Lateral-Directional Dynamics and Roll Control Power for the Landing Approach

G. WARREN HALL* AND EDWARD M. BOOTHE†
Cornell Aeronautical Laboratory, Inc. Buffalo, N.Y.

Lateral-directional handling qualities and roll control power requirements for executive jet and military Class II Airplanes in the landing approach flight phase were investigated in the USAF/CAL variable stability T-33 airplane. Particular emphasis was placed on the effects of crosswinds and turbulence. It was found that the ranges of lateral-directional dynamics investigated do not establish a limiting crosswind value. Roll control power requirements were determined from pilot control usage data and an investigation of the effects of limited roll control power. Available roll control power can establish a limiting crosswind component. A detailed comparison with MIL-F-8785B(ASG) requirements generally shows the present requirements to be too conservative in the landing approach phase.

Introduction

THE landing approach phase of flight is perhaps the most critical phase for executive jet and medium weight military Class II airplanes. The routine demands placed on the pilot-airplane combination are greater, and the margin for error less, in the landing approach than in the up-and-away mission phase. Pilot workload is especially high when performing an instrument approach in turbulence with the possibility of "breaking out" at a low altitude with a lateral offset from the runway and having to make the landing in a crosswind. Good handling qualities are desirable in order not to overload the pilot during this critical flight phase. The desire for low landing approach speeds means flight at high angles of attack and/or flight with various combinations of high-lift devices. The reduction in dynamic pressure alone influences the stability characteristics of the basic airplane and reduces the effectiveness of the controls. The result is often a deterioration in handling qualities.

A flight-test program,[1] was designed to investigate the lateral-directional handling qualities of executive jet and medium weight Class II airplanes in the landing approach flight phase. The investigation was conducted in the USAF/CAL variable stability T-33 airplane. Objectives of the program were to determine the effect of variations in the lateral-directional dynamics on the landing approach handling qualities of configurations representative of executive jet and medium weight military Class II airplanes and to determine roll control power requirements, including the effect of limited roll control power, on the landing approach handling qualities. The methods used to measure and to limit the roll control power either used by or available to the evaluation pilot provided data that applies directly to roll control power requirements and is not biased by variations in aileron controller sensitivity or controller deflection limits. A further objective was the acquisition of additional data for comparison with the requirements of the latest revision of MIL-F-8785B(ASG).

Specifically, the effects of Dutch roll frequency and damping ratio, roll-to-sideslip ratio, and roll mode time constant were evaluated during simulated IFR ILS approaches and VFR lateral offset and actual crosswind approaches. Throughout the entire investigation, pilot control usage data and pilot-selected control sensitivities were recorded which allowed the determination of roll control power requirements necessary to perform the landing approach task in varying crosswind and turbulence environment conditions. Additionally, a number of configurations were re-evaluated with varying degrees of limited roll control power to determine the effect of limited roll control power on the handling qualities. The longitudinal characteristics were held constant so that the evaluations of the lateral-directional dynamics would not be influenced by varying longitudinal handling qualities.

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* Head Flying Qualities and Simulation Section.
† Associate Aeronautical Engineer. Member AIAA.

Flight-Test Program

To completely study the effects of lateral-directional dynamics on the handling qualities in the landing approach is not practical in one investigation. Thus, it was necessary to select those parameters which were expected to contribute most significantly to the landing approach task. The evaluation matrix shown in Table 1 was chosen after careful analysis of available data on executive jet and medium weight military Class II airplanes in the landing approach. Each number in the matrix of Table 1 identifies an evaluation group, that is, a specific set of lateral-directional dynamics. A configuration was defined as a specific test point within a group, characterized by an assigned value of the aileron yaw parameter $N'_{\delta_{AW}}/L'_{\delta_{AW}}$. There was a minimum of five configurations within each evaluation group. These data and past flight research indicate that the parameters selected, which adequately cover the range of lateral-directional dynamics characteristic of this class of airplanes, are the most significant for the landing approach task.

The primary parameters varied were the roll mode time constant τ_R, the Dutch roll frequency ω_d, the Dutch roll damping

Table 1 Evaluation groups

ω_d	τ_R	ζ_d	$\lvert\phi/\beta\rvert_d$ 0.25	1.5	3.0
2.0	0.4	0.03		1	
		0.10		2	4
		0.30		3	
1.0	0.4	0.03		5	8
		0.10	11_L	6_L	9_L[a]
		0.30	12	7	10
	1.0	0.10	13	14_L	15
	2.0	0.10		16_L	

[a] L—re-evaluated with limited aileron control power.

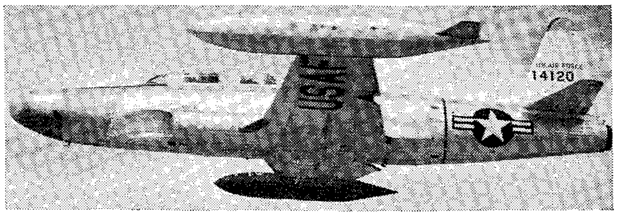

Fig. 1 USAF/CAL variable stability T-33 airplane.

ratio ζ_d, and the roll-to-sideslip ratio $|\phi/\beta|_d$. The roll mode is a primary factor in the way the airplane rolls in response to aileron control inputs. It is usually a short term response and strongly influences the pilot's control of bank angle. The Dutch roll characteristics strongly affect the control techniques the pilot will employ. Dutch roll frequency affects the pilot's ability to control heading and Dutch roll damping ratio can significantly affect bank angle controllability in the presence of external disturbances. Because of the coupling required between the lateral and directional controls in the cross-wind approach, the roll-to-sideslip ratio may also be an important Dutch roll characteristic that has a particularly strong influence on the airplane's handling qualities in a crosswind.

Since the spiral mode is a relatively long term response with little effect during a continuous closed-loop tracking maneuver, the spiral root in this investigation was held essentially neutral. Thus, the effects of varying spiral characteristics were not an object of the investigation.

