An Assessment of the Lateral-Disectional Handling Qualities of a Large Aircraft in the Landing Approach

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The use of analytical techniques to evaluate the lateral-directional handling qualities of a large aircraft in the landing approach is demonstrated. From an examination of the maneuvers the pilot may have to perform, a number of handling qualities parameters or factors are derived. Estimates for desirable values of these factors are obtained by comparing the analytical results with the pilot ratings and comments from an experimental study done on the Transport Landing Simulator at the NASA Ames Research Center. The maneuvers considered are tracking the localizer beam, large turns (such as the initial alignment with the localizer or a sidestep maneuver), and the decrab when landing in a crosswind. On the basis of these maneuvers, 12 interrelated handling qualities factors are derived. The analytical-experimental correlation is done for the three proposed supersonic transport configurations (both with and without stability augmentation) and a currently operational subsonic jet, which were tested in the simulator study.

Nomenclature

A_φ = high frequency gain of bank-angle-to-aileron transfer function
C_{n_p} = yawing coefficient due to roll rate
$C_{y_{\delta_a}}$ = aileron side force coefficient
$C_{y_{\delta_r}}$ = rudder side force coefficient
g = acceleration due to gravity
j = $(-1)^{1/2}$
K = gain
L_λ' = partial derivative of rolling acceleration with respect to λ where $\lambda = p, r, \beta, \delta_a$, or δ_r
N_λ' = partial derivative of yawing acceleration with respect to λ where $\lambda = p, r, \beta, \delta_a$, or δ_r
$N_{\lambda_{\delta_a}}$ = numerator of λ-to-aileron transfer function where $\lambda = \varphi$ or β
$N_{\lambda_{\delta_r}}$ = numerator of λ-to-rudder transfer function where $\lambda = r$ or β
$N_{\delta_a\delta_r}^{\varphi\, r}$ = coupling numerator for bank-angle-to-aileron and yaw-rate-to-rudder
p = stability axis roll rate
p_{max} = maximum roll rate
r = stability axis yaw rate
s = Laplace operator, $s = \sigma + j\omega$
T_L = pilot's lead time constant
T_r = time constant of first-order zero in numerator of yaw-rate-to-rudder transfer function
T_R = roll subsidence mode time constant
T_s = spiral mode time constant
T_ψ = time constant of dominant mode in closed-loop heading response
T_0' = closed-loop heading mode time constant
U_0 = steady-state velocity
Y_p = pilot's describing function
Y_v = partial derivative of side acceleration with respect to side velocity, v
Y_φ = transfer function for bank-angle-to-aileron feedback
β = sideslip angle
δ_a = aileron deflection
δr = rudder deflection
$(\delta r)_s$ = magnitude of step rudder deflection
Δ = denominator of aircraft transfer function
$(\Delta\psi_{max})_{t=2.0\ sec}$ = maximum yaw angle achievable in 2.0 sec in response to a step rudder input with ailerons used to maintain wings level
ζ_d = damping ratio of dutch roll mode
ζ_φ = damping ratio of second-order zeros in numerator of bank-angle-to-aileron transfer function
ζ_0' = damping ratio of second-order mode in closed loop heading response
θ_0 = steady-state pitch angle
σ = real part of complex variable, s
τ = transport lag
φ = bank angle
φ_c = commanded bank angle
φ_ϵ = bank angle error
$|\varphi/\beta|_{DR}$ = magnitude of the roll-to-sideslip ratio in the dutch roll mode
ψ = heading
ω = imaginary part of the complex variable, s
ω_d = undamped natural frequency of dutch roll mode
ω_r = undamped natural frequency of second-order zeros in numerator of yaw-rate-to-rudder transfer function
ω_φ = undamped natural frequency of second-order zeros in numerator of bank-angle-to-aileron transfer function
ω_0' = undamped natural frequency of second-order mode in closed-loop heading response
ω_1 = undamped natural frequency of lateral phugoid mode
$\mathcal{L}^{-1}$ = inverse Laplace transform operator
$(\ )_0$ = ( ) at time equals zero
$(\ )_{ss}$ = ( ) in steady-state condition
$|\ |$ = magnitude or absolute value of
$(\dot{\ })$ = derivative with respect to time
$\varphi \rightarrow \delta_a$ = bank-angle-to-aileron feedback
$\psi \rightarrow \delta_a$ = heading-to-aileron feedback
$r \rightarrow \delta_r$ = yaw-rate-to-rudder feedback

Introduction

When considering a piloted vehicle, the control system designer is faced with the problem of determining what handling qualities deficiencies, if any, exist. Frequently, this is a difficult task and the need exists for a simple method which can yield quick, although approximate, results. In recent years, analytical techniques have been developed[1–4] and used successfully to predict handling qualities problems.[5–7]

