figure 11. Both references conclude that "the Level 2 boundary should be lower and the Level 3 boundary much lower than in MIL-F-8785C, allowing negative ω_n^2 for large amounts of damping ($2\zeta\omega$). Clearly T_2 does not define the flying qualities for statically unstable aircraft."

Reference 10 also presents new parametric criteria for approach and landing. That reference shows convincing proof that other parameters are important. The new criteria are not recommended here since they are based on relatively small aircraft and, as the document states, "clearly additional verification is needed."



Data Source	$n_{z/\alpha}$ Approach	Pilot Rating Scale
● SST (TIFS)	5.20	Cooper-Harper
▲ LAHOS (T-33)	4.65	Cooper-Harper
⊡ VS B-26, Rough Air	6.4 (Est.)	Special

( ) No's in parentheses are configuration identifiers.

Numbers beside points are Cooper-Harper pilot ratings. B-26: A = Acceptable; AP = Acceptable Poor; U = Unacceptable.
Two repeats seperated by commas. Range is shown (e.g.,6.5-10) for multiple rating or repeats.

Figure 11 Flight Data on Minimum Longitudinal Stability, ω_n^2 vs. $2\zeta\omega_n$ (Reference 15) a)

There is little data available for cruise conditions. Reference 12 presents data using an unaugmented Boeing 757 model in a relaxed stability study. It presents pilot rating as a function of c.g. position and time to double. Those results were obtained from piloted simulation studies using a three-degree-of-freedom motion-based simulator for a relatively large aircraft in cruise. The results help substantiate the fact that a time to double limit of at least six seconds is conservative for a Level 3 boundary, just as in the landing cases.

3.2.1.2 Phugoid Stability.

REQUIREMENT

The long-period airspeed oscillations which occur when the airplane seeks a stabilized airspeed following a disturbance shall meet the following requirements:

a. Level 1 ζ_p at least 0.02

b. Level 2 ζ_p at least 0

c. Level 3 T_2 at least 55 seconds
(T$_2$ at least 6 seconds where relaxed static stability is permitted)

RATIONALE

Requirement Rationale

The purpose of this requirement is to insure that the Pilot is not required to provide constant attention to airspeed and altitude. If the aircraft has an identifiable second order phugoid mode, slow variations in attitude, altitude and airspeed occur. This requirement is intended to specify what minimum level of damping or maximum rate of divergence of this mode is needed for the various levels of flying qualities. The recommended values shown are considered adequate for large aircraft. The discussion in the following section provides considerations for changing these requirements as particular large aircraft missions dictate the need.

Rationale for Change

The original 8785 (Reference 16) specified that "there shall be no objectionable flight characteristics attributable to apparent poor phugoid damping." This was an excellent way of stating the requirement. It further added "In addition, if the period of a longitudinal oscillation is less than 15 seconds, the oscillation shall be at least neutrally stable." This requirement for neutral stability was therefore aimed at frequencies 0.41 rad/sec or higher. Reference 1 provides the justification for changing the requirement to the current :

Level 1 ζ_P at least 0.04
Level 2 ζ_P at least 0.0
Level 3 T_2 at least 55 seconds

It considered the previous requirement inadequate, stating pilots could handle airplanes with poor phugoid damping but would complain about "requires constant attention", "is frustrating to fly", etc. The results used to set the above requirements were based primarily on References 17 and 18, which used B-26 and T-33 aircraft, respectively. Both aircraft were under 30,000 lbs. and were variable stability research vehicles. Table 4 summarizes the data used.

The selection of a Level 1 value of .04 used only three experiments, with the majority of these data being landing approach conditions. The actual value selected was not an exact value, as noted by the following excerpt:

> "In summary, the Level 1 limit on ζ_p seems to lie between 0 and +0.10. After studying typical values of ζ_p for several existing airplanes, it was decided to use ζ_p = 0.04 as the Level 1 limit."

The selection of a Level 2 value of 0.0 used results from size experiments of which five were landing approach studies in the T-33. A conservative approach was used in the selection, as the following excerpt indicates.

> "The data then indicate that the Level 2 limit should be a time-to-double-amplitude between 10 and 13 seconds. In view of the uncertainties associated with the rather limited amount of data, it was decided that no instability would be allowed for Level 2. The Level 2 Limit was therefore set at $\zeta_p = 0$."

Table 4

Summary of Data from Reference 1 Used to Establish Phugoid Damping Requirements

Figure No. (of Ref. 1)	Aircraft	Task	$\omega_{n_{PH}}$ -rad/sec	ζ_{PH} Level 1	Level 2	Level 3
1	T-33	Landing Approach	.15	0 to +.10	-.28	-.47
2	T-33	Landing Approach	.15		-.30	
7	T-33	Landing Approach	.32	0 to +.10	-.17	-.22
8	T-33	Landing Approach	.32		-.21	-.27
11	T-33	Landing Approach	.45		-.14	-.18
12	B-26	Cruise & Landing Approach	.126	+.07	-.14	

A Level 3 selection for a time-to-double of at least 55 seconds used four T-33 landing experiments, all on landing approach with the following reasoning:

> "These data indicate a time-to-double-amplitude range of 8 to 10 seconds. Again, there is only a small amount of data on which to base the requirement. It was decided that it would be unwise to allow phugoid modes as unstable as the data allow, even for Level 3. A time-to-double amplitude of 55 seconds was therefore selected as a conservative limit for Level 3."

The data of Table 4 and the excerpts presented are to show the relatively arbitrary selection which had to be made on the available data, and not intended as criticism of those efforts. Table 5 presents representative data for a variety of large aircraft. These data show that the majority of the flying in large aircraft occurs at phugoid frequencies well below that used for the experiments of Table 4. The long periods seem to be easily controlled with no real adverse comments. Appendix A presents results of a pilot survey on the C-5A which tend to corroborate these findings. Resistance to atmospheric disturbances is much greater in the larger and heavier aircraft than that which characterized the aircraft used in gathering the initial data.

Rationale For Selected Damping

The phugoid damping is often approximated by $\zeta_p = (D/L)\ (1/\sqrt{2})$, which shows that it varies inversely with the lift to drag ratio, L/D. A level of 0.04 thus sets a limit on $(L/D)_{MAX}$ of 17.7. Designers of large, long-range aircraft are obviously always trying to increase that ratio to improve performance. Since the original data for assignment of Level 1 indicate that the Limit was between 0 and +.10, and since existing large aircraft operate as low as 0.02 without adverse effects, a value of 0.02 is suggested for the Level 1 limit on large aircraft.

Table 5

Representative Phugoid Data for Large Aircraft

AIRCRAFT	FLIGHT PHASE	PHUGOID RANGE	
		$\omega_{n_{PH}}$ ~ rad/sec	ζ_{PH}
L-1011 (REF. 19) CIVIL TRANSPORT	TO	.08-.15	.045-.15
	CL	.03-.09	.025-.28
	CR	.05-.11	.015-.30
	D	.05-.10	.026-.20
	PA	.08-.17	.037-.16
	L	.08-.16	.03-.23
C-130 (REF. 20) TACTICAL CARGO	CL	.11	.055
	CR	.08	.075
	PA	.18	.090
	L	.19	.030
P3V (REF. 21) PATROL/ ANTI-SUBMARINE WARFARE	CL	.10	.015
	CR	.09	.029
	D	.07	.073
	PA	.15	.071
	L	.16	.100
C-5 (REF. 22)a) HEAVY CARGO	CL	.05-.07	.03-.05
	CR	.026-.10	.02-.15
	D	.06	.04
	PA	.14	.048
	L	.16	.06

<u>LEGEND</u>

TO - TAKE-OFF
CL - CLIMB
CR - CRUISE
D - DESCENT
PA - POWERED APPROACH
L - LANDING

The Level 2 limit of 0.0 is suggested for retention, since conventional operational data available do not substantiate a change. The previously used data do show, however, that this is conservative. The level could go to a T_2 of 10 to 13 seconds.

The Level 3 value of $T_2 = 55$ seconds is suggested for retention if the short period is stable. This again appears to be conservative based on experimental data. The allowance for a $T_2 = 6$ seconds is provided for conditions of relaxed stability as described in 3.2.2.1 for compatibility with other sections of the requirements.

GUIDANCE

The phugoid damping requirements for large aircraft appear to be quite different from those of smaller aircraft. The larger mass interacting with the fixed spring constant of the atmosphere provides a longer period which is easier to control. The nature of the mission and the task involved could require either higher or more relaxed levels of damping.

Table 5 provides characteristics for a variety of large aircraft with different missions. Aircraft with additional missions and tasks such as LAPES or carrier landing would seem to need higher requirements. The C-130, however, has accomplished both of these tasks and its phugoid range is comparable to those of the others listed.

Not all references agree with these conclusions. Reference 23 proposed increased damping should be required at all levels when the frequency is greater than 0.1 rad/sec. Reference 3 warns of relaxed phugoid damping for missions requiring a fairly rapid "let down" to fly tactically at low altitudes, i.e., relatively close proximity to ground or water. It suggests further study for establishing these requirements, especially if it is desired to continue the mission in a Level 2 situation.

3.2.1.3 Flight Path Stability

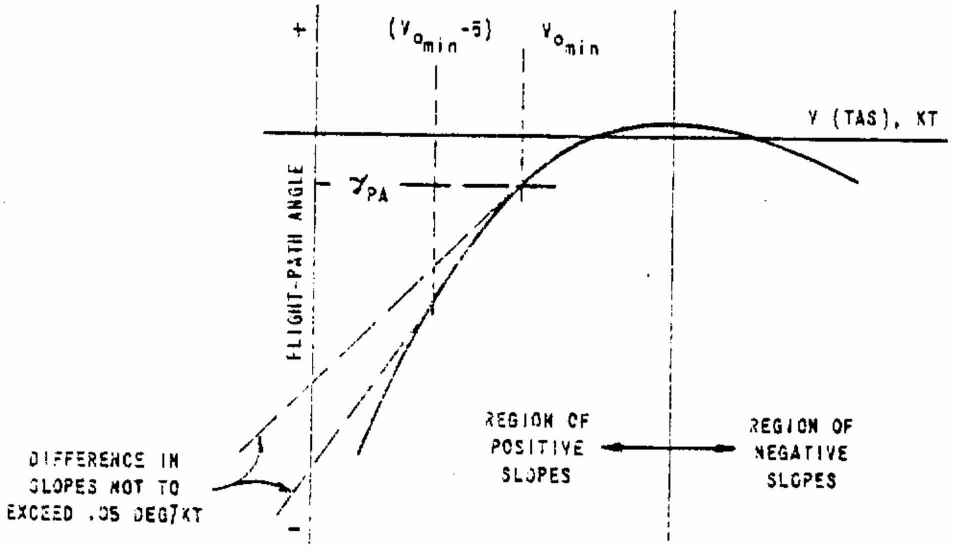
REQUIREMENT

Flight path stability is defined in terms of flight-path-angle change for airspeed changed by use of pitch control only (throttle setting not changed by the crew). For the landing approach flight phase, the curve of flight-path angle versus true airspeed shall have a local slope at $V_{0_{min}}$ that is negative or less positive than:

a) Level 1 0.06 deg/knot
b) Level 2 0.15 deg/knot
c) Level 3 0.24 deg/knot

The thrust setting shall be that required for normal approach glide path at $V_{0_{min}}$.

The slope of the curve of flight-path angle versus airspeed at 5 knots slower than $V_{0_{min}}$ shall not be more than 0.05 degrees per knot more positive than the slope at $V_{0_{min}}$, as illustrated by the sketch below:



Alternate Criteria

With flight path constrained to glide-path by use of the pitch controller, airspeed shall be stable or less divergent than the time to double amplitude, T_{2_s}, specified below.

Level 1 $T_{2_s} = 35$ sec.

Level 2 $T_{2_s} = 14$ sec.

Level 3 $T_{2_s} = 9$ sec.

RATIONALE

The accepted piloting technique for conventional aircraft is to adjust flight path with pitch attitude. This requirement is included to insure that long term flight path and airspeed response to pitch attitude changes are acceptable to the pilot. The first part of the requirement is unchanged from MIL-F-8785C. The alternate criteria, suggested as an addition, is taken from Reference 4 with a slight modification for consistency with the first part of the requirement.

Operation on the "backside" of the drag curve in the landing approach leads to problems in airspeed and flight path control. Backside operation is characterized by an unstable first-order zero in the aircraft altitude to elevator transfer function. This zero is usually designated as $1/T_{h1}$ and is commonly referred to as the backside parameter. The relationship of $1/T_{h1}$ to pilot ratings has been established in such works as Reference 18. Pitch-airspeed coupling, or "speed stability", with a constrained flight path is of primary importance in the flying quality evaluations. The close relationship of $1/T_{h1}$ to the speed stability establishes its utility as a flying qualities criteria.

The relationship between backside operation and speed stability, under reasonable assumptions and approximations, are related as:

$$1/T_{h_1} \equiv 1/T_s \tag{3}$$

with T_s defined as the speed stability time constant. The time for a speed deviation to double in amplitude with flight path tightly controlled is derived as

$$T_2 = 0.693\ T_s \tag{4}$$

The flight path-velocity gradient is related to the backside parameter and speed stability time constant as

$$\left(\frac{1}{T_{h_1}}\right)\left[\frac{1.688 \times 57.3}{32.2}\right] = \frac{d\gamma}{dU} = \tag{5}$$

$$\left(\frac{1}{T_s}\right)\left[\frac{1.688 \times 57.3}{32.2}\right]\ \frac{\text{deg.}}{\text{kt.}} \tag{6}$$

Hence, the more easily obtained quantity $d\gamma/dU$ provides a measure of "backsideness" and also airspeed-pitch coupling.

This alternate form of the criteria more directly addresses the flying qualities intent of providing speed stability. It also may be more useful in the analysis of highly augmented aircraft which have control systems that alter the fundamental relationship between $d\gamma/dU$ and speed stability; such as altitude rate feedback to throttle , hence making $d\gamma/dU$ a less desirable metric.

GUIDANCE

Since backside operation ($1/T_{h1} < 0$) is normally only critical during landing approach, the requirement is oriented toward that flight phase. It could be troublesome for takeoff or high altitude cruise and maneuvering especially near the absolute ceiling, however, there is little data to define criteria for these flight phases. Other specific mission tasks, such as aerial delivery or pickup at very low speed, could be critical.

Flight path stability is closely related to phugoid stability, and this requirement was predicated on a reasonable level of phugoid and short period damping. That relationship will be developed in the following section.

In the presence of instabilities allowed by Level 3 relaxed stability requirements, flight path stability should probably be required to meet Level 1 requirements.

The speed that defines backside operation ($1/T_{h1} = 0$) is critical since flight path stability deteriorates rapidly as a function of airspeed for airspeeds below this point. Therefore, this point should be well defined for each flight configuration of an aircraft.

In essence, no real change in this requirement has been suggested for large aircraft. The large aircraft considered typical and tested against these criteria under the "LESSONS LEARNED" seem to meet the requirement for Level 1. However, this does not necessarily mean these criteria are valid. The following discussion of how the requirements were established shows that large aircraft may indeed fly satisfactorily outside of the limits used.

Figures 12 through 14 are three of seven figures presented in Reference 1 for selection of $1/T_{h1}$ values used to obtain the $d\gamma/dV$ levels. Table 6 summarizes the values selected from each figure (using Reference 1 figure numbers.

TABLE 6

Selected $1/T_{h1}$ Values For Criteria in Reference 1

Figure		$1/T_{h1} \sim \frac{1}{sec}$		
		Level 1	Level 2	Level 3
1	(Ref. 18)		≥-.08	≥-.12
2	(Ref. 18)		≥-.05	≥-.08
3	(Ref. 18)		≥-.05	≥-.12
4	(Ref. 18)		≥-.05	≥-.12
5	(Ref. 26)	-.035	-.084	-.107
6	(Ref. 27)	-.020 to -.035	-.095	-.121
6	(Ref. 28)	-.010	-	-
7	(no thrust lag) (Ref. 29)	+.010	-.19	-.360
7	(thrust lag) (Ref. 29)	+.107	-.06	-.125
	Selected Values	-.02	-.05	-.08

The first four figures were used to establish the Level 1 and 3 requirements. Level 1 was selected based on these levels and with the reasoning that data with higher ζ_p and $\omega_{n_{SP}}$ was better than low values in conjunction with the Levels 2 and 3 values of $1/T_{h1}$. All of these data were based on the T-33 experiments. The reasoning for changes in the large aircraft requirements of Sections 3.2.1.2 (Phugoid Stability) and 3.2.2.1.1 (Short Period Frequency) are again applicable in this section. The comparatively light T-33 portrayed a phugoid frequency close to the high end of the large aircraft frequency range for the first two figures used. The next two figures used data with phugoid frequencies twice as high. The previously used values of minimum phugoid damping, .04, and minimum short period frequency were considered in the use of these data to select appropriate levels. If the lower levels of these boundaries proposed in this report for large aircraft had been used, the selected levels would be very conservative. Figures 5 through 7 (in Table 6) were used to compare the

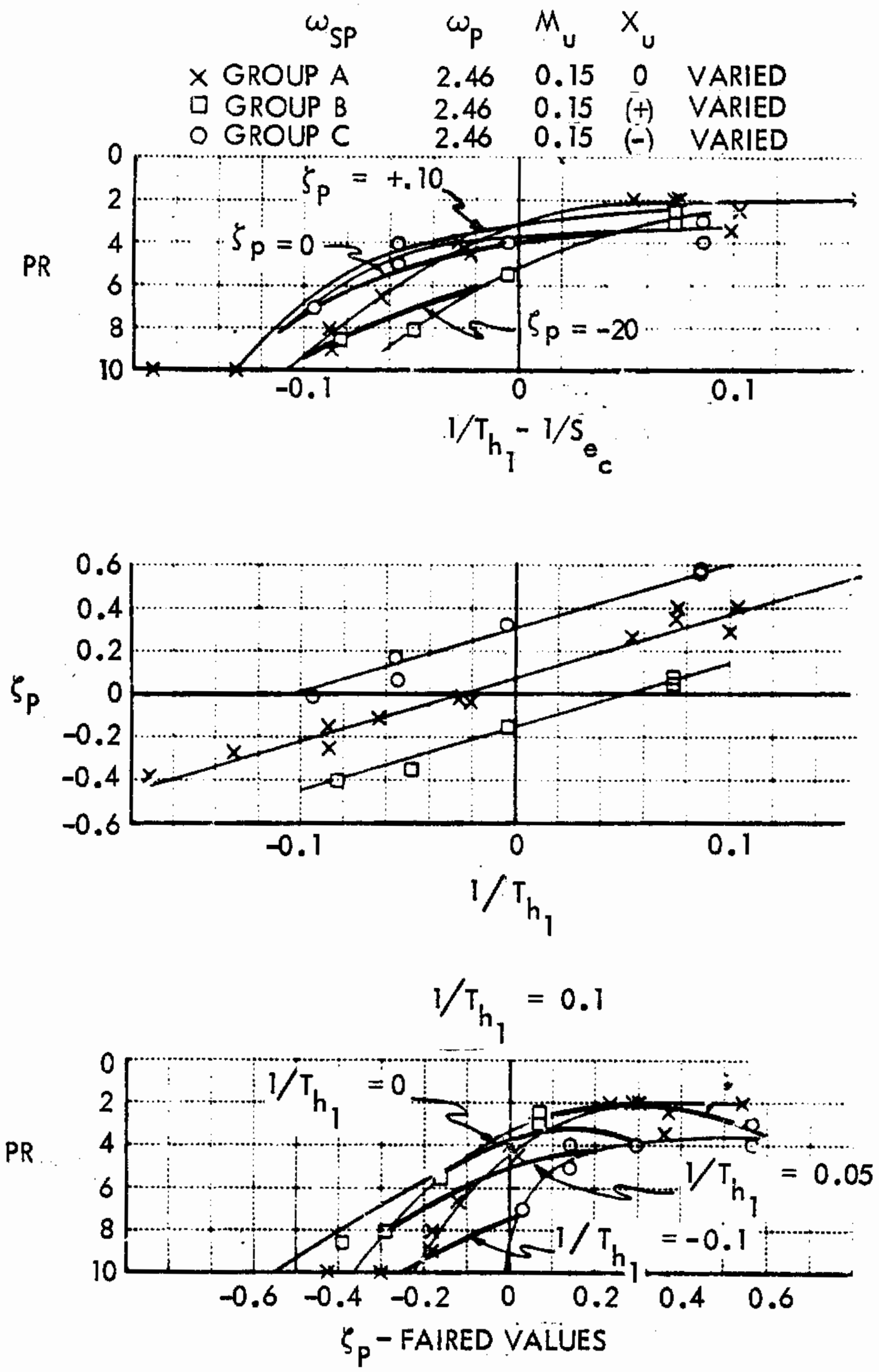


Figure 12 Landing Approach Results for In-Flight T-33 Experiment (Figure 1 (3.2.1.3) of Reference 1)

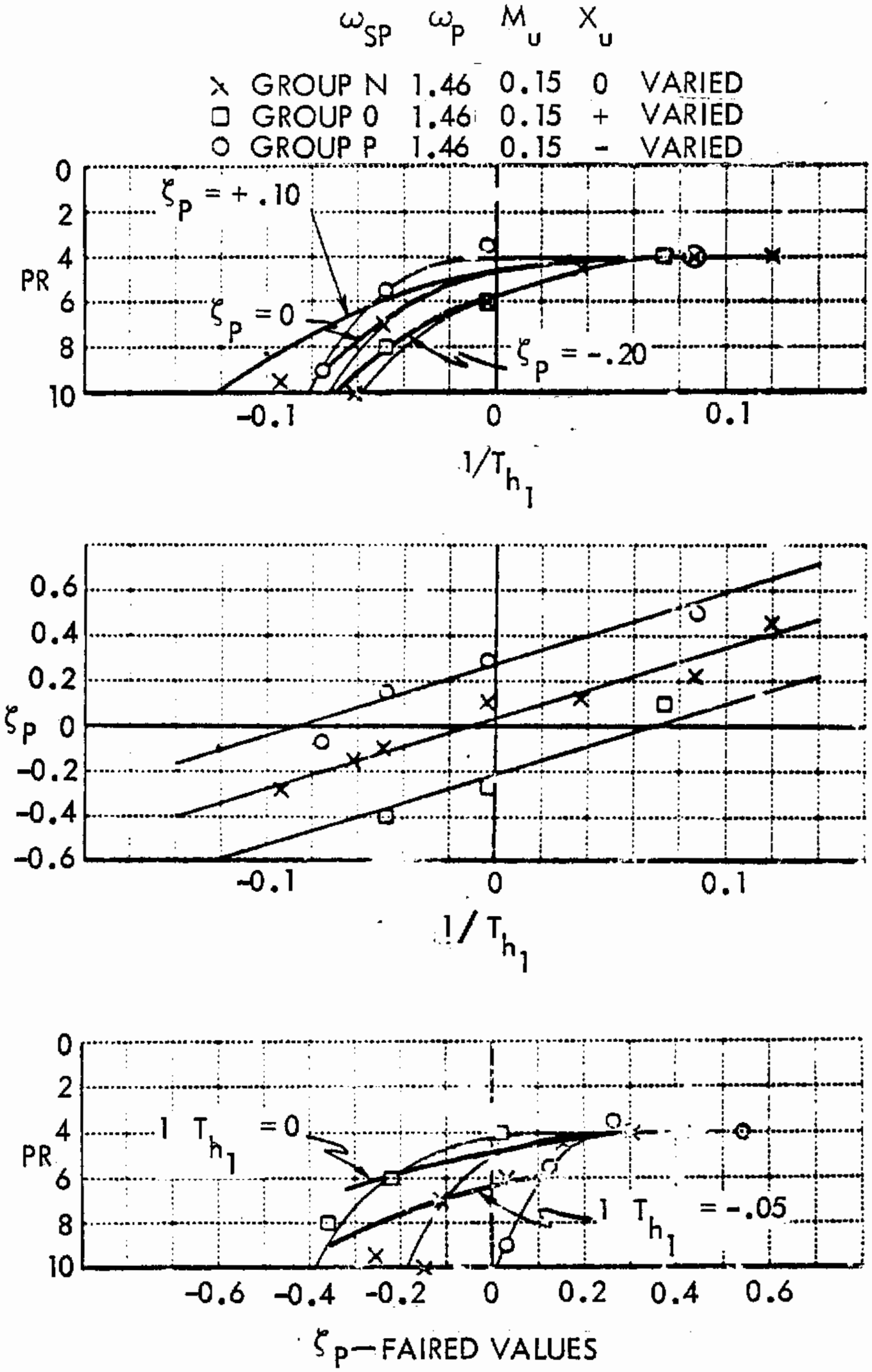


Figure 13 Landing Approach Results for In-Flight T-33 Experiment (Figure 2 (3.2.1.3) of Reference 1)

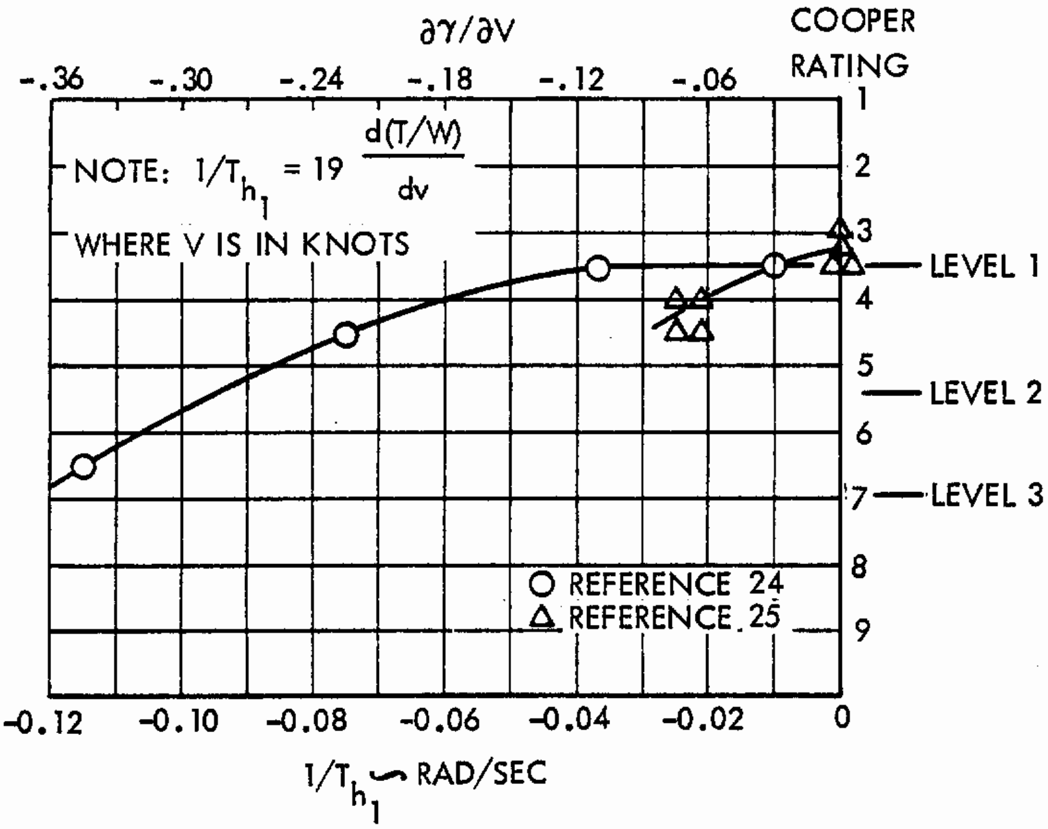


Figure 14 SST Landing Approach Data (Figure 6 (3.2.1.3) of Reference 1)

requirements derived from the first four figures with data reflected in their plots. Figure 14 is a repeat of Figure 6 of Reference 1 and is the only data which could be considered large aircraft. It has data from two SST ground simulator experiments, References 27 and 28. It was mentioned that "only the data for the highest static margin in Reference 28 were presented because the lower static margins result in values of $\omega_{n_{SP}}$ which are too low for Level 1." If those data and the other data in Figures 5 through 7 of Table 6 had been used exclusively for obtaining a set of large aircraft $1/T_{h1}$ requirements, the values tolerated would be almost double those selected from the first four figures. (The actual $d\gamma/dV$ values of 3.2.1.3 are obtained by multiplying the $1/T_{h1}$ values by -3, i.e., -(57.3) (1.689)/(32.2)).

Higher levels are not being suggested in this report, however, since there is insufficient data to justify them and current large aircraft appear to be able to meet the existing requirements. As a guide in future requirements of large aircraft, it is noted that it may be possible to exceed the existing maximum positive required levels of $d\gamma/dV$ and still have satisfactory handling qualities.

Analytical values of T_{h1}, $d\gamma/dU$ and T_s are shown below for a representative large aircraft. They were computed using aerodynamic data obtained from wind tunnel and flight tests. These calculations demonstrate the actual relationship between the parameters, i.e., the previously mentioned approximations were not used.

$$\left.\begin{array}{l}
T_{h_1} = 91.8 \text{ sec.} \\[2ex]
T_{2_s} = 78.6 \text{ sec.} \\[2ex]
\frac{1}{d\gamma/dU} \frac{(1.688)\ (57.3)}{32.2} = 72.86 \text{ sec.}
\end{array}\right\} \quad \begin{array}{l}\text{LAC C-5A -} \\ \text{Landing}\end{array}$$

The L-1011-500, C-5A, and C-141A meet the flight path stability Level 1 boundary, and hence, in this respect, support the requirement. Data for the L-1011-500 and the C-5A are presented in Table 7 and Figures 15 and 16. The data is taken from References 2 and 19.

Table 7

Flight Path Stability Data for Representative Large Aircraft

			$V_{o_{MIN}}$		$V_{o_{MIN}}$ -5KT		
AIRCRAFT	V_T KNOTS	C.G. % MAC	$T^*_{S_2}$ SEC.	$d\gamma/dU$ DEG/KT	T_{S_2} SEC.	$d\gamma/dU$ DEG/KT	Δ SLOPE DEG/KT
L-1011	145	13.6	150.3	0.020	88.3	0.034	0.014
L-1011	145	34.4	214.7	0.014	143.0	0.021	0.007
L-1011	125	12.	125.3	0.024	83.4	0.036	0.012
L-1011	125	35	200.4	0.014	136.5	0.022	0.007
C-5A	145	-	STABLE	-0.0020	682.7	0.0044	0.0064

* BASED ON $T_{S_2} = \left(1 / \frac{d\gamma}{dU}\right) * \frac{(57.3)\ (1.688)}{32.2}$

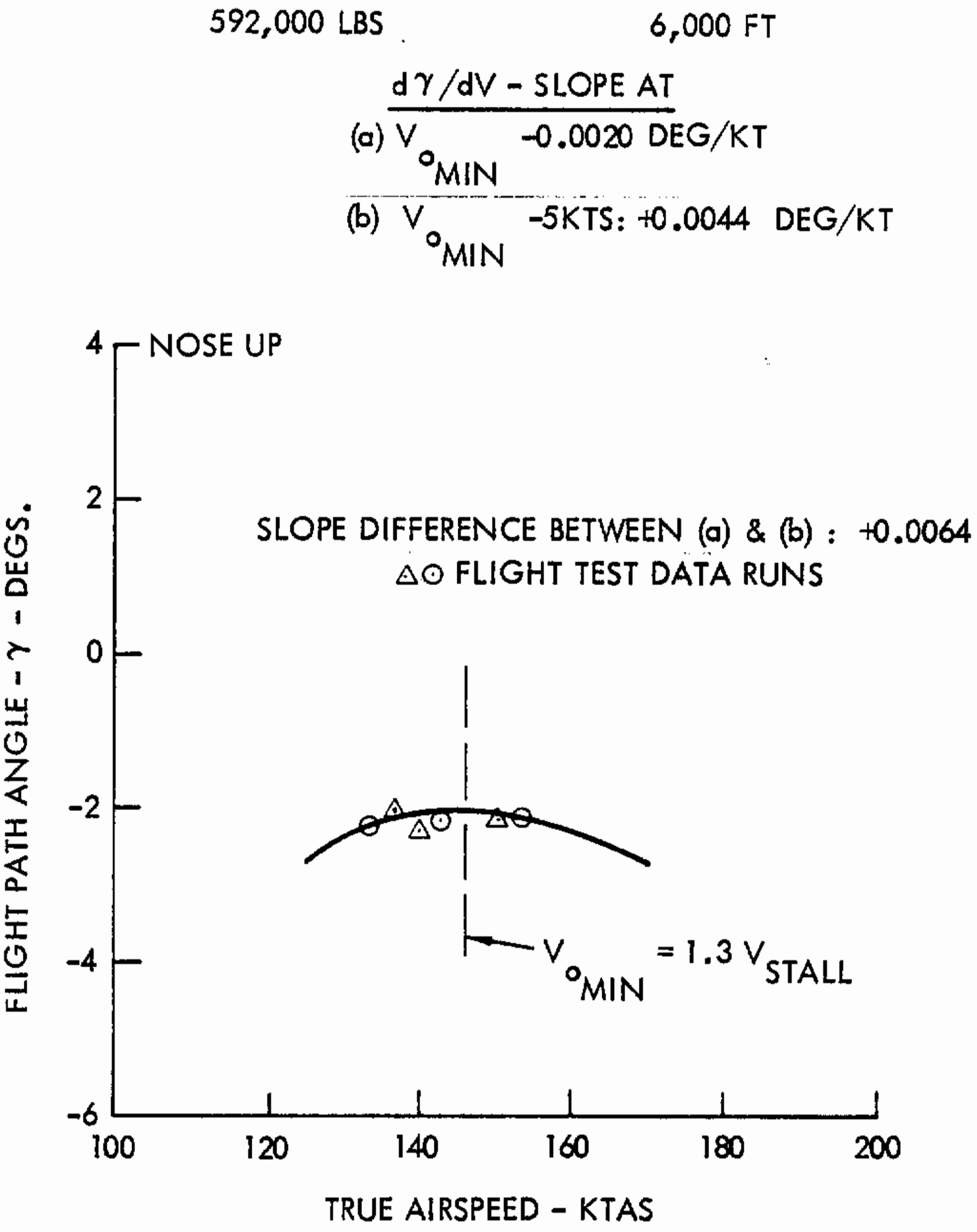


Figure 15 C-5A Flight Approach Data (Figure 6 (3.2.1.3) of Reference 2)

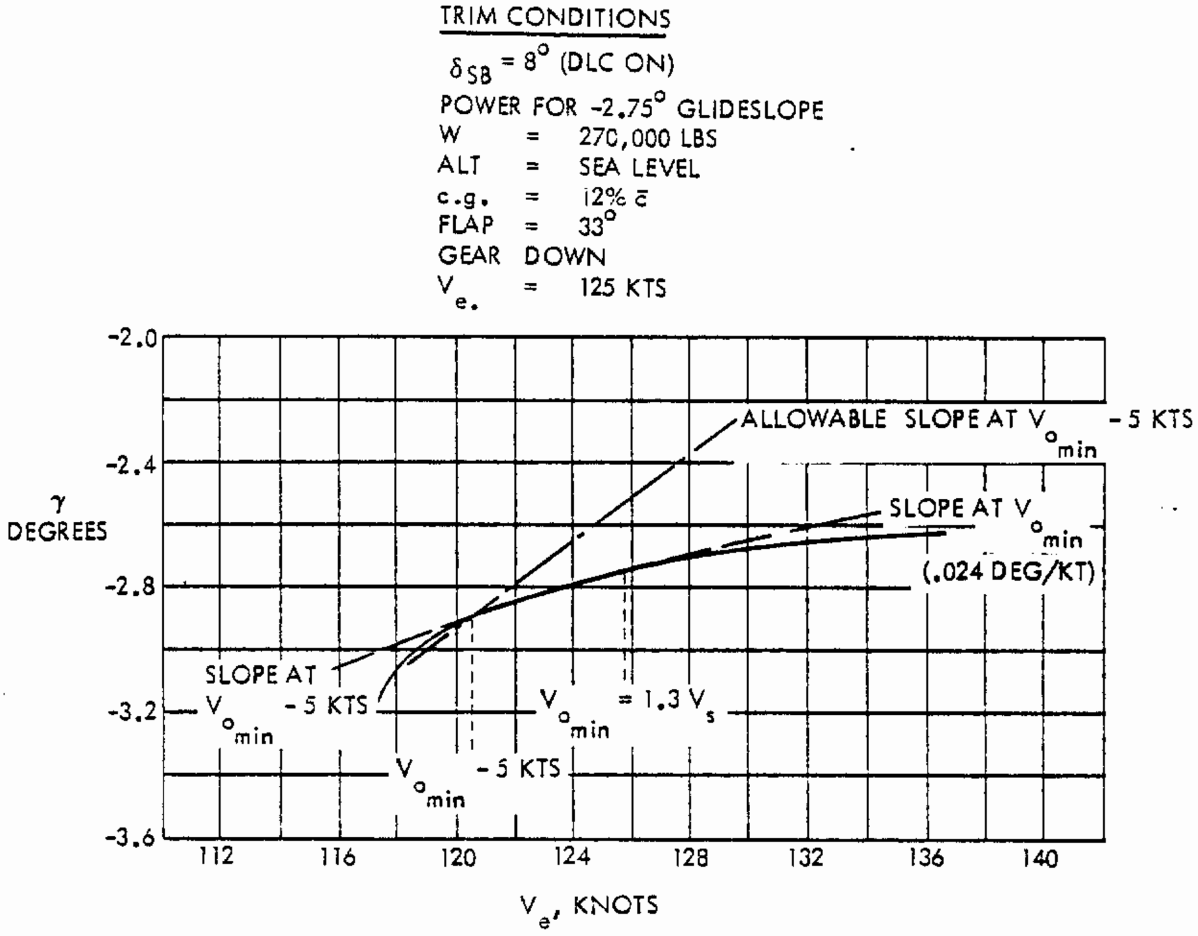


Figure 16 L-1011 Flight Path Stability Data (from Reference 19)

3.2.2.1.1 Short-period Frequency and Acceleration Sensitivity

REQUIREMENT

The equivalent short-period undamped natural frequency, $\omega_{n_{SP}}$, shall be within the limits shown on Figures 17, 18 and 19.

RATIONALE

This requirement is an attempt to provide a little more guidance in acceptable longitudinal dynamics than merely specifying short period frequency and damping ratio levels. Since the requirements are applicable throughout the flight regime, attempts have been made to identify and limit particular parameters where they become important. An example of this is when pitch rate response appears to be of primary importance at low speed, whereas normal acceleration is of primary importance at high speed. The parameter used to establish bounds on Figures 17-19, $\omega_{n_{SP}}^{2}/(n/\alpha)$, is called a control anticipation parameter (CAP). The name implies that it gives an indication of the dynamics a pilot expects to occur based on what he sees in the initial response.

The lower boundaries of Figures 17-19 have been deleted for large aircraft. Initial levels were assigned by Reference 1 based on available data. Existing data on large aircraft shows that they presently operate satisfactorily outside of the previous bounds. A new analytical breakdown of the CAP parameter in the following section explains the penalties of the old boundaries on large aircraft. It further shows how that parameter is really another way of stipulating the maneuver margin. The lower bounds are now stated in terms of static margin, maneuver margin and time to double amplitude.

