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F/A-18A-D Flight Control Computer OFP Versions 10.6.1 and 10.7 Developmental Flight Testing: Out-of-Controlled Flight Test Program Yields Reduced Falling Leaf Departure Susceptibility and Enhanced Aircraft Maneuverability

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To the Graduate Council:

I am submitting herewith a thesis written by Eric John Mitchell entitled "F/A-18A-D Flight Control Computer OFP Versions 10.6.1 and 10.7 Developmental Flight Testing: Out-of-Controlled Flight Test Program Yields Reduced Falling Leaf Departure Susceptibility and Enhanced Aircraft Maneuverability." I have examined the final electronic copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

Robert Richards, Major Professor

We have read this thesis and recommend its acceptance:

Richard Ranaudo, Frank Collins

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

(Original signatures are on file with official student records.)

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Accepted for the Council:

Anne Mayhew

Vice Provost and Dean of Graduate Studies

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F/A-18A-D Flight Control Computer OFP Versions 10.6.1 and 10.7 Developmental Flight Testing: Out-of-Controlled Flight Test Program Yields Reduced Falling Leaf Departure Susceptibility and Enhanced Aircraft Maneuverability

A Thesis

Presented for the

Master of Science Degree

The University of Tennessee, Knoxville

Eric John Mitchell
May 2004

DEDICATION

This thesis is dedicated to my wife and children. Dana and my sons, Matthew and Jacob, are the center of my world and their importance to me cannot be overstated.

ACKNOWLEDGMENTS

My sincere gratitude to the Faculty at the University of Tennessee Space Institute and the instructors at United States Naval Test Pilot School for their willingness to impart their knowledge and their assistance in earning this degree.

I would also like to thank Mr. Robert David, NAWCAD Engineer extraordinaire, my Test Pilot School cubical-mate and good friend, for knowledgeably assisting me in gathering information and resources regarding the test program for this thesis. I also would like to express my gratitude to all the members of the F/A-18 Integrated Test Team at NAS Patuxent River that expertly conducted this testing program.

And finally, I would like to thank my good friends and coworkers, those Navy and Marine Corps Aviators who are out on the tip of the spear, day and night, expertly employing the F/A-18 Hornet and Super Hornet aircraft, as well as the mighty Tomcat, to ensure the safety and freedom of our country. True professionals, all.

ABSTRACT

This thesis analyzes the recent Version 10.7 Operational Flight Program (v10.7 OFP) Flight Control System upgrade to the F/A-18A-D (legacy) Hornet fighter aircraft. This developmental program endeavored to improve high angle-of-attack (AOA) maneuverability while vastly reducing the aircraft's susceptibility to sustained out-of-controlled flight events.

Although the original F/A-18 Hornet, designated F/A-18A through F/A-18D, has been acclaimed for its departure resistance as well as its exceptional maneuverability as a fighter aircraft, the model, in actuality, has suffered from significant losses due to out-of-controlled flight (OCF) mishaps. Since its development in the early 1980s, eighteen Hornets have been lost to a particular OCF mode called "Falling Leaf", including eight aircraft crashed since 1999. With no improvements, 10 additional aircraft, at a cost of $40 million each, were forecast to be lost.

Two-seat aircraft are lost at a higher rate per flight hour than the more common single-seat version. Analysis of flight test data indicates that more two-seat aircraft sustain Falling Leaf mode due to their increased departure susceptibility. Additionally, it is apparent that the increased sprung mass of the control system, due to the addition of the rear cockpit control stick, may delay or inhibit recovery from a sustained Falling Leaf departure. This may be caused by uncommanded Flight Control System inputs from lateral control stick inertial motion induced by high sideforces encountered during a Falling Leaf.

The v10.7 OFP test effort conducted a complete out-of-control flight test program without the benefit of having an attached spin-recovery parachute during testing. The specific test method and risk mitigation techniques used during this test program are reviewed and documented in this thesis to provide a historical record for future testing. By using the lessons learned from the development of the F/A-18E/F Super Hornet testing conducted a few years earlier, the v10.7 Team was able to complete the test at a large cost and schedule savings.

The author concludes that the test program is an exceptional success. The new low airspeed and high AOA maneuvering capabilities inherent with the v10.7 software revolutionize how pilot aircrew will fight the aircraft. Further, the extremely enhanced resistance to sustained departure modes during out-of-controlled flight events will substantially reduce the frequency of aircraft mishaps and the associated loss of training and assets.

PREFACE

"I CAN'T BELIEVE THIS IS HAPPENING…."

It's 1998 and I've got less than 12 hours logged as hornet pilot. I'm airborne on my first local "day trainer" flight in a two-seat F/A-18D. At that time, I had amassed over 2000 total military flying hours, over 1000 of them mastering the quirky flying qualities of the departure prone F-14 Tomcat with its antiquated analog flight control computers (FCS). My previous total of four Hornet flights had all been administrative cross countries.

It's my second flight after reporting to my new test squadron after Test Pilot School (TPS) and I'd like to "bend the jet around" a little and take a look at the aircraft's famed superior flying qualities and extreme high angle-of-attack (AOA) capability. Although scheduled as a test-support flight to chase a Super Hornet during its test flight, the other jet was not ready on time, so I went out as a single aircraft, with my new Hornet Department boss in my back seat, on a good deal flight to help build my experience in the jet.

My backseater this day was not a pilot but instead a Marine Corps Weapons Systems Officer (WSO). He encouraged me to start right off with some rather extreme maneuvering right after climbing to altitude in the assigned Test Range. However, I was fresh out of TPS, so I elected to build up more gradually with some loops and rolls, then some level (1g) high AOA maneuvers. Boy, everyone's right—this jet's a dream to fly compared to the Tomcat. It seems like its on rails, almost magical in its capabilities.

With half of my fuel used, my backseater convinces me to “turn up the heat a little” and try something new. It was time to try an aggressive high AOA wingover-type maneuver called a pirouette maneuver—starting at 18,000 feet, 300 knots, I aggressively pull up, then start rolling left…down to 170 knots now at 22,500 feet, feeding in more left rudder pedal and left and aft stick…nose is still a hair above the horizon but should come down. I’m rolled left wing knife-edge down, but the nose has stopped as the jet decelerates through 120 knots. Hmmm? Oops, AOA is way up at 40 degrees, better add a hair of forward stick to reduce the AOA. Although I’ve got left stick and rudder inputs commanded, the jet stops responding and in fact starts a slight right roll. Darn, I’ve departed—I recite the NATOPS Procedures: CONTROLS—RELEASE, FEET OFF RUDDERS, Speed brake in, Throttles IDLE… My backseater is laughing at me.

I’m at 22, 800 feet, out-of-control on a beautiful CAVU summer day over the Chesapeake Bay. I’m waiting for the nose to come down, lawn-dart fashion, just like all the other jets I’ve flown. Still waiting. Finally, the nose is 40 degrees below the horizon, but there’s considerable side force (lateral g) building, pushing me forcefully to the right side of the cockpit. Time stands still. I hear the wind roaring sideways over the top of the cockpit canopy and windscreen. The yaw rate warning tone is screaming at me. Then, the nose comes back up, way up (it’s going the wrong way!). I notice the control stick deflecting laterally. At first I think somehow I must have inadvertently bumped it as I was flung sideways, but then realize that it’s actually moving in response to the same lateral g-forces pushing me around. I try to re-center the stick by hand but its weight under g, as well as the awkward sideways g-forces, prevents me from holding it stationary or being sure where the neutral position really is. As I briefly attempt to hold it neutral, I instantly understand why NATOPS says to just let go and not touch the controls so I let go again—one can't hold the lightly sprung controls stationary while subjected to these violent forces. More violent sideforces the other way, warning audio tones signaling that yaw rate is building, and disturbingly loud wind-like buffeting noise over the canopy and windshield. I'm grabbing the towelbar-like handles on the metal canopy bow for leverage to avoid having my head smash into the Plexiglas canopy. The laughter that I heard from my boss earlier in the backseat has stopped. We're falling through 17,000 feet. I think of reaching for the stick to shove it full forward per the falling leaf recovery procedure, but the NATOPS Manual warned of trying that procedure too early, and I don't think that the steady periodic characteristic of the falling leaf mode is quite established. Additionally, I've already seen a moment earlier holding the stick still would be tough to do. I wish my lapbelt was tighter.

Finally after a couple more oscillations, the nose comes down and stays down, the sideforces subside, and I've happily got a face-full of mother-earth to look at. I pull out from the dive, bottoming out at 8,000 feet over the Bay. I had lost about 14,000 feet during this OCF incident. I've had enough fun for the day and immediately return to base and land. I look over the jet carefully after I get out and verify it's none the worse for wear, as I contemplate the "Jeckle and Hyde" Hornet—effortless to fly 99.9% of the time, but able to truly "uncork" if grossly mishandled.

My new boss, an experienced WSO with over 2000 hours in the Hornet later tells me that although I had a good departure, he had seen and been through a worse one before.

Clearly, I realize the Hornet needs a fix to make this OCF characteristic go away.

DISCLAIMER

A portion of the information contained within this thesis was obtained through the author's participation in a United States Department of Defense sponsored program in conjunction with the Naval Air Warfare Center, Aircraft Division. The research, results and discussion, and conclusions presented are the opinion solely of the author and should not be construed as an official position of the Naval Air Systems Command, the United States Navy, nor the United States Department of Defense.

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LIST OF ABBREVIATIONS

α	Alpha, Angle of Attack
β	Beta, Sideslip
βdot	Beta dot, Sideslip rate
A/A	Air-to-air
A/G	Air-to-gun
ACI	Amplifier-Control-Intercommunications
ACLS	Automatic Carrier Landing System
ACM	Air combat maneuvering
AERO	Aerodynamics Engineer
AGL	Above Ground Level altitude
AOA	Angle of Attack
AOT	Angle off tail
ASM	Asymmetric
ASRM	Automatic Spin Recovery Mode
BFM	Basic fighter maneuvering
BIT	Built-in-test
BLIN	BIT Logic Inspection: Flight control computer built-in-test fault code
CAS	Control augmentation system (normal FCS mode of F/A-18A-D)
CAVU	Ceiling and Visibility Unlimited (beautiful weather)
CG	Center of Gravity normalized and referenced from MAC
Cz	Normal acceleration, aircraft referenced
DAF	Dial a Function
DDAS	Digital Data Acquisition system
DDI	Digital Display Indicator
Departure	Departure from controlled flight—the point an aircraft stops responding to pilot input
Diff-stab	Differential Stabilator deflection
EFT	External Fuel Tank
EMD	Engineering Manufacturing & Development
EPBS	Emergency Power Backup System
EPE	Enhanced performance Engine
ERC	Emergency Recovery Chute
FCC	Flight Control Computer
FCL	Fighter Escort with Centerline 330 gallon EFT
FCLP	Field Carrier Landing Practice
FCS	Flight Control System
FE	Fighter Escort Configuration
g's or Nz	Normal acceleration references to gravitational force

HOTAS	hands-on-throttle-and-stick
Hp	Pressure Altitude
HUD	Heads up display
IBIT	Initiated Built in test
IC	Interim Change of NATOPS
IMN	Indicated Mach number
In.	Inch
INT	Interdiction Loadout with A/G bombs
ITT	Integrated Test Team
KCAS	Knots, calibrated airspeed
KIO	Knock it off
Knot	Nautical Mile per hour
Lb	Pound
LEF	Leading edge flaps
LEX	Leading edge extensions
MAC	Mean Aerodynamic Chord
MAX	Maximum rated thrust—Full engine power with afterburner
MCs	Mission Computers
MFS	Manned Flight Simulator
MIL	Military rated thrust—Full power without afterburner
Mils	Angular measurement. One mil equals 1/1000th of a radian
MMP/MSP	Maintenance Monitor Panel Codes
MSRM	Manual Spin Recovery Mode
MUX	Multiplex digital communications bus
NATOPS	Naval Aviation Training and Operating Procedures Standardization
NAVAIR	Naval Air Systems Command
NAWCAD	Naval Air Warfare Center—Aircraft Division
NSC	Naval Safety Center
Nz	Normal acceleration, Gravity referenced
OCF (or OOCF)	Out of Controlled Flight
OFP	Operational Flight Program
PBIT	Periodic Built in test
PDG	Post Departure Gyration
RTB	Return to base
SAR	Search and rescue assets available in case of a mishap
SMI	Structural Mode Interaction
SRM	Spin Recovery Mode of the F/A-18 FCS
STBY	Standby
TC	Test Conductor
TED	Trailing edge up
TEF	Trailing edge flaps
TEU	Trailing edge down
TM	Telemetry

TPS	Test Pilot School
UFC	Up front control
USNTPS	United States Naval Test Pilot School
VMC	Visual Metrological Conditions
WDTs	Wind Down Turns
WSO	Weapons System Operator
WUT	Wind Up Turn (Test Technique)

CHAPTER I. PURPOSE OF THIS THESIS

INTRODUCTION

The departure characteristics of the F/A-18A-D Hornet received the personal attention of the author early on. Within the first month of flying the aircraft, the author experienced a rather disconcerting out-of-controlled flight (OCF) event. That event is described in detail in the Preface to this paper.

The purpose of this thesis is to: (a) detail the history of the legacy Hornet and the Falling Leaf character it exhibits, (b) discuss the methodology that was used to both suppress the Falling Leaf OCF characteristic and improve the high angle of attack (AOA) maneuvering capability of the aircraft, using technology that matured with the F/A-18E/F Super Hornet development program, (c) provide an historical record of the test methodology and risk mitigation techniques utilized by the test team to plan and conduct a high risk OCF flight test while achieving a moderately low cost goal, (d) discuss the results of the test program, and finally (e) draw conclusions based on those results.

LIMITATIONS TO SCOPE OF THIS THESIS

The scope of this thesis is limited to only the characteristics of the flight control software modifications that occurred during actual flight test. Only results that directly affect departure resistance, high AOA maneuverability, and Falling Leaf suppression are presented. The management of this developmental program, outside the realm of actual flight test, is not discussed. Simulation and software development techniques are also outside the scope of this thesis.

Furthermore, this thesis does not discuss the other aircraft issues that the new software was designed to improve. Those issues included F/A-18 flight control system redundancy management, Automatic Carrier Landing System (ACLS) improvement, and Datalink degraded modes.

CHAPTER II. BACKGROUND OF THE HORNET AND OUT-OF-CONTROLLED FLIGHT

DESCRIPTION OF F/A-18A-D

The F/A-18 Hornet first flew on November 18, 1978. A three-view of the single seat variant is depicted below as figure 1. The two-seat versions (F/A-18B and F/A-18D) are similar, however their cockpit canopies are longer due to the configuration of the seats.

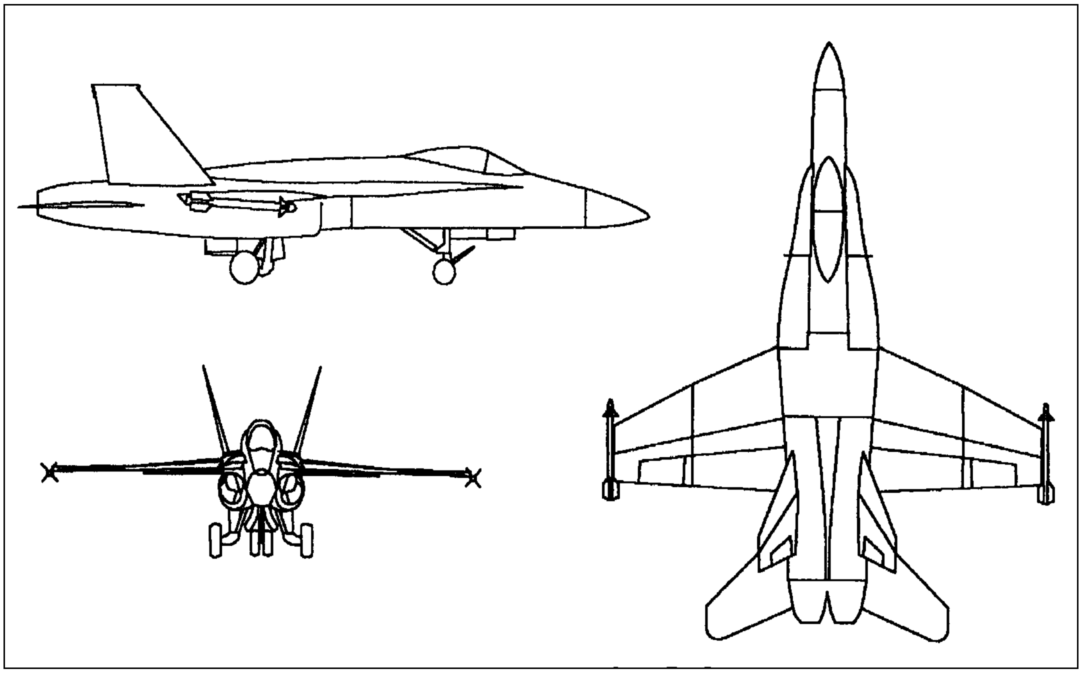


Figure 1. Three-View of F/A-18 Aircraft.

