Lateral-Directional Flying Qualities for Power Approach

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The results of a research program on aircraft flying qualities sponsored by the Naval Air Systems Command are presented. Lateral-directional handling characteristics were evaluated for a simulated carrier landing approach task. The investigation made use of a variable stability aircraft, a unique feature of which was the ability to simulate accurately the response of an aircraft to atmospheric turbulence. Handling characteristics data in the form of Cooper ratings and specific pilot comments were obtained from Navy test pilots for variations in roll damping, dihedral effect, Dutch roll frequency and damping, and roll to aileron transfer function numerator characteristics. The data are presented as iso-opinion maps for the various parameters. Aircraft turbulence response was found to be a factor of commanding importance in determining the handling characteristics of a configuration. Configurations with predominant yawing motions, such as those with low dihedral effect or high Dutch roll frequency, were undesirable. The flying qualities of these configurations were improved by increasing the Dutch roll damping. Configurations with low Dutch roll frequency were undesirable due to low directional stability as evidenced by large excursions in sideslip and the pilot's inability to make precise and rapid corrections in aircraft heading.

Nomenclature

IAS = indicated airspeed
K_d/K_{ss} = Dutch roll excitation parameter
L_p = roll damping, rad/sec² per rad/sec
L_r = overbanking tendency, rad/sec² per rad/sec
L_β = dihedral effect, rad/sec² per rad
$L_{\beta_{turb}}$ = roll due to sideslip gust derivative, rad/sec² per rad
$L_{\delta_r}/N_{\delta_r}$ = rudder roll
N_p = adverse yaw due to roll, rad/sec² per rad/sec
N_r = yaw damping, rad/sec² per rad/sec
N_β = directional stability, rad/sec² per rad
$N_{\beta_{turb}}$ = yaw due to sideslip gust derivative, rad/sec² per rad
$N_{\delta_a}/L_{\delta_a}$ = aileron yaw
rms = root mean square
V = velocity, fps
Y_β = crosswind force, ft/sec² per rad
g = acceleration due to gravity, 32.2 ft/sec²
j = $[-1]^{1/2}$
p = roll rate, rad/sec
p_{turb} = roll gate gust, rad/sec
r = yaw rate, rad/sec
r_{turb} = yaw rate gust, rad/sec
s = Laplace transform operator $s = \sigma \pm j\omega$
β = sideslip angle, rad
β_{turb} = sideslip gust, rad
δ_a = lateral stick deflection, in.
δ_r = rudder pedal deflection, in.
ζ_d = Dutch roll damping ratio
ζ_φ = φ/δ_a transfer function numerator damping ratio
σ = real part of Laplace operator
$\sigma_{\beta_{turb}}$ = rms of β_{turb}, rad
σ_φ = rms of bank angle deviations, rad
$\sigma_{\ddot\varphi}$ = rms of roll acceleration, rad/sec²
σ_ψ = rms of heading deviations, rad
τ_{rm} = roll time constant, sec
τ_{sp} = spiral time constant, sec
$\Phi_{\beta_{turb}}$ = power spectral density of β_{turb}
φ = bank angle, rad or deg
$\ddot\varphi$ = roll acceleration, rad/sec²
$|\varphi/\beta|$ = Dutch roll bank angle to sideslip ratio
$|\ddot\varphi/\beta|$ = Dutch roll roll acceleration to sideslip ratio
φ/δ_a = bank angle due to aileron transfer function
ψ_1 = Dutch roll phase angle
ψ/β_{turb} = heading due to β_{turb} transfer function
ω = undamped frequency, rad/sec
ω_d = undamped Dutch roll frequency, rad/sec
ω_φ = φ/δ_a transfer function numerator frequency, rad/sec

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I. Introduction

In the power approach configuration, the lateral-directional stability and control of some high-performance aircraft deteriorate with increasing angle of attack and decreasing airspeed. To compound the problem further, atmospheric disturbances, both natural and those caused by the carrier, are encountered during the final approach. There have been cases where the lateral-directional handling qualities problem has restricted the minimum approach speed. Granted, the longitudinal handling qualities have given the most trouble. However, these cases frequently require the full attention of the pilot, and a minor distraction in lateral-directional can be "the straw that broke the camel's back."

Most of the previous handling qualities investigations of the carrier approach task have dealt with the longitudinal mode. Although several studies have explored the lateral-directional case, in general, the test conditions did not simulate the low level approach task, and the important aspect of the turbulence response of the aircraft was not considered.

For the purpose of this investigation a series of flight tests with a number of Navy test pilots and a variable stability airplane was conducted in order to determine the importance of the lateral dynamic response parameters and turbulence response on precision carrier approaches. The effects of roll time constant, dihedral effect, Dutch roll frequency and damping, and the roll to aileron transfer function characteristics are discussed herein. The effects of other parameters and comparisons of the data with the existing military specifications and other investigations may be found in the published reports of this program.[1,2]

II. Background

Lateral-Directional Dynamics and Responses

The lateral-directional flying qualities of an airplane are determined by a complex set of interacting parameters. The pilot's evaluation of the effect of any one lateral-directional parameter is very dependent on the value of the remaining parameters. Also, the number of parameters is bewildering. There are the airplane derivatives such as roll damping, dihedral effect, directional stability, etc., the dynamic response parameters such as roll time constant, Dutch roll frequency and damping, roll to sideslip ratio, etc., as well as some closed-loop parameters such as ω_φ/ω_d, ζ_φ, phase dip, etc. There is, of course, a relation between the airplane derivatives and the dynamic response and closed-loop parameters; however, the relationship is not usually a simple one. In addition to the derivatives and parameters already mentioned, there is the matter of the aircraft response to turbulence. This too is a very complex interaction between the absolute and relative magnitudes of the various airplane derivatives.

The equations of motion which govern the lateral-directional handling qualities are

$$\begin{array}{ccccccccc}
\underline{\beta} & \underline{r} & \underline{\varphi} & & \underline{\delta_a} & \underline{\delta_r} & \underline{\beta_{\mathrm{turb}}} & \underline{r_{\mathrm{turb}}} & \underline{p_{\mathrm{turb}}} \\
(s - Y_\beta/V) & +1 & -g/V & = & & Y_{\delta r}/V & +Y_\beta/V & & \\
-L_\beta & -L_r & +(s^2 - L_p s) & = & L_{\delta a} & +L_{\delta r} & +L_\beta & +L_r & +L_p \\
-N_\beta & +(s - N_r) & -N_p s & = & N_{\delta a} & +N_{\delta r} & +N_\beta & +N_r & +N_p
\end{array}$$

Note that the right-hand sides of the equations contain both the pilot control inputs and the inputs due to turbulence. A change in the magnitude of any one of the aerodynamic derivatives will result in not only a change in the lateral-directional dynamics, but also a change in the applied disturbance moments and forces due to turbulence.

