Flight Tests of a Microprocessor Control System

Robert F. Stengel* and George E. Miller†

Princeton University, Princeton, N.J.

Flight experiments with a microprocessor control system have been conducted. The purposes of these tests were to provide information which will assist the development of flying qualities criteria for digital control systems and to investigate engineering characteristics of the research system. Four test pilots evaluated the effects of digital control system parameter variations on a research aircraft's longitudinal flying qualities during tracking and landing tasks. Critical ranges of sampling rate, quantization level, and time delay were identified as functions of the piloting tasks. In the subject aircraft, the limits for satisfactory control appear to be sampling rates of 4-10/s, control word lengths of 4-8 bits, and equivalent time delays of 50-250 ms, depending upon the task. Satisfactory flying qualities at lower sampling rates and resolution can be achieved with command and stability augmentation.

Introduction

DIGITAL electronics hold unprecedented promise for assuring the effectiveness, safety, and low cost of flight control systems, but there is a danger that inadequate understanding of the pilot's requirements for satisfactory control will lead to digital systems that are overly complex—or not complex enough—for their intended purposes. Among the many measures of manual control system performance, pilots' opinions of aircraft flying qualities, i.e., of ride characteristics and response to control, are dominant; so it is necessary to conduct research which correlates the subjective assessments of skilled pilots with quantities that can be specified and controlled during the design process. Flight research is an important element in this correlation; flying qualities criteria for unaugmented aircraft and those with analog control systems have been based, in large part, on flight test data, and it can be anticipated that flight testing will play an equally significant role in the development of criteria for digital flight control systems. (A bibliography of this prodigious literature is beyond the present scope; Refs. 1-7 provide a small sample for illustration.) Inferences about digital flying qualities criteria have been drawn from tests of higher order analog systems,[7,8] and digital systems have been flight tested to achieve specific engineering objectives (e.g., Refs. 9-12); however, comprehensive flying qualities criteria for digital control systems have yet to be established, and there is need for continuing flight research in this area.

The flying qualities of digitally controlled aircraft are being evaluated as part of a broad-based program to investigate applications of modern control theory and microprocessors in flight control system design. This paper presents fundamental results regarding the effects of sampling rate, pure and equivalent time delays, and control resolution on four pilots' opinions of longitudinal flying qualities while engaged in tracking, approach, and landing. Flight experiments have been conducted in the variable-response research aircraft (VRA), which is equipped with a microprocessor digital flight control system (Micro-DFCS). It is found that sampling rates

of 4 samples/s (and above) and control word lengths of 4 bits or more can provide acceptable control; advantages gained from increasing either parameter are aircraft- and task-dependent. Without exception, the evaluation pilots could distinguish between sampling delay and pure delay (or "transport lag"), although differences in subjective ratings were sensitive to piloting style and flight phase. Simulated turbulence degraded pilot opinions in predictable fashion with high control resolution and short time delay; however, turbulence tended to mask the effects of low control resolution and long time delay, resulting in better pilot ratings than had been anticipated.

Research Systems

Variable-Response Research Aircraft (VRA)

The VRA provides independent control of three forces and three moments using elevator, ailerons, rudder, thrust, direct-lift flaps, and direct-side-force panels. The VRA's safety pilot commands the controls through conventional mechanical linkages, while the evaluation pilot commands the controls through the aircraft's electrohydraulic variable-stability system. The evaluation pilot's controls are a center stick, foot pedals, and throttle lever for the present tests. The sensors used for most flight testing include angular rate gyros, linear accelerometers, vertical and heading gyros, angle-of-attack and sideslip-angle vanes, radar altimeter, indicated airspeed, control surface positions, and cockpit control positions. The sensors and actuators have analog outputs and inputs. The analog system provides the electronic interface for the digital system described next. Additional details of the VRA can be found in Ref. 13.

Microprocessor Digital Flight Control System (Micro-DFCS)

