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F/A-18 External Configuration Effects on High Angle of Attack Departure Resistance

Jessica Wilt
University of Tennessee - Knoxville

To the Graduate Council:

I am submitting herewith a thesis written by Jessica Wilt entitled "F/A-18 External Configuration Effects on High Angle of Attack Departure Resistance." 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 Aerospace Engineering.

Dr. Ralph Kimberlin, Major Professor

We have read this thesis and recommend its acceptance:

Peter Solies, Robert Richards

Accepted for the Council:
Carolyn R. Hodges

Vice Provost and Dean of the Graduate School

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F/A-18 External Configuration Effects on High

Angle of Attack Departure Resistance

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Jessica Aileen Wilt
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ABSTRACT

One of the challenges in defining tactical aircraft handling qualities is establishing flight envelopes for multiple external configurations. In the case of the F/A-18A/B/C/D Hornet, there are single seat and two seat variants, a wide variety of stores carriage options, and other outer moldline additions to the basic airframe that can affect aerodynamics. The F/A-18 aircraft has excellent maneuverability and departure resistance throughout the existing flight envelope, however, changes in external configuration affect departure resistance, particularly at high angle-of-attack (AOA). Various configuration effects have been studied throughout the long life of the Hornet, however this work attempts to collect that knowledge with respect to departure resistance in one document, provide insight into the reasons behind current aircraft operating limitations and overview the latest flight control system upgrade designed to improve the aircraft's departure resistance. The basic Hornet high AOA flying qualities, flight test history, and the current departure training program are reviewed. A review of documented Hornet out-of-control (OCF) mishaps and incidents is included with a correlation to configuration effects and Navy fleet concerns about aircraft configuration. Throughout, a variety of configuration effects on high AOA flying qualities are detailed based on early development and more recent follow-on data, including wind tunnel, simulation, flight test and fleet events. Finally the latest flight control software upgrade designed to improve departure resistance and the preliminary results relating to configuration effects will be briefly discussed.

PREFACE

The wind tunnel and flight test results contained within this thesis were obtained during United States Department of Defense sponsored Naval Air Systems Command projects. The analysis, opinions, conclusions and recommendations expressed herein are those of the author and do not represent the official position of the Naval Air Warfare Center, the Naval Air Systems Command, the Naval Safety Center, or the United States Department of the Navy. The author's recommendations should not be considered attributable to any of the aforementioned authorities or for any purpose other than the fulfillment of the thesis requirements.

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I would like to thank many people who have assisted me in the process of creating this document, as well as provided guidance throughout my graduate studies, both professionally and personally. I would like to thank Steve Donaldson for his continued support of this and all my projects at work. I have great appreciation for Bob Hanley for hiring me in the job that I love and instilling in me a love and respect for the Hornet. I thank Tom Lawrence for the hours of history, insight, and great stories. I also thank Dave Canter for paving the way for me in the world of Hornet FQ.

I am extremely lucky to have a wonderful relationship with my Boeing counterparts in St. Louis. Many thanks go out to Carol Evans for her help in gathering a great deal of the data presented here, and always being at the other end of the phone to answer my many questions. Thanks also to Mike Heller for teaching me so much about high angle of attack flight and flight controls.

I had the great opportunity of having Ivan Behel review this document (twenty years after flying with the initial Hornet flight test program), and thank him for his time. I also thank Pat Behel for her review and continued support from the F/A-18 program office.

I would like to thank my advisor, Dr. Kimberlin, for his assistance throughout the process. He and my committee have provided much-needed guidance and I thank them for their time.

Finally, thanks to my parents, Terry and Karen, for lifelong support and love. Without their guidance I wouldn’t be close to the person that I am today. All my love and thanks to my fiance’ Carl, whose love and patience has been amazing.

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LIST OF ABBREVIATIONS AND NOMENCLATURE

ACM	Air Combat Maneuvering
AOA	Angle of Attack
ATARS	Advanced Tactical Air Reconnaissance System
BFM	Basic Fighter Maneuvering
BIS	Board of Inspection and Survey
Boeing Corp.	Current Prime Contractor for the F/A-18
CIT	Combined Interrogator Transponder
CG	Center of Gravity, % mean aerodynamic chord
Cl_{β}	Rolling Moment Due to Sideslip
Cn_{β}	Yawing Moment Due to Sideslip
$Cn_{\beta\ dynamic}$	Dynamic Directional Stability Parameter
DDI	Digital Display Indicator
DEL	Direct Electrical Link
F/TF/A-18A/B/C/D Hornet	Designation of F/A-18 Aircraft (A/C are single seat, TF or B/D are two seat)
FCC	Flight Control Computer
FCL	Fighter Escort with Centerline Tank
FCS	Flight Control System
FE	Fighter Escort
FEO	Fighter Escort Overload
FMS	Foreign Military Sales

FRS	Fleet Replacement Squadron
FSD	Full Scale Development
Gain Override	Fixed flight control gain mode
HARV	High Alpha Research Vehicle
HUD	Heads Up Display
INS	Inertial Navigation System
INT	Interdiction
Ixx	Rolling Moment of Inertia in the body axes
Izz	Yawing Moment of Inertia in the body axes
LDT	Laser Designator Targeting pod
LEF	Leading Edge Flap
LEX	Leading Edge Extension
LSWT	Low Speed Wind Tunnel
MAC	Mean Aerodynamic Chord
McDonnell Douglas	Original Prime Contractor for the F/A-18 (bought by Boeing)
MECH	Mechanical backup control
MSRM	Manual Spin Recovery Mode
NATC	Naval Air Test Center (predecessor to NAWC-AD)
NATOPS	Naval Aviation Training and Operating Procedures Standardization
NAVAIR	Naval Air Systems Command
NAVFLIR	Navigation Forward Looking Infrared
NAWC-AD	Naval Air Warfare Center, Aircraft Division

NTE	Naval Technical Evaluation
Nz	Normal Acceleration, measured in G
OCF	Out of Control Flight
OpEval	Operational Evaluation
RECCE	Reconnaissance Modification of ATARS
RSRI	Rolling Surface to Rudder Interconnect
SAS/CAS	Stability Augmentation System/Control Augmentation System
SRM	Spin Recovery Mode
Stores	Weapons, fuel tanks, pods, etc, mounted externally on the aircraft
TEF	Trailing Edge Flap
TFLIR	Targeting Forward Looking Infrared
USNTPS	United States Naval Test Pilot School
VER	Vertical Ejector Rack
α	Angle of Attack
β	Angle of Sideslip

CHAPTER 1

INTRODUCTION

STATEMENT OF THE PROBLEM

One of the challenges in defining tactical aircraft handling qualities is establishing flight envelopes for multiple external configurations. In the case of the F/A-18A/B/C/D Hornet, there are single seat and two seat variants, a wide variety of stores carriage options, and other outer moldline additions to the basic airframe that affect the aerodynamics. The F/A-18 aircraft has excellent maneuverability and departure resistance throughout the existing flight envelope; however, changes in external configuration affect departure resistance, particularly at high angle-of-attack (AOA).