The left-hand sides of the equations form the characteristic lateral-directional determinant. The characteristic equation normally factors into two real roots and a complex pair. These correspond to the rolling mode, the spiral mode, and the Dutch roll. The inverse of the roll mode root τ_{rm} is the roll time constant and indicates the time required for the roll rate of this mode to reach 63% of its nominal value for a step aileron control input. The spiral mode presents itself to the pilot as a tendency of the airplane to recover slowly, or diverge slowly, from an initial bank. Because of its long-term nature, the pilot is normally unaware of its presence during continuous tracking maneuvers such as the landing approach. The Dutch roll mode is a nuisance and normally consists of a coupled banking, sideslipping, and yawing motion. It is excited by pilot control inputs and by turbulence. The degree of excitation is dependent on the relative magnitudes of the derivatives. The parameter K_d/K_{ss} is used in this paper to indicate the ratio of Dutch roll excitation in roll rate to the steady-state roll rate for step aileron control inputs. The use of this particular excitation parameter is somewhat arbitrary. Parameters of this type have been used by R. C. A'Harrah and E. Seckel. The excitation ratio used herein was selected because it could be calculated readily from the roll rate to aileron transfer function and measured graphically from transient response curves.

The roll rate response to a step input of aileron expressed as a function of time is the following:

$$p(t)/\delta_a = K_{sp}e^{(1/\tau_{sp})t} - K_{rm}e^{(1/\tau_{rm})t} - K_d e^{-\zeta_d\omega_d t}\sin(\omega_d t + \psi_1)$$

All of the configurations studied in this paper have a neutral spiral mode. Thus, the first term of the preceding expansion reduces to simply K_{sp}. This term represents the steady-state magnitude of the roll response after the roll mode and Dutch roll transients have subsided. Because of the steady-state nature of the response, the term has been redefined as K_{ss}. The K's can be determined by calculating the inverse Laplace transform of the roll rate to aileron transfer function or by the graphical measurement of the vectors between the poles and zeros of the transfer function.

Turbulence Simulation

As previously mentioned, the right-hand side of the equations of motion contain both the pilot control and turbulence forcing functions. The turbulence inputs have been separated into their individual components associated with aerodynamic derivatives. Thus, the airplane will respond in roll to a predominantly rolling air mass in proportion to the value of L_p. A pure side gust would roll the airplane in proportion to L_β and yaw the airplane in proportion to N_β. Also, these motions would initially oppose each other for the normal signs of L_β and N_β (right roll with left yaw, etc.).

The turbulence simulation signals were obtained from a random noise generator with band pass filters shaping the spectral characteristics. These signals were recorded on tape and introduced into the moment controls of the variable stability aircraft in proportion to the value of the configuration derivatives.[1] The rms values that were used represented a "mode-rate" turbulence that might be present near a squall line. It is neither the "everyday" nor the "once-a-year" occurrence. This description was given to the pilots in the program.

Some test configurations of this paper have significantly higher values of the derivatives N_r and L_r than those of contemporary aircraft. The yaw damping N_r is the primary derivative affecting the Dutch roll damping (L_β and N_p fixed) and the overbanking tendency L_r must follow the equation $L_\beta N_r = L_r N_\beta$ for the test restraint of a neutral spiral mode. Initial evaluations of the higher Dutch roll damping configurations revealed that they were unacceptable or harder to fly than their counterpart configurations with a lower damping ratio. This difficulty was traced directly to the higher turbulence response associated with the larger values of N_r and L_r. It was obvious that a strict adherence to the condition that the disturbance moments in turbulence be proportional to the magnitude of the derivatives was unreasonable. Although it is true that an airplane with the larger derivative magnitudes would be disturbed more, it is impractical to obtain these magnitudes of the N_r and L_r derivatives through aerodynamic means. That is, large values of yaw damping N_r can be obtained in a practical case only by artificial means (a stability augmentation system). If we consider the special case where all of the derivative was obtained by a rate gyro feedback, we would note the aircraft would not respond to a pure yawing gust but would have the same dynamic response to stick inputs as an airplane with "aerodynamic" yaw damping. With this in mind, it was decided to assume that part of the N_r and L_r derivatives was achieved by aerodynamic means, and the remainder by a stability augmentation system. The value of the aerodynamic contribution to the total was that of a typical Class III aircraft ($N_r = -0.222$, $L_r = 1.0$). The turbulence disturbance moments were made proportional to the aerodynamic part of the derivatives for all configurations (if the magnitude of the derivative was less than the numbers quoted previously, the actual value was used). The foregoing technique was applied to all configurations of this paper. Lack of time precluded applying the foregoing technique to 1) the high values of roll damping L_p, which normally would be obtained by artificial feedback and 2) other levels of the aerodynamic part of the total magnitude of the derivative.

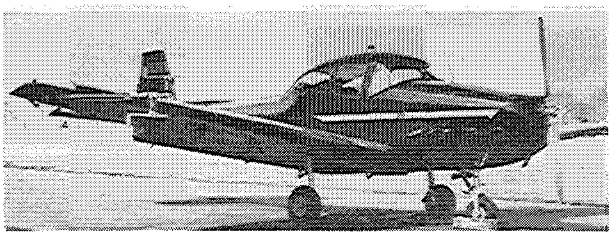


Fig. 1. Variable stability Navion.

III. Experimental Procedure

Description of the Variable Stability Airplane

The Princeton variable stability Navion airplane shown in Fig. 1 was used to obtain the several stability configurations investigated in this program. The airplane's variable stability control system consists of a three-axis autopilot and servo system which provides aileron, rudder, and elevator commands proportional to sensed angular rates, angle of sideslip, and angle of attack. The basic aerodynamic moment characteristics of the airplane may thus be altered to achieve a wide range of stability and control configurations. Side force, lift, and drag characteristics are those of the basic airplane, and were not varied in these tests. The lateral-directional simulation was not compromised since the side-force characteristics in sideslip were consistent with those of the class of airplane being simulated. Random noise signals stored on an onboard tape recorder were filtered and summed with other inputs to the controls to provide calibrated simulated turbulence in all three axes.

The right seat control and flight instruments for the evaluation pilot were configured similar to those of a typical Navy jet fighter. Stick force gradients were generally consistent with the artificial feel systems of contemporary jet fighters and were 4.0 lb/in. longitudinally and 4.5 lb/in. laterally. The rudder pedal gradient was 25 lb/in. A standard T arrangement of primary flight instruments was used. The left seat was occupied by a safety pilot who performed the tasks of monitoring over-all system performance for safe operation and of setting up the various test configurations.

The Flight Problem

The basic evaluation task of this study was a simulated power approach to a carrier landing under moderately turbulent conditions. The simulated approaches were made to the Princeton runway, whose width of 70 ft corresponds to the painted area on a carrier deck. Glide slope information was provided by an optical landing aid, developed for Marine Corps advanced airfield use, which was installed at the side of the runway. An approach speed of 105 knots was used to match the closure speed of a jet flying at 135 knots indicated airspeed (IAS), approaching a carrier with 30 knots of wind over the deck.

