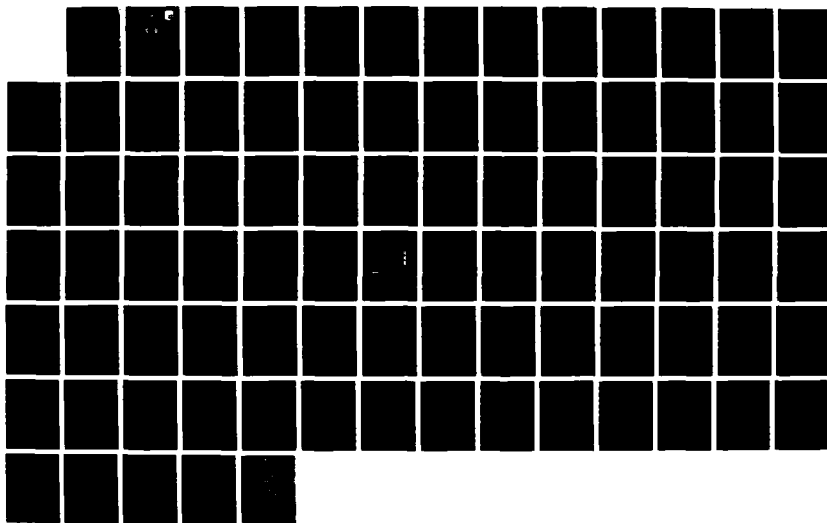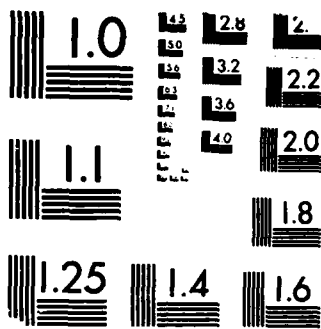AD-A193 617   IMPROVEMENT OF HEAD-UP DISPLAY STANDARDS VOLUME 4   1/1
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Volume IV

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IMPROVEMENT OF HEAD-UP DISPLAY STANDARDS

Volume IV: Head-Up Display Dynamics Flight Tests

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September 1987

Final Report for Period Oct 84 - June 87

NOTICE

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This report has been reviewed by the Office of Public Affairs (ASD/PA) and is releasable to the National Technical Information Service (NTIS). At NTIS, it will be available to the general public, including foreign nations.

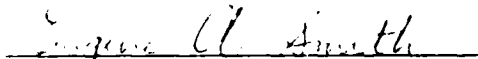This technical report has been reviewed and is approved for publication.

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19. ABSTRACT (Continue on reverse if necessary and identify by block number)

An in-flight investigation of the effect of head-up display symbol control laws has been conducted using a variable stability T-33 aircraft. The results indicate that HUD delays (pure time delays) of the order of 140 msec in up-and-away flight have little effect on flying qualities. Sampling at intervals of 100 msec (10 hz) has a marked effect and degrades Cooper-Harper pilot ratings from a rating of 2 (good with negligible deficiencies) to a rating of 6 (very objectionable but with tolerable deficiencies). For the power approach case, the delays of up to 230 msec have negligble effect. In the power approach case, sampling at 10 hz had no effect. Keywords:

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Summary

An in-flight investigation of the effect of head-up display symbol control laws has been conducted using a variable stability T-33 aircraft. The results indicate that HUD delays (pure time delays) of the order of 140 msec in up-and-away flight have little effect on flying qualities. Sampling at intervals of 100 msec (10 hz) has a marked effect and degrades Cooper-Harper pilot ratings from a rating of 2 (good with negligible deficiencies) to a rating of 6 (very objectionable but with tolerable deficiencies). For the power approach case, the delays of up to 230 msec have negligble effect. In the power approach case, sampling at 10 hz had no effect.

Acknowledgement

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List of Abbreviations

AFAMRL	Air Force Aeromedical Research Laboratory
AFFDL	Air Force Flight Dynamics Laboratory
AFIFC	Air Force Instrument Flight Center
AFWAL	Air Force Wright Aeronautical Laboratories
AGARD	Advisory Group for Aeronautical Research and Development
AGL	Above ground level
AHRS	Attitude heading reference system
AIAA	American Institute of Aeronautics and Astronautics
ASD	Aeronautical Systems Division
CCIP	Continuously computed impact point
CHPR	Cooper-Harper pilot rating
CPU	Central processing unit
CRT	Cathode ray tube
CTOL	Conventional take-off and landing
DEFT	Display evaluation flight test
DFBW	Digital fly-by-wire
EP	Evaluation pilot
FAA	Federal Aviation Administration
FCS	Flight control system
FDL	Flight Dynamics Laboratory (see AFFDL)
FOV	Field-of-view
FPM	Flight path marker (velocity vector)
GPIP	Glidepath intercept point
HUD	Head-up display
IFC	Instrument Flight Center (see AFIFC)
IFR	Instrument flight rules
ILS	Instrument landing system
IMC	Instrument meteorological conditions
INS	Inertial navigation system
INU	Inertial navigation unit
KIAS	Knots, indicated airspeed
LANTIRN	Low altitude navigation and targeting for night
MARS	Mid air retrieval system
MIL	Military (specification or standard)
NASA	National Aeronautics and Space Administration
NATC	Naval Air Test Center
PIO	Pilot-induced-oscilation
RAE	Royal Aircraft Establishment
STD	Standard
TAC	Tactical Air Command
UK	United Kingdom
USAF	United States Air Force
VFR	Visual flight rules
VMC	Visual meteorological conditions
VSS	Variable stability system
VSTOL	Vertical and short take-off and landing
VTOL	Vertical take-off and landing

List of Symbols

e	Base of natural logarithms
Fas	Control stick roll force (lb)
Fes	Control stick pitch force (lb)
g	Acceleration of gravity (32.2 ft/sec^2)
L	Airplane rolling moment (lb-ft)
L_α	Lift slope (lb/deg)
L_{δ_a}	$\partial L/\partial \delta_a$ (lb-ft/deg)
$L_{\delta_{as}}$	$\partial L/\partial \delta_{as}$ (lb-ft/in-sec)
M	Airplane pitching moment (lb-ft)
M_{δ_e}	$\partial M/\partial \delta_e$ (lb-ft/deg)
$M_{\delta_{es}}$	$\partial M/\partial \delta_{es}$ (lb-ft/in)
n	Normal load factor
p	Roll rate (deg/sec)
q	Pitch rate (deg/sec)
s	Laplace operator (1/sec)
α	Angle of attack (deg)
γ	Flight path angle [velocity vector] (deg)
δ_a	Aileron deflection (deg)
δ_{as}	Control stick roll deflection (in)
δ_e	Elevator deflection (deg)
δ_{es}	Control stick pitch deflection (in)
ζ	Natural damping ratio
ζ_{ph}	Phugoid damping ratio
ζ_{sp}	Short period damping ratio
θ	Pitch angle (deg)
τ	Experimental delay added (sec)
τ_{θ_2}	Lead time constant in pitch transfer function (sec)
ϕ	Roll angle (deg)
ω	Natural frequency (rad/sec)
ω_{ph}	Phugoid frequency (rad/sec)
ω_{sp}	Short period frequency (rad/sec)

List of Symbols (continued)

Software quantities:

AOA	Angle of attack (deg)
FPM	Velocity vector (deg)
HDOT	Derivative of altitude (same units as VG)
THET	Pitch angle (deg)
VE	Velocity in easterly direction (knots)
VG	Inertial groundspeed (knots)
VN	Velocity in northerly direction (knots)

I. INTRODUCTION

The designers of aircraft are rapidly adopting glass cockpit technology where conventional electromechanical and pneumatic instruments are being replaced by cathode ray tubes (CRTs) for presentation of information to the pilot and other crew members. Head-up displays (HUD) are being adopted as the primary flight reference for instrument meteorological conditions. This technology influx has created the potential for new and unique formats by which information critical to flight and mission success is conveyed to the flight crew. In fact, single seat, night/all-weather low altitude missions are being flown successfully only because of this technology. The steering group for night attack, as an advisory group for the introduction of LANTIRN (Low Altitude Navigation and Targeting Infrared System for Night), prioritized the head-up display as a critical technological element for this mission (1). In the LANTIRN mission, the flight is conducted essentially with sole reference to the cockpit display environment and the HUD is a critical component. Consequently, the influence of the HUD on flight information processing and manual flight control is critical.

The HUD is an outgrowth of the reflective gunsight of World War II. In such gunsights, the aiming symbol was generated as a collimated beam of light, projected upwards, and reflected toward the pilot by a semi-transparent mirror placed in his field-of-view (FOV) through the windshield. If the design is correct, the pilot will see the symbols floating in his view of the outside scene. The image of the symbols can be focused to form a virtual image which appears to lie in the same plane as the outside visual scene. From lead-computing gunsights, the next step was to place flight information in the virtual image.

The reasons for providing a head-up display are seemingly intuitive:

- A head-up display can reduce pilot workload when the piloting task requires head-up, outside-the-cockpit flight references.

- Improvements in accuracy and efficiency occur from the overlay of HUD-presented data with the external visual scene.

Much of the early development of HUDs took place at the UK's Royal Aircraft Establishment (RAE) in the late 1950s and early 1960s. These early studies indicated that a HUD need not be conformal to the real world, but rather only an approximate overlying of symbols and real world cues was required (2). Part of this may have been the result of a lack of technology to reliably generate a conformal contact analog.

The early work at the RAE was based on extensive flight test and simulator experiments. Most of the conclusions were based on a performance metric, that is, the success criteria for a display was based on the minimum tracking error.

At the present time, HUDs are in operational use on most fighter/attack airplanes. While these HUDs were placed on these airplanes to serve as gunsights or bombsights, pilots have found that they are extremely useful in routine flight. USAF pilots flying A-7D, F-15, and F-16 fighter aircraft report that they use the HUD as an important part of their instrument scan (3). The Navy recognizes the HUD as the primary flight reference for both the A-7E and F-18.

In the mid-1970s, Tactical Air Command (TAC) requested guidance on the use of HUDs from the Air Force Instrument Flight Center (AFIFC,IFC). In the resulting study, IFC found that while the HUD did represent a significant aid as a flight reference, the lack of adequate failure detection; an increased tendency toward spatial disorientation; and inadequate standardization limited HUDs usefulness as a primary flight reference (4).

A later study attempted to further define some of the problem areas noted in the IFC survey. This study (3) concluded that there appeared to be a dichotomy between useful HUDs and those HUDs which were not useful as a primary flight display. Based on pilot comments, the dynamic response of the HUD symbols appeared to be inadequately controlled by the specifications. (Most HUD specifications do not address the dynamic response of the symbols at all.)

The importance of the dynamic response of the HUD symbols had been recognized in previous research, yet the results of the early research had not been incorporated into display standards and specifications. MIL-STD-884C, for example, only describes the velocity vector as "generally damped to make it usable" (5).

It is well known in the design of flight control systems (FCSs) for modern aircraft that the human response must be considered during the design of the control system. The first detailed examination of the human response as it influenced control systems was Tustin's paper describing aiming systems for gunnery tracking (6).

An outgrowth of this problem, which was recognized within the flight control community, were the deficiencies in the handling qualities specification (MIL-F-8785B, reference 7) as control system responses introduce significant dynamic modes or delays into the overall system dynamics. This led to the suggestion that MIL-F-8785B be amended to reflect the widespread use of digital FCSs (8). The current version (MIL-F-8785C) does consider the effect of digital flight controls (9).

Historically, the problem was treated as an aircraft/flight control system problem only. No display effects were considered. The pilot's perception of the aircraft response was implicitly assumed to be perfect and immediate. Equivalently, we might say that the handling qualities were based on a visual task with no display other than the real world.

With classical displays, this may have been acceptable. (Although we could say that with classical airplanes, the requirements of MIL-F-8785B would have presented no problems either.) Our problem is no longer one of the airplane's response alone. We must also consider the feedback loops by which the pilot gains his cues of the airplane's response. These include visual perception of the real world, kinesthetic perceptions of the pilot's body, inner ear orientation, hearing, and perception of the instruments (10). Each of these will have its own feedback loop with individual dynamics and delays. A weighted sum of the individual feedback signals will determine the pilot's sensation of the motion of the airplane. Figure 1 shows a block diagram of the pilot/FCS/airplane system.

Classically, we have ignored these loops in our consideration of aircraft handling qualities. Implicitly, the first four cues (real world visual cues, kinesthetic cues, orientation cues, and hearing cues) have always been present. Since these tend to have the same feedback transfer function from airplane to airplane, this has not resulted in any problem (for visual flight).

As electronic displays are introduced, we find that they are quite compelling because of the perceived accuracy, because of the ability to combine information, and because of the novelty. Since they are so compelling, they may introduce a significantly greater amount of the feedback to the pilot. As a result, the display dynamics begin to enter into the flying qualities of the airplane. We can no longer speak of the airplane/FCS handling, but rather we must consider the airplane/FCS/display handling.

The earlier HUD study (3) identified HUD dynamics as a deficiency in the HUD specifications. The pilot comments often described the HUD symbols as "squirrelly" or as having excessive jitter. These descriptions were characteristic of a fairly high frequency, random motion of the symbols. The description could have been the result of one of several problems: a lack of meter damping in the HUD; excessive time delays during computation; excessive sampling intervals; or noise in the sensors. The most likely cause appeared to be either excessive time delays or excessive sampling intervals in the digital computations since the problem appeared to get worse as more and more computations were performed.

The effect of excessive time delays has been studied in an effort to find the maximum computation time for electronic visual systems for ground based simulators. In a study of a simulator for a ground attack airplane, one study concluded that 100 msec

was the maximum delay allowable for decent fidelity (11). For transport airplanes, the FAA criterion for visual scenes is that they should lag the motion cues by no more than 150 msec (12).

Early RAE studies indicated that compressed pitch scaling on the HUD improved piloting accuracy (5). This may also be an effect of problems encountered by pilots with very limited HUD experience who tend to track very aggressively because of the small angles which may be perceived with a HUD. Pilots can easily see angles of 0.1 degree, and until they detune their HUD tracking, excessive workload can result.
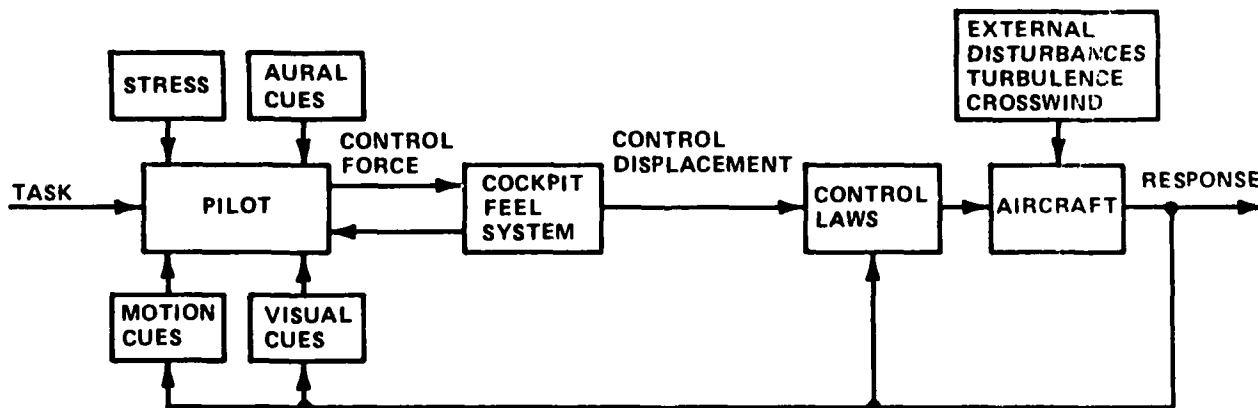
Figure 1

Pilot-Vehicle Dynamic System

II. OBJECTIVES

This experiment consisted of two tasks: Task A was an investigation of the effect of head-up display symbol dynamic response characteristics on flying qualities; Task B was an investigation of symbol accuracy requirements as they pertain to the accuracy by which a contact analog runway display symbol overlays the real world and the potential hindrance introduce by the HUD in the pilot's transition from instrument-to-visual flight reference.

Specifically, the objectives of Task A were to:

- Generate data documenting the effects of head-up display symbol dynamic response characteristics on aircraft flying qualities. These data consist of pilot ratings, pilot comments, and task performance records.

- Investigate the influence of flight phase and mission (evaluation task) on the data and, hence, for requirements for head-up display design.

- Examine the impact and interaction of the aircraft's dynamic response characteristics on the acceptability of the display response characteristics.

To satisfy these objectives of Task A, the experiment variables were:

- HUD symbol dynamic response characteristics.

- Aircraft handling qualities characteristics.

- Evaluation task (mission).

III. EXPERIMENT DESIGN

An in-flight investigation of Head-up Display (HUD) symbol accuracy requirements was conducted using the USAF Flight Dynamics Laboratory variable stability NT-33A aircraft. The NT-33A aircraft is an inflight simulator equipped with a programmable head-up-display which is part of the DEFT system. The handling qualities and display characteristics of the inflight simulator can be easily altered for experimentation purposes.

The NT-33 variable stability system capabilities are used to simulate different aircraft handling qualities characteristics for the evaluation pilot who sits in the front seat of the two-seat NT-33. The mechanization of the NT-33 simulation is not unlike a ground-based simulation; however, the NT-33 simulation is essentially unconstrained in motion response and the visual environment is real. The motion of these simulated configurations are sensed by appropriate transducers. These signals are conditioned and processed in the programmable display system of the NT-33 for head-up display presentation. Instrument meteorological conditions (IMC) are effectively and safely simulated by using a blue/amber system. The front canopy of the NT-33A is covered with an amber plastic sheet; when the front seat pilot lowers his blue visor, the complimentary colors produce an almost completely black outside environment. Flight, in this instance, is conducted by the evaluation pilot solely from the cockpit display environment. The simulated aircraft configurations, HUD format, symbols, dynamic response characteristics, and evaluation task were selected are tailored to satisfy the objectives of this experiment.

A. Experiment Variables

This experiment consisted of two tasks: Task A was an investigation of the effect of head-up display symbol dynamic response characteristics on flying qualities; Task B was an investigation of symbol accuracy requirements as they pertain to the accuracy by which a contact analog runway display symbol overlays the real world and the potential hindrance introduce by the HUD in the pilot's transition from instrument-to-visual flight reference. While the two experiments were conducted one the same flight, in reality they were two separate experiments.

The experiment variables for this study were:

- HUD symbol dynamic response characteristics;

- Aircraft handling qualities characteristics;

- Evaluation task (mission).

With the experiment objectives and variables thus defined, the experiment configurations and mechanization are documented in the following sections.

B.   USAF/FDL NT-33A Research Aircraft

The NT-33A aircraft is an extensively modified Lockheed T-33 jet trainer.   It is owned by the Flight Dynamics Laboratory and operated under contract by Calspan Corporation.   The front seat control system of the NT-33A has been replaced by a full authority fly-by-wire flight control system (FCS) and a variable response artificial feel system.   The evaluation pilot, who sits in the front cockpit, controls the aircraft through a standard centerstick and rudder pedal arrangement or a sidestick controller installed on a right-hand console as an alternate pitch and roll controller.

The front seat, fly-by-wire control system, and variable response feel system can be programmed to simulate several aircraft configurations.   The system operator in the rear cockpit, who also acts as safety pilot, controls the HUD and aircraft configuration.   It is important to note that the evaluation pilot cannot feel the control surface motions due to the actions of the variable stability system signals in the NT-33.   During this experiment, the evaluation pilot had no prior knowledge of the configuration characteristics.

Safety features are an essential and integral part of the NT-33 research aircraft.   Continuous safety monitors activate an automatic safety trip system to disconnect the evaluation pilot from the fly-by-mire control system before unsafe flight conditions or aircraft attitudes occur.   Aircraft control reverts to the safety pilot who occupies the rear seat with unmodified T-33 flight controls.   The safety pilot, who also acts as the systems operator, provides an additional, redundant margin of safety by his ability to disengage the variable stability system manually.

