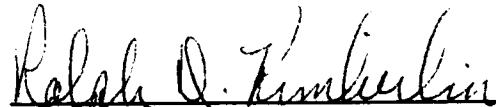
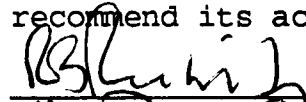
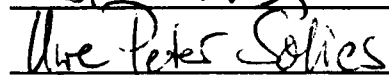


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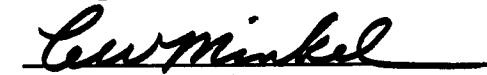
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Ralph D. Kimberlin
Major Professor

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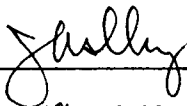

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USE OF THE NAVAL AIR TEST CENTER
MANNED FLIGHT SIMULATOR
FOR HANDLING QUALITIES EVALUATION OF
F/A-18 DIGITAL FLIGHT CONTROL SYSTEM DEGRADED MODES

A Thesis
Presented for the
Master of Science Degree

The University of Tennessee, Knoxville

Jeffrey S. Ashby
May 1993

ABSTRACT

The F/A-18 aircraft incorporates a digital "fly-by-wire" flight control system with four channel redundancy. In the event of a like failure in three or more of these channels, some control function is lost, and the system automatically reverts to a degraded (back-up) mode of operation. Degraded flight control modes of the F/A-18 are designed to enable the pilot to safely exit the combat arena, return to base, and land.

In 1988, an F/A-18 aircraft was lost after the flight controls degraded to a mode which had never been flight tested. Analysis of that mishap forced Navy testers to re-evaluate the need to flight test severely degraded flight control modes, and raised the question of whether results obtained from simulator testing could be used in lieu of high risk airplane tests.

This thesis compares degraded mode handling qualities of the F/A-18 Manned Flight Simulator (MFS) with those experienced in the actual aircraft during the approach and landing phases. The objective is to evaluate the accuracy of the simulator in predicting degraded mode handling qualities and to provide future testers with recommendations on conduct of handling qualities testing in the simulator.

Results show that the MFS could be used to predict aircraft degraded flight control mode handling qualities, provided that the test engineer and test pilot understand and

manage simulator characteristics, pilot aggressiveness and proficiency. Incorporation of motion cueing into the MFS would probably enhance the accuracy of simulator test results. The simulator was not accurate in predicting Pilot Induced Oscillation (PIO) tendency, and in particular, did not predict the tendency for lateral PIO during landing approach seen in actual flight test. Test pilots and engineers should continually be alert for the potential of dangerous PIO which may not be predicted due to subtle differences between the simulator and airplane.

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LIST OF ABBREVIATIONS

A/D	Analog/Digital
AOA	Angle of Attack
AOB	Angle of Bank
CAS	Control Augmentation System
CG	Center of Gravity
DEL	Digital Electric Link
FCC	Flight Control COmputer
FCS	Flight Control System
FREQ	Frequency
G	Normal Acceleration
GS	Glideslope
HQR	Handling Quality Rating
HUD	Heads Up Display
MECH	Mechanical Linkage
MFS	Manned Flight Simulator
MSEC	Microseconds
NATC	Naval Air Test Center
PIO	Pilot Induced Oscillation
RSRI	Rolling Surface to Rudder Interconnect
VIG	Visual Image Generator

CHAPTER I

INTRODUCTION

1.1 Background

In the summer of 1988, during an air combat training sortie over the Sea of Japan, one of the participating F/A-18 aircraft suddenly began to porpoise uncontrollably, the result of uncommanded oscillations of the horizontal stabilator from full up to full down. After several anxious seconds attempting to analyze the emergency, the pilot pulled the Flight Control System (FCS) circuit breakers, shutting down the Flight Control Computers and entering the Mechanical backup (MECH) mode. The aircraft immediately ceased porpoising, allowing the pilot to regain aircraft control and communicate his problem to technicians and other pilots on the ground.

Ground personnel relayed the following statement from the F/A-18 Operating Manual to the pilot: "Flight in this configuration (mechanical stabilator; ailerons and rudders inoperative) has not been demonstrated." There were no further recommendations in the operator's manual. Assuming that landing in Mechanical backup mode was not possible, the pilot reset the FCS circuit breakers in an attempt to regain a higher mode of flight control. The aircraft immediately

pitched nose down and rolled inverted. Unable to regain control, the pilot ejected.

Post mishap analysis raised the question of whether the F/A-18 could be safely landed in the mechanical backup mode. Research showed that this mode had never been flight tested because it was deemed too risky. Flight simulator testing had concluded that the aircraft could probably be safely landed in MECH, but the accuracy of simulator tests was questioned and the results were never published.

Discussion continued at the Naval Air Test Center (NATC), eventually leading to these questions:

1. Does the NATC Manned Flight Simulator (MFS) accurately replicate the F/A-18 aerodynamic response in backup/degraded modes?
2. Are pilot Handling Quality Ratings (HQR) for closed loop, degraded mode tasks in the simulator comparable to those in actual flight?
3. If not identical, can the simulator HQRs still be used to predict flight test results?

This thesis attempts to answer these questions by comparing HQR data from actual flight test of F/A-18 degraded flight control modes with results obtained from similar tests in the MFS.

1.2 Scope of Thesis

Closed loop task fidelity of modern flight simulators is a very complex topic, and one which is affected by nearly every simulation characteristic, including aerodynamic modeling, control loading, motion cueing and visual display system parameters. The scope of this thesis is limited to a primarily qualitative analysis of HQRs for six tasks in the approach and landing phase of flight. These tasks correspond to a given control axis and primary pilot reference as listed in Table I. Analysis is based on a comparison between actual flight test data and the results of similar testing done in the MFS at Patuxent River. The degraded mode of Mechanical stabilator with ailerons and rudders inoperative was not evaluated because there is no flight test data for this mode.

Table I.
Pilot Task Matrix - Approach and Landing Phase

Control Axis	Primary Pilot Reference		
	Internal	External	Both
Longitudinal (pitch)	angle of attack	glideslope	wave-off attitude
Lateral (roll)	angle of bank	runway line up	
Directional (yaw)	heading		

1.3 Pilot Handling Quality Rating

Closed loop handling quality evaluations rely heavily on subjective pilot interpretation of flying characteristics. These subjective assessments are quantified by observing the pilot compensation required to complete a specific control task within a given tolerance, for example, maintaining runway line-up within 5 feet of centerline during landing approach. A numerical value can be assigned, based on the level of compensation or pilot workload required. One widely used standard for handling quality testing, and the one used for this evaluation, is the Cooper-Harper Rating scale, Appendix C.

Many studies have been completed on simulator handling qualities concluding that transport delays, visual scene characteristics, and motion base characteristics all play a large role in how the simulator feels to the pilot.¹ For instance,

The computational accuracy of the simulator processors and A/D systems will affect the response threshold, and is similar to freeplay in a mechanical control system;

¹Horowitz, S. J., "Measurements and Effects of Transport Delays in a State-of-the-Art F-16C Flight Simulator," Proceedings of the Eighth Industry/NTSC Conference, NADC, Orlando, FL: November, 1986.
Sadoff, M., et al, The Use of Piloted Flight Simulators in General Research, NASA, Washington, D. C.: 1959.
Welch, B. L., "Characteristics of Flight Simulator Visual Systems.," Proceedings of the Fourth Industry/NTSC Conference, NADC, Orlando, FL: November 1982.

the bandwidth of the pipeline will cause increased phase delays as input frequencies increase, and can be compared to damping or inertia in mechanical systems; and the overall transport delay will cause a phase delay in the information presented to the pilot.²

The evaluation process itself adds even more variables, including task definition, environmental factors, performance tolerances, pilot aggressiveness and technique.³ The end result of all this is a complex system which must be well understood by the test team in order to properly interpret the pilot assigned Handling Quality Ratings.

1.4 Method of Test

This thesis compares Handling Quality Rating data from Manned Flight Simulator (MFS) testing with that obtained in actual flight tests. Test data has been gathered from several sources, including; Naval Air Test Center Flight Test Reports and Pilot Daily Reports, a Naval Air Test Center report on the aerodynamic fidelity of the MFS, and dedicated Handling Quality Rating testing in the MFS. Data from these sources is compiled and presented for ready reference in Appendix B.

²Poole, D., Evaluation of Simulator Bandwidth and Transport Delays Using Dynamic Techniques, VEDA Corporation, March, 1989.

³Parrag, M. and L. Knotts, L., Augmented Aircraft Handling Qualities, CALSPAN Corp., Buffalo, N. Y.: 1987.

During NATC flight testing of F/A-18 degraded flight control modes, it was observed that "open and closed loop flight characteristics and corresponding HQRs for a given task were primarily affected by the level of degradation in the task axis and could be evaluated independently of degraded conditions in other axes."⁴ This thesis makes the same assumption.

1.5 Test Configuration and Loading

Data used in this evaluation were taken under the following conditions:

<u>Configuration</u>	<u>Loading</u>
F/A-18A	Centerline mounted
FCC Software version 7.0	external fuel tank
Gross weight 26000-31300 lbs	No external wing stores
CG range 19% - 26.4% MAC	Symmetric loads
Half flaps	
Landing gear down	

⁴Canter, D., Second Interim Report on the User In-House Fidelity Evaluation of the F/A-18 Simulation at the Manned Flight Simulator Facility, NATC, Patuxent River, MD: 1990.

1.6 Author Participation in Testing

As an F/A-18 Test Pilot from 1988 to 1990, the author was directly involved in the analysis and discussions which followed the 1988 F/A-18 accident described in paragraph 1.1. The author participated in the technical evaluation tests of the MFS aerodynamic characteristics and conducted additional simulator testing to collect HQRs for use in this thesis.

The opinions expressed in this thesis are solely those of the author and have not been officially approved by the Naval Air Test Center or the United States Navy.

CHAPTER II

DESCRIPTION OF F/A-18 FLIGHT CONTROL SYSTEM

2.1 General

The F/A-18 incorporates a four channel, computer controlled, digital fly-by-wire flight control system (FCS) that hydraulically positions control surfaces.⁵ Electrical signals generated through a conventional control stick and rudder pedals are input to dual flight control computers (FCCs) which also receive reference information from the air data (pitot static) system, rate gyros, accelerometers, and angle of attack probes. The FCCs command deflection of the primary control surfaces which include all movable horizontal tails, twin rudders, ailerons, differential leading edge flaps, and differential trailing edge flaps. Roll coordination is provided by interconnects between the rolling surfaces and the rudders, and limiters are incorporated in the pitch and roll axes. Three axis trim is commanded by the pilot through the FCCs. The flight control system is shown in Appendix A, figure A-1.

