In-Flight Evaluation of Incremental Time Delays in Pitch and Roll

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An in-flight investigation of the effect of changes in pure time delays in pitch and roll was undertaken. The evaluation tasks consisted of low lift-to-drag-ratio landings of various levels of difficulty and formation flying. The results indicate that the effect of time delay is strongly dependent on the task. In the pitch axis, in calm air, spot landings from a lateral offset were most strongly influenced by time delay. In the roll axis, in calm air, formation flying was most strongly influenced by time delay. However, when landings were made in turbulence, flying qualities in pitch were only slightly degraded, whereas in roll they were severely degraded.

Nomenclature

AGL	= above ground level
ASL	= above sea level
a_y	= lateral acceleration, g
b	= span, ft
C_L	= coefficient of lift
C_ℓ	= coefficient of rolling moment
C_m	= coefficient of pitching moment
C_n	= coefficient of yawing moment
C_y	= coefficient of side force
$\bar{c}$	= mean aerodynamic chord
DFBW	= digital fly-by-wire
I_x	= roll inertia, ft-lb-s^2
I_y	= pitch inertia, ft-lb-s^2
I_z	= yaw inertia, ft-lb-s^2
KIAS	= indicated airspeed, knots
K_{LA}	= lateral-directional aileron gain
K_p	= roll rate feedback gain
K_q	= pitch rate feedback gain
K_r	= yaw rate feedback gain
L/D	= lift-to-drag ratio
PIO	= pilot-induced oscillation
p	= roll rate, deg/s
q	= pitch rate, deg/s
$\bar{q}$	= dynamic pressure, lb/ft^2
r	= yaw rate, deg/s
SAS	= stability augmentation system
s	= Laplace transform variable
VRA	= variable-response aircraft
VSA	= variable-stability aircraft
α	= angle of attack, deg
$\dot{\alpha}$	= angle-of-attack rate, deg/s
β	= angle of sideslip, deg
$\dot{\beta}$	= angle-of-sideslip rate, deg/s
δ_a	= aileron deflection, deg
δ_e	= elevator deflection, deg
δ_r	= rudder deflection, deg
γ	= flight-path angle, deg
Δ	= increment

Subscripts

$p,q,r,\alpha,\beta,\dot{\alpha},\dot{\beta},\delta_a,\delta_e,\delta_r$	= nondimensional stability derivatives with respect to indicated quantity

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Introduction

IN the late 1970s and early 1980s overcontrol and pilot-induced oscillation (PIO) tendencies were observed during flight tests of some of the new advanced technology vehicles, such as the Space Shuttle and F-16.[1] Assessments indicated that time delays associated with higher-order systems and digital flight control were a contributing factor. Consequently, a flight test program was conducted on the Ames-Dryden F-8 digital fly-by-wire (DFBW) aircraft to expand the data base on this subject.[2] The emphasis in this program was on pitch control in low lift-to-drag-ratio (L/D) landings such as those performed with the space shuttle. However, roll control data were also taken, although not reported in Ref. 2. Since that time, problems with time delay persist. Additional questions have arisen with regard to roll time delay in more recent advanced aerospace vehicles such as the F-18, AFTI/F-16, and X-29. This paper analyzes and reports the data for roll time delays obtained with the F-8 DFBW airplane, and compares them with the pitch results of Ref. 2.

Description of Aircraft and Flight Control System

The F-8 (DFBW) aircraft is a modified F-8C single-engine, single-place Navy fighter (Fig. 1). The aircraft has a two-position wing for reducing fuselage attitude during the landing approach. The F-8C was modified by removing the entire mechanical control system between the stick and rudder pedals and the actuators and replacing it with a DFBW control system implemented with onboard digital computers.

The F-8 DFBW aircraft includes several control law functions for use in active control applications that are pilot selectable. In this paper, only the stability augmentation system (SAS) modes are pertinent. The SAS pitch mode uses washed-out pitch rate feedback to improve short-period damping (Fig. 2). Figure 3 illustrates the lateral-directional SAS modes. (The pilot's rudder input channel is not shown because the pilots did not use a rudder in the experiment.) Although the roll and yaw SAS modes are individually selectable by the pilot, they are discussed collectively. This system provides improved Dutch roll damping and directional stability as well as turn coordination. A high-pass yaw rate provides increased Dutch roll damping with a minimal steady-state effect. Turn coordination is provided by a compensated aileron-to-rudder interconnect that utilizes a first-order lagged signal. Turn coordination is also enhanced by feeding back roll rate to the rudder.

