Effects of Manual Altitude Control and Other Factors on Short-Period Handling Quality Requirements

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Several factors that appear to affect short-period handling quality requirements are reviewed with particular attention paid to manual control of pitch attitude and altitude. The effects of the various short-period parameters on the pilot's closures of these two loops are examined. Other factors that are considered include attitude overshoots, flight-path and attitude consonance, gust responses, flight condition, and vehicle type. It is found that in several cases the factors produce conflicting requirements. For example, attitude and altitude-control requirements can be conflicting. A very encouraging correlation between the expectations based on analysis and existing experimental data is found. From this correlation, several handling quality requirements for landing and cruise conditions are formulated. It is also shown that short-period requirements cannot, in general, be reduced to two or three simple parameters.

Nomenclature

A_θ = gain factor in θ/δ_e numerator, see Eq. (1)
h = altitude
j = $(-1)^{1/2}$
K_h = low-frequency (Bode) gain of Y_h
K_θ = low-frequency (Bode) gain of Y_θ
M = Mach number
M_q = pitching acceleration due to pitch rate, $q = \dot{\theta}$
M_w = pitching acceleration due to velocity along Z axis, w
$M_{\dot{w}}$ = pitching acceleration due to linear acceleration along Z axis, $\dot{w}$
M_α = $U_0 M_w$
$M_{\dot{\alpha}}$ = $U_0 M_{\dot{w}}$
M_{δ_e} = pitching acceleration due to elevator deflection δ_e
N_x^y = numerator of y/x transfer function, where $y = \theta$ or h; $x = \delta_e$ or w_g
$N_{w_g \delta_e}^{h\ \theta}$ = $^{\theta}n/\eta$ and θ/δ_e coupling numerator
q = pitch rate, $\dot{\theta}$
s = Laplace operator, $s = \sigma + j\omega$
T_I = pilot lag-time constant
T_L = pilot lead-time constant
T_{θ_2} = time constant in θ/δ_e numerator, see Eq. (1)
U_0 = aircraft steady-state velocity
w = velocity perturbation along Z axis
w_g = vertical gust velocity
Y_h = pilot transfer function in altitude loop
$Y_{\dot{h}}$ = pilot transfer function in rate-of-climb loop
Y_θ = pilot transfer function in attitude loop
Z_w = acceleration along Z axis due to velocity along Z axis, w
Z_α = $U_0 Z_w$
Z_{δ_e} = acceleration along Z axis due to elevator deflection δ_e
α = angle of attack
δ_e = elevator deflection
Δ = denominator of aircraft transfer functions
ζ_{sp} = damping ratio of short-period mode
θ = pitch angle
σ = real part of s
τ = pilot time delay
ω = imaginary part of s
ω_{sp} = undamped natural frequency of short-period mode

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Introduction

SHORT-PERIOD handling quality requirements have been the subject of much experimental and analytical activity in recent years (e.g., Refs. 1–17). Numerous experiments have been run with fixed-base simulators, moving-base simulators, and variable stability airplanes. Attempts to correlate the data so generated have resulted in the proposed use of several widely different correlating parameters. Unfortunately, all of these have been unsuccessful in correlating all the data. To quote one of the more recent experimental studies,[1] "None of the currently proposed criteria are compatible with the data obtained in this flight program."

Analytical investigation of this problem area clearly shows that there are certain fundamental difficulties to correlating *all* of the data with a *few* parameters. The data must at least be segregated into different flight regimes. Even then there are several, often conflicting factors that apparently affect pilot ratings.

One objective of this paper is to provide a compendium of current knowledge on the factors that appear to affect short-period handling qualities. Accordingly, it collects and integrates material scattered throughout the existing literature which, hopefully, is given proper credit. However, not all of the basic material reported here has been published previously, the most notable original work being the analysis of manual "Altitude Control" in the article so titled.

After examining each of the factors, an attempt to correlate the analytical results with existing experimental data is made. Separate correlations are considered for two flight conditions—landing approach and cruise. The correlations are generally quite good, and several conclusions regarding short-period requirements are drawn.

Attitude Control

Attitude control is a basic requirement in almost all manual flight situations, and good attitude control is essential to good pilot ratings. Pitch angle θ feedback to the elevator δ_e is often used by the pilot to stabilize an aircraft and is frequently the inner loop for other tasks, such as altitude control. Fortunately, the analysis of manual control of attitude using the pilot describing function model[18] is in a quite well-advanced state-of-the-art except for the possible effects of motion cues.

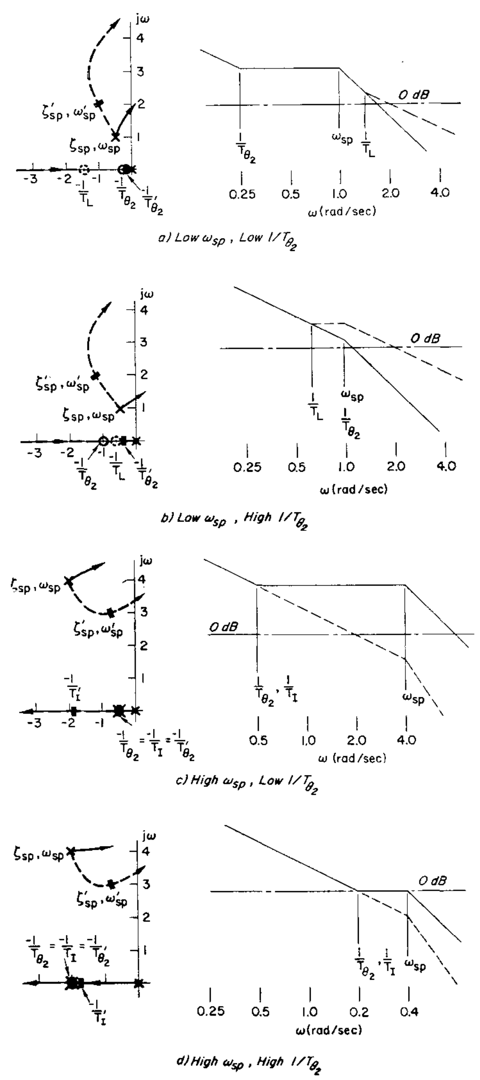


Fig. 1 Attitude control, single-loop closure ($\theta \rightarrow \delta_e$); - - - with pilot lead or lag; —— without pilot equalization.