OBJECTIVE OF THE STUDY

Various configuration effects have been studied throughout the long life of the Hornet, however this work attempts to collect that knowledge with respect to departure resistance in one document, provide insight into the reasons behind current aircraft operating limitations and overview the latest flight control system upgrade designed to improve the aircraft's departure resistance. The basic Hornet high AOA flying qualities, flight test history, and the current departure training program are reviewed. A review of documented Hornet out-of-control (OCF) mishaps and incidents is included with a correlation to configuration effects and Navy fleet concerns about aircraft configuration. Throughout, a variety of configuration effects on high AOA flying qualities are detailed based on early development and more recent follow-on data, including wind tunnel, simulation, flight test and fleet events. Finally review of the latest flight control software upgrade designed to improve departure resistance and the preliminary results relating to configuration effects will be briefly discussed.

CHAPTER 2

BACKGROUND

F/A-18A/B/C/D AIRCRAFT

The U.S. Navy F/A-18 Hornet first entered service in 1983 and became regarded as one of the most effective aircraft weapon systems deployed. The design was intended to serve the roles of fighter and attack aircraft, combining fighter maneuverability with extensive weapon carriage capability, to replace the A-7 Corsair and the F-4 Phantom aircraft. In the fighter arena, the Hornet has excellent turn rate capability and, coupled with its ability to attain and maintain high angles of attack, it is one of the premier fighter aircraft in the world. It can carry air-to-air weapons on 6 external wing stations and two fuselage mounted stations. In the attack arena, the Hornet can employ over 50 different stores types on its external weapons stations. The combined fighter and attack capabilities were proven in the Gulf War in 1991 when a F/A-18C, carrying a heavy air-to-ground weapons load, encountered and shot down an Iraqi fighter aircraft without jettisoning its weapon load and went on to complete its primary air to ground mission (ref 1).

The Hornet is a high performance, twin engine, supersonic aircraft manufactured by the Boeing Corp. The F/A-18 is considered one of the first digital warplanes and took digital fly-by-wire technology to an exciting new level in the 1980's. The F/A-18A/B/C/D flight control system (FCS) continually works to maintain stability and provide required controllability through Stability and Control Augmentation Systems (SAS/CAS). The aircraft, shown in Figure 1, has moderately swept variable camber wings, wing leading edge extensions mounted on the side of the fuselage from the wing

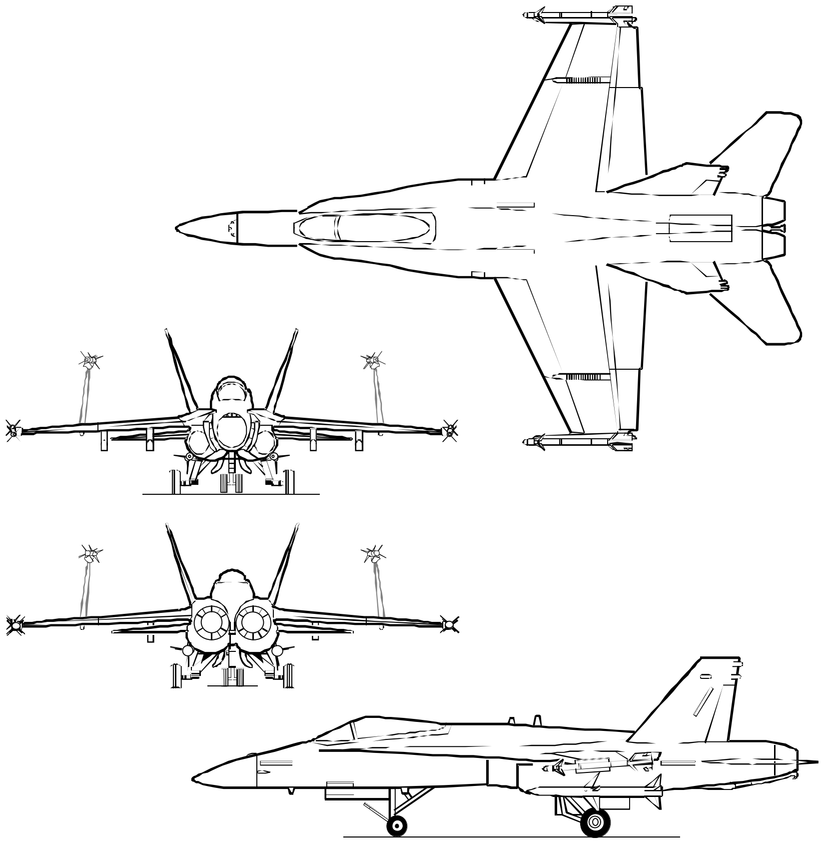

Figure 1 – F/A-18 drawing

root to just forward of the canopy, twin vertical stabilizers (tails), horizontal stabilators (tails), and a speedbrake. In addition it utilizes full span leading edge flaps, trailing edge flaps, and ailerons on the wings. The wings fold, as shown, for the aircraft carrier environment.

Due to the shift from 'seat of the pants' flight characteristics of older aircraft to the to the new fly-by-wire system of the Hornet, it became apparent to the Navy that pilots would have difficulty understanding the limits of controllability in some regions of the flight envelope. Pilots that transitioned from the A-7 and the F-4 were accustomed to aircraft indications of impending departures from controlled flight such as wing rock and buffeting. In the F/A-18 the indications of impending departure were not as evident, often not showing any signs of degradation until the limits of controllability were reached. This was found to be a serious problem at high angles of attack and with various weapons configurations. Partially due to the lack of experience with the digital FCS, the F/A-18 aircraft went through initial flight test with primarily classical flight test techniques that did not evaluate all of the nuances of a digital FCS. Consequently, the impact of integrators, gains and feedbacks on edge of the envelope flying were not fully evaluated during the initial test program (ref 2).

F/A-18 engineers from McDonnell Douglas, the Naval Air Systems Command (NAVAIR) and the Naval Air Test Center (NATC) believed that the new digital FCS would prevent the aircraft from departing controlled flight throughout most of the flight envelope. This mindset had its beginning in 1971, when the Air Force published MIL-S-83691 that reflected the increasing trend in flight test of focusing on stall or near stall characteristics and moving away from evaluating spin characteristics (ref 3). In the mid-1970s, as the Hornet specification was being written, the Navy accepted the Air Force philosophy and emphasis was placed on near stall, stall, and departure testing. Therefore, the OCF and recovery characteristics were explored only minimally and the early F/A-18 flight test program did not include a spin evaluation. Only after a F/A-18 was lost during the first operational test period due to OCF did a more comprehensive look at departure, OCF, and spin characteristics gain priority. Frequent fleet departures, particularly in the two-seat trainer version of the aircraft, led to follow-on engineering investigations and flight test periods. Various investigations into F/A-18 high AOA flying qualities and departure resistance have continued periodically over the entire span of the life of the

Hornet as modifications occurred to the moldline, weapons carriage, or flight control system.

