An In-Flight Investigation of Bank-Angle Control Parameters for Cruising Flight

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An in-flight investigation in a variable stability airplane has shown that some degree of spiral stability is desirable in cruising flight and that not all aspects of a stable spiral are necessarily good. The amount of spiral stability needed and the acceptability of the handling qualities are a function of roll damping, roll-to-sideslip ratio, and aileron friction characteristics. A basic configuration representative of a high altitude, high speed, executive jet airplane was selected. The Dutch roll frequency and damping ratio and longitudinal handling qualities were held constant. Two values of roll-mode time constant and roll-to-sideslip ratio were evaluated for a large variation in spiral characteristics. In addition, a subset of configurations was evaluated with aileron friction. The vehicle used was the USAF/CAL variable stability T-33 airplane equipped with a wheel controller. Both VFR and IFR conditions were investigated.

Nomenclature

F_{AW} = aileron wheel force, lb
g = acceleration of gravity, ft/sec²
I_x = moment of inertia about x axis, ft-lb sec²
I_y = moment of inertia about y axis, ft-lb sec²
I_z = moment of inertia about z axis, ft-lb sec²
I_{xz} = product of inertia, ft-lb sec²
kts = knots
L = rolling moment, ft-lb
L_β = $(1/I_x)(\partial L/\partial\beta)$, sec^{-2}
$L_{\delta a}$ = $(1/I_x)(\partial L/\partial\delta_a)$, sec^{-2}
$L_{\delta AW}$ = $(1/I_x)(\partial L/\partial\delta_{AW})$, sec^{-2} in.$^{-1}$
$L_{\delta RP}$ = $(1/I_x)(\partial L/\partial\delta_{RP})$, sec^{-2} in.$^{-1}$
L_p = $(1/I_x)(\partial L/\partial p)$, sec^{-1}
L_r = $(1/I_x)(\partial L/\partial r)$, sec^{-1}
L_ϕ = $(1/I_x)(\partial L/\partial\phi)$, sec^{-2}
L_i' = $[1 - (I_{xz}^2/I_xI_z)]^{-1}[L_i + (I_{xz}/I_x)N_i]$, $i = \beta,\delta_a,\delta_{AW},\delta_r,\delta_{RP},p,r,\phi$
N = yawing moment, ft-lb
N_β = $(1/I_z)(\partial N/\partial\beta)$, sec^{-2}
$N_{\delta AW}$ = $(1/I_z)(\partial N/\partial\delta_{AW})$, sec^{-2} in.$^{-1}$
$N_{\delta RP}$ = $(1/I_z)(\partial N/\partial\delta_{RP})$, sec^{-2} in.$^{-1}$
N_p = $(1/I_z)(\partial N/\partial p)$, sec^{-1}
N_r = $(1/I_z)(\partial N/\partial r)$, sec^{-1}
N_i' = $[1 - (I_{xz}^2/I_xI_z)]^{-1}[N_i + (I_{xz}/I_z)L_i]$, $i = \beta,\delta_a,\delta_{AW},\delta_r,\delta_{RP},p,r$
n_y = side force acceleration, g units
n_z = normal acceleration, g units
p = roll rate, rad/sec or deg/sec
PR = pilot rating
R/C = rate of climb
RMI = radio magnetic indicator
r = yaw rate
$T_{1/2}$ = time to one half amplitude, sec
T_2 = time to double amplitude, sec
V = true velocity, fps
Y = side force, lb
Y_β = $(1/mV)(\partial Y/\partial\beta)$, sec^{-1}
$Y_{\delta AW}$ = $(1/mV)(\partial Y/\partial\delta_{AW})$, sec^{-1} in.$^{-1}$
$Y_{\delta RP}$ = $(1/mV)(\partial Y/\partial\delta_{RP})$, sec^{-1} in.$^{-1}$
Y_p = $(1/mV)(\partial Y/\partial p)$, rad^{-1}
Y_r = $(1/mV)(\partial Y/\partial r)$, rad^{-1}
α = angle of attack, rad
β = angle of sideslip, rad or deg
δ_a = aileron deflection, rad
δ_{a_c} = aileron command, rad
ζ_{SP} = longitudinal short-period damping ratio
ζ_d = Dutch roll damping ratio
θ = pitch angle from trimmed level flight
τ_c = $K_{\delta a/p}/K_{\delta a/\phi}$
τ_R = roll mode time constant, sec
τ_S = spiral mode time constant, sec
ϕ = bank angle, rad or deg
$|\phi/\beta|_d$ = magnitude of roll-to-sideslip ratio in the Dutch roll mode
ψ = heading angle, deg
ω_d = Dutch roll undamped natural frequency, rad/sec
ω_{SP} = longitudinal short-period undamped natural frequency, rad/sec

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Introduction

In recent years, we have witnessed a tremendous change in both the physical characteristics and operational use of military, transport and general-aviation aircraft. In the latter category, the increased power available from light weight engines has led to the development of faster airplanes with heavier wing loadings. A review of the existing handling qualities of this present generation of airplanes indicated that the flying qualities have not kept pace with their performance developments.

