Flight Investigation of the Influence of Turbulence on Longitudinal Flying Qualities

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Flight evaluations using a variable stability airplane were made to determine the independent and interacting effects of turbulence disturbances and longitudinal dynamics on flying qualities for the ILS approach task. Turbulence was described in terms of the rms magnitudes of pitch and heave disturbances and the bandwidth of the turbulence power spectrum. Variations in dynamics included the frequency and damping of the short-period mode and the slope of the lift curve. Trends in pilot rating obtained in the test program with variations in turbulence disturbances and airplane dynamics are explained in terms of measures of precision of task performance and the pilot's control activity derived from time histories of the ILS approach.

Nomenclature

b = wing span
c = wing chord
D_α = drag derivative due to angle of attack $(1/m)(\partial D/\partial\alpha)$
g = acceleration due to gravity
I_y = pitch moment of inertia
j = imaginary number $(-1)^{1/2}$
l_t = tail length
M = pitching moment or pitch angular acceleration
M_{u_g}, M_{w_g} = pitch angular acceleration due to u_g, w_g
$M_{w_{g_w}}, M_{w_{g_t}}$, $M_{\alpha_{g_w}}, M_{\alpha_{g_t}}$ = stability derivatives of the wing and tail due to vertical gusts, e.g., $M_{w_{g_w}} = (1/I_y)(\partial M_w/\partial w_g)$
M_α = static angle-of-attack stability $(1/I_y)(\partial M/\partial\alpha)$
$M_{\dot\theta}$ = pitch damping $(1/I_y)(\partial M/\partial\dot\theta)$
M_{δ_e} = elevator control effectiveness $(1/I_y)(\partial M/\partial\delta_e)$
m = airplane mass
$N_M{}^i, N_Z{}^i$ = transfer function numerators relating response i to pitch and heave disturbances
n_z = normal acceleration
R_e = real part of a complex number
T_{h_1} = time constant of the numerator root of the h/δ_e transfer function
T_{θ_2} = time constant of the numerator root of the θ/δ_e transfer function
u, w; u_g, w_g = longitudinal and vertical airplane perturbation or gust velocities
V_o/L = parameter defining the corner frequency of the turbulence spectrum; V_o = true airspeed, L = integral scale of turbulence
X = longitudinal force or acceleration
X_{u_g}, X_{w_g} = longitudinal acceleration due to u_g, w_g
X_u = longitudinal force derivative due to forward speed $(1/m)(\partial X/\partial u)$
X_α = longitudinal force derivative due to angle of attack $(1/m)(\partial X/\partial\alpha)$
Z = vertical force or acceleration
Z_{u_g}, Z_{w_g} = vertical acceleration due to u_g, w_g
Z_u = vertical force derivative due to foward speed $(1/m)(\partial Z/\partial u)$
Z_α, L_α = vertical force derivative due to angle of attack $(1/m)(\partial Z/\partial\alpha) = -L_\alpha$
Z_{δ_e} = vertical force derivative due to elevator deflection $(1/m)(\partial Z/\partial\delta_e)$
α = angle of attack
Δ = open-loop longitudinal characteristic equation
Δ' = characteristic equation for closed-loop manual control
δ_e, δ_{Fs} = elevator deflection, longitudinal stick deflection or force
δ_f = flap deflection
ζ_p, ω_p = phugoid damping ratio and natural frequency
ζ_{sp}, ω_{sp} = short-period damping ratio and natural frequency
σ_i = root mean square of the variable
τ = incremental time delay
θ = pitch attitude
Φ_i = power spectral density of the variable i
ω = angular frequency
ω_{w1}, ω_{w2} = corner frequencies of the power spectral approximation of pitch and heave disturbances due to vertical gusts
$[\ ]^*$ = complex conjugate of $[\ ]$
$|(\ )|$ = absolute value of $(\ )$

Introduction

THIS paper presents the results of a flight investigation conducted at Princeton University under the sponsorship of NASA Headquarters to study the effects of turbulence on longitudinal flying qualities of piloted airplanes. The purpose of the study was to identify through in-flight simulation the independent and interacting influences of turbulence and airplane dynamics on longitudinal flying qualities. Results of a similar investigation concerning lateral-directional flying qualities were reported in Ref. 1.

In-flight simulation was performed using Princeton's variable stability Navion.[2] This airplane has a five-axis automatic control system (roll, yaw, heave, pitch, and longitudinal force) that is used to alter the dynamic response and control characteristics of the basic vehicle. Simulation of turbulence disturbances was provided by introducing tape recorded gaussian noise, suitably filtered to represent the turbulence power spectral characteristics, to the control surface actuators.

The characteristics of turbulence incorporated in the test program represented the disturbances as they appear to the pilot. These characteristics are the magnitude of the heave and pitch disturbances and the frequency content or bandwidth of the disturbance spectra. A thorough study of these effects was made for a vehicle configuration having good longitudinal dynamics. Combinations of turbulence and dynamics parameters were also studied to assess their interacting effects on longitudinal flying qualities.

Flight evaluations of the test configurations were obtained for the ILS approach task. These evaluations were conducted in a light, general aviation airplane that had variable stability and control capability that permitted the representation of dynamic response characteristics of a much wider class

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of vehicle. Therefore, the restrictions on the application of results noted in this report are those imposed by the task itself, by the range of turbulence and dynamics characteristics tested, and by the airspeeds associated with the conventional ILS approach. The limited number of pilots and evaluations per pilot also restrict the interpretation of these data to identification of the significant influences of turbulence on longitudinal flying qualities. Thus, these results should be used to distinguish between important and unimportant effects rather than to determine absolute levels of flying qualities as functions of dynamics and turbulence.

In the following discussion, first of all, the characteristics of the turbulence disturbances of interest are described in terms of their statistical properties. Next, the flight test program is outlined. Finally, the results of the flight program are presented in terms of pilot opinion ratings and commentary.

Description of the Turbulence Disturbances

The longitudinal equations of motion that define the airplane's response to control inputs and turbulence disturbances are:

$$[\Delta]\begin{Bmatrix} u \\ \alpha \\ \theta \end{Bmatrix} = \begin{Bmatrix} X_\delta \\ Z_\delta \\ M_\delta \end{Bmatrix}\{\delta\} + \begin{Bmatrix} X_{u_g} \\ Z_{u_g} \\ M_{u_g} \end{Bmatrix} + \begin{Bmatrix} X_{w_g} \\ Z_{w_g} \\ M_{w_g} \end{Bmatrix} \tag{1}$$

The open-loop characteristic matrix appears on the left side of the equation, while control input and turbulence disturbance matrices corresponding to u_g and w_g gust components are shown on the right. The terms of the turbulence matrices represent the longitudinal and vertical accelerations and the pitch angular acceleration due to the particular gust component. Thus, for example, Z_{w_g} is the vertical acceleration imposed on the airplane by the vertical gust disturbance w_g and should not be confused with the stability derivative $\partial Z/\partial w_g$.

