Longitudinal Flying Qualities Criteria for Single-Pilot Instrument Flight Operations

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Experiments to determine the flying qualities of more than a dozen dynamic configurations have been conducted using the variable-stability Avionics Research Aircraft. Particular attention was given to variations in long-period longitudinal characteristics and their effects on the performance of simulated instrument flight rule flights from takeoff through landing. Over the range of values tested, lift-slope variations ($-Z_w$) had the greatest effect on pilot opinion, workload, and tracking error. Bounds for satisfactory flying qualities were found for three parameters: phugoid-mode damping, stick force gradients (with respect to trim airspeed), and pitch/airspeed gradients.

Introduction

GENERAL aviation plays a vital yet often misunderstood role in our nation's transportation network, and while the potential exists for general-aviation (GA) operations to be of even greater value in satisfying our transportation needs, that potential will not be realized without further improvements in the safety, efficiency, and relative cost of GA aircraft. A significant proportion of the aircraft currently flying is equipped with what might be called "less than high-performance instrument flight rule (IFR)" avionics, and it can be expected that IFR operations in these aircraft frequently would be conducted by a single pilot.

Instrument flight in a congested terminal area is demanding for a two-person crew, and the workload imposed on the single GA pilot in this situation may well exceed reasonable safety margins. It is clear that advanced avionics can do much to reduce and distribute the single pilot's workload, but advanced systems will not become commonplace at the low end of the GA spectrum for some time; therefore, alternate means of aiding the single IFR pilot must be explored. A particular concern is the difficulty of normal piloting functions in the IFR environment, where visual cues are obscured, atmospheric disturbances may be high, additional procedures must be followed, and instructions from the traffic control center may conflict with the pilot's preferences. Not only is the pilot's subjective rating of the flying task likely to be degraded; there is increased probability of flight technical error, disorientation, fatigue, and error in judgment. Consequently, deficient IFR flying qualities aggravate the risk of incidents and accidents to a far greater degree for the single pilot than for the two-person crew.

There are compelling reasons to investigate flying qualities criteria for single-pilot IFR operations. Single-pilot IFR (SPIFR) flying qualities can be distinguished from more general definitions of flying qualities by the greater importance that atmospheric disturbances, duration of the flight-test period, information display, and secondary task workload have on experimental results. Of course, all of these factors have been addressed independently in prior research; however, the results related specifically to SPIFR operations are sparse. The flight research program presented here appears to be unique in its integration of several key issues of instrument flight.

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Background

Although GA aircraft continue to account for more flight hours per year than all other categories combined, the majority of past flying qualities research has been directed at military and transport aircraft. Princeton's Flight Research Laboratory has made important contributions to GA flight programs, principally through the work of Ellis and Seckel,[1] Ellis,[2-4] Franklin,[5,6] Ellis and Griffith,[7] and Seckel.[8] References 1-4 document basic research on GA aircraft flying qualities in the approach and landing. Definitive studies of the effects of turbulence on lateral-directional and longitudinal flying qualities are contained in Refs. 5 and 6. Reference 7 provides results on the effects of bobweights and downsprings, while Ref. 8 examines the landing flare. NASA (and its predecessor, NACA) has contributed significantly to the literature of GA flying qualities research.[9] Comparative studies of light aircraft are contained in Refs. 10 and 11; Ref. 12 presents the effects of advanced controls and displays during the landing approach, and Refs. 13 and 14 examine the landing practices of GA pilots.

One major diference between visual flight rule (VFR) and IFR piloting is that the form and content of information processed by the pilot in exercising control are altered by the lack of "out-the-window" cues and increased reliance on panel displays. (*Total* reliance might be a better way to express this for the skilled IFR pilot, who has learned to discount potentially disorienting motion cues.) Studies of pilot scanning behavior began shortly after the adoption of instrument low-approach systems (ILS),[14] and the pilot's attention allocation during IFR operations has continued to be a subject for experimental and analytical studies.[15-17] An area of particular interest is the effect of long-period dynamics on IFR flying qualities. Although Lanchester's[18] original concern was for the phugoid oscillation, little attention has been given to long-period motions, with the notable exception of Ref. 19.

Flight testing is an essential ingredient of flying qualities research because it is the only way to achieve completely realistic motion cues, because the fidelity of visual cues is rarely matched in ground-based simulation (and then only at great expense) and emotional stress and environmental factors are most accurately portrayed in flight. The research described herein involved extensive in-flight simulation of the IFR operations of aircraft with markedly different dynamic characteristics. The effects of variations in longitudinal stability-and-control derivatives were determined from in-flight simulation of SPIFR missions using the Avionics Research Aircraft (ARA). Subjective pilot ratings were evaluated, quantitative flight-path and control data were analyzed, and secondary task performances were studied. This provided new information on longitudinal flying qualities criteria for single-pilot IFR operations of GA aircraft.