In particular, the advent of the executive jet transport, as a replacement for the original piston powered fleet of executive airplanes, has brought with it a number of handling qualities problems. Their high-altitude, high-speed capabilities have greatly magnified the consequences of these problems. These consequences, namely loss of control, jet upsets or Mach tucks have been the cause of many incidents and accidents. A "jet upset" is aptly described as an inadvertent dive, characterized by very large excursions in altitude and airspeed from the normal cruise condition.[1] The Federal Aviation Administration, concerned with the seriousness of this problem, initiated a number of programs to determine possible factors that may contribute to its cause. These studies and other related research[2–9] pointed out, among numerous other factors, that lateral-directional handling qualities could influence the susceptibility of an airplane to a jet upset.

To this end, a flight test investigation was conducted to determine the effect of variations in the important bank angle control parameters on the cruise flight handling qualities for

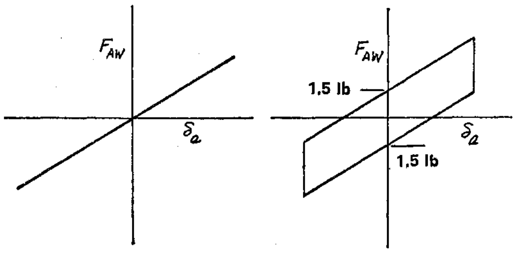

Fig. 1 Aileron wheel characteristics investigated.

an airplane representative of a high performance executive jet transport. Through an understanding of the effects of the important bank angle control parameters, it should be possible to determine how they affect the susceptibility of these airplanes to an upset/overspeed condition.

Specifically, the effects of the spiral mode, roll mode, roll-to-sideslip ratio and some of the interaction effects of the aileron wheel characteristics were examined for a representative executive jet transport. Briefly, the spiral mode determines the tendency of the airplane to remain at, right itself or diverge from an initial bank angle displacement. The roll mode is descriptive of the way in which the roll rate builds up following an external or control input and is usually a short-term response. The roll-to-sideslip ratio determines how much rolling motion is associated with a sideslip disturbance in the Dutch roll mode.

The longitudinal characteristics were held constant so that the evaluations of the bank angle control parameters would not be influenced by varying longitudinal handling qualities.

Flight Test Program

A comprehensive review and analysis of the characteristics of the modern subsonic executive jet, with particular emphasis on those characteristics which affect bank angle control, were made. Based on the results of this study and related flight research accomplished previously, the flight test program discussed below and the evaluation matrix shown in Table 1 were designed.

It was immediately obvious that spiral stability was important. All of the executive jets for which numerical data were available were found to possess some degree of spiral instability in cruising flight. The spiral mode has probably received less attention in past handling qualities research than most of the other bank angle control parameters. This has resulted primarily from the concept that the spiral mode is usually a very slow divergence which is easily controlled and therefore unimportant to the pilot. Now that airplanes are operating closer to their critical Mach number, the consequences of a spiral divergence are much greater. A spiral dive can directly establish the conditions for an upset or overspeed condition. Consequently the spiral mode was chosen as a primary parameter for this investigation.

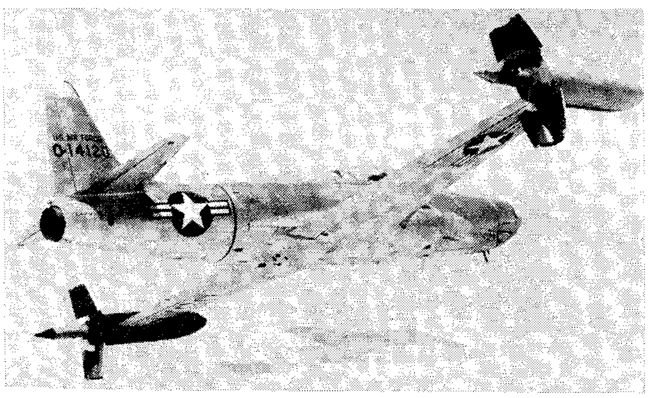

Fig. 2 USAF/CAL variable stability T-33 airplane.