For simplicity some of the turbulence disturbances that did not have an important contribution were eliminated in the simulation. For example, forces and moments due to the longitudinal gust component were eliminated from Eq. (1). The consequences of this simplification are not as severe as might be expected.[2] The predominant difference in the airplane's response, longitudinal gusts included or excluded, occurs at frequencies in the region of the phugoid mode. The pilot can effectively suppress the airplane's phugoid response by controlling pitch attitude excursions with the elevator, a primary control technique used by the pilot in either VFR or IFR flight. As a result of this control technique, the dominant response to turbulence, so far as the pilot is aware, is shifted to higher frequencies. At these higher frequencies ($\omega > 1.0$ rad/sec) neither pitch attitude nor altitude response is particularly influenced by the longitudinal gust component. Although a considerable difference exists in airspeed response spectra for $\omega > 1.0$ rad/sec, u_g included or absent, the magnitude of airspeed response at these higher frequencies can be shown to be sufficiently attenuated to be of little consequence to closed-loop speed control.

The turbulence simulation was simplified further by eliminating the longitudinal force disturbance due to vertical gusts ($X_{w_g} \sim (D_\alpha - g)w_g/V_o$) with no significant effect on pitch attitude or altitude response. Airspeed response is affected at low frequency; however, the error that results would be expected to be minimized by the pilot as he maintains precise control of pitch attitude to suppress the phugoid mode.

With the contribution of longitudinal gusts and longitudinal force excluded, the remaining disturbances to be considered are the vertical (heave) force and pitching moment due to vertical gusts. Contributions to these disturbances are due to forces and moments generated by the wing, fuselage, horizontal stabilizer, and their mutual interference effects. Lifting surfaces such as the wing and horizontal stabilizer would be expected to produce the dominant disturbances imposed on the airplane. By comparison, the effects of the fuselage are of secondary importance, with the exception of aft c.g. locations where the airplane is balanced so that the fuselage contribution to pitching moment is of the same order of magnitude as the total pitching moment itself. However, in this instance the total pitching-moment disturbance is unlikely to be of sufficient magnitude to degrade the pilot's task performance. The fuselage contribution, therefore, was neglected for the definition of longitudinal turbulence disturbances. The horizontal stabilizer's contribution to vertical force was also ignored for the sake of simplifying the vertical force respresentation.

The airplane's behavior in turbulence is typically considered in terms of the power spectra of the airplane response characteristics of interest. With the simplifications noted in the foregoing discussion, the power spectra of the airplane's response to turbulence may be written

$$\Phi_i = \left|\frac{N_{M_{w_g}}{}^i}{\Delta'}\right|^2 \Phi_{M_{w_g}} + \left|\frac{N_{Z_{w_g}}{}^i}{\Delta'}\right|^2 \Phi_{Z_{w_g}} + 2R_e\left[\frac{N_{M_{w_g}}{}^i}{\Delta'}\right]\left[\frac{N_{Z_{w_g}}{}^i}{\Delta'}\right]^* \Phi_{M_{w_g}Z_{w_g}} \tag{2}$$

The contributions of pitch and heave disturbances are evident in the pitching moment and vertical force power spectra $\Phi_{M_{w_g}}$ and $\Phi_{Z_{w_g}}$ and the cross-power spectrum $\Phi_{M_{w_g}Z_{w_g}}$. The description of these power spectra was based on a stationary, homogeneous, isotropic model of a frozen gust field represented analytically by a gaussian probability distribution and the Dryden spectral function.[3] A modified aerodynamic strip theory, which included transient lift buildup with gust penetration was utilized in the representation. A more complete derivation of the disturbance spectra is available in Ref. 2.

An example of the vertical force spectrum is shown in Fig. 1. This spectrum may be characterized in general by its associated rms magnitude and frequency bandwidth. As indicated in the figure, the expression for the spectrum is

$$\Phi_{Z_{w_g}} = [(Z_\alpha/V_o)]^2 \Phi_{w_e} \tag{3}$$

where Z_α is the aerodynamic stability derivative $(1/m)(\partial Z/\partial \alpha)$, and Φ_{w_e} is the power spectrum of a weighted average of all the spanwise vertical gusts as seen by the wing, with the weighting determined by the spanwise load distribution of the wing. Analytically, Φ_{w_e} may be approximated by[2]

$$\Phi_{w_e} = \{1/[(bc/V_o{}^2)\omega^2 + 1]\}\Phi_w \tag{4}$$

where Φ_w is the one-dimensional Dryden spectrum for vertical gusts[3]

$$\Phi_w = (L/\pi)\sigma_w{}^2\,[3(\omega L/V_o)^2 + 1]/[(\omega L/V_o)^2 + 1]^2 \tag{5}$$

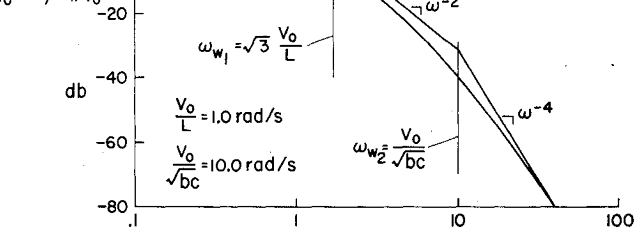

Fig. 1 Approximation of a typical vertical force spectrum due to vertical gusts.

Both the rms level of the vertical gust field and the magnitude of the slope of the lift curve determine the magnitude of the vertical force disturbance [i.e., $\sigma_{Z_{w_g}} = (\sigma_w/V_o)Z_\alpha$]. Wing geometry has an influence on the high-frequency attenuation of the spectrum due to the averaging effect of the wing that spans gust wavelengths in the spanwise direction (where V_o/b is the relevant parameter) and the attenuating influence of transient lift buildup associated with streamwise penetration of turbulence (where V_o/c is the relevant parameter). Planform influences such as aspect ratio and taper are, of course, inherent in the lift curve slope derivative. The dominant corner frequency of the spectrum which effectively characterizes the bandwidth of the turbulence is related to the equivalent angular frequency of a gust wavelength of dimension, L, traversed by an airplane at a trim speed, V_o (i.e., $\omega = V_o/L$).

The power spectra of the pitching moment contributions of the wing and horizontal tail are of precisely the same character as the vertical force spectrum shown in Fig. 1. In this case the rms magnitude of the disturbance is $\sigma_{M_{w_g}} = (\sigma_w/V_o)M_\alpha$ where M_α is the static angle-of-attack stability contribution of the wing or tail, whichever happens to be of interest. Bandwidth of either contribution is determined by the corner frequencies ω_{w_1} and ω_{w_2} of their respective spectra.