Details of the simulation mechanization are provided in Reference (13).

C. **Head-Up Display (DEFT)**

A fully programmable head-up display (HUD) which is part of
the display evaluation flight test (DEFT) system is installed in
the front cockpit. The DEFT system is described elsewhere (14).

Eight distinct display programs are available for loading in
flight. Within each program are data stored for six runways for
landing and approach evaluations.

The HUD optics, field-of-view, and design eyepoint were not
experimentally varied not formally evaluation. These hardware
items were the nominal DEFT system and are unique to the HUD and
its installation in the T-33. The instantaneous FOV is approxi-
mately 16 deg in azimuth and 18 deg vertical.   The design eye-
point is low and hence a potential hindrance to the pilot.   The
design eyepoint is restricted because of ejection envelope and
panel mounting constraints in the T-33 installation. These defi-
ciencies were noted by all of the evaluation pilots. Design eye-
point and limited FOV problems are typical of many HUD-equipped
aircraft.

Instrument meteorological conditions were simulated using a
blue/amber system. An amber vinyl plastic sheet covered the in-
side front half of the NT-33 canopy. Blue snap-on visors were
provided to the evaluation pilots. The complementary colors,
with the blue visor lowered, effectively present instrument me-
teorological conditions to the evaluation pilot, yet do not over-
ly restrict the visual conditions of the safety pilot.

The blue-amber system has several advantages over previously
tried systems:

*   It is, perhaps, the only means of simulating IMC
    while using a HUD which will retain adequate vis-
    ibility for the safety pilot.

*   The evaluation pilot cannot cheat the visual re-
    striction (such as is possible IMC visors).

*   The blue/amber is less cumbersome than canopy
    drapes.

*   The IMC restriction can be quickly and easily re-
    moved.

As in any simulation, the blue/amber simulation of instru-
ment conditions is not without its limitations. These imperfec-
tions are itemized for proper interpretation of the experiment
results:

*   The ability to transition quickly from IMC to VMC
    is a disadvantage as well as advantage of the

blue/amber simulation. Night flying instantly
can become full daylight VMC. This situation is
not completely realistic and some visual accommo-
dation is needed after the transition. The HUD
intensity, usually set for night conditions,
needs to be increased after the transition to VMC
to be legible.

- The blue/amber technique does not provide any
shades of gray between full VMC and IMC. Also,
the majority of flights were flown in very good
weather conditions (always under visual flight
rules) and typically good visibility (greater
than 10 miles). During a landing approach evalu-
ation, a somewhat unrealistic situation occurs
because the breakout from instrument conditions
in the blue/amber simulation yields limitless
visibility. Approach, threshold, and runway edge
marker lights are absent.

Although the IMC simulation was not perfect, it did provide
a constant and consistent IMC simulation for which to test head-
up display systems.

D. Aircraft Configurations Flown

Two flight phases were flown on each sortie:

- up-and-away (symbol response study)

- power approach and landing (symbol re-
sponse study and display accuracy study,
this study)

Details of the evaluation task, procedures, and flight phase are
given in Section IV.

1. Aircraft Configuration Characteristics

The NT-33 aircraft is a three degree-of-freedom in-flight
simulator. The fly-by-wire, front seat control system consists
of variable analog and digital control components. For this pro-
gram, only the analog FCS capabilities were used. The evaluation
pilot pitch, roll, and yaw cockpit control inputs were appropri-
ately modified in the fly-by-wire control system to simulate sev-
eral different aircraft configurations by proper deflection of
the T-33 elevator, aileron, and rudder control surfaces. Details
of the simulation mechanization are provided in the original Cal-
span report (15).

In the up-and-away flight phase, three fighters (Configura-
tions A, B, and C) were simulated. In the power approach flight

phase, two fighters (Configurations D and E) and one transport (Configuration T) were simulated. Configurations D, E, and T were, of course, in the landing configuration.

The components of the aircraft configuration simulation are illustrated in the schematic diagram of Figure 2. The characteristics of these components are described as follows.

2. Feel System

The NT-33 electrohydraulic feel system was programmed to provide fast response dynamics for the pitch and roll centerstick and rudder pedals. The force gradients (force per unit deflection), breakout, and hysteresis were tailored to the configurations.

The dynamics of the cockpit controller were held constant throughout the program. The response dynamics were essentially of second order whose natural frequencies and damping ratios were:

Pitch Centerstick: ω = 29.5 rad/sec; ζ = .85
Roll Centerstick: ω = 25.0 rad/sec; ζ = .90
Rudder Pedals: ω = 25.0 rad/sec; ζ = .90

For the fighter configurations (Configurations A, B, C, D, and E), a constant force gradient was simulated,

Pitch Centerstick: 9.0 lb/inch
Roll Centerstick: 3.0 lb/inch
Rudder Pedals: 100 lb/inch

For the transport configuration (Configuration T), heavier force gradients than the fighter configurations were simulated. The gradients were:

Pitch Centerstick: 15 lb/inch
Roll Centerstick: 10 lb/inch
Rudder Pedals: 100 lb/inch

In all cases, the feel system gradients were linear: 1.0 lb of breakout force with 0.5 lb of friction were implemented in the pitch and roll centerstick.

3. Flight Control System Dynamics

For this program, the dynamics of the FCS were negligible. The control system statics were used to provide the appropriate command gain for each configuration.

For the up-and-away configurations, the pitch command gain was selected for a steady-state stick force per unit normal acceleration of 8 lb/g. The roll command gain was adjusted to achieve good pitch/roll harmony and representative control authority. The approximate steady-state roll rate per unit lateral stick force for the up-and-away configurations were:

        Configuration A: 11.5 deg/sec/lb
        Configuration B: 9.5 deg/sec/lb
        Configuration C: 8.0 deg/sec/lb

For the power approach fighter configurations (Configurations D and E), the pitch command gain provided approximately 21 lb/g steady-state pitch stick force per unit normal acceleration. The roll gearing was also adjusted for good pitch/roll harmony and appropriate control authority. For the transport configuration, the pitch command gain provided approximately 35 lb/g stick force-per-g. The roll gearing was similarly sluggish.

4. Actuator

The control surface-to-actuator command transfer functions were of second order and are described as:

        Elevator: ω = 70 rad/sec; ζ = 0.7
        Aileron: ω = 60 rad/sec; ζ = 0.7
        Rudder: ω = 60 rad/sec; ζ = 0.7

5. Simulated Aircraft

For both the up-and-away and power approach flight phases the interaction of head-up display dynamics and aircraft response characteristics were to be investigated. Three configurations for the up-and-away flight phase were, therefore, selected to vary In response characteristics and yet be sufficiently acceptable in handling qualities so as to not overwhelm or dominate the evaluation. The three configurations were selected to span the Level 1 area of the MIL-F-8785C (9) short period frequency requirement, as shown in Figure 3. All other dynamic characteristics were held constant.

The pitch rate-to-stick deflection transfer functions, assuming constant speed for 250 KIAS, 10 K ft altitude, were:

Configuration A:

$$\left(\frac{q}{\delta_{es}}\right) = \frac{M_{\delta_{es}}\,(s + 1.25)}{s^2 + 2(.65)(6.5)s + 6.5^2}$$

Configuration B:
$$\left(\frac{q}{\delta_{es}}\right) = \frac{M_{\delta_{es}} (s + 1.25)}{s^2 + 2(.65)(4.0)s + 4.0^2}$$

Configuration C:
$$\left(\frac{q}{\delta_{es}}\right) = \frac{M_{\delta_{es}} (s + 1.25)}{s^2 + 2(.65)(2.7)s + 2.7^2}$$

The command gains for each of these configurations were selected to provide a constant steady-state stick force per g. The control authorities of each configuration are illustrated by:

$$M_{\delta_{es}} = M_{\delta_e}(\delta_e/\delta_{es})$$

The control authorities for each aircraft were:

    Configuration A: $M_{\delta_{es}}$ = 2.570 rad/sec^2/inch

    Configuration B: $M_{\delta_{es}}$ = 0.973 rad/sec^2/inch

    Configuration C: $M_{\delta_{es}}$ = 0.443 rad/sec^2/inch

The speed or phugoid mode characteristics were essentially those of the standard T-33 airplane and were unobtrusive to the evaluation task and aircraft handling characteristics. For each configuration, the natural frequency, ω_{ph}, was approximately 0.09 rad/sec and the damping ratio, ζ_{ph}, was 0.10.

The lateral-directional dynamics were selected to be good and, hence, not a factor in the evaluation. The roll rate-to-stick deflection transfer functions were approximately:

$$\left(\frac{P}{\delta_{as}}\right) = \frac{L_{\delta_{as}} (s^2 + 2(.50)(2.0)s + 2.0^2)}{(s + 3.30)(s^2 + 2.(.50)(2.0)s + 2.0^2)}$$

The roll command gains were selected for reasonable roll performance and good pitch/roll harmony. The roll command gains, therefore, varied concurrently with the pitch command gain. The command gain is described by the command authority:

$$L_{\delta_{as}} = L_{\delta_a}(\delta_a/\delta_{as})$$

Configuration A: $L_{\delta_{as}}$ = 1.92 rad/sec^2/inch

Configuration B: $L_{\delta_{as}}$ = 1.66 rad/sec^2/inch

Configuration C: $L_{\delta_{as}}$ = 1.40 rad/sec^2/inch

For the power approach task, two fighter and one transport configurations were selected for testing. The fighter configurations differed in short period and pitch and roll command gains.

The transport configuration was selected to be identical in dynamic characteristics to one of the fighter configurations, but differed significantly in command gain and feel system characteristics.

The pitch-rate-to-stick deflection transfer functions (assuming constant speed and the nominal approach flight condition of 135 KIAS, sea level) were:

Configuration D:

$$\left(\frac{q}{\delta_{es}}\right) = \frac{M_{\delta_{es}}(s + .80)}{s^2 + 2(.7)(2.6)s + 2.6^2}$$

Configurations E and T:

$$\left(\frac{q}{\delta_{es}}\right) = \frac{M_{\delta_{es}}(s + .80)}{s^2 + 2(.7)(1.3)s + 1.3^2}$$

The command gains for the fighter configurations were adjusted to yield a steady-state force per g of 21 lb/g. For the transport case, the command gain was adjusted for 35 lb/g. The control authority of each configuration is:

Configuration D: $M_{\delta es} = 0.527$ rad/sec²/inch

Configuration E: $M_{\delta_{es}} = 0.132$ rad/sec²/inch

Configuration T: $M_{\delta_{es}} = 1.32$ rad/sec²/inch

The phugoid characteristics were, again, essentially those of the NT-33. For each configuration, the phugoid natural frequency was approximately 0.17 rad/sec and the damping ratio was 0.15.

The lateral-directional dynamics of the fighter configurations were tailored to be good and, hence, not a factor in the evaluations. The roll-rate-to-stick deflection transfer function was approximately:

$$\left(\frac{P}{\delta_{as}}\right) = \frac{L_{\delta_{as}}(s^2 + 2(.40)(1.5)s + s^2)}{(s + 2.0)(s^2 + 2(.40)(1.5)s + 1.5^2)}$$

The roll control authority of each aircraft was selected for good harmony with the simulated longitudinal control characteristics. The control authorities were

Configuration D: $L_{\delta_{as}} = .314$ rad/sec²/inch

Configuration E: $L_{\delta_{as}} = .314$ rad/sec²/inch

The roll-rate-to-stick-deflection transfer function of the transport configuration was

$$\left(\frac{P}{\delta_{as}}\right) = \frac{.2618 \; (s^2 + 2(.15)(1.0)s + 1.0^2)}{(s + 1.0) \; (s^2 + 2(.15)(1.0)s + 1.0^2)}$$

With the airspeed decreasing from the approach to flare during a touch-and-go landing, the simulated short period dynamics change. The control authority decreases by approximately 20%. For Configuration D, the short period frequency decreases to approximately 2.3 rad/sec; the damping ratio remains at 0.7, and the pitch rate lead term $(1/\tau_{\theta_2})$ decreases to about 0.71 per sec.

For Configurations E and T, the short period frequency decreases to approximately 1.0 rad/sec: the damping ratio remains at 0.7 and the pitch rate lead-term decreases to 0.71 per sec. The simulated short period dynamics in the power approach task were selected to span the Level 1 region of MIL-F-8785C (9) short period frequency requirement during the landing flare. The correlation of the configuration dynamics and the short period frequency requirement is shown in Figure 3.

E. Head-Up Display Configurations

For this study, intentional misalignments between the real runway and a contact analog HUD runway symbol were introduced. Three different runway symbols were investigated.

A generic head-up display format was used as the baseline display format. This generic HUD format was used to keep display clutter to a minimum. Mission specific information was not programmed nor was it felt to be required. A generic HUD was suitable for our purposes since other tasks under this investigation of HUD requirements were intended to investigate optimal display formats and presentations. The generic HUD format used as the baseline display is sketched in Figure 4.

The primary features of the display are the digital airspeed, altitude, and heading information readout, with a 1-to-1 pitch ladder. The pitch ladder is marked in 5 degree increments; the pitch ladder below the horizon is dashed whereas a solid line is used for positive pitch attitudes. The ladder tails point to the horizon. Negative signs are not shown. This format is essentially the nominal DEFT system, which is similar in many respects to the presentation used in F-18 aircraft.

The waterline marker is a fixed reference approximately parallel to the aircraft waterline reference. The nominal velocity vector (FPM for flight path marker) was calculated using air mass quantities (i.e., FPM = THETA - ALPHA). When the velocity vector was freed in azimuth, it displayed sideslip. For the majority of

the program, a declutter option was available to the pilot. He had the option through a pushbutton on the front seat instrument panel to select either of three presentations of the waterline and velocity vector:

    Declutter (0):   waterline not displayed;
                     velocity vector displayed
                     (caged in azimuth)
             (1):   waterline displayed;
                     velocity vector displayed
                     (free in azimuth)
             (2):   waterline displayed;
                     velocity vector not displayed.

Two different velocity vectors were used in this experiment. The nominal velocity vector was calculated from air mass quantities. An inertial velocity vector was also available. The calculations are briefly detailed to highlight these calculations. For the air mass velocity vector:

- Pitch attitude is sensed by a gyro contained in the T-33 Litton-51 inertial navigation unit (INU). These data are updated at 50 hz rate, sent to the VSS patch panel, filtered at the patch panel and sampled at a 50 hz rate at the Rolm 1602 CPU, thereby creating the software quantity THET.

- Angle of attack is derived by low pass and notch filtering the vane angle-of-attack of the NT-33 and applying position correction factors. These data are processed by the Rolm 1602 CPU at a 50 hz and digitally filtered creating the software quantity AOA.

- Air mass velocity vector (software quantity FPM) is calculated as FPM = THET - AOA when the sideslip is zero.

For the inertial velocity vector:

- Vertical acceleration is derived from the INU and sent to the Rolm 1602 CPU via a synchronous link at a 50 hz rate. Vertical velocity is calculated in a complimentary fashion with barometric data, yielding the software quantity HDOT.

- Velocity, along north and east inertial directions, are computed by the INU and passed via a synchronous link to the Rolm 1602 at a 10 hz rate, creating the software quantities, VN and VE respectively.

- Inertial velocity vector is calculated as:

$$VG = \sqrt{VN^2 + VE^2}$$

$$FPM = \arctan(HDOT/VG)$$

When the inertial velocity vector is free in azimuth, the marker indicates track angle and impact point.

The primary difference between these two types of velocity vector indicators are the reference frame (air mass versus inertial) and the update rate. The 10 hz update rate of the inertial velocity is a limitation of the inertial platform and could not be easily changed for this program. Consequently, it was decided to use air mass velocity vector as the nominal case to provide faster dynamics. The advantages and disadvantages of air mass or inertial velocity vectors were, consequently, explored as part of this program.

Several display options were evaluated briefly. These included:

- Potential Flight Path Marker

- Angle of Attack Bracket

- Automatic Pitch Ladder Scale Switching

The potential velocity vector is a display feature adopted from the unique all-analog Klopfstein display (16). The potential velocity vector is, in essence, the rate of change of the flight path. The potential flight paths can be thought of as thrust/throttle flight directors. When the potential flight path and velocity vectors are aligned, thrust equals drag and the aircraft is stabilized on the indicated flight path angle.

The angle of attack bracket display provides an explicit target angle of attack marker for the power approach. The sense of the bracket is fly-to. The bracket shows a deviation of one degree from the target angle of attack. If the angle of attack exceeds the target by greater than 1.2 deg, a digital readout of the angle of attack is presented in the lower left hand corner of the display. The bracket is drawn with respect to the waterline marker. Both the potential flight path and angle of attack symbols are shown in references (15,16).

An examination of pitch ladder scaling was briefly examined. The nominal display used a 1-to-1 pitch ladder scaling. An alternate display was a switching methodology where the 1-to-1 pitch ladder scaling was displayed for (absolute) velocity vectors less than 11 deg, switching to a 2-to-1 pitch ladder for flight path angles greater than 11 deg.

F.   Dynamic Response Variables

In this study, the DEFT system was specifically altered to provide variations in the HUD symbology dynamic response characteristics and, thus, to investigate the effects of these variations on aircraft flying qualities.

To accomplish this, the interfaces between the motion sensors, CPU, the display generator, and the head-up display were not changed. Dynamic response variations were implemented exclusively by changing the software within the Rolm 1602 computer processing unit.

The dynamic response variations consisted of additional computational time delay and changes in the velocity vector dynamics. This program was intended as an initial investigation of dynamic response requirements. These variables were selected as the initial focus.

Variations in computational time delay were simulated by adding a table shifting routine in the CPU input routine. The input values of pitch attitude, roll attitude, glideslope error, heading and angle of attack were all simultaneously subjected to a variable delay. The delay values were integer multiples of the 50 hz frame time of the CPU. This implementation of delay simulated a pure time delay. The added delays for this task ranged from 0 to 320 msec of added delay in increments of 40 msec.

As noted earlier, the input and output interfaces of the CPU were not altered. The five delay parameters are sampled at the 50 hz sample rate for head-up display processing. The additional experimental delay was computational delay which is distinctly different from a delay introduced by discrete sampling. For example, the pure time delay and sampling delay are illustrated in Figure 5. The pure delay recreates the input exactly but is shifted in time. The sample delay, however, provides temporal distortion as well as amplitude distortion.

For the five delay parameters, the sampling rate was constant at a 50 hz rate. Delay was introduced downstream of the sampling process (Figure 6). The five parameters for delay were selected since this would delay, in essence, the entire head-up display scene with the exception of the digital airspeed and altitude. This would simulate a uniform computational delay of a display system.

In addition to the added delay configurations, variations in the velocity vector dynamics were also investigated in this task. The nominal velocity vector was derived by air mass quantities. The dynamics associated with the analog-to-digital interface and digital filtering of angle of attack for the displayed velocity vector are illustrated in Figure 7. The primary filtering is the digital equivalent of an analog 20 rad/sec, second-order filter on the angle of attack signal. When the landing gear was low-

ered, an additional 2 rad/sec, first-order filter is also introduced. In the up-and-away flight conditions, several evaluations were also conducted then the 20 rad/sec filter on angle of attack was changed to 40 rad/sec.

Also, the inertial velocity vector option was employed under this task. Although the inertial and air mass velocity vectors are fundamentally different, they are also very different, in terms of this experiment, because the inertial velocity vector is calculated from 10 hz updated quantities. If the assumption of no wind is made or if the pilot does not see or care about earth references, the difference in the references frames for the two velocity vectors can be ignored. In this case, the comparison of the inertial and air mass velocity vector displays is a comparison of the effect of different sampling rates in the display processing computer.

