4.3.1.2 Steady-state flight path response to attitude change.

For flight path control primarily through the pitch attitude controller, the steady-state path and airspeed response to attitude inputs shall be as follows: __________. For flight control modes using another designated flight path control the required flight path response to attitude changes is ____________.

REQUIREMENT RATIONALE (4.3.1.2)

The accepted piloting technique for conventional flight is to adjust flightpath via pitch attitude control. This requirement is included to insure that the long-term flight path response to pitch attitude changes is acceptable to the pilot.

For aircraft using another specified flight path controller for primary control of flight path, a relaxation is warranted when use of such a piloting technique is deemed acceptable. Examples might be some shipboard and STOL operations. In those cases the pilots must be trained appropriately.

REQUIREMENT GUIDANCE

The related MIL-F-8785C requirements are paragraphs 3.2.1.3 and 3.6.2.

For most conventional aircraft the first part of this requirement is applicable, and guidance is given herein. For such aircraft as STOLs in which primary control of flight path is not with pitch attitude, a relaxation of 4.3.1.2 (that is, to allow operation well on the back side of the thrust-required vs. airspeed curve) should be allowed. Although no guidance is presently available, current STOL flying qualities research addresses requirements such as this.

Recommended values:

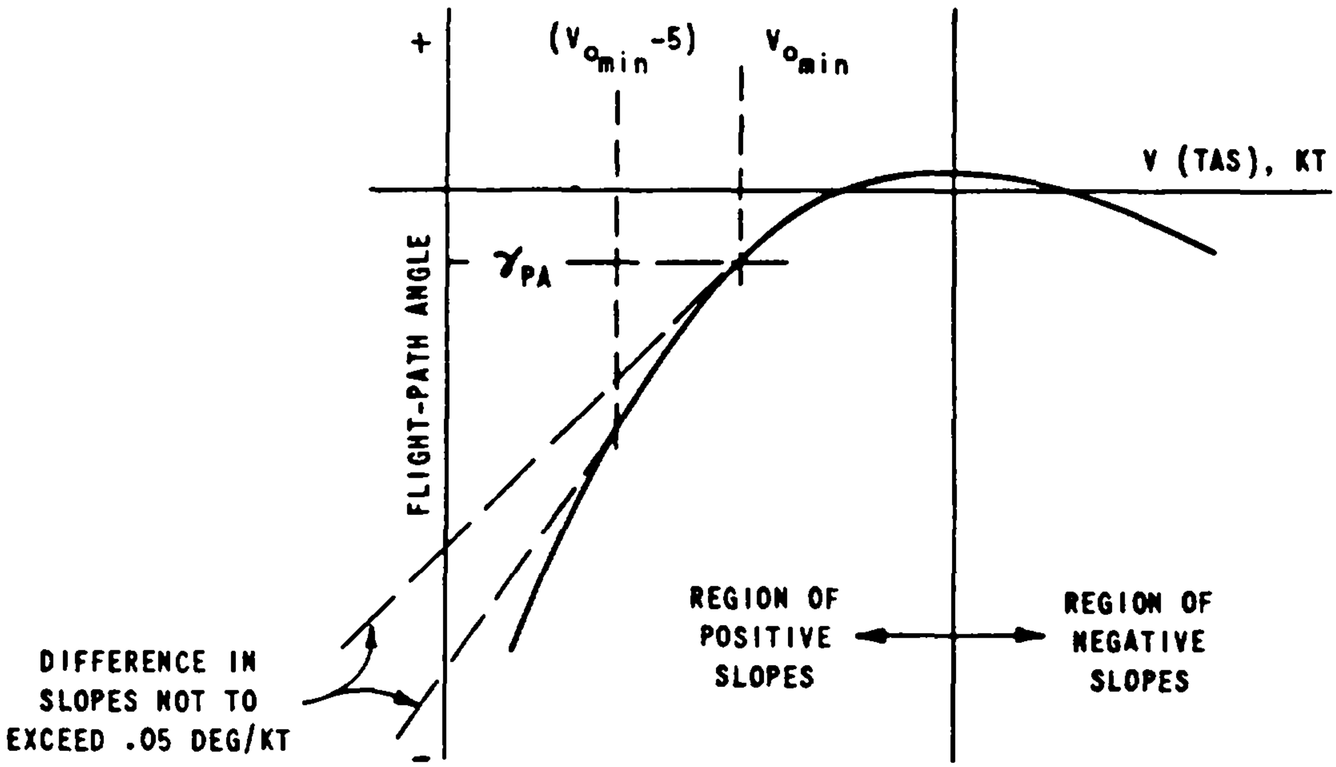
Flight-path stability is defined in terms of flight-path-angle change with airspeed when regulated by use of the pitch controller only (throttle setting not changed by the crew). For the landing approach Flight Phase, the curve of flight-path angle versus true airspeed shall have a local slope at $V_{o\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

Level 1: 0.06 degrees/knot

Level 2: 0.15 degrees/knot

Level 3: 0.24 degrees/knot

The thrust setting shall be that required for the normal approach glide path at $V_{o\ min}$. The slope of the curve of flight-path angle versus airspeed at 5 knots slower than $V_{o\ min}$ shall not be more than 0.05 degrees per knot more positive than the slope at $V_{o\ min}$ as illustrated by the sketch.



