Effect of Head-Up Display Dynamics on Fighter Flying Qualities

Randall E. Bailey*
Calspan Corporation, Buffalo, New York

A flight-test program was conducted investigating the effect of head-up display dynamic response characteristics on fighter aircraft flying qualities. The influences of computational time delay in the display system were addressed primarily. The aircraft motion response to cockpit control inputs remained satisfactory without improvement during the parametric display system delay variation. Three pilots were evaluation subjects performing up-and-away fighter maneuvering and power approach tasks. The data suggest that up to 250 ms of total display time delay can be tolerated before a significant degradation in flying qualities occurs for up-and-away flight tasks. For the power approach task, up to 300 ms could be tolerated before a degradation began. The importance of the motion and visual cues is stressed in highlighting the significance of display system time delay effects.

Introduction

THE head-up display (HUD), once purely a visual "task" aide, has become a focal point in the "glass cockpit" technology aircraft. The head-up display is being adopted as a primary flight reference under instrument meteorological conditions. The steering group for night attack, as an advisory group for the introduction of the low-altitude navigation and targeting infrared system for night (LANTIRN), prioritized the head-up display as a critical technological element for this mission.[1] In this scenario, the flight is conducted essentially with sole reference to the cockpit display environment, and the HUD is a critical component.

The pilot's role in this scenario can be described by the functional diagram of Fig. 1. The pilot, as the controller in this system, receives feedback of the aircraft response through motion and visual cues. The visual cues are composed of those being derived from the real-world "outside-the-cockpit" visual environment and the cockpit instrumentation (head-up and head-down) environment. As shown in Fig. 2, the visual cue feedback is determined by the meteorological condition VMC or IMC (i.e., visual or instrument meteorological condition). The pilot-vehicle system, as a closed-loop dynamic system, is, therefore, significantly affected by the display system and its characteristics.

Under IMC, the head-up display provides the primary visual cues. The form, format, symbology, and content of the display primarily affects the ability (speed and accuracy) of the pilot to process the displayed flight information. The dynamic characteristics of the head-up display symbology are a part of the dynamic system under pilot control. HUD dynamics impact the pilot as the control element, the closed-loop system performance, and the apparent flying qualities of the vehicle. Because of this influence and the anticipated use of the HUD in critical flight phases, the effect of HUD symbol dynamics becomes important.

Experimental data for head-up display dynamic response requirements are sparse. This fact is apparent from the lack of dynamic response requirements in the military specifications for head-up displays.[2,3] The research, to date, regarding head-up displays for flying qualities primarily concerns the design of flight directors. These works (for instance, Ref. 4) have led to accepted design principles related to the "added" dynamics of the director symbology and the relationships (senses and orientation) between the display symbols and aircraft cockpit controllers. Although these studies are appropriate for head-up display design, flight directors cannot be used in all flight phases and tasks. Also, the dynamics driving the display symbology are often assumed to be "fast." These results are, therefore, appropriate but not all-inclusive.

In this paper, the results of an experimental investigation of HUD symbol dynamic response characteristics on flying qualities are described. This investigation was initiated to develop the requisite data foundation from which requirements on head-up display system dynamics for flying qualities can be generated.

Experiment Design

This investigation of HUD dynamic response requirements was part of an overall investigation to address several problem areas being encountered by operational HUD-equipped aircraft.[5] By providing experimental data and attendant research, the intent was to develop design criteria and guidance.

NT-33 Aircraft

This experiment was performed using the variable stability U.S. Air Force NT-33A aircraft. The NT-33 is a highly modified Lockheed T-33 operated by the Calspan Corporation's Flight Research Department as a 3 degree-of-freedom in-flight simulator.

The front cockpit of the NT-33 has been modified to include a variable response artificial feel system and a head-up display that is part of a programmable display system.[6] The evaluation pilot controls the aircraft through a full-authority fly-by-wire control system using a standard centerstick and rudder pedal arrangement. The system operator, in the rear cockpit, acts as the safety pilot and controls the head-up display and aircraft configuration.

Instrument meteorological conditions are effectively and safely simulated using a "blue/amber" system. The front canopy of the NT-33 is covered with an amber plastic; when the front-seat pilot lowers his blue visor, the complimentary colors produce an almost black outside environment. Flight,

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*Principal Engineer, Flight Research Department, Advanced Technology Center. Member AIAA.