In the flight test program the spectral characteristics of the simulated pitch and heave disturbances due to vertical gusts were represented by two cascaded first-order, low-pass filters that produced the asymptotic approximation of the spectrum shown in Fig. 1.

The magnitude of the cross-power spectrum between the pitch and heave disturbances $\Phi_{M_{w_g}Z_{w_g}}$ is influenced by the correlation between the vertical force contribution of the wing and the pitching-moment contribution of the tail. This cross spectrum may be expressed as

$$\Phi_{M_{w_g}Z_{w_g}} = Z_w[M_{w_w} + M_{w_t}e^{-j(\omega l_t/V_o)}]\Phi_w \quad (6)$$

where l_t is the moment arm of the horizontal stabilizer's aerodynamic center about the center of gravity. For conventional approach speeds and small to medium size aircraft, the influence of the cross-spectral term on turbulence response is of little consequence. It was evaluated in flight[2] but will not be considered further in this discussion.

Definition of the Flight Test Program

Parameters of Longitudinal Dynamics and Turbulence

Longitudinal dynamics characteristics chosen for study in the flight program were those most strongly related to elements of manual control of the airplane on the ILS approach. Perhaps the most important single requirement for satisfactory longitudinal flying qualities in the presence of turbulence is the ability to control pitch attitude precisely. Many tasks performed by the pilot require pitch attitude control as a primary element (straight and level flight, turns, climb and descent maneuvers, takeoff rotation and climbout, landing approach, flare and touchdown) either as the actual means for performing the task or as an intermediate means for achieving the desired end result. Reference 4 provides an extensive review of previous investigations as well as a thorough analysis of pitch control. Reference 5 also is an interesting analytical study of the problem and provides some insights to the pilots' techniques in performing pitch attitude and altitude tracking tasks. Pitch attitude control with the elevator essentially reduces to direct control of the airplane's short period response. Although plugoid motion does appear in the open-loop pitch response the pilot has no difficulty in controlling pitch motions associated with this mode. Control of the short-period pitch response may be characterized by the short-period natural frequency ω_{sp}, the short-period damping ratio ζ_{sp}, the numerator root of the pitch attitude to elevator transfer function $1/T_{\theta_2}$, and the longitudinal control sensitivity M_{δ_e} and F_s/g, or suitable combinations of any of these. The short-period frequency affects the quickness of the response of the airplane in pitch to elevator inputs. Furthermore, since it is strongly related to the airplane's angle-of-attack stability [$\omega_{sp}{}^2 \doteq -M_\alpha + M_{\dot\theta}(Z_\alpha/V_o)$], the frequency is also associated with the airplane's static longitudinal stability and hence to the tendency of the airplane to hold a given trim airspeed. Short-period damping ratio in general would be expected to influence the oscillatory character of the short-period response. However, the range of ζ_{sp} encountered for many airplanes is sufficient to prevent appreciable pitch oscillations and, as a result, the damping ratio is more likely to manifest itself in terms of overshoots in pitch rate response. This characteristic tends to be more important in maneuvering flight than for control of perturbations about steady level, climbing, or descending flight. The pitch attitude numerator root $1/T_{\theta_2}$ affects the pilot's ability to achieve a tight control pitch attitude over a wide band of frequencies.

Precise control of the airplane's flight-path angle and altitude are also important. As Ref. 5 points out, the pitch attitude numerator root, $1/T_{\theta_2}$, is predominantly determined by the lift curve slope ($1/T_{\theta_2} \doteq -Z_\alpha/V_o + Z_{\delta_e}M_\alpha/V_oM_{\delta_e}$). Because control of the airplane's flight path through changes in pitch attitude is strongly dependent on the magnitude of the lift curve slope, $1/T_{\theta_2}$ provides an indication of the pilot's ability to achieve precise flight path and altitude control with the elevator. The stability of closed-loop control of flight-path angle or altitude with the elevator is related to the parameter, $1/T_{h_1}$, that is the low-frequency real root of the numerator of the altitude to elevator transfer function. Influences of this parameter are considered in detail in Refs. 4–6. It is related to the operating point on the throttle required curve ($1/T_{h_1} \doteq -X_u + (X_\alpha - g)Z_u/Z_\alpha$) that defines flight-path stability with speed.

Of these parameters, the short-period frequency and damping (ω_{sp},ζ_{sp}) and the pitch attitude numerator root ($1/T_{\theta_2}$) were chosen as variables for the current test program. Phugoid dynamics were essentially constant ($\omega_{ph} \doteq 0.25$ rad/sec $\zeta_{ph} \doteq 0.13$) with one exception where the phugoid decomposed into a pair of real roots, one of which represented a mildly unstable exponential divergence. Operation on the front side of the throttle-required curve was achieved in every instance, thereby keeping $1/T_{h_1}$ in a satisfactory range ($1/T_{h_1} = 0.04$ 1/sec). Longitudinal control sensitivity, M_{δ_e}, was set at the optimum value chosen for smooth air operation. These values corresponded to results for optimum control sensitivity.[7]

Combinations of these dynamics characteristics and the parameters of turbulence previously described were incorporated in the test program to: 1) permit an independent evaluation of rms pitch and heave disturbances and spectral bandwidth for good longitudinal dynamics, 2) determine the influence of short-period frequency (angle-of-attack stability) for selective variations in rms pitch disturbance magnitude and bandwidth with lift curve slope and damping ratio constant, 3) determine the influence of short-period damping for selective variations in pitch disturbances and bandwidth with lift curve slope constant and for two values of short-period frequency, 4) determine the influence of lift curve slope emphasizing variations in pitch and heave disturbance magnitude and bandwidth with short-period frequency and damping constant. Light turbulence was simulated in roll and yaw to keep the total turbulence environment more realistic. One lateral-directional dynamics configuration having good flying qualities[1,8] was used throughout the program ($T_R = 0.25$ sec, $\omega_d = 2.3$ rad/sec, $\zeta_d = 0.1$, $L_\beta = -16$ rad/sec^2/rad, L_{δ_a} and N_{δ_r} optimum).

Of the four aerodynamic controls of the Navion, only the flap authority restrictions were reached or exceeded in the flight program. Full flap deflection about the approach setting provides about 0.5 g incremental normal acceleration

Table 1 Effect of flap authority on heave disturbance simulation

Desired of simulation	Achieved in flight
0.09 g	0.09 g
0.2 g	0.18 g
0.4 g	0.3 g

for the approach flight condition. This flap authority was adequate for simulation of the nominal tested rms heave disturbance of 0.2 g. However, the fidelity of the largest heave disturbance simulated ($\sigma_Z = 0.4$ g) was compromised. Limitations on maximum attainable flap deflection produced a truncated gaussian probability density for flap response. Values of σ_Z determined from flap deflections measured in flight compared to the desired simulated values are noted in Table 1.