Table 1 Evaluation configuration matrix

Dutch roll →	$\omega_d = 1.9$ rad/sec, $\zeta_d = 0.05$				
Longitudinal →	$\omega_{SP} = 2.8$ rad/sec, $\zeta_{SP} = 0.36$				
Friction →	No				Yes
$\lvert\phi/\beta\rvert_d$ →	1.7		3.0		1.7
τ_R →	0.55	1.5	0.55	1.5	0.55
$\tau_S = -6$ sec	A[a]	A			A
	B[a]		B	B	
$\tau_S = -17$ sec	A	A	A	A	A
	B	B	B		
$\tau_S = -29$ sec	B	B			
$\tau_S = -\infty$	A	A	A	A	A
	B	B	B	B	
$\tau_S = 14$ sec	A	A		A	A
	B				
$\tau_S = 5$ sec	A	A	A	A	A
	B	B	B	B	

[a] A = pilot A, B = pilot B.

Just as the spiral mode strongly affects the long term bank angle control, the roll mode equally affects the short term bank angle control. With the trend toward wet wings and tip tanks, it is anticipated that low roll damping will be a characteristic that will be found in many of the newer executive jets. Since the roll mode time constant directly affects both the short-term and long-term bank angle control task, it is necessary to include it in this investigation.

The airplane response to turbulence is listed as a contributing factor in the jet upset problem. The magnitudes of the roll-to-sideslip ratio and the Dutch roll frequency and damping ratio strongly affect the susceptibility of a particular airplane to turbulence in the lateral-directional modes. Two values of roll-to-sideslip ratio were investigated. Most of the airplanes for which numerical data were available had damping ratios of 5% or less, thus, this value was selected. A representative Dutch roll frequency was selected and held essentially constant throughout the evaluation program.

Aileron friction was found to be present in some form in all of the airplanes studied. About half of the airplanes had sufficiently high friction in the aileron system to produce a band of low lateral centering. The sets of aileron wheel characteristics shown in Fig. 1 were investigated with the major emphasis on the no friction configurations.

Equipment

The evaluations were performed in the USAF/CAL variable stability T-33 airplane shown in Fig. 2. To more closely represent the executive jet transport, the variable stability T-33 was further modified to include a wheel controller for the evaluation pilot. The evaluation pilot's cockpit is shown in Fig. 3.

A variable stability airplane is one in which the stability and control characteristics of the basic airplane can be altered. Briefly, the system operator in the rear cockpit, who also serves as safety pilot, may vary the handling characteristics about all three axes by changing the settings of response feedback gain controls located on his right hand console. Since the evaluation pilot is only connected electrically to the control surface servos, he does not feel any of the control surface motions due to the variable stability signals. The block diagram shown in Fig. 4 illustrates the mechanism of the in-flight simulation.

The variations in roll damping were primarily obtained through changes in the rolling moment caused by roll rate derivative L_p' and the changes in roll-to-sideslip ratio through changes in the rolling moment caused by sideslip derivative

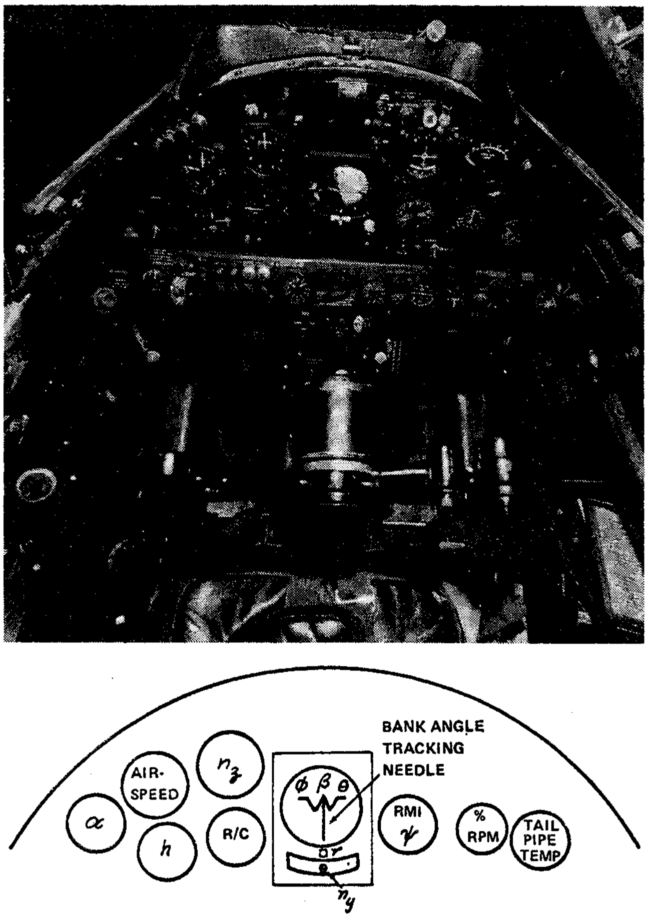

Fig. 3 Evaluation pilot's cockpit in variable stability T-33.