G.   Experiment Configurations

We must introduce the concept of the pilot as an active control element in the overall closed loop pilot-vehicle dynamic system. Numerous inputs are presented to the pilot of which the motion and visual cue feedbacks are predominant in the execution of a given task. The visual cues are differentiated between the cues derived from outside-the-cockpit and those derived from inside-the-cockpit instruments or the head-up display, for example. It is the intent of this research and experiment to understand more fully this closed-loop system and how the pilot utilizes these cue feedbacks. In order that this closed-loop system can be appropriately modeled, we must identify the plant dynamics of this system. These are described with supporting documentation in reference (15). This work is summarized in this section. Appropriate assumptions are made to simplify these models for clarity.

We will assume, for the moment, that the pitch and roll rate (or pitch and roll attitude, being the integral of these quantities) are the parameters of interest to the pilot in this closed-loop system. The transfer function for pitch and roll rate motion due to pilot force inputs on the centerstick are presented in Appendix I for the up-and-away and power approach flight conditions.

The dynamic elements in addition to the aircraft short period dynamics are of relatively high frequency. In manual flight control and flying qualities applications, the frequency range of interest to the pilot is typically limited to 10 rad/sec. It is a reasonable assumption to approximate the effect of control system dynamics above the 10 rad/sec as contribution only phase lag in the frequency range of interest. These elements do not affect the amplitude response in this frequency range. This phase lag presumably appears to the pilot as a time delay between stick input and aircraft response. Response delay of this type can be

characterized as an equivalent time delay (17). Equivalent time delay and the equivalent systems methodology is an acceptable method of characterizing high order systems for flying qualities applications. The equivalent system methodology has been adopted for the military specification for fixed-wing aircraft handling qualities (9). In accordance with these methods, the pitch and roll aircraft responses to pilot stick inputs are approximated as being the short period or roll rate transfer functions plus 80 msec equivalent tine delay in pitch and 85 msec equivalent time delay in roll. These equivalent time delay values are within the Level 1 requirement on delay as specified in MIL-F-8785C(9). The up-and-away and power approach augmented aircraft, pitch and roll transfer functions are approximately as shown in Appendix II.

These equivalent transfer functions will be used henceforth as the definition of the aircraft configurations and the aircraft motion response due to pilot stick inputs.

In IMC flight, the pilot is essentially flying with sole reference to the inside-the-cockpit displays. For this program, the head-up display was the primary flight instrument. The dynamic elements between the motion response and HUD symbol response have been described earlier.

From these data, the transfer functions of several prominent variables between their motion and displayed states are presented in Appendix III. The transfer functions are for the nominal or baseline system for this program in the up-and-away flight phase.

Note: In Appendix III, a pure time delay component is included. The pure time delay arises from two sources: (a) The computational time delay of the digital computers in the head-up display system, and (b) The assumption that the sampling delay can be equated to a pure time whose value is equal to one-half the sampling interval. As noted earlier, a sampling delay is not the same as a pure time delay; however, if the sampling rate is relatively fast (and we are assuming that a 50 hz sample is relatively fast), then the only apparent effective of the sampling operation is to reproduce the signal, but with a delay component. We assume the sampling procedure is a pseudo-random process with the delay ranging from 0 msec up to the sample interval and averaging 1/2 the sample interval. When the sampling rate decreases, this assumption may not be appropriate.

The sampling rate being equated to a pure delay is analogous to the derivation of an equivalent time delay. In the equivalent systems methodology, an analog filter can be emulated (with reasonable accuracy) to an equivalent time delay if the frequency of the filter is high enough such that the amplitude distortion with the frequency range of interest is negligible. In the analogy, if the sampling rate is high enough, the process will not affect the amplitude of the response (You don't notice the discrete nature of the signal.), but phase lag (delay) will be introduced. Conversely, a slow sampling rate will affect both the phase (de-

lay) and amplitude of the signal. It is the assumption that a 50 hz sample rate is not affecting the amplitude response of the input signal and, hence, the discrete nature of the signal is not noticeable. On the other hand, a 10 hz sampling rate is not considered to be well approximated by a pure delay element; a 10 hz sample rate affects both the phase and amplitude of the signal.

From this description, it is seen that all of the display-to-motion path dynamic elements are of high frequency relative to the aircraft short period frequency (ω_{sp}) and the 10 rad/sec frequency range of interest upper limit discussed previously. Using the equivalent systems technique again, the motion-to-HUD dynamic elements are equated to an equivalent time delay. Using this equivalent model description, the experimental set-up is shown in Figure 8 for the pitch axis. This figure highlights several important points:

- The temporal distortion (time delay) between pilot stick force input and motion (pitch rate) response is approximately 80 msec. According to the flying qualities requirements for fixed-wing military aircraft, this equivalent delay is within the Level 1 region (9). This level of delay should not degrade the aircraft's handling qualities.

- The visual HUD pitch response (pitch attitude) lags the motion response by approximately 64 msec of equivalent time delay. The total equivalent delay between pilot stick force input and HUD pitch attitude response is approximately 144 msec.

- The display computational delay was varied during the experiment. The temporal distortion between the motion and visual pitch attitude response varied in this program between 64 msec and 384 msec equivalent delay.

- The angle of attack response was delayed in its display by approximately 170 msec for the up-and-away configurations. When the landing gear was extended, an additional 2 rad/sec first-order lag prefilter in the DEFT system is incorporated. This filter contributes amplitude and phase distortion; therefore, its effect cannot be described as being an equivalent time delay element only.

- Very similar time delay values were present in the roll axis.

Because of the different dynamic elements in the pitch and angle of attack motion-to-visual path, the air mass velocity vec-

tor response differs from the actual flight path response of the aircraft.

For the case of constant airspeed, the equivalent aircraft flight path response to a stick force pilot input approaches the transfer function:

$$\left(\frac{Y}{F_{es}}\right) = \frac{{}^M F_{es}(1/\tau_{\theta_2}) \, e^{-.08s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

The displayed air mass velocity vector is drawn from the conditioned angle of attack and pitch attitude sensor signals. The different dynamic elements in the angle of attack sensor path (versus the pitch attitude path) essentially create high frequency phase lead in the velocity vector response. A lag filter on the angle of attack signal reduces the high frequency component of this signal in its contribution to the velocity vector. This, in essence, provides more pitch attitude content to the air mass velocity vector and, hence, alters the response. The resultant time history is presented in Figure 9 showing an overplot of the flight path angle and attendant velocity vector response to a step cockpit control input.

H.   Experiment Overview

The primary experiment matrix consisted of:

- For up-and-away flight condition, three fighter aircraft configurations (A, B, and C) with differing short period frequencies within the Level 1 military specification requirements but constant stick force per g.

- For the power approach condition, three aircraft configurations (D, E, and T), of which two were fighter configurations with different Level 1 short period frequencies, and one transport configuration.

- A constant temporal distortion (time delay) between stick input and motion response of 80 msec in pitch.

- Variable temporal distortion (time delay) between motion response and HUD-visual response, ranging from 64 msec up to 384 msec equivalent delay.

•   A constant relationship between the signal condi-
     tioning of the pitch attitude and angle of attack
     states such that the air mass flight marker char-
     acteristics are constant for the nominal, no-add-
     ed delay case.

During the course of the experiment, additional experimental
configurations were developed and evaluated for the sake of com-
pleteness.   Again, this matrix was developed to provide an ini-
tial investigation of dynamic response requirements for head-up
display-equipped aircraft.   The resources of this program could
not address all possible dynamic response requirements.   For ex-
ample, it was planned to address the effect of different sampling
rates more fully.   A lack of resources precluded a significant
effort in this area.
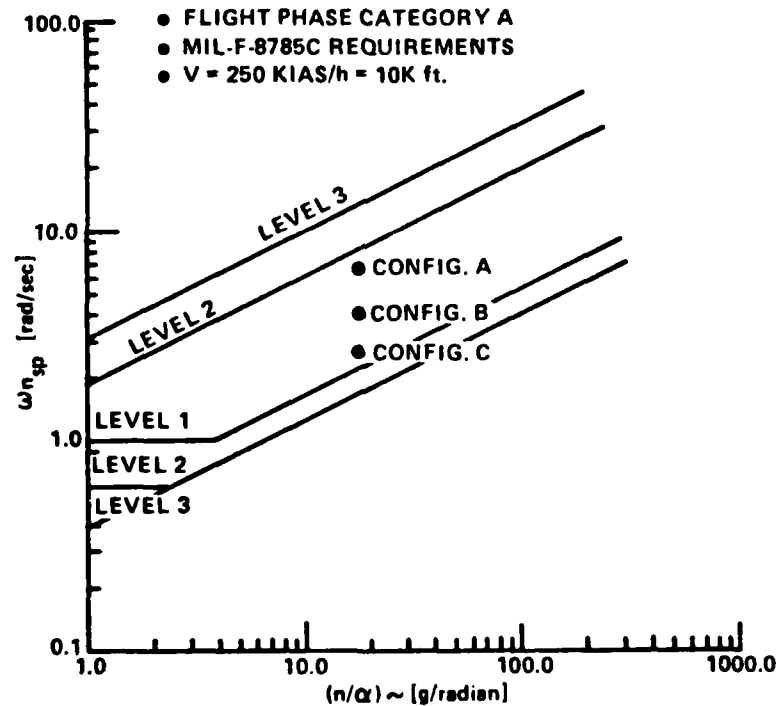
Figure 2

Up-and Away Fighter Configurations
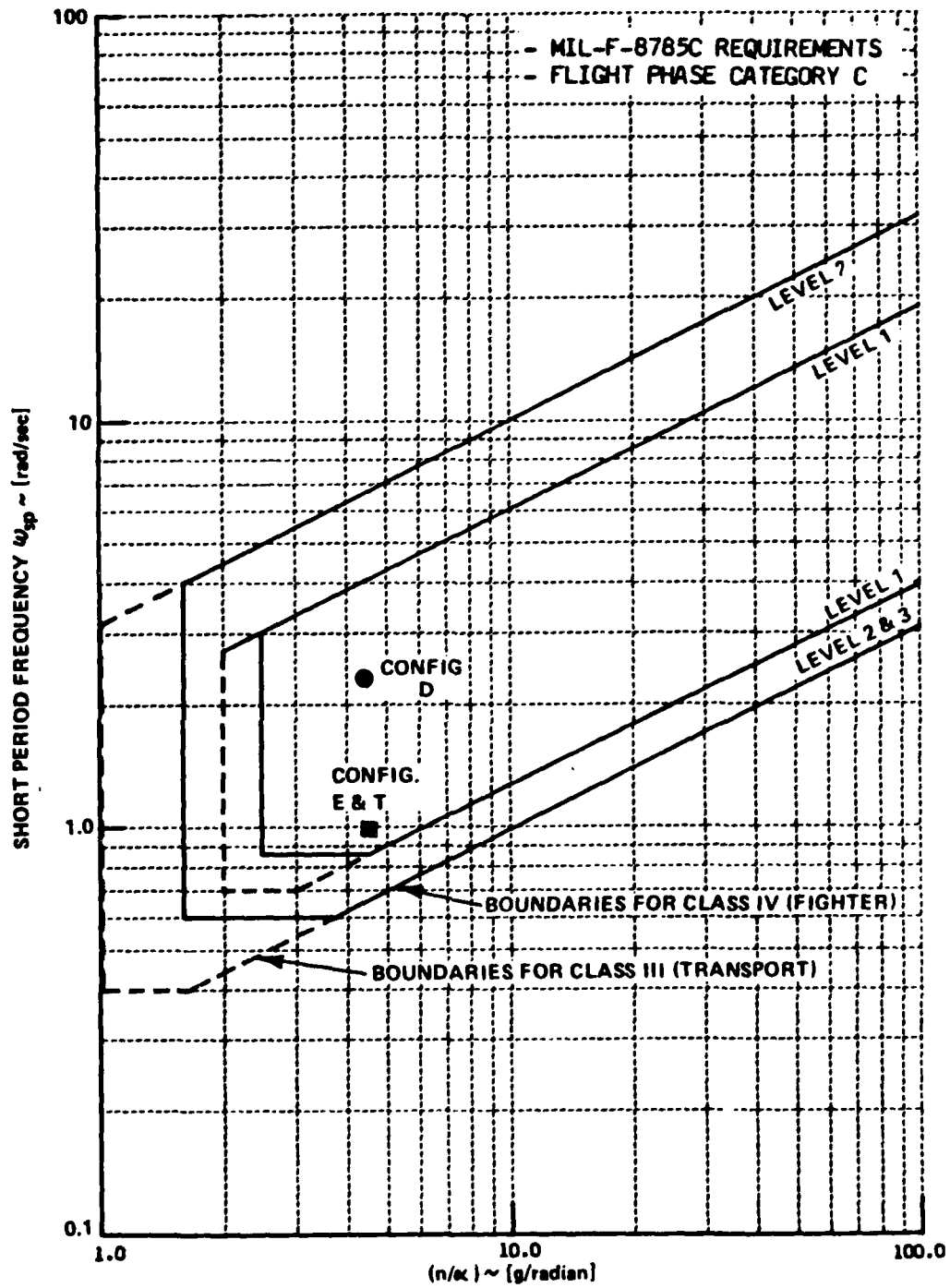
Figure 3

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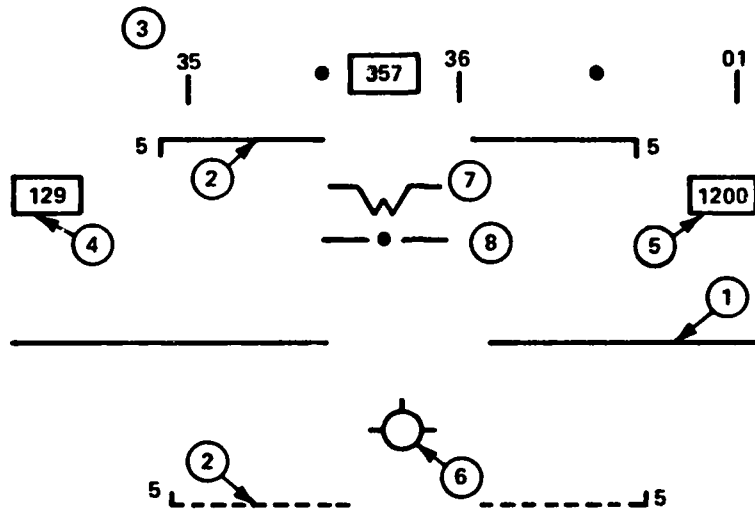
1. HORIZON LINE
2. PITCH LADDER (1:1 PITCH LADDER)
3. HEADING SCALE
4. INDICATED AIRSPEED
5. BAROMETRIC ALTITUDE
6. FLIGHT PATH MARKER (CAGED IN AZIMUTH AT PILOT OPTION)
7. WATERLINE (PITCH MARKER)
8. COMMAND BAR FOR HUD TRACKING TASK (IF SELECTED)

Figure 4

Baseline HUD Format
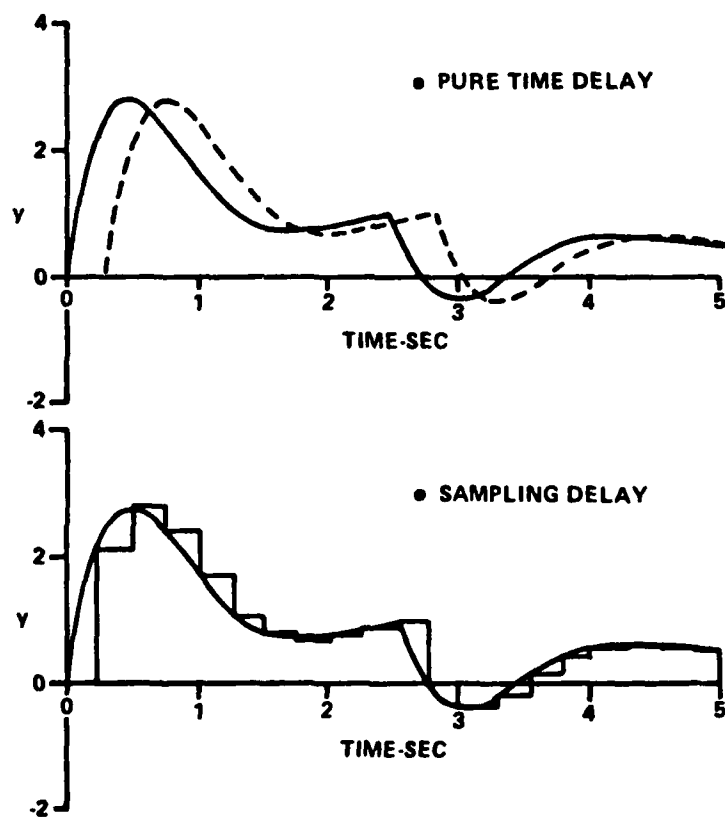
Figure 5

Digital Sampling and (Pure) Time Delay Illustration

ANALOG-TO-
DIGITAL
CONVERSION

(50 hertz)

ADDED
EXPERIMENTAL
DELAY

INPUT

$e^{-\tau s}$

PROCESSING
FOR HEAD-UP
DISPLAY

t_0

$t_0 + \Delta T_1$

$t_0 + \Delta T_1 + \tau$
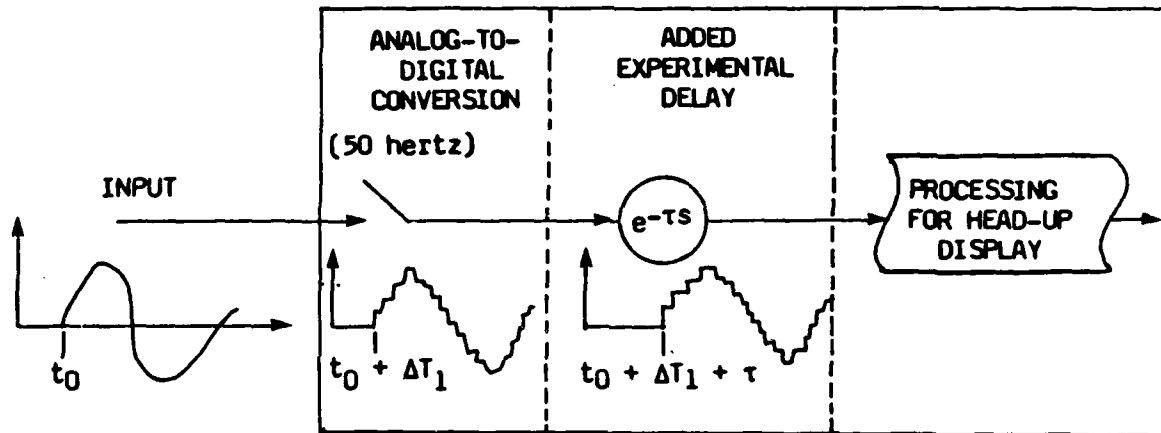
COMPUTER PROCESSING UNIT (CPU)

t_0 – Input Time

ΔT_1 – Delay due to sampling

τ – Experimental Delay Added

Figure 6

Added Computational Delay Illustration
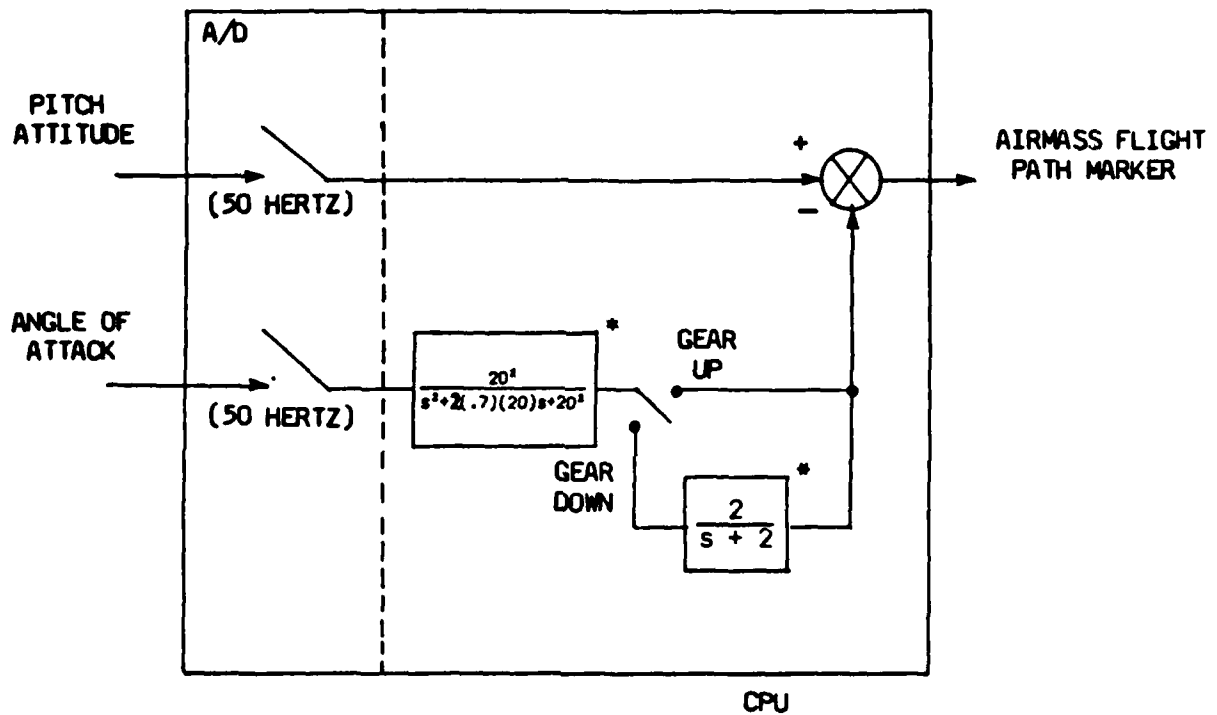
Figure 7