Flying Qualities Criteria

More than 60 years ago, the U.S. Army Signal Corps published a definition of satisfactory flying qualities which bears consideration today. The Army's first heavier-than-air aircraft procurement specification stated succinctly that an airplane "should be sufficiently simple in its construction and operation to permit an intelligent man to become proficient in its use within a reasonable length of time." Unfortunately, the specification gave no guidance regarding the criteria that should be employed in evaluating satisfactory flying qualities.

There is diversity of opinion as to the criteria that characterize aircraft flying qualities best, but generally it is accepted that such criteria should be predictive. Particular values of easily measured (or computed) criterion functions should have direct relationships with probabilities of mission success and the pilot's satisfaction with aircraft response, required mental acitivity, and physical workload. *Subjective criteria*, e.g., Cooper-Harper pilot ratings,[20] provide a measure of pilot satisfaction, although consistency between pilots can be a problem, the ratings cannot be measured prior to flight test or simulation, and there is no guarantee of equivalent mission performance. *Objective criteria*, including performance measures as well as predictions of pilot ratings, can be related to mission success probability, but the "cost function" is not easily chosen, and there is no guarantee that human pilots will be satisfied with the configuration that minimizes the cost function.

Because subjective and objective criteria play unique roles in flying qualties research, both were investigated in this program. Attention was directed at vertical path flying qualities criteria and the effects of variations in those longitudinal stability-and-control derivatives that most directly affect the vertical path. Although three-dimensional missions were flown, the motion variables of primary interest were velocity, flight-path angle, altitude, and range. Effects of variations in the stability-and-control derivatives associated with the phugoid mode and vertical path control (e.g., X_u, Z_u, Z_w, M_u, $Z_{\delta E}$, $M_{\delta T}$, and $Z_{\delta T}$) were examined.

Experimental Configurations and Flight Plans

A matrix of experimental configurations was defined, and abbreviated (30-min) flight paths representative of typical IFR missions were flown.[21] Configurations were simulated using the variable-stability features of Princeton's Avionics Research Aircraft; flights were conducted in the vicinity of Princeton's Forrestal Airfield.

Long-period motions and steady-state response characteristics are of particular interest because they affect the pilot's ability to achieve and maintain trim. Each time the pilot changes airspeed or altitude, he must upset the aircraft's equilibrium by a combination of column, trim, and throttle settings. A configuration that requires large or complex variations in control settings or which tends to diverge from trim may increase the pilot's workload under already-strained conditions, and it may contribute to flight technical error. Consequently, it is important to simulate a reasonable range of stability-and-control-derivative variations in any investigation of SPIFR flying qualities. It should be noted that control derivatives, i.e., sensitivities to control settings, affect transient and steady-state response without affecting the natural frequency or damping of the modes of motion. Stability derivatives—sensitivities to perturbed motions—change the modes as well as the response.

Table 1 Nominal ARA stability-and-control derivatives

$X_u = -0.08$	$X_{\delta E} = 0$
$X_w = 0.09$	$X_{\delta T} = 0.17$
$(X_q - w_0) = -19.95$	$X_{\delta F} = -0.24$
$X_\theta = -31.7$	
$Z_u = -0.55$	$Z_{\delta E} = -0.09$
$Z_w = -1.3$	$Z_{\delta T} = 0$
$(Z_q + u_0) = 129.1$	$X_{\delta F} = -34.7$
$Z_\theta = -5.25$	
$M_u = 0.004$	$M_{\delta E} = -9.82$
$M_w = -0.065$	$X_{\delta T} = 0$
$M_q = -2.124$	$M_{\delta F} = 0$

Table 2 Experimental configurations

Configuration No.	Description	Configuration No.	Description
1	Nominal	9	$M_u = 0.014$
2	$M_{\delta T} = -0.014$	10	$Z_u = -0.39$
3	$M_{\delta T} = -0.014$	11	$Z_u = -0.72$
4	$Z_{\delta T} = 0.13$	12	$X_u = 0$
5	$Z_{\delta T} = -0.13$	13	$X_u = -0.16$
6	$Z_{\delta E} = -0.18$	14	$Z_w = -0.65$
7	$Z_{\delta E} = 0.18$	15	$Z_w = -1.95$
8	$M_u = -0.006$		

Beginning with the nominal ARA stability-and-control derivatives shown in Table 1, individual derivatives, as defined in Ref. 22, were perturbed to obtain the 15 configurations described in Table 2. The derivatives of Table 1 were evaluated at a nominal indicated airspeed of 75 knots and an altitude of 2000 ft, including aerodynamic, gravity, and thrust effects. Actual airspeeds varied from 75 to 105 knots, while altitude ranged from 115 to 3000 ft above sea level during in-flight simulation, causing commensurate changes in the derivatives.