Aileron and rudder control sensitivities, $L'_{\delta_{AW}}$ and $N'_{\delta_{RP}}$, respectively, are important parameters because they largely determine the size of control input that must be used for the pilot to achieve the desired airplane response. Also, $L'_{\delta_{AW}}$ is a primary factor in the determination of roll control power. Therefore, in order to minimize the effect of control motion gradients on the evaluation of the given airplane dynamics, to provide additional data on the selection of these parameters, and to arrive at values which were to later be used for roll control power evaluation and determination; the evaluation pilot was required to select both the aileron and rudder sensitivities that he considered optimum for each evaluation configuration. Evaluations for this program were performed in the USAF/CAL three-axis, variable stability T-33 airplane, Fig. 1, modified and operated by CAL for the AFFDL, Air Force Systems Command. Since most medium weight Class II airplanes are wheel controlled, a wheel controller was installed in the front cockpit (Fig. 2) for the evaluations.

In this airplane, the system operator, who is also the safety pilot in the rear cockpit, may modify the handling qualities about all three axes by changing the settings of response feedback gain controls. Since the evaluation pilot is only connected electrically to the control surface servos, he cannot feel the control surface motions resulting from the variable stability system signals. Figure 3 illustrates the mechanism of the variable stability system which makes possible the in-flight simulation capabilities of the USAF/CAL T-33. This type of system is known as a response feedback variable stability system. A complete description of the NT-33 and the variable stability equipment is contained in Ref. 2.

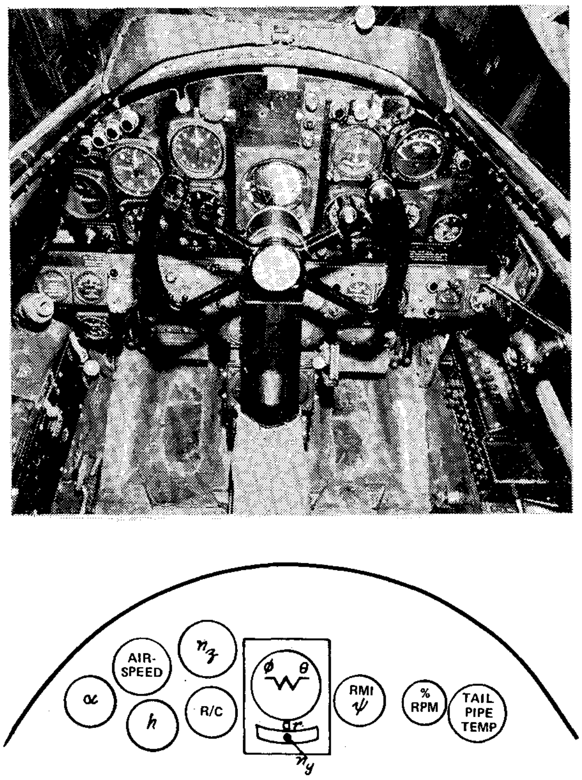

Fig. 2 Evaluation pilot's cockpit in the variable stability T-33.

The various configurations were evaluated by two engineering test pilots. An over-all pilot rating was assigned by the pilot to each configuration in accordance with the Cooper-Harper rating scale established and described in Ref. 3 and shown in Fig. 4. The mission evaluated was strictly the terminal task of IFR and VFR landing approaches, including an ILS approach under the hood, a VFR lateral offset maneuver, and a crosswind approach.

Discussion and Results

Crosswind Landings

The capability for proper execution of a crosswind approach and landing is a fundamentally important aspect of lateral-directional handling qualities in the landing approach. Two basically different techniques are usually used: the wing-down (crossed-controls) approach, and the drift (crabbed) approach. In the wing-down method, the airplane is aligned with the runway and thus experiences a steady-state sideslip which is proportional to the strength of the crosswind and inversely proportional to the approach speed. The resulting aerodynamic side force is countered by banking the airplane into

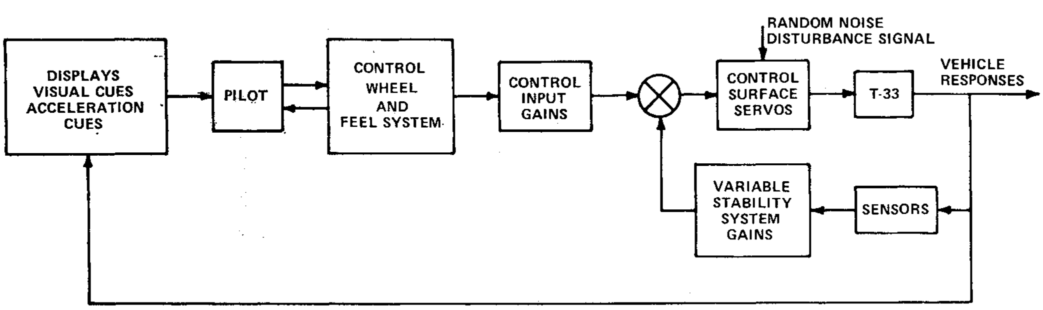

Fig. 3 Variable stability T-33 block diagram.

