Primary Display Latency Criteria Based on Flying Qualities and Performance Data

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ABSTRACT

With a pilots' increasing use of visual cue augmentation, much requiring extensive pre-processing, there is a need to establish criteria for new avionics/display design. The timeliness and synchronization of the augmented cues is vital to ensure the performance quality required for precision mission task elements (MTEs) where augmented cues are the primary source of information to the pilot. Processing delays incurred while transforming sensor-supplied flight information into visual cues are unavoidable. Relationships between maximum control system delays and associated flying qualities levels are documented in MIL-F-83300 and MIL-F-8785. While cues representing aircraft status may be just as vital to the pilot as prompt control response for operations in instrument meteorological conditions, presently, there are no specification requirements on avionics system latency. To produce data relating avionics system latency to degradations in flying qualities, the Navy conducted two simulation investigations. During the investigations, flying qualities and performance data were recorded as simulated avionics system latency was varied. Correlated results of the investigation indicates that there is a detrimental impact of latency on flying qualities. Analysis of these results and consideration of key factors influencing their application indicate that: (1) Task performance degrades and pilot workload increases as latency is increased. Inconsistency in task performance increases as latency increases. (2) Latency reduces the probability of achieving Level I handling qualities with avionics system latency as low as 70 ms. (3) The data suggest that the achievement of desired performance will be ensured only at display latency values below 120 ms. (4) These data also suggest that avoidance of inadequate performance will be ensured only at display latency values below 150 ms.

INTRODUCTION

This paper documents the results of two piloted simulations conducted to generate data regarding display latency effects on flying qualities. A theoretical foundation is presented first to facilitate discussion. In this introduction, latency, flying qualities and a general closed-loop system are defined. The predictions that provided the impetus for the simulation investigations are presented.

Definition of Latency

Latency associated with a system component can be viewed as a pure time delay between some input or change and the corresponding output. Avionics system latency can be defined as the time delay between aircraft motion and the corresponding indication of that motion on the aircraft displays. Based on this definition, the terms latency, time delay, and delay are considered equivalent and are interchanged throughout this paper.

Definition of Flying Qualities

The acceptability of aircraft dynamics and control characteristics can be quantified in terms of achievable mission task performance and resulting pilot workload. This quantification is typically performed using the Cooper-Harper pilot opinion scale shown in Figure 1.[1] Aircraft flying qualities evaluations and specification development are based on results obtained from the use of this scale tempered with actual task performance data. Military flying qualities specifications typically quantify acceptability in terms of flying qualities levels. Explicit in the definition of these levels is not only pilot workload, but also mission task performance as indicated in Figure 1.
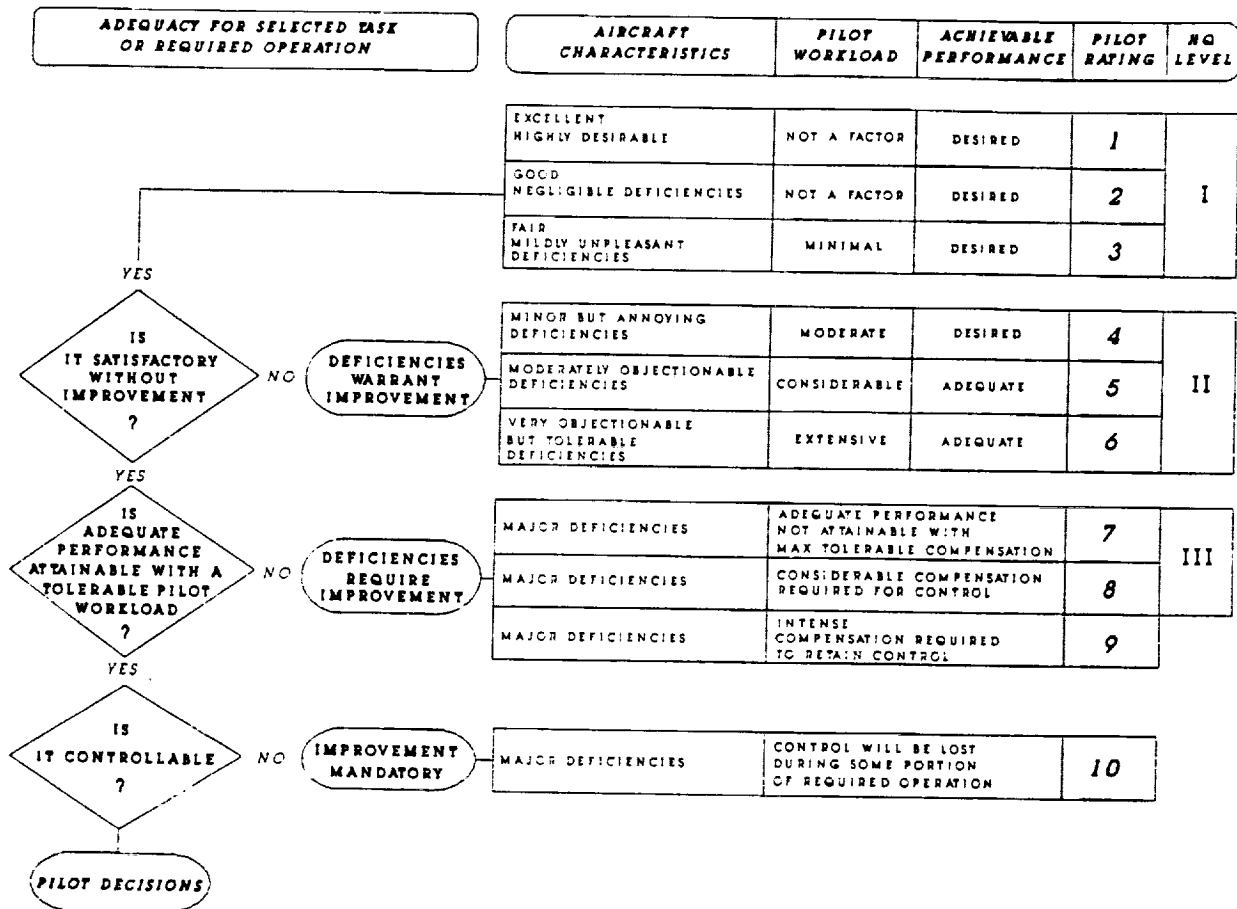
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Figure 1. Handling Qualities Rating Scale flowchart:

ADEQUACY FOR SELECTED TASK OR REQUIRED OPERATION

- IS IT SATISFACTORY WITHOUT IMPROVEMENT? — YES (up) / NO → DEFICIENCIES WARRANT IMPROVEMENT
- IS ADEQUATE PERFORMANCE ATTAINABLE WITH A TOLERABLE PILOT WORKLOAD? — YES / NO → DEFICIENCIES REQUIRE IMPROVEMENT
- IS IT CONTROLLABLE? — NO → IMPROVEMENT MANDATORY
- PILOT DECISIONS