Discussions for this section, including the supporting data, are taken from AFFDL-TR-69-72.

Operation on the backside of the drag curve [negative d(T - D)/dV] in the landing approach leads to problems in airspeed and flight-path control. Systems Technology Inc. TR-24-1, AGARD Rpt 122, RAE Aero. 2504, and AGARD Rpt 357 show that airspeed behavior, when elevator is used to control attitude and altitude, is characterized by a first-order root that becomes unstable at speeds below minimum drag speed. This closed-loop, constrained-flight path instability, even when the open-loop (unattended aircraft) phugoid motion is stable, is caused by an unstable zero in the h/δ_e aircraft transfer function. Specifically, Systems Technology Inc. TR-24-1 uses closed-loop analyses to show the importance of the factor $1/T_{h1}$ as an indicator of closed-loop system stability and throttle activity required. A useful measure of the quantity $1/T_{h1}$ is needed.

Working from the altitude-to-elevator transfer function, FDL-TDR-64-60 shows that $1/T_{h1}$ is closely approximated (the other two zeros generally are much larger) by the ratio D/C, where D and C are from the expression:

$$\frac{\dot{h}(s)}{\delta_e(s)} = \frac{As^3 + Bs^2 + Cs + D}{\left[s^2 + 2\zeta_p\omega_p s + \omega_p^2\right]\left[s^2 + 2\zeta_{sp}\omega_{sp} s + \omega_{sp}^2\right]}$$

The additional assumption that C is approximately equal to $V(Z_{\delta_e} M_w - M_{\delta_e} Z_w)$ is generally valid, so that (WADC-TR-58-82):

$$\frac{1}{T_{h1}} = \frac{D}{V\left(Z_{\delta_e} M_w - M_{\delta_e} Z_w\right)}$$

The climb angle γ is $\dot{h}/V$. Applying the limit value theorem to $\gamma(s)/\delta_e(s)$, for a step δ_e [$\delta_e(s) = |\delta_e|/s$] then

$$\frac{d\gamma}{d\delta_e} = \left.\frac{\gamma(s)}{\delta_e(s)}\right|_{SS} = \frac{1}{V} \cdot \frac{D}{\omega_p^2 \omega_{sp}^2}$$

In a similar manner, the slope of the steady-state u versus δ_e curve is obtained.

$$\frac{du}{d\delta_e} = \frac{u(s)}{\delta_e(s)} = -\frac{g\left(Z_{\delta_e} M_w - M_{\delta_e} Z_w\right)}{\omega_p^2 \omega_{sp}^2}$$

Then the slope of the steady-state γ versus u curve for elevator inputs can be written

$$\frac{d\gamma}{d\delta_e} = \frac{d\gamma/d\delta_e}{du/d\delta_e} = -\frac{1}{g} \cdot \frac{D}{V\left(Z_{\delta_e} M_w - M_{\delta_e} Z_w\right)}$$

$$= -\frac{1}{g} \cdot \frac{1}{T_{h_1}}$$

The $d\gamma/du$ limits, therefore, set limits on $1/T_{h_1}$.

The limit on $d\gamma/du$ at 5 knots slower than $V_{o\ min}$ was added to assure that the aircraft remains tractable at commonly encountered off-nominal speeds.

For design purposes, $d\gamma/du$ can be estimated from the dimensional stability derivatives (which must include any important thrust effects) as follows:

$$\frac{d\gamma}{du} = \frac{1}{g}\left[X_u - \left(X_w - \frac{g}{V}\right)\left(\frac{Z_u - M_u Z_{\delta_e}/M_{\delta_e}}{Z_w - M_w Z_{\delta_e}/M_{\delta_e}}\right) - \frac{X_{\delta_e}}{M_{\delta_e}}\left(\frac{M_w Z_u - Z_w M_u}{-Z_w + M_w Z_{\delta_e}/M_{\delta_e}}\right)\right]$$

or

$$\frac{d\gamma}{du} = \frac{1}{g}\left[X_u - \left(X_w - \frac{g}{V}\right)\left(\frac{Z_u - M_u Z_{\delta_e}/M_{\delta_e}}{1/T_{\theta_2}}\right) - \frac{X_{\delta_e}}{M_{\delta_e}} \cdot \frac{\omega_p^2 \cdot \omega_{sp}^2}{g\left(1/T_{\theta_2}\right)}\right]$$

For M_u and X_{δ_e} small, the following approximation is valid except for very-short-tailed aircraft:

$$\frac{d\gamma}{du} \doteq \frac{1}{g}\left[X_u - \left(X_w - \frac{g}{V}\right)\frac{Z_u}{Z_w}\right]$$

It is possible to violate this requirement by operating well on the back side of the power-required curve ($d\gamma/du > 0$) and still have a Level 1 aircraft as long as some other means of controlling flight path is provided (usually power or thrust). Naturally this other controller must have satisfactory characteristics. For example if the throttle is designated as the flightpath controller, good dynamic and steady-state flight path response to throttle changes (γ/δ_T) must be assured. Although there are no quantitative data to support this, it seems logical that progressively degraded γ/θ can be compensated with incremental improvements in $(\gamma/\delta_T)_{SS}$. Examples of aircraft that have poor $(\gamma/\theta)_{SS}$ characteristics but are acceptable because flight path control is augmented with thrust are the de Havilland Twin Otter, the DHC-7, and many carrier-based fighters (e.g., Systems Technology Inc. TR-124-1). But Pinsker (RAE-TR-71021) found that an autothrottle to hold constant airspeed can be quite destabilizing if the thrust line passes below the c.g. of a statically stable aircraft. Requirements on γ/δ_T are specified in 4.3.2 based on STOL aircraft research.