Calculation of Air Mass Velocity Vector

AIRCRAFT EQUIVALENT SYSTEM MODEL

PITCH STICK FORCE → $e^{.08S}$ → $\dfrac{.484\,(1.250)}{[\zeta_{sp};\,\omega_{sp}]}$ → $\dfrac{1}{S}$ → AIRCRAFT PITCH ATTITUDE (MOTION RESPONSE)

DISPLAY EQUIVALENT SYSTEM

$e^{.064S}$ → $e^{.7S}$ → AIRCRAFT PITCH ATTITUDE ON HEAD-UP DISPLAY (VISUAL RESPONSE)

VARIABLE ADDED PURE DELAY

*SHORT HAND NOTATION USED:

$(a) = \dfrac{1}{a}(S + a)$

$[\zeta_{sp};\,\omega_{sp}] = \dfrac{1}{\omega_{sp}^2}(S^2 + 2\zeta\omega_{sp}S + \omega_{sp}^2)$

WHERE $\zeta_{sp} = .65$ AND ω_{sp} GIVEN BY CONFIGURATION AS SHOWN

Figure 8

Experimental Set-Up for Up-and-Away HUD
Study Using Equivalent System Models

AIRCRAFT: Configuration B - ζ_{sp} = .60, ω_{sp} ≈ 4.05
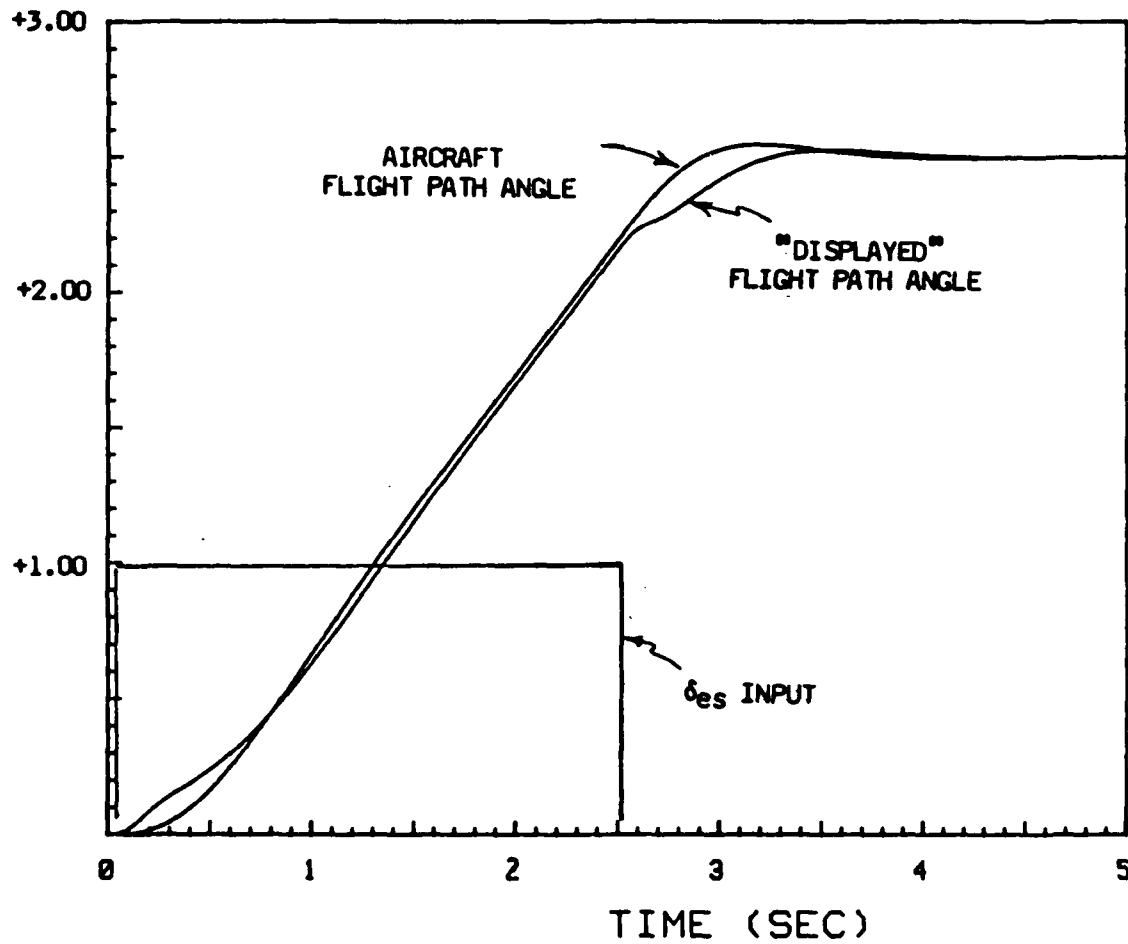
Figure 23   FPA - DISPLAY STEP RESPONSE

Figure 9

Velocity Vector -- Response to Step Input

IV. CONDUCT OF THE EXPERIMENT

This experiment was performed using the USAF variable stability NT-33A aircraft. The evaluation procedures were tailored to the maximum extent possible to satisfy the objectives of the experiment.

A.   Evaluation Pilots

Five evaluation pilots were used in the program. The experiment matrix was sized and planned for four evaluation pilots. Table I summarizes the background and experience of the evaluation pilots. The last piloting billet was shared by two pilots. Because of scheduling problems, the final evaluation totals were not evenly split among the four piloting slots.

B.   Evaluation Procedures

Each evaluation pilot was briefed as to the objectives of the experiment and the head-up display formats that they would be flying. Particular attention was made to defining the display formats and features because some of these were new to the pilot or contradictory in sense or meaning to what they were accustomed. Informal comments and discussion with the evaluation pilots were solicited to examine their initial thoughts and reactions. They were later re-questioned after some flight experience regarding the displays and formats.

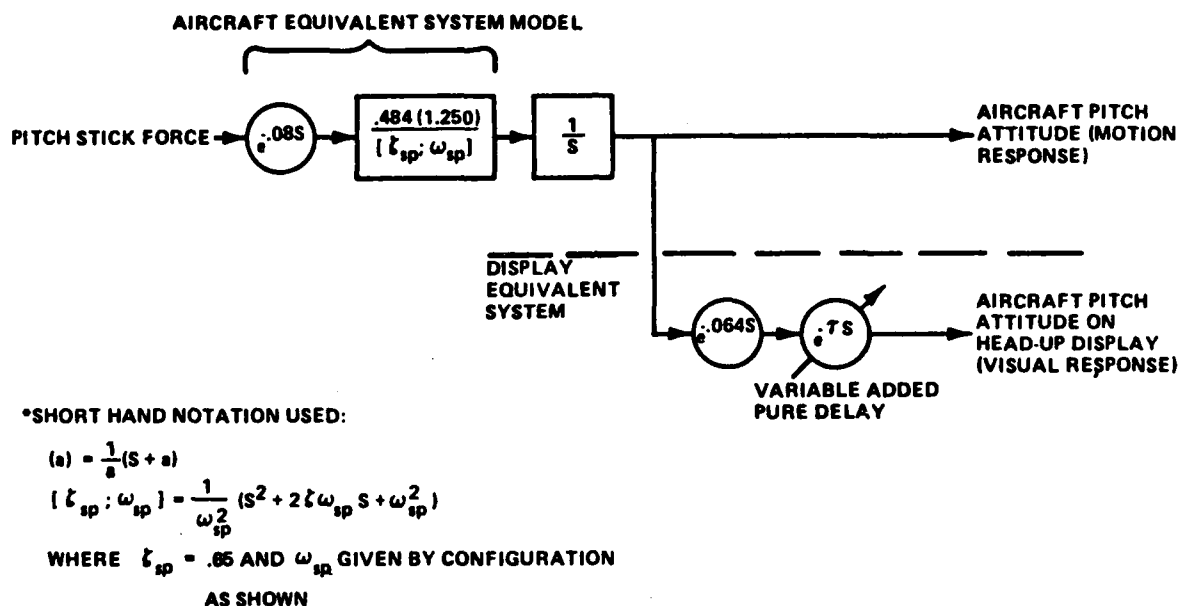Informal pilot comments were typically made during the evaluation. Also, the pilots were asked to rate the handling qualities of the aircraft/display combination using the Cooper-Harper pilot rating (CHPR) as outlined in Figure 10. The ratings were outlined using a pilot comment card at the end of an evaluation (Table II). The intent of the comment card was to provide a common question/response series for each of the pilots and configurations.

For each evaluation, the following procedure was taken:

- The evaluation pilot assumed control of the experimental aircraft configuration.

- Take a calibration record using a step control input (for later analysis).

- Perform the evaluation tasks.

- Return control to safety pilots and give pilot ratings and comments using a voice tape recorder.

C. Evaluation Tasks

An up-and-away evaluation lasted 15 minutes on the average. The evaluations were flown at 250 KIAS with an altitude between 6500 feet and 10,000 feet. Evaluations were conducted VFR in an area on the south shore of Lake Ontario. Power approach evaluations were flown to either Niagara Falls Airport (Runway 28R) or Greater Buffalo International Airport (Runway 5 and 23).

1. Up-and-Away Tasks

An up-and-away evaluation consisted of the following tasks:

- Air-to-Air Target Tracking (IMC):
  - Task provided by display of target command bar.
  - Waterline Marker used as aiming symbol.
  - The command bar is moved through a programmed series of step and ramp pitch and roll commands.
  - 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 seconds.
  - The time history of this command task is shown in Figure 11.

- Air-to-Ground (VMC):
  - Pitch down to the target dive angle using waterline as flight reference; stabilize.
  - Acquisition and tracking of ground target.
  - Acquisition and tracking of another ground target located approximately 50 mils away.
  - Break to a 2-1/2 g pull up with return to 10 K feet.

- Modified Clover Leaf (IMC):
  - Begin at 300 KIAS, 10 K ft AGL.
  - 2-1/2 g pull-up to 45 degrees pitch attitude.
  - Roll and pull so as to pass through the horizon, inverted with 90 degrees of heading change.
  - Pull to 30 degrees nose down.
  - Roll wings level.
  - Recover at 300 KIAS, 10 K ft AGL.

● Pop-Up Weapons Delivery (IMC):
- Begin at 300 KIAS, 10 K ft AGL.
- 2-1/2 g pull-up to 25 degrees flight path angle.
- Hesitate, then wingover so as to arrive with 60 degrees of turn in a 27 degree dive.
- Maintain precise dive angle.
- Roll wings level.
- Pull to level flight.
- Hard, level 90 degrees turn.

This sequence of maneuvers was performed for each up-and-away configuration. The maneuvers were chosen to cover a broad range of maneuver scenarios for which a HUD-equipped, fighter or attack type aircraft might be expected to perform.

The air-to-air tracking task, simulated using the HUD display compensatory attitude tracking task, has been used previously and provides a good fighter flying qualities test maneuver. The remainder of the tasks were intended to be more operationally oriented.

2. Power Approach Tasks

For power approach configurations, the evaluation consisted of series of ILS approaches while flying under simulated IMC (blue visor lowered). These approaches were flown to decision height using the HUD as the primary flight reference. At decision height, the evaluation pilot raised the blue visor and transitioned to a visual lineup and flare. Depending on the fuel weight and circumstances, a 20 ft AGL low approach, a touch and go landing, or a full-stop landing was made. Two or three approaches were performed at the discretion of the evaluation pilot.

The decision height was varied as part of the experiment from a maximum of 200 ft AGL 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.

3. Performance Standards

Integral to the CHPR scale is the definition of the required aircraft task and task performance standards. For the up-and-away evaluation, the aircraft's required task included all of the maneuvers. Hence, the CHPR for the configuration was based on performance in all maneuvers. The task performance standards are defined in Table III. The 5 mils error reference was easily gauged by the pilots since the waterline symbol height and radius of the velocity vector were both approximately 5 mils.

D.   Experimental Variables

The principal variables under investigation with these evaluations tasks were:

1.   Attitude Versus Flight Path Control

The air-to-air and modified clover leaf emphasized attitude control by explicitly dictating that the waterline marker be used in the execution of the task. Conversely, the velocity vector was explicitly called for in the pop-up weapons delivery task. For the air-to-ground task, the waterline or the velocity vector was dictated as the aiming symbol (pipper). After the first initial evaluation, there was concern, as described in Section V, that using velocity vector would bias the evaluations. The waterline was primarily used thereafter.

2.   Large Versus Small Amplitude Maneuvering

Two of the tasks, the air-to-air and air-to-ground maneuvers, were of relatively small amplitude, whereas the modified clover leaf and pop-up weapons delivery tasks were large amplitude maneuver tasks. The use of the adjectives, small and large, should be viewed cautiously and really only applies in comparison. The air-to-air task is by no means small in the sense of fine tracking. The air-to-air task commands up to 3 g target acquisitions. In comparison to the weapons delivery and modified cloverleaf maneuvers, the attitude changes are slight however and thus the small versus large comparison. Despite the large amplitude maneuvering nature of two of the tasks, specific aircraft attitude targets were stressed to ensure the integrity and accuracy of the task execution. For instance in the pop-up weapons delivery, the pilots were asked to arrive at a 27 degree dive angle while rolling out at a 60 degree heading change.

3.   IMC Versus VMC

Three tasks were performed IMC and one VMC to test if evaluation differences could be attributed to outside visual cues. It was also planned to test the VMC/IMC transition phase. This was not performed however because of the idiosyncrasies in the blue-amber simulation and the restriction of VFR flight for the T-33 during testing.

Table I

EVALUATION PILOTS

Pilot Ident	Flying Time	Aircraft Background	HUDs Flown (a)
A	2700	Air-to-Air	F-15
B	2700	Transport	
C	2900	Air-to-Ground	F-16
D	14000	Transport	(b)
E	3600	Reconnaissance, Flight Test	A-7, A-10, F-15, F-16

(a) All evaluation pilots had flown HUD evaluations in simulators of various types.
(b) Pilot D had flown several HUD evaluations in flight.

Table II

PILOT COMMENT CARD

- Assign overall Cooper-Harper Pilot Ratings
- Describe effect of aircraft handling qualities on task performance and pilot workload:
- Up-and-away
  - simulated air-to-air
  - air-to-ground
  - acrobatics/unusual attitude recovery
- Powered Approach
  - approach
  - flare and landing/waveoff
- Was the display (overall) adequate for mission?
- Effect of display on task performance
- Effect of display on pilot workload
- Good feature(s) of display:
- Bad feature(s) of display:
- Were display problems/deficiencies a function of
  - task
  - flight conditions (VMC/IMC)
- Any factor in evaluation due to
  - turbulence?
  - others?
- Summary/overall comments
  - any change in rating

Table III

EVALUATION TASK PERFORMANCE STANDARDS

| Desired Performance Standards	Adequate Performance Standards
ILS APPROACH:	
No PIO	Glide slope and localizer errors less than 1 deg for task.
Glide slope and localizer errors less than 1/3 deg 50 % of task, less than 2/3 deg remainder of task.	
SIMULATED AIR-TO-AIR:	
No PIO	Command attitude maintained within +/-5 deg in bank and 5 mils in pitch 90% of task (except for errors immediately following step command changes).
Command Attitude Maintained within +/-5 deg in bank and 5 mils in pitch 90% of task (except for errors immediately following step command changes).	
AIR-TO-GROUND TRACKING:	
Gross Acquisition	
Aggressively acquire aim point within 5 mils of pipper without overshoot.	Aggressively acquire aim point within 10 mils of the pipper with no more than one overshoot.
Fine Tracking	
No PIO	Pipper within +/-5 mils of aim point 10% of task, within +/-10 mils remainder of task. Would fire gun.
Pipper within +/-2 mils of aim point 50% of task, within +/-5 mils remainder of task. Would fire gun.	
LARGE AMPLITUDE MANEUVERS:	
Modified Clover Leaf	
Less than 3 deg deviation from 45 and -30 deg pitch attitude at maneuver initiation and ter-termination. Less than 5 deg deviation from 90 deg heading change command as passing through horizon.	Less than 3 deg deviation from 45 and -30 deg pitch attitude at maneuver initiation and termination. Less than 5 deg deviation from 90 deg heading change command as passing through horizon.
Pop-Up Weapon Delivery	
Less than 3 deg deviation from 25 deg pitch attitude at maneuver initiation. Less than 2 deg deviation from steady dive angle command.	Less than 3 deg deviation from 25 deg pitch attitude at maneuver initiation. Less than 2 deg deviation from steady dive angle command.