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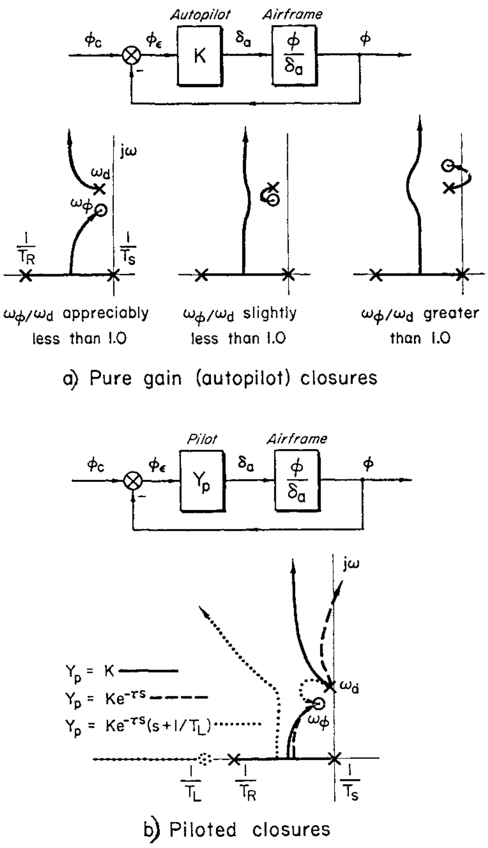


Fig. 1 Typical root loci for bank-angle-to-aileron feedback.

This paper describes the application of these analytical techniques to the assessment of lateral-directional handling qualities of a large aircraft in the landing approach.

The first step in the analysis method is to examine the various maneuvers the pilot may have to perform in the landing approach. From this study of the maneuvers, a number of handling qualities parameters or factors are derived. These factors can be used then to evaluate the handling qualities of a specific aircraft. The success of the method depends on determining which factors are significant and obtaining estimates for desirable values of these.

Preliminary estimates for desirable values of the factors used herein were obtained by comparing the analytical results with earlier studies and with pilot ratings and comments from an experimental study done on the NASA's fixed-base transport landing simulator at the Ames Research Center. These experiments[8] included three supersonic transport configurations and a currently operational subsonic jet (used as a standard for comparison).

The supersonic transport (SST) configurations tested were one SCAT 16‡ variable-sweep design and two SCAT 17 (noted here as SCAT 17A and SCAT 17B) canard-delta-wing designs. These SCAT configurations were only interim designs and do not represent actual proposed configurations. Reference 8 also describes augmentation schemes derived during the simulator tests, and the three SST configurations were evaluated for both the bare airplane and the airplane with sufficient augmentation to make the handling qualities satisfactory.

The next section of this paper examines three maneuvers found to be significant in the landing approach: tracking the localizer beam, large turns, and decrab. That section is followed by a description of 12 handling qualities factors derived from the examination of the maneuvers. The actual factors for the seven configurations considered are then discussed, and preliminary estimates for desirable values of these factors are obtained.

Basic Maneuvers

A pilot's evaluation of an airplane's handling qualities is based on his difficulty in performing the control tasks required for certain maneuvers. The instrument approach and landing of large aircraft has been examined, and the following have been found to be the important lateral maneuvers and pilot control tasks.

Tracking the Localizer Beam

The pilot's primary task is to keep the airplane on the localizer beam. He acts on a display of the airplane's deviations from the beam in a closed-loop compensatory manner and maneuvers the airplane to eliminate the errors. In general, it is not possible for a pilot to track the beam by just acting on the lateral displacement error; to provide the necessary lead, he will close two other loops, which are bank angle and heading. He prefers to make all lateral-directional corrections with the ailerons alone, and the pilot closures of the bank-angle-to-aileron ($\varphi \to \delta_a$) and heading-to-aileron ($\psi \to \delta_a$) loops are considered as handling qualities factors here. The lateral displacement closure is not considered as a separate factor, since it is dependent primarily on the bandwidth of the heading closure (i.e., good heading control insures good lateral displacement control).

While the pilot is tracking the localizer, and throughout the approach and landing, the airplane may encounter side gusts. An important effect of gusts, for the type of airplane being considered here, will be a disturbance of the aircraft's roll attitude. The most significant indication of the severity of roll disturbance is the magnitude of the roll-to-sideslip ratio in the dutch roll mode, $|\varphi/\beta|_{DR}$.

Large Turns

When turning onto the beam or in a sidestep maneuver the pilot will make large turns. Large turns are distinguished from small ones, such as those used when tracking the localizer, by a longer turning time and a greater emphasis on turn coordination. Large turns are made by bringing the airplane up to and holding a steady bank angle. In an airplane with good roll dynamics the pilot deflects the ailerons and the airplane quickly reaches a steady roll rate; he holds the ailerons until the airplane approaches the desired bank angle; then, by neutralizing the ailerons, he brings the airplane to a zero roll rate, constant bank angle condition. The two factors that will define the airplane's roll response (the roll subsidence time constant and the maximum roll rate) are discussed in the following section.

The difficulty of coordinating turns is also a handling qualities consideration and is related to the rudder motion required to eliminate sideslip, or, conversely, the sideslip developed if the rudder is not used. Simple, although not complete, measures of the required rudder motion are the initial rudder position and rate for perfect coordination with a step aileron input and the amount of rudder required in a steady-state turn. These parameters will be considered handling qualities factors.