Since backside operation (defined as having $d\gamma/du > 0$) is most critical during landing approach, this requirement is oriented toward that Flight Phase. To improve $d\gamma/du$ requires increasing the airspeed, which has obvious performance implications. Backside operation is also troublesome for takeoff, cruise, and high-altitude maneuvering, but it will probably not be as critical as for the landing approach, and there are virtually no data to define numerical limits for these Flight Phases.

In the event the aircraft is operated with a continuous flight path controller (e.g. DLC on the YC-15), which serves (one hopes) to improve the flight path response, allowing the relaxation for aircraft with designated flight path controller should be considered.

SUPPORTING DATA

The $1/T_{h_1}$ data used to set numerical limits on $d\gamma/du$ are given in AFFDL-TR-66-2, NASA-TN-D-2251, AGARD Rpt 420, AFFDL-TR-65-227, and "Simulator and Analytical Studies of Fundamental Longitudinal Problems in Carrier Approach" as in the following discussion.

It is apparent from figures 125 - 127 (from AFFDL-TR-66-2) that pilot ratings of $1/T_{h_1}$ are dependent on the values of ζ_p. For Level 1, 4.2.1.2 requires $\zeta_p > 0.04$; greater damping might result from autothrottle or similar augmentation. Therefore, the positive ζ_p data of figure 125 were used to establish the Level 1 requirement for $1/T_{h_1}$ or $d\gamma/dV$. (The data from figures 126 - 128 are obviously too conservative for Level 1. The configurations for figure 126 had ω_{sp} marginally close to the lower Level 1 boundary; while those for figure 128 were downrated because of the pitch response to horizontal gusts caused by M_u.) For Levels 2 and 3, the zero-ζ_p data seem appropriate:

Figure	Level 2	Level 3
125	$1/T_{h_1} > -0.08$	$1/T_{h_1} > -0.12$
126	$1/T_{h_1} > -0.05$	$1/T_{h_1} > -0.08$

From figure 127, with near-zero ζ_p:

Level 2	Level 3
$1/T_{h_1} > -0.05$	$1/T_{h_1} > -0.12$

From figure 128, with high ζ_p but in turbulence:

Level 2	Level 3
$1/T_{h_1} > -0.05$	$1/T_{h_1} > -0.12$

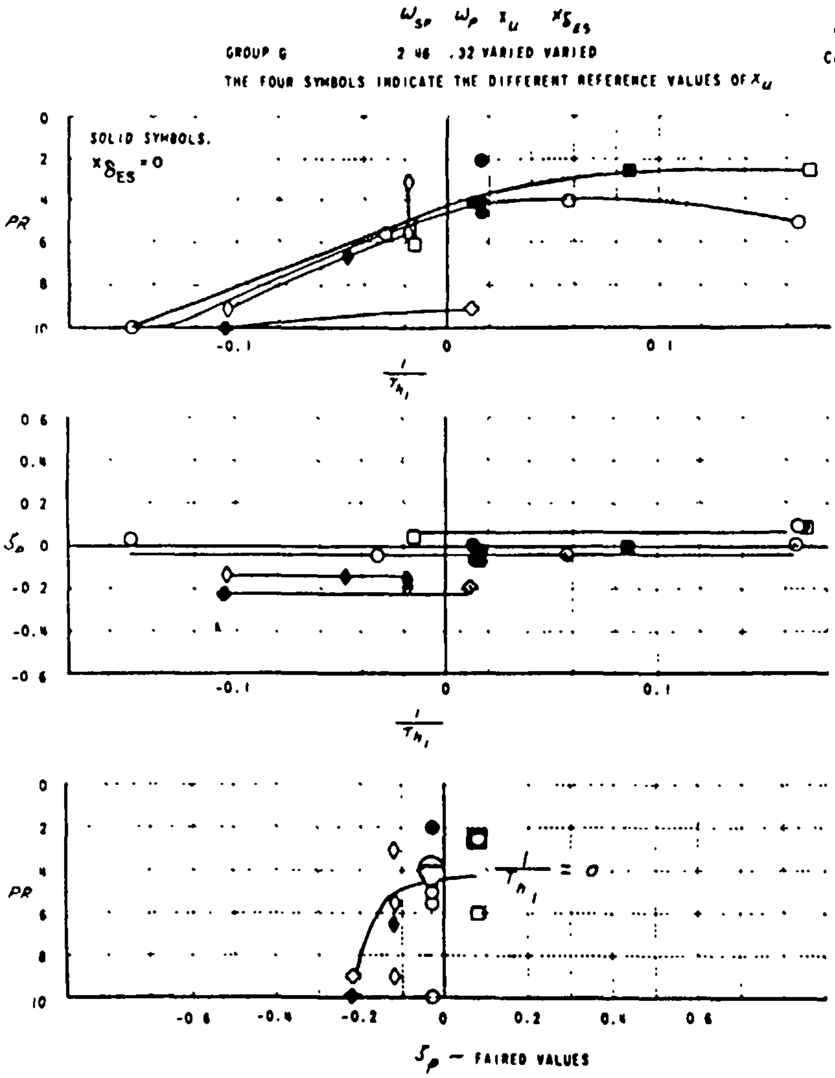


FIGURE 125. Landing approach (T-33, AFFDL-TR-66-2).