HANDLING QUALITIES RATING SCALE
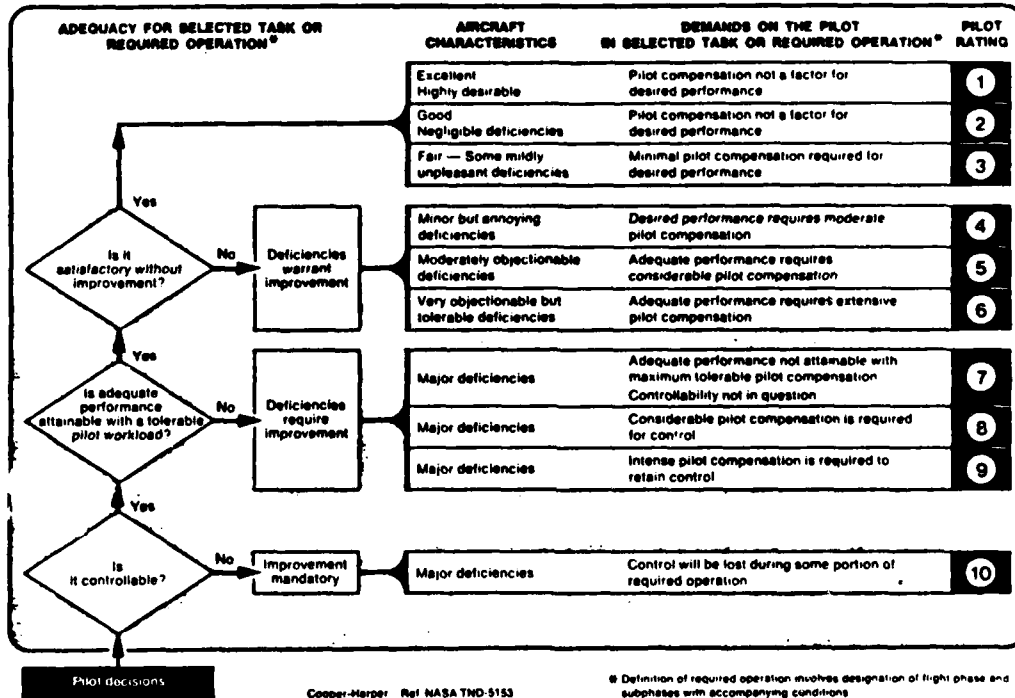
Figure 10
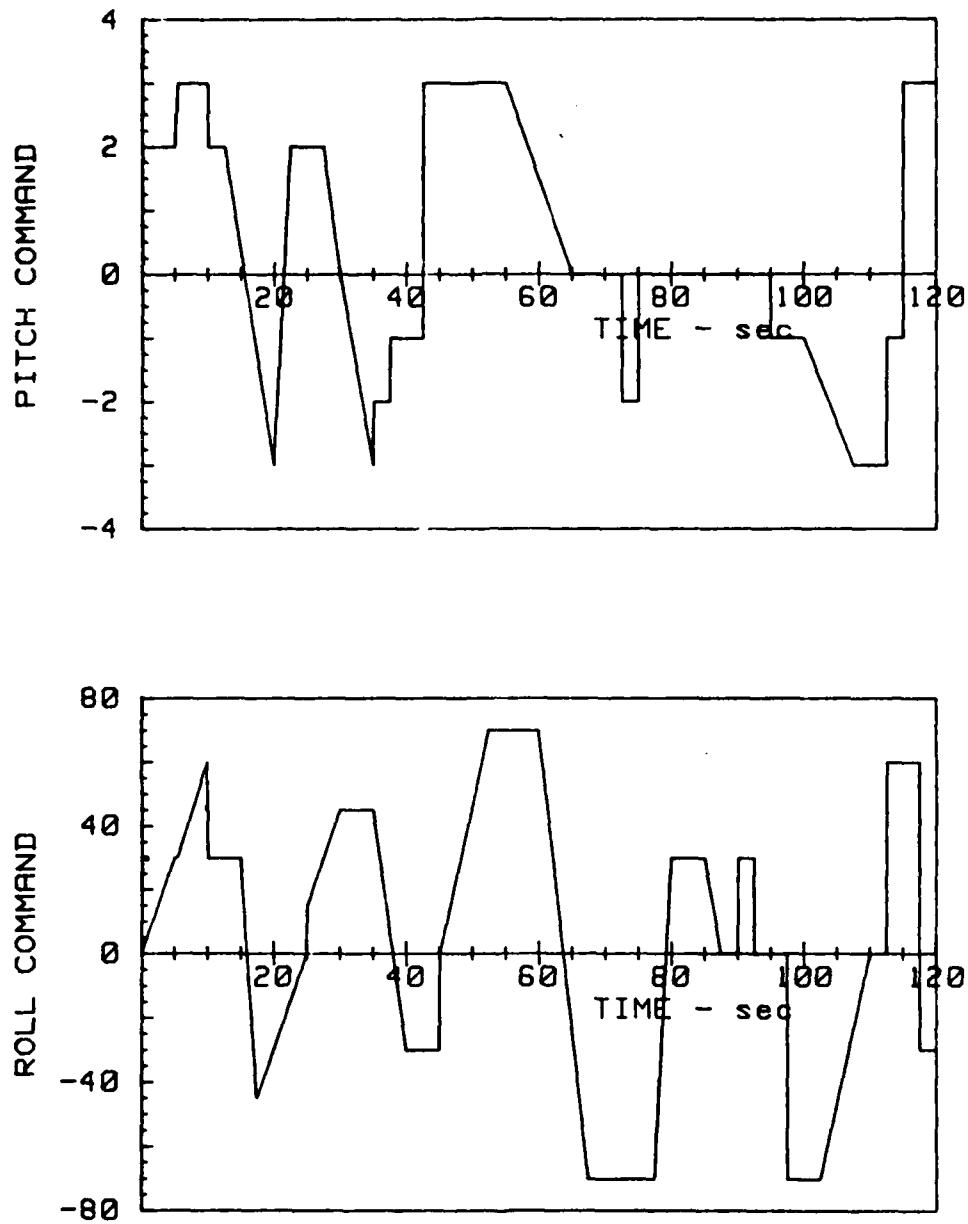
Pilot Rating Scheme (from Reference 18)

Figure 11

Command Pitch and Roll Attitudes For
Simulated Air-to-Air Tracking Task

V. EXPERIMENTAL RESULTS

The results of this in-flight experiment are presented in this section with discussion and additional data correlations.

A   Flight Program Summary

This flight program was performed in two phases.   Phase I was flown in October 1985 and Phase II in January 1986.   All flying originated from the Calspan Flight Research Facility in Buffalo, New York.   The program consisted of 36 flights totaling 49.5 flying hours.   96 piloted evaluations were performed as part of this study.   All of the evaluation pilots participated in the two flight phases with the exception of Pilot C who became unavailable for Phase II at the last moment due to a schedule conflict.   The breakdown of flights and evaluations by pilot is shown in Table IV below.

Each of the pilots was given an orientation/practice evaluation to become familiar with the evaluation tasks and procedures.

B.   Experimental Data

The experiment data consist of pilot rating, pilot comments, and task performance records.   The task performance records include data recorded on an on-board AR-700 digital flight recorder and video taken by a camera mounted just aft of the HUD combining glass.   The pilot comments for each evaluation are available in Reference (15).

Table V summarizes the results.   In Table V, the evaluation results of a configuration are grouped by whether the waterline or velocity vector was used as the aiming symbol in the air-to-ground task.   Similarly the power approach evaluation results are grouped by the presence or absence of the angle of attack bracket.   Both of these factors mere felt to be influences in the piloted evaluations and are delineated accordingly.   The influence of these factors will be further discussed in a later section.

C.   Dynamic Response Evaluation Data

Evaluation data for this dynamic response task were obtained in both the up-and-away and power approach flight phases.   These data are presented here with discussion contained in Section VI.

1.   Intra-Pilot Rating Comparison

Repeat evaluations of a configuration by the same pilot (un-beknownst to him) provide an indication into learning effects and the sensitivity of a configuration to piloting technique or other external factors (e.g., turbulence). The first and subsequent ratings of a configuration a pilot (intra-pilot rating comparison are shown in Figure 12. In this comparison, the configuration was classified as being different (not a repeat evaluation) if the aiming symbol (waterline or velocity vector) and angle of attack bracket were different. These factors, therefore, do not contaminate the intra-rating comparison.

The intra-pilot rating comparison for Pilot D and E is not available because of the lack of data.

The data of Figure 12 do not indicate any definite biases or trends; however, the correlation between first and subsequent evaluations does show scatter greater than the generally accepted +/-1 CHPR deviation. The probable reason for this scatter was the inexperience of the pilots in using the rating scale and in performing flying qualities evaluations. The pilots were thoroughly briefed (before evaluation flying began) on the rating scale, test objectives, and task performance standards. The use of the rating scale was continually reiterated and adherence to the task performance standards was stressed during the course of the experiment. Despite these efforts, inexperience and learning undoubtedly contributed to this scatter.

2.   Inter-Pilot Rating Comparison

A comparison of the ratings for a common configuration by different pilots is presented In Figure 13. This inter-pilot rating comparison is made to identify rating biases between pilots. Again, the influences of the aiming symbol in the up-and-away and angle of attack bracket in the power approach tasks have been factored out of this comparison.

Fairly good correlation is evident between the primary evaluation pilots (Pilots A, B, and C). Some points lie outside the +/-1 CHPR variability range, but considering the intra-pilot rating variability, this scatter was to be expected. The comparison of the three primary pilots to Pilot E, however, illustrates a definite bias toward worse ratings on the part of Pilot E compared to the others. Pilots A, B, and C were not trained flying qualities evaluators, whereas Pilot E was a test pilot school graduate. This rating bias could be attributed to a number of factors including flying qualities evaluation experience and task performance standards adherence. It may be that this rating bias is the normal rating bias between fleet pilots and trained flying qualities evaluation pilots who have different perspectives and different ideas for good flying qualities.

It may also be the case that the trained evaluation pilot may be more aware of pilot compensation. Often compensation on the part of the pilot to overcome aircraft deficiencies is subconscious in nature but not without a pilot workload penalty. The trained evaluator may be more alert to pilot compensation and workload. His rating will reflect this.

3. Effect of Added Display Time Delay - Up-and-Away

The effect of time delay in the head-up display was investigated by adding pure time delay to the display computer processing unit. Pilots A, B, C, and E were evaluation pilots for this phase. Three fighter-type aircraft configurations (A, B, and C) were used in the evaluations.

Cooper-Harper pilot ratings (CHPRs) are used to illustrate the aircraft flying qualities. The ratings are overall task ratings where the task included four distinct maneuver scenarios which the simulated aircraft was expected to perform in a mission. The attendant pilot comments (compiled in Reference 15) further depict and describe the aircraft's handling characteristics. These comments should always be referenced simultaneously with the pilot ratings to ensure correct interpretation of the results.

In Figure 14, the overall CHPRs are plotted as a function of the added display time delay. The figures are arranged by aircraft configuration. Also, evaluations which used the velocity vector for the air-to-air ground task are flagged.

During the calibration flight phases, it was noted that if the velocity vector was used as the aiming symbol (pipper), the overall task rating would be degraded because of the symbol lag and bounce. Reference (15) also includes two pilot comments summaries which were informal evaluations on the part of a Calspan test pilot who served as a practice evaluation pilot. These were the first indication of a potential biasing of the data because of the velocity vector dynamic response deficiencies. The practice evaluation pilot rated Configuration B, with no added delay, a 7 because of problems in air-to-ground task using the velocity vector. A similar degradation was noted during a practice evaluation with Configuration C. (Note that a PIO tendency was noted for Configuration B during the practice evaluation. Since the PIO tendency seemed to arise from a pitch sensitivity around trim, 0.5 lb of breakout force was added thereafter to all up-and-away configurations. It was confirmed that this change removed the PIO tendency.) The decision was made to begin evaluations using the velocity vector to serve as baseline data and also to attempt slight modifications to the display system dynamics to map out their effect. Thereafter, the waterline was used as the pipper.

The overall task ratings for a configuration in which the evaluation was performed using the waterline or velocity vector

as the pipper in the air-to-ground task are shown in Figure 15. The data clearly denote the degradation in flying qualities due to the velocity vector lag. Quantitatively, the ratings tended to degrade by approximately two rating units when the velocity vector was used. The evaluation pilot comments indicated that the velocity vector exhibited too much lag in its movement, and there was a tendency for the symbol to pop-up, overshoot, or bounce when attempting to settle on a target. These characteristics were essentially independent of the added display system time delay although added delay tended to accentuate the deficiency.

The velocity vector deficiencies are inherent to the aerodynamic sensors and are also dependent upon the experiment implementation. This area was not extensively investigated; rather, a quick look at the influence of velocity vector dynamics were investigated. For the air mass velocity vector, the velocity vector lags the pitch attitude response by the quantity $(1/\tau_{\theta_2})$ which equals the lift per unit angle of attack of the aircraft, l_α. Hence

FLIGHT PATH ANGLE (GAMMA) = THETA - ALPHA

In response to a pitch input, the velocity vector and pitch attitude response resemble the sketch of Figure 16. Traditionally, pilots have been trained to use pitch attitude and airspeed/angle of attack for flight path control through repetition of landings and ground attack runs. Flight path control is learned and pitch attitude, because of its inherent lead, is used as the primary flight path control reference.

With the head-up display, flight path (velocity vector) as well as pitch attitude can be explicitly displayed to the pilot. It becomes necessary, in this instance, in tasks which require precise and tight flight path control to quicken the velocity vector. The inherent lag in the velocity vector has to be compensated since it is explicitly displayed and controlled by the pilot.

In the nominal DEFT system, quickening of velocity vector is achieved by filtering angle of attack. Lead is provided to the marker by passing high frequency pitch attitude information without the angle of attack component. A time history overlay of the aircraft flight path and the air mass velocity vector responses was shown in Figure 9. This same comparison is made in the frequency domain in Figure 17. It is evident that a large phase lead occurs at high frequency in comparison to the flight path angle transfer function.

The flight test results indicate that these characteristics are not completely satisfactory for the up-and-away flight phase maneuvers. These response characteristics are conducive to overshoot and poor controllability in tight flight path control tasks.

One evaluation was performed where the dynamics of the velocity vector were altered. The angle of attack filter in the display computer was increased in frequency to 40 rad/sec from 20 rad/sec. This evaluation was with Configuration B and added display time delay did not show any significant change In flying qualities from nominal. The frequency domain overlay of this velocity vector transfer function with the aircraft flight path transfer function is shown in Figure 18.

In Figure 19, the velocity vector bias in the results is removed by plotting only those evaluations which used the waterline symbol in the air-to-ground task. The data of these figures show the degradation in flying qualities for added computational delay in the head-up display system. Further, the averaged pilot rating is plotted with the extremes in pilot rating indicated. Trend lines are drawn from these data indicating the mean pilot rating and the rate of flying qualities degradation with added display time delay. A threshold below which added display time delay does not cause any flying qualities effect was assumed to be 130 msec. The degradation rate was empirically determined by a least squares fit to the data beyond the 130 delay threshold.

The data indicate that:

- For Configuration A (high short period frequency, ω_{sp}), the mean pilot rating below the delay threshold was 3.80. The degradation rate was approximately 2.05 CHPR's per 100 msec added above the threshold.

- For Configuration B (medium ω_{sp}), the mean pilot rating below the delay threshold was 2.80. The degradation rate was approximately 1.75 CHPR's per 100 msec added above the threshold.

- For Configuration C (low ω_{sp}), the mean pilot rating below the delay threshold was 3.30. The degradation rate was approximately 1.45 CHPR's per 100 msec added above the threshold.

The pilot comments are dominated by the aircraft response characteristics. For the highest short period frequency configuration (Configuration A), pitch sensitivity dominated the pilot commentary, whereas, for Configuration C, comments indicated sluggish pitch.

As the added display delay increased, performance deteriorated. The definitive task for showing this performance degradation was the simulated air-to-air task. Flying qualities, as reflected in the CHPRs began to degrade after approximately 130 msec of delay was added to the display system. The degradation occurred at the highest rate for Configuration A, which also exhibited the greatest aircraft pitch sensitivity. The effects of

added display delay were not vividly evident in the modified cloverleaf or the pop-up weapon delivery maneuvers.

If the cross-model assumption is made (18), the pilot attempts to compensate for the aircraft dynamics such that the pilot/vehicle open-loop dynamics resemble a (k/s) system in the region of 0 dB crossover. Added display time delay introduces phase lag into the crossover region of the pilot-vehicle dynamic system Including the display system. The stability margins of the pIlot-vehicle system are most affected by display time delay for Configuration A because of its higher short frequency. As a result, the more severe flying qualities degradation for added display time delay could be expected for and was, in fact, for Configuration A.

The data also re-emphasize the importance of task and/or task performance standards for flying qualities. The effects of time delay for flying qualities have been associated with the analogy of falling off a cliff (19). For relatively open-loop, loose or low gain piloting control, the system time delay may not be noticeable; however, for tight control tasks or high pilot demand situations, the pilot-vehicle closed-loop stability may deteriorate rapidly as if falling off a cliff. The phase lag associated with time delay is directly proportioned to the control frequency and appears cliff-like on a logarithmic frequency scale. The modified clover leaf and pop-up weapons delivery tasks are open-loop in nature in that they do not require tight closed-loop piloting control. Some performance criteria demands were placed on the maneuvers by the institution of several attitude points, but these demands could not be construed as being precise tracking tasks.

Thus, the analogy of a flying qualities could not be exposed with these tasks. Conversely, the air-to-air task demands aggressive gross acquisition and precise fine tracking. In this task, time delay effects can be exposed given that the pilot uses a consistent and demanding task performance standard. Variations in task performance standards can be caused by differences in task performance levels. A large deviation in flying qualities could be expected if, in the presence of time delay, the pilots backed off in task performance to fly the maneuver. As a handling qualities test, a constant task performance standard is important, whereas, from an operations standpoint, whatever has to be done to get the job done, should be performed. Consequently, variation in task performance standards contributes to the rating scatter as time delay is added since the flying qualities cliffs may or may not have been exposed.

It has been shown in Reference 20 that the HUD compensatory tracking task is representative of actual air-to-air tracking. Direct comparison of the actual and simulated air-to-air tracking tasks showed that the simulated air-to-air task yielded similar flying qualities evaluation results. However, the rating results for the simulated air-to-air task demonstrated greater rating

scatter from that which occurred using actual air-to-air tracking.

4.   Effect of Sampling Rates - Up-and-Away

The effect of sampling rates for the head-up display was examined with Configuration B using the inertial velocity vector. The nominal air mass velocity vector operates on a 50 hz update rate.   For the inertial velocity vector, however, the inertial data are updated at 10 hz.

The pilot ratings for Configuration B with the different velocity vectors are shown in Figure 20.   The evaluation of the inertial velocity vector was performed with the marker caged in azimuth so that ground track angle was not displayed.   The reference frame differences between the inertial and air mass velocity vectors were transparent in this evaluation.   The pilot could not discern the influences of the reference frames in the markers. The pilot rating differences only reflect the sample rate differences.

The pilot comment for the 10 hz sample rate evaluation (using the inertial velocity vector) indicate that a rating of 6 was warranted primarily because of the unacceptable jitter and jumping of the display.   The velocity vector also exhibited unacceptable motion lag.   The critical control tasks in this evaluation were the large amplitude flight path control maneuvers (air-to-ground weapons delivery), i.e., where large rotation rates were incurred although even fine air-to-air tracking was not quite as accurate.

The poor ratings occurred because the discrete nature of the HUD symbology movement was noticeable and objectionable.   For small amplitude maneuvers, the stair-stepping of the response is not as noticeable and the sample rate effects are relatively transparent.

The results of this study would indicate that a 10 hz sampling rate is not satisfactory for an up-and-away fighter mission; conversely, a 50 hz sampling rate is sufficient.   At a 50 hz update rate, the effect of the sampling process can be accurately treated as a time delay component for flying qualities analysis.   Large amplitude maneuvers would appear to be the critical determinant of whether sampling rates are adequate.

5.   Effect of Added Display Time Delay - Power Approach

For the power approach evaluations, only Configuration D was used.   There were not enough evaluations to complete a display-aircraft compatibility matrix similar to the up-and-away flight phases.   The pilot rating results are shown in Figure 21, which shows an average pilot rating below an assumed threshold of 240 msec added display time delay of 3.40.

The degradation in flying qualities with additional pure delay added to the display (beyond the threshold) was approximately 2.0 CHPR/100 msec. This degradation was empirically determined by a least squares fit to the data beyond the threshold. The rating scatter increases beyond the generally accepted +/-1 CHPR variation from the mean when the delay becomes significant and degrading to flying qualities. This increase in scatter is a commonly observed feature of high time delay scenarios.