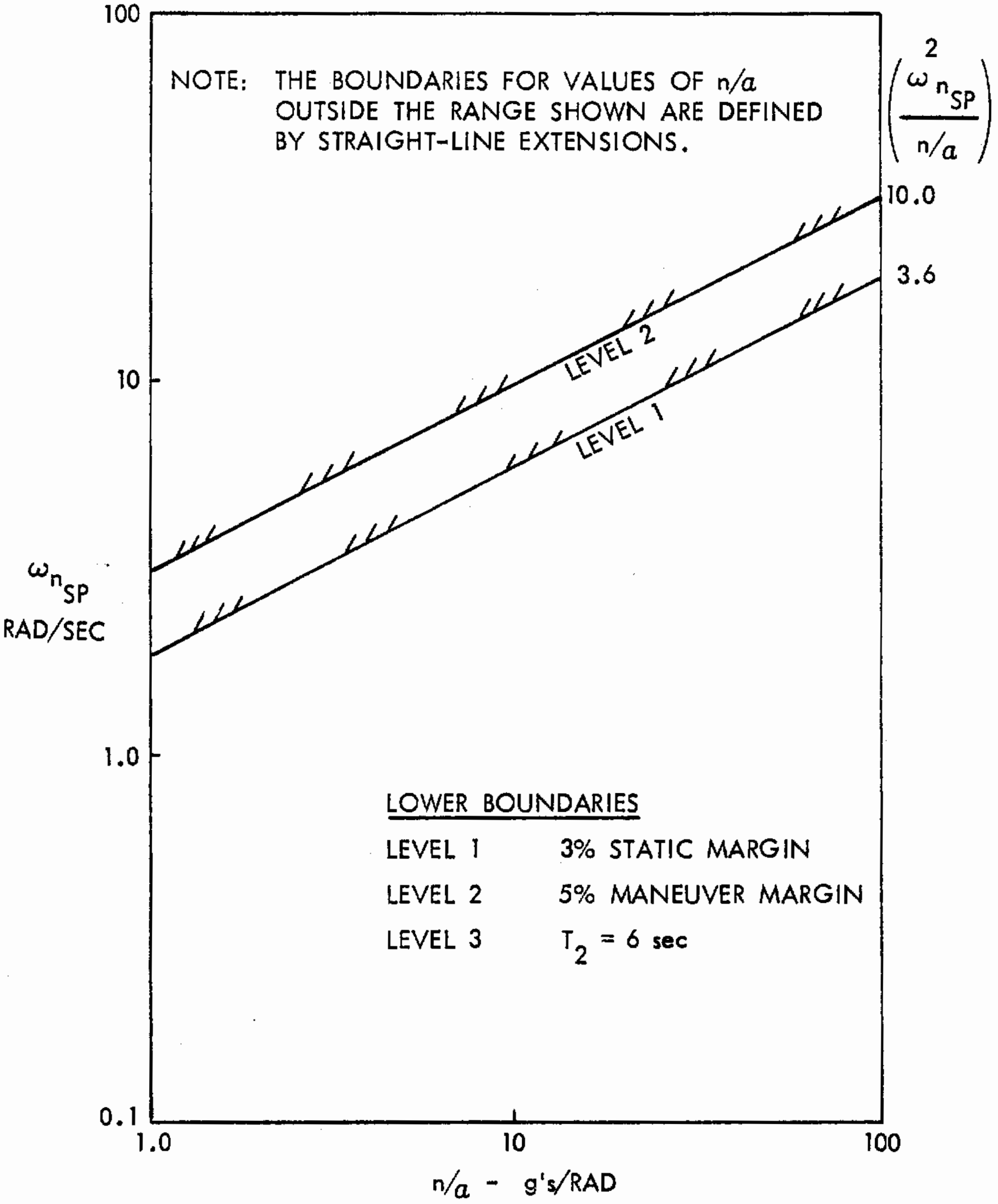


Figure 17 Class III Short Period Frequency Requirements - Category A Flight Phases

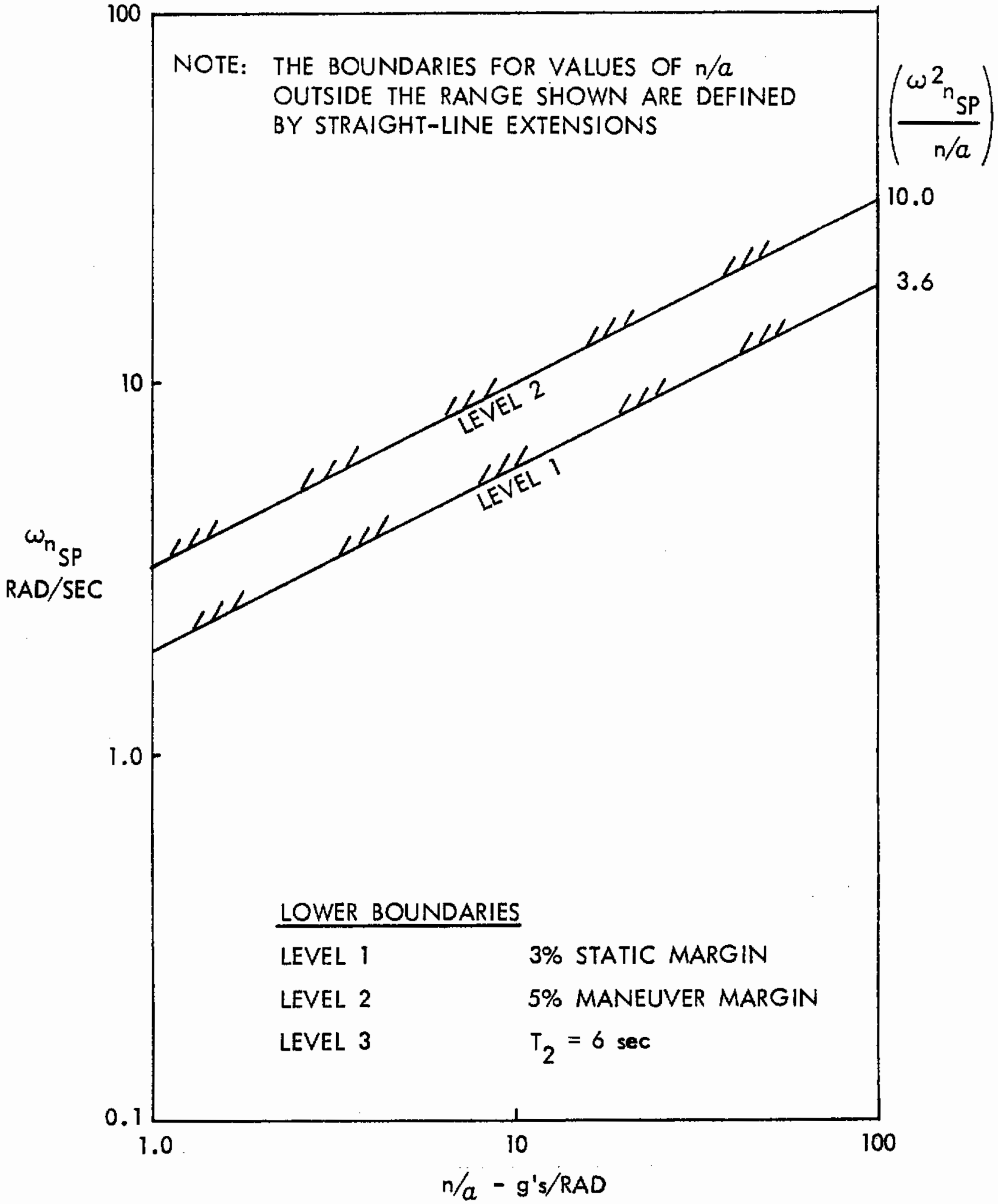


Figure 18 Class III Short Period Frequency Requirements - Category B Flight Phases

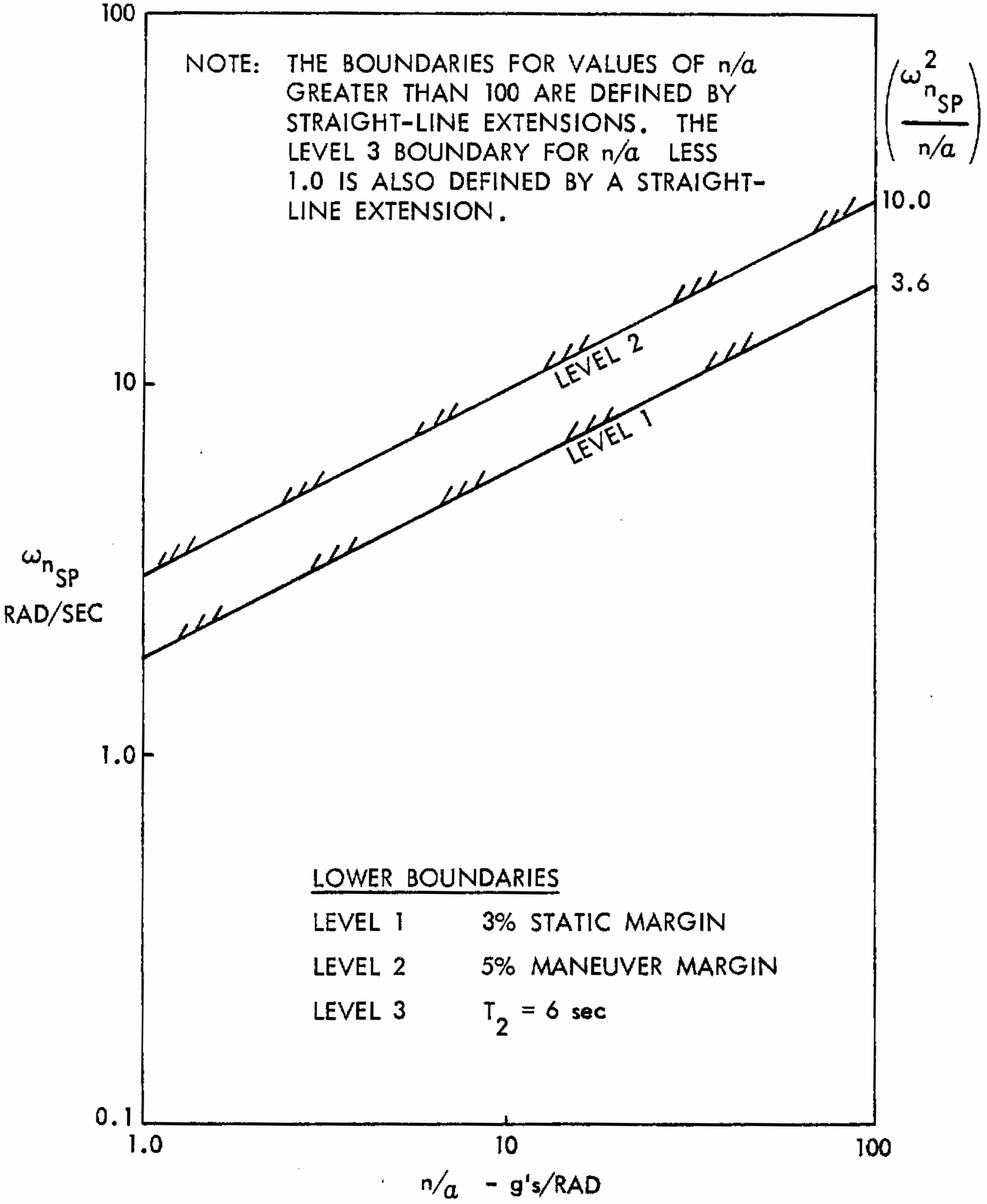


Figure 19 Class III Short Period Frequency Requirements - Category C Flight Phases

GUIDANCE

The short period frequency of a typical large aircraft is considerably lower than the levels associated with a small aircraft. Table 8 is a summary of C-5 flight data showing the short period frequency, damping ratio and n/α for all three flight categories with forward and aft c.g. positions. The highest short period frequency is 1.86 rad/sec. Figure 20 is a plot typical of the 22 figures of Reference 30 used to select the Category A boundaries. It contains results from Reference 21. Only four sets of data were used to establish the Category C boundaries and one plot for Category B. The last plot was for a large aircraft (the XB-70), and the CAP levels selected from that plot for Category B are much lower than the levels for the other two categories.

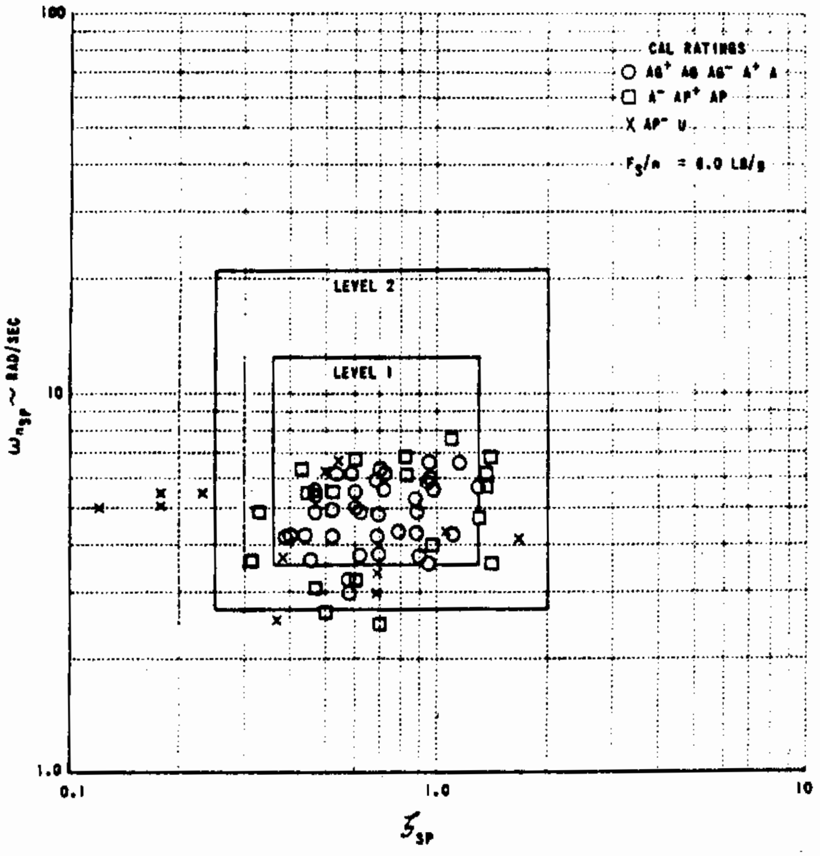


Figure 20 Typical Plot of Category A Flight Data (Figure 15 (3.2.1.1) of Reference 1)

Table 8

Short Period Response Summary of C-5A
Flight Data (Reference 2)

CATEGORY	CONFIG.	WEIGHT	C.G.	V_{KCAS}	ALT.	ζ	ω_{nsp}	ω_{sp}	n/α
C	T.O. (25)	670,900	22.6	149	9,178	.65	1.06	.81	4.03
C	T.O. (25)	661,800	40.6	151	10,470	.93	.71	.26	4.15
C	T.O. (25)	489,500	40.5	183	10,107	.93	1.05	.39	8.40
C	L	661,500	22.8	145	10,187	.65	1.01	.77	3.87
C	L	636,100	39.6	145	11,704	.84	.76	.41	3.98
C	L	700,150	40.7	165	8,611	.89	.77	.35	4.70
A & B	CR	495,850	22.3	180	9,941	.63	1.29	1.00	6.50
A & B	CR	691,925	22.9	268	10,178	.57	1.81	1.49	10.70
A & B	CR	503,200	22.5	269	9,941	.61	1.86	1.47	14.80
A & B	CR	682,700	40.1	270	9,978	.76	1.27	.83	10.90
A & B	CR	699,600	39.8	351	9,961	.76	1.55	1.01	18.40
A & B	CR	698,400	40.1	270	26,000	.61	1.08	.86	11.80
B	CR	499,200	40.7	235	35,045	.85	.80	.42	13.00
B	CR	513,400	40.5	272	35,175	.78	1.08	.68	18.70
B	D	505,643	40.7	245	14,150	.79	1.22	.75	11.70
B	D	475,724	40.8	231	34,700	.85	.83	.44	11.40

The CAP parameter has been analyzed in different ways. Reference 1 explained two distinct approaches. It was noted while examining experimental data that for each flight condition there was a range of short period frequencies for which the pilots could select rather well-defined optimum control gains. At lower and higher short period frequencies, however, they would encounter conflicting requirements which imposed unsatisfactory compromises in the selection of the control gain: A relationship between sensitivity and steady forces was developed in an effort to understand how these parameters relate to frequency. The following expression was derived:

$$\frac{F_s}{n} = \frac{\omega_{n_{SP}}^{2}}{\frac{\delta e}{F_s} M_{\delta_e} (n/\alpha)} = \frac{\omega_{n_{SP}}^{2}}{M_{F_s} (n/\alpha)} \qquad (7)$$

M_{F_s} is the initial pitch acceleration per pound of stick force, or sensitivity. The CAP parameter can therefore be viewed as

$$CAP = \frac{F_s}{n} M_{F_s} = \frac{\omega_{n_{SP}}^{2}}{(n/\alpha)} \qquad (8)$$

The reasoning follows that a CAP level which is too low means that either the stick force per g must be small to maintain adequate sensitivity, or the sensitivity must be low to maintain satisfactorily high stick force per g in maneuvers. This produced a condition where the pilot could not achieve a satisfactory compromise between sensitivity and steady forces. High values of CAP again produced a compromise problem. A sensitivity gain low enough to prevent abruptness and tendency to bobble for small inputs caused heavy steady forces during sustained maneuvers and turns.

The second interpretation of CAP in Reference 1 from Reference 31, relates the importance of initial pitch acceleration to steady state response. Assuming constant-speed equations of motion and by applying the initial value theorem to the $\ddot{\theta}/\delta_e$ and the final value theorem to the n/δ_e transfer functions, respectively, it was shown that for a step δ_e, the short-period approximation yields:

$$\frac{\left.\frac{\ddot{\theta}}{\delta_e}\right|_{t = 0^+}}{\left.\frac{n}{\delta_e}\right|_{ss}} = \frac{\omega_{n_{SP}}^{\;2}}{\frac{V}{g}\,\frac{1}{T_{\theta_2}}} \tag{9}$$

The term $1/T_{\theta_2}$, the numerator lead factor in the $\ddot{\theta}/\delta_e$ transfer function, may be approximated as

$$\frac{1}{T_{\theta_2}} = \frac{g}{V}\left(\frac{n}{\alpha}\right) \tag{10}$$

so the CAP equation is seen to be approximated by

$$\frac{\left.\frac{\ddot{\theta}}{\delta_e}\right|_{t = 0^+}}{\left.\frac{n}{\delta_e}\right|_{ss}} \approx \frac{\omega_{n_{SP}}^{\;2}}{(n/\alpha)} = \text{CAP} \tag{11}$$

This form is obviously very useful in the development of augmentation systems. It is the form which led to the decision to use only data from in-flight programs to select Level 1 and 2 limits. This was to insure that the motion cues and tasks were realistic.

A more revealing form of CAP with respect to large aircraft is the static stability intepretation noted in Reference 32. Since n/α is a function of C_{L_α} and $\omega_{n_{SP}}$ is a function of C_{m_α}, the CAP, which is a ratio of these two parameters, can be related to static margin, dC_m/dC_L, as follows:

$$\frac{n}{\alpha} = \frac{C_{L_\alpha} qS}{GW} \tag{12}$$

$$\omega_{n_{SP}}^{2} = \frac{q\,S\,\bar{c}}{I_{yy}} \left[-\,C_{m_\alpha} \quad - \left(\frac{\rho\,S\,\bar{c}}{4m} \right) C_{m_q}\,C_{L_\alpha} \right] \tag{13}$$

$$CAP = \frac{\omega_{n_{SP}}^{2}}{n/\alpha} = \frac{\bar{c}\;GW}{I_{yy}} \left[-\,\frac{dC_m}{dC_L} - \left(\frac{\rho\,S\,\bar{c}}{4m} \right) C_{m_q} \right] \tag{14}$$

The control anticipation parameter is therefore a physical parameter (composed of the ratio of mean aerodynamic chord times gross weight to pitch inertia) times the maneuver margin (the term in the brackets). Reference 32 chose to ignore the tail damping part of the brackets, C_{m_q}, and thus related it to static margin, dC_m/dC_L.

An interesting phenomenon is noted when comparing a large aircraft like the C-5A to a small aircraft like the T-33. The coefficient of the maneuver margin for the T-33 is approximately ten times the value for the C-5. Figure 21 is a plot showing how this ratio varies with aircraft size, represented by fuselage length. Therefore, a CAP boundary selected with a small aircraft could require the larger aircraft to have ten times the maneuver margin. Large aircraft are also seen to have inherently large contributions of pitch damping to the maneuver margin.

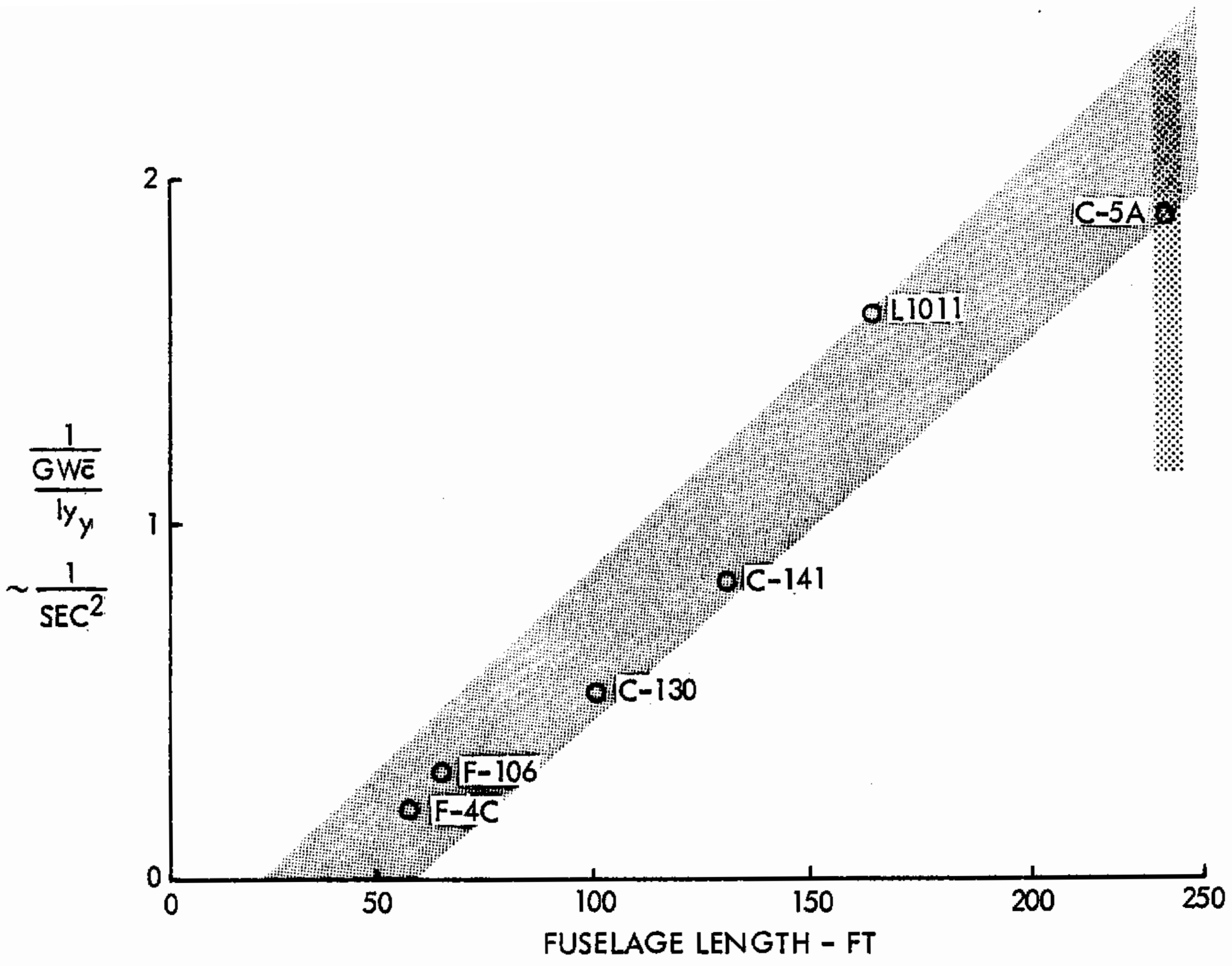


Figure 21 Physical Parameter Ratio Used in CAP as a Function of Aircraft Size

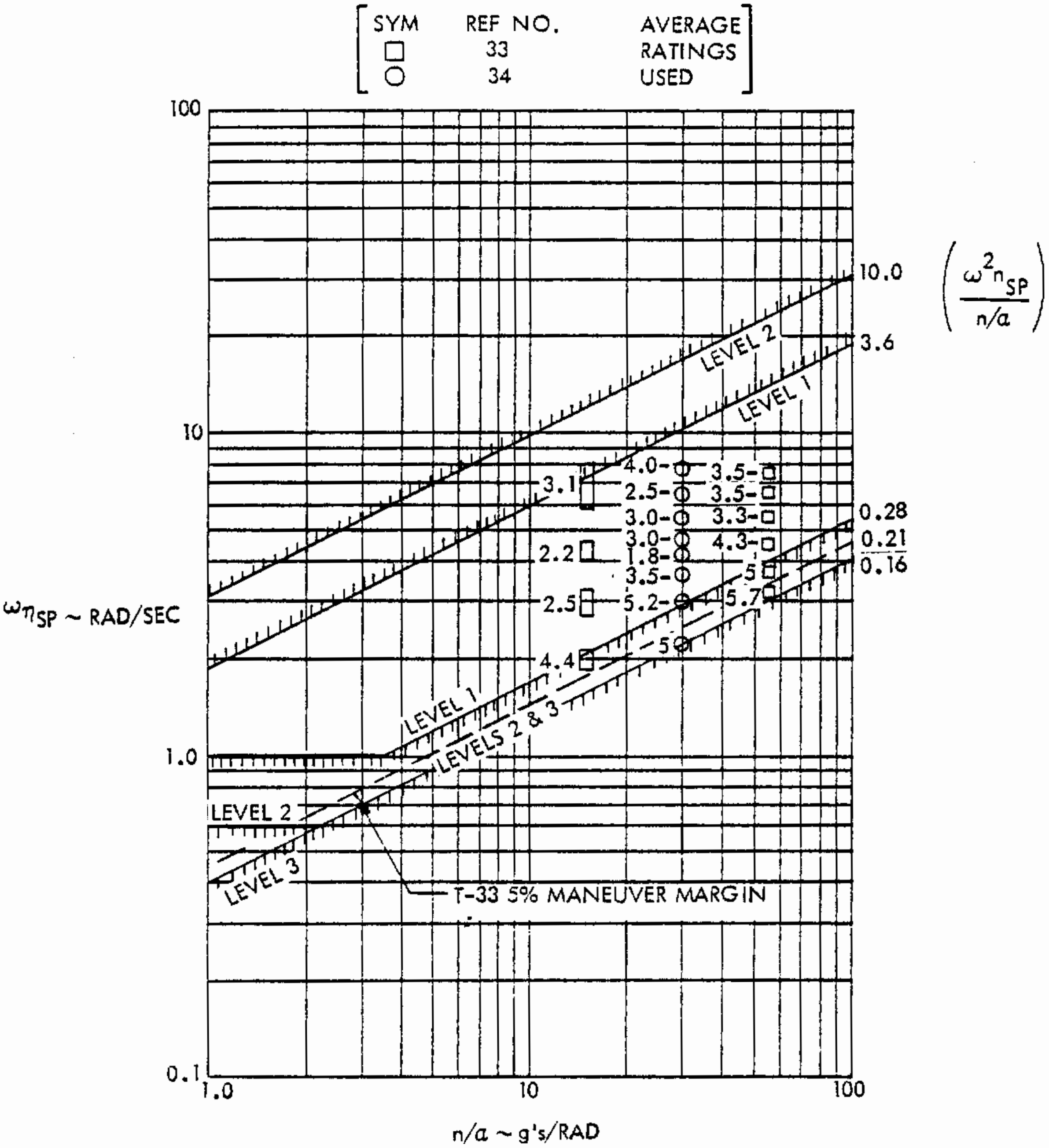


Figure 22 T-33 Data for Cateogry A Flight Compared to MIL Spec Boundaries and 5% Maneuver Margin

Ignoring the tail damping term to consider only static margin is a reasonable assumption for the small aircraft. The T-33 tail damping puts the maneuver point about 2% aft of the neutral point at sea level and less than 1% aft at 30,000 feet of altitude. The C-5 tail damping term causes a separation of the neutral and maneuver points of about 12% at sea level and about 7.5% at 30,000 feet.

Figure 22 shows the T-33 data of References 33 and 35 used to establish the Category A requirements. The appropriate MIL Spec boundaries are shown, as well as an arbitrary 5% maneuver margin (4% static margin) line. The Level 1 lower boundary has approximately a 5% static margin and the Level 2 boundary has approximately a 4% maneuver margin. Reference 1 stated that the Level 3 boundary was made coincident with that of Level 2 due to lack of data available to establish a true Level 3 boundary.

Figure 23 shows the XB-70 data from Reference 35, which was the only set of data for Category B. This was a relatively large aircraft and the CAP values are much lower than those of Categories A and C. The figure shows the 5% maneuver margin level, as well as the MIL Spec levels. The Level 1 boundary has a static margin of approximately 4%, while Levels 2 and 3 are approximately 2% with a 4% maneuver margin.

Category C boundaries for the short period response were established primarily with data from the T-33, Navion and the Boeing 367-80 experiments. Figure 24 compares the T-33 data with the specification and shows a 5% maneuver margin. The approximate static margin for this case is 3%. The Level 1 boundary corresponds to a 2% static margin and the Levels 2 and 3 boundary to a near zero static margin. Figure 25 shows data for the large aircraft with 3% static margin and 5% maneuver margin boundaries.

The data presented thus far are from experiments 15 to 20 years old. A renewed interest in minimum levels of stability has taken place more recently with the desire for greater efficiency in transports. The concept of relaxed stability has brought about a need to determine the Level 3 boundary particularly for highly augmented aircraft. Figure 26 shows data

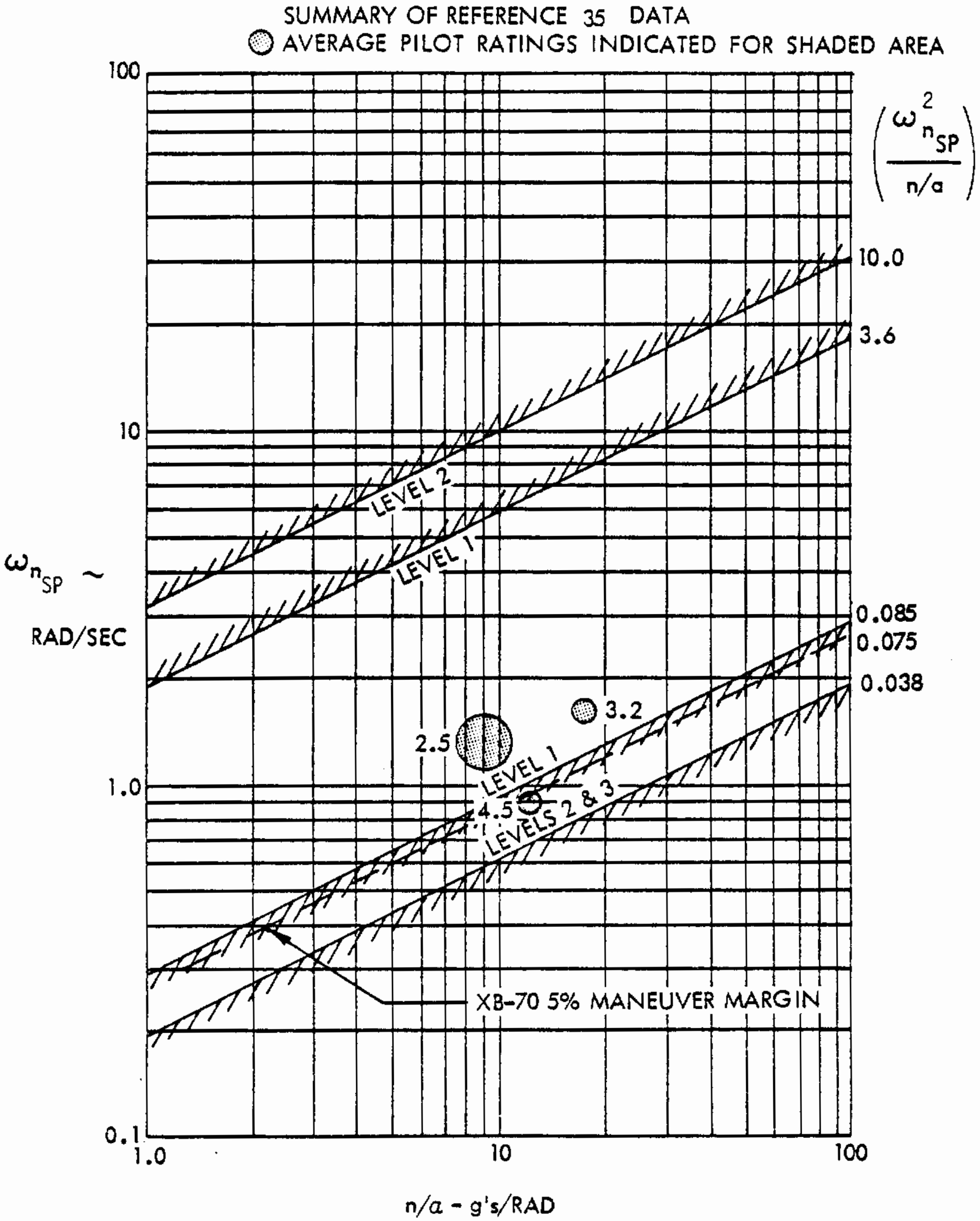


Figure 23 XB-70 Cateogry B Data Compared to MIL Spec and 5% Maneuver Margin Level

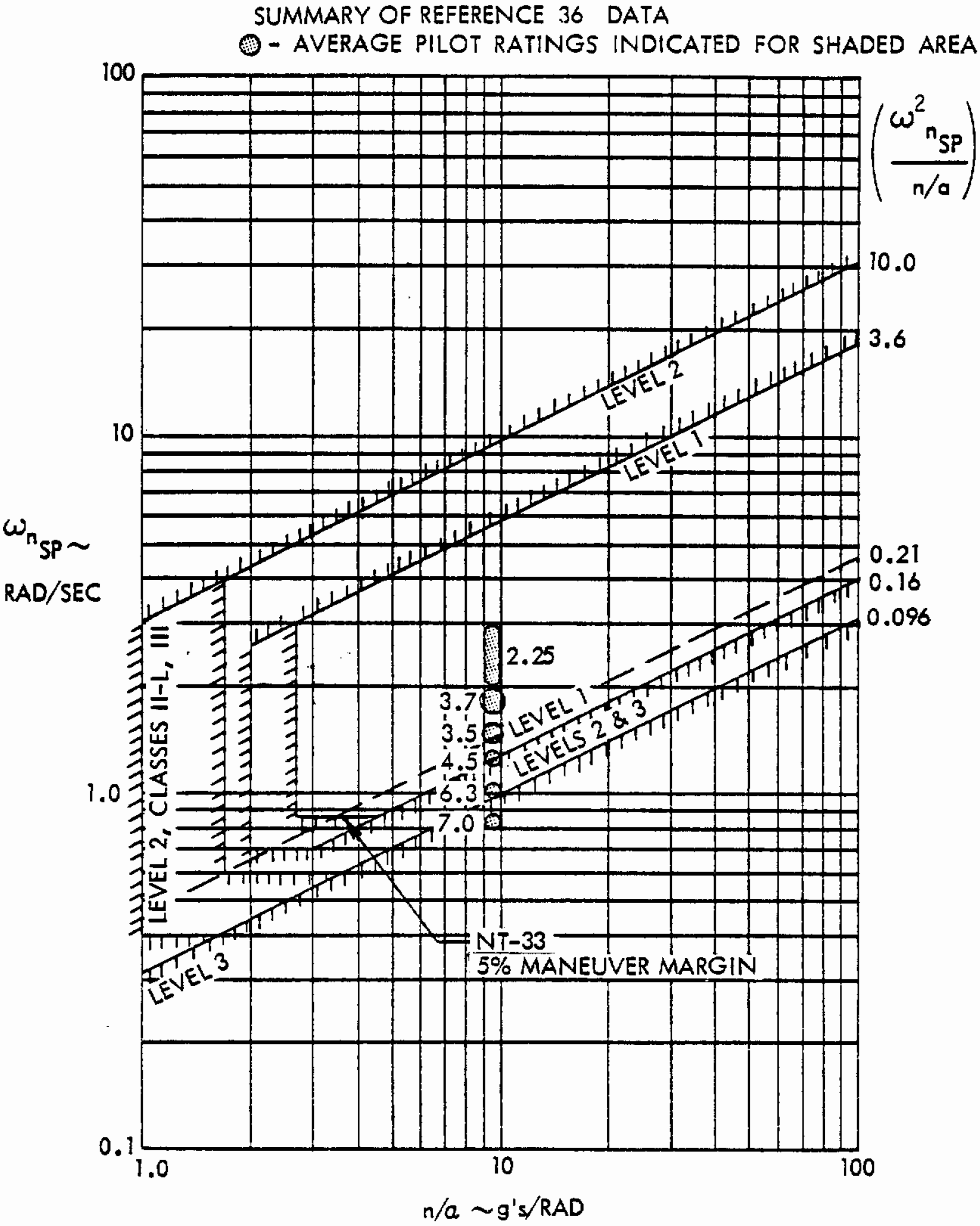


Figure 24 NT-33 Cateogry C Data Compared to MIL Spec and 5% Maneuver Margin

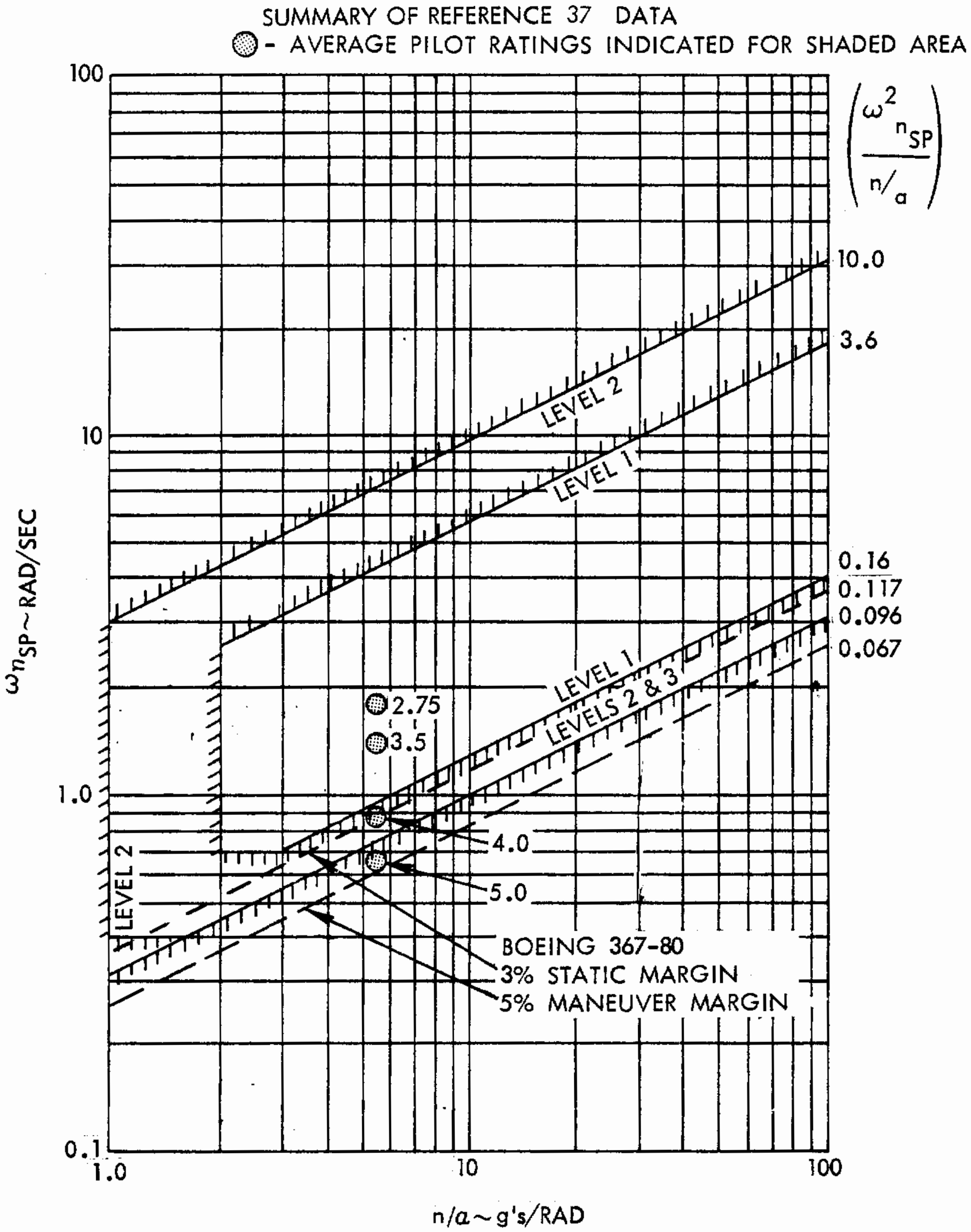
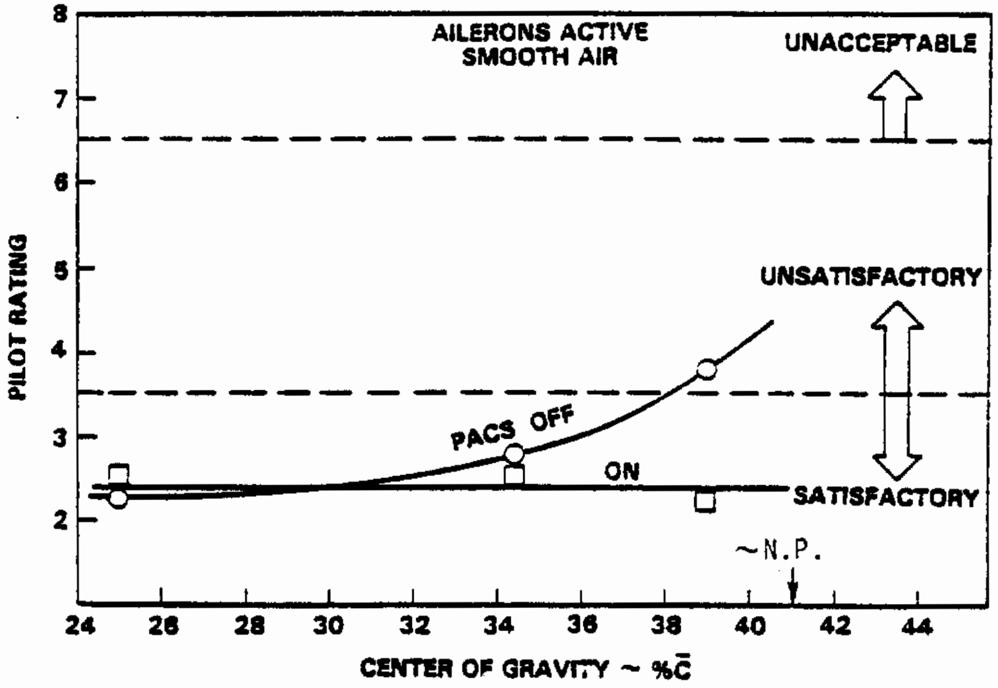