All filtering and control law computation, illustrated in Figs. 2 and 3, is performed in the digital computer. Sampling time is 20 ms and computation time is 6 ms for both pitch and roll. A summary of aircraft and flight control system characteristics is presented in Tables 1 and 2. The aircraft and systems are described in detail in Ref. 3.

Flight Test Procedures

Four basic tasks were evaluated during the flight program: normal low-L/D landings, low-L/D spot landings, low-L/D spot landings from a lateral offset, and formation flying. The formation flying was done to see if an up-and-away evaluation task could provide insight into the control problems that would occur on an actual landing.

During the low-L/D approaches, the engine was at idle power and the landing gear and wings were down. Approaches were initiated at 260 KIAS, 7000 ft above sea level (4800 ft above ground level), about 6 miles from touchdown point. A speed of 260 KIAS was maintained to 500 ft above ground level. The outer glide slope was approximately 10 deg. Flare was initiated 500 ft above ground level. A glide slope of approximately 1 deg was intercepted about 100 ft above ground level. Aim touchdown speed was 190 KIAS; actual touchdown speeds were between 180 and 210 KIAS. The outer glide slope aim point was about 1 mile from the runway threshold.

All landings were made on a concrete runway 15,000 ft long and 300 ft wide. The evaluation terminated at touchdown, and a go-around was initiated. The normal low-L/D landings were made from straight-in approaches with no particular aim touchdown point. Owing to the generous proportions of the runway, these were relatively unstressed landings. The low-L/D spot landings were made from straight-in approaches, but the pilot was asked to touch down at the 5000-ft marker on the runway. The low-L/D spot landings from the lateral offset consisted of an approach lined up with the edge of the runway, followed by an offset maneuver (initiated at 100 ft above ground level, approximately 1 mile to touchdown) to line up with the runway centerline and a touchdown at the 5000-ft marker. The lateral offset increased the pilot's workload and stress, providing a more demanding landing task. A representative flight profile for these landings is shown in Fig. 4.

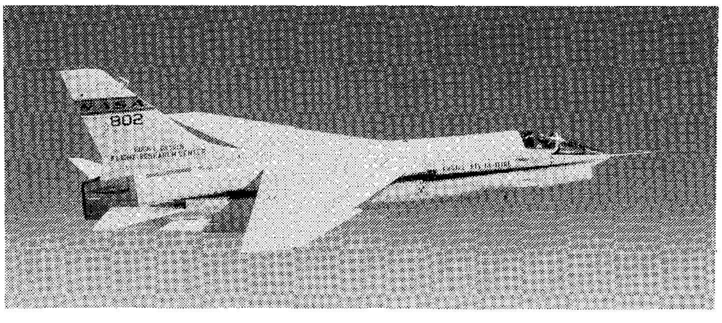

Fig. 1 The F-8 DFBW aircraft.

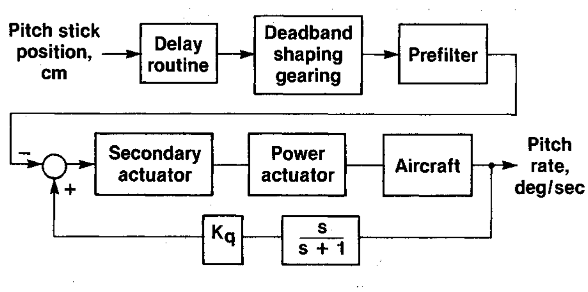

Fig. 2 Pitch SAS mode.

The formation flying task simulated an aerial refueling positioning. The aircraft was initially stabilized 25-50 ft below another aircraft at various horizontal distances, 100 ft being the farthest and 10 ft the closest. Abrupt pitch inputs positioned the F-8 approximately 10 ft below the "tanker" (Fig. 5), in the refueling position. Roll evaluation maneuvers for the simulated refueling formation task consisted of rapid lateral control inputs to move quickly, either from the refueling position to a wing-tip position, or from a position two to three wingspans abeam of the refueling position to the refueling position. After the final position was obtained, an attempt was made to maintain it precisely.