The conformal runway display without any added display delay was sometimes thought to be unrealistic in its movement, particularly in response to control inputs or turbulence. The conformal display was said to bounce excessively and be overly sensitive. In actuality, the movements of the runway display were not excessive nor inaccurate. The displayed runway position and Its relative motion were an accurate representation of the outside world. The pilot's observations were of a perceptual phenomenon. The runway outline display is projected against a virtual black (IMC) background. This display provides the pilot a relatively small foveal viewport to the outside world. Thus, control movements or turbulence which cause aircraft attitude changes create large displacements relative to the total FOV of the HUD. This perception was noted primarily on the first flights and subsided as experience grew. Certainly learning effects played a role in adapting to this display. For little or no added display delay, the landing guidance provided by this display yielded Level 1 flying qualities.

The pilot comments, as delay was added to the display, note increased and possibly annoying bouncing of the display. The experimentally added delay was such that the entire display was uniformly delayed. Of particular concern was the movement of the conformal runway which provided the landing guidance information. The pilot rating and flying qualities evaluation were decided by whether the pilot could compensate for the bouncing of the display or whether the bouncing deficiency warranted or required improvement. The pilot compensation for the bouncing was primarily to estimate the mean position of HUD symbols through their range of movement and attempt to control that movement. It was not the case that controllability problems occurred. At the highest time delay values, the pilots were seriously questioning the validity of the display and knowing that the movement on the display was not caused by turbulence or control inputs. In this case, the pilots ceased to track the velocity vector and runway display tightly.

The pilot rating data of Figure 21 are shown solid if the evaluation was performed in a high crosswind environment. Four evaluations were flown for this task in high crosswind environments and, in each case, poor ratings were given because of the FOV limitations. The rating degradation was 1 to 2 CHPR. 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 ap-

proximately 16 deg instantaneous lateral FOV or 8 deg from cen-
ter. For crab angles of greater than 7 deg, the runway display
symbology can be blanked because of FOV limitations. When this
occurred, the evaluation pilots had to transition to alternative
landing guidance in the approach. Unfortunately, for large crab
angles, no landing guidance at all is provided in the HUD. This
is a limitation of the current DEFT design and it was not altered
for this program. This issue and its solution were not a part of
the experiment. However, the overall rating for a configuration,
irrespective of the dynamic response characteristics, reflected
this FOV limitation and was downrated accordingly. These cross-
wind evaluations are excluded from the analytic discussion since
FOV was not a specific experiment variable.

For the power approach evaluations, a contact analog runway
symbology was used as the baseline HUD display. For the majority
of the evaluation pilots, it was their first exposure to this
type of display. in general, the runway display symbology was
found to be an effective, safe, and natural method for landing
guidance. The pilot comments were virtually unanimous in indi-
cating acceptance of the display. From informal comments, the
subject pilots were critical of the air mass velocity vector.
The majority of pilots desired an inertial velocity vector. This
desire may have also been prompted by the lack of a drift or
track angle marker for the air mass velocity vector. The
inertial velocity vector may not have been necessary if a track
marker was provided.

For the power approach task, the nominal air mass velocity
vector without turbulence was acceptable in terms of its dynamic
response characteristics. For the no-added delay cases, adverse
commentary was limited. Problems were encountered because of the
flight path reference frame, but these were not a dynamic re-
sponse deficiency. In power approach, the nominal 20 rad/sec
second-order angle-of-attack filter is augmented by a 2 rad/sec
first-order lag prefilter. The low frequency breakfrequency at-
tempts to restrict the turbulence input on the angle-of-attack
from corrupting the velocity vector. Also, the first-order fil-
ter on angle-of-attack again provides a lead component in the ve-
locity vector signal with respect to the actual aircraft flight
path by the increased pitch attitude contribution. The overlay
of the aircraft flight path and HUD displayed velocity vector
transfer function frequency responses for Configuration D is
shown in Figure 22. Qualitatively, the distortion of the veloc-
ity vector frequency response compared to the actual flight path
transfer function is less for the power approach task than for
the up-and-away task. This feature and possibly the attendant
task differences combined to yield satisfactory velocity vector
dynamic response characteristics.

One experiment factor that was not a controlled element was
turbulence. Turbulence may have a significant influence on these
results. This issue is discussed in a following section.

6. Effect of Sample Rates - Power Approach

Sample rate effects were investigated in the up-and-away flight phases using the 10 hz update rate of the inertial velocity vector. Pilot comments regarding use of the inertial velocity vector for the power approach task did not reflect any adverse commentary regarding the slower sampling rate for the inertial quantity. Apparently for the power approach flight phase, sample rates as low as 10 hz do not affect flying qualities.

Although the sample rate differences did not affect power approach flying qualities, the different reference frames between the inertial and the air mass velocity vector were a significant factor. In numerous instances, the nominal air mass velocity vector was criticized because of its inability to depict precisely the flight path in relation to the HUD runway display. The pilots did not feel that they were getting the help from the display that was possible because of the need to correct explicitly for wind variations. This situation was particularly acute for crosswind situations, where it was necessary to hold the velocity vector, some lateral distance from the no-wind aimpoint on the runway display. This situation is alleviated totally with an inertial velocity vector and might have been eased by the addition of a track marker to the air mass referenced display.

Table IV

EVALUATION SUMMARY

Pilot Identi- fication	Flights	Evaluations		
		This Study	Task B(a)	Total
A	10	38	13	51
B	7	26	5	31
C	4	19	6	25
D	4	5	8	13
E	3	8	2	10
Total	28	96	34	130

(a) Symbol Accuracy Study (21)

Table V

EVALUATION RESULTS

Additional Display Delay	Configuration A		Configuration B		Configuration C	
	V/V(a)	W/L(b)	V/V	W/L	V/V	W/L
0 msec	A: 3 B: 7	A: 5 C: 3 C: 3	A: 3 B: 4	A: 2 B: 3 C: 2	A: 4 B: 4	B: 4 C: 2 C: 4
40 msec	A: 5 A: 5	E: 4	A: 5	A: 3 B: 3 C: 3 E: 5		E: 6
80 msec	B: 4	A: 5 B: 4 C: 5	B: 5	C: 3		B: 3
120 msec		A: 2 B: 3	A: 5	A: 3 C: 3	A: 6 B: 4	C: 3 C: 4
160 msec	A: 5	A: 6 B: 6 C: 5	A: 5	A: 3 C: 3 C: 3 E: 6	A: 6	
200 msec		A: 3			B: 3	B: 4 C: 3
240 msec		E: 9		A: 2 B: 4		A: 6
280 msec		A: 5		A: 4		A: 6 B: 5
320 msec				A: 7		
AOA filter				A: 4		
INS V/V (10 hz)				A: 6		
1:1 to 2:1 Pitch Scaling			A: 3	C: 7	B: 5	
240 msec delay in FCS				A: 7		

KEY: Pilot: CHPR
(a) Velocity vector used as pipper in air-to-ground task
(b) Waterline used as pipper in air-to-ground task.

Table V (Continued)

EVALUATION RESULTS

Additional Display Delay	Configuration D		Configuration E		Configuration T	
	AOA(a)	NA (b)	AOA	NA	AOA	NA
0 msec	A: 5 B: 3	A: 3 D: 4		D: 3		C: 3 D: 3.5
40 msec		B: 3				
80 msec		C: 6 D: 4.5			C: 4.5	
120 msec		A: 4 B: 3 E: 4				B: 3(c)
160 msec						
200 msec		A: 3 B: 2 B: 4 C: 4 D: 5.5				
240 msec	A: 2 A: 5					
280 msec						
320 msec	A: 4 B: 7	B: 5				

KEY: Pilot: CHPR; All evaluations use symbol A, except as noted.
(a) AOA = Angle-of-attack bracket displayed.
(b) NA = Angle-of-attack bracket not displayed.
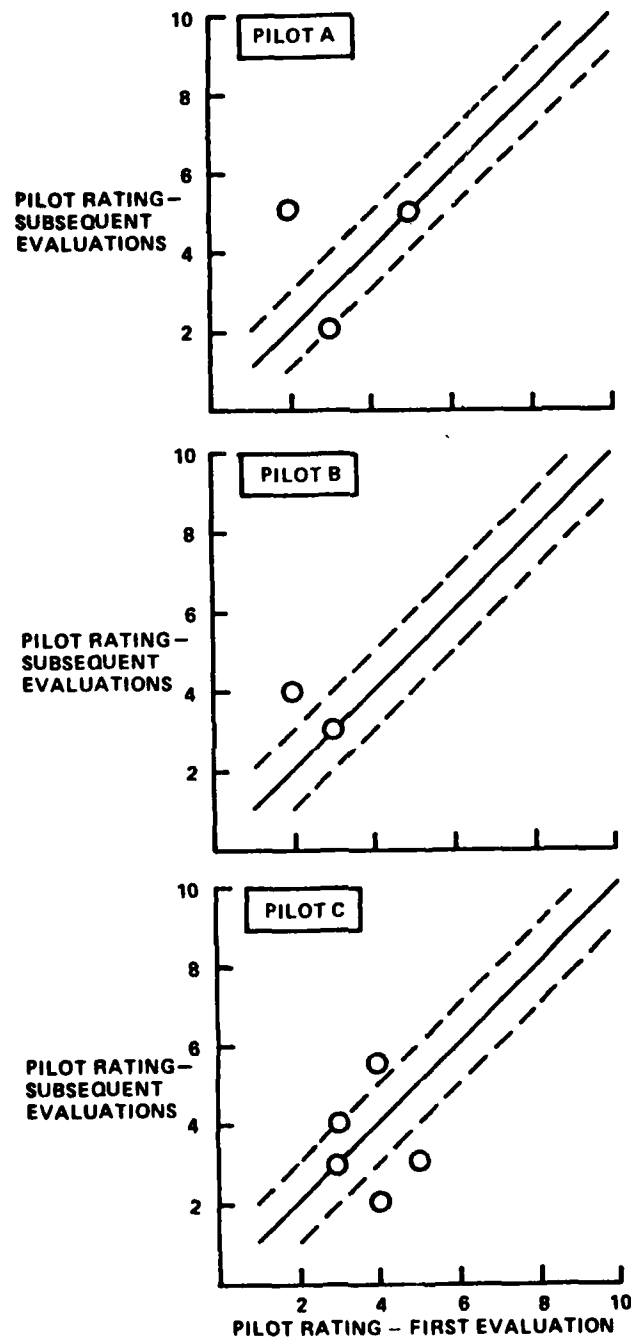(c) Symbol B used.
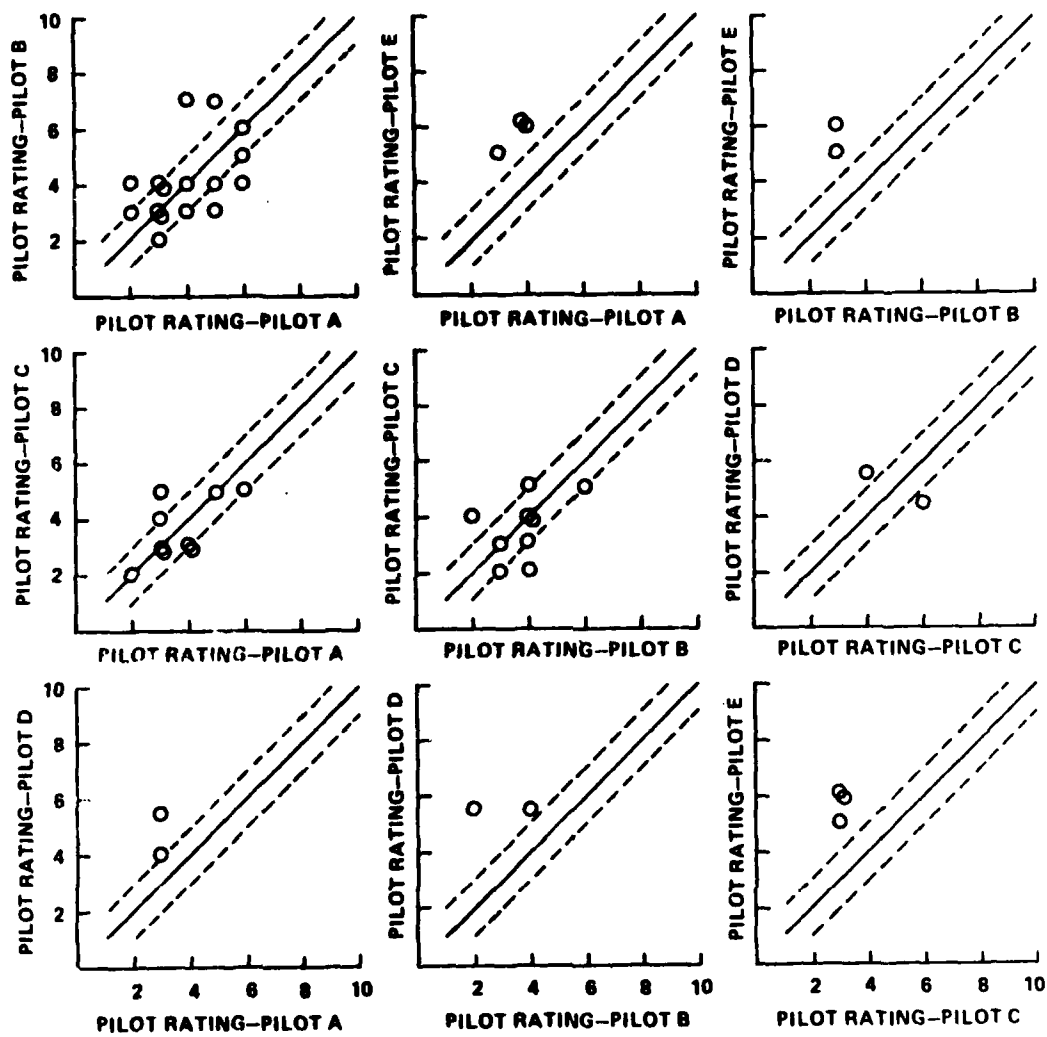
Figure 12

Intra-Pilot Rating Variation

Figure 13

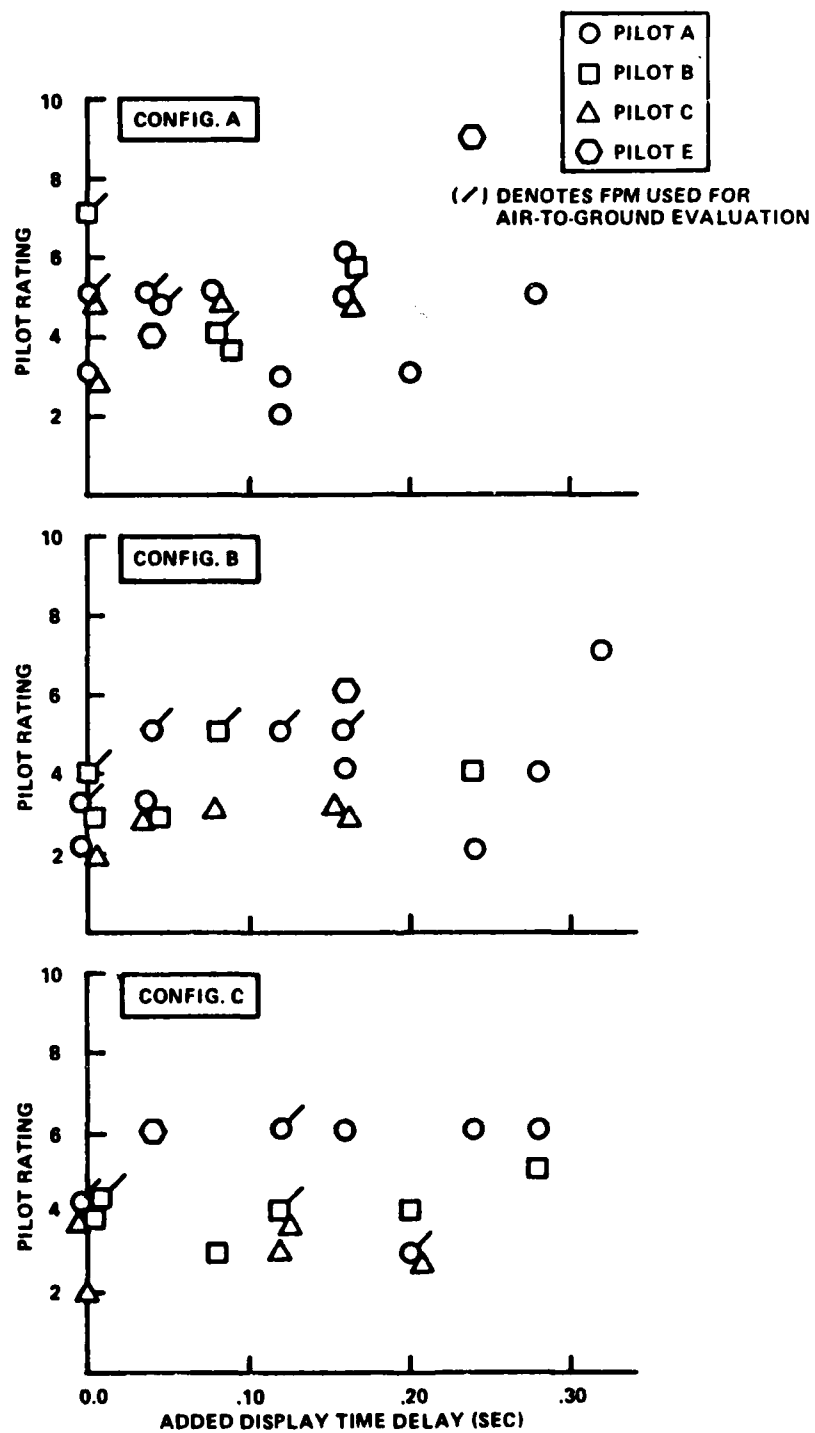Interpilot Rating Variability
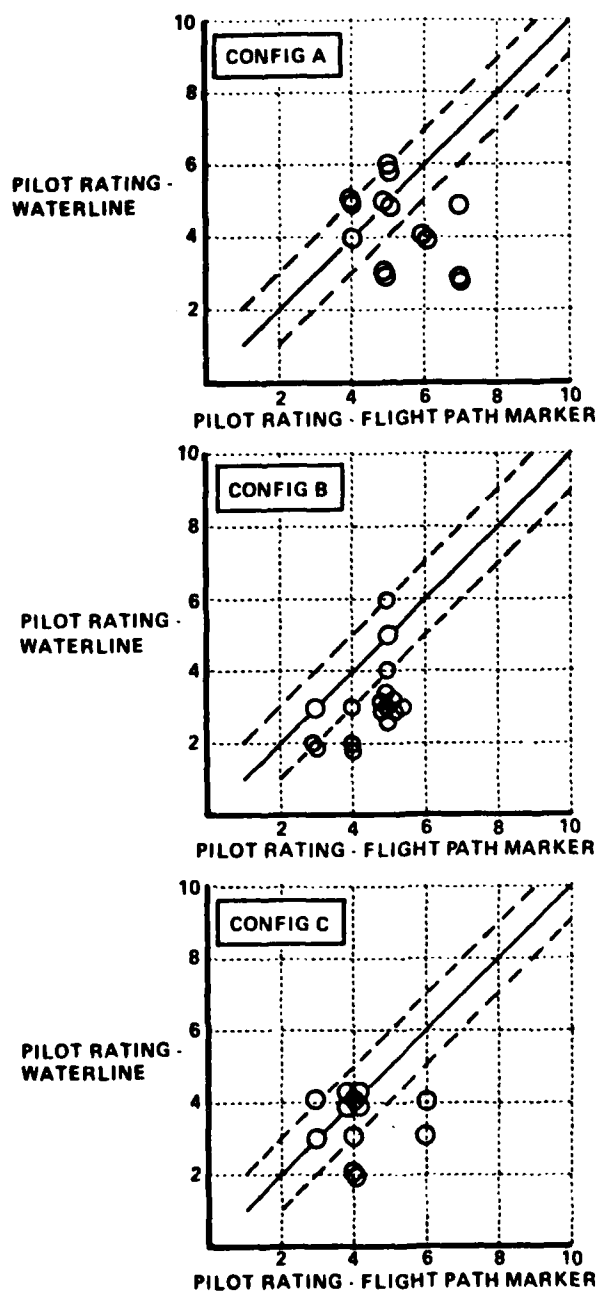
Figure 14