Physical interpretations can be given to the experimental configurations using configuration 1 as a baseline. The $M_{\delta T}$ variations (configurations 2 and 3) are analogous to repositioning the thrust line below or above the aircraft's centerline. $Z_{\delta T}$ variations (4 and 5) represent powered lift effects. $Z_{\delta E}$ variations (6 and 7) with fixed $M_{\delta E}$ represent canard or more-aft pitch control surfaces. M_u variations (8 and 9) relate to several possible effects, most notably aeroelastic deformation of the aircraft or thrust sensitivity to airspeed variation for engines mounted off of the centerline. Z_u variations (10 and 11) have a direct effect on the phugoid period, which normally is most sensitive to airspeed; hence these variations loosely correspond to the dynamic effects of changing the trimmed airspeed. X_u variations (12 and 13) have a direct effect on the phugoid damping, which is inversely proportional to the aircraft's lift-to-drag ratio. Consequently, low values of X_u correspond to "clean" configurations. Z_w variations (14 and 15) correspond to changes in the aircraft's lift sensitivity to angle of attack. This affects gust response and normal acceleration, as well as steady-state response to changes in commanded airspeed or flight-path angle. Selected mode and response characteristics of the experimental configurations are presented in Table 3. ω_{n_p} is the phugoid natural frequency and $(\zeta\omega_n)_p$ represents the total damping of the phugoid mode. $\Delta\theta^*/\Delta V_{\text{comm}}$, $\Delta f_s^*/\Delta V_{\text{comm}}$, and $\Delta f_s^*/\Delta\gamma_{\text{comm}}$ represent the steady-state pitch angle ($\Delta\theta^*$) and stick force (Δf_s^*) response to changes in commanded velocity (ΔV_{comm}) and flight-path angle ($\Delta\gamma_{\text{comm}}$).[22] τ_V and τ_γ are the step response rise times for elevator and throttle inputs.

Flight operations were conducted within a 25-mile radius of five Very-High-Frequency Omnidirectional Range/Tactical Air Navigation system (VORTAC) stations, which provided inputs for the evaluation pilot's task, as well as position data for post-flight-path reconstruction. The mission had to contain several typical flight-path segments, including

1) Climb, acceleration, and cruise with airspeed retrimming
2) Holding pattern

Table 3 Response characteristics of experimental configurations

Configuration No.	ω_{n_p}, rad/s	$(\zeta\omega_n)_p$, rad/s	$\Delta\gamma_{comm}=4$ deg, $\Delta V_{comm}=10$ knots: $\Delta\theta^*/\Delta V_{comm}$, deg/knot	$\Delta f_s^*/\Delta V_{comm}$, lb/deg	$\Delta f_s^*/\Delta\gamma_{comm}$, lb/deg	$\tau_V(\delta E)$, s	$\tau_V(\delta T)$, s	$\tau_\gamma(\delta T)$, s
1	0.34	0.054	−4.7	4.7	0.17	4.5	0.50	6.0
2	0.34	0.054	−4.7	4.4	1.66	4.5	8.0	3.5
3	0.34	0.054	−4.7	5.0	−1.38	4.5	2.0	8.0
4	0.34	0.054	−4.9	4.8	−0.69	4.5	1.0	7.0
5	0.34	0.054	−4.6	4.5	0.83	4.5	9.0	4.5
6	0.34	0.054	−5.1	5.0	0.18	4.5	0.50	6.0
7	0.34	0.054	−4.1	3.9	0.14	4.5	0.50	6.0
8	0.38	0.067	−4.7	6.2	0.17	4.0	0.25	5.0
9	0.28	0.040	−4.6	3.2	0.17	5.5	0.50	7.0
10	0.29	0.047	−3.7	3.4	0.17	5.5	0.50	7.0
11	0.38	0.060	−5.7	5.9	0.17	4.0	0.25	5.0
12	0.34	0.011	−4.7	4.7	0.17	4.0	0.50	5.0
13	0.33	0.096	−4.7	4.7	0.17	5.0	0.50	7.0
14	0.35	0.056	−9.1	9.8	0.36	3.75	0.50	6.0
15	0.33	0.052	−3.4	3.2	0.11	5.0	0.50	6.0