⁵Hoffart, T. and Stevens, M., Limited F/A-18A Degraded Flight Control System Modes Flying Qualities Evaluation, NATC, Patuxent River, MD: 1988.
F/A-18 NATOPS Flight Manual, U. S. Government Printing Office, Washington, D. C.: December, 1985.

2.2 Cockpit Controls

Pitch and roll commands are initiated through a conventionally mounted, two axis, position sensing control stick. Stick position sensors transmit an electric signal proportional to stick displacement from neutral to the FCCs. Directional commands are made through force sensing rudder pedals which displace for pilot feedback. Stick and rudder feel are provided by spring cartridges. There is no aerodynamic feedback to the stick and rudder pedals, however, the effect is simulated by FCC scheduling of control surface deflection versus pilot input as a function of flight conditions. Movement of cockpit trim switches electrically biases the flight control computers, and the control stick will not move.

2.3 Flight Control System Modes

Normally, inputs to the hydraulic actuators are provided by the two flight control computers (FCC A and FCC B) through the full authority control augmentation system (CAS). In the event of failure of rate gyro or accelerometer feedback, a direct electric link (DEL) is available from the FCCs to the horizontal stabilators, ailerons and rudders. DEL is normally a digital system but has an analog mode for backup aileron and rudder control. Multiple failures of stick position sensors or FCC digital processors can preclude DEL

mode operation, in which case the ailerons and rudders become inoperative, and a mechanical link (MECH) automatically provides roll and pitch control through direct mechanical input from the control stick to the stabilator actuators. MECH mode bypasses both FCCs and the stabilator actuator servo valves.

2.4 Control Augmentation System (CAS)

The normal mode of the flight control system is CAS. In CAS mode, control surfaces are moved by the flight control computers in response to pilot commands. Motion feedback information is taken from three axis rate gyros, lateral and normal accelerometers. Three cross-axis interconnects enhance the flying qualities of the airplane: rolling surface to rudder interconnect (RSRI) to provide better roll coordination, rudder pedal to rolling surfaces interconnect to provide better roll coordination at high AOA, and an aileron to collective stabilator interconnect to compensate for an uncommanded pitching moment in the approach configuration with ailerons drooped.

In CAS, the longitudinal control system uses air data scheduled pitch rate, normal acceleration, and angle of attack to compute stabilator actuator commands. The aircraft response is compared to the pilot command and the stabilator servo actuator is driven to reduce the difference to zero. Pitch rate and G feedbacks improve pitch characteristics and

G control at medium to high airspeeds. During takeoff or landing (flap switch in Half or Full), AOA and pitch rate feedbacks are used to augment inherent airframe pitch damping and stability.

The lateral control system in CAS uses ailerons, differential leading and trailing edge flaps, differential stabilator, and rudders to achieve the desired roll characteristics. Scheduled air data roll rate feedback is used to augment inherent airframe roll damping. Differential flaps are not used during takeoff or landing. At low airspeeds, aileron and differential stabilator travel are reduced with increasing AOA to minimize adverse yaw. Differential stabilator may also be limited due to pitch command priority. With lateral stick deflection, the RSRI schedules increasing rudder deflection as a function of decreasing airspeed and increasing AOA for roll control, coordination, and to reduce adverse yaw.

In CAS, the directional control system moves the twin rudders for yaw control. Yaw rate is nulled by the FCS to provide yaw damping. Lateral acceleration feedback, roll rate to rudder crossfeed, and the RSRI improve turn coordination. During takeoff and landing, rate of change of sideslip feedback augments aerodynamic directional damping and stability, and rudder toe-in is used to improve the longitudinal stability and improve rotation during takeoff or bolter. Rudder toe-in is a function of AOA with maximum toe-in of 30 degrees at low AOA, decreasing as AOA increases.

2.5 Direct Electric Link (DEL)

A direct electric link in each axis provides continued electrical operation of the flight controls after multiple rate gyro or accelerometer failures make CAS operation impossible. DEL operation will usually occur in only one axis, but Yaw DEL automatically forces the Roll axis into DEL. Air data and AOA are still used for gain scheduling in DEL mode.

Pitch digital DEL provides control of the stabilators after three similar pitch rate gyro or normal accelerometer failures. There is no analog DEL mode in pitch.

Roll digital DEL provides roll control after three similar roll rate gyro failures. RSRI continues to provide rudder displacement for roll coordination. Roll analog DEL provides an additional direct electric path from the stick sensors to the ailerons for roll control after three digital processor failures. Analog DEL provides rudder coordination through an analog stick to rudder interconnect. There is no aileron trim capability in roll analog DEL. Differential flaps are not used in Roll DEL.

Yaw digital DEL provides directional control after three similar yaw rate gyro or lateral accelerometer motion feedback sensor failures. Yaw analog DEL provides rudder control through rudder servo commands without airspeed correction (feel) after three digital processor failures.

2.6 Mechanical Linkage (MECH)

Mechanical linkage provides backup collective and differential control of the stabilators for pitch and roll control after stick position sensors or digital processor failures which prevent the use of CAS or digital DEL. In the mechanical mode, control stick movement directly moves the stabilator actuators bypassing all position sensors, the flight control computers, all air data, all motion feedbacks, servos, and associated electrical wiring. Stabilator movement versus stick movement is increased with the flap switch in half or full to provide added authority for landing. Pitch trim moves the stick neutral position in the MECH mode.

2.7 Secondary Flight Controls

Secondary flight controls are the collective leading and trailing edge flaps, drooped ailerons, and the speedbrake. Collective leading and trailing edge flaps are controlled as a function of airspeed, AOA, and flap switch setting. During takeoff and landing in CAS, the ailerons are drooped to match the trailing edge flaps.

CHAPTER III

DESCRIPTION OF NAVAL AIR TEST CENTER MANNED FLIGHT SIMULATOR

3.1 General

The NATC Manned Flight Simulator (MFS) was designed and built in the early 1980's with a generic modular approach to allow for growth and continued integration of new technologies⁶. The MFS is unique among simulators in that it was developed as a tool for aircraft test and evaluation. Unlike most flight simulators which emphasize psychologic fidelity, MFS prioritizes the accurate duplication of aircraft aerodynamic characteristics. A dome and visual scene were added in the late 1980's to increase psychological fidelity and capabilities for man-in-the-loop evaluations. A six degree-of-freedom motion base has been developed, but is not presently used for F/A-18 flying qualities evaluations.

3.2 Architecture

The MFS facility includes high fidelity flight dynamics system simulations, high fidelity avionics system simulations, and a wide field-of-view visual system. The current architecture consists of several VAX computers, micro

⁶Manned Flight Simulator, NATC Technical Information Department, Patuxent River, MD: 1988.

VAX computers, AD100 array processors, 1553 data bus interfaces, simulation stations (cockpits), operator stations, and multiport memory. MFS architecture is depicted in Appendix A, figure A-2.

The VAX computers process avionics models, bus interface drivers, and flight dynamics models. Array processors prepare the speed-critical equations of motion in real-time. The MicroVAX computers execute satellite processes such as the operator stations, control loaders, and Heads Up Display (HUD) symbology. Currently, the MFS facility executes all simulations with a transport delay (stick input to visual movement) of less than 100 msec at 60 hz update rate and less than 125 msec at 30 hz update rate.

The MFS communicates through multiport memory to provide a data link to avionics and flight dynamics models. Through the use of a 1553 data bus interface, the network of computers also communicates with the F/A-18 mission computers and flight control computers. The avionics models duplicate the functions performed by the actual avionics in the aircraft.

3.3 Control System

Just as in the aircraft, the simulator employs a fly-by-wire control system which interacts via signals from the stick position and rudder pedal force transducers through the signal conversion equipment directly to the flight control

system software model to provide all necessary flight dynamics.

3.4 Flight Dynamics Modeling

Full envelope nonlinear aerodynamic models are constructed and installed in the aircraft's mathematical model by using available wind tunnel and aerodynamic data along with advanced analysis techniques. Aircraft flight dynamics are then simulated through the mathematical model which provides a dynamic representation of the aircraft behavior.

3.5 Visual Display System

Visual simulation is provided through a COMPU-SCENE IV Visual Image Generator (VIG) system projected onto a 40 ft dome. The projection system produces a color image for display of realistic images on the inside of the dome. The display FOV is 360 degrees in the horizontal plane and +90 to -55 degrees in the vertical. Further, an area of higher resolution is displayed on the dome directly forward of the pilot, covering a rectangular area of +-40 degrees horizontal by +-30 degrees vertical. The advertised transport delay for the visual system is 68 msec.

CHAPTER IV

TEST RESULTS AND ANALYSIS

4.1 General

Analysis of the fidelity of the MFS for F/A-18 degraded mode flying qualities required evaluation of the entire simulator system, including the aerodynamic model, the control system model, pilot sensory feedbacks, and the pilot himself, as depicted in figure 1.

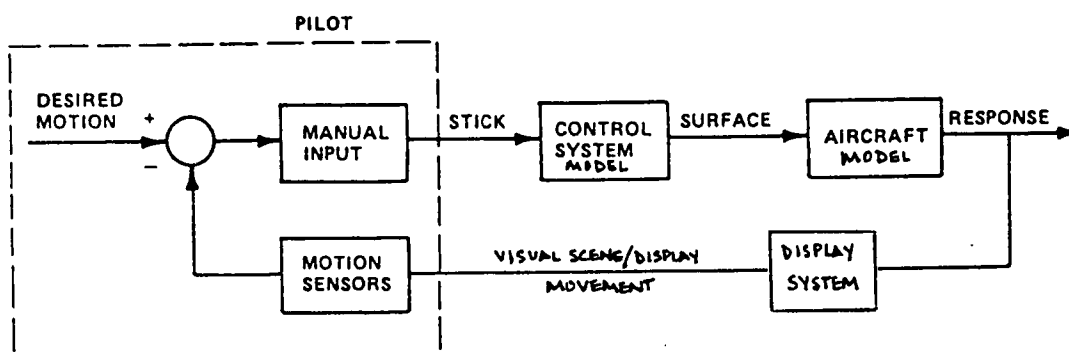


Figure 1.

Closed Loop Task Model⁷

⁷Ball, J. et al, Flight Syllabus and Background Material for US Navy Test Pilot School Variable Stability Program, CALSPAN Corp., Buffalo, N.Y.: 1986.

4.2 Aerodynamic Model Fidelity

The aerodynamic fidelity of the MFS was evaluated using data from a 1989 technical assessment of the simulator⁸. Open loop response data (computed from manual analysis of strip chart data) for the MFS and the F/A-18 aircraft in degraded flight control modes are presented in table II.

Table II.