The Model 1 Micro-DFCS consists of a flight control computer unit (FCCU) and hand-held control display unit (CDU). The FCCU contains six computer boards, as identified in Fig. 1, which provide central processing, analog input and output, floating-point mathematics, and instruction and data storage. All mathematical operations are carried out with 32-bit floating-point numbers, although the central processor is the 8-bit 8085 chip. The model 1 Micro-DFCS accepts 32 analog inputs and delivers 6 analog outputs, both with 12-bit resolution. There are more than 31,000 bytes of memory, of which about 4000 bytes were used in the initial flight control program. The FCCU is housed in an rf-shielded, shock-mounted aluminum box and has a net weight of 19 lb; it uses ±5 Vdc and ±12 Vdc, obtained by regulating the VRA's
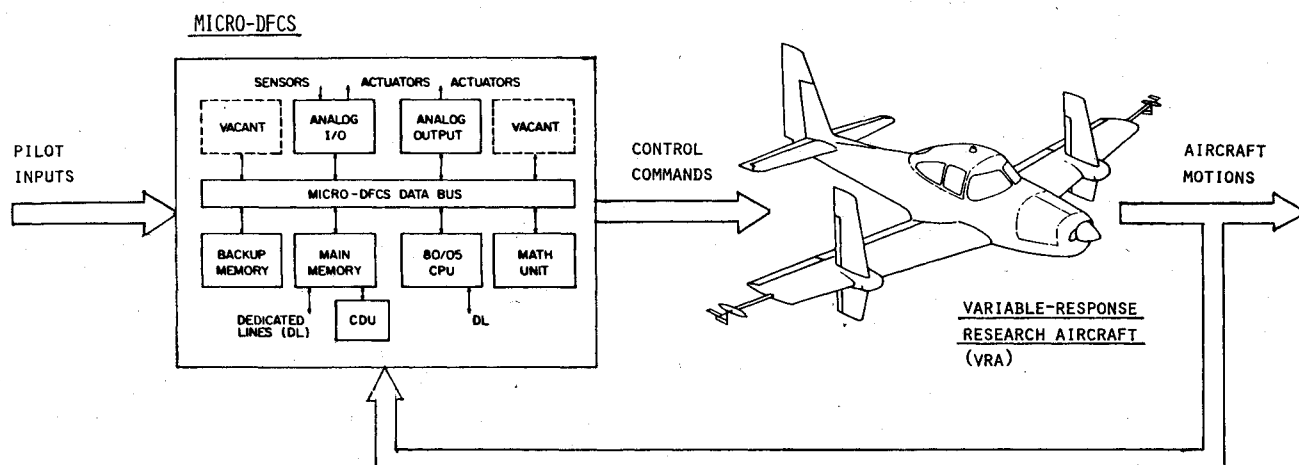
Fig. 1   Schematic diagram of the Micro-DFCS and the VRA.

primary 28-Vdc power source, and its power consumption is 100 W. The CDU provides double-stroke (keypad plus shift key) input and two-line, 12-character light-emitting diode display of ASCII characters.[14]

Flight Control Software

The flight control routines are performed every sampling instant and are coded to minimize the execution duty cycle. As shown in Fig. 2, they are supported by executive and utility routines which are designed to allow new flight control algorithms to be added easily. The executive routines perform initialization, CDU communication, and memory checking. The utility routines perform a variety of functions, as indicated in the figure. Together, these routines form the operational software for the first command augmentation system (CAS-1).

The flight control routines fall into two categories. Each control command mode has a dedicated setup routine and an interrupt service routine. When a mode change is requested by the CDU, the setup routine defines the parameters required for continuing execution of the control law. The corresponding service routine is called at each sampling instant established by a timed interrupt. The service routine contains the digital control algorithm, and it has the highest execution priority.

The selected CAS-1 command mode (pitch rate, normal acceleration, or direct) determines which signals are to be fed back, which actuators are to be controlled, and how the pilot's inputs are to be interpreted.[13,14] For example, in the pitch-rate mode, pitch rate and angle of attack are sensed, the elevator is commanded, and longitudinal stick motions are interpreted as commanded values of pitch rate. For the normal acceleration mode, pitch rate and normal acceleration are fed back, the elevator is commanded, and pilot inputs are interpreted as desired normal acceleration levels. In the direct mode (also called direct electrical linkage, or DEL), the computer merely provides a stick/elevator gearing ratio and a zero-order hold. Closed-loop control laws are designed as sampled-data linear-quadratic regulators,[15] using a reduced-order dynamic model of the VRA.[16] The present flight tests were preceded by hybrid simulations, in which the Micro-DFCS commanded a fourth-order analog computer model of the VRA. Additional details of system development can be found in Refs. 13 and 14.

Flight Tests of the Longitudinal Controller

Testing Procedures

Flight testing fell into the general categories of conventional and naval aviation operations. In both categories,
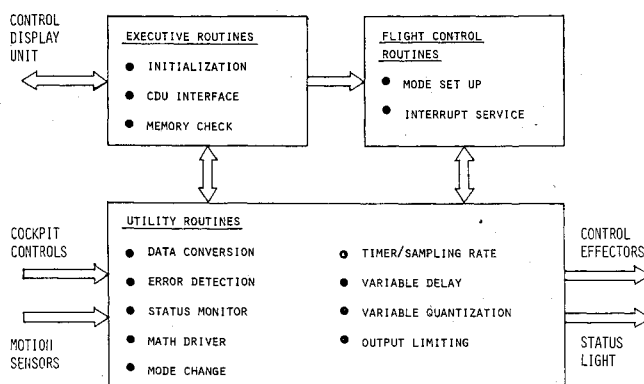