L_β'. Variations in the spiral mode were obtained by the introduction of the artificial stability derivative L_ϕ'. A discussion of the derivative L_ϕ' is included in Appendix I. In other words, a rolling moment was produced as a function of bank angle. The three-degree-of-freedom equations including the artificial derivative L_ϕ' are shown below:

$$\begin{bmatrix} Y_\beta - S & Y_r - 1 & (g/V) + (Y_p + \alpha_0)S \\ L_\beta' & L_r' & L\phi' + L_p'S - S^2 \\ N_\beta' & N_r' - S & N_p'S \end{bmatrix} \begin{bmatrix} \beta \\ r \\ \phi \end{bmatrix} = \begin{bmatrix} -Y_{\delta AW} & -Y_{\delta RP} \\ -L_{\delta AW}' & -L_{\delta RP}' \\ -N_{\delta AW}' & -N_{\delta RP} \end{bmatrix} \begin{bmatrix} \delta_{AW} \\ \delta_{RP} \end{bmatrix} \quad (1)$$

Evaluations

The various configurations were evaluated by two engineering test pilots. Since executive jet characteristics were being simulated in a jet trainer, it was necessary to clearly define the mission requirements before any meaningful evaluation of the handling qualities could be accomplished. The airplane evaluated was considered to be a relatively high performance executive jet operating in the high-altitude cruise configuration. Although most of these airplanes have dual controls, one constraint established was that the configurations be evaluated as if they were being flown by a single pilot. Emphasis was placed on both VFR and IFR operation in both smooth and turbulent flight conditions.

As part of the evaluation, the pilot was asked to perform a series of maneuvers normally required in the cruise mission. The evaluation pilot was asked to make comments on a number of specific items for each configuration evaluated. These comments were recorded in flight. In addition, the pilot was required to assign a pilot rating to each configuration. The Cooper-Harper rating scale shown in Table 2 was used. The pilot rating represents the pilot's evaluation of the suitability of the handling qualities for the cruise mission. Pilot comment data were likewise considered primary data and played an important part in the data analysis.

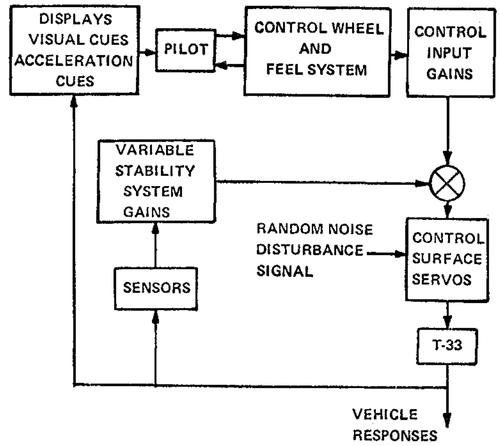

Fig. 4 Mechanism of in-flight simulation.

Summary of Results

The evaluation results for the high roll damping, low roll-to-sideslip configurations are shown in Fig. 5. In general, the pilots described the short-term bank angle control as excellent, very predictable and precise. Neither pilot liked the lightly damped Dutch roll which was easily excited in both real turbulence and in the presence of the random noise disturbances. With the good basic roll control characteristics, the pilots found an unstable spiral as divergent as a time to double amplitude of 13 sec to be acceptable and satisfactory. The pilot ratings, however, indicate a rapid deterioration in the handling qualities for unstable spirals with a time to double amplitude of less than 20 sec. The major pilot complaints for the unstable spiral mode were the poor unattended operation of the airplane and the need for continuous pilot attention to bank angle control. There is a wide range of acceptable and satisfactory stable spiral values which do not become unsatisfactory until a time to half amplitude of 2 sec. At this point, the pilots complain of the excessive aileron forces required to hold a steady turn. In general, the pilots expressed a high degree of confidence in the stable spiral configurations.