In the following general survey of attitude control,‡ we will use the short-period approximate equations of motion which assume constant airspeed and result in the attitude-to-elevator transfer function given by

$$\frac{\theta}{\delta_e} = \frac{A_\theta[s + (1/T_{\theta_2})]}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)} \quad (1)$$

where

$$A_\theta = M_{\delta_e} + Z_{\delta_e}M_{\dot{w}}$$

$$\frac{1}{T_{\theta_2}} = \frac{-Z_w + (Z_{\delta_e}/M_{\delta_e})M_w}{1 + (Z_{\delta_e}/M_{\delta_e})M_{\dot{w}}} \doteq -Z_w$$

$$2\zeta_{sp}\omega_{sp} = -Z_w - M_q - M_{\dot{\alpha}}$$

$$\omega_{sp}^2 = -M_\alpha + Z_wM_q$$

The pilot describing function model[18] has the general form

$$Y_\lambda = K_\lambda(T_Ls + 1)e^{-\tau s}/(T_Is + 1) \quad (2)$$

where for present purposes $\tau \doteq 0.3$ sec and λ particularizes the loop being closed (e.g., θ at present, h later).

We will now consider four different combinations of short-period frequency ω_{sp} and numerator inverse time constant $1/T_{\theta_2}$: ω_{sp} appreciably smaller or larger than the crossover frequency in the attitude loop, which is approximately 2 rad/sec in flight[19]; $1/T_{\theta_2}$ either relatively small or large.§ To establish a feeling for reasonable values of ζ_{sp}, ω_{sp}, and $1/T_{\theta_2}$, some typical values for these and other parameters, to be discussed later, are listed in Table 1.

The Bode amplitude asymptotes (right) and root locus sketches (left) of Fig. 1 show manual loop closures for these four cases. The closed-loop poles for the equalized pilot are indicated by the solid rectangular symbols and distinguished by the single prime notation. From Figs. 1a and 1b we see that if the short-period frequency is low, the pilot is required to generate lead to obtain a satisfactory attitude loop, i.e., to make the open-loop product $Y_\theta(\theta/\delta_e)$ look like K/s in the region of crossover. Furthermore, the amount of lead he must introduce increases ($1/T_L$ decreases) as $1/T_{\theta_2}$ increases. (Compare the $1/T_L$ locations in the root loci of Figs. 1a and 1b.) It can also be appreciated from the figures that if the damping ratio of the short period were decreased, the pilot would have to supply more lead. As ζ_{sp} decreases, the Bode phase near crossover (not shown) is decreased, and the pilot must increase his lead to restore the phase. Because of the degrading effects of lead on pilot rating, cases of low short-period frequency cannot achieve the best pilot ratings.

From Figs. 1c and 1d we see that for high short-period frequencies, the pilot introduces lag to make the open loop look like K/s in the region of crossover (he may also add a high-frequency lead if it would be beneficial). In this case, his lag time constant T_I is approximately T_{θ_2} to provide a long K/s-like region. Since pilot ratings are generally independent of the amount of lag required, $1/T_{\theta_2}$ should have a relatively unimportant effect on attitude control if the short-period frequency is high. In this case, the bandwidth limitations on the attitude loop are set primarily by the damping $\zeta_{sp}\omega_{sp}$ of the short-period mode as shown in Appendix II of Ref. 30. Accordingly, a given crossover frequency requires a minimum value of $\zeta_{sp}\omega_{sp}$; and for a given level of $\zeta_{sp}\omega_{sp}$, the open loop is largely invariant below crossover, with performance and pilot rating remaining fairly constant despite variations in ω_{sp} or $1/T_{\theta_2}$.[31]

The preceding discussion indicates that for good attitude control the pilot would prefer a high short-period frequency and relatively high damping, regardless of the value of $1/T_{\theta_2}$. However, upper limits on acceptable values of short-period frequency are set by two additional considerations. First, if high short-period frequency is produced by a very large value of $-M_\alpha$, then the pitch response to a vertical gust is quite severe. This particular constraint does not apply if the

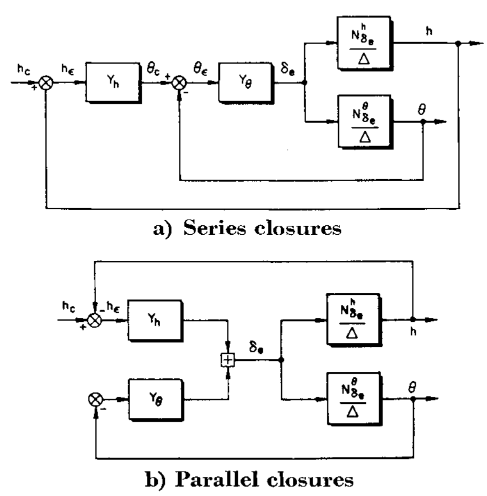


Fig. 2 Block diagram of series and parallel attitude and altitude closures.