Figure 25 Category C Flight Data for Boeing 367-80 Compared to MIL Spec. Maneuver Margin and Static Margin

a) FLIGHT SIMULATION RESULTS



b) FLIGHT TEST RESULTS

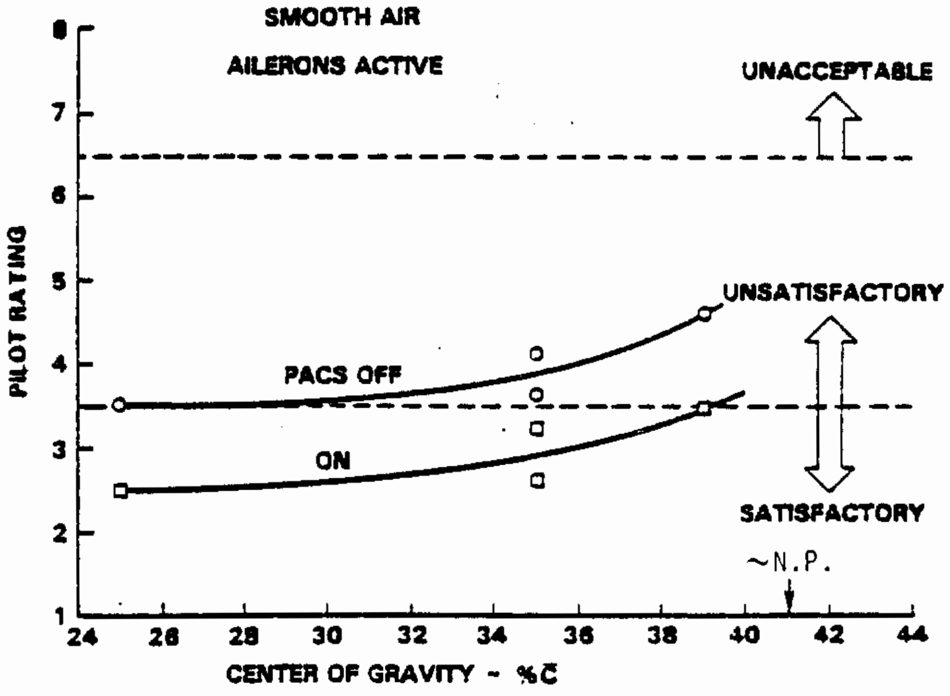


Figure 26 Ground Simulation and Flight Test Results for Relaxed Stability of the Lockheed L-1011 in Cruise

from Reference 15)b for both simulation and in-flight results. In-flight results are one pilot rating above the simulation results, but the trends are the same. These findings agree well with those of References 12 and 38. Data for the landing approach and cruise both show that the Level 1 boundary (PR = 3.5) occurs in the vicinity of 0 to 3% static margin. They also show the Level 2 boundary occurring at a maneuver margin of 0 to -10%.

The suggestion of returning the short period frequency requirement to a simple function of equivalent static margin, maneuver margin and time to double amplitude may seem to be an over-simplification. However, this seems to be more rational than having parameters arbitrarily chosen which impose undue requirements.

LESSONS LEARNED

Additional large aircraft data, based on flight data, are provided here to aid in the development of short period requirements. Included is data from the Lockheed C-5A and L-1011 plus the Aerospatiale France-British Aircraft Corporation's Concorde. All points are believed to be Level 1. Appendix A gives a summary of pilot opinions to corroborate the C-5A claim. Appendix B presents the flight conditions for the L-1011 cases shown. The Concorde data are from Reference 4.

The upper boundaries of Figures 17 through 19 have not been tested with respect to large aircraft data, and seem unlikely to be. Therefore, no rational change has been suggested to those boundaries. The 8785C lower boundaries would require excessively high levels of maneuver margin for an aircraft the size of the C-5 or 747. Table 9 shows representative values.

These values were obtained using the lower bands from 8785C with Equation (A). The same logic applied to the upper boundaries would show that those levels could not be achieved. Therefore, other limiting parameters such as control sensitivity and forces would be restrictive well before the upper CAP limits of 8785C.

Table 9

Representative Maneuver Margins to Meet Lower CAP
Boundaries of 8785-C for C-5A/747 Size Aircraft

CATEGORY	LEVEL	CAP	APPROXIMATE MANEUVER MARGIN
A	1	.28	56%
A/C	2/1	.16	32%
C	2	.096	19%
B	2	.038	8%

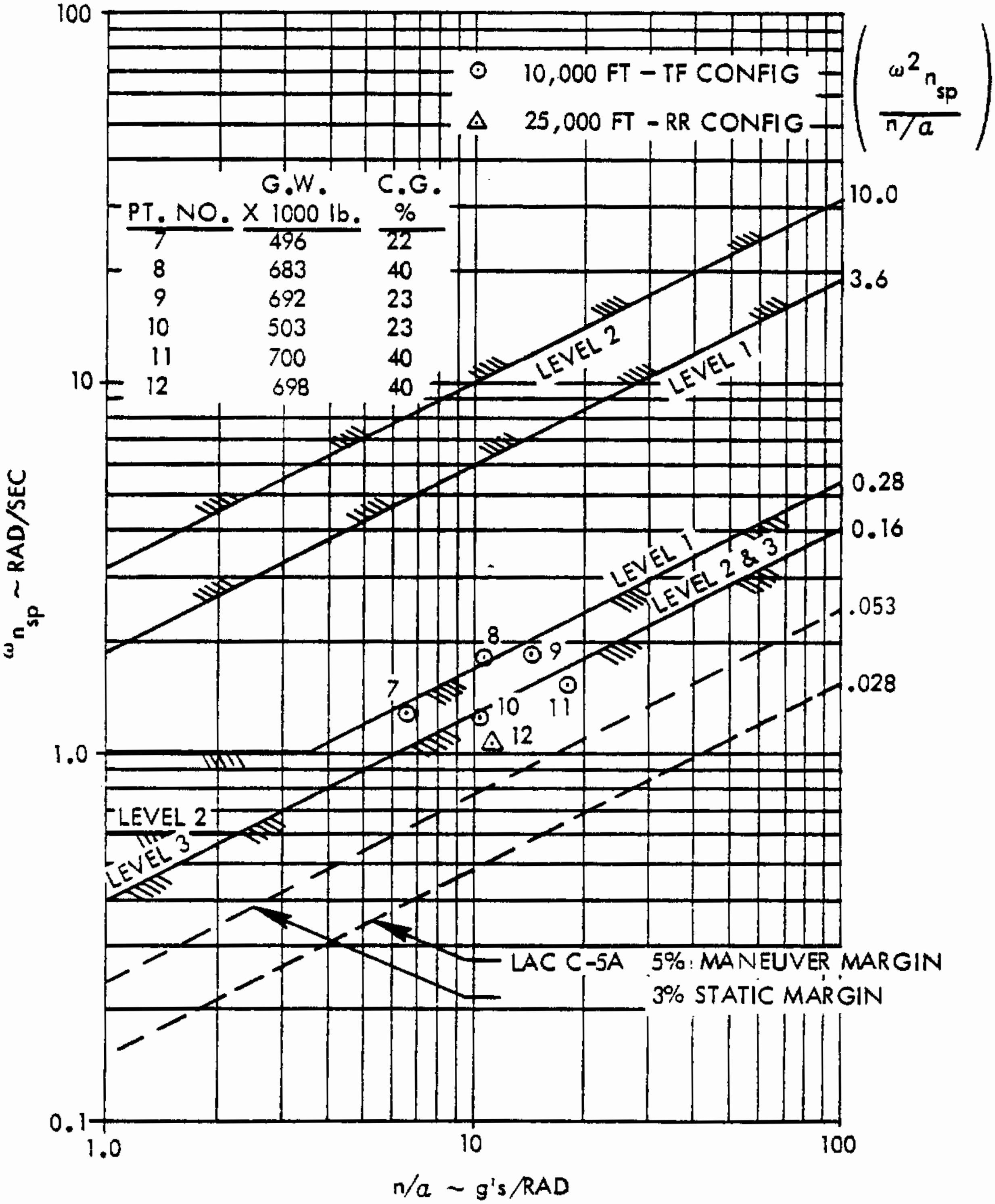
Figure 27 shows flight data for the C-5A for two Category A conditions. The 3% static margin and 5% maneuver margin lines are shown along with the MIL Spec boundaries.

Additional Category B data is provided in Figures 28 through 32 for the C-5, L-1011 and Concorde. The L-1011 data are separated in Figures 29-31 for the climb, cruise and descent configurations, respectively.

Category C data are presented in Figures 33 through 37. The L-1011 data are divided into take-off, power approach and landing configurations in Figures 34 through 36, respectively.

C-5A FLIGHT TEST DATA

CAT A

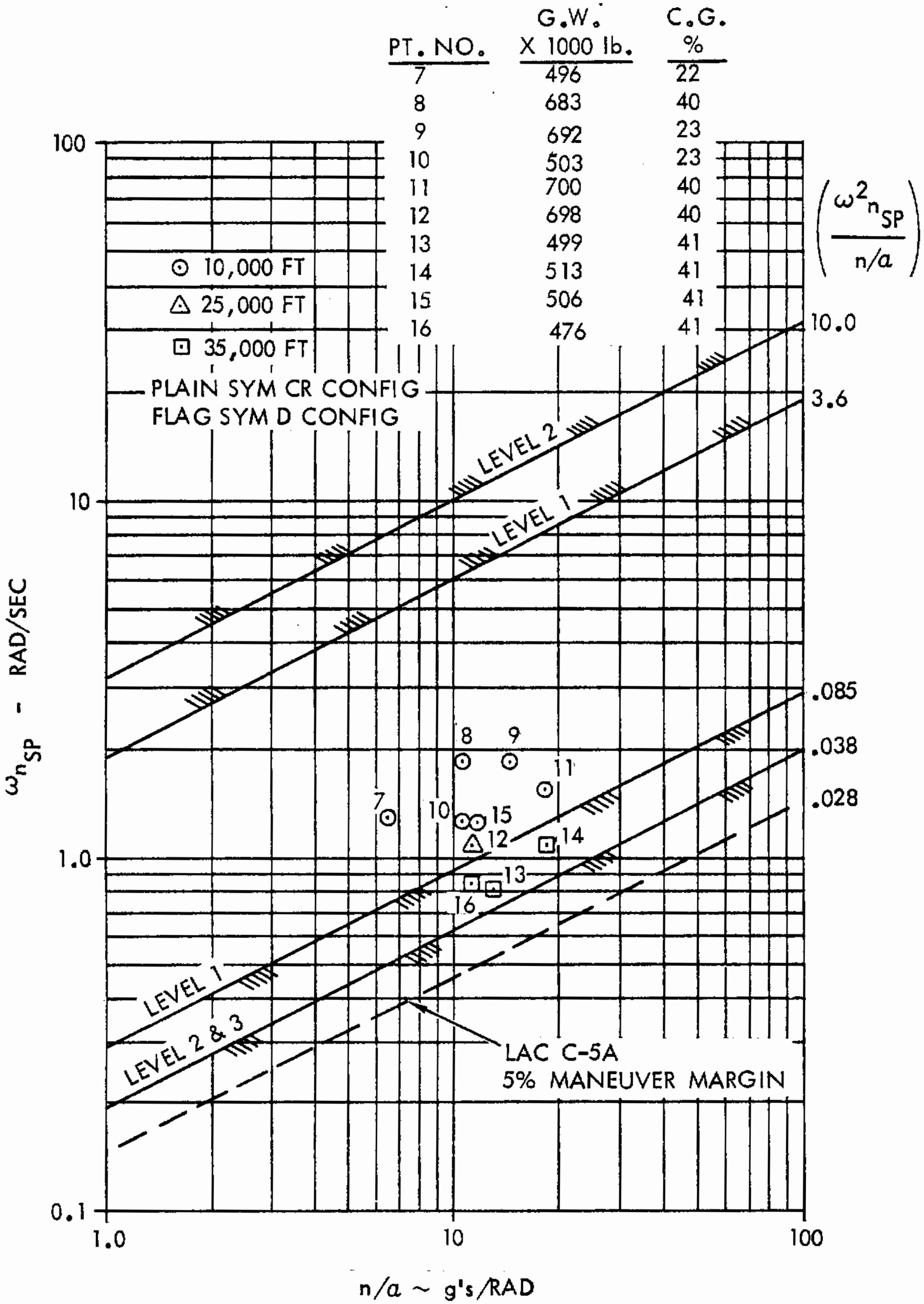


⊙ 10,000 FT – TF CONFIG

△ 25,000 FT – RR CONFIG

PT. NO.	G.W. X 1000 lb.	C.G. %
7	496	22
8	683	40
9	692	23
10	503	23
11	700	40
12	698	40

Figure 27 Category A C-5A Flight Test Data



PT. NO.	G.W. X 1000 lb.	C.G. %
7	496	22
8	683	40
9	692	23
10	503	23
11	700	40
12	698	40
13	499	41
14	513	41
15	506	41
16	476	41

Figure 28 Category B C-5A Flight Test Data

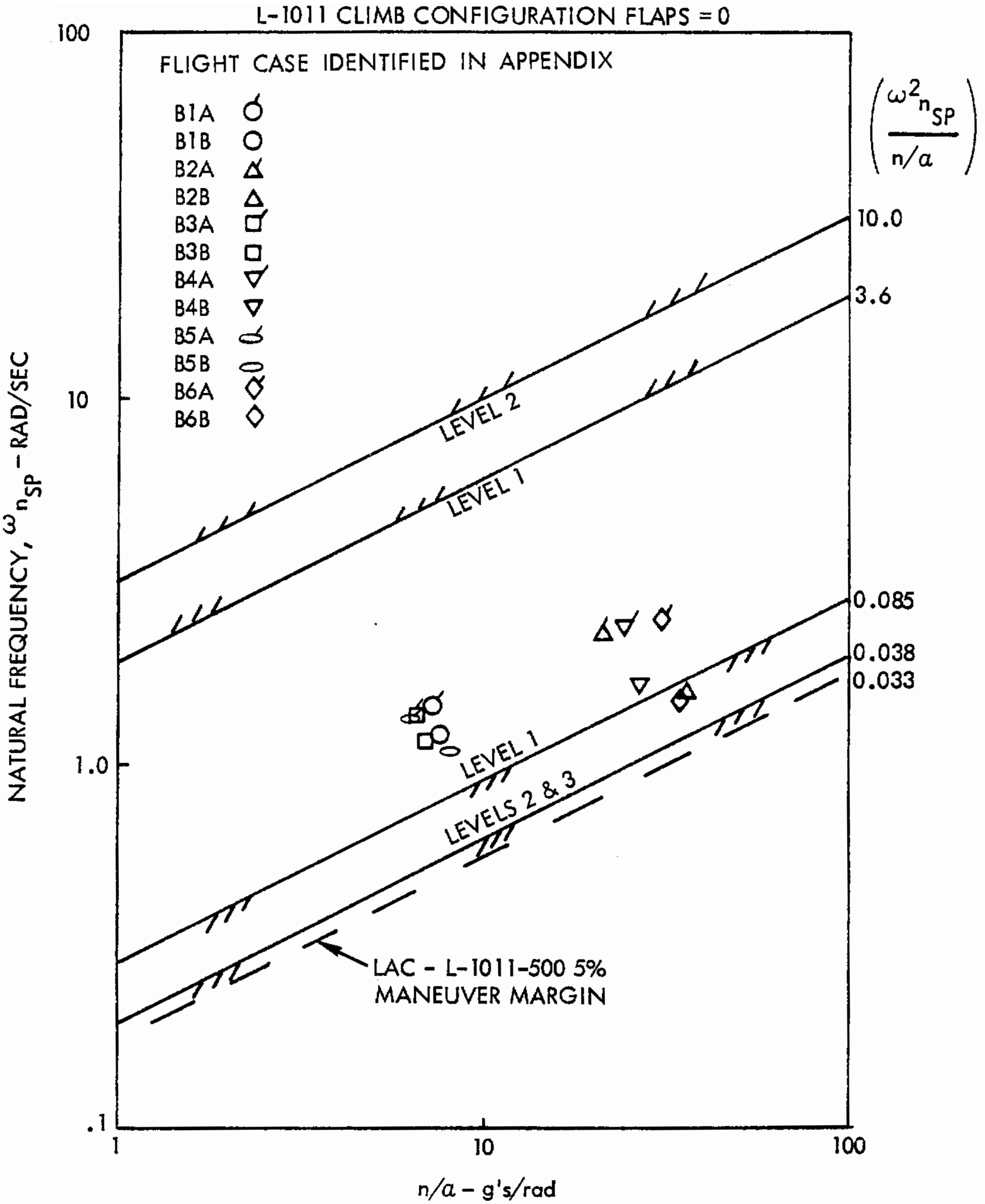


Figure 29 Category B Flight Data for the Lockheed L-1011 in the Climb Configuration

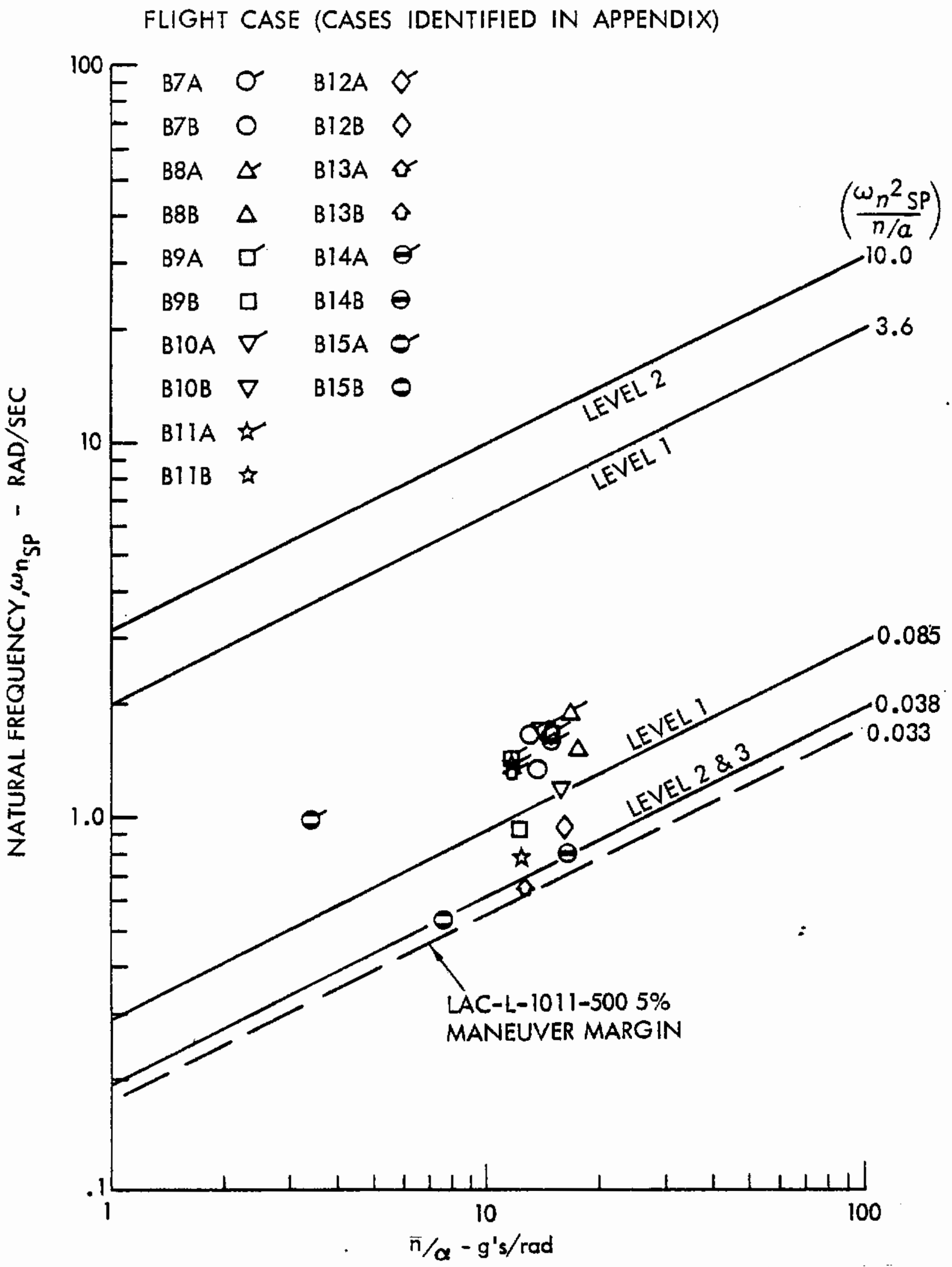


Figure 30 Category B Flight Data for the Lockheed L-1011 in the Cruise Configuration

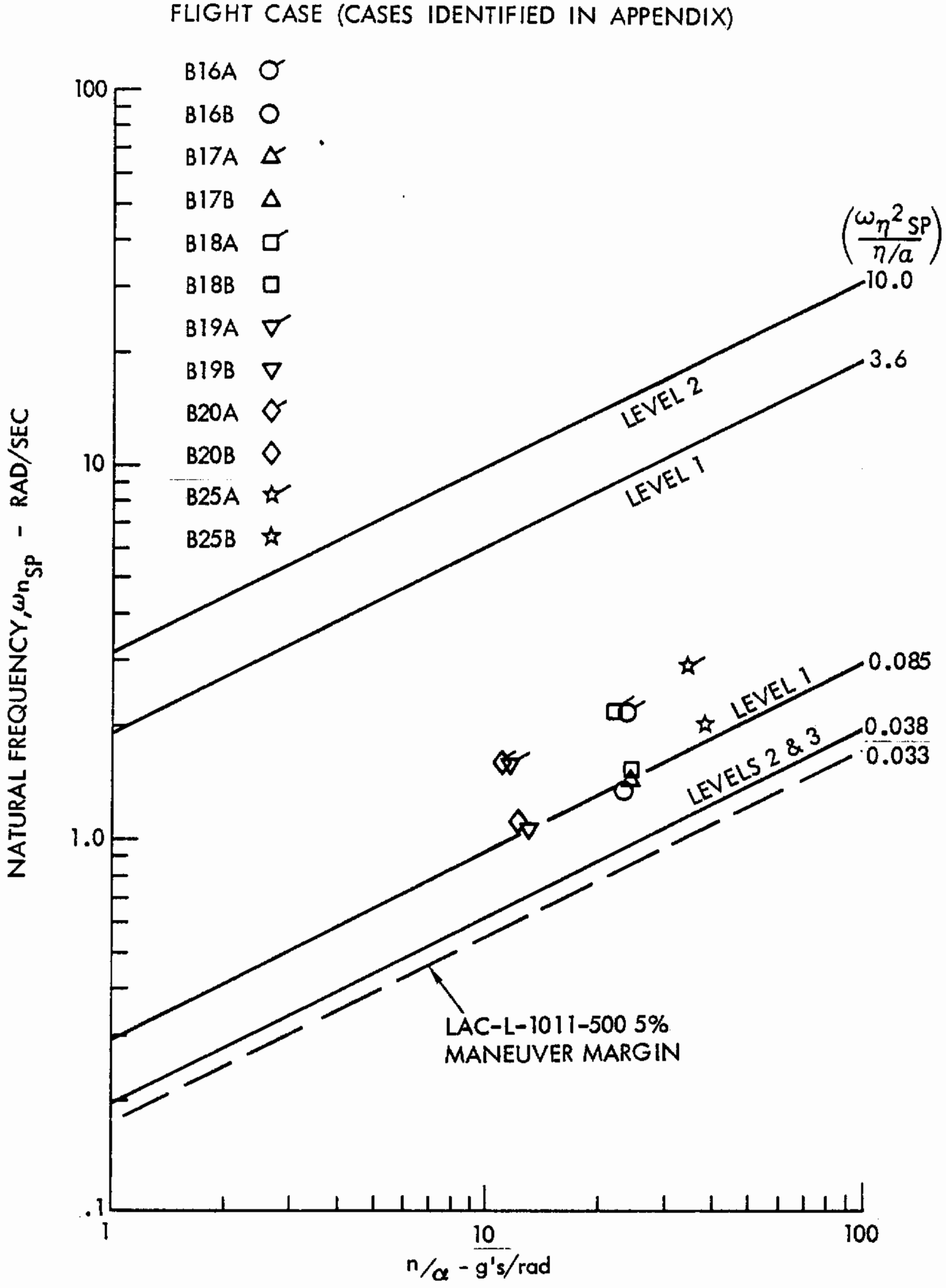


Figure 31 Category B Flight Data for the Lockheed L-1011 in the Descent Configuration

CONFIGURATION - CR
PITCH DAMPER OFF

SYM	MACH NO	ALTITUDE (FT)	WEIGHT (kg)	cg (pct $\bar{c}$)	ζ TEST	ζ MIL-F-8785B
□	1.54	41,120	127,800	57.9	0.225	0.15
◇	1.73	43,830	116,200	57.7	0.205	0.15
○	1.99	51,080	124,900	58.4	0.185	0.15
●	1.95	54,150	128,900	58.6	0.220	0.15
△	0.94	35,410	103,000	54.9	0.255	0.15

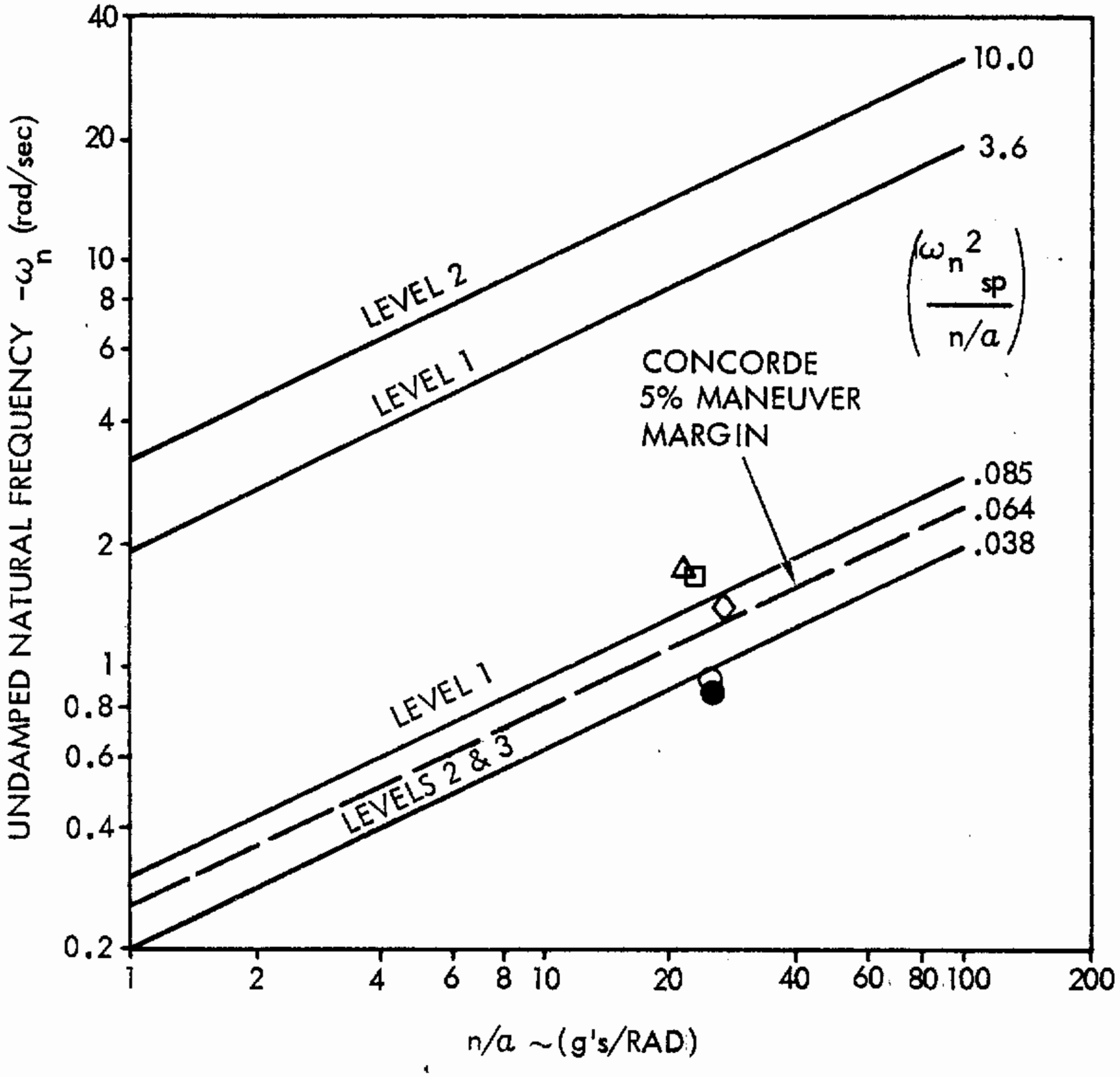
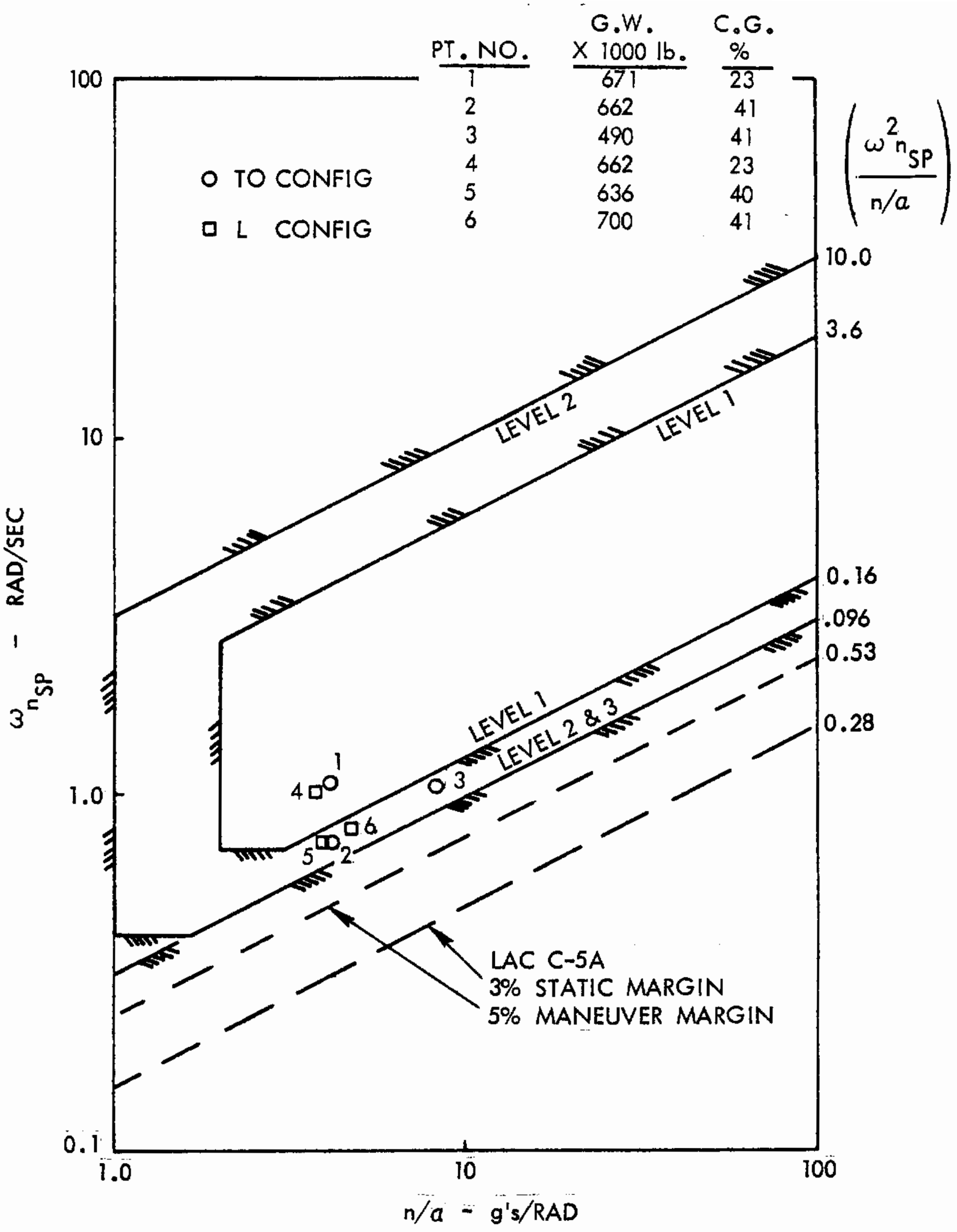


Figure 32 Category B Flight Data for the Aerospatiale France-British Aircraft Corporation Concorde 001



PT. NO.	G.W. X 1000 lb.	C.G. %
1	671	23
2	662	41
3	490	41
4	662	23
5	636	40
6	700	41

Figure 33 C-5A Category C Flight Data

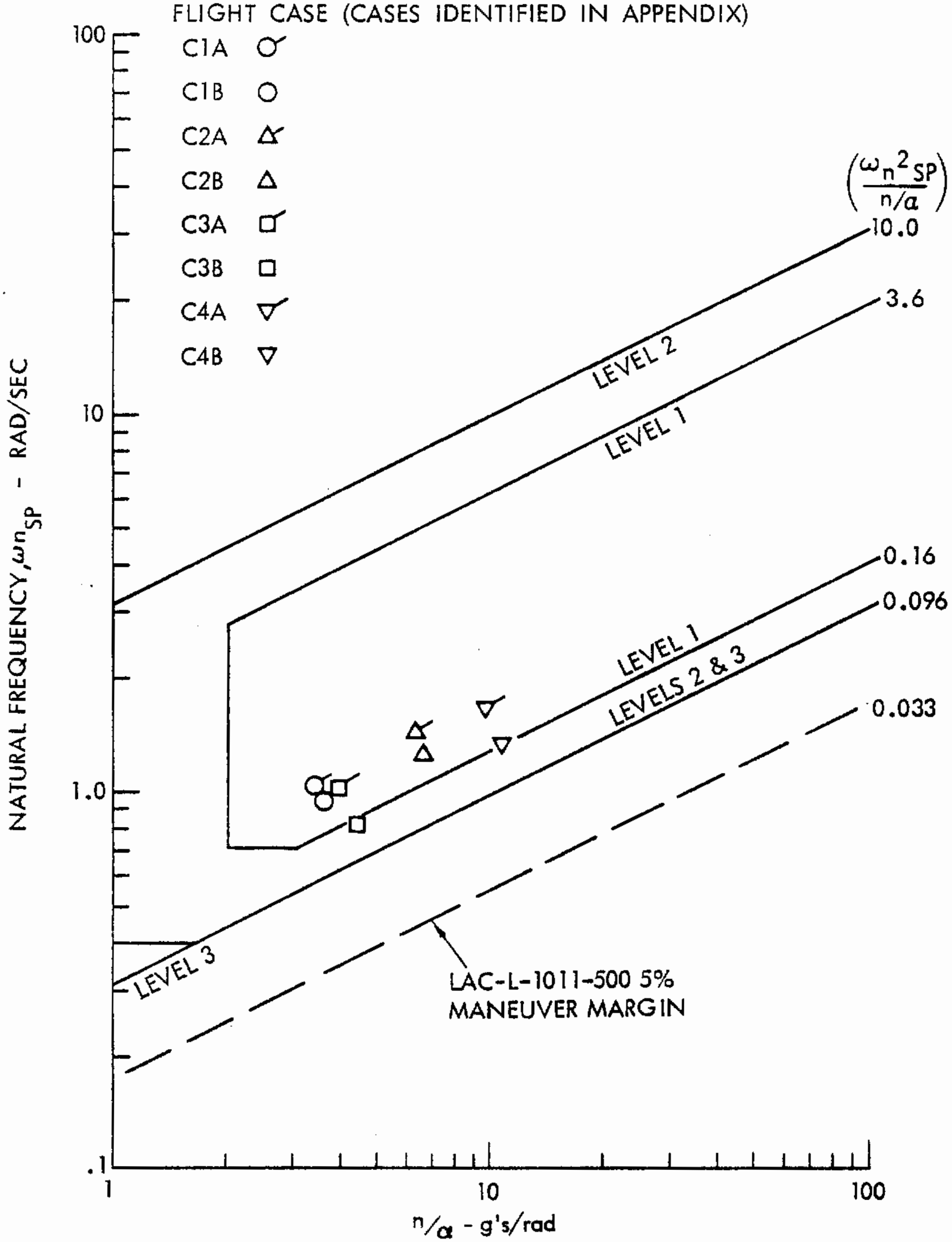


Figure 34 Category C Flight Data for the Lockheed L-1011 in Take-Off Configuration