Table 4 Flight evaluations of experimental configurations

Configuration No.	Complete task CHR	Complete task SSR	Holding pattern CHR	Holding pattern SSR	Glide slope CHR	Glide slope SSR	Airspeed retrimming CHR	Airspeed retrimming SSR	Reactions to workload lights	Adjustments of throttle plus elevator trim
1	3.0	3.25	3.0	3.25	3.0	3.25	3.25	3.25	28.2	49.5
2	3.0	3.25	3.0	3.25	3.0	3.0	3.0	3.0	25.0	48.4
3	3.75	3.75	3.5	3.5	3.75	3.5	4.0	4.0	26.9	54.9
4	3.25	3.25	3.0	3.0	3.25	3.25	3.25	3.25	28.6	45.5
5	3.0	3.0	3.0	3.0	3.0	3.0	3.5	3.5	25.0	46.0
6	3.0	3.0	3.25	3.25	2.75	3.0	3.25	3.0	28.3	45.7
7	3.0	3.0	3.0	3.0	3.0	3.0	3.25	3.25	28.5	42.8
8	3.25	3.25	3.0	3.0	3.0	3.0	3.25	3.5	28.9	41.5
9	3.5	4.25	3.0	3.0	3.25	4.5	4.5	4.5	29.2	57.4
10	3.0	3.5	3.0	3.0	3.0	3.5	3.25	3.5	28.4	56.8
11	3.25	3.5	3.0	3.0	3.0	3.25	4.25	4.5	29.2	41.3
12	3.25	3.5	3.0	3.0	2.75	3.5	4.0	4.5	28.0	48.5
13	3.0	3.5	3.0	3.25	3.0	3.0	3.5	4.0	28.6	51.6
14	4.0	4.5	3.5	3.75	3.75	4.5	4.5	4.5	27.7	52.2
15	3.0	3.0	3.0	3.5	2.75	3.0	2.75	2.5	28.8	39.0

3) Deceleration and descent
4) Interception of the landing system beam
5) Approach and missed-approach go-around

Also, a realistic Very-High Frequency Omnidirectional Range (VOR) navigation simulation should consist of engaging navigational stations in the "to" as well as "from" modes. These considerations roughly sized the flight plan to a duration of about 30 min, with the typical geometry shown in Fig. 1. This flight path contained many features representative of a typical IFR flight, including cross-radial and VOR fixes, inbound and outbound VOR legs, holding pattern, constant-altitude cruise, turns in both directions, time/distance descent, glide-slope intercept, Instrument Low-Approach System or ILS (actually TALAR‡ microwave landing system) approach, and visual landing. The safety pilot performed the takeoff, engaged the variable-stability system, and turned control over to the evaluation pilot, who then acquired the first VOR heading and flew the aircraft through touchdown.

Flying all missions along the same trajectory would have allowed the pilot to memorize control patterns, thus reducing the navigation workload to an unrealistic level for a real mission. To cope with this issue, additional flight-path variants were devised. All variants had different altitude and airspeed profiles but were of comparable structure and flight duration. Also, the order in which the various configurations and tracks were flown was randomized.

‡TALAR® is a registered trademark of the Kearfott Division of the Singer Corporation.

Preliminary flights showed that the chosen tasks were realistic simulations of the geometry and workload of IFR missions. The McGuire Air Force Base approach control frequency was tuned in for realistic background chatter. The safety pilot played the role of the air-traffic controller and delivered real-time clearances to the evaluation pilot. Clearances were delivered and read back, after being copied, using the voice-operated intercom. To avoid interference, the McGuire approach control audio was deselected during these communications. Tuning in VOR/DME (Distance Measuring Equipment) stations, VOR tracking and navigation to waypoints, executing holding-pattern turns, leveling off from climb, airspeed retrimming, changing altitude, localizer interception, and other elements of a typical SPIFR scenario were exercised during these flights.

Normally three SPIFR missions were flown per flight. Before a mission was initiated, the safety pilot had to "dial in" the control system gains for the next configuration. Then he turned the "new" aircraft over to the evaluation pilot for a brief familiarization period. During this period the safety pilot switched digital recording cartridges, brought the data acquisition system into the "standby" mode, and tuned in the McGuire Air Force Base approach control radio frequency.

Performance Indicators

Performance indicators are the various metrics that reflect the effects of SPIFR configuration changes. They may be classified into two distinct categories: subjective pilot opinion ratings (PORs), and objective system evaluations.