‡ Analysis procedure is similar to that employed in Ref. 15.

§ An upper limit on $1/T_{\theta_2}$ is $2\zeta_{sp}\omega_{sp}$ because $1/T_{\theta_2} \doteq -Z_w$, $2\zeta_{sp}\omega_{sp} \doteq -Z_w - M_q - M_{\dot{\alpha}}$, and $M_q + M_{\dot{\alpha}}$ is rarely, if ever, positive.

Table 1 Survey of typical short-period characteristics

Aircraft	U_0, fps	M	h, 10^3 ft	Z_α, ft/sec^2	Z_w, sec^{-1}	$1/T_{\theta_2}$, sec^{-1}	ζ_{sp}	ω_{sp}, rad/sec	Refs.
				Landing approach					
F-6A (F4D-1)	202	0.18	0	−180	−0.89	0.66	0.31	2.6	20
F-106B	223	0.20	0	−176	−0.79	0.77	0.69	0.87	21
F-94C	235	0.21	0	−160[a]	−0.69[a]	0.69	0.50	1.3	22
RA-5C (A3J-3)	211	0.19	0	−120	−0.57	0.53	0.46	0.91	23
Boeing 727	194	0.17	0	−110	−0.57	0.57[b]	0.50	0.90	24
Boeing 707-320	223	0.20	0	−130	−0.59	0.65	0.39	0.76	25
C5A	206	0.185	0	−81	−0.39	0.39[b]	0.61	0.81	26
B-52	333	0.30	2	−150	−0.46	0.46[b]	0.58	1.4	24
Delta wing SST	235	0.21	0	−210	−0.88	0.88[b]	1.0	0.68	27
				Low altitude, high speed					
F-106B	1004	0.90	0	−2600	−2.6	2.3	0.41	5.0	21
F-94C	960	0.86	0	−2800[a]	−2.9[a]	2.9	0.62	5.0	22
B-52	675	0.60	0	−740	−1.1	1.1[b]	0.57	2.4	24
				High-altitude cruise					
F-106B	1936	2.0	40	−1520	−0.79	0.64	0.13	5.3	21
F-94C	715	0.73	35	−540[a]	−0.75[a]	0.75	0.31	2.1	22
Boeing 727	728	0.75	40	−340	−0.47	0.47[b]	0.30	1.4	24
B-52	747	0.77	50	−135	−0.18	0.18[b]	0.29	1.2	24
Delta wing SST	2910	3.0	70	−380	−0.13	0.13[b]	0.15	1.7	11

[a] Estimated from $Z_w \doteq -1/T\theta_2$, $Z\alpha = U_0 Z_w$.
[b] Estimated from $1/T\theta_2 \doteq -Z_w$.

short-period frequency is high because of a pitch-angle-to-elevator automatic feedback, but then the load factor response becomes excessive. The second problem with very high short-period frequencies is that high control sensitivity $M_{\delta e}$ must be provided to obtain reasonable control forces per g. This will cause large initial pitching and linear accelerations at the cockpit if the control is moved abruptly, an eventuality that can be avoided by command shaping on a stick-steering control system. However, the high sensitivity may still present serious practical problems in trimming the aircraft.

Altitude Control

Direct control of altitude with the elevator is generally impossible because of the airplane-response lags involved. A direct rate-of-climb inner loop is obviously desirable, but unfortunately most rate-of-climb instruments have lags which are too large to make the instrument usable in a tight control situation. Accordingly, the pilot will usually use an attitude-to-elevator inner loop to provide lead for his altitude control. Simultaneous pilot closure of attitude and altitude loops can be effected with two different control techniques referred to as series or parallel closures as shown in Fig. 2.

Series closures are more consistent with pilot comments on how they fly an airplane than are parallel closures. In the series closures the pilot makes an altitude correction by biasing his attitude up or down an amount proportional to the altitude error. Although series closures might appear more consistent with general piloting technique, we will show that in some cases parallel closures would give better altitude control.

The primary difference between the series and parallel closures can be seen by comparing the characteristic determinants for the two types of control technique,

series closures

$$\Delta'' = \Delta + Y_\theta N^\theta_{\delta e} + Y_h Y_\theta N^h_{\delta e} \tag{3}$$

parallel closures

$$\Delta'' = \Delta + Y_\theta N^\theta_{\delta e} + Y_h N^h_{\delta e} \tag{4}$$

where the double prime indicates that two loops have been closed. In the series closures, equalization in the attitude loop is also effective in the altitude loop, whereas with parallel closures, equalization in the two loops is independent. To show how attitude-loop leads and lags get into the altitude loop, let us rewrite the characteristic determinants assuming that

$$Y_\theta = K_\theta(T_L s + 1)/(T_I s + 1) \tag{5}$$

and

$$Y_h = K_h \tag{6}$$

Then we have

series closures

$$\Delta'' = \underbrace{\Delta + \frac{K_\theta(T_L s + 1)}{T_I s + 1} N^\theta_{\delta_e}}_{\Delta'} + \frac{K_h K_\theta(T_L s + 1)}{T_I s + 1} N^h_{\delta_e} \tag{7}$$

$$\Delta''(T_I s + 1) = (T_I s + 1)\Delta + K_\theta(T_L s + 1)N^\theta_{\delta_e} + K_h K_\theta(T_L s + 1)N^h_{\delta_e}$$

parallel closures

$$\Delta'' = \underbrace{\Delta + \frac{K_\theta(T_L s + 1)}{T_I s + 1} N^\theta_{\delta_e}}_{\Delta'} + K_h N^h_{\delta_e} \tag{8}$$

$$\Delta''(T_I s + 1) = (T_I s + 1)\Delta + K_\theta(T_L s + 1)N^h_{\delta_e} + K_h(T_I s + 1)N^h_{\delta_e}$$

Thus with series closures, the attitude lead carries over into the altitude loop, while with parallel closures, the attitude-loop lag appears as an altitude-loop lead.