The procedure for conducting a test run is illustrated in Fig. 2. All runs were made in smooth air so that the response of the simulated configuration to the calibrated artificial turbulence would not be distorted. An analog matching technique was used to achieve an accurate correspondence between the dynamics and control response of the variable stability airplane and of each test configuration.

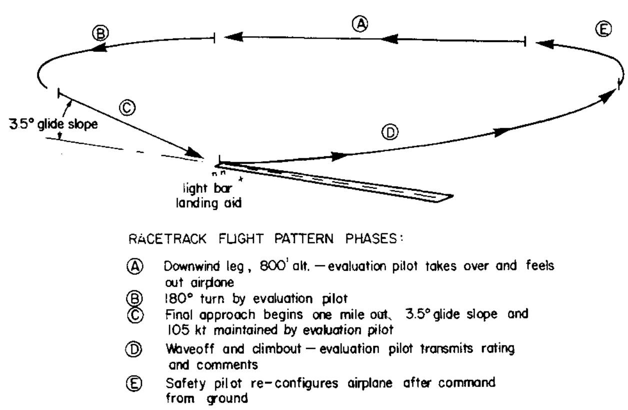
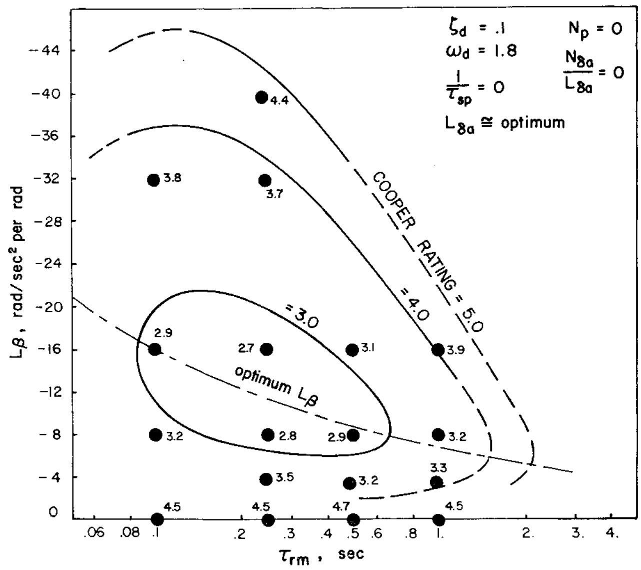


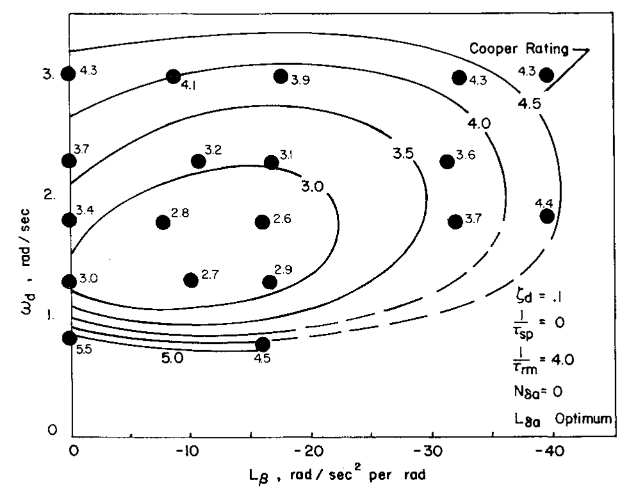
Fig. 2 Flight pattern.

Evaluation Pilots and the Rating System

Of the 26 evaluation pilots involved in this program all but two were provided by the Naval Air Test Center at Patuxent River, Md., and were graduates of the Navy Test Pilot School. They included representatives of the Flying Qualities and Performance, Carrier Suitability, and Rotary Wing branches and the staff of the Test Pilot School. One of the remaining pilots was a Navy jet carrier pilot currently stationed at the Naval Air Systems Command. The engineering test pilot at Princeton University also participated in one phase of this program. The Cooper rating scale, shown in Table 1, was used by the pilots to evaluate the various configurations.



a) L_β vs τ_{rm}



b) ω_d vs L_β

Fig. 3 Pilot opinion contours, low Dutch roll damping.

Table 1 Cooper pilot opinion rating system

Operating conditions	Adjective rating	Numerical rating	Description	Primary mission accomplished	Can be landed
		1	Excellent, includes optimum	Yes	Yes
Normal operation	Satisfactory	2	Good, pleasant to fly	Yes	Yes
		3	Satisfactory, but with some mildly unpleasant characteristics	Yes	Yes
		4	Acceptable, but with unpleasant characteristics	Yes	Yes
Emergency operation	Unsatisfactory	5	Unacceptable for normal operation	Doubtful	Yes
		6	Acceptable for emergency condition only[a]	Doubtful	Yes
		7	Unacceptable even for emergency condition[a]	No	Doubtful
	Unacceptable	8	Unacceptable—dangerous	No	No
No operation		9	Unacceptable—uncontrollable	No	No
		10	Motions possibly violent enough to prevent pilot escape	No	No

[a] Failure of a stability augmenter.

Data Acquisition

Flight tests were conducted during the summers of 1964 and 1965 and in the fall of 1966. A total of 80 flights with 1430 data runs were made. Test data in the form of Cooper ratings and pilot commentary obtained both in-flight and during postflight debriefings were compiled. These data provided the most consistent and enlightening source of information for the program. Attempts at measuring the performance of the pilot and of the pilot-vehicle system yielded results that were inconclusive in establishing flying quality trends.

IV. Results

Rolling Time Constant and Dihedral Effect, $\zeta_d = 0.1$, $\omega_d = 1.8$ rad/sec

The effect on pilot Cooper rating of varying the rolling time constant τ_{rm} and the dihedral effect L_β near optimum control sensitivity is shown in Fig. 3a. Iso-opinion lines are used to present the data. It should be noted that these data are for the case $N_p = N_{\delta a}/L_{\delta a} = 0$, $\omega_d = 1.8$ rad/sec, $\zeta_d = 0.1$, and a control sensitivity near optimum. The curves indicate that "it is desirable to have a little stable dihedral effect, but not too much." The deterioration of handling qualities at the higher values of the derivative L_β is due primarily to the increase in turbulence response of the aircraft. Additionally, the corresponding increase of K_d/K_{ss} with L_β is detrimental (see Fig. 7 discussion, which indicates the gradient of pilot opinion with K_d/K_{ss} or numerator zero location). Although these effects are minimized as the dihedral effect is reduced, small values of the dihedral effect are also unacceptable. In this case the problem appears to be the low resulting value of $|\varphi/\beta|$. As the magnitude of this ratio is reduced, the Dutch roll mode becomes predominantly a yawing one. Directional oscillations were found to be particularly annoying to the pilots in this program. As the value of $|\varphi/\beta|$ is reduced, the lateral and directional modes become less coupled, and in the limit of $L_\beta = 0$, $|\varphi/\beta| = 0$, become essentially uncoupled. Turbulence will excite the Dutch roll mode, but only in yaw and sideslip for these configurations. As this limit is approached, the pilot can no longer damp the yawing motions with the ailerons as he can in the more coupled case. His only recourse is to use an additional control, the rudder. The jet pilots generally did not use the rudder, and consequently, the yawing motions were sometimes large and lightly damped. Although the yaw, in itself, does not make the carrier approach difficult, it is intolerable because of the probability of damaging the gear during the landing. At all roll time constants very low values of L_β were unsatisfactory (Cooper rating of about 4.5) because of the yawing oscillations (see Fig. 3a).