FLIGHT CONTROL SYSTEM DESCRIPTION

The primary flight control system of the F/A-18A/B/C/D is a quadruplex redundant stability and control augmentation system implemented utilizing fly-by-wire techniques, using four digital flight control computers working in parallel. Effective use of flight control gain scheduling, cross axis interconnects, and closed loop control of aircraft response (feedbacks) works to augment the basic airframe stability, prevent airframe overstress, enhance flying qualities, and actively control structural mode oscillations. Gains are scheduled with AOA and three-axis (pitch, roll, and yaw) air data parameters for a variety of flight conditions. If there is a failure of AOA or air data sensing then fixed gain values are provided for safe control in a more limited flight envelope. Digital Direct Electrical Link (DEL) control laws provide open loop control if the motion feedback sensors fail. The DEL modes are gain scheduled if air data and AOA sensors have not failed; otherwise, they operate on fixed gains. In addition, backup mechanical control of the horizontal stabilator surfaces is available in the event three of the digital processors fail or if there is a total electrical failure. The mechanical backup (MECH) mode can provide limited pitch, roll and/or yaw control through symmetric or differential tail deflection (ref 4).

There are ten primary flight control surfaces on the Hornet airframe: left and right pairs of horizontal stabilators, rudders, ailerons, leading edge flaps (LEF), and trailing edge flaps (TEF). Additionally, the aircraft utilizes a speedbrake, which is located on the upper aft fuselage surface, between the two vertical tail surfaces. The aircraft is configured with a center control stick (with pitch and roll trim switches), rudder pedals, and throttles that include the speedbrake position switch and auto throttle engage switch. Control stick position (+/- 3 inches lateral and +5/-2 inches longitudinal) and rudder pedal force (+/-100 lbs) are provided as inputs to the flight control computers. Rudder trim and Gain Override (fixed flight control gain) switches are located on the flight control system control panel in the cockpit. A Heads Up Display (HUD) provides pertinent flight condition information to the pilot (the front seat only in the two seat aircraft). Two Digital Display Indicators (DDIs) provide display capability for various F/A-18 systems including the FCS status.

Handling qualities are dependent on the mode in which the FCS is operating, either flaps up or power approach (flaps half or full deflection) modes. The mode is determined by the flap switch position. However, if airspeed exceeds approximately 240 KCAS the flight controls automatically switch to flaps up control laws regardless of the flap switch position. The FCS control laws are designed to minimize transients when switching between modes. For the departure resistance assessment within this document, all results will be with flaps up.

The F/A-18 flight control system has pitch axis priority; meaning longitudinal stability is ensured first before the flight control system will attempt to satisfy other control demands. The longitudinal control system is designed to optimize load factor at mid to high dynamic pressures. At low dynamic pressures, the schedules are optimized for air combat maneuvering (ACM), which includes precise attitude control and increased stick force cues with increasing load factor. At high AOA, AOA feedback is introduced. The longitudinal commands are measured by stick position with feedbacks of pitch rate, normal acceleration and AOA. The error between the feedback sum and the command is processed through an integral and proportional path with the integrator providing zero steady state error. The lateral-directional control system relies on pilot commands from the lateral stick and rudder pedal sensors which are compared to aircraft motion feedback signals to generate error signals which drive the control surfaces through electro-hydraulic servo-actuators. The control surface deflections that are commanded by the lateral-directional control laws include the ailerons, rudders, differential stabilators and differential leading and trailing edge flaps. The lateral stick command is gain scheduled with air data to provide uniform roll rate. Maximum roll rate is limited when wing stores are carried because of wing pylon design load limitations and at higher AOAs due to increased departure susceptibility. In general, the aircraft is designed to roll about the stability axis, although sideslip feedback is not yet implemented in the production flight control computers. Instead, the aircraft has used a blend of lateral acceleration and stability axis yaw rate signals. Stability axis yaw rate is derived from body axis roll and yaw resolved through the velocity vector angle (AOA). Stability axes are orthogonal axes, which remain fixed with respect to the relative wind in pitch, but rotate with the aircraft in yaw and roll. The feedback blend is summed with shaped pedal commands and a Rolling Surface to Rudder Interconnect (RSRI) (ref 4).

The F/A-18 Hornet flight control system incorporates several feedbacks to provide desired high AOA flight characteristics. Normal acceleration, Nz, feedback is used to provide constant stick force with load factor at high speeds and is blended with pitch rate at lower speeds to improve high AOA controllability. Combined roll rate and yaw rate feedback reduces inertial coupling tendencies at moderately high AOA and vertical tail loads at high speeds. AOA feedback is used to increase stick force with increasing load factor at high AOA. The Hornet utilizes two AOA probes located on the forward fuselage for Flight Control Computer (FCC) AOA data. These probes read AOA to 35 deg (true AOA, derived from probe AOA), and an inertial navigation system (INS) computed AOA is used for values above 35 deg true AOA. A steady AOA tone is activated at high AOA as warning of aircraft limitations or possible departure susceptibility. In addition, a beeping yaw rate tone indicates aircraft yaw rate limitations.

A spin recovery mode (SRM) is automatically engaged to facilitate spin recovery with certain combinations of dynamic pressure and yaw rate. The SRM allows full authority aileron, stabilator and rudder command with the control stick and rudder pedal deflection. Giving the pilot full authority without feedbacks or interconnects allows full antispin control commands to assist with spin recovery. The leading edge flaps and the trailing edge flaps are commanded to fixed positions, which were determined to be the optimal spin recovery positions from analytical, spin tunnel and flight test results. Spin recovery mode can be entered automatically based on flight condition or manually by selecting a cockpit switch, provided the airspeed is below a threshold value.

FLIGHT ENVELOPE/OPERATING LIMITATIONS

The F/A-18A/B/C/D has an extensive operating envelope designed to allow performance of the fighter and attack missions while maintaining adequate flight safety margins. The FCS provides artificial pitch stability through its CAS that prevents significant handling qualities variation with center of gravity (CG) movement due to fuel transfer or stores release. Longitudinal control effectiveness and pitch damping are satisfactory up to approximately 55 deg AOA if maintained within the AOA/CG operating limitations, seen in Table 1(from ref 5). Appendix A shows various configurations and example weapons. Fighter Escort (FE) refers to the clean aircraft with or without pylons, fuselage stores, or wingtip missiles. All other configurations build upon the FE loading. These limits are partially based on aircraft pitch stability margins and prevent the aircraft from entering an AOA hang-up condition (described in detail in Chapter 3). They are also based on lateral-directional stability and departure resistance. During flight in a degraded FCS mode (MECH or pitch DEL) aircraft stability will be seriously degraded aft of the CG limit and controllability will be significantly reduced. Additional limitations are placed on the aircraft with lateral weight asymmetries and for the two-seat aircraft due to departure resistance and spin entry risk. Those limitations are summarized below, in Tables 2 and 3.