Fig. 2   Organization of the flight control computer program of the Micro-DFCS.

there were two similar tasks, tracking and landing approach, but the tasks differed in detail. The conventional flights were engineering test flights flown by pilots A and B. The tracking task corresponded to the correction of flight path errors which might be experienced in point-to-point cruising flight at 105 knots indicated airspeed (KIAS). The landing approach was pursued through flare and touchdown at the VRA's normal approach speed of 75 KIAS. In the second category, the first task actually consisted of two parts: acquisition and tracking of a specific point, usually on the ground. The landing approach was made using visual guidance from an aircraft carrier approach mirror. The angle-of-attack meter/indexer included a conventional Navy three-light "fast-slow" display for speed control during the landing approach. There was no flare or touchdown, the VRA "waving off" at an altitude of 10 to 15 ft. Because of the difference in size between the VRA and a typical carrier aircraft, the VRA evaluation pilot's height above the runway at waveoff is very nearly the same as the pilot's height above the deck at touchdown of a carrier aircraft. The project's pilots agreed with earlier pilots that this provided adequate simulation of the carrier landing for flying qualities evaluation.[17]

Two U.S. Navy test pilots performed the second category evaluations. Pilot C, whose experience has been gained primarily in antisubmarine warfare (ASW) aircraft, flew the field carrier landing practice (FCLP) at 105 KIAS. This speed is typical of the flight deck relative speed of carrier-based aircraft, and, therefore, closure effects were duplicated. The VRA's variable-stability features were not employed, and the aircraft's dynamics were somewhat faster than those of carrier-based aircraft. Pilot D, with fighter aircraft ex-

perience, flew the FCLP at 86 KIAS. Closure rates were not duplicated, but aircraft dynamics were representative of the larger, carrier-based aircraft. (Reference 18 documents a flight test program in which the VRA matched both closure rates and dynamics of the A-7 aircraft during power approach.) Both Navy pilots used an angle-of-attack meter/indexer properly calibrated for the desired approach speed. Thus, the flight test results present a spectrum of dynamic conditions for the landing approach task. Pilots C and D flew only the direct mode with various sampling rates, delays, and resolutions. They were aware of the differences between configurations and the test objectives; however, the specific configurations were not identified until the evaluation flight was completed.

In addition to providing commentary, the evaluation pilots used the Cooper-Harper Pilot Opinion Rating (POR) scale as a measure of pilot opinion. The Cooper-Harper scale[19] assigns numerical values between 1 and 10 to each configuration tested, with 1 indicating highly desirable flying qualities and 10 indicating deficiencies great enough to cause loss of control.

Open-loop VRA dynamic characteristics for the three flight conditions that were examined are summarized in Table 1. Natural frequencies (ω_n) and damping ratios (ζ) are given for the short period, phugoid, and Dutch roll modes (subscripts SP, P, and DR, respectively), while roll and spiral mode time constants are τ_R and τ_S. The normal force per unit of angle of attack, n_{z_α}, is a measure of the aircraft's flight path sensitivity to angular control. The control sensitivity $M_{\delta E}$ is the initial angular acceleration in pitch per unit angle of elevator surface deflection. By comparison to flying qualities specifications for maneuvering flight and landing approach,[20] it can be seen that all three flight conditions meet level 1 specifications, i.e., the response is "clearly adequate for the mission."

Digital control was applied to longitudinal motions only; the evaluation pilot's lateral-directional controls were executed through the analog system. For most flight conditions, VRA dynamics were unaugmented by closed-loop control. Evaluations focused on calm air flight, although turbulence was simulated in some cases. Natural turbulence was a minor factor on pilot C's FCLP flight and a moderate factor on pilot D's tracking flight; distracting disturbances were minimized by increasing Dutch roll damping with the variable-stability system in the latter case.

Conventional Flight Operations

Pilot A, with over 5000 h of flight experience in military and civil aircraft, evaluated open- and closed-loop sampling effects during tracking and landing approach, and he was the safety pilot for this series of tests. Pilot B evaluated closed-loop modes, sampling rate, pure delays, resolution, and turbulence effects during tracking and landing approach. He had the least experience as an evaluation pilot but the most engineering experience in flying qualities research. Pilot B was instrumental in establishing the protocol for testing and had the most comprehensive exposure to the control system configurations used in this program.

The closed-loop modes were designed for the 105-KIAS flight condition and were evaluated by tracking at altitude. As

reported in Ref. 14, pilot A preferred the 10/s pitch rate mode over the 10/s normal acceleration and direct modes; it provided "good response" with minimal overshoot. Control movements of the normal acceleration mode were crisp but potentially abrupt and "oversensitive." Both modes were designed for several combinations of linear-quadratic weights, and it was concluded that both modes could be designed to provide satisfactory conventional tracking characteristics at 10/s sampling rate.

