This value of e_{Lb} is then compared with the original value of e_{Lb} assumed and the process iterated on e_{Lb}.

The upper skin is assumed to remain stable for an optimum design. Therefore,

$$e_s = -K_{cs}(t_s/b_s)^2 \qquad b_s = A_s/2t_s \tag{50}$$

or

$$t_s = (A_s/2)^{1/2}(-e_s/K_{cs})^{1/4} \tag{51}$$

This value of t_s is then compared with the original value of t_s assumed and the process iterated on t_s.

Next a new value of the skin strain e_s is chosen, and the entire procedure outlined previously is repeated. After several values of e_s are chosen, a plot is made of A_T vs e_s (Fig. 9), where A_T is the total area of the I-beam and is calculated by

$$A_T = A_s + b_w t_w + A_L \tag{52}$$

Also, a plot must be made with room temperature values to determine the critical area. The minimum of this composite curve (combination of elevated and room temperature curves) is the point of optimum design. A typical example is shown in Fig. 10.

Restrictions and Applications

Optimization methods have been developed for honeycomb panels, integral skin-stringer panels, and I-beams subjected to variable temperature gradients. However, as with all methods, certain restrictions and limitations must be imposed.

For example, the I-beam optimization method is for a variable mold line, since the beam depth b_w is the distance between centroids of the upper and lower caps. The mold line varies, depending on the skin thickness, but this variation is small, so that a good approximation may be made of the optimum design. If the design limits permit, optimum depth b_w can be found for the I-beam by extending the method previously outlined to include a variable depth b_w.

The optimum design at elevated temperatures may not be optimum at room temperature and may, in fact, not be able to sustain the applied load at room temperature. Therefore, the methods presented here must be used to determine if the structure is indeed critical at room temperature. A plot may be made of the room temperature optimum curve superimposed upon the elevated temperature optimum curve as shown in Fig. 10. The intersection of these two curves is the optimum design point when both room temperature and elevated temperature are considered, except when the minimum of one of the curves lies inside the envelope described by the two curves.

This principle of superposition of optimum curves may be extended to other parameters produced by different conditions and a design envelope established to determine an optimum structure that will satisfy all of the conditions imposed upon it.

References

[1] Ericksen, W. S. and March, H. W., "Compressive buckling of sandwich panels having dissimilar facings of unequal thickness," Forest Products Lab., Forest Service, U. S. Dept. Agriculture 1583-B (1958).

[2] Holmboe, K. C., "An analysis of the thermal response of bonded aluminum honeycomb structure to nuclear detonations," North American Aviation Inc., NA60H-192 (1960), pp. 40–43.

[3] Perry, D. J., *Aircraft Structures* (McGraw-Hill Book Co. Inc., New York, 1950), Sec. 14.6.

[4] Gatewood, B. E. and Gehring, R. W., "Allowable axial loads and bending moments for inelastic structures under non-uniform temperature distribution," J. Aerospace Sci. **29**, 513–520 (1962).

[5] Gatewood, B. E., *Thermal Stresses* (McGraw-Hill Book Co., Inc., New York, 1957), Sec. 7-5.

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Low-Altitude, High-Speed Handling and Riding Qualities

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The results of a combined flight and ground-based dynamic flight simulator study of the handling and riding qualities problems associated with low-altitude, high-speed flight are presented in this paper. Wide variations of the longitudinal stability and control characteristics, which can be considered representative of current and future strike aircraft, were pilot evaluated. The influence of these stability and control characteristics, as well as the effects of low-altitude turbulence on the pilots' terrain-following performance, were measured. The results of this investigation are presented in terms of iso-opinion and iso-performance boundaries defining the desired and required combinations of stability and control parameters for low-altitude, high-speed flight. These acceptance boundaries are significantly different from the boundaries presently defined in the Military Specifications. Combinations of vehicle and control system characteristics, which tend to become unstable when coupled with the pilots' response (i.e., pilot-induced oscillations), have been defined.

Nomenclature

A	= numerator time constant in pitch acceleration-gust velocity equation, sec
D_{sp}	= $s^2 + 2\zeta\omega_n s + \omega_n^2$, 1/sec^2
D_{sp}'	= $(s^2/\omega_n^2) + (2\zeta s/\omega_n) + 1$
f_n	= natural frequency, cps
F_s	= stick force, lb
F_s/n_z	= stick force per unit load factor, lb/g
g	= acceleration due to gravity, 32.2 ft/sec^2
h	= altitude, ft
$\ddot{h}$	= climb acceleration, ft/sec^2
h_e	= altitude error, ft

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h_t = terrain altitude, ft
$K_{F_s/\delta}$ = static gain of control system feel equation, lb/in.
$K_{n_z/\delta}$ = static gain of load factor-control equation, g/in.
$K_{q/\delta}$ = static gain of pitch rate-control equation, rad/sec/in.
K_{θ/w_g} = static gain of pitch altitude-gust velocity equation, rad/ft/sec
l_{pilot} = distance from pilot to c. g., ft
L_δ = roll sensitivity, rad/sec^2/in.
M_n = Mach number
M_q = pitch damping, 1/sec
$M_{\dot{\alpha}g}$ = wing to tail lag term of gust encounter, 1/sec
M_δ = pitch sensitivity, rad/sec^2/in.
n_z = vertical load factor, g
$n_{z_{\text{gust}}}$ = gust-induced load factor, g
$n_{z_{\text{maneuver}}}$ = pilot-induced load factor, g
$n_{z_{\text{total}}}$ = sum of $n_{z_{\text{gust}}}$ and $n_{z_{\text{maneuver}}}$, g
p = roll rate, rad/sec
$\dot{q}$ = pitch acceleration, rad/sec^2
R/C = rate of climb, ft/min
rms = root mean square
s = Laplace operator, 1/sec
$T_{1/10}$ = time to damp to $\frac{1}{10}$ steady-state amplitude, sec
$T_{R_{1/10}}$ = rise time to $\frac{1}{10}$ steady-state amplitude, sec
U = forward velocity, fps
w_g = vertical gust velocity, fps
Z_α = heave damping, 1/sec
δ = appropriate cockpit control deflection, in.
δ/n_z = stick displacement per unit load factor, in./g
ζ = damping ratio
θ = pitch angle, rad
σ_{he} = RMS altitude error, ft
$\sigma_{n_{z_{\text{gust}}}}$ = RMS gust load factor, ft/sec^2
$\sigma n_z/\sigma w_g$ = gust sensitivity factor, g/fps
τ_p = roll mode time constant, sec
τ_s = spiral mode time constant, sec
ϕ = bank angle, rad
$\Phi w_g/\sigma w_g{}^2$ = normalized PSD of vertical turbulence, 1/rad/sec
ψ = azimuth, rad
ω = damped frequency, rad/sec
ω_n = natural frequency, rad/sec
$(\cdot)$ = d/dt, 1/sec

Introduction

ONE of the more promising current techniques for penetration of defenses by manned aircraft is to fly at extremely low altitudes at high speeds (e.g., on the order of 200 ft above local terrain and at speeds of about Mach 1.0). Flying low reduces the radar detection range by at least an order of magnitude over a higher altitude penetration. Even further reduction is realized if the local topography is hilly or mountainous so that the low-level aircraft penetration is masked from the radar. Another advantage of the low-altitude, high-speed penetration is the reduction in time spent in the "sights" of any defense complex when anti-aircraft weapons can be effectively fired.