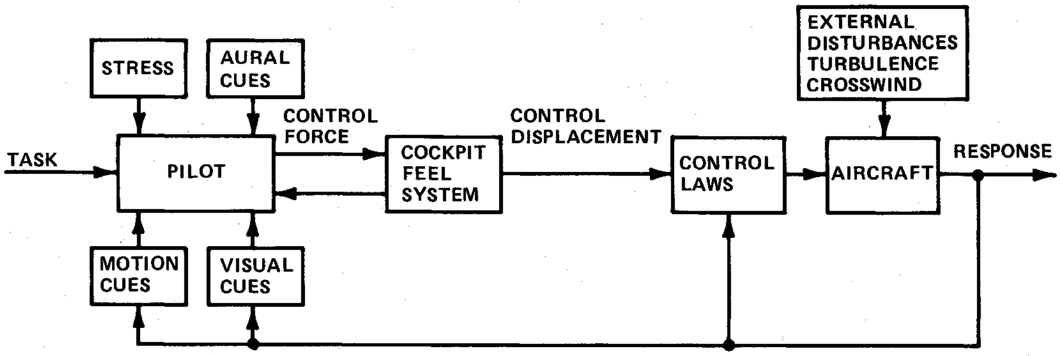


Fig. 1 Pilot-vehicle dynamic system.

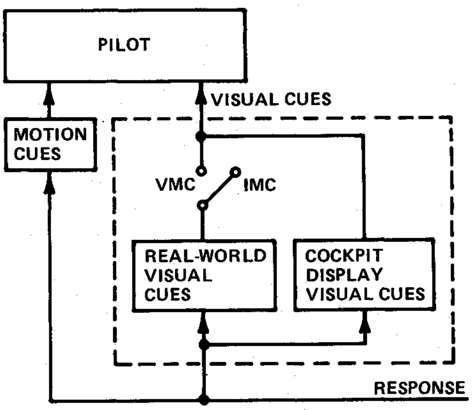


Fig. 2 Visual and motion feedbacks to pilot.

in this case, can be conducted by the evaluation pilot solely with reference to the HUD and cockpit instruments.

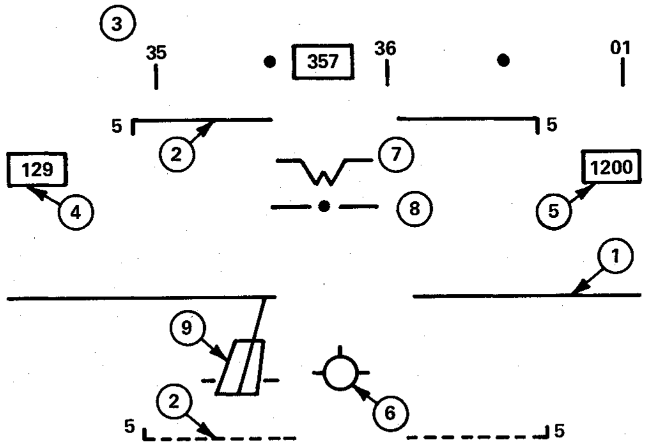
DEFT System

The display evaluation flight-test (DEFT) system was used to provide the requisite head-up display system variations for this program. The DEFT system is composed of a head-up display mounted in the front cockpit, a Rolm 1602 computer processing unit, and a Kaiser programmable display generator. Associated with this programmable display system are the appropriate aircraft motion sensors including a Litton-51 inertial navigation unit (INU). This experiment was an evaluation of head-up display dynamics; the HUD optics, field of view, and design eye point were neither varied nor experimentally evaluated.

A "generic" display format was established as the baseline. This format is sketched in Fig. 3 for the up-and-away flight phases. The design contains several features similar to or the same as the F-18 head-up display. The primary features of this display are 1) digital airspeed, altitude, and heading with heading "tape," 2) 1-to-1 pitch ladder scaling marked in 5-deg increments, and 3) flight-path marker (FPM) and waterline with declutter and lateral caging options.

A command bar, programmed as a target for simulated air-to-air tracking, provided a pitch and roll attitude command in a compensatory tracking task. When the task was not being performed, the command bar was not displayed.

For the power approach evaluations, a contact analog runway symbology (Fig. 3) was drawn for landing guidance. The contact analog display attempts to replicate the outside-the-cockpit visual runway scene. The runway outline changes size and shape to give the same perspective cues as a normal visual approach. Flight director-type guidance is not necessary since the pilot develops the required compensation naturally as he does when flying a visual landing. Presenting this



1. HORIZON LINE
2. PITCH LADDER (1:1 PITCH LADDER)
3. HEADING SCALE
4. INDICATED AIRSPEED
5. BAROMETRIC ALTITUDE
6. FLIGHT PATH MARKER (CAGED IN AZIMUTH AT PILOT OPTION)
7. WATERLINE (PITCH MARKER)
8. COMMAND BAR FOR HUD TRACKING TASK (IF SELECTED)
9. RUNWAY OVERLAY WITH GLIDESLOPE (IF SELECTED)

Fig. 3 Sketch of HUD format.

runway display head-up gives an additional advantage in that there is no transition from head-down to head-up for the flare and landing. The pilot does not need to cross-check between head-down and head-up for breakout. The contact analog runway shows explicitly where the pilot needs to look for the actual runway.