Let us first consider series closures for the four cases of short-period dynamics which were treated previously. Sketches of the resulting altitude-loop closures are shown in Fig. 3.¶ The key conclusions (explained below) to be drawn

¶ In the sketches of Fig. 3, the results of the attitude closure Δ' are transferred from Fig. 1, and the relatively high-frequency zeros of the h/δ_e numerator have been omitted.

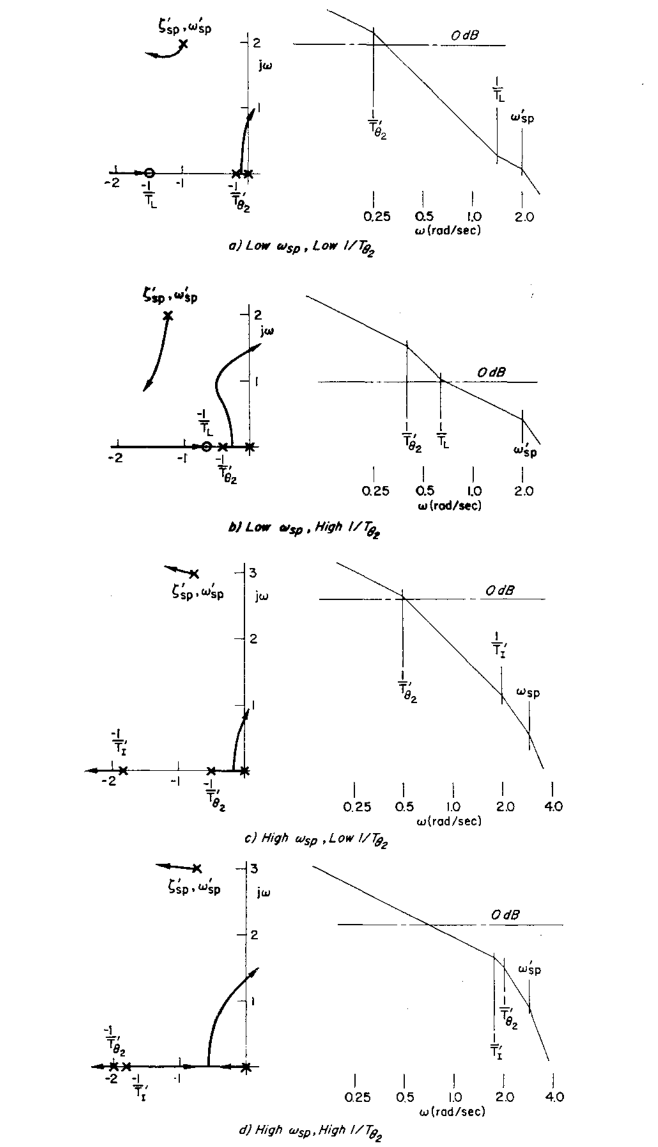


Fig. 3 Altitude control, series closures (θ, $h \rightarrow \delta_e$).

from this figure are 1) low $1/T_{\theta_2}$ results in poor altitude bandwidth; 2) the series closures are beneficial for the low short-period frequency cases because the attitude lead is helpful in the altitude loop; and 3) the series closures are detrimental for the high-frequency cases because the lag in the attitude loop degrades the altitude loop. The first conclusion is easily seen (see also Ref. 28). First consider the low ω_{sp} case. If $1/T_{\theta_2}$ is low, the attitude loop will drive the free s nearly into the zero at $-1/T_{\theta_2}$ (Fig. 1a). This low-frequency root $(-1/T_{\theta_2}')$ plus the additional free s in the altitude loop severely limit the altitude-loop bandwidth. In the high ω_{sp}, low $1/T_{\theta_2}$ case, the attitude loop will have a pilot lag $1/T_I$ near $1/T_{\theta_2}$, and there will again be a closed-loop root $1/T_{\theta_2}'$ near $1/T_{\theta_2}$. With series closures, this low-frequency root will then severely limit the altitude-loop bandwidth (even more than for the low ω_{sp} case).

The other two conclusions just stated follow directly from the observation that any additional lead usually improves the altitude loop. Thus, for low ω_{sp}, when the pilot is using lead in the attitude loop, series closures are desirable, because the attitude lead is then present in the altitude loop; for high ω_{sp}, when the pilot is using lag in the attitude loop, series closures are detrimental. For the high short-period frequency cases, better altitude-loop bandwidths are obtained if parallel closures are used. Then the attitude-loop lag acts as a lead in the altitude loop to offset the modified lag resulting from the inner-loop closure as illustrated in the sketch of Fig. 4. If parallel closures are used for the high-frequency cases, then the altitude-loop bandwidth is limited primarily by the damping of the short-period mode as modified by the inner loop.

Recent, unpublished experiments have verified these analyses for the low ω_{sp} cases. The measured pilot describing functions show series closures with lead equalization in the attitude loop and nearly a pure-gain altitude describing function. Data were obtained only for $\omega_{sp} = 0.76$ rad/sec. Consequently, several questions about the manual control of a configuration with low $1/T_{\theta_2}$ and high short-period frequencies remain unanswered. For example, will the pilot change to a parallel closure technique to improve his altitude-loop bandwidth? And if he does so, will he be conscious of an unusual control technique and degrade his opinion accordingly? If the pilot cannot or will not adopt the parallel closures, then for configurations with low $1/T_{\theta_2}$, better pilot ratings might be obtained with a low short-period frequency than a high frequency. With the low frequency, he would then have the beneficial effects of his inner-loop lead in the altitude loop.

