N94-13316

Handling Qualities Effects of Display Latency

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Abstract

Display latency is the time delay between aircraft response and the corresponding response of the cockpit displays. Currently, there is no explicit specification for allowable display lags to ensure acceptable aircraft handling qualities in instrument flight conditions. This paper examines the handling qualities effects of display latency between 70 and 400 milliseconds for precision instrument flight tasks of the V-22 Tiltrotor aircraft. Display delay effects on the pilot control loop are analytically predicted through a second order pilot crossover model of the V-22 lateral axis, and handling qualities trends are evaluated through a series of fixed-base piloted simulation tests. The results show that the effects of display latency for flight path tracking tasks are driven by the stability characteristics of the attitude control loop. The data indicate that the loss of control damping due to latency can be simply predicted from knowledge of the aircraft's stability margins, control system lags, and required control bandwidths. Based on the relationship between attitude control damping and handling qualities ratings, latency design guidelines are presented. In addition, this paper presents a design philosophy, supported by simulation data, for using flight director display augmentation to suppress the effects of display latency for delays up to 300 milliseconds.

Notation

AFCS	Automatic Flight Control System
CHPR	Cooper-Harper Pilot Rating
FCSIR	V-22 Flight Control Systm. Interface Rig
ILS	Instrument Landing System
IMC	Instrument Meteorological Conditions
K	Pilot control gain (in/deg)
N_{cw}	Pilot workload metric
N_{perf}	Tracking performance metric
MFD	V-22 cockpit Multi-Function Display
P	Aircraft roll rate (deg/sec)
T_L, T_I	Pilot model lead, lag time constants (sec)
$Y_c(j\omega)$	Aircraft + control system transfer funct.
$Y_p(j\omega)$	Pilot model transfer function
δ	Lateral stick control input (inches)
Φ	Phase of pilot-a/c-display system (deg.)
Φ_m	Phase margin pilot-a/c-disp. systm. (rad)
Φ_{mo}	Phase margin of aircraft system(rad)
σ	Tracking error standard deviation(deg)
$\Delta\gamma$	Localizer tracking error (deg)
$\Delta\Gamma$	Glideslope tracking error (deg)
ΔV	Airspeed tracking error (kts)
ξ	Pilot-a/c-display system damping ratio
ω_c	Pilot crossover frequency (rad/sec)
τ_c	Control system delay (sec)
τ_d	Display delay (sec)
τ_f	Display low-pass filter time constant (sec)
τ_p	Pilot delay (sec)

Introduction

The next generation of military rotorcraft are being designed to fulfill an astonishingly wide range of mission objectives. Due to an explosive growth in avionic system technology tasks which were unthinkable ten years ago, including nap-of-the-earth flight in low visibility, are now possible. Crew station designers are challenged to integrate the state-of-the-art technologies to provide the means to accomplish ambitious mission objectives, while also assuring that the performance of "routine" flight tasks is not degraded. Unfortunately, one side effect of complex avionic systems, known as *display latency*, stands as an obstacle to this challenge.

Display latency is defined as "the time delay between sensor detection of aircraft movement and the corresponding indication on the cockpit displays." The advent of the fully integrated all-glass cockpit allows pilots to selectively access a wide range of flight information including aircraft attitude, rates, navigation information, threat and/or target status, aircraft systems information, and engine parameters. Aircraft sensor information is digitally processed in onboard computers and may be accessed by the pilot through selectable cockpit displays, or through head-up/helmet-mounted display systems. However, the processing and

Presented at Piloting Vertical Flight Aircraft: A Conference on Flying Qualities and Human Factors, San Francisco, California, 1993.

transportation of the flight data takes time. During nighttime or adverse weather conditions the delay of fundamental flight information, such as aircraft attitude and rates, may adversely affect the pilot's ability to control his aircraft. Currently, there is no explicit military specification for display latency and little research data on the subject. Designers of new aircraft are thus faced with the unanswered question of how much latency is acceptable.

This paper evaluates the relationship between display latency and instrument flight handling qualities for the V-22 Tiltrotor aircraft. The three goals of this study were to quantify handling qualities trends (performance, workload, and pilot ratings) from varying levels of display latency, to generate methods to predict aircraft sensitivity to display latency, and to investigate methods to subdue latency effects. Using classical control theory, a second order linear model of the pilot-aircraft-display system was developed to analyze latency effects. Extensive piloted simulation was performed to support the analytical model and gather handling qualities data for different levels of latency. Finally, flight director displays were investigated as a means to augment the pilot control loop and suppress the latency effects.

Background

The V-22 Osprey Tiltrotor is a revolutionary aircraft designed to meet the mission requirements of all four military services. Besides providing basic control functions in multiple flight modes (helicopter - conversion - airplane), the V-22 digital flight control system and fully integrated avionic system provide maneuver limiting, fully coupled flight path tracking, integrated cockpit management, and thrust - power management regulation. Subsequently, the V-22 exhibits a substantial amount of display latency due to the digital processing and transportation of the sensor data as it is passed from an avionics data bus to the Flight Control Computer and the Mission Computer, where it is processed,

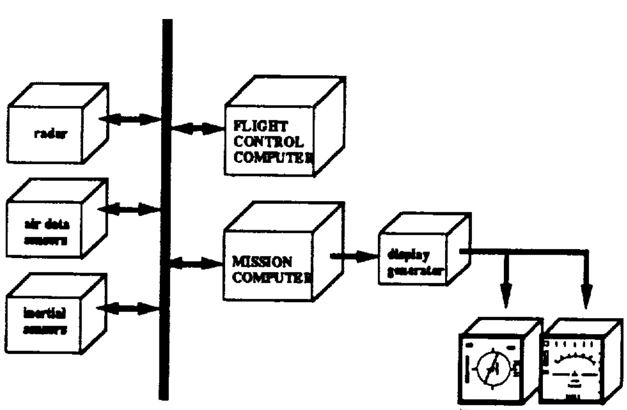

Figure 1. Avionics architecture

and then passed to the Display Electronics Unit (DEU) where the symbology is drawn on the cockpit Multi-Function Displays (MFD) as shown in Figure 1. Measurements indicate an average latency of 211 milliseconds (ms) for the V-22 attitude display.

It is intuitive to assume that in the absence of any out-the-window visual cues, a quarter-second display delay might be troublesome. For a precision flight task in instrument conditions, the pilot controls his aircraft by closing the loop between the cockpit displays and the aircraft control inputs as shown in Figure 2. The pilot acts as an optimal, adaptive, multi-loop control element by applying control inputs to track a prescribed flight condition indicated on the displays. System delays, such as control system and aircraft lags, have been shown to degrade aircraft handling qualities for tasks requiring high frequency control inputs (Ref. 1). Extensive research (Refs. 2,3) has shown that control system delays in excess of 100 ms are likely to degrade the ease and accuracy at which a pilot can successfully perform demanding visual tasks. Subsequently, control system lags are limited to 100 ms (for level 1 handling qualities) in flying qualities military specifications (Refs. 4,5). However, fundamental differences in pilot technique between visual flight and instrument flight preclude the direct application of control system delay specifications to display delay. Pilots are trained to fly instrument tasks with milder and more deliberate control inputs than corresponding visual tasks. Furthermore, precision instrument tasks often require display augmentation, visual aids, or selectable automatic control modes which are not considered in visual flight task specifications. Unfortunately, most of the previous research on display delays has been limited to simulator delays (Ref. 6) and highly maneuverable fixed-wing aircraft (Ref. 7).

