are 0.53 in. in diameter; air is supplied from the engine 13th-stage bleed with 15-psig nozzle pressure at idle engine power and regulated to 55 psig at higher engine powers. Figures 7 and 8 show the final aft blowing concept.

The dedicated efforts of many people within The Boeing Company, combined with assistance and understanding from the airlines involved, were the ingredients which made the entire program successful.

OCTOBER 1971 J. AIRCRAFT VOL. 8, NO. 10

Flight Investigation of the Influence of Turbulence on Lateral-Directional Flying Qualities

JAMES A. FRANKLIN*
Princeton University, Princeton, N. J.

Flight evaluations using a variable stability airplane were made to determine the independent and interacting effects of simulated turbulence disturbances and lateral-directional dynamics on flying qualities associated with a precision heading control task. Turbulence was described in terms of rms roll and yaw disturbance magnitude, correlation between roll and yaw disturbances, and the bandwidth of the turbulence power spectrum. Variations in dynamics included roll damping, directional stability, and Dutch roll damping. 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, pilot control workload, and pilot compensatory behavior derived from time histories of the flight evaluations.

Nomenclature

L = rolling moment or roll angular acceleration
L_{ug},L_{vg},L_{wg} = roll angular acceleration due to u_g,v_g,w_g
L_{β_g} = derivative of roll acceleration with respect to sideslip disturbance, $(1/I_x)$, $\partial L/\partial_{\beta_g}$
L_{pg} = derivative of roll acceleration with roll gust disturbance, $1/I_x \partial L/\partial_{pg}$
L'_i = Primed roll acceleration derivative $L_i + (I_{xz}/I_x)N_i/1 - (I_x^2/I_xI_z)$
N = yawing moment or yaw angular acceleration
N_{ug},N_{vg},N_{wg} = yaw angular acceleration due to u_g,v_g,w_g
N_{β_g} = derivative of yaw acceleration with respect to sideslip disturbance, $(1/I_z)$, $\partial N/\partial_{\beta_g}$
N_i = primed yaw acceleration derivative, $N_i + (I_{xz}/I_z)L_i/1 - (I_{xz}^2/I_xI_z)$
N_{L^i},N_{N^i} = transfer function numerators relating response i to roll and yaw disturbances
R_e = real part of a complex number
T_R = roll subsidence mode time constant
T_{v1},T_{w1} = time constants associated with the corner frequencies ω_{v1} and ω_{w1} of the disturbance spectra
V_0/L = parameter defining the corner frequency of the turbulence spectrum; V_0 = true airspeed, L = integral scale of turbulence
Y = lateral acceleration
Y_{ug},Y_{vg},Y_{wg} = lateral acceleration due to u_g,v_g,w_g
b = wing span
c = wing chord
g = acceleration due to gravity
p = roll rate
r = yaw rate
u,v,w = longitudinal, lateral, and vertical velocity perturbations
u_g,v_g,w_g = longitudinal, lateral, and vertical gust velocities
β = sideslip angle
Δ' = characteristic equation for closed loop manual control
δa_s = lateral stick deflection or force
δr_p = rudder pedal deflection or force
σ_i = root mean square of the variable i
Φ_i = power spectral density of the variable i
φ = bank angle
Ψ = heading
ω_d,ζ_d = dutch roll natural frequency and damping ratio
ω_{v1},ω_{w1} = bandwidth of the lateral and vertical gust disturbance spectra
$| \ |$ = absolute value
$(\ )^*$ = complex conjugate of $(\ )$

This research was supported by NASA Headquarters under Contract No. NSR 31-001-104.

* Presently a member of the Flight and Systems Research Branch, NASA Ames Research Center, Moffett Field, Calif. Member AIAA.

Index categories: Aircraft Gust Loading and Wind Shear; Aircraft Handling, Stability, and Control.

Introduction

TURBULENCE, whether encountered in VFR cruise flight or under a precisely controlled IFR terminal area maneuver, whether encountered as a pilot or as a passenger, can be a highly disconcerting, discomforting, and a potentially dangerous experience. And yet, in the history of study of airplane flying qualities, a conspicuously small amount of attention has been paid, either theoretically or experimentally, to the effects of atmospheric turbulence on the pilot's capability to control the airplane. Certainly there has been some degree of awareness that the airplane's turbulence response characteristics play a part in determining its over all handling characteristics. NACA Report No. 1 titled "Report on Behavior of Aeroplanes in Gusts" is an indication of the early interest in the general subject. Ample evidence is available from pilot commentary collected during operational use, airplane flight test programs, variable stability airplane programs, and the like, of the deleterious effects of turbulence on the pilot's ability to control the airplane satisfactorily. However, to this date, no systematic study has been made to achieve a fundamental understanding of the relationship of turbulence to flying qualities.

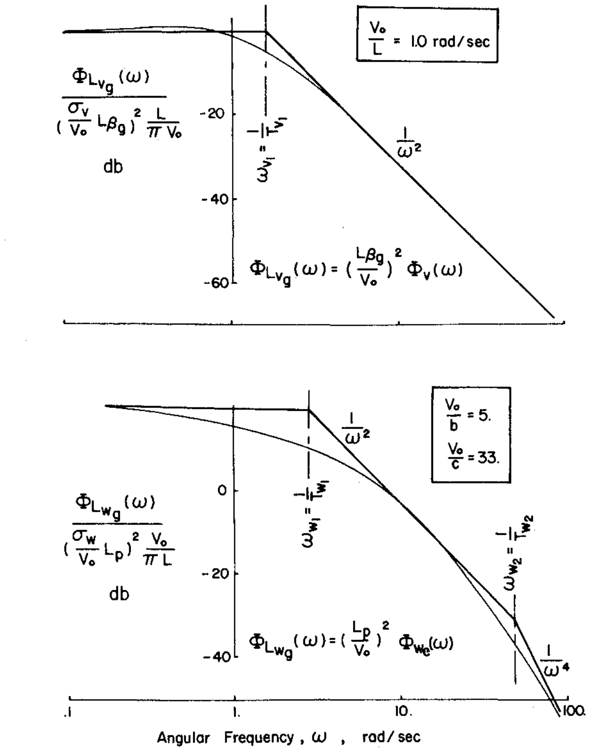

Fig. 1 Asymptotic approximation of typical rolling moment spectra.