This severe modification of the statistical properties for the large heave disturbance compromises that particular simulation since it significantly alters the maximum expected value of the disturbance (maximum Z_{w_g} encountered should be about 3 σ_Z for a gaussian distribution). However, the $\sigma_Z = 0.4$ g configuration was retained in the test matrix for the sake of evaluating a condition with more frequent large heave disturbances than were encountered for the low-disturbance cases where the gaussian distribution was not violated. Therefore, when considering the flight data for large heave disturbances shown in the next section, one must recall that the maximum heave disturbance encountered did not exceed approximately 0.5 g, instead of reaching approximately 1.2 g as anticipated in the extreme for gaussian turbulence.

Evaluation Task

The flight evaluation procedure is illustrated in Fig. 2. Each test configuration was set up on the downwind leg of the approach where the variable stability system was engaged and the evaluation pilot assumed control of the airplane. About one minute was available for the pilot to feel out the configuration before commencing a 135° turn to the left to intercept the localizer. After the localizer was acquired, the pilot had about one minute of level flight tracking before intercepting the glide slope. During this time the simulated turbulence was turned on. The ILS approach proceeded on a 3.2° glide slope at 120 mph indicated trim airspeed down to an altitude of 200 ft above the surface. At that point the evaluation pilot established visual contact with the ground and made a VFR offset maneuver, requiring a 25° heading change to aline with the runway. A waveoff was executed at 20 ft altitude and the safety pilot then assumed control of the airplane to permit the evaluation pilot to transmit his comments to the flight test monitor on the ground. Pilot opinion ratings (POR) were based on the revised Cooper-Harper scale.[9] If appropriate, the pilots distinguished in their comments between the IFR and VFR segments of the approach. Since the turbulence simulation was not considered representative of the characteristics of atmospheric turbulence below about 200 ft,[10] any comments regarding maneuvers during the final stages of the approach immediately prior to what would be the initiation of flare (or, in this case, the waveoff) were not given equal weight to ratings and commentary related to the IFR segment of the approach. All evaluations were based on the duration of the approach. No attempt was made to factor fatigue or extended exposure time into the ratings.

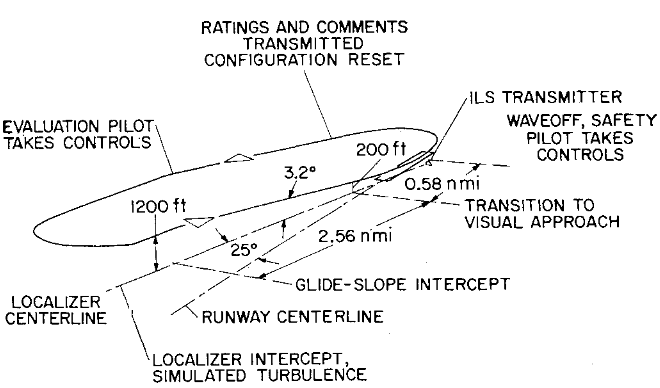

Fig. 2 Diagram of simulated approach.

Data in the form of pilot ratings, commentary, task performance, and control activity measures were provided by four evaluation pilots. Three of the pilots had combined military and general aviation backgrounds with current experience as flight test engineers and flying qualities evaluation pilots. The fourth pilot had an extensive background in single and multiengine general aviation airplanes and engineering experience in stability and control analysis. All were instrument rated. Time histories of the pertinent airplane response and control input variables were digitally processed for rms measures of precision of task performance and pilot control activity.

Results of the Flight Test Program

Data obtained during the flight test program consisted to a considerable extent of pilot opinion ratings and commentary relating to the flying qualities of individual airplane configurations for various simulated turbulence environments. Supplementary data in the form of time history measurements of the airplane's motion, the pilot's control activity, and the simulated disturbance inputs were obtained for a selected number of configurations for one of the evaluation pilots. These measures of the precision of task performance and the pilot's control activity are compared with the pilot rating data and commentary to provide quantitative support for the pilot opinion trends. The measure of performance shown is rms pitch attitude excursion. Rms normal acceleration is also shown as an indication of the distraction and discomfort experienced by the pilot. Control activity is measured in terms of rms elevator stick force.

Contribution of Turbulence—Good Longitudinal Dynamics

At the outset it is worthwhile to consider the independent influences of the various turbulence characteristics of interest with longitudinal dynamics held constant to remove any conflicting interactions that might obscure the contribution of turbulence. Of the characteristics included in the flight program (rms pitch and heave disturbance magnitude σ_M and σ_Z and turbulence bandwidth $\omega_{w_1} = 1.73\ V_o/L$), disturbance magnitude was found to have the dominant influence on pilot ratings for the ILS task. In this regard pitch disturbances had a more profound effect than heave disturbances. Bandwidth of the turbulence spectrum had considerably less influence than disturbance magnitude on pilot ratings.

Rms disturbance magnitude

The importance of precise pitch attitude control during the approach, which repeatedly appears in the pilots' remarks, is the basis for the serious objections to large pitch disturbances. Pilots' comments indicate that the basic airplane is easy to handle in light turbulence ($\sigma_M = 0.14$ rad/sec^2, $\sigma_Z =$ 0.09 or 0.2 g). Pitch attitude control is precise and pitch excursions and pilot workload (rms stick motion) are small. No problems were observed in flying the glide slope or in holding the trim airspeed for the approach. The airplane is quite stable in pitch, has adequate normal acceleration response for altitude control and tracking the glide slope, and has adequate speed stability associated with operation well on the front side of the throttle-required curve ($1/T_{h_1} = 0.04$). However, as pitch disturbances were increased the pilots began to complain of difficulty in achieving the precision of pitch attitude control desired. Increasing pitch excursions and control workload were the object of the pilots' complaints. In an extreme case ($\sigma_M = 0.55$ rad/sec^2), large pitch excursions (on the order of $\pm 10°$) detracted considerably from the pilots' ability to stay on the glide slope and hold airspeed. One of the secondary evaluation pilots, who gave the airplane an unacceptable rating (POR = 7), found glide slope control to be quite sensitive as he approached the 200-ft altitude for transition from IFR to VFR flight.

The pilots seemed to be more tolerant of increases in heave disturbances (that were independent of pitch disturbances) because they did not upset the airplane to the extent caused by pitch axis disturbances. When heave disturbances were increased to the maximum value tested in the flight program, the pilot's objections related to the increase in discomfort and distraction associated with the increased level of normal acceleration. The highest level of heave disturbance did not increase pilots' workload or appreciably degrade pilots' pitch control precision, airspeed control, or glide-slope tracking.