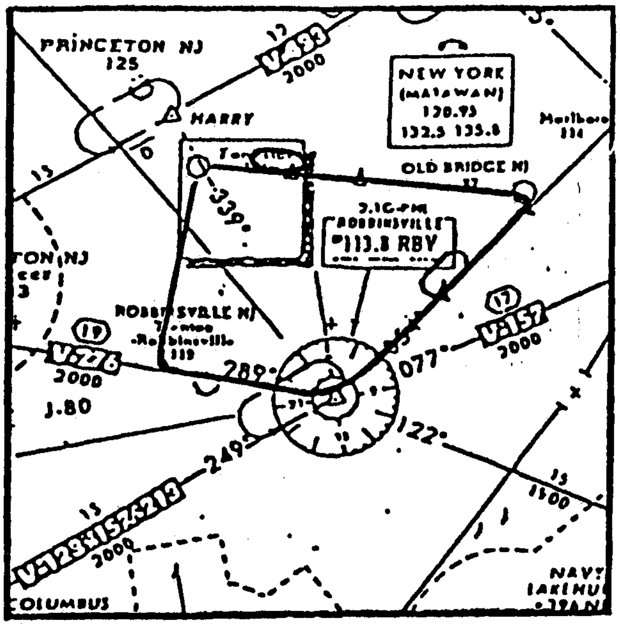

Fig. 1 Typical experimental ground track.

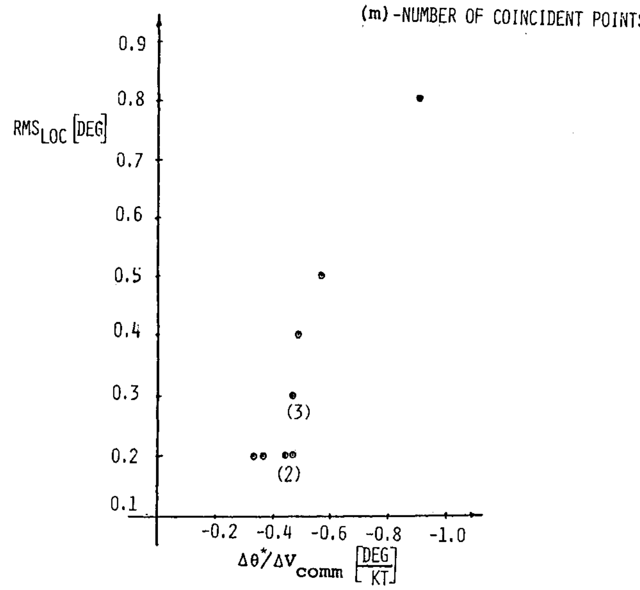

Fig. 2 Localizer tracking rms errors as a function of pitch attitude sensitivity to changes in airspeed.

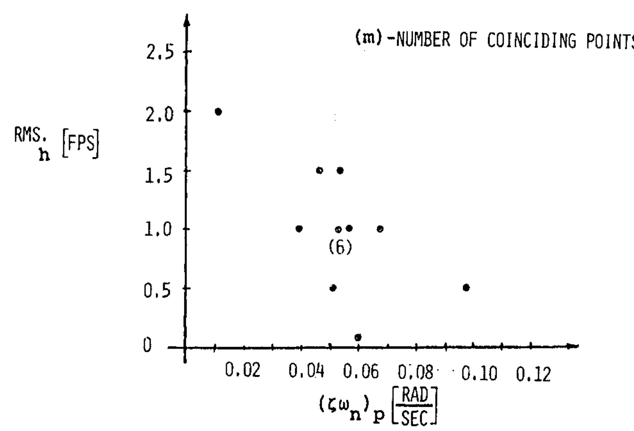

Fig. 3 Rate-of-descent holding rms error vs phugoid total damping.

Since the pilot is an integral part of the "control and guidance loop," the subjective PORs constitute important experimental results. One scale that relates pilot's opinions about the ease or difficulty with which airplanes can be controlled in a given flight situation to a numerical rating is the Cooper-Harper rating (CHR) 10-point scale.[20] The Simpson-Sheridan workload rating (SSR) 10-point provides an alternate workload scale.[23] Some researchers think that the CHR scale reflects workload as well as performance levels.[24] To study this problem with regard to the SPIFR flight regime, both the CHR and SSR scales were used in this program to provide experimental data for comparison. Since up to three missions were flown consecutively, knee-pad versions of both scales and the grading sheet were prepared for in-flight evaluation. The pilot was required to evaluate the airplane performance and workload levels over entire SPIFR missions as well as along individual mission segments. Flight evaluation was carried out by Princeton's chief test pilot. At the time the SPIFR experiments were conducted, he had accumulated over 600 logged IFR hours and a total time of about 5000 h. He flew each of the fifteen configurations twice.