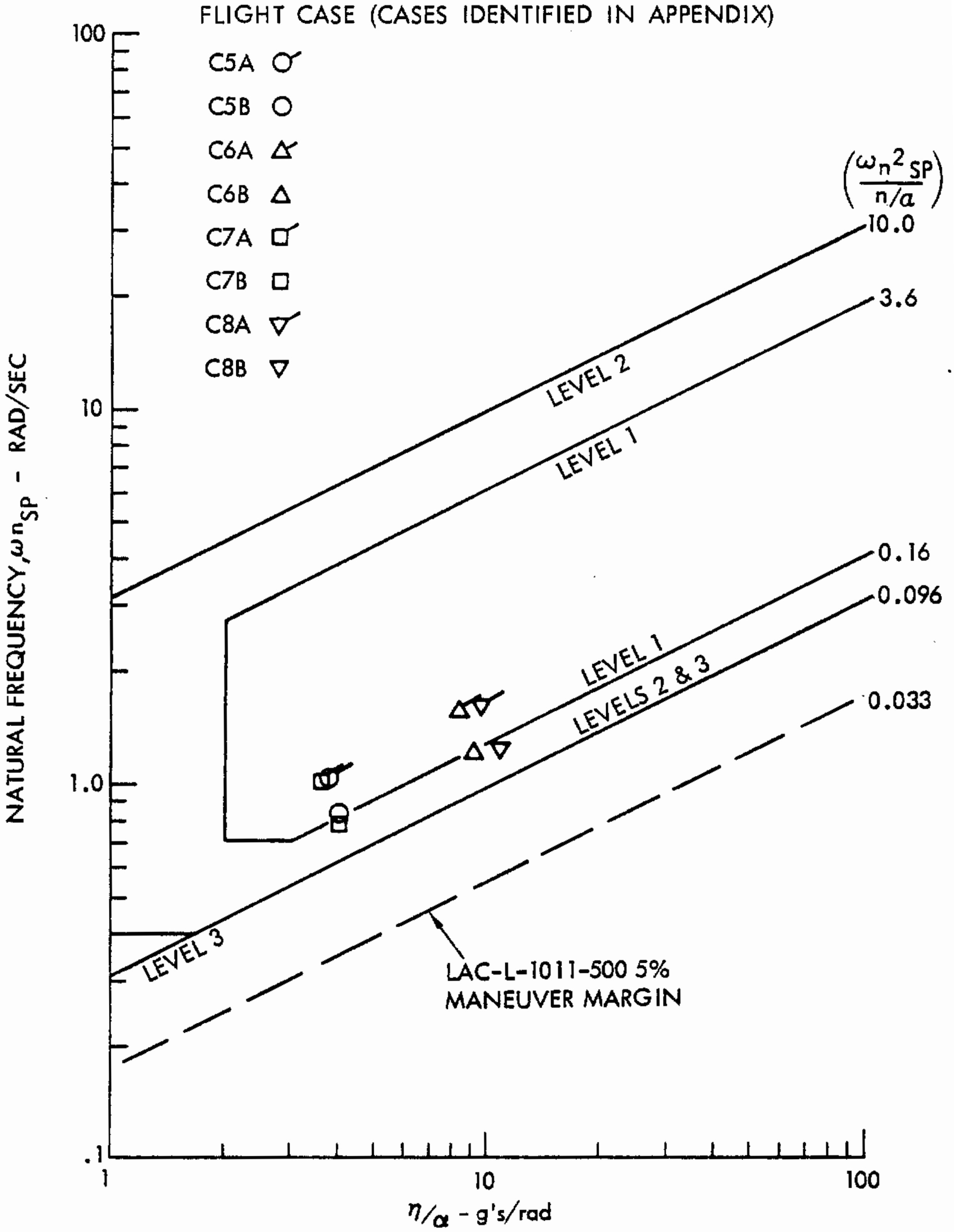


Figure 35 Category C Flight Data for the Lockheed L-1011 in Power Approach Configuration

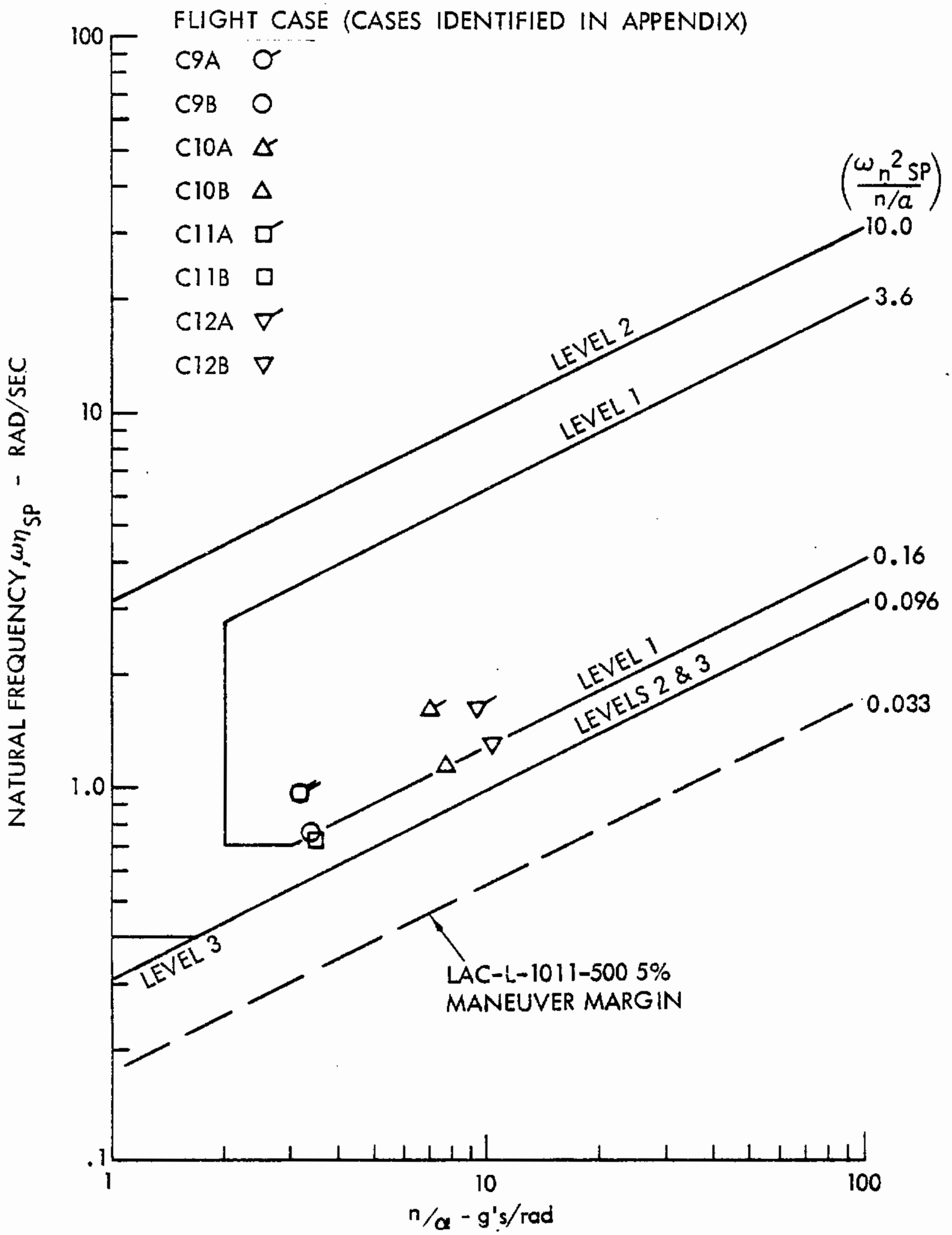


Figure 36 Category C Flight Data for the Lockheed L-1011 in Landing Configuration

SYM	MACH NO.	ALTITUDE (ft)	WEIGHT (kg)	cg (pct c)	ζ TEST	ζ MIL-F-8785B
○	0.32	5,360	108,800	52.7	0.22	0.15

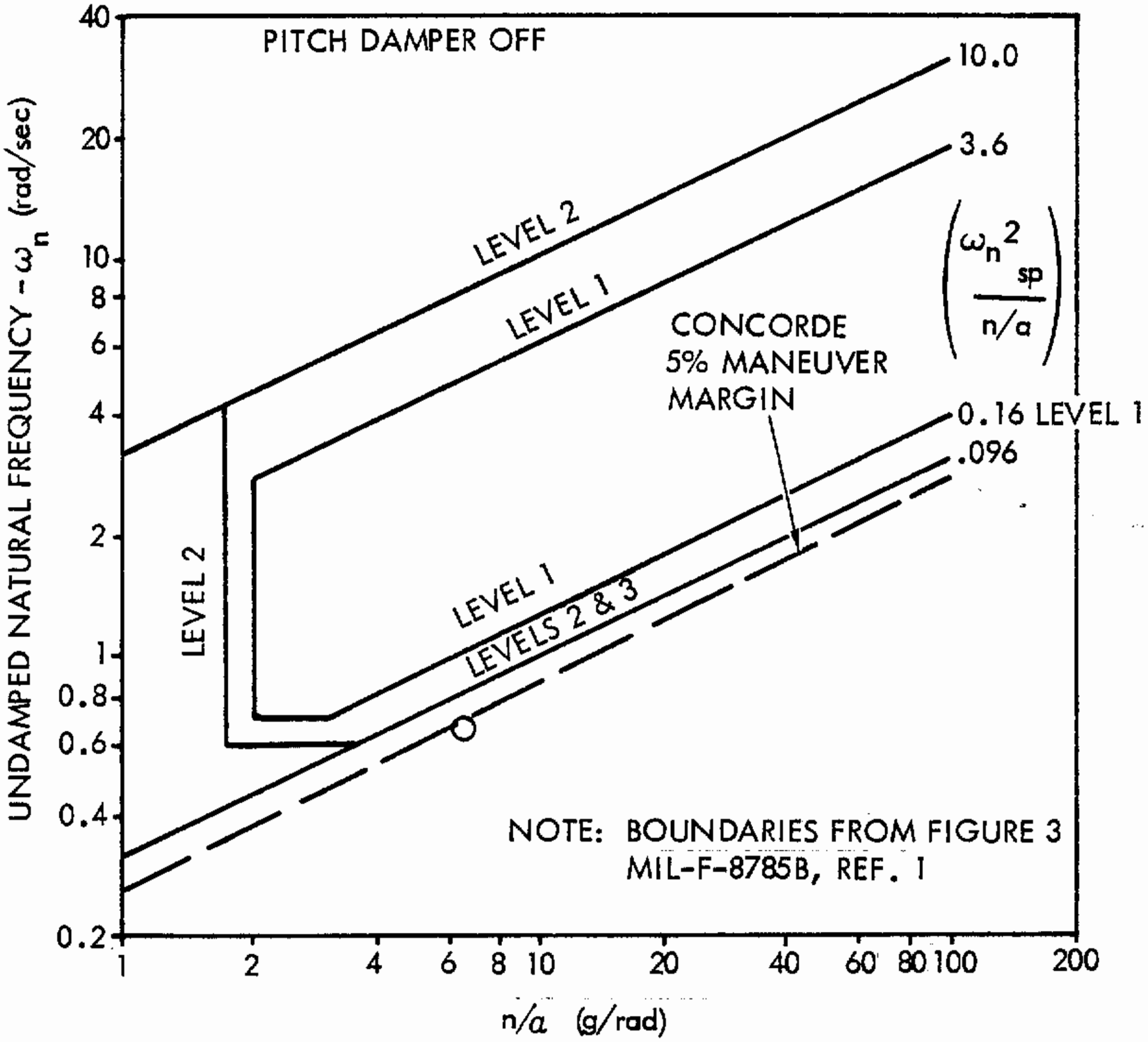


Figure 37 Category C Flight Data for the Aerospatiale France-British Aircraft Corporation Concorde 001

3.2.2.1.2 Short Period Damping

REQUIREMENT

The short-period damping ratio, ζ_{SP}, shall be within the limits of Table 10.

Table 10

Short-Period Damping Ratio Limits

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

* An instability of "no less than six seconds for a time to double amplitude" is permitted for Level 3.

RATIONALE

This criterion helps ensure adequate short period response. The necessity for a damping requirement is obvious. A damping that is too low results in aircraft overshoots and oscillations while the pilot tries to establish a new path. A damping that is too high causes an undesirable sluggish response.

The only change suggested for this requirement is not necessarily for large aircraft. It is intended to make this requirement consistent with the philosophy of allowing relaxed stability (3.2.1.1). As stated in the phugoid section (3.2.1.2), it is difficult to separate the longitudinal response modes into distinct short and long period modes for relaxed stability. Therefore, it should be noted that there may be instances where this requirement has lost its meaning.

GUIDANCE

The data used in Reference 1 to establish the Levels 1 and 2 criteria were the same data discussed in the short period frequency. The only relatively large aircraft data involved was the XB-70 data for Category B flight phases. However, the criteria selected do not seem to present the same problems to large aircraft that the frequency requirement imposed. The representative short period response summary of the C-5A, presented in Table 8, (3.2.2.1.1.) lists the damping ratios of flights in all three categories. These data all fall within the Level 1 boundaries. They are presented as representative data and obviously do not verify the boundaries. They do indicate, however, that the Level 1 boundaries are not excessively restrictive for the C-5A class of airplane.

Reference 1 indicated that there was very little data available to establish the Level 3 boundaries. The data summary did indicate that the damping ratio limits appeared to be "less than .05" for Category A and C and "less than .03" for Category B. The more recent investigations of References 10 and 12, for example, in addition to those listed in Reference 1, have added credence to the time to double amplitude value of six seconds as being not too unconservative. If this is allowed, the short/long period modes as such have lost their meaning. The note to the table is added to state that the requirement no longer exists.

LESSONS LEARNED

Additional large aircraft short period damping ratio data is provided in Table 11. These data are for Category B and C flight phases of the Lockheed L-1011. The cases are identified in Appendix B.

Table 11

Short-Period Damping Ratio from Lockheed L-1011 Flight Data

CATEGORY	CONFIGURATION	CASE	ζ_{SP}	$\omega_{n_{SP}}$ (rad/sec)
B	CLIMB	B1A	.47	1.44
		B1B	.57	1.22
		B2A	.55	2.26
		B2B	.85	1.58
		B3A	.40	1.38
		B3B	.50	1.17
		B4A	.50	2.38
		B4B	.77	1.65
		B5A	.35	1.32
		B5B	.48	1.08
		B6A	.46	2.49
		B6B	.33	1.47
B	CRUISE	B7A	.37	1.63
		B7B	.48	1.31
		B8A	.38	1.36
		B8B	.50	1.48
		B9A	.38	1.09
		B9B	.60	.92
		B10A	.36	1.71
		B10B	.57	1.13
		B11A	.37	1.32
		B11B	.58	.76
		B12A	.36	1.62
		B12B	.56	.93
		B13A	.36	1.29
		B13B	.78	.65
		B14A	.35	1.57
		B14B	.76	.76
		B15A	.28	.77
		B15B	.72	.53
B	DESCENT	B16A	.44	2.19
		B16B	.79	1.32
		B17A	.46	2.18
		B17B	.66	1.43
		B18A	.50	2.23
		B18B	.30	1.50
		B19A	.49	1.59
		B19B	.80	1.05
		B20A	.53	1.60
		B20B	.30	1.12
		B25A	.55	2.36
		B25B	.85	2.00
C	TAKE-OFF	C1A	.44	1.04
		C1B	.51	.94
		C2A	.44	1.43
		C2B	.51	1.26
		C3A	.51	1.03
		C3B	.70	.79
		C4A	.50	1.64
		C4B	.66	1.32
C	POWERED APPROACH	C5A	.48	1.04
		C5B	.63	.83
		C6A	.48	1.52
		C6B	.66	1.18
		C7A	.51	1.00
		C7B	.70	.77
		C8A	.51	1.60
		C8B	.72	1.21
C	LANDING	C9A	.49	.95
		C9B	.64	.75
		C10A	.47	1.60
		C10B	.63	1.12
		C11A	.55	.90
		C11B	.73	.73
		C12A	.54	1.57
		C12B	.73	1.25

3.2.2.1.3 Residual Oscillations

REQUIREMENTS

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 accelerations at the pilot's station greater than ± 0.5g will be considered excessive for any flight phase, as will pitch attitude oscillations greater than ± 3 mils for Category A flight phases requiring precise control of attitude. These requirements shall apply with the pitch control fixed and with it free.

RATIONALE

The primary purpose of this requirement is to prevent limit cycles in the control system or structural oscillations which might compromise tactical effectiveness, cause pilot discomfort, etc. No specific change in the requirement is suggested.

GUIDANCE

Very little data pertinent to this requirement - specifically for large aircraft - is available. References 2, 3 and 19 compare three large aircraft to the specification with no objections to this requirement. Discussions and the search for data have produced differences of opinion, however.

Reference 22)b reported on B-1 experience related to the specification. It reported that even though the early version of the B-1 "satisfied 3.2.2.1.3 requirements", pilots commented on inability to make small, precise pitch changes". Elimination of the residual oscillation solved the problem in the B-1 and may be the only answer for acceptable flying qualities."

3.2.2.2.2 Control Motions in Maneuvering Flight

REQUIREMENT

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 speed shall not be less than 5 pounds per inch for wheel and center-stick controllers for Levels 1 and 2.

RATIONALE

The purpose of this requirement is to call attention to the fact that required control motions to maneuver can be objectionably large or small. Since Category A flight is by nature a precision task sometimes requiring rapid control inputs, there is an attempt to quantify the force required for movement.

The change suggested in this requirement is the deletion of the "2.0 pounds per degree for side stick controllers." Recent experiments for side arm controllers in large aircraft have shown data contradictory to this requirement. Since it appears that insufficient data exists to substantiate a quantified value for side stick controllers in large aircraft, it is suggested that the requirement be deleted rather than having an erroneous requirement.

GUIDANCE

This requirement as stated in 8785B and substantiated in Reference 1 appears to be satisfactory for large aircraft. Reference 1 recognized that the "major differences in the desired maneuvering forces between fighter airplanes and transports are due to the type of controller, in addition to airplane class." Stick force gradients have thus been separated into those for center stick and wheel controllers. The requirement, in terms of motion, is for an average gradient of pitch-control force per unit of pitch-control deflection to be not less than 5 pounds per inch for wheel and center-stick controllers. Flight data for the C-5A, P3V and L-1011 were compared against this criterion in References 2, 3 and 19, respectively. The results tend to substantiate the requirement in all cases, in that the requirement is met and the gradients are judged satisfactory.

The requirement of 2.0 pounds per degree for side stick controllers has been deleted. Figure 38, from Reference 39, shows results from a large transport flying qualities experiment using a side stick controller. The experiment was conducted on a fixed base simulator using experimental test pilots with landing from a localizer offset as the task. The aircraft model of a one million pound class vehicle had been previously tested with a center stick controller by the same pilots for the same task. These data are considerably below the level required in 8785C (one-half pound vs two). That experiment used Reference 40 as a guide for initial gradients. The 2.0 pounds per degree requirement was based on Reference 41, an investigation of a fighter's side-stick force-deflection characteristics. In the discussion of justification for the criterion, Reference 11 selected the 2.0 pounds but noted that the design requirements guide, Reference 40, would give 1 pound per degree.

Reference 39 suggests that forces for side stick controllers be stipulated in relation to physical hand movement such as the 5 pounds per inch listed in the requirement. The data used in Reference 40 had a calculated fulcrum of slightly over 4 inches (gradient was presented as force per degree and per inch). Fulcrum, as defined here, is the distance from the pivot point to the center of pressure of the hand grip, which is considered to be approximately 1/2 to 1/3 from the top. A common gradient in force per "degree" of stick force deflection would require 7/4 times as much force to move the hand an equivalent distance with the short fulcrum as it would for the long fulcrum.

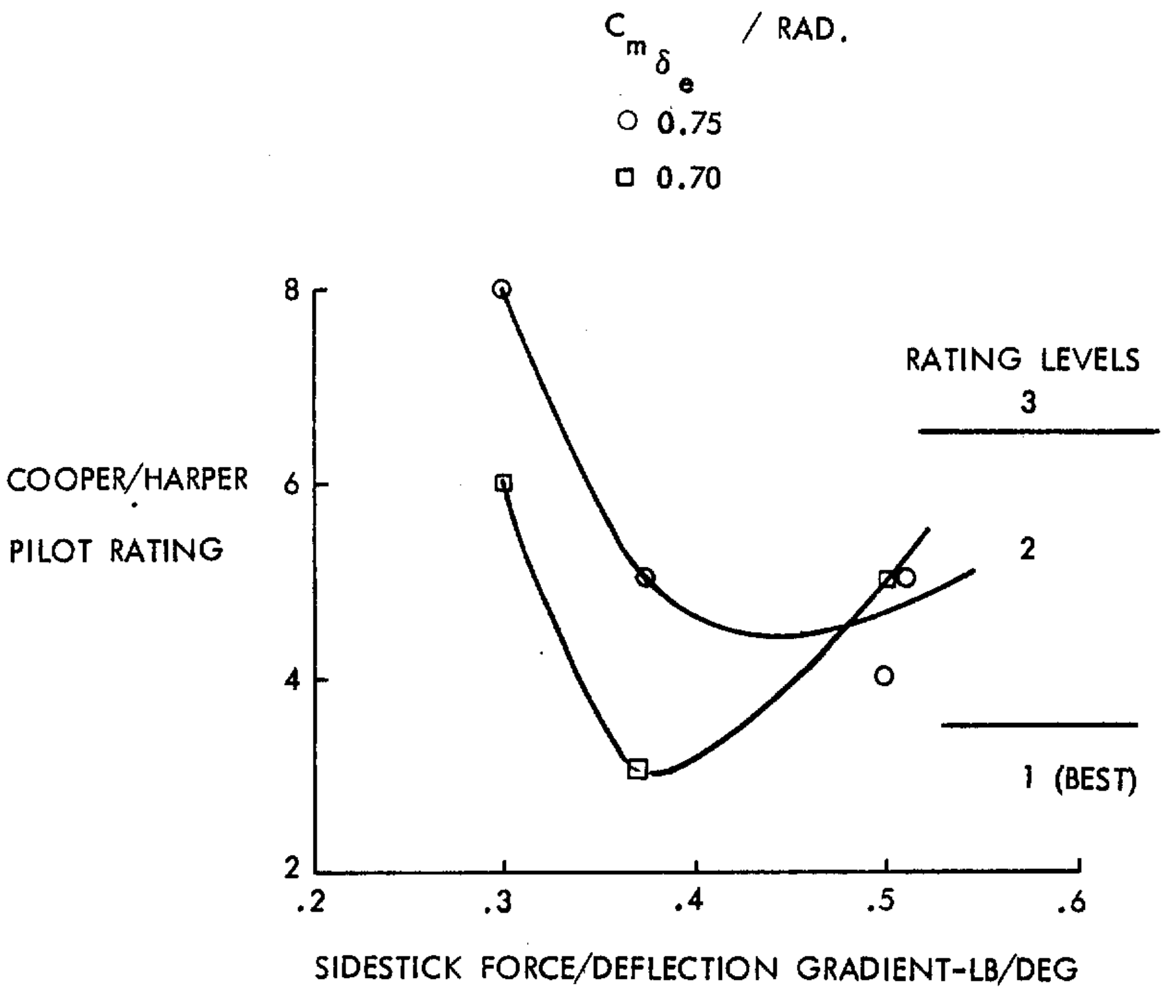


Figure 38 Pilot Rating vs. Longitudinal Stick Force/Deflection Gradient (Reference 39)

3.2.3.2 Longitudinal Control in Maneuvering Flight

REQUIREMENT

Within the Operational Flight Envelope, it shall be possible to develop, by use of the elevator control alone, the following ranges of load factors:

Levels 1 and 2 --- $n_o(-)$ to $n_o(+)$

Level 3 ---

"The elevator shall be capable of providing a load factor of 1.5 g's against the most adverse stabilizer trim position at the design dive speed."

RATIONALE

The purpose of this requirement is to assure that ample control is available throughout the flight envelope. The Levels 1 and 2 requirement, therefore, require that the airplane have the capability of meeting the stated operational envelope. The intent of the Level 3 requirement is to insure that adequate control is available to recover from a condition imposed by a mistrim from pilot error or system failure.

GUIDANCE

The Level 1 and 2 requirements have not changed. They are applicable for Class III aircraft as well as all others. The requirements for Level 3 in 8785C call for a Class III aircraft to arbitrarily be able to pull 2.0 g's with a mistrim of 15% in speed (or 50 knots, whichever is less) throughout the envelope. Reference 2 suggested that the 2 g requirement for a Class III airplane (which is commonly a 2.5 g maximum airplane) was unduly restrictive. In addition, the requirement, as stated, did not protect against the realistic condition of a full adverse mistrim which could occur with a trim system runaway. The change suggested is adapted from Reference

2. It requires that sufficient control be available to recover from the maximum adverse trim at design dive speed. The 1.5 g load factor is considered sufficient for a recovery.

3.3.1.1. Lateral-Directional Oscillations (Dutch Roll)

REQUIREMENT

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 12. 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 nonlinear 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.

RATIONALE

This requirement is an attempt to prohibit annoying lateral-directional oscillations. The required minimum Dutch roll damping is to limit the oscillations of the Dutch roll after it has been excited. A minimum damping ratio, ζ_d, governs the cycles to damp. A minimum total damping, $\zeta_d \omega_{n_d}$, governs the time to damp. The minimum frequency limit, ω_{n_d}, limits the excursion due to a disturbance and ensures a natural return to equilibrium that is rapid enough. These are the basic intentions stated in Reference 1. Unfortunately, for Class III aircraft, there were practically no data in the low frequency region of 1 rad/sec or lower. Table 13, from Reference 2, for augmentation off on the C-5A, which was rated Level 2 at the worse cases, shows the entire flight envelope to be composed of that region. Reference 2 concluded that the C-5A data tend to support the Level 1 boundaries, but show Level 2 to be too stringent. Reference 3 compared a P3B against these requirements and concluded that the entire Dutch roll damping should be reconsidered. It suggested a relaxation of Level 1 for some of its Category A missions - in particular visual ground attack.

Table 12

Minimum Dutch Roll Frequency and Damping

Flight Phase		Min ζ_d*	Min $\zeta_d\omega_{n_d}$* rad/sec.	Min ω_{nd} rad/sec.
Level	Category			
1	A	0.19	0.35 **	0.4**
	B	0.08	0.10 **	0.4**
	C	0.08	0.10**	0.4**
2	ALL	0.02	0.05**	0.4**
3	ALL	0	—	0.4**

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

** Class III airplanes may be excepted from the minimum ω_{n_d} and $\zeta_d\omega_{n_d}$ 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 $\omega^2_{n_d}/\phi/\beta/_d$ is greater than 20 $(\text{rad/sec})^2$, the minimum $\zeta_d\omega_{n_d}$ shall be increased above the $\zeta_d\omega_{n_d}$ minimums listed above by:

Level 1 - $\Delta\zeta_d\omega_{n_d} = .014(\omega^2_{n_d}/\phi/\beta/_d - 20)$

Level 2 - $\Delta\zeta_d\omega_{n_d} = .009(\omega^2_{n_d}/\phi/\beta/_d - 20)$

Level 3 - $\Delta\zeta_d\omega_{n_d} = .005(\omega^2_{n_d}/\phi/\beta/_d - 20)$

with ω_{n_d} in rad/sec.

Table 13

C-5 Dynamic Lateral - Directional Stability Summary

CONFIGURATION	WEIGHT (Lbs)	ALTITUDE (Ft)	C_L	ζ	PERIOD (Sec)	$1/C_{1/2}$	ω_{n_d} (Rad/Sec)
(CR)	HEAVY	10,000	.81	.10	10.4	0.90	.601
(CR)	HEAVY	10,000	.28	.13	7.8	1.17	.793
(CR)	HEAVY	26,000	.43	.055	8.5	0.50	.732
(CR)	HEAVY	26,000	.245	.110	6.5	1.0	.954
(CR)	HEAVY	26,000	.73	.03	10.0	.25	.624
(CR)	LIGHT	10,000	.20	.195	6.8	1.8	.899
(CR)	LIGHT	25,000	.73	.080	10.2	.75	.610
(CR)	LIGHT	25,000	.205	.12	6.0	1.05	1.03
(CR)	LIGHT	35,000	.73	.030	11.0	.30	.567
(CR)	LIGHT	35,000	.32	.10	7.0	.90	.885
(D)	HEAVY	10,000	.58	.155	10.0	1.45	.616
(D)	HEAVY	26,000	.55	.05	10.0	.50	.623
(L)	HEAVY	10,000	.89	.14	8.5	1.25	.726
(L)	HEAVY	10,000	1.56	.10	10.0	.94	.621
(L)	HEAVY	10,000	1.72	.10	10.5	.90	.591
(L)	LIGHT	10,000	1.35	.095	9.0	.85	.689
(L)	LIGHT	10,000	1.67	.105	8.0	.98	.775
(TO)	HEAVY	10,000	.78	.055	7.0	.50	.889
(TO)	HEAVY	10,000	1.49	.085	9.5	.75	.653
(TO)	MEDIUM	10,000	1.72	.110	10.2	.95	.608
(TO)	MEDIUM	10,000	1.035	.055	8.5	.50	.732
(TO)	MEDIUM	10,000	1.53	.09	9.0	.80	.690
(TO)	MEDIUM	10,000	1.53	.105	11.0	.95	.563

Although more data applicable to large aircraft are now available, there is still insufficient data to properly establish the true levels of frequency and damping, or even to verify that minimum values of those parameters are indeed the proper ones. Reference 1 noted that the more closely the low frequency data were examined, the more difficult it became to assess the importance of low Dutch roll frequency per se. The conclusion of Reference 2, that additional data are needed, is still valid.

Since the values listed in Table 12 are not truly substantiated, it is suggested that the total damping and the frequency minimum values be excepted by the procuring activity with verification by pilot opinions that the aircraft meets the various levels. The table is retained since it still may serve as a guide. The other change suggested is that the Category B Level 1 total damping minimum be reduced to 0.10 rad/sec. Reference 11 reduced this boundary for Classs II-L and III airplanes considering the relatively new data of References 42 and 43 as sufficient justification. It seems inconsistent that the Category B boundary be more stringent than Category C, therefore the B boundary was reduced to at least the C level. Some additional substantiation of the change is also included.

GUIDANCE

Although lateral-directional flying qualities metrics are difficult to isolate, data indicate that Dutch roll damping, ζ_d, Dutch roll natural frequency, ω_{n_d}, and the total damping, $\zeta_d \omega_{n_d}$, sometimes expressed as a function of $\omega^2_{n_d} |\phi/\beta|_d$, correlate well with pilot ratings, hence defining suitable criteria for this mode.

Higher Dutch roll data frequencies ($\omega_{n_d} > 2.5$) show pilot rating correlates strongly with Dutch roll damping, ζ_d. Lower frequency data, characteristic of large aircraft, show that ratings correlate better with total damping, $\zeta_d \omega_{n_d}$.

While not specifically addressed here, it is intended that equivalent values of frequency, damping and time delay be used for augmented airplanes. Due to the limited amount of work done to develop lower-order equivalent systems for the Dutch roll response, guidance in this area is limited. For most airplanes, an appropriate lower-order equivalent system for sideslip response to a rudder input is simply:

$$\frac{\beta}{F_{rp}} = \frac{K_{\beta}\, e^{-\tau_{e\beta} s}}{s^2 + 2\ \zeta_{n_d} \omega_d s + \omega_d^2}$$

Hence, for cases where $\tau_{e\beta}$ is small, simple measurements from a time response of sideslip to rudder kick will frequently be sufficient. Limits on the effective time delay are specified in 3.5.3.

Additional complications arise when $|\phi/\beta|_d$ is large and a significant portion of the Dutch roll response occurs in roll. This has been studied with empirically developed formulas for total damping, $\zeta_d\ \omega_{n_d}$. Studies using those expressions indicate that an incremental increase in the required total damping is necessary when $\omega^2_{n_d}|\phi/\beta|_d > 20$. This additional increment has been left in the requirement since no large aircraft data were found which could substantiate or refute it.

Most large aircraft to date have had low values of $|\phi/\beta|$, i.e., < 2.0. Sideslip control, therefore, assumes prime importance. The pilot uses rudder to control the sideslip and achieve precise heading control. In these cases, with low frequencies, the frequency and damping values become important as performance parameters rather than indicators of simply a nuisance mode. If roll rate or aileron control excite sideslip, the flying qualities are typically degraded by such motions as an oscillation of the nose on the horizon during a turn, a lag, or initial reversal in yaw rate during turn entry. In addition, the pilot cannot damp Dutch roll oscillations through the use of aileron control. There is a reasonably large data base of lateral-directional parameters which have been systematically varied for several types of aircraft. These are well documented, especially in summary reports such as References 1 and 32. Due to the fundamental nature of this requirement, the results are possibly generic to a wide variety of aircraft. However, most of the experiments did not enter the operating range of large aircraft parameters. Figures 39 through 43 contain data specific to large aircraft.

The low frequencies noted for one large aircraft in Table 13 are further substantiated in Figure 39. This plot of existing airplane Dutch roll data from Reference 1 (acquired from Reference 54)shows the change in trend with aircraft size. The requirement boundaries for Level 1 make it obvious that almost all large aircraft will require lateral-directional augmentation.

Figure 40 contains large aircraft data from a Category C simulation of a supersonic transport. These data are reported in Reference 32 as support for the boundaries. Since these data were from a moving-base simulator, they were corroborated by Figure 41 which compares flight and simulation pilot ratings of damping ratio, frequency and $(\omega_\phi / \omega_d)^2$. The major difference between simulation and flight appeared to be an insensitivity to $(\omega_\phi / \omega_d)^2$ ratio in flight tests. The lack of good, solid data for this Category C was noted and, therefore, only mild support is provided for the boundaries. The tabulated average of ratings in the three clusters of Figure 40 make it questionable as even mild support.

Category B data for a B-70 is presented in Figure 42. These data, from Reference 35, were compared to criterion of Reference 45 in that report with the conclusion that the boundary defining the "unacceptable" region is too severe in the region of $\omega_d = 1.0$, $\zeta = 0.1$. The 8785C boundaries tend to improve the correlation in that area, but one 3.0 rating is outside that Level 1 boundary. The suggested change in the Level 1 boundary would include the Level 2 pilot ratings. The data do not necessarily support the Level 1 boundary, however.