The digital computer was programmed to provide pilot-selectable incremental time delay values of 20, 60, 100, 140, and 200 ms independently in pitch and roll. These increments were added in the pilot input path ahead of the control system feedback summing junction (Figs. 2 and 3); consequently, the lags within the closed-loop portion of the system were unaffected. The emphasis of this study was to determine the influence of incremental time delays.

The study consisted of 16 flights and 170 evaluations, with four pilots participating. Each evaluation comprised one approach or formation flying task. Six flights were primarily pilot checkout and indoctrination flights in which the pilots familiarized themselves with the various configurations, explored various tasks, and conducted preliminary evaluations. On subsequent flights the pilots formally evaluated the various tasks for different time delays and provided comments and ratings. The Cooper-Harper rating scale was used.[4]

Table 1 Typical aircraft characteristics

Gross weight, lb	20,000	$C_{m_{\delta_e}}$	−0.8/rad
Wing area, ft^2	375	$C_{\ell_{\delta_\alpha}}$	0.049/rad
b, ft	35.67	$C_{\ell_{\delta_r}}$	0.01/rad
$\bar{c}$, ft	11.8	C_{ℓ_p}	−0.35
$\bar{q}$, lb/ft^2	100-270	C_{ℓ_r}	0.040
I_x, ft-lb/s^2	11,280	C_{ℓ_β}	−0.10/rad
I_y, ft-lb/s^2	87,490	C_{n_β}	0.14/rad
I_z, ft-lb/s^2	94,000	$C_{n_{\delta_r}}$	−0.17/rad
$C_{L_{\dot\alpha}}$	3.7/rad	$C_{n_{\delta_a}}$	0.006/rad
$C_{L_{\delta_e}}$	0.57/rad	C_{n_r}	−0.7
C_{m_q}	−6	C_{n_p}	0
C_{m_α}	−0.5/rad	C_{y_β}	−0.1/rad
$C_{m_{\dot\alpha}}$	−0.42		

Table 2 Typical control system characteristics

Secondary actuator (all axes)	$\dfrac{126^2}{s^2+176s+126^2}$
Power actuators	
Horizontal tail	$12.5/(s+12.5)$
Ailerons	$30/(s+30)$
Rudder	$25/(s+25)$
Stick shaping	
Pitch	Output = 0.35 × input + 0.45 × input- × |-input|
Roll	Output = 0.13 × input + 0.116 × input- × |-input|
Prefilter	
Pitch	$25/(s+25)$ landing; $50/(s+50)$ formation
Roll	$10/(s+10)$ landing and formation
K_q	0.5 deg/deg/s
K_p	1.0-3.0 deg/deg/s
K_{LA}	0.0435 deg/deg/s
K_r	0.4 deg/deg/s
$K_{p_{\delta_r}}$	0.005 deg/deg/s