AIRCRAFT CHARACTERISTICS	PILOT WORKLOAD	ACHIEVABLE PERFORMANCE	PILOT RATING	HQ LEVEL
EXCELLENT HIGHLY DESIRABLE	NOT A FACTOR	DESIRED	1	
GOOD NEGLIGIBLE DEFICIENCIES	NOT A FACTOR	DESIRED	2	I
FAIR MILDLY UNPLEASANT DEFICIENCIES	MINIMAL	DESIRED	3	
MINOR BUT ANNOYING DEFICIENCIES	MODERATE	DESIRED	4	
MODERATELY OBJECTIONABLE DEFICIENCIES	CONSIDERABLE	ADEQUATE	5	II
VERY OBJECTIONABLE BUT TOLERABLE DEFICIENCIES	EXTENSIVE	ADEQUATE	6	
MAJOR DEFICIENCIES		ADEQUATE PERFORMANCE NOT ATTAINABLE WITH MAX TOLERABLE COMPENSATION	7	
MAJOR DEFICIENCIES		CONSIDERABLE COMPENSATION REQUIRED FOR CONTROL	8	III
MAJOR DEFICIENCIES		INTENSE COMPENSATION REQUIRED TO RETAIN CONTROL	9	
MAJOR DEFICIENCIES		CONTROL WILL BE LOST DURING SOME PORTION OF REQUIRED OPERATION	10	

Figure 1. Handling Qualities Rating Scale

MIL-F-83300[2] and MIL-F-8785C[3] have been used to define the flying qualities requirements for many military V/STOL aircraft. These requirements are established with respect to the flying qualities levels as defined above. Most Navy aircraft in normal state conditions are required to exhibit Level I flying qualities. This level of flying qualities is required even during the more demanding tasks intended to be flown and in the more adverse environments expected to be encountered. In general Navy aircraft will be required to perform routine and tactical flight operations satisfactorily (including high-speed terrain following flight and shipboard operations) in adverse weather and combat conditions.[4]

General Latency Effects and Flight Control System (FCS) Latency Specifications

The effect of time delays on flying qualities is common knowledge in the flying qualities community. In summary, data from numerous experiments indicates that time delays reduce closed-loop system stability, thereby increasing pilot workload and degrading task performance. These data further indicate that latency will have an increasingly detrimental effect as task difficulty, aggressiveness and precision requirements are increased.

The data referenced above was generated in experiments designed to identify the effects of FCS latency and has been used to define FCS latency limits. Shown in Table 1, these limits have been associated with handling qualities levels and incorporated into military flying qualities specifications. [2,3]

Table 1. FCS Delay Specifications

Specification	Requirement	
	Flying Qualities	Time Delay
MIL-F-83300	Level I	≤ 100 ms
MIL-F-8785	Level I	≤ 100 ms
	II	≤ 200 ms
	III	≤ 250 ms

REF

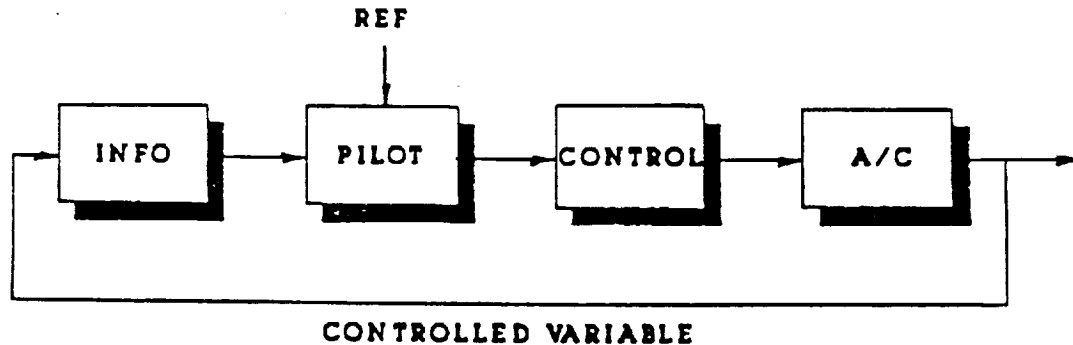INFO → PILOT → CONTROL → A/C →

CONTROLLED VARIABLE

Figure 2. Standard Closed-Loop System

The time delay limits shown are typical of delay limitations associated with high difficulty/high gain/high precision tasks and may appear conservative. However, it should be noted that most experiments used to support these limits have investigated delay effects with delays inserted in only a single axis of control. Delays in all axes, which is more representative of a real system may result in an even more severe degradation than that indicated above. In this sense, the specifications may be liberal.

Definition of a Closed-Loop System

A simplified closed-loop system is illustrated in Figure 2 and includes airframe, control, pilot and information components. A typical loop closure will involve pilot control of an aircraft state or flight parameter. During control, the pilot will attempt to minimize the difference or error between a reference or desired value of the selected state and the actual or perceived value of the selected state. Information on the reference value, controlled parameter and the error between the two will be available to the pilot through outside world visual cues, motion cues and displays. To close the loop, the pilot will apply control proportional to the error.

As an example, consider a precision approach to a ship. The pilot's goal is to track the instrument landing system (ILS) beacon, both vertically (glideslope) and laterally (localizer), with precision sufficient to allow a safe landing. Outer loop control is accomplished with closure around the pilot's reference parameters, glideslope angle, localizer and recovery heading. Inner loop control is accomplished with closure around descent rate, airspeed, and pitch and roll attitude.

Since precise glideslope and localizer error are available only from the displays, the displays can be considered the primary source of information in the above task. This is clearly the case during an approach with degraded visibility, where the displays are the pilot's only reliable source of flight

information.[5] Under these circumstances, the pilot would find it difficult, if not impossible, to distinguish between display dynamics, control dynamics and airframe dynamics. The effect of a delay in displayed information could, therefore, be considered equivalent to the effect of an airframe or control delay of the same magnitude.

The most severe delay-induced degradations in flying qualities are expected during high difficulty, high gain, high precision tasks requiring the use of displays as the primary source of flight information. In particular, the concern lies with the performance of manual, high frequency, precision control of aircraft attitude, position and vertical speed in degraded visual conditions (instrument meteorological conditions (IMC), visual meteorological conditions (VMC) with an obscured horizon, and night VMC). Under these circumstances, the head-down displays or helmet-mounted displays would most likely be used to provide the required flight information, either alone or superimposed on a Forward Looking Infra-red (FLIR) image.

FLIGHT SIMULATION INVESTIGATIONS AND RESULTS

Two manned flight simulations, one in an engineering simulator and one in a high fidelity developmental simulator, were conducted to generate data specific to avionics or display system latency effects on aircraft flying qualities. The first, conducted in a basic engineering simulator to generate initial data, simulated avionics system latency which was swept from 47 ms to 447 ms. The second, conducted in a high fidelity developmental simulator to produce high quality data, was conducted with latency values varying from 70 ms to 240 ms.

A precision approach task was selected as the primary task for the simulation. Performance constraints were established based on mission or safety requirements. Adequate performance constraints were based on maximum safe or

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acceptable spatial deviations. Desired perform-
ance constraints were established as limits reflect-
ing a desired margin of performance or safety
beyond adequate performance constraints. The
tasks and the corresponding performance con-
straints are described below.