The effects of the rms magnitude of turbulence disturbances in heave and pitch on pilot ratings are shown in Fig. 3. It is the practice in this paper to distinguish between the primary evaluation pilot, who flew every configuration in the test program at least twice (frequently three times and occasionally more often) and the other (secondary) pilots, who flew only a portion of the configurations in the test matrix, often making only one evaluation per configuration. Such a separation of the pilot rating data avoids obscuring the primary pilot's rating trends in the possible scatter of a number of singular ratings, while preserving these individual ratings and whatever message they may have in the way of each pilot's evaluations. The data are for a given set of longitudinal dynamics quite similar to those of the basic Navion ($L_\alpha/V_o = 2.0$ 1/sec, $\omega_{sp} = 3.0$ rad/sec $\zeta_{sp} = 0.8$) and for an intermediate spectral bandwidth corresponding to $V_o/L = 1.0$ rad/sec. Average pilot ratings are noted adjacent to each test point and lines of constant pilot rating are faired to the primary pilot's data.

The degradation in pilot rating with increasing turbulence level is apparent in the figure. The gradient of pilot rating

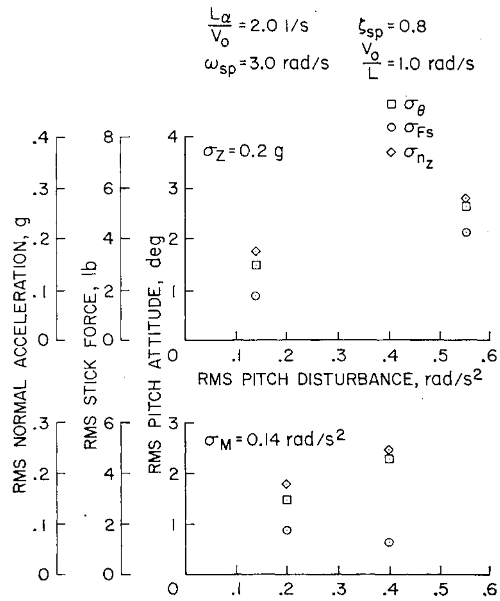

Fig. 4 Trends of task performance and control activity with disturbance magnitude.

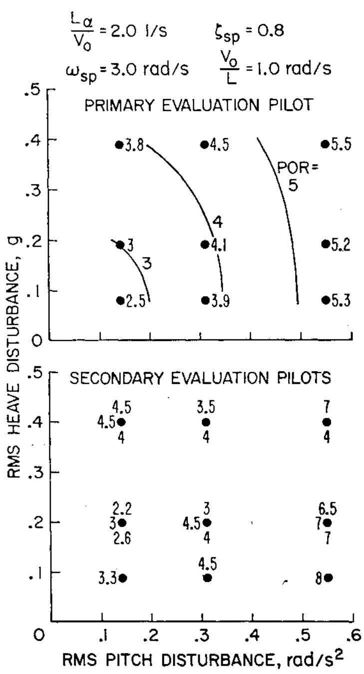

Fig. 3 Effect of rms pitch and heave disturbances on pilot rating.

with turbulence level is not too severe and only for extreme pitch disturbances do the pilot ratings approach the unacceptable level for the case of good longitudinal dynamics. It should be recalled from the previous section that the magnitude of simulated heave disturbances was limited by the restrictions on flap travel. While the data are plotted for the rms heave magnitude corresponding to the true gaussian distribution, the effect of the restricted flap deflection on the actual rms disturbance achieved in flight should be kept in mind.

The deterioration in pitch attitude control and the increase in control activity noted in the pilots' commentary are apparent in Fig. 4. Rms values of pitch excursions, stick force, and normal acceleration are plotted in the upper diagram of this figure for the lowest and highest levels of pitch disturbance ($\sigma_M \doteq 0.14$ and 0.55 rad/sec^2). Not only do rms pitch attitude and stick force reflect the increase in pitch disturbances, but rms normal acceleration also increases because of the larger transient g loads associated with large pitching motion and a large lift curve slope configuration. The data shown in the lower diagram of Fig. 4 as a function of heave disturbance magnitude also support the pilots' commentary. Both the pilot ratings of Fig. 3 and the performance-control activity data of Fig. 4 indicate the dominant influence of pitch disturbances over heave on these measures of longitudinal flying qualities.

Spectral bandwidth

Very little influence of turbulence bandwidth was apparent in the flight test program. The pilots, according to their commentary, could discern changes in the frequency content of the turbulence. However, only for the turbulence with the highest bandwidth ($V_o/L = 2.0$ rad/sec) did the pilots indicate that frequency content of the disturbances had any direct influence on their evaluations. For $V_o/L = 2.0$ rad/sec the pilots complained about high-frequency pitch attitude excursions. Typically, the pilots were unable to track the high-frequency pitch excursions or did not choose to do so. They felt the effort required to track these motions would not yield a significant improvement in performance, and occasionally they remarked that the pitch control situation was aggravated if they attempted to attenuate the higher frequencies. High-frequency attenuation of either the pitch

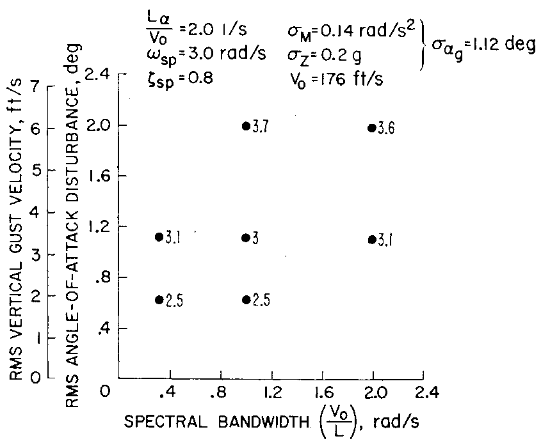

Fig. 5 Influence of spectral bandwidth on pilot ratings.

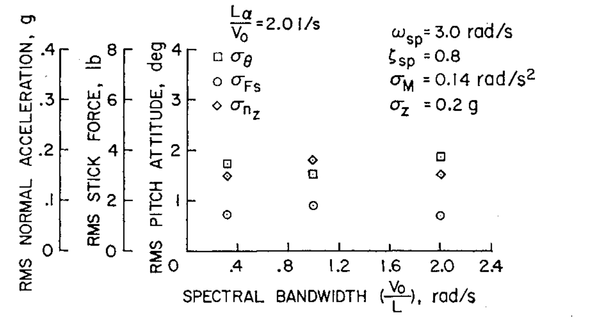

Fig. 6 Trends of task performance and control activity with spectral bandwidth.

or heave disturbances associated with the second corner frequency, ω_{w_2}, were only barely perceptible to the pilots because of the low-energy level of the turbulence in this region of the spectrum. No change in pilot rating was noted for variations in ω_{w_2} from 10–18 rad/sec.