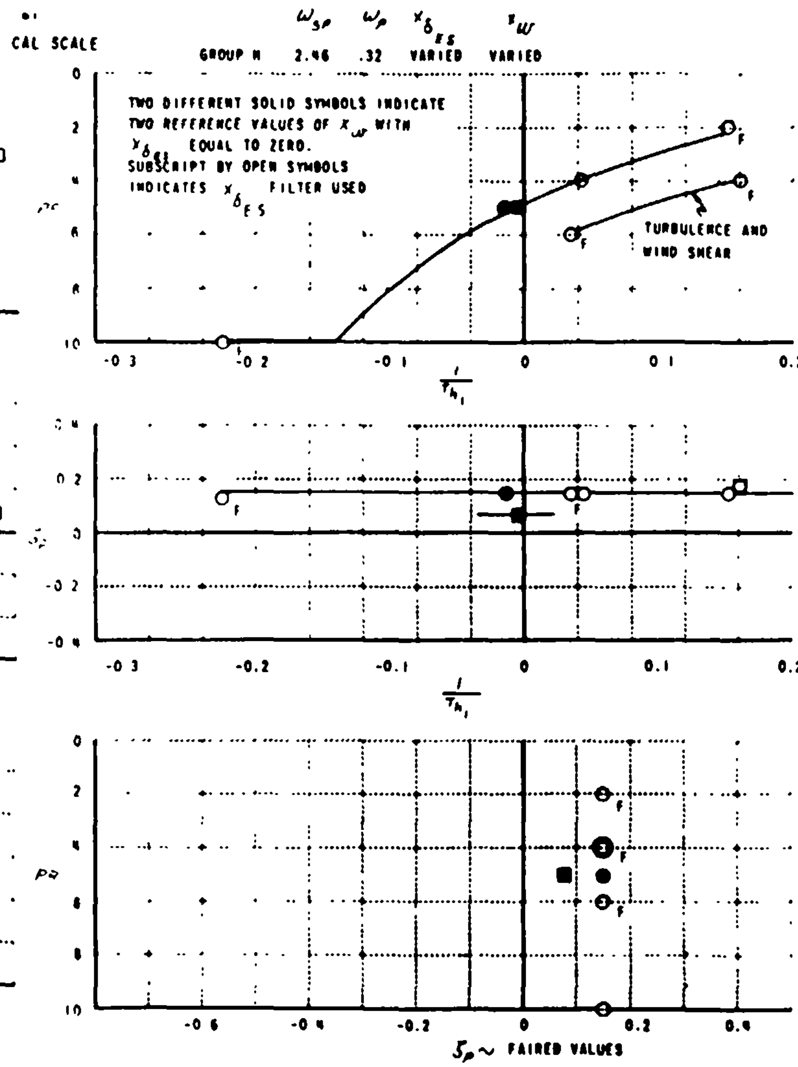


FIGURE 126. Landing approach (T-33, AFFDL-TR-66-2).