Dynamic Response -- Up and Away

Figure 15

Overall Task Pilot Ratings as Functions
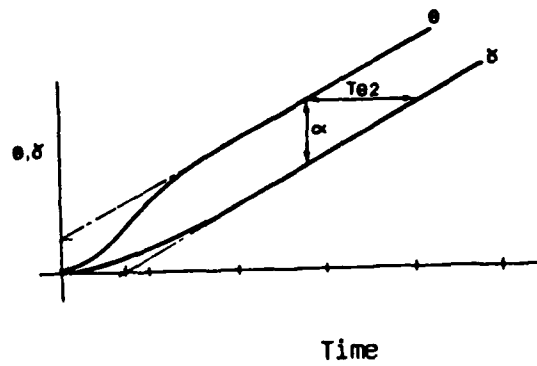of the Air-to-Ground Task Pipper Type

Figure 16

Pitch Attitude and Velocity Vector
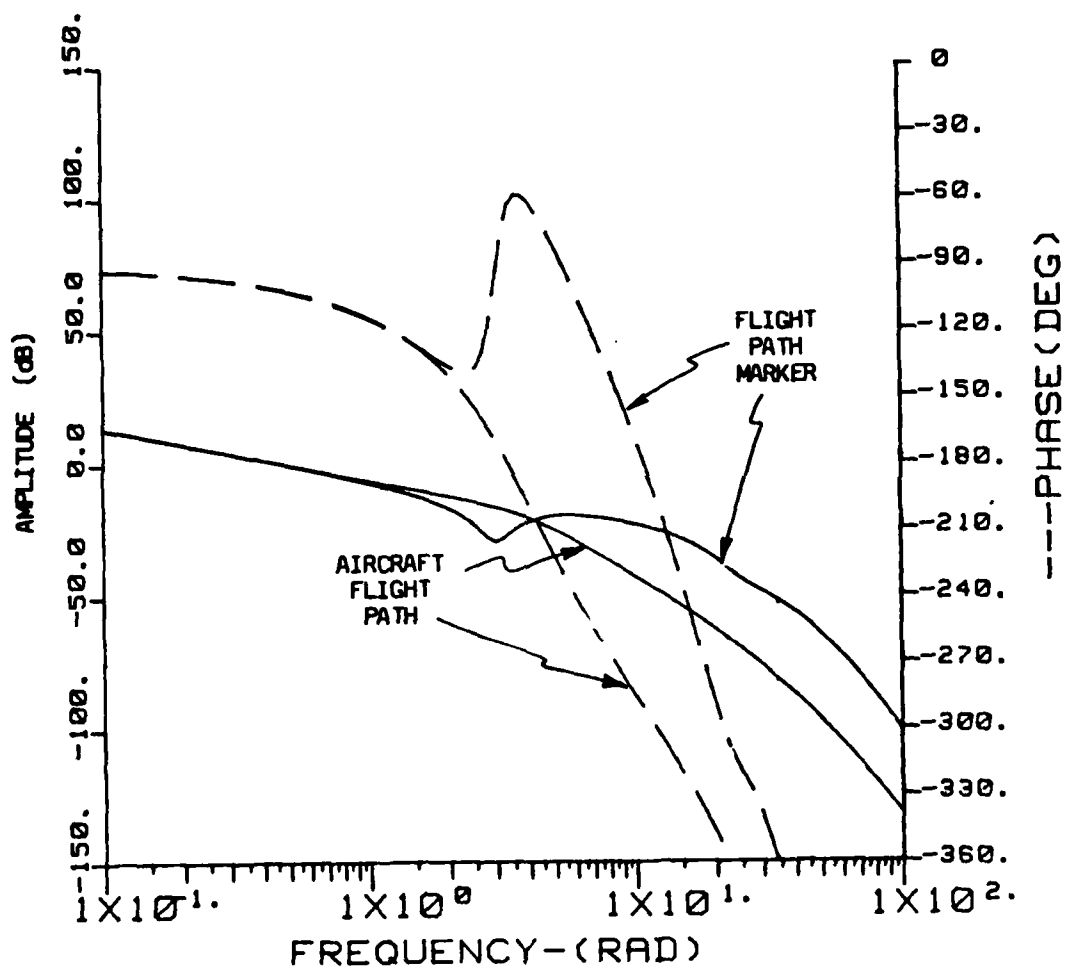Responses to a Step Command

Figure 17

Nominal Velocity Vector Frequency Response
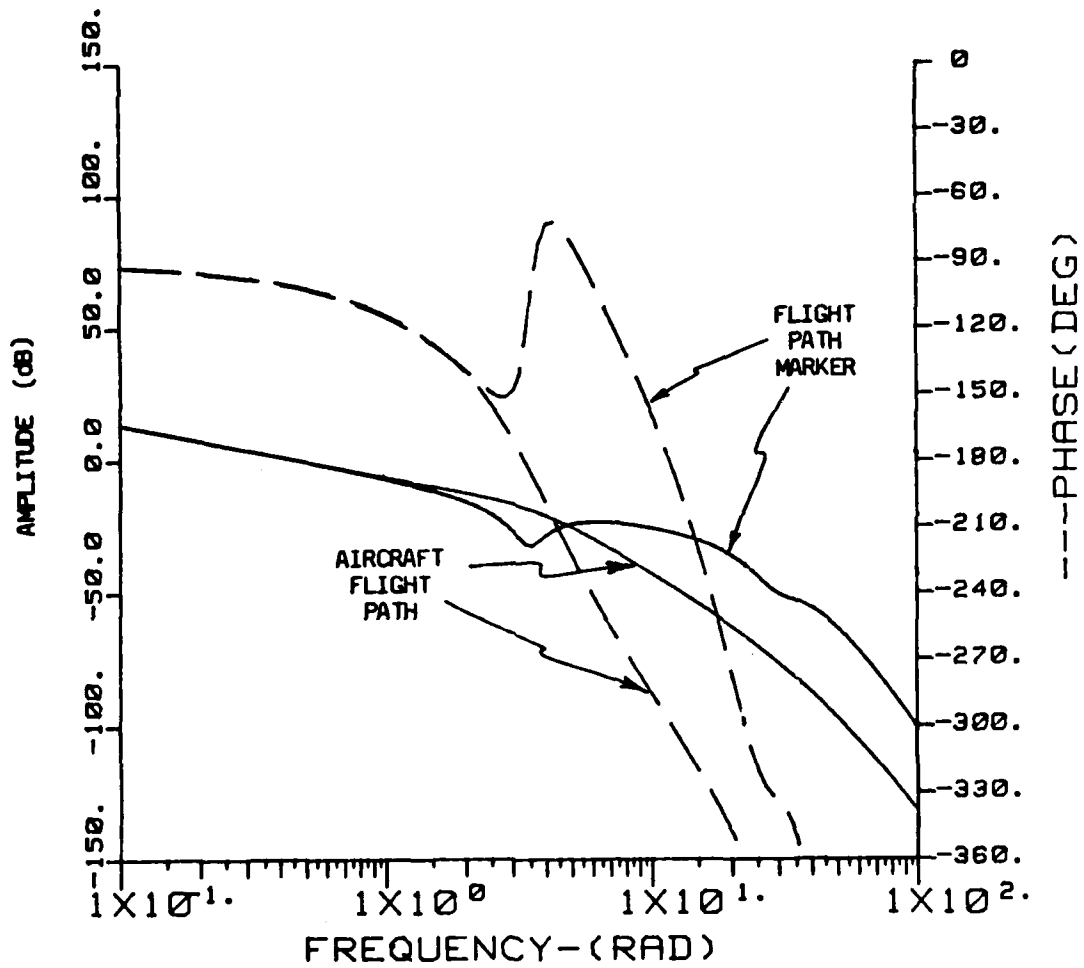(Configuration B)

Figure 18

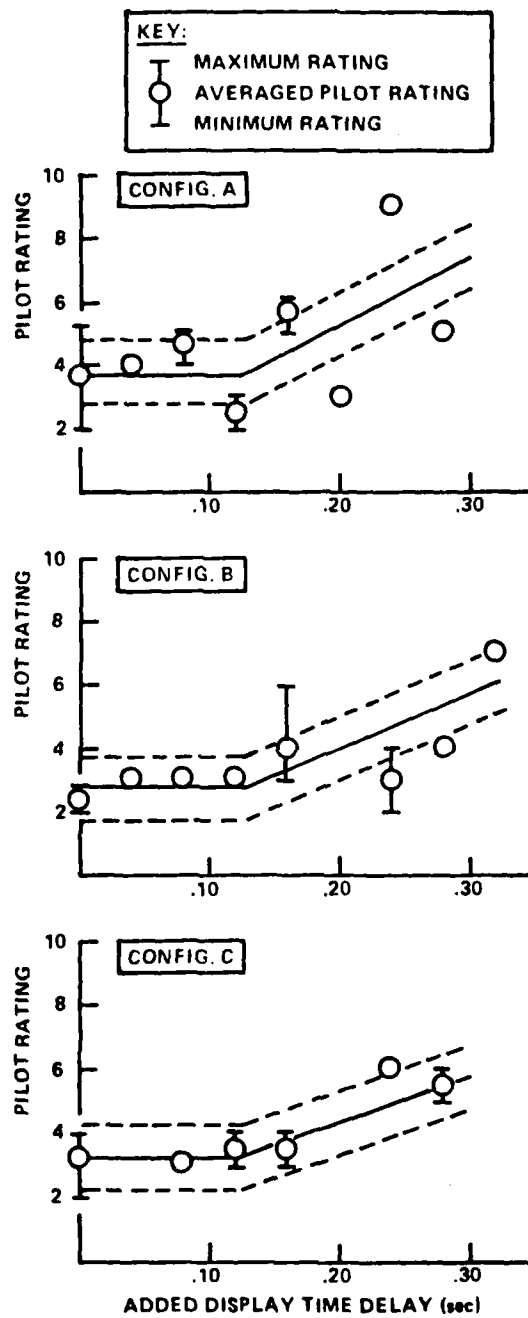Modified Velocity Vector Frequency Response
(Configuration B)

Figure 19

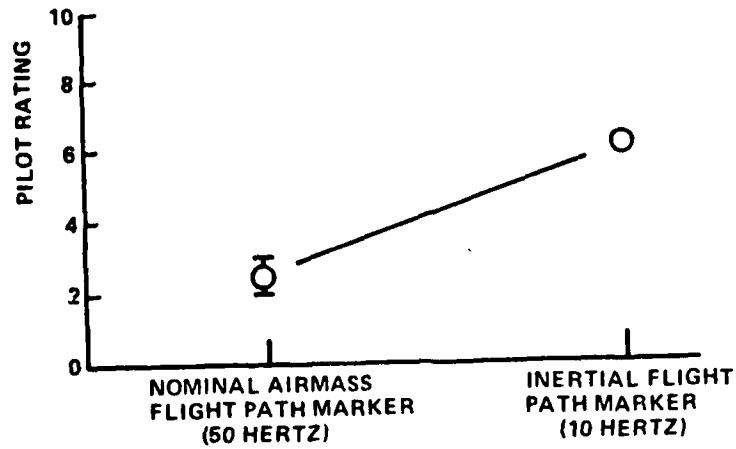Averaged Pilot Rating Results for Up and Away Task

Figure 20

Effect of Sampling Rate for Up and Away Evaluations
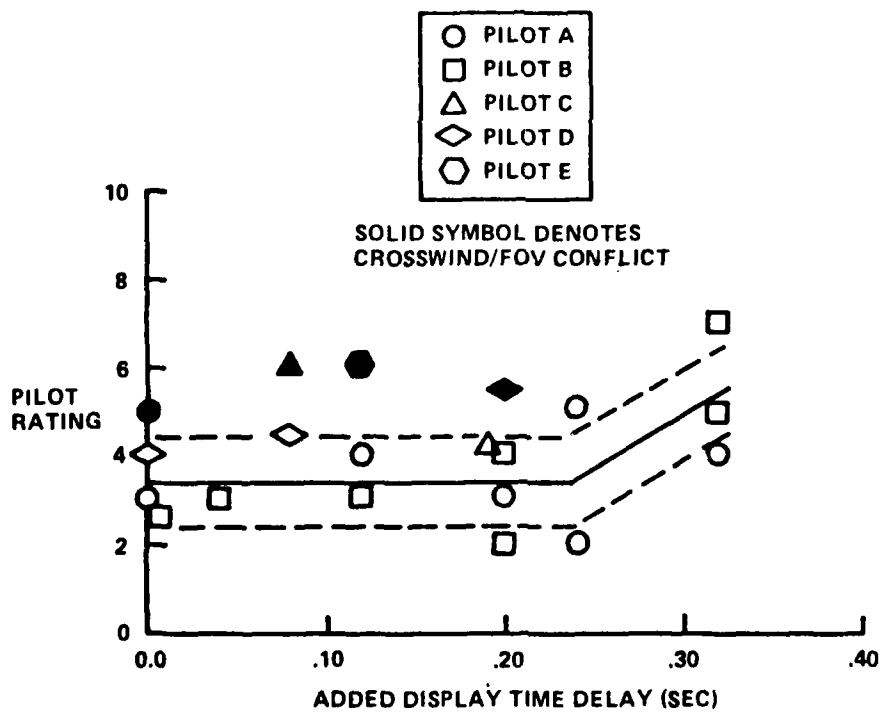

Figure 21

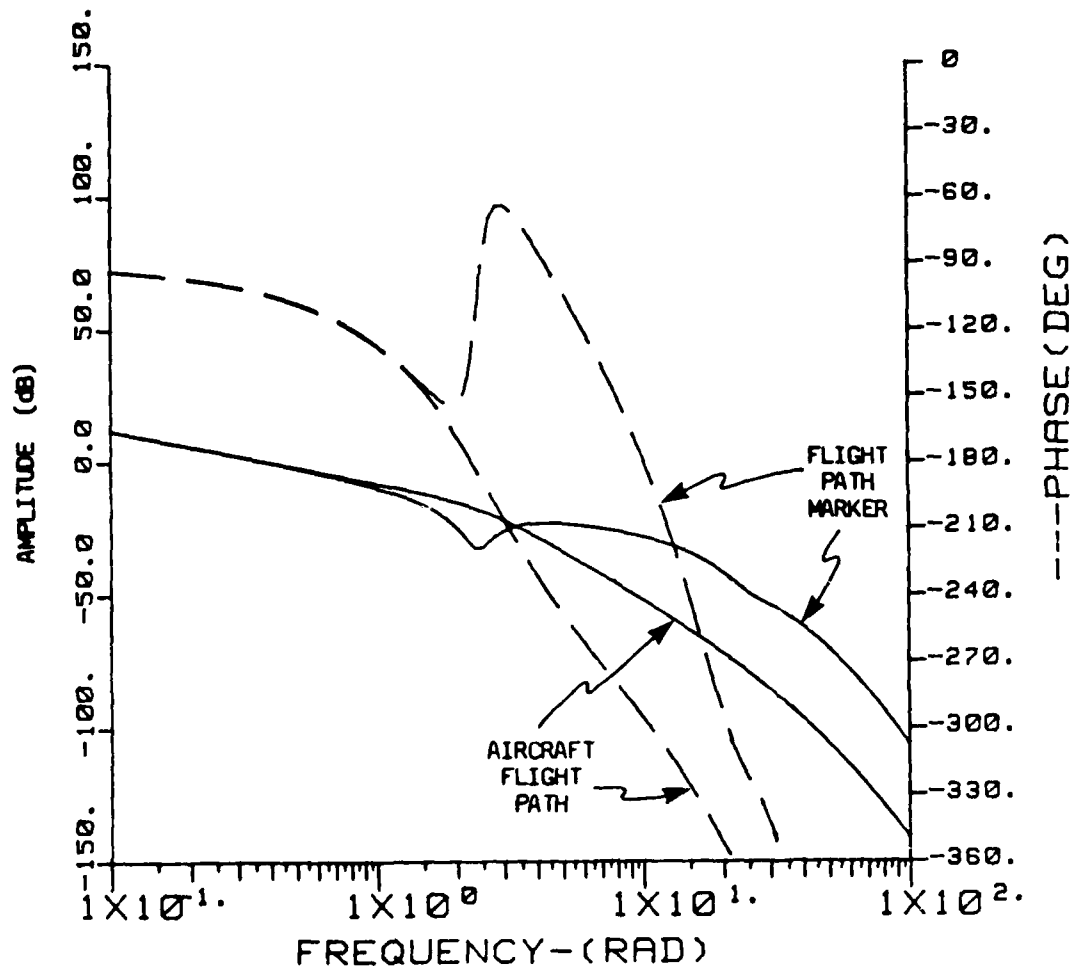Effect of Added Display Time Delay on Flying Qualities for Power
Approach Task

Figure 22

Power Approach Air Mass Velocity Vector Frequency Response

VI. DISCUSSION

This experiment was established because of the lack of data regarding the acceptability of HUD dynamic response characteristics for flying qualities. As such, there does not exist an abundance of other data from which to compare these results. Appropriate works are referenced in an attempt to relate these data to flight control and flying qualities and better understand how HUD dynamic response characteristics influences aircraft handling qualities.

A.   Effect of Time Delay on Flying Qualities

Considerable research has been expended in the investigation of the effects of time delay on flying qualities. Time delay in these studies was investigated between pilot input and motion response. Using the pilot/vehicle dynamic model of Figure 1, it is seen that control system time delay affects the motion and visual feedback equally; while the added time delay of this program was introduced only in the head-up display visual cue feedback. Added display delay in an IMC task generates temporal distortion between the motion and visual response cues.

The motion response in this study was characterized by an 80 msec delay between stick input and aircraft response. According to MIL-F-8785C, this delay level is within limits for Level 1 flying qualities (9).

1.   Up-and-Away Flight

In Figure 23, the pilot rating trends of Configuration B are plotted against the total visual equivalent time delay simulated. This delay represents the total delay between stick input and head-up display pitch attitude response. An equivalent system technique was used to compute the delay values. The 50 hz sampling delay for the DEFT system was assumed to be a pure delay element. Overplotted with this pilot rating functional are data from three other up-and-away flying qualities programs (23-25). For these three references, the equivalent time delay was added between the pilot input and motion response. The plots compare degradation of flying qualities for an otherwise good configuration with the addition of time delay. The threshold for each case is approximately the same (130 msec). The different degradation rates or line slopes are primarily a function of the task difficulty level. The more difficult task yields the greater rate of degradation with delays.

The data for added control system delay is dramatically different from the results of this program. The threshold below

which display delay does not affect flying qualities is 270 msec compared to 130 msec for the other data. However, the rate of degradation for added visual system delay beyond the threshold is similar.

A control system delay configuration was flown by the evaluation pilot A as a check during the evaluations. This evaluation was performed to verify that the rating process was being correctly applied and that the task performance standards were reasonable. The configuration had no added display delay but 240 msec of equivalent delay was added to the flight control system. The configuration was rated as PIO-prone and given a CHPR of 7. Control was not felt to be in question although concern of over-g was mentioned. This point, plotted in Figure 23 as "FCS Delay", closely matches the Reference (23) data. Thus, reasonable assurance is provided that the ratings for the display delay cases are accurate and that biases were not introduced by the experiment tasks and procedures. The task difficulty is also likely reproduced considering the good correlation between this point and the visual delay slope with Reference (23).

The pilot/vehicle dynamic system is referenced to explain these large differences between control system and display system delay effects. For each of the data bases, the overall task is essentially the same, although the specific evaluation tasks are slightly different; that is, whether delay is added to the control system or display system, the task was for the pilot to maneuver the aircraft such that the aircraft pipper is placed on the target. This task requires the pilot to null the visual error in pitch and/or roll attitude.