The F/A-18 airplane is a high performance, twin engine, supersonic fighter and attack airplane manufactured by McDonnell Douglas Corporation (now Boeing, St. Louis). The F/A-18A and F/A-18C are single seat aircraft while the B/D are tandem two-seat versions. The aircraft features mid-mounted, variable-camber wings with moderate sweep, twin vertical stabilizers canted out 20° from the vertical, and leading edge extensions (LEXs) along each side of the forward fuselage from the wing roots to just forward of the windshield. Basic aircraft weight is approximately 25,000 lb and maximum takeoff weight is 51,900 lb. Maximum internal fuel load is approximately 10,200 pounds with the option of adding up to an additional 6,600 pounds of fuel in three (2,200 lb/tank) externally mounted fuel tanks. The remainder of the gross weight capacity allows for carriage of external stores and pod mounted sensors. The airplane is configured with full span leading edge flaps, inboard trailing edge flaps, and outboard ailerons on each wing. The flight control system consists of two digital flight control computers with 701E processors that utilize a full authority control augmentation system to operate the hydraulically driven control surfaces. The aircraft is equipped with twin General Electric F404-GE-400 low-bypass turbofan engines with afterburners, which are designed to produce 10,700 lb thrust at MIL and 16,000 lb thrust at MAX at sea level conditions. Newer aircraft are equipped with F404-GE-402 Enhanced Performance Engines (EPE) with slightly higher thrust ratings. Flight controls are hydraulically actuated and computer-driven according to pilot control inputs and flight conditions. Pilot interface for the flight control system is through a conventional center mounted control stick, rudder pedals, and dual engine throttles on the left console. Spring cartridges in all modes are designed to provide the pilot control stick and rudder feel. The aircraft is designed to carry a variety of air-to-air (A/A) and air-to-ground (A/G) weapons, as well as up to three 330 gallon external fuel tanks (EFTs). The Hornet is equipped with systems designed to enable successful engagement of surface and airborne targets, and rapid switching between A/A and A/G modes. Avionics (software) system interface is through an up-front-control (UFC), three multi-function display (MFD) units in each cockpit, and a head-up display (HUD) for the forward cockpit. Additionally, extensive system control is accessible to the aircrew with controls located on the throttle and control stick through the hands-on-throttle-and-stick (HOTAS) system.

HORNET FLYING QUALITIES

Although very early on in the developmental program, the Hornet's overall flying qualities could be described as rather poor, that deficiency was rapidly remedied with minor structural changes and modification to its flight control system (FCS) software (Sweetman, 1987). Since that time, each successive version of the FCS software load, referred to as an Operational Flight Program (OFP), has either further enhanced the actual flying qualities of the aircraft or provided the pilot with better FCS displays or failure detection modes. The several revisions of the FCS software are listed in figure 2.

OFP Version 10.5.1, first introduced in 1996, has provided exceptional flying qualities and superior maneuverability for both U. S. Navy pilots as well as several foreign military services. The Hornet's key design features, including leading edge

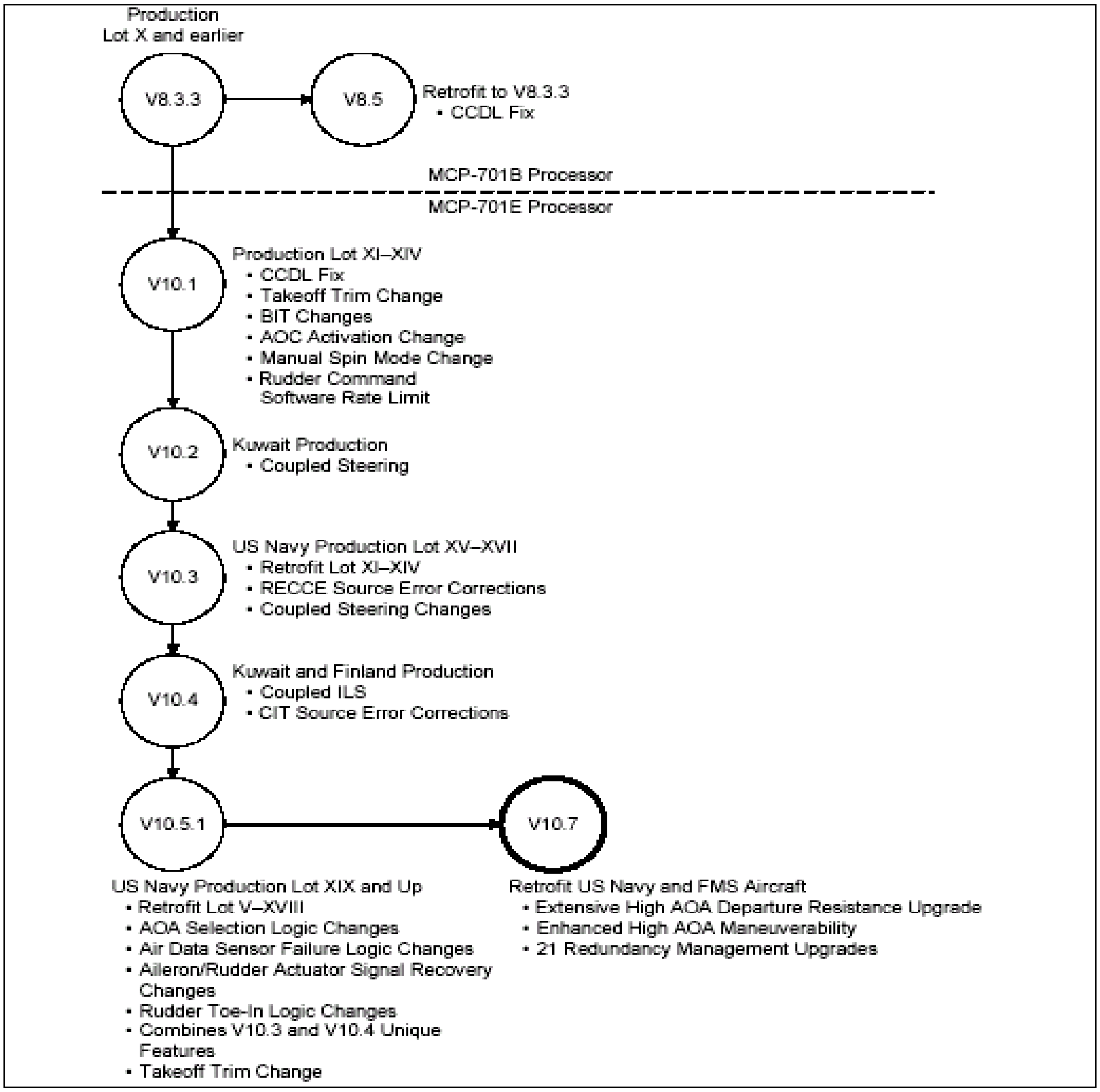


Figure 2. F/A-18A-D Flight Control Computer (FCC) Operational Flight Program (OFP) Developmental History from 1980 through 2004 (DeMond, 2003).

extensions forward of the wing and fully fly-by-wire advanced digital flight controls, truly enhanced its extreme low speed handling capabilities. To fight other aircraft, Hornet pilots were taught to exploit the Hornet's superior high angle of attack (AOA) maneuverability to ensure their best chance for victory in an air-to-air dogfight. Maneuvering the Hornet safely at slow speed however required special precautions and was not without risk. That is because the Hornet exhibits an unfortunate "cliff" in its handling characteristics. The exceptional flying qualities the F/A-18 exhibits from the well integrated Control Augmentation System (CAS) tends to lull the unwary pilot into attempting ill-advised maneuvers impossible to complete. The easily identified pilot feedback that typically accompanies flight near the aerodynamic limit in most aircraft (such as wind noise, buffet, or degraded flying qualities) is much more subtle in a Hornet. Therefore, the one glaring exception to the Hornet's brilliant reputation has been a continued susceptibility to an out-of-controlled (OCF) flight regime known as the "Falling Leaf" mode.

CHAPTER III. HISTORY OF THE FALLING LEAF MODE AND PROPOSED REMEDIES

EARLY TESTING

The first F/A-18 lost at sea was due to an Out-of-Controlled flight incident during Basic Fighter Maneuvering (BFM) testing. This incident occurred on 14 November 1980 at Patuxent River Naval Air Station, during the developmental testing of the Hornet. Since that time, 19 additional aircraft, and several pilot lives have been lost due to crashes caused by OCF.

There are two primary sustained departure modes of the Hornet—a spin mode and a Falling Leaf mode. The aircraft FCS is equipped with a Spin Recovery Mode (SRM) that includes flashing command arrows on the cockpit displays and simple pilot procedure to input lateral stick in the direction of the command arrow. However, the Hornet has rarely been found to spin operationally and the SRM has not assisted in many recoveries. Unfortunately, the Spin Recovery Mode has a tendency to falsely activate in a Falling Leaf departure. Of the twenty aircraft lost due to OCF, eighteen of the mishaps were attributed to the Falling Leaf sustained departure mode (Heller, 2003). In addition to this, numerous formal Hazard Report Messages detailing Falling Leaf departure near-mishaps have been submitted to the Naval Safety Center (Bates, 2004).

DETAILED DESCRIPTION OF THE FALLING LEAF MODE

The Falling Leaf motion can best be characterized as in-phase roll and yaw oscillation with basic characteristics similar to the well known Dutch roll mode. The Falling Leafmode has a 4-6 second period and is sustained with little or no damping. The motion is bounded by steeply banked rolls, large AOA and sideslip excursions, and with large sideforce peaks. AOA typically varies from –10 to 70°; Angle of Bank (AOB) can achieve +/-100°; and peak yaw rates may exceed 60°/sec with heading changes of up to 45°. This periodic motion generates 1-1 ½ g's of sideforce in the cockpit along with periods of near zero normal g causing a "light in the seat" sensation. This motion typically is sustained for significant time, resulting generally in altitude losses of 12,000 feet, but occasionally as much as 24,000 feet (Heller, 2003). An additional issue is that the falling leaf yaw rates generated were sufficiently strong to activate cycling spin recovery command arrows on the cockpit displays. This problem was addressed in 1984 by FCC OFP v10.1, designed to reduce the occurrence of false command arrows during Falling Leaf departures but the hazardous false spin arrow indications were not eliminated. According to several hazard reports and mishap reports, pilots have improperly "chased" the false spin arrows with lateral stick inputs and inadvertently aggravated, delayed, or prevented recovery (Potter, 2001).

Figure 3 depicts a time history of a typical Falling Leaf type departure captured during flight test on 7 April 2000. Pitch rates are lower in magnitude (up to 30°/sec) than the depicted roll and yaw rates, with peak pitch rates leading the roll/yaw peak rates by

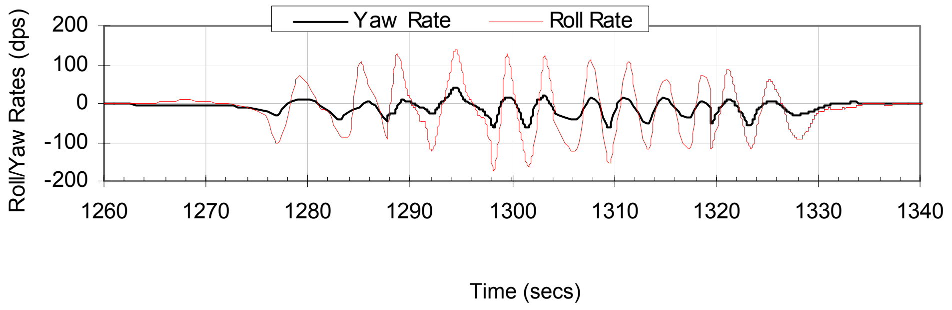


Figure 3. F/A-18B Falling Leaf Motion (Typical) (7 April 2000 flight).

about 90° phase difference. The horizontal axis is time in secs from an arbitrary initial value.

TWO SEAT VERSUS SINGLE SEAT FALLING LEAF SUSCEPTIBILITY

Of the 20 OCF mishaps in the history of the Hornet, 7 have been in two-seat F/A-18Ds. The remainder have been in single-seat F/A-18A or C aircraft. Although Potter concluded that there "appeared to be no difference between the various models in causing OOCF mishaps and this data suggested that OOCF accidents could occur in any F/A-18 model" (Potter, 2001), this is not necessarily the case if one looks at a OCF departure rate per 100,000 flight hours. Data obtained from the Naval Safety Center indicates that in Fiscal Year 2003, single-seat Hornets had 7 reported OCF events during 192,632 flight hours for a rate of 3.63. In the same time period, two-seat Hornets had 4 events in just 62,561 hours for a rate of 6.39 (Bates, 2004). Two aircraft were lost in crashes during Fiscal Year 2003, one single-seat C and one two-seat D. Therefore based on this data, two-seat aircraft have almost twice the likelihood of encountering an OCF departure and over 3 times the likelihood of crashing due to the occurrence than single-seat Hornets.

POSSIBLE PROBLEMS WITH THE TWO-CONTROL STICK MODIFICATION

As was observed by the author and noted in the Preface, the control stick tends to displace laterally due to the strong oscillatory sideforces present during post stall gyrations and the Falling Leaf departure. A time history of the hands free control stick position during the same Falling Leaf test event presented in figure 3 above, is provided in figure 4. Other recorded test data from two control stick configured aircraft revealed lateral stick motion of at least this magnitude and often times more than ¾ inch deflection, dependent apparently on the mechanicalical characteristics of each individual aircraft's flight control system.

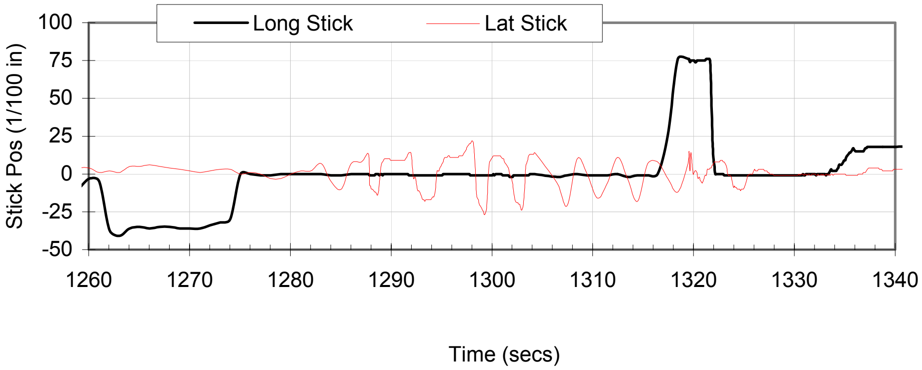


Figure 4. F/A-18B/D Uncommanded Control Stick Motion Data During Falling Leaf Departure (7 April 2000 Flight).

During a recent informal test by the author, a single seat F/A-18C control stick was found to be well damped, with one slight overshoot when released from an initial 2 inch lateral displacement. The stick exhibited similar damping characteristic in either left or right directions. However, a two-seat jet configured with two control sticks was found to exhibit three overshoots from similar initial displacements, with a damping ratio of about 0.4. This difference in mechanical characteristics of the flight control sticks in the two-seat aircraft becomes quite perceptible if the pilot observes carefully. This characteristic is due to the increased sprung mass of the 2-stick trainer-configured aircraft (Mitchell, 2003).

In flight test of two-stick equipped F/A-18B/D, uncommanded lateral stick displacements of up to 0.79 inches were observed during falling leaf motion (Flight Test Data, 5 April 2000). This is critical for two separate reasons. The first is that this control stick movement is providing undesirable and uncommanded inputs to the FCCs. The second issue is that in OFP 10.5.1, the Automatic Spin Recovery Mode (ASRM) is activated when the pilot—or inertial forces—slightly displaces the control stick laterally in the direction of the commanded spin recovery arrow greater than 0.3 inches. As uncommanded inertial stick movement may exceed 0.3 inch, the FCC improperly enters the spin recovery mode. As the aircraft is not in actuality in a spin regime, this characteristic delays recovery.