The bottom-line handling qualities criterion for a developmental aircraft such as the V-22 is to provide Level 1 Cooper-Harper pilot ratings. Cooper-Harper pilot ratings (Ref. 8) provide a qualitative assessment of the pilot's ability to successfully perform a given task with a tolerable amount of workload. A Level 1 rating implies the aircraft is "acceptable without improvement." In order to substantiate Level 1 compliance, the aircraft must be flight-tested

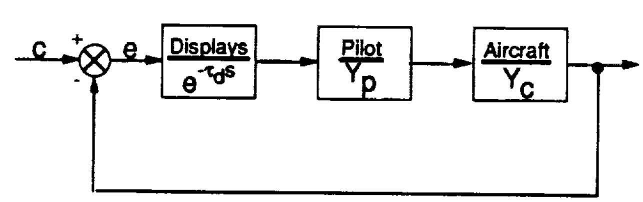

Figure 2. Pilot control loop

throughout its flight envelope including the full range of mission tasks. Subsequent handling qualities ratings depend on several variables including performance requirements, aircraft stability characteristics, flight control system functionality, cockpit displays, crew station format, and pilot proficiency. It is therefore not straightforward to isolate the effects of a single factor such as display latency on handling qualities results during limited flight testing of a developmental aircraft. In order to prevent display latency from unexpectedly handicapping a developmental aircraft late in its flight test program, system designers require either specific latency guidelines or simple techniques to evaluate latency effects.

Evaluation Procedure

Handling qualities engineers often employ analytical models of the pilot-aircraft closed-loop system to predict and analyze the effects of specific aircraft and control system parameters on simple flight task performance. The pilot is modelled as a servo-actuator control element which provides aircraft control inputs to follow a command profile. Various linear pilot models have been developed including single-input/single-output, multiple-input/multiple-output (Ref. 9), optimal control (Ref. 10), and structural models (Ref. 11). One of the simplest and most often used is the classical control theory *pilot crossover model*. The crossover model (Refs. 12,13) states that a sufficiently trained pilot linearly relates a control input to a tracking error such that the open-loop pilot-aircraft system provides the following frequency domain characteristics (Figure 3):

1) Sufficient bandwidth (crossover frequency) for task tracking and disturbance rejection,
2) Adequate stability margins (phase margin > 45 degrees), and
3) An integrator-like response at the crossover frequency.

Use of the crossover model has several advantages including: a) ease of implementation, b) flight task and aircraft characteristics sufficiently define pilot parameters, c) straightforward validation from flight or simulator data, and d) frequency-domain approach easily related to physical system. The primary limitation of the crossover model is that pilot behavior for most flight tasks cannot be accurately described in a fixed, linear, single-input/single-output (SISO) context. However, the display latency problem is well suited to the crossover model. Most instrument tasks are characterized by a control objective to maintain a displayed parameter (i.e. attitude, airspeed, vertical velocity) in a desired position (i.e. level, fixed speed, constant altitude). This results in a relatively simple control loop and describes the pilot's innermost control loop for each input axis. Also, there is less likelihood of "nonlinear" pilot behavior due to external stimuli such as abrupt motion and peripheral visual cues for instrument flight compared to visual flight. Research has shown (Refs. 12,13) that handling qualities ratings are best correlated with the stability characteristics of the inner control loop for the *most difficult control axis*. For the V-22 in helicopter and conversion modes (Ref. 17), the roll axis exhibits the lowest stability margins and will thus be the focus of the analytical study.

Fixed-base piloted simulation was used extensively to evaluate the handling qualities effects of display latency in a controlled environment. Since the reduced visual cue environment of simulators is not an issue for instrument flight, simulation provides a high fidelity platform for handling qualities testing. The display generator of the V-22 simulator at the Boeing Helicopters Flight Simulation Laboratory (Ref. 18) was reconfigured to allow latency to be varied from 70 ms to 400 ms in 33 ms increments. Two flight tasks were simulated in instrument meteorological conditions (IMC) to serve the dual purpose of validating the single-loop crossover model analysis and evaluating latency effects for a high-gain operational task. The first task consisted of single-axis roll attitude tracking where the pilot maneuvered the aircraft to track a commanded bank angle symbol which prescribed moderate rate roll maneuvers. In the second task, the pilot was required to capture and track the final leg of an Instrument Landing System (ILS) approach to a vertical landing at a VTOL pad. Both moderate and high speed approaches were tested with visibility lim-

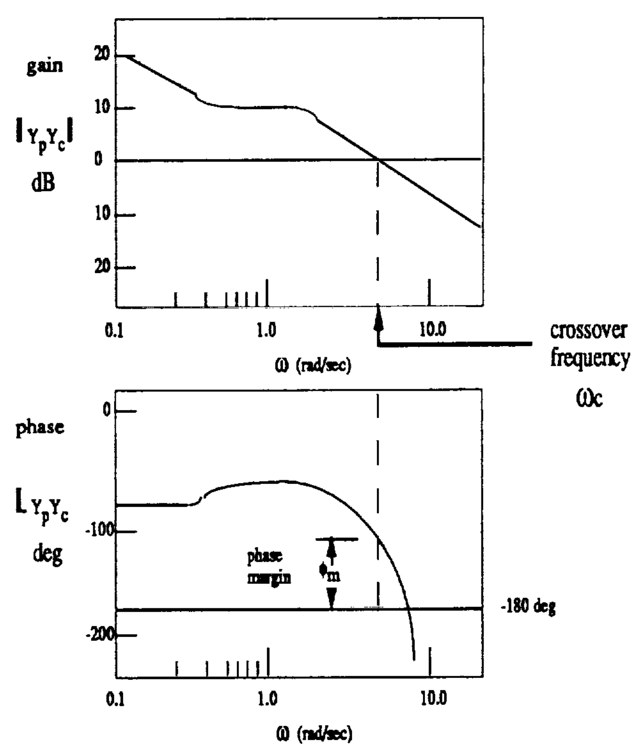

Figure 3. Pilot/aircraft system crossover model

ited to 2500 feet so that the landing pad was not observable until the approach Decision Height (200 feet above ground level) was reached. Moderate levels of turbulence, wind shear, and crosswind were utilized to demand constant pilot control inputs.

