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TENTATIVE STOL FLYING QUALITIES CRITERIA FOR MIL STANDARD AND HANDBOOK

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20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A move is underway in the military services to expand the scope of the military flying qualities specification, MIL-F-8785C to include STOL flying qualities. This report is the result of review, analysis and unification of existing STOL flying qualities data in a form facilitating inclusion into the new MIL Standard and Handbook, particularly in the area where STOL aircraft differ from CTOL aircraft. The report recommends proposed requirements where sufficient data exist; the report presents discussion where data are sparse or non-existant.

FOREWORD

The work reported herein was performed during the period from June 1982 to March 1983 under Contract F33615-80-C-3604 from the Air Force Wright Aeronautical Laboratories, Air Force Systems Command. Funding for this research was provided by the Naval Air Development Center. Captain Stanley G. Fuller (USAF) served as the Contract Technical Monitor. The STI Technical Director was Mr. Irving L. Ashkenas. Mr. Roger H. Hoh was the STI Project Engineer.

We would like to acknowledge the considerable technical and editorial contributions of Messrs. D. J. Moorhouse and R. J. Woodcock of the USAF Flight Dynamics Lab and Dr. James Franklin of the NASA Ames Research Center.

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SECTION I

INTRODUCTION

Aircraft intended to operate within the constraints implied by the short-takeoff-and-landing (STOL) designation possess flying characteristics peculiar to the design, operational, and mission needs of such aircraft. Generally, lower takeoff, approach and landing speeds, shorter field lengths, steeper flight path angles, and partial lift from propulsion units, are conditions used to define STOLs and to distinguish them from conventional aircraft (CTOLs). Similarly, STOLs are separate from vertical takeoff and landing (VTOL) aircraft by virtue of the fact that STOLs rely at least partially on aerodynamic lift, while VTOLs must, for part of their flight profile, derive full lift from propulsion.

Military flying qualities specifications exist for CTOLs (Reference 1) as well as for V/STOLs (Reference 2). Portions of both are applicable to STOLs, yet both have shortcomings in dealing with the most critical areas of STOL flying qualities. Reference 2 is more applicable to VTOL aircraft than to STOLs.

A move is underway in the military services to expand the scope of MIL-F-8785C (Reference 1) and modify its format to serve as a more universal specification. The replacement document will be divided into two parts: a MIL Standard, in which the procuring activity fills blanks to tailor a flying qualities specification for the anticipated mission elements; and a MIL Handbook, from which the numbers are taken for the blanks. A proposed MIL Standard and Handbook have been written (Reference 3), with the Handbook dealing exclusively with CTOL aircraft requirements.

A. SCOPE OF THE REPORT

The primary objective of this research has been to review, analyze and unify existing STOL handling quality data in a form which would facilitate modifications to Reference 3 to cover the particular areas where STOL aircraft differ from CTOL aircraft. Where possible, this report recommends tentative requirements to supplant those of Reference 3; in cases where the data is sparse only augmenting discussion is provided.

By their nature, STOLs are distinguishable from CTOLs only during the terminal phases of flight (Category C, Reference 1). For this reason the focus of this report is on the final approach and landing. Little will be discussed about takeoff, since the principles involved are generally similar to those for CTOLs (Reference 4), and because there are no indications from past research of any unusual flying qualities problems arising during takeoff.

As a result of the experimental data base available, the report will deal entirely with medium to large (Class II and III) aircraft. However, many of the results reported herein may be applicable to fighter-type (Class IV) aircraft as well, since the operational constraints would be similar in that precision landings are a key aspect of the mission.

With few exceptions, the STOL aircraft simulated and flown in the past have been of the powered-lift type — i.e., a percentage of lift is nonaerodynamic in origin, supplied by the propulsion units. It is to be expected that this will continue to be the case, since low-wing-loading STOLs (such as the deHavilland of Canada DHC-6 Twin Otter) carry weight and configurational penalties in the high-speed range. The result of this is that essentially all of the data and criteria discussed in this report pertain to powered-lift STOLs.

It is generally true that STOLs differ from CTOLs primarily in the area of flight path control. Therefore, the major effort in this program has been in defining flight path criteria. With the possible exception of operation with one propulsion unit inoperative, the lateral-directional requirements for STOLs are basically identical to those for CTOLs (see, for example, References 5-7). Differential loss of power on a STOL can result in differential loss of lift, causing extreme rolling moments. Therefore, for normal operations, the lateral-directional flying qualities requirements of Reference 1 are as applicable to STOLs as to CTOLs and will not be reviewed here.

B. BACKGROUND

In this research a great deal of emphasis has been placed on STOL flight path control during final approach and landing. A wide variety of possible STOL design concepts have been considered. These are summarized as follows:

- Powered Lift STOLs

  Examples of powered lift STOLs have been the Boeing YC-14, the Douglas YC-15, and the NASA-Ames Augmentor Wing Aircraft. Each one of these aircraft utilized highly effective flaps, sometimes in combination with thrust vectoring (the Augmentor Wing) to obtain a large effective thrust inclination angle. A great deal of in-flight and simulator data were taken for powered lift STOLs during the past decade, and hence most of the criteria in this report are directly applicable to this type of STOL. A plot of the typical steady state characteristics of a powered lift STOL is given in Figure 1. Here it can be seen that for normal approach speeds, the slope of the flight path angle vs. airspeed curves (γ-V plots) is either zero or positive indicating that such aircraft will be normally flown using throttle to control flight path. The lines of constant attitude which are superimposed on this curve indicate that when pitch attitude is held constant and thrust is varied, the resulting steady flight path response will occur with small or zero changes in airspeed — a desirable feature. The primary objective of using powered lift is to achieve low approach speeds for aircraft with very high wing loading consistent with large payloads and good cruise performance.

- Low Wing Loading STOLs

  These aircraft achieve short field performance using low wing loading to reduce the approach speed. A typical low wing loading STOL would be the DeHavilland Twin Otter. The steady state flight path response characteristics of the Twin Otter are shown in Figure 2. Here it can be seen that the slope of the flight path angle vs. airspeed responses are primarily negative over the normal range of approach air speeds allowing flight path to be controlled with pitch attitude. Many of these aircraft use highly effective flaps (e.g., the Twin Otter), and hence have a relatively large thrust inclination angle (48 deg in the case of the Twin Otter). Because of

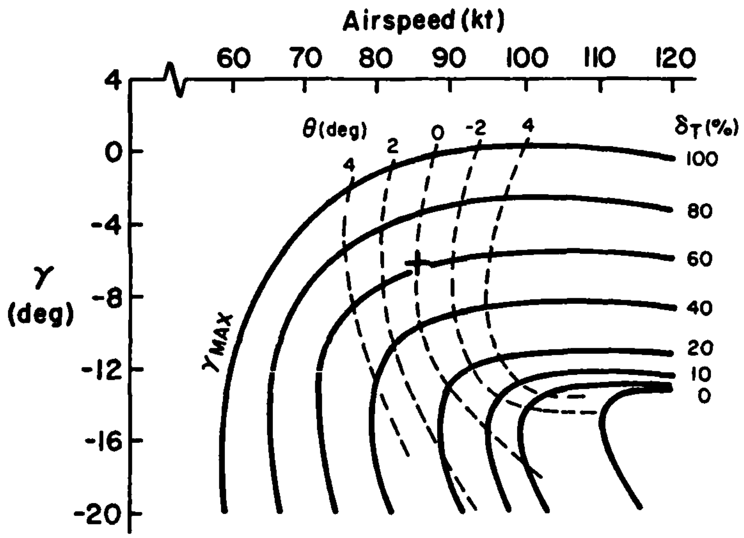


Figure 1. Steady-State Path Response -- Typical Powered-Lift STOL γ-V (AMST)

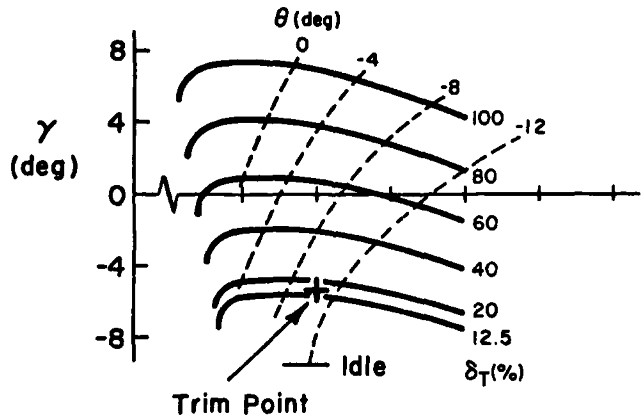


Figure 2. Steady-State Path Response -- Typical Low-Wing-Loading STOL γ-V (Twin Otter)

such large thrust inclination angles, the lines of constant attitude are nearly vertical with only small changes in airspeed occurring with changes in thrust. As a result flight path can be controlled either with pitch attitude or with thrust. The penalty for such desirable handling characteristics is, of course, drag due to the large wing area required.

- High Wing Loading Non-Powered Lift STOLs

  This concept of "short take-off and landing" is based on using conventional fighters to land on small portions of bomb-damaged runways, utilizing a slight reduction in approach speed and achieving short field performance with extremely precise flight path control and highly effective thrust reversing on the runway. While thrust vectoring is proposed for such aircraft, it is based on swiveling the engine at the aft end of the aircraft, resulting in large pitching moments which must be countered by the elevator, and hence, the net vertical force is essentially zero. Such thrust vectoring is primarily only useful for augmented pitch attitude control. Hence, the approach speeds of these aircraft cannot be significantly reduced. There is very little data available for this technique for obtaining STOL landing performance. Nonetheless, it is mentioned here because of the substantial interest in this concept at the present time.

The form of the handling quality criteria for STOL flight path control depends on whether flight path is controlled primarily with throttle or with pitch attitude. Control of path with throttle implies that air-speed is controlled either with pitch attitude or automatically, and is referred to as the backside control technique. When flight path is controlled with pitch attitude airspeed is generally controlled with thrust (or auxiliary surface) and is referred to as the frontside piloting technique. When the effective thrust inclination angle is large, it is impossible to control airspeed effectively with throttle; the backside technique is natural for these configurations. Likewise, when the effective thrust inclination angle is small, control of flight path with throttle is generally degraded and the frontside piloting technique is more natural.

The appropriate criterion to be utilized for STOL flight path control has been found to be dependent on the phase of flight (approach or landing) as well as the proposed piloting technique (frontside or backside) for a given configuration. There is considerable evidence to show that short final and landing is considerably more critical than glide slope tracking even when such tracking occurs in IMC conditions (see Reference 12). The proposed organization of flight path control criteria is given in flow chart form in Figure 3. Each of the end items of the flow chart in Figure 3 represents the necessity for a separate flight path criterion. It is quite common to use throttle to control flight path on the approach and to use attitude to control flight path in the flare, hence more than one criterion in Figure 3 may be applicable to a single aircraft.

The decision of whether to use throttle or attitude to control flight path is in most cases quite obvious and is strongly dependent on the total effective thrust inclination angle. The generic effect of flight path response to throttle as the effective thrust inclination angle progresses from zero (aligned with longitudinal axis of the aircraft) to 90 deg or greater (perpendicular to the longitudinal aircraft axis) is shown in Figure 4. Based on these generic time responses we can conclude the following:

- For total effective thrust inclination angles less than 60-70 deg the response of flight path angle to thrust appears to be too slow to be practical. In such cases it would be necessary to control flight path with pitch attitude. If the aircraft is operating well on the backside of the power required curve ($d\gamma/dV$ large and positive) it will be necessary to provide some type of flight path augmentation.

- For effective thrust inclination angles between approximately 60-90 deg the flight path response to throttle is seen to be quite good in a generic sense. Referring back to Figure 1, it can be seen that aircraft with such large thrust inclination angles generically have very small airspeed changes with changes in thrust. So the "natural" way to fly these aircraft is to use throttle to control flight path. It follows that criteria relating to the flight path

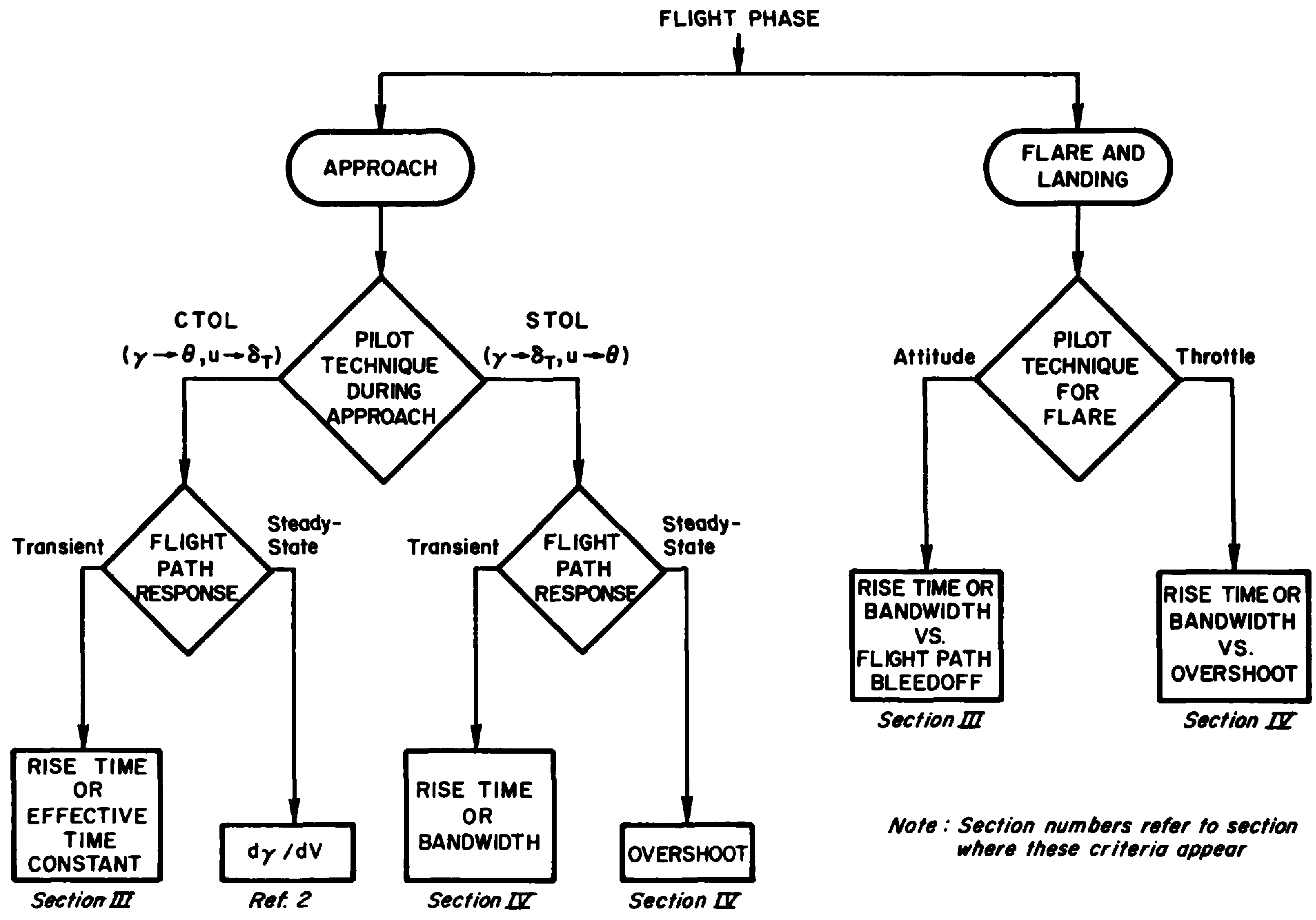


Figure 3. Combinations of Criteria Necessary to Develop a General STOL Flying Quality Specification

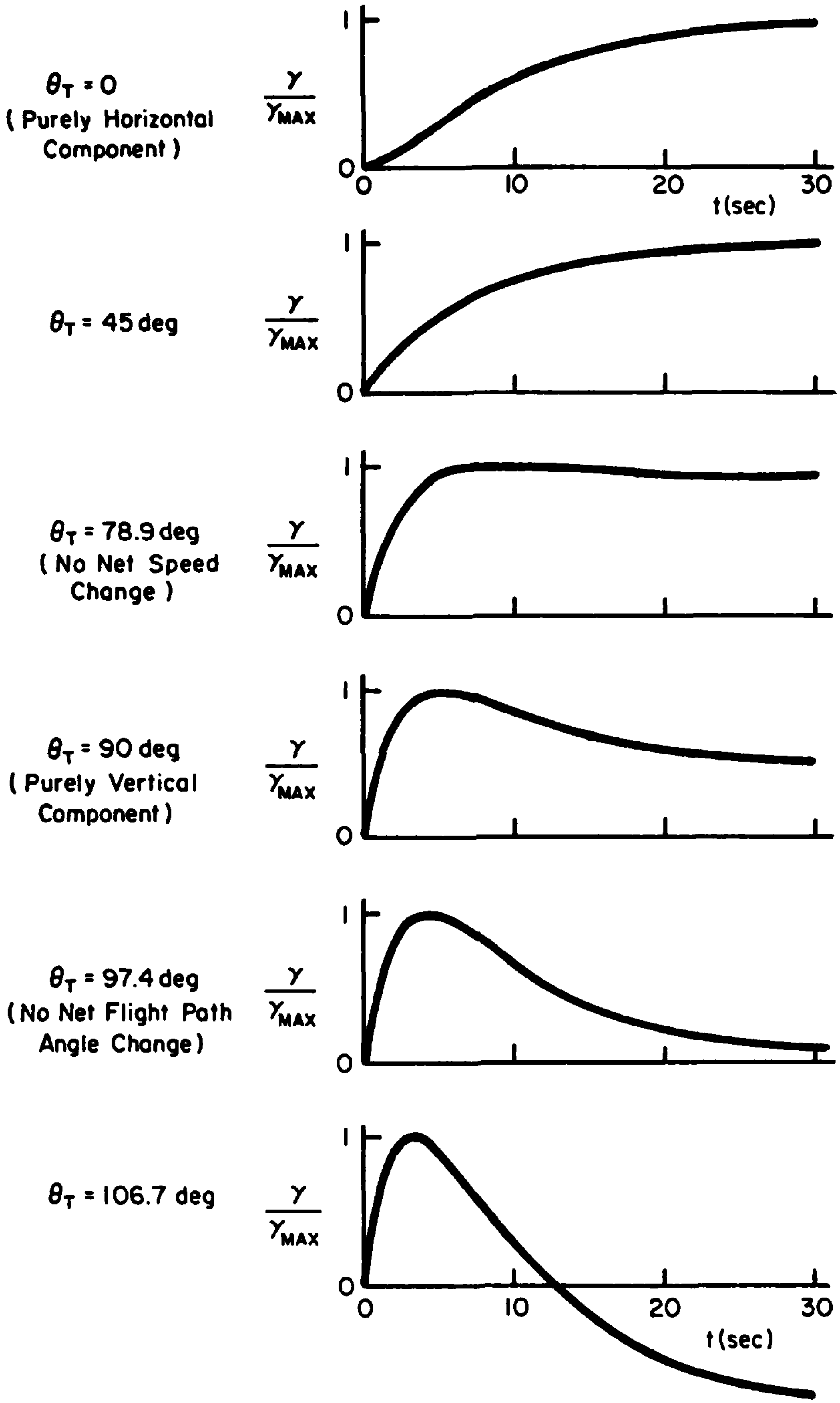


Figure 4. Shape of γ Response to Step δ_T for Varying θ_T

reponse to throttle are needed for such aircraft, as reflected in Figure 3.

- For effective thrust inclination angles greater than 90 deg the flight path bleedoff becomes quite drastic and unacceptable. The corresponding airspeed variations occur because these configurations tend to be unfavorably coupled; that is, increasing thrust to shallow the flight path angle tends to result in a reduction in airspeed. Limits on this are discussed in Section VI-E of this report.

The above observations highlight the natural response characteristics of STOL aircraft based on their thrust and aerodynamic characteristics. However, it is always possible to utilize flight path augmentation to make an aircraft with large thrust inclination angles fly on the frontside or to make an aircraft with small thrust inclination angles to fly very well on the backside. However, such augmentation systems nearly always involve the use of an auxiliary aerodynamic control, such as the Coanda flap on the YC-14 (to modulate drag).

The initial flight path response to attitude changes is extremely important for any frontside control technique. The parameter $(1/T_{\theta_2})_{eff}$ was developed in Section III of this report as a key criterion parameter for the initial flight path response of STOL aircraft, for both approach and landing. Attention is called to this parameter because it has not appeared previously and is a general extension to the $1/T_{\theta_2}$ parameter utilized in Reference 3. By using $(1/T_{\theta_2})_{eff}$ it will be possible to blend the STOL criteria suggested in this study directly into the MIL Standard and Handbook as proposed in Reference 3.

Tentative criteria for each of the end items in Figure 3 are developed in Sections III and IV of this report. These criteria are based on collecting and unifying a considerable amount of existing powered lift STOL data. Some of the requirement forms are not new and were selected as the most promising of a number of previously proposed criteria.

It should be noted that pitch attitude has been specified separately and independently from requirements on flight path control. The rationale behind this was that mixed criteria (such as ω_{sp} vs. n/α) have proven to be difficult to interpret physically and hence are not useful for fixing deficient flying qualities. For example, handling quality experts seem completely unable to agree on the physical implications of the above noted n/α term; is it the numerator of the pitch attitude ($\frac{n}{\alpha} \doteq \frac{g}{U_o} \frac{1}{T_{\theta_2}}$) response or is it the flight path response to changes in pitch attitude ($\frac{\gamma}{\theta} \doteq \frac{1}{T_{\theta_2} s + 1}$)?

The proposed criteria for pitch attitude control are covered in Section II of this report and are based on the bandwidth criterion for pitch attitude proposed in Reference 3.

Sections III and IV provide extensive discussions on STOL flight path control, including reviews of the possible alternative control techniques available to the pilot. New requirements are recommended for specifying minimum flight path response to changes in pitch attitude in Section III; in Section IV, a combination of previously suggested and new criteria are proposed for flight path response to any designated controller (e.g., exhaust gas, nozzle angle, RPM). Sections III and IV correspond to Paras. 3.3.1 and 3.3.2, respectively, of Reference 3.

Section V suggests limits on minimum flight path control power. The requirements replace Para. 3.3.4 of Reference 3.

Section VI contains information of a more general form, applicable to various parts of Reference 3. The subjects covered are the effects of wind shears and failures on STOL flying qualities, the definition of limiting flight conditions, and some aspects of path/speed coupling. There is insufficient data in these areas to devise flying qualities requirements, so the discussions are presented as an augmentation to similar sections of Reference 3.

Finally, Section VII serves to summarize the report in terms of conclusions on the status of development of STOL flying qualities criteria, and recommendations for future research.

SECTION II

PITCH ATTITUDE RESPONSE TO PITCH CONTROLLER

A. GENERAL

This section introduces the recommended STOL requirement for pitch axis response to the primary pitch controller. It is the STOL counterpart to Reference 3 Para. 3.2.1, "Pitch Attitude Response to Pitch Controller." The requirement on pitch attitude has been specified in terms of bandwidth.

B. STOL PITCH AXIS BANDWIDTH REQUIREMENT

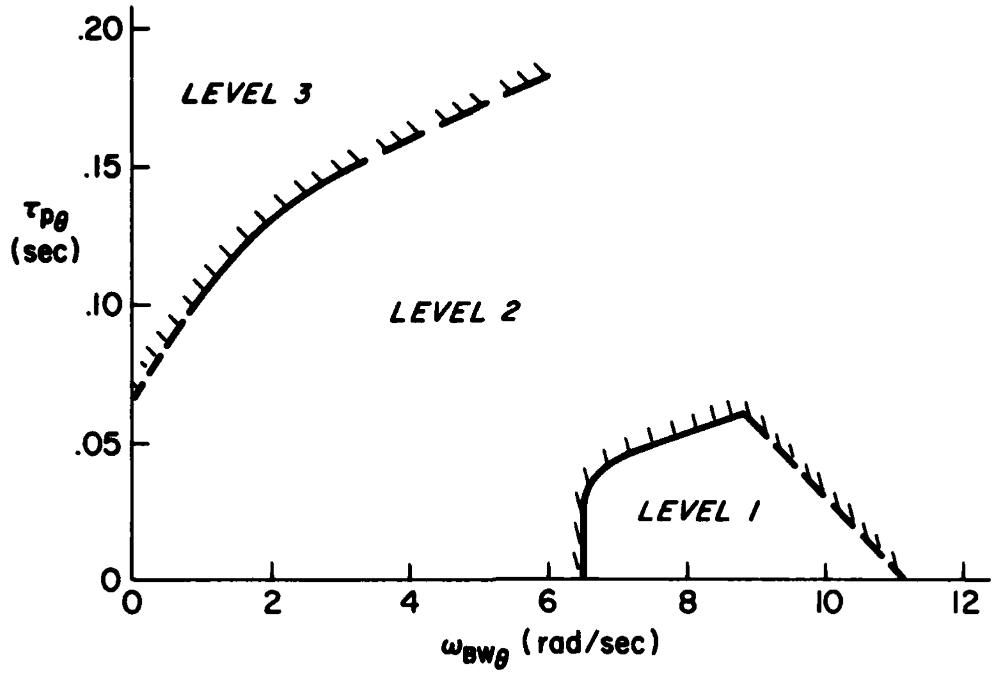
1. Reason for Requirement

A good measure of the handling qualities of an aircraft has been shown to be the aggressiveness that can be achieved when operating in a closed-loop compensatory tracking task. An aircraft that can be flown aggressively without pitch bobbling or concern over stability will have superior tracking performance when regulating against disturbances. The maximum frequency at which such closed-loop tracking can take place without threatening stability is referred to as "bandwidth" (ω_{BW}). No assumption of pilot dynamics is necessary in applying this requirement. Furthermore, the criterion can be applied directly to unaugmented and highly augmented aircraft with equal ease.

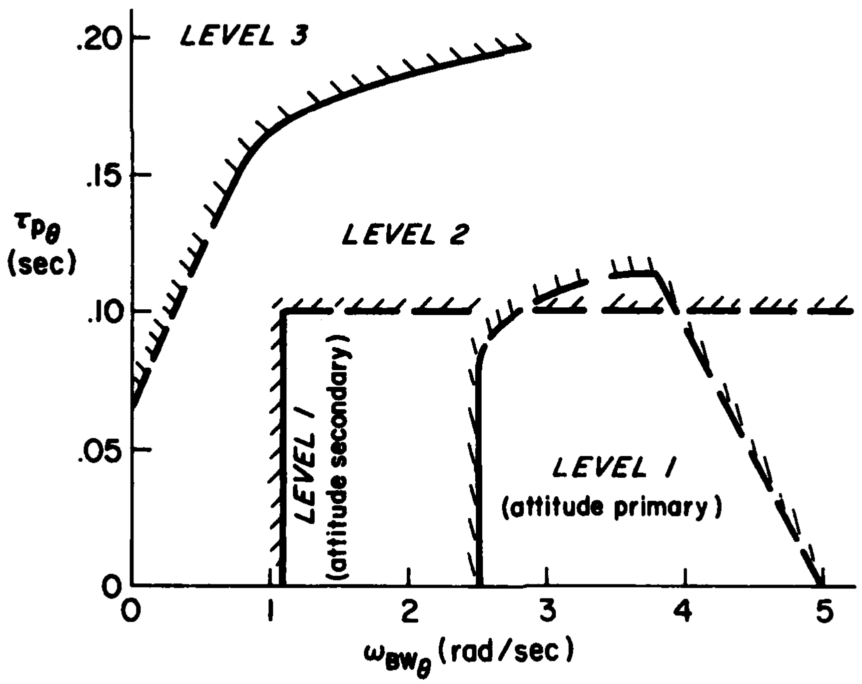
2. Statement of Requirement and Recommended Values

STOL pitch axis bandwidth requirement. The bandwidth of the open-loop pitch attitude response to pitch controller shall have the following characteristics: ________________________.

Recommended limits for the pitch attitude bandwidth are given as a function of the parameter τ_{p_θ} (defined in "Rationale Behind Requirement") in Figure 5 for Categories A and C. No recommendations for Category B are made at this time. "Attitude primary" refers to configurations where flight path is primarily controlled with attitude (see



a) Category A Flight Phases



b) Category C Flight Phases

Figure 5. Tentative Pitch Attitude Bandwidth Requirements for STOL Aircraft

Section III). "Attitude secondary" indicates that a separate flight path controller has been defined and the role of attitude is to control the flight reference — which is usually airspeed.

3. Rationale Behind Requirement

The role of pitch attitude as an inner loop for flight path control is preserved for STOL aircraft that meet the Level 1 requirements of Section III, i.e., when attitude is primary for flight path control. Most STOL aircraft utilize thrust modulation for glide slope tracking and hence attitude control becomes a relatively low frequency trim function to control the flight reference, usually airspeed. Therefore, we would expect a somewhat relaxed boundary on pitch attitude bandwidth for glide slope tracking. In the event that the landing flare is also accomplished with power, this relaxed boundary would apply all the way to touchdown. Practically speaking, the attitude bandwidth of the aircraft does not change between the approach and landing flight phases. Therefore, aircraft using attitude to flare will operate under the more stringent attitude bandwidth during the entire approach.

In the proposed MIL Handbook, Reference 3, several alternative criteria are suggested for specifying pitch attitude control. One set of alternatives (3.2.1.1 of Reference 3) retains the criteria of MIL-F-8785C (Reference 1) for short-period damping (ζ_{sp}) and frequency (ω_{sp}), where the latter is specified as a function of the parameter n/α. In Reference 3 it is recommended that the short-period characteristics be obtained through simultaneous equivalent systems matches of θ and n_z responses to a stick force input. The reason for such a simultaneous match is based on CTOL control of attitude and flight path. When the aircraft is flown with the STOL technique, flight path is controlled with a designated controller such as throttle, so that matching response of n_z to the pitch controller is not appropriate. For this reason the equivalent system criterion from Reference 3 is not recommended for STOL aircraft which do not utilize attitude for flight path control. Inasmuch as an acceptable time response parameter is not currently well developed the bandwidth criterion from Reference 3 (Para. 3.2.1.2) is proposed at this time.

The bandwidth as defined for handling quality criterion purposes is the frequency at which the phase margin of the actual aircraft plus flight control system is 45 deg or the gain margin is 6 db, whichever frequency is lower (Figure 6). Referring to Figure 6, this describes the pilot's ability to double his gain or to add a time delay or phase lag without causing an instability. In order to apply this definition, one first determines the frequency for neutral stability from the phase portion of the Bode plot (ω_{180}). The next step is to note the frequency at which the phase margin is 45 deg (ω_{135}). This is the bandwidth frequency as defined by phase, $\omega_{BW_{phase}}$. Finally, note the amplitude corresponding to ω_{180} and add 6 dB. Find the frequency at which this value occurs on the amplitude curve; call it $\omega_{BW_{gain}}$. The bandwidth, ω_{BW}, is the lesser of $\omega_{BW_{phase}}$ and $\omega_{BW_{gain}}$. If $\omega_{BW} = \omega_{BW_{gain}}$, the system is said to be gain-margin limited; that is, the aircraft is driven to neutral stability when the pilot increases his gain by 6 dB (a factor of 2). Gain-margin-limited aircraft may have a great deal of phase margin, ϕ_M, but increasing the gain slightly causes ϕ_M to decrease rapidly. Such systems are characterized by frequency response amplitude plots that are flat, combined with phase plots that roll off rapidly, such as shown in Figure 6.

4. Guidance for Application

The attitude bandwidth is easy to generate from analysis procedures once the vehicle and augmentor characteristics are defined; i.e., all that is needed is a Bode plot of the pitch response to pilot's control force input. Methods of obtaining the frequency response (Bode plot) from simulation or flight test are given in Reference 3 (Para. 3.2.1.2).

One word of caution is necessary, however. Frequency responses that are gain-margin-limited tend to have shelf-like amplitude plots as shown in Figure 7. With such systems a small increase in pilot gain results in a large change in crossover frequency and a corresponding rapid decrease in phase margin. The decrease in phase margin becomes critical for attitude control when τ_{p_θ} is moderately large (of order 0.1 to 0.2). The two configurations shown in Figure 7 are taken from the Reference 8

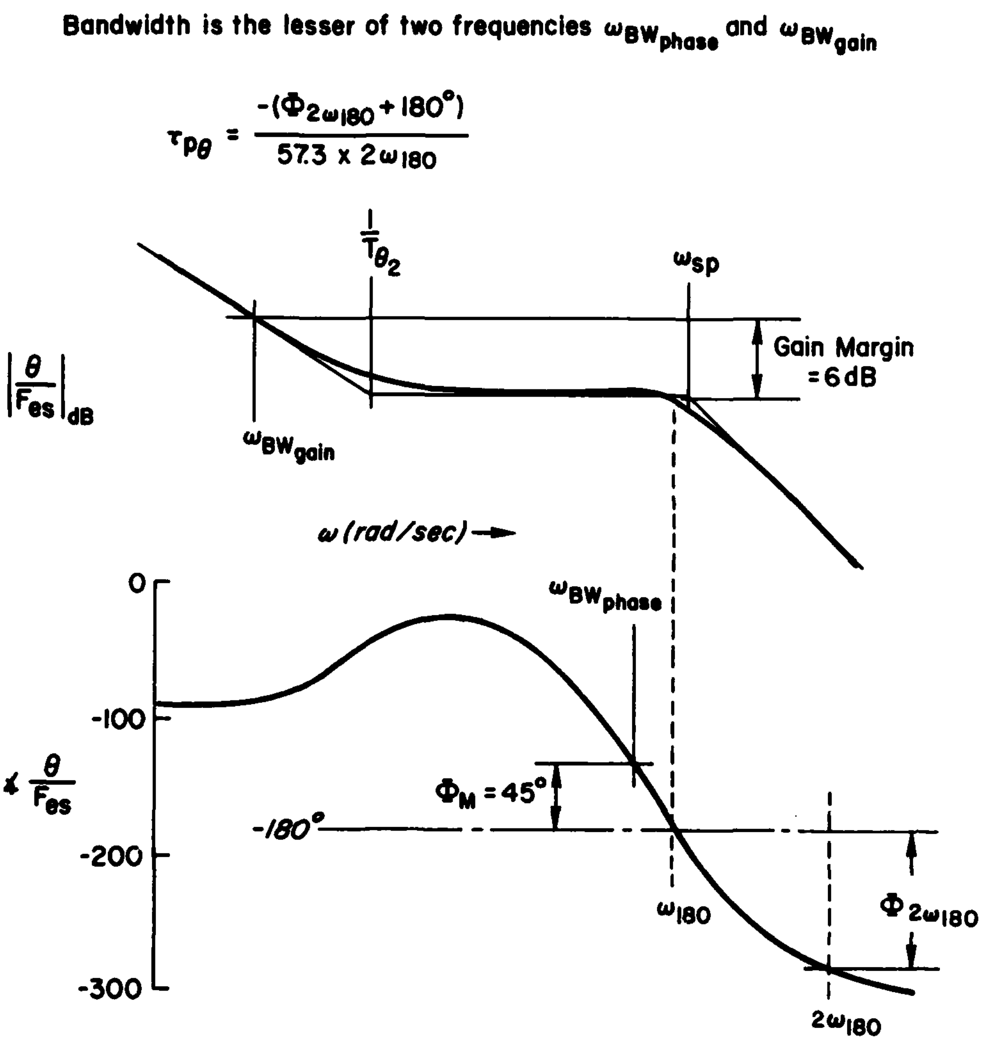


Figure 6. Definition of Bandwidth Frequency, ω_{BW_θ}, and Phase Delay, τ_{p_θ}, from Open Loop Frequency Response

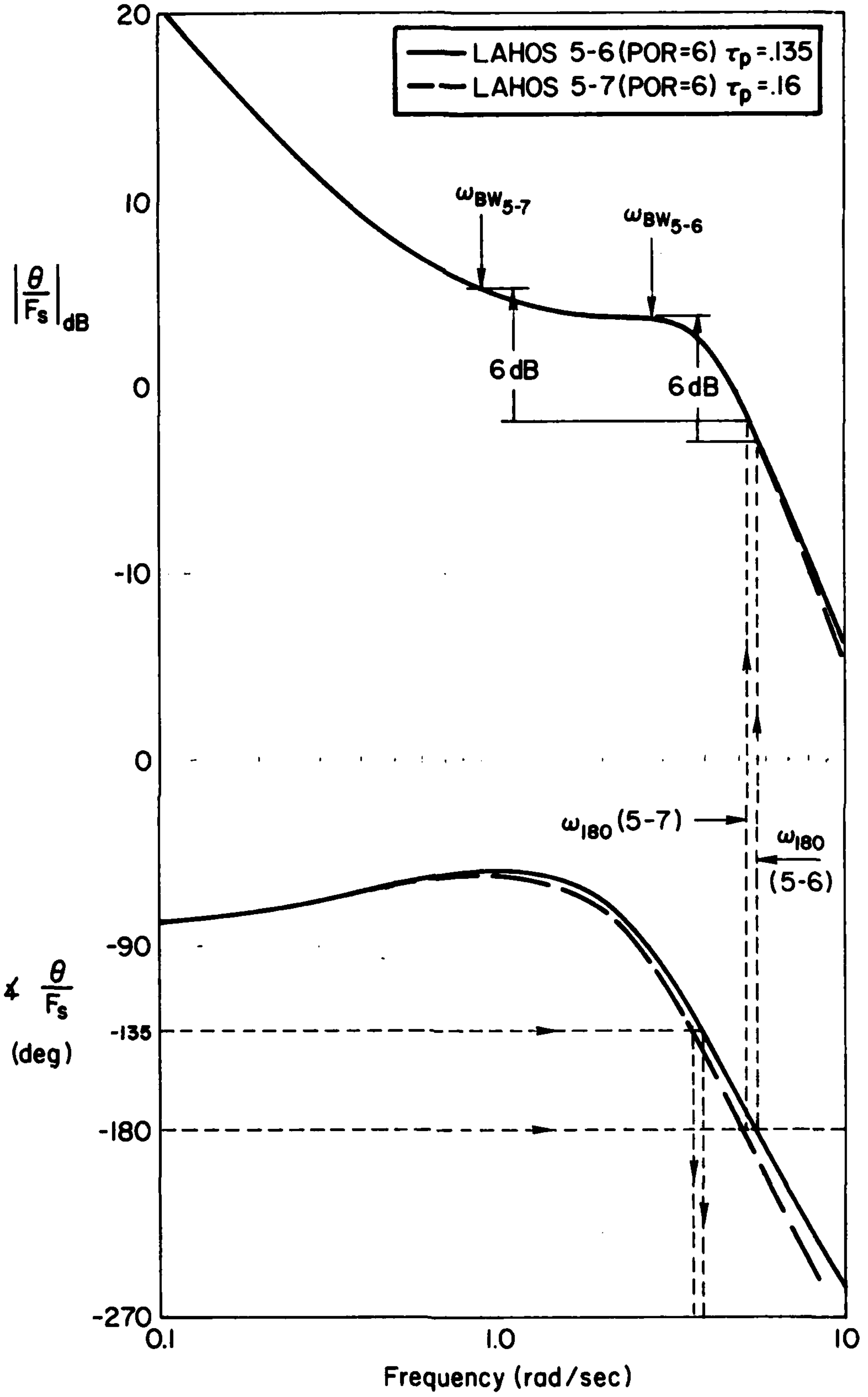


Figure 7. Large Difference in Bandwidth Due to Shelf Amplitude Plot Combined with Moderate Values of τ_{p_θ} (Configurations of Reference 8)

experiment. Applying the previously discussed definition of bandwidth, we find that both Configurations 5-6 and 5-7 are gain-margin-limited. Both configurations suffer from the same deficiency, i.e., moderate values of $\tau_{p\theta}$ combined with a shelf-like amplitude curve that results in a very rapid decrease in phase margin with small changes in pilot gain. However, the 6 dB limit selected to define $\omega_{BW_{gain}}$ does not "catch" Configuration 5-6. While this configuration is correctly predicted to be Level 2 (PR = 6) on the basis of $\tau_{p\theta}$, the value of ω_{BW_θ} is in the Level 1 region. Had a slightly higher value of gain margin been picked to define ω_{BW_θ}, the bandwidths for Configurations 5-6 and 5-7 would be approximately equal. However, because of the nature of shelf-like frequency responses, there will always be a case which can "fool" the criterion. An experienced handling qualities engineer would immediately recognize the shelf-like shape and moderate $\tau_{p\theta}$ as a significant deficiency. However, the purpose of a criterion is to eliminate such judgment calls. Nonetheless, it is not expected that this idiosyncrasy will result in problems with correlating or predicting pilot rating data inasmuch as moderate (poor) values of $\tau_{p\theta}$ are necessary to get misleading values of ω_{BW_θ} (i.e., rapid phase rolloff in a frequency region where the amplitude curve is flat must occur to get the effect shown in Figure 7).

5. Demonstration of Compliance

The values of $\tau_{p\theta}$ and ω_{BW_θ} required to demonstrate compliance with the Figure 1 boundaries are obtained from open-loop (flight control system active but pilot out of the loop) frequency responses of pitch attitude to pilot-applied force, as shown in Figure 6. These plots initially may be obtained from analyses and later from Fourier-transformed flight test or simulator data. The Air Force Flight Test Center (AFFTC) has had considerable success in Fourier transforming flight test data taken during operational tasks (as opposed to specially tailored frequency sweeps). This generates useful pilot commentary, saves flight test time, and identifies the actual configuration at the flight condition to be utilized operationally. In the Reference 9 flight test of

Direct Force Control modes it was found that excellent frequency responses could be obtained by Fast Fourier Transforming pilot-generated frequency sweeps. The instrumentation required to obtain this data was minimal, consisting of a yaw rate gyro and a pedal position transducer.

If significant nonlinearities are present in the system, the open-loop frequency response will depend on the size of the input used in the identification process. When such nonlinearities are suspected, several frequency sweeps should be accomplished with different input magnitudes. Data taken during operational tasks will implicitly account for nonlinear effects.

6. Supporting Data

The primary data base for developing the flight path criteria (Sections III, IV, and V) consists of six references (References 10-15); References 14 and 15 are flight test reports, while the remainder are moving-base simulations (Reference 12 also contains results of a limited flight test program). The details of these reports are discussed in Section III. All the cases considered in the development of flight path criteria included a pitch attitude hold or pitch rate SAS, in order to separate as much as possible the effects of attitude control from the effects of flight path control on pilots' assessments. For most STOLs, and especially those employing powered lift, bare-airframe characteristics are inadequate. The classical short-period mode degenerates into two first-order modes, one of which is often divergent. For this reason such STOLs will almost always require a pitch axis SAS to achieve satisfactory flying qualities. Limited flight test data for unaugmented STOLs in approach were also taken from Reference 16; this reference will be discussed shortly.

Table 1 summarizes the STOL aircraft used as the primary data base for the Category C boundaries of Figure 5b, including test facilities, SAS type, and vehicles simulated.