Unless specified otherwise, "Latency", "Delay",
"Display Delay" and are used in short for "Avionics
System Latency" in the following text.

Engineering Simulation

Simulation Facility

This investigation utilized a fixed-base engineering
research simulator. This simulator employs stan-
dard fixed-wing controls: center stick, pedals, and
throttle. The computer generated outside-world
image is projected onto a single, forward screen.
For this investigation, primary flight information
was superimposed on the outside-world image in
a standard uncluttered format. This format pres-
ented glideslope as a fly-to horizontal bar and
localizer as a fly-to vertical bar. Range and
airspeed data were digitally represented. The
symbology is shown in Figure 3.

The aircraft model used was a generic medium
weight, medium agility fixed-wing aircraft with level
I baseline handling qualities.

Evaluation Task

The primary task consisted of a precision
approach on a 3.5 degree glideslope to a ship.
Environmental conditions were extremely limited
visibility and crosswinds up to 45 kt. Direction and
magnitude were selected at random, prior to each
evaluation run. The initial conditions were glides-
lope (GS) and localizer (LOC) offsets of 1 degree
and 5 degrees, respectively. These were
combined randomly to result in four initial posi-
tions: above GS and left of LOC, below GS and
right of LOC, etc.. Range at the initial position was
24000 ft. Trim approach speed was 128 kt.

The pilot was instructed to capture GS/LOC prior
to reaching a 15,000 ft range and to track GS/LOC
to 1,500 ft range within the following performance
tolerances:

Desired	Adequate
± 5 kt	± 10 kt
± 1/4 degree GS	± 1/2 degree GS
± 1 degree LOC	± 2 degrees LOC

A given level of performance was to be maintained
for at least 80-percent of the approach (between
15,000 and 1,500 ft range) for that level to be
considered achievable during evaluation.

A secondary task was used to examine the effect
of side task workload on primary task perform-
ance. This secondary task consisted of the pilot
physically setting and verbally repeating the
barometric altitude pressure reference to random
values called by the engineer every 3000 ft range
(with the last call made at 4000 ft). No degrada-
tion in performance was tolerated in this task.

Latency Matrix and Evaluation Technique

Limited by hardware, minimum achievable simu-
lated delays were 57 ms flight controls (from stick
displacement to aircraft motion) and 47 ms
displays (from aircraft motion to head-up display
update). The matrix of delay configurations evalu-
ated is shown in Table 2.

Table 2. Delay Evaluation Matrix

Flight Control Delay (ms)	Display Delay (ms)
57	47
	167
	327
	447
107	47
	167
	327
	447

Two Marine Corps operational test and evaluation
pilots performed as evaluation subjects. Each
pilot was given between four and eight hours
familiarization time. During evaluation, each pilot
was given as many runs as necessary to confi-
dently assess achievable task performance and
his workload. This technique resulted in as many
as eight flights per delay configuration evaluation
(single pilot rating). Further, each pilot evaluated
each configuration at least twice.

Results

Result are presented in the form of pilot ratings
and sample time histories of stick activity and
tracking error. Pilot ratings as a function of dis-
play delay are shown in Figure 4. Sample longitu-
dinal and lateral stick activity with glideslope and
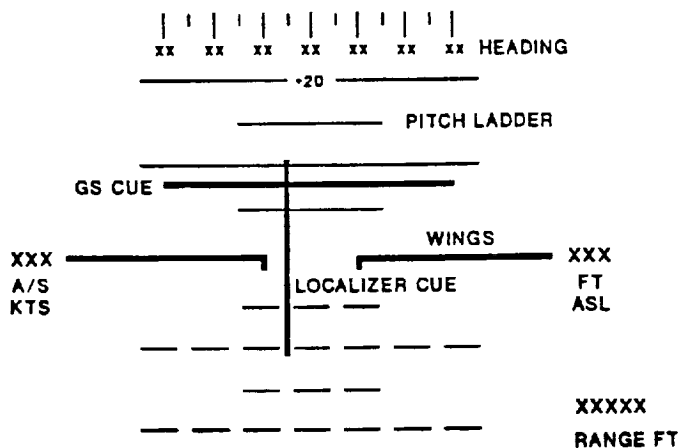localizer tracking error are shown in Figure 5 and
6, respectively.

Figure 3. Engineering Simulation Head Up Display
for Precision Approach

The engineering simulation study supported the
following conclusions:

a. No significant, quantifiable differences in
handling qualities were observable between
evaluations with 57 and 107 ms control delays.
As a result, the data for these control system
delay configurations were combined and
plotted together.

b. A handling qualities degradation with
increasing display delay, although shallow, is
observable. This trend, apparent in the pilot
rating data, is supported by stick activity and
actual tracking performance.

c. A transition from Level I to Level II occurs
between 47 and 167 ms display delay for the
primary task alone. A transition from desired to
adequate performance (HQR 4 to 5) for the
primary and secondary task also occurs
between 47 and 167 ms.

High Fidelity Simulation

Simulation Facility

The fixed-base simulator used in this investigation
employs a representative tilt-rotor cockpit with a
multi-window, high-resolution, computer-
generated, outside-world image. The simulator
mathematical model represents a low to medium
agility medium weight tilt rotor aircraft.

Evaluation Task

Again, the evaluation involved the performance of
a precision approach task. This task is similar to
that of the engineering simulation. The precision
approach task was flown at 85 kt (75° i_n) on a 3.5
degree glideslope. Environmental conditions con-
sisted of mild-to-moderate turbulence[3] with a mild
(10 kt) windshear (between 1000 and 100 ft AGL)
in addition to a moderate (20 kt) crosswind. A
ceiling was simulated at 300 ft AGL. A constant
altitude, 30 degree ILS intercept profile was flown
from the initial conditions. Tracking constraints for
evaluation were identical to those used in the
engineering simulation, with one exception. The
pilots were instructed to place emphasis on the
performance and the workload near decision
height, 200 AGL, which was the task termination
point.

The approach configuration flown was at 120 kt,
60° nacelle angle (i_n) and represented a nominal
combat or expedited recovery. Environmental
conditions were fixed with mild-to-moderate turbu-
lence, 10 kt windshear, 20 kt crosswind, 200 ft
ceiling. As illustrated in Figure 7, initial positions
were located at 5.9 nm range with randomly
selected offsets of 1 degree in glideslope and 5
degrees in localizer. The initial heading corre-
sponded to the recovery heading with a minor trim
adjustment for the crosswind.

The pilot was instructed to maneuver from his
initial position to intercept glideslope and localizer
by 4.8 nm range and to track glideslope and local-
izer to decision height (300 ft AGL). For evalu-
ation purposes the task began at initial glideslope
and localizer intercept and terminated at decision
height.