Attitude Loop Analysis

Time delay effects on aircraft controllability are best described by the innermost (attitude) control loop. For attitude control, the crossover model relates the pilot control input to the displayed attitude error in the transfer function form:

$$Y_p = K \frac{T_L s + 1}{T_I s + 1} e^{-\tau_p s} \tag{1}$$

where K is the pilot control gain and T_L, T_I, and τ_p are the pilot lead, lag, and neuromuscular delay time constants, respectively. The neuromuscular delay is defined as "the time required for the pilot to comprehend display information, determine, and physically apply the appropriate input." Included in the pilot delay parameter are fixed and variable components. The fixed component, estimated at around 60 ms - 100 ms (Ref. 12), is due to inherent physiological delays, and the adjustable component is due to the pilot display scan rate and concentration level. The adjustable delay component can be reduced, where necessary, at the expense of increased cognitive workload. The control gain and lead compensation parameters are optimized by the pilot in the same hierarchial fashion as a control system designer tunes a servomechanism. That is, the gain is set for stabilility, then compensation is added to meet bandwidth requirements with the parameters subject to energy constraints. For example, during a high frequency target tracking task the pilot will provide a control gain sufficient to minimize the tracking error while maintaining adequate stability margins. If system delays, or aircraft dynamics, do not allow stable, high frequency control, the pilot will be forced to add lead compensation to perform the task. Lead compensation, which may be perceived as "stick pulsing", significantly increases the pilot control workload. On the other hand, if the task is simply to maintain level flight with only moderate disturbances, the pilot will act to minimize workload in the form of lower control gain, no lead compensation, and a comfortable scan rate.

Simply stated, the pilot-aircraft crossover frequency may be estimated based on control theory given knowledge of the aircraft stability characteristics, system delays, and task control bandwidth requirements. In order to accommodate demanding visual tasks (i.e. shipdeck hovering, in-flight refueling), the V-22 digital flight control system provides high bandwidth control throughout its operational envelope. Figure 4 shows the frequency response of the lateral axis for the augmented V-22 (AFCS on, rate command-

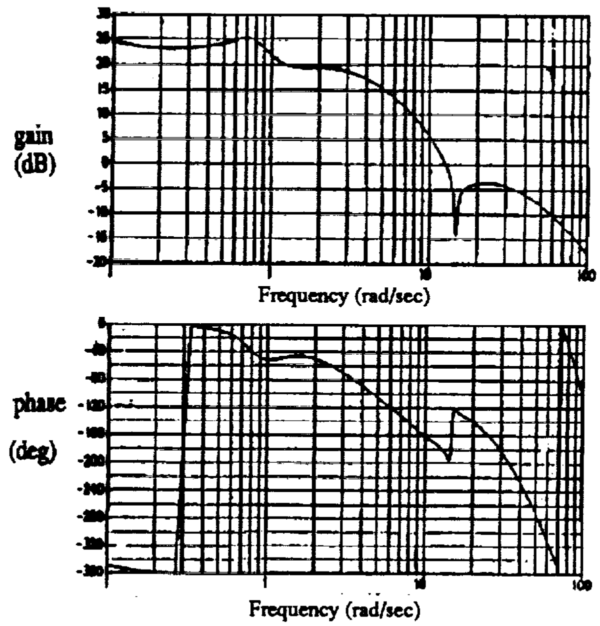

Figure 4. P/δlat (deg/sec/in) frequency response at 120 kts.

attitude hold system) at a 120 knot flight condition. It is seen from the Bode diagram that if the pilot-aircraft-display system contained no time delays, the pilot could maintain integrator response (-20 db/decade gain slope) for control bandwidths up to 6 rad/sec with pure gain compensation and sufficient stability margins. High gain flight tasks, such as precision hover, mandate control bandwidths in the range 1 rad/s < ω_c < 4 rad/s (Refs. 15,16).

The most demanding operational requirements for the V-22 in IMC consist of "flight path tracking tasks" at high speed and low altitude such as terrain following and aggressive approach-to-landings. Flight path tracking may be viewed as an "outer-loop" control function, as shown in Figure 5, where the pilot corrects for low-frequency flight path errors by adjusting commands to the high-frequency attitude control loop. In general, the flight path tracking outer-loop requires a bandwidth one-quarter of the attitude tracking inner loop. Therefore, for limited amounts of delay, the V-22 stability bandwidth (based on phase characteristics) is significantly greater than the required task bandwidth for flight path tracking instrument tasks. This implies that the pilot crossover frequency will be determined by workload factors alone. A general rule-of-thumb in this case (Ref. 16) is that the crossover frequency will equal the maximum of the phase plot such that

$$\omega_c = \omega_{\phi max}.$$

Applying the rule to Figure 4 indicates that for the V-22 lateral axis at 120 knots,

$$\omega_c = 2 \text{ rad/sec.} \tag{2}$$

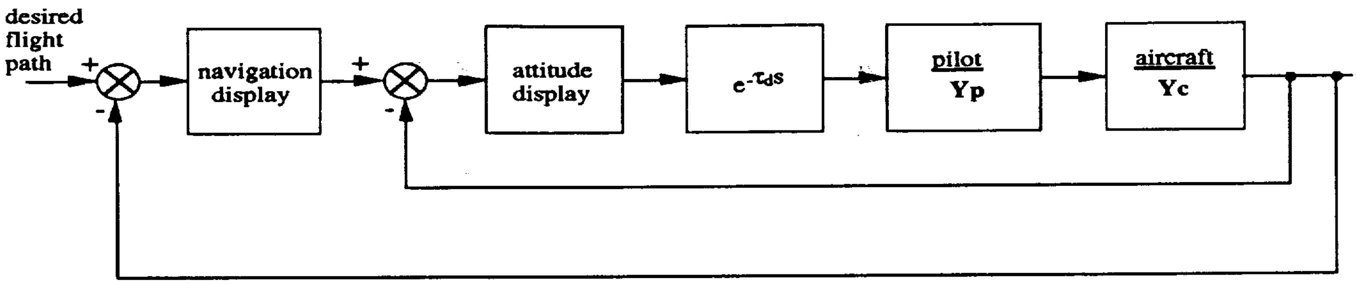

Figure 5. Pilot control structure for flight path tracking

Assuming that the crossover frequency is 2 rad/s for V-22 precision instrument tasks, the crossover model may be used to predict the effects of pilot and display delays. System delays act to linearly reduce the phase of the pilot-aircraft system such that,

$$\Phi = \Phi_o - \omega_c\,(\tau_p + \tau_d + \tau_c) \qquad (3)$$

where Φ_o is the phase of the aircraft alone and τ_p, τ_d, τ_c are the delay times of the pilot, displays, and control system, respectively. Control system delays for the V-22 have been measured through frequency response testing on the Boeing Helicopters Flight Control System Interface Rig (FCSIR) (Ref. 17) and the data is presented in Table 1. Using the second order system approximation between phase margin and damping ratio, and combining the maximum control system delay of 50 milliseconds with a conservative estimate of the pilot neuromuscular delay of 250 ms (based on simulator time history matches), the system damping ratio is related to the latency such that