Identification of appropriate pilot ratings for pitch attitude control required an extensive review of the data base. It was necessary to rule out any case where poor ratings might be due to factors other than

TABLE 1. SUMMARY OF DATA SOURCES FOR PITCH ATTITUDE CONTROL STUDY

REFERENCE NUMBER	AIRCRAFT SIMULATED	FACILITY[a]	SAS TYPE[b]
10	Breguet BR 941S	FSAA	ACAH
11	AWJSRA	FSAA	ACAH
12	Various Generic Powered-Lift	S-16	ACAH
12	Various Generic Powered-Lift	Navion[c]	ACAH
13	Generic (Based on Ref. 4)	FSAA	ACAH
14	AWJSRA	AWJSRA[c]	RCAH
15	Generic Powered-Lift	Navion[c]	RCAH
16	Generic Powered-Lift	X-22A	None

[a]FSAA = Flight Simulator for Advanced Aircraft (moving-base simulator, NASA Ames)

S-16 = Limited-motion simulator, NASA Ames

Navion = Princeton Variable Stability Aircraft

AWJSRA = Augmentor Wing Jet STOL Research Aircraft (modified DHC-8A Buffalo)

X-22A = Variable-stability V/STOL aircraft

[b]ACAH = Attitude-command/attitude-hold

RCAH = Rate-command/attitude-hold

[c]Actuation dynamics were estimated

pitch attitude (e.g., control of flight path and/or airspeed, atmospheric disturbances, etc.) First, all the aircraft configurations from the references listed in Table 1 were compared with the tentative flight path criteria; those meeting the Level 1 requirements with one controller (either pitch attitude or throttle) were considered candidates. Then the pilot comments for these configurations were reviewed for any signs of other objectionable characteristics. In general, none were found.

With only a single exception (Reference 11), all the cases reported in References 10-15 were flown with the pitch SAS active. As a result, the augmented-aircraft pitch attitude bandwidths for all configurations in any one study are essentially equal (i.e., configurational variations were in flight path, not pitch, response), so that a large number of pilot ratings can exist for any one value of ω_{BW_θ} and τ_{p_θ}. This makes the X-22A flight tests of Reference 16 very valuable in determining attitude bandwidth boundaries. No SAS was employed in that study; only basic vehicle characteristics (ζ_p, ω_p, ζ_{sp}, ω_{sp}) were varied. Two pilots flew IFR and VFR approaches at two airspeeds and three glide slope angles (-6 and -9 deg at 65 kt; -7 deg at 80 kt). Pilot comments, Cooper-Harper ratings, and turbulence effect ratings (Figure 8) were collected. Since actual landings were not performed, the data from Reference 16 can be considered useful only for developing approach boundaries, or for landings using the STOL technique (flaring with power).

INCREASE OF PILOT EFFORT WITH TURBULENCE	DETERIORATION OF TASK PERFORMANCE WITH TURBULENCE	RATING
NO SIGNIFICANT INCREASE	NO SIGNIFICANT DETERIORATION	A
MORE EFFORT REQUIRED	NO SIGNIFICANT DETERIORATION	B
	MINOR	C
	MODERATE	D
	MODERATE	E
BEST EFFORTS REQUIRED	MAJOR (BUT EVALUATION TASKS CAN STILL BE ACCOMPLISHED)	F
	LARGE (SOME TASKS CANNOT BE PERFORMED)	G
UNABLE TO PERFORM TASKS		H

Figure 8. Turbulence Effect Rating Scale Used in Flight Tests of Reference 16

Because of the large number of pilot ratings, the data will be shown in two forms. Figures 9 and 10 document all the relevant ratings in plots of ω_{BW_θ} vs. τ_{p_θ}. In Figure 9, each data point from References 10-15 has a large number of ratings associated with it corresponding to variation in flight path to throttle response characteristics, as well as trials by different pilots. All flight path response characteristics fell within the Level 1 boundary in either Figure 16 (Section III) or Figure 35 (Section IV). The Reference 16 X-22A data are shown separately on Figure 10, where each point represents one (and sometimes two) pilot ratings. Letters beside the ratings in Figure 10 correspond to the turbulence effect scale of Figure 8.

Pilot ratings as presented in Figures 9 and 10, while very complete, are difficult to review and analyze for trends. These figures are included primarily to show the ratings, bandwidths, and flight conditions of the various studies. In order to facilitate analysis, Figure 11 contains only averaged pilot ratings for the Figures 9 and 10 data. In keeping with Reference 3, which proposes to allow a degradation in Cooper-Harper rating in turbulence (see Table 2), a calm-air rating of 3.5 corresponds to a 5.5 in moderate turbulence in terms of defining the Level 1 limit.

Turbulence was measured and documented for the flight experiment of Reference 14 in terms of the peak u_g and w_g components and maximum wind shear measured during the approach. The authors of Reference 14 felt that these measures are more meaningful for real atmospheric data acquired during a limited time exposure, than are the statistically pure Gaussian measures such as standard deviations. An estimate of the standard deviations was obtained by dividing the peak magnitudes by 3. These results showed that turbulence varied from light ($\sigma_{u_g} \doteq 2$ ft/sec) to moderate ($\sigma_{u_g} = 5$ ft/sec) during the flight tests of Reference 14.

The Figure 5 criterion limit for pitch attitude secondary is based on Figure 11a. The boundary separates the data reasonably well between Levels 1 and 2. Notable exceptions include the SAS-off case from Reference 11, the Reference 12 flight test point, and two configurations from Reference 16 ($\omega_{BW_\theta} = .4$ rad/sec). The rating of 9.5 for the

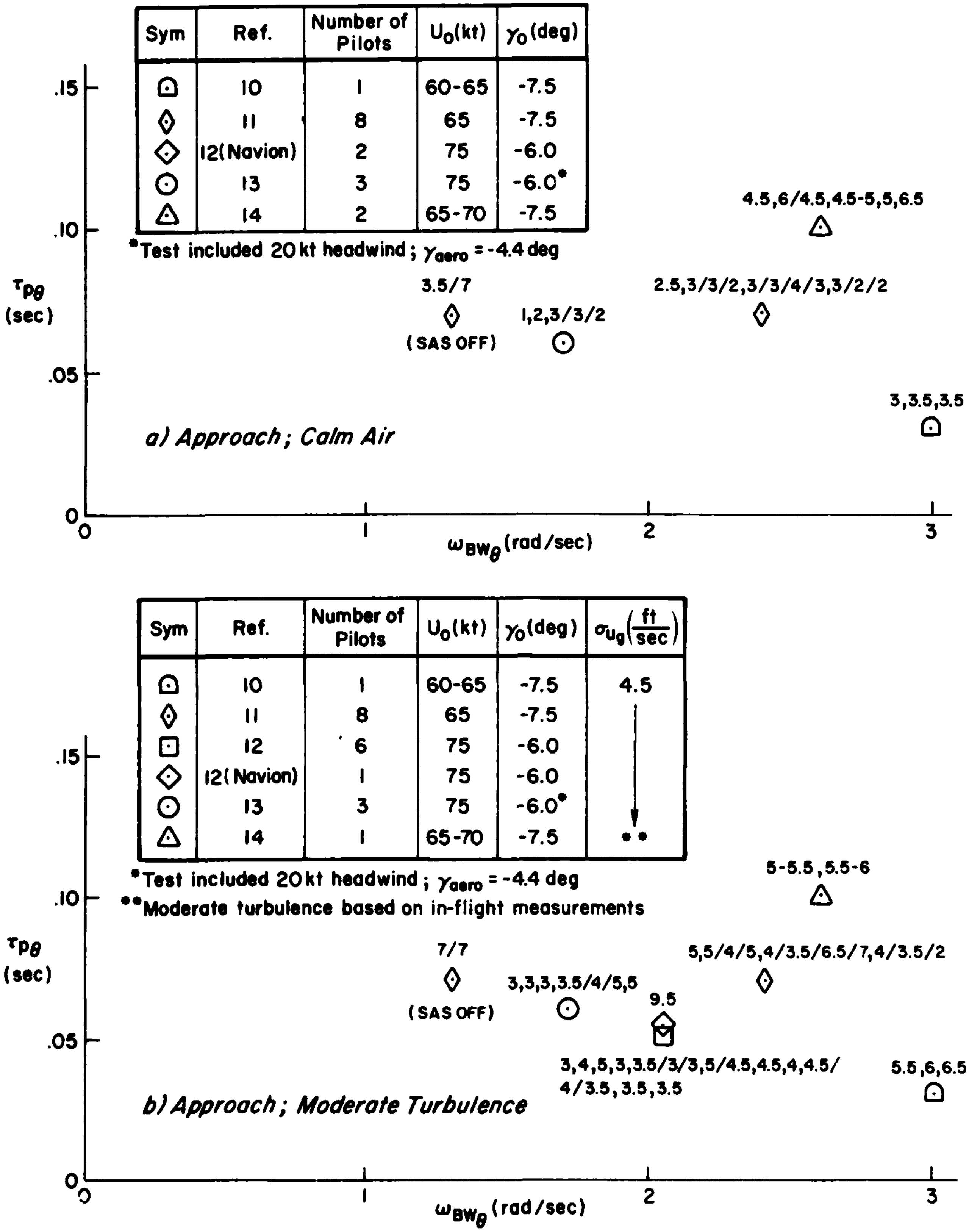
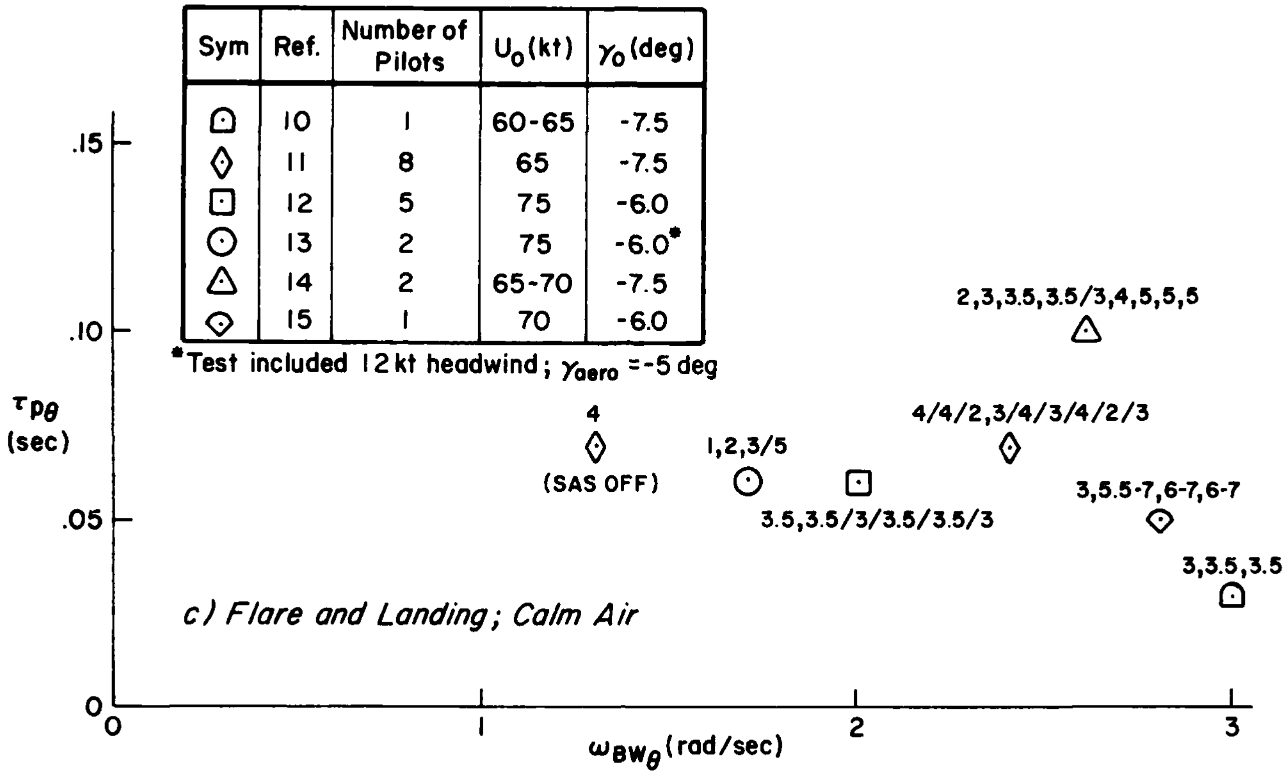


Figure 9. Summary of Pilot Ratings for STOL Approach and Landing (Reference 12 Ratings from Appendix A)



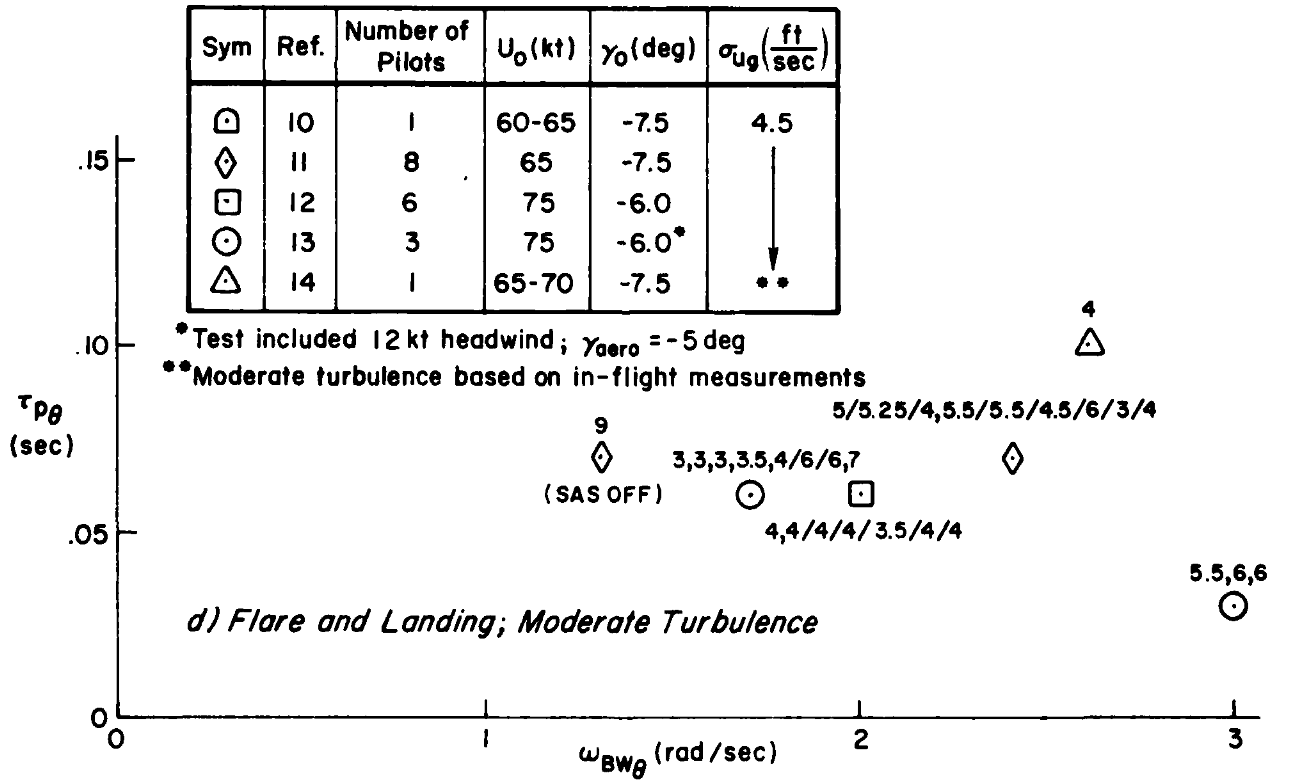


Figure 9. (Concluded)

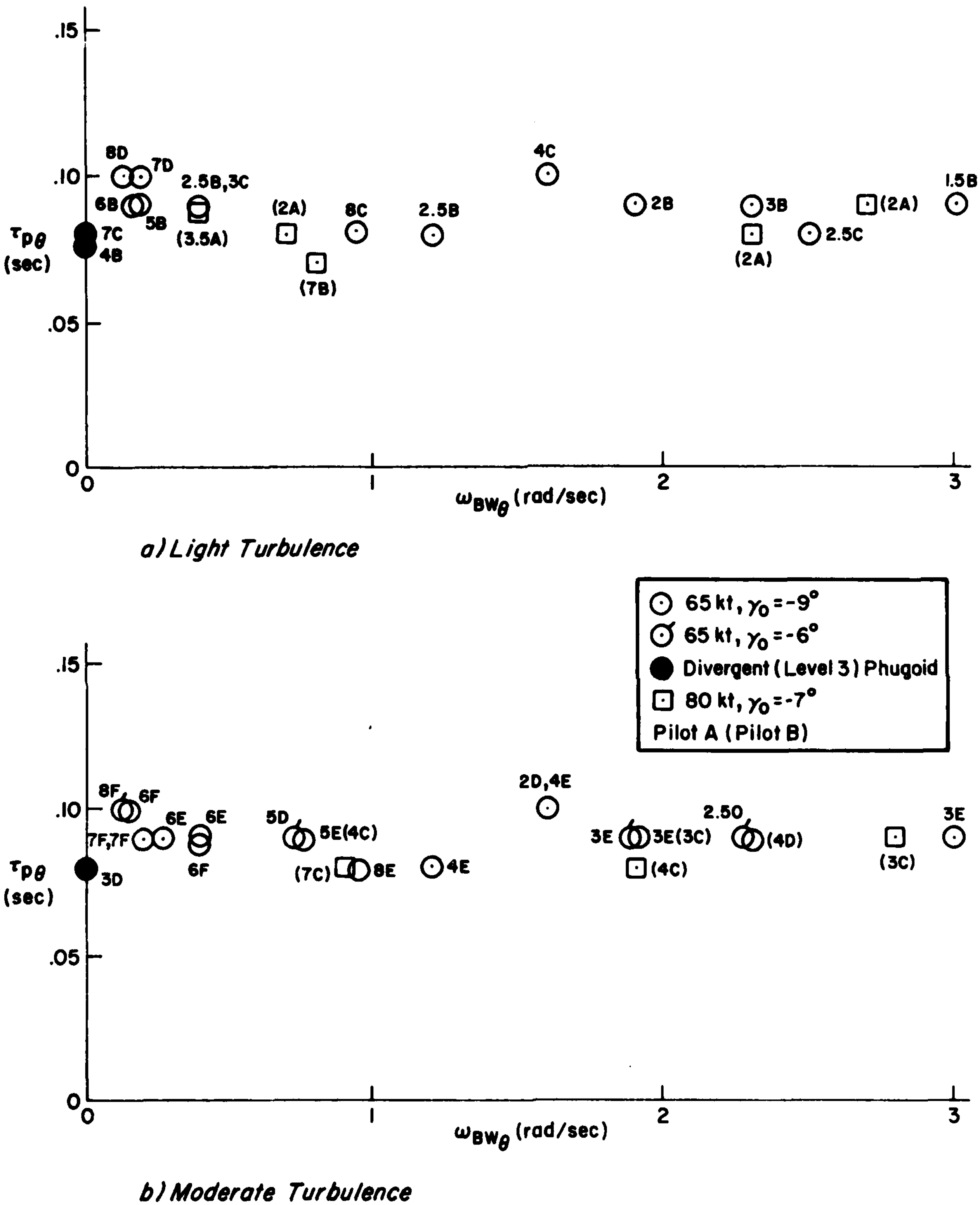
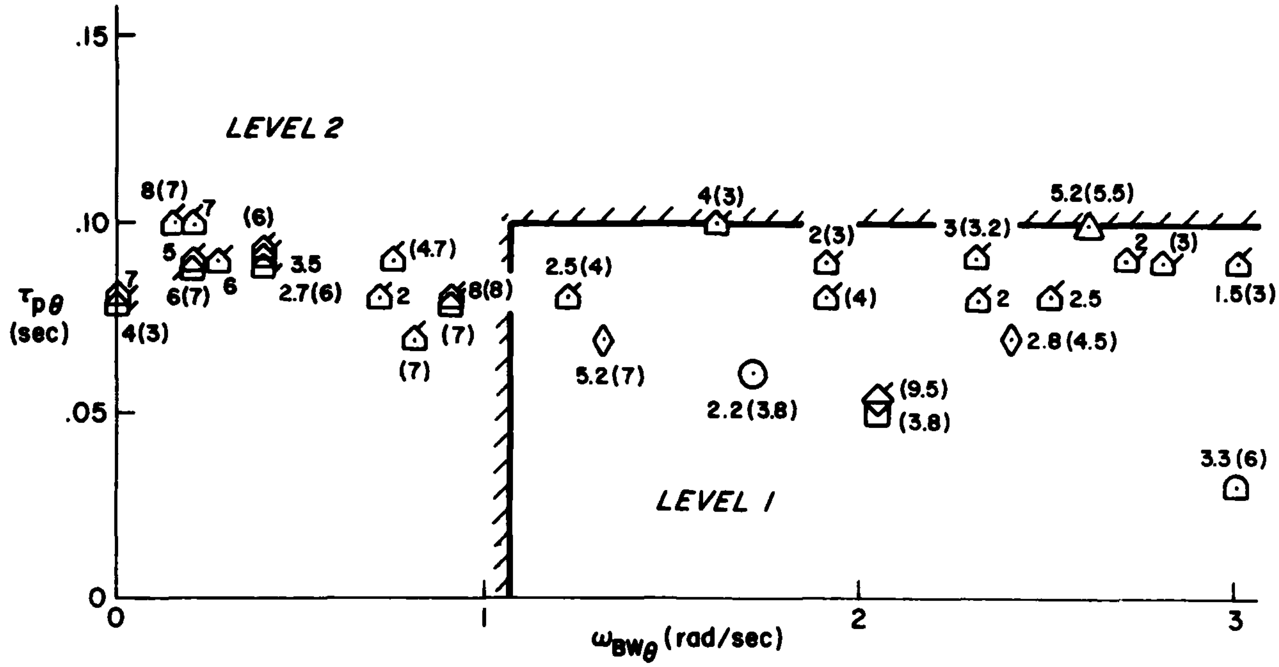
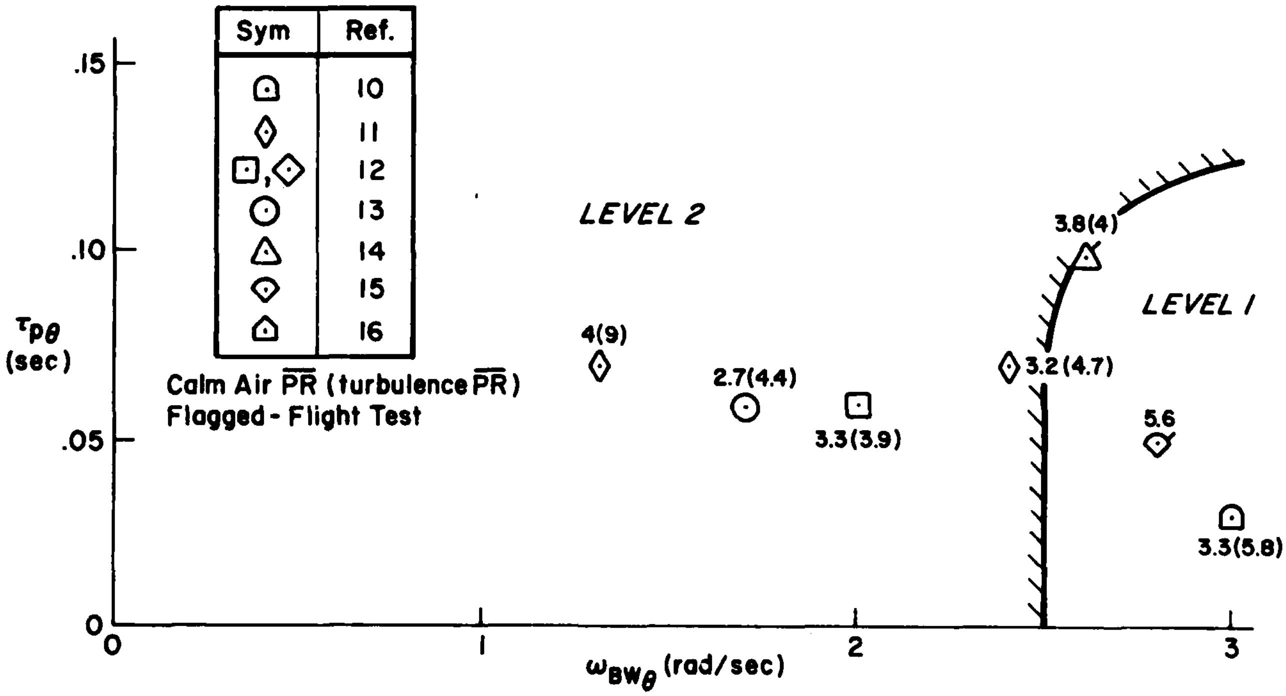


Figure 10. Pilot Ratings from STOL Approach Flight Tests Using X-22A (Reference 16). Overall Ratings; Letters Correspond to Turbulence Ratings (Figure 8)



a) Approach When the Primary Control of Flight Path is Throttle



b) Short Final, Flare and Landing When Attitude is the Primary Flight Path Control

Figure 11. Average Pilot Ratings for Data of Figures 9 and 10

TABLE 2. ALLOWABLE DEGRADATION IN COOPER-HARPER PILOT RATING IN THE PRESENCE OF ATMOSPHERIC DISTURBANCES (REFERENCE 3)

LEVEL	ATMOSPHERIC DISTURBANCES			
	LIGHT	MODERATE	SEVERE	EXTREME
1	3-1/2	5-1/2	7-1/2	Flying qualities such that control can be maintained long enough to fly out of the disturbance
2	6-1/2	7-1/2	Flying qualities such that control can be maintained long enough to fly out of the disturbance	Flying qualities such that pilot can regain control after being upset
3	9-1/2	Flying qualities such that control can be maintained long enough to fly out of the disturbance	Flying qualities such that pilot can regain control after being upset	No requirement

Reference 12 flight point was obtained on the Variable Stability Navion. A significantly higher bandwidth attitude system was tried and the pilot still indicated that the rating was 9-10. We therefore conclude that the poor rating is not attributable to attitude bandwidth problems.

The boundaries in Figure 11a are based on approach data. However, it has been assumed that no additional requirements are imposed on the pitch attitude response if the flare is accomplished primarily with throttle. Therefore, the Figure 11a boundary is assumed to be valid for the flare as well as in the approach as long as attitude is the secondary controller.

The available data for attitude flares is extremely sparse. Indeed, most of the points plotted in Figure 11b involve attitude plus throttle flares ($\theta + \delta_T$) which may explain why a number of Level 1 ratings fall well below the minimum CTOL bandwidth boundary (from Reference 3, Para. 3.2.1.2). Considering the lack of appropriate data, the CTOL boundary is recommended for pure attitude flares; i.e., the Level 1 region in Figure 16 (Section III).

Most of the data plotted in Figure 11b is from simulator studies, a fact which may explain the unusually good ratings for low-bandwidth systems. The inability of the pilots to adequately perceive sink rate when performing landings on the simulator would give rise to a low demand on pitch attitude, i.e., if you can't see it, you can't control it. Quantitative evidence of this was obtained in the Reference 12 simulation wherein the pilots were asked to rate their touchdown sink rate as "soft, medium, or hard." The result of this exercise is given in Figure 12, where it is seen that 50 percent of the 6 ft/sec landings were rated as soft. In a flight situation, 6 ft/sec represents a definite hard landing. It can be seen from these results that the required STOL landing data must be obtained in flight or perhaps in a simulator with advanced displays. The latter should be checked for fidelity, especially in terms of visual display lags before using such data in a specification requirement.

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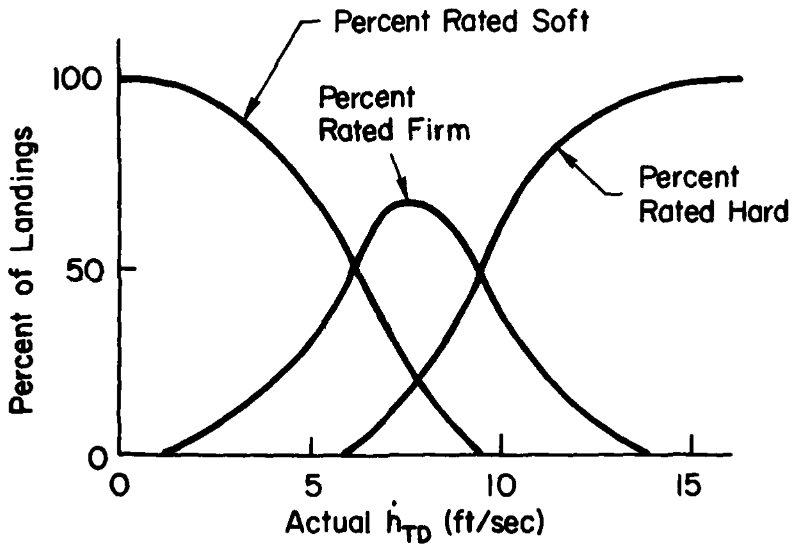


Figure 12. Distribution of Ratings for Soft, Firm, and Hard Landings from Reference 12 Simulation

SECTION III

VERTICAL AXIS RESPONSE TO ATTITUDE CHANGE

A. GENERAL

The information reported in this section would be appropriate for augmenting paragraph 3.3.1 (Vertical Axis Response to Attitude Change) of the MIL Handbook (Reference 3).

For powered-lift STOL aircraft, flight path control is generally accomplished with thrust during the approach. This is a consequence of the fact that the effective thrust inclination angle is nearly vertical. Additionally, STOL aircraft generally (but not always) operate well on the backside of the power required curve and at low airspeeds where heave damping (Z_w) is very low, a fact which degrades flight path response to attitude changes. Nonetheless, there are STOL configurations with reasonably good short term flight path response to attitude changes. For example, many STOL aircraft are flown using power to control flight path until the flare maneuver, at which time pitch attitude is used exclusively to arrest the sink rate for touchdown.

In the current specification (MIL-F-8785C, Reference 1) or in the proposed MIL Handbook (Reference 3) flight path control with attitude is implied in setting a requirement on $d\gamma/dV$. The consideration of powered-lift STOL aircraft requires the definition of a boundary which separates aircraft for which control of flight path with attitude is acceptable from those for which thrust must be used to control path.

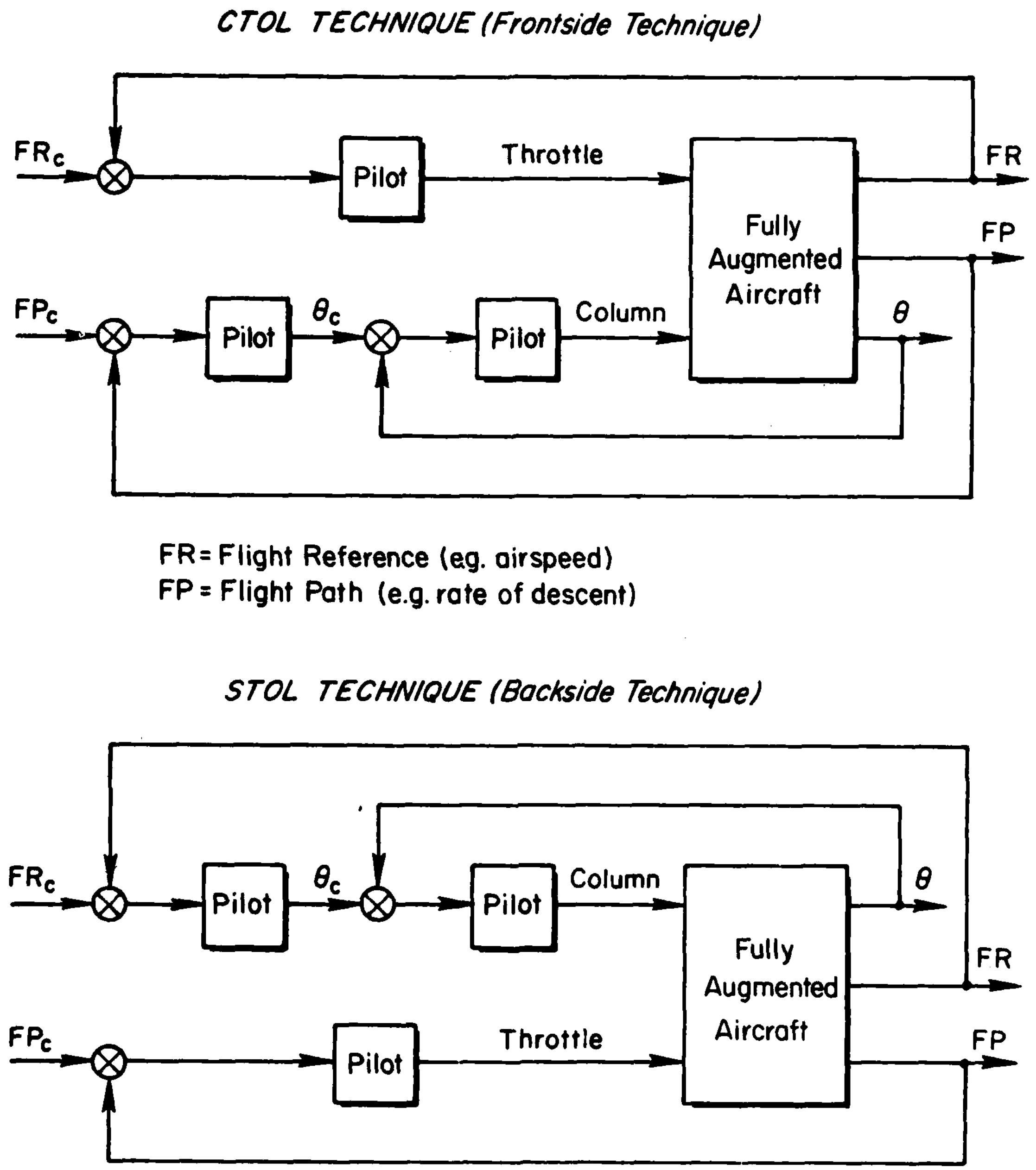
The purpose of this section and Section IV (Vertical Axis Response to Designated Flight Path Controller) is to place explicit requirements on flight path response for both CTOLs and STOLs. This discussion serves as an introduction wherein the differences between "CTOL" and "STOL" will be defined, and some guidance will be provided for using the requirements contained in Sections III and IV.

Figure 13 illustrates the control loop structures for the CTOL and STOL piloting techniques for flight path control. Simply stated, for the requirements that follow, the CTOL technique refers to control of flight path with pitch attitude and control of the pertinent flight reference (normally airspeed) with throttle. Similarly, the STOL piloting technique refers to control of flight path with throttle, and flight reference (airspeed) with pitch attitude.

There is, of course, a third possible mode of control involving simultaneous application of both controllers. Experience has shown, however (e.g., Reference 17), that such "coordinating" crossfeeds can become confusing to the pilot and lead to degraded performance and pilot opinion. The pilot will always prefer to have a clear separation between primary and secondary controller; though some crossfeed may still take place (e.g., pitch up and add power to augment flight path changes), there will still be a hierarchy of control.

From the standpoint of piloted control of flight path, the critical issue is definition of control strategy. While there is no explicit requirement in this section for the contractor to define the primary flight path controller (pitch attitude vs. throttle or DLC), it is clearly necessary that such a distinction be made. The most obvious example of this is the differing philosophies taken by the prime contractors in the Air Force's Advanced Medium STOL Transport (AMST) designs. The Boeing YC-14 utilized a speed feedback to the Upper Surface Blown (USB) flaps and a feedback of angle of attack to thrust, so that the aircraft flew like a CTOL (Reference 18); McDonnell Douglas chose to use the STOL technique on the YC-15, with a combination of asymmetric direct lift control (DLC) and throttle controlling flight path (Reference 19).

In addition to separating flight path requirements by control technique, a subdivision of tasks will be made. First it will be necessary only to concern ourselves with Category C Flight Phases, since this is where the differences between STOLs and CTOLs are most important. The Flight Phases of interest are then limited to the following:



Pilot 13. Pilot Loop Structure Forms

- Takeoff (TO)
- Catapult Takeoff (CT)
- Transition (T)
- Power Approach (PA)
- Wave-off/Go-Around (WO)
- Landing (L)

Experience with powered-lift STOLs has shown that, in general, concerns with takeoff are similar to those for CTOLs (see Reference 4).

The major focus of the flight path requirements is in approach and landing. For this reason it is important to clearly define the separation between the two regimes: Power Approach (PA) will begin at initiation of the specified approach flight path angle or acquisition of target glideslope, and terminate at the flare initiation. Landing (L) begins at flare initiation and ends at touchdown. Go-Around or Waveoff (WO) is assumed to be less critical than landing, since it generally involves arresting the sink rate in a non-precise maneuver. The landing flare is a very short-term event and experience has shown that the application of flare controls for most powered-lift STOLs occurs between 30 and 50 ft above the runway (Figure 14), which is consistent with CTOL flares. The flight test results of Ref. 14 indicate that the total time between flare and wheel touchdown is on the order of 6-7 sec, which is consistent with most simulation results, e.g., Figure 15 (in some cases the flare time was closer to 4-5 sec). This is an important factor in the development of flight path response criteria for landing.

In summary, the requirements of Sections III and IV are divided by control technique (CTOL and STOL) and by two fundamental Category C Flight Phases (PA and L). Figure 3 illustrates how the various Paragraphs are related. Specific flight path control criteria referred to in Figure 3 are defined in the section of the report noted below each box. This section deals with flight path control with attitude. The tentative requirements and their justifications are discussed at length in the paragraphs that follow.

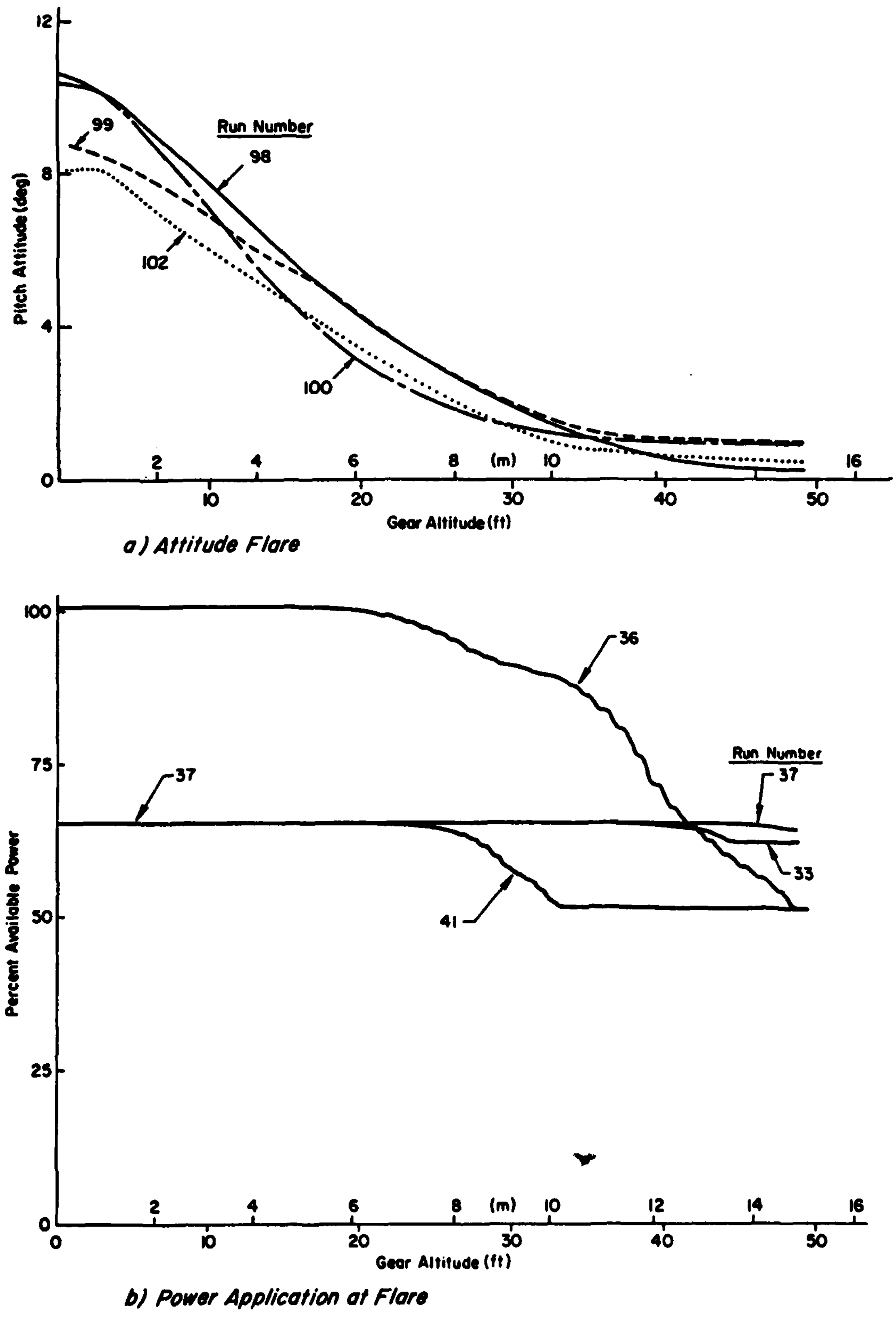


Figure 14. Typical Flare Control Applications in Calm Air (From Reference 13)

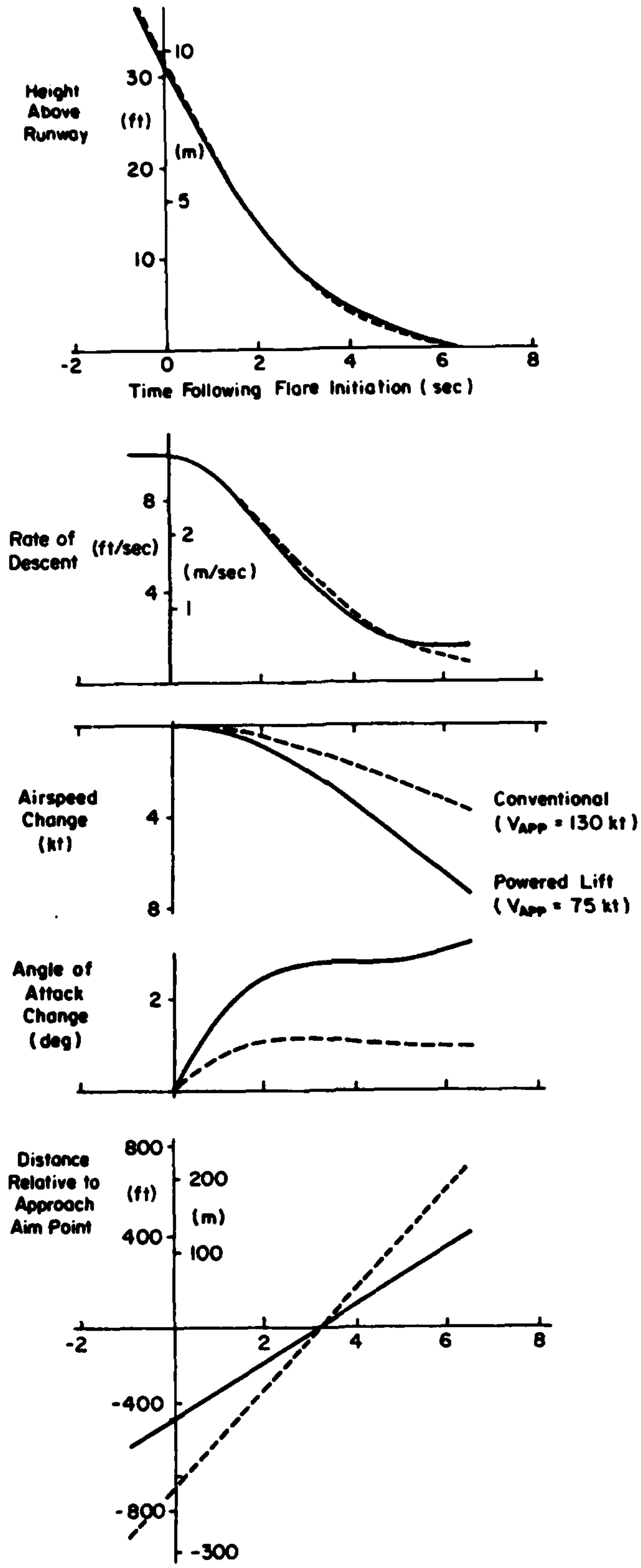


Figure 15. Comparison of Aircraft Categories with Regard to Flare (From Reference 4)

B. SHORT TERM RESPONSE OF $\dot{h} \rightarrow \theta$

This requirement is reasonably well developed and hence is written up in the recommended MIL Handbook format (Reference 3) to facilitate the transformation to a specification. In this format the recommended requirement will be given first, followed by the supporting rationale and data.