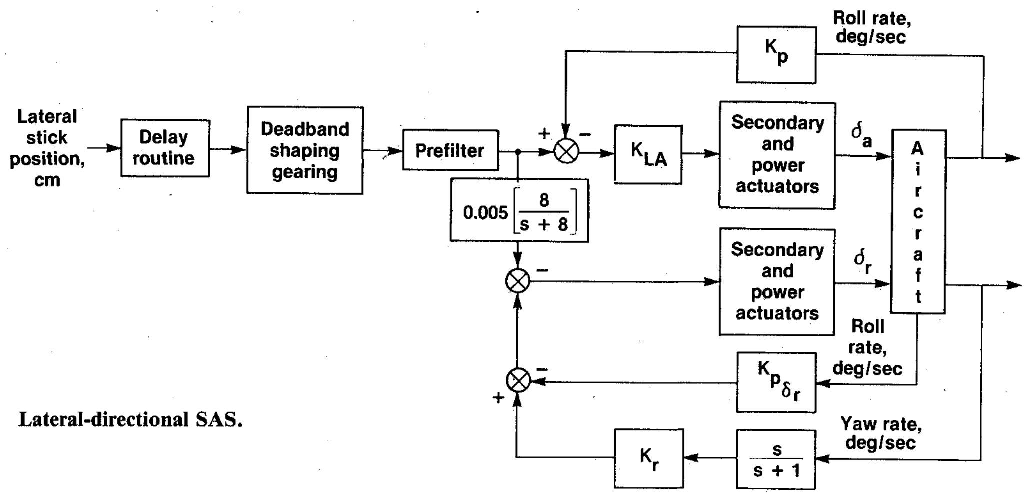

Fig. 3 Lateral-directional SAS.

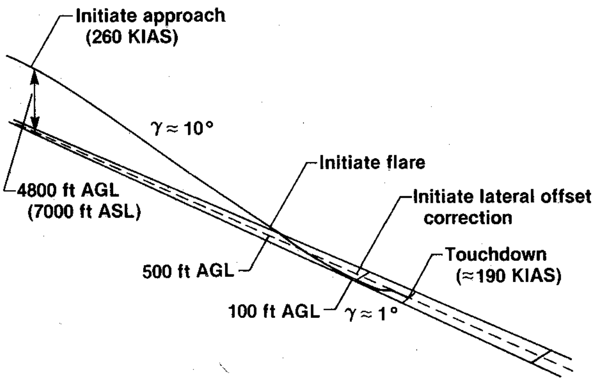

Fig. 4 Low-L/D landing approach pattern.

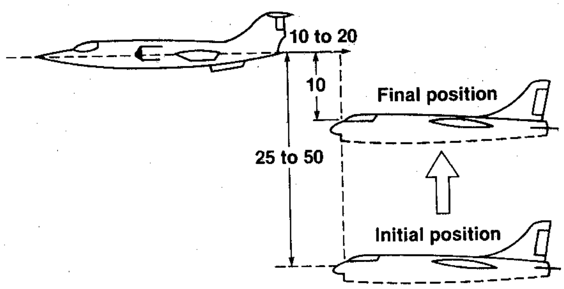

Fig. 5 Formation flying task (dimensions in feet).

Because of time and equipment constraints, the pilot was aware of the configuration he was selecting. In addition, in most cases, configurations were evaluated in order, starting with zero incremental time delay and increasing to maximum. This was done for flight safety reasons, so that the large and potentially hazardous time delays could be approached as an envelope expansion program. Although this introduced the possibility of reduced pilot objectivity, it is believed that a high degree of objectivity did exist because 1) all pilots were highly experienced test pilots who had displayed a high degree of objectivity and consistency over the years, 2) none of the pilots knew the ratings assigned by other pilots in the program, and 3) configurations were arbitrarily selected for repeat evaluations. This is confirmed by the good agreement in the ratings among the pilots and for repeated configurations with the same pilot.

Most of the evaluations were performed in air with no more than light turbulence. Data acquired in greater turbulence are so identified. Turbulence was based on pilot comments.

Results of Pilots Rating Trends

Figures 6a-d present pilot ratings in roll as a function of incremental time delay for the low-L/D landing tasks and formation flying. The lines are a least-squares, linear fit to the data. In most cases the scatter in the data is low and the data are well represented by the straight lines.

Figure 6a contains data for normal, relatively unstressed low-L/D landings. It is the only case for which data with turbulence are available, and the influence is quite evident. Figure 6b presents data for low-L/D spot landings. Figure 6c provides data for low-L/D offset spot landings. Figure 6d provides data for the formation flying task. The pilot ratings degrade with increasing transport delay as the task goes from normal landings to spot landings to offset spot landings and finally to formation flying. However, turbulence produces the greatest degradation (see Fig. 6a).

Pilot-induced oscillations occurred during the more demanding lateral tasks (such as formation flying and landing in turbulence with side gusts) and during the tasks having the larger time delays. Figure 7 illustrates a PIO that occurred during a landing approach with an incremental time delay of 60 ms. The pilot commented that he had a good crosswind gust near the ground which drove his gains up and resulted in a "pretty good roll PIO." This resulted in a pilot rating of 6. Figure 8 illustrates an example of PIO during formation flying. The incremental time delay was 140 ms, and the pilot rated this configuration a 7. Pilot comments indicate that the PIO could only be avoided by abandoning a tight formation flying task; however, overall control was not in question.