However, low-altitude, high-speed (LAHS) flight presents the pilot with the exacting task of maneuvering his aircraft over the terrain contour while being disconcertingly exposed to relatively high gust-induced accelerations. This need continually and precisely to maneuver the aircraft while being bounced around could logically be expected to impose more stringent handling qualities requirements on the vehicle design than presently exist. Also, since the effects of atmospheric turbulence on the aircraft can be alleviated by judicious choice of configuration or by gust alleviation systems, it is necessary to define the requirements for such alleviation in order to utilize fully the pilots' capabilities.

Previous studies[1–5] utilizing variable stability aircraft and flight simulators of assorted types have concentrated on the establishment of longitudinal handling qualities criteria based on the various tasks associated with flight at relatively high altitudes. The primarily theoretical work of Refs. 6 and 7 has provided valuable insight into the importance of the pilot as a control element in the performance of the closed-loop longitudinal response of the pilot-vehicle system. The influence of the longitudinal flying qualities characteristic on the pilots' tracking performance has been determined in Refs. 8 and 9. As a result of many of these studies, recommended revisions to the Military Specifications were presented in Ref. 10.

Although the foregoing studies contributed greatly to the appreciation of the potential longitudinal handling qualities problems and their solutions for a major portion of the flight regime, they could not be considered adequate for the LAHS regime with any degree of confidence. The higher levels of atmospheric turbulence, the increase in aircraft response characteristics, and the tedious nature of following terrain are all inherent to the LAHS mission and are potential confounding factors not considered previously.

Also, low-altitude, high-speed flight experience was not available in sufficient quantity to define adequately the pilot-aircraft compatibility problems. Based on these factors the combined flight test and dynamic flight simulator program presented in this paper was undertaken. The specific objectives of this program were to define the desired and required vehicle handling and riding qualities characteristics for the low-altitude, high-speed flight regime.

The flight test portion of the study consisted of six Navy test pilots flying approximately 30 low-altitude flights in a specially instrumented F9F-8T. During these flights, which were made through various levels of atmospheric turbulence, the pilots followed the artifically generated terrain later used in the dynamic flight simulator program. The purpose of these flights was to familiarize the pilots with the terrain following task and display under actual flight conditions. Pilot performance, in terms of terrain following error, and pilot opinion data of handling and riding qualities, were also obtained during the flight program for correlation with the simulation results.

The simulation program was divided into two phases: first, the simulator validation phase, and second, the general handling qualities and riding qualities phase. The validation phase consisted of the pilots' flying the simulated F9F-8T over the same section of artificially generated terrain and through the same set of turbulence conditions as they had on one of their actual flights. This was done to establish a confidence level in the dynamic flight simulator's ability authentically to reproduce the vehicle's dynamic response as required for the evaluation of the LAHS handling and riding qualities. The pilots' opinions (both in terms of numerical rating and written comments) and terrain-following performance were obtained.

The second portion of the simulation program consisted of 11 U. S. Navy and North American Aviation test pilots "flying" and evaluating approximately 200 combinations of stability, control, and riding qualities characteristics. The results of these evaluations constitute the most comprehensive compilation of pilot performance and opinion data under low-altitude, high-speed flight conditions to date.

The use of the dynamic flight simulator for the major portion of this program allowed safe and economical evaluation of the wide range of parameters necessary to insure results which would be considered applicable for current and future aircraft performing the LAHS mission. Also, from experimental design considerations, the ability to obtain the desired levels of the atmospheric turbulence on the simulator has a decided advantage over the uncontrolled turbulence levels experienced in actual flights.

Simulator Description

The dynamic flight simulator ("G" seat) utilized in this investigation consisted of a vertically moving cockpit having a total travel of approximately 12 ft with the capability of accelerations of ± 6 g, a functional control system and cock-

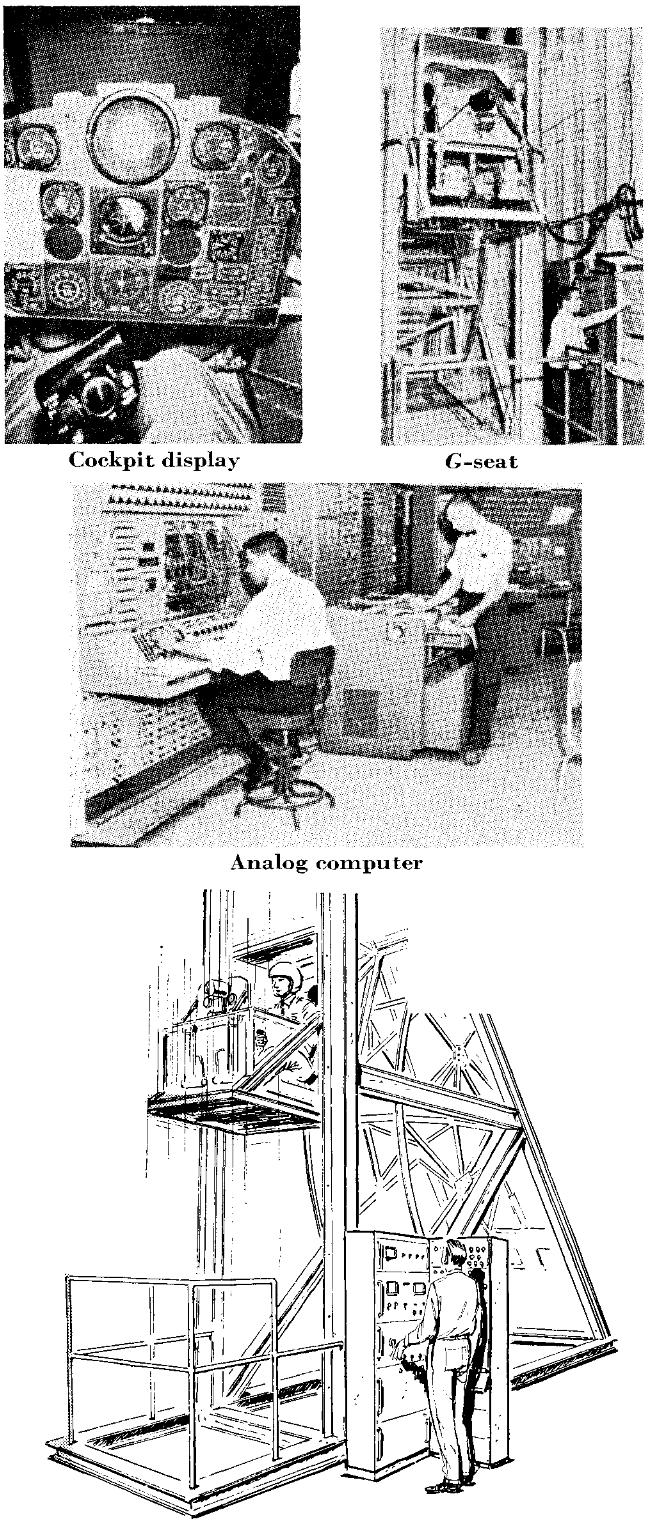

Fig. 1 Dynamic flight simulator.

pit display, and an analog computer for obtaining the solutions to the equations of motion. The solutions to the equations of motion (see Table 2) were then presented to the pilot by seat acceleration, control "feel" feedback, and the cockpit instrumentation. Figure 1 presents the major components of the flight simulator in pictorial form.