Open loop response data

Degrade Axis/ Mode	Parameter	Center of Gravity %MAC	Gross Weight lbs	Simulator Data		Flight Data	
				Average Damping Ratio	Average Natural freq (cps)	Average Damping Ratio	Average Natural freq (cps)
pitch CAS	short period	22.7	31300	dead beat	dead beat	dead beat	dead beat
pitch DEL	short period	23.9	30500	0.14	1.2	0.19	1.5
pitch MECH	short period	23.5-26.4	29500-31000	0.15	1.1	0.20	1.5
roll/yaw CAS	dutch roll	22.7	31300	dead beat	dead beat	dead beat	dead beat
roll/yaw DEL	dutch roll	23.5-26.4	29500-31000	0.11	1.4	0.23	1.4

Damping was light in all axes and in all degraded modes. In the longitudinal axis, the simulator damping ratio was slightly less than that of the aircraft (for a given degraded mode). Pitch axis natural frequencies are slightly lower in

⁸Canter, D., Second Interim Report on the User In-House Flight Fidelity Evaluation of the F/A-18 Simulation at the Manned Flight Simulator Facility, NATC, Patuxent River, MD: April, 1990.

the simulator, and when combined with slightly lower damping, may contribute to a feeling of "sluggishness" in simulator pitch tasks. Dutch roll damping ratio data for the simulator and aircraft in roll/yaw DEL also show a quantitative difference, but probably result in an insignificant difference in pilot closed loop handling qualities, given the exceptionally light damping in both cases. Natural frequency data for dutch roll in the simulator matches that of the aircraft. Based on this assessment, the aerodynamic model of the MFS for lateral and directional axes is considered to be accurate for the purposes of this evaluation, but longitudinal differences may affect simulator handling qualities by contributing to a sense of sluggishness in pitch axis tasks.

4.3 Control System Fidelity

The control system model of the MFS is described in paragraph 3.3. The model was evaluated qualitatively and quantitatively to assess the potential for non-representative mechanical characteristics during pilot closed loop task completions. Feel springs used in the simulator were identical to those used in the aircraft. Plots of stick force vs displacement and rudder force vs. displacement for the aircraft and the MFS are compared in Appendix A, figures A-III, A-IV, and A-V. Mechanical characteristics of the MFS stick and rudders essentially duplicate the characteristics

of the aircraft. A simple comparison of the dynamics of the MFS versus those of the aircraft was made by estimating the frequency and damping of the control stick when released from the full aft and full left/right positions. Data for this assessment are presented in Table III.

Table III.
Control Stick Dynamics

Axis	Simulator		Aircraft	
	Overshoots	Frequency	Overshoots	Frequency
Longitudinal	7	3 CPS	6	4 CPS
Lateral	Deadbeat	-	Deadbeat	-

Control stick dynamic frequency and damping values compare closely between the MFS and the aircraft. The MFS control stick and rudder pedal characteristics appear to be representative of the aircraft for the purposes of this evaluation.

4.4 Pilot Aggressiveness

Handling Quality Ratings for a selection of tasks, axes, and degraded flight control modes are presented in Table IV. For these conditions, aggressive attempts by the pilot to maintain the chosen parameter resulted in higher HQRs than

Table IV.

Handling Quality Ratings for Aggressive Task Completion

Task	Degraded Mode	Simulator/Flight	HQR Range	Pilot Comments
Angle of Attack	Pitch DEL	Simulator	4-6	Aggressively capturing 8.1 AOA was very difficult, requiring large, well-timed inputs (HQR6)
Angle of Attack	Pitch MECH	Simulator	3-5	Aggressively capturing 8.1 AOA required 3 to 4 inch stick deflections (HQR5)
Glide Slope	Pitch DEL	Simulator	4-6	HQR4 to maintain glideslope once established. Initial capture or large corrections much more difficult (HQR 6)
Glide Slope	Pitch MECH	Simulator	4-6	Much harder with aggressive or large glideslope changes
Pitch Capture	Pitch DEL	Flight	3-4	More aggressive pitch capture resulted in overshoot (HQR 4)
Pitch Capture	Pitch MECH	Simulator	5-6	Pitch attitude correction required a large stick input, taken out before movement noticed visually, or PIO would result
Runway Lineup	Roll+Yaw DEL	Simulator	4-5	Larger corrections produce strong adverse yaw which requires stick inputs to dampen overshoots (HQR 5)
Runway Lineup	Roll+Yaw DEL	Flight	5-6	Adverse yaw was pronounced when making aggressive AOB inputs. PIO might be induced if pilot gains were high.
Heading	Roll+Yaw DEL	Flight	6	Greatly increased pilot workload during high gain tasks.

less aggressive attempts. HQRs for the task of "capture" attitude in the simulator were higher than those for "maintain" tasks and showed a wider split from flight

results. By their nature, capture tasks invoke more aggressive flight control inputs by the pilot, producing higher pilot gains and higher HQRs. These results agree with previous studies which found that "pilot ratings varied over a large range, depending on how aggressively [the pilot] flew the task."⁹

Secondly, unlike actual flight, the simulator does not place the life of the pilot in danger. The result is a potentially more aggressive attempt by the pilot to complete tasks in the simulator, using control forces, displacements and input frequencies that he might be reluctant to use in an actual degraded mode landing approach. During simulator testing for this evaluation, many of the pilots remarked about the aggressiveness of their inputs, particularly when investigating a tendency to PIO.

In most cases, test pilots tend to be more aggressive in the flight simulator, resulting in higher HQR spreads and higher average HQRs than for similar tasks completed in the airplane. Pilot aggressiveness can be managed effectively by the intelligent definition of task tolerances, the pre-planned use of "capture" type tasks, the briefing of test pilots to fly the simulator as if their life depended on it, and by the careful analysis of pilot flight control inputs which produce PIO.

⁹Parrag, M. and Knotts, L., Augmented Aircraft Handling Qualities, CALSPAN Corp., Buffalo, N. Y.: 1987.

4.5 Non-Degraded (CAS) Handling Qualities

Pilot HQRs for the CAS flight control mode are presented in Table V.

Table V.

CAS Mode Handling Quality Ratings

Task	Simulator results		Flight test results	
	HQR Range	Comments	HQR Range	Comments
Angle of Attack	2-3	Absence of seat of pants feel makes aggressive corrections more difficult. Tendency to chase.	2	none
Glideslope	2-3	Glideslope control was more difficult, possibly due to absence of motion feedback- tended to generate a small amount of PIO	2	none
Pitch Capture	2-3	Aggressive pitch capture attempts resulted in several overshoots	2	none
Angle of Bank	2	none	2	none
Runway Lineup	2-3	Chased lineup. Required frequent 1/4 to 1/2 inch lateral inputs. Some PIO.	2	Required infrequent 1/4 inch lateral inputs
Heading	2	none	2	none

HQR values were 2 for all approach and landing tasks in the aircraft. Simulator tested HQRs were slightly higher at 2-3 for all longitudinal tasks and for the runway lineup task. Pilot comments suggested that high task aggressiveness and

the absence of motion cues in the simulator contributed to a tendency to overshoot and chase the required parameter, resulting in a slightly higher HQR. Some PIO tendency was noted when attempting externally referenced tasks (glideslope, lineup) in the simulator, but not in the aircraft.

Motion acts as a pilot alerting cue which dominates his initial response.¹⁰ Motion cueing is particularly important in anticipating a sluggish aircraft response, or predicting an abrupt one. In the absence of this cueing, pilots are less precise in applying control inputs to stop an aircraft motion, often resulting in overshoot of the desired attitude, and in some cases, PIO. The absence of motion cueing in the MFS will slightly degrade closed loop Handling Qualities, particularly during capture type tasks or aggressive maneuvering by the pilot.

4.6 Longitudinal Axis Tasks

Longitudinal task HQRs were evaluated by comparing MFS and flight data for the tasks of maintaining angle of attack and glideslope on landing approach, and capturing pitch attitude on approach waveoff. Pilot HQRs for longitudinal axis tasks with flight control degrades are presented in Table VI. HQRs for all longitudinal tasks in the MFS

¹⁰Parrag, M. and Knotts, L., Augmented Aircraft Handling Qualities, CALSPAN Corp., Buffalo, N. Y.: 1987.

Table VI.
Longitudinal Axis Task Handling Quality Ratings

Task	Flight Control Mode	Simulator results		Flight test results	
		HQR Range	Comments	HQR Range	Comments
Angle of Attack	CAS	2-3	Absence of seat of pants feel makes aggressive corrections more difficult	2	none
Angle of Attack	Pitch DEL	4-6	Aggressive corrections were more difficult-HQR 6. Excessively light damping led to pronounced PIO	4	No PIO tendencies noted
Angle of Attack	Pitch MECH	3-5	AOA felt looser than in the acft. Aggressive corrections were more difficult-HQR 5. No PIO	3-4	No PIO tendencies were noted
Glideslope	CAS	2-3	Glideslope control more difficult, possibly due to absence of motion feedback	2	none
Glideslope	Pitch DEL	4-6	Initial capture or large corrections much more difficult (HQR 6)	3-4	Airplane overly sensitive to pitch inputs
Glideslope	Pitch MECH	4-6	Much harder with aggressive or large GS changes. Pilot learned to anticipate movement. Motion cueing would help.	3	Pitch sensitivity sluggish, requiring pre-programmed inputs
Pitch Capture	CAS	2-3	three overshoots	2	none
Pitch Capture	Pitch DEL	4	3-4 overshoots	3-4	more aggressive attempts resulted in overshoot-HQR4
Pitch Capture	Pitch MECH	5-6	Pitch attitude correction required a large input, taken out before movement was noticed, or PIO would result. Motion base might help pilot anticipate movement.	3-4	more aggressive attempts resulted in overshoot (HQR4)

exceeded those observed during flight tests regardless of the primary pilot reference. The largest differences between MFS and flight HQRs were seen during externally referenced tasks (glideslope and pitch attitude capture) in the Pitch MECH mode. Some of this difference is attributable to pilot overaggressiveness in the MFS as described in paragraph 4.4.

Another primary factor is the absence of motion cueing as discussed in paragraph 4.5. Studies have shown that simulator motions are generally required when the pilot's ability to cope with stability augmentation failures is involved.¹¹ Motion has also been shown to improve airplane control in situations where visual information is degraded or inadequate.¹²

Lastly, the wide spread in simulator HQRs, along with higher HQRs for externally referenced tasks and aggressive maneuvers suggests a possible manifestation of visual display time delay effects.¹³ While both the HUD display and dome visual scene are possible culprits for time delay effects, pilot HQRs have been found to be much less sensitive to HUD delay.¹⁴

¹¹Sadoff, M., et al., The Use of Piloted Flight Simulators in General Research, NASA, Washington, D. C.: 1959.

¹²Vancott, H., and Kinkade, R., Human Engineering Guide to Equipment Design, U. S. Government Printing Office, Washington, D. C.: 1972.