Figure 9 illustrates the sensitivity of pilot ratings to changes in roll time delay. [The sensitivities are the slopes of the least-squares, linear fit of pilot rating as a function of incremental time delay (from Fig. 6).] In calm air, normal landings were the least sensitive, and formation flying the most sensitive. Spot landings were similar to normal landings, and offset spot landings were intermediate in sensitivity. Pilot rating sensitivity to time delay is an indication of task difficulty or stress. The lateral task for a spot landing is not much different from that for a normal landing. The offset spot landing and formation flying, however, have definite lateral tasks, and the data trends are consistent with this. The data show, however, that turbulence is a strong factor. Pilot comments indicate that the turbulence in these tests included side gusts that moved the aircraft off the runway centerline, adding significantly to the lateral task. Consequently, pilot rating sensitivity to time delay was very high.

Figure 9 also shows results for landing tasks from T-33 variable-stability aircraft (VSA) tests[5] and Navion variable-response aircraft (VRA) tests.[6] The T-33 data are for an offset

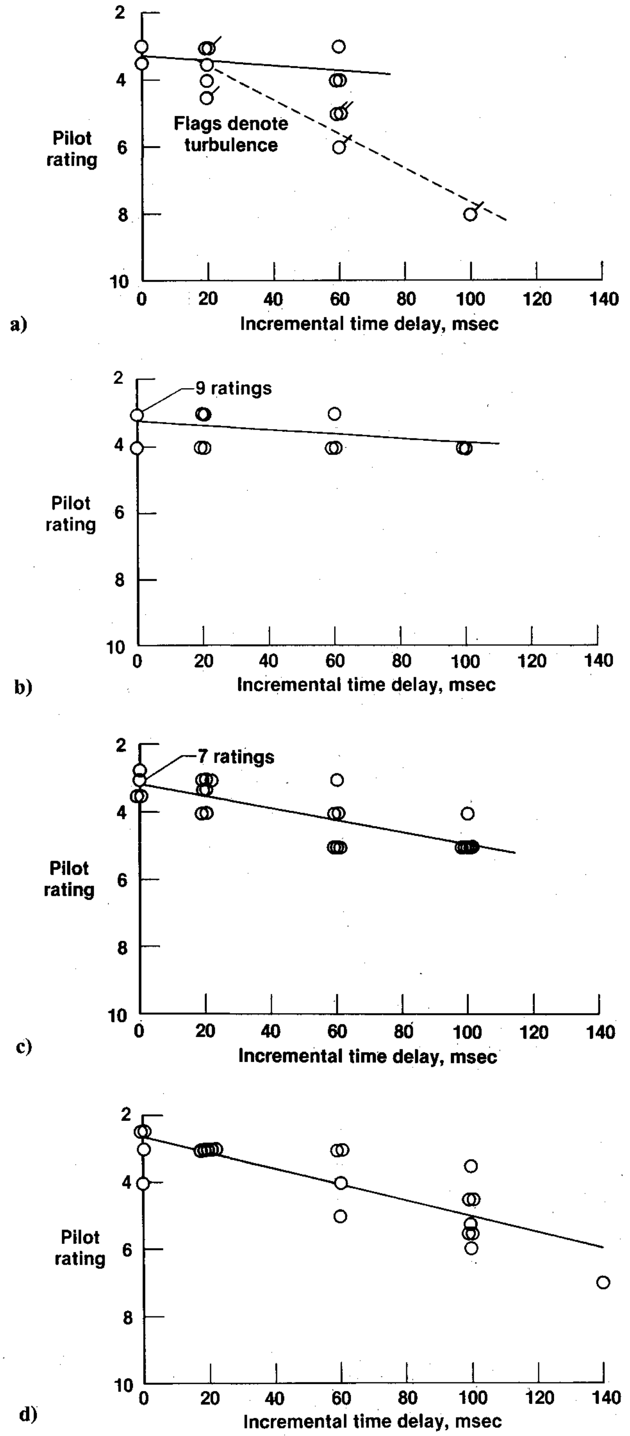

Fig. 6 Pilot ratings in roll axis. Coincident data points are shifted horizontally for clarity. a) Normal landings. b) Spot landings. c) Offset spot landings. d) Formation flying.