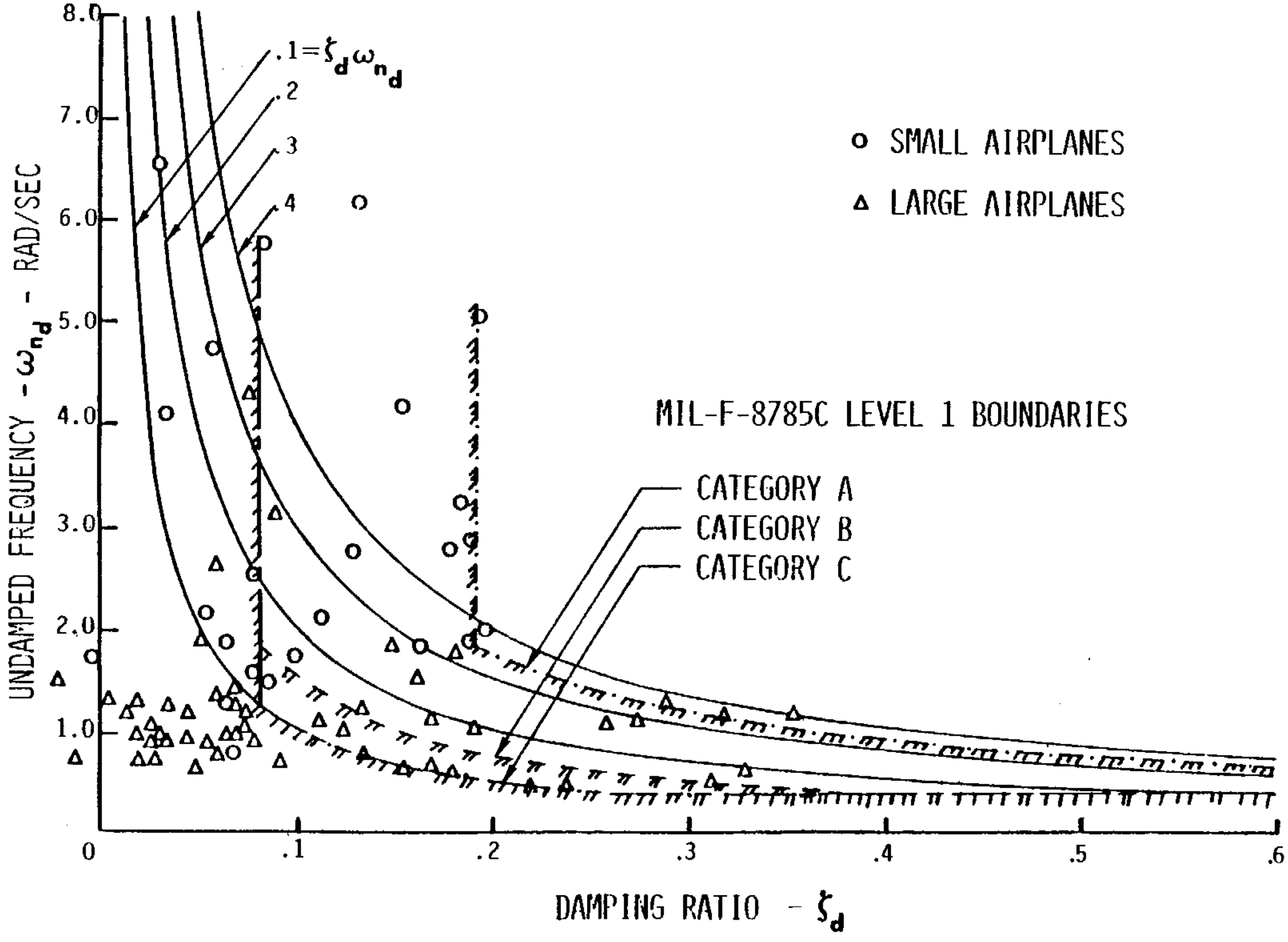


FIGURE 39. DUTCH ROLL DATA ON EXISTING AIRPLANES (REFERENCE 1)

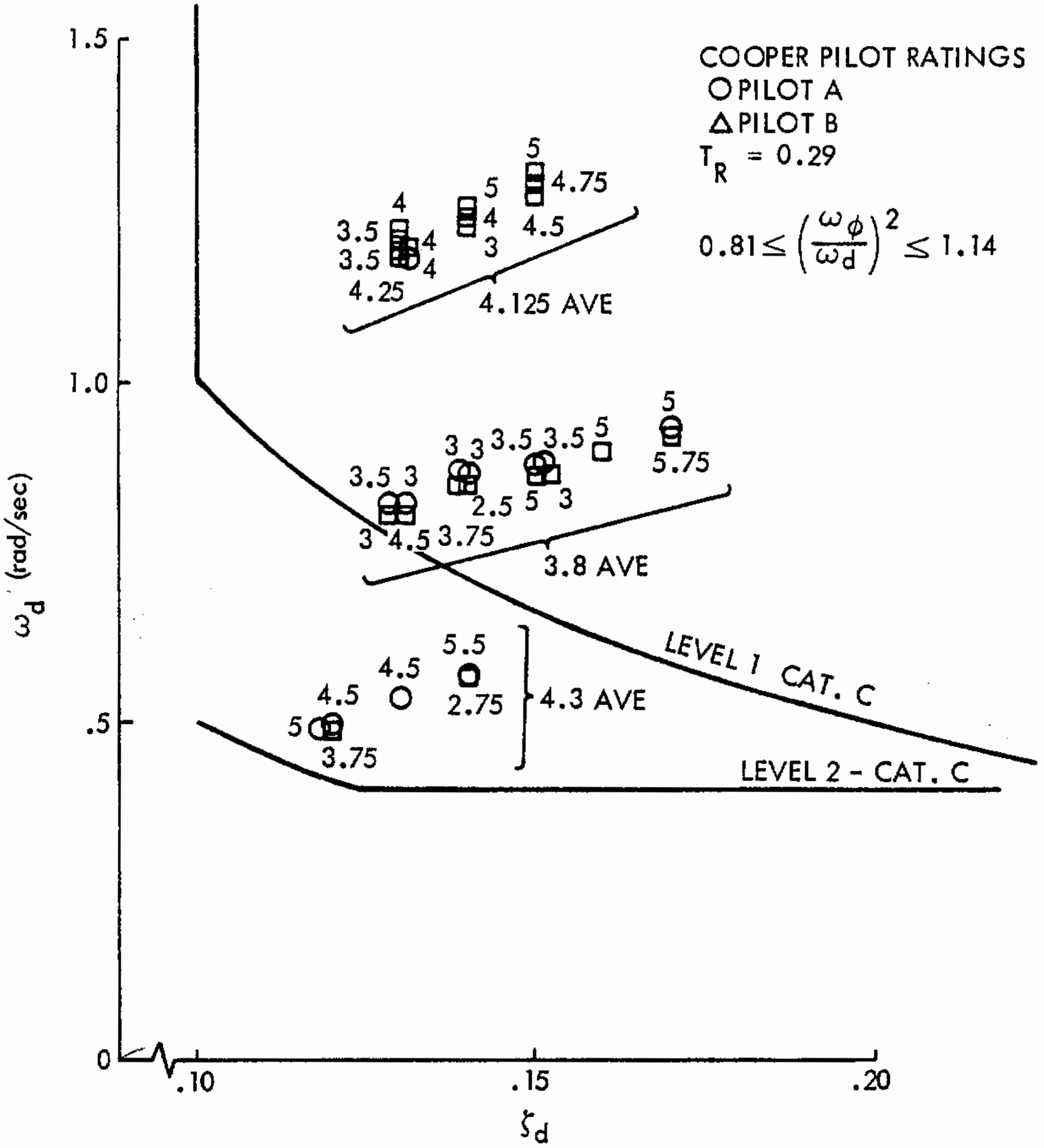


Figure 40 Dutch Roll Data from Moving-Base Category C Simulator Test - Supersonic Transport Study (Reference 44)

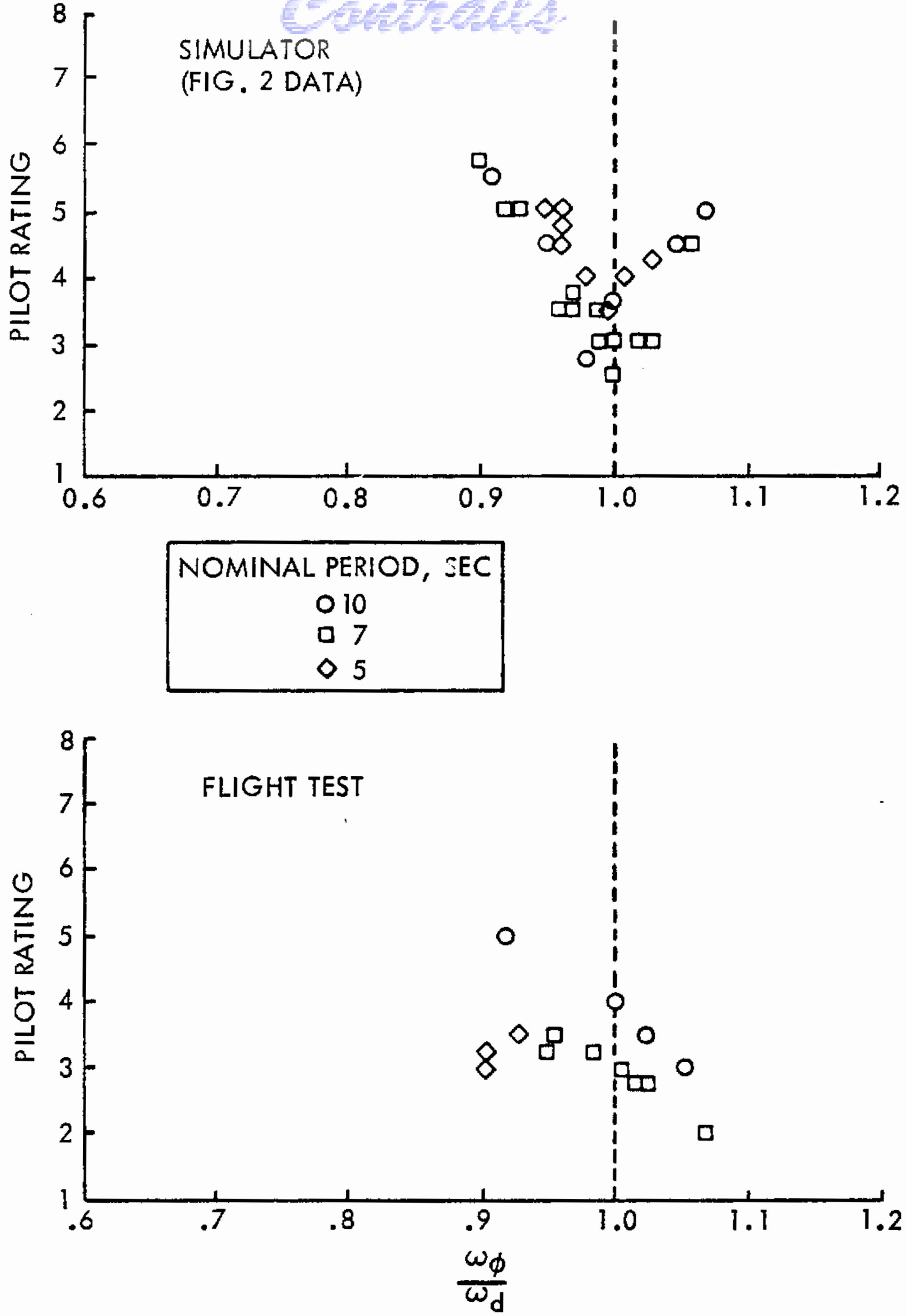


Figure 41 Comparison of Pilot Ratings Results for In-Flight and Simulator Experiments - Supersonic Transport Study (Reference 44)

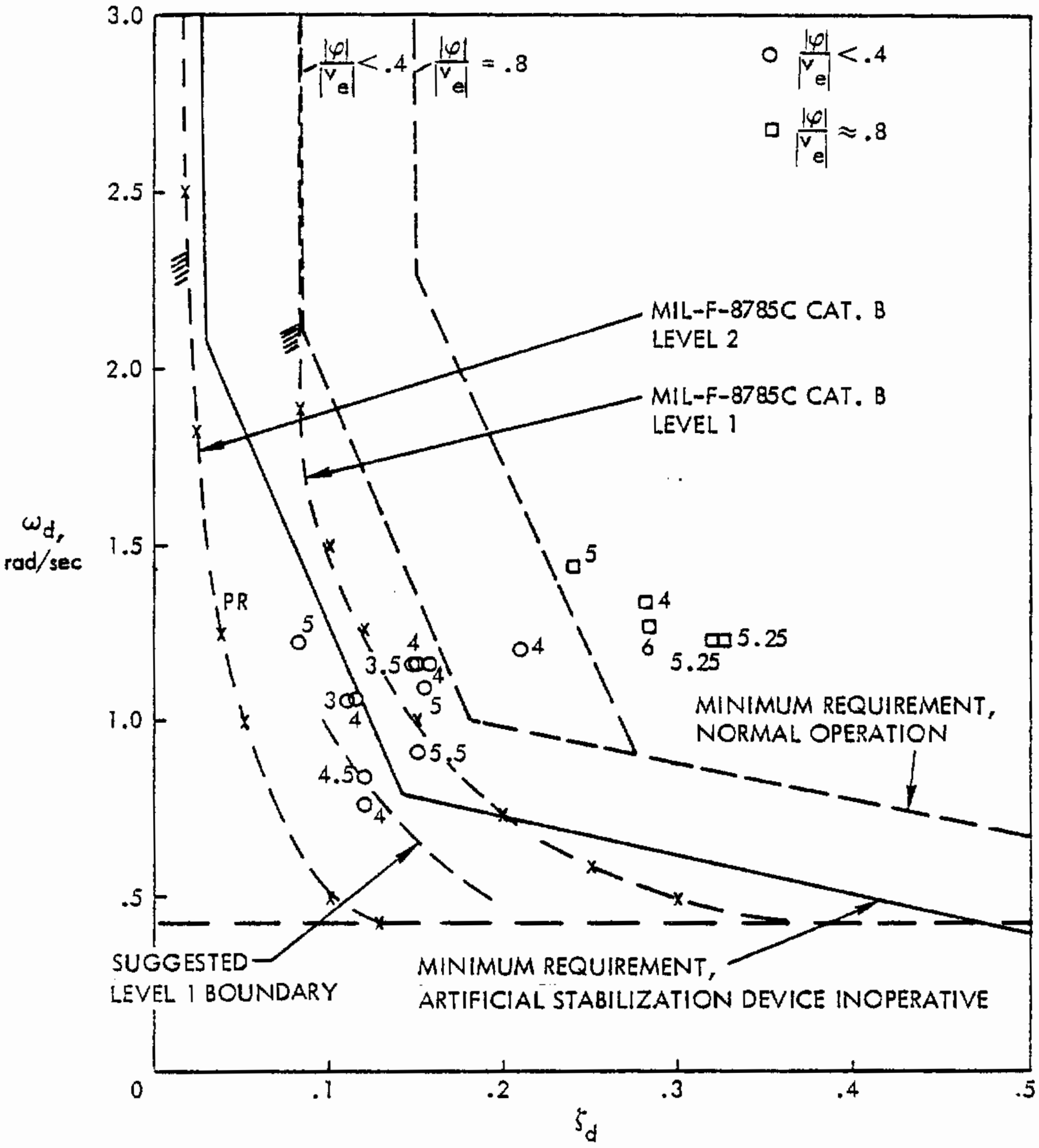
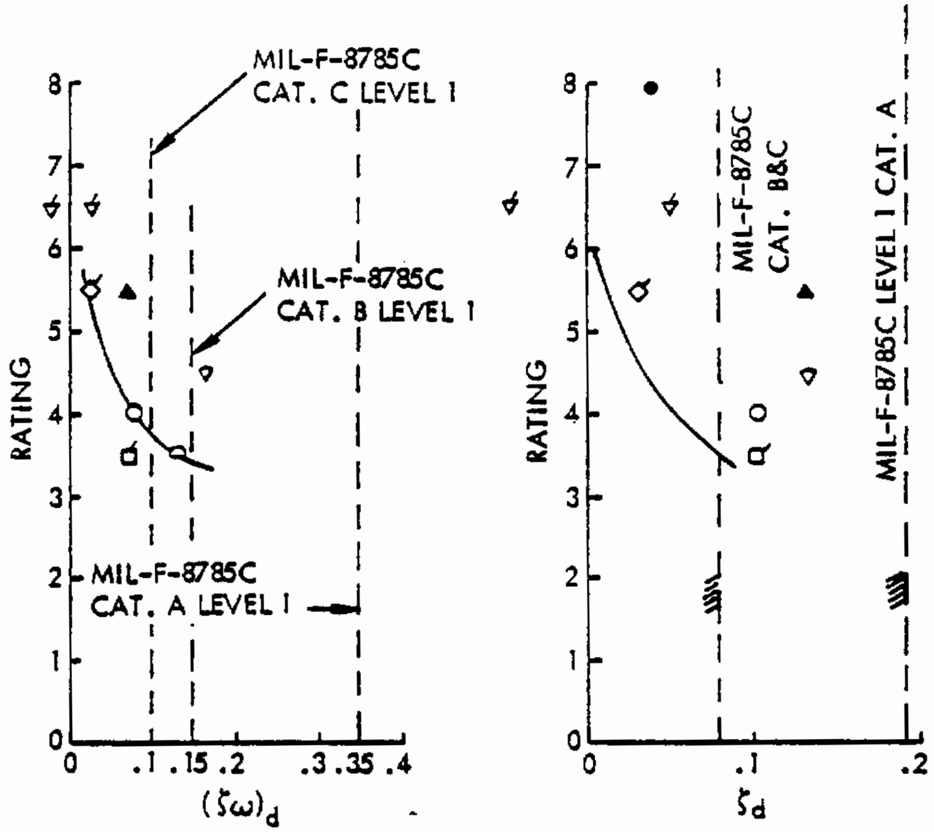


Figure 42 Comparison of Category B XB-70 Lateral - Directional Flight Ratings with Reference 45 and 8785-C Criterion



SYMBOL	REF	AIRPLANE	ω_d
○	47	BREGUET 941	.74
▲	48	C-130B	.5
◇	49	RB-52C	.7
□	50	C-133B	.7
▽	51	KC-135A	.8
⬭	52	F4D	UNREPT'D
▽	53	YC-134A	1.16

—— REF. 46 DATA (FIG.3) RAISED ONE RATING POINT

NOTE: FILLED SYMBOL DENOTES "ABNORMAL" CONTROL PROBLEM

FLAGGED SYMBOLS DENOTES RATING BY AUTHOR ON BASIS OF RECORDED VERBAL COMMENTS

Figure 43 Total Damping and Damping Ratio as Correlation Parameters

Figure 43 is a compilation of mostly large aircraft data found in Reference 55. These data from the various sources were compared with a correlation curve from Reference 46. The main point made with this plot was to show the much better data correlation of pilot rating with total damping than with damping ratio alone. In addition, the location of the Level 1 rating of 3.5 can be noted along with the effect of the suggested change to make Category B, as well as C, have the same requirement.

LESSONS LEARNED

The following data are included in this section as additional large aircraft data. They are from aircraft which are considered to be Level 1, or at are least Level 2 with augmentation. These data used in conjunction with a systematic variation of the parameters in a simulation study could help establish the true boundaries. The claim of Level 1 for the C-5A data points is further substantiated in Appendix A.

Figure 44 presents Category B lateral-directional damping flight data from Reference 22)a for the C-5A, C-141A, YC-141B and L-1011. The conclusion of that report was that the Level 2 requirement of total damping to be at least .05 is too stringent for the Level 2 boundary. The C-141 was reported to have pilot ratings of 2.0 to 5.0 based on Air Force Flight Test Center studies, Reference 56, which included over 100 Dutch roll maneuvers. Additional Category B data are presented in Figure 45 for the L-1011. These data (Reference 19) are for augmentation on and meet the 8785C requirements.

Figure 46, from Reference 2, shows C-5A data for Category B flight in cruise and descent configurations. Category C flight data are presented for the takeoff and landing configurations. All of these data should be Level 2 as a minimum. Quite a few points violate the low frequency and damping corner.

Additional Category C data are presented in Figures 47 and 48. The L-1011 with augmentation on, in Figure 47, should be a Level 1 airplane. Figure

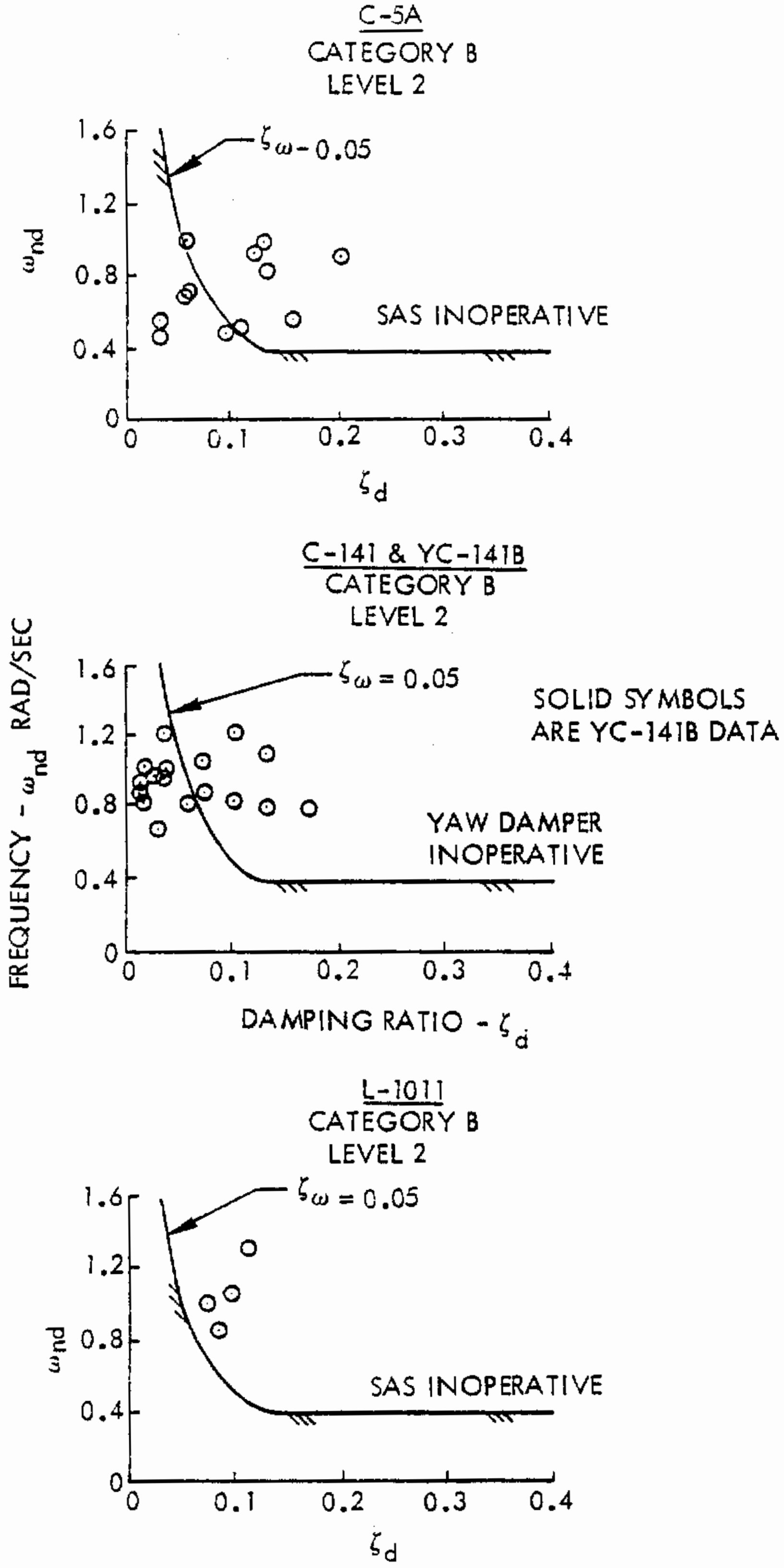


Figure 44 Category B Flight Data of the C-5A, C-141A, YC-141B and L-1011

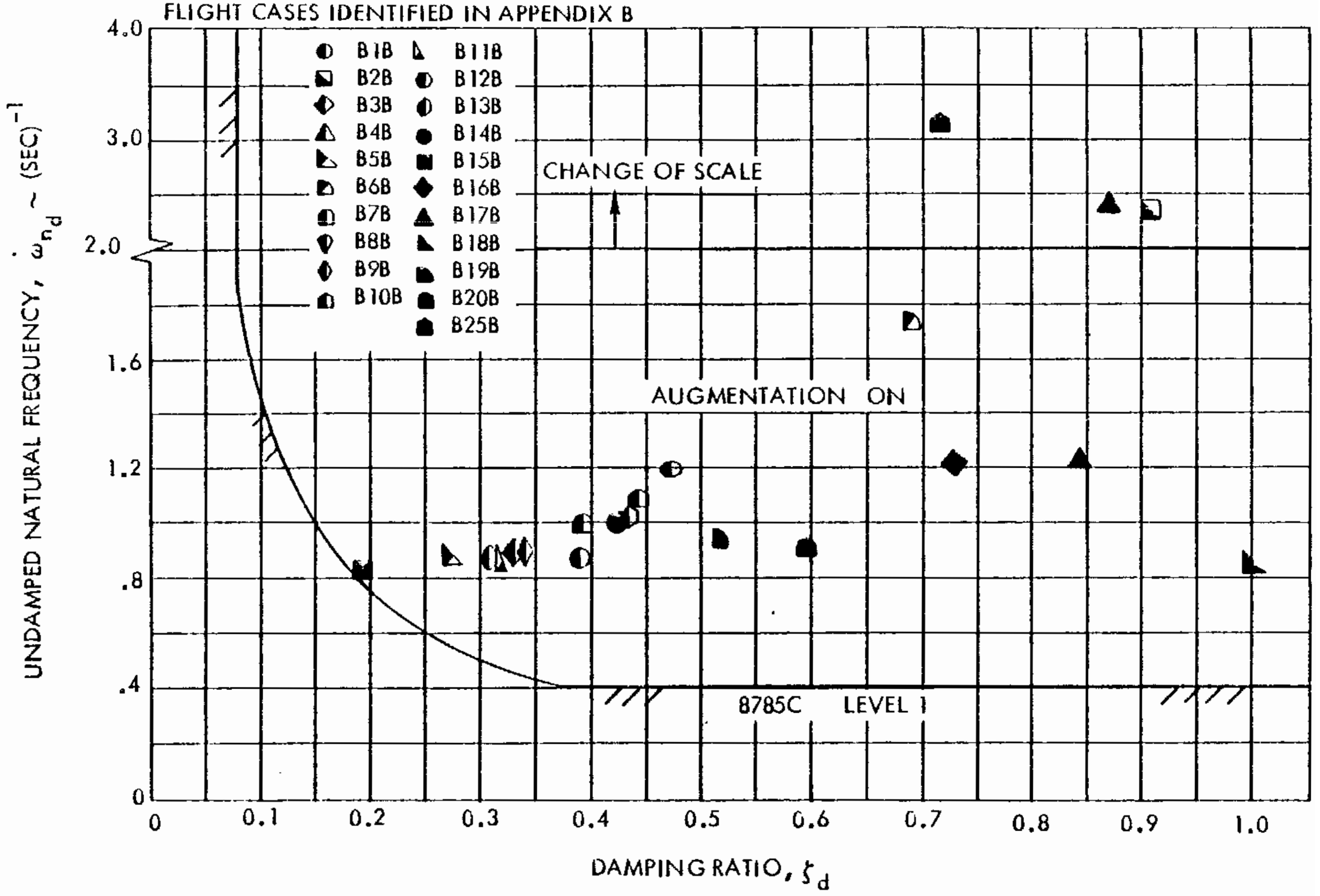


Figure 45 Lateral-Directional Data - Category B L-1011 Augmentation on - Level 1 Rating

C-5A FLIGHT TEST DATA
SAS OFF

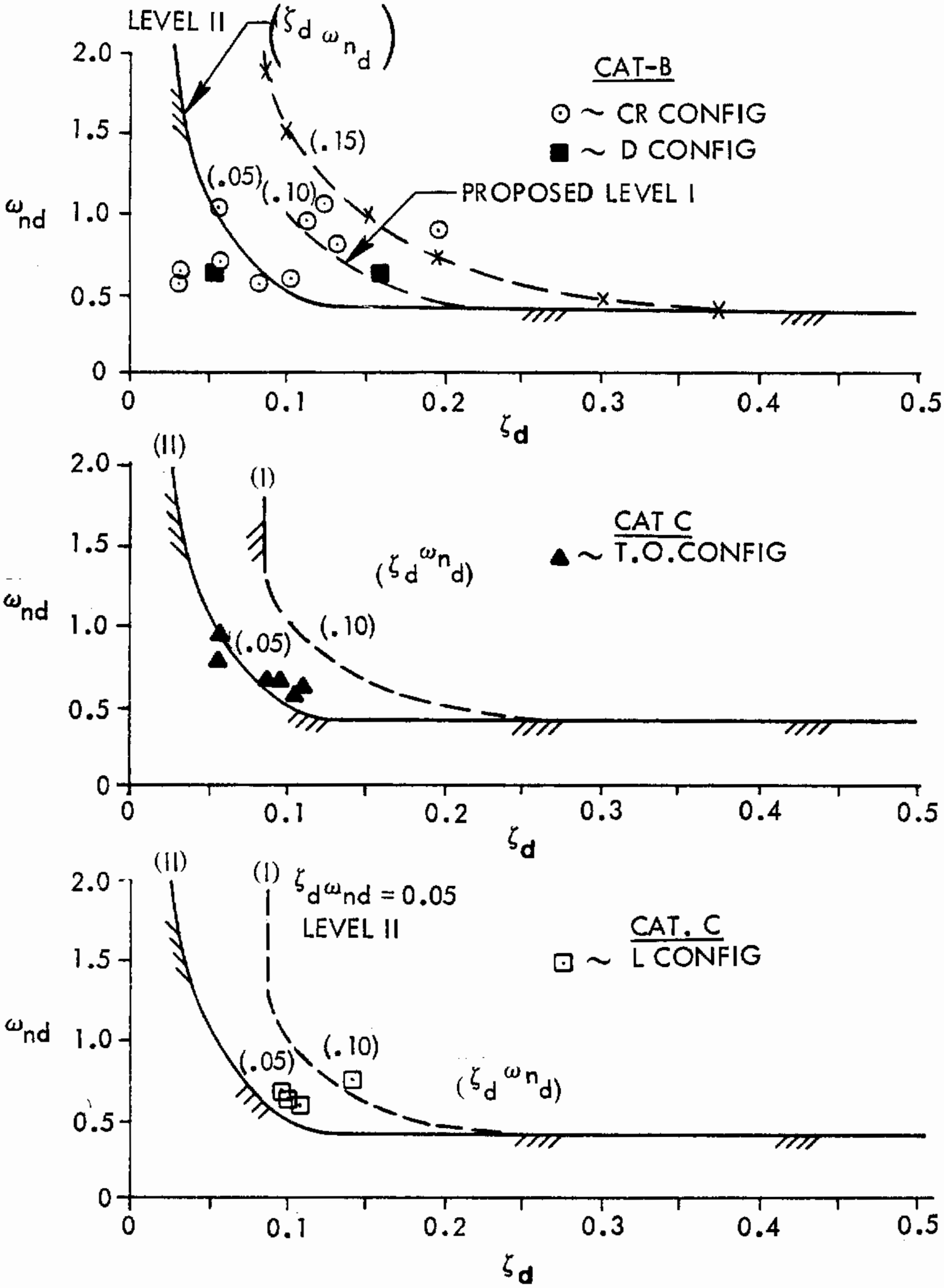


Figure 46 C-5A Lateral Directional Damping Flight Data - Augmentation Off

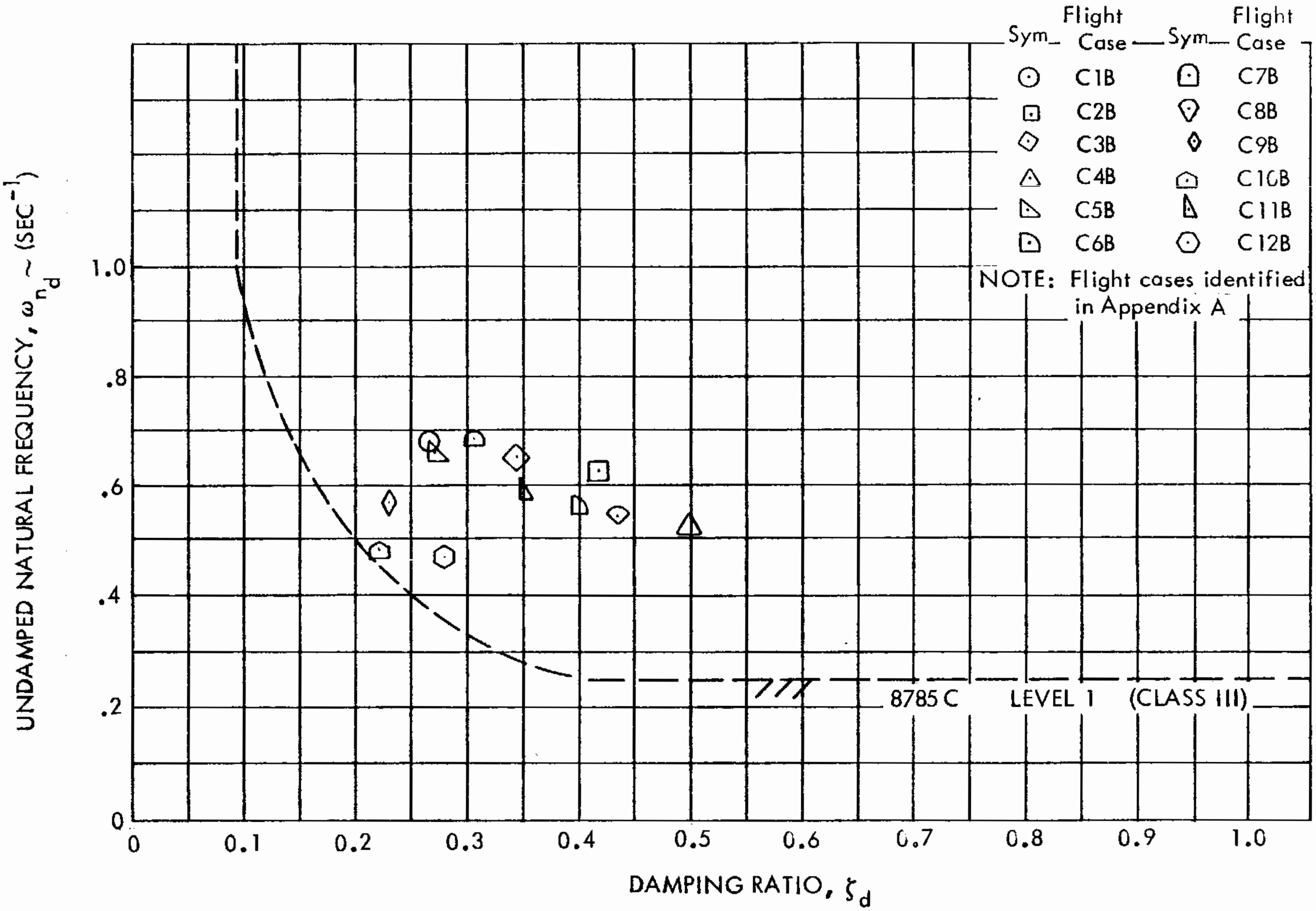


Figure 47 L-1011 Category C Lateral - Directional Data - Augmentation On

48 presents two additional Category C points for the C-5A. The landing point could support going from Level 2 to Level 1 as augmentation goes on. However, the approach case should be at least Level 1 with augmentation on and therefore violates that boundary.

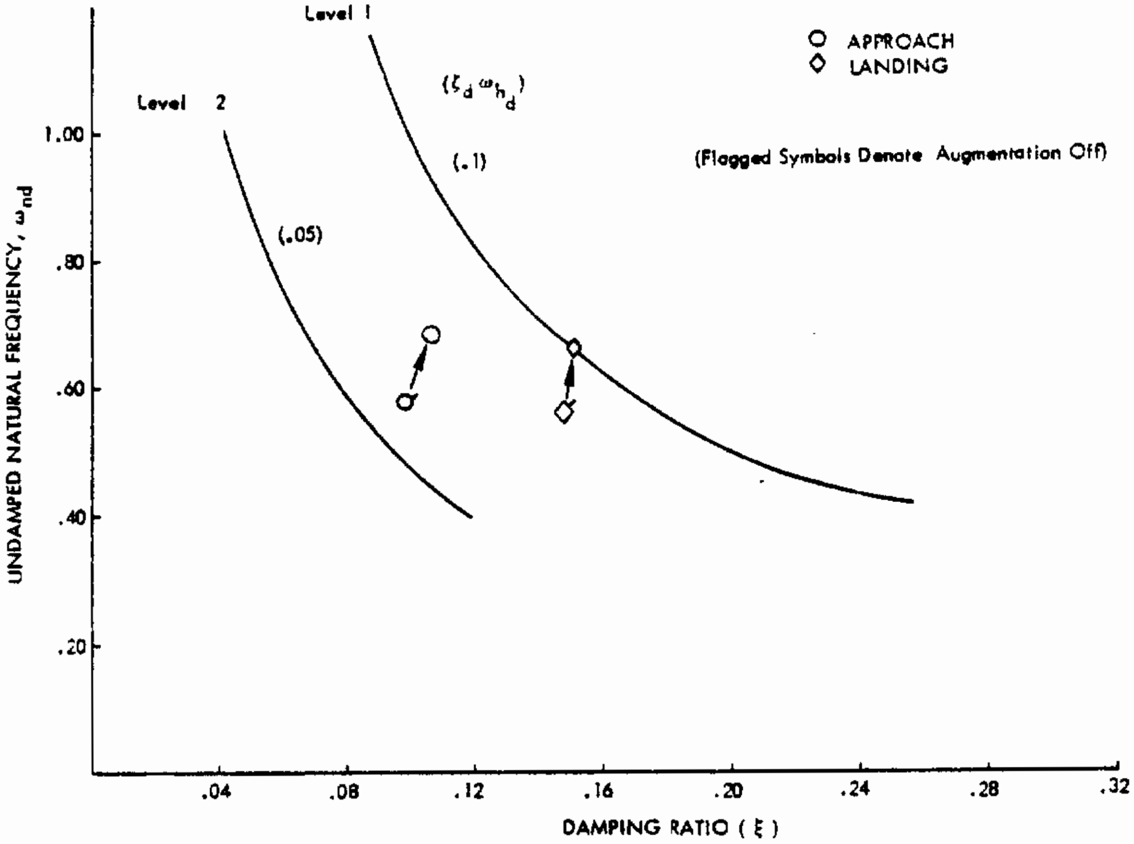


Figure 48 Category C - Lateral - Directional C-5A Data - Augmentation On and Off

3.3.1.2 Roll Mode

REQUIREMENT

The roll-mode time constant, τ_R, shall be no greater than the appropriate value in Table 14.

Table 14

Maximum Roll Mode Time Constant - Seconds

FLIGHT PHASE CATEGORY	LEVEL		
	1	2	3
A	2.3	6.0	10.0
B	2.3	6.0	10.0
C	2.3	6.0	10.0

RATIONALE

The reason for this requirement as stated in Reference 1 is to assure precision of control. Its purpose is to quantify the permissible levels of roll damping and to "shape" initial roll rate response. The reasoning given in Reference 1 continued that "considerable data show that pilot rating is a function of roll damping which can be expressed in terms of the first-order roll mode time constant, τ_R. Therefore, a direct requirement on τ_R was specified."

It is extremely difficult to quantify the many lateral-directional parameters involved to insure that an aircraft will have satisfactory roll characteristics. Experiments can be made on individual parameters while holding others constant to try to obtain the limiting boundaries on each parameter. However, since there are so many interactions and unknown other implications involved with this rationale, it may be better in many instances to state a given mission requirement and not try to quantify parameters. Large aircraft with high inertias have the same problems with lateral requirements that were found with the longitudinal mode. Specifying roll mode time constant will be shown to dictate the ratio of inertia to wing area times span squared. This requirement, therefore, inadvertently dictates physical configurational aspects.

Since this document can only suggest changes to the requirements and not specify the mission, the suggested change in Table 14 is to make the roll mode time constant less restrictive in Level 1 such that the physical configuration of present day large aircraft will not be restricted. Sufficient data exists to justify the change. Those data and the reasoning to raise the Level 1 time constant from 1.4 to 2.3 and Level 2 from 3.0 to 6.0 are presented here.

GUIDANCE

The basic assumption of this requirement is that pilot rating is a function of roll damping. Figure 49 from Reference 1 was used to support this, and during selection of Level 1 it was pointed out that, in general, there is a knee or break in the data at a time constant of 1.0. The trend lines indicated that "for a change in pilot rating from 3 1/2 to 5 1/2, τ_R goes from approximately 1.3 to 3 seconds." This was used to establish a Level 2 boundary. The Level 3 boundary was relatively arbitrary, but was based on fighter data from an ongoing experiment (Reference 61).