Recent NASA sponsored research at Princeton has had the objective of establishing the effects of turbulence on flying qualities in a more complete and general manner. This paper covers the first phase of the research program and is concerned with lateral-directional flying qualities. The purpose of this investigation was to experimentally define through in-flight simulation the independent influences of the turbulence induced disturbances and airplane dynamics as well as significant interactions between these two factors on lateral-directional flying qualities. In this paper first of all, the turbulence disturbances of interest are identified and their spectral characteristics are specified. Next, the flight test program is defined in terms of the appropriate parameters which describe the turbulence and dynamics characteristics of interest. Finally, the results of the flight test program are discussed in terms of pilot opinion ratings and commentary.

Description of the Turbulence Disturbances

The later-directional equations of motion which define the airplane's response to turbulence are

$$\begin{bmatrix} s - Y_v & s & -g/V_0 \\ -L'_\beta & -L'_r s & s(s - L'_p) \\ -N'_\beta & s(s - N'_r) & -N'_p s \end{bmatrix} \begin{Bmatrix} \beta \\ \psi \\ \varphi \end{Bmatrix} = \begin{Bmatrix} Y^*_\delta \\ L'_\delta \\ N'_\delta \end{Bmatrix} \{\delta\} + \begin{Bmatrix} Y_{u_g} \\ L_{u_g} \\ N_{u_g} \end{Bmatrix} + \begin{Bmatrix} Y_{v_g} \\ L_{v_g} \\ N_{v_g} \end{Bmatrix} + \begin{Bmatrix} Y_{w_g} \\ L_{w_g} \\ N_{w_g} \end{Bmatrix} \quad (1)$$

Primed derivative notation[1] is used to eliminate the cross product of inertia terms. The open loop characteristic matrix appears on the left hand side of the equation, whereas control input and turbulence disturbance matrices corresponding to u_g, v_g, and w_g gust components are shown on the right hand side. The terms of the turbulence matrices represent the lateral acceleration and roll and yaw angular acceleration disturbances due to a particular gust component. Thus, L_{v_g} is the roll acceleration due to lateral gusts, and should not be confused with the stability derivative $\partial L/\partial v_g$.

It is worthwhile at this point to consider which of the turbulence induced disturbances have an important bearing on the problem and which may be eliminated for sake of a clearer and simpler representation of the problem. One reasonable simplification may be made by disregarding the side force disturbance. This simplification is warranted since the contribution of side force can be shown to have substantially less effect on the airplane's response to turbulence in roll, yaw, or sideslip than either the contributions due to rolling or yawing moment disturbances.[2] Furthermore, lateral acceleration response to turbulence is not unduly affected by lack of fidelity of the side force simulation.[3]

Neglecting the side force contribution and considering rolling and yawing moment disturbances, it is reasonable to expect the dominant rolling moment contributions to be due to the wing encountering vertical and lateral gusts, whereas yawing moment can be defined in terms of the vertical tail contribution due to lateral gusts.[3] Although circumstances may exist where the fuselage yawing moment counteracts the yawing moment of the vertical tail, the net yawing moment in this case would be unlikely to be of a magnitude sufficient to compromise the pilot's effort. Hence, the greatest interest from the standpoint of turbulence response to yaw disturbances focuses on the vertical tail contribution.

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 roll attitude and heading response to turbulence may be written

$$\Phi_i = \left|\frac{N_{L_g}{}^i}{\Delta'}\right|^2 (\Phi_{L_{v_g}} + \Phi_{L_{w_g}}) + \left|\frac{N_{N_g}{}^i}{\Delta'}\right|^2 \Phi_{N_{v_g}} + 2R_e \left|\frac{N_{L_g}{}^i}{\Delta'}\right| \cdot \left|\frac{N_{N_g}{}^i}{\Delta'}\right|^* \Phi_{L_g N_g} \quad (2)$$

where $i = \varphi$ or ψ as the case may be. The contributions of roll and yaw disturbances are evident in the power spectra L_{w_g}, L_{v_g}, and N_{v_g}. The description of these power spectra is based on a stationary, homogeneous isotropic model of a frozen gust field which can be represented analytically by the Dryden spectral function.[4] A modified aerodynamic strip theory, which includes transient lift buildup with gust penetration is utilized. A more complete derivation of the disturbance spectra is available in Ref. 3.

Examples of the power spectra of rolling moment due to lateral or vertical gusts are shown in Fig. 1. These spectra may be characterized in general by their associated rms roll acceleration levels and by their frequency bandwidth. As indicated in the figure, the expression for the spectrum due to lateral gusts is

$$\Phi_{L_{v_g}} = \left(\frac{L_{\beta_g}}{V_0}\right)^2 \Phi_v \quad (3)$$

where L_{β_g} is the aerodynamic stability derivative $\partial L/\partial \beta_g$ and Φ_v is the Dryden spectrum for lateral gust disturbances. The rms roll acceleration disturbance due to lateral gusts is

$$\sigma_{L_{v_g}} = (\sigma_v/V_0)L_{\beta_g} \quad (4)$$

and it reflects the contribution of turbulence intensity and dihedral effect. Bandwidth of the spectrum is equivalent to the corner frequency $\omega_{v_1} = 1/T_{v_1}$, and if the asymptotic approximation is used the bandwidth becomes $1.73 \times V_0/L$.