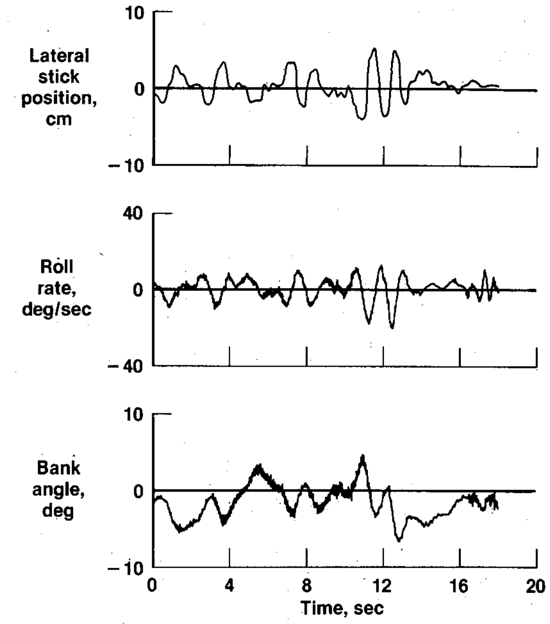

Fig. 7 Roll PIO during the landing approach (time delay = 60 ms).

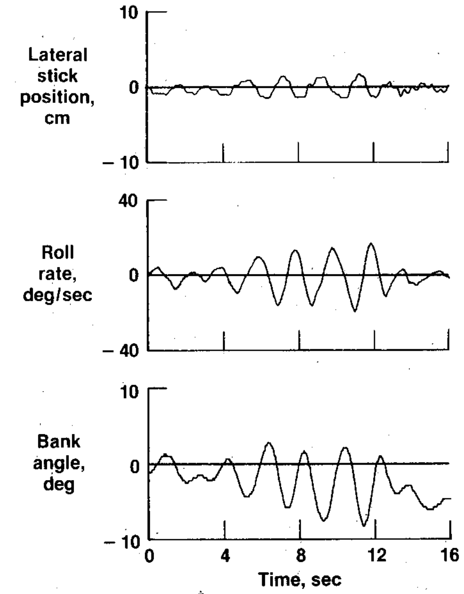

Fig. 8 Roll PIO during formation flying (time delay = 140 ms).

spot landing task. However, the offset task in the T-33 program was a 200-ft lateral correction ½ mile from the intended touchdown point, whereas in this study the task was a 150-ft correction 1 mile from the intended touchdown point. Considering the greater degree of difficulty of the T-33 offset task, the results corroborate the F-8 results reasonably well in that a greater pilot sensitivity to time delay would be expected with an increase in task difficulty.

The Navion results are for a carrier-type (unflared) landing with no lateral offset. The lack of a flare in these landings would not be expected to influence the roll task significantly. The results are comparable to the F-8 results for landings without an offset (normal and spot landings). The results of turbulence in the F-8 study, however, are in a class by themselves and indicate a very demanding task.

Figure 10 presents pitch results from Ref. 2 on the sensitivity of pilot rating to time delay for longitudinal tasks. It can be seen that longitudinal ratings from normal landings are least sensitive and offset spot landings are most sensitive. Offset spot landings do complicate the longitudinal task. The longitudinal task in formation flying, however, is apparently less demanding. Of particular interest is that turbulence had considerably less influence on the longitudinal ratings than on the lateral ratings. This could be the result of the turbulence environment or the gust sensitivities of the aircraft.