For the validation phase, the F9F-8T longitudinal control system feel characteristics, such as bob weight, viscous damping, friction, and bungee rate, were simulated by utilizing a feel simulator which was simply a hydraulic actuator with feedback from stick rate and displacement, normal load factor, and pitch acceleration. The pilot-seat-control relationships were duplicated for a nominal seat adjustment position. The simulator was equipped with a Martin Baker Mark V seat which utilized the integrated torso harness restraint system as did the back seat (test pilot's seat) of the F9F-8T.

For the general flying and riding qualities evaluations the fixed control system characteristics were a breakout force of 1.2 lb, a 0.10-in. deadband, and a friction level hardly detectable at the stick. The force gradient was a variable in the study, and bob weight effects were not included.

In order to minimize the peripheral distractions of the stationary room, the "*G*" seat was equipped with a closed cockpit and the room was darkened during the "flights." The terrain tracking task was presented to the pilot using a cathode ray tube (CRT) mounted in the instrument panel. The tracking task was presented on the CRT by a line horizon (terrain height plus 200-ft clearance altitude) which moved vertically to simulate the terrain variation at 0.9 Mach number. The relative position of the line horizon and a fixed "airplane" on the scope face ("inside-out" presentation) provided the pilot with an altitude error indication wherein 1-in. displacement on the scope was equal to 200 ft of altitude error. An integral part of the terrain-following display was the instantaneous rate-of-climb indicator, which was a distinct aid to the pilots in providing the lead compensation required to track an altitude error signal. In addition to the terrain-following displays, a radar altimeter (measures altitude above terrain), barometric altimeter, normal accelerometer, and an all-attitude indicator were utilized.

The terrain profile, which was generated mechanically from a cam arrangement, was nonrepetitive over a 20-min interval. The terrain structure, i.e., slopes of hillsides and frequencies of peaks and valleys, simulated a flight over hilly desert country at 0.9 Mach number. The terrain varied at 250 ft from the median base level.

This study was concerned with the effects of altering the denominator terms (ω_n, ζ) and the forward loop gains ($K_{n_z/\delta}$ $K_{F_s/\delta}$), which are the predominant factors influencing the handling qualities characteristics. The expressions for the numerator terms, which included the wing-to-tail lag term for encountering gusts ($M_{\dot{\alpha}_0}$) in the n_z/w_g equation, were grouped and assigned the nominal values presented in Table 3 for the course of the general flying and riding qualities investigation.

The values for the fixed numerator terms were carefully selected to yield broad applicability of the results. For example, the short-period lead-time constant $-1/Z_\alpha$ has been shown in Ref. 7 to degrade the handling qualities for values larger than 1.2 sec. Although this could be an important consideration for atmospheric re-entry vehicles, it is not anticipated to be a limiting factor for vehicles during LAHS flight, since even the highly swept wing configurations ($\Lambda \approx 75°$) exhibit $-1/Z\alpha$ values of less than 1.0 sec. The influence of the lift contribution due to longitudinal control (either canard or horizontal tail) has been shown to be negligible for all except extremely short coupled (i.e., short moment arm) configurations and therefore was not included in this study.

The simulation of atmospheric turbulence for the validation program was accomplished by subtracting the maneuvering load factor, as computed from the F9F-8T transfer function using the flight-recorded longitudinal control inputs, from the total flight-recorded load factor, and then using this gust-induced load factor signal to drive the simulator. For the general flying qualities portion, turbulence was simulated by shaping the output of a white noise generator with $K/(\tau s+1)$, where K is the noise-to-gust scale factor and τ is a constant inversely proportional to Mach number. Thus for a given Mach number the filter assumes a fixed value, which was tailored to comply with the power spectral densities obtained from Ref. 11. The distribution of the gust levels was randomized in a manner consistent with the probability distribution and sampled at a rate which varied inversely with the Mach number. The nominal sampling period was 6 sec for 0.9 M_n.

Experimental Procedure

Eleven pilots participated in the entire program. Seven were active Navy pilots, six of whom were from the Naval Air Test Center, Patuxent River. The remaining Navy pilot was on temporary engineering duty during this test period. Three pilots were North American Aviation test pilots and one was a former Air Force pilot, presently engaged in engineering work. The pilots' flying time ranged from 750–5300 hr with an average of 2520 hr. Their ages ranged from 29–38 years, with an average of 33 years. Six pilots had previous experience in flight simulators.

Each pilot was completely familiarized with the analog computer's basic operation, "G" seat hardware, operating procedures and safety features, as well as the program objectives. The first run in each case was "static" in order to acquaint the pilot with the control system and instrument display. After the tracking task and operating procedures became familiar to the pilot, the "G" seat was placed in motion with the pilot flying a constant-altitude tracking task without atmospheric turbulence. As the pilot became experienced in using the available instruments and equipment, atmospheric gusts were introduced in increasing amounts along with the terrain following task. In this manner each pilot had approximately 30 min of "G" seat time prior to any formal evaluation run. Because normal flight hazards did not exist in the "G" seat, the pilots progressed along the learning curve much more rapidly than during the actual flight program and therefore additional indoctrination time was not necessary. However, prior to a series of runs each pilot was given a 5-min practice run for warmup.

During the validation phase of the program each pilot flew the same tracking task, gust time history, and aircraft parameters as during the actual flight in the F9F-8T. The altitude error trace and pilot ratings of turbulence in the "G" seat were then compared with those obtained in flight.

The general flying qualities evaluation defined the effects of longitudinal stability and control system parameters, and atmospheric turbulence on low-altitude, high-speed flying qualities, riding qualities, and pilot terrain-following performance. Thirteen combinations of short-period natural frequency and damping were evaluated along with twelve control systems. Levels of atmospheric turbulence varying from 1–8 fps rms were simulated.

Each combination of stability and control characteristics was evaluated by a minimum of six pilots in order to insure that the "average" rating would be representative of the group. Evaluations were based on the conventional "stick rap" and low-amplitude maneuvering techniques, as well as the vehicle's response characteristics during the tracking portion of the flight. The pilots separately rated the stability characteristics and the control characteristics using the standard NASA Cooper Rating Scale. In addition to the handling qualities evaluations, each pilot rated the vehicle's riding qualities after each 5-min run.

The stability and control characteristics and the turbulence level were varied in a random manner during any given series of configuration changes. To preclude association between configurations, eight different series were used for the study. The pilots were not informed of the specific parameter changes between runs in order to reduce any prejudicial effect on the evaluation.

The pilots' consistency in rating a given stability configuration, control system, and gust level are presented in Table 1. The standard deviation values are an index of the dispersion of the rating about the average rating. These values are consistent with those obtained for previous studies and are considered acceptable.

Table 1 Standard deviation in terms of pilot rating

Parameter	Intrapilot	Interpilot
Stability	0.26	0.38
Control	0.54	0.97
Turbulence	0.43	0.85

Analog readouts were taken of the rms terrain-following altitude error, rms gust-induced load factor, rms total load factor, and rms of the terrain altitude. Time histories of the pilots' control inputs, the resulting vehicle motions, and a time-shared trace of the altitude profile of the aircraft and the terrain, were also recorded.