The data would suggest that there is a 140 msec deadband in the pilot's visual perception before which flying qualities are affected. The rate of flying qualities degradation beyond this threshold is similar to the control system delay case.

It is reasonable to assume that the Level 1 flying qualities in the motion response play a significant, although not completely defined role in these results. The human's motion (vestibular) sensors exhibit good high frequency response characteristics, good fidelity, and low thresholds. On the other hand, the visual motion sensors provide primarily low frequency, steady-state references of less than 0.1 hz frequency.

The visual system is known to have significant thresholds. Eye movements during visual tracking are characterized by three to four saccadic jumps per second which require approximately 100 msec. The accepted response time for visual tracking in the laboratory is 180 to 200 msec (26).

In the pilot/vehicle dynamic system, we separate the motion and visual cue feedback to the pilot. Under this assumption, two closed-loop paths exist, pilot(motion)-vehicle and pilot(visual)-vehicle. These systems are identical with the exception of the

pilot's (internal) sensors or cues. When a delay is added to the flight control system, the visual and motion cues are delayed equally. On the other hand, delay added only to the head-up display affects only the visual cue feedback to the pilot. Since a delay adds phase lag proportionally to frequency, closed-loop stability would be least affected by delay in the visual feedback path given that the visual cue sensors of the pilot are of low bandwidth. The high bandwidth motion cue feedback of the pilot should be more sensitive to delay effects.

Differences in the visual and motion plant dynamics is a problem in the ground-based flight simulator area. Research has been done for the visual/motion mismatch case in simulators. It should be noted that simulator motion cues are poor or impure when motion must be washed-out to remain within the physical confines of a ground simulator facility. These experiment results could mirror the case of a flight simulator with perfect motion reproduction, albeit an 80 msec motion delay and with various levels of computational delay in the visual scene generation. This data base suggests that given perfect motion cues an additional delay of up to 140 msec delay in the visual system can be tolerated before flying qualities are affected. This does not agree with the data of Smith, Geddes, and Honaker who indicated 100 msec to be the upper limit (11). These results are comparable with the FAA requirement (for transports) that the visual response should not lag the motion response of the simulator by more than 150 msec (12).

Available data from which to determine visual delay for current operational HUD-equipped aircraft are sparse. One suitable reference was found for the F-16 (27). Making several assumptions from the lack of detail in the reference, the F-16's displayed velocity vector can be said to exhibit approximately 60 msec delay from the actual flight path. In the F-16, inertial data are updated and processed at a 50 hz cycle time. In comparison with the data from this study, the 60 msec delay of the F-16 HUD should not noticeably affect its flying qualities. This conclusion is based on the assumption that the trends shown here for Level 1, low motion delay configurations also hold true for possible non-Level 1 motion configurations.

2. Power Approach

Once again, the relevant past work in this area concerns the effect of control system time delays on flying qualities. In Figure 24, the total visual delay configuration results from this program are plotted against three other data bases. A considerably different equivalent time delay threshold exists before the added delay effects flying qualities. For the control system delay data, the threshold is approximately 120 to 180 msec. For the visual delay of this program, a threshold is seen to exist at approximately 390 msec. This total includes approximately 80 msec of equivalent control system delay. These results are in-

consistent with the FAA requirement for transports that the visual response should not lag the motion response of the simulator by more than 150 msec (12).

The rate at which flying qualities degrade beyond the threshold has been postulated to be a function of the task difficulty. This relationship was experimentally verified in the power approach task in reference (24). Figure 24 shows two degradation rates for high stress and low stress tasks. The high stress task included a lateral offset correction maneuver prior to landing within a specified area; this task embodied considerable difficulty. The low stress landing task consisted of a straight-in approach with the landing not confined to any particular area of a 15000 ft runway; this task was fairly benign.

The evaluation task for the current program was the instrument approach with a visual landing. The program investigated the effects of systematically adding delay to the head-up display with a constant motion response delay. The motion delay itself, as indicated by other data, would suggest good flying qualities. In reference (19), it is noted that the effects of added (motion) delay are most dramatic in the final 50 feet to land when the pilot's control task becomes critical (high stress). The visual delay experiment of this program was, in actuality, only evaluated in the IMC approach phase. Delay added to the display are evaluated only on the approach phase up to breakout when the pilot transitions to VMC. In this case, the flying qualities due to added display time delay correspond appropriately to the low stress data of Figure 24. From reference (19), separate pilot ratings were given to various configurations for the approach task only. These results are compared in Figure 25. The rate of degradation of flying qualities beyond their respective threshold are almost identical. The thresholds are very different, however. The different delay thresholds are apparently due to the different manner in which the motion and visual cue feedbacks are used by the pilot in the pilot-vehicle system. Unlike the up-and-away case, the threshold difference approaches 200 msec. The different threshold values may be due to the difficult task requirements; the less demanding the task, the more tolerable the pilot is to visual delays.

B.   Effect of Sampling Rate

It was planned to investigate the effect of sampling at different rates between 10 hz and 50 hz in an effort to identify the threshold at which HUD display dynamics become unacceptable. Budget and time constraints limited this portion of the investigation to a single point with one aircraft (Configuration B). As shown in Figure 20, the CHPR degrade from approximately 2 for the 50 hz case to 6 for the 10 hz case. In other words, from a "good with negligible deficiencies" description to a "very objectionable but with tolerable deficiencies" description. The crossover

from satisfactory (CHPR < 3.5) to unsatisfactory (CHPR > 3.5) would occur somewhere around 20 to 40 hz.

This is clearly different from similar pure time delays. A 10 hz rate is the same as a 100 msec sampling interval. A pure time delay of 100 msec (but with 50 hz sampling) yields a CHPR of about 3 ("fair with some mildly unpleasant deficiencies").

A modification of the F-16 HUD has been reported to have developed unsatisfactory responses when the computer frame time was increased during the continuously computed impact point (CCIP) weapon delivery mode (28). Specific sampling rates were not reported.

C. Control/Display System Interaction

In this experiment, a generic HUD format was utilized which was specifically lacking in mission-oriented display features. In the up-and-away flight phases, it was shown that the air mass velocity vector dynamics were not acceptable for many tasks and the air-to-ground task in particular. Cursory analysis indicates that the HUD dynamics altered the displayed velocity vector in such a manner that the velocity vector symbol exhibited objectionable response characteristics. The symbol was described as being unacceptably sluggish with overshooting tendency under pilot control. It might have been more appropriate in this case to have mechanized a CCIP display for this task. In a similar light, the landing approach evaluations were conducted without any flight director guidance. Flight director guidance was inappropriate because of the desire to examine different contact analog runway formats.

Flight director or lead compensation displays become issues in terms of the influence of the display on flight control and flying qualities. The work here dealt primarily with added computational time delay. It is well established in the V/STOL community that head-up and head-down display systems can be used to augment the aircraft's flying qualities (29). Hence, there usually exists a tradeoff between flying qualities and display sophistication. In the program cited, excellent flying qualities were simulated using a status information display in various levels of degradation due to added display time delay. Future work could be directed along this tradeoff between pilot workload and cost. (It may be the case that this tradeoff does not exist for the CTOL aircraft since relatively good flying qualities are often available.)
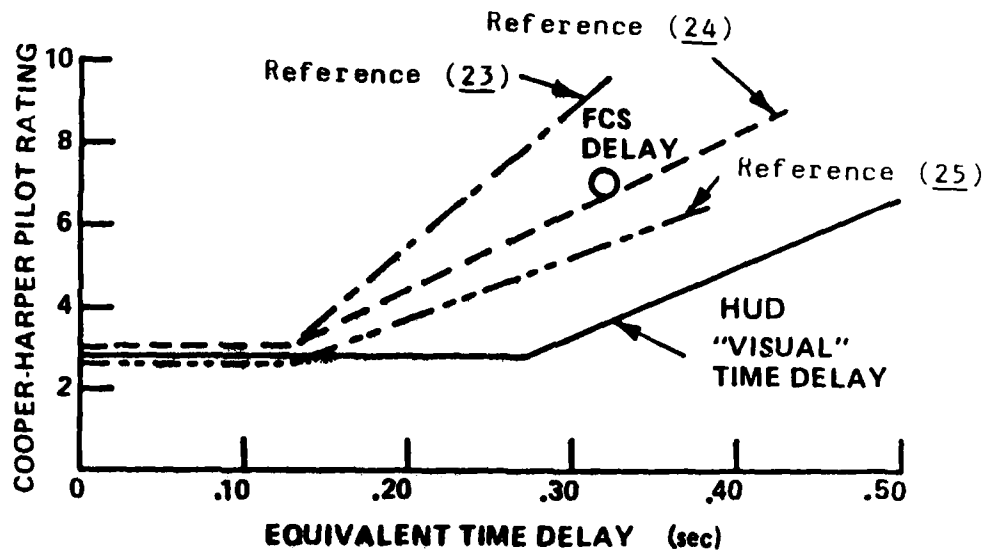
Figure 23

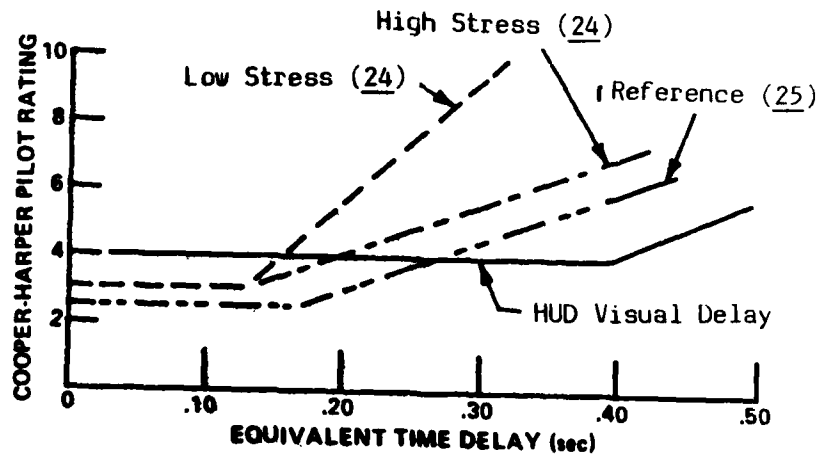Comparison of Time Delay Study Results for Up and Away Tasks

Figure 24

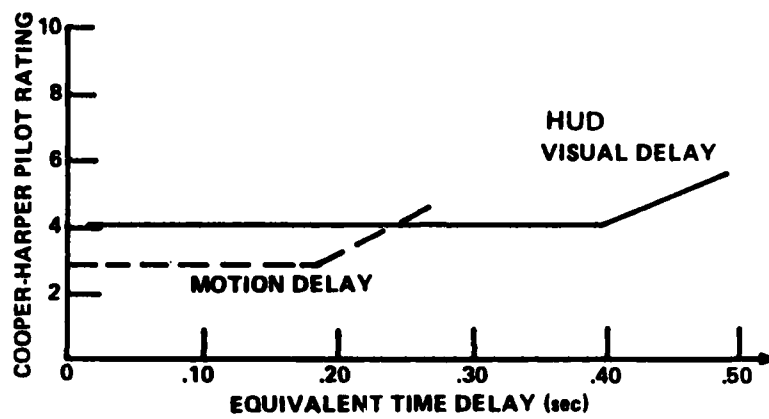Comparison of Time Delay Study Results for Power Approach Task

Figure 25

Comparison to Reference (19) Data -- Approach Task Only

VII. CONCLUSIONS

An in-flight investigation of the effect cf head-up display symbol dynamic response and symbol accuracy requirements was performed using the USAF NT-33A aircraft. The results of this study suggest that for the dynamic response requirements (Task A):

- There is a significant difference in the effect of time delay added to a head-up display system than that would be the effect for delay added to the flight control system. This effect can be understood by appropriately referencing the visual and motion cuing provided to the pilot.

- For a constant, Level 1 motion response, there is no effect on flying qualities in an up-and-away flight phase for up to 190 msec of equivalent delay added to the HUD display system.

- Beyond this threshold, flying qualities degrade by approximately 1.75 PR per 100 msec of computational delay added to the display.

- For the power approach task and a Level 1 motion response, there is no effect on flying qualities for up to 310 msec equivalent delay added to the HUD display system.

- Beyond this threshold, flying qualities degrade by approximately 1.95 PR per 100 msec of computational delay added to the display. The degradation rate is similar to that of added delay in the motion (control system) response for a low stress task.

- Sample rates as low as 10 hz do not affect flying qualities in the power approach task. The relatively benign maneuvers flown in this task may have been a factor.

- Conversely, a 10 hz sample rate for the up-and-away flight phase tasks was unacceptable because of the discrete nature of the display response. The 10 hz sample rate was a particular problem for the large amplitude evaluation tasks.

- These data suggest that there exists a substantial tolerance in temporal distortion between the motion and visual response cues which does not apparently affect the pilot as indicated by flying qualities evaluations.

There are inconsistencies between the results of this study and previous work. These differences are likely to be a result of the differences between pure time delays and sampling delays. The reader is cautioned against assuming that a fairly large delay with no effect will allow a computer frame time of the same length. Because computer frame times involve sampling, these results can not be directly compared.

VIII. RECOMMENDATIONS

Based on these results, several recommendations can be offered. In a follow-on program, the following ideas should be incorporated:

- Evaluate various sampling rate display configurations to determine the minimum acceptable sample rate for a given task. This task was only briefly examined in this experiment.

- Investigate other update (sampling) rates (20 to 40 hz) to identify point at which update rate becomes significant for both fighter and transport aircraft.

- Investigate filtering of slow (e.g., 10 hz) update rates to determine if the smoothing provided by a filter would eliminate the objectionable display characteristics of these sampling rates.

- Examine the effect of HUD dynamic response characteristics with motion flying qualities which are not Level 1.

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APPENDIX I

EQUIVALENT TRANSFER FUNCTIONS

<u>Up-and-Away</u> (250 KIAS/10 Kft)

Config A:
$$\left(\frac{q}{F_{es}}\right) = \frac{.484\ (1.25)}{[.85;\ 27.5][.7;\ 70.][.65;\ 6.5]}$$

$$\left(\frac{p}{F_{as}}\right) = \frac{11.0}{[.90;\ 25.][.7;\ 70.][.65;\ 4.0]}$$

- -

Config B:
$$\left(\frac{q}{F_{es}}\right) = \frac{.484\ (1.25)}{[.85;\ 27.5][.7;\ 70.][.65;\ 4.0]}$$

$$\left(\frac{p}{F_{as}}\right) = \frac{9.5}{[.90;\ 25.][.7;\ 60.](3.33)}$$

- -

Config C:
$$\left(\frac{q}{F_{es}}\right) = \frac{.484\ (1.25)}{[.85;\ 27.5][.7;\ 70.][.65;\ 2.7]}$$

$$\left(\frac{p}{F_{as}}\right) = \frac{8.0}{[.90;\ 25.][.7;\ 60.](3.33)}$$

<u>Power Approach</u> (135 KIAS, Sea Level)

Config D:
(Fighter)
$$\left(\frac{q}{F_{es}}\right) = \frac{.3.97\ (.80)}{[.85;\ 27.5][.7;\ 70.][.7;\ 2.6]}$$

$$\left(\frac{p}{F_{as}}\right) = \frac{5.0}{[.90;\ 25.][.7;\ 60.](2.0)}$$

- -

Config E:
(Fighter)
$$\left(\frac{q}{F_{es}}\right) = \frac{.397\ (.80)}{[.85;\ 27.5][.7;\ 70.][.7;\ 1.3]}$$

$$\left(\frac{p}{F_{as}}\right) = \frac{5.0}{[.90;\ 25.][.7;\ 60.](2.0)}$$

- -

Config T:
(Transport)
$$\left(\frac{q}{F_{es}}\right) = \frac{.239\ (.80)}{[.85;\ 27.5][.7;\ 70.][.7;\ 1.3]}$$

$$\left(\frac{p}{F_{as}}\right) = \frac{1.50}{[.90;\ 25.][.7;\ 60.](1.0)}$$

- -

NOTES: p and q = deg/sec

Short Notation Used: $(a) \triangleq \frac{1}{a}\ (s + a)$ $[\zeta;\ \omega] \triangleq (\frac{1}{\omega^2})\ [s^2 + 2\zeta\omega\ s + \omega^2]$

APPENDIX II

EQUIVALENT TRANSFER FUNCTIONS

Up-and-Away

Config A:
$$\left(\frac{q}{F_{es}}\right) = \frac{.484\ (1.25)e^{-.085s}}{[.65;\ 6.5]} \qquad \left(\frac{p}{F_{as}}\right) = \frac{11.0\ e^{-.080s}}{(3.33)}$$

Config B:
$$\left(\frac{q}{F_{es}}\right) = \frac{.484\ (1.25)e^{-.085s}}{[.65;\ 4.0]} \qquad \left(\frac{p}{F_{as}}\right) = \frac{9.5\ e^{-.808s}}{(3.33)}$$

Config C:
$$\left(\frac{q}{F_{es}}\right) = \frac{.484\ (1.25)e^{-.085s}}{[.65;\ 2.7]} \qquad \left(\frac{p}{F_{as}}\right) = \frac{8.0\ e^{-.080s}}{(3.33)}$$
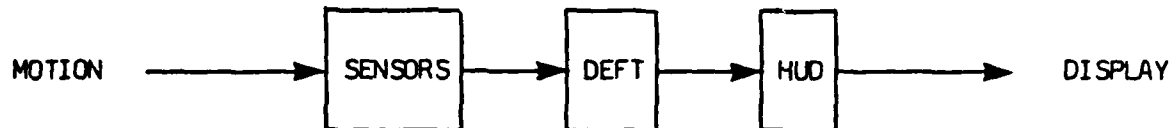
Power Approach

Config D:
$$\left(\frac{q}{F_{es}}\right) = \frac{.397(.80)\ e^{-.085s}}{[.7;\ 2.6]} \qquad \left(\frac{p}{F_{as}}\right) = \frac{5.0\ e^{-.080s}}{(2.0)}$$

Config E:
$$\left(\frac{q}{F_{es}}\right) = \frac{.397(.80)\ e^{-.085s}}{[.7;\ 1.3]} \qquad \left(\frac{p}{F_{as}}\right) = \frac{5.0\ e^{-.080s}}{(2.0)}$$

Config T:
$$\left(\frac{q}{F_{es}}\right) = \frac{.239(.80)\ e^{-.085s}}{[.7;\ 1.3]} \qquad \left(\frac{p}{F_{as}}\right) = \frac{1.5\ e^{-.080s}}{(1.0)}$$

APPENDIX III

MOTION-TO-DISPLAY TRANSFER FUNCTIONS

$$\left(\frac{\theta_{DISPLAY}}{\theta}\right)^* = \frac{e^{-.040s}}{[.5; 500.](500.)[.7; 69.]}$$

τ = 40 msec: 10 msec due to 50 hertz INS sample rate

10 msec due to 50 hertz DEFT sample rate

20 msec due to Rolm 1602 computational delay

$$\left(\frac{\phi_{DISPLAY}}{\phi}\right)^* = e^{-.030s}$$

τ = 30 msec: 10 msec due to 50 hertz INS sample rate

20 msec due to Rolm 1602 computation delay

$$\left(\frac{\alpha_{DISPLAY}}{\alpha}\right)^* = \frac{[0; 62.5] \, e^{-.040s}}{[.5; 500](500.)[.5; 62.5][.7; 75.][.7; .69][.7; 20.]}^{**}$$

τ = 40 msec: 10 msec due to 50 hertz INS sample rate

10 msec due to 50 hertz DEFT sample rate

20 msec due to Rolm 1602 computational delay

*   Short Hand Notation Used: $(a) = \frac{1}{a}(s + a)$

** Discrete filter represented by continuous equivalent; when landing
gear are extended, 2 rad/sec lag filter also is included.

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