Decrab

When making an approach in a crosswind, the pilot may crab the airplane to eliminate sideslip and maintain the ground track along the runway centerline. Shortly before touchdown he must decrab quickly so that the airplane lands headed down the runway centerline with low lateral drift

‡ The SCAT designations used here refer to the family of supersonic commercial air transports studied and reported on by NASA in recent years.

velocity. The pilot does this by kicking the rudder and using the ailerons to keep the wings level.

For good handling qualities, the pilot must have enough rudder power to yaw the airplane through the decrab angle before the lateral drift velocity becomes excessive. He also needs sufficient aileron power to keep the wings level, with some reserve for counteracting gust disturbances. Measures of rudder and aileron power are discussed in the next section.

Another factor is the pilot's control of yaw rate with rudder since this provides nearly all the damping of the dutch roll mode when the pilot is trying to keep the nose aligned with the runway centerline. This closure ($r \rightarrow \delta r$) is examined in the following section.

Some of the factors which are important for decrab are significant also for engine-out recovery. The pilot's actions in the two maneuvers are somewhat similar.

Handling Qualities Factors

From the previous discussion of the required maneuvers, it is clear that many factors must be considered to assess a given airplane's handling qualities in an approach and landing. Some of the factors may be expressed as explicit parametert, which can be assigned a numerical value, whereas others require interpretation of pilot loop closures. The latter types require the use of a mathematical model for the human pilot; the analyses presented here are based on the describing function model of Ref. 3.

The 12 factors that appear to be the most significant have been divided into five categories. There are interrelationships between factors in different categories; the grouping merely attempts to bring together those with the most interdependence.

Closed-Loop Control

Three loop closures are considered as handling qualities factors: simultaneous bank angle and heading-to-aileron, and yaw rate to rudder.

$\varphi \rightarrow \delta_a$: The control of bank angle with aileron forms the basic inner loop for all lateral control. Typical root loci for a pure-gain bank-angle-to-aileron feedback are shown in Fig. 1a. The usual form of the φ/δ_a numerator is a pair of complex zeros with a frequency ω_φ, which can be greater than or less than the dutch roll frequency ω_d. It can be seen in Fig. 1a that, when $\omega_\varphi/\omega_d < 1.0$ the damping of the dutch roll mode may be increased by controlling bank angle, whereas if $\omega_\varphi/\omega_d > 1.0$, the feedback tends to destabilize the dutch roll. Although the most common stab'lity problem in bank angle feedback is that due to $\omega_\varphi/\omega_d > 1.0$, other parameters that are important are ω_d, ζ_d, ζ_φ, and the roll subsidence time constant T_R.[1-3]

The root loci of Fig. 1a are for pure-gain closures. Figure 1b shows the effects due to a pilot making the bank-angle-to-aileron closure. The solid locus is for a pure gain (included for comparison); the dashed locus shows the effects of the pilot's lumped reaction time delay and neuromuscular system lags; and the dotted locus shows how the pilot can use lead to cancel his own lags and further increase the potential dutch roll damping. The key point to be made here is that the pilot must be able to control bank angle with ailerons alone without destabilizing the dutch roll mode. It should be noted that, while the pilot is willing to adopt a moderate amount of lead to increase damping, the pilot ratings get worse as the lead requirement increases.[9] This closure is treated as a handling qualities factor.

$\psi \rightarrow \delta_a$: When flying the localizer beam, bank-angle-to-aileron is an inner loop, and heading control with the ailerons is an outer loop. The need for an inner loop can be seen by examining a heading loop closure without an inner loop (Fig. 2a). Depending on the spiral mode, the closed-loop system will be stable for only very low gains at best. If the spiral

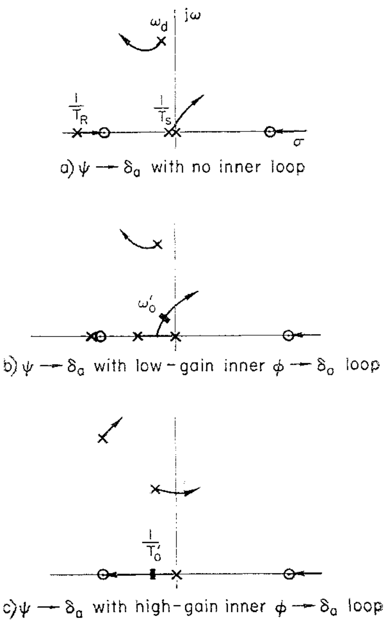


Fig. 2 Typical root loci for heading-to-aileron feedback.

mode is stable, it couples with the free s to form a second-order mode, which goes unstable at very low frequency and for very low gain. If the spiral mode is unstable, the closure is unstable for all gains. Consequently, the dominant mode,§ under the best conditions, is restricted to low frequencies.