HUMAN FACTORS ASSOCIATED WITH OCF

An out of control event has several very significant human factors issues lining up against the pilot. Most obviously, out-of-control flight is an unplanned event, at least in all operational OCF cases.

A summary of the adverse human factors issues present during typical unplanned OCF incidents are:

1. Substantial aircrew stress when faced with an unfamiliar situation that historically has not been adequately simulated during training.

2. Aircrew must quickly recover from the surprise, even shock, that they have seriously errored by departing the aircraft.

3. The pilot anxiety level is typically rather high, fearful that ejection may be necessary and loss of the aircraft may be eminent.

4. Disorientation from analytical or cognitive saturation or overload may occur due to the rapidity of changing flight parameters and display hysteresis, or sensor latency (Wiener, 1988).

5. Physical incapacitation due to dynamic load factors, including large side-forces, during a Falling Leaf departure. It is difficult or impossible to maintain precise control inputs in this dynamic environment. Unintentional stick or rudder pedal inputs due to the violent aircraft motion environment are not uncommon unless the pilot is secured tightly in the seat by his harness and the pilot grabs the handholds on the canopy bow for leverage.

These issues combine to result in diminished situational awareness (SA), as well as the physiological phenomena of time dilation, reduced mental capacity, fixation, and vestibulo-ocular disorientation (Zamka, et al, 1997). The problem is further exacerbated because Falling Leaf recovery takes time—and altitude. This is due to the aircraft's insufficient nose-down pitch control power available for recovery compared to the strong nose-up tendency caused by inertial pitch coupling (Potter, 1997). The NATOPS Flight Manual actually specifies that "extraordinary patience" is required for recovery (NATOPS, 2003). However, the mental trait of "extraordinary patience" is exceedingly difficult to achieve during any prolonged departure.

HISTORY OF FALLING LEAF RECOVERY PROCEDURES

For nearly twenty years of operation, the prescribed upright Falling Leaf recovery procedure in the Hornet was to place the control stick full forward while maintaining neutral lateral stick input and no rudder input (NATOPS, Change I, 1997). The problem with this procedure was two fold: it was difficult to accomplish physically and (based on mishaps and near-mishaps) did not work very well. Interestingly, this "Forward Stick" procedure was based only on simulation and was never flight tested during development (Potter, 2001). Finally in 1999, this procedure was flight tested when contradictory evidence suggested that full aft stick (instead of full forward stick) would provide for a more effective recovery from a sustained positive AOA Falling Leaf departure.

The results and conclusion from this five-flight test program were twofold:

1) “Within the scope of the test, releasing the controls provided ‘very dependable’ departure recoveries.”

2) “Full forward Stick Inputs aggravated the initial departure and the rapid nose down pitch to negative AOA caused subsequent re-departures. Additionally, this control input produced motion that was disorienting to the pilots due to the negative g conditions.” (Naval Message of Final Report, June 2000)

Based on the results of this test, NATOPS was revised to delete pilot flight control inputs during OCF. Therefore, unless a sustained spin was confirmed, recovery procedures for the pilot were to maintain controls released and (patiently) await recovery. In addition to the new procedure, a special “Departure Demonstration” flight syllabus was developed and implemented by NAWCAD to educate Fleet aviators on the Hornet departure characteristics. In his 2001 Thesis, “*Analysis of Programs and Procedures Designed to Mitigate F/A-18 Mishaps Caused by Out of Control Flight*”, Potter concludes, “These programs and procedures are likely to substantially reduce the number of aircraft lost to OOCF (out of control flight)” (Potter, 2001).

Unfortunately, Falling Leaf mishaps continued. In fact, 7 Falling Leaf mishaps have occurred since 2000. Of possible significance, 3 of the 7 aircraft were two-seat F/A-18Ds. Clearly, the conclusion of the 1999 recovery procedures testing, that “releasing the controls provided very dependable departure recoveries” was overly optimistic, if not down right incorrect. Additionally, the assertion that the Departure Demonstration flight syllabus would substantially reduce the aircraft loss rate appears to be unfounded.

THE HISTORY OF F/A-18 PROPOSED FLIGHT CONTROL FIXES

One of the first reports that sought to improve the departure resistance of the aircraft was released in 1990. This investigation was produced by McDonnell Douglas to propose FCC changes in response to a Navy request to improve known Falling Leaf departure issues with the F/A-18 B/ D aircraft. Those two-seat aircraft required significant AOA limitations above 0.7 Mach number and still were more susceptible to departure (NATOPS, prior to IC79). That 1990 report recommended adding sideslip and sideslip rate feedback to FCC gains when responding to pilot roll commands. The report was well received by the NAWCAD engineering community. However, there was substantial resistance from F/A-18 aircrew. The pilots were concerned that increased departure resistance would necessitate reduced high AOA maneuverability and roll performance. NAVAIR interest in support for this program was finally withheld in 1993, as funding was re-centered around the development of the Super Hornet Program (Heller, 2003).

F/A-18E/F SOLUTION

The F/A-18E/F Super Hornet appears to be, and was billed to be, geometrically and aerodynamically similar to the original F/A-18A-D Hornet—often referred to as the “legacy Hornet”. However, the E/F FCS was developed with significant funding that allowed for several advances to the flight control system. Fred Madenwald, the senior Boeing Test Pilot for the Super Hornet stated in 1997 that a primary goal during the Engineering, Manufacturing, and Development (EMD) phase of the E/F Super hornet was to suppress the Falling Leaf mode that was prevalent on the original C/D Hornet (Madenwald, 1997). The Super Hornet high AOA design ended up much more advanced than what was proposed to cure the Hornet in 1990.

The airframe and FCC software design changes to the Super Hornet that were incorporated to either directly or indirectly delete Falling Leaf departure characteristics were:

1. Increased Nose-Down Stabilator Travel from 10° nose down to 20° nose down.

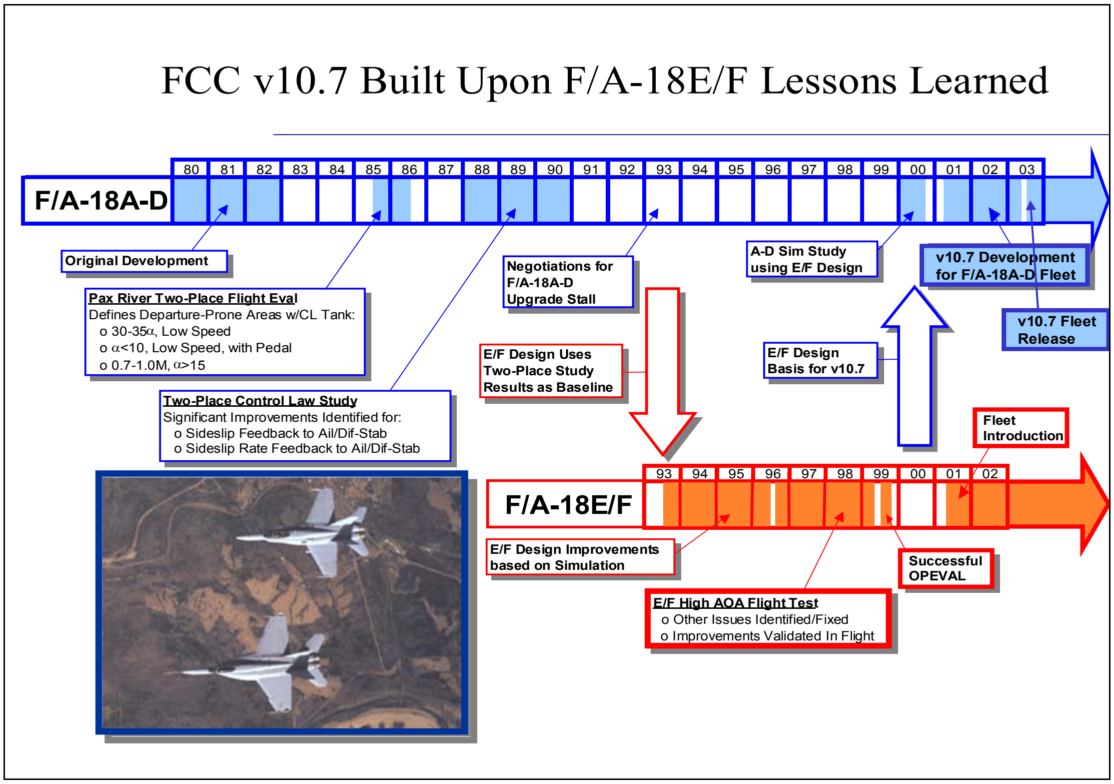
2. Differential Stabilator (Diff-stab) was used as a primary yaw device instead of a rolling device at elevated AOA (above 30°): This is because a significant amount of adverse yaw is generated by differential deflection of stabilators at greater than 20º AOA. The stabilator that is deflected trailing edge down (TED) creates very high induced drag on that side, producing yaw opposite the commanded roll. The Legacy Hornet's old v10.5.1 FCC software used considerable rudder (up to full 30º deflection) to coordinate even small lateral stick inputs due to this diff-stab induced adverse yaw. The old software therefore drastically limited roll command gains (diff-stab + aileron) when the rudders were saturated, resulting in sluggish roll performance when greater than 30° AOA. However, the E/F was able to achieve greater roll performance (roll rates) at elevated AOA by deflecting the differential stabilator opposite to the aileron. This method causes significant yaw moment in the direction that assists the rudder and prevents adverse yaw.

3. Sideslip rate feedback was fed back to the FCCs to control Dutch roll mode above 20ºAOA. This signal is derived from pitch and roll angles from the aircraft Inertial Navigation System (INS) and computed from a combination of lateral acceleration and the integration of sideslip rate.

4. Add a software algorithm to the flight controls that serves to provide tailored output for the limiting of simultaneous aircraft roll and pitch rates. This was accomplished by supplying added logic that automatically reduces the aircraft's actual roll rate when both pitch and roll rates are too high to avoid cross coupling departure regions. This effectively reduces the gain of lateral stick inputs when combined with large or abrupt aft stick longitudinal pilot inputs. The functionality of this limiter is that it gives the pilot the pitch rate or AOA that is commanded with longitudinal stick but at the expense of commanded roll rate to prevent aircraft departure.

DESCRIPTION OF THE LEGACY HORNET FCC OFP UPGRADE SOFTWARE

The upgraded F/A-18A-D FCC software version that was developed as a result of this test program is OFP v10.7. It was developed in large part by the lessons learned and the techniques developed on the Super Hornet F/A-18E/F program. Much of the upgraded legacy Hornet FCC architecture was taken directly from that developed for the Super Hornet. This extensive technology transfer scheme is depicted graphically by the timeline in Figure 5.



FCC v10.7 Built Upon F/A-18E/F Lessons Learned

Original Development

Pax River Two-Place Flight Eval
Defines Departure-Prone Areas w/CL Tank:
- 30-35α, Low Speed
- α<10, Low Speed, with Pedal
- 0.7-1.0M, α>15

Two-Place Control Law Study
Significant Improvements Identified for:
- Sideslip Feedback to Ail/Dif-Stab
- Sideslip Rate Feedback to Ail/Dif-Stab

Negotiations for F/A-18A-D Upgrade Stall

E/F Design Uses Two-Place Study Results as Baseline

A-D Sim Study using E/F Design

E/F Design Basis for v10.7

v10.7 Development for F/A-18A-D Fleet

v10.7 Fleet Release

Fleet Introduction

E/F Design Improvements based on Simulation

E/F High AOA Flight Test
- Other Issues Identified/Fixed
- Improvements Validated In Flight

Successful OPEVAL

Figure 5. Flight Control Technology Transfer Timeline between F/A-18A-D and F/A-18E/F (Wallace, 2003).

The FCC software actually used for the majority of the developmental test flight program was designated OFP v10.6.1. This software load was a flight worthy version of the software used for ground functional and structural mode interaction (SMI) testing (v10.6). The software load was based on existing legacy Hornet v10.5.1 OFP software integrated with Super Hornet derived changes that were designed to improve redundancy management, increase departure resistance, and improve recovery characteristics from out-of-control flight. Major changes to the OFP included E/F FCS features 2 through 4 as discussed in the preceding paragraphs.

OFP 10.6.1 FEATURES

The following features were incorporated in v10.6.1 (Heller, 2003):

1. Sideslip Rate Feedback: An accurate estimator of sideslip rate (β dot) can be calculated from true airspeed, g, Ny (lateral g), pitch and roll angles and rates, and AOA.

2. Sideslip Feedback: With the production F/A-18A-D lacking a sideslip probe, sideslip (β) is calculated by simply integrating the β dot estimate discussed above.

3. AOA Estimator >35° AOA: This estimator presented the highest technical risk of the program because it was not previously developed and tested during E/F Super Hornet development. The E/F AOA probes are accurate to 50°AOA by design while the F/A-18A-D probes are only valid to 35°. During Falling Leaf departures, AOA is typically 60-70°, well outside the capabilities of either A-D or E/F AOA probes. Accurate AOA input was essential to the calculation of sideslip rate, and successful suppression of the Falling Leaf was key to program success.

The concept of using data form the Inertial Navigation System (INS) to compute AOA was considered. However, that would have required a software change to the aircraft Mission Computers (MCs) that would have increased the cost and complexity of this program immensely.

Instead, the AOA estimator uses integration of a computed AOA rate signal. The AOA estimator uses actual stabilator position as the driver and uses a “look up table”. This method was based on AOA estimation techniques that was developed and is used on the F-15 fighter. This information required for this AOA estimation already completely resided within the FCCs and did not require expensive modification to the MC software. Although the F/A-18 is statically unstable in most flight regimes with typical fuel and ordnance loads, the aircraft is longitudinally stable at all AOAs above 35º. The FCS control law uses measured AOA below 31º AOA. When probe AOA reaches 31º, AOA selection logic starts to use a blend of probe AOA and the output of the AOA estimator. By 33º, the output of the AOA estimator is used as the sole AOA source for the lateral and directional axes.

4. Air Data Estimator for AOA>30°: At high AOA, dynamic pressure as measured by the Pitot tube is inaccurate. The estimation is a function of aircraft gross weight, Nz, and Cz (normal force).

5. Rudder Pedal Gain Change with Airspeed and AOA: The Hornet is susceptible to departure at low airspeed near zero AOA. Therefore rudder gain reductions were tailored in that flight regime.

6. Pitch and Roll Inertial Coupling Limiters: A means of the FCS to respond to aggravating simultaneous roll and pitch commands designed to provide improved forgiveness for multi-axis control inputs. Previous OFP v10.5.1 caused severe departures with abrupt full application of aft corner stick inputs. V10.6.1 design initially limits roll rate during high pitch rate maneuvers in effort to prevent departures.

7. Spin Recovery Arrow Improvements: Design reduces the commanded anti-spin aileron at the termination of a spin as the recovery occurs. This is designed to prevent re-departures in the opposite direction (“progressive spin”) if the anti-spin control input is held to long.

8. Pirouette Enhancer: The legacy Hornet pilots have developed a dogfight maneuver that capitalizes on the aircraft’s ability to generate controllable sideslip rates to rapidly reposition from nose-high to nose-low attitude. With the addition of β and βdot feedback, this maneuver would not work unless there was provision left for it. This “Pirouette logic” function is a means to boost the high AOA roll performance when lateral stick and pedal are fully deflected in the same direction. The software feature is designed to provide maximum controllable proverse sideslip commands in cases where rapid gross roll acquisition is desired by the pilot. The “Pirouette logic” essentially allowed commanded yaw rates approaching 40°/sec at elevated AOA and moderately low airspeeds (less than approximately 250 knots calibrated airspeed (KCAS)). The exact functionality and software gains would be adjusted to maximize performance during the testing.

The following is a summary of the high AOA related software changes incorporated into v10.6.1:

- Improve AOA maneuvering control Laws (High AOA Update)
- High Angle of Attack Air Data Estimation
- Angle of Attack Estimation > 35 deg
- Spin Logic Update to Eliminate Erroneous Spin Arrows

- Angle of Attack Failure Detection and Selection Logic Revisions
- High AOA Crossfeed Path Structural Filtering
- DAF Options to revise FCS gain settings during testing if required

In the event that deficiencies were found in the updated v10.6.1 control laws, alternate gains were built into the software that could be enabled real-time using a built in software feature called “Dial-A-Function (DAF)" that was previously engineered into the software.