Figure 10 also compares results to data from the T-33 and Navion tests.[7,8] The T-33 results show the greatest sensitivity to time delay. In this case, the T-33 program included a 150-ft vertical displacement from the glide path to be corrected ½ mile from touchdown, in addition to the 200-ft (lateral) offset. The F-8 study did not use a vertical displacement. Considering this, the results of the three tests compare favorably. The

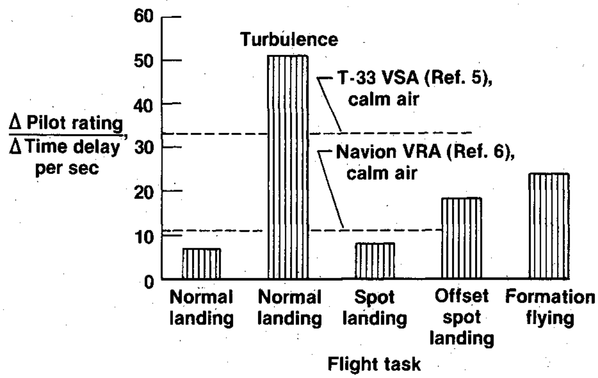

Fig. 9 Pilot sensitivity to roll time delay.

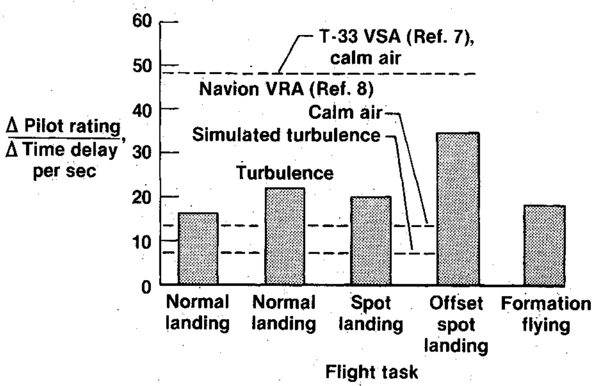

Fig. 10 Pilot sensitivity to pitch time delay.

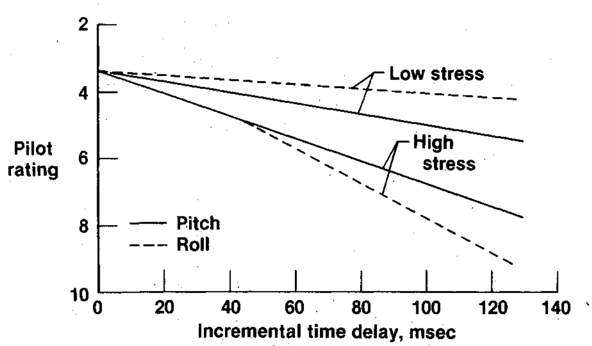

Fig. 11 Pilot rating summary.

results of Ref. 8 are for conventional flared landings, with no lateral offset or vertical displacement. In calm air, the results compare very well with the F-8 results for a comparable task. In simulated turbulence, however, the trend is contrary to the F-8 experience. This can be attributed to the fact that in Ref. 8 simulated random turbulence was used, whereas the results reported here are for natural turbulence with significant discrete gust components. In random turbulence the pilot tends to avoid precision control and instead flies "loosely" so that the aircraft can "average out" disturbances. This can mask the presence of time delays. In this study, however, discrete gusts near the ground force the pilot to react and take prompt action. Under these circumstances the influence of time delays can be magnified.

If the low pilot rating sensitivities are associated with low-stress situations, and the high pilot rating sensitivities are associated with high stress, the results of this study can be summarized in Fig. 11. Similar data from Ref. 2 for the longitudinal pilot ratings are also presented. The low-stress results are less severe for the lateral tasks, but the high-stress results appear to be more severe for the lateral tasks. Apparently this is caused by the greater sensitivity of the lateral results to turbulence. Unfortunately, it was not possible to document in a quantitative fashion the nature of the turbulence experienced in this program. However, these results do indicate the importance of examining the gust sensitivity of configurations when considering the influence of time delays.

Concluding Remarks

The effect of pure time delays in pitch and roll was investigated in flight. The evaluation tasks consisted of low-L/D ratio landings of various levels of difficulty and formation flying. The results indicate that the effect of time delay depends strongly on the task. In the pitch axis, in calm air, spot landings from a lateral offset were most strongly influenced by time delay. In the roll axis, in calm air, formation flying was most strongly influenced by time delay. However, when landings were made in turbulence, flying qualities in pitch were only slightly degraded, whereas in roll they were severely degraded.

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