Figure 6 shows the evaluation results for the low roll damping, low roll-to-sideslip configurations. This group of con-

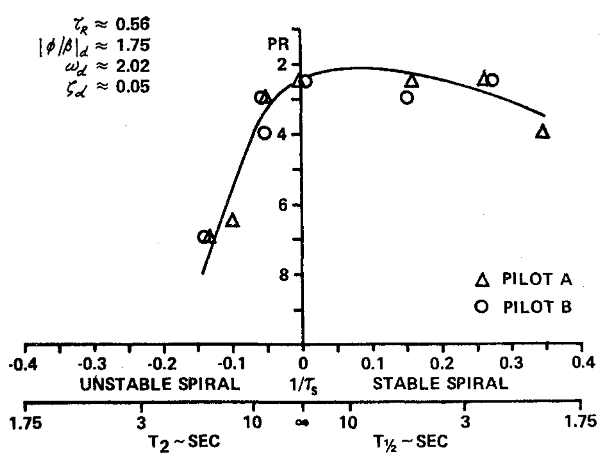

Fig. 5 Pilot rating data for the high roll damping, low roll-to-sideslip configurations without aileron friction.

Table 2 Pilot rating scale

CONTROLLABLE Capable of being controlled or managed in context of mission with available pilot attention.	ACCEPTABLE May have deficiencies which warrant improvement, but adequate for mission. Pilot compensation, if required to achieve acceptable performance, is feasible.	SATISFACTORY Meets all requirements and expectations, good enough without improvement. Clearly adequate for mission	Excellent, highly desirable.	A1
			Good, pleasant, well behaved.	A2
			Fair. Some mildly unpleasant characteristics. Good enough for mission without improvement.	A3
		UNSATISFACTORY Reluctantly acceptable. Deficiencies which warrant improvement. Performance adequate for mission with feasible pilot compensation.	Some minor but annoying deficiencies. Improvement is requested. Effect on performance is easily compensated for by pilot.	A4
			Moderately objectionable deficiencies. Improvement is needed. Reasonable performance requires considerable pilot compensation.	A5
			Very objectionable deficiencies. Major improvements are needed. Requires best available pilot compensation to achieve acceptable performance.	A6
	UNACCEPTABLE Deficiencies which require mandatory improvement. Inadequate performance for mission even with maximum feasible pilot compensation.		Major deficiencies which require mandatory improvement for acceptance. Controllable. Performance inadequate for mission, or pilot compensation required for minimum acceptable performance in mission is too high.	U7
			Controllable with difficulty. Requires substantial pilot skill and attention to retain control and continue mission.	U8
			Marginally controllable in mission. Requires maximum available pilot skill and attention to retain control.	U9
UNCONTROLLABLE Control will be lost during some portion of the mission.			Uncontrollable in mission	10

figurations was perhaps the most surprising and therefore the most interesting. There was a strong preference for a moderately stable spiral. The pilot ratings indicate a gradual improvement in handling qualities for an increase in stable spiral up to a time to half amplitude of about 4 sec. This improvement in the handling qualities is attributed to two factors: first, the improvement in unattended operation and secondly, the apparent change in the roll mode time constant resulting from the increased spiral stability. In other words, the rapidly convergent spiral mode makes it appear that the pilot has a better short-term roll response because he is able to reach a steady-state roll rate sooner. The degradation in pilot rating below a time to half amplitude of 3 sec is again the result of the increased aileron wheel forces required to hold a steady turn.

Figure 7 shows the pilot rating data obtained for the high roll damping, low roll-to-sideslip configurations with aileron friction. The pilots found that precise bank angle control was difficult and that there was a tendency to oscillate about a given bank angle. Because of the difficulty in centering the ailerons, trimming presented a problem and tended to mask the effect of a slightly stable or unstable spiral. In general, the aileron hysteresis caused the cruise flight characteristics to be evaluated as unsatisfactory. An unstable spiral tends to be accentuated by the aileron friction. A stable spiral does not necessarily make the airplane better to fly, but it does set a bound on the roll-off tendency. Thus, the consequences of a mistrim are much less with the stable spiral.

The evaluation results for the high roll damping, high roll-to-sideslip configurations are shown in Fig. 8. The major objection to these configurations was the large rolling response to external disturbances. The large rolling moment tended to excite the spiral mode making an unstable spiral quite objectionable. Because of the excessive rolling response and the requirement for continuous aileron inputs in turbulence, the forces required to hold a steady turn became objectionable for a moderately stable spiral value.