For completeness, additional v10.6.1 software changes that were designed to enhance FCS functionality, but not related to high AOA maneuverability and departure resistance are delineated below:

- MECH Reversion PBIT.
- PBIT GO Overriding IBIT Degrade.
- False Switching Valve BLIN and MSP Codes during Engine Shutdown.
- Eliminate Nuisance IBIT Failures when Atmospheric Pressure is Too High.
- Eliminate FCS Caution with MC1 Off.
- ASM LEF Stall Monitor.
- FLAP SCHED Caution not set for Right Leading Edge Flap in Hinge Moment.
- LEF Hydraulic Motor Fail Detect Logic Modifications.
- Throttle Backdrive Monitor Correction for Fast Reengagement.
- Flight Test Message Definition for F/A-18 A-D FCC OFP V10.6.
- Aileron / Rudder ASM Updates.

- TEF Asymmetry and Three Fail PBIT BLIN Codes.
- ACLS Changes to Increase Protection from Upstream Failures.
- Pitch Trim Initialization for PA Autopilot Disengage.
- Rudder Toe-In Rate Limiter Improvements.
- PBIT GO Overriding IBIT Degrade – MSP Code Changes.
- Updated Flight Test Message Definition for High AOA Estimation Update.

CHAPTER IV. FLIGHT TEST PROCEDURES USED TO SAFELY CONDUCT OCF AND HIGH AOA TESTING USING DEVELOPMENTAL FCC SOFTWARE

OVERVIEW OF TESTING

A total of sixty-eight test flights were flown by Test and Evaluation Squadron TWO-THREE (VX-23) during the development of the FCS upgrades. Testing was initiated in May 2002 with the v10.6.1 developmental software load and the final v10.7 tests were completed in April 2003. All developmental flights were conducted in the local Patuxent River in-shore restricted areas (Restricted Areas 4006 and R4008) during daylight visual metrological conditions (VMC). Testing was conducted in five phases as delineated in Table 1 below. Exclusive use airspace was used for all but Phase 1 flights. Chase aircraft were used for all flights, except for the initial instrumentation checkflight. In all cases, the chase aircraft was an F/A-18A-D Hornet flown by another developmental test pilot from VX-23 test squadron. The chase aircraft were used as a target for operational test points during Phase 4. In some instances, the target/chase aircraft were also equipped with FCCs loaded with v10.6.1. However, if the target/chase aircraft was equipped with v10.6.1, real-time telemetry from that aircraft was monitored by the test team as well. All test flights were flown by military aircrew assigned to VX-23 with the exception of two Contractor-supplied test pilots. Both of the Contractor

Table 1.
Planned Test Flights for FCC v10.6.1 and v10.7.

Test Phase	**Maneuvers Descriptions**	**Two-Place Aircraft Flights**							**Single Place Flights**
	Load-outs (3):	**FE**	**FE w/Aft CG**	**FCL**	**INT**	**FE + 2 Tanks**	**6K ft lbs Asym**	**12K ft lbs Asym**	**FCLP**
0	Instrumentation Checkflight			1					
1	1 g Stalls, WDTs, and 360 deg Rolls	3		3					3
2	OCF Recovery	1		3			1		
3	1 g Stalls, WDTs, and 720 deg Rolls, and Multi-Axis Inputs		1	7	2	1	6	2	1
3	INS- OFF/ Degraded Modes Evaluation			2					
4	Operational Maneuvers			2(1)					2
5	OFP v10.7 Final Regression Testing(2)	3	6	2	2	1	1	2	3
	Flight Totals:	**7**	**7**	**22**	**4**	**2**	**8**	**4**	**11**

Notes: (1) Operational maneuver flights in the FCL loading included inboard wing pylons.
(2) v10.7 testing was accomplished on a separate Test Program than v10.6.1 but spot checked all configurations and test points.
(3) FE = Fighter escort (Air-to-air (A/A) wingtip missiles only). No wing pylons.
FCL = FE plus Centerline External fuel tank (EFT).
INT = Interdiction Load (Air to ground (A/G) bombs plus, 2 x EFTs,& self-protection A/A missiles.
FCLP = Field carrier landing practice configuration, Centerline EFT + wing pylons.

pilots were employed by Boeing and were former military pilots with extensive Hornet experience.

The test and evaluation was performed over several separate test programs: ground functional and structural mode interaction tests, developmental flight tests, and regression flight tests of the fleet release OFP. There were three separate versions of the OFP. The first OFP, V10.6 was used for ground functional and Structural Mode Interaction (SMI) testing only. The results of the SMI testing were used to tune software structural filters for the second OFP version, v10.6.1, which was used for the developmental flight tests. Problems discovered during developmental testing had software fixes incorporated into the third OFP version, v10.7, which was the fifth test phase which consisted of regression testing prior to being released to the fleet. Changes from v10.6.1 to v10.7 included:

- Inadvertent Spin Mode Engagement Due to Lateral Stick Movement.
- INS Monitor Trips Due to Slow MUX Communication.
- Re-Departures during Spin Recovery.
- Inaccurate Estimated AOA with Stores.
- Pedal Sensitive during Guns Tracking.
- Departure during Roll with 6K ft-lbs Asymmetry.

- Additional MUX Variables - HIAOA Advisory & Incident Data.

TEST SPECIFIC AIRCRAFT MODIFICATIONS

General Modifications to the Aircraft

It was ultimately decided that the primary aircraft for this testing would be an F/A-18D model. This was due to the increased departure susceptibility of the two-place canopy configuration. The aircraft (Bureau Number 163434, known as Salty Dog 120) was equipped with a Digital Data Acquisition System (DDAS) instrumentation system. For this test program SD 120 was modified with several rather low cost systems for this test. These included an Over-the-Shoulder (OTS) video system, yaw rate and AOA gauges on the glare-shield, and a fuselage chin mounted sideslip vane. The location of the AOA and yaw rate gauges on the top of the glareshield is depicted in figure 6. The AOA gauge used a blend of AOA probe and INS derived AOA, which are the same sources of information as displayed on the HUD. The yaw rate gauge displayed INS yaw rate. The yaw rate gauge was fixed to the right side and the AOA gauge was on the left. Finally, a modification was completed to provide isolated signals from the flight control system to the instrumentation system for precise flight control surface position data.

Additionally, a pilot chest restraint strap was installed on the ejection seat in the forward cockpit of the test aircraft. This strap was designed to provide the pilot with additional restraint during high yaw rate or other violent maneuvers, and did not

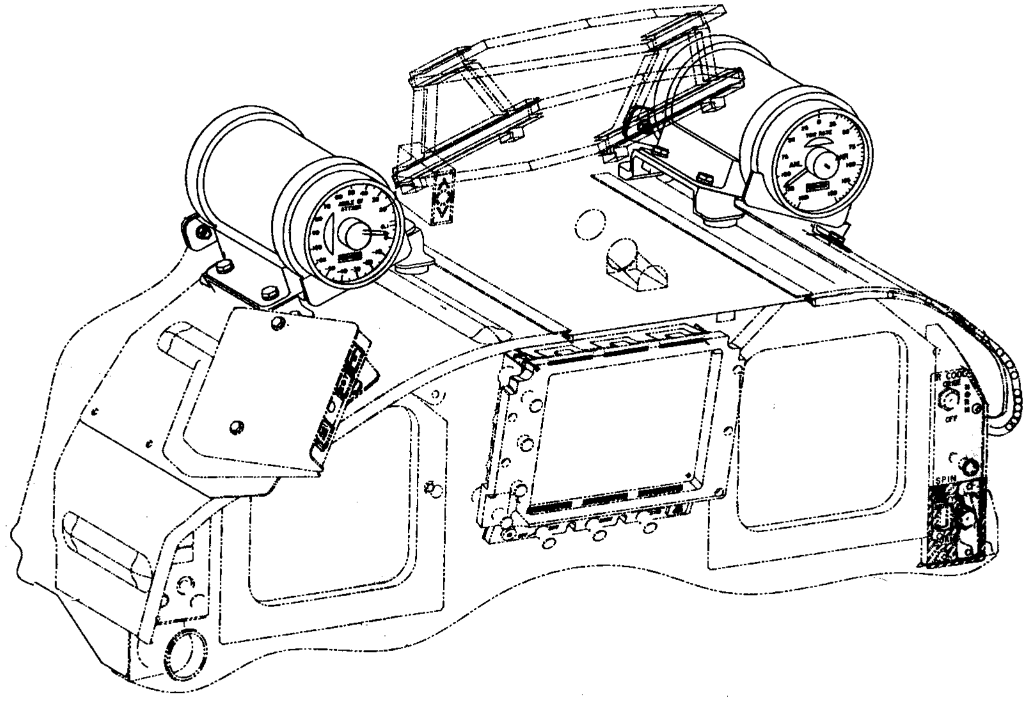


Figure 6. Front Cockpit AOA and Yaw Rate Gauge Locations.

adversely affect the pilot’s performance of cockpit duties nor ejection seat operation or procedures.

To compliment testing in SD120, a single seat aircraft was also used to verify the single place canopy configuration compatibility with the new FCC software. Both aircraft used for this test program were equipped with a yaw string attached on the centerline of the forward fuselage, forward of the windscreen and within view of the pilot.

Additionally, the Amplifier-Control-Intercommunications (ACI) panel was modified to provide the aircrew with control of FCC generated AOA/Yaw Rate tone volume. This feature allowed these normally very loud warning tones to be attenuated sufficiently to allow continuous and uninterrupted communication between the pilot and the test team and chase aircraft.

No Spin Chute Nor Other Typical Spin Test Risk Mitigators

Traditionally, high AOA and OCF developmental flight testing has required the use of an additional spin recovery chute (SRC) mounted on the tail of the aircraft for emergency recovery if normal recovery methods fail. A SRC was developed for the F/A-18 during the early development of the aircraft. The SRC system developed by the Navy was transferred to Edwards Air Force Base for NASA's use on their highly modified High α Research Vehicle (HARV) F/A-18. Photos of the SRC as installed on an F/A-18 are presented as Figure 7.

The VX-23 v10.7 Test Team considered the addition of either this original SRC or modifying the newer SRC developed for the Super Hornet. However, the team was concerned that SRC package weight and aerodynamic affects would interfere with test results. Additionally, the increased cost associated with that addition was a strong negative. After carefully application of the other risk mitigators added to the program the test team elected to forego the SRC.

Interestingly, after the testing of the NASA High α aircraft, NASA concluded that "operationally, the SRC consumed a great deal of time—time that could have been better

EC89 009-9

EC91-518-21

Figure 7. Spin Recovery Chute (SRC) as Installed and Demonstrated on an F/A-18 (NASA Photos).

spent on research tasks had the SRC been removed form the aircraft" (Bowers, 1996).

Engine Damage Risk Mitigation

Although the track record of the GE F404 engine in the Hornet is very good at extremely high AOA, the Team considered the use of an Emergency Power Backup System (EPBS) to provide battery power sufficient for flight control surface hydraulic power in the event of a dual engine flameout. This type of system was used in the F/A-18E/F Development as well as NASA's HARV.

Again, the team elected to use other available risk mitigation to manage the risk of dual engine failure. To prevent or reduce compressor rub during out of control flight, pitch, roll, and yaw rate limits were imposed during departures resulting from tailslides, spin maneuvers, MSRM Falling Leaf, and aggravated input maneuvers. The rate limits were pitch rate of ± 86°/sec, roll rate of ±200°/sec, and yaw rate ±115°/sec during departures.

If any of these limits was exceeded, the test flight would have been aborted and the aircraft would return to base (RTB) for engine borescope inspection. Post flight data analysis by propulsion engineers and the results of the borescope would determine if any additional engine inspections were required. Although the test engines were groomed for this program, several self-recovering pop stalls were detected during spin maneuvers.

TEST ENVELOPE

Testing was performed within NATOPS limits except as authorized by the NAVAIR flight clearance that was obtained prior to testing. Table 2 contains two-place and loading specific AOA and center of gravity (CG) limits as authorized by this flight clearance, along with the corresponding NATOPS limits.

FLIGHT CLEARANCE ISSUES

All Navy flight test programs that modify avionics software, especially FCS related software, or any physical modification to the aircraft require specific Flight

Table 2.
Angle of Attack Limits.

Aircraft Configuration	Flight Clearance Limits	NATOPS Limits (NATOPS, 2003)
Fighter Escort	Unrestricted with center of gravity (CG) 17 to 25.5% MAC	Unrestricted with CG 17 to 25% MAC
Fighter Escort with Centerline Tank	Unrestricted with CG 17 to 24% MAC	Unrestricted with CG 17 to 23.5% MAC
Fighter Escort with inboard wing tanks	-10 deg to 40 deg with CG 17 to 24.5 % MAC	-6 deg to 35 deg with CG 17 to 24% MAC
Interdiction	Unrestricted with lateral or pedal inputs to maintain bank angle only, with CG 17% to 24% MAC, otherwise –10 deg to 30 deg	-6 deg to 20 deg with CG 17 to 27% MAC
Up to 8,000 ft-lb lateral asymmetry	Unrestricted	-6 deg to 20 deg
Up to 12,000 ft-lb lateral asymmetry(1)	-6 deg to 25 deg	-6 deg to 20 deg
Two-place specific limits	Unrestricted	-6 to 20 deg from 0.7 to 0.8 Mach -6 to 15 deg from 0.8 to 0.9 Mach -6 to 12 deg above 0.9 Mach

Note: (1) After the two place testing in loadings FCL and 6KASYM was completed, the remainder of the test points for loading 12KASYM were defined, and an additional flight clearance was requested.

Clearance. Also, Flight Clearance is required to deviate from an applicable NATOPS Operators Manual. Therefore, a local NAVAIR Flight Clearance was obtained for the flight test instrumentation, cockpit analog yaw rate and AOA indicators, sideslip chin vane, pilot chest restraint, and the modified ACI panel.

Additionally, a NAVAIR Flight Clearance was obtained for the following items:

- Flight with FCC V10.6.1 and V10.7 OFP loaded in the FCC's.
- Clearance to perform testing within the AOA limits in table XX.

Also, clearance to perform the following maneuvers prohibited in the NATOPS Operators Manual was obtained:

- Intentional departures and zero airspeed tail slides.
- Zero g for up to 15 seconds during tail slides and 100 knot vertical recoveries.
- Intentional selection of the spin recovery switch to the RCVY position in controlled flight (below 250 KCAS).
- Intentional maneuvers with yaw rates in excess of 25°/sec. The maximum target yaw rate shall be 90°/sec.
- Full or partial stick aileron rolls up to 720° bank angle change (to verify Blue Angels Flight Demonstration Maneuvers.
- In-flight engagement of DAF.

- Negative g for up to 30 seconds with throttles MIL power or less.
- AOA unrestricted at or above 0.7 Mach number in the two place aircraft, except for the above loading specific limits.

Specific limits included in the NAVAIR Flight clearance that applied during FCC OFP developmental testing only included:

- All high AOA/high yaw rate maneuvering or intentional departures shall be conducted with less then 100 lb of fuel in each external fuel tank.
- Minimum altitude for intentional departures is 30,000 ft above ground level AGL (however, all testing was actually accomplished over water).

Additionally, the following alternate recovery inputs were authorized in case an intentional departure failed to recover using normal recovery procedures:

- If OCF below 20,000 ft and 12,000 ft has been lost during the departure, full aft stick may be applied.
- If OCF below 10,000 ft, MAX A/B may be selected.
- Pilot selection of MSRM if lateral stick with arrow in ASRM does not recover from a spin.
- If aerodynamic controls are insufficient to effect recovery from a spin, asymmetric thrust may be used.

- If still out of control below 10,000 ft, the pilot may select FCS gain override.
- If INS attitude angles errors are suspected, the attitude selector switch may be set to STBY.
- Authorization to restart an engine for landing, which had been shut down following an engine stall during a departure maneuver, provided that transient temperature limits were not exceeded.

The product of sideslip and dynamic pressure shall be monitored real time for all intentional departures and spins and shall not exceed +/- 5500 lb/ft^2.

For all intentional departures and spins of aircraft configured with stores the root mean square of roll and yaw rates shall be less than 220°/sec when carrying air-to-air stores, and less than 150°/sec when carrying air-to-ground stores.

TEST LOADINGS

The aircraft was weighed and the longitudinal, lateral, and vertical locations of the CG were determined. In general, testing was performed with fleet representative center of gravity locations. Ten test points were performed in the fighter escort (FE) loadout while in an aft CG condition. For the aft CG test points, the test aircraft was ballasted so that the CG was at the NATOPS aft limit with 2,000 lb of internal fuel. In this condition, the CG was aft of the nominal CG location as fuel is used during the flight, but remained just within NATOPS limits.