Except for a slight rumbling sensation due to discrete elevator deflections, the 10/s digital direct mode was indistinguishable from the analog direct mode. Tracking overshoot increased as sampling rate decreased, becoming objectionable at 6/s and "very bad" at 4/s. Flying qualities of the pitch rate mode also became worse as sampling rate decreased, but overshoot generally was less than in the direct mode. Delay was objectionable at 4/s but pilot A experienced "no trouble in attaining and keeping the track."

The direct longitudinal mode was used from landing approach through flare and touchdown with sampling rates of 10-2/s. Sampling effects first became objectionable to pilot A (at 5/s) on the short final approach. At 3/s, there still was no problem with sampling effects during flare, but 2/s proved to be the marginal case for both phases of the landing. The greater sensitivity of the short final approach is attributed, in part, to the definition of this landing task, which did not require a precision touchdown point. It is felt that the pilot accepts lower sampling rates during the flare because aircraft response generally is sluggish in this condition, and the nonprecision flare is less a tight closed-loop maneuver than a preprogrammed, anticipative action.

Figure 3 illustrates pilot B's opinion ratings of flying qualities with varying pure time delay effects. Averaged opinion ratings are plotted, and the approximate limits of these ratings are delineated by broken lines. Pure delay is defined as the total time between digital computer input and output. Direct mode computations accounted for 5 ms of delay, and increments of 100 ms were added for experimental purposes. Transmission delays external to the computer were negligible; actuator dynamic delays had an effective time constant of about 10 to 20 ms. Assuming that the timing of pilot inputs is a random process with rectangular distribution, the 10/s sampling rate introduced an average effective delay of one half the sampling interval, or 50 ms. In this paper, equivalent delay is defined as the pure delay plus the effective sampling delay.

With minimum delay, the POR was 2 for tracking and for approach and landing; simulated turbulence degraded the rating to 3, still a satisfactory level. The calm-air ratings degraded almost linearly with increasing pure delay, reaching the "deficiencies require improvement" range at 405 ms. POR trends are similar to those found in Ref. 21, although there were important differences in tasks and results. In the present case, a precise touchdown point was not specified, and there was a gradual degradation in pilot ratings. A precise touchdown point was specified in Ref. 21; ratings were virtually identical for time delays up to 0.1 s, but they degraded sharply for greater delays, reaching POR = 6-7 when the delay was 0.2 s. The results of Ref. 21 are more suitably compared to the carrier approach task described later, which requires

Table 1　VRA dynamic characteristics

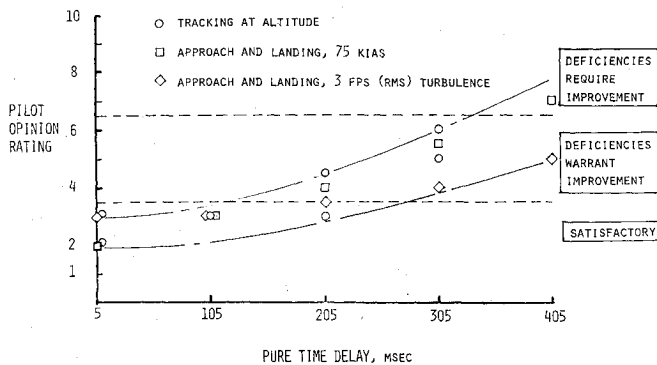| Airspeed, knots	Longitudinal						Lateral-directional			
	$M_{\delta E}$, $1/s^2$	ωn_{SP}, rad/s	ζ_{SP}	n_{z_α}, g/rad	ω_{n_P}, rad/s	ζ_P	$\omega_{n_{DR}}$, rad/s	ζ_{DR}	τ_R, s	τ_S, s
75	−6.4	2.60	0.77	5.04	0.29	0.21	1.96	0.26	0.21	104
86	−8.4	2.95	0.75	7.39	0.24	0.18	2.19	0.23	0.19	194
105	−12.5	3.54	0.71	11.02	0.21	0.15	2.62	0.17	0.15	4255

Fig. 3 Effects of pure time delay on pilot B's opinion rating: direct mode, 10 samples/s.
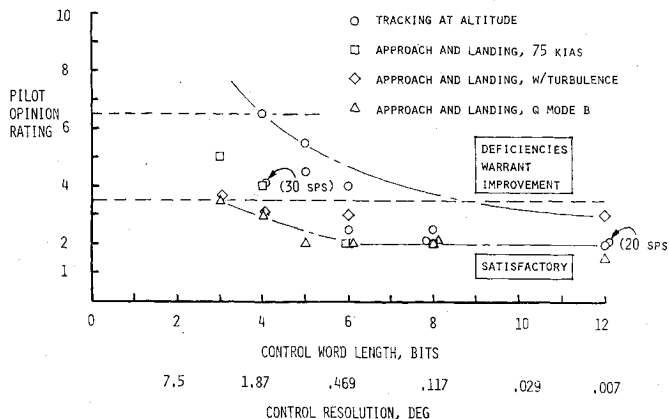

Fig. 4 Effects of control resolution on pilot B's opinion rating: direct mode, 10 samples/s.

precision tracking of the approach mirror display just prior to nominal touchdown point.