Experiment Configurations

The experiment variables required to satisfy the objectives of this program were 1) head-up display dynamics, 2) aircraft configuration, and 3) evaluation task.

Several aircraft configurations were simulated using the variable stability capabilities of the NT-33. The aircraft configurations consisted of variations in short-period frequency in the up-and-away flight phase. To place these configurations into the perspective of the military flying qualities specification,[7] an equivalent systems analysis[8] was performed. Using an upper limit of 10 rad/s for the frequency range of interest, the pitch and roll flight control system dynamics are shown to contribute approximately 80 ms of equivalent time delay. This value of time delay is below the current Level 1 requirement of 100 ms. The short-period frequency variations were within the Level 1 region of the MIL-F-8785C requirement, but span a wide range of response characteristics. The correlation of the three up-and-away configurations with the MIL-F-8785C short-period requirement is shown in Fig. 4. For the power approach flight phase, only one aircraft configuration was used. This configuration provided Level 1 flying qualities characteristics in accordance with MIL-F-8785C requirements.

In this investigation of dynamic response requirements, the hardware interfaces between the motion sensors and display processing unit, and between the individual display system, elements were not modified. Dynamic response variations were implemented in the display processor software.

The primary focus of this investigation was on the effect of added computational time delay in the head-up display system.

Variations in computation time delay were provided by adding a table shifting routine in the display processor input routine. The delay values were integer multiples of the 50-Hz frame time of the display processor. This mechanization simulated a "pure" transport time delay. The additional delay affected all HUD symbols that simulated a uniform computational delay of the display system. This experimental delay was in addition to any dynamic components of the nominal display system.

The dynamic elements in the signal path between the motion states and head-up display presentation constitute the display dynamic response characteristics. For this experiment, the dynamic response elements were comprised of high-frequency analog motion sensors, analog conditioning and antialiasing filters, and digital computing/processing elements related to the head-up display. In an attempt to quantify the effect of these elements, an "equivalent-systems" approach was employed. Since these elements are all of high frequency compared to the frequency range of interest to the pilot, these display system elements are assumed to be well-characterized as an equivalent time delay only.

The equivalent time delay, thus, approximates 1) phase lag contributed by high-frequency analog filters, 2) digital computation delay, and 3) "sampling" delay.

Under this assumption, the nominal display system contained approximately 65 ms equivalent delay. The experimental time delay was added in addition to this "irreducible" delay.

In calculating the equivalent delay for the display system, the assumption we made that the equivalent time delay due to sampling is equal to one-half the samping interval. Display input parameters are sampled at a 50-Hz rate for head-up display. The additional experiment delay was added downstream of the discrete sampling process. A sampling delay is not, however, the same as a pure time delay. For example, a pure computational delay and sampling delay are illustrated in Fig. 5. The pure delay recreates the input exactly, but is shifted in time. The sampling process produces temporal and amplitude distortion of the input signal. The assumption is that a 50-Hz sample rate is not affecting the amplitude response of the input signal. Hence, the discrete nature of the signal is not noticeable to the pilot so that the equivalent, pure delay is a good approximation. Slower sample rates may not necessarily be well-approximated by an equivalent delay. Also, different types of sampling schemes other than a sample-and-hold device affect this assumption.

The experimental setup for the flight control and display systems is shown in Fig. 6 using pitch attitude as a typical parameter. From a cockpit control force input, the aircraft pitch attitude (motion) response occurred after an 80-ms equivalent delay. Because of the analog and digital processing, this pitch attitude is displayed (the "visual," HUD response) 65 ms subsequent to the motion response. The total delay between HUD response and stick input is, thus, 145 ms plus whatever delay was experimentally added in the display system. Note that the 80 ms motion response time delay was held constant.

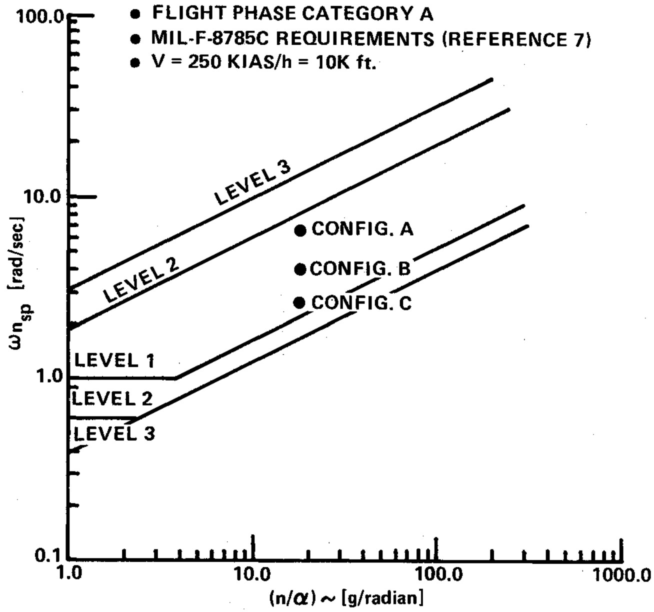


Fig. 4 Up-and-away fighter configurations.