As noted previously, large values of dihedral effect are unsatisfactory because of the increased turbulence response of the aircraft. Specificially, the pilot's problem is one of quickly correcting the bank angle disturbances. This is in contrast to the yaw case with low L_β or $|\varphi/\beta|$ where the magnitude of the motions in the Dutch roll (a relatively low-frequency yaw angle disturbance) are the problem. For a given value of dihedral effect, decreasing the roll time constant (increasing roll damping) reduces the bank angle excursions due to the disturbance moment and also enables the pilot to correct the excursions more readily. Consequently, the pilot is more tolerant, and will accept a larger variation of the dihedral effect if the roll time constant is small (see Fig. 3a).

The following items may be noted from the data presented in Fig. 3a and the previous discussions:

1) There is both a minimum and a maximum value of dihedral effect that is acceptable to the pilot.

2) The range of tolerable dihedral effect is larger when the roll time constant is small (roll damping is large).

3) As the dihedral effect is increased above the near optimum area, the pilot desires a smaller roll time constant (an increase in roll damping).

4) When the dihedral effect is very low, an unacceptable turbulence excited snaking motion occurs. No improvement can be expected with changes in the roll time constant (or roll damping).

Considering typical aircraft roll time constants, the designer of an aircraft that has a large dihedral effect must add a roll damper (or reduce the dihedral) to provide adequate handling qualities (see Fig. 3a). The improvement in handling qualities with the roll damper will probably be more than that shown in Fig. 3a since the aircraft will not increase its response to pure rolling gusts as it would if the aerodynamic roll damping were increased. If the aircraft has a very low dihedral effect and a low Dutch roll damping, a roll damper will not improve the yaw problem. In this case, the designer must add a yaw damper to increase the Dutch roll damping.

Dutch Roll Frequency and Dihedral Effect, $\zeta_d = 0.1$, $\tau_{rm} = 0.25$

Test configurations having different levels of Dutch roll frequency were also evaluated in this program. Several values of dihedral effect were tested at each level of Dutch roll frequency to establish the interrelationship of these two parameters with pilot opinion. Pilot opinion data for this series of configurations are presented in Fig. 3b, for a Dutch roll damping ratio $\zeta_d = 0.1$, for a roll time constant $\tau_{rm} =$

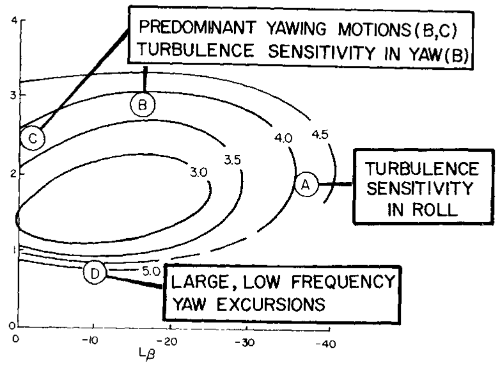


Fig. 4 Pilot commentary regarding unsatisfactory configurations—low Dutch roll damping.

0.25, and for optimum lateral control sensitivity. Aileron yaw $N_{\delta a}$ was 0 for these tests. However, the N_p derivative was adjusted to maintain a satisfactory relationship of the φ/δ_a zeros to the Dutch roll poles. This was necessary to eliminate or minimize the influence of ω_φ/ω_d and of the Dutch roll excitation parameter K_d/K_{ss}, either of which could contaminate the results. A more detailed discussion of the influence of ω_φ/ω_d and K_d/K_{ss} is presented in relation to the data of Fig. 7.

It may be observed in Fig. 3b that the pilots preferred intermediate ranges of both Dutch roll frequency and dihedral effect. As ω_d and L_β depart from the optimum region, pilot opinion ratings deteriorate. With the exception of the low ω_d region, for the ranges of ω_d and L_β tested, the pilot ratings did not deteriorate seriously. However, at low ω_d, a severe gradient of pilot rating with ω_d exists. Trends of the iso-opinion lines with L_β for constant ω_d agree with those shown in Fig. 3a at a roll time constant $\tau_{rm} = 0.25$.

Interpretation of the trends of pilot opinion with ω_d and L_β is appropriately related to four regions of unsatisfactory flying qualities. These regions are noted for convenient reference in Fig. 4, which reproduces the pilot opinion contours of Fig. 3b. They are, respectively, large L_β (A), high ω_d (B), low L_β (C), and low L_β (D). Typical pilot commentary pertaining to each region is also included.

Large dihedral effect

Configurations having large dihedral effect, region A, were found to be unsatisfactory because of excessive rolling moment disturbances imposed by side gusts, as was noted in the previous section. The question arose during this program whether these unsatisfactory flying qualities were chargeable to the large magnitude of $|\varphi/\beta|$ associated with large L_β or were strictly related to the magnitude of the rolling moment disturbance, which is proportional to L_β. The magnitude of the ratio of bank angle to sideslip in the Dutch roll mode $|\varphi/\beta|$, or variations thereof, have been indicated frequently in the literature as flying qualities parameters. This parameter is a measure of the coupling of sideslip into roll in the Dutch roll and is considerably influenced by Dutch roll frequency and dihedral effect. The relationship of $|\varphi/\beta|$ to ω_d and L_β is illustrated by the approximate expression,

$$\left|\frac{\varphi}{\beta}\right| \doteq \left|\frac{L_\beta}{\omega_d^2}\right| \left[\frac{1}{1 + (1/\tau_{rm}\omega_d)^2}\right]^{1/2}$$

The several combinations of ω_d and L_β tested in this program made it possible to evaluate pilot opinion as $|\varphi/\beta|$ was varied either proportionally to or independently of L_β. Thus, if the pilot opinion trends relate to $|\varphi/\beta|$, these trends should be apparent for variations in $|\varphi/\beta|$ achieved independently of L_β (by changing ω_d) as well as for those variations produced by L_β.