The rms terrain-following error was used as an index of the pilots' terrain-following performance. An indication of the consistency of this index is shown by the interpilot standard deviation of altitude error of only 19.3 ft and an intrapilot standard deviation of 8.5 ft.

Since a universal method of representing the terrain roughness has not yet been established, the rms altitude deviation was used as an index of the terrain roughness for this program. This approach would have been unacceptable for terrain having numerous plateaus intermixed with mountainous areas (e.g., a plateau 500 ft above the base altitude would have a higher rms value than sharp peaks to 1000 ft). However, the continuous "rolling hills" nature of the terrain used in this program lent itself to this approach, since the point of interest here was the normalization of the pilot's tracking error with the terrain roughness for one "flight" so that it could be realistically compared with the tracking errors from other "flights" over other portions of the terrain. As it turned out, for any 5-min portion of terrain, the average rms terrain altitude profile was 231 ft with a standard deviation of only 16.5 ft. Because of this small deviation in the roughness index, the terrain-following performance was not normalized but was used as recorded.

Stability

The 13 combinations of the longitudinal short-period natural frequency and damping were evaluated by eleven pilots while executing stick raps, small-amplitude maneuvers, and the terrain-following task under varying degrees of turbulence. It is significant to note that, although the pilots performed all of the foregoing maneuvers prior to recording their evaluation, the pilots felt that their opinion was primarily based on the stick raps and the small-amplitude maneuvers. The reason for this was undoubtedly that the terrain-following display, as utilized in this program, was relatively insensitive to the short-period dynamics. For example, the altitude error and, to a lesser degree, the instantaneous rate of climb displayed to the pilot (requiring two and one integrations of the command input, respectively) filtered out the short-period dynamics to the extent that they were not readily discernible by the pilots. Furthermore, the control inputs, continually introduced by the pilots, and the turbulence in which the terrain-following flights were conducted, masked any short-period oscillation "g" feedback to the pilots. Since the evaluation results were primarily determined from the conventional type of maneuver, the flying qualities results presented are considered to be generally applicable, and compatible with the terrain following mission as studied.

The region of satisfactory stability characteristics, which is defined by the iso-opinion boundary at a Cooper Rating of 3.5, is presented in Fig. 2. While this boundary was initially established for constant control system characteristics, namely, 5 lb/g and 0.2 in./g, it was later proven to be essentially independent of control characteristics as varied in this program (i.e., 1.0 to 10 lb/g and 0.1 to 1.0 in./g), with the exception of the pilot-induced oscillation considerations.

In addition to the 125 evaluations used to define the boundary, an additional 24 runs were made at 2.5 and 3.0 cps, to

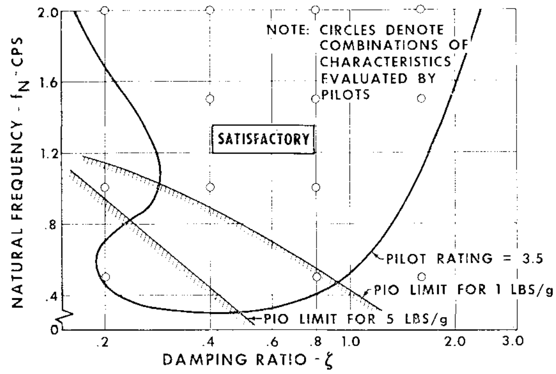

Fig. 2 Acceptance boundaries for stability characteristics.

verify further that higher short-period frequencies do not constitute a limiting factor for the satisfactory handling qualities region. The pilots' initial impression of the aircraft's response at these higher frequencies was that the aircraft "jumped" in response to their inputs. However, as the pilots reduced their inputs to compensate for the increased stiffness, they found the response to be satisfactory. In retrospect, the pilots' acceptance of the high-frequency characteristics is not surprising, since the increase in the aircraft stiffness was, in essence, reducing the "rubber band" effect between the pilots' commands and the aircraft responses. In other words, the higher frequencies made a pilot feel as though he had a more solid linkage between his controller and the ensuing vehicle response.

During the formal evaluation, the tendency to PIO the simulated vehicle (even at 1.0 cps, 0.2 damping ratio, and low force gradients) was not clearly evidenced because of the nature of the tasks involved. The stick raps were open loop, the small-amplitude maneuvers were finger controlled and mild, and the altitude tracking tended to filter the short-period dynamics per se as discussed in the foregoing. However, by requesting the pilots to maneuver the aircraft as they would while making corrections in close formation flying or in any tight spot where precision control of load factor or pitch attitude is critical, PIO characteristics were readily apparent for some combinations of the stability and control parameters. The results of the PIO evaluation for a moderate (5 lb/g) and light (1 lb/g) stick force gradient are superimposed on the satisfactory region of stability characteristics shown in Fig. 2.

A comparison was made of the results from this investigation with the results of a Cornell Aeronautical Laboratory investigation[4] utilizing a variable stability aircraft. Since the pilot rating system utilized in the variable stability aircraft study was not the Cooper Rating System, a direct comparison is difficult. However, the satisfactory region of this study combined with PIO boundary for the 5 lb/g force gradient (in Ref. 4, 4.8 lb/g was used) generally lies between the "Best Tested" and the "Fair" area defined by Cornell for frequencies lower than 1.0 cps. Above 1.0 cps, the results of this study indicate a widening of the acceptance region with increasing frequency, rather than closing as did the Cornell data. This apparent disparity occurs in the region where the Cornell boundaries were extrapolated due to a sparsity of data, as discussed in Ref. 4.

From Fig. 3 it is significant to note that this widening for the oscillatory portion follows a line of constant time to damp (specifically $T_{1/10}$ = 1.0 sec), and the aperiodic boundary follows a line of constant rise time ($T_{R_{1/10}}$ = 1.0 sec) for the full frequency range. Thus it can be concluded that the pilot's opinion is better indexed by the time required to reach the commanded condition than by the number of cycles required, as presently specified in Ref. 13.

The reason for the "toe" on the satisfactory region (extending out to the $T_{1/10}$ = 4 sec boundary) is that within this region the pilots were able to compensate for low static and low dynamic stability simply by introducing control inputs in a stabilizing manner (i.e., in the same manner as stability augmentation devices). However, for lower frequency and/or lower damping, the pilots felt that the amount of gain that they must furnish to provide the proper closed loop dynamics was prohibitive, and at the higher frequencies their response was being taxed to the extent of being considered unsatisfactory.

The effect of the longitudinal stability characteristics on the pilots' terrain following performance is shown in Fig. 4 for a range of gust-induced normal load factor of 0.2–0.4 g. These results show that higher frequencies and/or a level of damping approaching deadbeat, result in improved pilot performance for an essentially constant level of turbulence. While only one range of acceleration is shown, similar variations were obtained for 0 to 0.2 and 0.4 to 0.6 g's. The expected degradation of performance with increasing levels of gust-induced load factor was readily evident.