$$\begin{aligned}\xi &= \Phi_m \left(\frac{57.3\ \text{deg/rad}}{100\ 1/\text{deg}}\right) \qquad (4)\\ &= 0.573\,\Phi_{mo} - 0.573\,\omega_c\,(\tau_d + 0.3)\end{aligned}$$

where Φ_m is the phase margin of the pilot-aircraft-display system, and Φ_{mo} is the aircraft phase margin (1.92 radians). Figure 6 shows the system damping reduction due to display latency increases between 70 milliseconds and 400 milliseconds. Handling qualities studies (Refs. 17,18) have shown that for phase margins less than 45 degrees, task performance may be limited by overshoot tendencies for abrupt control inputs, and this corresponds to the required aircraft phase margin in the military specifications (Ref. 5). Therefore, it is expected that the pilot will reduce the control gain, or add lead compensation, to continually maintain stability margins over 45 degrees. It is observed from Figure 6 that the pilot is unable to sustain this criterion with pure gain compensation for latencies exceeding 317 milliseconds.

Input	Output	FCSIR delay	SIM delay
longitudinal stick	longitudinal cyclic	50.75 ms	50.0 ms
longitudinal stick	elevator	26.25 ms	50.0 ms
lateral stick	diff. collective pitch	50.75 ms	50.0 ms
lateral stick	flaperon	25.00 ms	50.0 ms
pedals	diff. collective pitch	50.75 ms	50.0 ms
pedals	rudder	34.85 ms	50.0 ms
thrust contrl. lever	collective pitch	50.75 ms	50.0 ms
thrust control lever	engine command (FADEC)	38.75 ms	50.0 ms

Table 1. V-22 control system delays

Piloted Simulation

The V-22 simulator consists of a validated aircraft mathematical model operated real-time on a multi-processor computer with a fixed-base emulation of the V-22 dual-place crew station. Cockpit cues are provided to the pilot through out-the-window scenes produced by an Evans and Sutherland CT-6 computer image generation system, a displacement cyclic controller with a programmable force-feel system, a small-displacement (+/- 2 inches) thrust control lever, and two CRT multi-function displays per pilot station. The simulator has been shown to be a high fidelity representation of the aircraft through time histories and handling qualities evaluations matched to flight test (Ref. 14). Real-time simulation processing is run at a

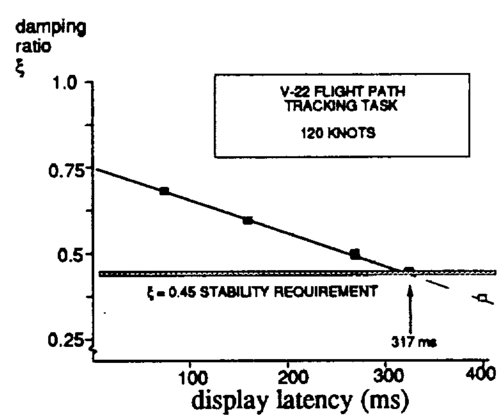

Figure 6. Predicted damping ratio vs. latency

frequency of 20 hertz which yields, on average, a control delay of 50 milliseconds. This falls within 25 ms of the aircraft control delays as shown in Table 1. A high performance Silicon Graphics IRIS-4D/80 CG display generator computer drives the simulator displays interlaced at a frequency of 60 hertz. In order to vary the display latency, a software buffer was inserted in the display generator which held the symbology data in multiples of two display cycles according to an operator selectable index. The inherent display delay, from the mathematical model output until completion of the display generation cycle, was measured at an average of 73 milliseconds. Therefore, the possible display latency test points were 73 ms, 107 ms, 140 ms, etcetera. In order to verify the latency values, measurements were taken prior to each simulation test by sending a discrete signal through the mathematical model and measuring the analog time difference between the model output and display generator optical output.

Attitude tracking task

Display delay effects on the attitude control loop were evaluated with a pilot-in-the-loop through an attitude tracking task simulation. The pilot was asked to track a commanded attitude symbol with the aircraft nose symbol on the displays, as shown in Figure 7, "to the best possible control accuracy." Moderate rate (3 to 5 deg/sec) bank angle captures of 10 degree amplitude were used to drive the command symbol. The commands were interjected in a random manner to prevent "pilot anticipation" from masking the results. Results were obtained with two highly trained V-22 evaluation pilots during a total of 4.6 hours simulation time. The data consisted of both tracking performance and workload measurements which were digitally recorded and statistically processed real-time, combined with qualitative pilot comments. All tests were run at a flight condition of 120 knots airspeed with the nacelles tilted at a 60 degree incidence (where 90 degrees is referenced at helicopter mode). This flight condition was chosen as representative of precision instrument tasks for the V-22.

A straightforward metric, referred to as the 2σ-bound, was used to gauge the attitude tracking accuracy. During each test run, which consisted of bank angle captures in each direction over a one minute test period, the 2σ–bound was calculated by doubling the standard deviation of the bank angle tracking error and adding the mean value. In simple terms, this statistic measures the aircraft dispersion about the commanded attitude. For a normally distributed tracking error, the 2σ–bound represents the absolute value such that the probability of exceeding the bound is approximately 5% at any instant in time.

In a similar manner, a workload metric referred to as the *control workload index* was used to quantify the magnitude of pilot control activity. The control workload index (N_{cw}) was calculated as

$$N_{cw} = \frac{1}{2}\left(\frac{\delta_{rms}}{\delta_{rms\text{-}req}} + \frac{\dot{\delta}_{rms}}{\dot{\delta}_{rms\text{-}req}} \right) \qquad (5)$$

where,

δ_{rms} = root-mean-square of lateral stick deflection
$\dot{\delta}_{rms}$ = root-mean-quare of lateral stick rate.

The normalizing parameters represent the minimum required stick activity to track the command as determined from the V-22 autopilot. By combining a measure of stick deflection variance and stick rate variance, the control workload index measures the amount the pilot is forced to move the controls and vary the control frequency. This provides a basis for comparing control activity between test runs.

Figure 8 presents the simulation performance and workload measurements plotted against latency value. The plots indicate the average values from four data runs at each latency value (for each latency test point the pilots were allowed a few training runs prior to data collection). From the workload plot it is clear that the display delay effects can be broken into three regions:

1) $\tau_d < 140$ ms: a no-effect region where the latency does not significantly impact attitude control,
2) 140 ms $< \tau_d <$ 307 ms: a degraded attitude control region where the pilot works harder to maintain desired attitude, and
3) $\tau_d >$ 307 ms: a gain reduction region where the pilot is forced to ease control aggressiveness to assure adequate system stability.