The effects of bandwidth of the turbulence spectrum on pilot rating, in combination with variations in turbulence magnitude, may be noted in the data of Fig. 5. The data are presented for the case of good longitudinal dynamics in terms of the rms vertical gust velocity (or the equivalent rms angle of attack for a trim speed, $V_o = 176$ fps) and the spectral corner frequency parameter V_o/L. The magnitude of rms pitch and heave disturbances is given in the upper right hand corner for the $\sigma_{\alpha_g} = 1.12°$ condition. Variations in the rms gust velocity produce proportional variations in rms heave and pitch disturbances. While a modest degradation in pilot rating occurs with the increase in magnitude of turbulence, there is essentially no change in rating for variations in bandwidth corresponding to $V_o/L = 0.314$ to 2.0 rad/sec.

Measures of precision of pitch attitude control and control activity for variations in spectral bandwidth confirm the pilot rating data. Figure 6 shows that there are no significant variations in either rms pitch attitude, stick force, or normal acceleration over the range of bandwidths tested. Closed-loop manual control analyses of the pilot-vehicle system substantiate this behavior by revealing the pilot's ability to produce a relatively flat frequency response for the airplane's pitch attitude to vertical gust transfer function over the bandwidth of the disturbance inputs.[2] Hence, so long as the rms disturbance magnitude is held constant, the closed-loop airplane response would not be expected to change as the disturbance bandwidth is varied.

Interacting Effects of Turbulence and Longitudinal Dynamics

Considering the importance of pitch attitude control, it is necessary to account both for the effects of longitudinal dynamics and the characteristics of turbulence that have a bearing on the pilot's ability to control attitude precisely. In this regard the combined effects of short-period frequency and damping, and disturbance magnitude and bandwidth were evaluated in the flight test program. Flight-path control characteristics as influenced by the airplane's lift curve slope and by the disturbance magnitudes were of concern as well and will be dealt with separately in the discussion to follow.

Short-period frequency and turbulence characteristics

Flight test results confirm the importance of the short-period mode to pitch attitude control. As might be expected, pitch disturbances are least tolerable for those short-period configurations leading to poor attitude control. Low short-period frequency (low static angle-of-attack stability) is the most objectionable characteristic as regards short-period dynamics. The combined effects of short-period natural frequency with rms pitch disturbance magnitude is shown in Fig. 7. These data are presented for constant values of slope of the lift curve, real damping of the short-period mode, and spectral bandwidth ($L_\alpha/V_o = 2.0$ 1/sec $\zeta_{sp}\omega_{sp} = 2.4$ rad/sec, $V_o/L = 1.0$ rad/sec). Average ratings from the primary evaluation pilot are shown to the right of each test point and contours of constant rating units are faired to these data. Ratings from one of the other pilots are also included.

Considering the trends of pilot rating it is apparent that independently increasing the level of pitch disturbances or reducing the short-period frequency (angle-of-attack stability) is detrimental to the ILS task. The adverse influence of increasing the pitch turbulence level had been demonstrated in Fig. 3 for a satisfactory level of short-period frequency. It is further apparent from Fig. 7 that pilot rating becomes increasingly sensitive to pitch turbulence as the short-period frequency is reduced. By the same token, changes in short-period frequency have the greatest influence on pilot rating at the highest pitch disturbance level tested. In fact, when pitch disturbances are small, short-period frequency has very little effect on pilot rating until the angle-of-attack stability boundary is approached. Perhaps the trends of this figure may best be summarized by saying that the pilot likes more static longitudinal stability when pitch disturbances are large and otherwise will tolerate quite a wide variation in static stability.

Pilot commentary emphasizes difficulties in achieving precise pitch attitude control for the lowest short-period frequency. It was necessary to pay close attention to pitch attitude and to airspeed to fly the glide slope acceptably. The pilots were aware of the slight static instability of the

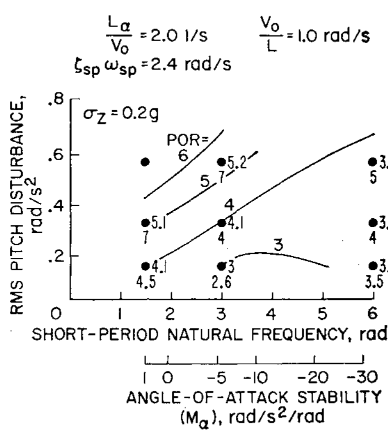

Fig. 7 Effects of short-period frequency and pitch disturbances on pilot rating.

lowest frequency configuration tested and they complained of the tendency of pitch attitude and airspeed to wander if their attention was distracted to some other aspect of the task (such as lateral-directional control, power management, or communications).

Pilot-vehicle analyses[2] indicate that good closed-loop attitude control can be achieved with a moderate amount of lead compensation (pitch damping augmentation). However, this implies that the pilot can pay continuous attention to pitch attitude and is willing to accept the workload thus involved. According to their commentary, such a situation is apparently unsatisfactory to the pilots. Increases in pitch disturbances similar to those imposed on the higher frequency configurations brought more vociferous complaints about the size of pitch excursions and the effort required to control them. An inadvertent test run was made for the low-frequency configuration with extremely large pitch disturbances ($\sigma_M = 0.55$ rad/sec, $\omega_{sp} = 1.5$ rad/sec). Although no numerical rating is shown for this configuration in Fig. 7, the one unfortunate pilot who flew it rated it in the 9–10 category, emphasizing the likelihood that control could easily be lost since adequate pitch control power was not always available in the presence of such large disturbances. Turning to the highest frequency configuration, pilot commentary was generally favorable with the exception of complaints about the high-frequency pitch bobble excited by turbulence or by continuous control activity by the pilot. The pilots would generally decline to track the highest frequency motions, typically commenting that their effort was producing no commensurate improvement in pitch performance. In general, the bobble was considered an annoying and sometimes distracting characteristic of the configuration, but one that did not seriously affect the ILS task. Airspeed control and glide-slope tracking were good. Increasing the level of pitch disturbances had much less influence than for the lower-frequency configurations.