In the case of rolling moment due to vertical gusts, the spectral expression is

$$\Phi_{L_{w_g}} = (L_{p_g}/V_0)^2 \Phi_{w_e} \quad (5)$$

In this case the spectrum Φ_{w_e} which is related to the equivalent vertical gust gradient is a complicated expression containing modified Bessel functions of argument $b/L(1 + (\omega L/V_0)^2)^{1/2}$. The asymptotic approximation shown in Fig. 1 permits the spectrum to be defined as a more simple function of frequency, where the time constants of the approximation are defined empirically[3] as

$$1/T_{w_1} = 0.35(V_0/b)^{.75}(V_0/c)^{.25}$$
$$1/T_{w_2} = 5.7(V_0/b)^{.75}(V_0/c)^{.25} \quad (6)$$

Based on the spectral approximation, the *rms* roll disturbance is

$$\sigma_{L_{w_g}} = \left[\frac{\pi}{2}\left(\frac{\sigma_w}{V_0}L_p\right)^2\frac{V_0}{L}\left(\frac{V_0}{b}\right)^{.75}\left(\frac{V_0}{c}\right)^{.25}\right]^{.5} \quad (7)$$

The power spectrum of yawing moment due to lateral gusts is of precisely the same character as the rolling moment spectrum due to lateral gusts shown in Fig. 1. In this case the *rms* yaw acceleration disturbance is

$$\sigma_{N_{v_g}} = \frac{\sigma_v}{V_0}N_{\beta_g} \quad (8)$$

and the contributions of lateral gust magnitude and directional stability are evident. The spectral bandwidth is ω_{v1}, the same as that of the lateral gust disturbance.

The cross-power spectrum between roll and yaw disturbances $\Phi_{L_gN_g}$ comes about by virtue of the correlation between the roll and yaw disturbances due to lateral gusts. No correlation exists between roll due to vertical gusts and either of the other two disturbances. The cross-spectral density function may therefore be expressed as[3]

$$\Phi_{L_gN_g} = \Phi_{L_{v_g}N_{v_g}} = L_{\beta_g}N_{\beta_g}\exp\left(-jl_t\frac{\omega}{V_0}\right)\Phi_v \quad (9)$$

where l_t is the vertical tail length. The wing-tail separation gives rise to this term and acts to reduce the correlation between these two disturbance components.

In the flight test program, the spectral characteristics of the simulated roll and yaw disturbances due to lateral gusts were represented by a first-order low-pass filter corresponding to the asymptotic approximation of the top diagram of Fig. 1. Roll disturbances due to vertical gusts were represented by two cascaded first-order filters corresponding to the spectral approximation of the lower diagram. Correlation of roll and yaw disturbances was controlled through a first-order time delay (where $\tau = l_t/V_0$) between the roll and yaw inputs.

Definition of the Flight Test Program

Parameters of Turbulence and Airplane Dynamics

The test parameters of turbulence were chosen to represent the character of turbulence disturbances as the pilot experiences them. In this regard, the over-all magnitude of roll and yaw disturbances, the correlation (or cross-spectrum) between roll and yaw disturbances, and the bandwidth of the disturbance spectra provide a suitable and complete description. Variations in lateral-directional dynamics were made in roll damping, directional stability, and Dutch roll damping. The pilot's success in achieving satisfactory closed loop control to suppress the effects of the turbulence disturbances is strongly dependent on the airplane's open loop dynamics. The roll mode is important since it affects the pilot's ability to make rapid and precise changes in the airplane's wing attitude. This mode is characterized by the roll mode time constant T_R which is strongly associated with the airplane's damping in roll ($T_R \doteq -1/L_p$). Directional stability (or ω_d) and the damping of the Dutch roll mode, ζ_d, have a strong bearing on the pilot's ability to achieve precise control of heading. Furthermore, while the airplane response associated with the Dutch roll is not a motion which the pilot induces to maneuver the airplane (unlike the roll mode or short period) it can be annoying and burdensome to the pilot if it is large enough or so poorly damped as to interfere with control of either bank angle and heading.

In this test program, a rather thorough study of the effects of turbulence were made for a set of satisfactory lateral-directional dynamics (pilot rating 3.0 in smooth air based on the revised Cooper-Harper scale[5]). A more selective variation in the turbulence characteristics was conducted for several other combinations of lateral dynamics. Particular combinations which were chosen include: variations in rms roll and yaw disturbances (σ_L and σ_N) and correlation (l_t) and turbulence bandwidth (V_0/L) for the good lateral dynamics configuration; variations in roll time constant for selected variations in turbulence, emphasizing rms roll disturbance and bandwidth (ω_d and ζ_d constant); variations in Dutch roll frequency for selected variations in rms yaw disturbance and bandwidth (T_R and ζ_d constant); and increased Dutch roll damping ratio for the lowest ω_d configuration with a re-evaluation of the effects of rms yaw disturbances (T_R and ω_d constant). A neutral spiral mode was maintained for all configurations with exception of the high Dutch roll damping case. For large ζ_d, an unrealistically large value of L_r is required. In this case the neutral spiral requirement was relaxed in order to maintain $L_r \doteq 1.0$ to 2.0 rad/sec² per rad/sec. Aileron yaw and yaw due to roll characteristics ($N_{\delta a}$ and N_p) were controlled so as to minimize the effect of Dutch roll excitation on the pilot's evaluation. Aileron and rudder effectiveness were kept near the optimum chosen in smooth air operation. ($L_{\delta a s} = 1.3, 1.8, 2.3$ rad/sec²/in. for $T_R = 0.5, 0.25, 0.1$ sec. respectively, $N_{\delta rp} = -0.8$ rad/sec²/in.). Longitudinal dynamics of the airplane were maintained throughout the flight tests. A light level of pitch and heave disturbances due to vertical gusts was included in the simulation to provide a more realistic turbulent environment. These longitudinal disturbance characteristics were kept constant throughout the entire program.

Evaluation Task

Flight evaluations of the test configurations were obtained from pilots performing a precision IFR heading control task. This task makes realistic demands of the pilot and as interpreted here, it is a complete task in itself. It is also significant as a subtask for localizer tracking on the ILS approach. Heading control was chosen for the test program because it was felt that the level of pilot-airplane performance required was sufficient to permit a reasonably sensitive distinction to be made between good and bad combinations of turbulence and airplane dynamics.