Tracking constraints were also similar to those
used in the engineering simulation, with additional
emphasis placed on the last half of the approach.
Because of the evolution of these constraints,
they are summarized in Table 3. Precision
approach flight symbology was mildly cluttered
with a vertical bar for localizer, and an arrow indi-
cator for the glideslope and is shown in Figure 8.
The above desired, geometric, GS and LOC
constraints corresponded to 1/2 of a display tic
and 2/3 of a display tic, respectively. Airspeed was
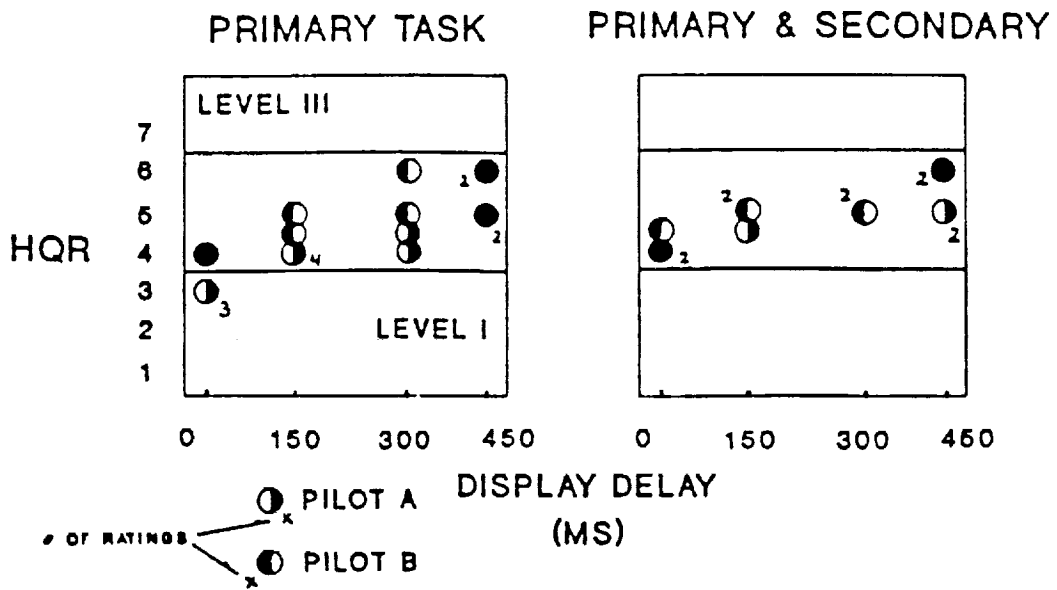indicated with a digital numeric display.

PRIMARY TASK   PRIMARY & SECONDARY

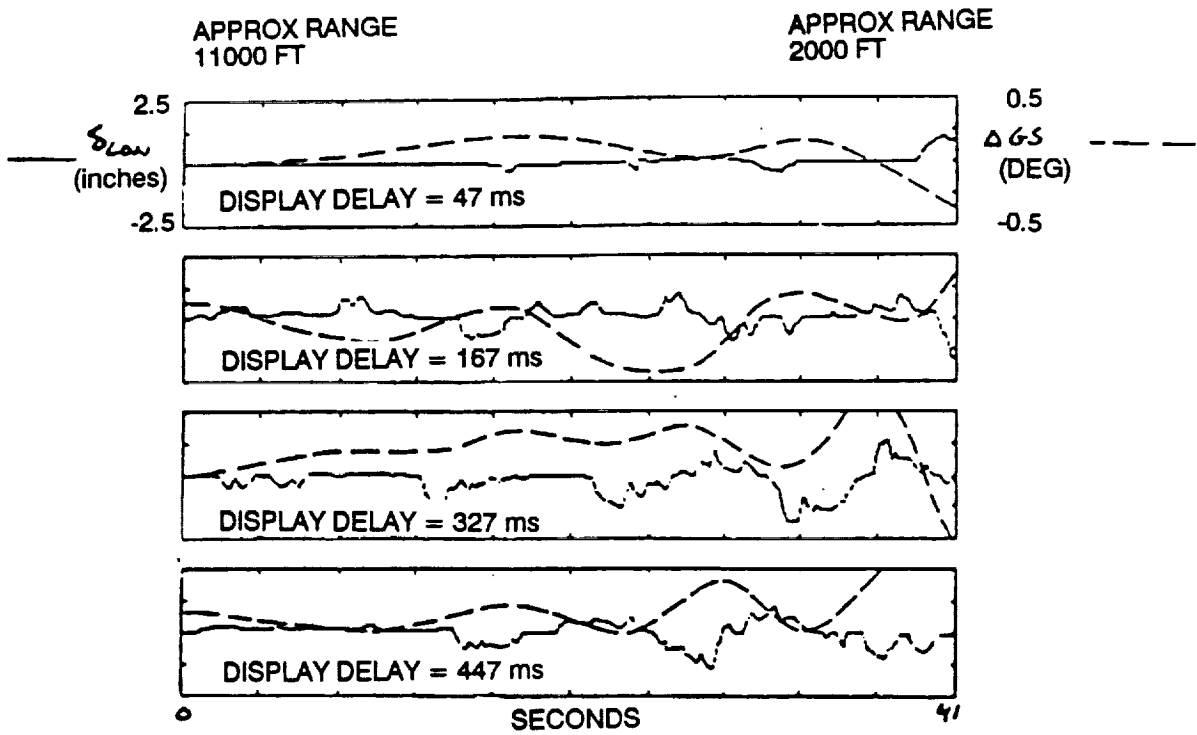Figure 4. Handling Qulaities as a Function of Display Delay - Engineering Simulation

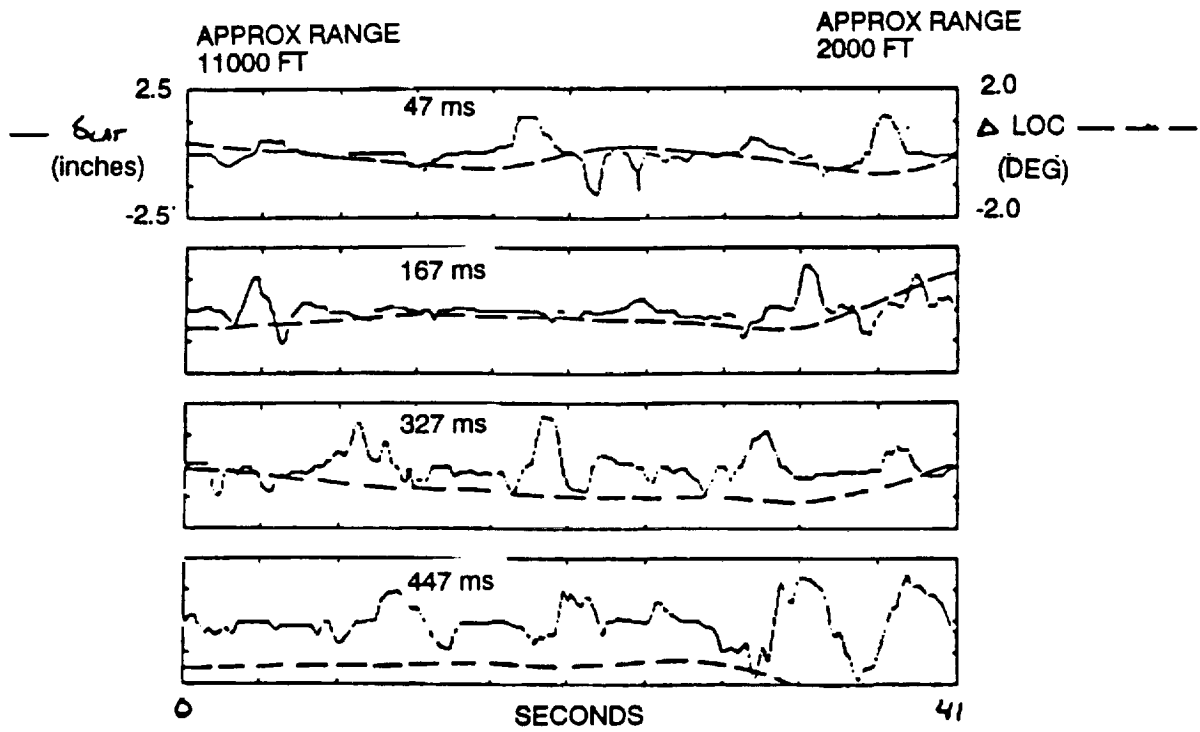Figure 5. Longitudinal Stick Activity and Glideslope Tracking Error - Engineering Simulation