The effects of an inner $\varphi \rightarrow \delta_a$ loop appear in the outer $\psi \rightarrow \delta_a$ loop as modifications to the effective values of $1/T_s$, $1/T_R$, ω_d, and ζ_d (Fig. 1). A low-gain inner loop increases $1/T_s$, decreases $1/T_R$, and slightly modifies the dutch roll mode. In the resulting heading closure (Fig. 2b), the new spiral mode and the free s are driven together, couple, and finally, for high enough gain, go unstable. The heading response can be greatly improved over the no-inner-loop case because the dominant mode ω_0' can be of much higher frequency. Because of the frequency separation, the heading closure has a negligible effect on the $\varphi \rightarrow \delta_a$ inner loop.

For a high-gain inner loop, the spiral and roll subsidence modes will have coupled so that, in the outer loop, the airplane has two second-order modes: one located near the zeros of the φ/δ_a transfer function, and the second pair at higher frequency. In this case (Fig. 2c), it is the pair of roots near the φ/δ_a zeros that is driven unstable by the heading loop; and the dominant mode in the heading response is the first-order pole $1/T_0'$, which originated at the free s. The heading loop gain is limited by the requirement of keeping the second-order mode from going unstable; this in turn limits the location of the dominant first-order mode. Whether the high-gain inner loop provides better heading response than the low-gain inner loop depends primarily on the damping of the second-order mode in the high-gain case and on the locations of the ψ/δ_a zeros.

Because of the relatively low frequency of the heading closure, the effects of the pilot's dynamics in this loop are small. In the comparisons of the following section, the pilot model that was used consisted of a gain plus a time delay.

For the comparison of various configurations, it is desirable to have a simple quantitative parameter that is a valid indicator of relative speeds of heading response. The time constant of the dominant mode T_ψ appears useful, and where the mode is of first order, it is simply $T_\psi = T_0'$. When the dominant mode is of second order, an equivalent time constant[10] is

$$T_\psi = 2.9\zeta_0'/\omega_0' \quad (1)$$

§ The dominant mode is that which contains the largest portion of the response of a command input.

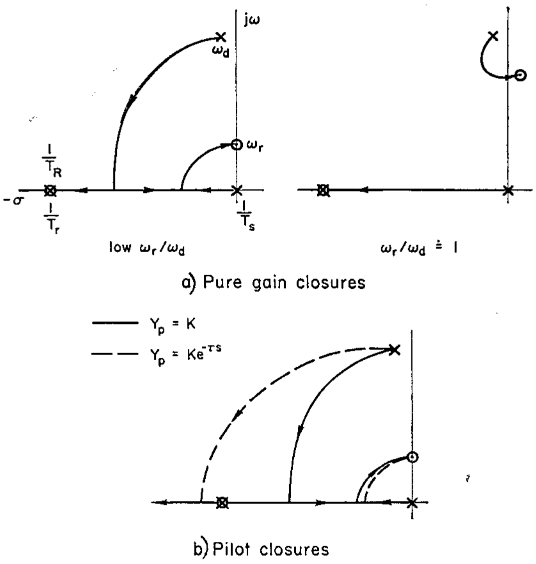


Fig. 3 Typical yaw-rate-to-rudder feedback.

A small value of the time constant indicates a fast response, which is desirable.

$r \rightarrow \delta_r$: The third loop closure to be considered as a handling qualities factor is the control of yaw rate with rudder to damp the dutch roll mode. The yaw-rate-to-rudder numerator is third order, with one root usually near the roll subsidence mode, and a second-order pair of very low frequency ω_r and damping. Examples of good and bad closures are shown in Fig. 3a. Normally, ω_r/ω_d is very small, so that the yaw-rate-to-rudder feedback can add a great deal of damping to the dutch roll. For ω_r/ω_d near 1.0, this feedback can do little to damp the dutch roll, and in an extreme case, it may reduce the damping.

The closures of Fig. 3a are for pure-gain feedbacks, and the human pilot effects can be seen in Fig. 3b. The solid locus is for a pure-gain feedback (included for comparison); the dashed locus shows the effects of the pilot's reaction time delay and neuromuscular system lags.

The primary condition which can produce a poor yaw-rate closure is a high value ($\doteq 1.0$) of ω_r/ω_d; an approximation to this frequency ratio is given in Ref. 11 as

$$\omega_r/\omega_d = [g(L_{\delta_r}'/N_{\delta_r}' - L_\beta'/N_\beta')/U_0 L_p']^{1/2} \qquad (2)$$

This equation clearly indicates that the elements which can contribute to a poor yaw rate closure are: 1) low speed U_0, 2) low directional stability N_β', 3) high dihedral effect L_β', and 4) low roll damping L_p'. The approximation of Eq. (2) is given only to indicate the effects of various parameters. The exact r/δ_r transfer functions were used to evaluate the configurations considered.

Roll-to-Sideslip Ratio

The magnitude of φ/β in the dutch roll mode is a measure of the roll response to yaw inputs: inadvertent rudder motions, rudder to decrab, and side gusts. Consequently, it is desirable to have the magnitude of φ/β small. Normally,[1]

$$\left|\frac{\varphi}{\beta}\right|_{DR} \doteq \frac{|L_\beta'|}{\omega_d[\omega_d^2 + (1/T_R)^2]^{1/2}} \qquad (3)$$

From Eq. (3) it can be seen that $|\varphi/\beta|_{DR}$ can be reduced by decreasing the effective dihedral (reducing L_β'), increasing the directional stiffness (increasing the dutch roll frequency ω_d), or increasing the roll damping (decreasing the roll subsidence time constant T_R).