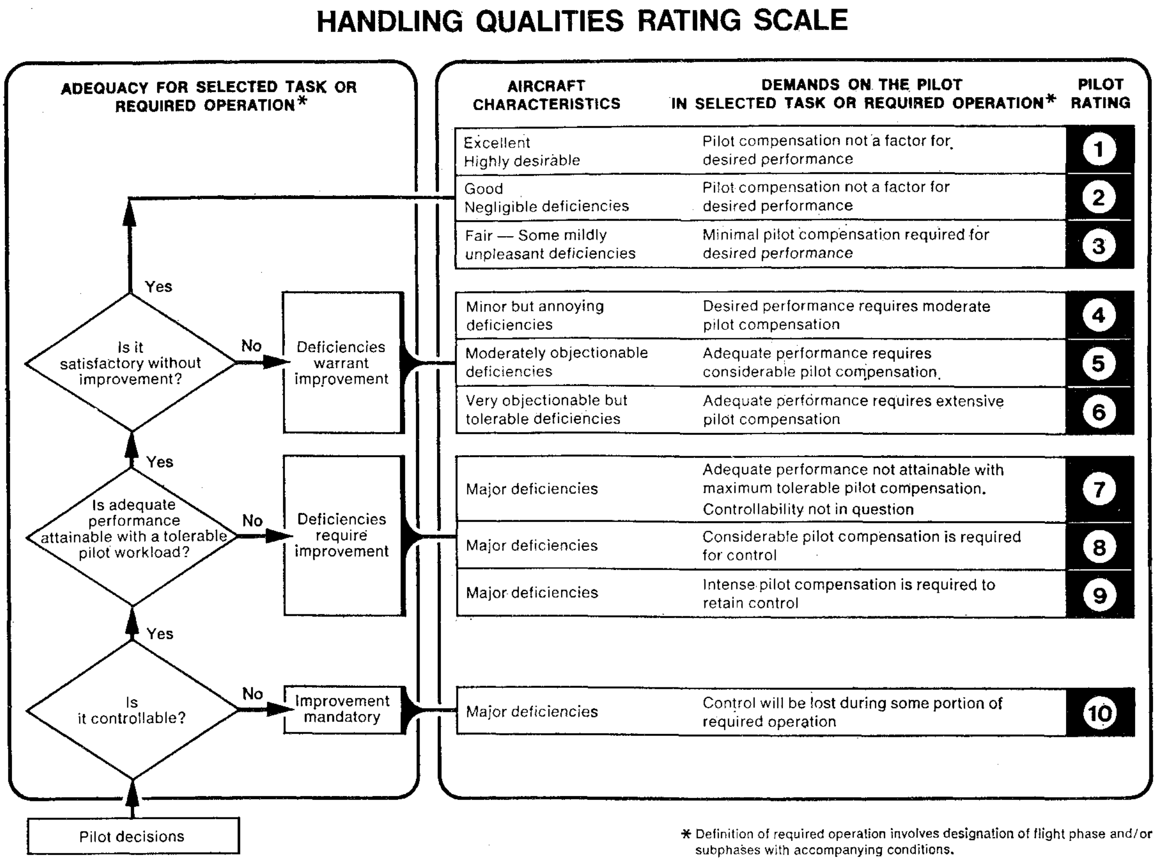

Fig. 4 Cooper-Harper handling qualities rating scale.

the wind and trimming out the sideslip-induced yawing and rolling moments by appropriate control movements. In the crabbed approach, the airplane is flown with zero sideslip but with a heading correction into the wind to keep the airplane from drifting with respect to the ground. Because of the lack of sideslip, the rudder and ailerons are essentially held neutral and the wings are level. Just before touchdown, the airplane heading is aligned with the runway. Crossed controls are required in either type of approach. In the wing-down method, the rudder and ailerons are crossed during the entire approach; for the crabbed approach, during the decrab maneuver only. In practice, however, the two techniques are usually combined.[4]

The crosswind landing approach was considered a primary evaluation task. Since flights were performed on a day-to-day basis, the available wind provided the crosswind. The bar chart shown in Fig. 5 indicates the number of configurations evaluated for 5 knot intervals of the crosswind component. At least one configuration out of each of the sixteen evaluation groups was evaluated with a 90° crosswind component exceeding 15 knots, and at least one configuration in all but three groups was evaluated for a cross-wind exceeding 20 knots. None of the approaches was flown to touchdown; however, all were flown to a level flare to assess the line-up and/or decrab capabilities of the configuration. The various combinations of lateral-directional dynamics evaluated did not prevent completing the crosswind approach in any of the cases for which sufficient aileron and rudder control power were available. This does not mean, however, that the pilots found all combinations desirable or even acceptable, only that with sufficient control power they were able to perform the crosswind approach in the maximum crosswinds available.

In the crosswind approach, low Dutch roll damping ratio, ζ_d, was not a serious problem at the high Dutch roll frequency, but became a major problem at the low frequency. The low-static directional stability resulted in a slow directional response, making it difficult to be precise with heading control in either a wing-down approach or when recovering from a crabbed condition. The continuous nose oscillations resulting from the low-damping ratio required continuous rudder inputs during the final approach. There was a strong tendency to set up a directional oscillation when attempting to execute the decrab maneuver.

The most significant effect on crosswind performance can be attributed to the roll-to-sideslip ratio, $|\phi/\beta|_d$. At the low $|\phi/\beta|_d$ evaluated ($|\phi/\beta|_d \approx 0.25$), the ability to handle the crosswind, even under extreme conditions (26 gusting to 33 knots), was considered good with either approach technique. There were occasional complaints about high-rudder

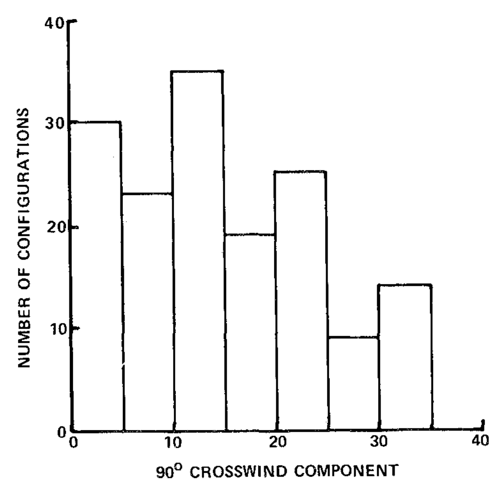

Fig. 5 Configurations evaluated at crosswind component intervals.

forces as the crosswind component became 20 knots or greater, but no complaints about the aileron forces. The story was completely different for the high $|\phi/\beta|_d$ configurations ($|\phi/\beta|_d \approx 3$) evaluated. The large roll response to rudder required large aileron forces to counteract the large and rapid roll response to rudder. Heavy aileron forces were a common complaint for these configurations even when the pilot stated that he had selected the ailerons as sensitive as he thought compatible for small maneuvers. The large roll response due to rudder created an uncomfortable transient for most decrab maneuvers in even modest crosswinds. The effects of the high $|\phi/\beta|_d$ at the high Dutch roll frequency ($\omega_d \approx 2.0$ rad/sec) were less objectionable than at the low frequency. The higher directional stability tended to reduce the total bank angle excursions even though the initial roll response to a turbulence input was quite rapid. With the high $|\phi/\beta|_d$, it was possible to use up the available aileron control power with increasing rudder input.