Figure 9 shows the evaluation results obtained for the low roll damping, high roll-to-sideslip configurations. The large

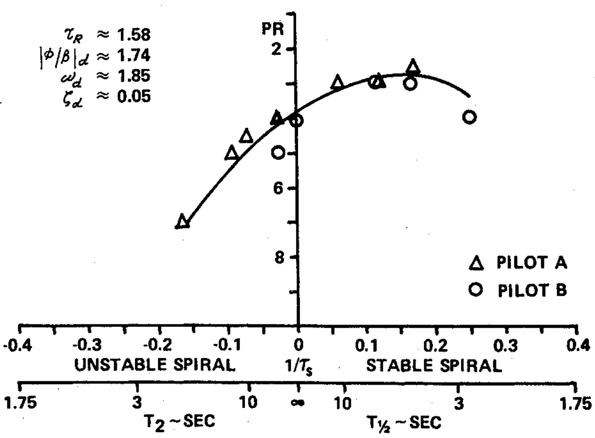

Fig. 6 Pilot rating data for the low roll damping, low roll-to-sideslip configurations without aileron friction.

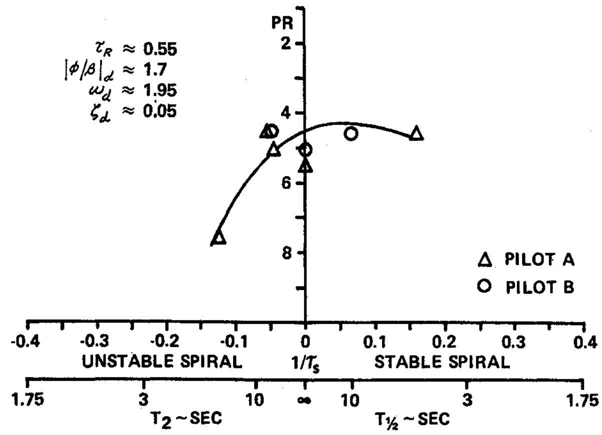

Fig. 7 Pilot rating data for the high roll damping, low roll-to-sideslip configurations with aileron friction.

rolling response to external disturbances, associated with the high roll-to-sideslip ratio, are magnified by the low roll damping. Consequently, none of these configurations were very good. The airplane is difficult to trim and very sensitive to out-of-trim conditions. There is also a tendency to overcontrol and set up bank angle oscillations during a tight tracking task.

In general, an unstable spiral increases the pilot attention required for bank angle control and generally results in overcontrolling tendencies. The consequence is that airspeed control is difficult and the trend is toward speeds higher than the normal trim speed. Thus, a moderately unstable spiral greatly increases the susceptibility of an airplane to a jet upset or Mach tuck. On the other hand, a moderately stable spiral usually resulted in speeds lower than the normal trim speed. This is perhaps explained by observing that the pilot will have to hold an elevator force which is a function of bank angle for turning flight. When the airplane tends to overbank beyond what the pilot expects, because of an unstable spiral, the pilot will normally not be holding enough elevator force to keep the airplane from tending to pitch nose down. The opposite is true with the stable spiral where the bank angle tends toward wings level and the pilot will usually have too much elevator force resulting in an increase in pitch attitude.

Low roll damping likewise increases the jet upset susceptibility of the airplane but not to the same extent as a moderately unstable spiral. Again, with low roll damping, increased attention to bank angle control is required. The airplane is sensitive to out-of-trim conditions and equally difficult to trim. The tendency is toward overcontrolling in bank angle which leads to increased airspeeds.

An increase in roll-to-sideslip ratio only indirectly influences the tendency for a jet upset. In turbulence, it increases the attention required for bank angle control and acts as a triggering device for an unstable spiral. This was especially true for the low Dutch roll damping simulated in this experiment.

The numerous aileron wheel inputs required when aileron friction was present in the system caused many inadvertent elevator inputs. The consequence was that pitch attitude and airspeed control were poor. The poor trimmability and increased attention required for bank angle control also influenced the pilot's control of airspeed. Thus, the introduction of aileron friction does increase the susceptibility of the airplane to a jet upset.