Average values of the performance indicators are presented in Table 4. Pilot opinion ratings are given for entire missions and for three individual tasks, while responses to secondary tasks and trim adjustments are tabulated for entire missions. Compared to much flying qualities testing, the CHR range is relatively narrow (2.75-4.5), while the SSR range is similarly narrow (2.5-4.5). It can be immediately concluded that none of the configurations tested provided a difficult control challenge to the pilot, although some configurations had "deficiencies warranting improvement" (CHR > 3.5). Overall and during glide-slope tracking and airspeed retrimming, the pilot's opinion was degraded most by negative pitch response to throttle (nose up) and low lift slope. The pilot was not particularly sensitive to configuration during holding, while positive M_u, more negative Z_u, and reduced X_u magnitude degraded pilot opinion during airspeed retrimming.

Workload ratings (SSR) were comparable to CHR in most instances. The principal exceptions were that negative M_u had a more adverse effect on workload overall and on glide-slope tracking, while reduced magnitudes of X_u and Z_w also increased the glide-slope tracking workload.

It has been suggested that the time available to perform secondary tasks is inversely proportional to the primary workload. To test this hypothesis, the pilot was asked to push buttons to turn off panel lights that were switched on in pseudo-random fashion. The prerogative for his reaction was that it should take place only if his primary task of flying the SPIFR mission was not affected with the following priorities: 1) control, 2) navigation, 3) communications, and 4) other. The number of reactions per thousand seconds also are recorded in Table 4. It can be inferred that the pilot had the least time to switch off the lights with configurations 2, 3, and 5, and the most time with configurations 9 and 11. This result does not correlate particularly well with the SSR. A similar tabulation of the sum of discrete throttle and elevator trim adjustments indicates slightly better correlation with SSR; configurations 3, 9, and 10 required the most adjustments. Configuration 15 (high lift slope, $-Z_w$) required the fewest adjustments and got the best workload ratings, yet configuration 11 (high Z_u magnitude) required only a slight adjustment and received poor ratings.

The rms values of the yoke activity throughout a complete mission or along a particular flight segment also may constitute a useful performance indicator. Table 5 illustrates that there is a notable lack of difference in these rms values, except that reduced lift slope (configuration 14) does lead to increased column activity.

Tracking performance was quantified using two different methods; the results are summarized in Table 6. Rms values of

Table 5 rms values of longitudinal column deflections

Configuration No.	Complete mission, deg	Constant altitude, deg	Constant airspeed, deg	Climb, deg	Descent, deg
1	0.5	0.4	0.4	0.5	0.5
2	0.5	0.4	0.3	0.6	0.6
3	0.5	0.5	0.3	0.4	0.5
4	0.4	0.3	0.3	0.4	0.4
5	0.5	0.4	0.4	0.5	0.5
6	0.4	0.4	0.3	0.4	0.4
7	0.4	0.3	0.3	0.5	0.4
8	0.4	0.3	0.3	0.4	0.4
9	0.3	0.3	0.3	0.4	0.4
10	0.3	0.3	0.2	0.3	0.3
11	0.3	0.3	0.3	0.4	0.4
12	0.4	0.4	0.4	0.4	0.4
13	0.4	0.4	0.2	0.4	0.3
14	0.9	0.5	0.4	0.6	1.0
15	0.3	0.3	0.3	0.4	0.3

Table 6 rms values and out-of-band time percentages of MLS and VOR tracking

Configuration No.	rms_{LOC}, deg	rms_{GS}, deg	rms_{VOR}, deg	T_{LOC}, %	T_{GS}, %	T_{VOR}, %
1	0.2	0.3	2.2	5	43	36
2	0.3	0.2	3.0	7	29	51
3	0.2	0.3	2.0	5	30	20
4	0.4	0.4	2.8	8	66	48
5	0.2	0.3	2.0	5	30	30
6	0.2	0.2	2.4	4	31	27
7	0.3	0.4	2.8	3	50	33
8	0.4	0.3	2.0	14	37	30
9	0.3	0.3	2.1	4	41	29
10	0.2	0.1	2.1	1	2	31
11	0.5	0.3	2.1	30	32	35
12	0.3	0.2	2.1	16	43	30
13	0.3	0.1	2.1	6	15	38
14	0.8	0.3	2.5	45	53	40
15	0.2	0.2	2.6	1	32	40