It should be re-emphasized that the data points of Fig. 7 represent independent variations of short-period frequency and pitch disturbance magnitude. While short-period frequency and the magnitude of pitch disturbances can be interrelated for a given aircraft configuration through the aerodynamic pitching-moment derivatives M_α and $M_{\dot\theta}$ (or M_{α_w} and M_{α_t}), that is

$$\omega_{sp}^2 \doteq -[M_\alpha + (L_\alpha/V_o)M_{\dot\theta}]$$

$$\sigma_M^2 = [M_{\alpha_{gw}}^2 + M_{\alpha_{gt}}^2 + 2M_{\alpha_{gw}}M_{\alpha_{gt}}e^{-1.73(l_t/L)}](\sigma_w/V_o)^2$$

$$M_\alpha, M_{\dot\theta} = f(M_{\alpha_w}, M_{\alpha_t}, l_t)$$

this interrelationship did not in general hold for the test configurations in Fig. 7. However, as is illustrated in Fig. 8, there are a loci of points in the matrix of configurations of Fig. 7 where this interrelationship does apply. In Fig. 8, the dashed lines describe the variation of pitch disturbances and short-period frequency with M_α. Moving along any one of these dashed lines from left to right, M_α increases negatively (increasing static stability) and pitch disturbances and short-period frequency vary according to the functional

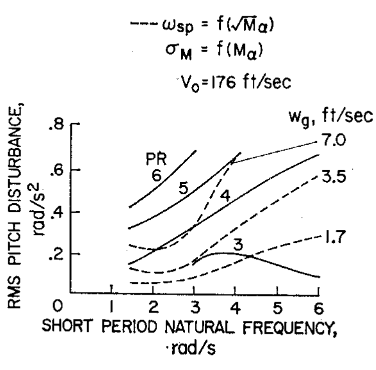

Fig. 8 Combined effects of static stability and gust level on pilot rating.

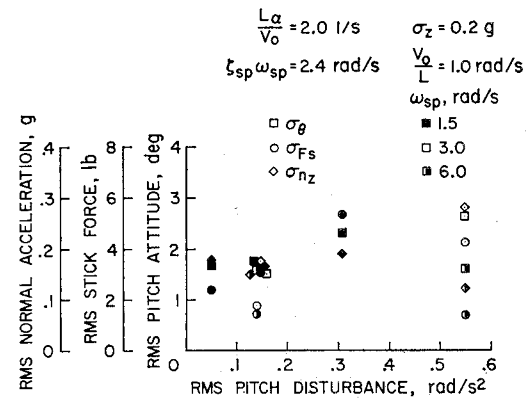

Fig. 9 Combined effects of short period frequency and pitch disturbances on task performance and control activity.

relationships shown at the top of the figure. Effects of different levels of vertical gust intensity are indicated by the three individual lines, corresponding to $\sigma_{w_g} = 1.7$, 3.5, and 7.0 fps, respectively. A comparison of the trend of these dashed lines with the pilot rating contours of Fig. 7 (superimposed here for convenience) identifies an intermediate region of M_α where pilot rating is insensitive to changes in M_α and is optimum for each vertical gust level. At higher or lower M_α pilot ratings deteriorate: at higher M_α, because the adverse effects of large pitch disturbances override improvement in attitude control accompanying the increased stiffness in pitch; at lower M_α because of attitude and airspeed control problems related to low-static stability. This behavior applies generally and tends to be more pronounced at the higher vertical gust levels.

Performance-control activity measures for this series of configurations are presented in Fig. 9. The combined effects of short-period frequency and pitch disturbance magnitude are indicated for constant heave disturbance and turbulence bandwidth. The variation of control activity with pitch disturbance magnitude increases to a considerable extent as short-period frequency is reduced. Pitch attitude excursions and normal acceleration show trends similar to those of control activity. The control activity data in particular substantiate the pilot commentary and pilot rating trends of Fig. 7. It may well be that the rms stick force does not entirely reflect the pilots' workload for these low frequency configurations. The necessity to pay close attention to pitch attitude and airspeed control represents an additional demand on the pilot that may also account in part for the degraded ratings.

In concluding this section, it is worth noting that the generally innocuous influence of spectral bandwidth observed previously was not altered by variations in ω_{sp}. Neither pilot rating nor performance-control activity data revealed significant trends over the range of V_o/L of 0.3 to 2.0 rad/sec at either extreme of ω_{sp} noted in the foregoing discussion.

Short-period damping and turbulence characteristics

While short-period damping might be expected to have an appreciable effect on pitch attitude control and the ILS task as well, only a minor influence was observed for the range of damping investigated in this program. Damping was varied, either in terms of damping ratio (ζ_{sp}) or real damping ($\zeta_{sp}\omega_{sp}$) for two levels of short-period frequency. The combined effects of frequency and damping on pilot rating are shown in Fig. 10. Lift curve slope, heave disturbance magnitude, and spectral bandwidth are constant ($L_\alpha/V_o = 2.0$ 1/sec; $\sigma_Z = 0.2\,g$, $V_o/L = 1.0$ rad/sec). Two levels of real damping are shown, ranging from a value comparable to the basic Navion at the given flight condition down to a value corresponding closely to neutral pitch damping. Damping ratios range from 0.5–1.6.

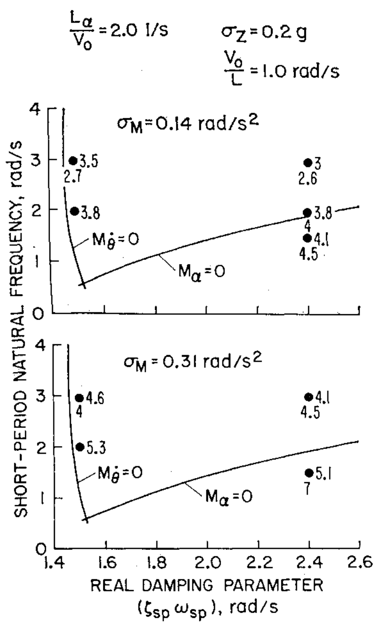

Fig. 10 Effects of short-period frequency and damping on pilot rating.

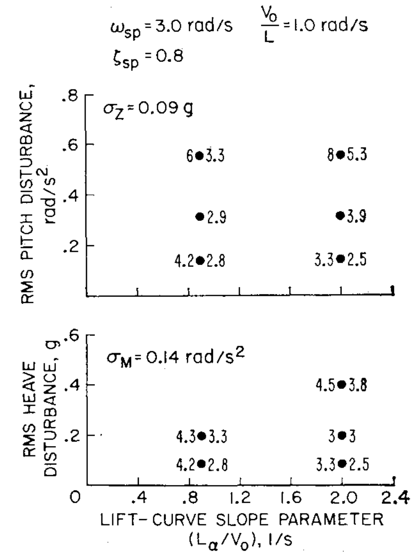

Fig. 11 Combined effects of lift curve slope with pitch and heave disturbances on pilot rating.