1. Reason For Requirement

This requirement is included to provide a separate and independent criterion for flight path response to pitch attitude changes. Two criteria are necessary: one for "conventional" flight path control where pitch attitude is primary, and the second for STOL flight path control where pitch attitude plays a secondary role in path control and/or is used to control speed.

2. Statement of Requirement - Vertical Axis Response to Attitude Change — Transient Response (MIL Handbook Paragraph 3.3.1.1).

a) Attitude Primary: The short-term flight path response to attitude changes shall have the following characteristics: __________________________.

b) Attitude Secondary: If a designated controller other than attitude is the primary means of controlling flight path, the flight path response to an attitude change can be degraded to the following: __________________.

Recommended values:

Requirement a):

- Power Approach Flight Phase (PA): Allowable limits on the Table 3 short term path-to-attitude response are specified in terms of $(1/T_{\theta_2})_{eff}$ [the lowest frequency where $\Phi(\gamma/\theta) = -45$ deg for pitch control inputs] and the equivalent short period frequency as defined in Paragraph 3.2.1.1 of Reference 3.

- Landing Flight Phase (L): Limits are specified in terms of the parameters $(1/T_{\theta_2})_{eff}$ and t_{rev} in Figure 16.

Requirement b): $.14 < (1/T_{\theta_2})_{eff} < 1.33\ \omega_{sp}$

TABLE 3. ACCEPTABLE VALUES OF $(1/T_{\theta_2})_{eff}$

LEVEL	CLASS	$(1/T_{\theta_2})_{eff}$ (rad/sec)
1	I, II-C, IV	$0.38 < (1/T_{\theta_2})_{eff} < 0.77\ \omega_{sp}$
	II-L, III	$0.29 < (1/T_{\theta_2})_{eff} < 0.77\ \omega_{sp}$
2	I, II-C, IV	$0.24 < (1/T_{\theta_2})_{eff} < 1.33\ \omega_{sp}$
	II-L, III	$0.14 < (1/T_{\theta_2})_{eff} < 1.33\ \omega_{sp}$

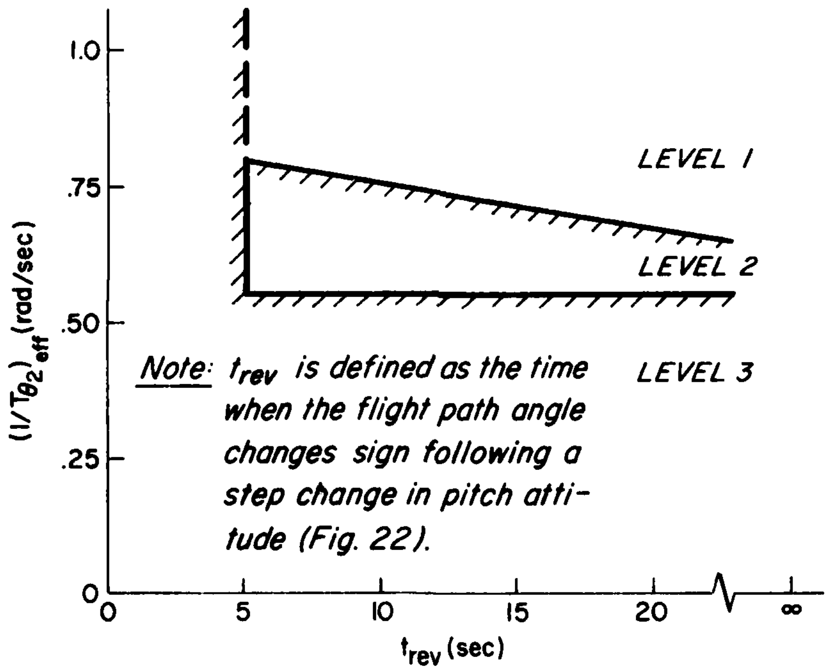


Figure 16. Limits on Short-Term Vertical Axis Response to Attitude Change for Flare and Landing (Flight Phase L)

3. Rationale Behind $(1/T_{\theta_2})_{eff}$ Limits of Requirement (a)

a. Lower limit on $(1/T_{\theta_2})_{eff}$

Aircraft operating on the front side of the power-required curve, and possessing sufficient short-term response (i.e., bandwidth), utilize pitch attitude to control flight path. In fact, the primary motivation for the pitch axis requirements of Reference 3 (see Para. 3.2.1 of that document) is to provide the good inner loop which is required to allow aggressive, precise outer-loop (path) tracking. The short-term flight path response is related to the aircraft pitch attitude change by

$$\frac{\gamma}{\theta} \doteq \frac{1}{T_{\theta_2}s + 1} \qquad (1)$$

The equivalent system requirements for pitch attitude control (Para. 3.2.1.1, Reference 3) involve $1/T_{\theta_2}$ directly (i.e., $\omega_{sp}T_{\theta_2}$ limits) or indirectly [i.e., ω_{sp} vs. n/α where $n/\alpha \doteq (U_o/g)(1/T_{\theta_2})$]. Hence these requirements appear to involve pitch and path control in a single criterion. However, because the experimental data (basically all NT-33) used to develop correlations for the criteria do not contain independent variation of speed and $1/T_{\theta_2}$, it is not possible to determine whether the boundaries do indeed account for path as well as pitch. The lack of availability of such data also makes it difficult to establish a quantitative requirement for this paragraph. However, it is clear that for adequate flying qualities, $(1/T_{\theta_2})_{eff}$ should be at least greater than the values specified in Table 3 for Power Approach. The lower limits on $(1/T_{\theta_2})_{eff}$ in Table 3 are simply the lower boundaries on n/α from Reference 3 at an approach speed of 135 kt.*

*The approximation in Eq. 1 assumes $1/T_{\theta_1} \ll 1/T_{\theta_2}$. Since this is not always the case, we define a $(1/T_{\theta_2})_{eff}$ which is the frequency at which γ lags θ by 45 deg. Note that when Equation 1 is valid, $(1/T_{\theta_2})_{eff} = 1/T_{\theta_2}$. Interestingly, the lower limits on n/α in Reference 1 are based on a $(1/T_{\theta_2})_{min}$ which was converted to n/α. While this original data was never published, we have at least preserved this intent.

Generally speaking, for CTOL aircraft $1/T_{\theta_2}$ is well above these minimums in the up and away flight conditions. Hence no data are available (or needed) to establish lower limits for these cases.

b. Upper Limit on $(1/T_{\theta_2})_{eff}$

Experience has shown that the path response bandwidth should be well separated from the pitch response bandwidth. Evidence to support this is given in the analysis and flight test results obtained by DFVLR (using an HFB-320 in-flight simulator) and reported in Reference 20. These results indicate that an appropriate criterion parameter would be the phase angle between path and attitude at the short-period frequency, i.e.,

$$\phi(\gamma/\theta)\big|_{\omega = \omega_{sp}}$$

Noting that $\phi(\gamma/\theta)|_{\omega = \omega_{sp}} = \tan^{-1} \omega_{sp}T_{\theta_2}$, the criterion on $\omega_{sp}T_{\theta_2}$ (Reference 3) can be easily converted to $\phi(\gamma/\theta)|_{\omega=\omega_{sp}}$ with the results shown in Table 4. The upper limits on $1/T_{\theta_2}$ in Requirement (a) were obtained from the values of $(\omega_{sp}T_{\theta_2})_{min}$ in Table 4, which in turn were taken from the *Category C requirements* in the proposed MIL Handbook (Reference 3). It should be noted that the upper limits on $1/T_{\theta_2}$ could also be considered as a lower limit on ω_{sp}. This, of course, is a

TABLE 4. CONVERSION OF $\omega_{sp}T_{\theta_2}$ TO A PHASE ANGLE CRITERION

CATEGORY	LEVEL	$(\omega_{sp}T_{\theta_2})_{min}$	MAXIMUM ALLOWABLE $\phi(\gamma/\theta)\|_{\omega=\omega_{sp}}$ (deg)
A	1	1.6	-58
	2	1.0	-45
B	1	1.0	-45
	2	0.58	-30
C	1	1.3	-52
	2	0.75	-37

direct consequence of the physical interpretation of $\omega_{sp}T_{\theta_2}$ as a measure of path/attitude consonance. More specifically, when controlling flight path with pitch attitude, the pilot desires that the path response lag the attitude response. Unfortunately, there is not a great deal of data to document this particular aspect of the pilot-centered requirements for path control; that is, very few experiments include configurations where $1/T_{\theta_2}$ is nearly equal to or greater than ω_{sp}. For now we must rely on Reference 20 as well as undocumented pilot commentary from various sources to support the path/ attitude consonance requirement; however, our rationale leads us to avoid ever having $1/T_{\theta_2} > \omega_{sp}$. This conclusion was reached independently by other researchers (i.e., Refs. 20 and 44).

The phase angle criterion in Table 4 would be applicable as an alternate to the upper limit on $(1/T_{\theta_2})_{eff}$ for interpreting simulator or flight test results. Unfortunately it is necessary to determine an equivalent system to obtain ω_{sp} in both cases.

If an attitude augmentation system (as opposed to rate augmentation) is utilized, the lower-order equivalent system fit should be accomplished using the pitch equation only and with $T_{\theta_2} = 0$ in the attitude numerator. Of course, $(1/T_{\theta_2})_{eff}$ remains unaffected since it is defined as the lag between γ and θ and is not dependent on the pitch attitude numerator in any way.

4. Derivation of Figure 13 Landing Criteria for Requirement (a)

Experience has shown (see Supporting Data) that powered-lift STOLs with good short-term path response to pitch attitude will be flared conventionally (i.e., using pitch attitude) even though the approach was flown with throttle (i.e., STOL technique). This clearly creates a requirement for a criterion which can successfully determine what constitutes "good" control of flight path with pitch attitude.

A logical choice for a correlating parameter would be $1/T_{\theta_2}$ or n/α. Reference 4 contains recommended limits on n/α for pitch attitude flares (see Figure 17). The data base was small, however, and the limits

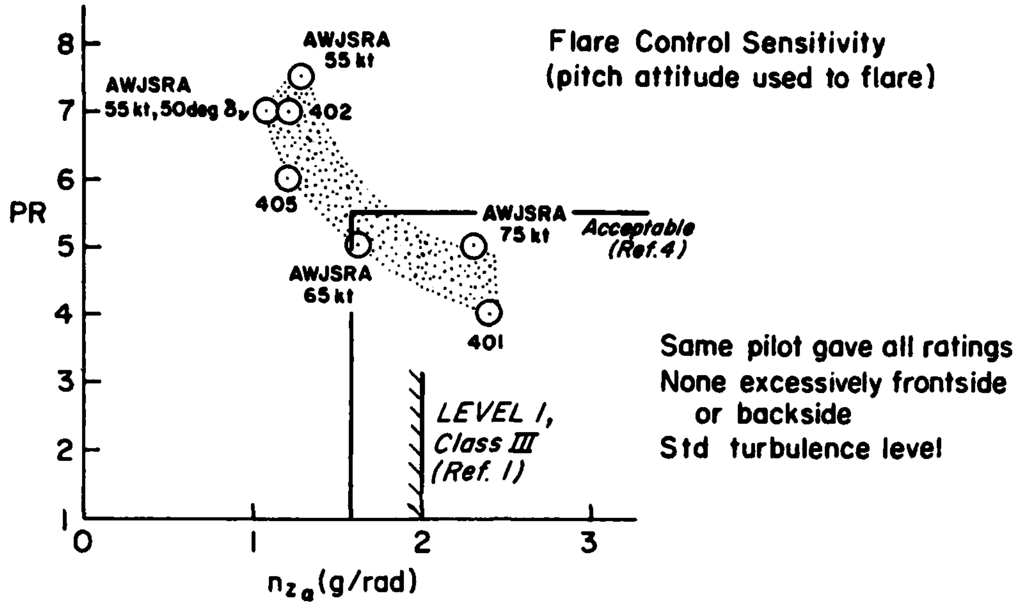


Figure 17. Comparison of Proposed Attitude Flare Parameters from MIL Handbook (Reference 3) and Criteria Development Program (Reference 4)

suggested in Reference 4 are reasonably consistent with the n/α and limits of Para. 3.2.1.1 of the proposed MIL Handbook (Reference 3), as Figure 17 shows. We would hope that STOL attitude flare criteria would also work for CTOLs, since the task details in flaring with attitude are not significantly different: e.g., STOL landing speeds are generally less, but tight runway length constraints make the task more demanding. While $1/T_{\theta_2}$ defines the path/attitude relationship for CTOLs (Equation 1), it is, in many cases, inadequate for powered-lift STOLs with dynamic coupling, necessitating the use of $(1/T_{\theta_2})_{eff}$ as will be shown subsequently.

a. Short Term Flight Path Response for Flare and Landing

For powered-lift STOLs we continue to neglect $Z_{\delta_{es}}$ in the pitch attitude-to-control deflection numerator, $N^{\theta}_{\delta_{es}}$, but we must consider the u derivatives. The approximation for $N^{\theta}_{\delta_{es}}$ (Reference 21) is now:

$$N^{\theta}_{\delta_{es}} \doteq M_{\delta_{es}}[s^2 - (X_u + Z_w)s + X_u Z_w - X_w Z_u] \qquad (2)$$

When the crosscoupling term $X_w Z_u$ is small, the roots of this equation are those encountered on CTOLs:

$$N^{\theta}_{\delta_{es}} \doteq M_{\delta_{es}}(s + 1/T_{\theta_1})(s + 1/T_{\theta_2})$$

$$\doteq M_{\delta_{es}}(s - X_u)(s - Z_w) \tag{3}$$

However, it is common with powered-lift STOLs to have dynamic coupling, where the path and speed responses occur at the same frequency; i.e., the product $X_w Z_u$ is not small and

$$N^{\theta}_{\delta_{es}} \doteq M_{\delta_{es}}(s^2 + 2\zeta_\theta \omega_\theta s + \omega_\theta^2) \tag{4}$$

The condition for such dynamic coupling (Reference 12) is that $\zeta_\theta < 1$. Algebraic manipulation of Equation 2 with this condition yields

$$(Z_w - X_u)^2 < -4X_w Z_u$$

Clearly, as $1/T_{\theta_1}$ increases and $1/T_{\theta_2}$ decreases in value, the path/attitude relationship of Equation 1 becomes less exact. This relationship is more fully given by:

$$\frac{\gamma}{\theta} = \frac{(s + 1/T_{h_1})}{(s + 1/T_{\theta_1})(T_{\theta_2}s + 1)} \tag{5}$$

$1/T_{h_1}$ is the classical low-frequency flight path zero of the h/δ_{es} numerator $[1/T_{h_1} \doteq -0.333(d\gamma/dV)$, deg/kt, Reference 21]. Normally, both $1/T_{h_1}$ and $1/T_{\theta_1}$ are so small that in the short term they are both taken to be zero. For conventional airplanes in low-speed flight, the factors of Equation 5 are related by the following function (Reference 22) derived from the approximate factors of Reference 21, neglecting C_{L_u}:

$$\frac{1}{T_{\theta_1}} - \frac{1}{T_{h_1}} \doteq 2\left(\frac{g}{U_o}\right)^2 T_{\theta_2} \tag{6}$$

At normal approach speeds and values of T_{θ_2} found for CTOLs, $1/T_{\theta_1} \doteq 1/T_{h_1}$ and Equation 2 is well approximated by Equation 1. Figure 18 shows the validity of Equation 3 using the dynamics from Reference 23.

When $1/T_{\theta_1}$ is much greater than $1/T_{h_1}$ the flight path response to attitude changes becomes a function of $1/T_{\theta_1}$, $1/T_{\theta_2}$, and $1/T_{h_1}$, and hence a valid criterion must be based on limiting values of all three of these parameters. A better alternative in such cases might be to define criteria that are based on the overall frequency response or time response (rise time). We have considered both approaches in developing flare and landing criteria in terms of γ/θ.

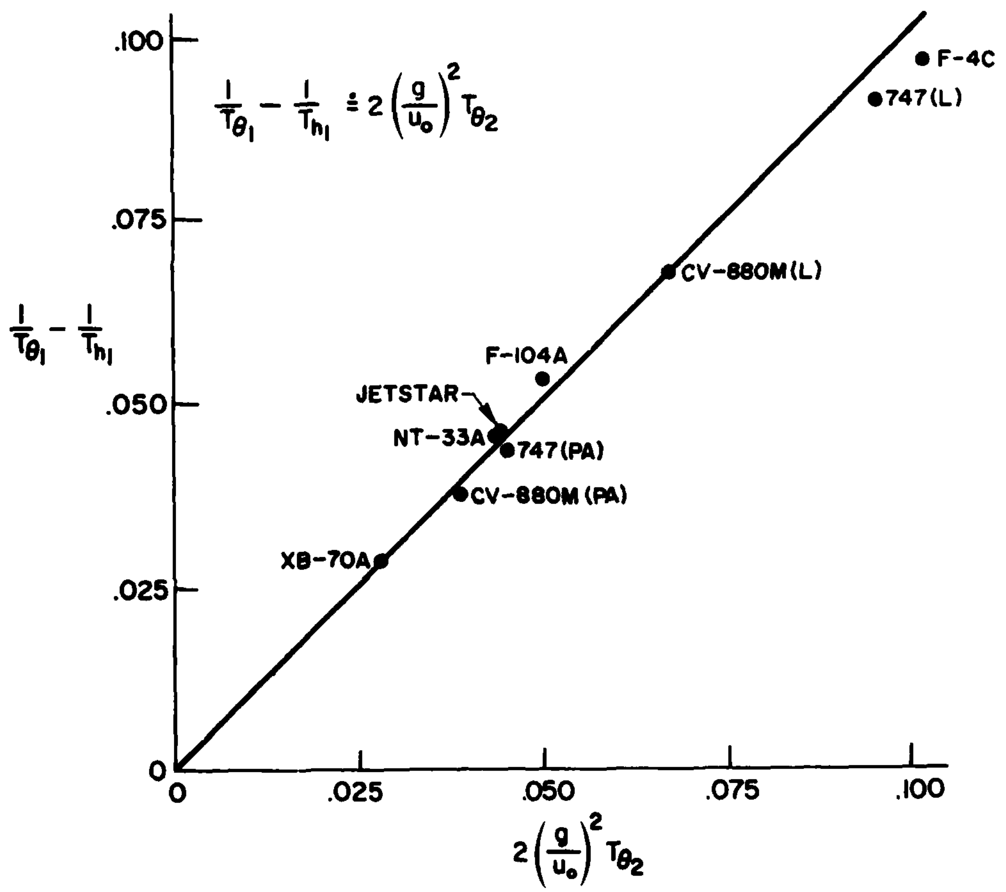


Figure 18. Verification of Approximation for $1/T_{h_1}$ for Conventional Airplanes in Approach and Landing

The requirement for flare and landing (Figure 16) is based on the $\dot{h}/\theta$ response characteristic. Clearly the flare maneuver is a combination of h and $\dot{h}$ control. The concept that $\dot{h}/\theta$ adequately defines the flare handling qualities is based on the flare model developed in Reference 12. This model was developed using simulation data which indicated that the pilot flare technique was caused altitude to vary linearly with sink rate; i.e., an exponential flare law. The closed-loop structure of Figure 19 was derived from that observation. With the requirements of Section II satisfied, the pilot should be able to close the attitude loop tightly so that

$$\frac{\theta}{\theta_c} = 1.0$$

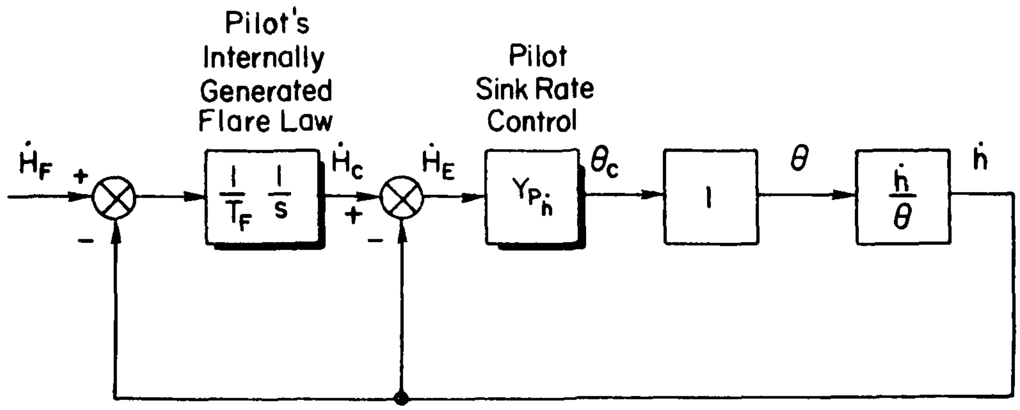
at the frequencies of interest, i.e., in the region of the path mode $\left(\omega \doteq 1/T_{\theta_2}\right)$. The effect of the pilot's efforts at controlling flight path $\left(Y_{p_{\dot{h}}}\right)$ on the closed-loop characteristic response may be obtained from Figure 19 as follows. The closed loop characteristic equation is:

$$\Delta = 1 + Y_{p_{\dot{h}}}(s + 1/T_F)(h/\theta) = 0$$

This equation indicates that at frequencies below the flare mode time constant ($s \ll 1/T_F$) the pilot is primarily controlling altitude (to follow the exponential path). At frequencies above $1/T_F$ ($s \gg 1/T_F$), the primary concern is with the sink rate response to attitude changes or $\dot{h}/\theta$. Since for practical STOL flares $1/T_F$ is on the order of 0.2 to 0.3 rad/sec (Ref. 12), our primary concern is with the sink rate response ($\dot{h}/\theta$). For non-dynamically coupled airplanes

$$\frac{\dot{h}}{\theta} = \frac{U_o}{T_{\theta_2}s + 1}$$

Hence the lag between sink rate and pitch attitude is well defined by $1/T_{\theta_2}$. Recall that this was the rationale for setting limits on $1/T_{\theta_2}$ in the Power Approach portion for Requirement (a) of this section. The



- Assume tight piloted closure of pitch attitude so $\theta \doteq \theta_c$

- Definitions

H	=	altitude
H_F	=	altitude of flare initiation
h	=	perturbation altitude $h = h - H_F$
$\dot{H}_F$	=	sink rate at flare initiation
T_F	=	flare mode time constant

$$\frac{1}{T_F} = \frac{\dot{H}_{TD_C} - \dot{H}_F}{H_F}$$

$\dot{H}_{TD_C}$	=	pilot's target touchdown sink rate
$\dot{H}_C$	=	pilot's internally generated sink rate command required to follow the exponential flare path. Note that $\dot{H}_E = -[\dot{h} + (1/T_F)h]$, an exponential flare law.

Figure 19. Closed Loop Pilot/Vehicle System for Flare

logical extension of this criterion for dynamically coupled aircraft is to specify the frequency where $\dot{h}$ lags θ by 45 deg, i.e., an "effective value" of $1/T_{\theta_2}$. The suggested criterion is

$$\left(\frac{1}{T_{\theta_2}}\right)_{eff} = \omega \text{ at which } \Phi(\dot{h}/\theta) = -45 \text{ deg}$$

First consider the application of the criterion parameter to a non-coupled aircraft with $T_{\theta_1} \ll T_{\theta_2}$. The complete representation of $\dot{h}/\theta$ is:

$$\frac{\dot{h}}{\theta} = \frac{N^{\dot{h}}_{\delta_{es}}}{N^{\theta}_{\delta_{es}}} = \frac{-Z_{\delta_{es}}/M_{\delta_{es}}(s + 1/T_{h_1})(s + 1/T_{h_2})(s + 1/T_{h_3})}{(s + 1/T_{\theta_1})(s + 1/T_{\theta_2})} \quad (7)$$

Figure 20 shows a typical Bode plot for this case. Note that $(1/T_{\theta_2})_{eff}$ is close to $1/T_{\theta_2}$. This is expected since $1/T_{h_1}$(slightly nonminimum-phase, or backside, in Figure 20) is close in magnitude to $1/T_{\theta_1}$ and both are small, while $1/T_{h_2}$ and $1/T_{h_3}$ are relatively large.

As Figure 21 shows, $(1/T_{\theta_2})_{eff}$ differs considerably from ω_θ for the dynamically coupled condition.

Time-domain rise time criteria have been considered in the past (e.g., References 4, 14, 24) with varying success. As indicated by the flare model discussed above, the sink rate response to attitude changes is the appropriate measure. Noting that $\dot{h} = U_0\Delta\gamma$, we have elected to base the correlating parameter on the Δγ response to a step attitude change. As Figure 22 illustrates, we have defined the effective rise time, $t_{R_{\gamma\theta}}$, as the time that Δγ reaches 50 percent of maximum. While this may not necessarily be the most appropriate rise time parameter, it is used here because it has been utilized in a number of references (References 14 and 24) and was therefore readily available. As would be expected, $(1/T_{\theta_2})_{eff}$ is directly related to $t_{R_{\gamma\theta}}$. This is shown for the particular configurations from References 12, 13, and 14 in Figure 23 but should be applicable in general.

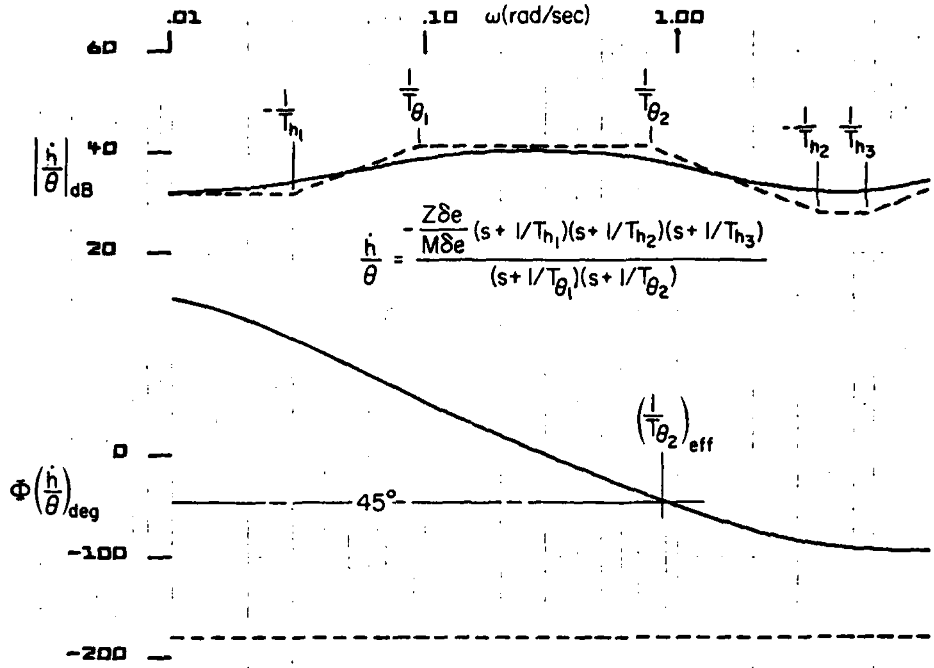


Figure 20. Definition of $\dot{h}/\theta$ Frequency Response Parameters for Conventional Aircraft: $1/T_{\theta_1} \ll 1/T_{\theta_2}$; $(1/T_{\theta_2})_{eff} \doteq 1/T_{\theta_2} = -Z_w$

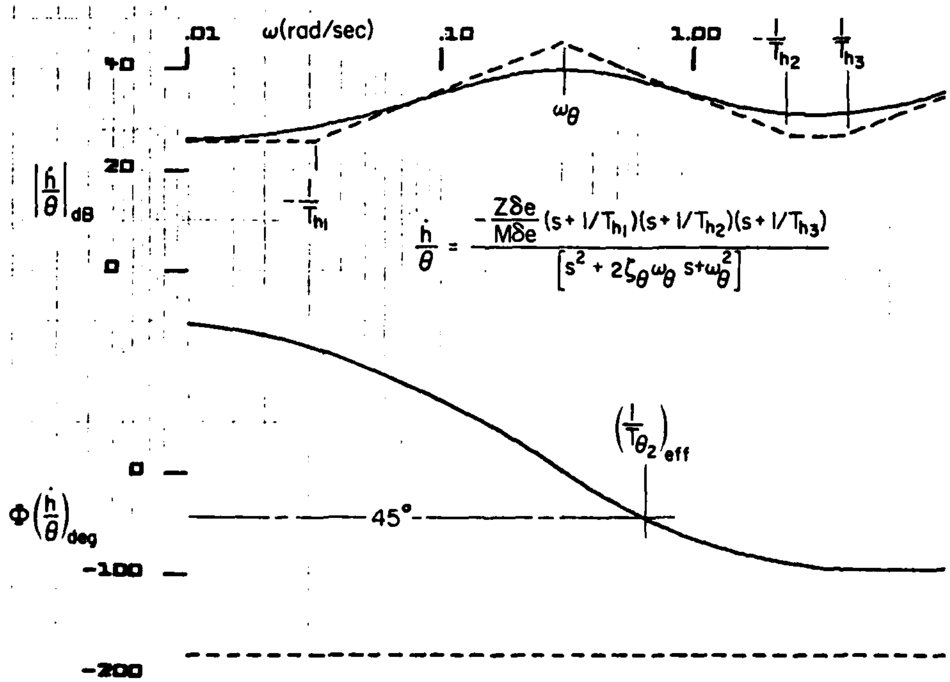


Figure 21. Definition of $\dot{h}/\theta$ Frequency Response Parameters for Dynamically Coupled Aircraft: $(1/T_{\theta_2})_{eff} \neq \omega_\theta$

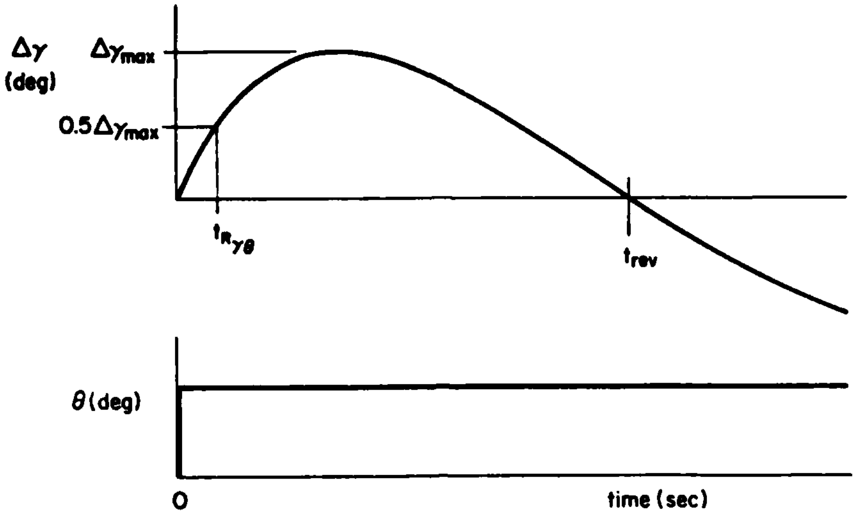


Figure 22. Definition of γ/θ Time Response Parameters

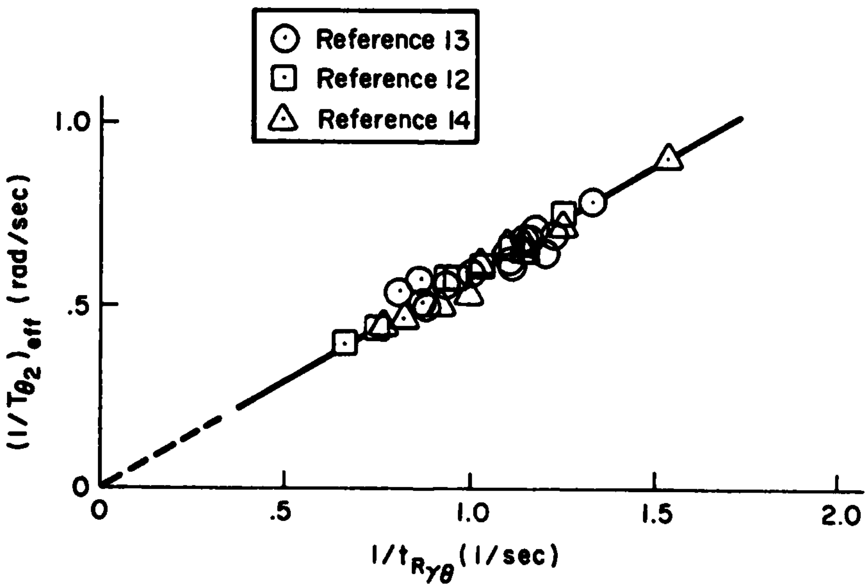


Figure 23. Relationship Between $(1/T_{\theta 2})_{eff}$ and Rise Time for Typical Powered-Lift STOLS

b. Mid-Term Path Response For Flare and Landing

Long-term path control is typically measured by the steady-state change in flight path angle due to a change in airspeed which, in turn, has been induced by a change in pitch attitude with power held constant ($d\gamma/dV$). The parameter $d\gamma/dV$ has proven to be reasonably good for the power approach flight phase and when the frontside control technique is employed. However, for the flare and landing maneuver, $d\gamma/dV$ is not an effective parameter for the following reasons:

- For the landing flare, the pilot is more concerned with flight path changes to attitude changes as opposed to airspeed changes.
- The "steady state" flight path response does not adequately characterize flight path washout for landing. The mid-term response is felt to be more representative of the flare maneuver.

The flight path washout phenomenon is illustrated in Figure 22. Here, the time for flight path angle to reverse sign is suggested as more representative of the "mid-term" flight path response for the landing flare. The effect of t_{rev} on the pilots' control technique in the flare is well illustrated by looking at some actual STOL flight path data. The Augmentor Wing flight tests of Reference 14 provide a good data set, including pilot ratings and comments for flare and landing. Flight path time histories for the landing configurations from Reference 14 are shown in Figure 24. Also indicated are the flare controls used, based upon pilot comments (θ = pitch attitude, T = throttle).

The first significant point of Figure 24 is that, for most of the configurations, $\Delta\gamma$ has reversed in direction within 10 sec after the commanded change. Inasmuch as the total time from flare initiation to landing is 10 sec or less for most STOLs, there is some time, probably around 10 sec, beyond which the pilot doesn't care if "backside" characteristics become evident.

MIL-F-8785C (Reference 1) specifies flight path stability in terms of the classical backside parameter, $d\gamma/dV$ (in deg/kt), which, in the steady state, is given by:

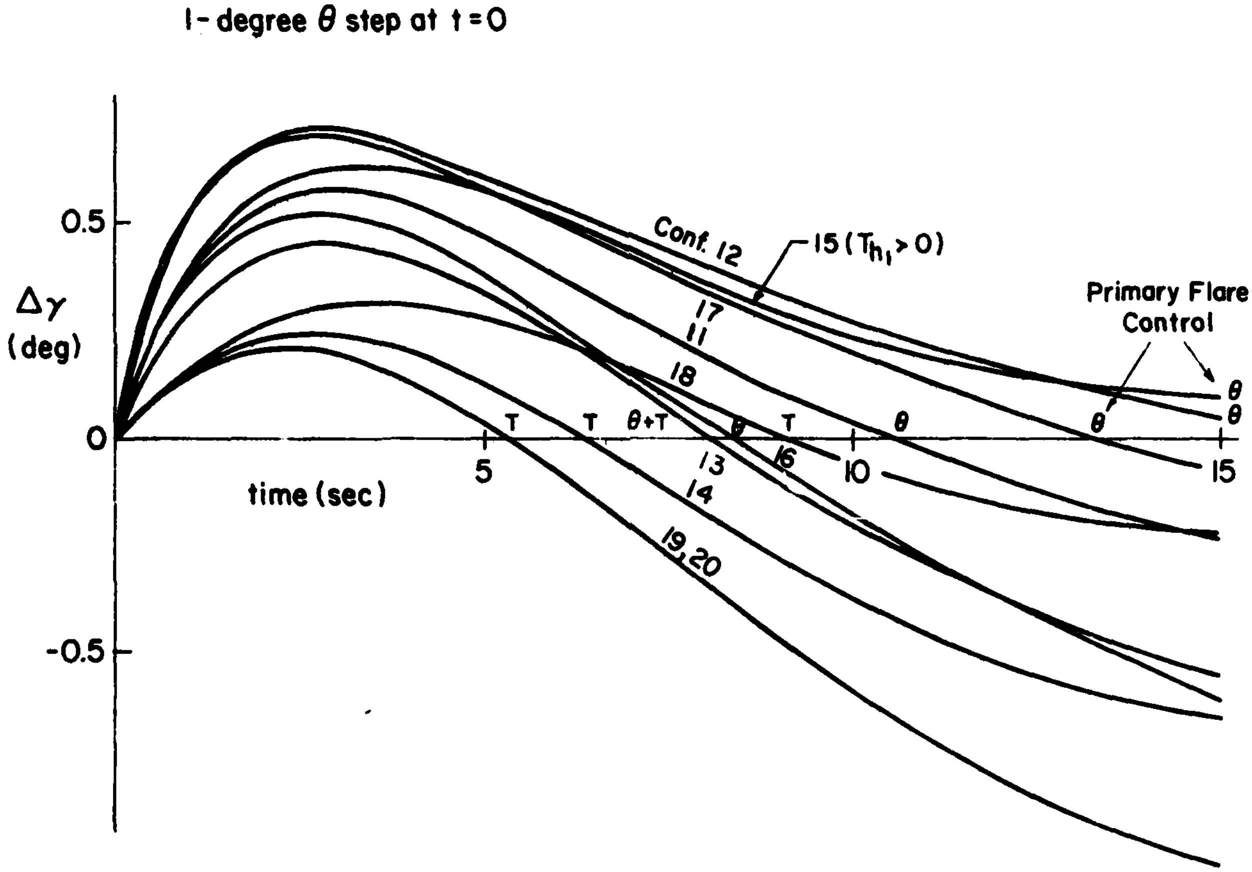


Figure 24. Δγ Time Responses to Unit Step θ Input for Flare and Landing Configurations of Reference 14

$$\frac{d\gamma}{dV} = \frac{-(57.3)(1.689)}{g} \frac{1}{T_{h_1}} \doteq -3\left(\frac{1}{T_{h_1}}\right)$$

It is logical to raise the question as to whether a unique relationship exists between t_{rev} and $d\gamma/dV$. This is explored in Figure 25 for the Reference 14 configurations, where it is shown that Configurations 11, 17 and 18 have approximately identical $d\gamma/dV$ while t_{rev} varies over a wide range. These differences are not surprising since $d\gamma/dV$ is a function only of $1/T_{h_1}$, while t_{rev} can be affected significantly by all the terms of the $\dot{h}/\theta$ response (Equation 7).

As an example, consider the effects of variations in $1/T_{\theta_1}$ and $1/T_{\theta_2}$ at a fixed value of $1/T_{h_1}$ (i.e., $d\gamma/dV$ of 0.06 deg/kt; $1/T_{h_1}$ = −0.02 rad/sec). Figure 26 shows that t_{rev} varies over a great range as a function of $1/T_{\theta_1}$ and $1/T_{\theta_2}$. The shaded regions on Figure 26 represent typical values of $1/T_{\theta_1}$ and $1/T_{\theta_2}$ for conventional aircraft and for STOL aircraft. For STOLs t_{rev} is seen to be considerably more rapid than for CTOLs. Figure 27 shows how t_{rev} varies as $1/T_{\theta_1}$ approaches $1/T_{\theta_2}$, and as $1/T_{h_1}$ becomes more negative.