It should be pointed out that the previous discussion of low $1/T_{\theta_2}$ effects might be altered significantly if the pilot had available a good rate-of-climb display, i.e., a rate-of-climb display with very low lags. In that case, the pilot could close a series altitude rate loop to increase effectively the frequency of the root near $1/T_{\theta_2}$. An example for the low ω_{sp}, low $1/T_{\theta_2}$ case is shown in Fig. 5.

Additional Factors

In addition to the previous considerations, several other open- and closed-loop factors may enter the picture. One of these, already mentioned, is the altitude response to a vertical gust which, with a tight attitude inner loop, is approximated by

$$\left(\frac{h}{w_g}\right)_{\theta\rightarrow\delta_e} = \frac{N^h_{w_g} + Y_\theta N^{h\ \theta}_{w_g\ \delta_e}}{\Delta + Y_\theta N^\theta_{\delta_e}} \doteq \frac{N^{h\ \theta}_{w_g\ \delta_e}}{N^\theta_{\delta_e}} =$$

$$\frac{Z_w M_{\delta_e} - Z_{\delta_e} M_w}{s[(M_{\delta_e} + Z_{\delta_e} M_{\dot{w}})s - Z_w M_{\delta_e} + Z_{\delta_e} M_w]} \doteq \frac{-1}{s(T_{\theta_2} s + 1)} \quad (9)$$

Consequently, increasing $1/T_{\theta_2}$ increases the altitude and acceleration responses to a vertical gust [not very surprising in view of $1/T_{\theta_2} \doteq -Z_w$, Eq. (1)]. This is the second detrimental effect of large $1/T_{\theta_2}$. The first was the requirement for increased pilot lead in the attitude loop if the short-period frequency were low.

Other closed-loop factors include those related to the parameter Z_α, which is equal to $U_0 Z_w$. When $|Z_\alpha|$ is very large, the aircraft can be maneuvered with very small angle-of-attack and attitude changes; and the pilot cannot discern the desired pitch changes on a conventional artificial horizon. This problem has occurred, for example, in simulations of the supersonic transport during cruise. In this case, because of the high speed, $|Z_\alpha|$ is large, about 380 ft/sec^2/rad or 0.2 g/deg, even though $|Z_w| \doteq 0.13$ sec^{-1} is small. One solution to this problem is to provide the pilot with an attitude dis-

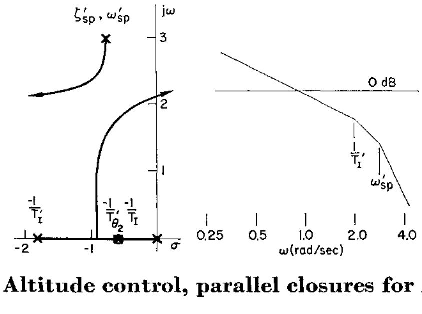


Fig. 4 Altitude control, parallel closures for high ω_{sp}.

play with increased sensitivity. If such an improved display is not furnished, the pilot will substitute some other inner loop for the attitude loop. In the simulations of Ref. 2, the subjects said they used normal acceleration in place of attitude. However, substituting normal acceleration for attitude replaces the zero at $1/T_{\theta_2}$ with one very near the origin.** The potential altitude-control problems due to having, in effect, a very small $1/T_{\theta_2}$ were discussed earlier. Apparently, the Ref. 2 subjects compensated for the adverse effects of replacing attitude with acceleration feedback by making more use of the rate-of-climb display. It should also be noted that the Ref. 2 simulations were for cruise conditions where the altitude-control requirements are rather loose.

A second problem resulting from large $|Z_\alpha|$, also noted in Refs. 2, 15, and 31, is the selection of control sensitivity. With the control sensitivity selected to give good attitude control, a large $|Z_\alpha|$ will make the acceleration response of the vehicle much too sensitive. The pilot would then be concerned about inadvertently overstressing the aircraft (or jostling the passengers in a transport). In the simulations of Ref. 2, it was found that if $|Z_\alpha|$ were less than about 320 ft/sec²/rad, a pilot would pick the control sensitivity that gave him essentially the same attitude gain in the frequency band of 2–3 rad/sec for all configurations. For larger $|Z_\alpha|$ the pilots had to compromise their desire for good attitude-loop gain with that for avoiding overstressing the airplane. Consequently, they would select a control sensitivity less than the optimum on the basis of attitude control alone.

Large $|Z_\alpha|$ problems should be most severe for low-altitude, high-speed flight, where the largest $|Z_\alpha|$'s usually occur (see Table 1). Configurations in which $|Z_\alpha|$ is very small also have a problem; then large attitude excursions are required to get reasonable altitude response. Physically the explanation is quite simple—if $|Z_\alpha|$ is low, the pilot must use large attitude changes to get sufficient angle of attack to generate enough lift to move the airplane vertically. This effect is clearly shown in the attitude-to-altitude ratio for elevator inputs, which for the short-period approximation and the generally valid inequalities $|Z_{\delta_e}M_w| \ll |Z_wM_{\delta_e}|$; $|Z_{\delta_e}M_{\dot{w}}| \ll |M_{\delta_e}|$ is given by

$$\frac{\theta}{h} = \frac{N^{\theta}_{\delta_e}}{N^{h}_{\delta_e}} \doteq \frac{M_{\delta_e}s(s - Z_w)}{-Z_{\delta_e}[s^2 - (M_q + M_{\dot{\alpha}})s + Z_\alpha M_{\delta_e}/Z_{\delta_e}]} \quad (10)$$

The asymptotes of this ratio are sketched in Fig. 6. Thus, over the broad frequency region from $-Z_w$ to $|Z_\alpha M_{\delta_e}/Z_{\delta_e}|^{1/2}$, the attitude deviations required to obtain a specified altitude response are inversely proportional to $-Z_\alpha$.