Simulated turbulence had a counter-intuitive effect on this trend: although POR = 3 with minimum delay, increasing delay caused less opinion degradation than in the calm-air case. For delays greater than 205 ms, turbulence actually improved the landing approach ratings, which were, nevertheless, in the 4-5 range. The most plausible explanation for this is that the pilot reduces his compensatory gain and/or bandwidth when flying in turbulence. He expects greater errors due to the turbulence excitation, and he issues less precise commands; hence, increasing delay has less effect on his perception of degraded flying qualities.

Again holding sampling rate at 10/s (with two exceptions), the effects of varying control resolution were evaluated in flight. With 12-bit granularity, the least significant bit of the ±15-deg elevator command was scaled to a deflection of

0.007 deg. It is important to note that the incremental acceleration associated with the least significant bit is the principal concern of the pilot. At 105 KIAS, the twelfth bit corresponded to an initial angular acceleration of 0.09 deg/s^2, while the third bit corresponded to 46.9 deg/s^2.

For this experiment, the elevator command word was truncated without rescaling from 12 bits to a minimum length of 3 bits, or 3.75 deg per least significant bit, and the effects on pilot B's opinion rating are shown in Fig. 4. The POR variation in reducing resolution from 12 to 8 bits was negligible. Whereas pure delay had similar effects on tracking and landing approach ratings, decreasing resolution (below 8 bits) had greater effect on tracking than on landing. Flying qualities became unsatisfactory for the former at about 6 bits and at 4 bits for the latter. While this difference may reflect a greater need for precision in tracking, the difference in airspeed used for these two tasks also should be taken into account. Because the dynamic pressure was higher, a unit elevator deflection caused twice the angular acceleration at 105 KIAS than it did at 75 KIAS. The command's sixth bit produced the same acceleration at 105 KIAS that the fifth bit caused at 75 KIAS, and the pilot experienced the same control granularity in these two cases.

Three additional points should be noted in Fig. 4. The first is that 3 ft/s (rms) vertical turbulence masks the flying qualities effects of decreased resolution. As before, this can be attributed, in part, to the pilot's decreased expectations of control precision; however, the effects of increased control granularity are similar to buffeting or turbulence. The granularity is "in the noise" at 5 bits and above; it feels like an increased turbulence level at 4 bits or less. The second is that increased sampling rate has a "dithering" effect which smooths low resolution response. With 4-bit resolution, increasing the sampling rate from 10 to 30/s improved the POR by 1, whereas 20/s sampling had no effect on the 12-bit rating. The third point is that a closed-loop pitch rate mode that is described in Refs. 13 and 14 provided slightly better baseline (12-bit) performance, as well as better low-resolution (3-5-bit) flying qualities.

Carrier Approach Task

The carrier approach and tracking tasks conducted by the Navy pilots were more demanding than the conventional flight tasks and were based on the matrix of ten flight conditions listed in Table 2. These ten conditions allowed the effects of sampling rate, pure time delay, and resolution to be investigated; they also let distinctions be made in the contributions of sampling and pure delays to fixed values of equivalent delay. Cases 1, 2, 7, and 9 constituted a sweep of sampling rates with minimum pure time delay. Holding sampling rate at 20/s, pure time delay was varied in cases 1, 6, 8 and 10. Resolution varied from 12 to 4 bits in cases 2-5, with fixed sampling rate and delay. Cases 6 and 7 both produced equivalent lags of 130 ms using different values of sampling