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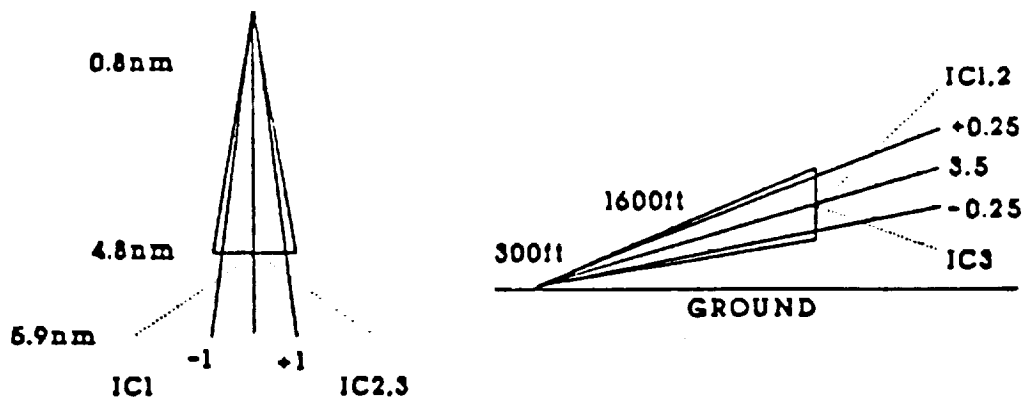Figure 6. Lateral Stick Activity and Localizer Tracking Error - Engineering Simulation

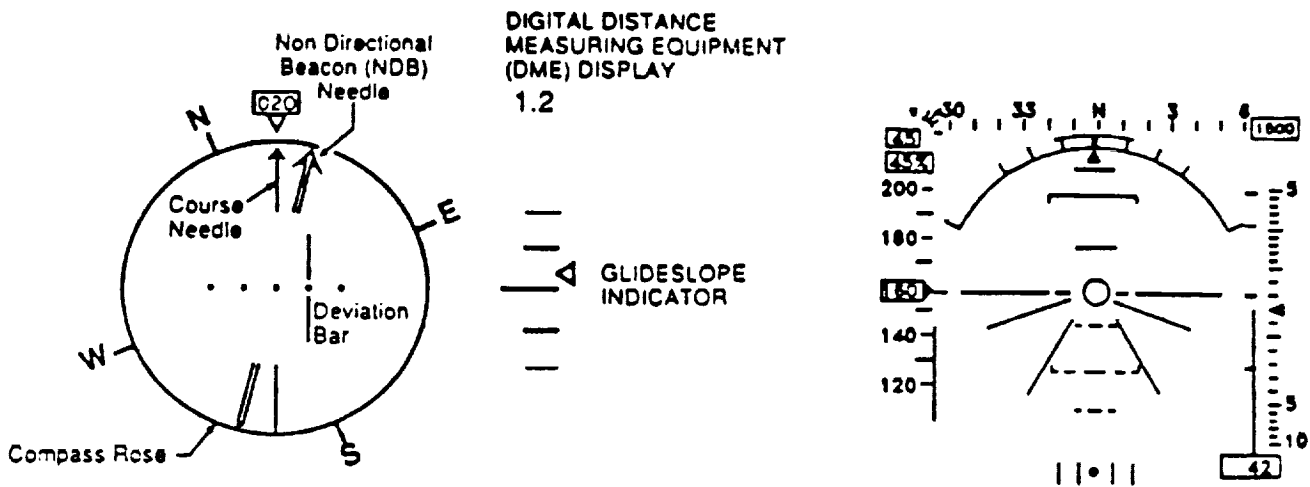Figure 7. Precision Approach Geometry

A) Horizontal Situation Display **B) Vertical Situation Display**

Figure 8. High-Fidelity Simulation Display - Simulated Precision Approach Mode

Table 3. Tracking Constraints

Geometry: Desired: ± 5 kt A/S
± 1/4 degree GS
± 1 degree LOC

Adequate: ± 10 kt A/S
± 1/2 degree GS
± 2 degree LOC

Time: - maintain given level of perform-
ance for at least 80% of task for
given level to be considered
achievable

- exceedance of adequate per-
formance constraints for 5 sec-
onds or more could not be
considered desirable

Emphasis: - performance and workload dur-
ing last half of approach (ap-
proximately 60 seconds, 1000 ft
to 300 ft AGL)

- performance and wor ' ad at
decision height

Latency Matrix, Pilots, Evaluation Technique

i. Latency Matrix - The FCS latency was fixed at 50 ms. Three display latency configurations (73, 179, and 241 ms) were evaluated.

ii. Pilots - Four military test pilots served as evaluation subjects. The pilots and their backgrounds are listed in Table 4.

Table 4. Government Pilot Evaluation Team

| PILOT A | 2100 HRS HELO (H-53)
250 HRS FW
HMX-1 OT+E 1 YR
V-22 SIM |
|---|---|
| PILOT B | 1900 HRS HELO (H-1)
1500 HRS FW (T-34)
HMX-1 OT+E 4 YRS
HQ EVAL EXPERIENCE
V-22 SIM |
| PILOT C | 4000 HRS HELO
1000 HRS FW
TPS RW INSTRUCTOR 2 YRS |
| PILOT D | 3400 HRS HELO (H-3)
400 HRS FIXED WING
TPS/RW
V-22 SIM + FLT |

iii. Evaluation Technique - Each pilot underwent extensive familiarization prior to evaluations. This familiarization was accomplished with the mini-

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mum latency and proceeded as follows. Each pilot took approximately 1 hour of free-flight without turbulence or wind to become familiar with the cockpit and math model. An additional 2 hours was taken by each pilot to fly approximately 20 precision approaches with and without turbulence and wind. During evaluations, the pilots provided an HQR following each run. A complete evaluation consisted of, at least, three runs. When both the pilot and the engineer were satisfied that the delay configuration had been adequately evaluated, the engineer informed the pilot that the delay configuration was to be changed and the next evaluation commenced. The pilot was not informed of the latency value during evaluations. Each pilot performed a minimum of two evaluations per latency configuration.