The importance of this problem depends not only on the value of $-Z_\alpha$, but also on the frequency range of interest.

Table 2 Three short-period factors

Refs.	Factor	Effect of key parameters
2 12 24 34	Pitch rate (or attitude) overshoot for step (or impulse) elevator deflection	ζ_{sp} or $1/T_{\theta_2}\ \omega_{sp}$ much less than unity produces large overshoots
2 29	Flight path and attitude consonance	Lag between flight-path angle and pitch attitude is excessive for small $1/T_{\theta_2}$
	Open-loop gust response	Increasing ω_{sp} increases θ response and decreases h response Increasing $\lvert Z_w\rvert$ increases h response

** In the short-period approximation, the zero is exactly at the origin. The acceleration numerator also has two zeros which are generally of too high a frequency to significantly affect manual control.

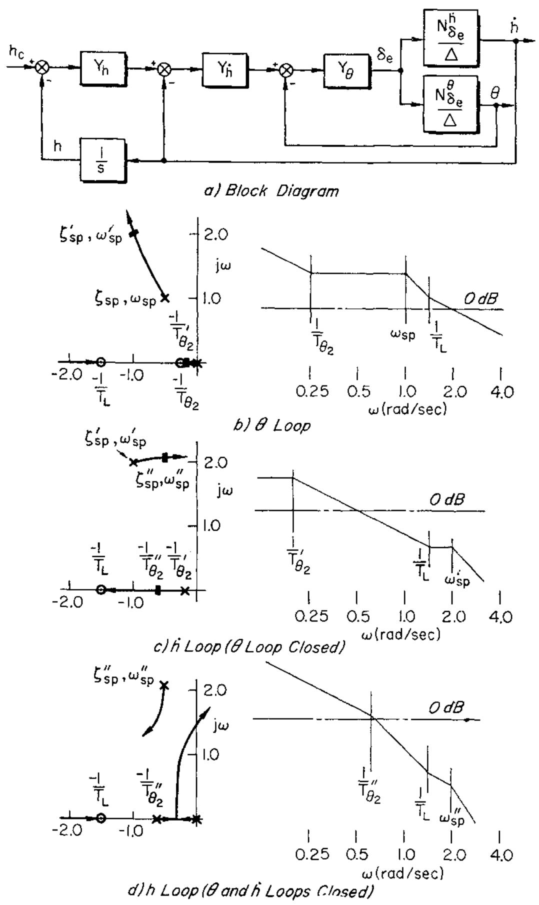


Fig. 5 Altitude control with rate-of-climb loop.

Situations where tight altitude control is unnecessary and the altitude bandwidth can be low, as in cruise flight, are not nearly so critical as during landing approach, where $|Z_\alpha|$ may be small, large attitude changes undesirable, and good altitude control a necessity.

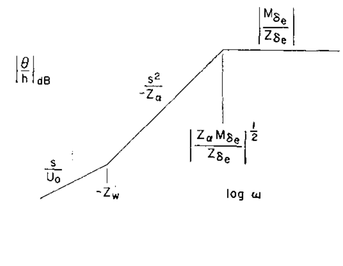
Three other widely recognized factors are listed in Table 2 (and more fully discussed in Ref. 30).

Effects of Flight Condition and Vehicle Type

Many attempts to correlate data from different sets of experiments have been frustrated by the differences in flight condition or type of vehicle being considered. Requirements for accurate tracking are clearly a strong function of the flight condition; e.g., the pilot is more interested in maintaining tight path (altitude) control in the landing approach than he is during cruise. Consequently, differences in flight condition can lead to differences in the pilot's emphasis on his ability to maintain close control over attitude or altitude.

Maneuver limitations on normal acceleration and pitch attitude are also strongly dependent on vehicle type and flight condition. The maneuver limitations on a fighter aircraft are certainly different from those of a commercial transport, and the limitations in landing approach differ from those in a combat condition. In considering closed-loop tracking ability for a given configuration, we must therefore consider

Fig. 6 Attitude/altitude ratio.



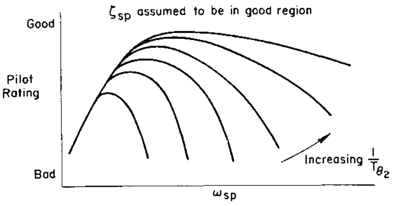


Fig. 7 Expected form of pilot rating data.

not only the achievable bandwidth in the loops, but also the variations in certain parameters which will result from the closures. Even good tracking performance is not acceptable if achieving it requires excessive attitude or acceleration excursions.[34]

Clearly, the preceding effects should be taken into account when attempting to correlate different sets of experimental data. Although it is not suggested that experiments with some differences are completely uncorrelated, some adjustments must be made to account for the change in emphasis which is inherent in either using a variety of flight conditions or simulating a different class of vehicle.