There was little difference in the pilot's ability to handle the cross-wind approaches for roll mode time constants, τ_R, of 0.4 sec and 1.0 sec. The effect of roll mode time constant did show up, however, for the configurations with $\tau_R \approx 2.0$ sec where the tendency to overcontrol in roll was particularly disturbing when encountering gusty crosswinds near the ground.

It was concluded that even though the lateral-directional dynamics, per se, when flown with no limits on roll control power, did not establish a limiting crosswind value, they did in fact determine the difficulty or ease with which the pilot could counter crosswind effects.

Roll Control Power

The provision of adequate roll control power is necessary to cope with a combination of normal landing approach maneuvers while the pilot is simultaneously dealing with the problems of crosswinds and turbulence or gust upsets. A lateral offset may further make stringent demands on the roll control power available. The minimum acceptable approach speed can, and has been in some cases, dictated by the provision for adequate roll control power.

In the landing approach configuration with the associated slow speed, the aerodynamic forces, including aileron effectiveness, are reduced from those acting at high-speed cruise conditions. The use of small airports by high-speed executive jets requires low landing approach speeds. But approach speeds cannot be reduced if adequate roll control power is not maintained at the low speeds. In a strong crosswind, both the wing-down and "decrab" approach may make heavy demands on roll control; i.e., balancing the roll due to the sideslip and rudder with aileron control while maintaining runway alignment, or maintaining wings level with aileron while using the rudder to decrab. As the landing approach speed is reduced, the sideslip required to maintain runway alignment for a similar crosswind component is increased or the crab angle relative to the runway is increased. Hence, with either crosswind approach method, decreasing final approach airspeed increases the demands on roll-control power. Without adequate roll control power it may be impossible to maintain the necessary sideslip or to hold the wings level during the decrab maneuver. This may restrict, possibly severely, the crosswind capability of the airplane or induce accidents since it would not be possible to precisely position the airplane relative to the runway.

Roll control power requirements are also related to the differences in gust response of various airplanes. If the airplane is susceptible to a large rolling response to side gusts, as with a large dihedral effect, then roll control power requirements may be greater than for airplanes with low dihedral. The gust response is of prime importance during the approach and landing. Lateral gust upsets from which a recovery cannot be made fast enough may lead to aborted landing attempts or to wing tips or wing tip fuel tanks actually striking the ground, possibly with catastrophic results.

In this flight-test program, evaluations were performed under varying turbulence and crosswind conditions for a wide spectrum of lateral-directional dynamics. The pilots were evaluating the actual landing approach task, therefore roll control power obtained from measurements during this phase should realistically determine the roll control power requirements for executive jet military Class II airplanes in the landing approach. Table 2 shows the maximum, average and minimum values of roll control power used for each evaluation group. These values were determined from the pilot selected values of aileron wheel sensitivity, $L'_{\delta_{AW}}$, and cumulative probability density plots of the pilot's aileron wheel inputs which were recorded during the in-flight evaluations.

The range between the minimum and maximum values shown in Table 2 reflects the variations in atmospheric conditions, variations in the aileron yaw parameter and individual pilot technique, but since they are the values that the pilot actually used, they represent the roll control power necessary for maneuvering to accomplish the landing approach task. The values presented do not include the increment of additional roll control power that may be necessary to cope with asymmetric power or loading conditions or other states of aircraft failure.

Having accumulated aileron wheel sensitivity data and aileron wheel deflection data, a basis was formed from which further investigation of roll control power requirements for selected configurations could progress. Additional evaluations were performed to investigate the effects of limited roll control power and to determine those parameters that are most significant in establishing minimum roll control power requirements. Several options were available to limit the roll control power, including: 1) selection of aileron control sensitivities to limit the maximum roll control power, 2) mechanical stops to limit the aileron wheel travel, and 3) limits on the electrical signal representing wheel deflection. In this case, the mechanical stops remain fixed at $\pm 45°$. It was decided not to change the aileron wheel sensitivities from those previously selected by the evaluation pilots as optimum. Maintaining the previously selected sensitivity values avoided the introduction of another variable into the evaluation of roll control power. In this way, the evaluation pilot was presented with the same configuration he had previously evaluated with the single exception of available roll control power.

Mechanical stops were not used since the evaluation pilots would have been aware of hitting the stops and, therefore, would have had a priori knowledge of roll control limitations. Roll control power was therefore limited by mechanizing the aileron control system as shown in Fig. 6. Thus, the aileron deflection was limited by limiting the maximum electrical signal from the aileron wheel to the aileron surface servo-

Table 2 Maximum, average and minimum values of roll control power (deg/sec²) used by the pilots in evaluation of the sixteen basic groups of modal parameters

ω_d	τ_R	ζ_d	$\lvert\phi/\beta\rvert_d$ 0.25	1.5	3.0
2.0	0.4	0.03		51/46/38[a]	
		0.10		50/42/31	86/44/25[a]
		0.30		59/45/30	
1.0	0.4	0.03		61/45/34	79/61/45
		0.10	57/43/25*	42/36/30	93/50/47
		0.30	58/46/37	56/47/35	72/43/30
	1.0	0.10	45/30/21	32/24/17	38/31/22
	2.0	0.10		24/20/14	

[a] Maximum, average, and minimum values, respectively.

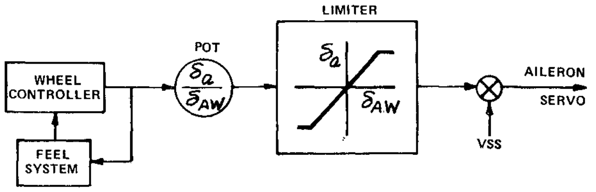

Fig. 6 Aileron limiter schematic.