Results

Among all pilots, 254 approaches were flown during six days of simulation. Results presented here take the form of pilot ratings and tracking performance as a function of display delay. Pilot rating data is shown in Figure 9. Tracking performance, in terms of time outside desired glideslope envelope, weighted time outside desired glideslope envelope, and time outside adequate glideslope envelope, is shown in Figures 10, 11, and 12 respectively.

Localizer tracking and airspeed maintenance performance is not shown for the following reasons:

- with two exceptions in 254 runs, airspeed error was within desired performance constraints for all values of latency evaluated;

- even though lateral-axis workload seemed to increase as latency increased, no trend in localizer tracking error as a function of latency was apparent;

- glideslope tracking performance drove both pilot ratings and comments.

Returning to the glideslope tracking performance data shown in Figures 10, 11, 12, several issues are worth mentioning. First, these data represent the last 60 seconds of the task (from approximately 1000 to 300 ft AGL). Following the time constraints and evaluation emphasis specified, 12 seconds (20% of 60 seconds) can be considered the time constraint associated with desired performance. Any runs with excursions outside of the desired glideslope envelope beyond 12 seconds, during the last 60 seconds of the task, were considered to have, at best, adequate performance. Second, examining time outside of constraints as an isolated performance metric may be misleading if the magnitude of the angular excursion is inversely related to the time of the excursion. To examine this possibility, the time of the excursions were weighted by the corresponding magnitude of the excursions outside of the desired glideslope envelope. These weighted values are plotted in Figure 11. A trend similar to that of the

unweighted data exists. This indicates that time outside of constraints may legitimately be used as a measure of performance.

Finally, considering adequate performance (Figure 12) and following the time constraints and evaluation emphasis, 5 seconds can be considered the time constraint associated with adequate performance. With the time constraint defined, specifying that "exceedance of adequate performance constraints for 5 seconds or more could not be considered desired," any excursion beyond 5 seconds could legitimately be classified as either adequate or inadequate. Nearly all excursions outside of the adequate glideslope envelope occurred, however, just prior to decision height. The pilots, observing the emphasis on performance near decision height, typically classified the excursions beyond the adequate glideslope envelope of 5 seconds or more as inadequate.

Examining the results, one general observation can be made:

A handling qualities degradation with increasing display delay is apparent in both the pilot ratings and tracking performance.

The nature of this degradation and its applicability to defining an acceptable level of latency is discussed in the following section.

DEFINING AN ACCEPTABLE LATENCY LEVEL

When attempting to define a limit on any flying qualities parameter, several criteria may be considered:

- achievement of Level I handling qualities

- achievement of desired performance (note that achievement of desired performance does not mean that Level I handling qualities are achievable; Level II handling qualities (HQR 4) could result if workload is moderate or greater - see Figure 1)

- avoidance of inadequate performance

Regarding these criteria the results will first be considered in isolation. A discussion of the issues affecting the definition of delay limits will be discussed subsequently.

PILOTS ■ A ▨ B ▨ C ▢ D

70 ms DELAY

170 ms DELAY

240 ms DELAY

COOPER HARPER RATING
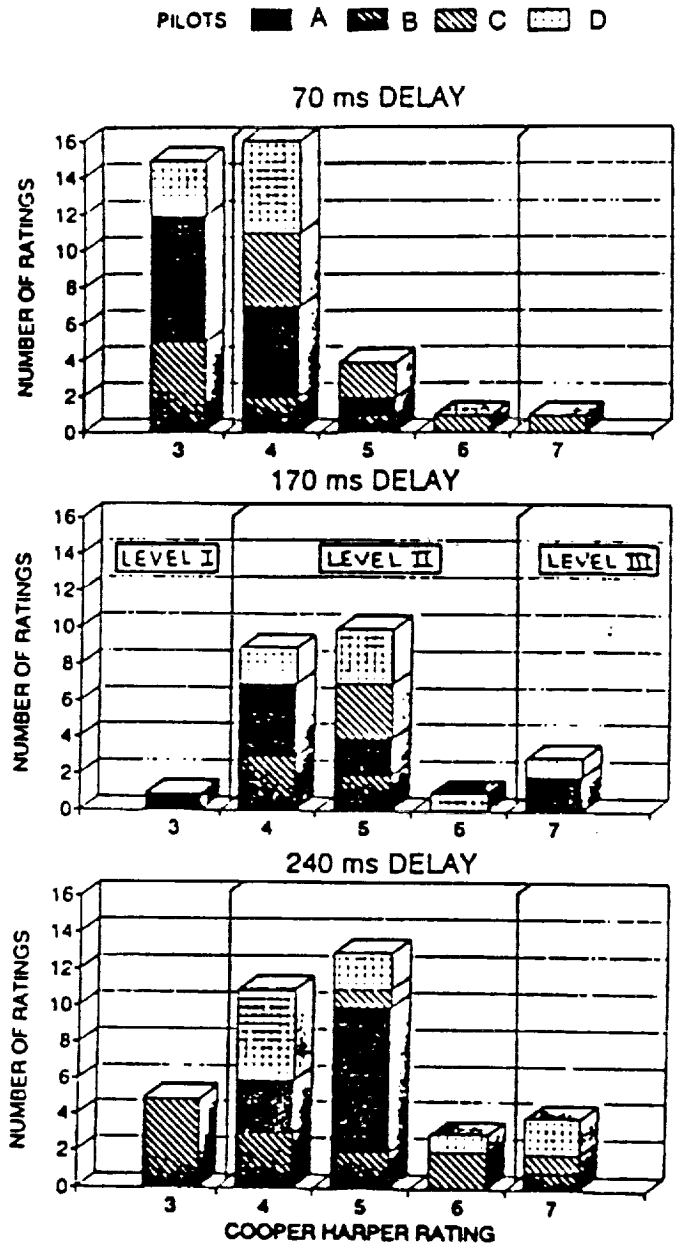
NOTE: The data shown above are the result of two modifications of the raw data. During the evaluation process pilots were permitted to give a rating of 4.5 for either of two reasons: desired performance was achievable with maximum pilot compensation only adequate performance was achievable but with minimal pilot compensation. Ratings of 4.5 with desired performance achievable and 4.5 with adequate performance achievable ᵥ ⁻ʳe redistributed to HQR 4 and 5 respectively. The other modification involved adjustment of ratings to reflect ᵣ   ,ponding actual performance. In this case, the minimal possible adjustments were made and only when the original   .ng clearly was not supported by actual performance. Here, 3, 1, and 8 ratings were adjusted at 70, 170, and 240 ms, ;   ,pectively. Neither of these modifica-tions altered the true nature of the results.