Table 1 – F/A-18 AOA Limitations Based on Aircraft Configuration (ref 5)

CONFIGURATION	AOA LIMIT (°)	CG (% MAC)
Fighter Escort (FE)	Unrestricted -6° to +25°	17 to 25% 25 to 28%
FE plus centerline tanks/stores (FCL)	Unrestricted -6° to +25°	17 to 23.5% 23.5 to 28%
FE plus inboard tanks/stores (with centerline tank/stores)	-6° to +25°	17 to 27.5%
FE plus inboard tanks/stores (without centerline tank/stores)	-6° to +35° -6° to +25°	17 to 24% 24 to 27.5%
FE plus outboard tanks/stores (centerline tank/stores optional)	-6° to +25°	17 to 27.5%
FE plus inboard and outboard tanks/stores (centerline tank/ stores optional)	-6° to +20°	17 to 27%

Table 2 – F/A-18 Lateral Weight Asymmetry AOA Limitations

Lateral Weight Asymmetry, ft-lbs	Limit
6000 - 12000	-6 to 20 deg AOA
12000 - 26000	-6 to 12 deg AOA
22000 - 26000	• Abrupt lateral stick inputs prohibited • 180 deg Bank Angle change maximum with smooth ½ stick roll inputs • Rudder pedal inputs authorized to maintain balanced flight only

Table 3 – F/A-18 Two-Seat Mach/AOA Limitations

Mach Number	Maximum AOA, deg
0.7 - 0.8	20
0.8 – 0.9	15
>0.9	12

HIGH ANGLE OF ATTACK FLIGHT TEST HISTORY

The F/A-18 full scale development (FSD) program was conducted at McDonnell Douglas, St. Louis and the NATC, Patuxent River, from 1979 through July 1982. Extensive flight control changes occurred during that time period and approximately 60 different versions of the flight control laws were lab or flight tested (ref 2). The design of the FCS was to provide excellent departure and spin resistance and spin recovery capability. The early part of the developmental effort focused high AOA flying qualities efforts on evaluating departure and spin resistance. As mentioned previously, the mindset of most of the team at the time was that the new digital FCS would prevent departures and spin and therefore a detailed, more expensive OCF and spin flight test program was not necessary. However, the high AOA program took an abrupt turn on November 14, 1980 when an F/A-18A was lost during an operational flight test evaluation period. The aircraft was suspected to have entered "a low rate spin mode which was not predicted by [wind tunnel] model tests. This had a dramatic effect on the course of subsequent testing. The scope of the test program was expanded to include identification of all spin modes and determination of optimum spin recovery control techniques" (ref 6).

The many changes to the flight control laws made through the early 1980's and the high AOA flight test corresponding to those changes is documented in various McDonnell Douglas and Navy reports (ref 7-13). Appendix B lists the significant flight control modifications affecting departure resistance through 1986. Most of this work was evaluated during the flight systems Navy Technical Evaluation (NTE) flight test program (ref 12) and the Navy Board of Inspection and Survey (BIS) flight test trials (ref 13). These were comprehensive evaluations of the Hornet with a wide variety of stores loadings, throughout the flight envelope. NTE was the fifth Navy evaluation period of the F/A-18A/B (then called F/TF/A-18 representing single and two-seat) and served as the basis for certification of the readiness of the F/A-18 for operational evaluation (OpEval).

In addition to the flight control changes, many aircraft external configuration changes were made throughout the early life of the Hornet. Two that were of particular significance to the departure resistance of the aircraft were LEF scheduling changes and Leading Edge Extension (LEX) modifications. In order to maintain lateral-directional stability and control at high AOA, the LEFs are deflected on a schedule as AOA increases. Initial development testing evaluated flying qualities from 15 deg to 45 deg

AOA and the maximum deflection of the LEFs was 25 deg, occurring at about 25 deg AOA. Lateral-directional stability levels were not acceptable at high AOA. Additional testing showed significant improvement in lateral-directional stability with more LEF deflection and the maximum deflection was increased to 34 deg (ref 6). A generalization of LEF effects on departure resistance is shown in Figure 2.

The LEX was designed to create vortices at high AOA to increase lift and provide directional stability. In 1986 an investigation into structural problems led engineers to the discovery that the vortices created by the LEX were impinging on the vertical tails with an unexpected high level of force. In order to decrease the strength of the LEX vortices a LEX fence was installed on each side of the aircraft, shown in Figure 3. A full

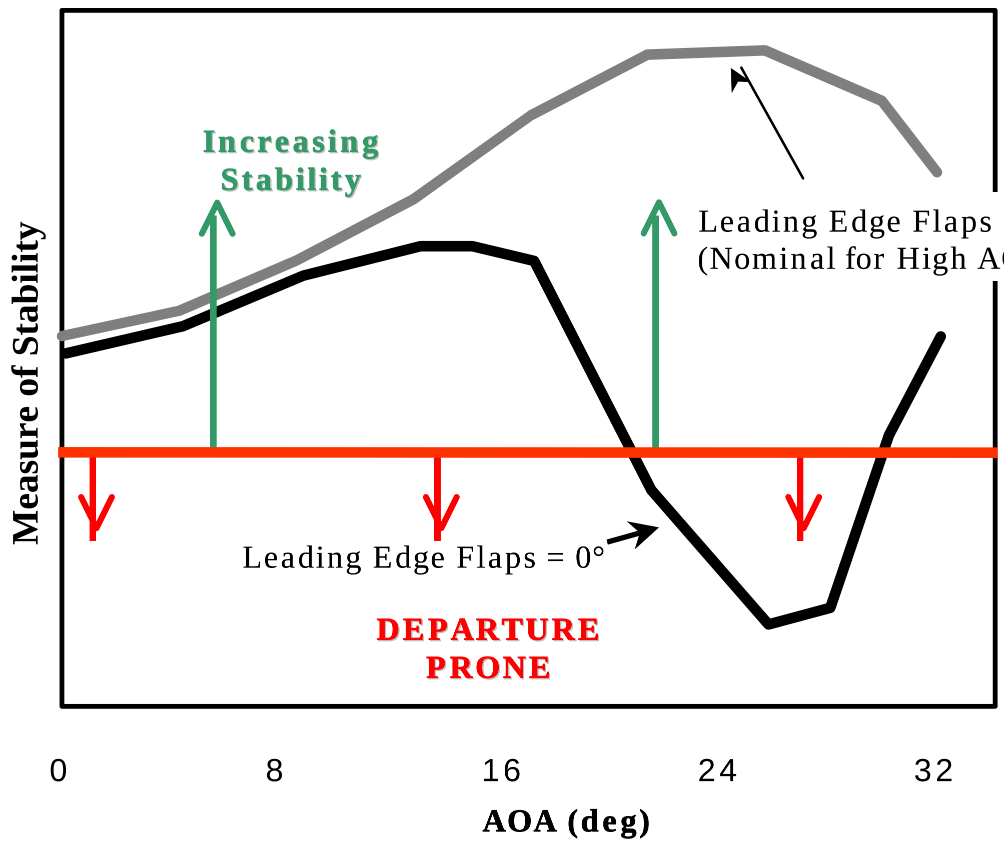

Figure 2 – Lateral-Directional stability levels with leading edge flap deflection