Conclusions

It was shown that the acceptability of the lateral-directional handling qualities for cruising flight are a function of

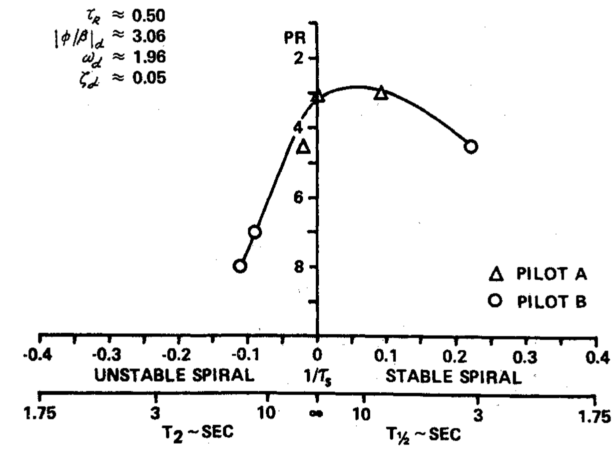

Fig. 8 Pilot rating data for the high roll damping, high roll-to-sideslip configurations without aileron friction.

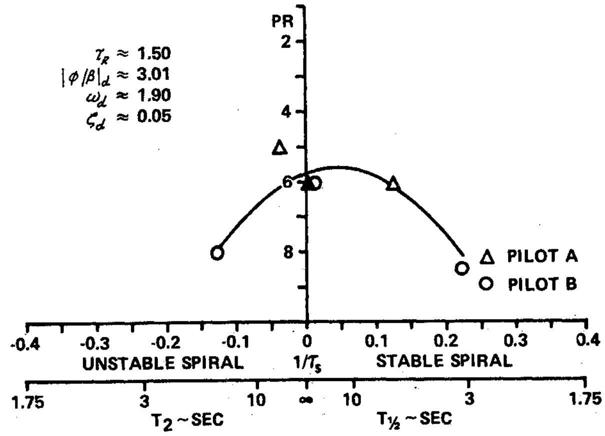

Fig. 9 Pilot rating data for the low roll damping, high roll-to-sideslip configurations without aileron friction.

roll damping, spiral stability, roll-to-sideslip ratio and aileron friction.

It was shown that some degree of spiral stability is desirable. However, the amount of spiral stability desired varies as a function of the other bank angle control parameters present.

For cruising flight, the pilots were quite intolerant of a mildly unstable spiral but found a wide range of stable spirals highly desirable. However, a highly stable spiral was found to have a degrading effect on the handling qualities because of the excessive forces required to hold a steady turn.

With low roll damping, the basic handling qualities can be significantly improved by the introduction of a moderately stable spiral. The stable spiral not only gives better long term and unattended characteristics, but causes an apparent change in the roll damping, resulting in better short-term roll control characteristics.

The introduction of aileron hysteresis causes a marked degradation in the handling qualities and tends to mask the effects of a slightly stable or unstable spiral mode. There is a greater preference for a stable spiral when aileron hysteresis is present.

The combination of high roll damping and high roll-to-sideslip ratio caused only a slight degradation in the basic handling qualities. However, with the high roll-to-sideslip ratio, the pilots were quite intolerant of even a slight spiral instability. They were also intolerant of a high degree of spiral stability, because of the excessive forces required to hold a turn as well as to fight the increased rolling motions due to external disturbances.

The combination of low roll damping and high roll-to-sideslip is just barely acceptable. The low roll damping tends to magnify the large rolling motions that occur in turbulence.

The following conclusions were made concerning the effect of lateral-directional handling qualities on the susceptibility of an airplane to a jet upset: 1) A moderately unstable spiral greatly increases the susceptibility of an airplane to a jet upset or Mach tuck. 2) Low roll damping likewise increases the jet upset susceptibility but not to the same extent as a moderately unstable spiral. 3) An increase in roll-to-sideslip ratio only indirectly influences the tendency for a jet upset and this shows up mostly in turbulence. 4) The introduction of aileron hysteresis was found to increase the susceptibility of an airplane to a jet upset.

Appendix I: Artificial Derivative L_ϕ'

Since L_ϕ' was an artificial stability derivative introduced to obtain the desired spiral mode characteristics, it was necessary to analyze the effects that it may have on the other modal parameters. This was done by comparing the variations in the numerator and denominator characteristics for the p,

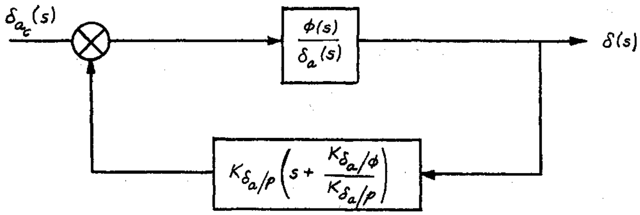

Fig. 10 **Block diagram for closed-loop system.**

β, and r transfer functions obtained with variations in L_ϕ' with those variations obtained by a set of stability derivatives that produced the same roll mode, spiral mode, and Dutch roll characteristics. For the configurations studied, it was found the L_ϕ' derivative was quite powerful in controlling the spiral mode root, had little effect on the Dutch roll mode, but did cause a significant change in the roll mode root.