The approximation of Eq. (3) is given only to indicate the effects of various parameters. In the comparisons of the following section, the exact values of $|\varphi/\beta|_{DR}$ (as determined from the ratio of numerators) are used.

Turn Coordination

The problem of turn coordination can be examined from two aspects: the rudder deflection necessary to keep the sideslip zero or the amount of sideslip which develops in an aileron-alone turn. The first approach will be used here, because in commercial transports there is considerable emphasis on maintaining zero sideslip for piloting precision and passenger comfort.

Sample calculations for a step aileron input have shown that the rudder motion to maintain zero sideslip is quite complicated. Generally, the difficulty in coordinating turns can be at least qualitatively determined by examining the three factors considered here: 1) the initial step rudder deflection required for perfect coordination with a step aileron input, 2) the initial (immediately after the step) rate of change of rudder deflection required for perfect coordination with a step aileron input, and 3) the rudder required to coordinate a steady-state turn.

In a perfectly coordinated turn, we have

$$\beta(s) = \frac{N_{\beta\delta_a}(s)}{\Delta(s)}\,\delta_a(s) + \frac{N_{\beta\delta_r}(s)}{\Delta(s)}\,\delta_r(s) = 0 \qquad (4)$$

Therefore, the rudder required for coordination is

$$\delta_r(s) = -\frac{N_{\beta\delta_a}(s)}{N_{\beta\delta_r}(s)}\,\delta_a(s) \qquad (5)$$

The preceding can be used to calculate the initial rudder position and rate (from that position) for a step aileron by means of the initial value theorem of Laplace transforms.

For a step aileron input, a step in rudder position is also necessary, so that the resultant angular acceleration is about the airplane velocity vector. Thus, the ratio of the initial rudder step to the aileron input is (for $C_{y\delta_a} = C_{y\delta_r} = 0$)

$$(\delta_r/\delta_a)_0 = -(N_{\delta_a}'/N_{\delta_r}') \qquad (6)$$

The initial rudder rate is necessary to counteract the effects of the cross-coupling term N_p' and the gravity term in the side force equation, and is given by

$$\left(\frac{\dot{\delta}_r}{\delta_a}\right)_0 = \left[\frac{(L_{\delta_a}'N_{\delta_r}' - L_{\delta_r}'N_{\delta_a}')(g\cos\theta_0/U_0 - N_p')}{(N_{\delta_r}')^2}\right] \qquad (7)$$

If $(\delta_r/\delta_a)_0$ and $(\dot{\delta}/\delta_a)_0$ are of opposite sign, extra precautions in the interpretation of the results should be taken. When these two parameters are of opposite sign their effects tend to cancel and it may be that, although the magnitudes of both are large, little sideslip would develop if the p lot d:d not apply rudder.

The necessity for holding large amounts of rudder in a steady-state turn is an undesirable characteristic. For constant altitude steady-state turns within the bank angles normally used for commercial transports, the rudder required for zero sideslip [implies $r \doteq (g/U_0)\varphi$] is well approximated by

$$\left(\frac{\delta_r}{\varphi}\right)_{ss} \doteq \frac{-g}{U_0}\left(\frac{L_{\delta_a}'N_r' - L_r'N_{\delta_a}'}{L_{\delta_a}'N_{\delta_r}' - L_{\delta_r}'N_{\delta_a}'}\right) \qquad (8)$$

Roll Response

An airplane's role rate response to aileron inputs is principally defined by the roll subsidence time constant T_R and the maximum roll rates p_{max}. Superimposed on the first-order response due to the roll subsidence mode are dutch roll oscillations. Because of its very low frequency, the spiral mode will usually have a negligible effect.

Table 1 Summary of handling qualities factors[a]

Handling qualities factors		Subsonic Jet	SCAT 16	Augmented SCAT 16	SCAT 17A	Augmented SCAT 17A	SCAT 17B	Augmented SCAT 17B
Closed-Loop Control	$\phi \to \delta_a$	Good	Very Good	Very Good	Good	Very Good	Very Bad	Very Good
	T_ψ (sec)	6.3	11.8	1.5	5.6	2.2	—	4.1
	$r \to \delta_r$	Very Good	Very Good	Very Good	Fair	Very Good	Very Bad	Very Good
$\lvert\phi/\beta\rvert_{DR}$		1.4	1.2	1.2	2.2	1.5	4.8	1.7
Turn Coordination	$(\delta_r/\delta_a)_0$	0	1.6	1.6	1.0	1.0	0	0
	$(\dot{\delta}_r/\delta_a)_0$ (sec^{-1})	0.6	3.1	-2.1	0.8	-0.1	-0.6	-0.4
	$(\delta_r/\phi)_{ss}$	-0.08	-0.10	-0.36	-0.18	-0.38	-0.21	-0.21
Roll Response	T_R (sec)	0.9	0.6	0.5	1.2	0.9	—	0.5
	p_{max} (deg/sec)	9.0	10.0	16.0	11.0	16.0	—	14.0
Decrab	N'_{δ_r} (sec^{-2})	-0.38	-0.08	-0.08	-0.23	-0.23	-0.21	-0.21
	$(\Delta\psi_{max})_{t=2\,sec}$ (deg)	9.8	3.5	3.0	8.3	5.5	7.9	7.9
	$\lvert L'_\beta/L'_{\delta_a}\rvert$	1.3	0.6	0.7	1.6	1.3	1.8	1.8

[a] Items in shaded areas are deficient.