METHOD OF TESTS

Test Method and Procedures

Before any testing started with the upgraded OFP, a flight with V10.5.1 was flown to checkout the flight test instrumentation, the FCS rigging, and the suitability of the radome for maneuvers at HI AOA. Also, baseline data for HI AOA roll performance was collected during the checkout flight.

Testing of the upgraded FCC OFP 10.6.1 was evaluated during four phases. Departure resistance to single-axis inputs was evaluated during Phase 1 and no departures were performed. OCF flight recovery characteristics were evaluated during Phase 2 while the aircraft inertial navigation system (INS) was operating normally and while it was disabled. After the recovery characteristics were verified, departure resistance to aggravated inputs was evaluated during Phase 3. Additionally during Phase 3, the effects of AOA failures on flying qualities and departure resistance was evaluated. Flying qualities during operational maneuvers were evaluated during Phase 4. Detailed test method descriptions and a detailed description of the buildup process are presented in appendix A.

Due to the risk of high angle of attack testing, manned and off-line simulation was used extensively to mitigate the risk of the program. The off line sim was a PC based, Boeing developed, Modular Six-Degree-of-Freedom simulation. Off-line simulation was used to generate predicted trajectories for each maneuver. The test team used these predictions during test flights and compared them with actual results. High risk and high workload test points (test Phases 1 though 3) were practiced in the Manned Flight Simulator (MFS) facility at NAWCAD. Many hours of MFS testing was used during this program. The MFS's data link capability was used to provide real-time simulated flight data to the test team (over 3 miles away) at ground control room, known as the Real-Time Telemetry Processing Stations (RTPS). This functionality allowed the test team to rehearse test missions using the same strip chart and graphical displays that were used during flights.

OPERATIONAL PROCEDURES

Flight Briefing

The Test Conductor (TC) and the test team that supported the test flights at RTPS conducted a thorough flight brief approximately 2 hours prior to the start of the scheduled takeoff time. Emphasis of the flight brief was on test procedures, expected performance, emergency, and safety considerations. Applicable test team communications were reviewed for both normal and emergency procedures for each flight. Flight test cards, which detailed communications, flight profiles, test parameters, and the sequence of events, were provided to the pilot and the rest of the test team the day prior to a flight.

Test Profiles

Each test flight followed a similar administrative flight profile. After ground checks (NATOPS, control sweeps, and Manual Spin Recovery Mode check), taxi (including yaw rate gauge check) and takeoff was accomplished. After transiting to the R4006/R4008 inshore restricted area, the Phasing maneuver, g-awareness maneuver, and wind calibration in climb were accomplished prior to performing the test points.

Go/ No-Go Criteria

The following items were considered go/no-go:

- Chase aircraft (except for the instrumentation checkflight) and Search and Rescue (SAR) support.
- Ground Tracking mount video coverage for Phase 2 test flights.
- RTPS telemetry room operational.
- Hot mike telemetry available at RTPS.
- Good weather, clear of clouds, discernable horizon, and view of ground.
- Cockpit Video Recording System operational.

In addition, the following items were considered go/no-go for the two seat aircraft:

- Chest restraint required during Phase 2.

- Glareshield yaw rate analog gauges for all flights during Phases 1, 2, 3, and 5 flights.
- ICS if the aft cockpit was occupied.

Lastly, any malfunction or situation that the aircrew determined as unsafe constituted a No-Go situation. Any downing discrepancy as defined by NATOPS or local Standard Operating Procedures (VX-23 SOP, 2003) constituted a No-Go situation.

Real-time Data Monitoring Plan

Specific real-time monitoring requirements were detailed in the test planning documents and are listed in Appendix C. Additionally, to ensure that critical information was provided to the test aircrew in a timely manner, critical test team members were identified with specific real-monitor monitoring responsibilities. In general, the plan directed that each critical test team member was responsible for identifying specific “knock-it-off” (KIO) or emergency conditions, and provided information to the test conductor, as required. The test conductor then relayed that information to the test pilot. The only exception were “Knock-it-off” calls to prevent an impending departure. For this case, the flying qualities engineers provided KIO calls directly to the pilot, limited to either "Recover – Yaw rate” or “Recover – Sideslip”. All other information was channeled through the test conductor. To ensure that the critical members of the test team maintained familiarity with KIO and emergency procedures, each critical test team member had an initial simulation qualification and was required to maintain currency. For the initial simulation qualification, that member practiced all of the emergency procedures related to their role. Project aircrew, test conductors, and flying qualities engineers either participated in a simulation session or a test flight within 14 calendar days to maintain currency. Flight control and propulsion engineers either participated in a simulation session or a test flight within 30 calendar days to maintain currency.

Alternate OCF Recovery Procedures

Looking at the numbers of aircraft lost to OCF over the years, it was apparent the published NATOPS recovery procedures were not as effective as desired. As this test was attempting to put the aircraft into situations that caused Falling Leaf departures in v10.5.1 software, concern that v10.6.1 Falling Leaf suppression might be ineffective led the team to plan and rehearse alternate recovery procedures. This would preclude having the pilot simply release the controls (per the NATOPS departure procedures) and passively wait all 35,000 ft as the jet fell to earth. Previous OCF testing in 2000 as well as some Fleet mishap data suggested that other techniques had merit and were added as authorized recovery procedures for this testing. These techniques included applying full aft stick and selecting full afterburner, and are detailed in Appendix B.

Cost of the FCC Development Flight Testing

Table 3 contains a list of the estimated Navy costs for this test program. These costs only relate to preparing and conducting the flight test program.

Table 3.
Total Cost Breakdown for All FCC Developmental and Regression Testing (from David, 2002 and David, 2003).

TASK	10.6.1 Development Cost	10.7 Regression Cost	REMARKS
Project management	$219,000	$182,000	
Project support	$40,000	$29,000	
Aircraft Preparation	$113,000	$32,000	Aircraft instrumentation, test support, and data tapes
Real Time Processing Station	$153,000	$48,000	Software development and real-time monitoring telemetry
Ground Tracking Mount Photo-theodalyte	$34,000	$10,000	Video coverage of OCF flights
Aircraft Ground Usage	$30,000	$16,000	Ground charges during aircraft lay-up.
Aircraft Flight Usage	$1,888.000	$603,000	F/A-18 test aircraft and chase flight hours
	$367,000	$95,000	KC-130 Tanker hours
Total:	$2,844,000	$1,015,000	

CHAPTER V. TEST RESULTS

FLIGHT TESTING RESULTS

Departure Resistance Testing

The combined v10.6.1 and 10.7 test program consisted of approximately 600 specific test points. These included 400 rolls, 48 spins, and 63 tailslides. Significantly, more tailslides were done in this development program than were accomplished in the entire three-year F/A-18E/F development program (Swanson, 2003).

During flight testing, the OFP v10.6.1/10.7 AOA estimator output was compared to the presumably more accurate INS derived AOA. Test data verified the accuracy of the estimation method with satisfactory results. Throughout this program, the Falling Leaf mode was successfully suppressed. That result, in and of itself made the program a tremendous success.

However, during initial testing of 10.6.1 (test phases 1 through 4), several deficiencies were present. Examination of the flight data during post-departure gyrations indicated that automatic spin recovery mode (ASRM) was inadvertently engaged if the stick moved left or right due to initial forces while a ASRM command arrow was present. The Test Team was surprised to observe lateral stick deflections greater than one inch during violent post stall gyrations in the two seat aircraft. When ASRM was engaged by this uncommanded lateral stick activity, all feedback to the FCS was removed. This included the very important sideslip and sideslip rate feedbacks. This served to negate the effectiveness of this upgrade, and delay departure recovery.

An additional FCS deficiency not related to Falling Leaf type departures (but OCF related) was that the aircraft would occasionally re-depart after a spin recovery. The software pertaining to ASRM was modified to more quickly disarm the spin mode when yaw rate stopped.

Lastly, several non-OCF related deficiencies were found in 10.6.1 and addressed successfully in v10.7. Rudder inputs were found to be too sensitive at high AOA for predictable guns tracking. Additionally, accurate INS information to the FCCs was lagging due to slow updates on the aircraft's Multiplex Bus (MUX Bus).

Based on the 10.6.1 test results phases 1 through 4, the following changes were incorporated into v10.7:

a) The lateral stick deflection threshold for spin recovery mode engagement was increased from approximately 0.3 to 0.75 inches. This change successfully inhibited incorrectly engaging ASRM due to all but the highest inertial lateral forces on the stick(s).

b) The INS monitor logic was changed to compensate for MUX bus communication delays.

c) The spin recovery mode disengagement threshold was reduced to when yaw rates were less than 17 deg/sec.

d) A nonlinear pedal gradient was added to reduce rudder pedal sensitivity during tracking maneuvers at high AOA.

e) Sideslip and sideslip rate feedback gains were increased around 30° AOA at speeds from 0.8 to 0.9 Mach number.

Creation of OFP v10.7 after the testing of v10.6.1 software was a preplanned part of the software developmental process. This iterative software building process assured that discovered deficiencies could be rectified quickly. All of the listed issues in v10.6.1 were addressed in v10.7. Subsequent regression testing followed. All noted OCF departure related discrepancies were successfully resolved.

Roll Performance Results

The roll performance of the aircraft at elevated AOA was found to be significantly improved over v10.5.1. This increase is presented graphically in Figure 8.

As an example from the figure, at 40° AOA, the old v10.5.1 aircraft had very little roll capability at all. The aircraft felt sluggish and rather unpredictable in roll forcing the pilot to reduce or limit AOA to maneuver. With v10.7 however, roll rates were predictable and usable at 15-25°/sec. Pilot comments were very positive. The figure further shows that roll rates of over 20°/sec are possible at very high AOA with v10.7 up to essentially full longitudinal aft stick sustained AOAs of 50-55º. Lastly, the effectiveness of the “Pirouette logic” is apparent, allowing the pilot to command

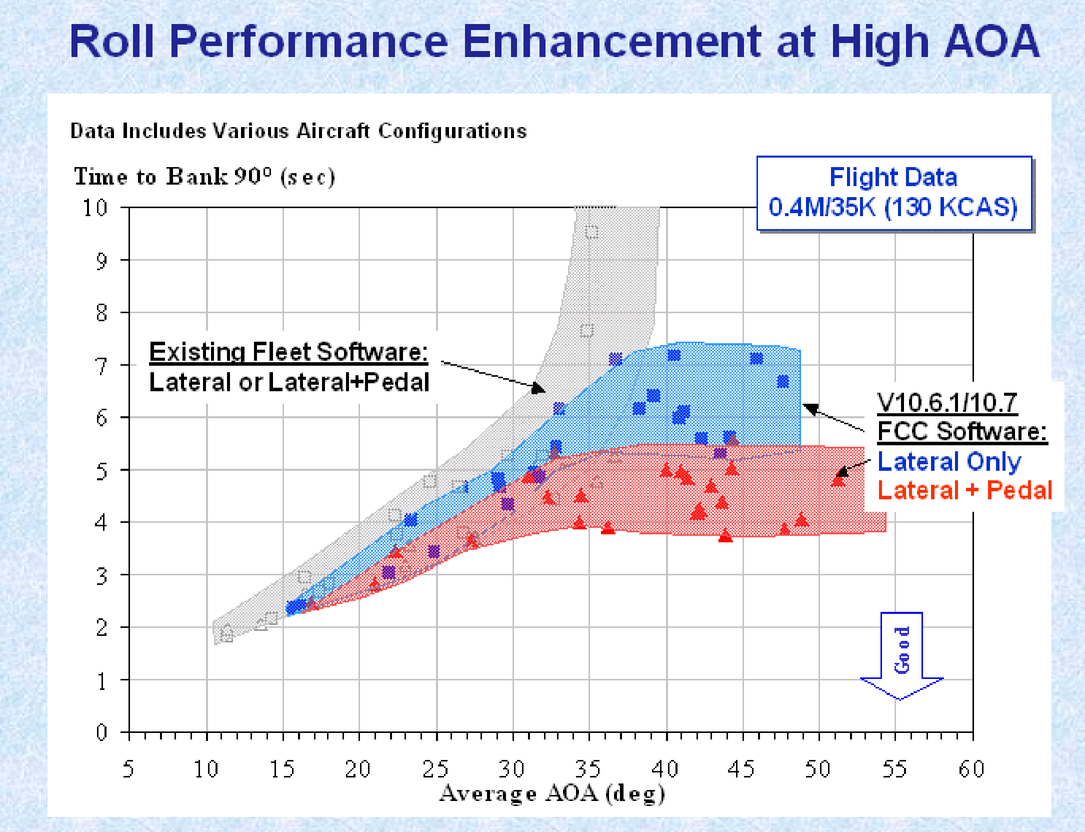


Figure 8. F/A-18A-D Time to Roll 90 Deg at High AOA with FCC OFP 10.7 vs. OFP 10.5.1 (Adapted from Heller, 2003).

progressively higher lateral aircraft response with the addition of coordinated rudder pedal. Although not unusual for most aircraft to exhibit (classically referred to as dihedral affect), the functionality was not mechanized in v10.5.1 software.

Previously, the Hornet did not roll well at high AOA (> 30° AOA). Legacy Hornet pilots had discovered that cross control inputs (e.g., lateral stick in opposite direction of rudder input and desired roll direction) could increase roll performance during maneuver at high AOA. Analysis indicated that these cross control inputs produced proverse sideslip, which combined with the natural tendency of the aircraft to roll away from sideslip at high AOA, improved roll performance.

Although the Hornet has had a great reputation as a “pitch pointer” that could use high AOA excursions to its benefit, v10.7 provides additional capability to effectively command roll and yaw at extreme AOA where the “old Hornet” could only pitch. The v10.7 FCS high AOA sideslip control law designers created provided the pilot direct control over sideslip at elevated AOA, with the sum of coordinated rudder and lateral stick as the controller. For this control law, full rudder pedal input is equal to 3 inches of lateral stick. At high AOA, combined inputs (sum of lateral stick and rudder) less than 3 inches are pure roll commands. Any combined command that is greater than 3 inches introduces a bias signal into the sideslip feedback path, creating what is essentially commanded sideslip. This resulting sideslip produces an increase in roll rate via dihedral effect.

During v10.7 evaluation flights by the author, the aircraft maneuverability with v10.7 was truly eye-watering. The author found that “simple performance graphs do not do the new maneuvering capability justice…the high AOA roll and yaw capabilities now are so astounding that after the flights, one must be careful not to attempt to describe them with your hands, or you risk breaking your wrist” (Mitchell, 2003).

CHAPTER VI. CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

Adequacy of the AOA and Sideslip Estimators

Real time comparison of the AOA and sideslip estimators with truth data computations derived from inertial data were displayed in the control room and constantly monitored during testing. The comparisons were consistent and acceptable in all flight conditions. From a performance standpoint, the measure of effectiveness of the estimators was the successful suppression of Falling Leaf motion. Immediate damping of residual oscillations after high AOA peaks during tailslide testing proved that the estimators functioned satisfactorily.

Adequacy of the Risk Mitigation During the Test Program

The use of simulation to rehearse the flight benefited not only the test pilots, but also the entire Test Team. The planned test sequence carefully selected by the team and reviewed by the Test Coordination Team during the extensive test planning stages was effective in overall risk mitigation.

The most significant surprise that occurred was the uncommanded lateral stick movements encountered. In response to this, the test team ceased testing and “stood-down” for a week to review data and formulate a solution (David, 2004). This was an excellent example of good risk mitigation in response to an unexpected result.

Decision to Test Without a Spin Recovery Chute (SRC) nor Emergency Power Backup System (EPBS)

After evaluating the risks associated with this testing, the v10.7 Test Team deleted the requirement for traditional SRC and EPBS equipment. They utilized Operational Risk Management (ORM) techniques and found ways to mitigate risk that were effective. This resulted in a cost efficient, yet safe and successful flight test program. Although a rather expensive test program, it should be noted that the nearly $4 million total cost estimate for this test program is approximately ten percent of the cost of a single F/A-18C/D aircraft.

Departure Susceptibility and High AOA Maneuvering Capability of OFP v10.7

The 10.7 test team efficiently planned and executed a challenging test program and provided the Navy with a revised F/A-18A-D FCS that enhances the maneuverability and reduces departure susceptibility. Additionally, the v10.7 software is apparently very effective at suppressing the dangerous sustained Falling Leaf mode after a departure occurs. However, more time and Fleet operational flying with the new software is required before that can be determined with certainty.