Since $1/\tau_R \approx L_p'$, it was logical to vary L_p' as a function of L_ϕ' in a manner which keeps τ_R constant.

Starting with the open-loop transfer function,

$$\frac{\phi(S)}{\delta_a(S)} = \frac{L_{\delta_a}'(S^2 + 2\zeta_\phi\omega_\phi S + \omega_\phi{}^2)}{(S + 1/\tau_S)(S + 1/\tau_R)(S^2 + 2\zeta_d\omega_d S + \omega_d{}^2)} \quad (2)$$

and using δ_a/ϕ and δ_a/p feedback loops, the aileron inputs from the variable stability system would be

$$\delta_{ac}(S) = K_{\delta_a/p}p + K_{\delta_a/\phi}\phi = (K_{\delta_a/p}S + K_{\delta_a/\phi}\phi) \quad (3)$$

$$\delta_{a_c} = K_{\delta_a/p}(K_{\delta_a/\phi}/K_{\delta_a/p} + S)\phi \quad (4)$$

The block diagram for the resulting closed-loop system is shown in Fig. 10 and the closed-loop transfer function is

$$\frac{\phi(S)}{\delta_{a_c}(S)} = \frac{\phi(S)/\delta_a(S)}{[1 + \phi(S)/\delta_a(S)][K_{\delta_a/p}(S + K_{\delta_a/\phi}/K_{\delta_a/p})]} \quad (5)$$

The closed-loop roots are obtained from

$$\frac{\phi(S)}{\delta_a(S)}\left[K_{\delta_a/p}\left(S + \frac{K_{\delta_a/\phi}}{K_{\delta_a/p}}\right)\right] = -1 \quad (6)$$

The objective is to vary $K_{\delta_a/p}$ and $K_{\delta_a/\phi}$ in such a fashion that the closed-loop Dutch roll and roll mode roots are held constant at their open-loop locations, while the spiral root is varied. This may be seen by plotting the locus of the closed-loop roots from their zero-gain locations. We obviously want closed-loop zeros located on top of the open-loop roots which are to be invariant. Substituting Eq. (2) into Eq. (6) we have

$$\frac{L_{\delta_a}'(S^2 + 2\zeta_\phi\omega_\phi S + \omega\phi^2)(K_{\delta_a/p})[S + (K_{\delta_a/\phi})/(K_{\delta_a/p})]}{[S + (1/\tau_S)][S + (1/\tau_R)](S^2 + 2\zeta_d\omega_d S + \omega_d{}^2)} = -1 \quad (7)$$

It can be seen that if $(K\delta_{\delta_a/p})/(K_{\delta_a/\phi}) = \tau_R$, $\zeta_\phi = \zeta_d$, and $\omega_\phi = \omega_d$, then the root locus will be as shown in Fig. 11 and

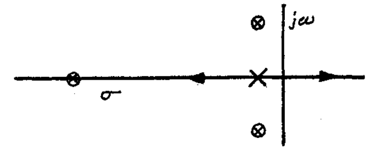

Fig. 11 **Root locus diagram.**

Eq. (7) reduces to

$$-1 = L_{\delta_a}'K_{\delta_a/p}/[S + (1/\tau_S)] = L_{\delta_a}'\tau_r K_{\delta_a/\phi}/[S + (1/\tau_S)] \quad (8)$$

Thus, to keep the roll mode constant, it is necessary to make $K_{\delta_a/p} = \tau_r K_{\delta_a/\phi}$ as $K_{\delta_a/\phi}$ is varied to change the spiral mode root.

From Eq. (8), we can see that if we wish S to be the desired spiral mode root and $1/\tau_S$ is the spiral root when $K_{\delta_a/\phi} = 0$, then the $\delta_{a/\phi}$ gain required to provide the desired spiral mode root is given by

$$K_{\delta_a/\phi} = \frac{(1/\tau_{S_{\text{desired}}}) + (1/\tau_{S_{\text{basic}}})}{\tau_r L_{\delta_a}'} \quad (9)$$

This combination of gains kept the roll mode essentially constant and satisfied the condition that the desired modal characteristic variations were small for changes in L_ϕ'. An additional study was performed to show that the proper aileron and rudder pedal forces were obtained in a steady coordinated turning maneuver.

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