In Fig. 5, the pilot opinion contours of Fig. 3b are superposed for comparison on the constant $|\varphi/\beta|$ lines. In this case, $|\varphi/\beta|$ was computed precisely, rather than with the approximation of the previous paragraph by taking the ratio of the numerators of the bank angle and sideslip transfer functions for the Dutch roll characteristic root. The slopes of these iso-opinion contours with respect to the $|\varphi/\beta|$ lines provide a qualitative indication of the ability of $|\varphi/\beta|$ to correlate pilot opinion. If flying qualities are strongly related to $|\varphi/\beta|$, the pilot opinion contours would be expected to parallel the $|\varphi/\beta|$ lines (i.e., constant $|\varphi/\beta|$ and constant pilot opinion would coincide).

Consulting the figure, it may be concluded that, on the whole, $|\varphi/\beta|$ exhibits little facility for correlating pilot opinion. The general impression received from the figure is that the $|\varphi/\beta|$ lines and the iso-opinion contours are normal to rather than parallel to each other. In particular, for configurations having large L_β, region A, the $|\varphi/\beta|$ trends do not account for the closure of the iso-opinion contours. In order to maintain constant pilot opinion, a given level of L_β cannot be exceeded, whereas constant $|\varphi/\beta|$ may be maintained for increasing L_β by an appropriate increase in the Dutch roll frequency. The closure of the contours at large L_β is attributed to the excessive turbulence disturbances, which are proportional in magnitude to L_β and independent of ω_d. $|\varphi/\beta|$, being dependent on ω_d, cannot account for this influence.

Although the source of the pilots' complaints is attributed to the large magnitude of the rolling moment disturbances associated with large L_β, the pilot can only be aware of this influence through some particular characteristic(s) of the airplane's response to the gust disturbance. The airplane's initial roll acceleration response to a side gust ($\ddot{\varphi} \doteq L_{\beta_{\text{turb}}} \cdot \beta_{\text{turb}}$, before corrective control inputs and aerodynamic restoring moments become significant) is a cue to the pilot of the magnitude of the disturbances applied to the airplane. It is possible that the pilots' rating of a configuration is determined, at least in part, by the magnitude of these initial disturbances and the effort the pilot puts forth in correcting for them, rather than on the magnitudes of the ensuing bank angle excursions. The latter depend not only on the size of the gust-induced rolling moment, but also on the directional stability and roll damping of the configuration. Also, control of bank angle is performed closed loop, and the pilot may provide suitable compensation to keep the roll attitude response within tolerable limits for a wide range of configurations. However, the pilot has no way of anticipating gust disturbances, and the initial acceleration response to a gust is solely a function of the gust amplitude and the gust sensitivity

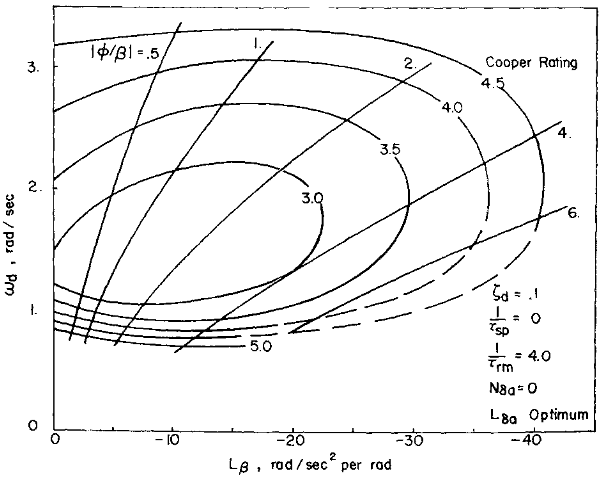


Fig. 5 Flying quality trends with the $|\varphi/\beta|$ parameter.

of the configuration (which, for the situation of interest, is defined by $L_{\beta_{turb}}$).

Although the initial roll acceleration response conceivably explains how the pilot interprets and evaluates the airplane's turbulence response characteristics, there is no firm basis in these results for asserting that this is a cue of primary importance. Pilot commentary did not explicitly reveal roll acceleration to be a factor of importance, although complaints about abrupt and severe roll disturbances could be construed to imply an awareness of the initial acceleration induced by a gust. Rather, this response characteristic is offered as a possible explanation of an as yet imperfectly understood situation. It is worthwhile noting that roll acceleration parameters have been used to correlate and predict pilot opinion for large L_β configurations.[3] The success with which open-loop response parameters such as rms roll acceleration and the ratio of roll acceleration to sideslip in the Dutch roll mode, $|\ddot{\varphi}/\beta|$, were used in this regard suggests that roll acceleration cues may well be of some consequence to the pilot. A comparison of rms roll acceleration and rms bank angle with pilot rating data indicated that the acceleration parameter was the more effective of the two in correlating the data trends. It is also interesting to note that, for the data of this program, the variation of open-loop rms roll acceleration with L_β and ω_d is more characteristic of the trends of pilot rating for large L_β than is rms roll attitude. Curves of rms roll acceleration and roll attitude per unit β gust are superposed on the pilot opinion contours in Fig. 6. Rms roll attitude is observed to be frequency-dependent in much the same fashion as $|\varphi/\beta|$, and does not account for the restriction on pilot rating at high L_β.

High Dutch roll frequency

Returning to Figure 4, the deterioration of pilot opinion at high ω_d, region B, was attributed to excessive turbulence sensitivity in yaw and to the predominant yawing motions in the airplane's response. In general, the pilots felt that the level of gust disturbances compelled them to attempt to control the yawing motions. Although these yawing motions were not overly objectionable during the approach itself, they were considered intolerable in that an asymmetric touchdown might damage the airplane. Since the ailerons are ineffective for making rapid corrections in heading, the pilots attempted to use the rudder to maintain heading alignment. They also found it difficult to control heading precisely with the rudder and often chose not to use it at all. Consequently, the pilots were faced with undesirable heading excursions, which they were more or less forced to live with.

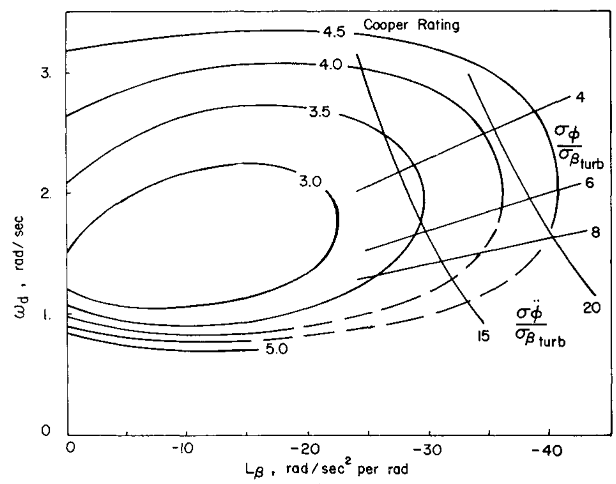


Fig. 6 Flying quality trends with rms turbulence response characteristics.