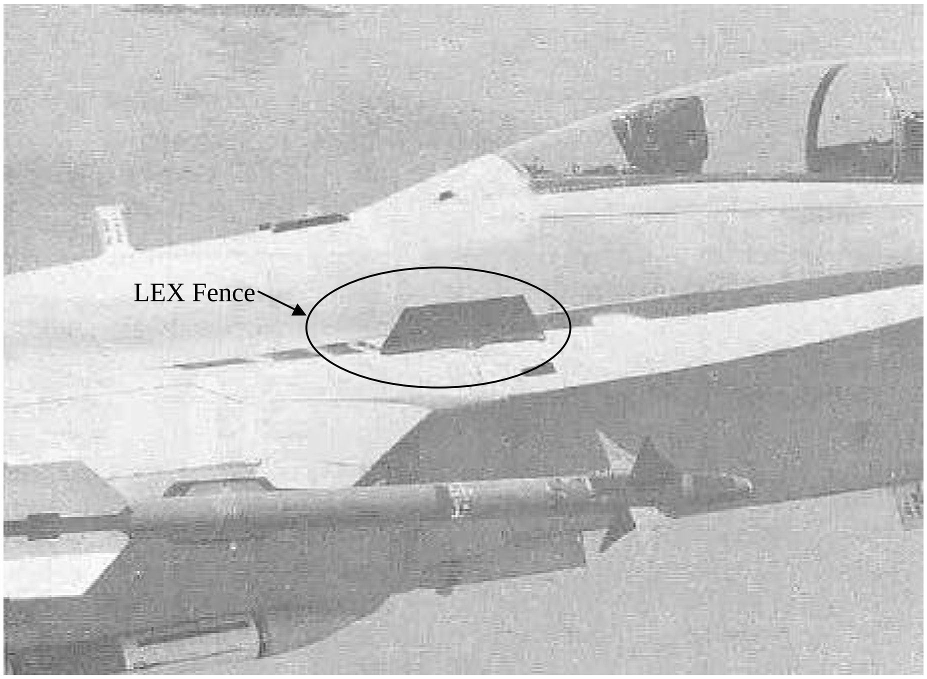

Figure 3 – Leading edge extension fence modification (ref 15)

flying qualities evaluation was performed to determine effects of the LEX fence addition in 1988 and is documented in ref 15. Flight test for this investigation included an extensive flying qualities evaluation with a concentration on high AOA flying qualities. Significant data was gathered with this production configuration that serves as a good source of high AOA information.

In the mid 1980's there were additional wind tunnel and flight test programs initiated to investigate the flying qualities and departure resistance of the two-seat aircraft. Some aircraft delivered from McDonnell Douglas to the training squadrons were rejected due to roll-off tendencies. Also, concerns remained after FSD testing that the two-seat aircraft was more departure prone and was not satisfactory for the trainer mission. During 1985 and 1986 a number of flight test programs were flown to investigate individual aircraft departure concerns and two-seat aircraft concerns in general and are documented in ref 16 and 17. These will be discussed in detail in Chapter 5.

CHAPTER 3

F/A-18A/B/C/D HIGH ANGLE OF ATTACK

GENERAL HIGH AOA FLYING QUALITIES AND DEPARTURE RESISTANCE

The F/A-18A/B/C/D aircraft has excellent handling qualities and departure resistance throughout the flight envelope. A departure is defined as the point at which the aircraft is no longer responding to pilot control input. For the purposes of this analysis, OCF is considered developed motion that follows a departure from controlled flight. As AOA increases, various cues to decreasing departure resistance are provided naturally by the control system. Above 22 deg AOA the longitudinal control stick forces increase and may be accompanied by a very mild lateral wing rock. As AOA increases above 32-35 deg AOA a mild Dutch roll can be encountered along with increasingly reduced roll capability. As the AOA reaches max (50-60 deg AOA) the Dutch roll encountered can be more developed and aircraft aerodynamic asymmetries become pronounced.

Control of the lateral-directional motion of the aircraft at high AOA is a combination of aileron, differential tail and rudder inputs. The aileron and differential tail contributions are reduced at high AOA due to large adverse yaw effects. Above 25 deg, the rudder pedal and the lateral stick both command the same deflections of aileron and differential tail. However, at high AOA rudder pedal does command slightly more rudder deflection than lateral stick alone resulting in a slightly faster roll rate (due to sideslip generation in the direction of the roll).

The F/A-18 Hornet is also an extremely spin resistant aircraft. Early spin wind tunnel testing identified 3 spin modes, upright and inverted. Flight test uncovered an additional mode, a low yaw rate spin. Spins are more likely to be entered following a departure from controlled flight with a lateral weight asymmetry configuration. During spin flight test, repeatable spin entry requires aft stick (~1g stall), pro-spin lateral stick and/or rudder input, and often asymmetric thrust application. To obtain high yaw rate spins during test judicious use of the Manual Spin Recovery Mode (MSRM) has been required to generate required yaw motion.

To evaluate configuration effects on departure resistance of the F/A-18 Hornet, a combination of open-loop lateral-directional stability parameters (wind tunnel data) and qualitative flight test data will be analyzed. The basic aircraft lateral-directional characteristics at specific sideslip values are represented by Cl_{β} (rolling moment due to sideslip) and Cn_{β} (yawing moment due to sideslip). The Cl_{β} and Cn_{β} are determined from wind tunnel force and moment data or from flight test data. Flight test coefficients are derived by taking the measures Cl and Cn and subtracting the rolling and yawing moment coefficient increments which combine the effects of control surface deflections and roll/yaw rates, ref 11.

Basic airframe departure resistance can be evaluated using the dynamic directional stability parameter, $Cn_{\beta dynamic}$, defined by equation 1. In the late 1950's a NACA study revealed that "free flight wind tunnel tests of aircraft models having static directional instability (Cn_{β} negative), settled upon the 'dynamic' stability, $Cn_{\beta dyn}$, …" (ref 18). This parameter has been widely used as an indicator of departure from controlled flight throughout flight dynamics communities for over thirty years. As described in ref 18, $Cn_{\beta dyn}$ is computationally simple and it requires only static stability derivatives and approximate moments of inertia. Other work in the early 1970's correlated departure AOA to negative values of $Cn_{\beta dynamic}$ for fighter and attack aircraft (ref 19). At this time, while it was “considered a good guideline for design and evaluation, many investigators in the field of high angle of attack phenomena [felt] that it [was] by no means the whole story…”. Today in the Hornet engineering community $Cn_{\beta dynamic}$ is widely used as a guideline for departure resistance and particularly for comparison purposes when evaluating various aircraft configurations.

$$Cn_{\beta dynamic} = Cn_{\beta} \cos(\alpha) - (Ixx/Izz)Cl_{\beta} \sin(\alpha)$$ **Equation 1**

where, α = angle of attack (AOA)

β = angle of sideslip

Ixx/Izz = Moment of Inertia Ratio

$Cn_{\beta dynamic}$ is considered a measure of the aircraft’s ability to generate restoring moments about the yaw stability axis. Positive values indicate an ability to generate restoring moments with change in sideslip and a zero value indicates that the basic airframe can no longer generate a restoring moment with a change in sideslip. Traditional Navy design guidelines say that $Cn_{\beta dynamic}$ must be greater than 0.004 with 5 deg of sideslip in order to be considered departure resistant (refs 3, 17). The $Cn_{\beta dynamic}$ vs. AOA plot for the clean single seat aircraft is shown in Figure 4 as derived from flight test data and in Figure 5 from wind tunnel data (various scale models and test facilities). These two charts illustrate one of the difficulties with analyzing departure resistance data in that often the wind tunnel data and the flight test results do not align due to variations in inertia values used, the sideslip values the data was referenced to or additional errors in data calculations and derivations.