To this point, the discussion has covered the effects of the short-period dynamics on the pilots' acceptance of handling qualities and on the pilots' performance. It is appropriate now to review the effect of the short-period dynamic characteristics on vehicle's sensitivity to gusts (i.e., the load factor level induced by vertical turbulence). Although the effects of the vehicle's wing loading, lift curve slope, and flight condition on gust sensitivity are readily apparent, the influence of the short-period dynamics is not widely appreciated and is often grossly approximated by an empirical factor or even neglected completely.

The fact that the short-period dynamics has an appreciable influence on the gust sensitivity is graphically displayed in Fig. 5. This figure presents the effect of the short-period dynamics on the gust sensitivity at the pilot's compartment for a typical aircraft flying at 0.9 M_n. Note that a considerable amount of gust alleviation can be realized by augmenting either the static stability or the level of damping. The

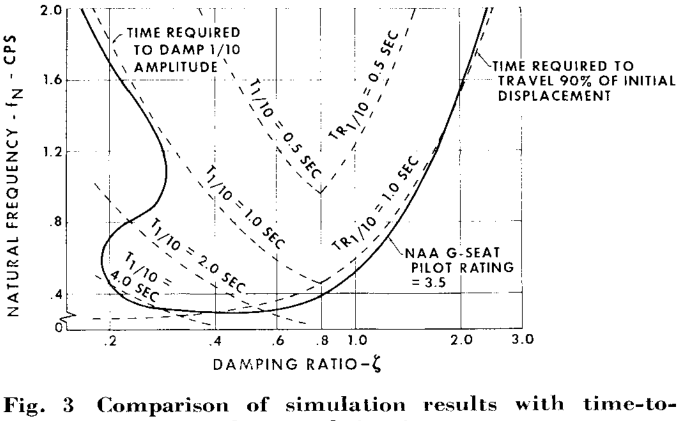

Fig. 3 Comparison of simulation results with time-to-damp and rise time.

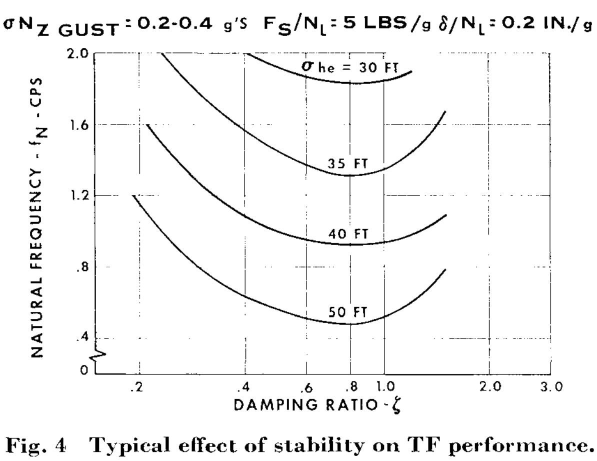

Fig. 4 Typical effect of stability on TF performance.

amount of alleviation realized by either approach, which is dependent on the dynamic characteristics of the basic vehicle, certainly should not be overlooked in future LAHS design considerations.

Based on the considerations of improved riding qualities (i.e., lower gust sensitivity), improved pilot terrain-following performance, and satisfactory handling qualities, the results of this study indicate the desirability of obtaining considerably higher levels of the short-period frequency than are presently considered optimum.

Control

The twelve combinations of stick force gradient and control sensitivity designated by circles in Fig. 6 were evaluated at the following three combinations of short-period frequency and damping: 1.0 and 2.0 cps at 0.8 damping, and 1.0 cps at 0.2 damping. Once again, each combination of characteristics was evaluated by a minimum of six pilots, with their mean rating being used to establish the iso-opinion lines.

The control characteristics for the well-damped ($\zeta = 0.8$) short-period characteristics were evaluated by the pilots during the basic handling qualities phase while flying the terrain-following task and small-amplitude maneuvers. The results of these evaluations are presented in Fig. 6 and indicate that the satisfactory region lies between 3 lb/in. and 25 lb/in. for both the 1.0 and 2.0 cps configurations. [There is obviously an upper limit on both the force gradient (F_S/n_L) and the displacement gradient (δ/n_L); however, these limits were not reached for the range of control characteristics investigated.] To find the pilot acceptance regions defined in terms of the stick spring constant rather than the force/load factor gradient was rather unexpected. However, a discussion with the pilots pointed out that, for the mission under evaluation, the piloting technique utilized for the low-force gradients and high sensitivities (i.e., lower left-hand corner of Fig. 6) consisted of a very light grasp of the stick (i.e., control primarily with the fingers). This technique tended to filter out most of the jostling inputs due to turbulence. On the other hand, the higher force gradients combined with low sensitivities (upper right-hand corner of Fig. 6), requiring a firm grasp on the stick, were also acceptable since the fore and aft arm deflection caused by the vertical motion of the pilot resulted in relatively low amplitude load factor inputs.

It should be emphasized here that the amplitude of fore and aft arm motion caused by the vertical jostling of the pilot is relatively independent of the spring constant on the stick. This was shown by vertically jostling a pilot who was restrained with an integrated torso harness snubbed down as for a low level pass in turbulent air, and recording the stick deflections for 14 lb/in. and 80 lb/in. force gradients. The rms load factor for these runs was approximately 0.6 g (i.e., heavy turbulence) and the pilot's task was to hold the stick firmly at a position requiring approximately 10 lb of push force. There was no feedback from the stick to the vehicle equations, so that only gust-induced accelerations were felt by the pilot. Both the forearm resting on the upper leg and the "free" arm technique were utilized. The lower force gradient (14 lb/in.) resulted in involuntary rms stick deflections of 0.30 in. for the arm resting on the knee and 0.37 in. for the "free" arm. Increasing the stick force gradient to 80 lb/in. resulted in a decrease of involuntary deflections to 0.2 and 0.25 in., respectively. Thus, increasing the force gradient by a factor of 6 resulted in only an approximately one-third decrease in the involuntary stick deflection. For high stick sensitivities, this 0.2-in. deflection would result in an incremental 1.0 to 2.0 "g" involuntary input or even higher for the "force" stick type of control. Thus, it is apparent that involuntary pilot-induced load factors due to vertical jostling can be a problem for high stick sensitivities, and that increasing stick force gradients will not solve that problem.

The control characteristics for 1.0 cps and 0.2 damping were evaluated from the formation flying viewpoint with PIO being the paramount consideration. The results of this evaluation are presented in Fig. 7 and indicate that the predominate factor influencing the PIO tendency to be the force gradient (F_S/n_L). As was expected, some relaxation of the required level of force gradient (i.e., level not conducive to PIO) is realized as the sensitivity is reduced.

The effect of the control characteristics on the pilots' terrain-tracking performance is presented in Fig. 8 for a

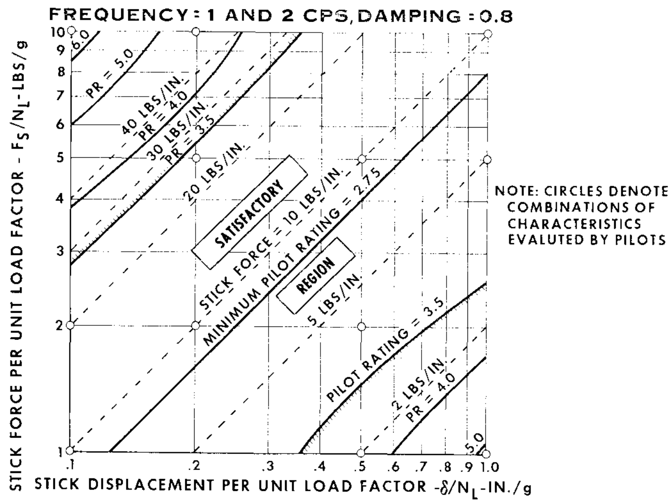

Fig. 6 Pilot rating of control systems.