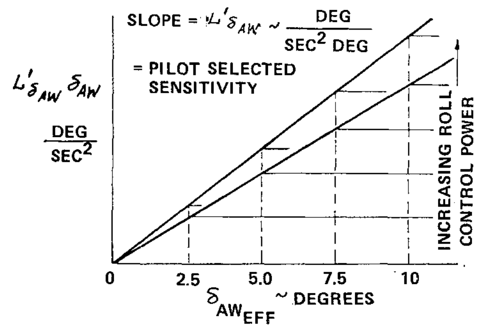

Fig. 7 Limiting of $\delta_{W_{EFF}}$.

actuator. This mechanization allowed the system operator/safety pilot to select the effective wheel deflection, $\delta_{AW_{EFF}}$. Thus, the wheel was allowed to move a full 45° right and left but would command aileron deflections only through a predetermined range of its travel. Since the control sensitivities were held constant at those previously selected by the evaluation pilots, the only variable was the limited roll control power. Figure 7 shows the effect on roll control power of limiting the effective wheel deflection.

As indicated by Fig. 7, the same $\delta_{AW_{EFF}}$ provided each pilot with slightly different values of $L'_{\delta_{AW}}\delta_{AW_{EFF}}$ because, as previously noted, sensitivities were maintained at values that the evaluation pilots had selected as optimum. The selection of values of $\delta_{AW_{EFF}}$ was based on an examination of the control usage data recorded during the evaluations of the groups depicted in Table 1. During the initial evaluations, wheel deflections, δ_{AW}, greater than 15° were seldom used. Therefore, to study the effects of limited roll control power, $\delta_{AW_{EFF}}$ was limited to values less than or equal to 15°.

Figure 8 shows the degradation of pilot rating with decreasing roll control power for the five groups evaluated with limited roll control power. The distinguishing lateral-directional modal parameters associated with each curve are shown in the figure. Table 1 gives a complete description of each evaluation group, all of which had a Dutch roll frequency, ω_d, of approximately 1 rad/sec, and a Dutch roll damping ratio, ζ_d, of approximately 0.1. Evaluations with limited roll control power were conducted for only one configuration within each group, each configuration having the same value of the aileron yaw parameter, $N'_{\delta_{AW}}/L'_{\delta_{AW}}$. The value of the aileron yaw parameter selected for these configurations was a slightly proverse value, $L'_{\delta_{AW}}/N'_{\delta_{AW}} = 0.05$. This value was near the best pilot rating obtained for each group. This allowed limited roll control power data to be compared to near optimum pilot ratings for the cases previously evaluated with no limits on roll control power.

Both evaluation pilots generally tended to complain about decreased sensitivity as the effective aileron wheel throw was progressively limited, only occasionally mentioning the need for more aileron control power. As the wheel moved beyond the effective wheel throw against a constant spring gradient, the pilot would observe a reduced roll rate and consider the control sensitivity reduced. As the control power became more severely limited, both evaluation pilots commented on the low steady-state roll rates available. Even with severely limited roll control power, neither pilot encountered much difficulty with small magnitude maneuvers, but performing crosswind and lateral offset approaches, especially in turbulence, often became a formidable task. Neither pilot recognized that a nonlinearity existed in the control system.

Groups 6 and 11, both of which had a roll mode time constant, τ_R, of approximately 0.40 sec, but roll-to-sideslip ratios of 1.5 and 0.25, respectively, showed the same trend in pilot rating with decreasing roll control power. Both groups had a maximum roll control power usage of approximately 50 deg/sec². Both were flown in crosswinds exceeding 20 knots and were rated satisfactory for roll control power as low as 30 deg/sec². There were essentially no differences between these two groups.

The salient feature of group 9 was the high roll-to-sideslip ratio, $|\phi/\beta|_d$, of 3.1, twice that of group 6. The Dutch roll frequency and damping ratio, and the roll mode time constant were the same as groups 6 and 11. The plot of this group on Fig. 8 clearly shows the effect of crosswind component on required roll control power for an airplane with appreciable dihedral. A pilot rating of 6.5 was found to correspond to roll control power of 40 to 45 deg/sec² for crosswinds of 10 to 15 knots, but 70 to 80 deg/sec² was required with crosswinds of 25 to 30 knots. Group 9 was never rated satisfactory, therefore requirements for a pilot rating of 3.5 could not be defined. The major objections to this group were large lateral upsets near the ground which were difficult to correct and the large rolling reponse due to rudder which must be countered with ailerons.

Group 14 was characterized by a moderate roll mode time constant ($\tau_R = 1.1$), otherwise this group was similar to group 6. The maximum roll control power used for this configuration was 17 deg/sec². Satisfactory ratings were obtained in

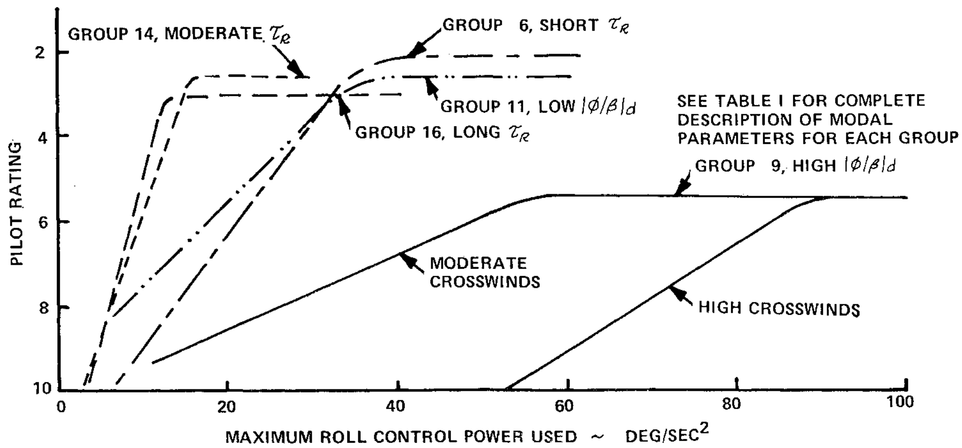

Fig. 8 Pilot rating vs maximum roll-control power used-comparison of groups.