Based on the historical data regarding Hornet mishap rates, it is clear to the author that if this initial test data is proved accurate and correct, this flight control enhancement will function to save several expensive aircraft during the remainder of the Hornet operational lifetime.

Future Training Program Still Required to Minimize OCF

Concern is justified that operational pilots may overestimate the capabilities of the new FCS software. OPF 10.7 does not prevent departures nor make the aircraft "bulletproof". Pilot errors that cause OCF departures at low altitude will still lead to the loss of the aircraft.

RECOMMENDATIONS

Recently, Secretary of Defense Donald Rumsfeld challenged the military to reduce the military mishap rate by 50 percent in the next two years. "This software will be a major benefit to the fleet and should greatly reduce the number of mishaps resulting form out-of-control flight incidents," said Admiral (Select) Jeff Wieringa, former Navy F/A-18 Program Manager (Boeing News Release, June 2003). The danger is that pilots will push the aircraft even harder or disregard training rules to win at any cost. The potential for a substantial reduction in OCF related Hornet mishaps would only be realized if training is effective and a proper safety culture in the Fleet is maintained. Historically, 64% of all Naval aircraft mishaps were the result of "Skill Based Error", otherwise known as "Human Error" (Naval Safety Center, 2004). Therefore, an effective Hornet OCF training program is an essential companion to the new FCC software.

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APPENDICES

APPENDIX A: DETAILED METHOD OF TEST

GENERAL TEST APPROACH

The flight testing that was conducted during this program was sequenced and prioritized to provide the safest and most efficient buildup to the different phases in an attempt to most effectively accomplish the objectives. The majority of the testing was focused on evaluating the updated controls at flight conditions where the modified control laws are active. However, all phases of flight were spot checked as well. The detailed method of test discussed in this appendix has been adapted from the VX-23 Test Plans (David, 2002 and 2003) as well as lessons learned by the team during the test program.

The approach was split into four phases during OFP v10.6.1 testing. Phase 1 consisted of controlled flying qualities maneuvers to verify aircraft flying qualities. Those maneuvers consisted of 1 g stalls, wind-down-turns (WUTs), break turns, lateral stick plus rudder pedal rolls, lateral stick only rolls, and rudder pedal only rolls. No intentional departure maneuvers were planned for this phase. Phase 2 assessed and confirmed the recovery characteristics of the aircraft from known high altitude OCF situations such as tail-slides, spins and falling leafs using controlled buildup entries. Confirming the OCF recovery characteristics from fully developed OCF modes during Phase 2 provided buildup for the maneuvers that were conducted during Phase 3. Phase 3 maneuvers were either predicted to result in OCF or could unintentionally result in OCF.

Phase 3 evaluated aircraft departure resistance with actual departure maneuvers, as well as test departure resistance and recovery characteristics in the INS off mode and with AOA failures. Phase 4 consisted of operational types of tactical maneuvers including flat, rolling, and vertical scissors. Phase 5 was OFP v10.7 regression testing.

PLANNING FOR PROBLEMS

In the event the minor problems with the OFP were found during testing, Dial-a-function (DAF) options for minor changes to the control laws had been incorporated into the OFP. If a deficiency was found during testing that a DAF option may correct, the software gain change would be first evaluated in simulation, then a flight clearance for the option would be requested and then that overall test plan would be amended.

TWO PLACE BUILDUP APPROACH

Testing in the single place aircraft in the FCL loading, and in the two place aircraft in the FCL, 6KASYM, and 12KASYM loadings were required to clear the two place placarded region. The Hornet aerodynamic simulation database, which is used to generate predictions of expected results, is known to be inaccurate for the single place clean aircraft at high angles of attack above 0.6 Mach number. Predictions for the two place aircraft with a centerline tank were inaccurate as well, since these effects are modeled with increments off of the single place clean aircraft. To evaluate the aerodynamic database and to provide buildup for the two place aircraft in loading FCL, lateral stick rolls were performed in the single place FCL loading during phase 1. This was the only testing performed in the single place aircraft with the wing pylons removed. Since the aerodynamic effects of wing pylons are not well understood, removing the pylons removed one unknown for evaluating the aerodynamic database. After the accuracy of the database was evaluated against the single place aircraft and any updates are incorporated, predictions were generated for the two place aircraft in the FCL loading, and lateral stick rolls were performed during phase 3.

The envelope that was cleared for the two place aircraft with 12,000 ft-lb lateral asymmetry loadings was based on the test results of the two place aircraft in loadings FCL and 6KASYM, and the predictions for the 12KASYM loading. The current database predicted violent departures and probable structure overloads for the two place aircraft in the 12,000 ft-lb loading at 0.9 Mach number and 20° AOA. During a previous flight test program, a two place aircraft with 11,200 ft-lb of lateral asymmetry departed during a lateral stick roll at 20° AOA. After the lateral stick rolls in the two place aircraft were performed in the FCL loading and the database was updated and predictions for the two place aircraft in the 12KASYM loading were generated. The team then used those predictions to determine how much of the envelope could be cleared and the team submitted a test plan amendment with the finalized buildup approach for the 12KASYM loading.

STANDARD TEST PROCEDURES AND PRACTICES

The following procedures were performed in conjunction with each flight as specified. Along with these procedures, a historical database of the preflight data values obtained from the preflight listings was maintained.

Preflight Procedures

Preflight of the instrumentation was accomplished prior to each flying day by the instrumentation personnel. Normal preflight activities included recorder checks, TM checks, Instrumentation BIT, and preflight listings. The null measurements were taken after the aircraft was set up to standard conditions, as defined in aircraft preflight checklists, so that parameter preflight references were consistent from day to day.

Hangar Initialization Record

A 30 second hangar initialization record was recorded using the on-board instrumentation data tape during preflight procedures. These were performed in the hangar with the engines off, no airflow in the ECS or the engine bleed ducts, and with no avionics cooling supplied. This information was used for instrumentation initialization and validation for each flight.

Control Cycles

Full throw cycling of the flight controls were performed and recorded on the onboard instrumentation data tape as part of the pre-taxi procedures. These operations were used for telemetry parameter verification and post-flight instrumentation/data measurand validation. If half stick or half pedal maneuvers were planned for the flight, the pilot also practiced half stick inputs with the Test Conductor critiquing each input.

MSRM Ground Check

Ground check of the manual spin recovery system was accomplished by the pilot with engines running on flights that planned to use MSRM. The pilot selected MSRM and checked that leading edge flaps drove to 34°, trailing edge flaps drove to 0°, and the spin mode display appears on the DDI.

Cockpit Analog Yaw Rate Gauge Taxi Check

The cockpit analog yaw rate gauge was operationally checked with a hard turn during taxi prior to flight. The turn verified that the direction and magnitude of yaw rate indicated was correct.

Phasing Maneuver

A phasing maneuver was performed and recorded on the onboard data tape shortly after takeoff and prior to beginning in-flight tests. This phasing maneuver served as a final check of the ground station and onboard data system polarities. The maneuver consists of the following consecutive control inputs:

Partial left stick input to achieve approximately 30 deg left wing down.
Partial right stick input to achieve approximately 30 deg right wing down.
Partial left rudder (aircraft nose left).
Partial right rudder (aircraft nose right).
Left and right throttle bodes
Aft stick (2g pull up).
Forward stick (-1.0 g push over).

G Awareness Maneuver

A g awareness maneuver was performed prior to beginning test maneuvers on flights that required load factors in excess of 4 g's. The maneuver was performed above 10,000 ft above ground level (AGL) and consisted of a 4 g turn for 90 degrees of heading change, followed by 6 g's for another 90 degrees of heading change.

SPECIAL SAFETY PROCEDURES

Due to the unique nature of departure resistance and departure recovery testing, special safety procedures and considerations were followed, including:

1. All of the intentional departures were performed in the two place aircraft to clear intentional departures in the single place aircraft. The two place aircraft was equipped with a pilot chest restraint and cockpit analog gauges for AOA and yaw rate. The chest restraint was used when intentional departures are planned. Tailslides were only performed in the single place aircraft after the two place aircraft previously cleared them.

2. When available, project pilots occupied the aft cockpit of the two seat aircraft during Phases 1, 2, and 3 for currency and test continuity.

3. Entry and knock-it-off (KIO) criteria for test points were briefed before each flight. KIO communication procedures will be practiced during every pre-flight brief. Both NATOPS and the alternate recovery procedures listed in appendix B were briefed prior to each flight.

4. All high risk or high workload test maneuvers were practiced in the Manned Flight Simulator (MFS) prior to being performed in-flight. Emergency procedures that were developed using the manned simulator were practiced and refined on a periodic basis, to remain familiar and proficient with anticipated aircraft response and normal and emergency procedures.

5. Predictions were generated for all test maneuvers during phases 1, 2, and 3. The test team used these predictions to monitor trends in AOA and Mach number. Examples of parameters that were monitored real-time included sideslip, roll rate, and yaw rate, and errors between estimated and INS derived AOA and sideslip. Members of the test team used experiences from simulation practice and engineering judgment to determine if the next test point should be attempted.

6. All flights were conducted in daylight Visual Meteorological Conditions (VMC) with a discernable horizon above 5,000 ft. to test altitude with a clear view of the ground. Additionally, unobstructed visibility to obtain ground video tracking of the aircraft was required during Phase 2.

7. Lateral weight asymmetry was monitored during flight, with no maneuvers initiated with asymmetries beyond those identified for each phase of testing. The longitudinal location of CG was monitored during the flight to ensure that all maneuvers were performed within the clearance limits.

8. Standard and consistent terminology was used for test conduct. TM room to aircraft radio transmissions followed an "ACTION - REASON"

format. The “action” element will direct the pilot to take an action as appropriate for the situation, such as terminating maneuvering and returning the aircraft to straight/level flight (“recover”), reducing power to IDLE (“throttles IDLE”), or inputting a recovery control (“stick right”). The “reason” will be added when appropriate to clarify the cause for the action, such as “sideslip”, “yaw rate”, “loads”, or “engine stall”. Anticipated KIO calls are presented in appendix B as well.

9. Throttles remained fixed (or brought to IDLE) for all maneuvers except as specified in the maneuver description, such as asymmetric thrust. Engine parameters were monitored during all testing. If the propulsion engineer observed a pop stall that clears without any action by the pilot (self-recovering pop stall), the maneuver would be allowed to continue. These are of short duration and may or may not be noticeable to the aircrew and do not result in any damage. If the aircrew observed a stall, the throttles would be retarded to IDLE and the maneuver terminated. If the stall clears, the propulsion engineer will analyze the engine data and determine if testing may continue. If the stall cannot be attributed to a known condition, the aircraft will RTB. For hung stalls, defined as stalls that do not clear after the throttles are moved to IDLE, the affected engine would be secured and the aircraft returned to base IAW NATOPS. If temperature transient limits were not exceeded, the pilot

may re-start the engine prior to landing. If temperature transient limits were exceeded for any stall event, the pilot would RTB for precautionary hot section inspection. Engine history and component life data from the pool of available engines was studied to ensure selection of healthy engines for the test aircraft. Engines were borescoped prior to the start of testing to document baseline engine condition. Any replacement engine will also be borescoped prior to testing.

10. To reduce the possibility of an engine flameout due to fuel starvation, the feed tanks were verified to be full of fuel before all negative g maneuvers, with at least one minute with positive load factor between negative g maneuvers.

11. NATOPS recovery procedures were to be used during both intentional and unintentional departures. However, if NATOPS recovery procedures failed to recover the aircraft, alternate recovery procedures were identified and were briefed prior to each flight. Alternate recovery procedures are presented in appendix B. Included in the alternate recovery procedures were the use of asymmetric thrust to recover from spins and the selection of maximum afterburner during delayed recoveries from sustained Falling Leaf departures. However, the use of

thrust to assist recovery was only to be attempted after sustained aerodynamic recovery controls have proven ineffective.

12. If a FCS failure occurred or a Master Caution annunciated during a maneuver, the maneuver was to be aborted. If a FCS failure occurred during a departure, the flight controls engineer would examine the FCS display and make an advisory call to the pilot on whether or not a FCS reset should be attempted.

13. Recovery controls were to be initiated by at least 25,000 ft AGL for maneuvers started at 35,000 ft AGL and above. If the aircraft departed controlled flight during any maneuver initiated below 35,000 ft Hp, recovery controls were to be applied immediately.

14. The pilot will eject if dive recovery is not indicated by 6,000 ft AGL.

15. For the purposes of this test, the aircraft will have departed controlled flight if the aircraft does not respond to pilot inputs. The following are examples of departures: the aircraft motion is uncommanded (aircraft rolls opposite pilot input), the aircraft does not roll in the direction commanded by the pilot, or the aircraft diverges in yaw.

FLIGHT TEST PROCEDURES

The maneuvers described below were flown to collect the desired data to satisfy the objectives of this test plan.

Due to the potential for rapid altitude and energy loss during HI AOA maneuvering, unless otherwise specified, the allowable altitude band for maneuver entry for 35,000 ft pressure altitude (Hp) maneuvers was 32,000 to 38,000 ft Hp. For the 25,000 ft Hp maneuvers the allowable altitude band was 22,000 to 28,000 ft Hp. For the 15,000 ft Hp maneuvers the allowable altitude band was 12,000 to 18,000 ft Hp. Operational maneuvers were performed down to 10,000 ft AGL during the first two flights for operational maneuvers, and down to 5,000 ft AGL during the last two flights for operational maneuvers.

F/A-18 A-D DAF Operation

The flight test DAF option in the FCC software allowed predetermined, pre-tested alterations of selected constants inside the control law software during flight. This option could be used to optimize parameters (e.g., roll rates) or be used to reduce risk in the flight control system development by allowing for quick changes to the flight control software in areas where changes were likely to be needed during flight test.

After selecting the desired option and engaging DAF, the constants contained in the DAF table and option replace their control law counterparts. Faders are used, as appropriate, to minimize engage transients. The test pilot evaluates the performance with the DAF option and can, if desired, choose another DAF option or baseline (DAF disengaged) for comparison.

DAF is a special flight test mode that is inhibited in production software releases. There are several safety interlocks that prevent it from operating in a production box and it requires several special procedures to enable it for flight test purposes.

INSTRUMENTATION CHECK OUT AND RIG CHECK

Maneuvering Objectives

A single flight was flown with FCC V10.5.1 to verify proper operation of instrumentation, proper rig of the test aircraft's control surfaces, and that the radome on the test aircraft was suitable for maneuvers at high AOA. The FCS rig check and HI AOA radome check were also performed on the single seat aircraft as required. The rig check tested the roll off with neutral trim at airspeeds of 300, 400, 500, and 550 KCAS. The radome check determined if radome surface imperfections generated excessive directional divergence or yaw rate during at high AOA from pure longitudinal stick inputs. This check used a 1g full aft stick stall an abrupt aft stick pull accelerated stall. Failure criteria was if yaw rate exceeded 15 deg/sec, sideslip exceeded 10 deg, the aircraft departed, or the spin mode logic activated during either the 1g or accelerated stalls.

Lateral Stick Rolls

Rolls were performed to baseline the roll performance of the aircraft with OFP v10.5.1 software as follows:

1. Establish 1-g level flight 2,000 ft above specified altitude.
2. Establish bank angle as required.
3. Pull to specified AOA and attempt to hold flight condition by applying power or diving as required.
4. When stabilized at the target AOA, maintain longitudinal stick ($\pm^1/_2$ in.) and apply abrupt lateral stick to roll under the bottom.
5. Remove control inputs after 360 degree roll angle change or after 15 seconds.

Success Criteria:

- Longitudinal stick maintained within $\pm\,^1/_2$ in during roll.
- Roll conducted at altitude within 2,000 ft of target altitude.
- Full lateral stick input within 0.3 sec.

Abrupt Pull-Ups

1. Establish the desired test conditions.
2. Select MIL power and abruptly apply full aft stick (within 0.25 seconds), and hold for 2.5 seconds. Monitor load factor and angle of

attack. If Nz ref or an AOA limit is reached, terminate maneuver by relaxing aft stick input.

3. Recover to wings level flight.

4.5 – 5.0 g Loop

1. Establish 1 g level flight at 0.8 IMN and 10,000 ft Hp.
2. Select MIL power and smoothly apply aft stick to capture and maintain desired initial load factor. Decrease load factor following the "1 percent rule" (load factor 1 percent of calibrated airspeed). Maintain bank angle using lateral stick inputs and referencing the horizon.