Table 7 rms values of indicated airspeed tracking errors

Configuration No.	Cruise, rms_V, ft/s	Climb, rms_V, ft/s	Descent, rms_V, ft/s		
			On glide slope	Except for glide slope	Overall
1	2.5	2.5	3.0	7.2	5.1
2	2.5	1.5	4.0	8.0	6.3
3	3.0	3.5	3.1	3.0	3.0
4	3.0	4.5	4.0	3.0	3.5
5	2.5	3.0	3.1	3.2	3.1
6	2.0	2.5	4.0	4.5	4.3
7	3.1	3.3	3.0	4.5	4.0
8	4.0	3.5	3.5	3.5	3.5
9	3.0	3.0	3.0	6.0	4.5
10	3.0	3.5	4.0	8.1	6.3
11	2.0	2.5	3.0	2.0	2.5
12	3.5	4.0	3.0	4.5	4.0
13	3.0	3.1	3.0	2.5	2.7
14	3.5	5.0	6.0	3.0	4.2
15	3.0	2.5	3.2	4.5	4.0

localizer, glide slope, and VOR radial tracking provide one approach, while percentage out-of-band dwell time for the same signals provides the other. The bands were defined to be plus or minus one coarse deviation ("one dot") on the respective tracking instruments, amounting to ± 0.5 deg for the localizer, ± 0.2 deg for the glide slope, and ± 2.0 deg for the VOR radial. The two methods identify reduced lift slope and more negative Z_u as major longitudinal sources of localizer tracking error. Positive $Z_{\delta T}$ and $Z_{\delta E}$ led to the largest glide-slope tracking errors (by both methods), while reduced lift slope also increased out-of-band glide-slope error. Positive $M_{\delta T}$ and $Z_{\delta T}$ had the largest contributions to VOR errors.

Performance indicators also could be based on energy-management variables. The evaluation pilot was instructed to track certain flight-path variables, maintaining them at prescribed values. These included:

1) Indicated airspeed of 75 knots along holding patterns, climb, and descents, and 105 knots along straight-and-level segments.

2) Altitudes of 1500, 2000, or 3000 ft (depending on the particular segment of a specific flight track) for altitude-holding tasks.

3) Rates of climb and descent of 500 ft/min.

Table 7 indicates that reduced lift slope increases the air speed holding error in climb and on the glide slope. Positive M_u provided the largest cruising airspeed error, and positive $Z_{\delta T}$ (negative powered lift) increased airspeed error during climb. For the descent prior to glide-slope acquisition, positive $M_{\delta T}$ and more negative Z_u contributed the most to airspeed error.

For constant-altitude tracking, Z_u variations above or below the normal ARA value resulted in the largest errors, although the effect of reduced lift slope was nearly the same as that of reduced Z_u magnitude (Table 8). Negative $M_{\delta T}$ had the largest adverse effect on maintaining climb rate, while positive $M_{\delta T}$ and more negative Z_u had the most adverse effect on maintaining descent rate.

Correlation of Performance Indicators and Response Characteristics

Possible correlations between experimentally determined performance indicators and the modal/response characteristics of the test configurations were evaluated in two ways. The first was simply to plot one against the other to identify discernible patterns. The second was to perform a regression analysis, which provided functional relationships between the indicators and the characteristics. In both cases, the configuration characteristics are taken to be the predicted values tabulated previously rather than those obtained in flight. Matching errors of the 15 in-flight simulations yielded phugoid natural frequencies about 6% lower than predicted, while steady-state pitch response averaged 5% lower than anticipated. Only the most significant correlations are discussed in this section.

Figures 2 and 3 present examples of reasonably good plotted correlations. Localizer tracking error proved to have a strong correlation with the pitch angle sensitivity to trim airspeed variation, $\Delta\theta^*/\Delta V_{\text{comm}}$ (Fig. 2). (The numbers in parentheses indicate the number of cases represented by the plotted point.) With 95% confidence, 86% of the variation can be expressed by the linear relationship

$$\frac{\Delta\theta^*(\text{deg})}{\Delta V_{\text{comm}}(\text{knots})} = -0.19 - \text{rms}_{\text{loc}}(\text{deg}) \tag{1}$$

To derive a numerical criterion, recall that the pilot tried to maintain the localizer needle within ± 0.5 deg of the intended course. This suggests the criterion

$$\frac{\Delta\theta^*}{\Delta V_{\text{comm}}} \geq -0.7 \text{ deg/knot} \tag{2}$$

Regressions of $\Delta\theta^*/\Delta V_{\text{comm}}$ against glide-slope rms and localizer out-of-band dwell time tend to verify this result. Designs with a low-lift slope may have difficulty satisfying this criterion.