¹³Poole, D., Evaluation of Simulator Bandwidth and Transport Delays Using Dynamic Techniques, VEDA Corp: 1989.

¹⁴Parrag, M. and Knotts, L., Augmented Aircraft Handling Qualities. CALSPAN Corp., Buffalo, N. Y.: 1987.

Absence of motion cueing made longitudinal task completion more difficult in the MFS. Higher HQRs for simulator tests are also the result of pilot over-aggressiveness which may manifest the detrimental effects of time delay in the visual scene and display systems. The MFS could be an accurate tool for prediction of longitudinal task flight HQRs if a motion base is added and pilot aggressiveness level is properly managed.

4.7 Lateral-Directional Axis Tasks

Lateral and directional task handling qualities were evaluated by comparing MFS and flight data for the tasks of maintaining heading, angle of bank, and runway lineup during landing approach. Pilot HQRs for task completion with flight controls in roll and yaw DEL are presented in Table VII.

Handling quality ratings for all lateral and directional tasks were lower in the simulator than those observed during flight tests, regardless of the primary pilot reference. Pilot comments for flight tests with degraded roll and yaw axes included: "uncomfortable motions of the lightly damped dutch roll made the task more difficult;"¹⁵

¹⁵Canter, D., Second Interim Report on the User In-House Flight Fidelity Evaluation of the F/A-18 Simulation at the Manned Flight Simulator Facility, NATC, Patuxent River, MD: April, 1990.

Table VII.

Lateral and Directional Task Handling Quality Ratings
(Roll and Yaw axes in DEL)

Task	Simulator results		Flight test results	
	HQR Range	Comments	HQR Range	Comments
Angle of Bank	3	Easier to maintain AOB in simulator than airplane. Adverse yaw in simulator is annoying - would be uncomfortable in the airplane.	4	Difficult to maintain stable conditions due to the easily excitable Dutch roll oscillations.
Runway Lineup	4-5	Directional stability of the simulator felt higher than that of the airplane. Small corrections produced mild, nuisance dutch roll - wing rock more noticeable than yaw.	4-6	Lineup difficult due to constant roll and yaw oscillations. Adverse yaw increases pilot workload while trying to maintain lineup.
Heading	4	Directional stability of the simulator felt slightly higher than that of the airplane. Precise control not possible due to adverse yaw and light damping.	4-6	Easily excited and lightly damped dutch roll motion contaminated all mission tasks and greatly increased pilot workload during high gain tasks.

"Sideslip excursions caused by turbulence were very uncomfortable;"¹⁶ and "adverse yaw was more evident by 'feel' to the pilot."¹⁷ None of the pilots in the simulator tests mentioned the uncomfortable feel of the dutch roll, suggesting that they were not affected by it. The effects of

¹⁶Wirt, R. and Harney, R. J., F/A-18A Degraded Flight Control System Carrier Approach Flying Qualities Evaluation, NATC, Patuxent River, MD: 1987.

¹⁷Hoffart, T. and Stevens, M., Limited F/A-18A Degraded Flight Control System Modes Flying Qualities Evaluation, NATC, Patuxent River, MD: 1988.

varying pilot aggressiveness were again evident in the larger spread of HQR values for simulator tests. HQR spread is greatest for the externally referenced task of runway lineup, suggesting the possibility of detrimental effects from the simulator response time delay.

For the lateral and directional axes, the absence of motion in the simulator reduces the impact of "uncomfortable" or "nuisance" dutch roll oscillations on the pilot, resulting in slightly lower HQRs for a given task. The MFS could be a more accurate tool for prediction of lateral directional handling qualities if motion is added to properly represent the nuisance effect of lightly damped dutch roll.

4.8 Pilot Induced Oscillations

PIO tendencies were evaluated by comparing MFS and flight data for all six landing and approach tasks. Pilot assessment of PIO tendencies are presented in Table VIII. An attempt has been made to quantify the level of PIO, based on pilot comments.

Pilot comments on PIO were inconsistent for all tasks in the simulator and in flight, sometimes ranging from none to pronounced PIO for the same task, degraded axis and platform. This is due, in part, to varying levels of aggressiveness, and possibly due to different pilot interpretations of what constitutes PIO. Table VIII data shows that longitudinal

Table VIII.

Tendency for Pilot Induced Oscillation

Task	Flight Control Mode	Simulator PIO	Flight PIO
maintain angle of attack	CAS	none	none
	Pitch DEL	none-pronounced	none-slight
	Pitch MECH	none-moderate	none-very slight
maintain glideslope	CAS	slight-moderate	none
	Pitch DEL	slight-pronounced	none
	Pitch MECH	pronounced	none
capture pitch attitude	CAS	none	none
	Pitch DEL	slight	slight
	Pitch MECH	moderate	none
maintain angle of bank	CAS	none	none
	Roll/yaw DEL	none-slight	moderate
runway lineup	CAS	slight	none
	Roll/yaw DEL	none-slight	moderate
maintain heading	CAS	none	none
	Roll/yaw DEL	none	slight

PIO was much more prevalent in the simulator than in the airplane. Possible explanations include varying pilot aggressiveness, absence of motion cueing, and the slightly less damped and lower frequency short period. Lateral-directional task data indicates a tendency for lateral PIO in flight that is more serious than that predicted in the MFS. In this case, absence of motion in the simulator may have improved the pilot perceived handling qualities.

MFS testing did not accurately predict PIO tendency, a potentially serious drawback. PIO prediction might be improved by addition of a motion base to the MFS and proper management of pilot aggressiveness.

4.9 Pilot Learning Curve

The affect of pilot training and proficiency on degraded flight control mode HQRs was qualitatively evaluated by analysis of pilot comments and by general observation. During shipboard landing evaluation in degraded modes it was observed that "The [pilot's] ability to fly the airplane with degraded flight controls increases significantly with time (steep learning curve)."¹⁸, Pilots also noted that:

The learning curve was such that... [adverse yaw and dutch roll characteristics] were easily compensated for. Lateral PIO could be reduced with some concentration once the handling characteristics were learned. Learned compensation for the longitudinal control deficiencies was also noticeable, but to a lesser degree."¹⁹

The presence of a pilot learning curve for degraded mode tasks was also seen in the MFS. In the simulator, however, the learning curve applies to compensation for reduced fidelity as well.²⁰ This learning curve has the effect of reducing the pilot gain and thereby reducing the HQR assigned for a given task.

¹⁸Wirt, R. and Harney, R. J., F/A-18A Degraded Flight Control System Carrier Approach Flying Qualities Evaluation NATC, Patuxent River, MD: 1987.

¹⁹Rutherford, R., Degraded Mode Flight Test Daily Report, NATC, Patuxent River, MD: 23 May 1988.

²⁰Stonge, J. R., "The Role of Psychological Fidelity in Training Systems Acquisition," Proceedings of the Tenth Industry/NTSC Conference, NADC, Orlando, FL: December 1988.

The use of pilots with varying levels of degraded flight control proficiency contaminated the results used in this evaluation, and may have contributed to both the HQR spread for some tasks and the inconsistent PIO results. Pilot proficiency in degraded flight control modes (resulting from learning to compensate) should be considered and managed by the test engineer during high gain HQR testing.

The MFS is clearly a good tool for training test pilots to compensate for the poor handling qualities in degraded FCS modes. This capability should be used prior to actual flight tests to enhance safety and reduce the risks involved with degraded flight control testing. Test conduct and the resulting conclusions must consider, however, that fleet pilots who will land the F/A-18 with degraded flight controls may be relatively inexperienced.

CHAPTER V

CONCLUSIONS

5.1 General Conclusions

The Manned Flight Simulator at Patuxent River, Maryland, is a very mature simulator, having incorporated much flight test data into its data base. Yet for all its cost and effort, it appears to be a somewhat inaccurate tool for prediction of F/A-18 degraded flight control mode handling qualities, and in particular, PIO tendency. The primary factors which contribute to this inaccuracy are:

- Absence of motion cueing in the simulator.
- Visual scene time lag in the simulator.
- Pilot over-aggressiveness in the simulator.
- A generally lower pilot proficiency when testing degraded modes in the simulator.
- Lower visual scene resolution in the simulator.

Of these factors, pilot aggressiveness and proficiency can be managed by the test team to produce more accurate results. A good understanding of the effects of other factors will assist in proper interpretation of the simulator handling qualities.

5.2 Specific Conclusions

1. MFS was representative of the aircraft for dutch roll damping and natural frequency in the landing configuration with half flaps.
2. Longitudinal short period natural frequencies and damping were slightly lower in the MFS when compared to the airplane in the landing configuration with half flaps.
3. MFS control system loading and dynamics were representative of the airplane.
4. Pilots are more aggressive in the MFS, resulting in higher HQR spreads and higher average HQRs compared to those for similar tasks completed in the airplane.
5. The absence of motion cueing in the MFS reduced the accuracy of handling quality ratings, particularly during capture type tasks or when correcting for large deviations.
6. HQRs for longitudinal axis tasks were consistently higher in the MFS due primarily to the absence of motion cueing and pilot over-aggressiveness.
7. MFS visual display time lag may have contributed to higher HQRs during aggressive maneuvering by pilots.

8. HQRs for lateral-directional tasks were consistently lower in the MFS due to the absence of nuisance dutch roll motions of the platform which were distracting to the pilot in actual flight.

9. The MFS did not accurately predict airplane PIO tendency. In particular, the failure to predict lateral PIO during landing approach is a serious pitfall.

10. Degraded F/A-18 flight control mode handling qualities may be generally characterized as unpredictable (sluggish or abrupt) which leads to a steep learning curve by test pilots attempting approach and landing tasks. This learning curve is seen in both the simulator and in flight, and has the effect of reducing the pilot gain and thereby reducing the HQR assigned for a given task over time.

11. The MFS would more accurately predict HQRs for all tasks if a motion base were added, and pilot aggressiveness and proficiency were properly managed. The potential for accurate prediction of PIO could not be assessed.

CHAPTER VI

RECOMMENDATIONS

1. Control pilot aggressiveness in the simulator. Use capture tasks to invoke more aggressive control inputs by the pilot. Use wider tolerance margins to produce less aggressive control inputs. Manage the "absence of fear" factor by ensuring that test pilots are briefed to consciously fly the simulator like they would the aircraft. Differentiate between large or rapid control inputs used to exaggerate the tendency for PIO and more natural inputs used to complete normal tasks.
2. Manage pilot proficiency. Separate data obtained by "low time" pilots from those who are more experienced at the compensation required for degraded mode task completion. Recognize that most flight data is taken by relatively "experienced" pilots, but pilots who must make an emergency landing with degraded flight controls will probably be doing it for the first time.
3. Incorporate a motion base in the MFS for future degraded mode handling quality evaluations. In addition to providing the necessary pilot cues, a motion system will reduce the

detrimental effects of visual scene characteristics (time delay and reduced resolution).