A typical sequence of events in the evaluation process consisted of the following items. First, the pilot was given the lateral dynamics configuration of interest and permitted to feel it out to his satisfaction in smooth air. During this interval, he would select what he felt to be the optimum aileron and rudder control sensitivities. Next, with the simulated turbulence turned on he continued to feel out the airplane's response and to settle on a desirable control technique, e.g., whether to use rudder in heading control, how effective aileron was in heading control, etc. He then performed his formal evaluation run for the turbulence and dynamics combination of interest. The evaluation was based on the duration of the test run which was on the order of the time elapsed between the outer and middle markers of an ILS, i.e., approximately 2 to 3 min. No attempt was made by the pilot to extrapolate his evaluation to factor fatigue or exposure time into his rating. The pilot also made note whenever his longitudinal control situation detracted from the lateral-directional evaluation. Pilot ratings were based on the revised Cooper-Harper scale. The pilot also performed a separate series of runs to provide a set of data suitable for quantitative measurement of heading tracking performance. Under these circumstances, the task became one of holding constant heading over a period of time with the same performance objectives adopted for the qualitative evaluation. The pilot was instructed to pay strict attention to heading

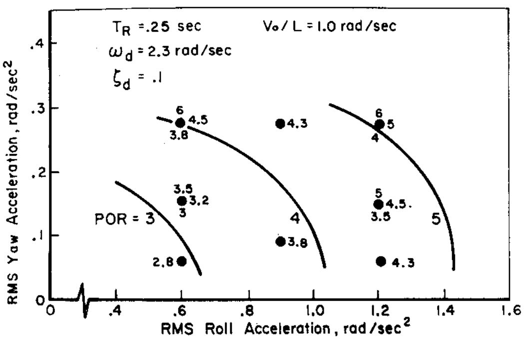

Fig. 2 Effect of rms roll and yaw disturbances on pilot opinion ratings.

control for the duration of the run, with no diversions permitted for navigation or communication or for anything but cursory attention to the longitudinal (air speed and altitude) situation.

Experimental Equipment and Data Acquisition

In-flight simulation was performed using Princeton's variable stability Navion.[3] This airplane has a five axis automatic control system (roll, yaw, heave, pitch, and longitudinal force) which is used to alter the dynamic response and control characteristics of the basic airplane. Simulation of turbulence disturbances was provided by introducing tape recorded Gaussian noise, filtered as indicated in the previous section, to the control surface actuators. Significant aerodynamic cross-couplings between controls are effectively cancelled by electrical interconnects in the automatic control system with exception of the rudder sideforce term which could not be eliminated, but which was helpful in compensating for the lack of side force simulation due to lateral gusts. Pilot ratings, commentary, performance and workload data were provided primarily by two evaluation pilots, both of whom were experienced in flying qualities evaluation and who had the bulk of their flight hours in single and multi-engine airplanes of the general aviation class. Time histories of the pertinent airplane response and control input variables were digitally processed for rms measures of task performance and control workload. Selective measures of pilot describing functions were also made to determine the extent of pilot compensation in the rudder control loop.

Results

Contribution of Turbulence—Good Lateral-Directional Dynamics (T_R = 0.25 sec, ω_d = 2.3 rad/sec, ζ_d = 0.1)

RMS disturbance magnitude

The effects of the rms magnitude of the turbulence disturbances on pilot opinion ratings are shown in Fig. 2. Average pilot opinion ratings are noted adjacent to each test point. The primary evaluation pilot's rating is located at the right whereas the secondary pilots' ratings (if any) are found above and below the point. Iso-opinion contours are faired to the primary pilot's data. The consequences of increasing the rms turbulence level appear not too severe for the range of rms levels shown and in the case of good lateral-directional dynamics.

Pilots' commentary indicates that the degradation with increasing turbulence level is due to the increase in bank angle and heading excursions. Furthermore, the pilots seem to be able to judge the magnitude of the actual disturbances by sensing the initial acceleration associated with the disturbance, although this does not appear to be the predominant basis for their ratings. This sensing of the turbulence appears to provide a cue to alert the pilots to the general level of the turbulence and may, because of the poor ride characteristics and the anxiety associated with the larger disturbances, have a partial influence on the opinion rating. However, the dominant reason given during the flights and in post flight debriefings for the degradation in ratings is the magnitude of the airplane's excursions in rough air or, conversely, the effort required of the pilot to maintain a desired level of task performance regardless of the magnitude of turbulence. For the case of large yaw disturbances, the pilot was forced to use the rudder to control heading excursions. While slower, low-frequency heading changes were still made through bank angle commands to the ailerons, it was absolutely necessary to resort to the rudder for control of higher frequency yawing motions. Some note was also taken of increasing sideslip accompanying the large yaw disturbances and the distracting influence this had on the heading tracking task.

It should be understood that the objective of this analysis is to identify the significant influences on lateral-directional flying qualities of the turbulence and dynamics parameters considered in this test program. This is an attempt to distinguish between important and unimportant effects, and not to establish absolute levels of flying qualities as functions of turbulence or dynamics. Neither the number of pilots nor the number of evaluations per pilot suffice to provide a set of data to which pilot opinion boundaries can be assigned with a high degree of confidence. However, it is reasonable to expect that a professional test pilot when presented with a number of test variables, each of which cover a wide range, can identify the important influences among these variables on his ability to perform an assigned task.

In general, it can be stated that the degradation in pilot ratings with increasing turbulence level is accompanied by increases in pilot workload and by degradation in task performance. This behavior is apparent in the variation in rms task performance and workload with the turbulence disturbance level which are shown in Fig. 3. For a bandwidth of 1.0 rad/sec, the adverse effect of large roll disturbances appears to be both in an increased roll workload and larger excursions in bank angle. An increase in the level of yaw disturbances increases rudder workload while the level of heading excursions reflecting the precision of task performance remain essentially constant. These data, shown as open symbols

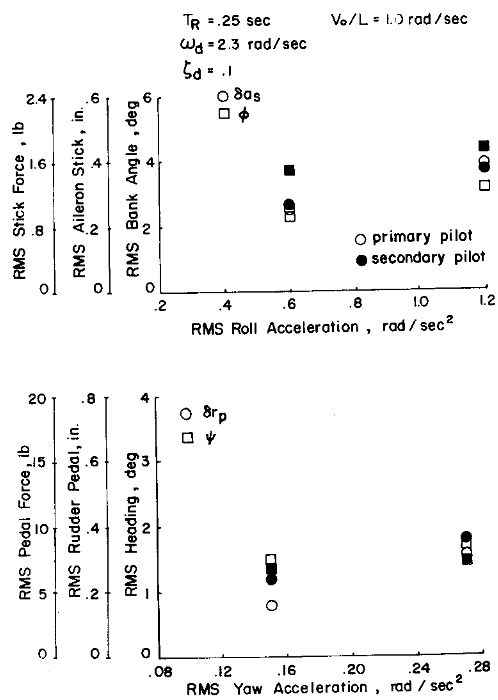

Fig. 3 Trends of task performance and pilot workload with roll turbulence and yaw turbulence.