Table 3 Roll performance measures found to correspond to $PR = 3.5$, $\omega_d \approx 1.0$ rad/sec, $\zeta_d \approx 0.10$, $|\phi/\beta|_d \approx 1.5$

Conf.	τ_R sec	Roll Control Power deg/sec²	ϕ_1 deg	$\phi_{1.8}$ deg	p_{ss} deg/sec	Maximum X-wind Knots
6P1[a]	0.4	30	7.4	15.9	10.4	22
11P1[b]	0.4	30	7.1	15.1	10.4	26
14P1	1.1	14	5.5	14.4	13.8	30
16P1	2.0	12	6.5	16.6	16.6	20

[a] Indicates $N'\delta_{AW}/L'\delta_{AW} = +0.05$
[b] $|\phi/\beta|_d = 0.25$ for configuration 11P1.

crosswinds of 20 to 30 knots. With a roll control power limit of 8 deg/sec², the pilot was still able to cope with a 19-knot crosswind, but found his roll control barely adequate for the lateral offset approach and cautioned that rapid rolling maneuvers should be avoided. When the roll control power was reduced to 5 deg/sec², the pilot could not perform the crosswind approach.

Group 16 differed from group 6 only by its long roll mode time constant, τ_R, of 2 sec. The maximum control power used for this configuration was 25 deg/sec². This group was evaluated in a crosswind of 18 gusting to 22 knots with no limits on the roll-control power (within, of course, the constraints of the T-33 variable stability airplane) and was rated satisfactory with a maximum roll power usage of 14 deg/sec². With the roll control power reduced to 8 deg/sec², the pilot had no difficulty with a 25 gusting to 33 knot crosswind. The major problem was the inability to stop a given roll rate with sufficient precision close to the ground.

The values of roll control power found to correspond to a $PR = 3.5$ are shown in Table 3 and, in the case of group 9, roll control power values found to correspond to a $PR = 6.5$ are shown in Table 4. In general these values agree well with the minimum values shown in Table 2 indicating that it was possible to limit the roll control power only to the minimum values recorded during the basic group evaluations without degrading the pilot ratings.

MIL-F-8785B(ASG) places a requirement on roll control power in the landing approach for Class II airplanes of 30° in 1.8 sec for Level 1 flying qualities. Other studies have suggested bank angle in 1.0 sec as a measure of roll performance in the landing approach. The values of roll control power, bank angles in one second, ϕ_1, and 1.8 sec, $\phi_{1.8}$, and steady-state roll rates, p_{ss}, found to correspond to a pilot rating, PR, equal to 3.5 are shown in Table 3. In the case of group 9, which was never rated better than a pilot rating of 5, similar values found to correspond to a pilot rating of 6.5 are in Table 4. Except for the high $|\phi/\beta|_d$ case, satisfactory pilot ratings were obtained for bank angle in 1.8 sec of near 16°, considerably less than 30°.

In summary, adequate roll control power is a function of roll mode time constant as well as roll-to-sideslip ratio. As the roll mode time constant is increased, the requirement on roll control power is reduced. As the roll-to-sideslip ratio is increased, the requirements on roll control power are correspondingly increased. The roll control power available can establish a limiting crosswind value. Steady-state roll rates, p_{ss}, of 10 deg/sec to 20 deg/sec were found to provide satisfactory roll performance for this class of airplanes in the landing approach flight phase.

Table 4 Roll performance measures for configuration 9P1[a] $\omega_d \approx 1.0$ rad/sec, $\zeta_d \approx 0.10$, $|\phi/\beta|_d \approx 3.0$

Conf.	τ_R sec	Roll Control Power	ϕ_1 deg	$\phi_{1.8}$ deg	p_{ss} deg/sec	Maximum X-wind Knots
9P1[a]	0.4	77	18.4	38.5	22.3	30
9P1[a]	0.4	42	10.1	20.8	12.2	10

[a] Configuration 9P1 was never rated better than $PR = 5$; thus, numbers represent roll control power requirements for a $PR = 6.5$.

Lateral-Directional Dynamics

The best configurations evaluated were those with the high Dutch roll frequency ($\omega_d \approx 2.0$ rad/sec), high damping ratio ($\zeta_d \approx 0.3$), short roll mode time constant ($\tau_R \approx 0.4$ sec), and moderate roll-to-sideslip ratio ($|\phi/\beta|_d \approx 1.50$).

Low Dutch roll damping ratio ($\zeta_d \approx 0.03$) was more acceptable at the high Dutch roll frequency ($\omega_d \approx 2.0$ rad/sec) than at the low ($\omega_d \approx 1.0$ rad/sec). With $\zeta_d \approx 0.03$, both high- and low-frequency configurations were degraded because of coordination requirements associated with the slow directional response that resulted from the reduced static directional stability. The low-directional stability leads to overcontrol with the rudder, and the low damping ratio results in persistent directional oscillations. There was essentially no difference in the pilot ratings obtained for the configurations evaluated at the low and high Dutch roll frequencies ($\omega_d \approx 1.0$ and $\omega_d \approx 2.0$ rad/sec) for a Dutch roll damping ratio of $\zeta_d \approx 0.1$ and a moderate roll-to-sideslip ratio ($|\phi/\beta|_d \approx 1.5$). The effect of a high roll-to-sideslip ratio ($|\phi/\beta|_d \approx 3.0$) was less degrading at the high Dutch roll frequency ($\omega_d \approx 2.0$ rad/sec) than at the low frequency ($\omega_d \approx 1.0$ rad/sec). The low-directional stability associated with the low Dutch roll frequency leads to larger side-slip excursions and consequently larger roll angles with a corresponding degradation in roll control. The large roll disturbance in turbulence was objectionable at both frequencies evaluated. The combination of low Dutch roll frequency ($\omega_d \approx 1$ rad/sec), low-damping ratio ($\zeta_d \approx 0.03$), and high roll-to-sideslip ratio was unacceptable for all evaluation points. The combination of low ζ_d and high $|\phi/\beta|_d$ created severe coordination problems and resulted in sustained lateral oscillations in turbulence.

For the medium roll-to-sideslip configurations, the majority of the improvement in pilot rating occurred when Dutch roll damping ratio was increased from $\zeta_d \approx 0.03$ to $\zeta_d \approx 0.1$. A further increase in damping ratio to $\zeta_d \approx 0.26$ did not improve the pilot ratings proportionately. Although an increase in Dutch roll damping ratio above $\zeta_d \approx 0.1$ does not significantly improve the handling qualities, it does produce a dramatic improvement in the turbulence response (i.e., turbulence rating) and riding qualities. The desired level of Dutch roll damping ratio was also strongly influenced by the amount of roll-sideslip coupling. When the roll-to-sideslip ratio is high, the Dutch roll damping ratio should also be high.