A good approximation for T_R is

$$T_R \doteq -1/L_p' \tag{9}$$

where L_p' is the dimensional stability derivative form for the aerodynamic damping in roll. The maximum roll rate can be approximated by

$$p_{max} \doteq (\omega_\varphi/\omega_d)^2 T_R L_{\delta_a}'(\delta_a)_{max} \tag{10}$$

The pilot's desire for a rapid roll response implies a small roll time constant. The best maximum roll rate is a compromise between an airplane that is too sluggish and one that is too sensitive. Earlier experiments for fighter aircraft are reported in Ref. 4.

Decrab

A key factor in the decrab maneuver is rudder power, and a good indication of rudder power is the angular acceleration about the yaw axis produced by the rudder. Consequently, N_{δ_r}' will be used as a handling qualities factor.

In a typical decrab maneuver, if the pilot kicks the rudder to yaw the airplane's nose to the right, the rudder will also produce a left-wing-down roll acceleration ($L_{\delta_r}'\delta_r$). A rolling moment due to yaw velocity ($L_r'r$) will prevent the airplane from rolling very far ($L_r'r$ acts in the opposite direction as $L_{\delta_r}'\delta_r$, but it lags the moment directly due to the rudder). As sideslip begins to build up it lags yaw velocity ($\dot\beta \doteq -r$), and a moment due to the dihedral effect ($L_\beta'\beta$) is produced which adds to that due to yaw velocity (i.e., right-wing-down) and, after the first few seconds, is the dominant source of roll motion. The primary requirement on aileron power appears to be the ability to cancel the dihedral effect; therefore, L_β'/L_{δ_a}' will be used as a handling qualities factor.

The third decrab parameter to be considered is the yaw angle that can be obtained in a specified time. It will be assumed that the pilot puts in a step rudder deflection and holds it while using the ailerons to keep the wings level. With the wings held level, the yaw response is the same as it would be with an infinite-gain bank-angle feedback. Using the multiloop analysis technique,[12] gives

$$\frac{r}{\delta_r} = \lim_{Y_\varphi \to \infty} \frac{N_{r\delta_r} + Y_\varphi N_{\delta_a\delta_r}^{\varphi\, r}}{\Delta + Y_\varphi N_{\varphi\delta_a}} = \frac{N_{\delta_a\delta_r}^{\varphi\, r}}{N_{\varphi\delta_a}} \tag{11}$$

For $C_{y\delta_a} = C_{y\delta_r} = 0$, the $\varphi \to \delta_a$, $r \to \delta_r$ coupling numerator is given by

$$N_{\delta_a\delta_r}^{\varphi\, r} = (L_{\delta_a}'N_{\delta_r}' - L_{\delta_r}'N_{\delta_a}')(s - Y_v) \tag{12}$$

Consequently, the yaw angle for a step rudder input is

$$\Delta\psi(t) = \mathcal{L}^{-1}\frac{(L_{\delta_a}'N_{\delta_r}' - L_{\delta_r}'N_{\delta_a}')(s - Y_v)(\delta_r)_s}{A_\varphi s^2(s^2 + 2\zeta_\varphi\omega_\varphi s + \omega_\varphi^2)} \tag{13}$$

For the comparisons of the next section it is assumed that the full rudder authority of 25° is used and that the angle is evaluated at a time of 2.0 sec, which is considered near the desirable maximum for the decrab maneuvers. It should be noted that, for the approach speeds being considered, a crosswind of 25 knots gives a crab angle of approximately 10°.

As discussed in the previous section, there are other parameters, besides the three considered previously, which are important in the decrab. Nevertheless, these three, combined with some of the factors discussed earlier in this section, should give a fair indication of piloting problems in decrab.

Configuration Review

This section reviews the handling qualities of the subsonic jet, which is used as a standard for comparison, and the three SST configurations with and without augmentation. The review is in terms of the handling qualities factors previously described, and the correlation between major comments of the pilots and these factors is discussed. The pilot comments are taken from the experimental study of Ref. 8; for a more detailed description of the configuration, see Ref. 13.