Figure 49 data have been replotted in Figure 50 on a linear scale for time constant, rather than a log scale. There are a few interesting conclusions which could be drawn from such a plot. The scatter in pilot ratings for

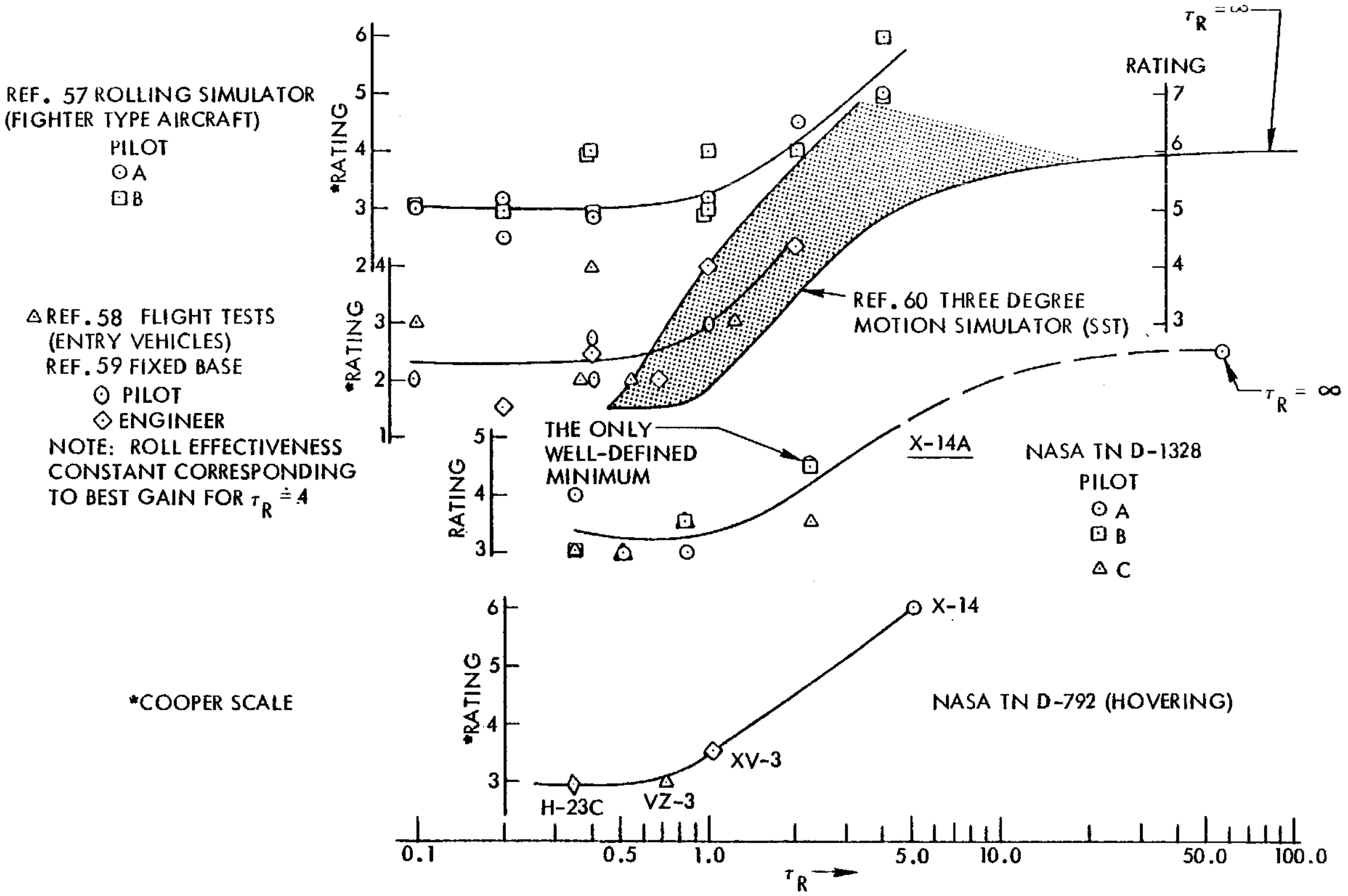


Figure 49 Ratings Versus Roll Damping - Flight Test, Moving Base, Fixed-Base with Random Input

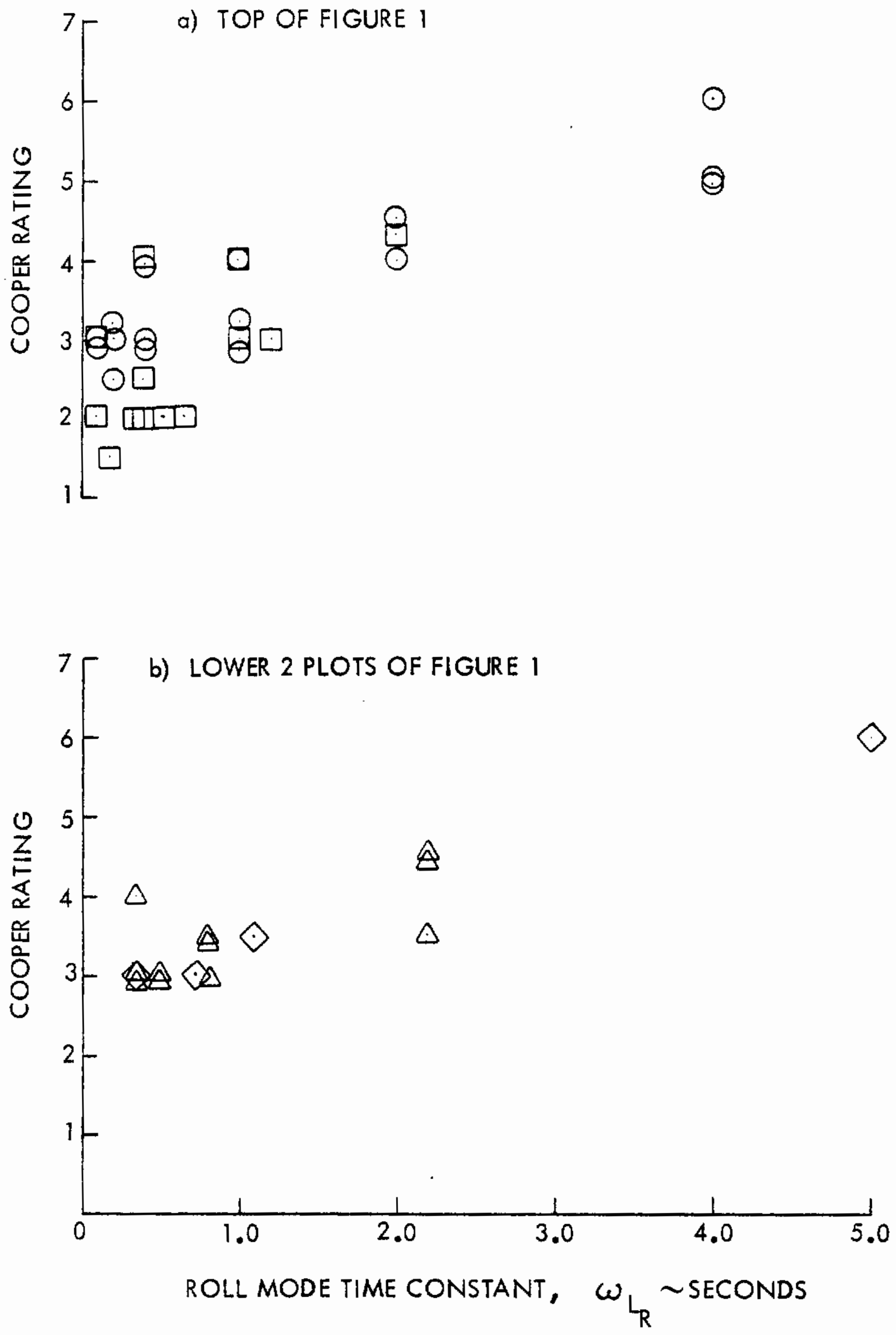


Figure 50 Data of Figure 1 Replotted to Linear Scales

low time constant range of 0 to 1.0 is such that it would be hard to establish a trend from those data. The apparent break in the data at a time constant of 1.0 is not so clearly defined. There are relatively few data points above a time constant of 1.0 to enable one to determine a Level 1/Level 2 boundary.

Figure 51, from Reference 62, shows results of a very large airplane study using the ground-based and in-flight simulator of the Boeing Model 367-80. Those data are intended to show the trend of pilot rating degradation with increasing time constant. Except for the three lower points, however, the remaining 17 points would show no change or trend.

Figures 52 and 53, from Reference 1, show rather extensive data for fixed-base and motion-base studies where time constant was varied from 0.1 to 4.0. Some conclusions one could draw from these data are that the minimum (best) rating achievable did decrease as roll time constant increased, but Level 1 ratings were achievable even at a time constant of 4.0. The important trend appears to be that a proper blend of roll mode time constant and instantaneous acceleration must be established.

A large aircraft study described in Reference 63 resulted in the recommended boundaries of Figure 54. This chart was developed from analysis of the required maneuver for an offset on landing approach. It included data and pilot assessments of lateral maneuverability on nineteen large aircraft with spans from 89 to 142 feet and two with approximately 180 feet (the maximum time constant was 1.8 seconds). That reference suggested time constants of 2.3 and 6.0 for Level 1 and 2 boundaries. Reference 1 decided, however, that "careful examination of the rating terminology definitions indicates that this value of τ_R (2.3) is probably more applicable to the Level 2 than the Level 1 requirements." The analytically developed boundaries appear to be an excellent method for establishing desired performance. This suggested roll criterion, which was adopted in the Concord SST Standards, was used for a comparison with XB-70 lateral-directional flight rating in Figure 55, from Reference 35. Those flight results were considered representative of the cruise or loiter flight

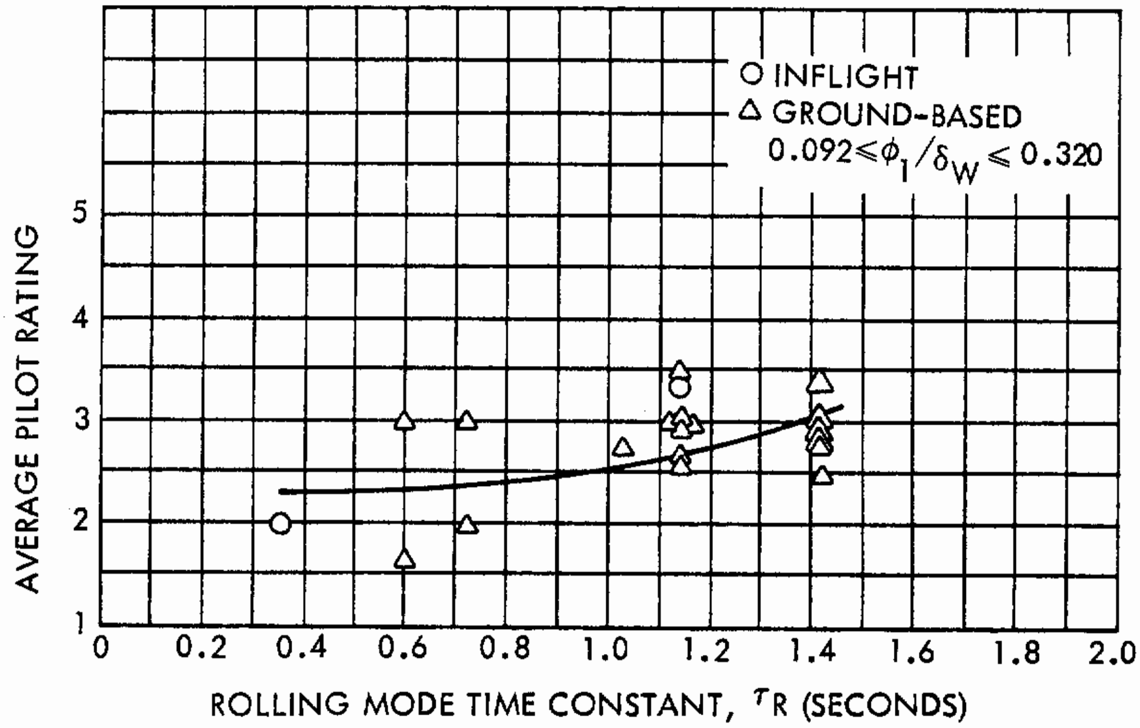


Figure 51 Variation of Pilot Rating with Rolling Mode Time Constant (NASA-CR-635)

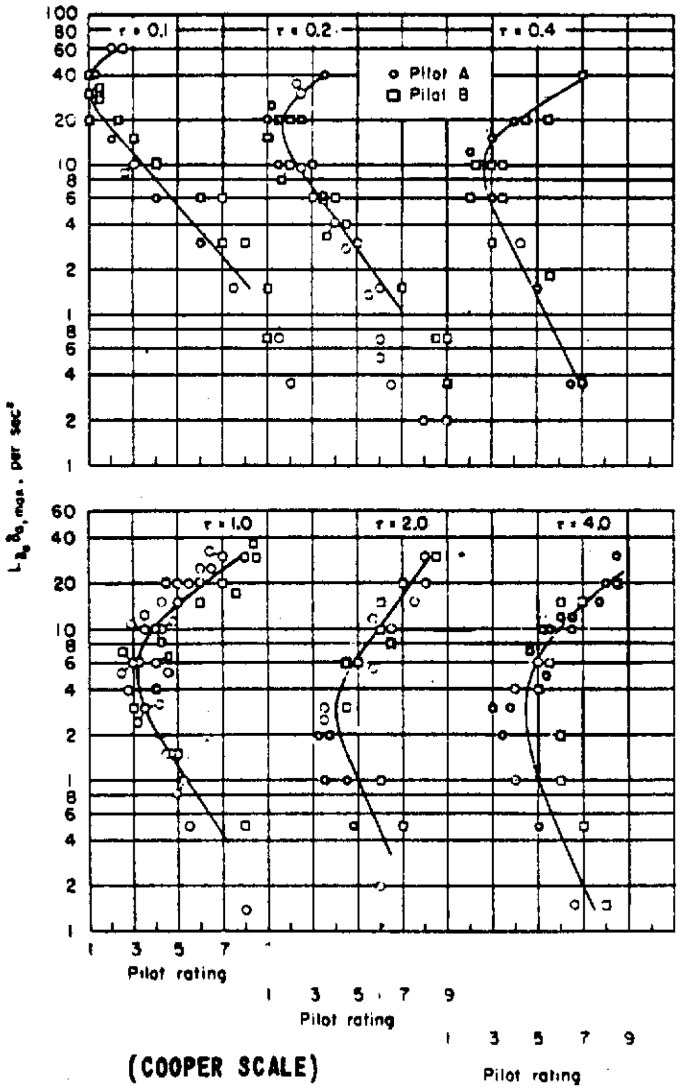


Figure 52 Variation of Pilot Opinion with $L_a \delta a_{max}$, for Constant Values of τ_R as Obtained from the Stationary Flight Simulator (Reference 57)

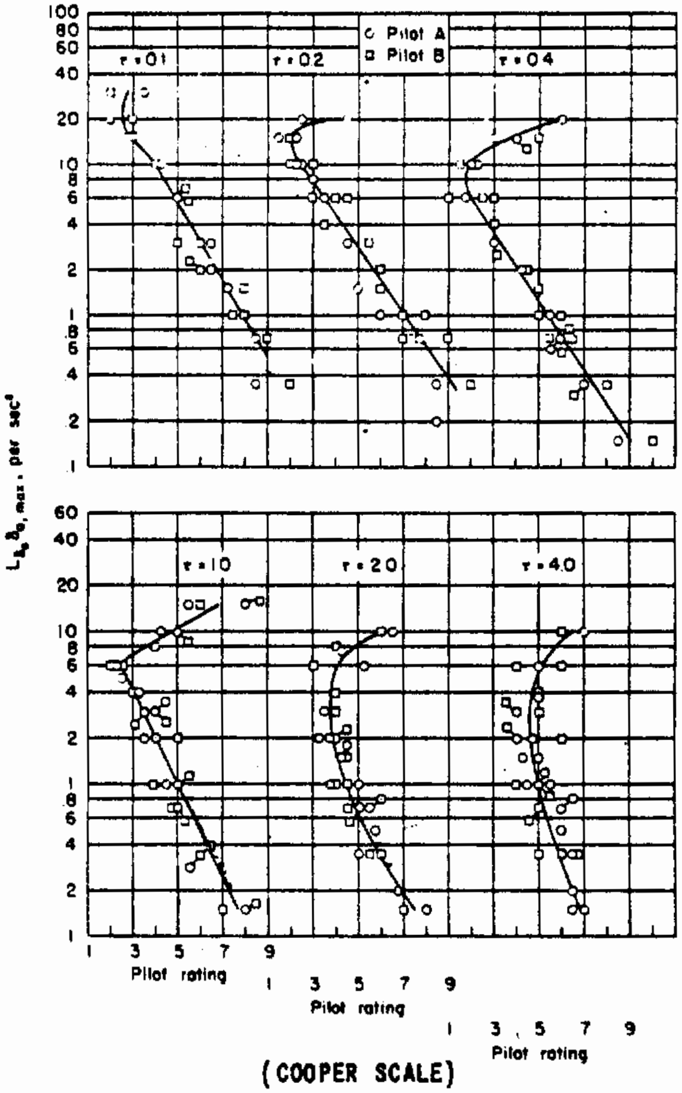


Figure 53 Variation of Pilot Opinion With $L_{\delta_a} \delta_{a\,max}$, for Constant Values of τ_R as Obtained from The Moving Flight Simulator (Reference 52)

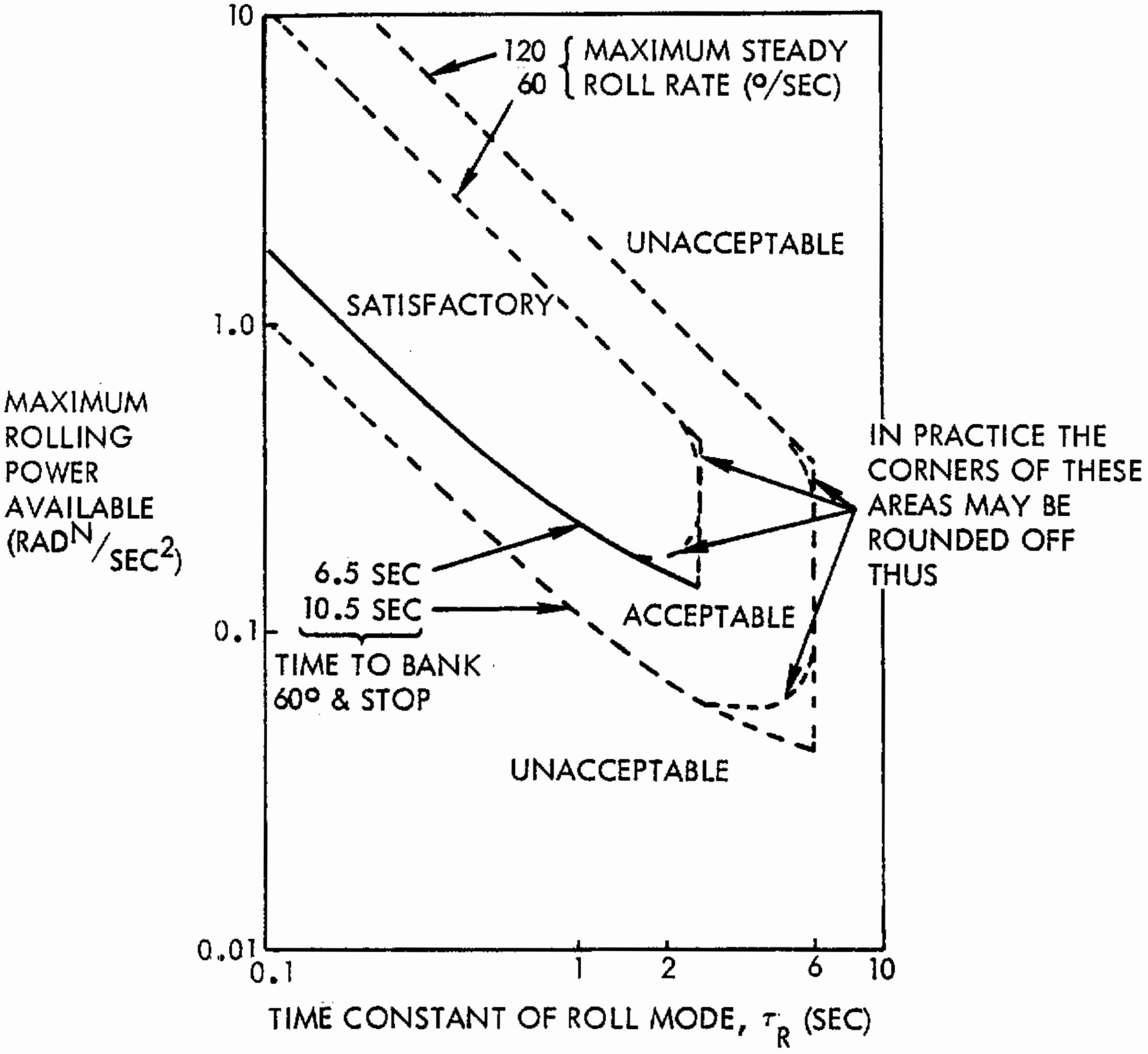


Figure 54 Suggested Roll-Response Boundaries for Large Aircraft - Approach Conditions (Reference 63)

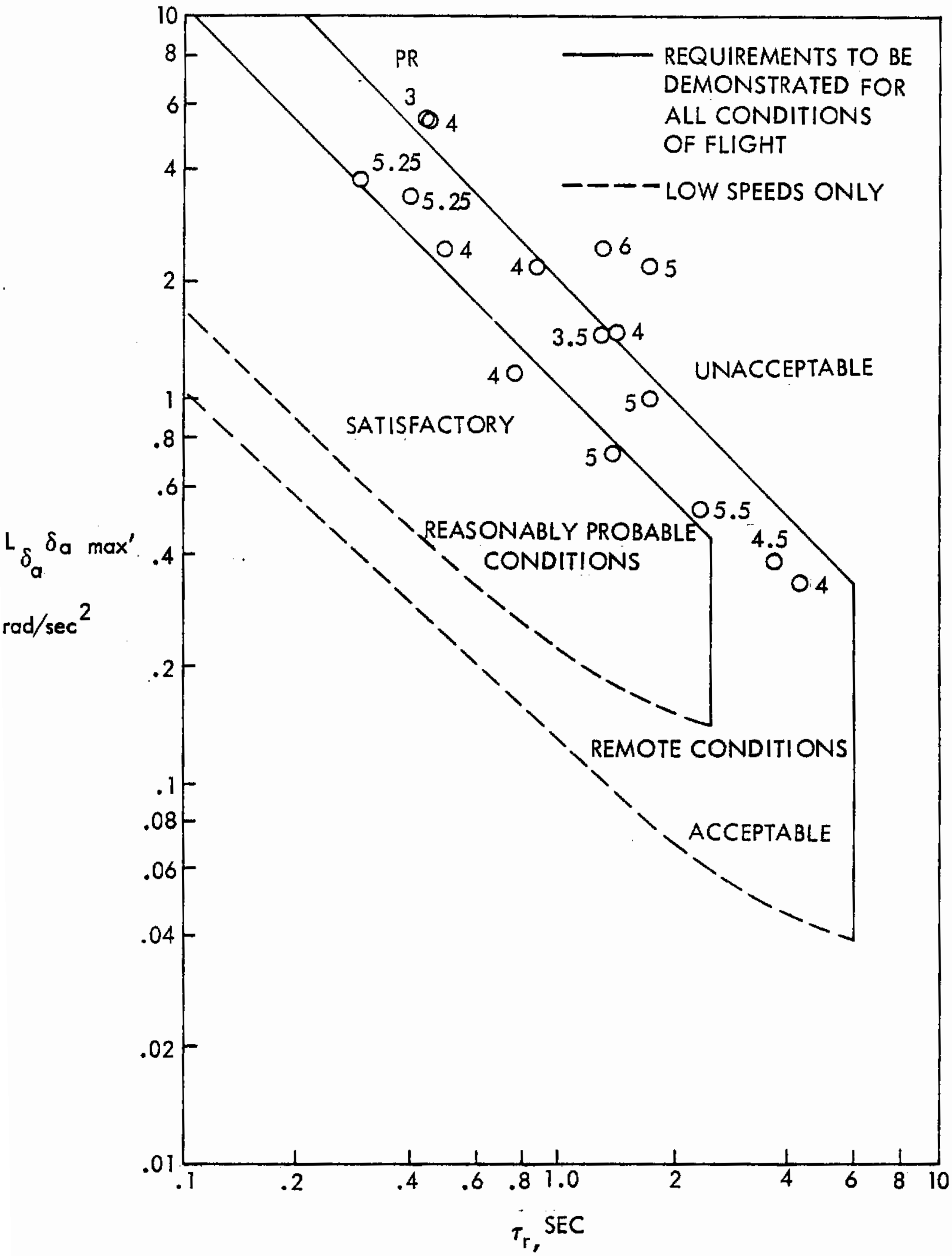


Figure 55 Comparison of XB-70 Lateral - Directional Flight Ratings with the Roll Criterion of Reference 63

regime (Category B). Although the ratings do not substantiate the boundaries, they do substantiate the fact that there is no apparent degradation in pilot rating due strictly to roll time constant-even for values over 4.0.

Reference 1 also showed data from Reference 64 on re-entry vehicles where a satisfactory rating was obtained with a time constant of 5.53. It was concluded that although the re-entry task has many elements of Flight Phase Category B tasks, the duration differs, making those results not directly applicable. It was indicated, however, that those data show that under some circumstances a satisfactory rating can be achieved with a long roll mode time constant.

Flight test data for the C-5A was presented in Reference 2, which compared the roll mode time constant values against the criteria. Figures 56 thru 58 from that reference show Category B and two Category C flight configurations, take-off and landing. These data show points into the Level 3 area yet the aircraft has been substantiated as Level 1 (see Appendix A).

Experimental and flight data from large aircraft thus support the relaxation of the roll mode time constant from the levels of 8785C. It is usually understood that roll damping interacts with such characteristics as roll performance and roll sensitivity. An increase in roll damping or a lower time constant has other implications which can be noted by examining the time constant in terms of airplane physical and aerodynamic parameters.

$$\tau_R \sim -\frac{I_x}{L_p} \tag{16}$$

$$\text{where } L_p = (q\ S\ b)\left(\frac{C_{l_p}\ b}{2V}\right) \tag{17}$$

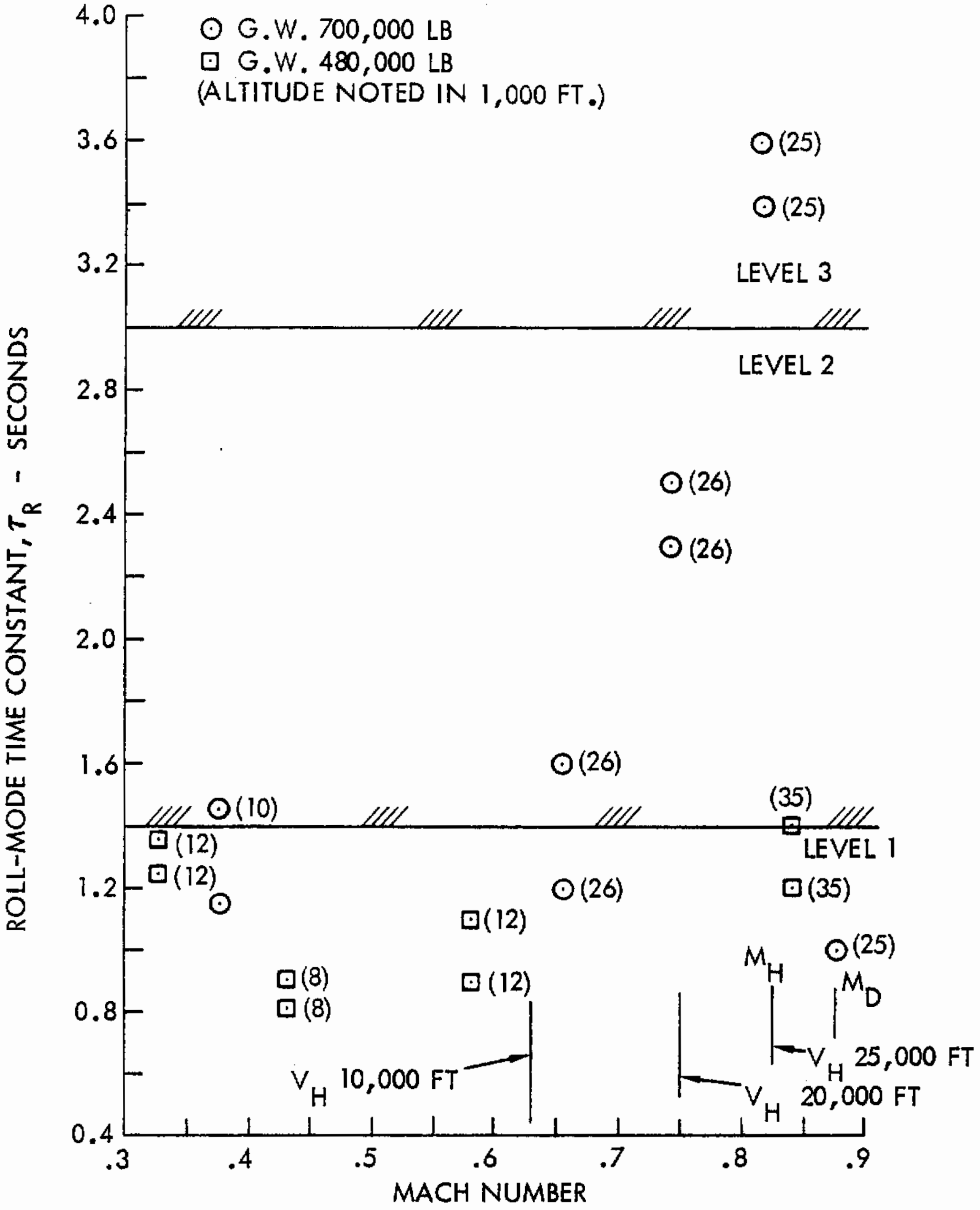


Figure 56 Category B Roll Mode Time Constant Data from C-5A Flight Test (Reference 2)

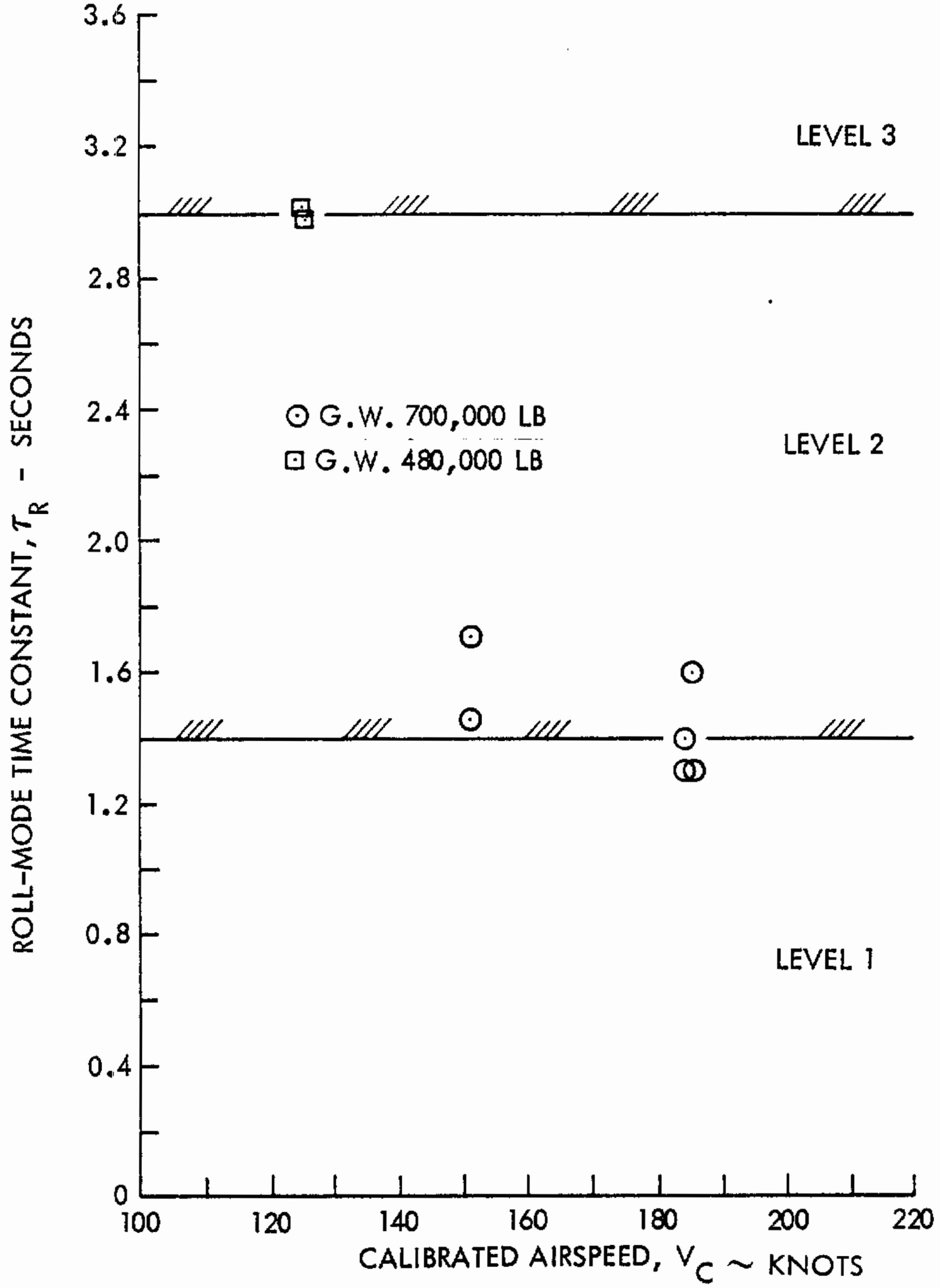


Figure 57 Category C Roll Mode Time Constant Data from C-5A Flight Test - Take-Off Configuration (Reference 2)

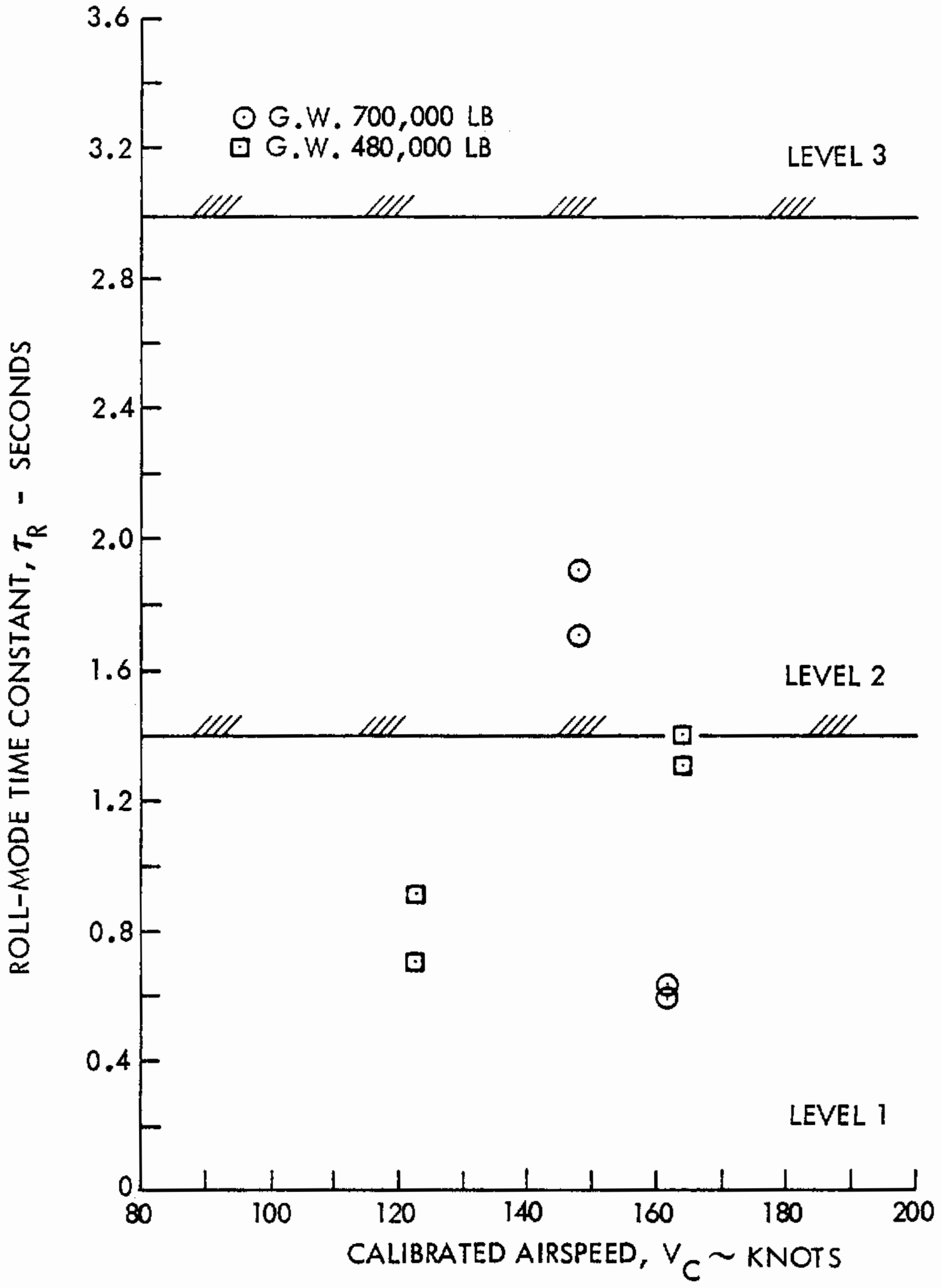


Figure 58 Category C Roll Mode Time Constant Data from C-5A Flight Test - Landing Configuration (Reference 2)

therefore $$\tau_R \sim \left(\frac{I_x}{S\ b^{\ 2}}\right)\left(\frac{4}{\rho V}\right)\left(-\frac{1}{C_{l_p}}\right) \qquad (18)$$

The aerodynamic roll damping, C_{l_p}, is set primarily by the wing planform and span loading. It is usually shown as a function of aspect and taper ratios, increasing with aspect ratio and decreasing with taper.

A change requiring a decrease in the roll time constant thus requires: a) artificially increased C_{l_p} by use of a roll damping system; b) a change in the operating flight envelope to a higher dynamic pressure region (ρV); or c) a decrease in the ratio $I_x/(S\ b^{\ 2})$. The consequence of a seemingly arbitrary limit on the roll mode time constant could be a) an expensive unneeded system which adds complexity and could reduce performance; b) alteration of the desired operational envelope; or c) dictation of maximum roll inertia or the combinations of inertia, wing area and span.

Another obvious impact of requiring high roll damping for a given roll control effectiveness could be to reduce the capability to roll to a given angle in a specified time. Since the present specification states roll performance in that manner, a low roll time constant achieved by higher roll damping will probably reduce the roll performance.

LESSONS LEARNED

Initial C-5A design studies indicated that there was a need for a roll damping system. Such a system would have had the effect of a lower roll mode time constant. Flight test showed that pilots preferred the aircraft without the system. Satisfactory ratings were attained (see Appendix A), and the roll time constant remained higher than the specification. It should be noted that the large displacement of the pilot from the roll axis causes a very noticeable side acceleration on the pilot during very abrupt rolls. A roll damper tends to increase the abruptness if the forward loop gain is increased to keep the same maximum roll rate.

The impact of a maximum roll mode time constant of 1.4 seconds on the C-5A can be shown by the following example:

$$\tau_R \le 1.4 \sim \left(\frac{I_x}{S\ b^2}\right)\left(\frac{4}{\rho V}\right)\left(\frac{1}{-C_{l_p}}\right) \qquad (19)$$

A typical Category C flight condition would be 150 knots at sea level. The only variable left in this situation would be the inertia. Solving for the inertia would give a value of 26.7 x 10^6 slug ft.^2. A large aircraft such as a C-5 cargo vehicle has a tremendous range for inertia. The rolling moment of inertia envelope in the 600 to 700 thousand pound gross weight range varies from 13 to 38 million slug ft. squared. This requirement would, in effect, reduce the top half of the permissible inertia envelope to severely reduce the mission capability.

A B-70 flying M=2.9 at 70,000 ft. has a roll mode time constant of 4.3. A reduction to 1.4 would cause the altitude to be reduced to 47,000 feet.

Additional large aircraft data are shown in Figures 59 and 60. Figure 59, from Reference 22)a, compares Category B time constant data for three aircraft with the 8785C Level 1 boundaries. Figure 60, from Reference 19, shows Category C data for the L-1011. The flight cases of Figure 60 are identified in Appendix B, with all points shown meeting the present Level 1 requirement.