4. Continue efforts to reduce MFS processing delays which contribute to time lag in the visual scene and cockpit displays. Increase the resolution and brightness of the visual scene for degraded modes testing.

5. Be alert to the possibility that dangerous PIO tendencies in the actual airplane may not be seen in simulator testing.

6. To enhance flight safety, use the MFS to train pilots in the characteristics of F/A-18 degraded mode flying qualities prior to the conduct of actual flight tests.

BIBLIOGRAPHY

BIBLIOGRAPHY

1. Ball, J. et al, Flight Syllabus and Background Material for U. S. Navy Test Pilot School Variable Stability Program, CALSPAN Corp., Buffalo, N.Y.: 1986.
2. Booth, G. R., "Visual Simulation for Advanced Fighter Training," Proceedings of the Tenth Industry/NTSC Conference, NADC, Orlando, Fl: December 1988.
3. Brown, J. L. et al, The Effect of Simulated catapult Launching on Pilot Performance, NADC, Orlando, Fl: 1957.
4. Canter, D., Second Interim Report on the User In-House Fidelity Evaluation of the FA-18 Simulation at the Manned Flight Simulator Facility, NATC, Patuxent River, MD: 1990.
5. Cooper, J. C., et al, "Digital Control Loading and Motion The Final Word?," Proceedings of the Seventh Industry/NTSC Conference, NADC, Orlando, Fl: November 1985.
6. Cooper, J. C., "Effects of Visual System Time Delay on Pilot Performance," Proceedings of the Eighth NTEC/Industry Conference, NADC, Orlando, Fl: November 1975.

7. DeMaio, J., "Visual Cueing Effectiveness: Comparison of Perception and Flying Performance," Proceedings of the Fifth Industry/NTSC Conference, NADC, Orlando, Fl: November 1983.
8. Dixon, K., et al, "The Effects of Field-of-View on Pilot Performance in the C-130 WST," Proceedings of the Tenth Industry/NTSC Conference, NADC, Orlando, Fl: December 1988.
9. Anonymous, F/A-18 NATOPS Flight Manual, U.S. Government Printing Office, Washington, D.C.: December, 1985.
10. Hoffart, T. and Stevens, M., Limited F/A-18A Degraded Flight Control System Modes Flying Qualities Evaluation, NATC, Patuxent River, MD: 1988.
11. Horowitz, S. J., "Measurements and Effects of Transport Delays in a State-of-the-Art F-16C Flight Simulator," Proceedings of the Eighth Industry/NTSC Conference, NADC, Orlando, Fl: November, 1986.
12. Hutchinson, R. D., New Horizons for Human Factors in Design, McGraw-Hill, New York: 1981.

13. Jacobs, R. S., and Roscoe, S. N., "Simulator Cockpit Motion and the Transfer of Initial Flight Training," Proceedings of the Eighth NTEC/Industry Conference, NADC, Orlando, Fl: November 1975.
14. Johnson, K. and Bogumill, M., "F-16 and A-10A OFT Simulators Flight Systems Development and Test," Proceedings of the Fourth Industry/NTSC Conference, NADC, Orlando, Fl: November 1982.
15. Kellogg, G. and Wagner, C., Effects of Update and Refresh Rates on Flight Simulation Visual Displays, NASA, Washington, D. C.: May 1988.
16. Kinkade, R. G. and Wheaton, G. R., Human Engineering Guide to Experiment Design, U.S. Government Printing Office, Washington, D. C.: 1972.
17. Loftin, A., Quest for Performance: The Evolution of Modern Aircraft, NASA Scientific and Technical Information Branch, Washington, D. C.: 1985.
18. Anonymous, Manned Flight Simulator, NATC Technical Information Department, Patuxent River, MD: 1986.
19. McCormick, E. J., Human Factors Engineering, 3rd ed., McGraw Hill, New York: 1970.

20. Anonymous, MIL-F-8785C Flying Qualities of Piloted Airplanes, U.S. Government Printing Office, Washington, D.C.: 1980.
21. Moore, T., Airplane Dynamics, USNTPS, Patuxent River, MD: 1984.
22. Parrag, M. and Knotts, L., Augmented Aircraft Handling Qualities, CALSPAN Corp., Buffalo, N. Y.: 1987.
23. Poole, D., Evaluation of Simulator Bandwidth and Transport Delays Using Dynamic Techniques, VEDA Corp.: March, 1989.
24. Powell, J., Airplane Performance: Fixed Wing Flight Mechanics, USNTPS, Patuxent River, MD: 1985.
25. Richards, R., Aircraft Flight Control Systems, USNTPS, Patuxent River, MD: 1987.
26. Sadoff, M., et al, The Use of Piloted Flight Simulators in General Research, NASA, Washington, D.C.: 1959.
27. Schweikhard, W. and Schueler, D., "Why Simulators Don't Fly Like the Airplane - Data," Proceedings of the Thirteenth Industry/NTSC Conference, NADC, Orlando, Fl: December 1991.

28. Shirachi, D. and Shirley, R., Visual/Motion Cue Mismatch in a Coordinated Roll Maneuver, Computer Sciences Corporation, Mountain View, CA: May 1981.
29. USNTPS Staff, Static Stability and Control, USNTPS, Patuxent River, MD: 1986.
30. Stonge, J. R., "The Role of Psychological Fidelity in Training Systems Acquisition," Proceedings of the Tenth Industry/NTSC Conference, NADC, Orlando, Fl: December 1988.
31. Anonymous, The Use of Pilot Rating in the Evaluation of Aircraft Handling Qualities, NASA, Washington, D. C.: April, 1964.
32. USNTPS Staff, U.S. Naval Test Pilot School Flight Test Manual No. 103, Fixed Wing Stability and Control, USNTPS, Patuxent River, MD: 1981.
33. USNTPS Staff, U.S. Naval Test pilot School Flight Test Manual No. 104, Fixed Wing Performance, USNTPS, Patuxent River, MD: 1977.
34. Vancott, H., and Kinkade, R., Human Engineering Guide to Equipment Design, U.S. Government Printing Office, Washington, D.C.: 1972.

35. Welch, B. L., "Characteristics of Flight Simulator Visual Systems," Proceedings of the Fourth Industry/NTSC Conference, NADC, Orlando, Fl: November 1982.
36. Wightman, D., et al, "Transfer of Training of Simulator Visual and Training Features for the Carrier Landing Task with Undergraduate Pilots," Proceedings of the Seventh Industry/NTSC Conference, NADC, Orlando, Fl: November 1985.
37. Wirt, R. and Harney, R. J., F/A-18A Degraded Flight Control System Carrier Approach Flying Qualities Evaluation, NATC, Patuxent River, MD: 1987.

APPENDIX A

FIGURES

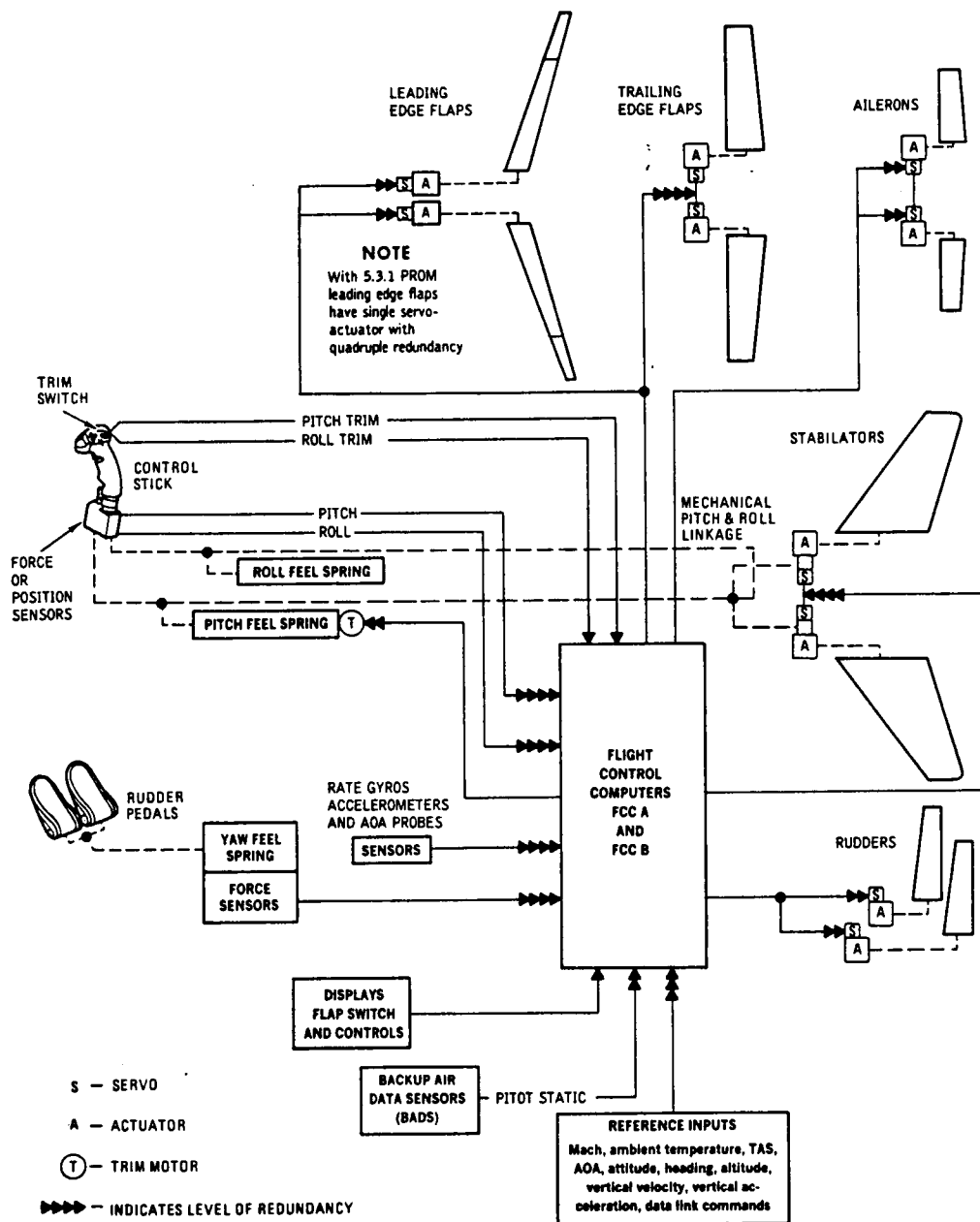


Figure A-1.