There was essentially no difference in the desirability of the handling qualities between the configurations evaluated with the same Dutch roll frequency and damping ratio and roll mode time constant for roll-to-sideslip ratios in the order of 0.25 to 1.5. There was little difference in the pilot ratings and pilot comments for similar configurations evaluated at roll mode time constants of 0.4 and 1.0 sec. However, a roll mode time constant of 2.0 sec is only marginally satisfactory (i.e., $PR \approx 3.5$) for the landing approach phase of flight. The combination of high roll-to-sideslip ratio ($|\phi/\beta|_d \approx 3$) and moderate roll mode time constant ($\tau_R \approx 1$ sec) is not satisfactory for the landing approach. The large roll rates that result from sideslip excursions or rudder inputs are difficult to counter with the longer roll mode time constant.

In summary, a good or satisfactory set of lateral-directional dynamics allows considerable variation in each of the lateral-directional parameters while retaining a configuration with satisfactory handling qualities. Acceptable tradeoffs can occur over quite a wide range, for example, a low Dutch roll damping ratio is more acceptable if the Dutch roll frequency is high, which was an expected result. Long roll mode time constants are more acceptable with a low-effective dihedral as manifested by a low value of $|\phi/\beta|_d$. Combinations of high roll-to-sideslip ratio, $|\phi/\beta|_d$, and low Dutch roll damping ratios, ζ_d, lead to degraded handling qualities. The data included in Ref. 1 provides information which can guide the airplane designer in arriving at a satisfactory set of lateral-directional parameters for the landing approach flight phase for medium weight Class II airplanes.

Comparison with MIL-F-8785B(ASG)

The configurations evaluated during this flight program were considered to be Land Based (L), Class II airplanes in the terminal or landing approach Flight Phase (Category C). MIL-F-8785B(ASG) requires the minimum Dutch roll frequency and damping ratio for Level 1 flying qualities to be greater than $\zeta_d = 0.08$ or $\zeta_d\omega_d = 0.15$ rad/sec with the governing requirement being that which yields the larger value of ζ_d. Five groups of configurations (6, 11, 13, 14, and 16) received satisfactory pilot ratings (i.e., $PR \leq 3.5$) for a value of $\zeta_d\omega_d \approx 0.10$. These occurred for $\omega_d \approx 1$ rad/sec and $\tau_d \approx 0.1$. The large number (41) of satisfactory pilot ratings obtained for this combination of Dutch roll frequency and damping ratio indicate that, for the landing approach flight phase, the MIL-F-8785B(ASG) requirements on minimum $\zeta_d\omega_d > 0.15$ for Level 1 may be too restrictive.

Groups 1 ($\omega_d \approx 2$ rad/sec, $\zeta_d \approx 0.3$) and 5 ($\omega_d \approx 1$, $\zeta_d \approx 0.03$) indicate that requiring a Level 2 minimum of $\zeta_d \geq 0.02$ is probably a good boundary but requiring a minimum $\zeta_d\omega_d \geq 0.05$ is possibly too restrictive for the landing approach. The results of this experiment indicate that a roll mode time constant as long as 2 sec may result in pilot ratings less than 3.5. This result must, however, be exercised with caution since in this flight experiment the zeros in the ϕ/δ_a transfer function were located such that the phasing of the Dutch roll mode tends to reduce the effect on the long roll mode time constant. To provide a more direct evaluation of the roll mode time constant, per se, it would be best to evaluate configurations which have very little Dutch roll excitation due to aileron inputs.

In order to compare the data obtained in this program to the roll-sideslip coupling requirements of MIL-F-8785B(ASG), it was necessary to calculate the parameters p_{osc}/p_{AV} and $\Delta\beta_{max}/\kappa$ from the flight-test data. p_{osc}/p_{AV} is a measure of the ratio of the oscillatory component of roll rate to the average component of roll rate following a rudder-pedals-free aileron step control command. $\Delta\beta_{max}$ is the maximum sideslip excursion at the c.g., occurring within two seconds or one-half period of the Dutch roll, whichever is greater, following a step aileron command. The parameter κ is the ratio of the "commanded roll performance" to the "applicable roll performance requirement" established for the class and flight phase of the airplane being evaluated. The requirement on roll performance allows rudder pedals to be used to reduce sideslip that retards roll rate but not to produce sideslip that augments roll rate, provided rudder pedal inputs are simple, easily coordinated with aileron-control inputs, and are consistent with the piloting techniques for the particular airplane class and mission. For this reason, the commanded bank angle used to determine κ for these configurations was determined to be the bank angle achieved for the configuration which had minimum sideslip but which was not in the proverse sense. This value of commanded bank angles was then used to compute the value of κ for all configurations that had sideslip in the more adverse sense. For those configurations which did have proverse sideslip, the actual commanded bank angle was used to determine the desired value of κ. The Level 1 roll requirement for land-based Class II airplanes in the landing approach was given in Ref. 5 as 30° in 1.8 sec. This value was used as the "applicable roll performance requirement".

Having defined and computed the roll-sideslip coupling parameters p_{osc}/p_{AV} and $\Delta\beta_{max}/\kappa$, a decision was required as to whether to test only those configurations for Level 1 roll-sideslip coupling requirements which met the Level 1 Dutch roll frequency and damping requirements, or to test all configurations which met some standard, to be defined, which was less than Level 1. The experimental results of this investigation indicate that the Dutch roll damping criteria requiring $\zeta_d\omega_d \geq 0.15$ for Level 1 flying qualities may be too restrictive. The minimum damping ratio requirement of $\zeta_d \geq 0.08$ could neither be confirmed nor refuted. For this reason, those configurations which did not meet the $\zeta_d \geq 0.08$ were not considered to meet the Level 1 requirements. Those configurations which met the $\zeta_d \geq 0.08$ but which did not satisfy the $\zeta_d\omega_d \geq 0.15$ were considered to meet the Level 1 criteria for the comparison of p_{osc}/p_{AV} and $\Delta\beta_{max}/\kappa$ to MIL-F-8785B (ASG) requirements. Figure 9 shows the p_{osc}/p_{AV} locations of the configurations which met the $\zeta_d \geq 0.08$ damping ratio requirement and the $\Delta\beta_{max}/\kappa$ Level 1 criteria. Figure 10 shows the $\Delta\beta_{max}/\kappa$ locations for the configurations which meet the $\zeta_d \geq 0.08$ damping ratio requirement and p_{osc}/p_{AV} criteria. Only four configurations which pass the Level 1 test for both the p_{osc}/p_{AV} and $\Delta\beta_{max}/\kappa$ criteria are rated worse than a pilot rating of 3.5 and three of these configurations fall on the Level 1 boundary for p_{osc}/p_{AV}. There are twelve configurations which are rated 3.5 or better which fail to meet the Level 1 criteria for either or both oscillatory requirements.