Table 2 Navy test configurations

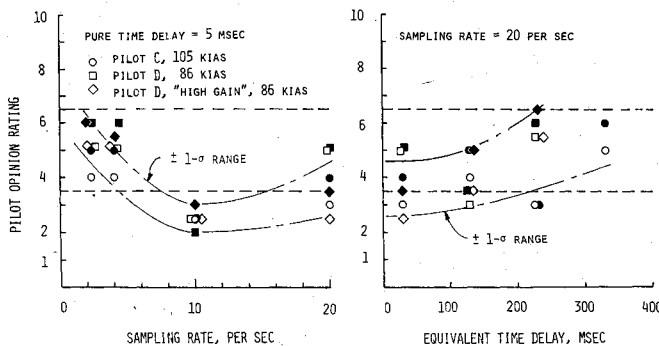| Number	Sampling rate, s^{-1}	Sampling lag, ms	Pure time lag, ms	Equivalent lag, ms	Resolution, bits (deg)
1	20	25	5	30	12 (0.007)
2	10	50	5	55	12 (0.007)
3	10	50	5	55	8 (0.117)
4	10	50	5	55	6 (0.469)
5	10	50	5	55	4 (1.87)
6	20	25	105	130	12 (0.007)
7	4	125	5	130	12 (0.007)
8	20	25	205	230	12 (0.007)
9	2.22	225	5	230	12 (0.007)
10	20	25	305	330	12 (0.007)

Fig. 5 Pilots C's and D's opinion ratings for field carrier landing practice with varying sampling rates and equivalent time delays: open symbol—approach; solid symbol—close in.

Fig. 6 Effects of control resolution on pilot opinion ratings for field carrier landing practice and tracking at altitude.

Fig. 7 Pilot's C's and D's opinion ratings for tracking at altitude: open symbol—acquisition; solid symbol—tracking.

rate and pure delay; similarly, cases 8 and 9 produced 230-ms equivalent lags in two ways.

Pilots C and D elected to assign two ratings to each landing approach, and Pilot D repeated the entire FCLP sequence using a different piloting technique. The approach to 0.5-n.mi. slant range was rated separately from the "close in" flight to waveoff. Distinctions between pilot D's "normal" and "high gain" techniques can not be quantified, but his high gain method could be interpreted as an increased conscious effort to minimize tracking errors in the mirror's visual display and to penalize such errors more severely in the evaluation of each configuration.

Figure 5 presents the effects of varying sampling rate and equivalent time delay on pilot ratings of the simulated aircraft carrier approach. The ratings assigned by each pilot, averaged over one to three repetitions, are plotted together with curves that define the standard deviations of all data points (both pilots, all repetitions, both approach phases) at each test condition. Trends noted in the conventional operations appeared again, but there are important differences as well. The increased ratings for slow sampling rates could be predicted, subjective ratings of the 10/s sampling rate agreed with pilot B's assessment, and there was a standard deviation of less than one rating unit for sampling rates of 10/s and below. (The points at 2.22 and 4/s were treated as a single point for this computation.) However, the degraded ratings and increased scatter for higher sampling rate were not anticipated. It is believed that this is an indirect effect of the control stick's minimal breakout force and negligible output deadband. About five months after the initial tests, pilot C re-evaluated the 20 and 10 sample/s configurations. He again preferred the 10/s sampling rate. Pilot C conjectured that slowing the rate from 20 to 10/s made the center stick less sensitive to inadvertent tremor-level inputs, which contribute to the nonlinear remnant and "motor noise" of classical and optimal-control pilot models.[22,23] This theory is supported by the markedly improved ratings which pilot D assigned in his high gain mode and which both pilots assigned in the higher bandwidth tracking task discussed below.

Unfortunately, the 20/s sampling rate was used for the time delay sweep, and the large standard deviation shown in Fig. 5 is believed to carry over. Nevertheless, the upper curve and pilot D's "close in" results bear resemblance to the precision landing task results of Ref. 21, with POR≈6 for 230-ms equivalent delay. The importance of piloting technique can not be underestimated; pilot D represents the fighter-pilot community (as do the pilots of Ref. 21), whereas pilot C is an ASW aircraft pilot. Consequently, they are likely to judge specific attributes differently.