5. Rationale Behind Requirement (b) (attitude secondary)

If the flight path response to pitch attitude changes falls in the Level 2 or Level 3 regions defined in Requirement (a), flight path must be controlled via thrust modulation. In such cases, $t_{R_{\gamma T}}$ or $\omega_{BW_{hT}}$ (see Section IV) are the appropriate parameters. It is not clear at this time whether some downgraded level of path response to attitude should be required; i.e., is requirement (b) even necessary? If the path response to thrust is on or near the Level 1 boundary, some minimum path response to attitude is probably desirable. Therefore, we have elected to specify the lowest Level 2 value of $1/T_{\theta_2}$ from Requirement (a) as a tentative minimum until substantiating data can be obtained. If the path response to thrust is well above the Level 1 boundaries (see limits on $t_{R_{\gamma T}}$ and $\omega_{BW_{hT}}$ in Section IV) it is probably only necessary to

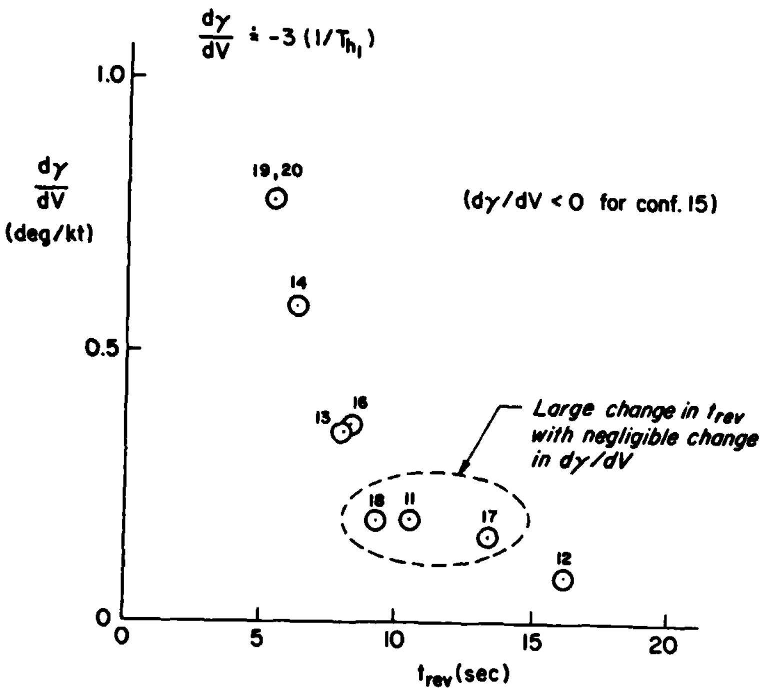


Figure 25. Relationship Between $d\gamma/dV$ and t_{rev} for Configurations of Figure 24

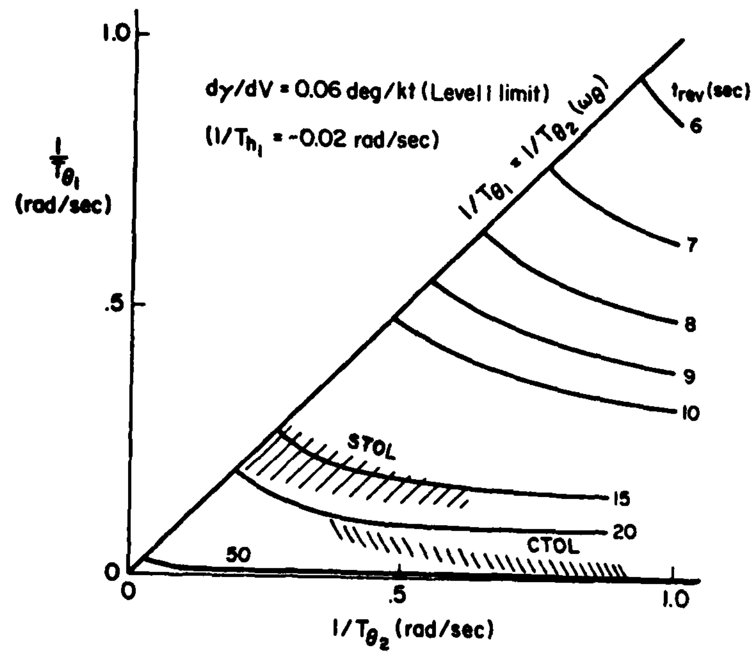


Figure 26. Range of $1/T_{\theta_1}$ and $1/T_{\theta_2}$ for Typical Aircraft, and t_{rev} Corresponding to Level 1 $d\gamma/dV$ Limit from Reference 1

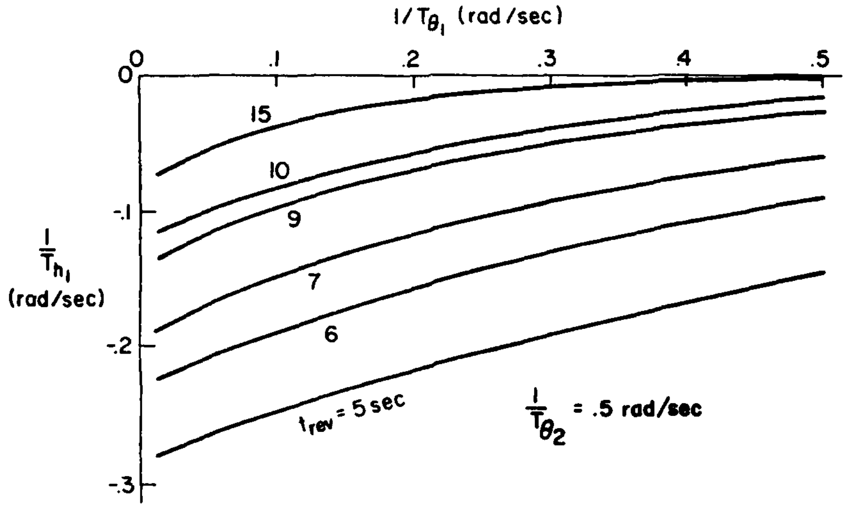


Figure 27. Variation of t_{rev} with $1/T_{\theta_1}$ and $1/T_{h_1}$

specify that the short-term path response to an attitude change not be negative. That is, a negative initial path response to a positive attitude change would be unacceptable under any conditions.

6. <u>Supporting Data for Transient Response of $\dot{h} \rightarrow \theta$</u>

a. Power Approach

Requirements on $(1/T_{\theta_2})_{eff}$ were taken from Reference 3, as discussed in Rationale Behind Requirement. The data used to justify these requirements will not be repeated here.

b. Flare and Landing

In collecting data for this section, many pertinent reports were reviewed. Of these, five (References 10 and 12-15) serve as the base for extensive analysis. The overall volume of reports dealing specifically with STOL flight path control is limited; however, the range of configurations, conditions, pilots, and flight path response variations provided by these five reports is quite broad.

In analyzing the pilot ratings and comments from the STOL approach and landing tests, it became clear that pilot ratings would not be of as much value as the pilot comments. For example, a poor Cooper-Harper rating could be due solely to a slow path/attitude response, or to a sluggish throttle, or to a combination of these. By relying primarily upon commentary, it is possible to better separate the effect of pitch attitude as the primary path controller from the throttle effects. The latter are the subject of Section IV.

Several common characteristics for all the configurations analyzed affect the applicability of the data. Firstly, only aircraft with a pitch attitude hold augmentation system were studied. This removed, or at least minimized, the additional pilot workload of controlling pitch attitude. Secondly, the aircraft simulated (or flown) are representative of Class II or III vehicles only. There is little in the way of test data available for tactical (Class IV) STOL fighters.

References 10, 12, and 13 involve piloted simulations conducted at the NASA Ames Research Center. These studies were in support of a jointly-sponsored NASA-FAA effort to develop civil airworthiness criteria for powered-lift aircraft (see References 4 and 25). The program included representatives from the FAA and NASA, as well as American private industry, and the British CAA, French CEV, and Canadian Department of Transport.

The Reference 10 simulations were performed at NASA Ames on the Flight Simulator for Advanced Aircraft (FSAA). The simulated aircraft was the French Breguet 941S, which is a four-engine, turbo-prop, deflected-slipstream, STOL transport in the 50,000 lb class. The flight path control system included variation of transparency, which is differential pitch between the inboard and outboard propellers. Four pilots evaluated the aircraft over a range of airspeeds, approach angles, wind and turbulence conditions, with transparency in (12 deg differential) and out (0 deg). Two separate simulations are reported in Reference 10; the first did not include a SAS and there were pilot complaints about the visual scene. The second simulation used an attitude command/attitude hold (ACAH) SAS and improved visuals. Two pilots flew the latter extensively. The task involved ILS approach and visual breakout (at 200 ft) to a landing on an 1800-ft STOLport. Figure 28 summarizes the range of airspeeds and transparency evaluated on a plot of $(1/T_{\theta_2})_{eff}$ vs. t_{rev}. Representative pilot comments reflect the preferred flight path controller for flare; this is given in brackets beneath the comments. Comments are based upon landings in both calm air and moderate turbulence (σ_{u_g} = 4.5 ft/sec).

The simulations of Reference 12 were conducted in three phases, using the Ames S-16 Moving-Base simulator, the Princeton Variable Stability Navion, and the FSAA. The latter two phases were primarily validation and verification studies, while most of the data was collected in phase one. Eleven separate configurations, covering a wide range of STOL characteristics, were evaluated. For the flare and landing tasks, the initial conditions were an ILS approach from 300 ft altitude, 75 kt airspeed, and 6 deg approach angle, in calm air and in moderate turbulence (σ_{u_g} = 4.5 ft/sec), and sometimes including wind shears. Figure 29 contains representative comments by the three pilots on $(1/T_{\theta_2})_{eff}$ vs. t_{rev} plots. Comments on problems in flare control are quite consistent among pilots and as a function of $(1/T_{\theta_2})_{eff}$ and t_{rev}. As for Reference 10, consideration of the comments led to identification of the preferred flare controller, given in brackets on Figure 29. The comments for all the pilots were weighed in defining a control technique for each configuration.

Reference 13 involved a series of piloted simulations, using a variety of STOL designs (most generic powered-lift designs, based upon the Reference 12 aircraft, but including the Twin Otter) on the FSAA. This very extensive program contains an abundance of information on STOL flight path control in takeoff, landing, and cruise, varying safety margins, turbulence, and short-term response. Three basic configurations (the "400-series" aircraft in Reference 13) were used; some comments are also available from the Twin Otter simulation. Landings were flown at 75 kt on a 6 deg glideslope. The manner of these tests differs from those already discussed since the pilots were allowed only one flare control technique at a time: either pure attitude, pure power, or a combination. This allowed a clearer delineation of preferred technique,

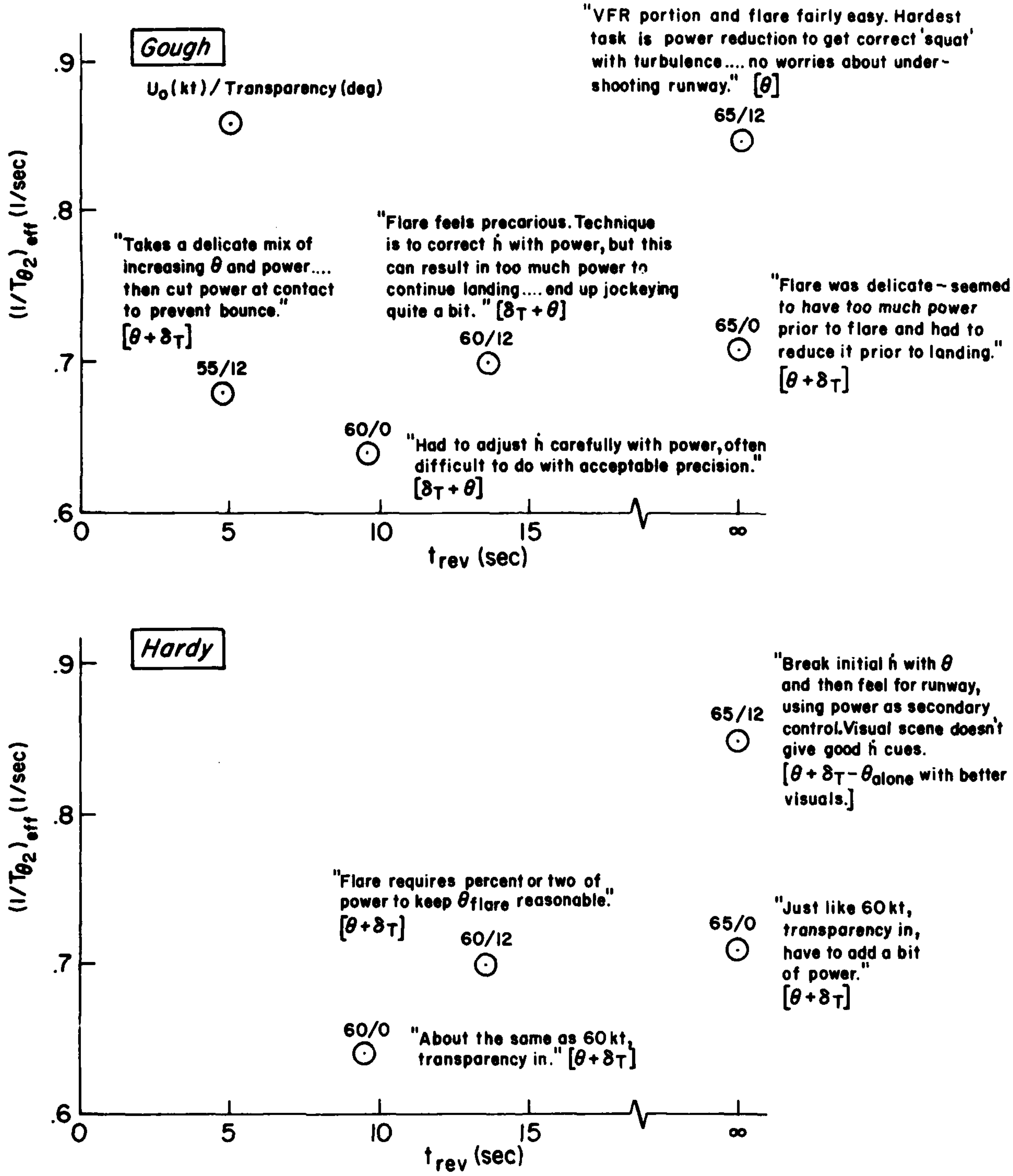
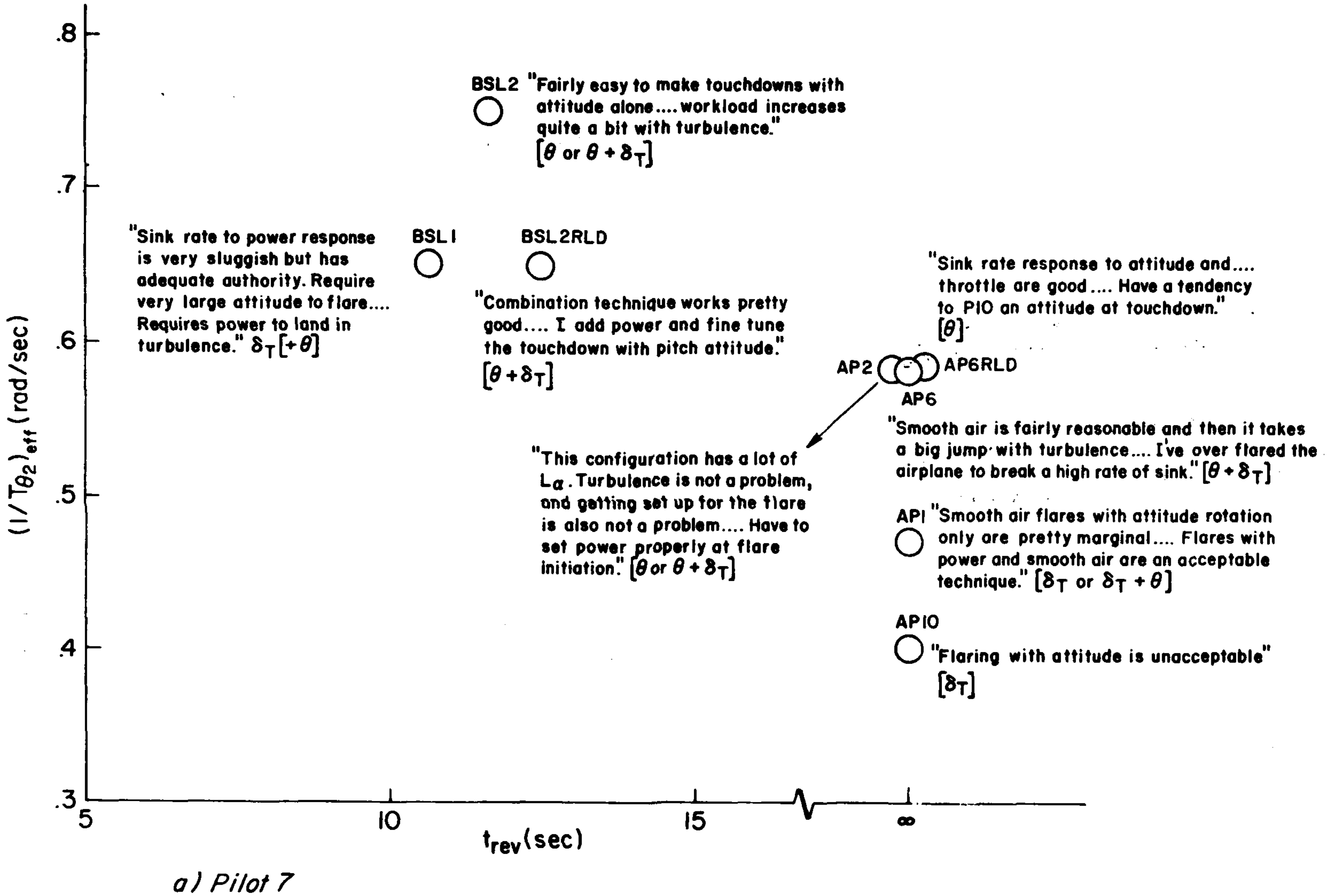
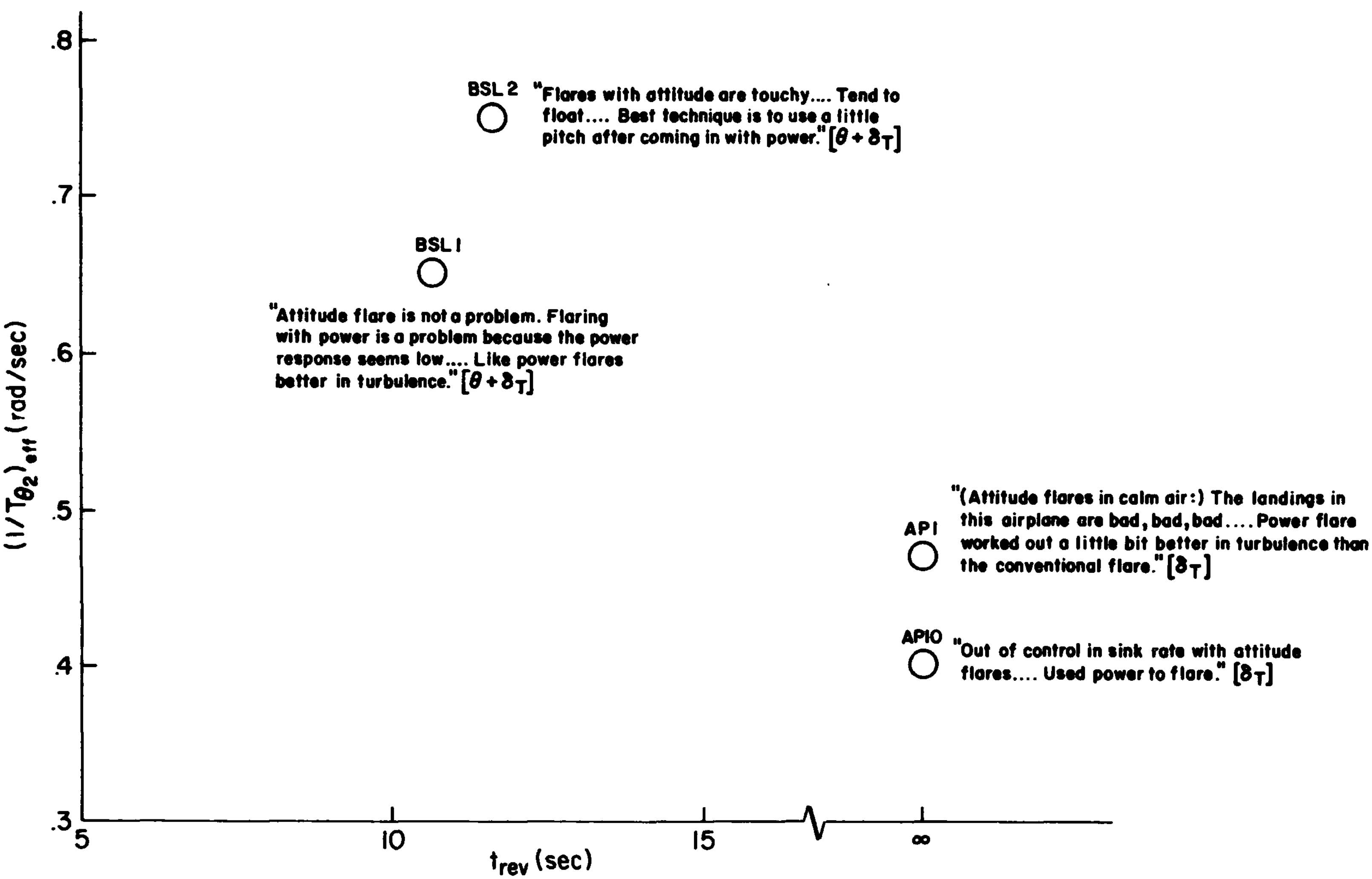


Figure 28. Selected Pilot Comments for Flare and Landing from BR941S Simulation on FSAA (Reference 10). γ_o = -7.5 deg



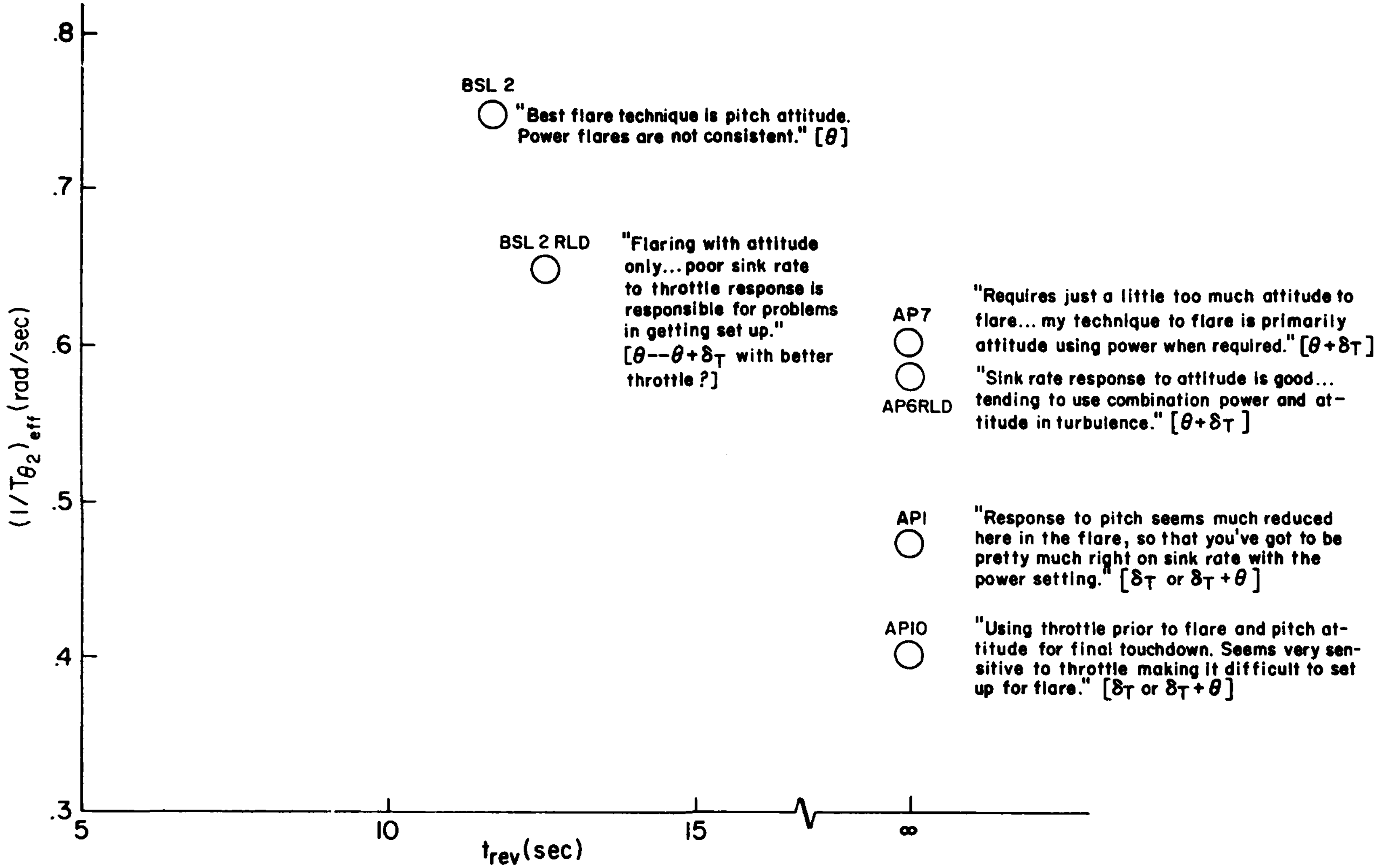
a) Pilot 7

Figure 29. Respresentative Pilot Comments for Flare and Landing from Moving-Base Simulation (Reference 12)



b) Pilot B

Figure 29. (Continued)



c) Pilot 9

Figure 29. (Concluded)

but does not represent real-world operations. Table 5 lists the flare technique, pilot comments, and flare parameters $(1/T_{\theta_2})_{eff}$ and t_{rev}, for the 400-series and Twin Otter aircraft. These results indicate that both pilots preferred the combination technique for aircraft 401; only Pilot A flew 402, and preferred power alone; for 405, Pilot A chose power-only flares, while B preferred combination flares. Attitude flares were chosen by Pilot B for the Twin Otter.

The Reference 14 flight tests used the NASA Ames Augmentor Wing Jet STOL Research Aircraft (AWJSRA), a modified de Havilland C-8A Buffalo. The characteristics of this powered-lift STOL were varied to produce a range of different flight path and speed responses. A pitch rate-command/attitude hold SAS was used for attitude stabilization. Approaches and landings were flown on a 7.5 deg glideslope at airspeeds from 65 to 70 kt to a 1700-ft STOL runway. While there was no attempt to simulate winds or turbulence, several of the flights were made in headwinds as high as 45 kts and in occasional light turbulence. When the two evaluation pilots felt that turbulence was a factor, a separate pilot rating was given. Reference 14 contains summary comments based upon both pilots' commentary and these are summarized in Figure 30. Preferred flare technique (in brackets) is based on specific comments in Reference 14. This is a good set of comments for examining the interrelationship between $(1/T_{\theta_2})_{eff}$ and t_{rev}. For example, Configurations 14, 18, 19, and 20 (see Figure 30) were all considered to be similar in that the path response to pitch was very sluggish, and Configurations 16, 11, and 15 required a combination flare due to marginal $(1/T_{\theta_2})_{eff}$. The comment for Configuration 16, "slight tendency to drop in from an intentionally extended flare," may be a direct reflection on the t_{rev} parameter (total time from flare to touchdown was about 4-10 sec). The reader may want to consult the $\Delta\gamma$ time histories given in Figure 24 in conjunction with Figure 30.

Reference 15 is essentially an independent analysis of the limited Navion flight testing conducted for Reference 12. However, four separate configurations were included. These covered a wide range of $(1/T_{\theta_2})_{eff}$ and t_{rev} (see Figure 31). The simulated STOL included an

TABLE 5. PILOT COMMENTS FOR FLARE AND LANDING INVESTIGATION OF REFERENCE 13

A/C	PILOT	$(1/T_{\theta_2})_{eff}$ (rad/sec)	t_{rev} (sec)	TECHNIQUE	COMMENTS
401	A	0.79	14.6	θ	Comparatively easy to recognize a potential float and pitch forward slightly to place the aircraft on the ground without producing a high sink rate....High θ is required....Fairly acceptable flare capability....Considerable effort required to compensate for shears....This technique was not preferred.
	B				For landing in calm air, minimum pilot compensation is required to make the touchdown zone and sink rate is acceptable in most cases....Marginal in tailwind due to a floating tendency. Pilot workload is extensive in turbulence.
	A			$\theta+\delta_T$	Preferred over the pitch only technique.
	B				Worked very well in calm and turbulence conditions....Seems to be best for this configuration.
	A			δ_T	Generally flare with power works better than expected but it is still not liked....Combination of power and θ may well be optimum.
	B				Sink rate control was no problem....Results in good touchdowns but it is difficult to compensate for short and long landings.
402	A	0.55	10.3	θ	Extreme pitch attitudes required (about 15 deg). Rapid and continuous pitch required....Apparently insufficient flare capability. Tendency to land hard and short.
				$\theta+\delta_T$	Substantial scatter in $\dot{h}_{TD}$ and X_{TD}.
				δ_T	Power modulated throughout flare giving quite tight control of flare profile....Produced reasonably consistent sink rate with less consistency of X_{TD}.
405	A	0.50	11.6	θ	Flare capability on θ seemed limited resulting in higher than desirable sink rates with tendency toward short touchdowns.
	θ	B			Response is very sluggish and difficult to control....Pitch attitudes in turbulence during flare varied considerably from one landing to the next.
	A			$\theta+\delta_T$	It was found difficult to modulate θ and RPM (having realized that RPM was incorrect) to achieve a reasonable flare profile. Turbulence produced a marked deterioration of performance, particularly of X_{TD}.
	B				The use of pitch and thrust show some improvement over pitch only but still judged poor because of sluggish pitch response....The best technique was to pitch up to a predetermined attitude (7 deg) and modulate power to control sink rate.
	A			δ_T	Consistently better control of sink rate in flare resulted in consistently low sink rates on touchdown.
	B				Unable to land within the touchdown zone with any certainty....There was no problem in regulating sink rate. This would be a good technique for a long runway.
Twin Otter	B	0.92	∞	θ	Normal CTOL technique was used similar to that which is used in the aircraft (3-5 deg pitch up about 15 ft above the ground and squeeze off power).

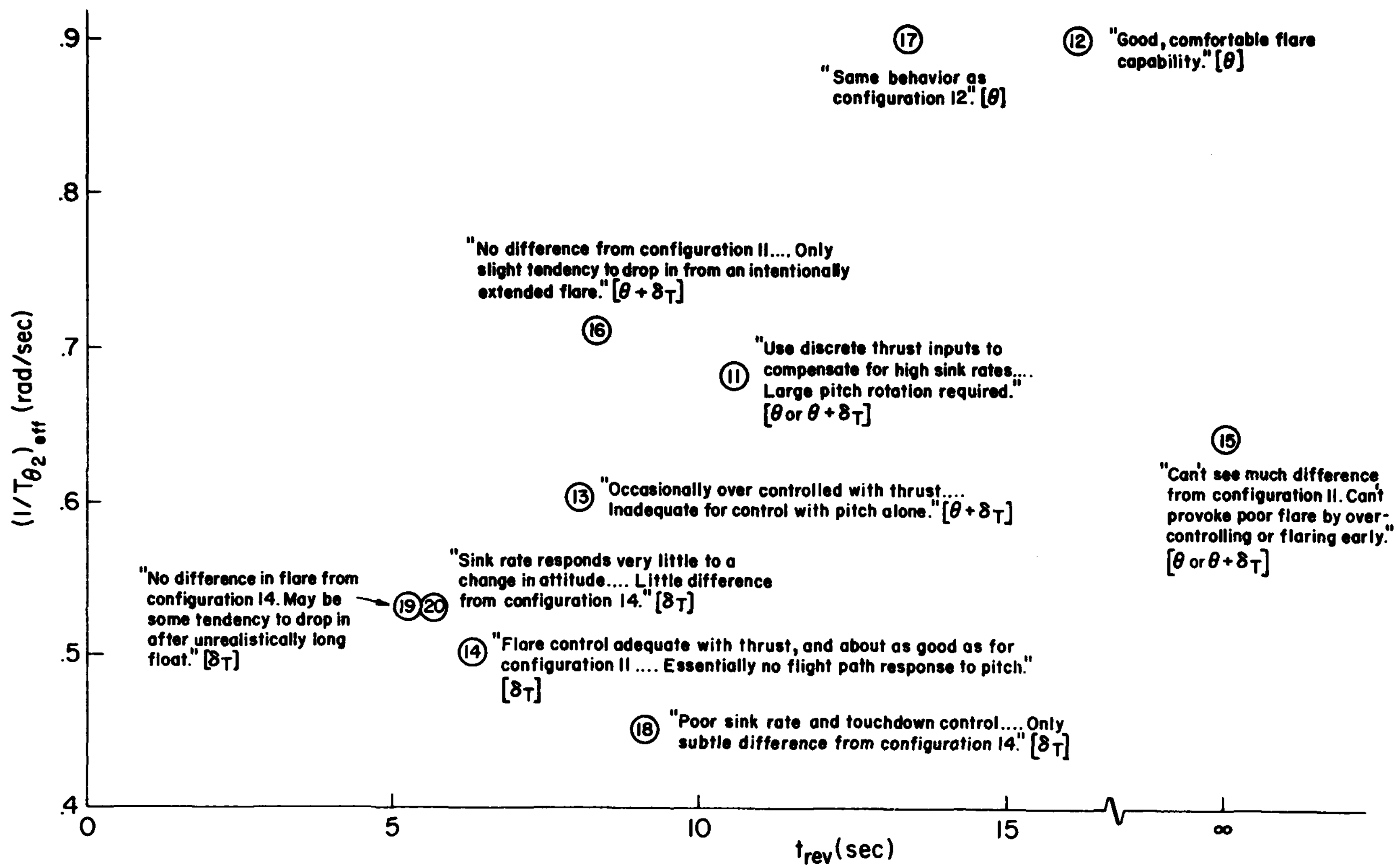


Figure 30. Representative Pilot Comments from Flight Tests of NASA AWJSRA Powered-Lift STOL (Reference 14). Numbers in Circles Refer to Configurations

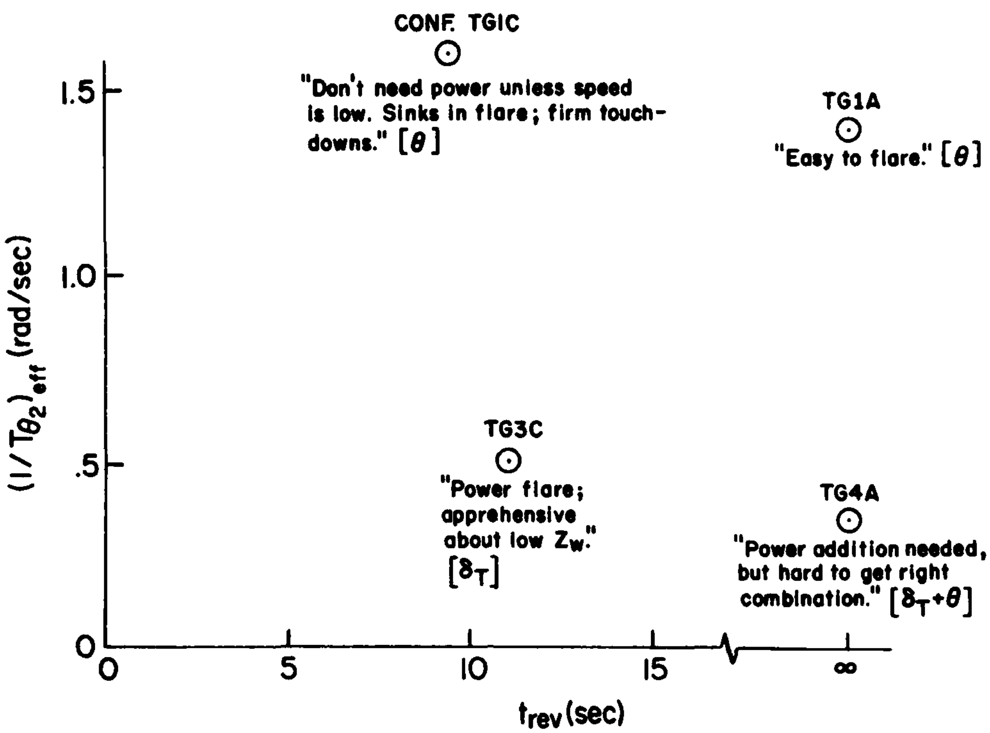


Figure 31. Pilot Comments from Flare and Landing of Navion (Reference 15). Calm Air

RCAH SAS, 70 kt approach speed on a 6 deg glideslope, without turbulence. Configuration TG4A (Figure 31) appears to have required a combination flare technique, though it is possible that the results might be different in turbulence.

In summary, the five reports discussed provide us with a wide range of aircraft, flight conditions, and flight path response characteristics. By carefully reviewing the pilot comments it has been possible to determine the pilot's preferred flare technique. Figure 32 summarizes the data base and forms the basis, in part, for the Figure 16 boundaries. It is notable that the variation in $(1/T_{\theta_2})$ with t_{rev} is based entirely on data from Reference 12. Because of the very limited motion of the S-16 simulator used for most of the data runs in Reference 12, it is undesirable to place a great deal of weight on these data points. The dashed boundary in Figure 32 reflects this concern. The rationale for extrapolating the preferred technique to Level 1, 2, and 3 boundaries is based on the fact that the pilot ratings for attitude flares

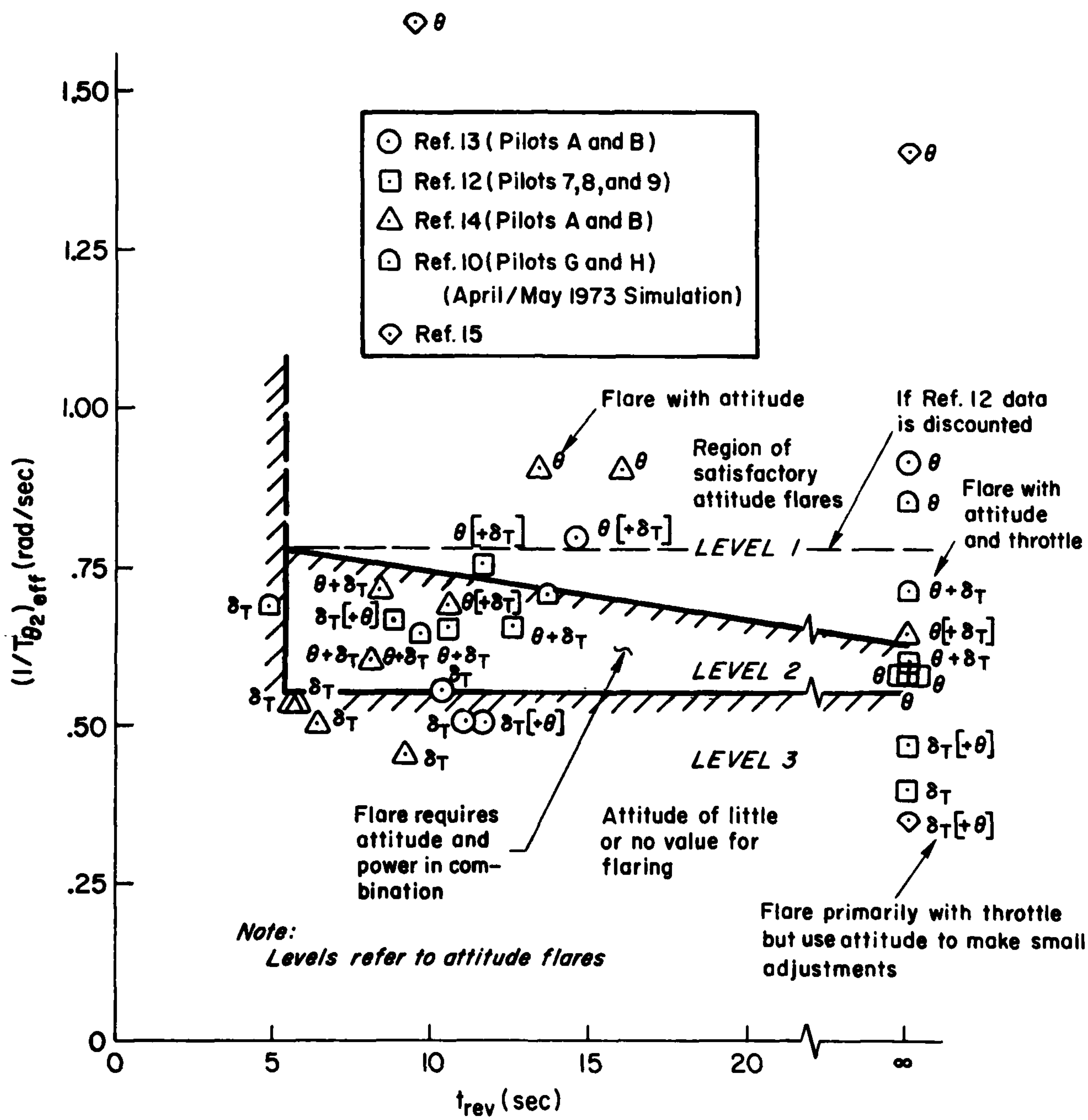


Figure 32. Flare Control Techniques Based Upon Pilot Comments

where $(1/T_{\theta_2})_{eff}$ was low were generally Level 2, i.e., 3-1/2 to 6-1/2 on attitude and thrust in combination were required were generally Level 2, i.e., 3-1/2 to 6-1/2 on the Cooper-Harper scale(see Figure 33). This is discussed in the following paragraphs.

Pilot ratings for the configurations presented above show substantial variation, due to the contaminating factors mentioned earlier. However, there are a few ratings from References 12, 13, and 14 that are worth documenting. The 400-series landings of Reference 13 (see Table 5) using pitch attitude alone are useful, as are cases from References 12 and 14 where the pilots specifically rated pure attitude (or attitude-primary) flares. In the latter instances, it is not possible to confirm whether the pilots actually performed such flares, or just extrapolated based on experience. Nevertheless, these ratings can be used to at least superficially check the levels given by Figure 16.

A total of eleven configurations (including the Twin Otter) are available from References 12, 13, and 14 and ratings are given in Figure 33. Ratings from References 12 and 13 came from two pilots in both calm air and moderate turbulence (σ_{u_g} = 4.5 ft/sec). As elaborated on in Section II, the proposed atmospheric disturbance requirements of Reference 3 allow a degradation in pilot rating in moderate disturbance (σ_{ug} = 4.5 ft/sec) such that ratings better (smaller) than 5-1/2 are Level 1, and Level 2 is between 5-1/2 and 7-1/2. On this basis, correlation with the Figure 13 boundaries is quite good, with two exceptions: Reference 12 Configuration AP1 $[(1/T_{\theta_2})_{eff} = 0.47$ rad/sec, $t_{rev} = \infty]$, and Reference 13 Aircraft 405 $[(1/T_{\theta_2})_{eff} = 0.50$ rad/sec, t_{rev} = 11.6 sec$]$, both of which are rated better than expected. Some scatter in ratings is of course anticipated, as is the need for more precise definition of the boundaries. Regardless, the results of Figure 32 and 33 are promising and hence we have elected to propose these boundaries as a tentative specification.

7. An Alternative Criterion for Flare with Attitude

The authors of Reference 14 have taken a somewhat different point of view in specifying pitch attitude requirements for the landing flare.

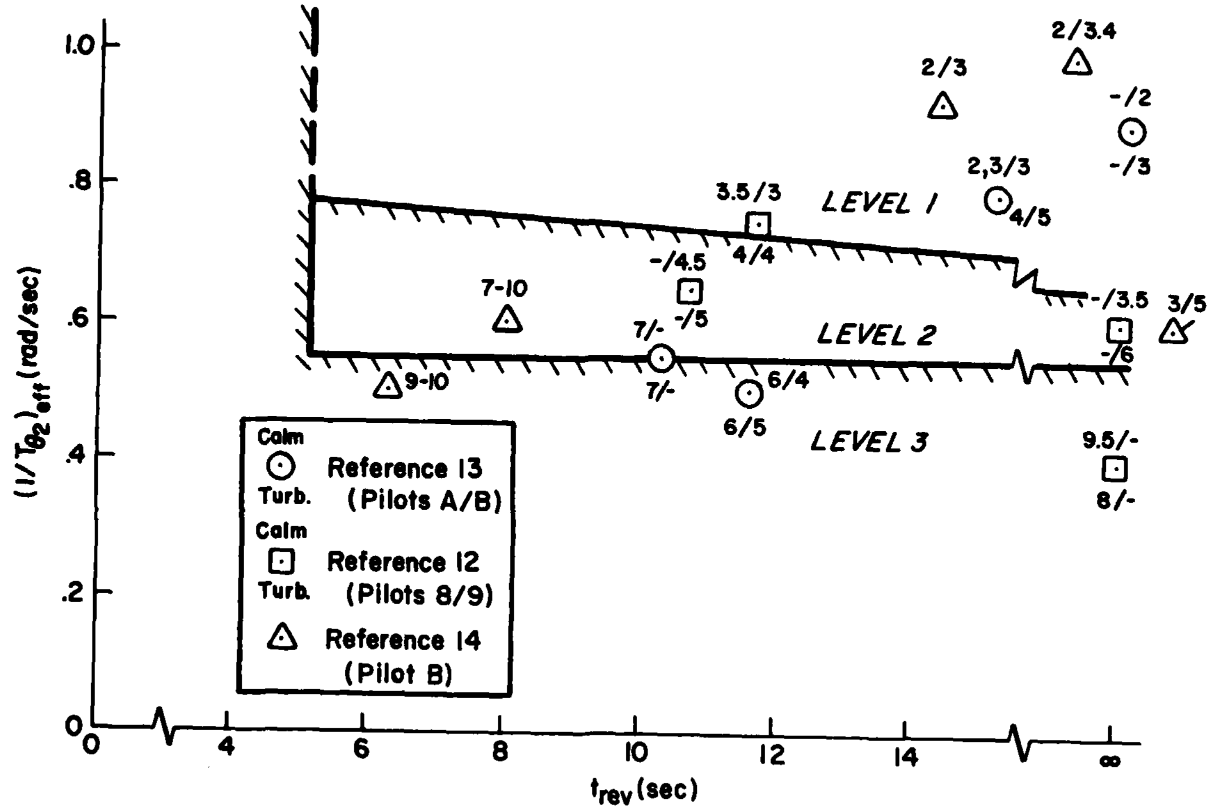


Figure 33. Pilot Ratings for Pure Attitude Flares (Reference 13) or for Attitude Flares Based on Pilot Comments (References 12, 14)

These are summarized as follows:

- the magnitude of the change in flight path corresponding to a change in pitch attitude,

  $(\gamma_{max}/\Delta\theta_{ss})$, is of primary importance for the landing flare

- the lag between flight path and pitch attitude is not a dominant factor in that, for flare, the pilot probably does not close an inner pitch attitude loop

- t_{rev} is not a factor in that the flare is over before the flight path reverses and the typical pitch attitude time history is a ramp which tends to minimize any reverse tendency

The resulting criterion, developed in Reference 14, is shown along with supporting data in Figure 34. It would seem that the resolution of these issues requires additional data, especially in the region where $(1/T_{\theta_2})_{eff}$ is Level 21 and t_{rev} is very low. An example of such a configuration might result from blended DLC spoilers (to augment a low $1/T_{\theta_2}$) which are washed out rapidly.