If the $\Delta\beta_{max}/\kappa$ requirement, between $\psi_\beta = -200°$ and

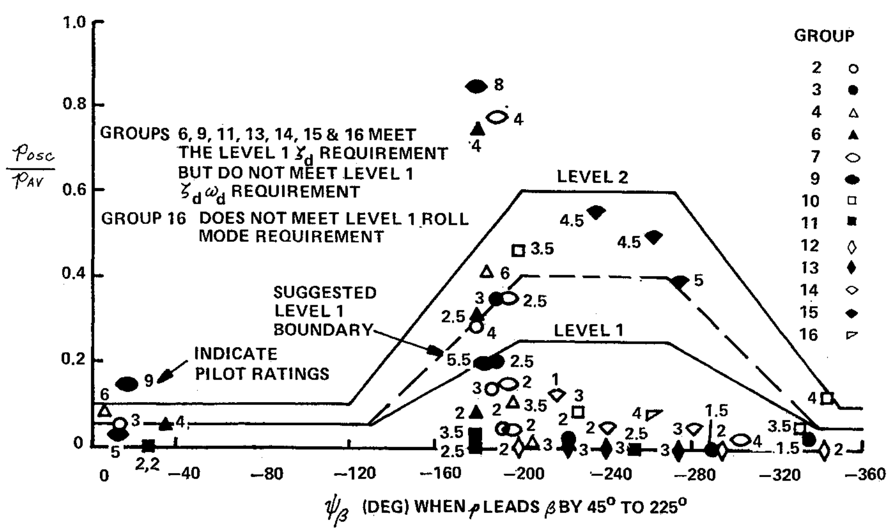

Fig. 9 p_{osc}/p_{AV} vs ψ_β for configurations which meet appropriate $\Delta\beta_{max}/\kappa$ criteria.

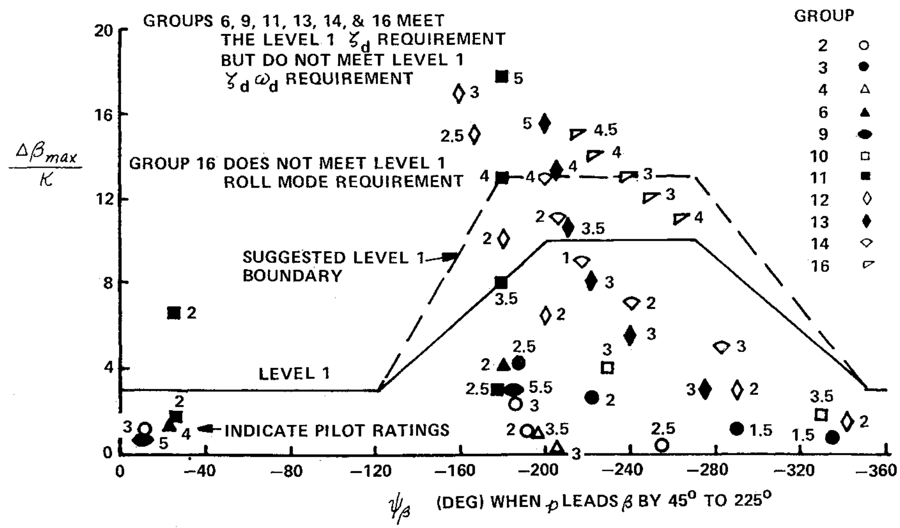

Fig. 10 $\Delta\beta_{max}/\kappa$ **vs** ψ_β **for configurations which meet appropriate** p_{osc}/p_{AV} **criteria.**

$-270°$, where ψ_β is the phase angle in a cosine representation of the Dutch roll component of sideslip, were raised from $\Delta\beta_{max}/\kappa = 10$ to $\Delta\beta_{max}/\kappa = 13$, Fig. 10, six configurations that were rated $PR = 3.5$ or better would meet the Level 1 criteria. Only one configuration, which is rated worse than 3.5, $PR = 4$, would be included since all other points which were rated worse than 3.5 in this area either fail to meet the $\zeta_d \geq 0.08$ or p_{osc}/p_{AV} criteria. Raising Level 1 p_{osc}/p_{AV} boundary from 0.25 to 0.4 in the region between $\psi_\beta = -200°$ and $-270°$ would include three configurations rated better than 3.5 and three configurations rated worse than 3.5. Two of the points rated worse than 3.5 also met the Level 1 $\Delta\beta_{max}/\kappa$ criteria. Raising the Level 2 p_{osc}/p_{AV} boundary, Fig. 9 from 0.6 to 1 in the region between $\psi_\beta = -200°$ and $-270°$ would include three configurations rated $3.5 < PR \leq 6.5$ and not pick up any rated $PR > 6.5$. Data from this experiment are sparse in this area, however.

In general, the results of this investigation indicate that the present MIL-F-8785B(ASG) requirements on lateral-directional flying qualities parameters in the landing approach Flight Phase are conservative, i.e., only a few poorly rated configurations passed all of the requirements but several configurations were rejected by one or more of the requirements even though the pilot rating did not warrant rejection. Further, as indicated by the results of the roll control power study, the bank angle requirements of 30° in 1.8 sec may be too high for airplanes with low-effective dihedral, but when the effective dihedral, or roll-to-sideslip ratio is large, more than 30° of bank angle in 1.8 sec may be required.

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