Figure 9. Handling Qualities Ratings for Precision Approach
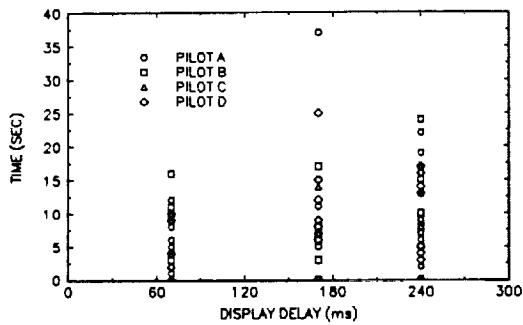
Figure 10. Tracking Performance - Time Outside of Desired Glideslope Envelope
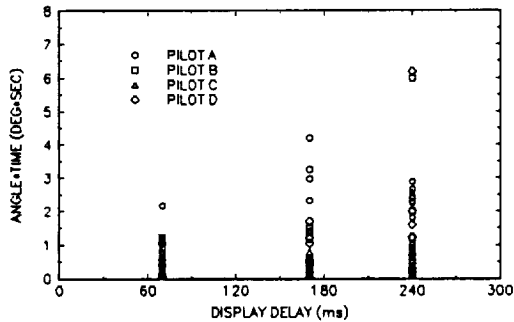

Figure 11. Tracking Performance - Weighted Time Outside of Desired Glideslope Envelope
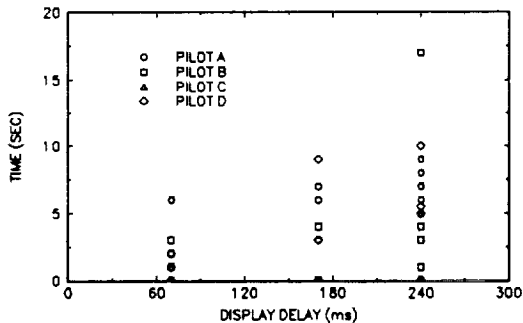

Figure 12. Tracking Performance - Time Outside of Adequate Glideslope Envelope

Achievement of Level I Handling Qualities

In applying the first criterion, pilot rating data (Figure 9) and performance data (Figure 10) must be examined. From Figure 9, it is apparent that, although there is a clear improvement in handling qualities between 170 and 70 ms, consistent Level I handling qualities are still not achievable at 70 ms. Further, from Figure 10, an improvement in

tracking performance through a reduction in time outside of constraints is apparent with decreasing latency. A continuation of this trend, although shallow, is reasonable to assume if latency were dropped below 70 ms. It may also be reasonable to assume based on the available data that, as latency is reduced below 70 ms, workload would first incrementally decrease and then level off at some baseline. Taken together, these observations and assumptions lead to the conclusion that reducing latency below 70 ms should result in consistent Level I handling qualities.

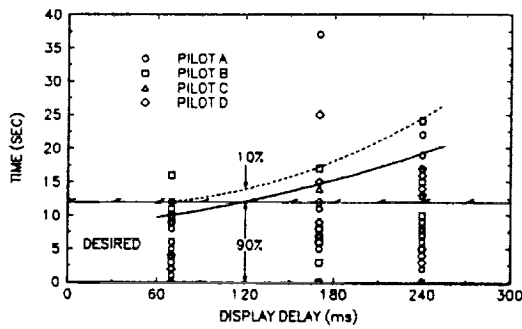## Achievement of Desired Performance

Workload is not a consideration when applying this criteria. Tracking performance may therefore be examined directly. For this purpose, time outside of the desired glideslope envelope as a function of latency is shown in Figures 13 A, B, C.

The probability bands in Figure 13 are defined by the worst 10, 20, or 30 percent of the main body of the performance data. Examination of these bands reveals the nature of latency effects on flying qualities. The following observations are made regarding achievement of desired performance.

- As latency increases, an increasing rate of performance degradation is apparent.

- Extrapolating the bands below 70 ms, very little performance benefit is expected with a latency reduction below 70 ms.

- If an increased probability of exceeding overall desired performance constraints is tolerable, then a higher latency is acceptable. As an example, if a 10-percent probability of exceeding desired constraints is tolerable, then a latency of 120 ms is acceptable. If a 20 percent probability of exceeding desired constraints is tolerable, then a latency of 170 ms is acceptable.
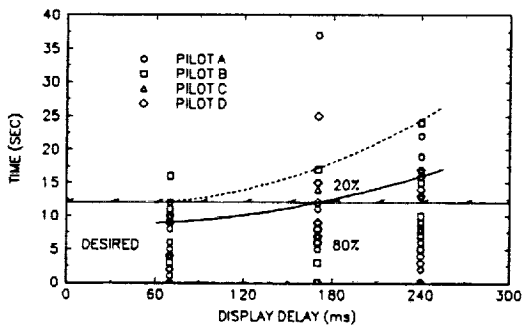
However, noting that there are significant occurrences of inadequate performance at 170 and 240 ms (see Figure 9), avoidance of inadequate performance must be considered.
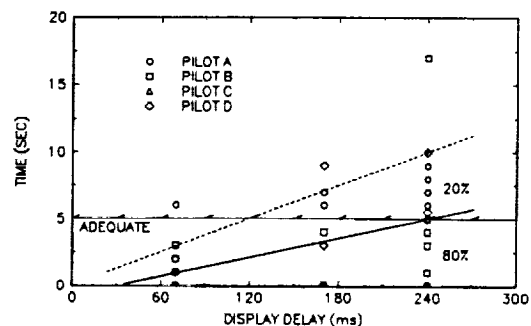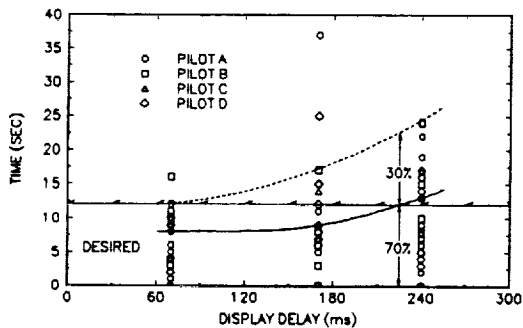
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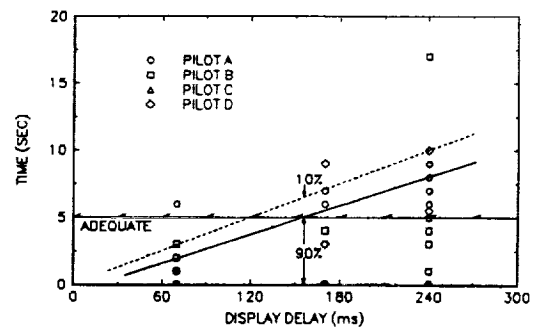
A) 10 percent probability

B) 20 percent probability

C) 30 percent probability

Figure 13. Probability of Exceeding Desired Performance Envelope for More Than 20 Percent of the Last Half of the Approach

Avoidance of Inadequate Performance

Tracking performance can also be examined directly in this section. Here, however, time outside of adequate glideslope envelope is used in the analysis. As in Figure 13, the probability bands shown in Figures 14 A and B are defined by the worst 10 and 20 percent of the main body of the performance data.