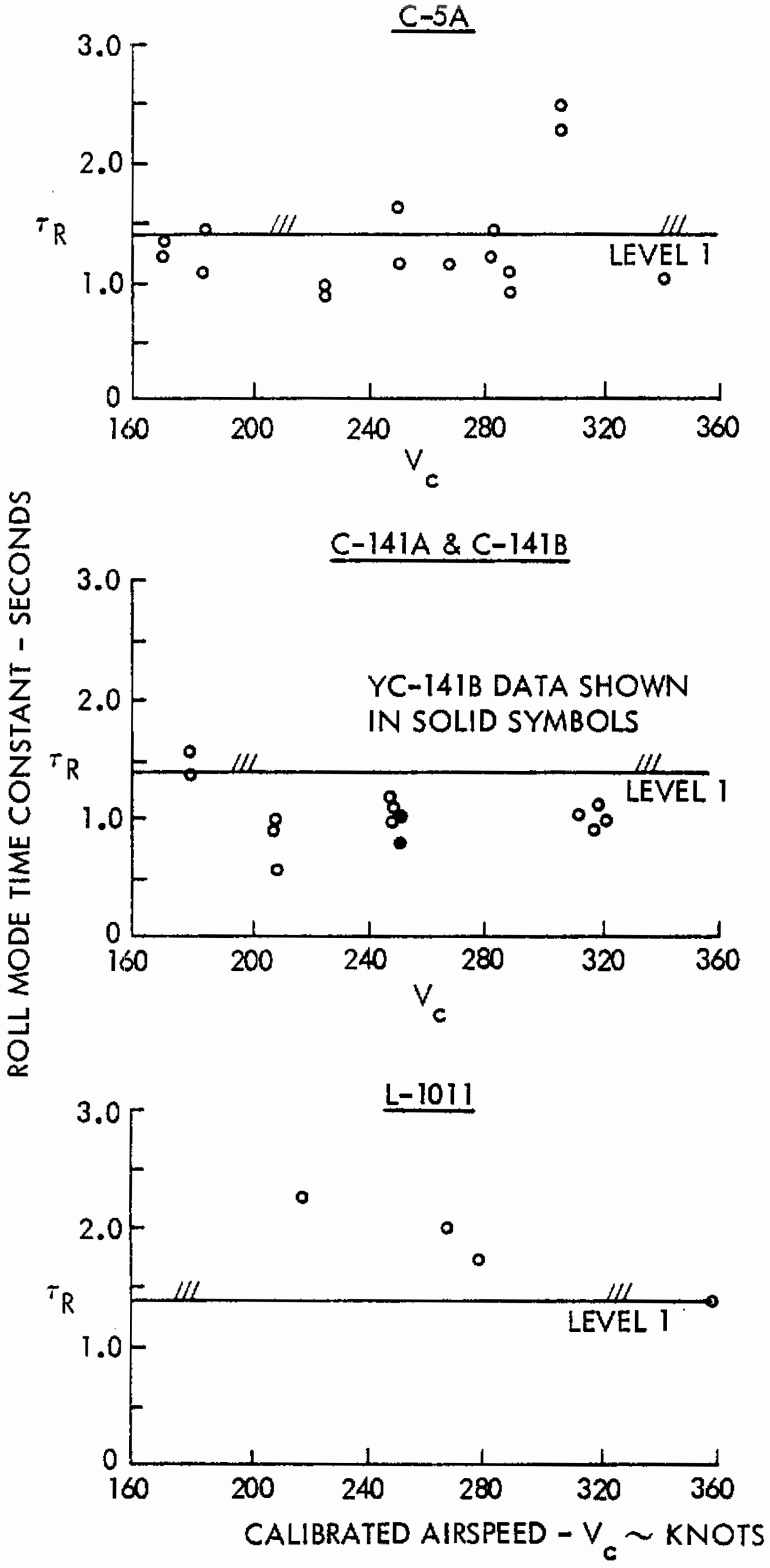


Figure 59 Category B Roll Mode Time Constant Data for Three Aircraft Compared to MIL-F-8785-C Criterion

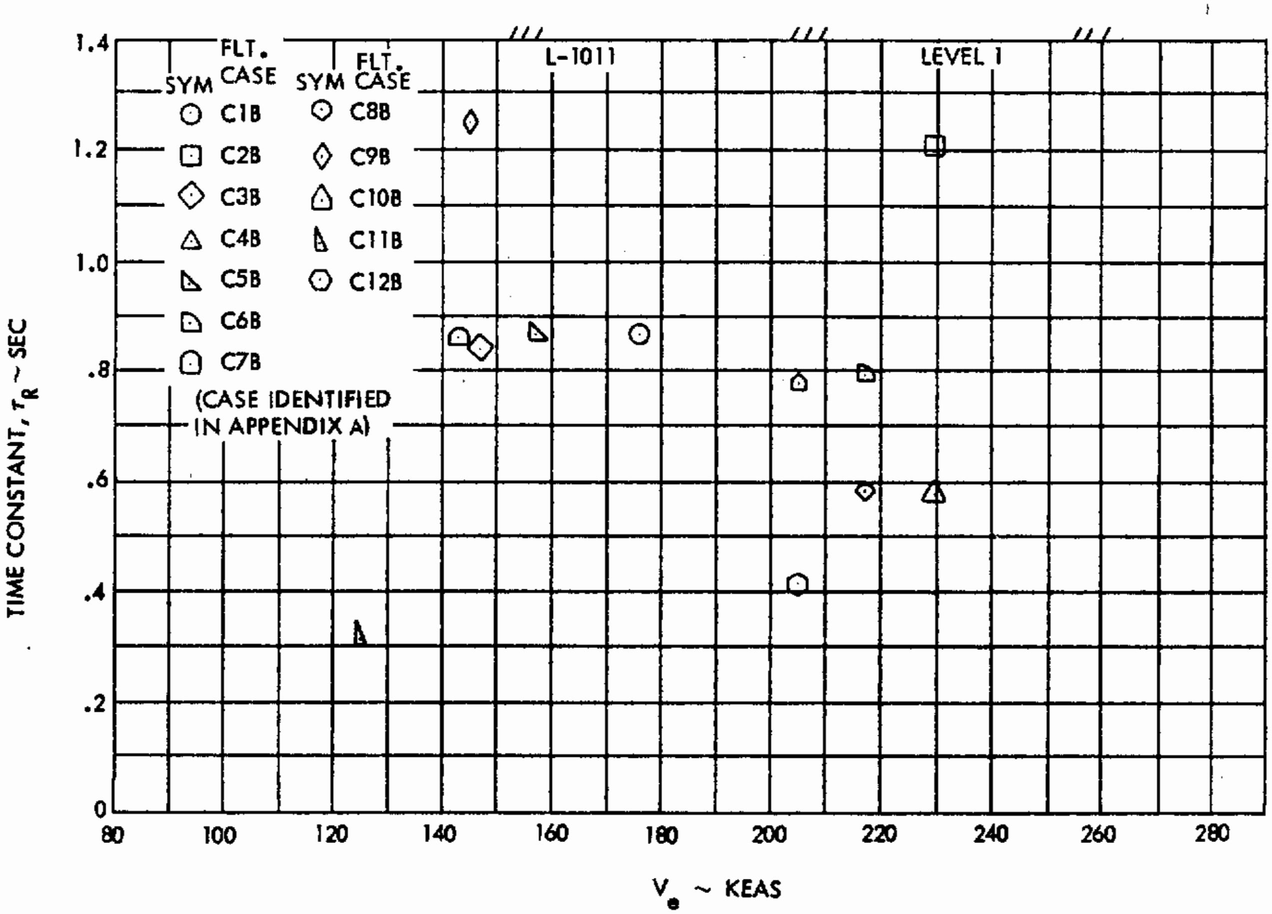


Figure 60 Category C Roll Mode Time constant for L-1011-500 (Reference 19)

3.3.2.2 Roll Rate Oscillations

3.3.2.2.1 Additional Roll Rate Requirement for Small Inputs

3.3.2.3 Bank Angle Oscillations

REQUIREMENT

(deleted)

RATIONALE

These requirements appear to be directed at aircraft other than Class III. They are concerned with "abrupt turn entries" and "especially for control precision of aircraft with high $(\phi/\beta)_d$" (Reference 1). Although the basic idea of quantifying these characteristics is well intended, there is very little data to substantiate such a detailed requirement. Reference 2 compared the C-5A with both of these requirements for SAS on and off. Since that large of an aircraft was limited to 45 degrees of bank, the full 90 degrees of bank angle change was not used. However, the data obtained showed that all points for Category B and C were easily met, even with SAS off (Category A requirements are the same as Category C). Since the SAS is mainly for turn coordination, all points easily meeting Level 1 are not indicative of a meaningful criterion. By contrast, the one plot in Reference 1 which showed existing Class III aircraft data on the p_{osc}/p_{av} vs. ψ_β chart was not substantiating in the opposite manner (i.e., 14 points were Level 1, 10 points were Level 2 and 3 points were outside of the Level 2 boundary). Aileron control impulses "as abrupt as practical within the strength limits of the pilot and the rate limits of the aileron control system", as called for in 3.3.2.3, can cause very objectionable problems in large aircraft. The lateral accelerations to personnel located considerably above the rotational axis, as in the C-5, were reported in Reference 2. Several other large aircraft studies have investigated this phenomenon since it is obviously of concern.

Figures 61 and 62, from Reference 2, show Category B and C data for 3.3.2.2.1. The data all meet Level 1 requirements for SAS on and off. These requirements do not appear to be substantiated. As explained above, a turn coordinating system was installed to improve flying qualities. The charts show all points are Level 1 with SAS on or off.

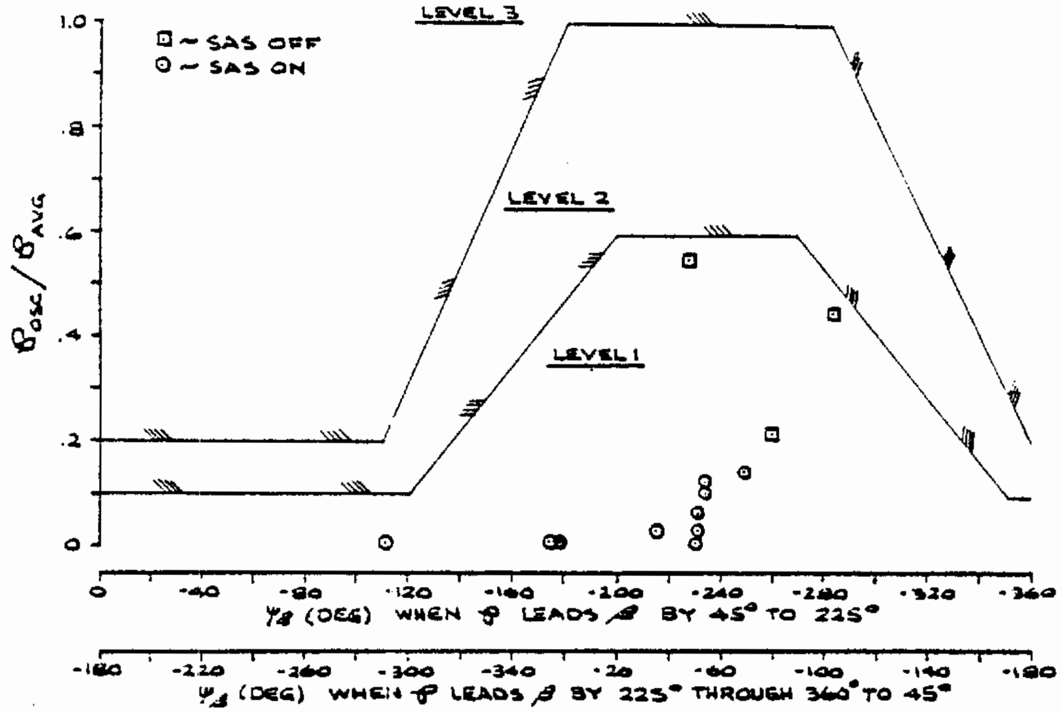


Figure 61 C-5A Category B Flight Test Roll Rate Oscillation Data

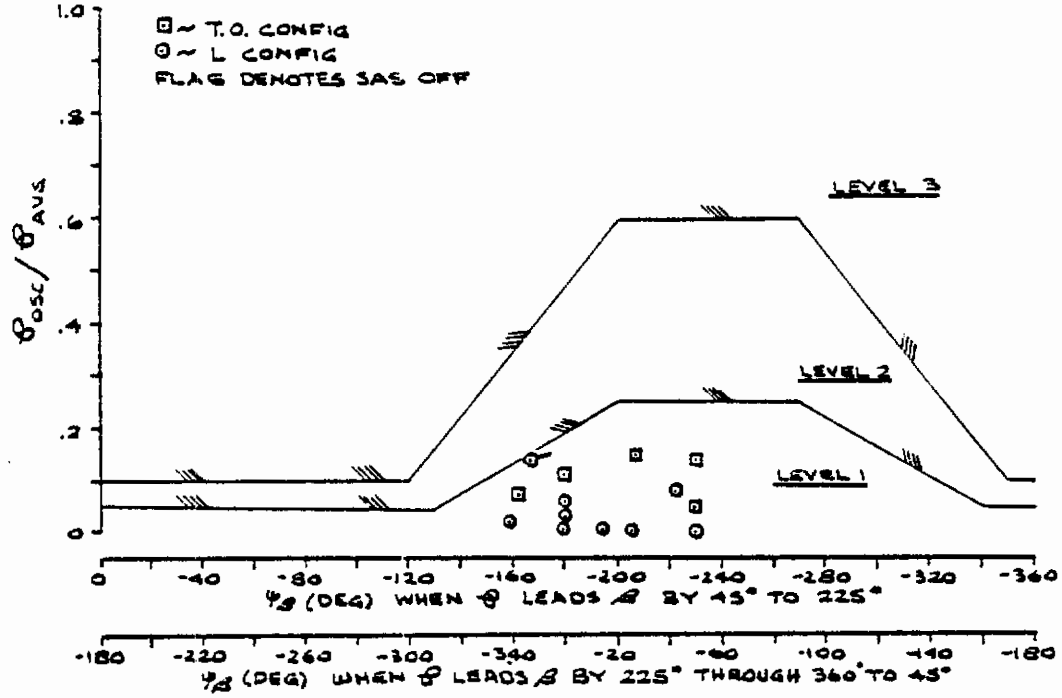


Figure 62 C-5A Category C Flight Test Roll Rate Oscillation Data

3.3.2.4 Sideslip Excursions

REQUIREMENT

Following a yaw-control-free step roll control command, the sideslip increment shall be less than the values specified herein. The roll command shall be held fixed until the bank angle has changed at least 50 degrees (i.e., 25 degrees right or left bank to 25 degrees the opposite direction).

TABLE 15

MAXIMUM SIDESLIP EXCURSIONS

Level	Flight Phase Category	Adverse Sideslip (Right Roll Command Causes Right Sideslip)	Proverse Sideslip (Right Roll Command Causes Left Sideslip)
1	A	6 Degrees	2 Degrees
	B & C	10 Degrees	3 Degrees
2	All	15 Degrees	4 Degrees

3.3.2.4.1 Additional Sideslip Requirement for Small Inputs

REQUIREMENT

The amount of sideslip following yaw-control-free step roll command shall be no greater than the values of 3.3.2.4 reduced by the ratio of bank angles used to 50 degrees. The requirement shall apply for step roll commands up to the magnitude which causes a 40 degree bank change. The rate of control input should be scaled proportional to that required to meet the roll performance of 3.3.4.

RATIONALE

The purpose of this requirement is to insure that the pilot can easily make coordinated turns. The maneuvers to be performed are roll reversals without using rudder to quantify the approximate pattern and magnitude of rudder command which the pilot will have to use for a coordinated turn. There is more tolerance of adverse yaw since that is what the pilot normally expects (i.e., right rudder in a right turn, etc.)

The change suggested in the tolerable yaw for large control inputs (3.3.2.4) was to eliminate the "k" and to reduce the required bank angle change to that commensurate with development of a SAS for large aircraft. The "k" factor was a method for ratioing the amplitudes found for the maneuver prescribed here to relate it to the required roll performance. Since the purpose of this requirement is to quantify a yaw, limits in the table can easily be adjusted to the proper level as more data become available.

The suggested changes for small inputs (3.3.2.4.1) include: elimination of the figure showing the sideslip parameter as a function of phase, a reduction in the magnitude of the bank angle change to make it more meaningful to small angles for large aircraft, and using words to relate the small input requirement to the large input. There was insufficient data available to justify the basic levels of sideslip. Since the table of 3.3.2.4 addresses the difference in adverse and proverse sideslip, the complexity of the change in levels as a function of phase seems unwarranted. The words "rate of control input" are to attempt to obtain sideslip in the same manner that the controls will normally be used. It is hoped that the roll performance requirement will reflect the normal control application to do the mission.

GUIDANCE

The magnitudes of sideslip given in this requirement are not validated with large aircraft data. Until such time as they are, the actual requirement imposed should be "not objectionable." Since there will probably be a requirement to quantify sideslip, the original 8785C levels are retained in the most direct manner. Very little large aircraft data is available to compare with the requirement. Figures 63 through 66 are from Reference 2 and compare Categories B and C flight test data to the criteria. Figures 63 and 64 show the effect of SAS on one set of flight points. The aircraft is Level 1 with SAS on and at least Level 2 with SAS off. These data seem to support both boundaries although pilot ratings are not available to establish the boundaries. Figures 65 and 66 are for another set of data. These data will not support either boundary. Due to the difference in the parameter levels, it would seem that one set of data is in error or the method of defining the "k" parameter was invalid for one set of data. This is a good reason to keep the specification as simple and direct as posible.

Figure 67 shows data from Reference 22)a for the C-5A, C-141A, YC-141B and L-1011. These data do not support the Level 1 boundaries, yet they were reported to be Level 1 data. That reference commented on the uncommonly large angle needed to acquire the large aircraft data.

Reference 3 compared the P3V with the criteria. Data was not shown, but comments and information were provided. The authors felt that the parameters in the specification were not clearly defined. Values of $\Delta\beta/k$

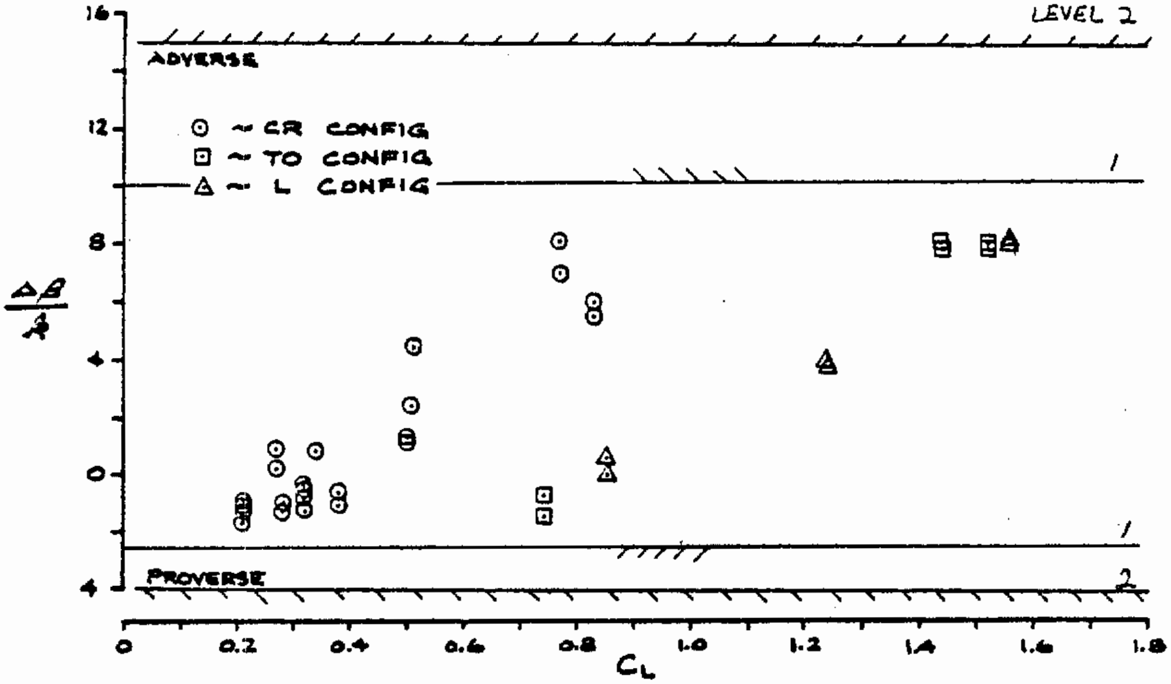


Figure 63 C-5A Sideslip Excursion Data - SAS On (Level 1 Flying Quality)

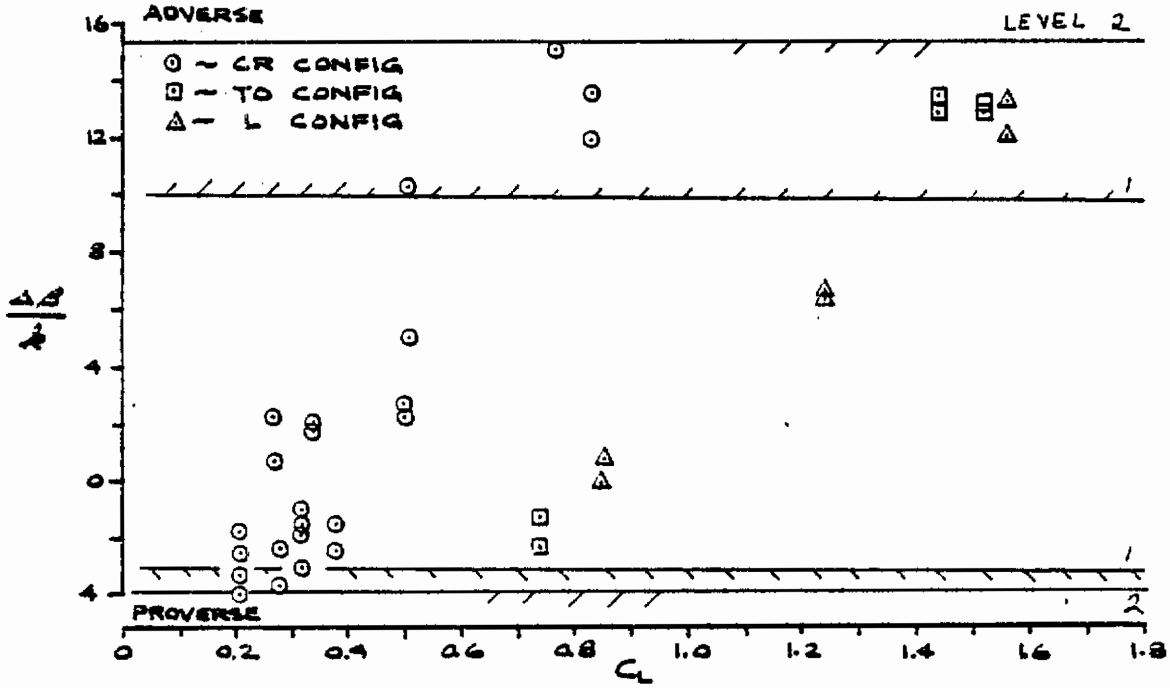


Figure 64 C-5A Sideslip Excursion Data - SAS Off (Level 2 Flying Qualities as a Minimum)

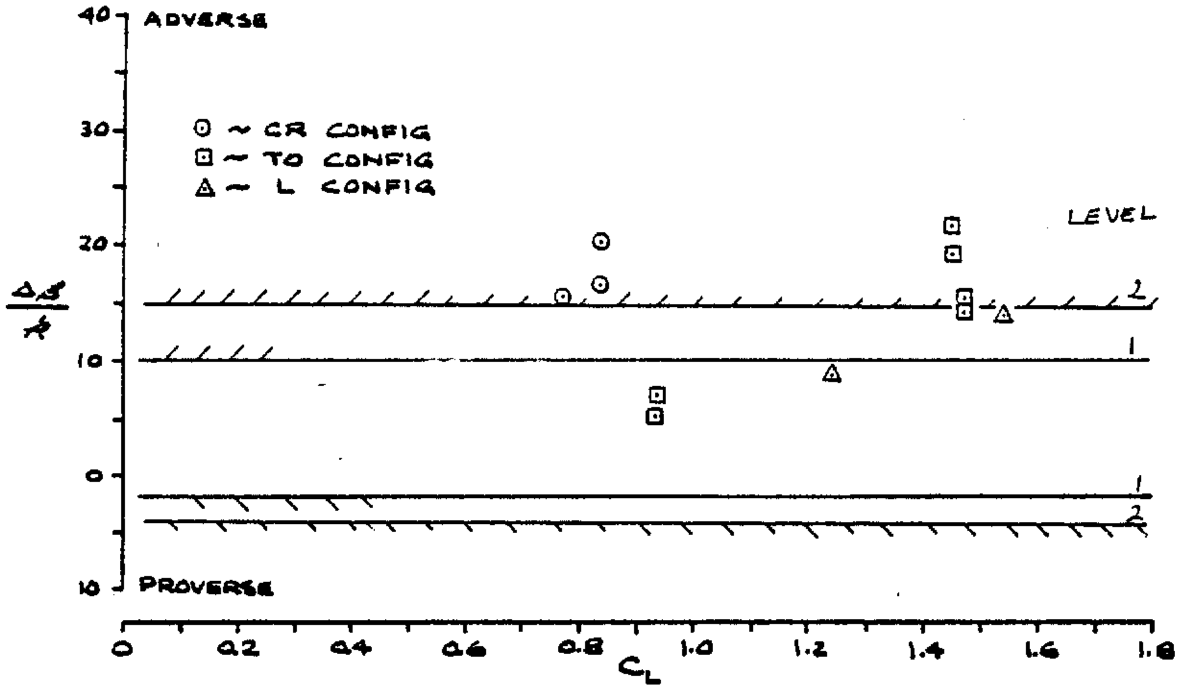


Figure 65 C-5A Sideslip Excursion Data - SAS On (Level 1 Flying Quality)

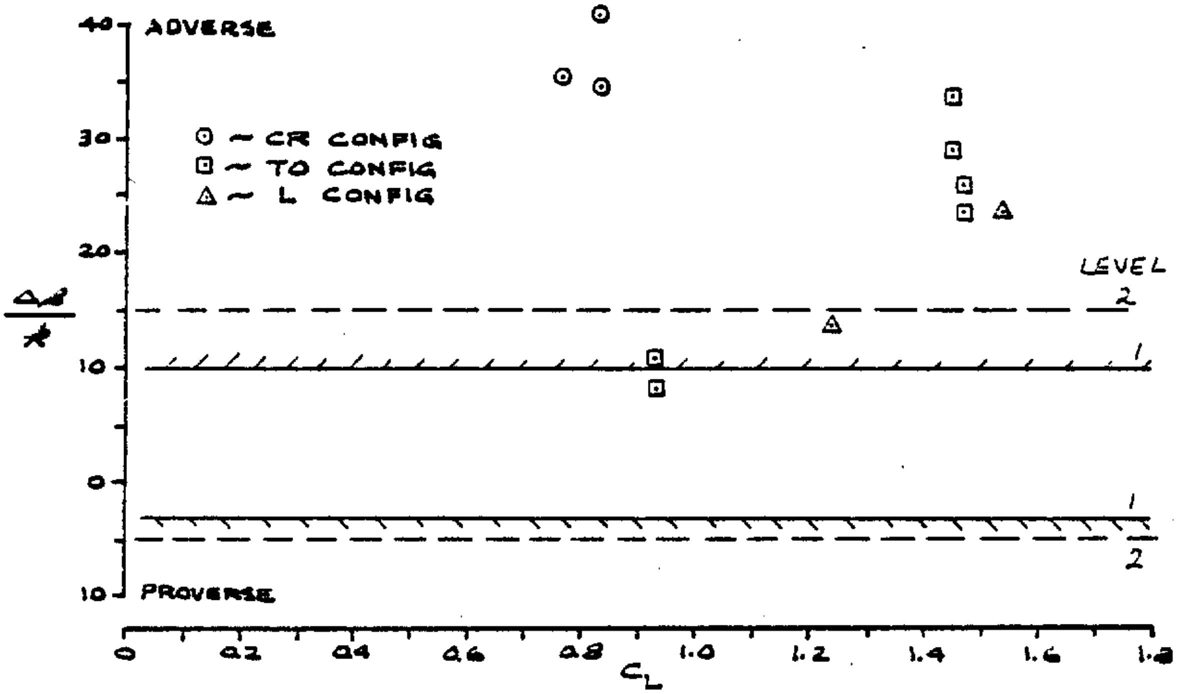
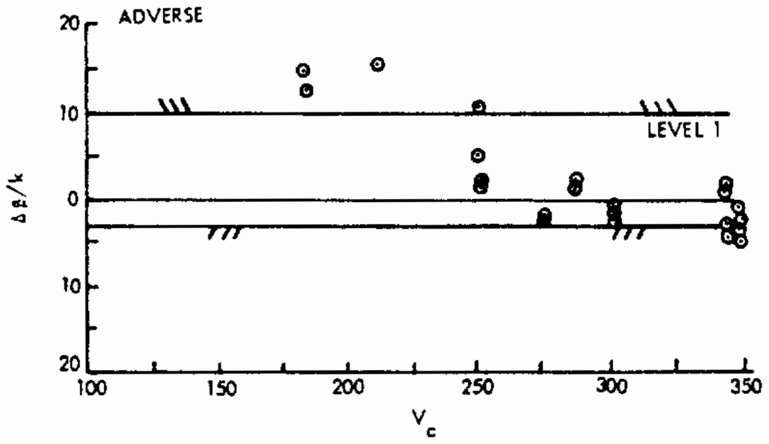


Figure 66 C-5A Sideslip Excursion Data - SAS Off (Level 2 Flying Qualities as a Minimum)

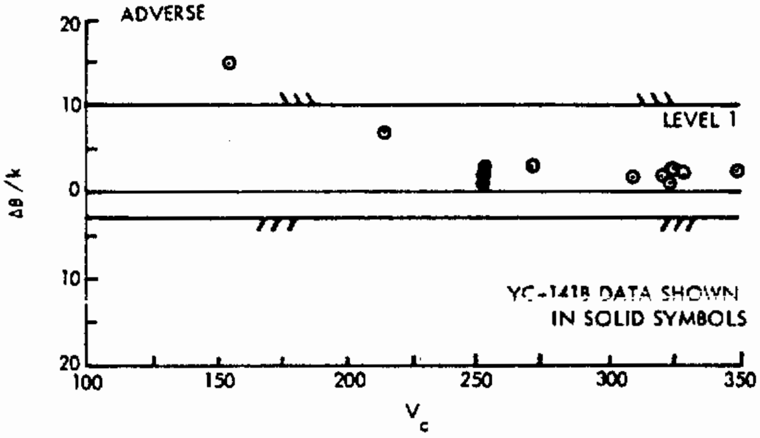
C-5A

CATEGORY B



C-141A & YC-141B

CATEGORY B



L-1011

CATEGORY B

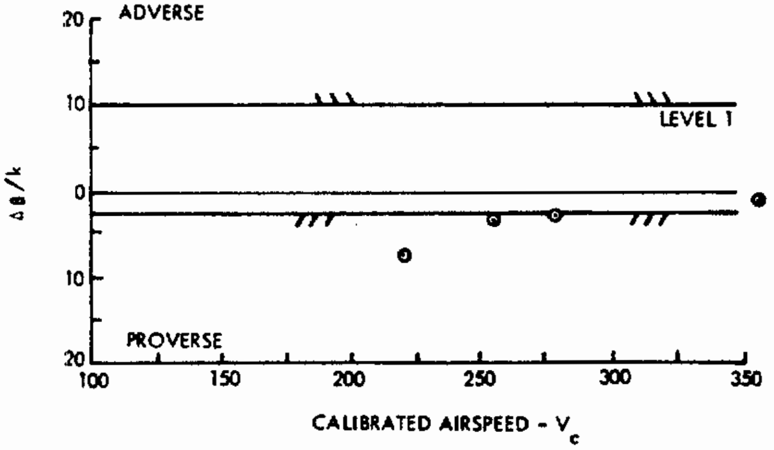


Figure 67 Sideslip Excursion Data for Four Large Aircraft (Reference 22)

of 25 and 13 degrees were reported in two Category A mission configurations which they considered Level 1 capability. They then stated that using Level 2 roll performance to evaluate Level 2 adverse yaw corroborated the Level 2 boundary.

It seems obvious that the method of using a $\Delta\beta/k$ type parameter is not popular.

3.3.4 Roll Control Effectiveness

REQUIREMENT

Roll performance in terms of a bank angle change in a given time, ϕ_t, is specified in Table 16 of 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 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.

3.3.4.2 Roll Performance for Class III Airplanes

REQUIREMENT

Roll performance in terms of ϕ_t for Class III airplanes is specified in Table 16. These requirements apply over the applicable speed range for each category of Flight Phase.

Table 16

Class III Roll Performance

Time To Achieve 30° Bank Angle Change (Seconds)

Level	Category A	Category B	Category C
1	4.0	6.0	6.0
2	6.0	7.5	7.5
3	7.5	9.0	9.0

RATIONALE

Roll control effectiveness is the fundamental characteristic in determining lateral maneuverability. The purpose of this requirement is to quantify, by some measureable parameter, what it takes to insure adequate maneuverability. There was a great deal of discussion in Reference 1 as to the rationale for choosing time to achieve a given bank angle as a meaningful parameter. An angle of 30 degrees was selected for Class III aircraft as one representative of the normal maneuvers in all flight categories.

As stated in numerous other requirements, the ideal requirement would be to specify the mission and then insure that there is ample roll control effectiveness to do the task. Class III aircraft cover a tremendous range of weights, inertias, size and missions. Very little data was available on very large aircraft when these requirements were initially set. The changes suggested here are to reduce the requirements enough to include the large aircraft. An obvious consequence of this is that aircraft on the low end of the Class III range would not be rated acceptable with these capabilities. Also, aircraft with an entirely different mission than heavy cargo or transport would not be satisfactory. The times in Table 16 would be especially applicable to large cargo type Category B and C missions with tasks of inflight refueling for Category A. Smaller aircraft with LAPES type missions would require more stringent times.

Two changes were suggested in 3.3.4. Information concerning other class aircraft was eliminated. The time increase allowable for take-off configurations proportional to the inertia ratio of maximum landing cases was eliminated. The recommended changes in times are so large that this change is relatively insignificant for cargo type aircraft.

The changes suggested in 3.3.4.2 are of a much more drastic nature. Reference 11 provided three speed ranges applicable to each category to reduce the requirement on the low and high speed end of the range. The idea is realistic and commendable. Since the suggested increase in times are more than double in some instances, it is unrealistic to try to further quantify such a reduction based on existing data. The increased time allowance for 30 degrees is substantiated for a landing offset maneuver in Category C conditions. Category B was made the same arbitrarily. The Category A Level 1 limit was set by an existing large aircraft capability which has Level 1 handling qualities during an in-flight refueling task.

GUIDANCE

Although relatively little data was available for large aircraft in Reference 1, the existing Class III data was evidently considered too lax. A table from Reference 43 was presented in which five large aircraft were listed with time to bank to thirty degrees. These times were 4.1, 2.9, 3.9, 3.5 and 2.3 seconds for the landing approach configuration. Only the 3.5 second aircraft had a comment of minimum acceptable; the rest were rated satisfactory by comments.

Reference 2 compared a very large aircraft, C-5A, to the requirements. This aircraft - rated Level 1 and substantiated as such in Appendix A - had times of up to 4.3 seconds for Category B and 4.0 for Category C flight. In fact, commentary is noted where the "excellent lateral control" was mentioned.

The data presented thus far is based on existing aircraft. Future aircraft, especially novel designs, could be seriously hampered by unnecessarily stringent criteria. Reference 65 presents results of a flight simulation study to determine the roll requirements for a multi-body aircraft. That design, shown by the sketch in Figure 68, has a weight savings which depends on the separation of the fuselages. As the fuselages are moved farther apart, the rolling inertia increases in a square-law fashion. The limiting constraint in this design was the rolling criterion. Since the available rolling moment was limited, the required roll performance limited the fuselage separation.

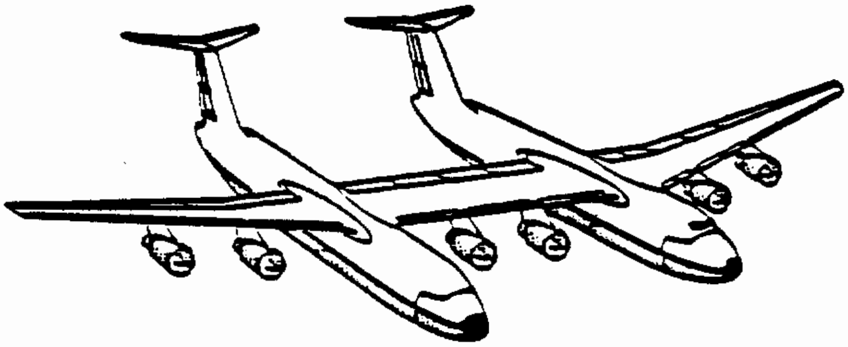


Figure 68 Sample Sketch of Multibody Aircraft

Figures 69 and 70 are preliminary plots of data from the moving base flight simulation experiment. The figures show pilot rating as a function of fuselage location (η_B) which also determines the roll performance expressed as time to bank to 30 degrees. A Category C landing task was used in the experiment. Figure 69 shows results for a pilot experiencing a visual break out from a 300 ft. ceiling to find a 200 ft. lateral offset with a 15 knot adverse cross wind. Figure 70 shows results for the same conditions except the crosswind is replaced by a 16 knot, 90-degree horizontal crosswind shear for the last 200 ft. of altitude. These preliminary results for a very large (2 million pound class) aircraft design show a Level 1 rating achieved with a t_{30° of 5.5 to 6 seconds. The Level 2 boundary is 7.5 seconds for Figure 69 and is not determined in Figure 70 although it is greater than 8 seconds.

LESSONS LEARNED

The initial roll design requirement on the C-5A was to bank 8 degrees in 1 second. Early in the design, it became obvious that this requirement would seriously compromise the design. The procuring agency and Lockheed determined the landing offset task as being a critical design maneuver. The requirement was changed to one which required a satisfactory pilot rating to accomplish that maneuver. The design was successful, with excellent handling qualities reported by a joint company and Air Force pilot team. As reported in Reference 2, the time to a 30 degree bank angle was as high as 4 seconds. Reference 66 presents flight test data to verify the design maneuver in flight. During those tests, the maximum bank angle used in the maneuver was 12 degrees. Reference 7, on the multibody experiments, had average maximum bank angles of approximately 8 degrees to perform the required offset landing task.