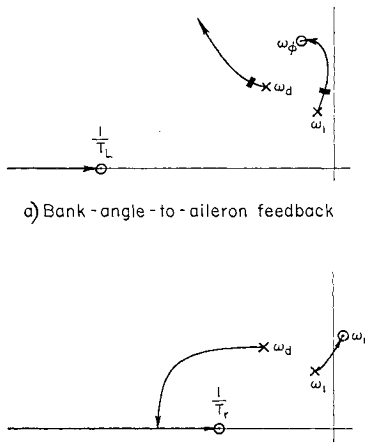
The configuration review discusses the five groupings of handling qualities factors in the same order as they are presented in the previous section. Only those configurations that appear deficient in a particular category are discussed, and then, generally, the discussion starts with the worst case and ends with the marginal ones. Values for all the factors and all seven configurations are listed in Table 1, with those factors that appear deficient indicated by shading.

Closed-Loop Control

Pilot closure of the $\varphi \to \delta_a$ loop for all configurations, except SCAT 17B, bare airplane, is good or very good. For those rated very good, the pilot is not required to adopt lead; those rated good require a moderate amount (less than 0.7 sec) of lead, which is not enough to significantly degrade pilot opinion.[9]

The dynamics of SCAT 17B, bare airplane, are rather unusual. Because of a large positive value of C_{n_p}, the roll subsidence and spiral modes couple into a lateral phugoid. Thus, the lateral characteristics consist of two second-order modes of low frequency but relatively high damping ratio. Pilot closure of the $\varphi \to \delta_a$ loop with a lead of 0.67 sec is shown in Fig. 4a. The figure clearly shows that this is a very bad closure; the pilot is destabilizing the lateral phugoid and actual stability is critically dependent on the pilot lead. The pilot is capable of generating much higher leads, but extreme leads always result in poor ratings.

One pilot commented that the only way he could fly this airplane was by pulsing the ailerons. By applying a large acceleration for a short time, the pilot can get a reasonable



a) Bank-angle-to-aileron feedback

b) Yaw-rate-to-rudder feedback

Fig. 4 Pilot closures for SCAT 17B.

roll rate, and after he neutralizes the ailerons, the roll rate decays slowly because of the low frequencies of the lateral modes.

An interesting point on SCAT 17A, bare airplane, is that the value of ω_φ/ω_d, 0.62, is less than the 0.75 required to avoid roll rate reversals.[1,3] One pilot reported that he noticed the reversal but did not consider it highly objectionable. The reason for the acceptance of this characteristic is not clearly understood.

The time constant of the dominant mode in the heading response T_ψ for six of the configurations ranges from 1.5 to 11.8 sec. Because of the very poor quality of the $\varphi \rightarrow \delta_a$ closure, heading control for SCAT 17B, bare airplane, is not even considered. For SCAT 16, bare airplane, the pilot comment "low directional stability, difficult to hold a heading" is not surprising; $T_\psi = 11.8$ sec. The primary cause for poor heading control in this airplane is the low value of aerodynamic yaw rate damping N_r'.

The time constant for the subsonic jet (6.3 sec) appears high and, although detailed pilot comments are not available, it is known that many of these aircraft have been equipped with yaw dampers and that the airline pilots prefer to have the damper on during approach. A yaw damper can greatly improve heading control, as well as eliminate the need for pilot lead, in the $\varphi \rightarrow \delta_a$ closure.

Even with the pilot lead in the $\varphi \rightarrow \delta_a$ loop, the heading control for SCAT 17A, bare airplane, is only fair ($T_\psi = 5.6$ sec). A preliminary estimate of the requirement for good heading control is $T_\psi < 5.0$ sec.

Control of yaw rate with rudder is very good for all configurations except the unaugmented SCAT 17A and SCAT 17B. For SCAT 17B the $r \rightarrow \delta_r$ closure is very bad (Fig. 4b). As with the $\varphi \rightarrow \delta_a$ loop for this airplane, the closure destabilizes the lateral phugoid. The pilot experienced extreme difficulty controlling the airplane whenever he used the rudder.

The $r \rightarrow \delta_r$ control for SCAT 17A is only fair; the pilot cannot increase the dutch roll damping ratio beyond 0.35. This is because of the relatively large value of ω_r/ω_d due to the high dihedral and low roll damping [Eq. (2)]. A preliminary estimate of the requirement for good $r \rightarrow \delta_r$ control is that the pilot should be able to increase the dutch roll damping ratio to at least 0.5.

Roll-to-Sideslip Ratio

A small value of φ/β in the dutch roll mode indicates that the aircraft's roll attitude should not be sensitive to yaw inputs. The extremely large value for SCAT 17B, bare airplane, is unimportant since the closed-loop control for this configuration is so bad that it was rated unacceptable even for emergency conditions.

For SCAT 17A bare airplane, the magnitude of φ/β is high and, as would be expected, the pilot complained about the large roll motions caused by side gusts, engine failures, and the decrab maneuver. In the augmented version of SCAT 17A, the magnitude of φ/β is reduced to $\frac{2}{3}$ of its original value. This, coupled with increased roll and yaw damping, significantly decreases the roll response to lateral inputs; however, the pilots indicated that they would prefer an even smaller $|\varphi/\beta|_{DR}$. For a good rating it appears that the magnitude of φ/β in the dutch roll mode should be less than 1.5.