Pilots C and D generally gave better ratings to the early approach than to the close-in phase. While this may appear to be at odds with pilot A's evaluation of the conventional landing with flare, the conventional "short final" approach is analogous to the close-in carrier approach that normally proceeds to touchdown without flare.
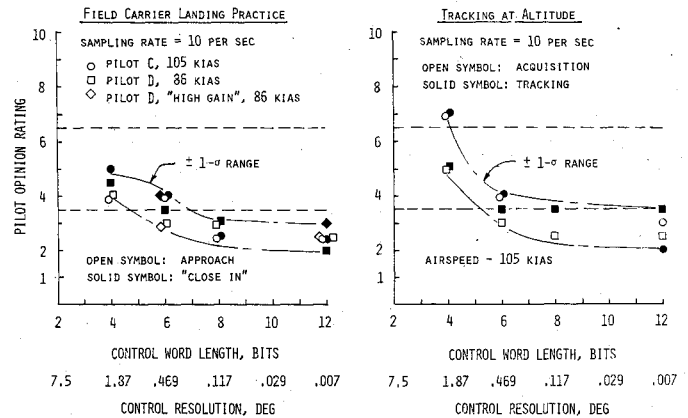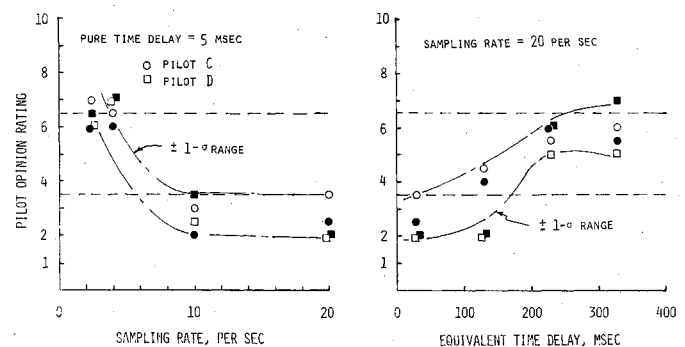
Pilot-induced oscillations (PIO) are "sustained or uncontrollable oscillations resulting from the efforts of the pilot to control the airplane"[20]; particular configuration may be PIO-prone,[24] but occurrence of the oscillation depends upon the piloting task and the actual perturbations which affect each flight. Although specific causes vary, all PIOs have the common characteristic that the oscillation decays when the pilot relinquishes active control of the aircraft. Seven PIO's were encountered in the 53 approaches performed by pilots C and D, and their severity increased with increasing equivalent delay. Pilot C's three PIOs, ranging from slight to pronounced intensity, occurred in the close-in phase with cases 6, 9, and 10 during a total of seven approaches in these configurations. Pilot D experienced a possible PIO in case 7 and three PIOs in case 8, all in the close-in phase during a total of ten approaches. Three of the four incidents occurred when he used his high-gain technique. Using his normal technique, pilot D found it easy to overcontrol case 8, and the PIO built up for several seconds before he recognized it.

Figure 6 presents pilot ratings of control resolution effects for both the FCLP and tracking tasks. The trends were very much the same in both cases, and POR values were similar to those depicted in Fig. 3. Degradation in perceived flying qualities was negligible as word length decreased from 12 to 8 bits. The FCLP ratings crossed over to unsatisfactory levels in the 5-7 bit range, while the tracking task ratings degraded at slightly higher resolutions. Ratings for the tracking task with 4-bit resolution were off sharply, reflecting the greater precision required in the task, as described next.

Tracking at Altitude

Both Navy pilots used similar maneuvers to evaluate the acquisition and tracking of fixed objects on the ground, and they assigned separate ratings for each phase. Fiducial marks were drawn on the VRA's windscreen, providing a ±40-mil

reference field with a ±2-mil center. Pilot D began the acquisition phase by selecting a point 45 deg off the nose and pulling the aircraft up to a 10-deg nose-high attitude. At 75 KIAS, he rolled into a 10-deg dive, accelerating to 100 KIAS, and attempting to center the object in the field of view. The tracking phase began when the object was within 5 mils of the center and continued for 15-20 s while maintaining 100 KIAS.

The effects of sampling rate and equivalent time delay on POR are shown in Fig. 7. The trends were similar to those shown in Fig. 5. Standard deviations were smaller than in the previous task, but there was less agreement on the relative ratings given to the two phases of the task: pilot C tended to give better ratings for tracking, while pilot D gave better ratings for acquisition. Pilot C's POR varied smoothly with equivalent delay, whereas pilot D's ratings took an abrupt jump between 130 and 230 ms. Pilot D perceived gradual degradation with decreasing sampling rate, but pilot C again preferred 10/s sampling to 20/s sampling.

There was one PIO in 34 trials. Both pilots found acquisition unnecessarily difficult with the 330-ms equivalent delay of case 10. Precise tracking was not possible, and high-gain control led pilot D to the PIO.

Distinctions Between Sampling Delay and Pure Delay

The notion of an equivalent delay consisting of the effective delay due to sampling plus the pure delay of computation is attractive in its simplicity, but the validity of this parameter for use in flying qualities criteria remains to be proven. This section illustrates that caution should be exercised in using equivalent delay, because pilot ratings differ for configurations with identical equivalent delay but unequal sampling rates.

A rationale for equivalent delays can be based on the transfer functions of the pure delay, the sample- and zero-order hold, and their truncated series expansions. The pure delay transfer function and approximation are, to first degree,

$$H(s) = e^{-\tau s} \simeq 1 - \tau s \tag{1}$$

where τ is the dead time or transport lag and s is the Laplace operator. The normalized transfer function for the zero-order hold[25] and its second degree approximation are

$$H(s) = (1 - e^{-Ts})/Ts$$

$$\simeq \{1 - [1 - Ts + (Ts)^2/2]\}/Ts$$

$$\simeq 1 - Ts/2 \tag{2}$$

T is the sampling interval, and Eq. (2) is seen to be equivalent to a pure time delay with dead time of $T/2$. If the expansions are carried beyond the terms shown, it is clear that the two equations are not identical; hence, the equivalence is valid only when the higher order terms are negligible, i.e., when Ts is small.