The ambiguity in defining an appropriate turbulence response characteristic to explain the pilots' objection to turbulence sensitivity exists in yaw as it did in roll. Since increasing N_β accompanies increasing ω_d, the disturbance moment due to a side gust naturally is larger at the higher frequencies. The increased magnitudes of yaw acceleration, such as the initial response to a side gust ($\ddot{\psi} \doteq N_{\beta_{turb}}\beta_{turb}$) or the rms yaw acceleration $\sigma\ddot{\psi}$, may account for the deterioration in pilot opinion. Interestingly enough, the magnitude of the yaw attitude excursions would not be expected to increase with larger N_β. The expression for the open-loop rms heading response reveals this:

$$\sigma_\psi = \left[\frac{1}{2\pi}\int_0^\infty \left|\frac{\psi}{\beta_{turb}}(\omega)\right|^2 \Phi_{\beta_{turb}}(\omega)d\omega\right]^{1/2}$$

where the ψ/β_{turb} transfer function may be approximately expressed as

$$\frac{\psi}{\beta_{turb}}(\omega) \doteq \frac{N_{\beta_{turb}}}{\omega_d^2}(-L_p\tau_{rm}) \times \left[\frac{\left(-\dfrac{\omega}{L_p}+1\right)}{(\tau_{rm}\omega+1)\left(\dfrac{\omega^2}{\omega_d^2}+\dfrac{2\zeta_d}{\omega_d}\omega+1\right)}\right]$$

and where the Bode gain of the ψ/β_{turb} transfer function is approximately 1 when $\omega_d^2 \doteq N_\beta$ and $L_p \doteq -1/\tau_{rm}$. In this case, σ_ψ may actually decrease with increasing frequency as ω_d becomes progressively larger than the bandwidth of the turbulence spectrum.

It was also considered that the high frequency of the Dutch roll mode might have been objectionable to the pilot and could have influenced his ratings. To evaluate the effects of frequency independently of turbulence sensitivity, the magnitude of yaw disturbance moments due to side gusts ($N_{\beta_{turb}}$) for the high ω_d configurations was reduced to a level comparable to configurations within the 3.0 Cooper rating contour. The dynamic response characteristics were kept the same, thereby maintaining the high Dutch roll frequency. Specically, the configurations tested were for ω_d = 3.0 rad/sec, and L_β = 0, −8, −16 rad/sec² per rad. $N_{\beta_{turb}}$ for these configurations was reduced to the level of $N_{\beta_{turb}}$ for the corresponding ω_d = 1.8 rad/sec configurations. By so doing, the pilot ratings were improved and were found to be comparable to those of the ω_d = 1.8 rad/sec configurations. Pilot commentary indicated an improvement in yaw turbulence sensitivity, and in some cases indicated that the heading excursions were acceptable with no counteracting control. As a reverse check on these results, the test configurations having ω_d = 1.8 rad/sec were evaluated with $N_{\beta_{turb}}$ at the level of the ω_d = 3.0 rad/sec configurations. Pilot ratings were found to be comparable to those of the high-frequency configurations because of the objectionable turbulence sensitivity. The unsatisfactory flying qualities at high ω_d therefore were attributed to turbulence sensitivity rather than to the frequency of the Dutch roll mode.

Low dihedral effect

For low L_β configurations, region C, the pilots objected to the predominant yawing or snaking oscillations in the airplane's response to gusts and control inputs, as was previously noted in the discussion of results. For low levels of L_β it might be expected that pilot opinion could be correlated by some factor that indicates the relative magnitudes of roll and yaw response to turbulence or controls. The magnitude of the ratios of roll to yaw or roll to sideslip would provide this information, $|\varphi/\beta|$ being one parameter of this type. However, the relationship of $|\varphi/\beta|$ to pilot opinion at low L_β shown in Fig. 5 is hardly any better than for the other three

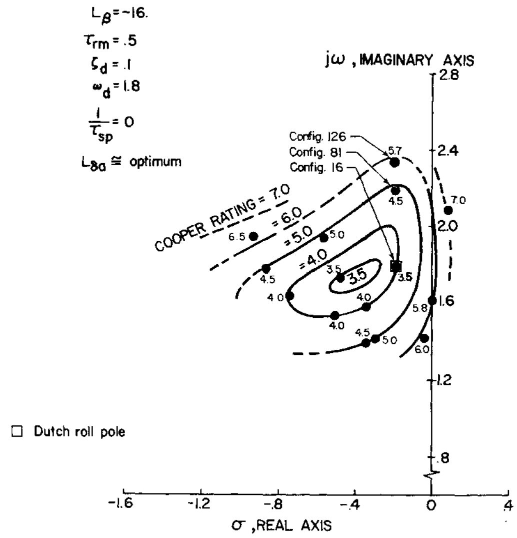


Fig. 7a Pilot opinion contours (Dutch roll zero location, $\zeta_d = 0.1$).

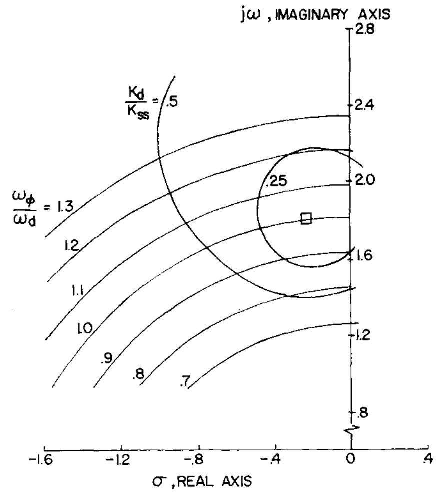


Fig. 7b Lateral flying qualities parameters.

regions. Since the airplane is being disturbed by a random input, it is possible that the pilot is more concerned with the rms magnitudes of roll and sideslip or heading excursions than with some identifiable Dutch roll oscillation. $|\varphi/\beta|$ defines the roll to sideslip ratio in the Dutch roll mode, and may not provide a good indication of the relative magnitudes of the rms rolling and sideslipping motions.

Low Dutch roll frequency

The configurations having low Dutch roll frequency, $\omega_d = 0.8$ rad/sec, were found to be objectionable because of the large yaw excursions prevalent during the approach and because of the considerable effort the pilots had to devote to maintaining heading alignment. The low level of directional stability which characterized these configurations was conducive to large sideslip angles in response to turbulence disturbances and control inputs. The pilots had direct reference to bank angle and heading information through the primary flight instruments and from external visual cues. However, sideslip could only be sensed through side acceleration as felt by the pilots or as displayed by the turn-and-bank indicator. No sideslip indicator such as might be driven by a relative wind sensor was present in the cockpit (this instrument is also not normally installed in operational Navy fighter aircraft). If side acceleration was not of sufficient magnitude to serve as an effective cue to the pilots (which it apparently was not), they would have had no useful sideslip reference. In the presence of large sideslip excursions it was necessary for them to pay continual attention to bank angle and heading to keep the airplane from drifting off of the approach flight path. The low frequency of the Dutch roll mode compounded the problem by making it difficult for the pilots to determine quickly the steady-state level of the airplane's motions. For this reason, precise and rapid corrections in heading could not be made.