Break-Turns

1. Establish the desired initial conditions.
2. Smoothly roll to 90 deg angle of bank. Reduce throttles to idle and abruptly pull to maximum load factor and/or AOA.
3. After maximum AOA is reached, recover.

FLIGHT TEST BUILDUP APPROACH DURING OFP V10.6.1 DEVELOPMENT

The test sequencing during initial OFP v10.6.1 development was divided into four major phases, with each phase having specific maneuvering objectives and buildup sequencing:

Phase 1 – Prediction Model and Control Law Algorithm Assessment

Phase 2 – Out-of-Control Recovery Demonstration

Phase 3 – Departure Resistance/Susceptibility/Recovery; Failures

Phase 4 – Operational Assessment

The test objectives, test loading and test point sequencing, maneuver descriptions, and KIO criteria for each phase are described below:

PHASE 1 TEST MANEUVERS

Maneuvering Objectives

The objective of Phase 1 was conduct single-axis maneuvers with very low risk of departure so that the accuracy of the prediction models and control law algorithms could be assessed. Test points in Phase 1 were selected based on simulations that predict a clear absence of departure, with knock-it-off criteria also established to avoid a departure. Any point known to depart with V10.5.1 control laws but predicted fixed in the V10.6.1 control laws were not flown in this phase to further mitigate departure risk.

Test Sequencing

Test sequencing was a buildup of external loadings, maneuvers, and AOA. Mach number was sequenced from low to high as a buildup, following by a buildup of high altitude to low altitude. The buildup utilized was specifically as follows:

Loading Buildup

The aircraft is flown first without a centerline tank, transitioning to flights with a centerline tank.

Maneuver Buildup

Longitudinal-only maneuvers were conducted first before rolling maneuvers within each configuration. All longitudinal points at all flight conditions were conducted prior to rolling maneuvers. The objectives of the longitudinal points were to show adequate lateral-directional damping of small perturbations, and to also exercise the AOA Estimator used to compute AOA beyond the probe limit of 35 degrees.

Rolling maneuvers were conducted next, in the order of low-AOA to high AOA at each flight condition progressing from low Mach to high Mach number at high altitude, then transitioning to lower altitude. Lateral-only inputs were conducted first, followed by pedal-only, followed by lateral+pedal. Lateral+Pedal inputs are designed to engage the new "Pirouette logic" to substantially boost high AOA roll performance and was considered the highest risk for roll overshoots – but with sideslip excursions predicted to be well-controlled for all configurations. Roll maneuver test points with the two-place aircraft configured with a centerline tank were limited to 25 degrees AOA to avoid the V10.5.1 departure-prone regime near 35 degrees AOA. Roll maneuver test points of 30 degrees and above were conducted on the single-place aircraft with centerline tank – a more stable configuration – to collect the needed data while mitigating the departure risk.

Maneuver Entry and KIO Criteria

All roll maneuvers were terminated at 360 degrees of roll angle change or 15 seconds duration, whichever came first. Sideslip was monitored with a knock-it-off criteria of 15 degrees. The FCC lagged yaw rate used to determine a spin condition was also monitored with a knock-it-off criteria of 15 degrees – 2 degrees less than the 17-degree threshold used for the spin condition indication. This knock-it-off criterion was used to guard against immediate spin mode entry during a normal roll maneuver if a spin arrow should inadvertently be presented. Note that the spin arrow presentation is both a condition of lagged yaw rate greater than 17 degrees, and also indicated compressible dynamic pressure (q_c) less than 50 psf. Since indicated dynamic pressure can read erroneously low at high AOA, the $q_c<50$ condition was assumed to always exist.

Test Maneuvers

Longitudinal Maneuvers--1g Stalls

1. Establish 1-g level flight 5,000 ft above specified altitude.
2. Reduce power to IDLE and allow AOA to increase.
3. Sample handling qualities every 5 deg AOA by performing pitch, lateral, and rudder doublets.
4. Gradually apply aft stick to increase AOA
5. Apply lateral stick and rudder pedal inputs as required to offset any roll-off tendencies.

6. At full aft stick, hold for 5 sec and sample handling qualities in each axis.

Terminate maneuver by releasing controls.

Success Criteria: Maneuver conducted within 5,000 ft of target altitude.

Wind-Down/Break Turns

Wind-down turns (WDTs) were used to evaluate the accuracy of the AOA estimator when AOA is greater than 35 deg:

1. Establish the specified initial conditions.
2. Smoothly roll into an overbanked turn, applying aft stick at a target rate of 1 inch/sec. Selected test points will be repeated as a break turn, with an abrupt full aft stick input (full input within 0.25 sec).
3. Maintain full aft stick until airspeed reaches 80 KCAS.
4. Terminate maneuver by releasing controls.

Success Criteria:

- Full aft stick is attained within ± 0.05 Mach of target Mach.

Lateral Maneuvers -

Lateral Stick Rolls:

1. Establish 1-g level flight 2,000 ft above specified altitude.
2. Establish bank angle as required.

3. Pull to specified AOA and attempt to hold flight condition by applying power or diving as required.
4. When stabilized at the target AOA, maintain longitudinal stick ($\pm{}^{1}/_{2}$ in.) and apply abrupt lateral stick to roll over the top, or under the bottom (as required).
5. Remove control inputs after 360 degree roll angle change or after 15 seconds.

Success Criteria:

- Longitudinal stick maintained within $\pm\ {}^{1}/_{2}$ in during roll.
- Roll conducted at altitude within 2,000 ft of target altitude.
- Full lateral stick input within 0.3 sec.

Sustained Pedal Rolls

1. Establish 1-g level flight 2,000 ft above specified altitude.
2. Establish bank angle as required.
3. Pull to specified AOA and attempt to hold flight condition by applying power or diving as required.
4. Maintain longitudinal and lateral stick (±1/2 in.) and apply abrupt pedal.
5. Remove control inputs after 360 degree roll angle change or after 15 seconds.

Success Criteria:

- Longitudinal and lateral stick maintained within ± $^{1}/_{2}$ in. of neutral during roll.
- Roll conducted at altitude within 2,000 ft of target altitude.
- Full pedal input within 0.3 sec.

<u>Combined Lateral Stick plus Pedal Rolls</u>

1. Establish 1-g level flight 2,000 ft above specified altitude.
2. Establish bank angle as required.
3. Pull to specified AOA and attempt to hold flight condition by applying power or diving as required.
4. When stabilized at the target AOA, maintain longitudinal stick (±$^{1}/_{2}$ in.) and apply abrupt simultaneous lateral stick and pedal to roll over the top or under the bottom.
5. Remove control inputs after 360 degree roll angle change or after 15 seconds.

Success Criteria:

- Longitudinal stick maintained within ± $^{1}/_{2}$ in. of neutral during roll.
    - Roll conducted at altitude within 2,000 ft of target altitude.
    - Full control inputs within 0.3 sec.

PHASE 2 TEST MANEUVERS

Maneuvering Objectives

The objective of this phase was to verify recovery from post-departure gyrations (PDGs) and sustained OCF modes. Recovery from OCF modes was evaluated during Phase 2 to reduce the risk and minimize the consequences of entering OCF modes during Phase 3. Departure recoveries from PDGs resulting from tailslides and vertical recoveries, upright spins, and falling leafs were evaluated. Inverted spins were not planned since the control law update has not affected negative AOA, and no large negative AOA points were planned. Only NATOPS recovery techniques were evaluated, however, alternate recovery techniques were available if NATOPS recovery techniques fail to recover the aircraft.

Test Sequencing

Test points were conducted on the most stable external loading first (FE), progressing to less stable with a centerline tank. Full-up control laws were flown first, followed by a simulated failure of the INS attitudes (INS-OFF mode). The final Phase 2 testing was conducted with a 6K ft-lb lateral weight asymmetry since lateral weight asymmetries have historically resulted in the longest recovery times.

Loading Buildup

Two-place Fighter Escort was flown first, followed by the two-place FCL loading, followed by INS-OFF testing in the two-place FCL loading, followed by the two-place 6K asymmetry loading. The first three loadings were flown consecutively in preparation for the Phase 3 testing with similar loadings. Recovery in INS-OFF mode was demonstrated in this phase in case the mode is unexpectedly entered during follow-on testing. The Phase 2 testing with the 6K asymmetry loading was flown later in the program, but prior to the majority of the test points in that configuration. Out-of-control recovery points in the INS-OFF mode and in the 6K asymmetry loading were preceded with longitudinal maneuvers, which were not predicted to depart controlled flight.

Maneuver Buildup

Spins were conducted first, in the order of increasing maximum yaw rate target buildup. A half turn incipient spin was conducted in loading FE and 6KASYM prior to the fully developed spins for buildup and to evaluate NATOPS recovery techniques. Spins were conducted stepping up at 30, 60, and 90 degrees/second. Three spins were conducted at each target yaw rate before moving up to the next rate.

Vertical recoveries and tailslides were conducted next. Tailslides were also be performed with the nose of the aircraft biased just prior to and just beyond the vertical, and then with the nose of the aircraft biased left and right of vertical. Low-speed banked flight has been shown to be a common way that falling leaf motion has been entered in fleet events, giving the tailslide with the nose biased either left or right of vertical the best chance of entering falling leaf motion.

Intentional falling leaf entry maneuvers using MSRM for entry were conducted last, being historically the motion requiring most altitude for recovery. Because the v10.6.1 control laws were designed to damp this motion, sustained falling leaf motion was not possible once MSRM was disabled.

Real Time Trend Analysis

Spins were evaluated in a yaw rate buildup of 30, 60, and 90 deg/sec. The Test Team evaluated each recovery and determined if the recovery met expectations. The next highest yaw rate point would then be attempted only if the test team felt that the recovery would be adequate based on the trends of the buildups and predictions. Time for yaw rate to decay, number of turns before recovery, and altitude lost during recovery were used as metrics to measure the recovery performance.

Falling leaf motion should be damped promptly after MSRM is disabled. The test team evaluated each recovery and would have recommended that further entry attempts not be made if the recovery was prolonged and not as predicted (i.e. any prolonged departure that descends below 20,000 ft Hp).

Test Maneuvers

Descriptions of OCF mode entry and recovery techniques are given in the following sections.

Spins

All spin entries were made using asymmetric thrust. MSRM was used if target yaw rate could not be attained using asymmetric thrust. Maximum target yaw rate was 90 deg/sec. A single half turn incipient spin was performed in loadings FE and 6KASYM. Buildup spins were flown using target yaw rates of 30 and 60 deg/sec, both to the left and right. Recovery was made by moving the throttles to IDLE, deactivating MSRM (if used), and applying NATOPS recovery controls.

Asymmetric Thrust Upright Spin Procedures

1. Stabilize at wings level, 150 KCAS and 35,000 ft Hp.
2. Slowly reduce both throttles to IDLE, set 20 to 25 deg pitch attitude, and hold.
3. At 35 deg AOA, smoothly apply full aft stick.
4. Smoothly increase thrust on left/right engine to MIL with the other engine at IDLE until target yaw rate is achieved. Apply full pro-spin rudder pedal input, relax aft stick, and pro-spin lateral stick as required.
5. To recover, bring both throttles to IDLE, remove rudder pedal input, relax full aft stick and apply NATOPS recovery controls.

MSRM Upright Spin

Stabilize at wings level, 150 KCAS and 35,000 ft Hp.

Select spin recovery switch to RCVY and reduce power to IDLE.

Establish downward flight path angle of approximately 20 degrees.

Smoothly apply full aft stick.

After spin mode engages, smoothly apply full rudder pedal.

Smoothly increase thrust on engine opposite of rudder pedal input to MIL with other engine at IDLE until target yaw rate is achieved.

Slowly apply lateral stick opposite rudder pedal input while coming off the aft stop.

At the target yaw rate, neutralize controls and bring both throttles to IDLE.

Select spin recovery switch to NORM and apply NATOPS recovery controls.

Tailslides / 100 KCAS Vertical Recoveries

Tailslide maneuvers were performed to evaluate departure resistance:

Start at 30,000 ft Hp / 300-350 KCAS.

In MIL power, pull to an upward, near vertical attitude.

When the aircraft no longer responds to control inputs, reduce power to IDLE, release the controls and allow the aircraft to recover.

Variations to this maneuver included:

1. Biasing the nose attitude of the aircraft in the following ways: nose forward, nose back, nose left, and nose right.
2. At 100 KCAS, apply full forward or full aft stick, releasing controls and reducing power to IDLE when the aircraft no longer responds to control inputs.
3. At 100 KCAS, apply full forward or full aft stick, reducing power to IDLE when the aircraft no longer responds to control inputs, and releasing controls when sustained oscillations develop or when the aircraft descends through 30,000 ft Hp.
4. At 180 KCAS, apply full lateral then either full forward or aft stick after maximum roll rate is reached, releasing controls and reducing power to IDLE when the aircraft no longer responds to control inputs.
5. At 180 KCAS, apply full lateral then either full forward or aft stick after maximum roll rate is reached, reducing power to IDLE when the aircraft

no longer responds to control inputs, and releasing controls when sustained oscillations develop or when the aircraft descends through 30,000 ft Hp.

Falling Leaf Test Points

Not all falling leaf entry attempts were successful. For the purpose of this test, a sustained falling leaf was defined as at least two cycles of in-phase rolling and yawing motion.

MSRM Falling Leaf Entry:

1. Stabilize at wings level, 0.5 IMN /40K (145 KCAS).
2. Select spin recovery switch to RCVY to enter MSRM and reduce power to IDLE.
3. Establish dive angle of approximately 20 degrees.
4. Smoothly apply full aft stick and hold.
5. Apply lateral stick to generate sideslip (some side-to-side cycling may be necessary to generate largest sideslip).
6. Neutralize controls. Falling leaf motion is characterized by large sustained oscillatory yaw rate motion with approximate 5 second period. Allow motion to persist for two cycles or until 25,000 feet altitude.
7. Recover by selecting spin recovery switch to NORM and neutralizing controls. Falling leaf motion should be damped promptly after CAS is

enabled due to the sideslip rate feedback and other control law features incorporated in the upgraded flight control system.

PHASE 3 TESTING

Maneuvering Objectives

The objectives of Phase 3 were to evaluate departure resistance and to evaluate recovery from departure.

Test Sequencing

Test sequencing in Phase 3 was in the order of test points least likely to depart with single-axis input to intentional departures with multi-axis inputs, and then to failure modes. Configurations were flown in the order of most-stable symmetric to least-stable symmetric, then to asymmetric loadings – smallest asymmetry to largest asymmetry, then to a symmetric loading with an aft CG.

Loading Buildup

The external loadings were sequenced generally from most-stable to least-stable for the series of single-axis long-duration inputs, including those points that were predicted to depart in the V10.5.1 control laws. Loading sequencing were two-place FCL (high AOA points), single-place FCL (low AOA points), Interdiction, Two-Tank, 6K asymmetry, 12K asymmetry, and aft CG Fighter Escort. Once those points were completed, the loading shifted back to a more stable loading of the two-place FCL to perform the multi-axis aggravated inputs, followed by multi-axis inputs repeated in the 6K asymmetry loading. Simulated FCS failures were tested last in the two-place FCL loading.

Maneuver Buildup

AOA/Mach number/Altitude buildup for the long-duration single-axis maneuvers were similar to Phase 1. Roll maneuvering buildup was also be similar to Phase 1, starting with lateral-only, progressing to pedal-only, progressing to lateral+pedal. For test points for which sideslips were predicted to be greater than 15º or yaw rates were predicted to be greater than 40º/sec, the onsite test team added half input or 180º or 360º buildup test points. Operational assessment of the pirouette maneuver was conducted after the long-duration lateral+pedal maneuvers were conducted. An extra assessment of inadvertently engaging the Automatic Spin Recovery Mode was conducted upon evaluating the results of the long-duration single-axis control inputs.

The order of the aggravated multi-axis inputs was in the order of those maneuvers that were predicted to remain controlled, to maneuvers that were predicted to depart.

Since Phase 2 testing had already demonstrated OCF recovery, the risk of departure had been mitigated whether the Phase 3 maneuvers departed or not. The assumption was that all Phase 3 maneuvers will depart and that the recovery risk had been mitigated.

For the failure modes, INS-OFF was conducted first, followed by other redundancy management failure modes. Failure mode sequencing was not vital, since no testing depends on the other.