An example of flight condition effects is contained in the data of Ref. 11. This was a moving-base simulator study of a supersonic transport during cruise. Pilot ratings of 1.5 on the Cooper scale were obtained for a set of augmented vehicle characteristics given by

$$\zeta_{sp} = 0.61 \qquad \omega_{sp} = 1.34 \text{ rad/sec}$$
$$Z_w = -0.13 \text{ sec}^{-1}$$

An analysis of this flight condition showed that the achievable bandwidth of an altitude loop with an attitude inner loop was very low, on the order of 0.1 rad/sec. Although such poor altitude bandwidth would be unacceptable in a landing approach, it is apparently quite acceptable during cruise where the altitude control requirements are greatly reduced.

Analytical-Experimental Correlation

In this discussion we will attempt to show that the analytical factors discussed earlier are consistent with the existing handling quality data. Because of the strong effects of flight condition, the correlation will consider two conditions separately: landing approach and cruise.

Landing Approach

During landing approach the pilot places heavy emphasis on his ability to control altitude. As shown in the closed-loop analyses already presented, altitude control is primarily a function of three variables: short-period frequency ω_{sp}, short-period damping ratio ζ_{sp}, and attitude zero $1/T_{\theta_2}$. Let us consider how we would expect pilot rating to vary with ω_{sp} for different $1/T_{\theta_2}$'s, but with ζ_{sp} held constant at a "good" value.

For very low ω_{sp}, appreciably less than 1 rad/sec, the pilot ratings should be poor regardless of $1/T_{\theta_2}$ because of the large amount of pilot lead required in the attitude loop. Decreasing $1/T_{\theta_2}$ will somewhat reduce the amount of pilot lead required but will also degrade the altitude control. For very low ω_{sp}, the net effects of $1/T_{\theta_2}$ are uncertain.

For high ω_{sp} and high $1/T_{\theta_2}$, pilot ratings should be good. Required pilot equalization in the attitude loop is at worst a slight amount of lag, and altitude control is good. For very large ω_{sp}, pilot ratings may deteriorate because of the factors mentioned at the end of "Attitude Control"—pitch response to gusts and problems associated with high control sensitivity. However, for the maximum frequencies usually associated with approach conditions, such deterioration is expected to be mild.

Let us now consider what happens at high ω_{sp} if $1/T_{\theta_2}$ is low. A large amount of pilot lag is required in the attitude loop, and the attitude responses to step (or impulse) inputs have large overshoots. Also, the altitude bandwidth will be poor unless the pilot uses the unfamiliar parallel closure technique. Even then, although theoretical improvements in bandwidth are possible, these can only be obtained with increased pitch overshoots which the pilot may (subconsciously) reject as unacceptable, so that the net practical improvement in bandwidth is probably small. Consequently, with low $1/T_{\theta_2}$, pilot ratings should be poor at both very low and high ω_{sp}. If $1/T_{\theta_2}$ is above some unknown minimum, there should be some ω_{sp} for which both the attitude equalization and achievable altitude bandwidth are acceptable. Thus, we would expect the variations of pilot ratings with ω_{sp} to take the forms sketched in Fig. 7.

We will now examine some actual pilot rating data plotted in similar form. In selecting the data to be used in this comparison, the following restrictions on the test conditions were imposed. 1) The simulated flight condition must have been landing approach. 2) The short-period damping ratio ζ_{sp} must have been good (the data actually used fall in the range $0.35 \leq \zeta_{sp} < 0.8$). 3) Pilot ratings were not significantly degraded because of problems not related to short-period dynamics, such as operating on the back side of the drag curve, poor lateral-directional characteristics, or poor stick gain.†† The available data that meet these restrictions are given in Fig. 8, and additional information on the test conditions is listed in Table 3. The range of ω_{sp} tested for the lowest $1/T_{\theta_2}$ (approximately 0.30 sec^{-1}, + symbol) is too small to give a complete picture, but that which is shown is not inconsistent with the predicted trends. The data for moderate values of $1/T_{\theta_2}$, 0.47 − 0.80 sec^{-1} (open symbols) clearly agree with the trends predicted in Fig. 7; likewise for the data for large $1/T_{\theta_2}$, 1.0–2.0 sec^{-1} (solid symbols). Furthermore, the data show a remarkable consistency considering the differences in test conditions (fixed base, moving base, and flight) and in the type of aircraft simulated (from fighters to very large transports).

Based on this analytical-experimental correlation, the following conclusions would seem valid for landing approach:

1) There is a minimum ω_{sp}, roughly 1 rad/sec, below which satisfactory pilot ratings cannot be achieved, regardless of the value of $1/T_{\theta_2}$.

2) Satisfactory ratings for $1/T_{\theta_2}$ as low as about 0.5 sec^{-1} are possible if ω_{sp} is in a narrow range centered roughly about 1 rad/sec, and ζ_{sp} is also good.

3) Increasing $1/T_{\theta_2}$ broadens the satisfactory ω_{sp} region and shifts it to higher frequencies and improves the pilot rating at the optimum ω_{sp}.

4) The various effects of ζ_{sp}, ω_{sp}, and $1/T_{\theta_2}$ are too complex to be correlated with one or two parameters even for optimum M_{δ_e}; in general, all four parameters must be considered.

Cruise

The major difference between cruise and landing approach is the lower requirement on altitude control during cruise.

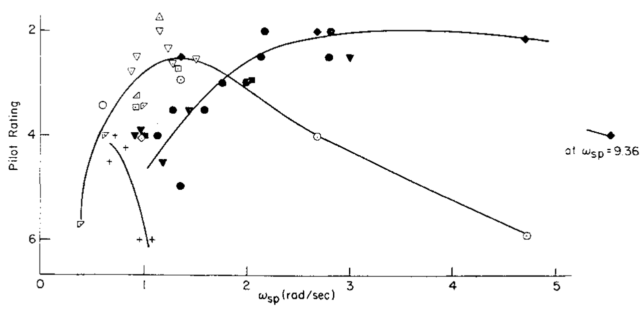


Fig. 8 Pilot rating data for landing approach.