Similar problems with lateral-directional dynamics have been observed in tests of STOL aircraft by NASA and are noted in the literature.[4-6] The objectionable features were observed to be excessive yaw excursions during approach maneuvers, sluggish directional response, and a lack of cues to the buildup of sideslip. In some cases, adverse aileron yaw presented a problem. Differences in aileron yaw characteristics and control system response between the STOL airplanes and Princeton test configurations make a valid comparison of the two sets of data difficult. Also, it is reasonable to expect that the demands of the approach task for each of these STOL airplanes would have been less stringent than for the carrier approach. This factor should be considered when comparing the STOL and Princeton data, in that the same configuration would likely be rated better for the less demanding task.

The airplane of Ref. 4, a Lockheed NC-130B, was rated a 6.5 based on its lateral-directional dynamics ($\omega_d \doteq 0.5$ rad/sec, $\zeta_d \doteq 0.1$). It should be noted that the level of adverse aileron yaw for the NC-130B ($N_{\delta a}/L_{\delta a} \doteq -0.22$ compared to $N_{\delta a}/L_{\delta a} = 0$ for the Princeton tests) and objectionable levels of friction in the aileron and rudder control systems may well have contributed to the 6.5 Cooper rating. However, general agreement between the two results does exist when the Princeton data are extrapolated to the lower frequency of the NC-130B. The lateral-directional characteristics of the airplane of Ref. 5, a Breguet 941 ($\omega_d \doteq 0.75$ rad/sec, $\zeta_d \doteq 0.1$, $N_{\delta a}/L_{\delta a} \doteq -0.01$, $L_\beta \doteq 0.3$ rad/sec² per rad) were given a Cooper rating of 4.0. This pilot rating is somewhat more favorable than would be expected from the iso-opinion contours of Fig. 3b, which, for this configuration, would be approximately 5.5. The test airplane of Ref. 6, the UF-XS seaplane (originally the Grumman UF-1) was given a rating of 3.5. In this case, $\omega_d \doteq 1.0$ rad/sec, and the Dutch roll damping was higher, $\zeta_d \doteq 0.3$. This pilot rating is slightly more favorable than the current results, which in this case indicate a Cooper rating of 4.0.

The influence of aerodynamic cross-coupling effects ($N_{\delta a}/L_{\delta a}$ and N_p) on the pilot's ability to control bank angle and heading has been shown in many instances to be an important factor of lateral-directional flying qualities. It is apparent from the current test program that the cross-coupling effects can be particularly significant at low levels of directional stability. These influences merit further study, particularly for the low-frequency region, to establish more definitely their influence on flying qualities. In addition, a study of the importance of cues to the pilot of the airplane's asymmetry in sideslip would also be useful in the low ω_d region.

φ/δ_a Zero Location, $\zeta_d = 0.1$, $\omega_d = 1.8$ rad/sec

A series of configurations was devised to explore the effect of aircraft control response. The parameters held fixed for this series were τ_{rm}, τ_{sp}, ζ_d, ω_d, and L_β. The values chosen were a rolling time constant of $\tau_{rm} = 0.5$ and a dihedral effect of $L_\beta = -16.0$. The two independent parameters ω_φ/ω_d and K_d/K_{ss} were varied by moving the numerator zero location of the φ/δ_a transfer function.

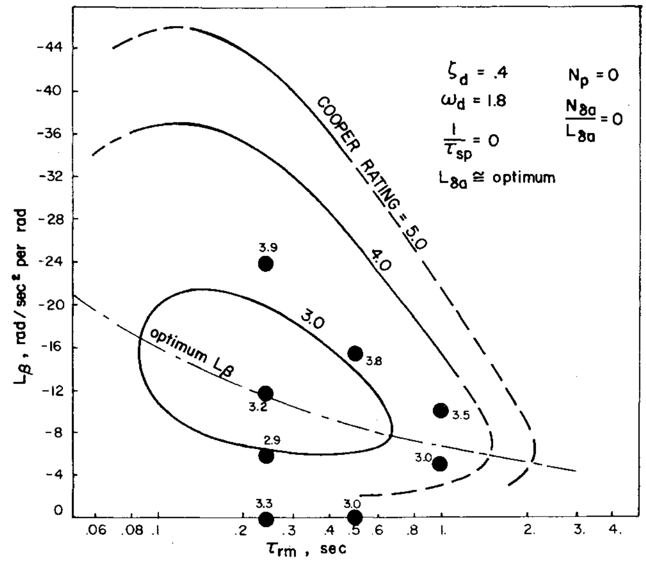
The results of the K_d/K_{ss}, ω_φ/ω_d or numerator zero location series of configurations are shown in the presentation of Figs. 7a and 7b (Fig. 7b shows the variation of K_d/K_{ss} and ω_φ/ω_d with numerator zero location). The rolling time constant of $\tau_{rm} = 0.5$ and dihedral effect of $L_\beta = -16.0$ were held fixed for all configurations. As can be seen the pilot will accept relatively large values of K_d/K_{ss}. Also, the optimum K_d/K_{ss} is not zero (Figs. 7a and 7b). The problem with $K_d/K_{ss} = 0$, $\omega_\varphi/\omega_d = 1.0$ (configuration 16) was the yaw dynamics. From the pilot's standpoint, configuration 16 with a $|\varphi/\beta| = 3.45$ is quite similar to the configurations with zero dihedral effect ($|\varphi/\beta| = 0$). The pilot commentary for successive runs reflected the good lateral characteristics and poor directional qualities of these configurations: "The problem that pass wasn't as much in roll as it was in yaw. I could maintain wings level pretty well but had to get on the rudder to keep the airplane in anywhere near balanced flight. Seemed to be yawing back and forth quite a bit" (configuration 16, $\tau_{rm} = 0.5$, $L_\beta = -16.0$; this run rated 4.0). "That pass had a lot of similarities to the last pass (configuration 16) but with the yaw problem a little more intense. I had a lot of a problem keeping the airplane down the centerline, at least the nose of the airplane down the centerline because of the yawing. Just a bit worse than the last pass with a 4.5 over-all rating" configuration 14, $\tau_{rm} = 0.5$, $L_\beta = 0$; this run rated 4.5). As in the case of $|\varphi/\beta| = 0$, the pilot cannot sufficiently damp the Dutch roll mode with ailerons alone. Consequently, the pilot must contend with a turbulence-excited Dutch roll in yaw. The roll portion of the Dutch roll can be controlled adequately though the ailerons; however, the yaw motions cannot be damped sufficiently with this technique.