C. MID- AND LOW-FREQUENCY RESPONSE OF $\dot{h} \rightarrow \theta$

1. Discussion of Requirements

These requirements apply when the primary control of flight path is with pitch attitude. For aircraft without flight path augmentation (e.g., autothrottles, direct lift control, or direct drag control) the requirement limits the degree of allowable backsideness and insures that the speed control with power is adequte to prevent flight path reversals without excessive pilot workload. For aircraft with an operative flight path augmentation system, a more stringent set of low frequency response characteristics is defined since the pilot is left without a secondary controller to improve the flight path response to attitude changes. It is recommended that the pilot could add his inputs on top of the flight path augmentation. However, this would tend to increase his workload. We therefore take the somewhat "hard nosed" position that flight path augmentation should not require pilot assistance.

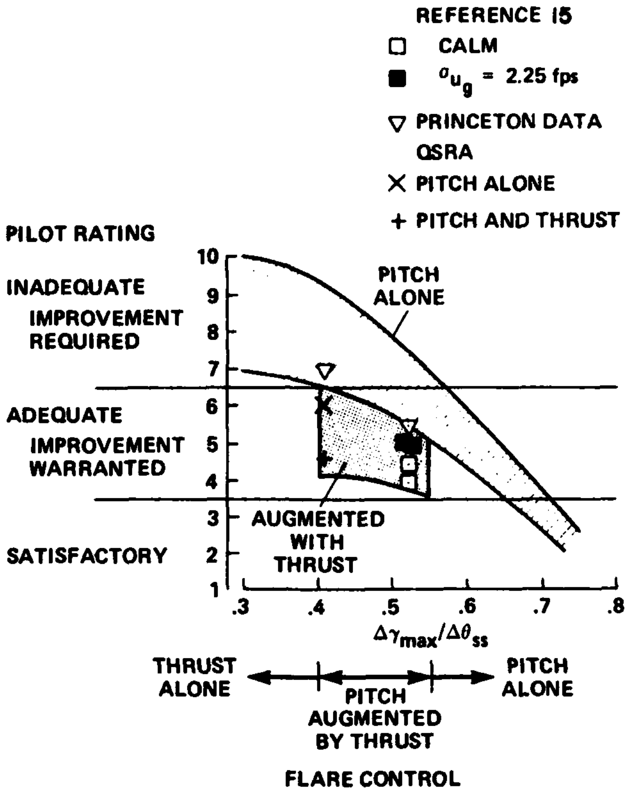


Figure 34. Landing Flare Criterion and Supporting Data from Reference 14

This section of the report includes tentative criteria, and discussions where such criteria are not available, which would be included in two sections of the MIL Handbook: 1) 3.3, Handling Quality Requirements for Vertical Flight Path Axis; and 2) 3.4, Handling Quality Requirements for Longitudinal (Speed) Axis. Subsections 2b and 4 would be particularly appropriate to high wing loading non-powered lift STOLs which will most likely employ flight path augmentation (see Section IB). These aircraft require extreme flight path precision to accomplish landings on short runways at nearly normal approach speeds in severe operating environments.

2. Statement of Requirements for Vertical Axis Response to Attitude Changes -- Mid and Low Frequency Responses

a) Attitude Primary with Designated Airspeed Controller Available: The steady-state flight path response to variations in pitch attitude shall have the following characteristics __________. In addition, the designated airspeed controller shall have the following characteristics ____________.

b) Attitude Primary When a Designated Airspeed Controller is not Available): When flight path is to be controlled solely by pitch attitude, the mid-term and long term flight path and airspeed response characteristics to variations in pitch attitude shall be ____________.

Recommended Values:

Requirement a)

The variation of steady state flight path angle with changes in airspeed, with thrust held constant, shall have the following characteristics:

Level 1 $\left(\frac{\partial \gamma}{\partial V}\right)_T < 0.06$ deg/kt

Level 2 $\left(\frac{\partial \gamma}{\partial V}\right)_T < 0.15$ deg/kt

Level 3 $\left(\frac{\partial \gamma}{\partial V}\right)_T < 0.24$ deg/kt

In addition, the airspeed response to variations in the designated airspeed controller shall have the characteristics designated in Para 3.4.2 of the MIL Handbook (Reference 3), Speed Response to Speed Controller. This is given below as Subsection 3.

Requirement b)

1) The excursions in angle of attack due to variations in pitch attitude shall be minimized such that $\gamma/\theta > 1.0$ shortly following each disturbance. Specific limits on γ/θ are not available at this time. However,

References 26 and 27 indicated that a γ/θ of 1.2 to 1.3 would be optimum and that $\gamma/\theta = 1.0$ elicited complaints of larger than desired attitude changes required for glide-slope control.

3. Statement of Requirement for Speed Response to Speed Controller

The airspeed response to changes in speed controller setting shall have the following characteristics ______.

Recommended Values Need to be Determined

4. Requirement for Speed Response to Attitude Changes with an Operative Flight Path Augmentation System

A tentative requirement is not available at this time. However, the speed variations about trim should be very small whenever the speed holding function has been delegated to a flight path augmentor. An additional requirement is necessary to specify the speed response to horizontal gusts and to turning flight. Speed control is of importance primarily because it has a significant effect on the mid-frequency flight-path response, and of course, as a margin from stall.

5. Rationale Behind Requirements

The requirement for flight path control in MIL-F-8785C (Reference 1) presumes that attitude is primary and sets limits on $\partial\gamma/\partial V$ which allow operation with a nearly conventional technique on the backside of the power required curve ($\frac{d\gamma}{dV} > 0.06$ deg/kt for Level 1). This is based on data correlations for conventional aircraft wherein the thrust is oriented almost entirely along the x axis. The piloting technique in this case is to make short-term flight path corrections with attitude and to hold airspeed near its target value with low frequency changes in the thrust setting. This pilot technique eliminates the flight path reversal that occurs when $d\gamma/dV$ is positive. Limiting $d\gamma/dV$ to small positive values has the effect of minimizing the pilot workload required to hold speed constant with throttle. MIL-F-8785C takes for granted that throttle is a good (albeit low frequency) airspeed controller and no separate requirement on $u \rightarrow \delta_T$ is included. However, for STOL aircraft the thrust inclination angles may be nearly vertical. In such cases, throttle would yield poor control over airspeed leaving the pilot no way to avoid the flight path reversals associated with positive values of $d\gamma/dV$, with the result that control of flight path with attitude would be unacceptable. For this reason, a separate requirement on airspeed control with throttle is felt to be necessary in a STOL specification when attitude is designated as the primary flight path controller.

When a flight path augmentation system (e.g., autothrottle or direct drag control) is incorporated, the pilot's control of flight path is restricted to attitude only. This may be necessary to reduce workload when the touchdown precision requirements are high and the environment is severe. The basic concept of such systems is that path follows pitch attitude with only very small variations in angle-of-attack. Care must be taken with such systems to avoid excessive responsiveness to gust inputs since the natural feedbacks are aerodynamic quantities such as angle-of-attack and airspeed.

SECTION IV

VERTICAL AXIS RESPONSE TO DESIGNATED FLIGHT PATH CONTROLLER

A. GENERAL

Requirements under this paragraph are applicable only to aircraft equipped with a designated flight path controller other than pitch attitude. The form of controller is irrelevant; STOL designs have used spoilers, flaps, nozzle vectoring, and throttles to provide flight path control. Throughout these requirements the controller will often be described as "throttle" for convenience, since "designated flight path controller" is unwieldy. The use of "throttle" to represent the flight path controller should not be construed to indicate any preconceptions as far as specific design.

The reader should review Part A of Section III (which covers the γ/θ transient response) to see how these requirements mesh with those of that section. For example, it would be expected that a designated flight path controller will be required for many powered-lift aircraft because: 1) a significant component of the thrust vector is vertical, and/or 2) the aircraft operates well on the backside of the power required curve.

In some cases the designer may choose to augment the STOL aircraft so that it has frontside path control characteristics. Such augmentation requires a feedback of airspeed to some auxiliary force producer in the X direction. For example, the Boeing version of the AMST utilized the Coanda flap. The requirements of Section III would be appropriate for such an aircraft.

B. VERTICAL AXIS RESPONSE TO DESIGNATED FLIGHT PATH CONTROLLER — TRANSIENT RESPONSE

1. Reason For Requirement

For aircraft flown using the STOL technique, this is the primary requirement to assure good short-term flight path control. Any aircraft with inadequate path response to pitch attitude for landing approach or for flare (i.e., does not meet the $(1/T_{\theta_2})_{eff}$ vs. t_{rev} requirement of Section III) must meet this requirement.

2. Statement of Requirement and Recommended Values

Vertical axis response to designated flight path controller — transient response. When used as a primary controller the short-term flight path response to designated flight path controller inputs shall have the following characteristics: ________________.

Recommended values: Effective rise time, $t_{R_{\gamma T}}$, and overshoot ratio, $\Delta\gamma_{max}/\Delta\gamma_{ss}$, from a step change in designated flight path controller, should be within the Level 1 boundaries of Figure 35. There are insufficient data to define the boundary between Level 2 and Level 3. Aircraft which fall outside the Level 1 boundaries in Figure 32 should be required to have Level 1 vertical axis response to attitude changes.

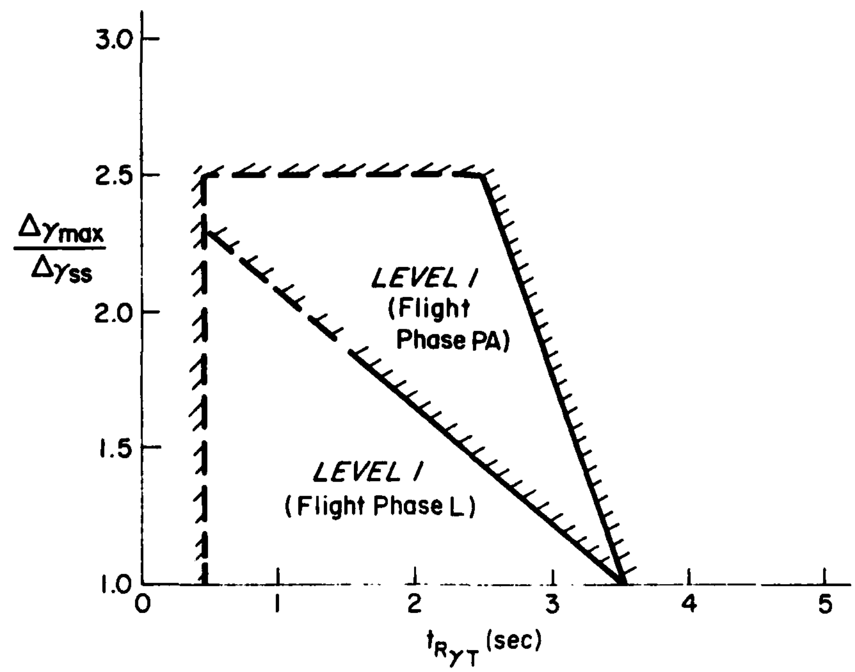
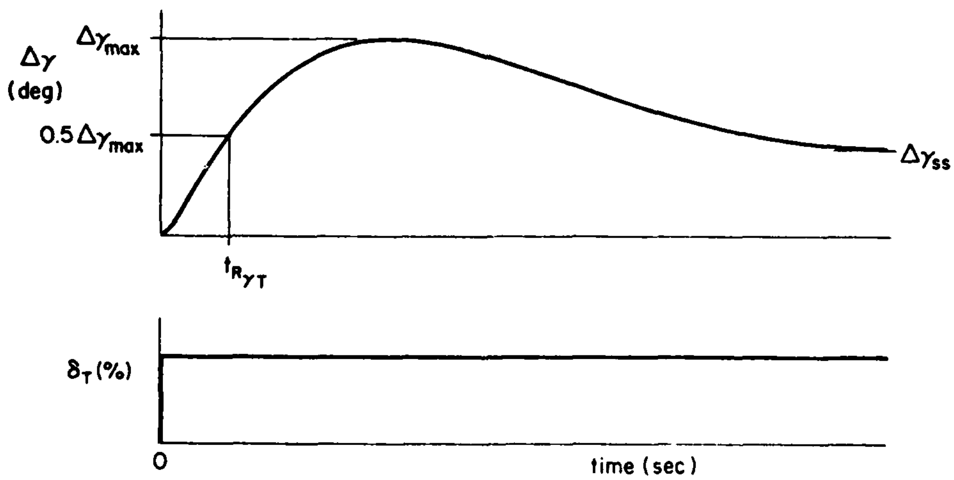


Figure 35. Level 1 Limits for Short-Term Vertical Axis Response to Step Input of Designated Flight Path Controller

3. Rationale Behind Requirement

The most important short-term requirements for the designated flight path controller are rapidity of response and effectiveness in changing the flight path. Consistent with the similar attitude requirement (Section III, Part B), rapidity is defined here in terms of rise time, $t_{R_{\gamma_T}}$. In Section III the parameter $(1/T_{\theta_2})_{eff}$ was specified as a measure of flight path bandwidth with rise time allowed as an alternate (see Figure 23). Here we have chosen to use the time response parameter as the primary requirement, with flight path bandwidth as an alternative, primarily because of the extensive work that has been done on this rise time parameter (see, e.g., References 4, 14, 15, 24 and 25).

Overshoot ratio, $\Delta\gamma_{max}/\Delta\gamma_{ss}$, determines how well the commanded flight path change stabilizes in the short term. It is similar in intent to the path/attitude parameter t_{rev}. Figure 36 illustrates how $t_{R_{\gamma T}}$ and $\Delta\gamma_{max}/\Delta\gamma_{ss}$ are defined. Note that $t_{R_{\gamma T}}$ is identical to the parameter $t_{0.5\Delta\gamma_{max}}$ of Reference 14 and that it is also closely related to the bandwidth of $\dot{h}/\delta_T$ (normal pitch SAS on) as defined by the example in Figure 37.* Figure 38 shows the relationship between $\omega_{BW_{hT}}$ and $t_{R_{\gamma T}}$



Note: Pitch attitude controller is free during response

Figure 36. Definition of γ/δ_T Time Response Parameters (Pitch SAS Active)

*The definition of the bandwidth as used here is identical to the definition of the bandwidth of θ/F_s in Section II.

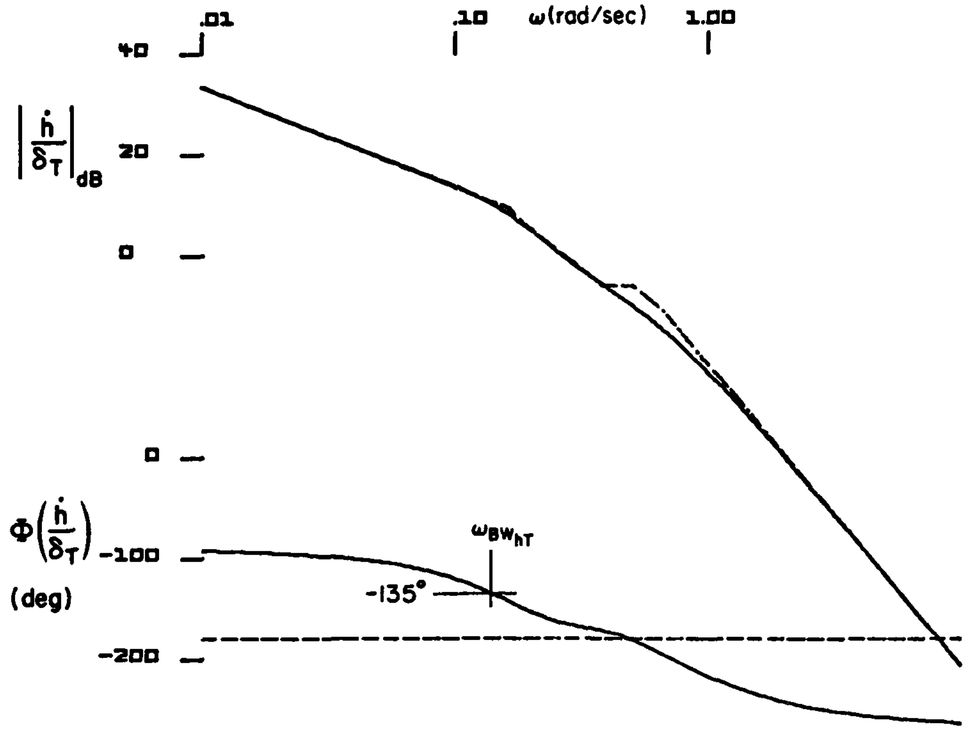


Figure 37. Definition of $\dot{h}/\delta_T$ Frequency Response Parameters (Pitch SAS Active)

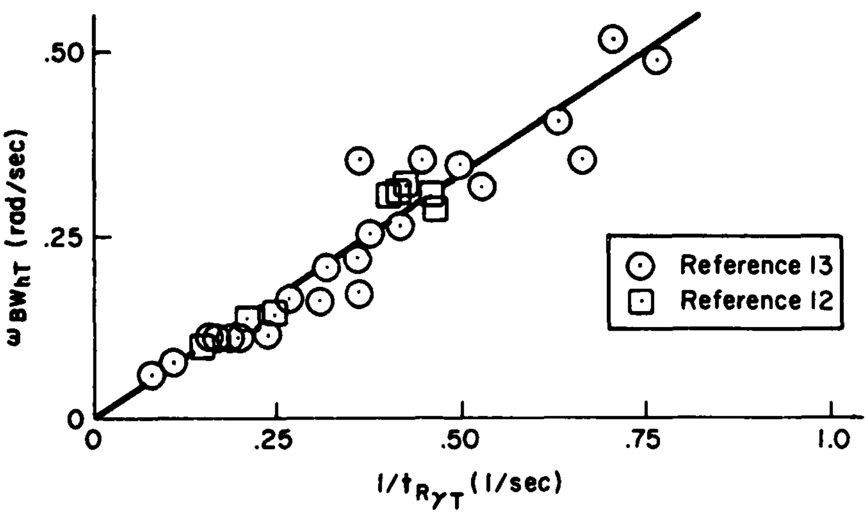


Figure 38. Relationship Between Throttle Bandwidth and Rise Time for Typical Powered-Lift STOLs

for the data of References 12 and 13. This figure may be used to convert the Figure 35 requirement to $\omega_{BW_{hT}}$ vs. $\Delta\gamma_{max}/\Delta\gamma_{ss}$, if desired.

The scatter in the available data base (discussed later) makes it difficult to accurately define response limits. Therefore, the boundaries of Figure 35 are very tentative and should be investigated with further analysis and testing. Additionally, a boundary between Levels 2 and 3 is needed in Figure 35.

The limits of Figure 35 reflect pilot acceptance of less precise flight path control (i.e., more overshoot) during the approach than for flare and landing. For flare, large path overshoots generally lead to high workload and touchdown dispersions. The dashed lines on the Level 1 boundaries reflect uncertainty (primarily due to a lack of data) in pilot opinion for small values of $t_{R_{\gamma T}}$. It is likely that the excessive abruptness consistent with $t_{R_{\gamma T}} \rightarrow 0$ would be unacceptable to the pilot. However, the lower limit on $t_{R_{\gamma T}}$ in Figure 35 is not based on any existing data and should be the subject of piloted simulation or flight test experimentation.

4. Supporting Data

The body of data used to support this requirement includes all the configurations discussed in Section III (References 10 and 12-15), plus References 11 and 24.

The first step in the data correlations was to separate the effects of pitch attitude as a flight path controller from those of throttle. After all, if pitch is a good controller and throttle is poor, the pilot will just fly the aircraft like a CTOL — a condition covered in Section III. It follows that we desire to isolate those cases where the pilot had to use throttle* as the primary path control. That is, we want the configurations for which γ/θ is the worst, not the best, for supporting data.

*Again we point out that "throttle" is used here to represent any designated flight path controller.

a. Approach Data

An extensive review of configuration characteristics and pilot comments from References 11-14 shows that, with only one exception, all the aircraft tested were flown using STOL technique ($\dot{h} \rightarrow \delta_T$, $u \rightarrow \theta$) on final approach. This is, of course, to be expected, since all these aircraft represented powered-lift designs. The single exception was a simulated aircraft with an effective horizontal thrust inclination and adequate path/attitude bandwidth (Reference 13) -- i.e., a non-powered-lift CTOL-type airplane. Table 6 summarizes this review of References 11-14, including representative pilot commentary and, where it was discernible, the pilots' preferred path and speed controls. A review of Table 6 reveals that control of flight path was accomplished primarily with throttle (δ_T) in all cases. It should be noted that many of the Reference 12 configurations were on the frontside of the power required curve but that the pilot still utilized the STOL technique for flight path control. This was primarily because of the large thrust inclination angle that renders throttle ineffective as a speed controller. In fact, a review of the pilot commentary reveals that speed/path coupling was actually adverse in many cases, i.e., speed decreased with a power addition. Path/speed coupling is further discussed in Section VI. The parameter θ_T is the effective thrust angle, in stability axes, i.e.,

$$\theta_T = \tan^{-1}\left(-\frac{Z_{\delta_T}}{X_{\delta_T}}\right)$$

This is one measure of the extent of powered lift, where θ_T = 90 deg is a purely vertical component. The parameters $t_{R_{\gamma T}}$ and $\Delta\gamma_{max}/\Delta\gamma_{ss}$ can be related to θ_T. Figure 4 shows the generic effect of θ_T on flight path response. As this figure suggests, sluggish rise time ($t_{R_{\gamma T}}$ large) is often associated with relatively horizontal thrust, while overshoot ($\Delta\gamma_{max}/\Delta\gamma_{ss} > 1$) occurs as a result of relatively large values of θ_T.

TABLE 6. CONFIGURATIONS AND REPRESENTATIVE PILOT COMMENTS FOR LANDING APPROACH

REF.	CONF.	θ_T (deg)	$(\frac{1}{T_{\theta_2}})_{eff}$ (rad/sec)	t_{rev} (sec)	$t_{R_{\gamma T}}$ (sec)	$\frac{\Delta\gamma_{max}}{\Delta\gamma_{ss}}$	PILOT	CONTROL OF Y	CONTROL OF U	COMMENTS
11	65 kt	90	0.61	∞	1.6	2.0	A	δ_T	θ	No problem in smooth air. Turbulence increased G/S workload considerably and IAS workload slightly.
							B	δ_T	θ	No real problem in calm air. Good response to pitch and power. Turbulence introduced additional workload requiring constant monitoring of power and IAS.
							C	δ_T	θ	Small power corrections led to minor IAS variations which were easily managed with θ. No problem in trimming or tracking ILS under any condition.
							D	δ_T	θ	Tracking the G/S using power was the easiest task during the approach.
							E	δ_T	θ	With turbulence workload becomes marginal and shears make the workload too high.
							F	δ_T	θ	Turbulence increases tracking task dramatically to an unacceptable level. Response to power is immediate and easy to over-control.
							G	δ_T	θ	Calm air was easy....In turbulence tracking became more difficult.
							H	δ_T	θ	There appears to be no interaction between speed and trajectory control for small corrections....Makes the aircraft easy to fly.
	65 kt (T_E = 1.5 sec)	90	0.61	∞	1.55	2.7	A	δ_T	θ	Increased lag not detected.
	65 kt (T_E = 2.5 sec)	90	0.61	∞	1.5	3.3	F	δ_T	θ	Degraded response appealing for VFR calm air conditions. Throttle action appeared smoother. In turbulence and shear the tracking task was less precise with excursions in sink rate.
	65 kt (DLC)	90	0.61	∞	1.6	1.2	C	DLC	θ	DLC performs as the pilot expects it to, i.e.: • Direct effect on G/S error • Minimum cross coupling • Excellent response for handling shears and gusts.
12	BSL1	61	0.65	10.7	4.0	1.0	1	δ_T	θ_{const}	Considerable amount of juggling between pitch attitude to control airspeed and throttle to control altitude.
							2	$\delta_t(+\theta)$	θ	Vertical speed response to normal throttle motions is very low with a lot of lag. Basic technique was backside with pitch inputs to get an initial response out of it. Tried frontside with zero results.
							6	δ_T	θ	No problem tracking glide slope.
							8	δ_T	θ	Airspeed to attitude is sluggish.
							9	δ_T	θ	My technique is to command glideslope with IVSI because of long engine lag.
	BSL2	61	0.75	11.7	6.5	1.0	1	δ_T	θ	Glide slope tracking is straightforward.
							2	$\delta_T(+\theta)$	θ	Short-term effect of attitude changes is greater in influencing vertical speed than airspeed. Basic technique was backside, but modified by extensive use of attitude for quick response.
							7	δ_T	θ	Once I get the speed under control then I know that the power-to-flight-path angle relationship is giving me one less thing to do when I intercept glide slope.
							9	δ_T	θ	Primary problem is sink rate to power.

TABLE 6. (CONTINUED)

REF.	CONF.	δ_T (deg)	$\left(\frac{1}{T_{\theta_2}}\right)_{eff}$ (rad/sec)	t_{ref} (sec)	$t_{R_{\gamma T}}$ (sec)	$\frac{\Delta\gamma_{max}}{\Delta\gamma_{ss}}$	PILOT	CONTROL OF Y	CONTROL OF U	COMMENTS
12	BSL2RLD	61	0.65	12.5	4.7	1.0	1	δ_T	θ	Airspeed response to pitch attitude seems adequate. Sink rate to throttle response is a little sluggish and barely adequate.
							7	δ_T	θ	Low initial sink rate to throttle response. Throttles seemed insensitive. Good airspeed control.
							9	δ_T	θ	No apparent coupling between airspeed and throttle.
	AP1	81	0.47	-	2.5	1.8	1	δ_T	θ	This configuration has very low C_{L_α}, but this is not a problem because altitude response to power is adequate.
							7	δ_T	θ_{const}	My technique is to fly constant attitude and let airspeed vary. If the airspeed variations are not too big and we don't end up getting too close to the margins, then there is no problem.
							8	δ_T	θ	Adding power you have to push over the nose to hold your speed up.
							9	δ_T	θ_{const}	You could get to a trim attitude that would fairly well hold a speed.
	AP2	90	0.58	-	2.3	2.4	1	$\delta_T(+\theta)$	θ	Used a crossfeed of throttle to column for large power changes and used airspeed to attitude and sink rate to throttle for glide slope tracking.
							2	$\delta_T(+\theta)$	θ	Airspeed/flight-path coupling is very bothersome....Since my ability to track the glide slope does not appear to be affected by the poor airspeed control, I can live with it.
							7	δ_T	θ	Long as I don't worry about speed it's okay.
	AP6	90	0.58	-	2.4	1.9	1	δ_T	θ	Primary task of glide slope tracking is quite straightforward and variations of speed do not seem to affect this task.
							6	δ_T	θ	The only problem with this configuration was to maintain airspeed. Airspeed is very hard to manage and responds very slowly.
							7	δ_T	θ	Main objection to the airplane is the adverse coupling between speed and flight path....If you just let the airspeed vary, it works out pretty good.
	AP6RLD	90	0.58	-	2.4	1.9	1	δ_T	θ	Airspeed throttle coupling.
							7	$\delta_T(+\theta)$	θ	Glideslope tracking is adequate. I don't worry about indicated airspeed....Large L_α allows me to control sink rate at glideslope intercept.
							9	δ_T	θ	I don't like reverse speed path coupling ....speed excursions do not seem to affect my ability to track.
	AP7	77	0.60	-	2.8	1.3	1	δ_T	θ	Very limited down capability with power.... Seems to have reasonably good sink rate to power and airspeed to attitude.
							9	δ_T	θ	Slight adverse speed to throttle coupling ....A little slow on down sink rate to throttle.
	AP10	90	0.40	-	2.7	3.2	1	δ_T	θ	Sluggish airspeed to attitude response but this does not seem to affect the glideslope tracking....Pilot rating would be much worse if speed control were a dominant part of the task. Large adverse speed throttle coupling.

TABLE 6. (CONTINUED)

REF.	CONF.	θ_T (deg)	$(\frac{1}{T_{\theta_2}})_{eff}$ (rad/sec)	t_{rev} (sec)	$t_{R_{\gamma T}}$ (sec)	$\frac{\Delta\gamma_{max}}{\Delta\gamma_{ss}}$	PILOT	CONTROL OF γ	CONTROL OF U	COMMENTS
12	AP10	90	0.40	-	2.7	3.2	7	δ_T	θ_{const}	Any effort to control airspeed is not practical....This does not appear to affect my ability to track the glide slope with power.
							8	δ_T	θ	Could not get my target airspeed.... speed goes the wrong way with power addition....Glide slope tracking is adequate.
							9	δ_T	θ	No way to hold speed....Large attitude changes with no speed changes. Very confusing.
13	Twin Otter	48	0.92	-	4.3	1.0	B	δ_T	θ	Target speed of 70 kt was used at all times. Speed regulation is very important for STOL performance.... Crosscoupling in turbulence.
							E	δ_T	θ	Airspeed regulation was not difficult because it tended to hold well except for random excursion due to turbulence ....Turbulence increases the workload on throttle activity and glide slope tracking.
	1210	80	0.68	12.6	2.8	1.0	A	δ_T	θ	Airspeed was not regulated as tightly as desired due to the high workload on the glide slope tracking tasks.
							B	δ_T $(+\theta_{trim})$	θ	Use of pitch and power results in good flight path control....Airspeed corrections were not a problem since airspeed held relatively constant without correction.
							C	δ_T	θ	Response of airspeed to pitch attitude was satisfactory.
							D	δ_T	θ	A little crossfeed into pitch attitude from throttle to deal with slight proverse coupling....Airspeed was not regulated too tightly because the workload was too high.
							E	δ_T	θ	No corrections were made for airspeed errors.
	1220	45	0.62	6.9	5.4	1.0	A	δ_T	θ	Large [pitch attitude] changes were required for small airspeed errors.
							B	$\delta_T(+\theta)$	θ	Airspeed control turns out to be the primary factor in the approach.
	1230	95	0.65	6.5	1.5	1.5	A	δ_T	θ	Small [airspeed] errors were accepted. Quite strong reversed airspeed coupling from power.
							B	δ_T	θ	Appears to be a well behaved stable airplane when flown within ±5 kt speed margin.
	1240	10	0.59	-	9.2	1.0	A	θ	δ_T	[Flew both CTOL/STOL; preferred CTOL].
							B	θ	δ_T	[Same] - Power for control of flight path was not acceptable....The effect on airspeed would make it unacceptable.
	1250	92	0.69	-	2.0	1.1	A	δ_T	θ_{const}	No real problems were encountered holding the desired glide slope....In the short term, no airspeed corrections were made.
							B	$\delta_T(+\theta)$	θ	Power up/pitch down....Resulted in very good control of flight path....Usually a constant attitude...would result in good airspeed control.
							C	δ_T	θ	Pilot can either track airspeed or use a constant pitch attitude.

TABLE 6. (CONCLUDED)

REF.	CONF.	θ_T (deg)	$(\frac{1}{T_{\theta_2}})_{eff}$ (rad/sec)	t_{rev} (sec)	$t_{R_{\gamma T}}$ (sec)	$\frac{\Delta\gamma_{max}}{\Delta\gamma_{ss}}$	PILOT	CONTROL OF		COMMENTS
								γ	u	
13	1260	50	0.58	-	3.7	1.0	B	$\delta_T+\theta$	$\theta+\delta_T$	[Found δ_T only, θ only, combination, all acceptable]. No problem with flight path control or airspeed.
	1270	91	0.53	-	2.7	1.0	A	δ_T	θ_{const}	There was no attempt to control airspeed and no changes to pitch attitude were made....CTOL technique was examined briefly, but dismissed due to large pitch changes for glideslope tracking and strong effect of power on glideslope.
	1210	80	0.68	12.6	2.8	1.0	C	δ_T	θ_{const}	Pitch attitude was held constant within ±1 deg. With a reduction in power the nose would pitchup very slightly.
							E	δ_T	θ_{const}	Noticeable nosedown pitching moment with the addition of power but no compensation for airspeed was made.
	1240 ($\Delta\tau_E$ = 2.5 sec)	10	0.59	-	11.8	1.0	C	θ	δ_T	Airspeed control was important IFR.... Proverse coupling ($+\delta_T \rightarrow +U$) but it was hard to control.
14	1	73	0.68	10.5	2.5	1.0	A,B*			Decoupling of flightpath and airspeed response allows approach to be made at more constant pitch attitude....Glideslope tracking reasonably good.
	2	90	0.68	10.5	1.8	1.9		δ_T	θ	Some difficulty with coupled flightpath-airspeed-angle-of-attack responses to thrust. Airspeed variations influence flight path response....Easy to get low/slow due to path-speed coupling.
	3	93	0.68	10.5	1.7	2.9		$\delta_T(+\theta)$	θ_{const}	Best to maintain constant attitude; otherwise large speed and angle-of-attack excursions occur. Flightpath overshoot and path-speed coupling apparent....If path corrections not accompanied by large attitude changes, path control is limited.
	4	98	0.68	10.5	1.7	13.5				Flightpath is not controllable. Large adverse path-speed coupling.
	5	84	0.90	16.1	1.7	1.0				Glideslope tracking OK....About the same as Configuration 1 for IFR tracking.
	6	58	0.50	6.3	3.7	1.2				Must be accustomed to making large and rapid throttle corrections. Glideslope control noticeably worse than Configuration 1....Tracking is oscillatory.
	7	42	0.68	10.5	5.1	1.0				Sluggish flightpath response to throttle....Tend to overshoot glideslope corrections. Large speed changes during path corrections. Must use coordinated attitude to throttle control technique and amount of coordinated control required is almost too much.
	8	90	0.48	7.6	2.2	3.2				Large path speed coupling causes significant workload. Flightpath control doesn't seem much different than Configuration 6. Difficult to keep speed under control.
	9	90	0.53	5.3	2.4	2.5				Difficult to see much difference from Configuration 6. Glideslope tracking is oscillatory....Flightpath-airspeed coupling noticeable but not excessive. Airspeed wanders quite a bit.
	10	57	0.60	3.0	3.5	1.0				Poor glideslope tracking, but not as bad for overcontrolling as Configuration 6.

*No distinction made between pilots.

Observing from Table 6 that the pilots used throttle as the designated flight path controller, we may assume that θ becomes primarily a speed controller. However, Table 6 indicates that the pilots also used attitude for short term path control when the throttle response was sluggish. Nonetheless, throttle was unquestionably the primary flight path control. It follows that the pilot ratings for approach flight path control from References 10-14 can be used to define limits on $t_{R_{\gamma T}}$ and $\Delta\gamma_{max}/\Delta\gamma_{ss}$. Figure 39 is a summary of these ratings. The test conditions, vehicles flown, and facilities are described in detail in Part B of Section III, and summarized in the following table.

REF	TEST FACILITY	AIRCRAFT	VARIABLES
10	FSAA (Simulator)	BR941S	U_o, γ_o, σ_{u_g}, Transparency
11	FSAA	Augmentor Wing	U_o, γ_o, Winds, T_{ENGINE}
12	S-16 (Simulator)	Generic Powered-Lift	U_o, h_o, γ_o, σ_{u_g}, Winds
13	FSAA	Generic Powered-Lift	σ_{u_g}, Winds, T_{ENGINE}
14	Augmentor Wing	AWJSRA	X_w, Z_w, θ_T

The flight test data on Figure 39 have poorer pilot ratings than the simulations. The reasons for this are not fully known, although it is possible that the overall flight test environment (which almost always included some winds and turbulence) was more severe than the simulated environments. A similar degradation in pilot ratings in flight test was found in Reference 12 (compare simulator and Navion data on Figure 39).

It is important to remember that the proposed MIL Standard/Handbook (Reference 3) allows a degradation in pilot ratings due to turbulence; for example, the Level 1 limit drops from 3-1/2 to 5-1/2. Therefore a rating of 5 in moderate turbulence is equivalent to a 3 in calm air. This two-point shift is supported by the data of Figure 39.

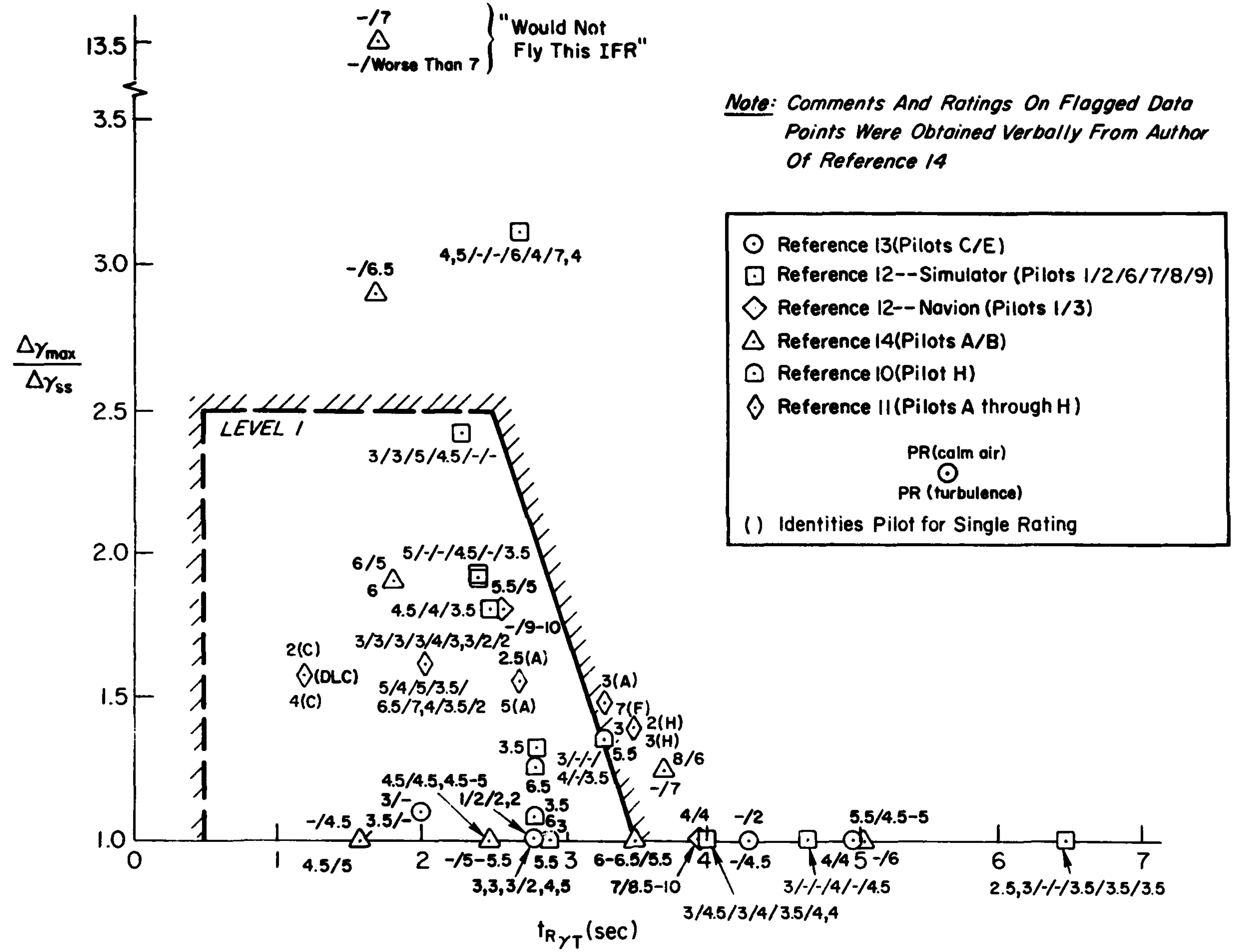


Figure 39. Pilot Ratings for Control of STOL Aircraft in Landing Approach

There is considerable scatter in the ratings shown in Figure 39. For example, in one case Level 1 pilot ratings were given to a configuration with an extremely sluggish response ($t_{R_{\gamma T}}$ = 6.5 sec). This is explained by the good short-term path/attitude characteristics of this configuration $[(1/T_{\theta_2})_{eff}$ = 0.75 rad/sec; Configuration BSL2 from Reference 12]. The pilot comments for BSL2 in Table 6 verify that the pilot used throttle for basic path control but relied on pitch attitude for quickening the path response. In fact, the primary reason the pilots stated that they used the backside technique on this configuration was that the thrust inclination was nearly vertical, making it impossible to control airspeed with power. However, close investigation of the pilot commentary strongly suggests that pitch attitude was primary for short term path control.

The boundaries drawn are based on a combination of the data shown, and on what previous researchers have recommended. For example, Reference 4, using most of the same data, suggested $t_{R_{\gamma T}}$ less than 3 sec. Reference 14 utilized the AWJSRA flight test data and much of the data from References 12, 15, and 24 to recommend a) $t_{R_{\gamma T}} < 3.5$ sec (with no overshoot) and b) $\Delta\gamma_{max}/\Delta\gamma_{ss} < 2.5$ (with good rise time) for <u>adequate</u> flying qualities, i.e., PR < 6.5. This is quite different from the Level 1 limits of Figure 39. As discussed above, there may be other factors in the Reference 14 flight test data that influenced these ratings. The AMST specification (Reference 28) defined the rise time for reaching 90 percent of steady-state, and set the limit at 5 sec for flight at the minimum operational speed. For a typical $\dot{h}/\delta_T$ response this would be equivalent to $t_{R_{\gamma T}}$ of approximately 2.8 sec (Configuration 1210 in Table 6).