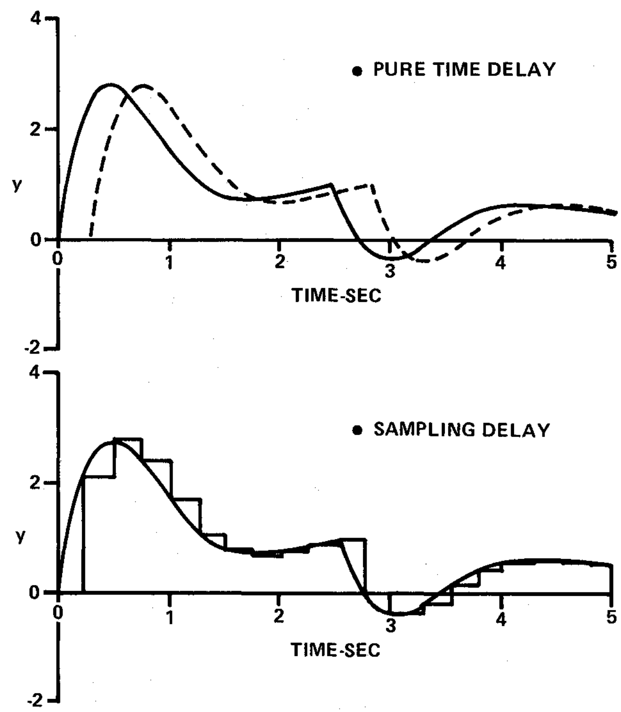


Fig. 5 Digital sampling and computational (pure) time delay illustration.

The final experiment variable was the evaluation task. Two flight phases were simulated: up-and-away and power approach. The up-and-away evaluation consisted of several maneuvers each emphasizing different maneuver amplitudes, attitude references, and meteorological conditions.

An up-and-away evaluation consisted of four tasks:

Target Tracking (IMC)

1) Task provided by display of target command bar.

2) Waterline marker used as aiming symbol.

3) The command bar is moved through a programmed series of step and ramp pitch and roll commands.

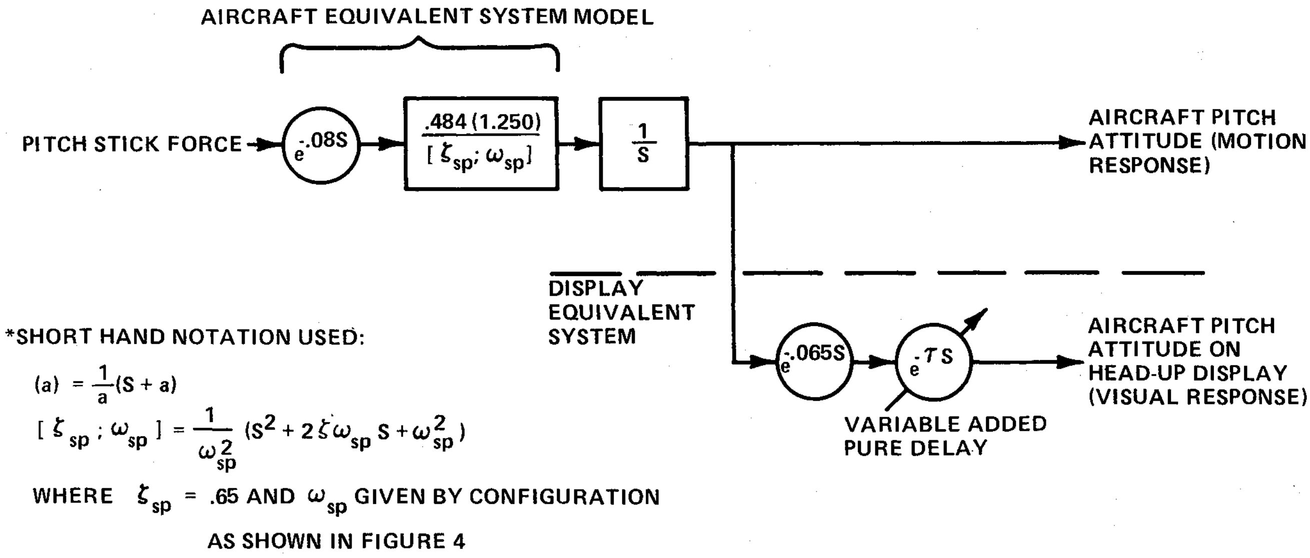


Fig. 6 Experimental setup using equivalent system model description (pitch attitude response shown as example).

4) The pilot's task is to keep the pipper (waterline) aligned with the command bar. The sense of the target is "fly-to." The tracking task lasted approximately 90 s.