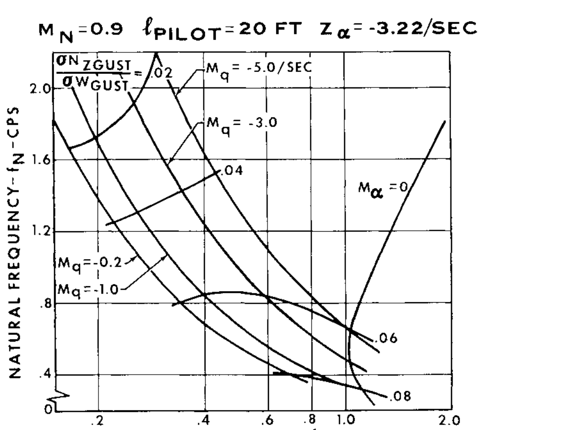

Fig. 5 Typical effect of vehicle stability on gust sensitivity.

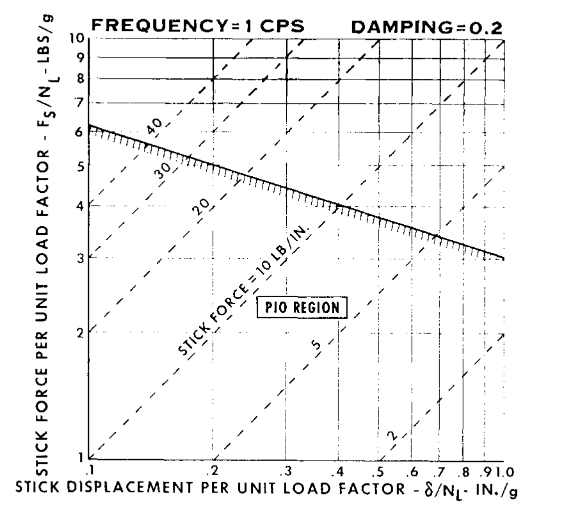

Fig. 7 Influence of control system on PIO tendencies.

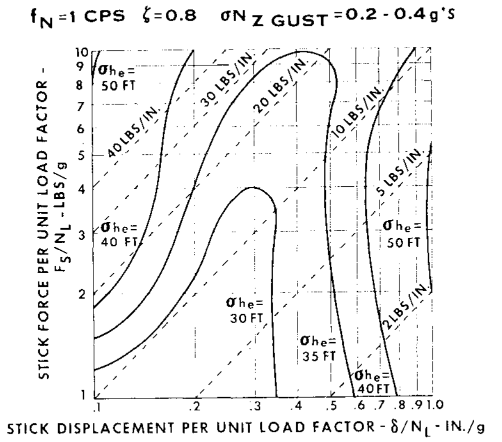

Fig. 8 Typical effect of control system on TF performance.

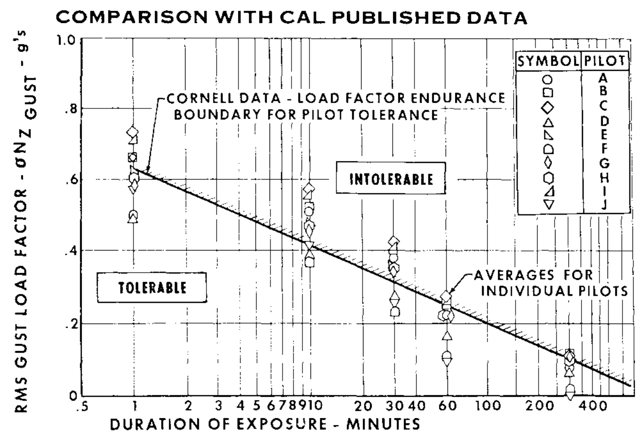

Fig. 9 Pilot tolerance for gust-induced load factor.

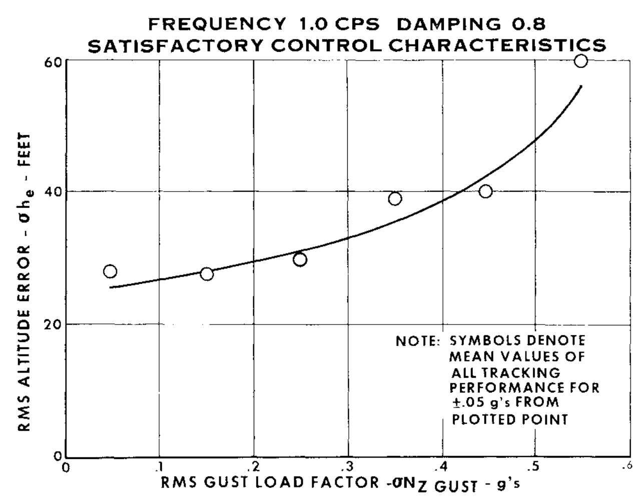

Fig. 10 Typical effect of gust-induced load factor on TF performance.

nominal level of turbulence. These results indicate the pilots' performance to be best for the low-force gradient, high-sensitivity control configurations which are amenable to fingertip control. This is consistent with the conclusions reported in Ref. 9. However, the higher stick force gradients and moderately low sensitivities are shown to have only a slight degradation in performance. The high-force gradients coupled with high sensitivities, and the low sensitivities at all force gradients evaluated indicate a marked degradation in tracking performance.

Based on pilot opinion and performance, while terrain-following in turbulent air, the following conclusions regarding