Although there is more scatter in the relationship between rate of descent and total phugoid daming (Fig. 3), the corresponding linear regression yields

$$(\zeta\omega_n)_p(\text{rad/s}) = [1.96 - \text{rms}_{\dot{h}}(\text{ft/s})]/17.81 \tag{3}$$

There is no fixed requirement on descent-rate deviation, but a value of ± 100 ft/min could be considered a reasonable piloting objective, implying that

$$(\zeta\omega_n)_p \geq 0.02 \tag{4}$$

for acceptable flying qualities. For the configurations under consideration, $\omega_{n_p} \simeq 0.34$; hence, the corresponding damping ratio requirement would be $\zeta_p > 0.06$. It should be noted that Ref. 25 specifies $\zeta_p > 0.04$ for level 1 operations ("adequate to perform the mission") and $\zeta_p > 0$ for level 2 operations ("increased workload"), tending to confirm this result. Reference 26 does not provide similar guidance.

Regression analysis also uncovered the following functional relationship between stick-force gradient and Cooper-Harper rating for the entire mission:

$$\frac{\Delta f_s^*(\text{lb})}{\Delta V_{\text{comm}}(\text{knots})} = \frac{\text{CHR} - 2.5}{1.4} \tag{5}$$

This linear relationship obviously would not apply for low CHR; it predicts a value of 0.7 lb/knot at the level 1-level 2 boundary (CHR = 3.5), and 2.9 lb/knot at this level 2-level 3 boundary (CHR = 6.5).

Of the 15 aerodynamic configurations examined in this research, only Z_w and X_u were found to have ranges of values that could be very significant under SPIFR conditions. Effects of the other derivatives did not stand out above the high background navigation/communication workload. Each of the performance indicators discussed previously led to functional relationships with high correlation at the 95% confidence level. All other performance indicators failed to exhibit trends as a function of the aerodynamic configurations. This includes both the physically obvious metrics, such as rms values of airspeed and altitude holding errors, and the secondary workload measures. In addition, the CHR and SSR scales, as interpreted by a single test pilot, produced essentially similar evaluations.

Table 8 rms values of altitude and altitude gradient tracking errors

Configuration No.	Constant altitude tracking, rms_h, ft	Altitude gradient tracking, $\text{rms}_{\dot{h}}$, ft/s	
		Climb	Descent
1	25	0.2	1.0
2	32	0.1	1.5
3	29	1.3	1.0
4	46	1.1	1.2
5	45	1.0	1.0
6	46	1.1	1.0
7	42	1.0	1.1
8	36	1.0	1.1
9	60	0.2	1.0
10	50	1.0	1.5
11	30	0.5	0.1
12	32	0.2	2.0
13	24	1.0	0.5
14	49	1.2	1.0
15	27	0.5	0.5

Conclusions

Experiments to identify longitudinal flying qualities criteria pertinent to single-pilot instrument flight operations were conducted using a variable-stability research aircraft to simulate 15 dynamic configurations. Emphasis was placed on long-period motions and trim requirements in simulated instrument flight rule missions, because these are of concern in normal climb, cruise, hold, and descent. Flight-test results combine subjective pilot opinion ratings with objective performance measures. The latter was made possible by an integrated flight-path reconstruction technique based on sequential Distance-Measuring Equipment navigation, air data measurements, and optimal postflight data smoothing, as described in Ref. 21.

For the most part, variations of long-period longitudinal parameters within reasonable ranges did not unduly complicate the already complicated task of single-pilot instrument flight rule (SPIFR) navigation and control. The principal exceptions are in the lift slope ($-Z_w$ or L_α) and speed damping ($-Z_u$ or D_V) stability derivatives and in the steady-state changes in pitch angle ($\Delta\theta^*$) and stick force (Δf_s^*) that accompany trim airspeed changes (ΔV_{comm}). Bounds on total phugoid damping, $\Delta\theta^*/\Delta V_{\text{comm}}$, and $\Delta f_s^*/\Delta V_{\text{comm}}$ for satisfactory SPIFR flying qualities were derived by correlating flight-test results with configuration characteristics.

Flight evaluations were performed by a single experienced test pilot. It would be valuable to repeat these tests with pilots of various skill levels. Similar experiments should be flown to identify lateral-directional SPIFR flying qualities criteria and to provide a better understanding of interactions betweeen SPIFR flying qualities and control-display formats.

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