Air-to-Ground (VMC)

1) Pitch down to the target dive angle using waterline as flight reference; stabilize.
2) Acquisition and tracking of ground target.
3) Acquisition and tracking of another ground target located approximately 50 mrad.
4) Break to a 2.5-*g* pullup with return to 10,000 ft.

Modified Clover Leaf (IMC)

1) Begin at 300 knots indicated airspeed (KIAS), 10,000-ft above ground level (AGL).
2) 2.5-*g* pullup to 45 deg pitch attitude.
3) Roll and pull so as to pass through the horizon, inverted, with 90 deg of heading change.
4) Pull to 30 deg nose-down.
5) Roll wings level.
6) Recover at 300 KIAS, 10,000-ft AGL.

Pop-Up Weapons Delivery (IMC)

1) Begin at 300 KIAS, 10,000-ft AGL.
2) 2.5-*g* pullup to 25 deg flight-path angle.
3) Hesitate, then wingover so as to arrive with 60 deg of turn in a 27-deg dive.
4) Maintain precise dive angle.
5) Roll wings level.
6) Pull to level flight.
7) Hard, level 90-deg turn.

Each maneuver emphasized different maneuver amplitudes, attitude references, and meteorological conditions. Performance standards were established accordingly.[4]

For power approach configurations, the evaluation consisted of an instrument loading system (ILS) approach under simulated IMC to decision height. The HUD was used as the primary flight reference. At least two approaches were flown in each evaluation. The decision height was varied as part of the experiment from 200- to 40-ft AGL. Typically, a 100-ft decision height was used.

Each approach was dictated as a "must land" situation. The evaluation pilots did not have any prior knowledge of the simulated configuration characteristics.

Flight-Test Results

After performing the evaluation sequence for each configuration, the pilot gave an overall task Cooper-Harper pilot rating[9] and attendant pilot comments. The data from this experiment consisted of pilot ratings, pilot comments, and task performance records.

Flight Summary

This program, consisting of 36 flights and 96 evaluations, was conducted from the Calspan Flight Research facility in Buffalo, New York, during October 1985 and January 1986.

Five pilots participated in this study. The three primary evaluation pilots were from the U.S. Air Force/Instrument Flight Center at Randolph Air Force Base, Texas. These pilots were not trained test pilots. Their flight experience consisted of over 2500 h total time, and their HUD flight experience ranged from naive to over 100 h in the HUD-equipped aircraft.

Effect of Added Display Time Delay—Up-and-Away

For the "up-and-away" configurations, four maneuvers comprised an entire evaluation. An overall Cooper-Harper pilot rating was given following completion of these tasks.

The overall pilot ratings are shown as a function of the added display time delay in Fig. 7. Mean pilot rating and standard deviations were calculated and are used to illustrate flying qualities. A trend line is drawn showing an estimate of the flying qualities degradation with added display time delay based on a least-squares fit to the raw rating data. The pilot rating data are not shown with regard to the aircraft configuration characteristics, although three different up-and-away configurations were flown. The pilot rating and comment data did not reflect a significant influence of configuration response characteristics.

For the up-and-away configurations, the pilot rating and comment data indicate the following:

1) As the computational delay for head-up display processing increased, flying qualities reflected by the Cooper-Harper pilot ratings (PR) degraded after an apparent threshold. Below this threshold (approximately 250 ms delay) the display dynamic response characteristics were only slightly worse than the nominal no-added delay system. The pilot rating data suggest borderline Level 1 ($PR < 3.5$) to Level 2 ($3.5 < PR < 6.5$) flying qualities below 250 ms added display delay. Flying qualities degraded markedly beyond the 250 ms display delay value. Level 3 ratings ($PR > 6.5$) were given for 320 ms of added display delay.

2) The overall task ratings were primarily based on the pilot compensation/workload and task performance in the simulated air-to-air gun tracking. To a lesser degree, the ratings were also based on the subjective opinion as to the degree by which the display characteristics were deficient. As display time delay increased, "bounce" in the pitch ladder and lag in the flight-path marker became more noticeable.

3) The added pure delay in the head-up display did not significantly affect performance or flying qualities for the large-amplitude maneuvering tasks (modified cloverleaf and pop-up weapons delivery). Because aggressive pilot control was not required in these tasks, the effect of display time delay was relatively transparent to the pilot, except for pitch ladder bobbling and flight-path marker lag at the "corners" of these maneuvers.

4) Control was not in question for any of the configurations. Thus, the pilot rating range was essentially limited to a maximum of 7. Added display time delay, unlike added control system time delay,[10] did not evoke pilot-vehicle dynamic instabilities.

These results suggest that flying qualities are not significantly affected until 250 ms delay exists in the display system. This delay is in addition to the 80 ms of delay between the cockpit control input and aircraft motion response. The 80 ms "motion" delay was held constant and is below the Level 1 MIL-F-8785C time delay requirements.