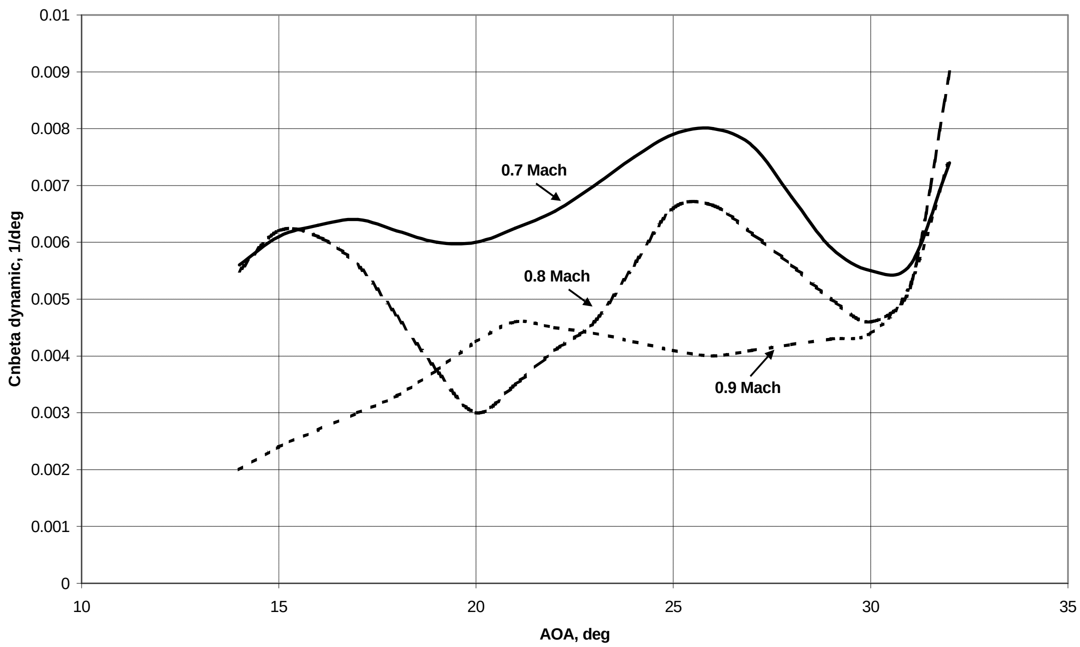

Figure 4 – F/A-18 Single Seat, Clean Departure Resistance (FSD flight test derived)

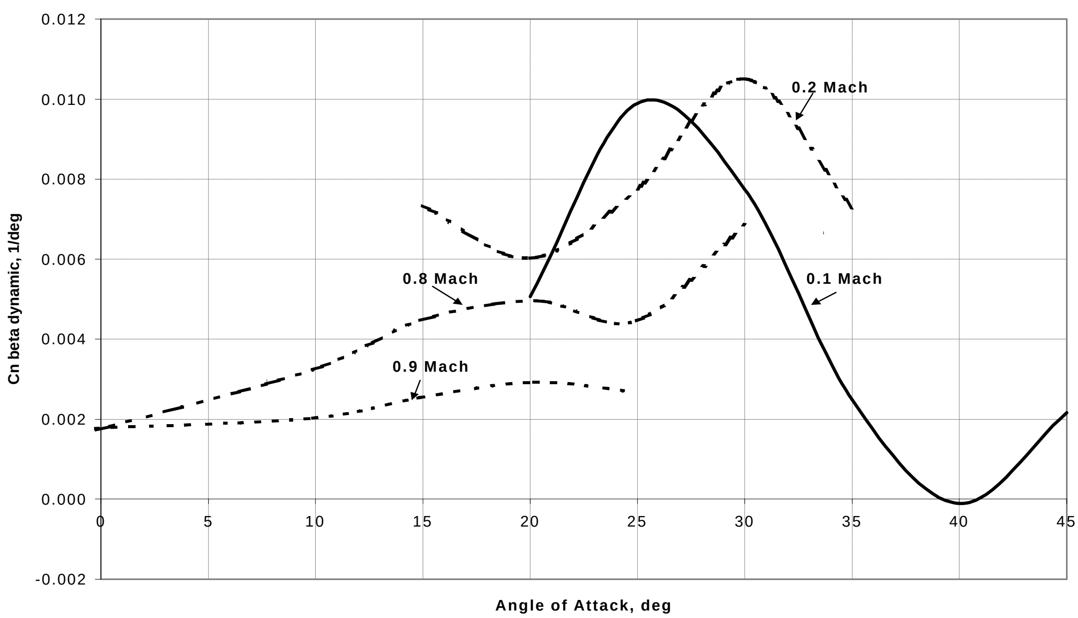

Figure 5 – F/A-18 Single Seat, Clean Departure Resistance (wind tunnel data)

Data from multiple sources is evaluated in order to create an aerodynamic database that is as accurate as possible for departure resistance predictions and engineering simulations. However, in the case of the Hornet, only some of the external configurations have been modeled in simulation. Therefore the wind tunnel data will be utilized during this evaluation and will be built upon as the various configuration effects are described. A sideslip value of positive or negative 4 deg was used for all plot generation.

Pilot qualitative comments and flight test data were gathered in accordance with the standards set forth in the United States Naval Test Pilot School (USNTPS) Flying Qualities Flight Test Manual (ref 21) and the F/A-18 Maneuver Library (ref 22). The pilot Handling Qualities Ratings scale and the Navy deficiency rating scale are shown in Appendix C and were utilized in the flight test evaluations.

HIGH AOA HANG-UP AND FALLING LEAF MODES

Understanding the departure resistance of an aircraft is critical to safe mission performance. For the Hornet, departures from controlled flight have led to more serious consequences such as losing the air-to-air combat battle (in training) and dangerous OCF conditions. In early flight test it was discovered that the F/A-18 Hornet has a sustained out-of-control flight mode, AOA Hang-up, that resulted in extended post departure gyrations and significant altitude loss. AOA Hang-up is a condition where little to no pitch restoring moment is available to recover from a high AOA condition, considered by some a deep stall, and is aggravated by the effects of external stores. In the Hornet this mode is entered at aft cg and high AOA conditions and recovery is not guaranteed.

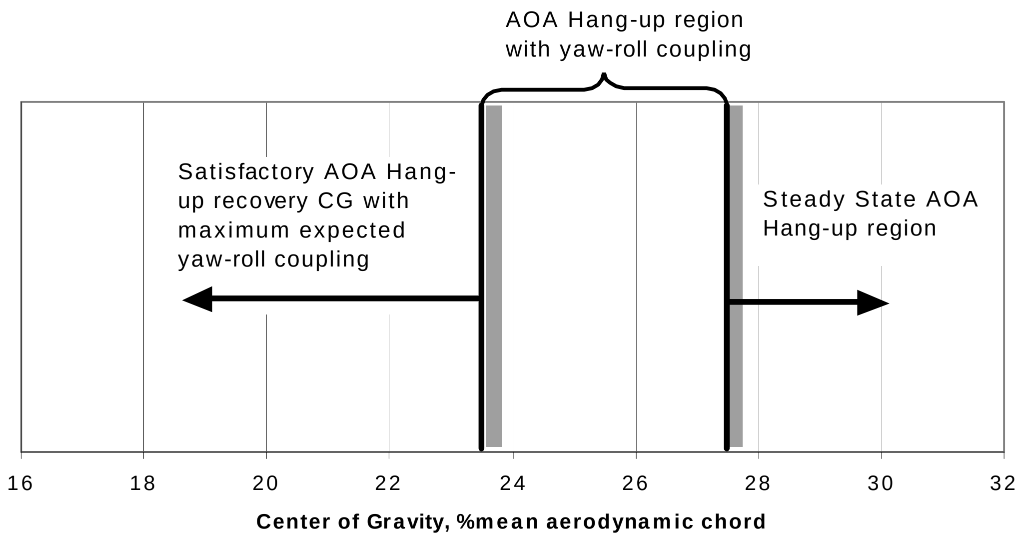

Figure 6 – Example of Center of Gravity Margin Placed on the Hornet due to AOA Hang-up (Fighter Escort with Centerline Tank)

Discovery of this OCF mode led to the current AOA limitations based on CG location that the aircraft has today. The region of AOA Hang-up susceptibility can be avoided by maintaining CG approximately 4% forward of this deep stall region. Figure 6 shows an example the cg margin required to avoid AOA Hang-up.