Data from Reference 24 are given in Figure 40. These data are from an FSAA simulation of the Augmentor Wing with variations in X_u, X_w, and θ_T. The data were not included on Figure 39 because the task in this experiment only included ILS tracking -- a relatively undemanding task. This is reflected in Figure 40 where the Reference 24 data are compared with the proposed boundaries. The fact that Level 1 pilot

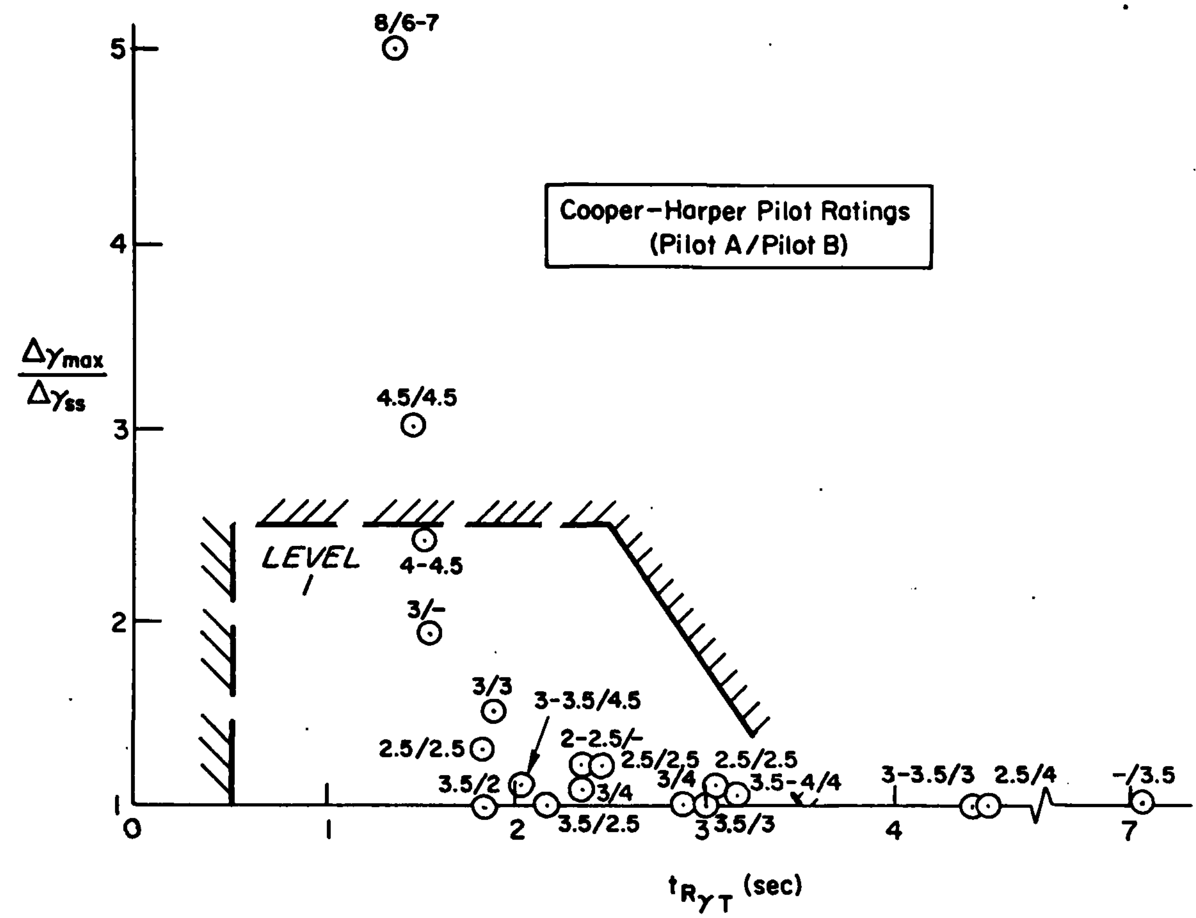


Figure 40. Pilot Ratings for ILS Tracking Task with Simulation of Augmentor Wing; Calm Air (Reference 24)

ratings were given to configurations with very sluggish response characteristics ($t_{R_{\gamma T}} \doteq 5$) emphasizes the fact that the visual portion of the landing task on short final and in the flare is much more demanding than the ILS approach (see discussion in Reference 12). Regardless, the data are still worth considering, and support at least the $\Delta\gamma_{max}/\Delta\gamma_{ss}$ limit.

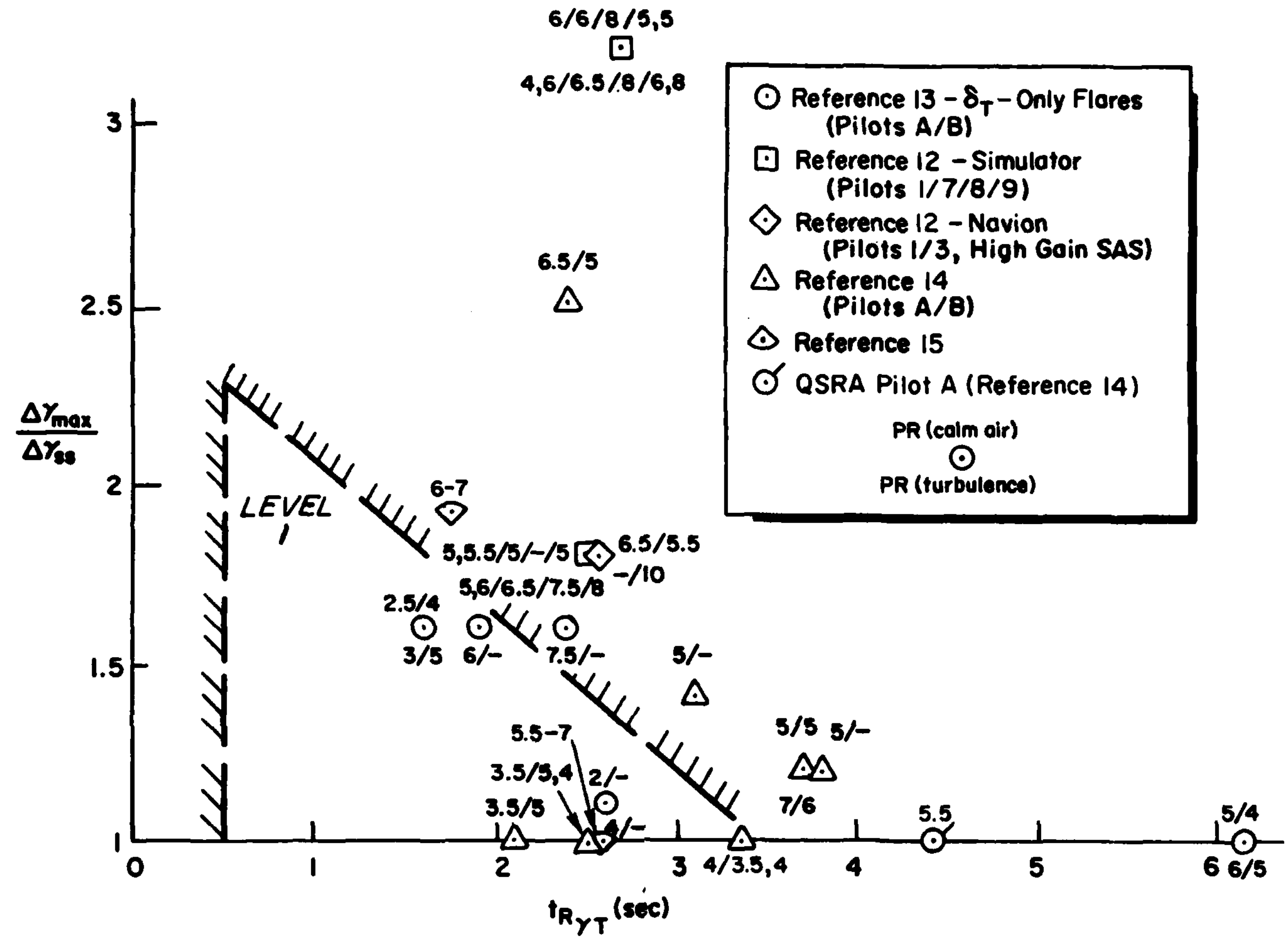
Figures 39 and 40 lack sufficient data to support a Level 2 limit in either rise time or overshoot, and thus there is no such limit in the Figure 32 requirement.

b. Flare and Landing

It is here that we must be careful in filtering out inappropriate data. Unlike the approach, wherein throttle was always used to control flight path, attitude is as likely a flare controller as throttle. This is discussed in Section III, and shown clearly in Figure 30 of that section. Since we don't want to base a throttle response requirement on attitude flares, we will focus on those configurations that fall in the δ_T region of Figure 32 -- i.e., cases where throttle must be used to flare. In addition, since the $\theta + \delta_T$ area on that figure may include throttle-primary flares, these data will be checked against the throttle response boundaries. Figure 41 shows data for both cases.

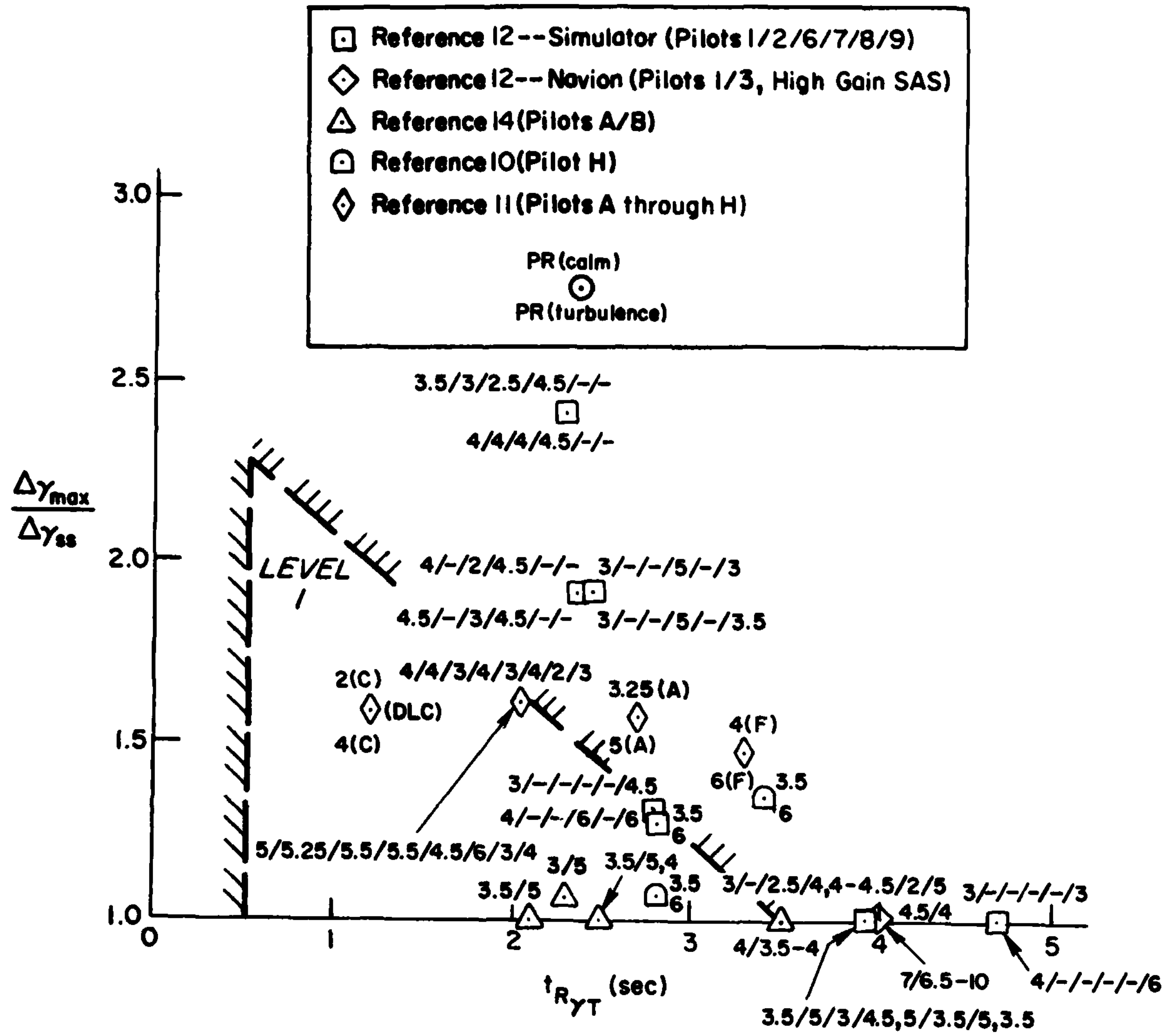
The data points in Figure 41a correspond to the δ_T cases of Figure 32. There is somewhat stronger support for the Level 1 limit here than in the approach region. This is probably attributable to the fact that there was less time to correct for responses that were sluggish or had overshoot in the flare maneuver; i.e., landings require more precision than approaches. This important result has been observed during all approach and landing experiments, STOL and CTOL. The flight test data of Reference 12 correlate quite well. The ratings suggest much less tolerance for overshoot, as one would expect. (It should be noted that the authors of Reference 14 concluded from their data that flight path overshoot may not be important as a flare criterion.) Again, a Level 2 boundary cannot be drawn.

Figure 41b shows that the combination flare cases ($\theta + \delta_T$) receive Level 1 ratings over an expanded region, i.e., outside the Figure 41a Level 1 boundary. This suggests that even though attitude is in itself Level 2, it can be effective as a secondary controller for flare. More work needs to be done to further quantify the usable interrelationship between throttle and attitude for STOL flares. However, we would be hesitant to recommend relaxation of the γ/δ_T requirements for flare based on possible use of attitude as a secondary controller. Such complex flare techniques should be allowed only as a last resort.



a) Configurations That are in δ_T Region in Figure 30

Figure 41. Pilot Rating Data for Flare and Landing



b) Configurations That are in $\theta + \delta_T$ Region in Figure 30

Figure 41. (Concluded)

C. VERTICAL AXIS RESPONSE TO DESIGNATED FLIGHT PATH CONTROLLER — STEADY-STATE RESPONSE

1. Reason For Requirement

The long-term response to a commanded flight path change should be consistent with the pilot's expectations.

2. Statement of Requirement

Vertical axis response to designated flight path controller -- steady state response. At all flight conditions the flight path controller will produce flight path motions in the same direction as the applied control and which are of the same sign as the steady-state values.

3. Rationale Behind Requirement

This requirement is a counterpart to the long-term path/attitude requirement, usually $d\gamma/dV$ (see Section III). In this case no specific criterion exists. The STOL data examined for a steady-state parameter did not reveal any single, adequate correlating criterion. In addition, "steady-state" flight path control was seldom a problem as long as long-term control power was adequate. This requirement is included to preclude any problems with steady-state response.

SECTION V

FLIGHT PATH CONTROL POWER

A. GENERAL

Powered lift STOL aircraft typically are quite limited in terms of flight path control power in the power approach (PA) configuration. This requirement is intended to insure adequate authority for glideslope tracking and landing, rather than a discrete event such as go-around. Adequate control power does not tend to be a problem for such discrete events when the pilot has time to reconfigure the aircraft.

B. RECOMMENDED FLIGHT PATH CONTROL POWER REQUIREMENT

1. Reason for Requirement

For most current STOL designs, flight path is primarily controlled with throttle. For such cases, this requirement applies directly to the limits of travel for the thrust controller. For configurations which are augmented so that flight path is controlled exclusively with attitude (such as the Boeing YC-14), the requirements of this section apply except that the limits apply to attitude control rather than throttle. The use of a separate auxiliary cockpit controller (such as spoilers) is considered to be a way of reconfiguring the aircraft and therefore does not apply.

2. Statement of Requirement and Recommended Values

a. It shall be possible to produce a steady state flight path angle of ______________ without reconfiguring the aircraft.

b. It shall be possible to achieve the required flight path angle without a change in the trim airspeed for the approach flight condition. Any airspeed bleedoff associated with the $\Delta\gamma_{up}$ required for flare and landing shall not be excessive.

c. If an augmentation scheme is employed to allow flight path to be controlled solely with pitch attitude, the attitudes required to achieve the specified flight path angle shall not be excessive.

3. Rationale Behind Requirement

The recommended values for $\Delta\gamma$ are based on moving-base simulations (References 10, 11, and 13). The data for these simulations are reviewed in the following subsection. Values for $\Delta\gamma$ must include consideration of control in turbulence and ability to counter horizontal wind shears.

A requirement on $\Delta\gamma$, as opposed to $\Delta\dot{h}$ or Δn_z, has the advantage of being independent of speed (since $\Delta\gamma = \Delta\dot{h}/U_0$). Both the Air Force AMST specification (Reference 28) and the AGARD V/STOL document (Reference 29) set requirements on minimum incremental normal acceleration — the former at ±0.1 g for all STOL operations, the latter at +0.2 g for flare. For typical STOL approach speeds and flight path angles, these values are reasonably consistent with the Table 7 requirement to achieve 1.5 deg above level flight. This can be illustrated by assuming the exponential flare model in Section III. For ideal path control:

$$\dot{h} = \dot{h}_0 e^{-t/T_F}$$

TABLE 7. RECOMMENDED MINIMUM FLIGHT PATH CONTROL POWER

FLIGHT PHASE	LEVEL	MINIMUM FLIGHT PATH CHANGE (MEASURED FROM γ_{TRIM})(DEG)	
		UP $\Delta\gamma$	DOWN $\Delta\gamma$
PA	1	4	4
	2	2	2
	3	2	2
L	1	LEVEL FLIGHT $+1.5^\circ$	4
	2	LEVEL FLIGHT -1°	2
	3	LEVEL FLIGHT -1°	2

where T_F is the flare mode time constant defined in Section III and $\dot{h}_o$ is the sink rate at flare initiation. For an ideal path mode response $\left(t_{R_{\gamma T}}\right.$ very small$\left.\right)$ the peak normal acceleration is:

$$(n_z)_{peak} = \frac{1}{g}\frac{\dot{h}_o}{T_F}$$

For typical STOL flares T_F varies between 3 and 5 sec. If we assume $\dot{h}_o$ is approximately 18 ft/sec to account for the initial sink rate plus the required 1.5 deg up capability (e.g., if $\gamma_o = -6$ deg and $V_{ref} =$ 85 kts) then $(n_z)_{peak}$ varies from 0.11 g to 0.19 g for values of T_F of 5 and 3 sec, respectively. This is consistent with the 0.10 to 0.20g requirements specified in References 28 and 29.

Large discrete horizontal windshears near touchdown represent a limiting condition on flight path control power. From the results of Reference 30 it is found (see Section VI) that unless $(1/T_{\theta_2})_{eff}$ is quite large (greater than about 0.9 rad/sec), a powered lift STOL cannot safely negotiate horizontal windshears corresponding to the aircraft performance limits, i.e., $\dot{V}_W = g\gamma_{max}$ or $g\gamma_{min}$. It follows that to insure the capability for negotiating a design windshear, one can either augment $(1/T_{\theta_2})_{eff}$ or provide excess control power over the design windshear. If we insist that a powered lift STOL be no more vulnerable to windshear than the low wing loading STOL (Twin Otter), the required flight path control power can be approximated from Figures 48 and 49 in Section VI-B with the following result.*

$$\gamma_{max} > 1.5 \text{ deg}$$

$$\Delta\gamma_{min} < -6.5 \text{ deg}$$

---

*These values were obtained by noting the values of γ_{max} where the lines for iso-accident potential rating of 4 become asymptotic, and subtracting 6 deg (nominal approach angle) from this value.

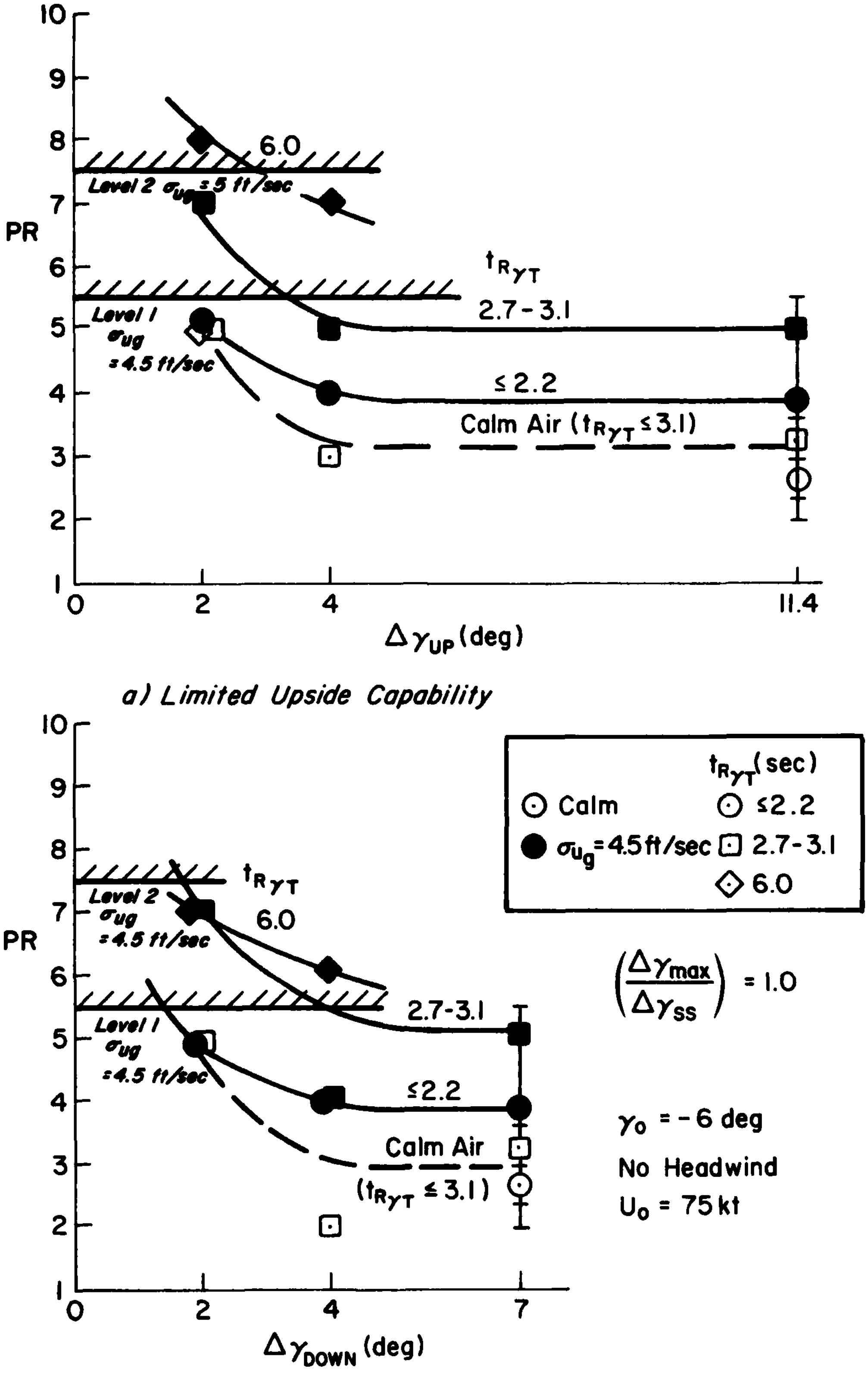
The Table 7 γ_{max} requirement for landing (level flight +1.5 deg) is consistent with the windshear requirement. However, the $\Delta\gamma_{min}$ requirement is substantially greater than the recommended -4^{o} requirement in Table 7 -- a result of the fact that the Reference 13 experiment upon which Table 7 is based did not include large discrete decreasing tailwind windshears.

The possibility of relaxing the flight path control power as a function of $(1/T_{\theta_2})_{eff}$ should be considered in future handling quality experiments. For the present, the question of whether or not the $\Delta\gamma_{min}$ requirement in Table 7 should be made more stringent based on the above noted windshear considerations must be addressed by the procuring activities in developing the final STOL specification.

4. Supporting Data

The primary source of data for developing the Table 7 requirements was a flight path margin study in Reference 13. A series of approaches and landings was flown on the NASA Ames FSAA simulator. Tasks covered VFR approaches and ILS approaches to breakout on a 6-deg glideslope, and flare and landing. Aircraft coupling, engine response time, and turbulence conditions were varied. Winds included calm air, headwinds, tailwinds, and crosswinds, and some shears. Turbulence levels were $\sigma_{u_g} = 0$ and 4.5 ft/sec (moderate). Both up- and down-γ capability were limited systematically. The pilots were told to accomplish all flight path control, including flare, with the throttle in order to avoid the "contaminating" effects of $(1/T_{\theta_2})_{eff}$ noted above.

Figure 42 shows the results of the flight path margin investigation. Cooper-Harper pilot ratings for two pilots are shown as a function of maximum $\Delta\gamma$ available. The pilots rated the aircraft after flying a full profile of ILS tracking to breakout, visual approach, flare, and landing. The ratings may therefore be considered composites for the entire task. Figure 42 indicates that pilot ratings did not degrade until maximum $\Delta\gamma$ was 4 deg or less, up or down.



b) Limited Downside Capability

Figure 42. Effect of Flight Path Margin on Pilot Ratings. ILS Approach and Visual Landing, Reference 13 (200- and 300-Series Configurations)

Another simulation experiment, also reported in Reference 13, provides additional data. The task and initial conditions were identical to those for Figure 42 with the exception that a steady headwind and decreasing headwind shear was added. The wind velocity was 20 kt at altitudes over 200 ft above ground, and varied down to 12 kt at touchdown. Therefore, while the inertial approach angle, $\gamma_{inertial}$, was -6 deg, the aerodynamic angle, γ_{aero}, varied from -4.4 deg at 200 ft and above to -5.0 deg at touchdown.

For this simulation, pilot ratings are available for three separate mission segments: ILS approach, breakout (at 220-300 ft) to pre-flare (about 35 ft), and flare and landing. However, only upside $\Delta\gamma$ was limited. Figure 43 shows the ratings for this simulation.

Ratings for the approach portion (Figures 43a and 43b) show trends consistent with Figure 42a: pilot ratings degrade to Level 2 at around $\Delta\gamma = 4$ deg for $t_{R_{\gamma T}}$ near the Level 1 limit of 3.5 sec (see Section IV). The data indicate a possible relaxation in the $\Delta\gamma$ requirement for faster path response characteristics (lower $t_{R_{\gamma T}}$). However, this has not been reflected in the recommended requirement in Table 7 because of the limited amount of data available to support this trend. The data in Figures 42, 43a, and 43b indicate that $\Delta\gamma$ can be decreased to ±2 deg for Level 2 flying qualities in the approach flight condition (PA).

Considerably more control power is required in the upside direction ($\Delta\gamma_{up}$) for flare and landing (L) than is required in power approach (PA), according to the data in Figure 43c. This is not surprising since the flare ideally involves a change in flight path angle equal to the inertial approach angle corrected for wind (5 deg in Reference 13). Based on fairing the few available data points in Figure 43c, the recommended Level 1 and Level 2 limits are 6.5 deg and 4 deg respectively. For the purpose of formulating the requirement (Table 7), this has been interpreted as 1.5 deg above level flight for Level 1 and 1 deg below level flight for Level 2. This Level 1 requirement seems reasonable when compared to practical STOL designs. For example, the YC-15 had a maximum γ of about 4 deg at a 75 kt approach speed. The downside limits for flare are unchanged from the approach values, i.e., Level 1 is -4 deg and Level 2 is -2 deg.

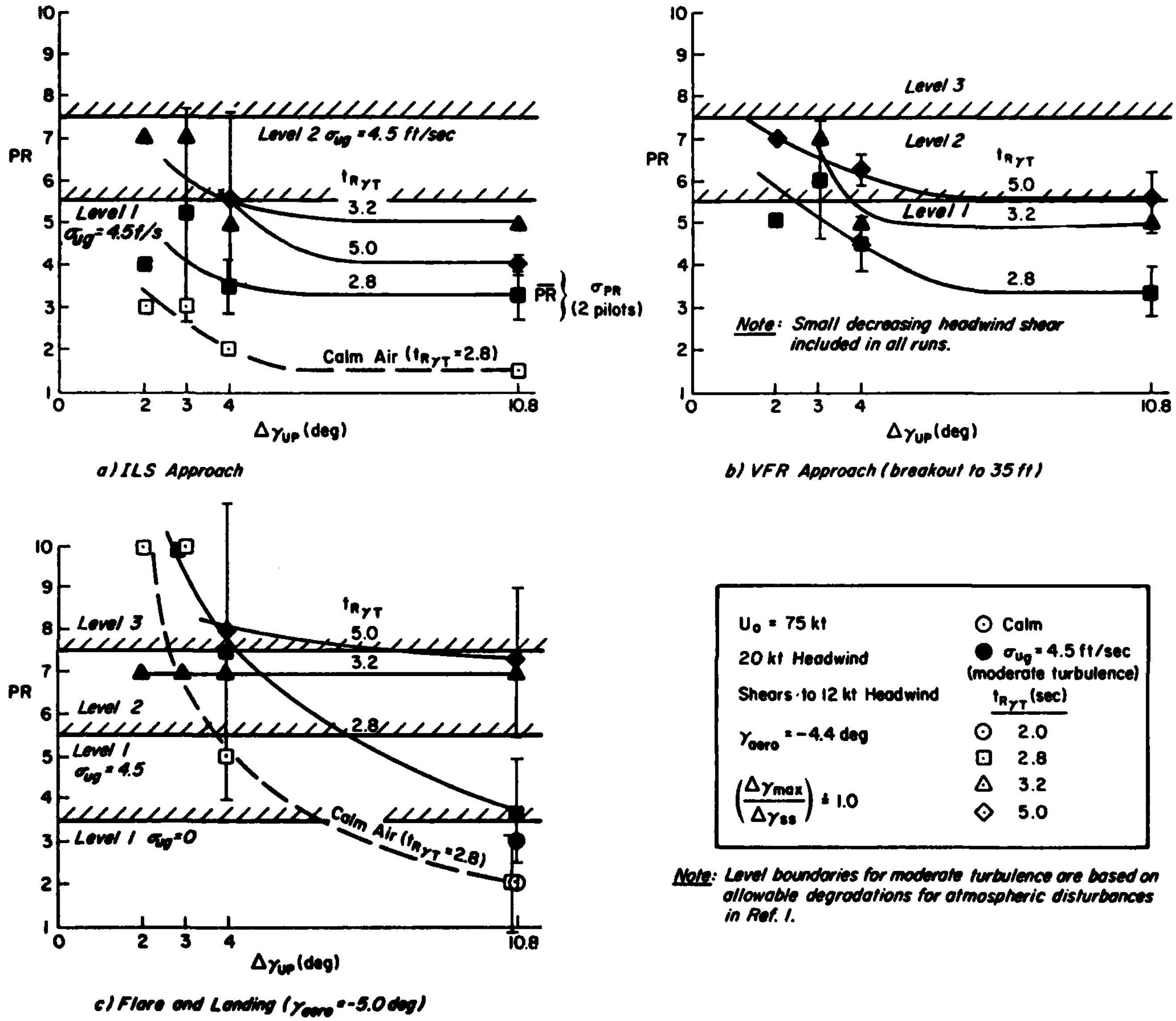


Figure 43. Effect of Upside Flight Path Margin on Pilot Ratings of Reference 13 (1200-Series Configurations)

It must be emphasized that the Table 7 values are based on fairing a few widely spread data points and that more data are highly desirable to refine these limits.

The FAA, in developing tentative airworthiness criteria for STOLs (Reference 25), specified a $\Delta\gamma$ of ±4 deg. Most subject pilots in the FAA STOL simulations generally agreed that "airworthy" corresponded to a Cooper Harper Rating of about 5; i.e., a little better than Level 3. With this interpretation, the Level 2 limit on $\Delta\gamma$ in Table 7 for the PA flight condition would increase from 2 deg to about 3-1/2 deg.

All of the data in Figures 42 and 43 are based on flight path control with power and the pilots were specifically requested to avoid the use of attitude. Therefore, the data may be somewhat conservative. As discussed at length in Section III, most powered lift STOLs must be flown using the backside technique wherein flight path is controlled primarily with power on the approach. However, it is quite common to flare with attitude. It was felt that the path control power required to flare is probably not dependent on whether the flare controller is throttle or attitude and that the Figure 43c data are applicable in both cases. The requirement allows a "reasonable" airspeed bleedoff when meeting the $\Delta\gamma$ requirements for landing to account for the use of attitude to flare. It should be noted that pure attitude flares require reasonably large values of $(1/T_{\theta_2})_{eff}$ (Figure 32) which essentially guarantees meeting the $\Delta\gamma_{up}$ requirement for flare and landing. An additional requirement for such aircraft is that excessive pitch attitudes are not required to achieve the limits specified in Table 7.

The $\frac{\Delta\gamma_{max}}{\Delta\theta_{ss}}$ criterion suggested in Reference 14 (see Figure 34) would be appropriate to assure adequate flight path control power for landing flares with attitude (θ) or attitude plus throttle ($\theta + \delta_T$). Whether or not $\frac{\Delta\gamma_{max}}{\Delta\theta_{ss}}$ is simply a control power criterion to be used in combination with $(1/T_{\theta_2})_{eff}$ and t_{rev} (Figure 32) or an autonomous criterion for flare should be experimentally investigated.

SECTION VI

OTHER CONSIDERATIONS FOR STOL FLYING QUALITIES

A. INTRODUCTION

Preceding sections of this report have addressed specific areas of STOL flying qualities, introducing criteria and reviewing data where such areas are lacking in the MIL Handbook (Reference 3). The intent of this section is to discuss several topics of concern to STOL flying qualities for which there is no corresponding recommendation for requirements. Such topics are either: a) of general interest for STOL design and analysis; or b) subjects for which there is insufficient data to develop criteria.

B. EFFECTS OF WIND SHEARS

A major finding in the STOL simulation of Reference 12 was the significant impact of atmospheric disturbances on pilot ratings in the approach and landing. The overriding contributor was the low-frequency part of the random gust model — i.e., wind shears. Configurations with minimally acceptable path control characteristics were found to degrade rapidly with increased turbulence.

These results have obvious implications for STOLs in the future, and especially for tactical aircraft that may be called upon to take off and land in adverse weather at runways located in rough terrain. However, severe windshears have occurred even in major air traffic centers. Several examples of these conditions, discussed in more detail in References 31, 32, 33, and 34, are summarized below.

- Shears as large as 30 kt/100 ft (about 7 ft/sec^2 at a sink rate of 800 ft/min) lasting for 8 sec were recorded during acceptance testing of an autoland system in Toulouse, France. The terrain was flat and the air was relatively smooth.

- The DC-10 crash at Logan Airport in Boston, Massachusetts, in 1973 was attributed to a wind shear where the longitudinal wind changed from a 17 kt tailwind to a 7 kt headwind between 500 ft and 150 ft. The crosswind changed from 23 kt left to 7 kt left during this same interval.

- Analysis of the crash of a 727 at Kennedy Airport in New York in 1975 during thunderstorm conditions suggests that a mean headwind shear of 30 kt over 300 ft altitude existed, with fluctuations of 4 kt. The instantaneous headwind shear could have been as much as 14 kt in 2.5 sec.

- Wind tower data (see Reference 33) indicate that the probability of a 20 kt/100 ft shear during an approach is on the order of 1 in 10^4. However, these data are of little value because they do not contain information regarding time duration of the shear; also, the effect of wind speed changes with position along the approach path are not included.

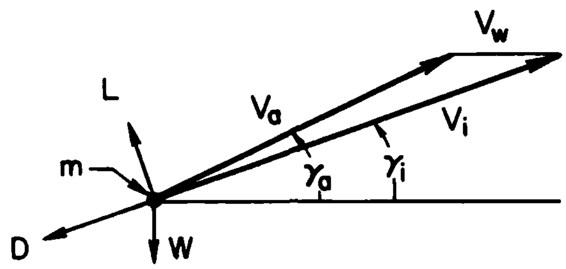
- The data currently available on low-altitude wind shears are insufficient to allow estimation of probabilities of occurrence.

Reference 34 contains a review of the flying qualities implications of wind shears.

Several of the STOL simulation studies of References 10-13 included some investigation of the effects of wind shears. However, in most cases the time and resources available for assessing other equally important flying qualities issues led to only cursory looks at shears. This resulted in the Reference 30 study, where the sole purpose of the piloted simulation was to determine the influence of horizontal shears on STOL landings. The discussions that follow will rely heavily on that document for reviewing the ramifications of shears on STOL performance. Data will show conclusively that wind shears can be the single most critical limiting condition on STOL flying qualities in the approach and landing. Powered lift STOL aircraft tend to be more sensitive than CTOL configurations because of the nearly vertical thrust inclination angles which render thrust ineffective against horizontal disturbances.

1. Effect of Wind Shear on Performance Margins

The concept of an "effective flight path angle," γ_{eff}, was found in Reference 30 to be useful in relating windshear to aircraft performance margins such as may be defined on a plot of γ vs. V, as shown in Figure 44. The definition of γ_{eff} is based on the kinematic equations of motion resolved along the flight path axes, as illustrated below.



$$L - W\cos\gamma_a = m\dot{V}_i \sin(\gamma_i - \gamma_a) \tag{8}$$

$$-D - W\sin\gamma_a = m\dot{V}_i \cos(\gamma_i - \gamma_a) \tag{9}$$

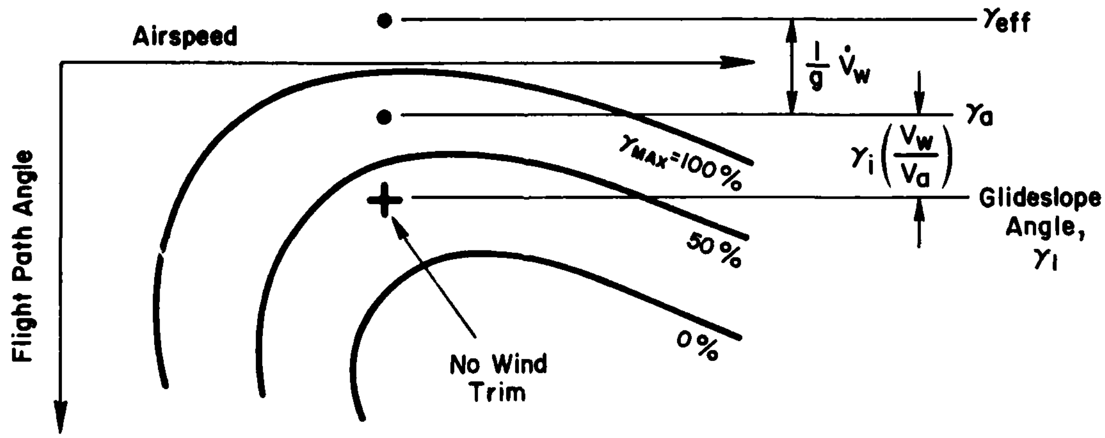


Figure 44. Effect of Wind and Wind Shear on Performance Margins

The following definitions and assumptions apply:

- i = inertial
- a = with respect to the air mass
- L and D contain both aerodynamic and thrust components
- Variable horizontal wind (V_W) results in a variable inertial velocity (V_i) along an inertially fixed glideslope (γ_i).

Implicitly define γ_{eff} as

$$-\frac{D}{L} = \frac{\sin \gamma_a + (\dot{V}_i/g)\cos(\gamma_i - \gamma_a)}{\cos \gamma_a + (\dot{V}_i/g)\sin(\gamma_i - \gamma_a)} = \tan \gamma_{eff} \qquad (10)$$

(In the steady state, $\gamma_{eff} = \gamma_a$).

$$\text{For } |\gamma_a| , \left|\frac{V_w}{V_a}\right| , \left|\frac{\dot{V}_w}{g}\right| \ll 1 \text{ and constant } V_a,$$

$$\gamma_{eff} = \gamma_a + \frac{\dot{V}_w}{g}$$

Thus, at any given V_a we take

$$\gamma_{eff} = \gamma_i\left(1 + \frac{\dot{V}_w}{V_a}\right) + \frac{\dot{V}_w}{g} \qquad (11)$$

The angle γ_{eff} is a fictitious flight path angle used to define a speed/power equilibrium point on the usual γ-V representation. This point represents the acceleration/deceleration capability required to regulate against wind and wind shear in terms of flight path angle capability in calm air.

The aircraft performance capability may be compared to the performance required to maintain zero glide slope error in wind and wind shear by comparing γ_{eff} with the maximum or minimum achievable γ on a γ-V plot. This is illustrated in the generic sketch shown in Figure 44 (γ-V shapes typical of an externally blown flap STOL concept). This sketch is indicative of the effects of a large steady headwind which is shearing towards zero (effects of negative wind and positive wind shear are additive). The effective flight path angle is a function of the wind speed, V_w, and therefore changes during the time the airplane is in the wind shear as follows:

$$\gamma_{eff} = \gamma_i\left(1 + \frac{V_w}{V_a}\right) + \frac{\dot{V}_w}{g} + \gamma_i \frac{\dot{V}_w}{V_a} t \qquad (12)$$

Thus, for the usual case where wind is decreasing during the approach, a given wind shear may initially exceed the aircraft control power ($\gamma_{max} < \gamma_{eff}$) until the steady component of wind decreases sufficiently to allow control, as illustrated in Figure 45. A shear that is large enough to produce an initial γ deficiency will by definition result in a perturbation from the desired path. It therefore seems logical to define the combinations of steady wind and wind shear where $\gamma_{eff} = \gamma_{max}$ at $t = 0$, e.g., flight path control margin equals zero at the beginning of the

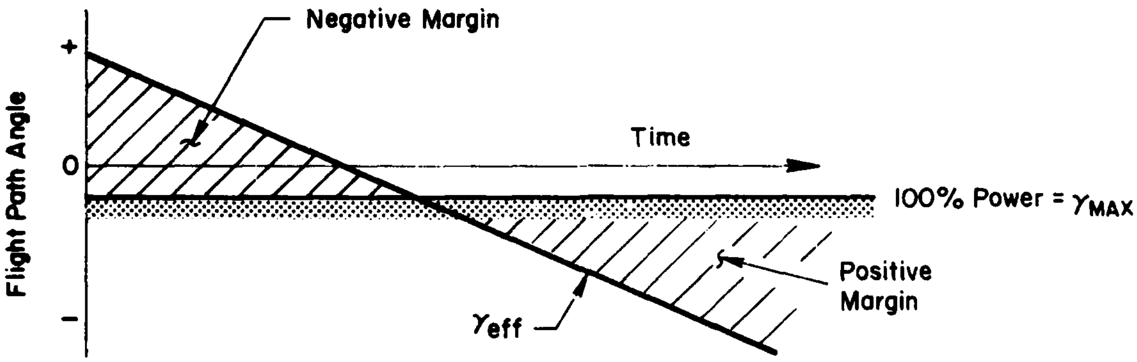


Figure 45. Illustration of Change in γ_{eff} with Time in a Decreasing Headwind Shear

shear. This is done by substituting γ_{max} and γ_{min} for γ_{eff} in Equation 12 and solving for limiting values of wind shear, $\dot{V}_w$, i.e.,

$$\dot{V}_w = g\left[\gamma_{\substack{max \\ (min)}} - \gamma_i\left(1 + \frac{V_w}{V_a}\right)\right] = g\left(\gamma_{\substack{max \\ (min)}} - \gamma_a\right) \tag{13}$$

The boundaries which derive from Equation 13 are plotted in Figure 46 where γ_{max} was taken as zero and γ_{min} as -10 deg. These numbers were chosen to be consistent with the flight path control power requirement of Section V, which dictates a capability of 4 deg below the glide path and essentially level flight in the up direction. For decreasing winds (second and fourth quadrant) the path control margin is zero ($\gamma_{eff} = \gamma_{max}$) when the shear starts and is positive ($\gamma_{eff} < \gamma_{max}$) for the remainder of the shear. For increasing winds the path control margin is initially positive ($\gamma_{eff} > \gamma_{max}$) and degrades to zero when the shear ends ($t = t_f$). With the usual approaches into the wind, the shears which result in decreasing winds on the approach are more common because of friction effects near the ground. Therefore, the most critical areas are Quadrants 2 and 4. Quadrant 3 is less critical because of the low groundspeed and favorable effect on lift in the flare of an increasing headwind shear. Quadrant 1 is not practical because it implies a tailwind at touchdown.