Effect of Added Display Time Delay—Power Approach

The pilot rating data for the power approach task are shown in Fig. 8 as a function of display time delay. Mean pilot ratings are plotted with standard deviations about the mean illustrating the rating trends. A trend line is drawn based on these data. These data indicate the following:

1) Flying qualities do not degrade until after 300 ms of display time delay, as indicated by the rating data. The average pilot rating below 300 ms of display time delay was essentially Level 1 (PR < 3.5). The contact analog runway landing symbology was well-received. IMC landings to low-decision heights could be easily performed after only a little practice.

2) Ratings worse than Level 1 for display time delay less than 300 ms were given because of the limited HUD field-of-view in NT-33 aircraft. These are not shown in Fig. 8 because the ratings were unrelated to the dynamic response of the HUD. In the presence of a crosswind, the contact analog runway display will be offset from the center of the HUD. The NT-33 HUD has an approximately 16 deg instantaneous lateral field of view. For crab angles of greater than 7 deg, the runway display symbology can be blanked because of field-of-view limitations and the 1:1 conformal display. When this occurred, the evaluation pilots had to transition to alternative landing guidance in the approach. This issue and its solution were not a part of the experiment. The pilot evaluation for a configuration, irrespective of the dynamic response characteristics, reflected this field-of-view limitation, and poor ratings were assigned.

3) The degradation of flying qualities with display time delay was less severe in power approach than up-and-away flight. The pilot comments indicate that the pilot ratings were primarily determined by the pilot workload demands as display time delay increased. Added display delay amplified the "bouncing" and "wobbling" of the runway projection. This, consequently, increased the pilot workload to keep the display centered and maintain the approach course.

An angle-of-attack bracket was sometimes presented to the pilot in the landing evaluation. The available data suggest that with the angle-of-attack bracket displayed, the tolerable level of added delay in the task decreased. The data are not sufficient to establish this observation definitely, however. The angle-of-attack bracket highlighted the bouncing characteristics of the display with added time delay. Similarly, turbulence precipitated flying qualities degradation. Turbulence level during the inflight evaluations could not be experimentally controlled.

The influence of the evaluation task is also evident in these data. The power approach evaluation task was the instrument approach with a visual landing made after instrument breakout. The visual delay experiment was, in actuality, only evaluated in the IMC approach phase. In Ref. 11, it was noted that the effects of added (motion) delay were most dramatic in