†† For those tests in which pilot stick-to-elevator gain was varied, only the data for the optimum gain were used.

For example, as noted in "Effects of Flight Condition and Vehicle Type," altitude bandwidths as low as about 0.1 rad/sec are apparently quite satisfactory. Consequently, $1/T_{\theta_2}$ is expected to have considerably less effect, in cruise than in landing, on pilot ratings for high ω_{sp}. This is shown in Fig. 9 by the satisfactory pilot ratings for $1/T_{\theta_2}$ as low as 0.13 sec^{-1}.

Unfortunately only a relatively small amount of cruise data could be found. It should be noted that the almost classic data from Refs. 10 and 14 were omitted for three reasons. First, a different rating system was used; second, some of the ratings are bad because of poor stick gains; and third, the ratings considered combat maneuvers as well as cruise.

It appears that the handling quality requirements for cruise are much simpler than for landing. A minimum ω_{sp}, on the order of 1 rad/sec, is required as well as a good damping ratio.

Summary and Recommendations

Summary

Several factors that appear to affect short-period handling quality requirements have been reviewed. These factors include attitude control, altitude control, attitude overshoots, flight path and attitude consonance, gust responses, and flight condition and vehicle type. It was found that in several cases the factors produced conflicting requirements; for example, the effects of short-period frequency in landing approach if $1/T_{\theta_2}$ is low. When ω_{sp} is very low, pilot ratings will be poor because of the large amount of pilot lead required for attitude control; for high ω_{sp}, attitude control is good, but altitude control is poor, and there are large pitch overshoots. The optimum ω_{sp} is then a compromise between attitude and altitude control.

An attempt was made to correlate the analytical results with existing handling quality data for two flight conditions: landing and cruise. The results were very encouraging. From the analytical efforts and the experimental data, the following conclusions were drawn for the landing case considering optimum control gain:

1) Satisfactory pilot ratings cannot be achieved if the short-period frequency is below a minimum value, which is roughly 1 rad/sec.

2) Satisfactory ratings can be achieved with $1/T_{\theta_2}$ as low as about 0.5 sec^{-1} if the short-period frequency is in a narrow range, roughly centered about 1 rad/sec, and the damping is good.

3) Increasing $1/T_{\theta_2}$ broadens the satisfactory ω_{sp} region and shifts it to higher frequencies, and improves the pilot rating at the optimum short-period frequency.

Table 3 Key to Fig. 8 data

Symbol	Estimated $1/T_{\theta_2}$, sec^{-1}	Type of simulator[a]	Optimum gain	ζ_{sp}	Ref.
+	0.30	MB		0.49–0.72	33
⊙	0.47	FB		0.64	12
⊡	0.50	VS 367-80	Yes	0.70	33
◇ (dotted)	0.50	FB	Yes	0.50	6
▽ (dotted)	0.57–0.93	MB	Yes	0.57–0.76	33
△ (dotted)	0.65	VS 367-80		0.53	33
□	0.74	FB		0.70	7
□	0.80	VS B-26	Yes	0.70	26
●	1.0	VS T-33	Yes	0.35–0.76	13
■	1.0, 2.0	FB	Yes	0.75, 0.63	6
◆	1.9	FB		0.64	12
▼	2.0	VS NAVION	Yes	0.36–0.75	1

[a] FB = fixed base; MB = moving base; VS = variable stability airplane.

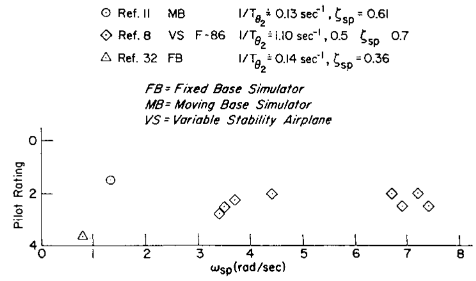


Fig. 9 Pilot rating data for cruise.

4) The effects of short-period frequency and damping and $1/T_{\theta_2}$ are too complex to be correlated with one or two parameters; all three, plus control gain, must be considered.

For the cruise conditions the effects of $1/T_{\theta_2}$ are much reduced. The primary short-period requirements for cruise appear to be short-period frequency greater than a minimum, which is roughly 1 rad/sec, and good damping.

Recommendations

Although the results of the analytical-experimental correlation are highly encouraging, additional experimental and analytical activity is desirable. Further experimental verification of the analytically predicted trends should be obtained and more accurate parameter boundaries should be established. A series of carefully planned, systematic experiments, with a great deal of analytical support, are therefore recommended.

The first step should be an investigation of the effects of $1/T_{\theta_2}$, ζ_{sp}, ω_{sp}, and Z_α on altitude control. Differences in flight condition and class of vehicle should be examined for optimum values of control gain. The effects of a good (very little lag) rate-of-climb display should also be studied. Future aircraft may have such instruments, and that could relieve some of the tracking problems described earlier.

This first phase could be accomplished on a relatively simple, fixed-base simulator. Although not essential, measurements of the multiloop pilot-describing functions during this task are highly desirable. This would allow more generalization of the results for this task, and the data should also be applicable to other multiloop piloting tasks, such as hovering over a spot. In the second phase, the effects of other factors should be investigated by using a more realistic simulation, preferably moving-base or a variable stability airplane. Correlation of the phase one and two results should help quantify the effects of the other factors.

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