2. Effect of Windshears on STOL Landings

The results of the Reference 30 simulation provide considerable insight into the handling qualities aspects of wind shears during approach and landing. This simulation, performed on the Flight Simulator for Advanced Aircraft (FSAA) at NASA Ames Research Center, involved six different aircraft configurations. Five aircraft were powered-lift; the sixth was the Twin Otter, representing a low-wing-loading STOL. Following is a description of each vehicle:

- Baseline STOL configuration. This configuration was a typical externally blow flap (EBF) or upper surface blowing (USB) aircraft with a minimum amount of stability augmentation. That is, the SAS consisted of a simple attitude hold system.

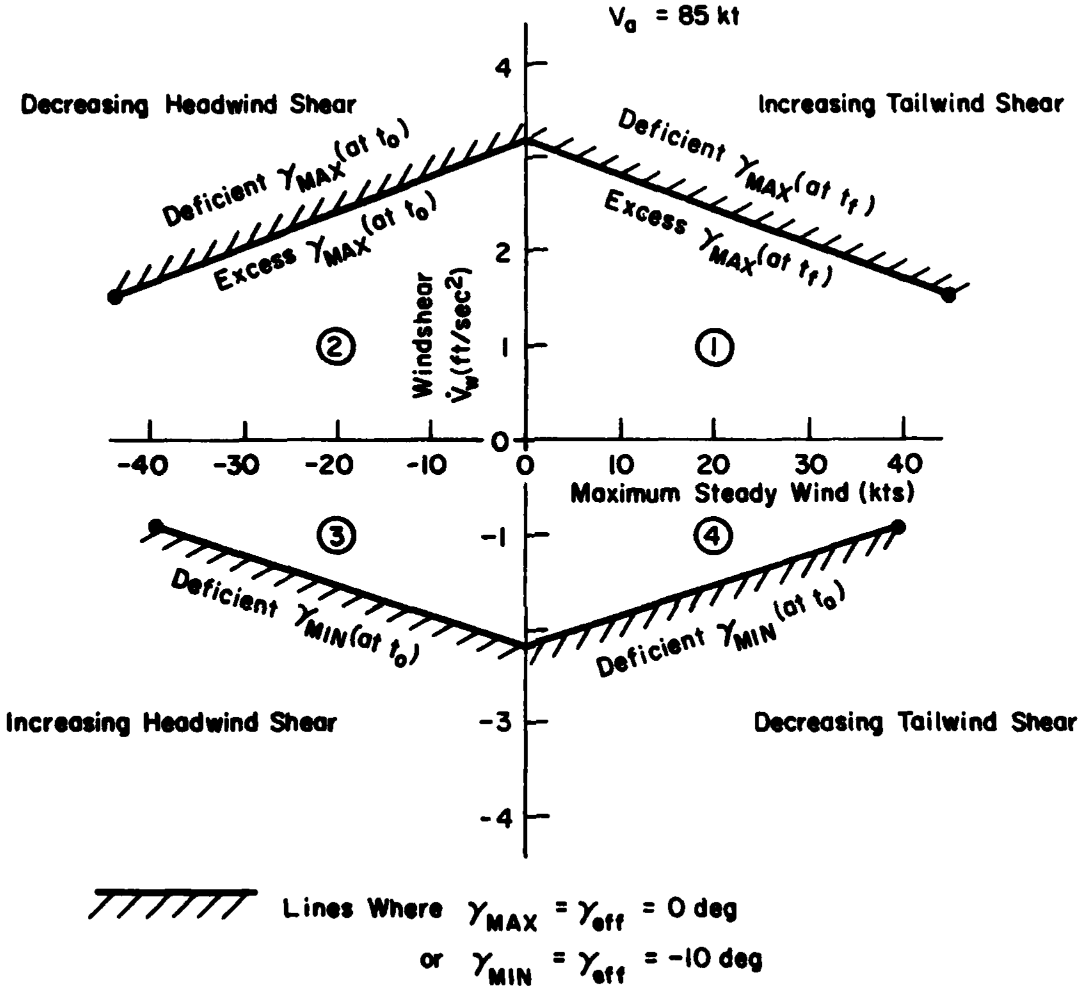


Figure 46. Boundaries Where Flight Path Control Margin Equals Zero $\left(\gamma_{\substack{max \\ (min)}} = \gamma_{eff}\right)$

- Backside SAS configuration. This configuration was the Baseline STOL with the addition of a path control SAS. This SAS consisted of a throttle-to-spoiler crossfeed to augment the path control response to throttle inputs.

- Manual DLC configuration. This configuration was the same as the Baseline STOL configuration except that the pilot had manual control of the wing spoilers for additional path regulation capability (using the spoiler controller on the throttle quadrant).

- Frontside SAS configuration. The aerodynamics for this configuration were the same as for the Baseline STOL. However, in addition to wing spoilers, a direct drag control was also added. A stability augmentation system was designed to allow the pilot to fly this configuration as if it were on the front side of the power-required curve; that is, the pilot controlled flight path with pitch attitude and airspeed control was automatic.

- Hooker configuration. This configuration was more representative of an Augmentor Wing design and was termed the hooker configuration because of the nonlinear flight path response which tends to bend or "hook" at power settings slightly below the nominal for approach.

- Non-powered-lift configuration. The Twin Otter was used to represent a configuration which derives its STOL performance from low wing loading rather than powered lift. No attitude SAS was required on this configuration.

Three pilots were involved in the simulation effort. The task was an ILS approach starting at 1500 ft altitude with breakout to VFR at 300 ft. Approach speeds were 70 kt for the Twin Otter and 85 kt for all other configurations, on a 6 deg glide slope. A fairly complicated missed approach procedure was established to serve as a realistic motivation to complete the landing rather than go around at the slightest provocation.

One immediate observation in the simulation was the inadequacy of the Cooper-Harper rating scale in evaluating the wind shear hazard. The major problem was the decision tree structure of the scale, in that one rating implied a certain level of three separate categories (adequacy for selected task, aircraft characteristics, and demands on the pilot). The most common conflict was between the demands on the pilot and aircraft characteristics categories. In cases where the wind shear reduced the safety margins to unacceptable levels, the aircraft characteristics for that task would be rated a 7, 8, or 9. However, in many cases where control margins were negative or zero, the pilot workload was very low, in that it was just simply a matter of hoping that you would make it. That is, the corresponding Cooper-Harper ratings for demands on the pilot would be a 1, 2, or 3. A four-part rating scale was devised to allow independent evaluations of the factors involved in flying in wind shears. The scale, illustrated in Figure 47, was based on a similar system successfully applied to rating vortex hazards (Reference 36). A related scale has also been used with success to evaluate flying qualities at high angles of attack (Reference 37).

The results of the FSAA piloted simulator program are summarized in Figures 48 and 49 by fairing approximate boundaries where the accident potential rating (from Figure 47) was equal to 4 on a grid of steady wind vs. wind shear. The separation between these pilot rating boundaries and the performance boundaries defined by Equation 13 and plotted in Figure 46 is a measure of shear vulnerability. That is, when the experimental boundary lies below the performance boundary in Figure 48, the configuration tends to be highly vulnerable to decreasing headwind shears. For the decreasing tailwind shears in Figure 49, highly vulnerable configurations are indicated when the experimental boundary lies above the performance boundary. It must be emphasized that the boundaries in Figures 48 and 49 are based on approximate fairings of the pilot rating data. However, the relationships between the experimental and performance boundaries were found to be in excellent agreement with the pilot commentary and are therefore felt to be a valid way to quantify the simulation results.

The results presented in Figures 48 and 49 are summarized in the following paragraphs.

The Twin Otter and Baseline STOL configurations were designed to have identical flight path angle performance capabilities (γ_{max} = -0.5°

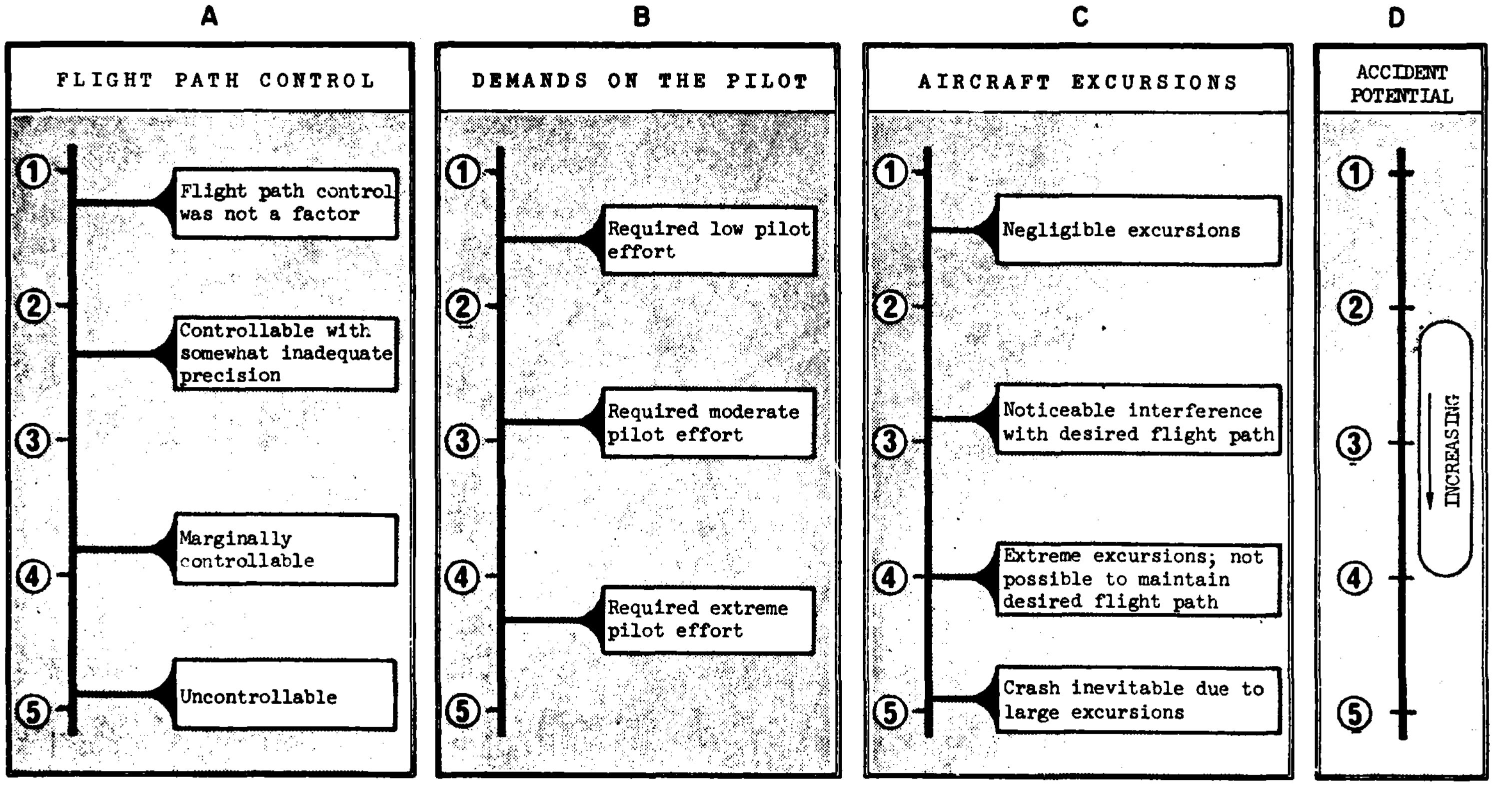


Figure 47. Rating Scale Used in Windshear Investigation (Reference 30)

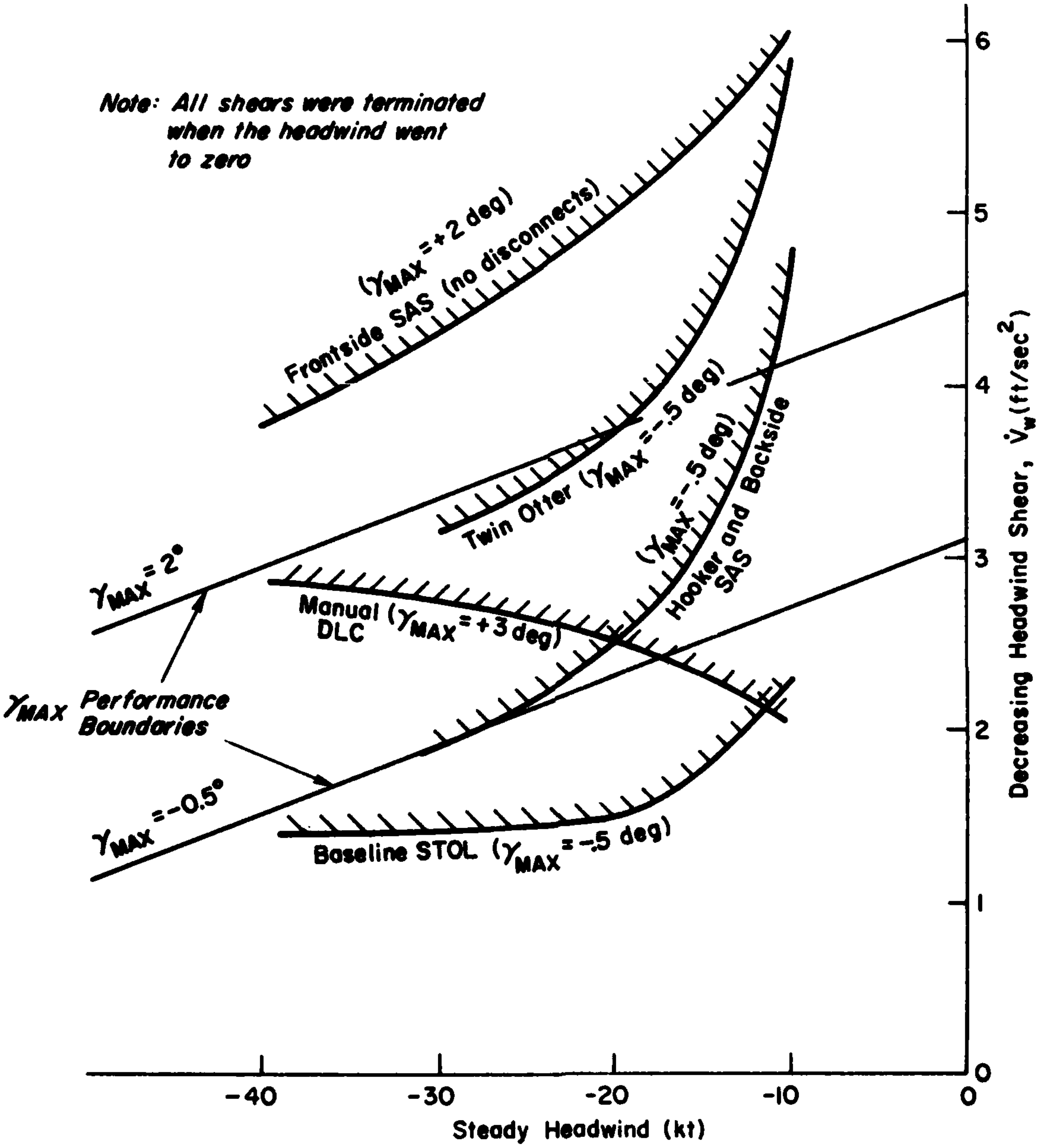


Figure 48. Approximate Boundaries Where Accident Potential Ratings Equal 4 for Decreasing Headwind Shears (From Reference 30)

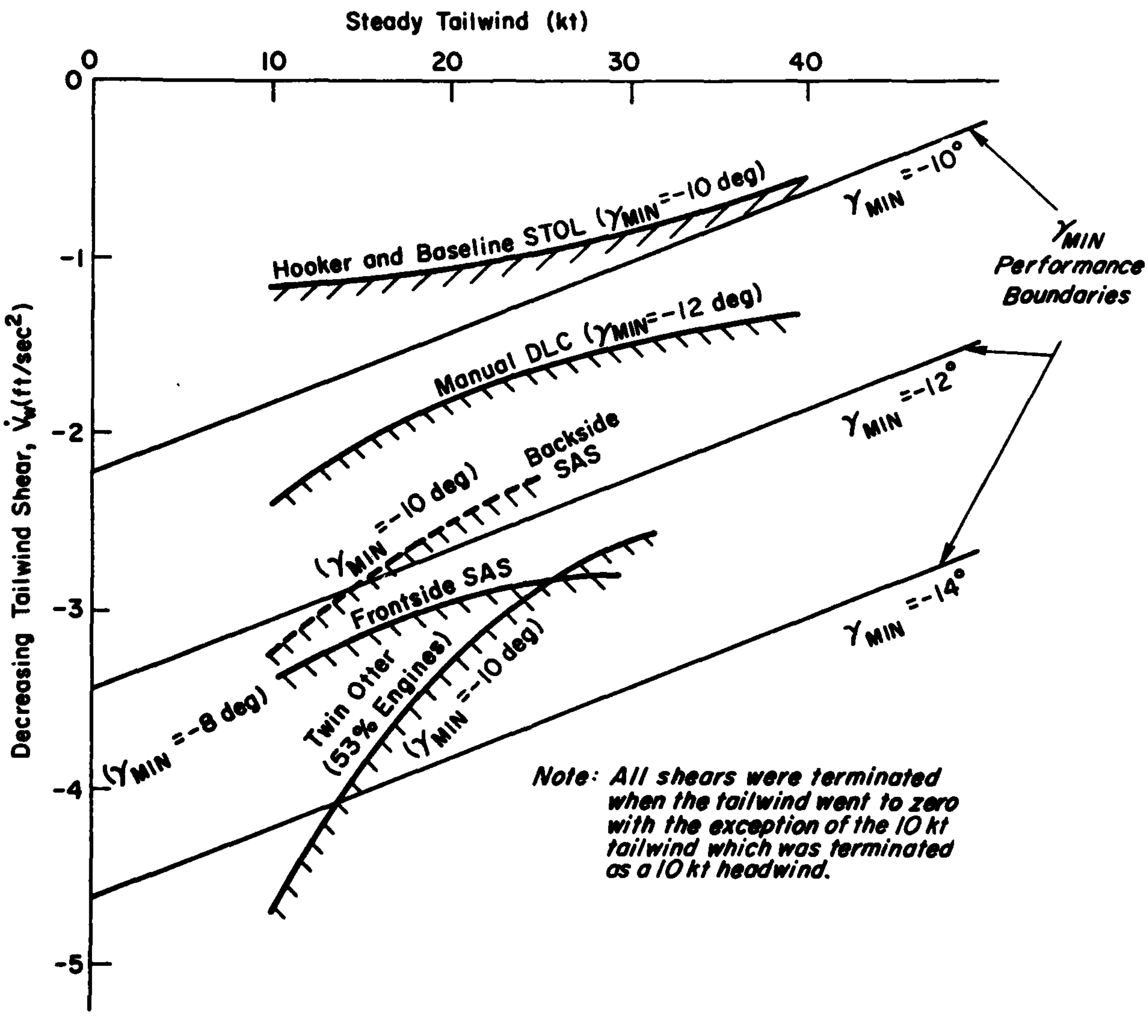


Figure 49. Approximate Boundaries Where Accident Potential Ratings Equal 4 for Decreasing Tailwind Shears (From Reference 30)

and $\gamma_{min} = -10^o$). Recall that the Twin Otter is a non-powered-lift STOL, whereas the Baseline aircraft obtains its STOL performance via powered lift. The boundaries in Figures 48 and 49 indicate that the powered-lift configuration was significantly more vulnerable to wind shear than was the non-powered-lift STOL. This was due to the nearly vertical thrust inclination angle of the powered-lift STOL (θ_T = 79 deg vs. 48^o for the Twin Otter) which resulted in very little thrust component in the horizontal direction to regulate against the shear disturbance. Additionally, the low-wing-loading STOL (Twin Otter) had significantly better heave damping and was slightly on the front side of the power-required curve. The following comparisons of flight path criteria (defined in Sections III and IV) show the consequences of these differences:

	$\left(\frac{1}{T_{\theta_2}}\right)_{eff}$	t_{rev}	$t_{R_{\gamma T}}$	$\Delta\gamma_{max}/\Delta\gamma_{ss}$
Baseline STOL	0.55 rad/sec	10 sec	3.0 sec	1.0
Twin Otter	0.90 rad/sec	∞	4.5 sec	1.0

Although the Twin Otter's throttle response was sluggish, the pilots could make flight path corrections with pitch attitude to augment the primary path control with throttles. This characteristic was especially useful in decreasing tailwinds on final. Finally, the handling characteristics were essentially independent of power in the Twin Otter, which made it possible for the pilots to make aggressive power reductions. This was not possible with the Baseline STOL due to highly nonlinear flight path response to changes in thrust at constant attitude which occurred at low power settings (see, for example, Figure 1). A consequence of this nonlinearity was unacceptable pilot ratings in decreasing tailwind shears. The pilots were very conservative in staying away from the nonlinear region (occurred at 20 percent power), rarely going below 40 percent power in the Baseline STOL.

Manual control of flight path with spoilers was used by the pilots to regulate against shear disturbances and to reconfigure the airplane in strong steady winds. Only small improvements over the Baseline STOL were realized. Hence, the boundaries in Figures 48 and 49 fall far short of the calculated performance potential of $\gamma_{max} = +3^o$ (Figure 48) and $\gamma_{min} = -12^o$ (Figure 49) for this configuration. The trend towards increased shear vulnerability with decreased values of steady headwind for the Manual DLC configuration in Figure 48 is inconsistent with all the other configurations. This is a direct reflection of the closed-loop control problems which were induced by short duration (pulse-like) shears. Increased pilot workload to deal with three separate controllers (spoilers, column, and throttle) contributed to the increased accident potential.

The backside SAS configuration resulted in a significant improvement in closed-loop path control and performance for the short duration decreasing headwind shears in Figure 48. This improved performance ($t_{R_{\gamma T}}$ decreased from 3.0 to 1.7 sec; see Section IV) was a direct consequence of the throttle-to-wing-spoiler crossfeed which increased the γ/θ bandwidth and the flight path angle performance capability. However, as the shear duration approached the spoiler washout time, the Backside SAS configuration was no different from the Baseline STOL. This is reflected in Figure 48 where the Baseline STOL and Backside SAS boundaries are seen to be converging for higher steady winds (longer duration shears). The Backside SAS boundary for decreasing tailwind shears is plotted in Figure 49 as a dashed line because it is representative of only one pilot (Pilot 1). Pilot 3 only flew one formal data point in this series and that point was rated significantly worse than Pilot 1's rating.

The Hooker configuration was characterized by highly nonlinear path/airspeed coupling characteristics at power settings below trim. Its response characteristics were identical to the Backside SAS in decreasing headwind shears where high power settings are required. Hence, the boundaries for these two configurations are identical in Figure 48 (headwind shears). The adverse path/speed coupling of this configuration at low power settings was highly objectionable in tailwinds and tailwind shear situations. Even though the accident potential rating boundary of this configuration was identical to the Baseline STOL

(Figure 49), the commentary indicated that the aircraft was considerably worse than Baseline STOL in tailwinds. The pilot's primary objections were centered about excessively high airspeeds at touchdown. Path/airspeed coupling is discussed in more detail in Subsection E.

The frontside SAS pilot opinion boundaries in Figures 48 and 49 exceeded the calculated performance limits (Equation 13) by a considerable margin for both decreasing headwind and tailwind shears, indicating a low level of vulnerability to wind shear. However, the pilots tended to disconnect the SAS at very low altitudes when airspeed deviations became greater than 7 to 8 kt low or 15 kt high. The boundaries in Figures 48 and 49 represent cases in which the pilots did not disconnect. Because of the necessity to change piloting technique (frontside to backside) and to make a go/no-go decision just prior to touchdown, the disconnect cases were judged by the pilots to have high accident potential. Lacking any better cue, the pilots utilized airspeed as a system performance monitor. In all cases, the pilots would have been better off leaving the system on, either to complete the landing or to waveoff. It is therefore clear that a more comprehensive display is required to allow the pilot to monitor the performance of such complex stability augmentation systems.

The foregoing reviews indicate that accident potential in the presence of wind shears can be very high even when the STOL aircraft meet all the flight path criteria of Sections III, IV, and V. As an example of the implications of this, consider the Baseline STOL of Reference 30. It has good pitch attitude control provided by the SAS, good path control with throttle ($t_{R_{\gamma T}}$ = 3 sec, $\Delta\gamma_{max}/\Delta\gamma_{SS}$ = 1.0), and almost meets the Level 1 requirements for path control power (Section V); the Baseline STOL can achieve γ_{max} = −0.5 deg and 4 deg below glide path (γ = −10°). This would be considered an acceptable aircraft by the STOL criteria introduced in this report. Yet the accident potential for the Baseline STOL is worse than 4 for windshears at the performance limits in Figures 48 and 49. In fact, only the Twin Otter and Frontside SAS exceed their performance limit conditions with accident potential ratings better than 4. Therefore, for aircraft flown with the STOL technique, it is almost mandatory that the short-term path response to attitude (γ/θ) as defined by $(1/T_{\theta_2})_{eff}$ (Section III) be devised to approach that of the Twin Otter $[(1/T_{\theta_2})_{eff} = 0.9]$ in order to counter large discrete wind shears. Such a requirement is highly restrictive and points out the extreme vulnerability of powered lift STOLs to large discrete windshear. It should be noted that augmenting $1/T_{\theta_2}$ via a column-to-DLC (spoiler) crossfeed represents a less complex solution than a complete frontside augmentation system (e.g., such as the YC-14).

C. LIMITING FLIGHT CONDITIONS (STALL)

Flight at high angles of attack (or high lift) can be quite different for some STOLs when compared to CTOLs. Non-powered-lift STOLs, such as the Twin Otter, will generally exhibit high-α stall characteristics similar to those for CTOLs. However, powered-lift STOLs are very dissimilar. The dynamics of powered-lift STOLs in this flight regime are worth of some review. The following paragraphs will address stall characteristics, stall warning, and safety margins.

1. Definition of Limiting Flight Conditions

It is in approach and landing configurations that STOLs most differ from CTOLs. For a CTOL aircraft, the power-off stall is likely to be the defining feature of its limiting flight condition. At or near aerodynamic stall, conventional flight dynamics cease to exist and a significant percentage of aerodynamic lift may be lost, with a large drag increase, and only a small angle of attack increase. In some cases the adversity which dominates is related to loss of control in the lateral-directional axes. These limiting flight conditions can normally be associated with a unique angle of attack. In addition, there can also be a limiting flight condition created by inadequate dynamic pressure, e.g., the minimum control speed related to propulsion failure. This, then, would be tied to airspeed as opposed to angle of attack. But, a single equivalent airspeed is all that is needed to essentially define the 1 g limiting flight condition for a conventional aircraft (for a given wing loading) whether it be primarily a function of angle of attack or of airspeed. The nearly one-to-one relationship between C_L and angle of attack allows this simplification.

For the powered-lift aircraft, on the other hand, there can be a wide range of airspeeds and angles of attack at which aerodynamic stall occurs, due to the strong influence of power on C_L. Figure 50 illustrates the different types of stall as described below.

- Power-off stall: This condition has little significance for powered-lift STOLs where approach speeds are typically below the power-off stall speed.
- Stall with approach power: Accelerated stalls at approach speed follow a constant contour of thrust coefficient, $C_j = \frac{1}{2}\rho V^2 ST$, while 1 g stalls involve an increase in C_J as the aircraft slows. Thus, $C_{L_{max}}$ for a 1 g stall is greater than that for an accelerated stall.
- Maximum power stall: A 1 g stall in this condition represents the maximum obtainable lift coefficient, and consequently the lowest obtainable trim airspeed in level flight.

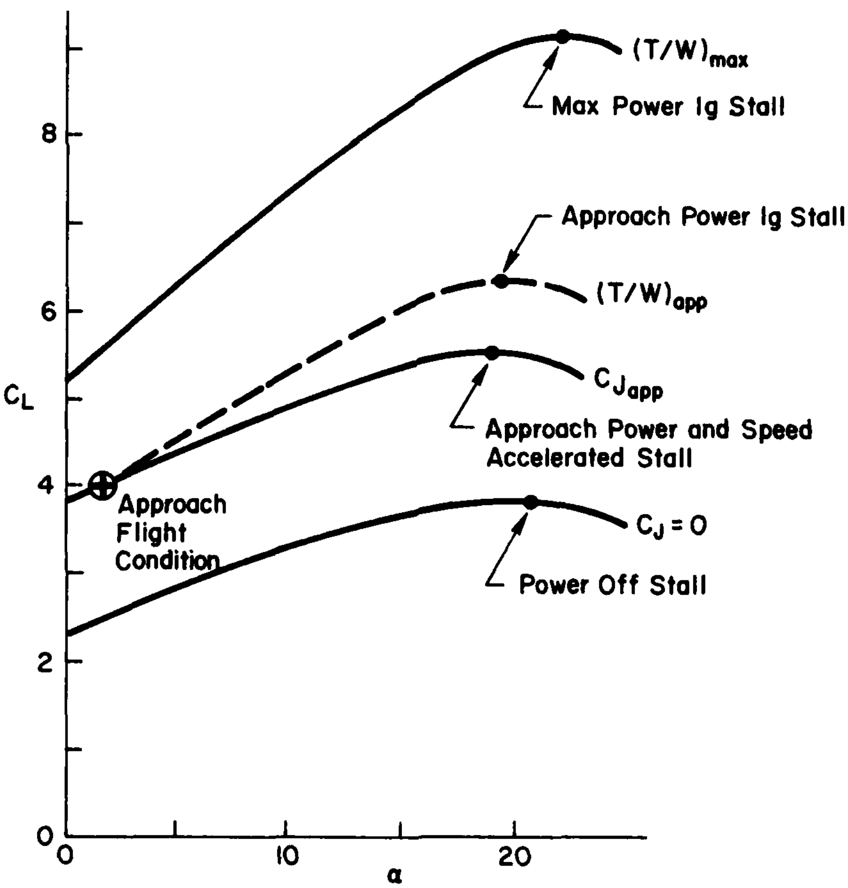


Figure 50. Variety of Stall Types for Powered-Lift Aircraft

All of these stalls can be characterized in terms of either α_{max} or V_{min}, both of which are strong functions of power. An interesting result of the simulation of Reference 10 is that 1 g stalls were relatively mild, with no abrupt loss of lift or control. High sink rates developed, but the pilots found it easy to recover by increasing power and lowering the nose. In any event, operating above $C_{L_{max}}$ serves no useful purpose and still should be avoided.

Results such as that described above have led to possible separation of flight limits into "soft" and "hard" limits (Reference 4). Aerodynamic stall would thus be a soft limit; Reference 4 suggests the following be considered hard limits:

- A sharp loss of lift following aerodynamic stall
- An uncontrollable nose slice or wing drop associated with stall
- Uncontrollable pitch up to a deep stall condition
- Severe aerodynamic buffet
- Stalling of an aerodynamic control surface

The most important distinction about these conditions is that soft limits are potentially unsafe, while hard limits are clearly unsafe to encounter.

The problem of defining approach to a limiting condition can be illustrated using a γ-V curve, such as shown in Figure 51. A nose-level ($\theta = 0$) 1 g stall would follow the trajectory labeled A. However, a slight nose-down ($\theta = -4$ deg) condition, curve B, results not in a stall but in an acceleration and stable glide above the stall speed. In Reference 39, where this condition was studied, it was noted that if the γ-V curve were as nonlinear as that of Figure 51, an insidious situation could develop during attempted recovery from trajectory B: if the pilot leveled the nose (trajectory C) and then added power, the result could actually be a stall (curve D). Nevertheless, Reference 4 still concludes that, in general, the best stall recovery technique is addition of power at constant attitude.

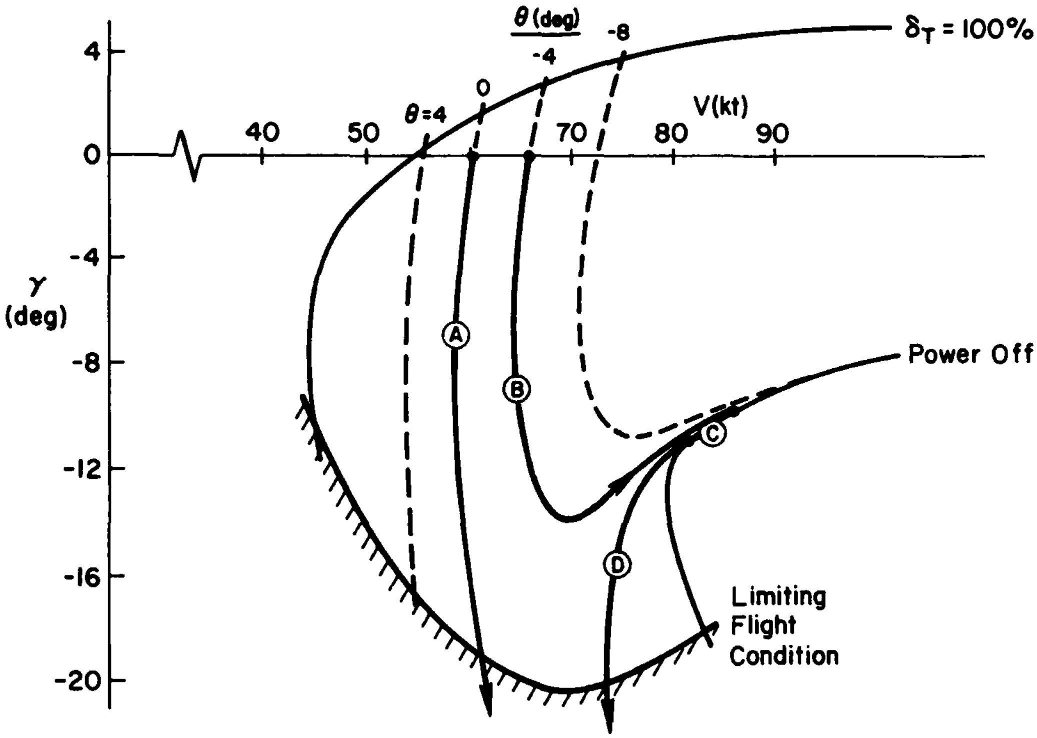


Figure 51. γ-V Trajectories for Approach to α_{max} from Low Thrust Condition

2. Definition of Safety Margins

Need for artificial warning of stall onset may be greater for STOLs than for CTOLs, since the latter often have some natural aeodynamic warning cue. The military specification, MIL-F-8785C (Reference 1), contains the following limits on the range for warning onset in both 1 g and accelerated stalls during the approach:

1 g Stalls:

Minimum Speed for Onset	Maximum Speed for Onset
Higher of $1.05V_S$ or V_S + 5 knots	Higher of $1.10V_S$ or V_S + 10 knots

Accelerated Stalls:

Minimum Lift at Onset	Maximum Lift at Onset
82% C_L stall	90% C_L stall

Reference 4 contains a discussion of various forms of safety margins. One observation made there (and implied in the previous review of stall conditions) is that $C_{L_{max}}$ is not a sufficiently discriminating parameter for stall warning due to its strong dependence on power setting. The safety margins considered in Reference 4 were:

- Relative speed margin
- Absolute speed margin (horizontal gust margin)
- Angle of attack margin
- Vertical gust margin
- Lift margin

Reference 4 recommends a relative speed margin of 16% and an absolute speed margin of 9 kt. If the MIL-F-8785C stall warning speeds are interpreted as STOL safety margins (a fair assumption because of the lack of a clear "stall" with STOLs), these speed margins agree closely with MIL-F-8785C in the region of normal stall (see Figure 52). The MIL-F-8785C requirement was retained for the AMST STOL requirements (Reference 28), and was applied to both 1g and accelerated stalls.

3. Safety Margin Systems

Concerns over defining a comprehensive and useful system for displaying safety margins for STOLs led to a NASA-sponsored analytical investigation of candidate systems (Reference 39). The results of that investigation have bearing on meeting requirements for supplying the pilot with a warning or approach to limiting flight conditions. The recommended system from Reference 39 is shown in Table 8. Flight reference (FR) was provided by sensing airspeed, V (or angle of attack, α),

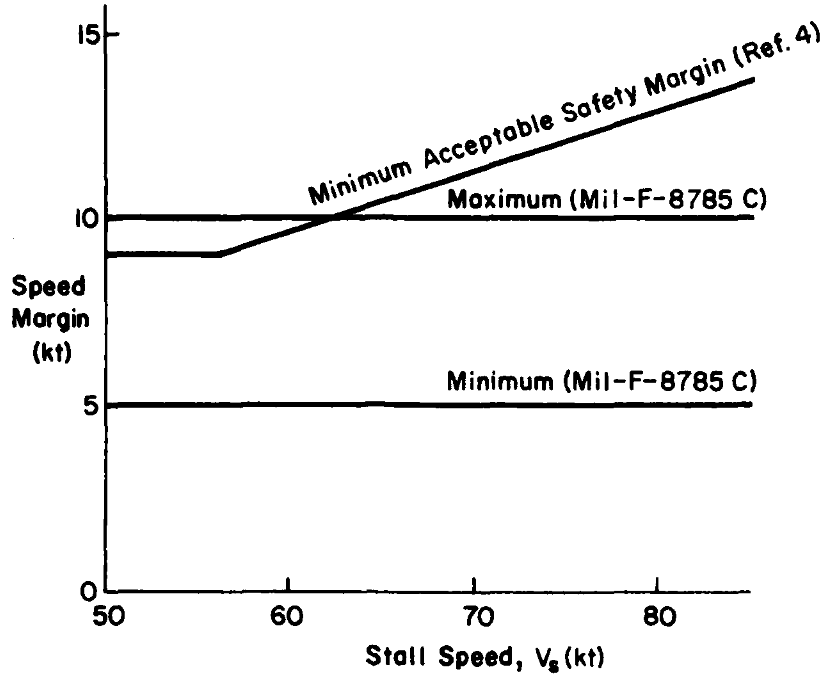


Figure 52. Comparison of MIL-F-8785C (Reference 1) Stall Warning Onset Range with Minimum STOL Safety Margin Proposed in Reference 4

comparing it with minimum airspeed for maximum thrust, V_{min_m} (or maximum angle of attack, α_{max}), and combining the resulting dynamic safety margin (DSM) with a pitch attitude increment ($\theta - \theta_0$), and displaying a lagged version of the combination to the pilot. Safety reference (SR) consisted of the lesser of the dynamic safety margins.

A system such as that shown in Table 8 may be a necessity for powered-lift STOLs, where natural warnings are uncommon and deterrents (stick shakers or pushers, soft stops) may be undesirable.

D. FAILURES

For most STOL aircraft loss of an engine could be catastrophic in the final approach; this is especially true of powered-lift STOLs. Similarly, in some cases failure of an augmentation system can lead to

TABLE 8. SAFETY MARGIN SYSTEM
(REFERENCE 39)

<u>FLIGHT REFERENCE (AUTOMATIC AND MANUAL):</u>

$$FR = FR[DSM + k_{\theta}\theta]$$

$$= \min(FR_1, FR_2)$$

$$FR_1 = \frac{DSM_1 + g(\theta)}{0.5\,s+1}$$

$$FR_2 = \frac{DSM_2 + g(\theta)}{0.5\,s+1}$$

where

$$DSM_1 = 100\% \times \frac{V - V_{min_m}}{20\text{ kt}}$$

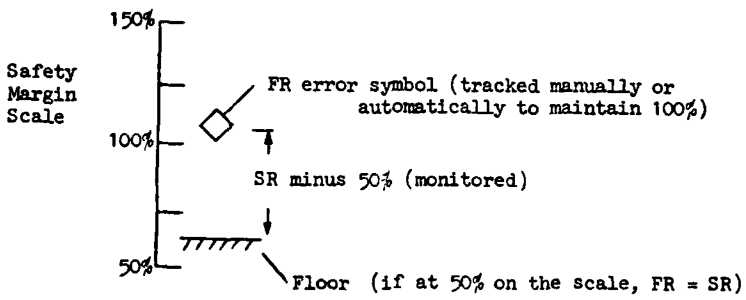
$$DSM_2 = 100\% \times \frac{\alpha_{max} - \alpha}{\sin^{-1}\frac{20\text{ kt}}{V}}$$

$$g(\theta) = -10\,\frac{\%}{\text{deg}} \times (\theta - \theta_0)$$

<u>SAFETY REFERENCE:</u>

$$SR = \min(DSM_1, DSM_2)$$

<u>DISPLAY FORMAT:</u>



hazardous conditions. Both types of failure have been investigated to some extent in piloted simulations. The following paragraphs will summarize the results of these investigations.

1. Loss of Augmentation

Typically, STOLs have deficient longitudinal handling characteristics due to the low airspeeds and high lift coefficients required for STOL approaches and landings. This will almost always necessitate at least a pitch attitude SAS, as discussed in Section II. As that section shows, the pitch attitude bandwidths required for Level 2 operation are quite low. This suggests that loss of a simple pitch SAS might be expected to result in no worse than an unsatisfactory but acceptable (i.e., Level 2) aircraft.

However, there is evidence to indicate that some SAS failures could be potentially hazardous. This is the case when the SAS is devised with an autothrottle and/or automatic direct drag control to allow the pilot to fly the aircraft using the CTOL technique. Loss of SAS would require reversion to the STOL technique, perhaps during a critical portion of the mission where pilot adaptation would be difficult. Reference 11 briefly investigated such an event and found that the pilot easily reverted to the STOL technique. However, it was difficult in that study to properly introduce the element of surprise, and the pilot suggested that his ability to revert to the STOL technique was enhanced by his participation in the STOL simulation program. A pilot unfamiliar with STOL aircraft might not have reacted as well.

The wind shear program of Reference 30 also sheds some light on this issue. In that simulation (see Part B of this section) a frontside SAS was mechanized and found to be of great value in flying through shears. In a few cases the pilot disconnected the SAS in the approach when he observed an excessive airspeed error (a result of direct drag control saturation). The pilot then had difficulty controlling the aircraft even though he had flown without the SAS earlier in the program. He rated the situation as quite hazardous.

2. Loss of Propulsion

For aircraft that rely on power to attain sufficient lift to fly, loss of propulsion can clearly lead to catastrophe. Effects of such losses fall into two categories: the failure transient, and ensuing flight in a failed state. The following will rely heavily on a more detailed treatise in Reference 4.

a. Failure Transients

It is important to consider the effects of failure transients in powered-lift aircraft because the transients themselves are significantly different from those occurring in conventional aircraft. The most obvious difference between powered-lift and conventional aircraft is the loss of lift that occurs from the failure. This loss of lift results from the lost engine thrust which was actually generating a portion of the lift force supporting the aircraft. Figure 53 illustrates these and other major differences from conventional aircraft.