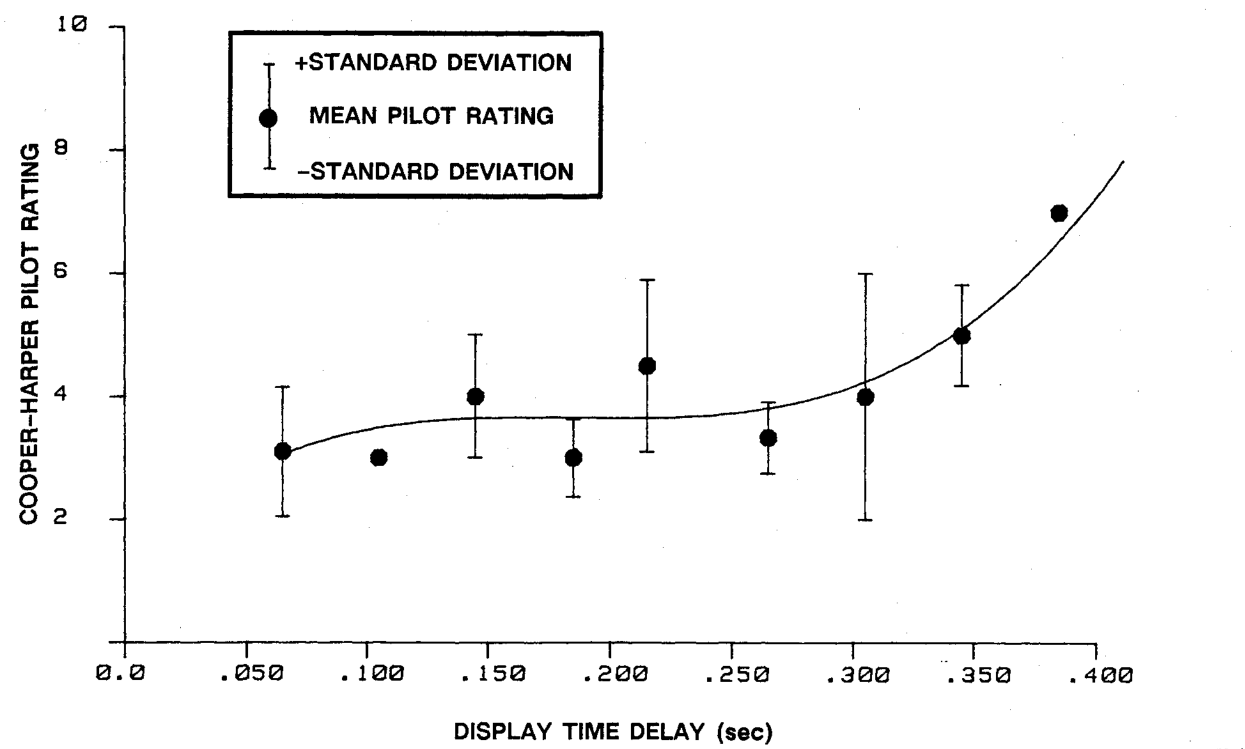


Fig. 7 Pilot rating data for up-and-away evaluation tasks.

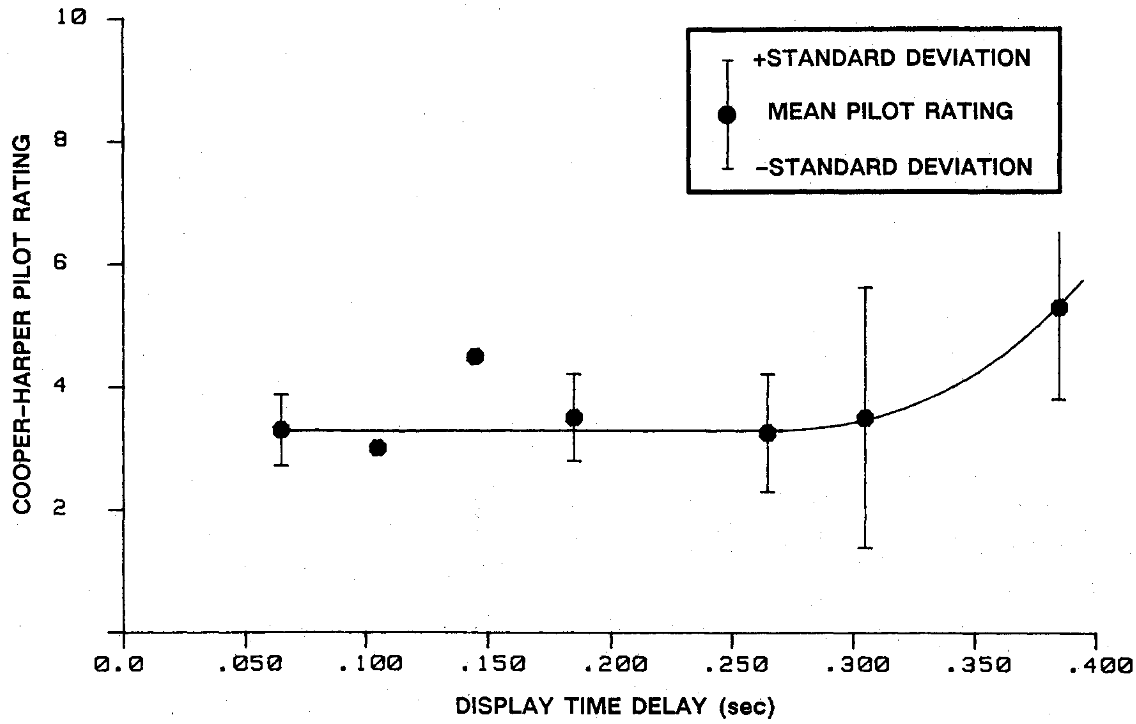


Fig. 8 Pilot rating data for power approach evaluations.

the final 50 ft to landing when the pilot's control task becomes critical (high stress). In this program, the effects of delay added to the display were evaluated only on the approach course to breakout. Consequently, the flying qualities degradation with display delay would not be expected to be as severe as a demanding task, such as the up-and-away gun tracking task. The effects of turbulence have been noted to be significant, however, and must be considered in this case.

Pilot-Vehicle System Implications

Considerable research has been expended in the investigation of the effects of control system time delay on flying qualities (e.g., Refs. 10–13). The apparent 250 ms threshold in allowable display system time delay for the up-and-away evaluations contrasts these previous works from which the 100 ms MIL-F-8785C time delay requirement evolved. Control system time delay has been shown to significantly impact the pilot-vehicle dynamic system. Flying qualities have been demonstrated to degrade from Level 1 to Level 2 by 100–150 ms of control system time delay with pilot-vehicle instabilities occurring from 250 ms delay. Much larger delays were tolerated in this program when delay was added to the display system. The significant difference between control system and display system time delay effects can be demonstrated by examining the pilot-vehicle dynamic system.