It seems apparent that the pilot can readily control disturbances in roll and that he finds yaw control in turbulence difficult. There are many possible reasons for this. For example, it seems likely that he can sense roll deviations (acceleration, rate, and angle) readily; whereas, it is difficult to sense sideslip, yaw rate, and yaw acceleration. Also, the pilot's hand coordination is much more developed than his leg coordination.

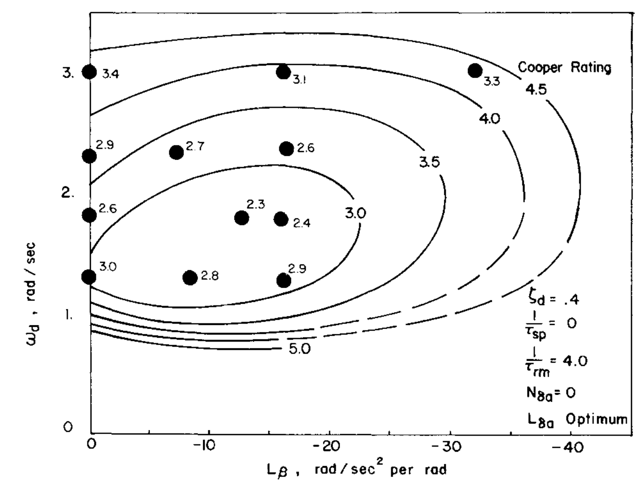
As would be expected, configurations that have their φ/δ_a numerator zeros in the right half plane are unacceptable. Configuration 81 (zero at $-0.19 \pm 2.19j$), which has a large value of ω_φ/ω_d, did not show any PIO tendencies during the approach task. This configuration was tested extensively to verify the ability of the pilot to control an aircraft with a high ω_φ/ω_d and low damping ratio. The over-all Cooper rating of the nine pilots who evaluated this configuration was 4.5. Although some test flights of configuration 81 at altitude resulted in a PIO, the configuration did not exhibit PIO tendencies during the visual approach. It is felt that during the visual approach the pilot senses roll rate effectively and uses this as a feedback in addition to roll angle to stabilize the aircraft. Pilot comments on configuration 126 ($\omega_\varphi/\omega_d = 1.3$) indicate that the problems are due to the directional motions associated with stick inputs (the high proverse yaw) rather than pilot closed-loop stability.

Effect of Dutch Roll Damping

Dutch roll damping was increased from $\zeta_d = 0.1$ to $\zeta_d = 0.4$ where additional evaluations were made for configurations covering the ranges of roll time constant, dihedral effect, Dutch roll frequency, and bank angle to aileron numerator roots previously tested. Figure 8a presents the results of the effect of Dutch roll damping on the $L_\beta - \tau_{rm}$ series of configurations. The Cooper rating boundaries of Fig. 3a are superposed on these data points. The configurations having a dihedral effect of $L_\beta = -8.0$ or larger do not show any appreciable difference in the average Cooper rating between high and low damping ratios (see Fig. 8a). Comparisons between the two sets of configurations were also made for the data of individual pilots and revealed the same results. This is significant since most of the higher damping ratio configurations were rated just before or after the corresponding configuration with low Dutch roll damping. Increasing the Dutch roll damping does significantly improve the flying



a) L_β vs τ_{rm} (contours reproduced from Fig. 3a where $\zeta_d = 0.1$)



b) ω_d vs L_β (contours reproduced from Fig. 3b where $\zeta_d = 0.1$

Fig. 8 Pilot opinion data for $\zeta_d = 0.4$ compared to contours for $\zeta_d = 0.1$.

qualities of the low dihedral effect configurations. The improvement is slightly more than a full Cooper unit. As mentioned previously, these low dihedral effect configurations are weakly coupled in roll and yaw, and the yaw oscillation could only be damped through use of the rudder. An increase in damping ratio for these configurations permitted the pilot to make a "feet off" approach.

For similar reasons, the flying qualities of the high Dutch roll frequency configurations are improved by an increase in Dutch roll damping. In Fig. 8b the iso-opinion contours for variations in Dutch roll frequency and dihedral effect for a Dutch roll damping ratio $\zeta_d = 0.1$ (from Fig. 3b) are superposed on the data points for $\zeta_d = 0.4$. At the highest frequencies tested and at zero dihedral effect for the intermediate frequencies, pilots' opinion ratings are improved a full Cooper unit. Configurations which were given good ratings for low Dutch roll damping, i.e., those configurations within the 3.0 boundary, exhibited little or no improvement for increased damping.

The effect of variations in the bank angle to aileron numerator roots seems to follow the trend previously discussed for Fig. 7a. The results are presented in Fig. 9. The rating of corresponding points from both figures can be seen to differ by approximately one Cooper unit.

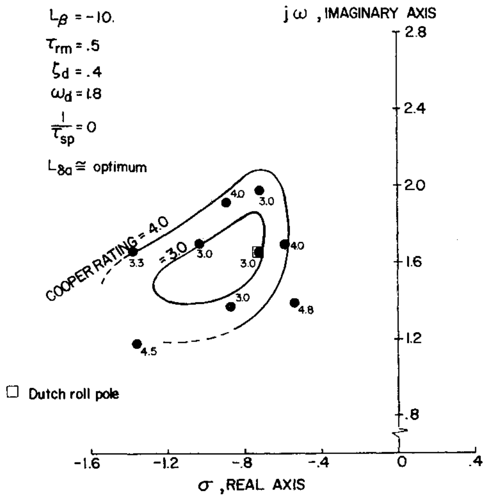


Fig. 9. Pilot opinion contours (Dutch roll zero location, $\zeta_d = 0.4$).

V. Conclusions

The test conditions and range of parameters studied in this report were the following: 1) daylight, visual landing approach, 2) moderate turbulence, and 3) neutral spiral mode, and damping ratios of 0.1 and 0.4. In view of these qualifications, the following general conclusions are drawn:

1) Turbulence is a factor of commanding importance in the lateral-directional handling qualities for the power approach condition.

2) The adverse qualities found in configurations with high L_β were determined to be chargeable against the derivative L_β and the associated sensitivity to turbulence rather than to the attending high values of $|\varphi/\beta|$ mode shape.

3) There is a maximum permissible roll time constant. As the roll time constant is increased (beyond optimum) to this value, the range of the other parameters for good flying qualities becomes more and more restrictive.

4) Configurations with predominant yawing motions, such as those for low dihedral effect or high Dutch roll frequency or both, are undesirable. The flying qualities of these configurations can be improved by increasing the Dutch roll damping.

5) Configurations having a low Dutch roll frequency are undesirable due to low directional stability as evidenced by large excursions in sideslip and by the pilot's inability to make precise and rapid corrections in the airplane's heading.

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