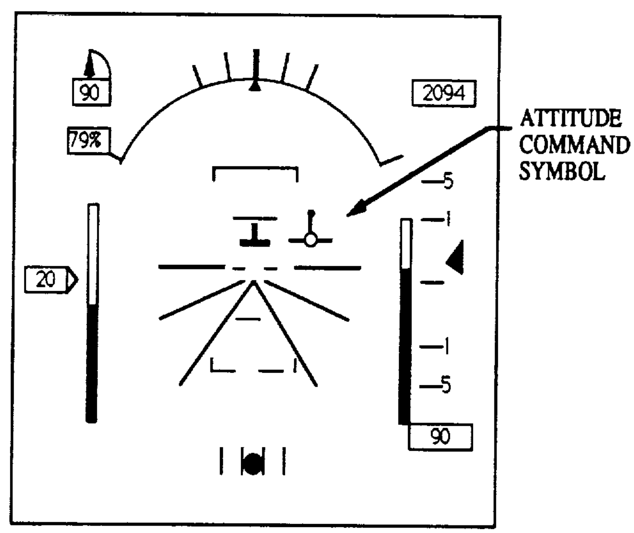

Figure 7. Attitude tracking display

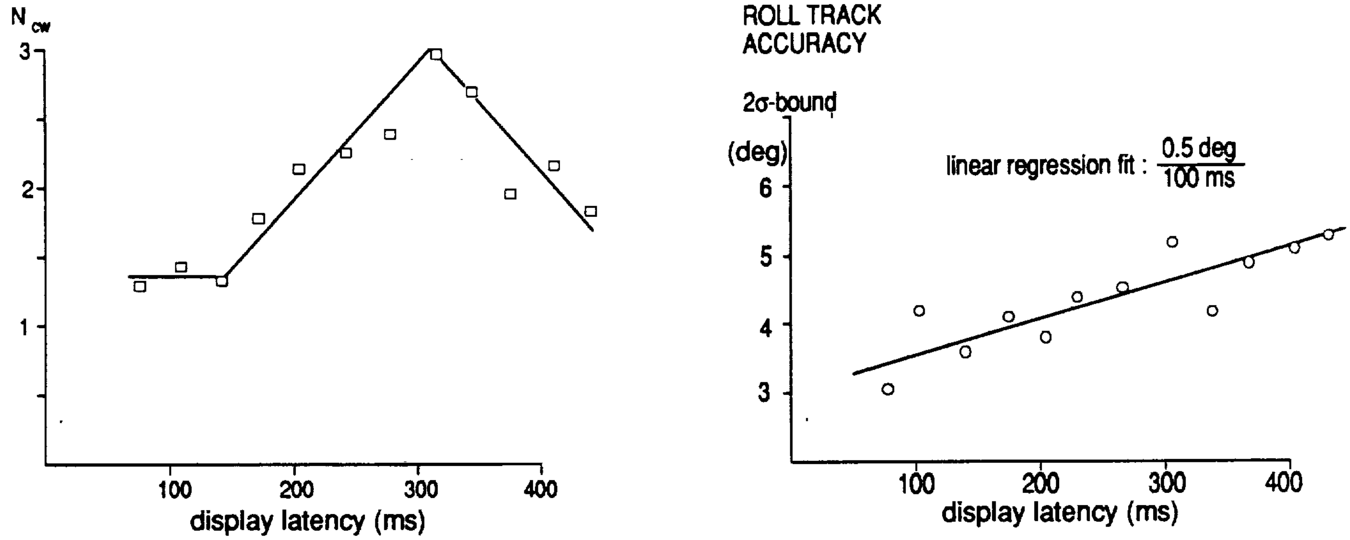

Figure 8. Attitude tracking simulation results

The pilot gain reduction breakpoint corresponds well with the pilot model analysis which predicted that the 45 degree phase margin criterion would not be met for latencies exceeding 317 ms. Sample time histories for one run in each of the three regions are shown in Figure 9 and illustrate the loss of control damping with latency variations. Superimposed on the plots are time histories from the second order analytical model. At the higher latency values, the control oscillations of the simulator data were more prominent than the model predicted and are most likely due to nonlinearities in the pilot compensation.

Accordingly, the tracking performance plot indicates that as the delay increases and stability margins are reduced, tracking difficulty increases. A linear regression fit to the tracking performance data shows a bank angle control degradation of one-half degree for every 100 ms of added latency. Pilot comments indicated that lead compensation was applied for latencies over 240 ms in an attempt to alleviate tendencies to overshoot the commanded attitude.

ILS approach task

The final leg of a low-visibility ILS precision approach was simulated with six different latency values between 70 ms and 400 ms. The task was initialized with an inital offset from the desired glidepath at approximately 2000 feet above ground level, challenging the pilot to acquire the ILS glidepath and track to a decision height of 200 feet. The approaches were flown at airspeeds of 85 knots and 120 knots, and the task was terminated at decision height. Turbulence, wind shear, and crosswind models were implemented in the simulation to induce disturbances. The turbulence consisted of a body-fixed sampling Dryden model with the intensity and scale length parameters set according to "moderate" specifications of MIL-F-8785C (Ref. 4). In addition, a 20 knot wind at a 45 degree azimuth from the approach course was implemented with a "moderate" wind shear profile added per MIL-F-8785C.

The flight displays consisted of the vertical situation display

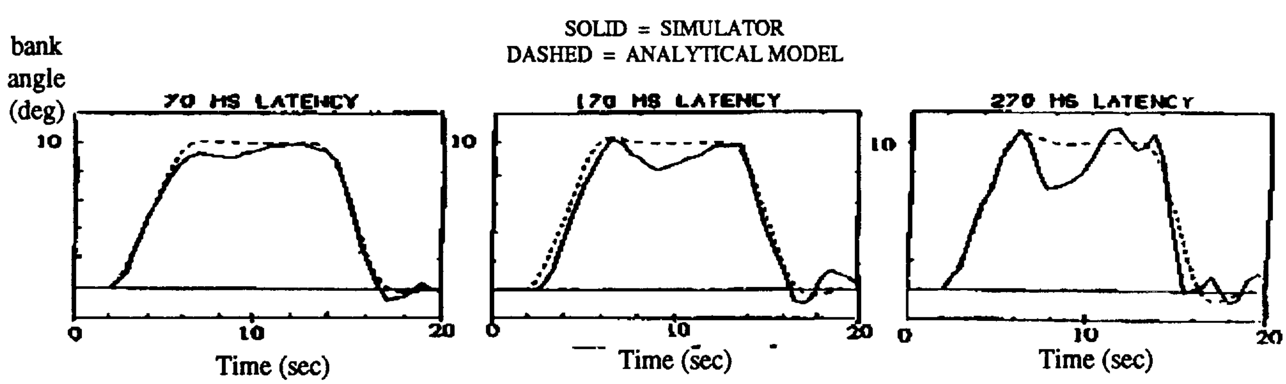

Figure 9. Attitude tracking time histories

of Figure 7 plus a horizontal situation display with the ILS localizer and glideslope deviation indicators as shown in Figure 10. In order to receive pilot handling qualities ratings per the Cooper-Harper scale, performance constraints were issued to the pilot. For "desired" performance the pilot was required to track the glidepath within the following constraints for more than 80% of the approach and be within constraints at decision height: localizer deviation ($\Delta\gamma$) less than +/- 1 degree, glideslope deviation ($\Delta\Gamma$) less than +/- 0.25 degree, and airspeed deviation (ΔV) less than +/- 5 knots. Yaw axis control was not required since the V-22 control system automatically provides trun coordination and heading hold features. "Adequate" performance constraints were set at double the desired constraints. It should be noted that in the V-22 the pilot is required to scan an azimuth of approximately 10 degrees to monitor all necessary ILS flight information on the two displays.