F/A-18 Flight Control System Functional Diagram

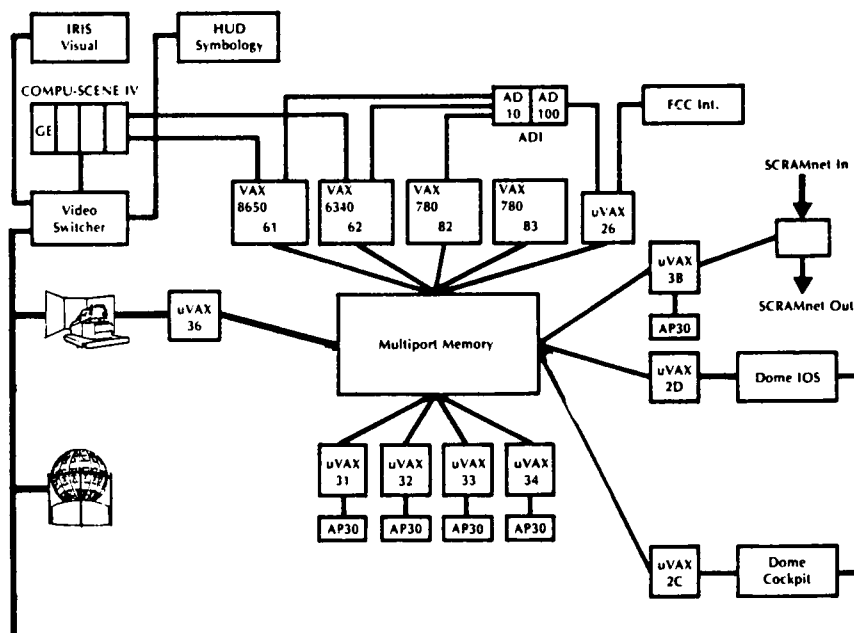


Figure A-2.

Manned Flight Simulator Architecture

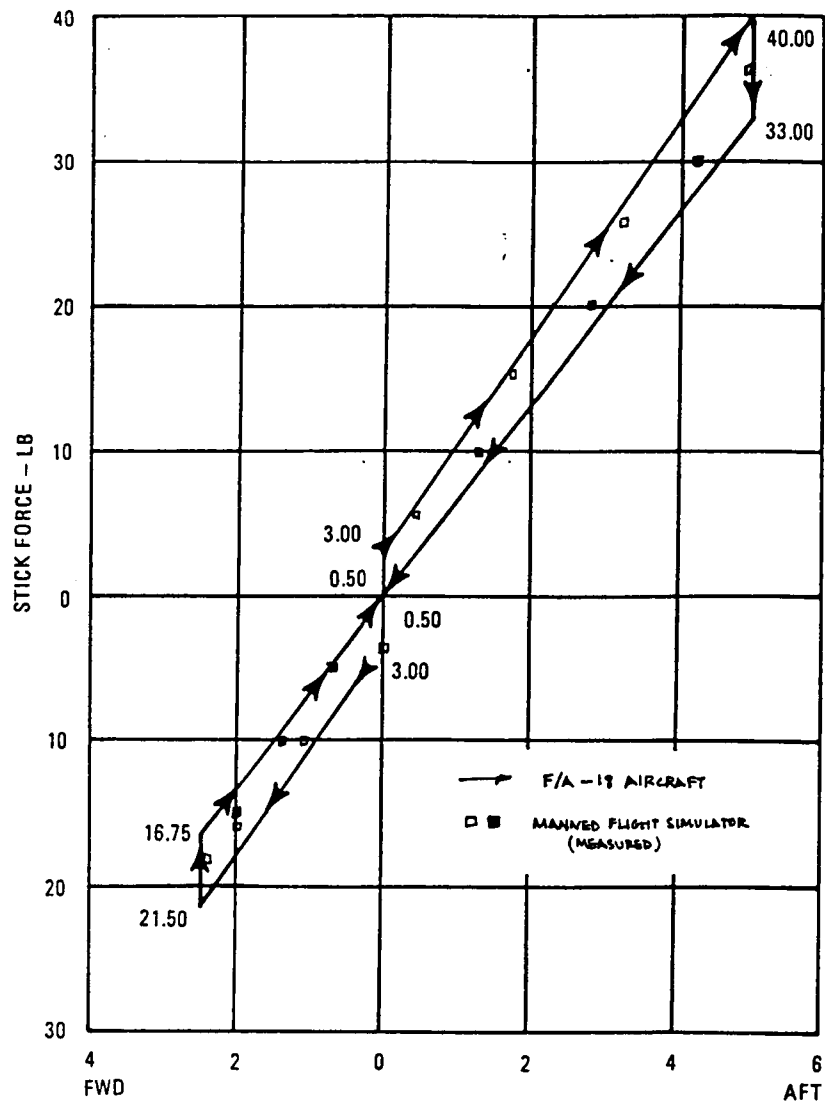


Figure A-3.

Longitudinal Stick Force versus Deflection

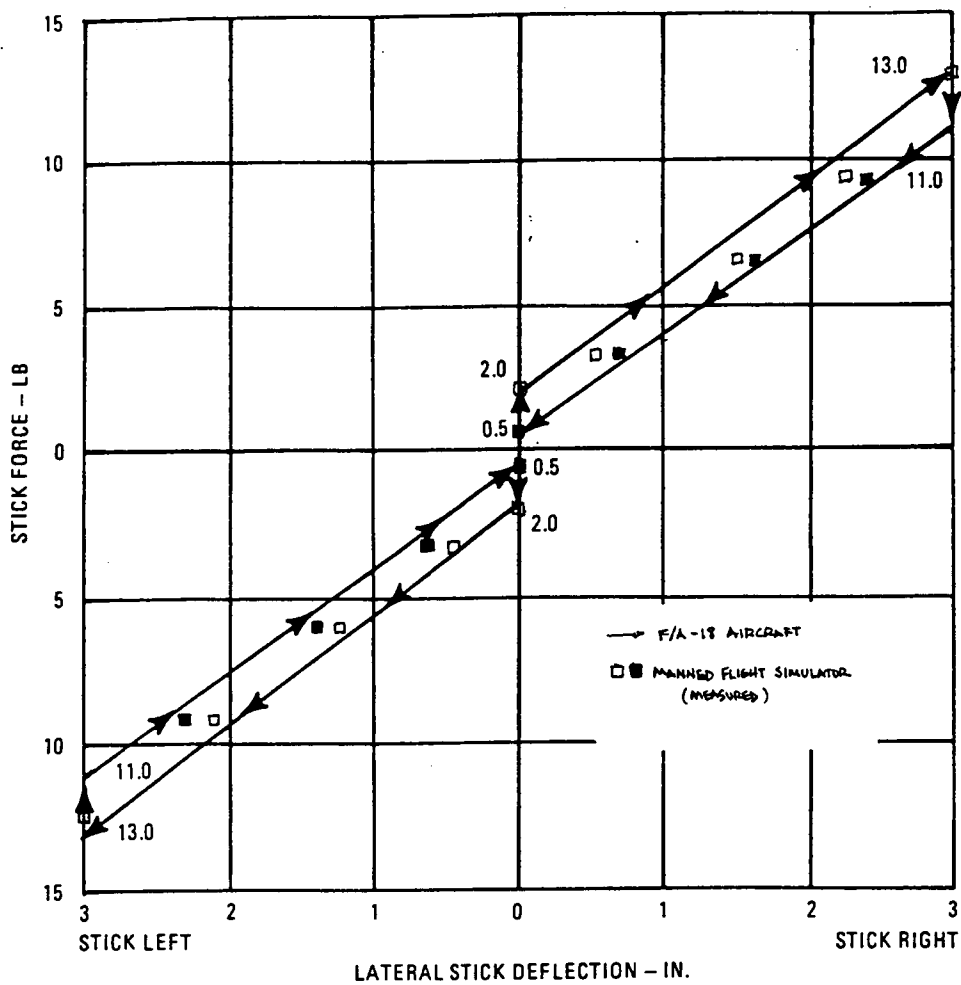


Figure A-4.
Lateral Stick Force versus Deflection

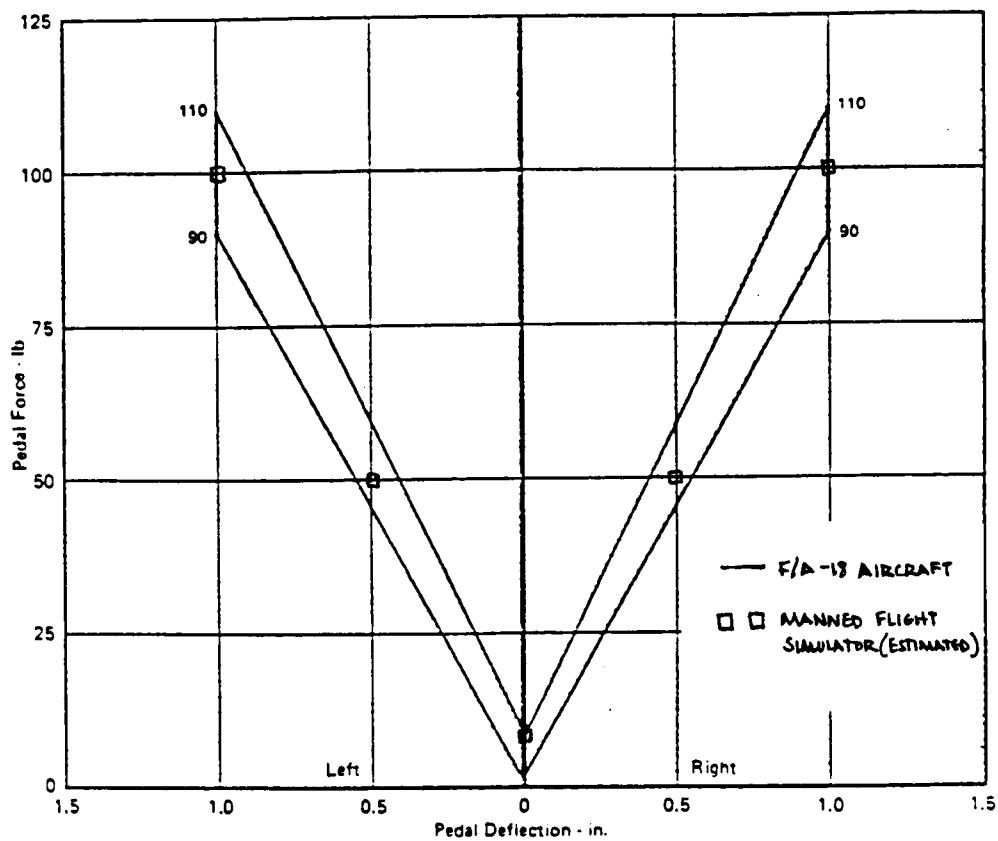


Figure A-5.