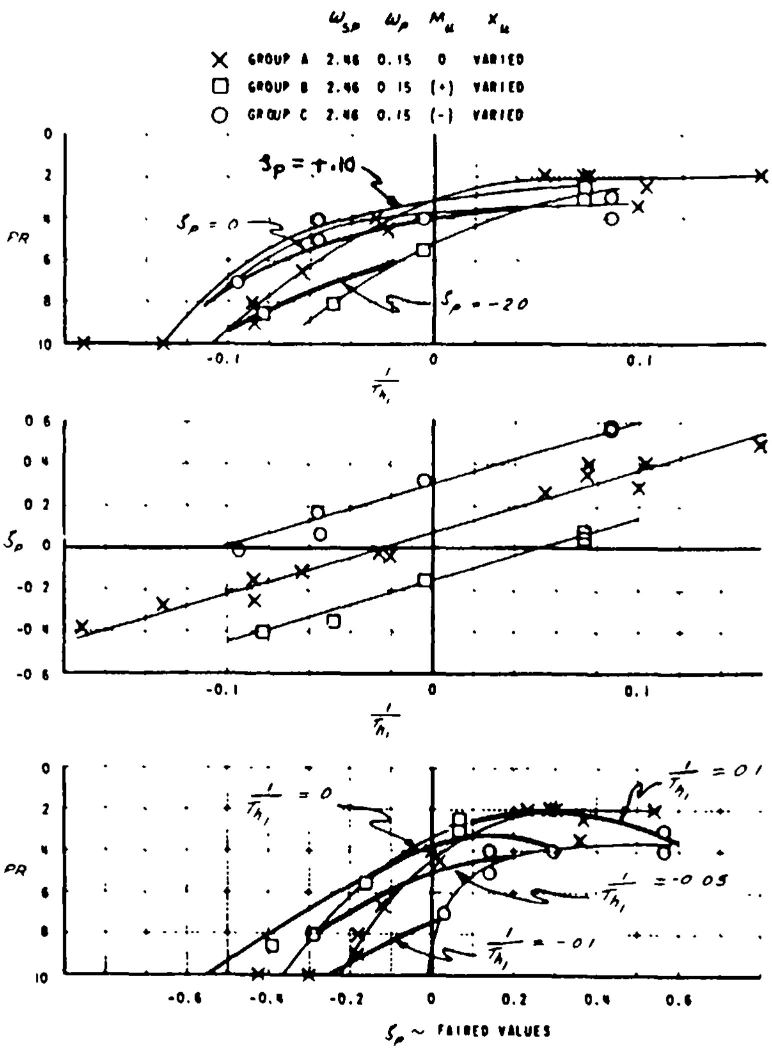


FIGURE 127. Landing approach (T-33, AFFDL-TR-66-2).

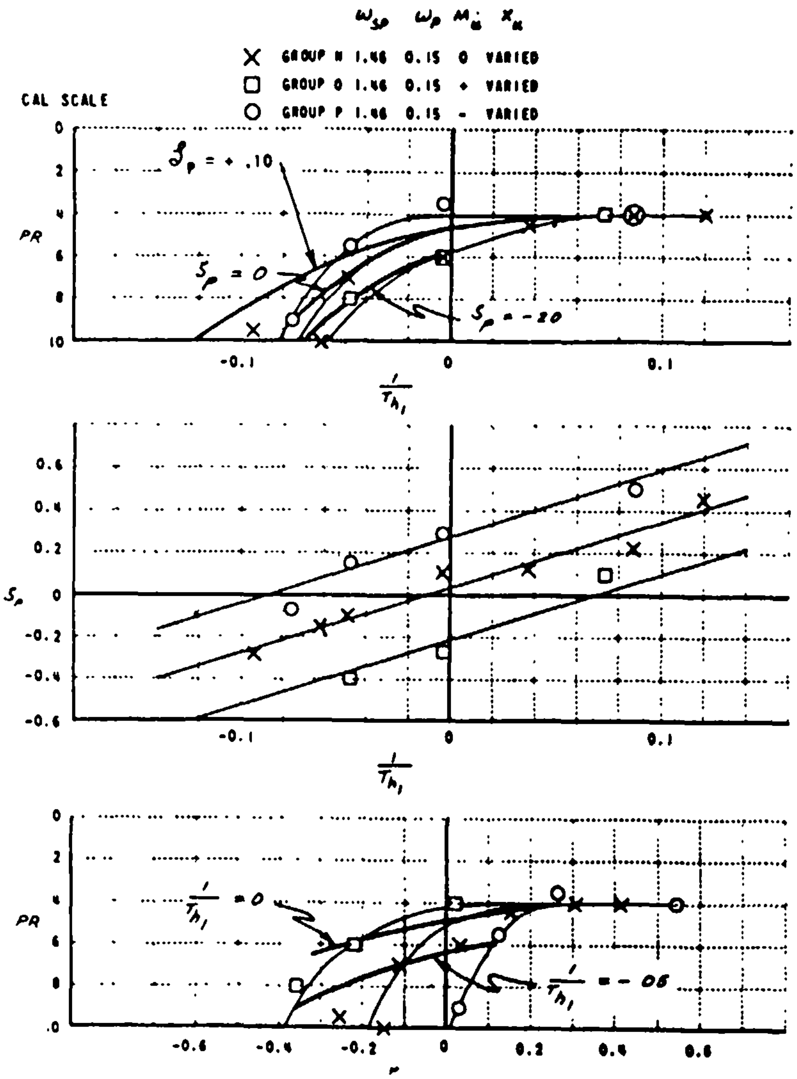


FIGURE 128. Landing approach (T-33, AFFDL-TR-66-2).

Combinations of Level 2 or 3 values of $1/T_{h_1}$ with low ζ_p, ω_{sp} , or both appear worse than cases with high ζ_p and ω_{sp} . With these considerations in mind, T_{h_1} = -0.02 was chosen for the Level 1 boundary, -0.05 for Level 2, and -0.08 for Level 3. These values of $1/T_{h_1}$ correspond to the $d\gamma/dV$ values specified: multiply $1/T_{h_1}$ by -(57.3) (1.689)/(32.2) = -3.

The ground simulator experiment of “Simulator and Analytical Studies of Fundamental Longitudinal Control Problems in Carrier Approach" altered $1/T_{h_1}$ by changing X_w and X_{δ_e} and also considered the influences of thrust-line inclination and thrust-line offset on the flying qualities. There are very limited data for thrust-line offset, and the decision was made to assume that designers will take reasonable steps to keep the offset as small as possible. The data for zero thrust-line offset are presented in figure 129 for different values of thrust-line inclination. The data do seem to indicate that some thrust-line inclination is desirable, but the variations in rating due to inclination are well within the scatter of the data considered as a whole.