Data was recorded for five highly trained evaluation pilots during simulation spanning over 34 hours. In addition to 126 data runs, more than 200 runs were performed for pilot training purposes. Simulation studies (Refs. 18,19) have shown that biases may result in handling qualities evaluations between alternate configurations due to *cross-training* effects. This means that variations in pilot rating between different configurations may depend on the order in which they are tested. To subdue cross-training effects, latency values were tested in varying sequence and several runs were alloted for training at each test point. For each data run, performance and workload metrics were calculated real-time. The performance metric consisted of the normalized 2σ-bound averaged between the three tracking variables such that

$$N_{perf} = \frac{1}{3}\left(\frac{\Delta V_{2\sigma}}{5\text{ kts}} + \frac{\Delta\gamma_{2\sigma}}{1\text{ deg}} + \frac{\Delta\Gamma_{2\sigma}}{0.25\text{ deg}}\right) \quad (6)$$

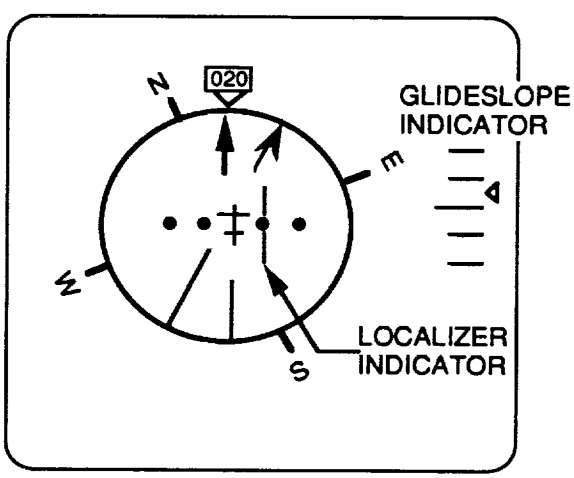

Figure 10. ILS displays

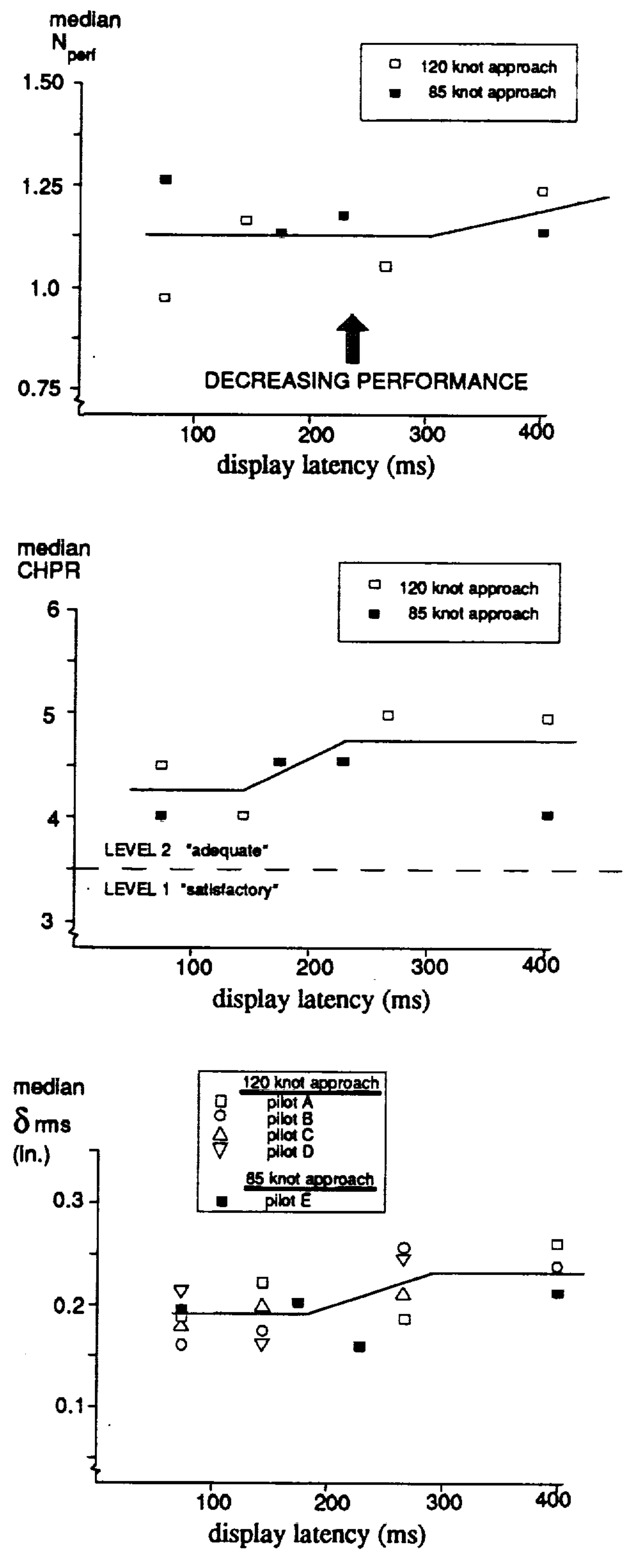

Figure 11. ILS task simulation results

The desired constraint parameters were used as the normalizing factors such that performance indices less than unity indicate that the aircraft was maintained within desired constraints for at least 95% of the run. The root-mean-square of the control deflections from trim were used as the workload metric.

Figure 11 displays the median performance indices, Cooper-Harper pilot ratings (CHPR), and lateral stick workload metric (lateral inputs were by far the most active) versus display latency. Median values, as opposed to averages, were used to eliminate the weighting effect of poor performance data during a few runs when the pilot aborted the approach and prepared for a go-around. The performance plot indicates that, although variations in performance resulted, there were no discernable trends relating tracking performance to latency for test points between 70 ms and 300 ms, and only a slight reduction in tracking accuracy at 400 ms, as indicated by the relatively flat distribution of the median values. This was predicted by the attitude loop analysis which showed that delays up to 300 ms are not sufficient to degrade the performance of the low bandwidth flight path tracking outer loop. However, the pilot ratings and workload plots do indicate a control degradation for latencies between 140 ms and 300 ms which is consistent with the "degraded attitude control region" identified in the attitude tracking task. Comments indicated that the pilots were perceptually unaware of latency changes between configurations, but that they acquired different control techniques due to "slight changes in aircraft response characteristics." The altered control techniques appeared as lateral stick pulsing during small heading changes at the 270 ms and 400 ms latencies which was not required at 70 ms. This was caused by the loss of attitude control damping and resulted in a one-half Cooper-Harper point degradation between 140 and 270 milliseconds.