Using the pilot-vehicle model of Fig. 1, it is seen that control system time delay affects the motion system and display system equally. From previous experimental results, control system time delay has a significant effect on the pilot-vehicle closed-loop stability. The results of this experiment indicate that with constant Level 1 motion flying qualities, a substantial threshold exists where added visual delay does not affect flying qualities. It could be deduced because of the different flying qualities effects that the pilot, as the closed-loop controller in the pilot-vehicle dynamic system, was either unaffected by the visual delay, or he could easily compensate (without workload or performance penalty) for its influences. From a physiological viewpoint, it could be logically defended that the visual cue feedback to the pilot was not a critical cue in task performance in the presence of a visual delay. Since time delay adds deleterious phase lag proportionally to frequency, the high-frequency spectrum of the cue feedback to pilot would be most impacted by delay. However, the visual senses are primarily used during piloting tasks for low-frequency cuing or steady-state reference. Conversely, the motion response primarily provides the high-frequency response cue such as onset or acceleration cuing. The pilot blends the motion and visual senses, in a complementary fashion, to provide a full-fidelity, broad-frequency response estimate. Hence, significantly greater time delays in the visual feedback would be required to affect the low-frequency visual cue feedback than that introduced in the motion feedback due to the physiological nature of the human pilot. This was shown experimentally. Motion cue effects must, therefore, always be referenced in assessing the influence of display system dynamics.

Concluding Remarks

An in-flight investigation of the effects of head-up display symbol dynamic response requirements was performed using the U.S. Air Force NT-33A aircraft. The results of this study suggest the following conclusions:

1) There exists a substantial tolerance in temporal distortion between the motion and visual response cues, which does not apparently affect piloted flying qualities evaluations.

2) For a constant, Level 1 aircraft motion response, there is only a slight effect on flying qualities in an up-and-away flight phase for up to 250 ms delay associated with the HUD.

3) Beyond this threshold, flying qualities degrade from Level 1 to Level 3 with an additional 100 ms of display delay.

4) For the power approach task and a Level 1 motion response, there is no effect on flying qualities for up to 300 ms delay added to head-up display.

5) The degradation of flying qualities with display time delay is affected by the evaluation task demands. For a "low-stress" task such as the IMC approach task only, flying qualities are less affected by display time delay than a demanding task such as the up-and-away gun tracking task. It is suggested that the flying qualities degradation due to display time delay may be enhanced by turbulence.

Acknowledgments

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References

[1]Martin, W. L., et al., "Night Attack Workload Steering Group," U.S. Air Force, ASD-TR-82-5002, June 1982.

[2]"Aircraft Display Symbology," U.S. Air Force, MIL-STD-1787, Dec. 1984.

[3]"Military Specifications: General Specification for Head-Up Displays," MIL-D-8164 (AS), June 1972.

[4]Bailey, R. E., "Investigation of Head-Up Display Dynamic Response and Symbol Accuracy Requirements," Calspan Corp., Buffalo, NY, Calspan Rept. 7205-14, Aug. 1986.

[5]Lebacqz, J. V. and Aiken, E. W., "A Flight Investigation of Control, Display, and Guidance Requirements for Decelerating Descending VTOL Instrument Transitions Using the X-22A Variable Stability Aircraft," Calspan Corp., Buffalo, NY, Calspan Rept. AK-5336-F-1, Vols. I and II, Sept. 1987.

[6]Monagan, S. J. and Smith, R. E., "Display Evaluation Flight Test," Calspan Corp., Buffalo, NY, Calspan Rept. 6645-F-2, May 1980.

[7]"Military Specification–Flying Qualities of Piloted Airplane," U.S. Air Force, MIL-F-8785C, Nov. 1980.

[8]Hodgkinson, J. and LaManna, W. J., "Equivalent Systems Approaches to Handling Qualities Analysis and Design Problems and Augmented Aircraft," AIAA Paper 77-1122, Aug. 1977.

[9]Cooper, G. C. and Harper, R. P., Jr. "The Use of Pilot Ratings in the Evaluation of Aircraft Handling Qualities," NASA-TND-5153, April 1969.

[10]Smith, R. E. and Bailey, R. E. "Effect of Control System Delays on Fighter Flying Qualities," AGARD Flight Mechanics Panel Symposium on Criteria for Handling Qualities of Military Aircraft, Ft. Worth, TX, April 1982.

[11]Smith, R. E., "Effects of Control System Dynamics on Fighter Approach and Landing Longitudinal Flying Qualities," Air Force Flight Dynamics Lab., Wright-Patterson AFB, OH, AFFDL-TR-78-122, March 1978.

[12]Berry, D. T., Powers, B. G., Szalai, K. J., and Wilson, R. J., "A Summary of an In-Flight Evaluation of Control System Pure Time Delays During Landing Using the F-8 DFBW Airplane," AIAA Paper. 80-1626, Aug. 1980.

[13]Stengel, R. F. and Miller, G. E., "Flight Tests of a Microprocessor Control System," *Journal of Guidance and Control*, Vol. 3, Nov.–Dec. 1980, pp. 494–500.