Table 2 Transfer functions for LAHS program

Equation	Unit
Short period longitudinal equations	
$\frac{\Delta n_{z_{cg}}}{\delta} = \frac{K_{n_z/\delta}}{D_{sp}'}$ where $K_{n_z/\delta} = -\frac{UZ_\alpha M_\delta}{g\omega_n^2}$	$\frac{g}{\text{in.}}$
$\frac{\dot{q}}{\delta} = K_{q/\delta}\, s\, \frac{\left[-\frac{s}{Z_\alpha}+1\right]}{D_{sp}'}$	$\frac{\text{rad/sec}^2}{\text{in.}}$
where $K_{q/\delta} = -\frac{Z_\alpha M_\delta}{\omega_n^2} = \frac{g}{U} K_{n_z/\delta}$	$\frac{\text{rad/sec}}{\text{in.}}$
$\frac{\Delta n_{z_{cg}}}{w_g} = -\frac{Z_\alpha}{q}\left[\frac{s^2 - 2Mqs}{\omega_n^2 D_{sp}'}\right]$	$\frac{g}{\text{fps}}$
$\frac{\Delta n_{z_{\text{pilot}}}}{\delta} = \frac{\Delta n_{z_{cg}}}{\delta} + \frac{l_{\text{pilot}}}{g}\frac{\dot{q}}{\delta}$	$\frac{g}{\text{in.}}$
$\frac{\dot{q}}{w_g} = K_{\theta/w_g} s^2 \left[\frac{As-1}{D_{sp}'}\right]$	$\frac{\text{rad/sec}^2}{\text{fps}}$
where $K_{\theta/w_g} = \frac{\omega_n^2 - 2Z_\alpha Mq}{U\omega_n^2}$	$\frac{\text{rad}}{\text{fps}}$
$A = \frac{M_{\dot{\alpha}_g}}{\omega_n^2 - 2Z_\alpha Mq}$	sec
$\frac{\Delta n_{z_{\text{pilot}}}}{w_g} = \frac{\Delta n_{z_{cg}}}{w_g} + \frac{l_{\text{pilot}}}{g}\frac{\dot{q}}{w_g}$	$\frac{g}{\text{fps}}$
$\ddot{h} = g \cos\phi \Delta n_{z_{cg}}$	$\frac{\text{ft}}{\text{sec}^2}$
$\frac{F_s}{\delta} = K_{F_s/\delta}$	$\frac{\text{lb}}{\text{in.}}$
$D_{sp}' = \frac{s^2}{\omega_n^2} + \frac{2\zeta s}{\omega_n} + 1$	
Lateral equation	
$\frac{p}{\delta} = \frac{L_\delta}{\left[s+\frac{1}{\tau_s}\right]\left[s+\frac{1}{\tau_p}\right]}$	$\frac{\text{rad/sec}}{\text{in.}}$
Auxiliary equations	
$\dot{\theta} = q\cos\phi - \frac{g}{U}\sin^2\phi\cos\theta$	$\frac{\text{rad}}{\text{sec}}$
$\dot{\phi} = p + \dot{\psi}\sin\theta$	$\frac{\text{rad}}{\text{sec}}$
$\dot{\psi} = q\frac{\sin\phi}{\cos\theta} + \frac{g}{U}\sin\phi\cos\phi$	$\frac{\text{rad}}{\text{sec}}$
Scoring equations	
$h_e = h - h_T$	ft
$\text{rms}^2 h_e = \frac{1}{T}\int_0^T h_e^2 dt$	ft^2
$\text{rms}^2 h_T = \frac{1}{T}\int_0^T h_T^2 dt$	ft^2
$\text{rms}^2 n_z = \frac{1}{T}\int_0^T \Delta n_z^2 dt$	g^2

the basic control characteristics can be made: 1) low-force gradients and high sensitivities (including "force" sticks), which are conducive to fingertip control, are optimum where PIO is not a consideration for the short-period dynamics of either the basic vehicle or for a single failure of the longitudinal augmentation system, and 2) moderate force gradients and sensitivities are desirable for vehicles having PIO tendencies with the basic or single-failure longitudinal dynamics.

Turbulence

The pilots evaluated the level of turbulence-induced load factor for rms turbulence levels of 1, 2, 4, 6, and 8 fps and for each stability and control configuration. The results of these evaluations indicated that the pilots' turbulence rating was solely dependent on the level of induced load factor and

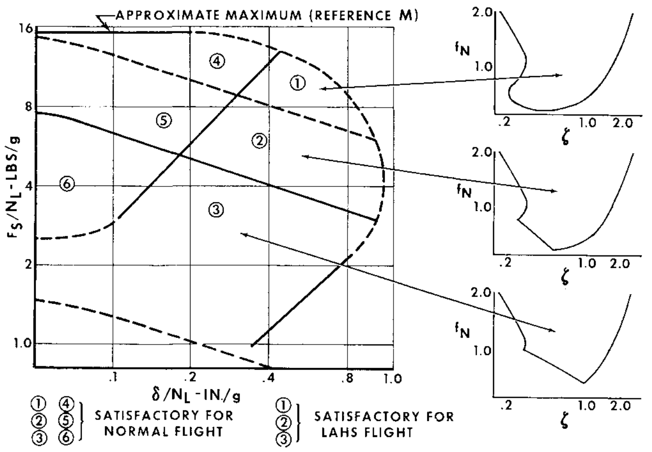

Fig. 11 Application of handling qualities results.

not discernibly dependent on the stability and control characteristics, per se.

The turbulence-induced load-factor tolerance boundary presented in Fig. 9 was derived. The reader is reminded that all "flights" on the simulator were of 5-min duration and that the transition from the pilot rating to a corresponding endurance time was based on the description of the numerical rating, which was defined in terms of the tolerable time duration. It is of interest to note that a pilot tolerance boundary, established in Ref. 12 from three isolated flight programs, agrees remarkably well with the data from this program. Thus, it is felt that the confidence level of the pilot's ability to evaluate his long-term tolerance from short-period sampling, and the confidence level of the tolerance boundary itself, has been appreciably improved.

A typical variation of the pilots' terrain-following performance with turbulence-induced load factor is presented in Fig. 10 for all control configurations considered to be satisfactory by the pilots and for short-period dynamics of 1.0 cps and 0.8 damping. The results presented here were obtained by subdividing the performance data into groups corresponding to the range of turbulence-induced load factors to which the pilots were exposed and then taking the average (e.g., all data for 0–0.1 *g* rms load factor were averaged together and plotted at 0.05 *g*'s etc.). These data indicate that even for the short-exposure duration of the simulator runs, which would tend to minimize the fatigue effects such as would be experienced in actual flights, there is a very appreciable degradation of performance with high levels of turbulence.

The rapidity of encountering various levels of turbulence (i.e., frequency characteristics) and the time spent at a specific level of turbulence (sampling duration) is dependent on the aircraft's speed. Both these characteristics have been held constant to this point (representing a speed of 0.9 M_n) and only the amplitude of turbulence has been altered. Since the turbulence simulation is the only variable implicitly dependent on speed, the influence of speed was established by appropriately altering the turbulence characteristics for 0.6 and 1.2 M_n, which was considered the range of interest for this study. The results of this evaluation indicated that the change in the frequency characteristics and the sampling rate had no discernible effect on the pilot ratings. This was further verified by the pilots' comments that although the change in speed is readily apparent, the amplitude of the turbulence-induced load factor was by far the more important parameter. Therefore, it was concluded that the results of this study are applicable for the speed range from 0.6–1.2 M_n.

Application of Results

In order that the reader may more readily appreciate the significance of the preceding results, a short discussion dealing

Table 3 Values of fixed parameters

Parameter	Value	Units
M_g	−2.0	1/sec
Z_α	−3.22	1/sec
$M\dot{\alpha}_g$	1.0	1/sec
A	0.05	sec
K_{θ/w_g}	0.001	rad/ft/sec
$K_{q/\delta}$	0.0322	deg/sec/in
l_{pilot}	20.0	ft
L_δ	2.0	rad/sec²/in
τ_p	0.25	sec
τ_s	−0.72	sec

with their application is considered relevant at this point. Realizing that the results of this study are not in themselves complete, the author has combined them with previously published data to form a practical and generally applicable set of handling and riding qualities criteria based on both the conventional and the LAHS flight considrations.