Rudder Pedal Force versus Deflection

APPENDIX B

DATA TABLES

APPENDIX B

DATA TABLES

Data from all sources is presented in this Appendix. The data is organized in pilot task and flight control mode combinations as listed in Table B-I.

Table B-I.
Data Table Organization

Degraded Mode	Pilot Task					
	Angle of Attack	Glide slope	Wave-off Attitude	Angle of Bank	Runway Line-up	Heading
CAS	B-II	B-V	B-VIII	B-XI	B-XIII	B-XV
Pitch DEL	B-III	B- VI	B-IX			
Pitch MECH	B-IV	B-VII	B-X			
Roll/Yaw DEL				B-XII	B-XIV	B-XVI

Data source references for Appendix B data are as follows:

- A Rutherford, R. MFS Flight Test Daily Report. 27 Feb 1989.
- B Hoffart, T. MFS Flight Test Daily Report. 14 July 1989.
- C Ashby, J. MFS Flight Test Daily Report. 17 April 1990.
- D Wirt, R. and R. J. Harney. F/A -18A Degraded Flight Control System Carrier Approach Flying Qualities Evaluation. Patuxent River, MD: NATC, 1987.
- E Rutherford, R. Degraded Mode Flight Test Daily Report. 23 May 1988.
- F Hoffart, T. and M. Stevens. Limited F/A-18A Degraded Flight Control System Modes Flying Qualities Evaluation. Patuxent River, MD: NATC, 1988.
- G Benjes, C. Degraded mode Flight Test Daily Report, 14 May 1988.

Table B-II.

Pilot Handling Quality Ratings- Angle of Attack/CAS

Task: Maintain Angle of Attack at 8.1 degrees alpha
 Tolerance: ± 1.0 degree alpha
 Conditions: F/A-18 landing approach/Half flaps/onspeed AOA
 Flight controls in CAS

Data Source	Flight/simulator	HQR	Comments
A	simulator	3	Frequency of required AOA correction using coordinated stick and power inputs was a little higher than in the airplane. Tendency to chase AOA.
B	simulator	-	none
C	simulator	2	Absence of seat of the pants feel in the simulator makes aggressive corrections more difficult.
D	flight	-	not tested
E	flight	-	not tested
F	flight	-	not tested
G	flight	2	none

Table B-III.

Pilot Handling Quality Ratings- Angle of Attack/Pitch DEL

Task: Maintain Angle of Attack at 8.1 degrees alpha
 Tolerance: +- 1.0 degree alpha
 Conditions: F/A-18 landing approach/Half flaps/onspeed AOA
 Pitch axis in DEL

Data Source	Flight/simulator	HQR	Comments
A	simulator	5	Pitch axis in DEL appeared too lightly damped and the SP frequency seemed a little longer leading to pronounced longitudinal PIO. Airplane seems to be damped better [than the simulator].
B	simulator	-	Longitudinal axis loose, resulting in poor AOA control and pitch sensitivity.
C	simulator	4-6	Once captured, required frequent, small (1/2 inch) stick inputs to maintain. Aggressively capturing 8.1 AOA was very difficult, requiring large, well timed stick inputs HQR 6.
D	flight	4	Required frequent +-1/2 inch longitudinal stick inputs. Short period was easily excited, lightly damped, and low frequency. Airplane was overly sensitive to pitch inputs. No PIO tendencies were noted.
E	flight	4	Fighting attitude most of the time. Airplane attitude selection appeared to be subject to longitudinal PIO.
F	flight	-	AOA control required slightly more pilot concentration due to pitch coupling
G	flight	4	none

Table B-IV.

Pilot Handling Quality Ratings- Angle of Attack/Pitch MECH

Task: Maintain Angle of Attack at 8.1 degrees alpha
 Tolerance: ± 1.0 degree alpha
 Conditions: F/A-18 landing approach/Half flaps/onspeed AOA
 Pitch axis in MECH

Data Source	Flight/simulator	HQR	Comments
A	simulator	-	not tested
B	simulator	-	AOA control felt a little looser than the airplane. Could not determine if caused by the aero model, the stick, the visual scene, or a combination thereof.
C	simulator	3-5	Holding AOA alone was HQR 3. Simultaneous AOA and glideslope changes was HQR 5 (GS change set up PIO). Aggressively capturing 8.1 AOA required 3 to 4 inch stick deflections with HQR 5.
D	flight	3	Required frequent 1/2 inch longitudinal stick inputs to correct deviations. Pitch sensitivity about trim was sluggish, requiring pre-programmed pilot inputs. No PIO tendencies were noted.
E	flight	3	Longitudinal axis more heavily damped than in pitch DEL. Not as prone to PIO, less tendency to overshoot attitude. [AOA control] easy in the approach turn and on final, using care to make small, tightly controlled inputs.
F	flight	-	AOA control required more concentration due to pitch coupling and sluggish pitch response. No PIO tendencies noted. Required an initial high amplitude input (1 inch), followed by one or two small (1/4 inch) longitudinal inputs.
G	flight	4	none

Table B-V.
Pilot Handling Quality Ratings- Glideslope/CAS

Task: Maintain Glideslope at 3.5 degrees
Tolerance: ± 0.5 degree (simulator)/1 ball (flight)
Conditions: F/A-18 landing approach/Half flaps/onspeed AOA
Flight controls in CAS

Data Source	Flight/simulator	HQR	Comments
A	simulator	3	Glideslope control was more difficult, possibly due to absence of motion feedback. Tended to generate a small to medium amount of longitudinal PIO.
B	simulator	-	Simulator felt representative of the aircraft
C	simulator	2	Absence of seat of the pants feel in the simulator makes aggressive corrections more difficult.
D	flight	-	not tested
E	flight	-	not tested
F	flight	-	not tested
G	flight	2	none

Note: No Optical lens was available in simulator. Glideslope tasks were simulated by designating visual touchdown point and flying 3.5 degree glideslope on HUD.

Table B-VI.

Pilot Handling Quality Ratings- Glideslope/Pitch DEL

Task: Maintain Glideslope at 3.5 degrees
 Tolerance: ± 0.5 degree (simulator)/1 ball (flight)
 Conditions: F/A-18 landing approach/Half flaps/onspeed AOA
 Pitch axis in DEL

Data Source	Flight/simulator	HQR	Comments
A	simulator	5	Pitch axis in DEL appeared too lightly damped and the SP frequency seemed a little longer leading to pronounced longitudinal PIO. Airplane seems to be damped better [than the simulator].
B	simulator	-	Simulator felt representative of the aircraft
C	simulator	4-6	HQR 4 to maintain GS once established. Initial capture or large GS corrections much more difficult HQR 6. Visual scene characteristics may have affected HQR.
D	flight	3	Required small coordinated throttle and stick inputs to correct deviations. Short period was easily excited, lightly damped, and low frequency. Airplane was overly sensitive to pitch inputs. No PIO tendencies were noted.
E	flight	4	Glideslope control not overly difficult once glideslope established.
F	flight	-	Glideslope control was good.
G	flight	3	none

Note. No Optical lens was available in simulator. Glideslope tasks were simulated by designating visual touchdown point and flying 3.5 degree glideslope on HUD.

Table B-VII.

Pilot Handling Quality Ratings- Glideslope/Pitch MECH

Task: Maintain Glideslope at 3.5 degrees
 Tolerance: ± 0.5 degree (simulator)/1 ball (flight)
 Conditions: F/A-18 landing approach/Half flaps/onspeed AOA
 Pitch axis in MECH

Data Source	Flight/simulator	HQR	Comments
A	simulator	-	Not tested
B	simulator	-	not tested
C	simulator	4-6	Difficult to control GS (frequent 1 to 2 inch stick inputs). Much harder with aggressive or large GS changes. Abrupt longitudinal corrections resulted in pitch PIO ± 1 degree pitch attitude HQR 6. Visual scene characteristics may have affected HQR. Pilot learning curve was steep - initially, PIO induced during GS changes. Eventually, pilot learned to anticipate nose movement (before indicated visually), and take out stick input early, preventing PIO. Motion base would help pilot to anticipate and lessen PIO tendency.
D	flight	3	Required small coordinated throttle and stick inputs to correct deviations. Pitch sensitivity about trim was sluggish, requiring pre-programmed pilot inputs. No PIO tendencies were noted.
E	flight	3	Maintaining glideslope fairly easy if no line up corrections are required.
F	flight	-	glideslope control was good
G	flight	3	none

Note. No Optical lens was available in simulator. Glideslope tasks were simulated by designating visual touchdown point and flying 3.5 degree glideslope on HUD.

Table B-VIII.

Pilot Handling Quality Ratings- Pitch capture/CAS

Task: Capture pitch attitude of +2 degrees flight path angle
 Tolerance: ± 1.0 degree flight path angle
 Conditions: F/A-18 landing approach waveoff/Half flaps/onspeed AOA
 Flight controls in CAS

Data Source	Flight/simulator	HQR	Comments
A	simulator	2	none
B	simulator	-	Not tested
C	simulator	3	Aggressive pitch capture attempts resulted in 3 overshoots, which required 1/4 inch longitudinal stick inputs to counter
D	flight	-	not tested
E	flight	-	not tested
F	flight	-	not tested
G	flight	2	none

Table B-IX.

Pilot Handling Quality Ratings- Pitch capture/Pitch DEL

Task: Capture pitch attitude of +2 degrees flight path angle
 Tolerance: ± 1.0 degree flight path angle
 Conditions: F/A-18 landing approach waveoff/Half flaps/onspeed AOA
 Pitch axis in DEL

Data Source	Flight/simulator	HQR	Comments
A	simulator	-	Not tested
B	simulator	-	Not tested
C	simulator	4	Required 1 to 2 inch stick inputs to move nose to +2 degrees, then to dampen 3 to 4 overshoots.
D	flight	3-4	Capturing pitch attitude on waveoff was easy, requiring slight forward stick. More aggressive pitch capture resulted in overshoot HQR 4.
E	flight	4	Decided tendency to overshoot the target attitude.
F	flight	3	Required an initial high amplitude (1 inch) input followed by continual small (1/4 inch) longitudinal inputs.
G	flight	4	Overshoot and slight PIO

Table B-X.

Pilot Handling Quality Ratings- Pitch capture/Pitch MECH

Task : Capture pitch attitude of +2 degrees flight path angle

Tolerance : ± 1.0 degree flight path angle

Conditions: F/A-18 landing approach waveoff/Half flaps/onspeed AOA

Pitch axis in MECH

Data Source	Flight/simulator	HQR	Comments
A	simulator	-	Not tested
B	simulator	-	Not tested
C	simulator	5-6	Pitch attitude correction required a large (3-4 inch) stick input, taken out before movement noticed visually, or PIO (± 1 degree pitch) would result. Motion base might help pilot anticipate movement.
D	flight	3-4	Capturing pitch attitude on waveoff was easy. More aggressive pitch capture resulted in overshoot HQR 4. Pitch sensitivity was sluggish, requiring pre-programmed pilot inputs [to stop nose movement.] No PIO tendencies were noted.
E	flight	3	Fairly easy to modulate stick force to maintain onspeed AOA through the waveoff.
F	flight	3	Required an initial high amplitude (1 inch) input followed by one or two small (1/4 inch) longitudinal inputs.
G	flight	3	Little nose slice and dutch roll

Table B-XI.