Only a modest influence on pilot rating can be seen in the figure up to the point of neutral pitch damping. This conclusion applies for either of the values of short-period frequency shown and for the two levels of pitch disturbance. According to their commentary, the pilots were aware of reduced pitch damping of the $\zeta_{sp}\omega_{sp} = 1.5$ rad/sec configurations primarily through increased pitch rate overshoots associated with the lower damping ratio. However, the pilots remarked that the pitch overshoot tendency did not have any significant effect on their ability to fly the approach. At the higher short-period frequency ($\omega_{sp} = 3.0$ rad/sec), control workload was considered light to moderate, and airspeed control and glide-slope tracking were satisfactory. The same remarks would apply as well to the case of larger pitch disturbances shown in the lower diagram, except that the level of difficulty of the task in terms of pitch attitude precision and control workload increased with the turbulence magnitude.

Lift curve slope and turbulence characteristics

The speed and precision with which flight-path corrections can be made through changes in attitude have been noted as primarily dependent on the airplane's lift curve slope. For the range of L_α/V_o covered in this program, very little effect was noted on flight path or glide slope control independent of the contributions of turbulence. However, the lift curve slope magnitude was found to have a decided influence on the effect of pitch disturbances on the ILS task.

Pilot rating data for combined variations in the parameter L_α/V_o, and pitch and heave disturbance magnitude are shown in Fig. 11. Short-period dynamics and the turbulence bandwidth are constant ($\omega_{sp} = 3.0$ rad/sec, $\zeta_{sp} = 0.8$, $V_o/L = 1.0$ rad/sec). Reducing the lift curve slope to a little less than half that of the basic Navion (reducing L_α/V_o from 2.0–0.9 1/sec) has only a modest influence on the ILS approach, so long as pitch upsets are light ($\sigma_M \doteq 0.14$ rad/sec^2). The primary pilot's ratings degrade less than one-half unit for this reduction in L_α/V_o, while the secondary pilot's rating degrades by about a full rating unit. Pilot commentary indicates an awareness of the reduced lift curve slope, and the degraded ratings, when they are observed, relate to the slower flight-path response to pitch attitude commands. Longer time was required to make glide slope corrections, and as a result glide slope control demanded more attention by the pilot during the approach. Airspeed control was good for the lower L_α/V_o configuration.

All of the foregoing applies when pitch disturbances are light, as is the case for the lower diagram of Fig. 11 and for a portion of the upper diagram. It is apparent in the upper diagram that a reduction in lift curve slope improves the pilot's rating of the ILS approach when pitch disturbances are large. For the extreme pitch disturbances shown ($\sigma_M = 0.55$ rad/sec^2), an improvement in pilot rating of two units accompanies the reduction in L_α/V_o from 2.0–0.9 1/sec. Depending on which pilot's ratings are considered, the approach is improved from one moderately objectionable to one generally satisfactory and acceptable (primary pilot), or it is improved from an inadequate to an adequate, though very objectionable approach (secondary pilot). The reason for this improvement in rating for the lower L_α/V_o configuration is its reduced heave response to pitch excursions. Glide slope excursions are smaller when L_α/V_o is low and the ride itself is not as uncomfortable or distracting as when L_α/V_o is on the order of the basic Navion. While the pilots still object to the large pitch excursions associated with large pitch disturbances and will work to reduce their magnitude, the pilots' difficulty in flying the ILS is distinctly reduced for the lower L_α/V_o airplane.

Data of Fig. 12 make it apparent why lowering L_α/V_o improves pilot rating in the presence of large pitch disturbances. These data show the effect of pitch disturbance magnitude on the usual performance-control activity measures for the two levels of L_α/V_o tested. The significant improvement in rms pitch attitude, stick force, and normal

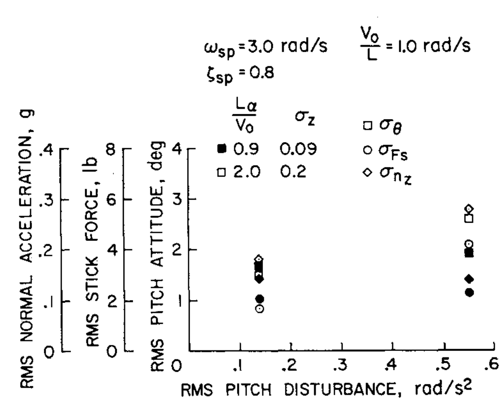

Fig. 12 Combined effects of lift curve slope, pitch, and heave disturbances on task performance and control activity.

acceleration at the extreme pitch disturbance level ($\sigma_M = 0.55$ rad/sec^2) as L_α/V_o is reduced concurs with the pilots' commentary and, along with a similar improvement in glide slope performance, offers the basis for their ratings.

Conclusions

These flight test were conducted in a light, general aviation airplane with variable stability and control capability that permitted characteristics of a much wider class of vehicle to be represented. Therefore, the restrictions on the application of results discussed previously are those imposed by the ILS task, by the range of turbulence and dynamics characteristics tested, and by the airspeeds associated with the conventional ILS approach.

From the flight test results of this program, it is apparent that the dominant influences on longitudinal flying qualities for the ILS approach are the pilot's control activity required to fly the ILS approach satisfactorily and the precision of performance of the task as measured in terms of pitch attitude, airspeed, and glide slope or altitude excursions. The effects of turbulence disturbances and airplane dynamics on the ILS task may be explained in terms of these performance and control activity factors.

The specific influences of turbulence and dynamics on longitudinal flying qualities for the ILS that have been identified in this program may be summarized as follows. 1) The dominant influence of turbulence is the magnitude of the aerodynamic disturbances. Pitch disturbances have a more adverse effect than heave disturbances. 2) Increasing turbulence bandwidth has a mildly degrading influence on pitch attitude control. Higher frequency attenuation of the disturbance spectrum is of no consequence to the ILS task. 3) The adverse effect on pitch attitude control, airspeed control, and ILS performance of increasing pitch disturbances is most pronounced for low short-period frequencies (low-static stability). When pitch disturbances are large, more static stability (higher ω_{sp}) is desired. 4) Combined effects of short-period frequency and pitch disturbance magnitude, where the two effects are interrelated through the aerodynamic angle-of-attack stability derivative (M_α), degrade flying qualities for either the high or low extremes of short-period frequency. Little influence is noted for changes in frequency in the range from 2.0–5.0 red/sec. 5) Reducing short-period damping at intermediate short-period frequencies ($\omega_{sp} = 3.0$ rad/sec) has very little effect on the ILS. Lowest damping ratios tested corresponded to neutral pitch damping ($M_{\dot\theta} \doteq 0$). The only difficulty that accompanied the reduction in pitch damping was a modest degradation in pitch attitude control. 6) The reduction in pitch damping has no worse effect on flying qualities when pitch disturbances are large than when they are small. 7) Reducing the lift curve slope has only a modest effect on the ILS task. Glide slope tracking deteriorates slightly for reductions in L_α/V_o to 0.9 1/sec. 8) The minor influence of turbulence bandwidth observed for the case of good longitudinal dynamics was not changed by variations in short-period frequency or damping or lift curve slope.

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