The data from ground simulator experiments of NASA-TN-D-2251 and AFFDL-TR-65-227 are presented in figure 130. It should be mentioned that only the data for the highest static margin in NASA-TN-D-2251 are presented because the lower static margins result in values of ω_{sp} that are too low for Level 1.

The data from the in-flight experiment of AGARD Rpt 420 are presented in figure 131. There are several factors that influence interpretation of this data. First, the pilot rating scale used is a modified version of the Cooper scale and is rather difficult to interpret. Second, the speed stability was changed by altering $\partial T/\partial V$ as well as a $\partial T/\partial \alpha$, which means that unstable values of speed stability were accompanied by negative values of phugoid damping. Since the speed stability was altered in this experiment by using engine thrust, the pilot could use the engine noise as an airspeed cue. The final (and probably most significant) factor is that most of the approaches were flown VFR, with a ground controller supplying continuous flight-path information by radio using a theodolite. AGARD Rpt 420 states that this type of technique resulted in very tight control of flight path. A few approaches were made using precision-approach radar, these were much more difficult for the pilot to successfully accomplish. The relationship between the speed stability parameter $1/T_2$ of figure 131 and $1/T_{h_1}$ is as follows:

$$1/T_{h_1} = 0.693\ (1/T_2)$$

A comparison of the requirements derived from figures 125 through 128 and the data from figures 129 through 131 are presented in the following tabulation. Note that in figures 129 through 131, the pilot rating scale is the Cooper scale. The Levels are qualitatively equivalent to those of the Cooper-Harper scale, but their boundaries on the scale are different. On the Cooper scale the Level 1 boundary is at 3.5, the Level 2 boundary is at 5.5, and the Level 3 boundary is at 7 (see AFFDL-TR-69-72).

	Level 1	Level 2	Level 3
Requirement of 4.3.1.2	-0.02	-0.05	-0.08
Figure 129	-0.035	-0.084	-0.107
Figure 130	-0.020 to -0.035	-0.095	-1.121
Figure 130	-0.010	-	-
Figure 131 (no thrust lag)	+0.010	-0.190	-0.360
Figure 131 (thrust lag)	+0.017	-0.060	-0.125

The primary problem with figure 129 seems to be that the majority of the data points are for VFR approaches with unusually good flight-path information available to the pilot (see AGARD Rpt 420)

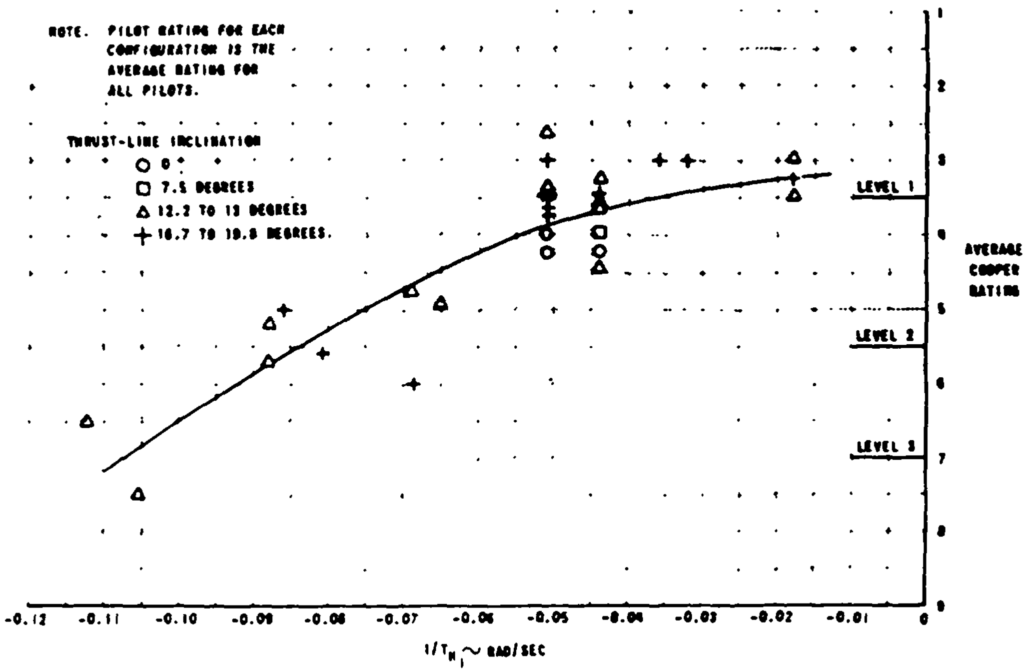


FIGURE 129. Carrier approach (Ground simulator experiment, "Simulator and Analytical Studies of Fundamental Longitudinal Control Problems in Carrier Approach").