Pilot Handling Quality Ratings- Angle of Bank/CAS

Task: Maintain Angle of Bank at 25 degrees

Tolerance: ± 2 degreeConditions: F/A-18 landing approach turn/Half flaps/onspeed AOA
Flight controls in CAS

Data Source	Flight/simulator	HQR	Comments
A	simulator	2	Lateral stick force gradient, breakout, and friction seemed higher than airplane.
B	simulator	-	not tested
C	simulator	2	none
D	flight	-	not tested
E	flight	-	not tested
F	flight	-	not tested
G	flight	2	none

Table B-XII.

Pilot Handling Quality Ratings- Angle of Bank/Roll+Yaw DEL

Task: Maintain Angle of Bank at 25 degrees

Tolerance: +- 2 degree

Conditions: F/A-18 landing approach turn/Half flaps/onspeed AOA

Lateral and Directional axes in DEL

Data Source	Flight/simulator	HQR	Comments
A	simulator	3	Very similar to aircraft in Roll DEL. Hallmark is wing rock PIO in approach turn. Actual airplane had a little more wing rock (+-2 deg AOB). Easier to maintain AOB in simulator than airplane. Adverse yaw same as airplane. Dutch roll damps out in 3 cycles.
B	simulator	-	Pitch coupling with a lateral input is not as severe in the simulator as it was in the airplane. May be due partly to the fidelity of the visual scene in the simulator.
C	simulator	3	Adverse yaw in simulator is annoying. Would be uncomfortable in airplane.
D	flight	-	Lateral control was highly responsive, often resulting in overcontrol of angle of bank. Lightly damped, low frequency dutch roll produced a mild wing rock (2 degrees). Wing rock combined with sensitive lateral control could induce a roll PIO when pilot gains are high.
E	flight	-	+2 degree wing rock and lateral PIO
F	flight	-	Difficult to maintain stable conditions due to the easily excitable Dutch Roll oscillations. Lack of roll rate limiting was very evident.
G	flight	4	none

Table B-XIII.

Pilot Handling Quality Ratings- Line Up/CAS

Task: Maintain runway centerline line up
 Tolerance: $\pm$ 5 feet
 Conditions: F/A-18 landing approach/Half flaps/onspeed AOA
 Flight controls in CAS

Data Source	Flight/simulator	HQR	Comments
A	simulator	3	Line up control seemed more difficult in simulator because of lateral stick mechanical characteristics (simulator stick force gradient, breakout, friction higher than airplane). Chased lineup. Some PIO.
B	simulator	-	not tested
C	simulator	2	Maintaining lineup required frequent lateral stick inputs of 1/4 to 1/2 inch.
D	flight	2	Requires infrequent 1/4 inch lateral stick inputs.
E	flight	-	not tested
F	flight	-	not tested
G	flight	2	none

Table B-XIV.

Pilot Handling Quality Ratings- Line Up/Roll+Yaw DEL

Task: Maintain runway centerline lineup

Tolerance: +- 5 feet

Conditions: F/A-18 landing approach/Half flaps/onspeed AOA

Lateral and Directional axes in DEL

Data Source	Flight/simulator	HQR	Comments
A	simulator	4	Lateral PIO while maintaining line up just prior to touchdown. Not as bad in airplane.
B	simulator	-	Directional stability of the simulator felt higher than that of the airplane. Never saw neutral directional stability as seen in the airplane.
C	simulator	4-5	Small corrections produced mild, nuisance dutch roll- wing rock more noticeable than yaw. Larger corrections produce strong adverse yaw which requires 1 to 2 inch stick inputs to dampen 3 to 4 overshoots HQR 5.
D	flight	5-6	Line up was difficult due to constant roll and yaw oscillations. Adverse yaw and the corresponding dutch roll during line up corrections exacerbated the line up control task. At night, diminished perceptual cues made it difficult to dampen the dutch roll, which, in turn, made the line up task more difficult. PIO might be induced if pilot gains were high.
E	flight	4	Maintaining line up required [coordinated rudder and aileron] inputs to control dutch roll on line up corrections. Adverse yaw was pronounced when making aggressive AOB inputs [centerline overshoot].
F	flight	-	Adverse yaw produced with rapid lateral inputs was more evident by "feel" to the pilot than by a degradation in mission performance. The adverse yaw is a nuisance and will increase pilot workload while trying to maintain lineup.
G	flight	4	Dutch roll

Table B-XV.

Pilot Handling Quality Ratings- Heading/CAS

Task: Maintain constant Heading
 Tolerance: ± 2.5 degrees
 Conditions: F/A-18 downwind leg/Half flaps/onspeed AOA
 Flight controls in CAS

Data Source	Flight/simulator	HQR	Comments
A	simulator	2	none
B	simulator	-	not tested
C	simulator	2	none
D	flight	-	not tested
E	flight	-	not tested
F	flight	-	not tested
G	flight	2	none

Table B-XVI.

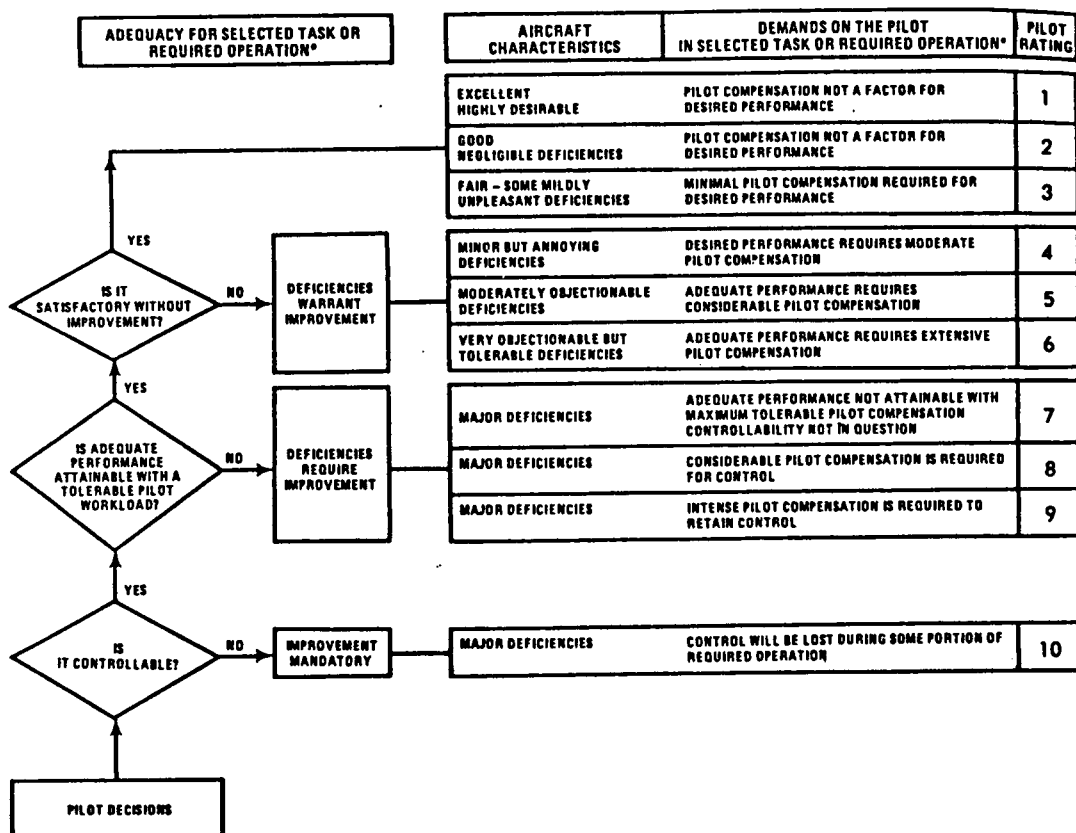
Pilot Handling Quality Ratings- Heading/Roll+Yaw DEL

Task: Maintain constant Heading
 Tolerance: ± 2.5 degrees
 Conditions: F/A-18 downwind leg/Half flaps/onspeed AOA
 Lateral and Directional axes in DEL

Data Source	Flight/simulator	HQR	Comments
A	simulator	4	HQR results primarily from effect of adverse yaw (approx 3 deg) which damps out over 3 cycles. Easier to control with the rudders than the ailerons.
B	simulator	-	Directional stability of the simulator felt slightly higher than that of the airplane.
C	simulator	4	Precise control not possible due to adverse yaw and light damping (nose wanders back and forth).
D	flight	-	Directional stability was reduced. Lightly damped, low frequency dutch roll and mild wing rock (2 degrees) were apparent. Lateral control inputs of 1/2 inch induced 2-3 degrees of adverse yaw.
E	flight	-	Noticeable adverse yaw. Dutch roll excited with even small AOB changes. Dutch roll most predominant when rolling out of turns.
F	flight	6	Easily excited and lightly damped Dutch Roll motion contaminated all mission tasks and greatly increased pilot workload during high gain tasks. Required continual small (1/4 inch), high frequency lateral inputs.
G	flight	4	none

APPENDIX C

COOPER-HARPER RATING SCALE



Cooper-Harper Handling Qualities Rating Scale

VITA

Jeffrey S. Ashby was born on June 16, 1954 in Dallas, Texas. He was raised in the mountains of Colorado where he began his career in aviation. After graduating from the University of Idaho with a Bachelor of Science degree in Mechanical Engineering, he was commissioned an Officer in the United States Navy.

Mr. Ashby finished Naval Flight Training in June, 1978, and subsequently completed several overseas carrier deployments, flying both the A7E Corsair and the F/A-18 Hornet. He graduated from the U.S. Naval Test Pilot School in Patuxent River, Maryland in 1988 and immediately assumed duties as the Naval Air Test Center F/A-18 Program Manager and test pilot for F/A-18 aircraft modifications and upgrades. After 2 years as a test pilot, Mr. Ashby returned to fleet duty in VFA-195 aboard the carrier USS MIDWAY where he flew 33 combat missions in Operation Desert Storm.

Mr. Ashby has accumulated over 4800 flight hours in 52 different aircraft, including over 4000 hours in Navy Tactical Jet airplanes. He is presently assigned as Executive Officer of Strike Fighter Squadron 94, operating from the carrier USS LINCOLN in the Western Pacific Ocean.