(O), are for the primary evaluation pilot and are substantially supported by the secondary test pilot's results indicated by solid symbols (●).

Spectral bandwidth

Trends of pilot opinion ratings with turbulence spectral bandwidth are shown in Fig. 4. The data are presented for the case of good lateral dynamics and are given in terms of the equivalent rms sideslip disturbance and the spectral break frequency, $\omega_{v_1} = 1.73 \times V_0/L$. For a given cruise speed the sideslip disturbance may be interpreted as a specific lateral gust velocity. Furthermore, while the data are presented for various levels of rms sideslip for a specific magnitude of dihedral and directional stability ($L_\beta = -16$, $N_\beta = 5$) the results can be considered equally well in terms of increasing L_β and N_β for a constant rms sideslip disturbance.

Spectral bandwidth was found to have only a modest influence on flying qualities for the heading control task. Somewhat of a degradation in pilot rating with increasing bandwidth can be observed in the data of Fig. 4. Most of this degradation is noted for bandwidths up to $V_0/L = 1.0$ rad/sec. However, the dominant influence in this set of data is still the rms level of the turbulence. Pilot commentary reveals no direct influence of the frequency content of the turbulence on the flight task. The pilots were able to detect gross changes in frequency content and their typical comments mention an apparent decrease in the over-all magnitude of the turbulence when higher frequencies are present. This observation reflects the reduction in amplitude of the low frequency components of turbulence as bandwidth increases in order to maintain a constant rms turbulence level. Furthermore, the pilots typically chose to ignore the highest frequency disturbances and excursions. They felt the effort required to track these motions would not be reflected in a commensurate improvement in performance. It was generally possible to live with the high-frequency motion and still discern the average heading to the desired accuracy.

Task performance and workload measures are presented in Fig. 5 for a variation in spectral bandwidth. For good lateral dynamics the roll axis data, shown for a high level of roll disturbance, indicate a reasonably constant aileron workload and a modest increase in rms bank angle excursions in the low to intermediate frequency range. For the case of large yaw disturbances, the heading tracking performance is nearly constant over the range of bandwidths while rudder workload increases for bandwidths up to $V_0/L = 1.0$ rad/sec. From the pilots' commentary, it is apparently these degradations in task performance or increases in control workload which influence

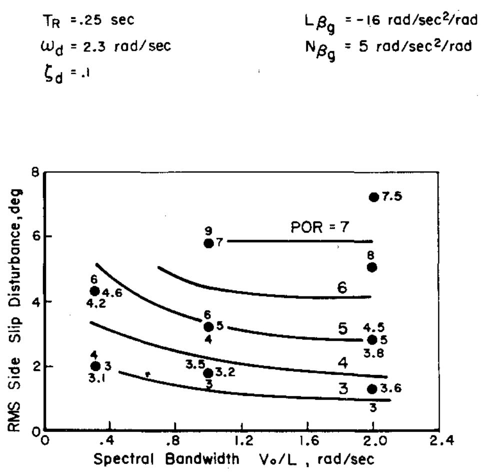

Fig. 4 Influence of spectral bandwidth on pilot opinion ratings.

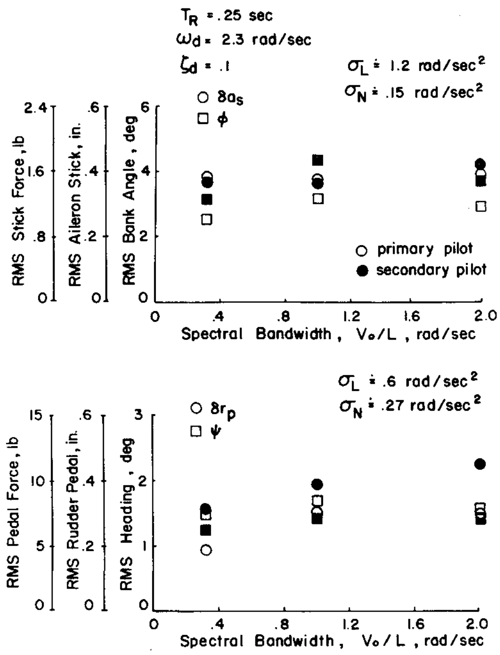

Fig. 5 Influence of spectral bandwidth on task performance and workload.

his rating of the airplane in turbulence, rather than the frequency content of the turbulence as such.

Closed loop pilot-vehicle systems analyses[3] provide an understanding of the flight data and predict trends in the performance-workload measures which agree with flight test measured values. The explanation offered by pilot-vehicle analysis of the insensitivity of the closed loop airplane response to variation in frequency content of the disturbances lies in the pilot's ability to compensate for any dominant modes such as a poorly damped Dutch roll to produce a flat response over a wide-frequency band. Hence, when the bandwidth of the turbulence spectrum is varied, so long as the rms turbulence magnitude is unchanged, there will be very little, if any, change in the rms magnitude of the airplane's response of the pilot's control activity.