To show the relationships between compatible control system characteristics and short-period dynamics, the data from Figs. 2, 6, and 7 have been combined in Fig. 11. This figure indicates that for ranges of short-period dynamics shown in the top insert, the satisfactory control characteristics are restricted to regions (1) and (4) for normal flight and to region (1) for LAHS flight. However, if the range of short-period dynamics for an aircraft does not extend into the low-frequency, low-damping region and, for example, could be contained in the envelope of the bottom insert, then the satisfactory control region would expand to include regions (1), (2), and (3) for LAHS considerations and regions (1) through (6) for normal flight. Since these regions of compatible control systems and short-period characteristics have been defined, the decisions regarding control system complexity and stability augmentation requirements should be more easily resolved. It is noteworthy that the flight test data subsequently presented in Ref. 14 indicates good agreement with the results presented here.

An approach to using the riding qualities boundary of Fig. 9 is shown in Fig. 12. By multiplying the abscissa of the cumulative probability distribution for low-altitude turbulence by the gust sensitivity, $\sigma n_z/\sigma w_g$, for the aircraft being evaluated, a probability distribution of gust-induced load factor is obtained, as shown at the top of Fig. 12. The pilot tolerance limit for the desired duration of the LAHS mission is obtained, as shown at the bottom of Fig. 12, and superimposed on the load factor probability distribution. The probability value at which the tolerance limit intersects the curve can be interpreted as the percent of flights on which

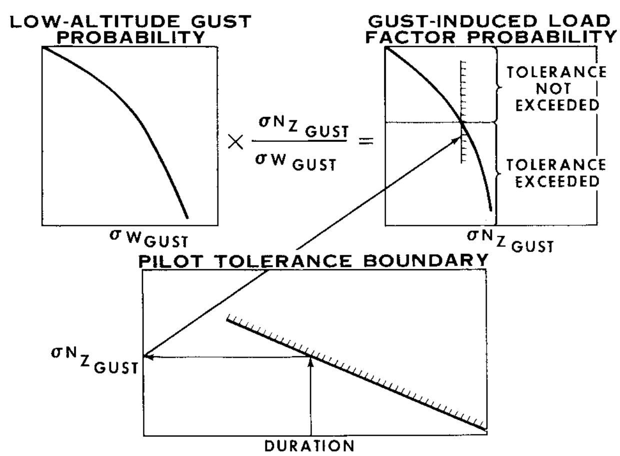

Fig. 12 Application of pilot tolerance results.

the pilot tolerance will be exceeded. This approach should be helpful in the preliminary establishment of gust alleviation requirements and in comparing the merits of various LAHS vehicles. However, it is strongly emphasized that further study is required to define the degradation boundaries of pilot performance before the riding qualities requirements are firmly established. Since these boundaries could logically be affected by numerous factors, e.g., pilots' task complexity, the terrain-avoidance system, cockpit display, pilot anxiety, etc., as well as the turbulence level and mission duration, it is expected that studies related to specific designs will be required to insure pilot-vehicle-mission compatibility.

Conclusions

Based on the results of this combined flight and moving-base simulator program, the influence of the primary LAHS flying qualities and riding qualities characteristics on pilot acceptance and terrain-following performance has been determined. The results as presented should provide a valuable guide in orienting the design of aircraft in decisions regarding stability augmentation, control characteristics, and gust alleviation. The primary conclusions based on the results of this study are given in the following.

1) The moving-base flight simulator ("G" seat) utilized in this program provided a realistic and efficient means by which pilots can evaluate the short-period longitudinal stability, control, and gust response characteristics for LAHS flight.

2) Consistent pilot ratings of combinations of short-period natural frequency and damping ratio were obtained. A satisfactory area was determined which extends to frequencies as high as 3 cps. This satisfactory area of short-period dynamics is relatively insensitive to the control characteristics, with the exception of PIO considerations.

3) Considerably higher levels of short-period frequency than are presently considered optimum, are desirable, based on improved riding qualities, improved terrain-following performance, and satisfactory handling qualities considerations.

4) Consistent pilot ratings of combinations of stick force gradients and stick sensitivity were obtained. A satisfactory area was determined, which lies between a force/stick-deflection of approximately 3 lb/in. and 25 lb/in. within the force gradients and stick sensitivities covered in this study.

5) Based on the control system investigations: a) low-force gradients and high sensitivities (e.g., 1 lb/g to 3 lb/g and 3 g/in. to 10 g/in.) conducive to fingertip control are optimum for terrain following in turbulent air; however, they should only be used on vehicles where PIO is not a consideration; and b) moderate force gradients and sensitivities (e.g., 5 lb/g to 10 lb/g and 1 g/in. to 3 g/in.) should be used for aircraft having short-period dynamics which would indicate PIO tendencies.

6) A pilot tolerance boundary for gust-induced load factor has been established which is consistent with previously published data.

7) The pilots are sensitive to the amplitude of the gust-induced load factor rather than the frequency content for variations of M_n from 0.6 to 1.2. Therefore, the results of this study are considered applicable from 0.6 to 1.2 M_n.

References

[1] Bull, G., "Minimum flyable longitudinal handling qualities of airplanes," Cornell Aeronaut. Lab. Rept. TB-1313-F-1 (December 1959).

[2] McFadden, N. M., Pauli, F. A., and Heinle, D. R., "A flight study of longitudinal-control-system dynamic characteristics by the use of a variable-control-system airplane, NACA RM A57L10 (March 1958).

[3] Sadoff, M., McFadden, N. M., and Heinle, D. R., "A study of longitudinal control problems at low and negative damping and stability with emphasis on effects of motion cues," NASA TN D-348 (January 1961).

[4] Chalk, C. R., "Additional flight evaluations of various longitudinal handling qualities in a variable-stability jet fighter," Wright Aviation Dev. Center WADC TR 57-719 (Part II) Armed Services Tech. Information Agency Doc. AD 206071 (July 1958).

[5] McFadden, N. M., Vomaske, R. F., and Heinle, D. R., "Flight investigation using variable-stability airplanes of minimum stability requirements for high-speed, high altitude vehicles," NASA TN D-779 (April 1961).

[6] McRuer, D. T., Ashkenas, I. L., and Guerre, C. L., "A systems analysis view of longitudinal flying qualities," Wright Aviation Dev. Div. WADD TR 60-43 (January 1960).

[7] Jex, H. R. and Cromwell, C. H., III, "Theoretical and experimental investigation of some new longitudinal handling qualities parameters," Aeronaut. Systems Div. TN ASD-TR-61-26 (June 1963).

[8] Brown, B. P., Johnson, H. I., and Mungall, R. G., "Simulator motion effects on a pilot's ability to perform a precise longitudinal flying task," NASA TN D-367 (May 1960).

[9] Faber, S., "Qualitative simulator study of longitudinal stick forces and displacements desirable during tracking," NASA TN 4202 (February 1958).

[10] Koven, W. and Wasicko, R., "Flying qualities requirements for United States Navy and Air Force aircraft," AGARD Rept. 336 (April 1961).

[11] Saunders, K. D., "RB-66 low level gust study," Wright Aviation Dev. Div. WADD TR 60-305 (March 1961).

[12] Notess, C. B., "The effects of atmospheric turbulence upon flight at low altitude and high speed," FDM No. 325 (October 1961).

[13] "Military specifications-flying qualities of piloted airplanes MIL-F-8785," Amendment (April 4, 1959).

[14] Richardson, J. D. and A'Harrah, R. C., "The application of flight simulators to the development of the A-5A Vigilante," AIAA Simulation for Aerospace Flight Conference, Columbus, Ohio, (August 26-28, 1963).