When AOA Hang-up was discovered it was classified in two ways, static AOA hang-up or dynamic AOA hang-up, ref 12. The static AOA Hang-up was described as a prolonged hesitation at 50-55 deg AOA (much like a deep stall). The dynamic Hang-up was described as inertia coupled, sustained AOA with oscillations in roll and yaw rate, considered now to be the Falling Leaf mode. The Falling Leaf is characterized by in-phase roll and yaw rates, and large oscillations in AOA and sideslip values. The mode is entered following a departure from controlled flight; occasionally following recoveries from spins and most often from a nose high,low airspeed condition. Though encountered at forward and mid cg ranges, the Hornet is more susceptible to entering the Falling Leaf mode at aft cg conditions and recovery takes extreme patience and altitude, particularly when the CG is located in the 4% CG margin prior to the AOA Hang-up. The exact mechanics of the Falling Leaf motion have been the subject of many investigations over the past 20 years, due to the complexity of the mode and the difficulty of modeling the mode with simulation.

RADOME AND RIGGING EFFECTS ON DEPARTURE RESISTANCE

The forebody nose cone of the Hornet, or radome, is a long slender shape with a pointed tip that can produce significant vortices at high AOAs. It has been long known to wind tunnel experts that strong lateral forces can be generated on ogive bodies at high AOAs due to asymmetric vortex separation (Figure 7). Research on NASA's High Alpha Research Vehicle (HARV), the X-31 aircraft, and production F/A-18 aircraft in the early 1990's showed significant aerodynamic effects of small asymmetries on forebodies at high AOAs. Large yawing moments can be generated on the F/A-18 forebody at high AOA that lead to aircraft departure from controlled flight. The Navy has documented nose slice and spin tendencies on F/A-18 aircraft as a result of radome asymmetries and repairs near the tip, ref 23. Flight tests have shown that damage, or even poor repair, in the first 6-12 inches of a radome tip can lead to departures during abrupt maneuvering above approximately 40 deg AOA with yaw rates reaching 60 degrees per second.

In the late 1980's and early 1990's a number of reports were surfacing from Navy squadrons about 'bent' or misrigged aircraft that experienced roll and/or yaw-off at high AOA. The Naval Air Warfare Center Aircraft Division (NAWC-AD), Patuxent River

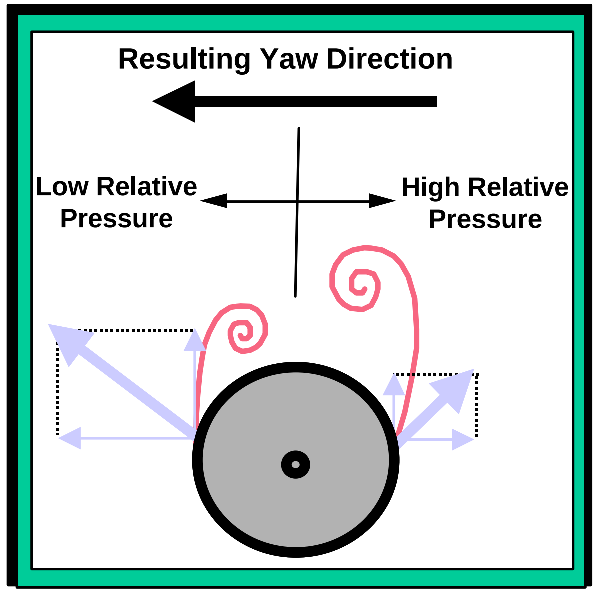

Figure 7 – Force Generated by Asymmetric Vortex Separation

(successor of the NATC) began investigating these occurrences and discovered that a majority of the aircraft thought to be deformed due to aircraft overstress or normal life cycle airframe stresses could be greatly improved by re-rigging flight control surfaces. Flight control surfaces are attached with tolerances to ensure the surface is aligned on the aircraft, or rigged, properly. On the F/A-18, often a surface can become misrigged or be at the edge of rigging tolerances and exhibit uncommanded rolling moments during accelerated and unaccelerated flight. The research and flight test performed at NAWC-AD resulted in a set of flight control surface rigging procedures for the F/A-18. These procedures have proven effective in determining flight control surface rigging issues and targeting specific control surfaces. This effort became the current Navy F/A-18 procedure during functional check flights. Reference 24 details this effort and results.

NAVY HORNET DEPARTURE TRAINING

The U.S. Navy currently has a F/A-18 Fleet Departure Training and Standardization Program that introduces advanced high AOA handling characteristics to F/A-18 Navy and Marine Corps Fleet Replacement Squadron (FRS) students. This training is based on NAWC-AD departure flight test and departure demonstrations, which have been provided to U.S. Navy and Foreign Military Sales (FMS) customers since 1994. The demonstration flights were established to improve a F/A-18 pilot's awareness and understanding of impending departure cues, departure characteristics, and recovery procedures. The training gives pilots an ability to understand the edges of the flight envelope in a controlled environment with experienced flight instructors. Actual high AOA and departure flight conditions are flown in known departure regions but at high altitude and with no threat of structural impact to the airframe. Details of the Navy program can be found in NAVAIR Instruction 3502.1 dated 16 Mar 2001. Since its establishment in 2001, the Navy fleet departure training program has received excellent reviews from students and instructors, though direct effects on fleet departure events are still inconclusive.

CHAPTER 4

U.S. NAVY F/A-18 OUT-OF-CONTROL FLIGHT

HISTORICAL REVIEW

The F/A-18 Hornet has been plagued by departures leading to out-of-control flight since it was first deployed in the early 1980's. An average of about 1 aircraft per year is lost in an OCF mishap. Many more departures and OCF events are encountered that recover prior to ejection altitude. Some of these recoverable events are documented in flight hazard reports however, historically many go undocumented. A summary of the F/A-18A/B/C/D OCF mishaps (unrecoverable prior to ejection) and relevant hazard reports (recoverable incidents) from the Naval Safety Center is contained in Appendix D. A majority of the departures occur during Basic Fighter Maneuvering (BFM) or ACM flight resulting in a nose high, low airspeed condition. Pilots lose situational awareness in a maneuvering fight and the resulting high AOA and low airspeed situation leads to a departure. Often defensive maneuvers are flown at angles of attack closer to stall/departure than offensive maneuvers due to the urgency of the situation. Occasionally departures have occurred due to leading edge flap failures and those incidents were not utilized in this evaluation of configuration effects.