Although no data are shown in support of the following results, it should also be mentioned that variations in frequency content of the roll disturbances due to vertical gusts were found to have no effect on pilot ratings or commentary. This result is reasonable since the airplane's closed loop (pilot in the loop) transfer function relating roll response to vertical gusts has no dominant peak which would render roll response sensitive to a change in the turbulence frequency content. Any higher frequency attenuation in the L_{w_g} spectrum associated with the second corner frequency (ω_{w_2}) also was not apparent to the pilots. Furthermore, correlation between roll and yaw disturbances had no effect on the heading control task.

Contributions of Dynamics—Roll Damping ($\omega_d = 2.3$ rad/sec, $\zeta_d = 0.1$)

A study of the combined effects on pilot rating of roll damping (or roll mode time constant) with rms roll disturbance level is summarized in Fig. 6. These data are presented for a low level of yaw disturbance ($\sigma_N \doteq 0.15$ rad/sec²).

Variations in roll damping along with variations in the roll disturbance level for a constant bandwidth ($V_0/L = 1.0$ rad/sec) indicate that reductions in roll damping or increases in roll disturbances or both degrade flying qualities. It is apparent that higher levels of roll damping (lower T_R) are desired with increasing roll disturbance magnitude. At the lowest level of roll damping ($T_R = 0.5$ sec), pilot commentary emphasizes the increasing magnitude of roll excursions and

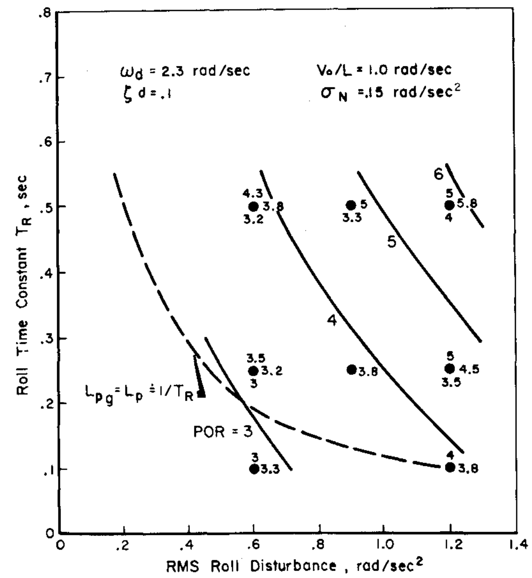

Fig. 6 Trends of pilot opinion rating with roll damping and roll disturbance.

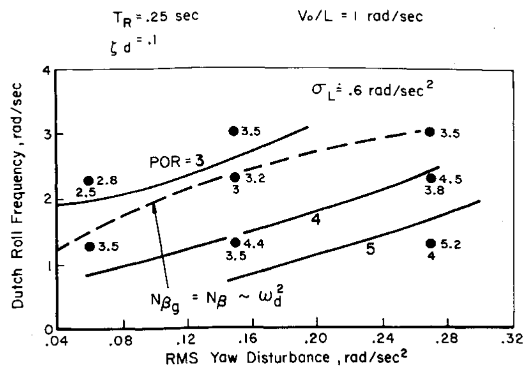

Fig. 8 Trends of pilot opinion rating with directional stability and yaw disturbance.

the difficulty in controlling bank angle to reduce roll excursions to a level which does not distract from the heading tracking task.

It should be emphasized that the data points of Fig. 6 represent independent variations of roll damping and roll disturbance magnitude. Thus, T_R and σ_L are not in general interrelated for the configurations of Fig. 6. As a matter of interest, the conditions where T_R and σ_L would be interrelated, that is where T_R is determined entirely by aerodynamic roll damping ($T_R \doteq -1/L_p$ and $L_p = L_{p_g}$), are indicated by the dashed line. The relation of this dashed line to the POR contours permits an assessment to be made of the effect of a combined variation in roll damping and roll turbulence due to L_p on the pilot's rating. In the range corresponding to the lowest values of L_p tested (high T_R, low σ_L) an increase in roll damping causes no change in pilot rating, apparently because the improvement in roll control characteristics is counteracted by the increase in roll turbulence. However, further increases in L_p corresponding to $T_R = 0.25$ sec and less begin to degrade pilot ratings because the severity of the roll disturbances now overrides the accompanying improvement in roll dynamics. On the other hand, if changes in T_R are accomplished using inertial roll damping (where roll rate sensed by a rate gyro is fed back to the ailerons through a servo control system) then variations in T_R may be made without correspondingly changing the level of roll disturbances. As Fig. 6 indicates, reducing T_R in this manner (increasing inertial roll damping) generally improves pilot rating.

Flight test bank angle excursion and aileron workload data are shown in Fig. 7. The results are presented in a manner to compare the effects of roll damping and roll disturbance

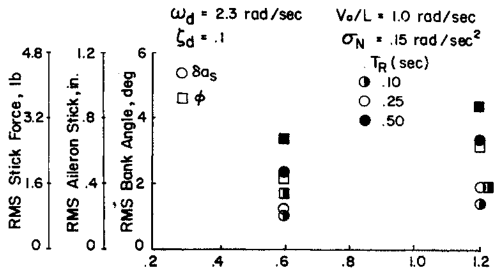

Fig. 7 Combined effects of roll damping and roll disturbance on bank angle performance and aileron workload.

level on performance and workload. The increase in roll excursions and aileron workload with increasing roll disturbances is somewhat more pronounced for the lower value of roll damping. This confirms the impression gained from pilot rating trends that less in the way of roll disturbances can be tolerated at the lower levels of roll damping. This result is apparently due to the limitation placed on the pilot's ability to control bank angle tightly by closed loop stability requirements.[3] In other words, he can raise his gain only so far to suppress disturbances. The combined effect of low damping, which permits large roll excursions, and large disturbances, which increase the excursions even more apparently pushes the pilot-airplane combination beyond desirable operating limits. The pilot could provide lead compensation (roll damping augmentation) to relieve this situation somewhat by increasing stability margins; however, a penalty in pilot rating would also accompany this increased lead requirement. Hence the pilot must either work harder or provide increasing amounts of lead compensation or both as roll damping is reduced and as the turbulence level increases. In any case the associated flying qualities will deteriorate accordingly.