Corrective Measures

At 211 ms of display latency, the loss of attitude control damping produced a slight degradation (less than 1/2 CHPR point) in V-22 instrument approach handling qualities relative to a minimum latency of 70 ms. Furthermore, the handling qualities ratings for all latency values tested were consistently a level 2 classification which implies that "deficiencies warrant improvement." Pilot comments indicated that workload issues mandated the level 2 ratings, and the workload was increased by a difficulty in assimilating all the necessary flight information and determining the proper input to zero the ILS tracking deviations. It is therefore desirable to 1) suppress the latency-induced attitude damping reduction and 2) reformat the presentation of ILS information to the pilot. These two objectives may be accomplished by the addition of *flight director* displays.

Flight director

Flight director displays provide the pilot with pursuit-type cues to steer the aircraft along a commanded path. The command path is based on the flight path tracking error, such as an ILS deviation, and all control cues are presented to the pilot in a centralized location. Figure 12 shows the V-22 flight director symbology on the vertical situation display which consists of power, roll, and pitch cues. The dynamics of the flight director cues are selected to augment the stability characteristics of the closed-loop pilot-aircraft-display system to provide sufficient tracking performance with only pure gain pilot compensation. Several methodologies to optimize flight director designs are presented in the literature (Refs. 20,21) but do not address the issue of display latency.

Flight director designs can be used to suppress latency effects to only a limited degree. From Equation 3 it is observed that for pure gain pilot compensation and a fixed amount of display latency, the phase margin of the pilot-aircraft-display system can be increased by 1) reducing the pilot delay, 2) adding phase lead at the crossover frequency through display compensation, or 3) decreasing the crossover frequency. The ability of a flight director to reduce the pilot delay is easily recognizable. By using centralized cues, the display scan time will be reduced. And any time spent from pilot cognition (deduction of control input from flight path deviation indicators) will lessen since the flight director processor assumes the responsibility of calculating control inputs from the tracking error. However, benefits gained from adding phase lead or reducing the crossover frequency are mostly counter-productive since a reduction in the crossover frequency, through smaller gains or low-pass filtering, precludes any effect of phase lead. Similarly, adding phase lead in the displays will increase the crossover frequency unless the display gains are reduced. Therefore, with inherent display latency, the potential performance

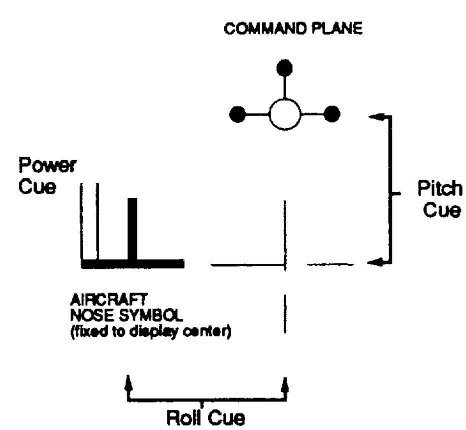

Figure 12. Flight director symbology

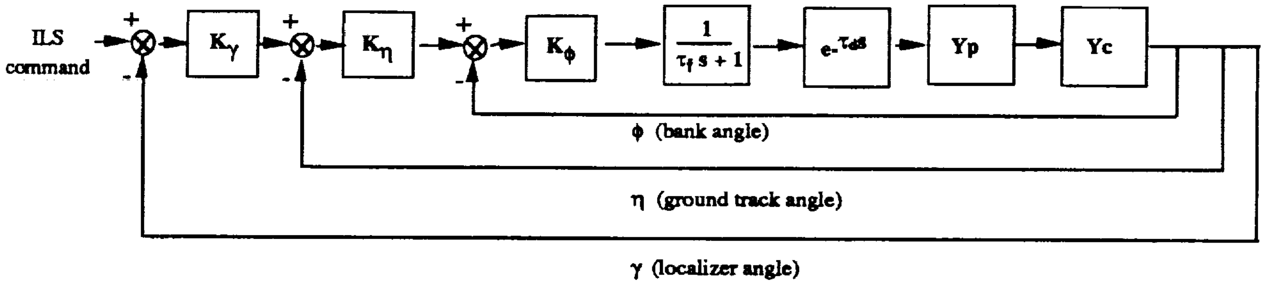

Figure 13. Flight director lateral cue processing

gains of a flight director are limited, but the flight director can improve instrument handling qualities by reducing the pilot delay and forcing the pilot to control at an "acceptable" crossover frequency.

For an ILS task the V-22 flight director lateral cue (Ref. 22) is driven by the localizer deviation shaped by washed-out bank angle and ground track angle feedback signals as shown in Figure 13. The gain ratios between the three feedback loops determine the relationship between the localizer deviation and the commanded lateral stick input. By increasing the gain on the bank angle loop, lead compensation is introduced which increases the crossover frequency of the pilot's attitude control loop. By adjusting the flight director gains, the inner loop crossover frequency can be selected to tradeoff the adverse effects of display latency with the benefits of increased tracking bandwidth. For the V-22 ILS task, the tradeoff can be biased toward subdueing the latency effects since sufficient tracking performance was obtained with raw-data displays.

ILS re-simulated

The ILS approach task was repeated with the V-22 flight director active at a fixed latency value of 300 ms. Initially, several training runs were used to tune the flight director parameters at the fixed latency value. Since the baseline design did not account for large latency values, underdamped control responses were initally observed, and the flight director parameters were adjusted to reduce the system bandwidth. Figure 14 presents the median tracking performance and pilot rating results for six flight director runs with two evaluation pilots superimposed on the results from the raw-data runs. Level 1 pilot ratings, with tracking performance well within performance constraints, were consistently obtained with the flight director active. Furthermore, it was observed that consistency between runs was greatly improved, described by one pilot as "an improvement in damping and predictability with milder control inputs commanded from the flight director." Apparantly, by forcing the pilot to control at a lower crossover frequency, the flight director improved the overall response characteristics of the pilot-aircraft-display system.