A) 10 Percent Probability

B) 20 Percent Probability

Figure 14. Probability of Exceeding Adequate Performance Envelope for More Than 5 Seconds During the Last Half of the Approach

Examination of these bands provides additional insight into the effects of latency on flying qualities. The following observations can be made regarding the avoidance of inadequate performance:

- A linear degradation in tracking performance and consistency with increased latency is apparent.

- Extrapolating the bands below 70 ms, a substantial performance benefit is expected with a latency reduction below 70 ms. This extrapolation indicates that below 10 to 20 ms no excursions outside of adequate constraints would occur.

- If an increased probability of exceeding overall adequate performance constraints is tolerable, then a higher latency is acceptable. As an example, if a 10-percent probability ~f exceeding adequate constraints is tc -.ile, then a latency of 150 ms is accepta⊦ . If a 20-percent probability of exceeding ⊥dequate constraints is tolerable, then a latency of 240 ms is acceptable.

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ISSUES AFFECTING DEFINITION OF A LATENCY LIMIT

Due to the origin and quantity of data used in the analysis, the following issues must be considered when applying the results of the previous section to definition of a latency limit:

- Data Quality

- Simulation vs. Actual Flight
  - Simulation Fidelity
  - Cues Available to the Pilot
  - Pilot Gain

- Severity of Task/Environment

- Training

Data Quality

The data used in the previous analysis were generated under controlled conditions using accepted flying qualities evaluation techniques. The evaluation pilot population was diverse and representative of the general pilot population. Minor adjustments were made to the pilot rating data to better reflect actual performance; actual performance data were used "as is."

A general qualitative check on both the experiment and data validity can be made by examining the trends in Figures 10, 13, and 14. These trends are what is physically expected from the effects of latency on tracking performance and workload.

Based on the above, the data used in the analysis are considered to be "high quality."

Simulation vs Actual Flight

Motion cues are not available in a fixed-base simulator. As a result, lead information available through actual commanded aircraft acceleration was not available. In the task used in evaluation this is not a factor for several reasons. First, tracking error information is only available to the pilot from the display. Motion cues do not provide any tracking error information. Even though motion cues aid inner-loop control this provides only marginal benefit in a primary visual tracking task[6]. Second, during precision approach in IMC, the displays are the only reliable source of flight information[5]. Anomalous aircraft motion cues, from both the pilot's head orientation and turbulence, force the pilot to rely on display information for an accurate assessment of the flight condition. A detrimental effect, if any, is expected due to the display latency induced mismatch between actual dynamics and display dynamics.

Finally, pilot gain would be higher in flight than in the simulator. Pilots would be less tolerant of tracking errors. This tolerance change would manifest itself through an increase in control activity. In turn, this increase in control activity would accentuate the effects of latency.

Therefore, given the same task, configuration and conditions, tracking performance and workload in flight are expected to be worse than that in the simulator.

Severity of Task and Environment

The precision approach evaluation task used was representative of a nominal combat or expedited recovery in IMC. This task should be able to be performed with Level I handling qualities. Potentially more demanding tasks such as terrain following or target tracking have not been explored.

The wind and turbulent environment can be classified as mild to moderate. Much more severe environments are frequently encountered in the field.

A lower limit than that associated with a nominal precision approach may be required to ensure satisfactory performance of potentially more demanding tasks or nominal tasks in more severe environments.

Training and Pilot Compensation Techniques

Pilots, with sufficient training will develop delay compensation techniques. In compensation, the pilot would reduce his input magnitude and frequency. This technique would not only allow the aircraft and display to respond, but also limit the response magnitude to a controllable level. This technique, by its nature prohibits high frequency precision control, and requires the acceptance of task performance degradations.

Another technique that can be used is lead compensation. This technique involves an initial control overshoot by the pilot to quicken the response followed by a reduced steady state input to limit the response magnitude. As with lead compensation implemented with the avionics or FCS, pilot lead is effective, but only over a given frequency range. Furthermore, this technique, by its nature, requires the pilot to stay in the control loop, with his energy split between two primary control frequencies, one associated with his application of lead (high frequency), and one associated with the fundamental task requirements.

Under normal conditions, pilot compensation can be effective. In emergency conditions or during sudden severe disturbances, the pilot tends to abandon compensation techniques instinctive control. Under these circumstances, the pilot will increase input magnitude and frequency in an attempt to retain control of his aircraft. This, however, accentuates the detrimental effects of latency and only aggravates the control problem. In the extreme, an aircraft with large delays, but readily controllable with appropriate pilot compensation, will become uncontrollable in emergency conditions or during sudden severe disturbances.

Negative training is also an issue. Although the compensation techniques described above can be effective with large delays, they can be detrimental if applied to a system with low delays. If compensation techniques used in IMC are retained in performance of a visual task, a degradation in task performance and increase in workload are expected.

Integrating the above issues, the net impact on the application of the simulation data is minimal. Any latency limit, based on analysis of the previously presented simulation data, is expected to be applicable to an actual production aircraft.

CONCLUSIONS

The results from the Navy simulations correlate well. These studies further indicate that performance and flying qualities degradations can be expected to occur with increasing avionics system latency. Considering the simulation data, several latency limits are suggested.

- 70 ms or below to ensure Level I handling qualities.

- 120 ms or below to ensure desired performance (with a maximum 10-percent probability of exceeding constraints).

- 150 ms or below to ensure the avoidance of inadequate performance (with a maximum 10-percent probability of exceeding adequate performance constraints).

These limits were established from analysis of data generated during simulation where the flight control latency was 50 ms. If actual flight control latency differs significantly from 50 ms, the above limits must be examined from a system latency point of view.

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REFERENCES

1. Cooper, G.E. and Harper, R.P., *The Use of Pilot Rating in Evaluation of Aircraft Handling Qualities*, NASA TN D-5153, April 1969.

2. Anon., Military Specification, *Flying Qualities of Piloted V/STOL Aircraft*, MIL-F-83300, 31 Dec 1969.

3. Anon., Military Specification, *Flying Qualities of Piloted Airplanes*, MIL-F-8785C, 5 Nov 1980.

4. Anon., *Joint Services Operational Requirements, Joint Services Vertical Lift Aircraft*, 14 Dec 1982.

5. U.S. Department of Transportation, Federal Aviation Administration, Instrument Flying Handbook, AC 61-27C, 1980.

6. Jex, H.R., et al., *Roll Tracking Effects of G-Vector Tilt and Various Types of Motion Washout*, Fourteenth Annual Conference on Manual Control, NASA Conference Publication 2060, November 1978.

7. Clement, W.F., et al., *Systematic Manual Control Display Design*, 13th AGARD Guidance and Control Panel Symposium, Paris, France, Oct 1971.

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