Turn Coordination

The turn coordination characteristics for SCAT 16, bare airplane, show that initially a large amount of rudder into the turn is necessary to limit sideslip, but that the steady-state value is quite low. The pilots objected to the large amount of adverse yaw which developed in turn entries. In the augmented SCAT 16 the coordination problem has been eased by creating a proverse yaw due to roll rate ($C_{n_p} > 0$) to offset the adverse aileron yaw. This is evidenced by the change in the initial rudder rate for coordination from a large positive value to a large negative one. As previously mentioned, the canceling effects of different signs of the initial position and rate may result in negligible sideslip if the pilot does not use the rudder. In fact, the pilot commented that reversing the sign of C_{n_p} made turn entries much easier.

The SCAT 16 augmentation includes a yaw damper, which greatly increases the amount of rudder required to hold a steady turn. This is a feature that the pilots complained about. This could be reduced by a washout in the $r \rightarrow \delta_r$ feedback of the damper.

For SCAT 17A a moderate amount of rudder is needed for turn entries and, although considerably less than that required for the SCAT 16, was still considered objectionable. In the augmented version the initial rudder position for turn coordination is unchanged, but the initial rate is reduced to a small negative value by a change in C_{n_p}. As in the case of the SCAT 16, the rudder for coordinating turn entries is reduced, but that required for steady turns is more than doubled because of a yaw damper. The steady-state requirement was considered excessive by the pilots, but could be reduced by a washout in the $r \rightarrow \delta_r$ feedback, as previously discussed in the SCAT 16 case. It is worth mentioning that more damping would have been used, had it not increased the steady-state-turn requirement.

The preliminary estimates of the requirements for good turn coordination are: the magnitude of the sum of $(\delta_r/\delta_a)_0$ and $(\dot{\delta}_r/\delta_a)_0$ should be less than 1.0, and the magnitude of $(\delta_r/\varphi)_{ss}$ should be less than 0.3.

Roll Response

The SCAT 17A, bare airplane, is quite sluggish in roll because of the high roll time constant and slightly low maximum roll rate (a deficiency noted by the pilots). In the augmented airplane, the response is improved considerably by a 50% increase in maximum roll rate (through increasing ω_φ/ω_d) and a 25% decrease in the roll time constant. The maximum roll rate for the subsonic jet and SCAT 16, bare airplane, may be a little low; however, there was no record of a pilot complaint. It appears that good roll response requires a roll time constant less than 1.0 sec and a maximum roll rate greater than 10°/sec.

Decrab

The rudder power for SCAT 16, bare airplane, is quite low, as shown by the relative small values of N_{δ_r}' and $(\Delta\psi_{\max})_{t=2.0 \text{ sec}}$. This, coupled with the difficulty of maintaining a heading, could explain the pilot's difficulties in making crosswind landings in this airplane. The rudder power is still low for the augmented SCAT 16; in fact, the achievable yaw angle is reduced because of the increased yaw damping and directional stiffness. The pilots indicated that they would prefer a more powerful rudder.

The aileron required to offset the dihedral effect in the decrab maneuver appears large for all configurations except SCAT 16. Although a pilot complaint on this specific point was not noted, simulator tests showed that a reduced L_β' improved pilot ratings for both SCAT 17A and 17B. With the SCAT 17A, bare airplane, and SCAT 17B, full aileron authority is not enough to cancel the L_β' term for a 10° sideslip.

Preliminary estimates of the rudder and aileron power required for decrab are

$$|N_{\delta_r}'| > 0.2 \text{ sec}^{-2}$$

$$(\Delta\psi_{\max})_{t=2.0 \text{ sec}} > 5°$$

$$|L_\beta'/L_{\delta_a}'| < 1.0$$

Summary

A simple analytical method for evaluating the lateral-directional handling qualities of large transport-type aircraft in landing approach has been developed. The method involves 12 handling qualities factors. Preliminary estimates of the values necessary for a good pilot rating (acceptable for normal operation) have been developed from previous studies and from tests of several supersonic transport configurations evaluated on the transport landing simulator of the NASA Ames Research Center as follows: 1) $\varphi \rightarrow \delta_a$ closure: "good" closure with pilot lead less than 0.7 sec; 2) $\psi \rightarrow \delta_a$ closure with $\varphi \rightarrow \delta_a$ inner loop: $T_\psi < 5.0$ sec; 3) $r \rightarrow \delta_r$ closure: $\zeta_{\max} > 0.5$; 4) $|\varphi/\beta|_{DR} < 1.5$; 5) $(\delta_r/\delta_a)_0$ and 6) $(\dot{\delta}_r/\delta_a)_0$: the magnitude of the sum of these two parameters should be less than 1.0; 7) $|\delta_r/\varphi|_{ss} < 0.3$; 8) $T_R < 1.0$ sec; 9) $p_{\max} > 10°$/sec; 10) $|N_{\delta_r}'| > 0.2 \text{ sec}^{-2}$; 11) $(\Delta\psi_{\max})_{t=2.0 \text{ sec}} > 5°$; and 12) $|L_\beta'/L_{\delta_a}'| < 1.0$.

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