Conclusions

It is the general belief in the rotorcraft handling qualities community that display latency degrades an aircraft's instrument flight capabilities, but, up to this point, no requirements on allowable latency have been produced. This paper investigates the handling qualities effects of varying levels of display latency analytically through the pilot crossover

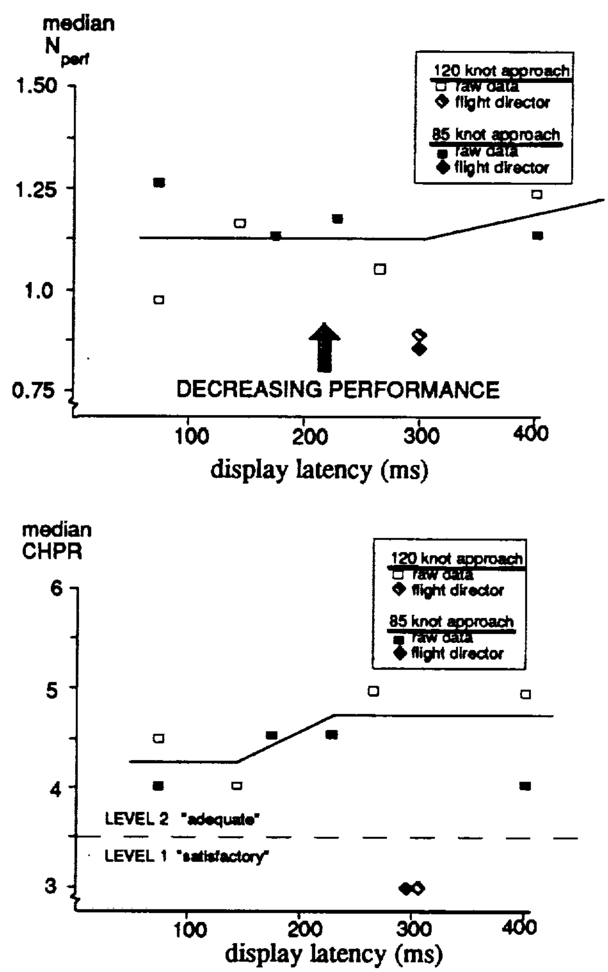

Figure 14. Flight director simulation results

model and experimentally through piloted simulation of the V-22 Tiltrotor aircraft. Latency effects on the lateral axis of the V-22 Tiltrotor aircraft were predicted through a second order crossover model of the attitude control loop, and the effects were tested through piloted simulation of both an attitude tracking task and a precision ILS approach. The results showed that the pilot workload involved in the ILS approach was directly related to a linear reduction in the damping ratio of the roll attitude control loop from 0.60 to 0.45 as latency was increased from 140 ms to 310 ms. The control damping reduction was predicted by the model based on the V-22 frequency response characteristics, control system lags, and instrument task bandwidth requirements. The display latency did not degrade flight path tracking performance, due to its low bandwidth, until the attitude loop phase margins fell below 45 degrees and the pilot was forced to reduce control gain. For an ILS approach task, the results indicated that pilot workload was increased as the attitude control damping was reduced, resulting in pilot rating degradations of 1/2 CHPR between 140 ms and 270 ms of latency.

Flight director displays were then investigated as a means to suppress the increased workload effects of display latency. The results showed that flight director displays improve instrument flight handling qualities by reducing pilot cognitive workload, and they can suppress latency effects by regulating pilot control at an "optimal" crossover frequency.

Based on the results of this study the following conclusions were reached:

1) The handling qualities effects of display latency, in terms of pilot workload and task performance, are driven by the stability characteristics of the pilot's inner control loop.

2) In general, an aircraft's robstness to display latency is proportional to its stability margins, and inversely proportional to the bandwidth required for its instrument flight mission tasks. Based on the test results which showed that damping ratios below 0.6 induce difficulties in precise attitude control, and damping ratios below 0.45 degrade precise flight path control, proposed latency guidelines are presented in Figure 15. The guidelines specify maximum delay values such that the latency will not significantly degrade handling qualities. The maximum delay values (display latency plus control system delay) are shown as a function of the aircraft phase margin and crossover frequency.

3) The benefits of flight director lead compensation ("display quickening" - which increases control bandwidth), often used for high bandwidth instrument tasks, is limited by display latency since latency-induced reductions in control damping are linearly proportional to the crossover frequency.

4) The V-22 exhibited "satisfactory" (level 1) handling qualities for latency values less than 300 ms based on its instrument task requirements and the use of flight director displays. Without flight director displays, an aggressive ILS approach task with moderate disturbances yielded level 2 handling qualities even at a minimum display latency of 70 milliseconds.

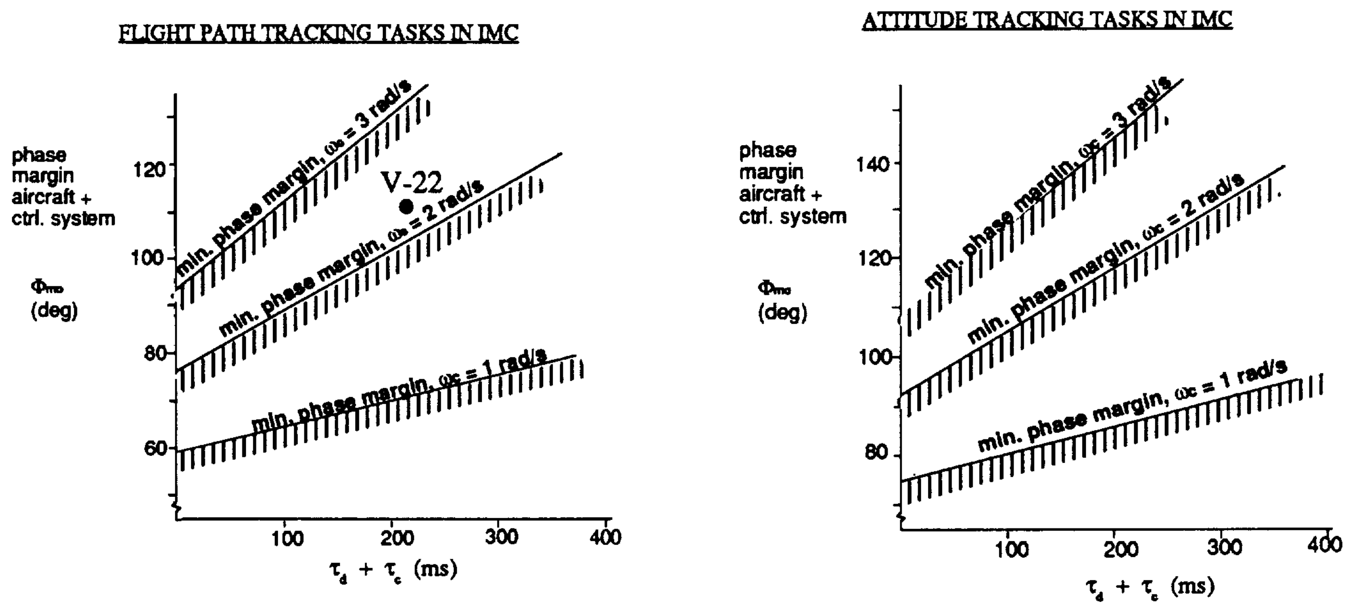

Figure 15. Proposed latency guidelines

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