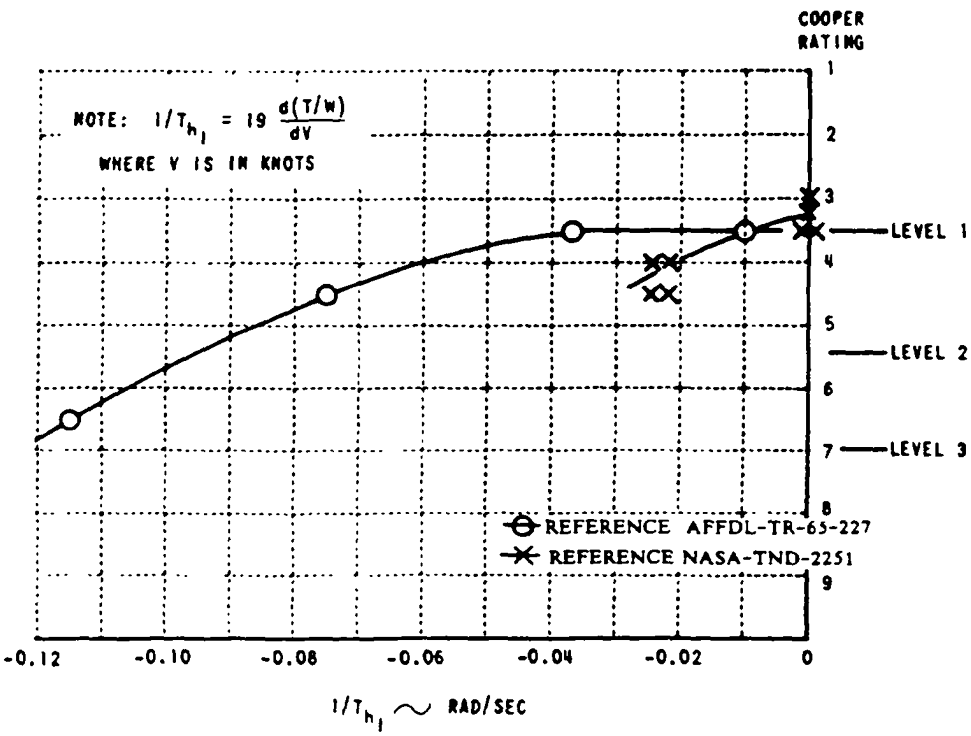


FIGURE 130. SST landing approach (Ground simulator experiments, NASA-TN-D-2251 and AFFDL-TR-65-227).