Directional Stability ($T_R = 0.25$ sec, $\zeta_d = 0.1$)

Joint influences of directional stability (or Dutch roll frequency) and rms yaw disturbance level on pilot rating are shown in Fig. 8. These data are presented for constant values of roll damping, Dutch roll damping ratio, and spectral bandwidth ($T_R = 0.25$ sec, $\zeta_d = 0.1$, $V_0/L = 1.0$ rad/sec) and for a low level of roll disturbance.

Considering the primary evaluation pilot's data it is apparent that reducing the airplane's directional stability or increasing the level of turbulence upsets in yaw degrade flying qualities in the heading task. The trends of pilot rating also show that higher levels of directional stability are desired as yaw disturbance magnitude increases. Pilot commentary emphasizes the difficulty in performing the heading tracking task with a reasonable rudder workload when the directional stability is low. Complaints of occasional very large excursions in heading (10° or more) were made for several test runs. Large yaw disturbances serve to further complicate an already difficult problem. The low directional stiffness associated with the lowest frequency configurations permits large sideslip excursions to occur, particularly at the higher levels of yaw disturbances. Pilot commentary indicates that these sideslipping motions were disconcerting to the heading tracking task and were occasionally uncomfortable as well. They eventually reach a level which forces the pilot to take compensatory action to eliminate them. He does this by including the turn and bank in his instrument scan and applying correcting control by "stepping on the ball" in the pilots' idiom. Occasionally, the sideslip excursions would become large enough to divert the pilot's attention from the heading task to a considerable degree. In one instance, one of the

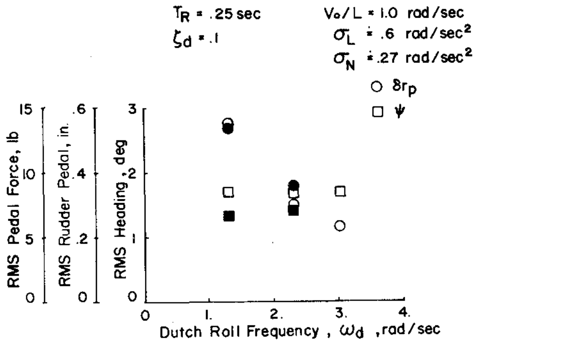

Fig. 9 Effects of directional stability (ω_d) on task performance and workload.

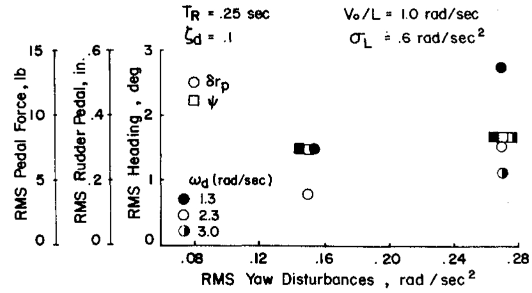

Fig. 10 Combined influence of directional stability and yaw disturbances on heading performance and rudder workload.

secondary evaluation pilots noted that he completely disregarded heading to track sideslip exclusively in order to return the airplane to a generally symmetrical attitude. Under these circumstances the pilot is distracted from his primary objective of maintaining tight control of heading and his rating of the primary task suffers accordingly.

Problems in obtaining good closed loop control of heading with the rudder for the low ω_d configuration can be shown to relate to the pilot's inability to track heading tightly without seriously destabilizing the Dutch roll made.[3] It is possible to close this loop at an acceptable high gain, so to speak, if the pilot can apply sufficient lead compensation (or yaw damping augmentation) to maintain a stable closed loop Dutch roll. In fact, pilot lead compensation for control of heading with rudder as measured in the flight test program was observed to increase by a factor of two to three when ω_d was reduced from 2.3 to 1.3 rad/sec. This requirement for increased lead compensation was objectionable to the pilot due to the associated increase in attention and effort demanded of him to track heading and accounts in part for the degradation in pilot rating as ω_d is reduced. An increase in rudder control workload with decreasing ω_d also supports the POR trend as will be noted subsequently.

It again should be emphasized that the flight test program was designed to explore the effects of lateral-directional dynamics and turbulence disturbances separately. While the Dutch roll frequency and the magnitude of yaw disturbances can normally be interrelated by the airplane's directional stability ($\omega_d \sim (N_\beta)^{1/2}$, $\sigma_N \sim N_\beta$), the test configurations corresponding to the data points of Fig. 8 represent independent variations in ω_d and rms yaw disturbance magnitude. Thus, in general, N_β (which determines ω_d) and the yawing moment due to lateral gusts are not related in Fig. 8. To evaluate the combined effects of dynamics and turbulence, it is of interest to consider the case where ω_d and σ_N are related by $N_\beta = N_{\beta_g}$. Configurations in the test program to which this applies are indicated by the dashed line of Fig. 8. Over the range of configurations tested the dashed line generally follows the iso-opinion contours and in this region the tradeoff between directional stability (ω_d) and yaw turbulence magnitude tend to counteract each other. However, at the higher levels of directional stability in the neighborhood of $\omega_d = 3.0$ rad/sec, further increases in directional stability apparently begin to degrade pilot rating. This behavior is most likely the result of an unacceptable increase in the yaw disturbance level for which the increase in directional stability (and improved heading control) does not fully compensate.

Effects on task performance and workload for the yaw axis are shown in Fig. 9 as a function of Dutch roll frequency (directional stability). The data, for the combination of low-roll and high-yaw disturbance levels, show little or no trend in heading excursions with ω_d. The penalty for reducing ω_d appears as a substantial increase in rudder activity. This trend in control workload along with increased requirements for lead compensation are the basis for the adverse pilot ratings for low directional stability configurations.

The influence of ω_d on the trend of performance-workload data with rms yaw disturbance are presented in Fig. 10. Essentially no change in heading excursions occurs with increased turbulence level for either of the values of ω_d shown. Rudder workload show somewhat more of an increase with yaw disturbance for the low frequency configuration than for the intermediate frequency case. This result helps to justify the trend in pilot rating noted in Fig. 8.