Maneuver Entry and KIO Criteria

Maneuvers were terminated at 720 degrees of roll angle change or 15 seconds, whichever came first, while under controlled flight

Test Maneuvers - The maneuvers for this phase are summarized below

Longitudinal Maneuvers

1g Stalls - See maneuver descriptions for Phase 1.

Wind-Down Turns - See maneuver descriptions for Phase 1.

Lateral Maneuvers - Rolls were performed in alternating directions. Rolls in the asymmetric loadings were performed in both directions, and rolls were performed in the non-critical direction first (based on simulation predictions). The exception to this was rolls selected for regression testing, which were performed in the most critical direction based on simulation predictions,

Lateral Stick Rolls

1. Establish 1-g level flight 2,000 ft above specified altitude.
2. Establish bank angle as required.
3. Pull to specified AOA and attempt to hold flight condition by applying power or diving as required.
4. When stabilized at the target AOA, maintain longitudinal stick (±$^1/_2$ in.) and apply abrupt lateral stick to roll over the top, or under the bottom (as required).

5. Remove control inputs after 720 degree roll angle change or after 15 seconds.

Success Criteria:

- Longitudinal stick maintained within ± $^1/_2$ in during roll.
- Roll conducted at altitude within 2,000 ft of target altitude.
- Full lateral stick input within 0.3 sec.

Sustained Pedal Rolls For conditions above 1 g Nz.

1. Establish 1-g level flight 2,000 ft above specified altitude.
2. Establish bank angle as required.
3. Pull to specified AOA and attempt to hold flight condition by applying power or diving as required.

For conditions at or less than 1 g Nz.

1. Establish 1-g level flight 1,000 ft below specified altitude. Select wing fuel transfer to INHIBIT.
2. Establish a pitch attitude with the nose of the aircraft above the horizon.
3. Apply forward stick to capture specified AOA and attempt to hold flight condition by applying power as required.

When established on conditions:

4. Maintain longitudinal and lateral stick (±1/2 in.) and apply abrupt pedal.
5. Remove control inputs after 720 degree roll angle change or after 15 seconds. Select wing fuel transfer to NORM (as required).

Success Criteria:

- Longitudinal and lateral stick maintained within ± $^1/_2$ in during roll.
- Roll conducted at altitude within 2,000 ft of target altitude.
- Full pedal input in within 0.3 sec.

In addition to the general KIO criteria for Phase 3, the plan terminated the maneuver once any of the following criteria were exceeded:

- 30 seconds at negative Nz.
- Engine oil pressure caution.
- Fuel boost pressure low caution.

Combined Lateral Stick plus Pedal Rolls

1. Establish 1-g level flight 2,000 ft above specified altitude.
2. Establish bank angle as required.
3. Pull to specified AOA and attempt to hold flight condition by applying power or diving as required.

4. When stabilized at the target AOA, maintain longitudinal stick (±$^1/_2$ in.) and apply abrupt simultaneous lateral stick and pedal to roll over the top or under the bottom.
5. Remove control inputs after 720 degree roll angle change or after 15 seconds.

Success Criteria:

- Longitudinal stick maintained within ± $^1/_2$ in during roll.
  - Roll conducted at altitude within 2,000 ft of target altitude.
  - Full control inputs within 0.3 sec.

Pirouettes

Establish 1-g flight at the specified initial conditions.

Coordinate a pull to approximately 30 to 40 degrees AOA with a pitch attitude of approximately 50 to 90 degrees nose high.

Holding aft stick to maintain AOA, insert a combined lateral stick and pedal input to perform a nose-high to nose-low heading reversal.

Continuing to hold aft stick to maintain AOA, apply aggressive opposite lateral stick and pedal to capture the target heading.

Aggravated Control Inputs - The set-ups to these maneuvers were identical to a lateral stick roll. Instead of applying lateral stick, however, one of the following inputs as specified was applied:

- Simultaneous lateral and aft input (to aft corner).

- Simultaneous lateral and forward input (to forward corner).

- Simultaneous lateral and pedal input in same direction with aft stick input.

- Simultaneous lateral and pedal input in same direction with forward stick input.

- Simultaneous lateral and pedal inputs in opposite direction.

- Simultaneous lateral and pedal input in opposite direction with aft stick input.

    - Full lateral stick to achieve maximum roll rate at the test flight condition. At maximum roll rate, apply full aft stick for the remainder of the maneuver.

Flat and Rolling Scissors

As buildup for the operational maneuvers in Phase 4, flat and rolling scissors were performed to evaluate the performance of the AOA estimator during prolonged maneuvers above 35 deg AOA.

Failure Modes

The following failure modes were evaluated during phase 3: True airspeed or MUX bus invalid, INS attitude angles invalid, AOA probe failures and stuck AOA probes. The following paragraphs describe how each of these failures were simulated.

True Airspeed or MUX Bus invalid True Airspeed

True airspeed is used by the upgraded control laws in the calculation to estimate AOA when the mechanical AOA probes are pegged. The software includes a calculation to estimate true airspeed when either the Mission Computer declares true airspeed invalid, or in the event of a MUX Bus failure. For this test program, a DAF option was used that forced the FCCs into using estimated true airspeed.

INS Attitude Angles

INS roll and pitch attitude angles are used in the AOA and sideslip estimation logic. In the event that the INS attitudes become invalid, the AOA and sideslip estimators are designed to degrade to a backup mode. In the production aircraft, selecting the attitude selector switch to STBY on the on the HUD results in the INS attitudes being declared invalid. With v10.6.1 and v10.7, this forces the FCC to ignore the INS attitudes and degrade the AOA and sideslip estimators to their respective backup modes.

AOA Probe Failures

Changes that are designed to improve the handling of stuck AOA probes or total failures of the AOA probe were included in v10.6.1 and v10.7. To evaluate these improvements, DAF was used to simulate a single stuck AOA probe or a total AOA failure. Testing was performed with the left AOA probe simulated stuck at 0.1 degrees and with a simulated total AOA probe failure.

PHASE 4 TESTING

Maneuvering Objectives

The objectives of Phase 4 were to evaluate departure resistance and evaluate flying qualities during operational maneuvers. All flights were flown with adherence to the Navy standard air combat maneuvering (ACM) training rules. The FCLP loading of centerline fuel tank and empty wing pylons was flown in this phase.

Test Sequencing

Test sequencing consideration was only in terms of single-place/two-place test order. The successful completion of the first three phases allowed full aircraft usage under NATOPS limitations, except removal of the subsonic two-place placard regarding AOA and Mach number restrictions.

Loading Buildup

Even though the single-place was the more stable of the two configurations, the two-place aircraft was flown first since it contained more detailed instrumentation.

Maneuver Entry and KIO Criteria

Maneuvers were constrained under NATOPS limitations, except as modified or expanded based on Phase 3 testing. The hard deck (minimum altitude for ACM) was 10,000 ft Hp for the first two flights, and 5,000 ft Hp for all subsequent flights.

Test Maneuvers

Test maneuvers included Air-to-Air Target Gross Acquisition and Fine Tracking at High AOA, flat and rolling scissors, pirouettes. Additionally, other operationally representative ACM drills and engagements were conducted including offensive and defensive maneuvering, snapshot drills, guns defense, butterfly sets and abeam sets.

APPENDIX B: OUT OF CONTROL EMERGENCY RECOVERY PROCEDURES

(NOTE: NATOPS procedures appear in normal font, alternate recovery procedures appear in italics. From David, 2003)

RECOVERY INDICATIONS AND PROCEDURES

Recovery is indicated when AOA and yaw rate tone is removed, side forces subside, and airspeed is increasing above 180 KCAS.

One g roll to nearest horizon
Throttles – MAX (MIL if altitude not critical)
Pull to and maintain 25 to 35 deg AOA until positive rate of climb established (AOA configuration dependent). *With LEF failures do not exceed 10 deg AOA.*

DEPARTURE/FALLING LEAF RECOVERY PROCEDURES

Controls – release / feet off rudders / speedbrake in
If still out of control – Throttles – Idle
Altitude, AOA, airspeed, and yaw rate – Check
When recovery indicated by AOA and yaw rate tones removed, side forces subsided, and airspeed accelerating above 180 knots - Recover
Passing 6,000 ft AGL, dive recovery not initiated - Eject

SUSTAINED OSCILLATORY MOTION RECOVERY PROCEDURES

If INS angle errors are suspected (HUD or RTPS call) - Attitude Selector Switch – STBY.

If recovery not indicated below 20,000 ft Hp and 12,000 ft of altitude lost – Apply full aft stick

If recovery not indicated below 15,000 ft Hp – FCS -- Reset

If recovery not indicated below 10,000 ft Hp - Throttles – MAX A/B

If still no sign of recovery and below 10,000 ft AGL - FCS Gain Override Switch – ORIDE

When recovery indicated by AOA and yaw rate tones removed, side forces subsided, and airspeed accelerating above 180 knots – *Check FCS Gain Override Switch NORM and* Recover

Passing 6,000 ft AGL, dive recovery not initiated - Eject

SPIN RECOVERY PROCEDURES

Command arrow present - Lateral stick – full with arrow

Command arrow not present – Spin recovery switch – RCVY

Lateral stick – Full with arrow

When yaw rate stops – Lateral stick – Smoothly Neutral

Spin recovery switch – Check NORM

When recovery indicated – Recover

Passing 6,000 ft AGL, dive recovery not initiated – Eject

SUSTAINED SPIN RECOVERY PROCEDURES

If INS angle errors are suspected (HUD OR RTPS call) Attitude Selector Switch – STBY.

Yaw rate not arresting with full lateral stick
Spin recovery switch – RCVY
Lateral stick – Full with arrow

If spin shows no sign of recovery:
Right yaw rate – Right engine MAX A/B
Left yaw rate – Left engine MAX A/B

WHEN YAW RATE STOPS
Engines - Idle
Lateral stick – Smoothly neutral
Spin recovery switch – Check NORM

When recovery indicated
Recover
Passing 6,000 ft AGL, dive recovery not initiated -
Eject

Dual Engine Flameout or Single with Imminent Dual Engine Flameout due to Fuel Starvation During Departures:

Recover to controlled flight

Accelerate to 350-375 KCAS approximately 50-60 deg nose-down.

Decrease and maintain pitch to not exceed 20 deg nose-down

Maintain RPM >/= 12% (accelerate if necessary to maintain).

Monitor fuel flow indicators for fuel flow (may take ~60 sec.)

Initiate relight procedures per NATOPS once fuel flow is indicated.

If windmill relight is unsuccessful or fuel flow does not respond by 10,000 ft, push to 20 deg nose-down, gently pull approximately 2g to increase fuel pressure head, then reset to 20 deg nose-down.

Below 10,000 ft Hp, decelerate below 250 KCAS, start APU and attempt to crank either engine. If propulsion engineers suspect either engine has been damaged, they will advise pilot which engine should be started.

Passing 2,000 ft AGL with no indications of relight, EJECT.

Note: All procedures for dual engine flameout are immediate action items. Single engine flameout without BOOST LO warning is likely NOT fuel deprivation related. In this case, normal NATOPS flameout emergency procedures should be followed.

HIGH AOA EMERGENCY PROCEDURE BRIEFING GUIDE

EMERGENCY SITUATION	CONTROL ROOM CALL	PRIMARY MONITOR/COMMUNICATOR
AERO/FQ		
Unexpected Departure	**“Recover – Sideslip (Yaw Rate)”**	**FQ/FQ**
	“Controls – Release”	**TC/TC**
	“Speedbrake – In”	**TC/TC**
	“Throttles – IDLE”	**TC/TC**
Sustained Out-Of-Control Suspect INS angles (AOA or sideslip errors)	**“Attitude – Standby”**	**FQ/TC**
or Channel 2 or 4 fail		**FC/TC**
Oscillatory Yaw Rate (FL): Alt < 20,000 ft Hp and 12,000 ft lost	**“Cleared for full aft stick”**	**FQ/TC**
Alt < 10,000 ft Hp (with no engine anomalies)	**“Throttles – MAX”**	**FQ/TC**
No Recovery	**“25,000”, “20,000”, “15,000”, “10,000”** (advisory altitude calls)	**TC/TC**
	“6,000 – Eject, Eject, Eject”	**TC/TC**
PROPULSION		
Engine Stall/Stagnation /Flameout	**“Recover – Throttles IDLE – (Reason)”**	**Prop/TC**
Unrecoverable Stall/Stag /Flameout Or Overtemp	**“(Left/Right) Throttle – Off – (Reason)”**	**Prop/TC**
Engine Restart (Aircraft recovered within airstart envelope)	**“(Left/Right) Throttle – IDLE”**	**Prop/TC**
Dual Engine Flameout	**“Start APU”**	**TC/TC**
(and below 10,000 ft Hp and < 250 KCAS)	**“Crank (Left/Right)”**	**TC/TC**
Below 2,000 ft AGL	**“2,000 – Eject, Eject, Eject”**	**TC/TC**
OTHER		
FCS “X” Out During Departure/OOC and no HYD 1B caution with Left LEF failure or HYD 2A caution with Right LEF failure	**“Flight Controls – Reset”**	**FC/TC**

APPENDIX C: SAFETY OF TEST MEASURAND LIST

(Excerpt from David, 2003)

Parameter Description	**RTPS Monitor**
Pressure Altitude	TC
Airspeed	TC
Fuel Weight	TC
Lateral Asymmetry	TC
Percent CG	TC
Corrected AOA	FQ1
FCC Estimated AOA	FQ1
AOSS	FQ1
FCC Estimated AOSS	FQ1/FQ2
Pitch Attitude	FQ1/FQ2
Roll Attitude	FQ1/FQ2
Pitch Rate	FQ1/FQ2
Roll Rate	FQ1/FQ2
Yaw Rate	FQ1/FQ2
Lagged Yaw Rate	FQ1/FQ2
Nz	FQ1/FQ2
Longitudinal Stick Position	FQ1/FQ2
Lateral Stick Position	FQ1/FQ2
Rudder Pedal Force	FQ1/FQ2
Spin Mode Engaged	FQ1/FQ2
Beta * Q	FQ1/FQ2
$SQRT(P^2+R^2)$	FQ1/FQ2
FCS Status Display	FC
L/R Power Lever Angle	Prop
L/R N2	Prop
L/R Engine T5	Prop
L/R Engine PS3	Prop

Notes:

TC = Test Conductor
FQ1/2 = Flying Qualities Engineers
Prop = Propulsion Engineer

VITA

LCDR Eric J. Mitchell grew up in Virginia Beach, VA. He received a Bachelor of Science degree in Aerospace Engineering from Texas A&M University in 1986. After graduation, he was employed as an engineer by General Dynamics-Fort Worth Division, where he tested the F-16, YF-22, and other aircraft. In 1988, he moved to St. Louis and was employed as a design engineer, on contract to McDonnell Douglas developing advanced aircraft.

LCDR Mitchell changed career paths in 1989 and was commissioned as an Ensign in the United States Navy, receiving his wings as a Naval Aviator in 1991. He reported to NAS Oceana, Virginia where he flew the F-14 Tomcat in the world famous *"Jolly Rogers"* Fighter Squadron. He deployed aboard USS ROOSEVELT to support Operation Deny Flight in Bosnia. In 1996, he was selected to attend U.S. Naval Test Pilot School (USNTPS) at NAS Patuxent River, Maryland and graduated in 1997. During his test tour, he was selected to return to USNTPS as an Instructor Pilot for both the Fixed Wing Test and Systems Test Curriculums. In 2000, LCDR Mitchell returned to the fighter community by reporting to the *"Black Aces"* (VF-41) as Department Head. There, in the fall of 2001, he led strikes into Afghanistan and Iraq from the deck of USS ENTERPRISE in the navy's oldest Tomcat fighters. Subsequently, as Operations Officer, he led the squadron's relocation to Lemoore, California and their transition into the brand new F/A-18F Super Hornet.

LCDR Mitchell returned to Patuxent River as a developmental test pilot and VX-23 Department Head in 2002. He worked in the F/A-18 Integrated Test Team (ITT) as the senior Navy test pilot and Platform Operations Coordinator during the flight testing and fleet introduction of FCC 10.7 OFP software.

LCDR Mitchell is currently the Ordnance Support Team Leader for the Atlantic Test Wing. He oversees the flight testing of all ordnance on all fixed and rotary wing naval aircraft at Patuxent River.

LCDR Mitchell has amassed over 3500 flight hours, over 400 carrier arrested landings, and piloted more than 40 different fixed and rotary wing aircraft types. He currently resides in Patuxent River, Maryland, with his wife, Dana, and two sons, Matthew and Jacob.