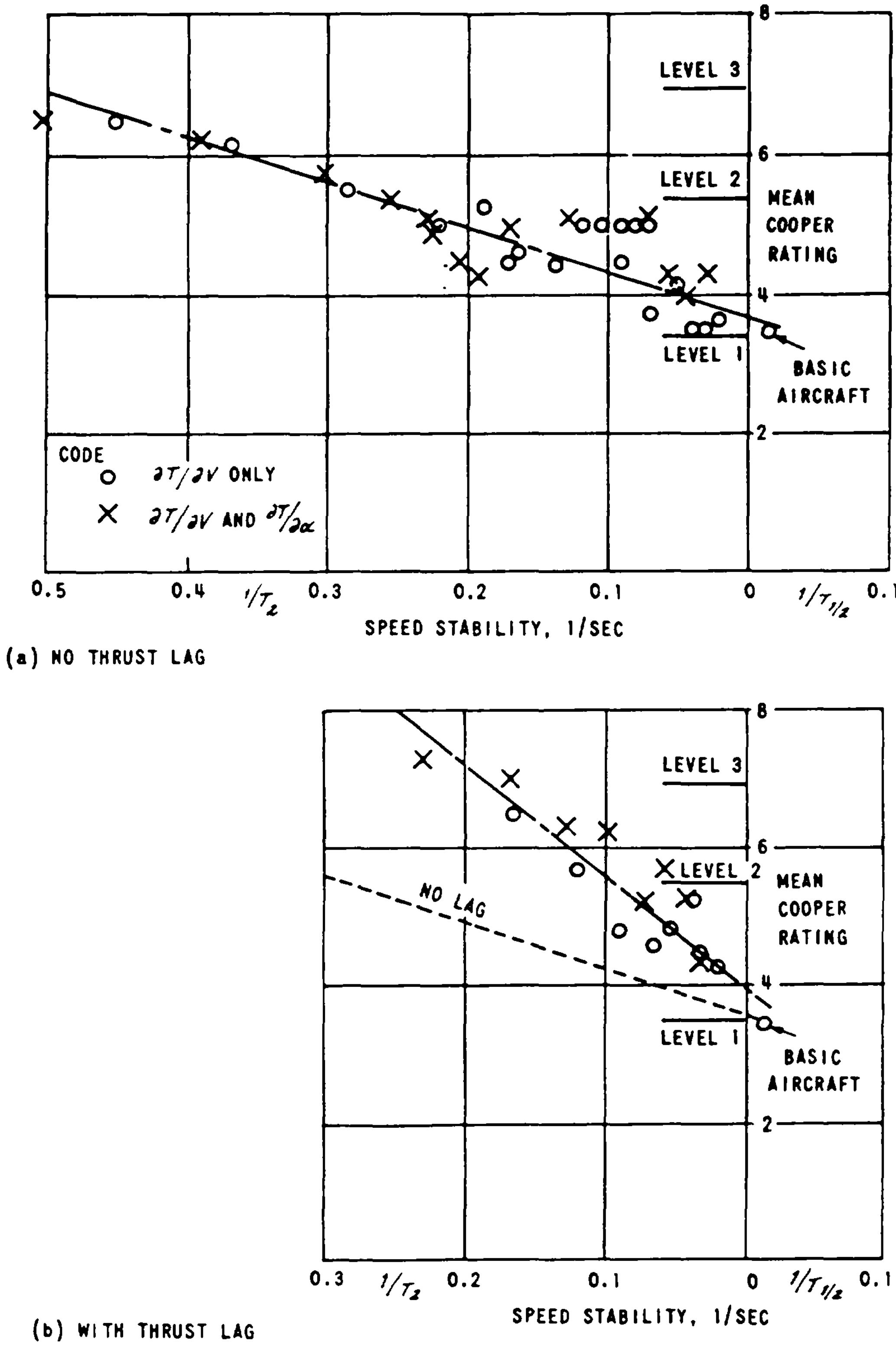


FIGURE 131. Landing approach (AVRO 707, AGARD Rpt 420).

REQUIREMENT LESSONS LEARNED

There have been numerous aircraft judged unsatisfactory or even unacceptable because of backside characteristics. A recent case is the F-16, which had notable deficiencies (AFFTC-TR-79-10) in the landing approach flight condition. These deficiencies were specifically attributed to flight path instabilities. $d\gamma/dV$ at the approach angle of attack (13 deg) was 0.15 (Level 2). It was also noted that pitch attitude control was imprecise, which compounded the problem.

5.3.1.2 Steady-state flight path response to attitude change-verification.

Verification shall be by analysis, simulation, and flight test.

VERIFICATION RATIONALE (5.3.1.2)

The climb-angle-versus-airspeed data used to demonstrate compliance can be obtained during the stabilized-airspeed tests for static stability at low airspeeds.

By its nature, the climb angle to be measured is relative to the air, not the ground. When using Doppler radar or ground-based tracking equipment to obtain the data, the wind must be calm, or at least constant and accurately measured.

VERIFICATION GUIDANCE

In terms of nondimensional quantities, for small γ, neglecting C_{D_δ} , C_{D_u} , C_{L_u} , C_{m_u} , and $\partial T/\partial \alpha$,

$$\frac{d\gamma}{dV} \approx -\frac{2}{U_0}\left\{\left[\left(\frac{T}{W}-\frac{V}{2}\frac{\partial(T/W)}{\partial u}\right)\cos(\alpha+i_t)-\gamma\right]\left[1+\frac{\gamma_0\, C_L/C_{N_\alpha}}{1-\dfrac{C_{L_\delta}C_{m_\alpha}}{C_{m_\delta}C_{N_\alpha}}}\right]\right.$$

$$\left.-\frac{C_{L_1}}{C_{N_\alpha}}\left[\frac{\dfrac{T}{W}\sin(\alpha+i_t)+C_{D_\alpha}/C_{L_1}}{1-\dfrac{C_{L_\delta}C_{m_\alpha}}{C_{m_\delta}C_{N_\alpha}}}\right]\left[1+\left(\frac{z_t}{\bar{c}}\frac{C_{L_\delta}}{C_{m_\delta}}-\sin(\alpha+i_t)\right)\left(\frac{T}{W}-\frac{V}{2}\frac{\partial(T/W)}{\partial u}\right)\right]\right\}$$

showing the effects of flight path angle, thrust offset, and thrust variation with airspeed at constant throttle.

The most straight forward measurement method is probably to use a well-calibrated airspeed indicator and an accurate measure of vertical speed, such as a radar altimeter. The climb angle is then equal to

$$\sin^{-1}\left|\frac{\text{Vertical speed}}{\text{True airspeed}}\right|$$

VERIFICATION LESSONS LEARNED

Still air is necessary in any case, to minimize data scatter. Because of thrust and density variation it has been found necessary to keep altitude excursions small (less than 1000 ft) to get an acceptably accurate curve of flight path angle versus speed. The trim flight-path angle can have a marked effect on the results; the range of glide slopes expected in the operational and training missions should be tested.

4.3.2 Flight path response to designated flight path controller.
When a designated flight path controller (other than the pitch controller) is used as a primary flight path controller, the short-term flight path response to designated flight path controller inputs shall have the following characteristics:__________. At all flight conditions the pilot-applied force and deflection required to maintain a change in flight path shall be in the same sense as those required to initiate the change.

REQUIREMENT RATIONALE (4.3.2)

These requirements are intended to be the primary flight path control criteria for STOL aircraft. These aircraft operate well on the back side of the power-required curve and therefore use a designated controller other than pitch attitude (such as throttle) to control flight path.

REQUIREMENT GUIDANCE

The related requirement of MIL-F-8785C is paragraph 3.6.2.

There is a large body of data for STOL flight path control with thrust and DLC devices. These data will be incorporated. Static stability is an obvious starting place. Also see Pinsker (RAE-TR-68140).

REQUIREMENT LESSONS LEARNED

5.3.2 Flight path response to designated flight path controller-verification.
Verification shall be by analysis, simulation and flight test.

VERIFICATION RATIONALE (5.3.2)

Verification will depend on the characteristics of the particular controller.

VERIFICATION GUIDANCE

Verification will depend on the characteristics of the particular controller.

VERIFICATION LESSONS LEARNED