Dutch Roll Damping Ratio

Of all the instances where an increase in Dutch roll damping might prove beneficial, the case of low directional stability was considered the most interesting to study. Pilot ratings and commentary indicate a substantial improvement in flying qualities is possible for these configurations through an increase in damping. On the other hand, for higher levels of directional stability, little or no improvement is apparent to the pilot with increased damping. The combined effects of Dutch roll damping ratio and yaw disturbances on pilot rating are shown in Fig. 11 for the lowest ω_d tested. Data for a low level of roll disturbance, for a roll time constant, $T_R = 0.25$ sec, Dutch roll frequency, $\omega_d = 1.3$ rad/sec, and bandwidth $V_0/L = 1.0$ rad/sec are given in the figure. Improvements in pilot rating on the order of a full rating unit are observed for an increase in damping ratio from $\zeta_d = 0.1$ to 0.4 regardless of the level of yaw disturbances. Although no data are shown for other dynamics configurations some brief evaluations indicated little or no improvement in rating for the same increment in ζ_d at the highest Dutch roll frequency, $\omega_d = 3.0$ rad/sec.

Flight test data reveal a reduction in the rudder workload for the case of large roll and yaw disturbances when the damping ratio is increased from $\zeta_d = 0.1$ to 0.4. These results are shown in Fig. 12 for $T_R = 0.25$ sec, $\omega_d = 1.3$ rad/sec, $V_0/L = 1.0$ rad/sec. No change in the magnitude of heading excursions is noted, hence, the improvement in pilot rating is attributed to the reduced workload required to achieve the precision of performance indicated in Fig. 12.

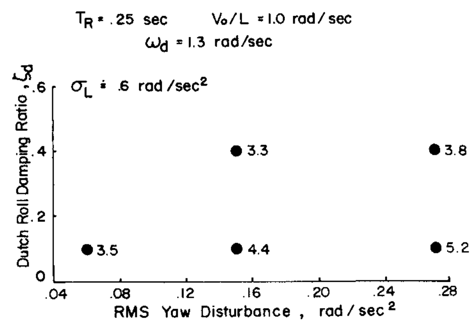

Fig. 11 Effect of Dutch roll damping ratio on pilot opinion.

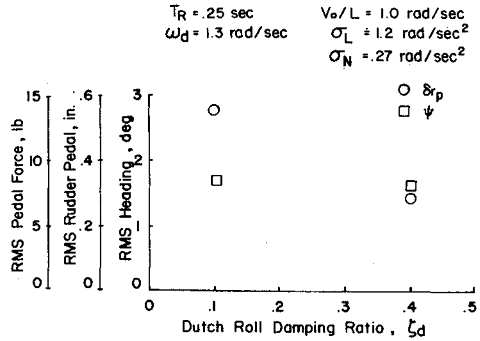

Fig. 12 Effect of Dutch roll damping ratio on task performance and workload.

Conclusions

It is apparent from the results of this flight test program that the dominant influences on flying qualities associated with the heading control task are the precision of task performance, specifically rms heading excursions and to a lesser extent rms bank angle excursions, the control workload required of the pilot to achieve the desired task performance, and the extent of compensation required of the pilot to overcome deficiencies in the airplane's dynamics and to reduce his control workload. The effects of turbulence disturbances and airplane dynamics on flying qualities may be explained in terms of these three factors.

The influences of turbulence and dynamics on the heading tracking task which have been identified in this program may be itemized as follows. The dominant influence of turbulence is the rms magnitude of aerodynamic disturbances. Yaw disturbances degrade the heading tracking task more than roll disturbances. Increasing turbulence bandwidth over the low to mid frequency range tested ($V_0/L = 0.314$ to 1.0 rad/sec) degrades flying qualities. This effect is of secondary importance compared to the influence of disturbance magnitude. Higher order attenuation of the disturbance spectra and correlation between roll and yaw disturbances have no influence on flying qualities. Reducing roll damping adversely affects flying qualities in roll, to a greater extent when disturbances are large compared to the case when these disturbances are small. Changes in aerodynamic roll damping ($L_p = L_{p_g}$) have little influence for roll time constants between 0.2 and 0.5 sec. Increases in aerodynamic roll damping corresponding to T_R less than 0.2 sec degrades flying qualities in roll due to the increase in roll disturbance magnitude which accompanies the increase in L_p. Increased roll damping provided by a stability augmentation system using inertial sensing of roll rate improves flying qualities by effectively increasing roll damping without correspondingly increasing roll disturbances due to turbulence. Reducing directional stability degrades the heading tracking task to a more significant degree when yaw disturbances are large as compared to when these disturbances are small. Changes in aerodynamic directional stability ($N_\beta = N_{\beta_g}$) have little effect on the heading tracking task for Dutch roll frequencies between 1.3 and 3.0 rad/sec. Increases in aerodynamic directional stability corresponding to ω_d greater than 3.0 rad/sec degrades flying qualities in yaw due to the increase in yaw disturbance magnitude which accompany the increase in N_β. Increasing the Dutch roll damping ratio improves flying qualities for the lowest level of directional stability tested ($\omega_d = 1.3$ rad/sec). No improvement with increased ζ_d occurs for the configuration having the highest directional stability ($\omega_d = 3.0$ rad/sec).

References

[1] Ashkenas, I. L. and McRuer, D. T., "Approximate Airframe Transfer Functions and Application to Single Sensor Control Systems," WADC TR 58-82, June 1958, Wright Air Development Center, Wright-Patterson Air Force Base, Ohio.

[2] Eggleston, J. M. and Phillips, W. H., "The Lateral-Directional Response of Airplanes to Random Atmospheric Turbulence," TR R-74, 1960, NASA.

[3] Franklin, J. A., "Turbulence and Lateral-Directional Flying Qualities," CR-1718, 1971, NASA.

[4] Houbolt, J. C., Steiner, R., and Pratt, K. G., "Dynamic Response of Airplanes to Atmospheric Turbulence Including Flight Data on Input and Response," TR R-199, June 1964, NASA.

[5] Cooper, G. E. and Harper, R. P., Jr., "The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities," TN D-5153, April 1969, NASA.