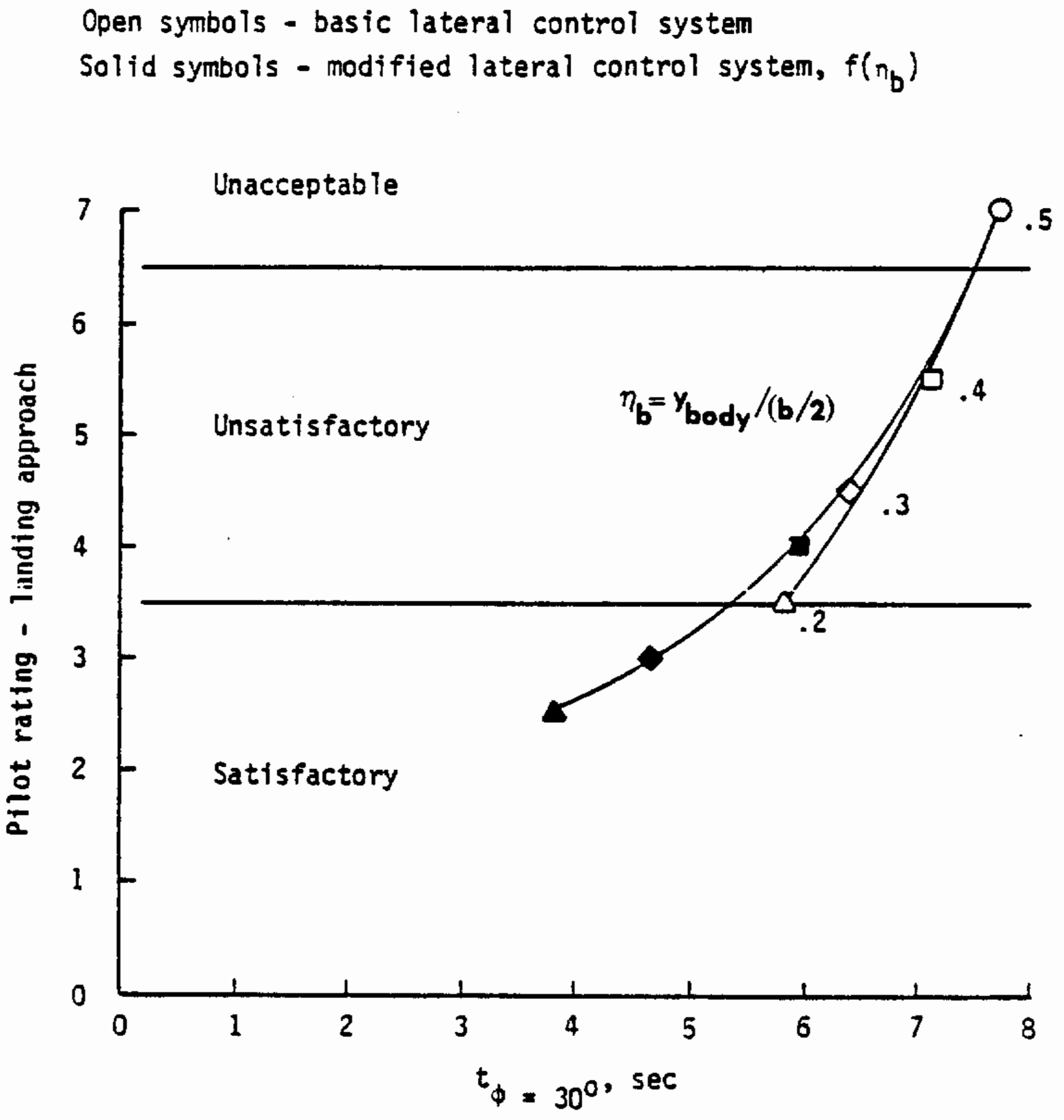


Figure 69 Roll Performance in Landing Configuration – Landing Task: Ceiling = 300 ft, Y–offset = –200 ft. V_{XW} = Steady 15 kt. (Reference 65)

Open symbols - basic lateral control system

Solid symbols - modified lateral control system, $f(\eta_b)$

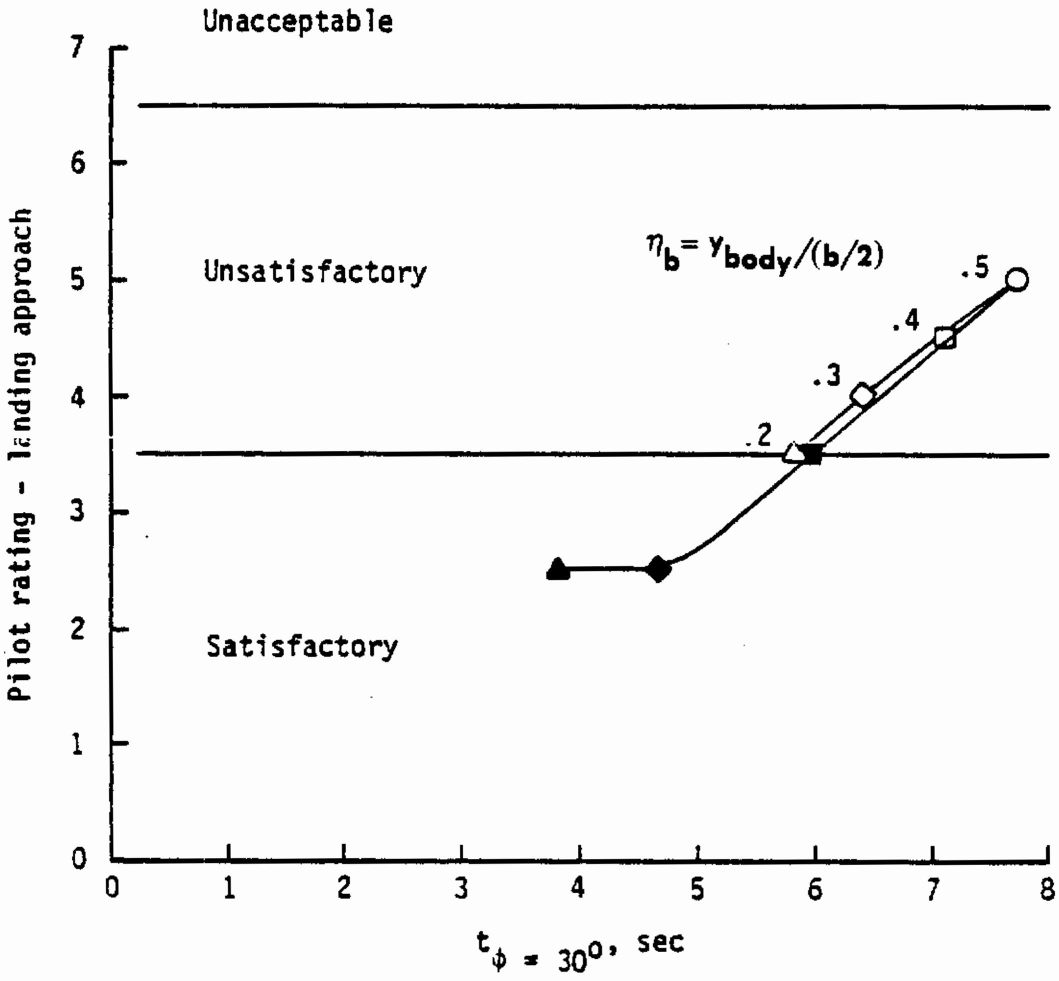


Figure 70 Roll Performance in Landing Configuration - Landing Task: Ceiling = 300 ft., Y-Offset = -200 ft., V_{xw} = Shear 16 Kt/200 ft. (Reference 7)

3.4.3 Cross-Axis Coupling in Roll Maneuvers

REQUIREMENT

During combat-type maneuvers, 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 III airplanes, these requirements apply in rolls commensurate with the mission and rolls which are checked at a given bank angle.

RATIONALE

The intent of this requirement is to make certain that the cross-coupling effects while in rolling maneuvers will not hamper mission effectiveness. The suggestion has been made to separate Class III aircraft into combatant and non-combatant classifications. The suggested change in this requirement applies to combatant type Class III airplanes and the maneuvers associated with them. The currently required rolls through 120 degrees are excessive for very large aircraft, so the specific angle requirement is deleted.

3.5.3 Dynamic Characteristics

REQUIREMENT

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 specified in Table 17, for frequencies equal to or less than the frequencies specified in Table 17.

Table 17

Allowable Control Surface Lags

	Allowable Lag, deg.	
Level	Category A & 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 $\omega_{n_{SP}}$ & 2.0
Roll & Yaw	The largest of ω_{n_d}, $1/\tau_R$ and 2.0.

In addition, the response of the airplane motion shall not exhibit a time delay longer than the times of Table 18 for a pilot-initiated step control force input.

Table 18

Allowable Airplane Response Delay

Level	Allowable Delay, Sec.
1	0.40
2	0.60
3	0.70

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 18.

RATIONALE

The purpose of this requirement is to insure a smooth airplane response to cockpit control deflections in order to avoid any objectionable or annoying lag while performing a particular task. Since, in general, large (Class III) aircraft missions do not require quick pilot inputs, such as would be the case with a fighter tracking a target, the pilot is less apt to detect a system lag. The present MIL-F-8785C specification for allowable time delay is based primarily on small aircraft data and, therefore, appears to be much too stringent when considering the specific missions and relatively low pilot workload associated with large aircraft. The proposed maximum time delays better represent the boundaries of the various levels of flying qualities for large airplanes as defined in paragraph 1.5 of MIL-F-8785C.

GUIDANCE

Table 18, which was added to the specifications with the "C" version, was explained in Reference 11 to be based on mainly Class IV aircraft data. It is stated as appearing to be "applicable to both pitch and roll axes for demanding task [which was approach and landing for the majority of the data]. The time delay is to be measured from the pilot's initiation of a step control input until the first indication of overall airplane response in the commanded motion variable for that control input." The values of equivalent time delay derived from equivalent system match of aircraft response are to be used for comparison with Table 18. Pure time delays or prefilters not included in the match should be added directly to the equivalent time delay to determine the total airplane response delay. Due to the many methods used to measure response time such as time constant, equivalent time delay, effective time delay and t_{max}, care must be used when comparing data from a variety of sources. The difference in time between the methods can be appreciable. The majority of the data presented here have pure time delays which are usually far in excess of the difference due to methods of measuring the delay to compare with Table 18.

The possibility that higher maximum time delays may be acceptable for Class III airplanes was suggested in Reference 67 as a result of B-1 flight test data. Equivalent time delays were derived for five flight cases where pilot ratings were available. The conclusion was that the implication of a time delay criterion of 0.1 seconds, not being restricted to aircraft class, points up the need for more work for Class III aircraft.

Reference 5 presents results from a large aircraft flying qualities experiment which had command path time delays as a primary variable. The authors consider the maximum allowable time delays for the various levels of flying qualities to be inversely proportional to the bandwidth of the task involved. A functional relationship used to develop the ratings as a function of boundaries was developed from data by References 14, 68 and 69. These were all fighter aircraft, but the tasks were judged to be of distinct bandwidths of 1.5, 2.5 and 3.5 rad/sec. Figure 71 from that reference shows results of the in-flight simulation, considered to be of the 1.5 bandwidth task, compared to the desired relationship. A conclusion of that study was that the degradation in pilot rating with time delay was much less severe than previously believed. In fact, as noted in Figure 71, there is little substantiation for the actual time delays selected to separate the level 1 and 2 flying quality regions. At the T_1 = B delay of approximately 0.23 second, which should be in the level 2 region, two of the five ratings are level 1. At the T_1 = C delay of approximately 0.3 second, which should be in the level 3 range, four of the five ratings are level 2. These results are for the longitudinal mode. In the lateral mode, there were points where the time delay was 0.37 seconds with level 1 ratings.

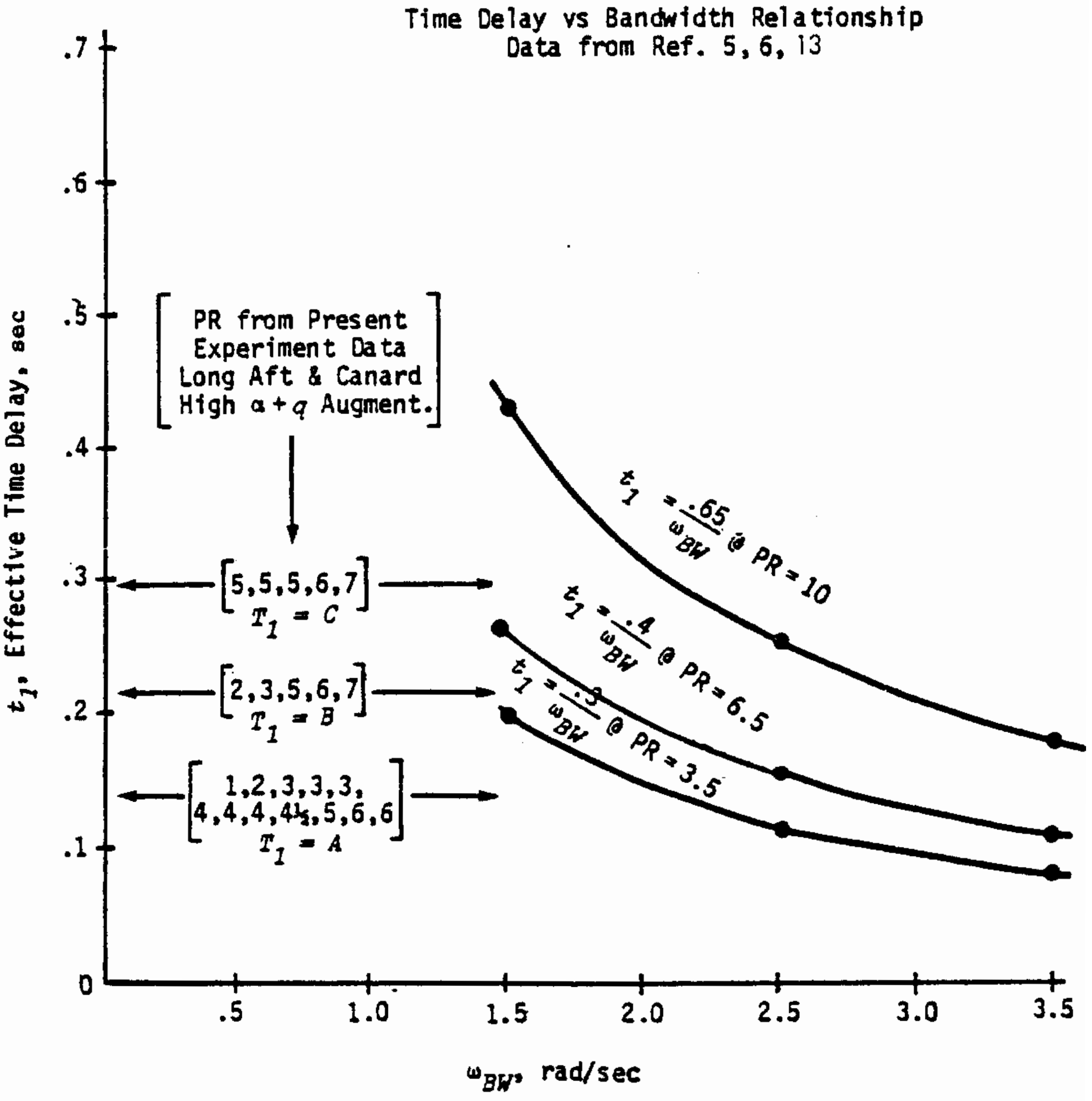


Figure 71 Time Delay Vs. Bandwidth @ PR = 10, 6.5, 3.5 (Reference 5)

Table 19 compares time delays derived from Reference 5 with those from Reference 4 and 8785C. As the table shows, these values are significantly higher than those of the present MIL-F-8785C specification and those resulting from the supersonic cruise research study in Reference 4.

Table 19

Recommended Allowable Aircraft Time Delay

Allowable Delay - Sec.				
Level	8785-C	SCR (Ref. 4)		TIFS Expt. (Ref. 5)
		Pitch	Roll & Yaw	
1	.10	.12	.17	.20
2	.20	.17	.20	.27
3	.25	.21	.28	.43

Further support for a change in the requirement is provided by a large aircraft in-flight and ground-based simulation study described in Reference 62. The NASA-Ames moving base simulator was used for the ground-based phase of the study and the Boeing 367-80 inflight simulator was used for the air work. The primary evaluation tasks for both phases of the study were the approach and landing maneuvers. A lateral offset was selected as the most demanding maneuver to consider close to the ground. Some results from this test are summarized in Figure 72. The system response time shown, t_{max}, is a composite measure of control dynamics and approximates the effects of pure time lags, cable stretch, system rate limit, aerodynamic lags and airplane flexibility. Time is measured from control input till the time the maximum rolling acceleration is reached rather than till the start of aircraft response. A time history plot of control deflection and roll angle for a t_{max} of 1.0 second shows that t_{max} could be as much as 0.3 seconds greater than response time as measured for specification compliance. Results in Figure 72 show very little degradation in pilot rating out to 1.4 seconds of t_{max}, which is equivalent at least to a response time

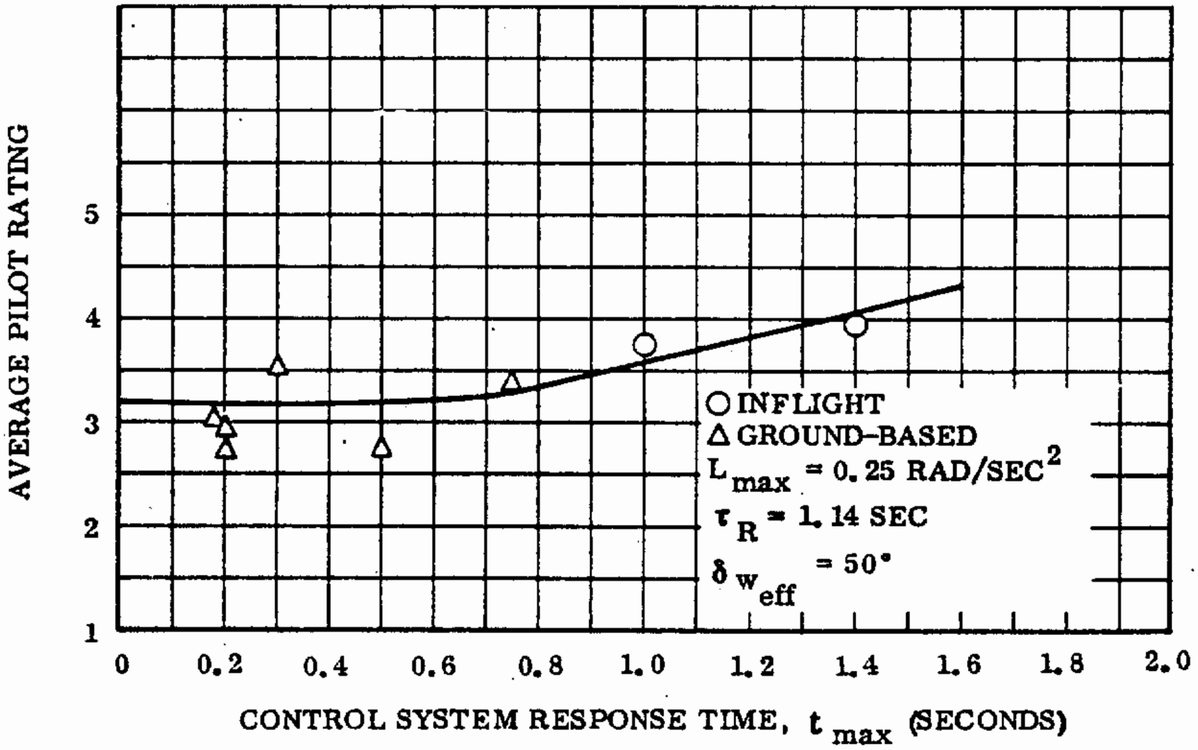


Figure 72 Control System Response Time, t_{max} (Seconds) (Reference 62)

of over 1.0 second. The trend line in the figure, unfortunately, has ground based results only up to 0.75 seconds and in-flight results for delays of 1.0 second and beyond. There is only a one quarter of pilot rating point decrease for a t_{max} change from 1.0 to 1.3 seconds in-flight. A trend line based on ground simulation alone or in-flight simulation alone could be even less severe than the one shown.

The allowable time delay in large aircraft has been the subject of recent studies at the Lockheed-Georgia Company. Reference 70 describes flight simulation tests in which a series of time delays were incorporated in the longitudinal and lateral responses of a C-5 airframe simulation model to establish the flying quality level boundaries. The study was not indicative of the C-5 since a side stick controller was used. The pilot ratings obtained during simulated approaches and landings are presented in Figures 73 and 74 for the lateral and longitudinal axes, respectively. The initial delay was comparable to that of a C-5A which is rated Level 1 (see Appendix A). One pilot commented in his initial rating that, in his opinion, simulations are downrated from actual flight due to the inability of a simulation to effectively reproduce every characteristic of the airplane. The purpose of the study was to establish degradation trends as a function of time delay. Therefore, the trends established by the data were shifted downward to indicate an arbitrary level 1 rating of 2.5 at minimal time delay. Although the present MIL-F-8785C specification does not distinguish between the longitudinal, lateral, and directional axes when specifying maximum allowable time delays, comparison of Figures 73 and 74 suggests that there may be varying degrees of pilot sensitivity to time delays about the various axes. Although one would think that the pitch axis would be the most critical to the flying qualities of large aircraft, these data show that the roll axis is the most restrictive, with allowable delays of .4, .6, and .7 seconds for Levels 1, 2, and 3 boundaries, respectively. A possible explanation is the relatively low lateral control power characteristic of Class III airplanes compared to pitch control. Directional data was also obtained which showed that the relatively infrequent use of rudder control in Class III airplanes substantially reduces the pilot's sensitivity to a directional time delay.

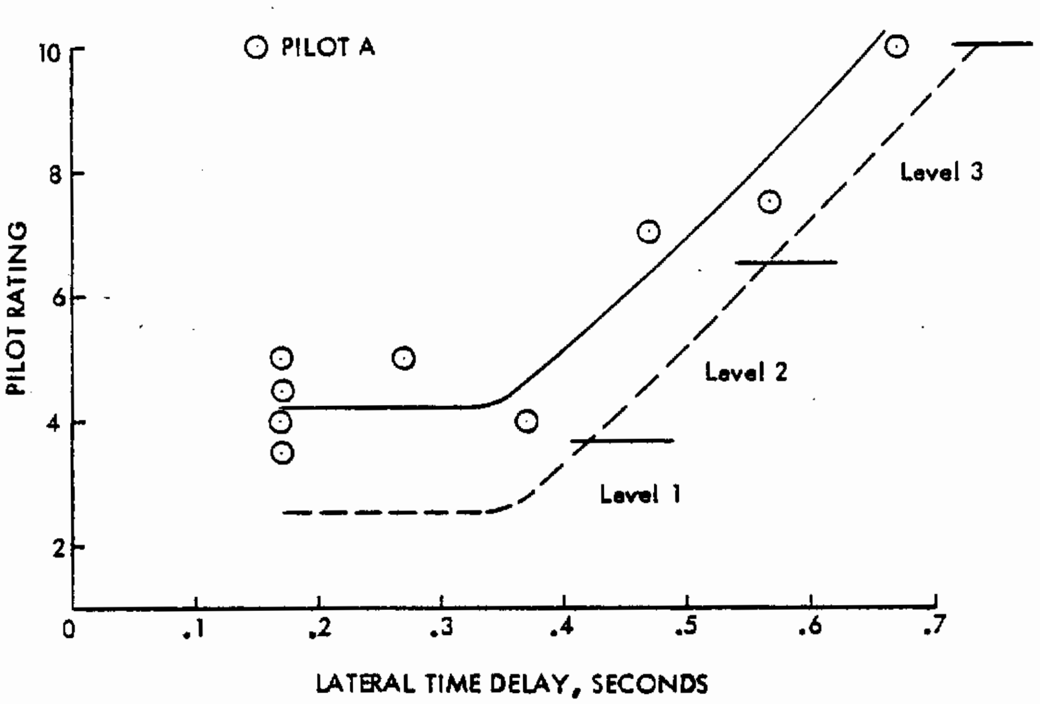


Figure 73 Variation of Pilot Rating with Lateral Response Time (Reference 70)

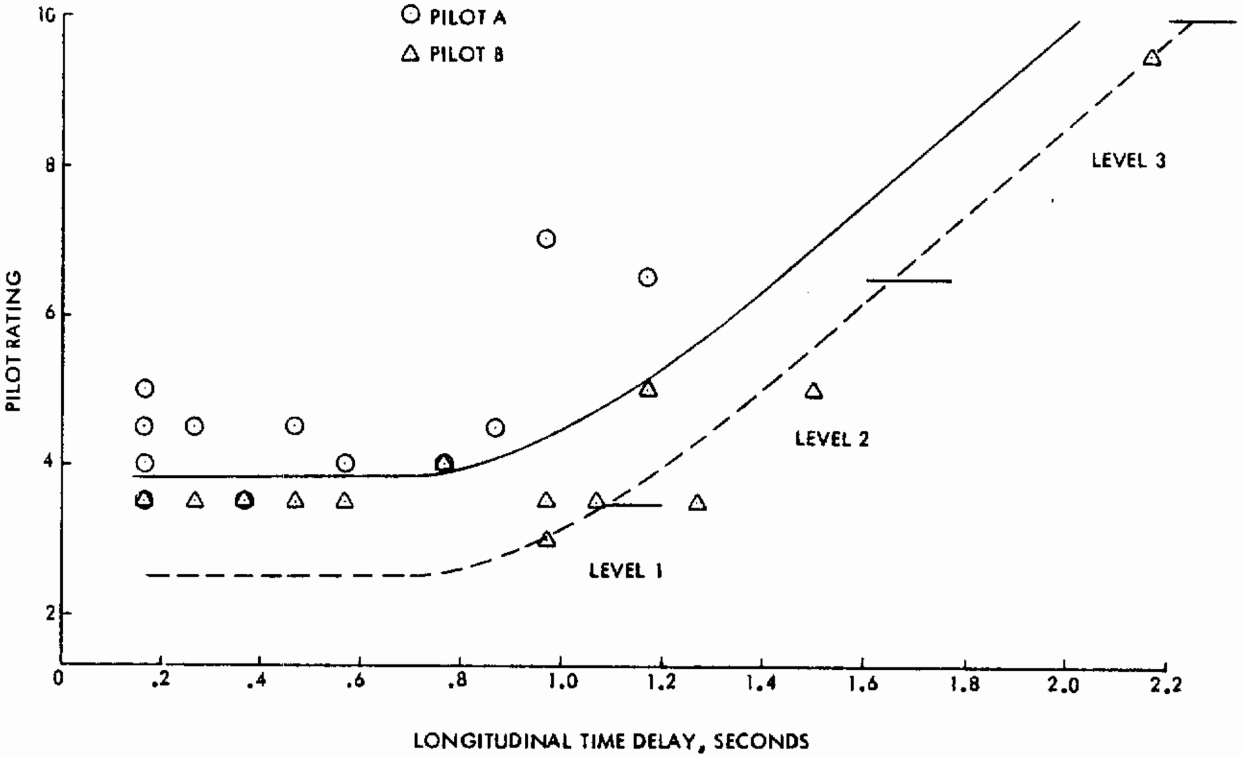


Figure 74 Variation of Pilot Rating with Longitudinal Response Time (Reference 70)

No quantitative distinction is made between the suggested maximum allowable time delays in pitch and roll in Table 18. The most critical of the two was used to establish the requirement.

Data exists to show that Level 1 aircraft are flying with delays which exceed the 8785C values. The suggested values considered for this requirement are considered to be as well founded as those of Reference 11. The in-flight delays of Reference 62 shown by Figure 72 far exceed the levels of 8785C and would appear to make these suggested levels still conservative.

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APPENDIX A

Appendix A - Operational Pilot Survey of C-5A Flying Qualities

The C-5A is the world's largest flying aircraft. Therefore, the data from it, lessons learned, and flying characteristics are invaluable to a large aircraft flying qualities specification. Inevitably, when frequent reference is made to that aircraft, it is mentioned that "just because the C-5A flies that doesn't mean that all aircraft should!" That point is well taken and agreed with. Since such frequent reference is made to the C-5, however, it was decided to attempt a survey of pilot opinion from operational pilots who use the plane daily in their normal missions.

Figure A-1 is a sample of the form sent to MAC Headquarters. The form was devised to be easily completed with a minimum of interruption to normal activities. It contains sufficient information to explain the rating system and encourage comments. There will, no doubt, be some disagreement among data users as to the validity of ratings by pilots not indoctrinated in the same manner as test pilots. It is believed, however, that the opinions of the operational pilots is as valuable, if not more so, than those of highly skilled test pilots.

A summary of the data collected is presented in Table A-1. These data corroborate the use of C-5A data as that of a Level 1 flying qualities aircraft under normal operational activity. The results were obtained from both East and West Coast Air Force Units. In addition to the many completed forms summarized in the table, the letter cover sheet that accompanied the completed forms is presented as Figure A-2. It says that most pilots find the characteristics to be excellent, adding credence to a Level 1 rating. The interesting unsolicited comment on excellent lateral control for turbulent and crosswind conditions should add to the substantiation of suggested changes with respect to the lateral mode.

PILOT RATING SHEET

Type Aircraft ________________ Date ____________________________

Flight or Simulator No. ________ Pilot (Optional) ________________

This rating information will be used to improve flying qualities specifications for large aircraft. Your sincere evaluation and comments will be greatly appreciated.

Rate on a scale of 1 to 10 using as a guide:

1-3.5	Can easily do job I want to do with respect to putting aircraft where I want to and have it stay there (i.e. pitch attitude, flight path, speed, etc.)
3.5-6.5	Can do the job I want but requires extensive effort.
6.5-9	Requires extreme effort, and still can't attain desired performance.
10	Can't be assured of complete control.

(NOTE: If desired, additional aid in rating logic is provided on back of form).

	Flight Segment	Gross Weight	C. G.	Alt.	V_i Kts.	Weather/ Turbulence	Pilot Rating
	Take-Off						
	Climb						
	Cruise						
	Descent						
	Approach						
	Landing						
Special Missions	In-Flight Refueling						
	Airdrop						
	Other						

NOTE: Approximations of these conditions are essential to obtain the dynamic characteristic you were rating. A rating on any segment (or preferably all segments) would be helpful.

This evaluation is valuable, but it obviously must not deter or distract in any way from your normal safe mode of flying. The intent is to rate (after the fact) how well you were able to do your normal job.

If you can evaluate these same conditions on a flight simulation, it will add greatly.

(USE BACK OF FORM FOR ANY ADDITIONAL COMMENTS)

Any comments suggesting what influenced your rating would be extremely helpful.

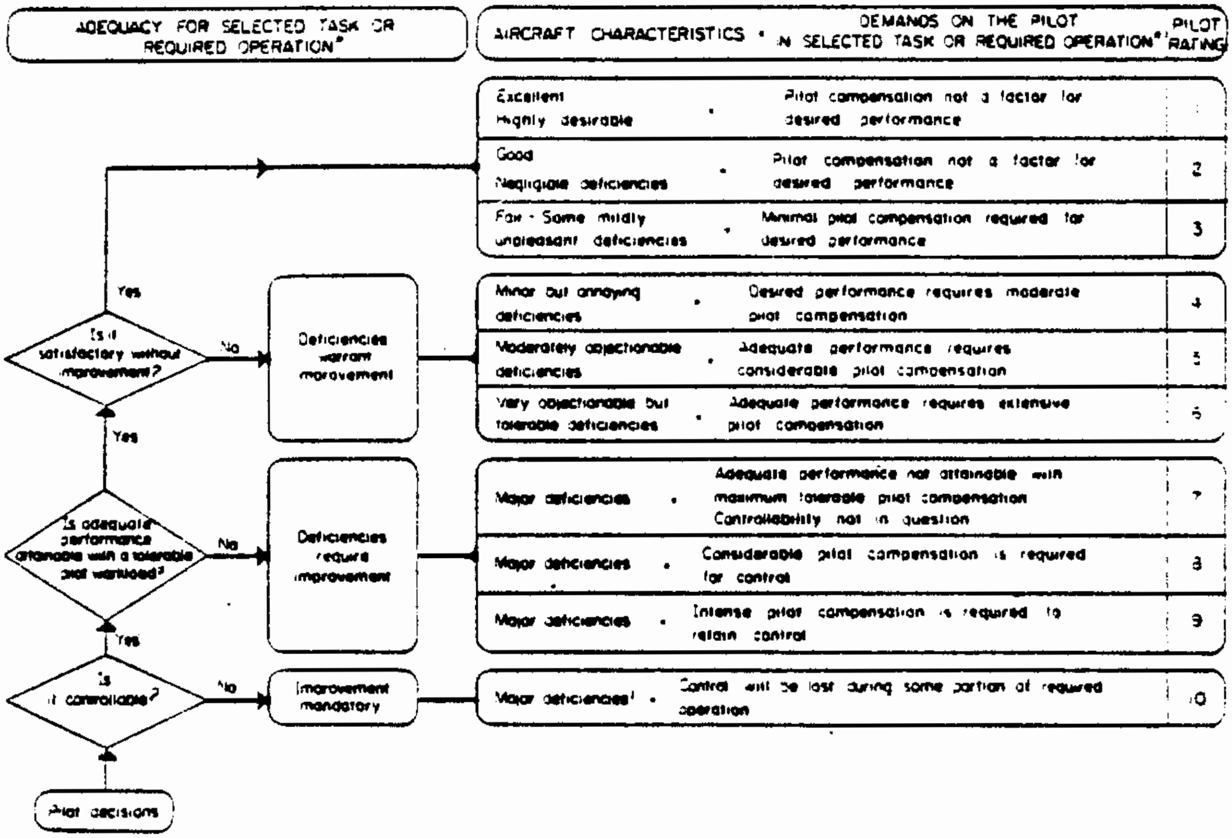
Approximate number of these forms you have completed.

Flight ________

Simulator ________

Figure A-1a Front of Pilot Rating Sheet

DECISION LOGIC FOR ESTABLISHING PILOT RATING



COMMENTS

Figure A-1b Back of Pilot Rating Sheet

Table A-1 Summary of Results of Pilot Opinion Survey - Operational C-5 Pilots

PILOT RATING

GROSS WEIGHT X 1000 LB.	TAKE-OFF	CLIMB	.60-.75M CRUISE	.76-.90M CRUISE	DESCENT	APPROACH	LANDING	AIR-AIR REFUEL
(29 - 32% C.G.) 300-400								
400-500	3	3		3^T	2,3,3^T	2,2^X,3^T,5^T	2,2^X,4,4	
500-600	1.5	1.5		1.5,3^T	2	2	2,2	
600-700	1,2,2	1,2,3	2,2					
(33 - 36% C.G.) 300-400					1	1^T	1	1.9^T
400-500	1	1,1	1	1,2^T,3	1,1,1,1.5, 2,2,3,3,3, 3.5,3.5,3.5, 4	1,1.5,2,2,2, 2,2,2,2.5^T, 3,3,3.5,4,4	1,1.5,2,2,2 2,2,2,2,2, 2^T,3,4,4	
500-600	1,1.5,2,2, 3.5^C	1.5,2,2,2, 3.5,4	2	1,1^T,1.5,2 2,2,2,2,2^T, 3.5	2^T,4	1^T,3	2	
600-750	1,2,2,2, 2,2,2^X	2,2,2,2		1,2^T,3				5
(37 - 40% C.G.) 300-400					1,2,3.5	1,1^T,2,2	1,2,2	
400-500	1,1,1,2,2, 2,2,2,2,3^T, 4	1,1,2,2,2, 2,2,2,2,2^T, 3^T	2,2,2,3.1	1,1,1,1, 2	1,1,1,1,2, 2,2,2,2,2, 2,2.9^T,3.5, 3.5^X	1,1^T,2,2,2, 2,2,2,2,2,2^C, 3,3,3.2^T,3.5	1,1,1,2,2,2, 2,2,2,2.5, 3,4,4,4^T	2,3,3.5,3.5, 4,4,5^T,5.5
500-600	2,2,2,2, 2,4^T	2,2,2,2^T, 3,4	2^T	1^T,2,2,2, 2^T,3,3^T,3.5^T	2,2,3,3			
600-750	1,1,1,2, 2,4	1,1^T,2,3, 3,3.5,3.5^T						

T - LIGHT TURBULENCE
X - 10 TO 20 KT. CROSSWIND
C - 400 TO 500 FT. CEILING

DEPARTMENT OF THE AIR FORCE
HEADQUARTERS 60TH MILITARY AIRLIFT WING (MAC)
TRAVIS AIR FORCE BASE, CALIFORNIA 94535

[illegible] DOV (Lt Col Sorum, 3647) 1 - OCT 1982

[illegible] Pilot Questionnaires Regarding C-5 Flight Characteristics
(22 AF/DOV Ltr, 13 Sep 82)

[illegible] 22 AF/~~DOV~~
MAC/XPQT
<u>IN TURN</u>

Completed questionnaires are forwarded per your request.

~~EDWARD A. KLEIN, Lt Col, USAF~~
Chief, Aircrew Standardization
and Evaluation Division

1 Atch
37 Questionnaires

1st Ind, 22AF/DOV 18 Oct 82

TO: HQ MAC/XPQT

1. Subject questionnaires are returned as requested by your letter, same subject, 7 September 1982.

2. Most C-5A pilots find that the manual flying characteristics of the C-5A are excellent. The autopilot roll rate is too fast for passenger comfort unless the pilot exercises extra care in making normal turns. Air Refueling presents some control problems because of bow wave effects on the KC-135. Control of the C-5A during turbulence and strong crosswinds is very good because of the amount of aileron control available with flaps extended beyond 80 percent. Crosswind gear is seldom needed for takeoff and landing due to exceptional aileron control available.

3. Recommendation: Change the C-5A autopilot roll rate to be similar to the C-141B.

ROBERT T. GRABLE, Colonel, USAF
Director, Aircrew Stan/Eval
DCS/Operations

1 Atch nc

Cy to: HQ MAC/DOVA,
w/o questionnaire

Figure A-2 Cover Letter for Completed Pilot Rating Forms

APPENDIX B

APPENDIX B

The tables in this appendix clarify the flight cases of the L-1011 referenced throughout the report. These data were obtained from Reference 19.

They contain an analysis of takeoff, approach, landing, climb, cruise and descent flight phases over a weight range of 270,000 to 550,000 pounds. The c.g. range covered is from 12 to 35 percent of the mean aerodynamic chord (the normal forward and aft limits).

THE FOLLOWING TABLES PROVIDE THE FLIGHT CONDITIONS FOR THE POINTS SHOWN IN LOCKHEED L-1011 DATA

TABLE	FIGURE NO.
C-1	29
C-2	30
C-3	31
C-4	34
C-5	35
C-6	36

Table B-1 Key to L-1011 Cases for Figure 29

CASE	FLIGHT PHASE	WEIGHT (LBS)	ALTITUDE (FT)	V_e (KNOTS)	FLAPS (DEG)	C.G. % $\bar{c}$
B1A	CL (CLIMB)	496,000	S.L.	256	0	17
B1B						28
B2A		314,500		350		12
B2B						35
B3A		492,000	12,000	256		16.8
B3B						28.4
B4A		314,500		366		12
B4B						35
B5A		488,000	25,000	255		16.7
B5B						28.7
B6A		314,500		355		12
B6B						35

Table B-2 Key to L-1011 Cases for Figure 30

CASE	FLIGHT PHASE	WEIGHT (LBS)	ALTITUDE (FT)	V_e (KNOTS)	FLAPS (DEG)	C.G. % $\bar{c}$
B7A	CR (CRUISE)	483,000	31,000	290	0	16.5
B7B						29
B8A				310		16.5
B8B						29
B9A		448,000	35,000	263		15.6
B9B						31.8
B10A				284		15.6
B10B						21.8
B11A		368,000	39,000	239		13.6
B11B						34.4
B12A				258		13.6
B12B						34.4

Table B-3 Key to L-1011 Cases for Figure 31

CASE	FLIGHT PHASE	WEIGHT (LBS)	ALTITUDE (FT)	V_e (KNOTS)	FLAPS (DEG)	C.G. % $\bar{c}$
B16A	D (DESCENT)	314,500	25,000	330	0	12
B16B						35
B17A			18,000	337		12
B17B						35
B18A			10,000	346		12
B18B						35
B19A				253		12
B19B						35
B20A			2,000			12
B20B						35
B25A			4,000	431		12
B25B						35

Table B-4 Key to L-1011 Cases for Figure 34

CASE	FLIGHT PHASE	WEIGHT (LBS)	ALTITUDE (FT)	V_e (KNOTS)	FLAPS (DEG)	C.G. % $\bar{c}$
C1A	TO (TAKE-OFF)	496,000	S. L.	176	10	17
C1B						28
C2A				230		17
C2B						28
C3A		314,500		147		12
C3B						35
C4A				230		12
C4B						35

Table B-5 Key to L-1011 Cases for Figure 35

CASE	FLIGHT PHASE	WEIGHT (LBS)	ALTITUDE (FT)	V_e (KNOTS)	FLAPS (DEG)	C.G. % $\bar{c}$
C5A	PA (POWERED APPROACH)	368,000	S. L.	157	22	13.6
C5B						34.4
C6A				220		13.6
C6B						34.4
C7A		314,500		143		12
C7B						35
C8A				220		12
C8B						35

Table B-6 Key to L-1011 Cases for Figure 36

CASE	FLIGHT PHASE	WEIGHT (LBS)	ALTITUDE (FT.)	V_e (KNOTS)	FLAPS (DEG)	C.G. % $\bar{c}$
C9A	L (LANDING)	368,000	S. L.	145	33	13.6
C9B						34.4
C10A				205		13.6
C10B						34.4
C11A		270,000		125		12
C11B						35
C12A				205		12
C12B						35