The first apparent motion resulting from a propulsion failure is a marked rolling and increase in sink rate, which is simply the direct result of a decrease in powered lift. Also, with thrust acting primarily in the vertical direction there is little tendency for the aircraft to slow down as a conventional aircraft does following an engine failure. In fact, some powered-lift aircraft could tend to increase speed.

The failure of a propulsion system unit produces a set of lateral-directional upsetting moments which are also illustrated in Figure 51. For a powered-lift airplane in approach configuration, the lift on the wing supplied by the failed engine can be substantially less than the lift on the opposite wing. The net difference in lift produces a rolling moment, and the drag difference produces a yawing moment. The yawing moment for a powered-lift airplane is much less than for a conventional airplane if the effective thrust angle is nearly vertical.

The pilot in the propulsion failure situation must first recognize the failure. Next he must cope with the motion transients described above and reattain a reasonably well-trimmed flight condition which

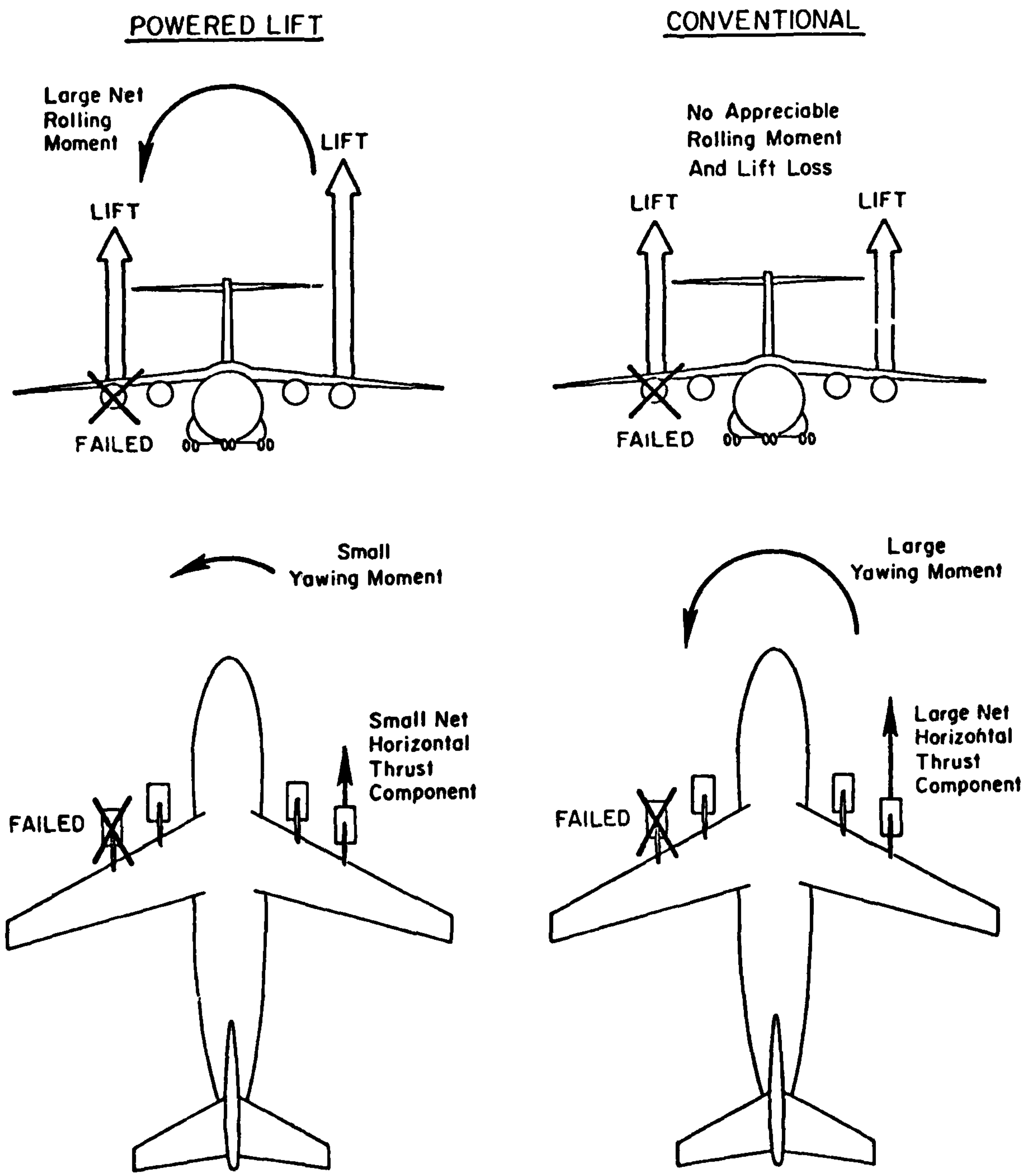


Figure 53. General Propulsion System Failure Effects on Forces and Moments (From Reference 4)

permits either (i) the successful continuation of the approach or (ii) initiation of a missed approach. The findings relating to this process are broken down in the following manner:

- Recognition of the propulsion system failure
- Piloting technique during the failure transient
- Lateral-directional control requirements
- Longitudinal control requirements

Delay in recognition of a propulsion system failure represents a time lag in dealing with a potentially hazardous situation. Based on the results of the Reference 40 simulation, dependence upon motion cues or engine instruments to warn of propulsion failure is not adequate. In this experiment, it was found that the quickest reaction times under ideal conditions were on the order of 1.2 to 1.5 sec. The most readily detectable cue of engine failure to which the pilot could respond was the bank angle excursion induced by the roll asymmetry when the engine failed. Vertical acceleration cues from the simulator were not of sufficient magnitude to be detected. The increase in vertical velocity did not become apparent visually until a sizable sink rate had already built up. Engine instruments were located on the center instrument panel and were not included in the pilots' continuous pattern. The lateral SAS limited the rolling and yawing excursions to about 6 deg and consequently limited their effectiveness as a cue to a failure. Reference 40 concluded that it is likely that artificial warning will be required.

Not all simulation experience has involved low levels of motion following a propulsion system failure. In Reference 41 it was found that a sudden failure in an engine produced a very noticeable roll and yaw for certain powered-lift designs. It appeared that the pilot would have little trouble in identifying an engine failure in those cases.

The use of cross ducting can produce motion cues that are somewhat confusing when an engine fails. In the simulation of Reference 11 it was noted that the aircraft rolled in a direction opposite to that expected (i.e., loss of a right engine produced a net loss of lift on the left wing because of cross ducting), yet the nose yawed to the right which was normal. The addition of thrust, in this case, only aggravated the peculiar combination of lateral-directional asymmetries.

Propulsion system failures in the Reference 38 simulation of the BR 941 were difficult for the subject pilot to detect because of the lack of asymmetry due to propeller cross shafting. Also, while a failure of one engine did produce a 25 percent loss of power this resulted in only a 15 percent loss of net thrust. The governor changed propeller pitch to maintain propeller RPM which resulted in a net increase in propeller efficiency. Therefore, thrust loss was not as great as power loss. Aside from the audible warning, the only other warning of propulsion system failure in the simulated Breguet airplane was a relatively mild increase in sink rate.

In conventional transport aircraft, the pilot generally experiences substantial cockpit side accelerations due to the asymmetric yawing moment produced by an engine failure. In powered-lift aircraft, a rolling moment may be produced following a failure. If the pilot is located close to the roll axis of rotation, the cockpit accelerations produced by the asymmetric rolling moment are low. Thus, the acceleration cues provided to the pilot of a powered-lift aircraft may not, in general, be as effective as those in conventional aircraft.

In summary, the elapsed time between a propulsion system failure and the pilots' identification of that failure will vary depending on the particular characteristics of that aircraft. Generally, the reaction times for failure recognition will be longer for powered-lift aircraft than for conventional aircraft. Therefore, it may be necessary to require some type of artificial failure warning system. At the same time it should be noted that any real failure warning system will have some inherent delay although it might be insignificant.

For longitudinal control, the two main functions are regulation of flight path and flight reference. The aspects of pitch attitude control are adequately described in Section II since the impact of propulsion system failure on pitch attitude control is not considered significant.

For aircraft having a large powered-lift effect, a propulsion unit failure has a strong and immediate effect on flight path. Failures call for prompt and immediate action, especially near the ground. Airspeed, per se, is not likely to be immediately affected if the thrust angle is near vertical, but this does not mean that flight reference is correspondingly free from being disturbed during the transient.

In general, there is a longer time frame associated with the longitudinal control functions than with the lateral-directional ones. This is because the latter mainly involves roll and yaw attitude control and their effective time constants are relatively short. A change in flight path and especially in airspeed is usually a slower process, though.

For the broad class of powered-lift aircraft any power failure will result in an increase in rate of descent forcing the airplane below its nominal glide path. It is necessary to provide sufficient incremental flight path control power so the pilot can quickly reverse the sinking trend, regain the nominal glide slope, and stabilize on it. The most critical constraints are clearance of obstacles beneath the approach path and proximity to the runway.

In general, the subject of flight path control power could be approached in the same way as for the normal approach and landing conditions (Section V). The main added element in the propulsion system failure situation is the degree of initial flight path error build-up prior to recognition and application of the appropriate piloting technique. This suggests that the flight path control power capability be commensurate with the degree of flight path upset as a result of the failure, or that altitude loss is a factor to consider in recovery from a failure.

In the STOL-X simulation (Reference 38) and in various investigations connected with the STAI (STOL Tactical Aircraft Investigation) program (References 42 and 43), roll was the primary axis concerning the pilot immediately following an engine failure. This contrasts with conventional aircraft, for which the yaw axis is the main concern.

The degree of dominance of roll control problems is, of course, configuration dependent. As described in the beginning of this section, the influential factors are proportion of powered lift, effective thrust angle, and the effective lateral position of the net loss in powered lit (the asymmetry effect).

Since a rolling moment appears to be a major characteristic of the propulsion system failure transient, the Military standard for powered-lift STOLs should specifically address the need for reasonably low lateral control forces, rapid and easy to use means of lateral trim, and possibly an indication of the amount of correction required. The standard should also consider the use of automatic power and roll compensation systems such as considered in Reference 41.

b. Steady-State Flight Following a Failure

The physical characteristics which are important to this situation arise from asymmetric powered lift as shown in Figure 53. These ideas are developed in further detail for the steady state continued approach in the diagram of Figure 54 (taken from Reference 4). Each of the elements of this figure is expanded in the following discussion.

The objective of Figure 54 is to show the cause and effect relationships resulting from a propulsion system failure. The top diagram represents a conventional airplane with an asymmetric horizontal thrust loss. The other two diagrams represent powered-lift aircraft; one involving an asymmetric lift loss, the other, a symmetric lift loss. The direct effects shown are those resulting from the failure itself and the secondary effects are those stemming from the compensating actions taken by the pilot.

One general feature which Figure 54 shows is that there are significant differences between a conventional aircraft and a powered-lift vehicle regarding a continued approach following engine failure. The fundamental difference, again, is the loss in vertical force versus a loss in horizontal thrust. This difference propagates through the direct effects, compensating actions taken, and resulting secondary effects.

Engine failure effects for powered-lift vehicles are configuration-dependent. Two extremes are shown in Figure 54. These consist of the

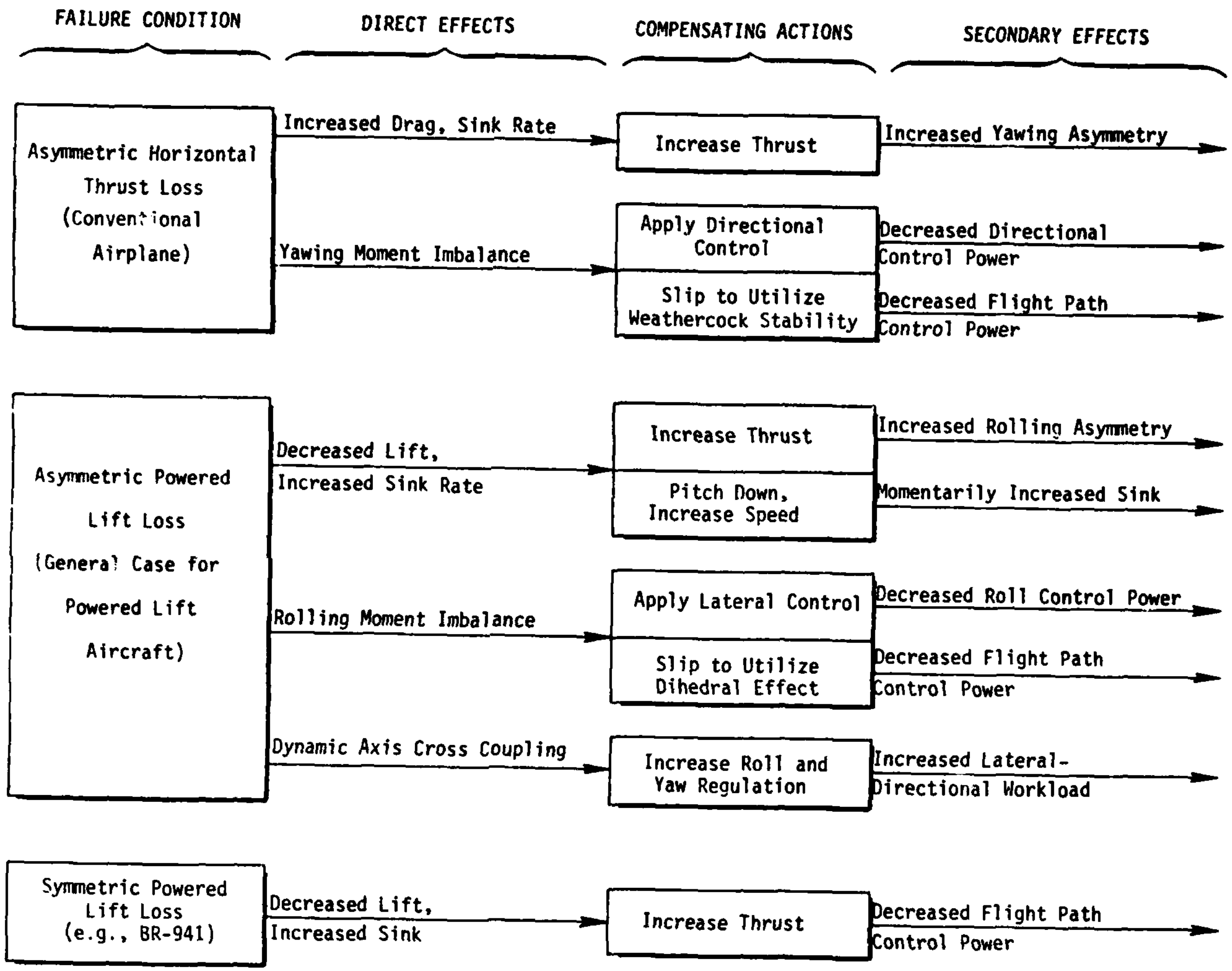


Figure 54. Propulsion System Failure Cause and Effect Relationships (From Reference 4)

clearly asymmetric powered-lift loss cases versus simple symmetric lift loss cases.

One important distinction between thrust loss in a conventional aircraft and a powered-lift aircraft is the change in the critical lateral-directional control. For a conventional aircraft where a yawing moment is produced, then the rudder is most likely to be the critical control. In contrast, the powered-lift aircraft experiencing an asymmetric lift loss is likely to be critically limited in roll control. In both cases the critical lateral-directional control is subject to some relief or aggravation through use of sideslip.

E. PATH/SPEED COUPLING

Path/speed coupling refers to the steady state change in airspeed that occurs when throttle is varied to control flight path, assuming that pitch attitude is held constant. The steady-state γ-V characteristics of a configuration with adverse path/speed coupling are shown in Figure 55. The constant-attitude lines are seen to be highly nonlinear with extremely adverse path/speed coupling occurring at power settings

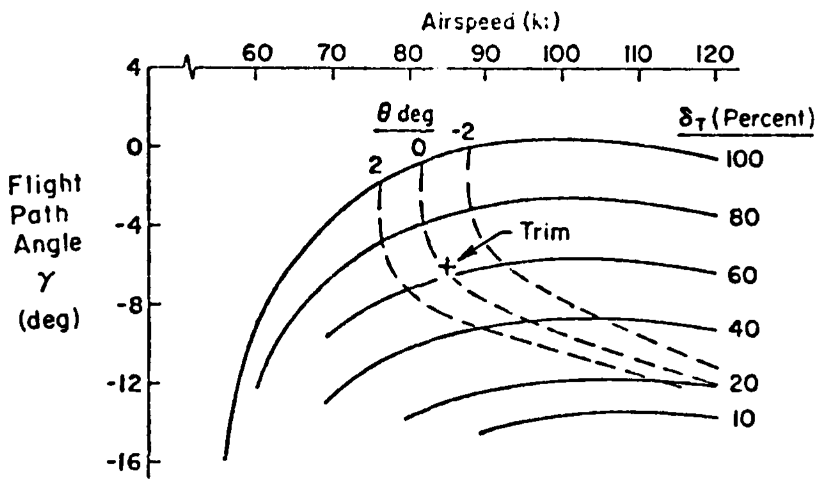


Figure 55. γ-V Characteristics for the Hooker Configuration
(From Reference 30)

below trim and neutral coupling occurring at power settings above trim. Adverse path/speed coupling means that if attitude is held constant and power is reduced, the speed tends to increase, i.e., the opposite of conventional airplanes. The configuration in Figure 55 was derived in Reference 30 by increasing the powered-lift efficiency, η_p, from a baseline value of 0.263 to 0.426, where

$$\eta_p = \frac{\partial C_L}{\partial C_\mu} \frac{C_\mu}{C_L}$$

An increase in η_p tends to rotate the constant attitude lines in a direction to cause increased adverse path/speed coupling. It also tends to decrease Z_u, which is an important measure of path disturbances due to horizontal wind shear.

$$Z_u \doteq -\frac{2g}{U_o}\left(1 - \eta_p\right)$$

It can be seen that a theoretical tradeoff exists between decreased horizontal wind shear sensitivity (lower Z_u) and increased adverse path/speed coupling as the STOL efficiency is increased.

Path/speed coupling is generally quantified (for example, see Reference 14) as the slope of the constant attitude lines $\left[\left(\frac{\partial U}{\partial \gamma}\right)_{\theta=const}\right]$ on the γ-V plot.

The effect of coupling on STOL handling qualities has been shown to involve two important considerations.

1) A moderate level of coupling during glideslope tracking is of major significance only when it affects the margin from stall.

2) Adverse path/speed coupling can result in excessive airspeed (which is unacceptable for the STOL mission) near touchdown.

The first of these considerations was addressed in References 12 and 14. In the simulator results of Reference 12 it was noted that, while the pilots found that adverse path/speed coupling was undesirable, it was not a major factor in the final pilot ratings. The evidence upon which this conclusion was based is summarized below.

- Quantitative measurements of the pilot's closed-loop tracking behavior via describing functions showed no evidence of active (closed-loop) speed control.

- A review of the pilot commentary indicated that speed was monitored rather than controlled for adverse coupled configurations. Additionally, some pilots volunteered that the adverse path/speed coupling represented a rating degradation of only 1/2 to 1 point on the Cooper-Harper scale.

- The strip chart records of the simulation showed evidence of changes in trim pitch attitude with long-term speed excursions but no evidence of closed-loop speed control. This result held true for the IFR glide slope tracking portion of the approach, as well as the visual aim point control after breakout and before the initiation of flare.

The above results apply for configurations where the speed variations caused by path/speed coupling did not result in stall. However, if the coupling has any tendency to induce a stall, it is unacceptable, as illustrated by the Reference 12 configuration shown in Figure 56. The pilot rating for this configuration (AP6 RLD) was initially a 9. This rating was given after a run where the pilot got low on short final and added power. Because of the strong adverse coupling on this configuration, the airspeed decreased to below stall and control was lost (too low to recover). The stall speed was decreased slightly (64 kt to 61 kt) so that increasing power at the trim pitch attitude could not result in a stall (increased $C_{L_{max}}$ by 10 percent) as shown in Figure 56. The pilot rating then improved to a 5 even though the path speed coupling was significant ($\partial U/\partial \gamma \doteq -4.5$ kt/deg).

In summary, the above results indicate that as long as the flight path response or aircraft safety margins were not degraded, the pilots tended to simply monitor speed and fly constant attitude. Adverse path/speed coupling had only a minimal effect on the pilot ratings, which tended to be more directly associated with ability to control the flight path.

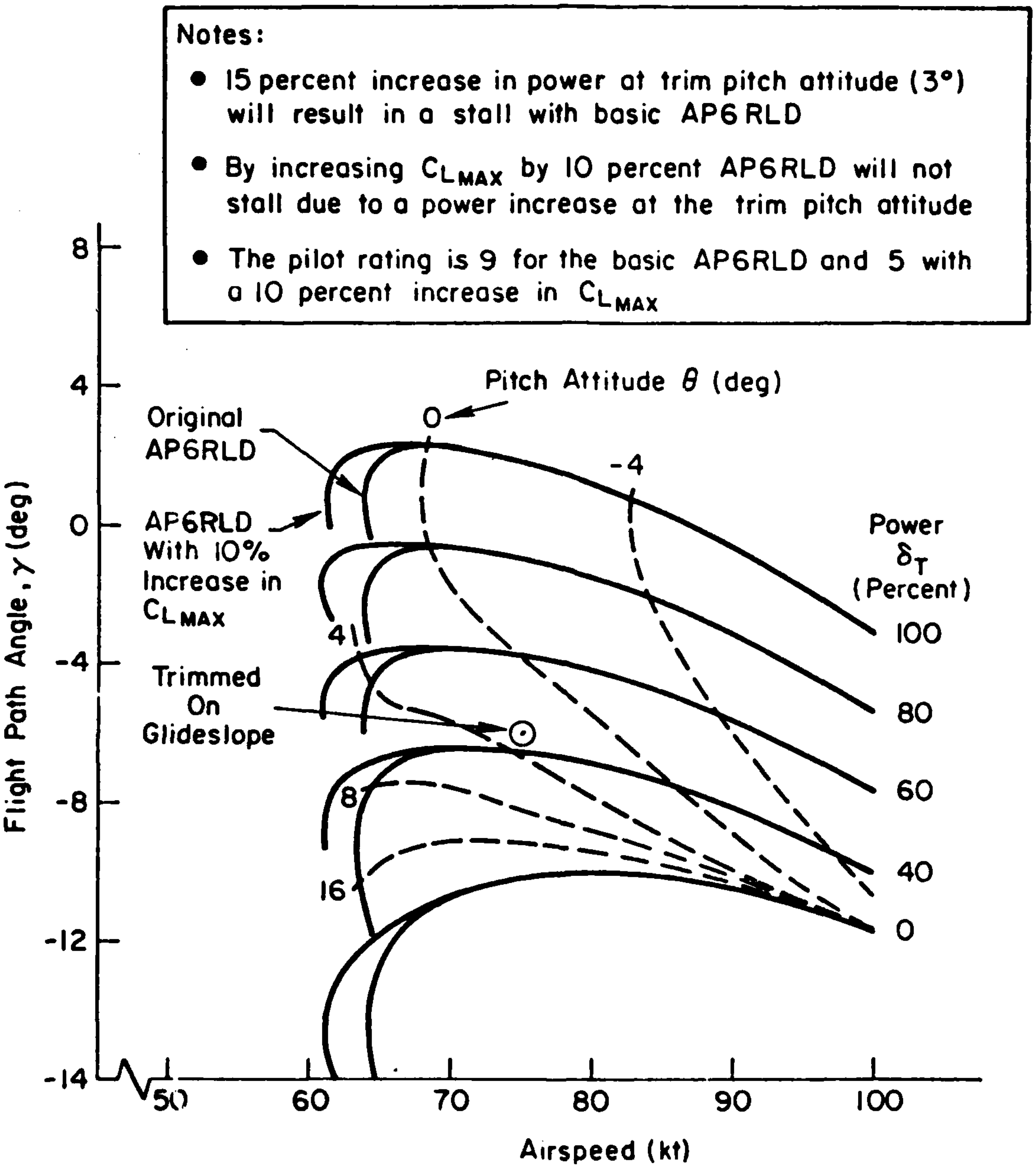


Figure 56. Effect of 10 Percent Increase in $C_{L_{max}}$ on Stall Characteristics

Reference 14 alludes to the fact that configurations with path/speed coupling invariably seem to also have a moderate path overshoot $[(\Delta\gamma_{max}/\Delta\gamma_{ss}) > 1.0]$. Hence, such coupling serves as an additional complicating factor, a fact which led the authors of Reference 14 to recommend limiting negative values of $(\Delta U/\Delta\gamma)_{ss}$ to less than 5 kt/deg (about the value for AP6RLD in Figure 56). Of course, any tendency for adverse coupling to induce a stall as in Figure 56 would be unacceptable, regardless of its magnitude as measured by $(\Delta U/\Delta\gamma)_{ss}$.

The stall problem discussed above is not the only safety margin that can be affected by adverse steady-state path/speed coupling. As an example of a safety margin that would be affected by poor speed control consider the excess flight path capability variation with airspeed of some typical powered-lift airplanes (see Figure 57). On many current STOL designs, the flight path performance in the up direction (γ_{max} at 100 percent power) is somewhat reduced when thrust is added at constant attitude due to adverse path/speed coupling. It is, therefore, important to consider safety margins other than stall when evaluating the effect of adverse path/speed coupling.

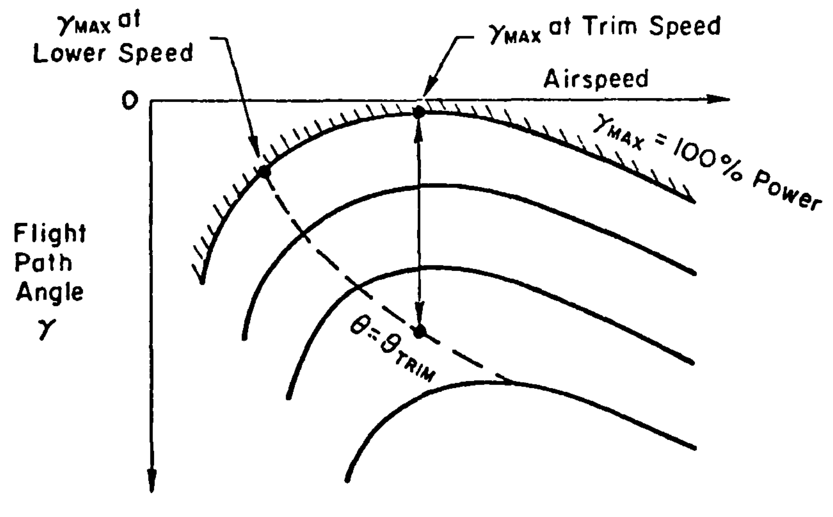


Figure 57. Illustration of Effect of Speed on Maximum Achievable Flight Path Angle

In addition to the speed variations that occur during glide path tracking, adverse path/speed coupling can also result in excessive airspeed at touchdown, a deficiency which is highly undesirable for the STOL mission. Excessive speed at touchdown can be induced by a decreasing tailwind shear which necessitates a reduced power setting to maintain glideslope. From Figure 55 it can be seen that such power reductions will result in a significant increase in speed. This occurred during the flight test phase of Reference 12, conducted on the Princeton Variable Stability Navion, when several approaches were made in a tailwind which sheared to a slight headwind near touchdown. The configuration being tested was AP1, which had moderate adverse steady-state path/speed coupling ($\partial U/\partial \gamma$ = -5 kt/deg). Because of the reduced power required to maintain glide slope in a tailwind, the airspeed tended to be quite high coming into the flare (90 kt, or 15 kt above the target speed), making it difficult to get into the touchdown zone. Several approaches were made with increased pitch attitude (about 10 deg was required) to keep the airspeed within reason coming into the flare. This was unsuccessful because it left no pitch attitude for the flare itself. Flares with power (pitch attitude held constant) were unsuccessful because of the very large engine lag (T_E = 1.5 sec) used in the Reference 12 experiment.

Based on this experience, a configuration with moderate adverse path/speed coupling ($\partial U/\partial \gamma \doteq -5$ deg/kt; see Figure 55) was tested in the Reference 30 windshear experiment (dubbed "hooker" because of the hook-like shape of the constant attitude lines). However, unlike AP1 of Reference 12, Hooker was augmented to have Level 1 handling qualities for backside flight path control:

$$t_{R_{\gamma_T}} = 2 \text{ sec}$$

See Figure 35, Section IV

$$\frac{\Delta\gamma_{max}}{\Delta\gamma_{ss}} = 1.6$$

ω_{BW_θ} = 2.5 rad/sec

See Figure 5, Section II

$\tau_{p\theta}$ = 0.05 sec

The aircraft was well on the backside of the power required curve so flight path control on approach was accomplished using the STOL technique.

Initial Cooper-Harper pilot ratings for approaches in light-to-moderate turbulence were about 4. However, when subjected to a series of decreasing tailwind shears, this rating was modified to a 6.5. The following pilot commentary further elucidates this result:

> "Let me make a couple of comments on that last configuration (Hooker). I gave it a (Cooper-Harper) pilot rating of 4 on both the glide slope track and the flare. That was, of course, based on the disturbances that we had seen to that point, which were only fairly light turbulence on the order of 3 ft/sec rms. The thing had the deficiency of having poor speed control when we got into the larger shears though. It seems to get into a condition where you're ballooning due to the wind shear (decreasing tailwind) and the speed would go up due to that. At the same time, you're taking the power off. So you have two things causing the speed to go up. Several times during the shear runs we went into the touchdown with excessive speed. So that would downgrade the final glide slope track portion for that task -- that is, handling those types of shears -- down to a 6.5 (Cooper-Harper rating)."

The accident potential (see Figure 47) in all tested tailwind conditions with this configuration was rated very high (4 or worse) due to excessive airspeed coming into the flare. The inability to keep the airspeed from getting unreasonably high in the tailwind shears was the predominant deficiency of the Hooker configuration. Two basic additive effects were responsible for these unacceptable airspeed excursions. One, the fundamental requirement to decelerate in a decreasing tailwind shear results in high airspeed; and the second, the reduced power required to keep from ballooning (due to the higher airspeed) causes a further increase in speed because of the adverse path/speed coupling.

Further work is required to determine limits on adverse path/speed coupling. However, a tentative limit of $(\partial U/\partial \gamma)_{\theta=\text{const}} > -5$ kt/deg seems reasonable.

The results for adverse path/speed coupling may be summarized as follows:

1. Adverse path/speed coupling results in a high level of accident potential and Level 2/3 Cooper-Harper pilot ratings for decreasing tailwind shears.

2. The primary problem is high airspeed at touchdown with consequent overrun potential and increased probability of large sink rates at very low altitudes.

3. The deficiencies noted above were obtained by increasing the STOL efficiency, η_p; therefore, it is expected that these problems may well become reality in the next generation of powered-lift STOLs.

4. The adverse path/speed coupling is less of a problem on the approach as long as it does not result in violating a safety margin.

SECTION VII

SUMMARY

A considerable amount of STOL research has been reviewed, analyzed, and unified into a collection of potential handling qualities criteria. In most cases the data are not sufficiently complete to allow the formulation of criteria suitable for inclusion in the MIL Handbook. However, there is sufficient information to provide substantial design guidance and to clearly define the requirements for additional data and research. A brief overview of each of the STOL handling quality topics follows.

1. Pitch Attitude Control

The pitch attitude control criterion has been formulated to account for the fact that the requirements are less stringent when flight path is controlled with throttle. The relaxed pitch attitude boundary is well supported by data for the approach phase. However, if pitch attitude is the primary control for flare and landing, a more stringent set of boundaries applies. That is, the relaxed attitude requirement only applies for cases where throttle is primary for approach and landing. There was little available data on pitch attitude control since the STOL problem logically centers about path control. The basic assumption made in these programs was that pitch attitude control for STOLs is not appreciably different than for CTOL. In keeping with this philosophy, we have adopted the MIL-F-8785C CTOL boundaries for cases where the primary control of flight path is with attitude.

2. Flight Path Control

Flight path control with pitch attitude (Section III) and with a designated controller other than attitude (Section IV) was considered. The requirements on the precision of flight path control were found to be considerably more stringent for flare and landing than for the approach. It is therefore important to establish the preferred flare technique (attitude or throttle) since it is critical in setting the criterion boundary for flight path response to that controller. A criterion was established in Section III which defines acceptable characteristics for attitude flares and for throttle flares. Flares requiring a combination of attitude and power were deemed unacceptable for Level 1. A small region of combination flares was established as tolerable for Level 2 flying qualities.

Two types of flight path response with pitch attitude primary were defined: 1) conventional response in which airspeed and sink rate are traded off and 2) response with an auxiliary speed control (termed an "autothrottle") to hold speed constant. In both cases the short-term path to attitude response, γ/θ, is specified as limits on $(1/T_{\theta_2})_{eff}$, the frequency at which the phase lag of γ to θ is 45 deg. An alternate rise time criterion $(t_{R_{\gamma_\theta}})$ is also defined and is equivalent to $(1/T_{\theta_2})_{eff}$.

The long term path response for case 1 above involves the same basic considerations as for CTOL aircraft and therefore we chose to invoke the $(\partial\gamma/\partial V)_{\delta T = const}$ requirement from MIL-F-8785C. However, for case 2, the path requirements are considered to be quite severe in order to justify a complex SAS such as an autothrottle. An example would be a requirement for precision touchdown with relatively high approach speeds in turbulence and low visibility. In this case there is a necessity for automatic speed holding to keep the pilot workload at a reasonable level. There is very little data available upon which to base criteria for such a system, and hence, only a very broad overview is presented.

Flight path control with a designated controller other than pitch attitude (e.g., throttle) is specified in terms of rise time $(t_{R_{\gamma_T}})$ and flight path angle overshoot $(\Delta\gamma_{max}/\Delta\gamma_{ss})$ as discussed in Section IV.

3. Flight Path Control Power

The critical disturbance which sets flight path control power was found to be a discrete windshear on short final approach. The tentative requirements on control power are given in terms of maximum achievable flight path angle, γ_{max}, and the maximum change in flight path angle in the down direction, $\Delta\gamma_{min}$. The requirements are written so that reconfiguring the aircraft to achieve the stated limits is not allowed.

4. Effect of Windshear

Powered-lift STOLs tend to be more vulnerable to windshear than low-wing-loading STOLs, given the same level of flight path control power. It is recommended that the powered-lift STOL should be required to be no more vulnerable to windshear than the low-wing-loading STOL either through augmentation or through increased flight path control power. The DHC-6 Twin Otter was suggested as a reference aircraft for low-wing-loading STOL performance in wind shear. This is covered in Section VI-B.

5. Limiting Flight Conditions

The results of reviewing the literature are presented in Section VI-C. However, no specific recommendations are made in view of the very sparse data base in this area.

6. Path/Speed Coupling

Path/speed coupling tends to be adverse (decreasing speed for increasing power) for highly efficient powered lift STOLs using throttle to control flight path. It was found that the primary issues are:

- Possible speed reduction to stall when adding power to correct for a low and slow condition.
- High airspeed at touchdown in decreasing tailwind shear on short final.

A maximum level of path/speed coupling is recommended in Section VI-E.

APPENDIX A

PILOT RATINGS FROM SIMULATIONS REPORTED IN REFERENCE 12

Throughout this report, the results of the piloted simulation documented in Reference 12 are relied upon as a major data source. The pilot ratings were presented in that reference in a format different from their use in this report. Specific ratings — used in this report — were not included in Reference 12. Since the unpublished ratings are available, the purpose of this appendix is to document them for future use in investigating STOL handling qualities. Table A-1 lists the tasks and corresponding task codes, and Table A-2 contains pilot ratings for the seven pilots involved in the S-16 simulation, and three pilots who flew a follow-up study on the FSAA.

TABLE A-1. TASK CODE

1.01	ILS tracking (IFR) from 1500 ft to breakout at 300 ft — no landing — 4.5 ft/sec rms turbulence
1.1	High fast I.C. — 85 kt IAS and 350 ft above glide slope turbulence off
1.2	Low slow I.C. — 65 kt IAS and 350 ft below glide slope turbulence off
1.7	Turbulence off — change speed on glide slope ±10 kt
2.0	Landing without turbulence; I.C. = 200 ft; all VFR
2.1	Task 2.0 with σ_{u_g} = 4.5 ft/sec
2.4	Task 2.1 with 10 kt crosswind from left
2.7	Task 2.1 with discrete shear — zero wind at 200 ft to a 10 kt headwind at 100 ft (10 kt/100 ft)
3.0	Composite — intercept LOC — intercept glide slope — breakout at 300 ft — land — turbulence off
3.1	Task 3.0 with σ_{u_g} 4.5 ft/sec
3.2	Task 3.1 with a steady 10 kt headwind
3.3	Task 3.1 with a steady 10 kt tailwind

TABLE A-2. PILOT RATINGS FROM SIMULATIONS OF RERERENCE 12

a) S-16 Simulation

CONFIGURATION	TASK	PILOT 1	PILOT 2	PILOT 6	PILOT 7	PILOT 8	PILOT 9
BSL1	1.01	3	4.5	3	4	3.5	4,4
	1.1	4	7	4	4	3.5	4,5
	1.2	4	4.5	3.5	4	3.5	4,4
	1.7	3				3.5	4.5
	2.0	3		2.5	4,4-4.5	2	3.5,4.5(θ),5(δ_T)
	2.1	3.5	7,5(T_e=.5)	3	4.5,5,5(T_e=.5)	3.5	3.5,5
	2.4		7				5
	2.7	3			7,5,4.5(T_e=.5)	3.5	7,5
	3.0	2.5,2.5,2.5	3.5,5,5.5	2,2,2.5		3,3,3	3.5,4,4,4
	3.1	3.5,3.5,3.5	4,7,7	3,3,3	4.5,5,5	3.5,3.5,3.5	4,4,4,4
	3.2		4,7,7	3,3,3			
	3.3						
BSL2	1.01	2.5,3			3.5-4	3.5	3.5
	1.1	4,4	4		3.5-4,3.5-4	4	4
	1.2	4,4	4		3.5-4	4	4
	1.7	5					
	2.0	3.5,3.5		3	3.5	3.5(θ),3(δ_T)	3(θ),4.5(δ_T)
	2.1	4,4	4	4	3.5	4(θ),3.5(δ_T)	4
	2.4	4					
	2.7					5.5	4.5-5
	3.0	3,4,3.5,3,4,3.5		3,3,3		3,2.5,3.5	4,3.5,3.5
	3.1	3,4,3.5,4,4.5,4.5	4,4,4	3,3,4	4.5,5.5,5.5	4.5,5,5	4.5,4,4.5
	3.2			4,4.5,4.5		5,3,4.5	4,3,3.5
	3.3			4.5,4.5			
BSL2 RLD	1.01	3			4*		4.5-5
	1.1	5			5		
	1.2	4.5					
	1.7	4			5.5		
	2.0	3					3
	2.1	4					6
	2.4						
	2.7	4			5		5
	3.0	3,3,3					
	3.1	4,4,4			4,5,5		6,5,6
	3.2						
	3.3						

*Flown at 65 kt (10 kt below design approach speed).

TABLE A-2. (Continued)

a) (Continued)

CONFIGURATION	TASK	PILOT 1	PILOT 2	PILOT 6	PILOT 7	PILOT 8	PILOT 9
AP1	1.01	2,3.5			4.5	4	3.5
	1.1	7,4			4.5	7.5	7
	1.2	6,5.5			4.5	6	5
	1.7	5	4*			6,3	5
	2.0	5.5,5			5	3.5(θ),4(δ_T)	5
	2.1	6,5	8*		6.5	7.5;4,6(θ);3.5,5(δ_T)	8
	2.4				7		7
	2.7				7	7.5	
	3.0	4,5,5	3*			4.5,4,4.5	3.5
	3.1	5,5,5	7,8,7*		4.5,6.5,6.5	5,5,5,3.5,4,4	4,6,5
	3.2						5,5
	3.3						
AP2	1.01	3	3	5	4.5**		
	1.1	7	7	6	5		
	1.2	4	7	7	4.5		
	1.7	5			5		
	2.0	3.5	3	2.5	4.5		
	2.1	4	4	4	4.5		
	2.4		4		4.5		
	2.7			6	4.5		
	3.0			4,4,4			
	3.1	4,4.5,4.5	4	5,5,5	4.5,4.5,4.5		
	3.2						
	3.3						
AP6	1.01	4		3	4.5		
	1.1	6	3.5	4			
	1.2	4	3.5	5			
	1.7						
	2.0	4		2	4.5		
	2.1	4.5		3	4.5		
	2.4				5.5		
	2.7				6.5		
	3.0	4,4.5,4.5		6,3,5	4.5,4.5,4.5		
	3.1	4,4.5,4.5	3,3,3	6,3,5,5,5,5.5	4.5,4.5,4.5		
	3.2	4,4.5,4.5	3,4,4	6,3,5,5,5,5.5			
	3.3		5,7,7	6,3.5,5			

*Ratings for pilot 5 (pilot 2 did not fly AP1)
**Pilot 7 flew AP2 with T_e = 0.5 sec.

TABLE A-2. (Continued)

a) (Continued)

CONFIGURATION	TASK	PILOT 1	PILOT 2	PILOT 6	PILOT 7	PILOT 8	PILOT 9
AP6 RLD	1.01	5			4.5		3.5–4
	1.1	7			4.5		4
	1.2	6			4.5		4
	1.7	5			4.5		5
	2.0	3			5		3
	2.1	3			5		3.5
	2.4						
	2.7	4					3.5
	3.0						
	3.1	5,4,5			4.5,5,5		4,3.5,4
	3.2						
	3.3						
AP7	1.01	3			4		3.5
	1.1	7					
	1.2	4					
	1.7	3			5		4
	2.0						3.5(θ),4.5(δ_T)
	2.1	4			6		6
	2.4	3					
	2.7	4.5			6		
	3.0	3,3,3					
	3.1	3.5,3.5,3.5			4,6,6		4.5,6,6
	3.2	3.5,4,4					
	3.3						
AP10	1.01	4,5			6	4	7,7
	1.1	7,8			6	8	9,10
	1.2	6,8			6	8	9
	1.7	6,8				8	5
	2.0	3.5,6			6	9.5(θ),8(δ_T)	5,5
	2.1	4,6			6.5	8	8,6
	2.4						
	2.7	7,7			7,5(T_e=1.5),4.5(.5)		8,9
	3.0	5,6,6				5.5,5,6	9
	3.1	5,6,6,7,6,7				6,8,7	7,7,7,9,9,9
	3.2						
	3.3						

TABLE A-2. (Concluded)

b) FSAA Simulation

TASK	AP7 PILOT			AP10 PILOT		
	1	7	9	1	7	9
1.01	3	4	3	3	5	7
1.1	4	4	7	7	7	10
1.2	4	4	4.5	7	5.5	10
1.7	4	5	4.5	5	5.5	7
2.0	4			4	5	3
2.1	5	5	4	4	5.5	5
2.4						
2.7		7		5		5
3.0						
3.1	3.5,5,5	4,5,5		7,4,7	5,5.5,5.5	5,5,5
3.2						
3.3						

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