Figure 8 provides a graphical example of this distinction in the time domain. An arbitrary signal is shown, along with a sampled version and a continuous version that is delayed by half the sampling interval. On the average, the sampled and delayed signals compare rather well, but the sampled signal's "staircasing" is absent in the delayed signal. Furthermore, the sampled signal completely misses the small, high-frequency feature (in the center of the figure) that is passed without modification in the delayed version. It should be concluded that equivalent delay is a useful characterization of sampling effects only if the bandwidths of motions and control inputs that characterize the flight phase and piloting task are small in comparison to the sampling rate.

It remains to be shown whether or not pilots can distinguish between the two types of delay, and if so, to identify the type of delay that has the greater impact on flying qualities. The results of such a comparison are given in Fig. 9, where ratings and POR standard deviations for 42 separate runs are shown. Pilots C and D flew 25 FCLP approaches and 17 tracking segments with two values of equivalent delay (130 and 230 ms), each of which was obtained through two combinations of sampling rate and pure delay. The figure clearly indicates the two pilots' general preference for higher sampling rate, although there are a few trials that run against the trend. It is concluded that the pilot can adapt more readily to pure delay than to loss of control bandwidth.

Fig. 8   Comparison of the actual effects of sampling and pure delay.

Fig. 9   Comparison of sampling and pure delay effects.

Conclusion

A microprocessor digital flight control system and research aircraft have been described, and results of their use in studying flying qualities criteria have been presented. The emphasis of this paper is on the manner in which sampling rates, time delay, and control resolution affect pilot opinions of longitudinal response. Limiting values for satisfactory control are established by the findings of four pilots who flew the digitally controlled aircraft in tracking and landing approach tasks, including simulated carrier operations.

It is concluded that the lower limits on sampling rate and angular acceleration granularity are in the ranges of 4-10/s and 23-1.5 deg/s², respectively. These ranges corresponded to pilot opinion boundaries of 6.5 and 3.5. Simulated turbulence degraded pilot opinions in a predictable way, but it tended to mask the effects of low resolution and long time delays on pilot ratings. The upper limit on equivalent time delay, i.e., the sum of pure delays and the effective sampling delays, was in the range of 50-250 ms; however, the concept of an equivalent delay should be used with caution, as it does not provide a precise description of the delay process. The results of flight testing indicate that pilots can distinguish between
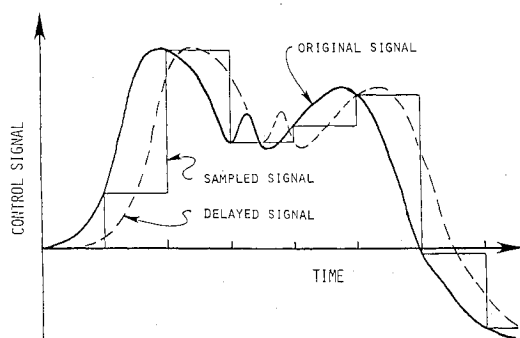
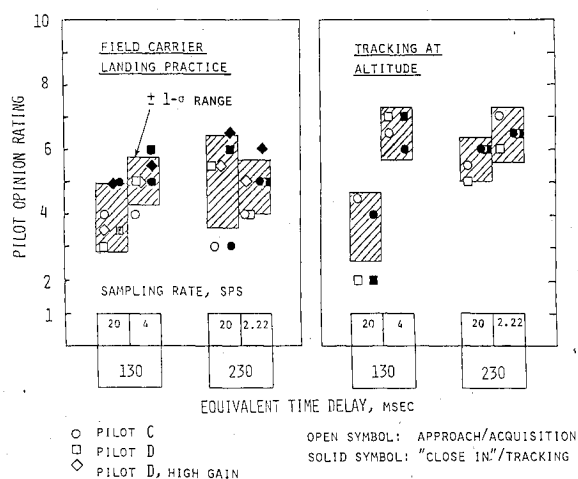the effects of sampling and pure delay. Pilot opinion ratings are task-dependent, and they degrade with increasing delay. For a given equivalent delay, this project's evaluation pilots generally preferred the configuration with higher sampling rate (and, therefore, greater pure delay). Pure delay can be reproduced in either an analog or digital system, but sampling and granularity are fundamentally digital phenomena. Consequently, it is important to use digital control systems to establish associated flying qualities criteria.

Acknowledgments

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