CORRELATION TO CONFIGURATION

A majority of fleet mishaps have occurred in aircraft with the centerline tank loaded. This loading, in combination with the two-seat canopy (F/A-18B or D) is considered the most departure prone configuration with an unlimited AOA envelope based on lateral-directional stability. However, statistics show that the single seat aircraft has a higher percentage of documented OCF events. One reason is that significantly more single seat aircraft exist. The two-seat aircraft are mainly employed in the training squadrons and the Marine squadrons. Figure 8 shows the number of reported departures based on single or two seat canopy, along with the two-seat with centerline tank (TFCL) events. Figure 9 shows the number of Navy reported departures sorted by external configuration.

The centerline tank configured aircraft has the majority of the documented mishaps and departure incidents in the Navy and Marine Corps Hornet squadrons. A vast majority of the events are described as being in the two-seat centerline tank departure regions of the flight envelope (described in detail in Chapter 5). Asymmetric stores loadings are the second highest cause of fleet departures, but rarely do they result in an unrecoverable situation. A large amount of the hazard reports have not adequately documented the external configuration.

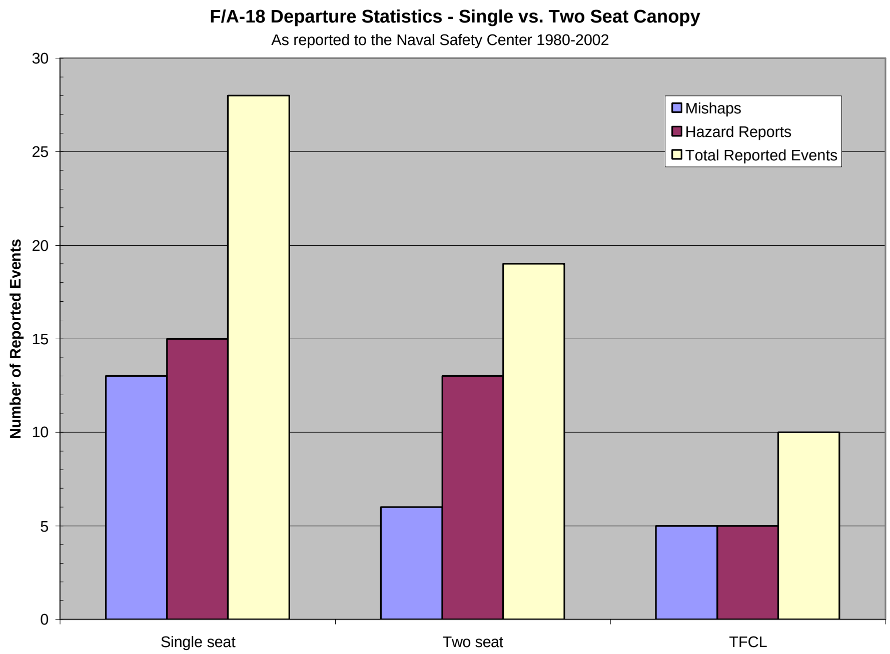

Figure 8 – F/A-18 Departure Events with Single or Two Seat Canopy

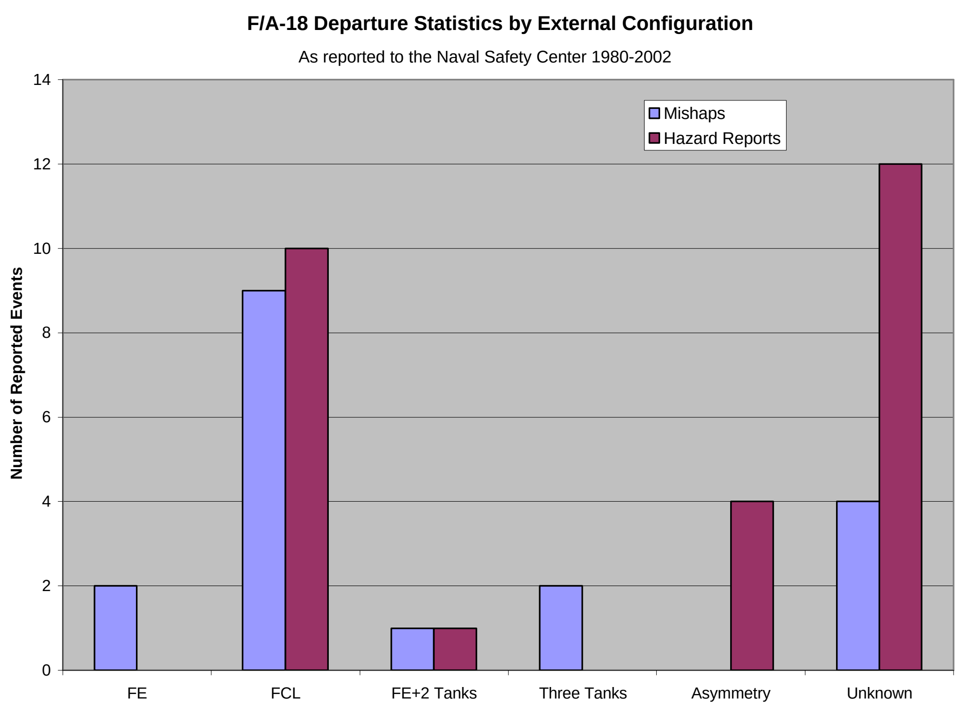

Figure 9 – F/A-18 Departure Events by External Configuration

CHAPTER 5

CONFIGURATION EFFECTS EVALUATION

SINGLE VS TWO-PLACE CANOPY

The original intent of the F/A-18 was to be a single seat fighter and attack aircraft. In order to adequately train pilots to fly the Hornet, a two-seat trainer version of the aircraft was designed and produced as well, but in limited quantities. The original developmental flight test program did not focus on detailed, separate high AOA flying qualities flight test efforts with the two-seat aircraft. The area of the flight envelope that was of most concern for departure resistance in the early days of Hornet flight test was high subsonic Mach number, high AOA region (0.7 to 0.95 Mach number, greater than 20 deg AOA). Limitations were put in place on the single and two-seat aircraft to prevent entering this departure prone region of flight. When the update to the flight control computer software v7.1.3 was released it was considered the fix that would correct these departure tendencies of the aircraft (ref 17). Though the single seat aircraft was found to be adequately departure resistant, the two-seat aircraft still exhibited departure tendencies in the high Mach number and high AOA region and retained the flight restrictions. Once the aircraft was deployed, initial fleet incidents of departures were higher in the trainer version of the aircraft, see Appendix E. The incidents led to more investigation and in 1985 NAVAIR initiated wind tunnel testing followed by a dedicated F/A-18B flight test program at NATC, Patuxent River. With the design of the upgrade F/A-18C/D a more missionized aircraft was desired. The F/A-18D became the Marine Corps choice for a new fighter/attack, placing the two-seat aircraft in full-time operational use.

Wind tunnel testing was performed in low speed and transonic facilities throughout the 1980’s. Low speed wind tunnel (LSWT) testing with the 16% scale F/A-18 model was performed at the NASA Langley 30 ft by 60 ft tunnel in 1984 to investigate high AOA stability and control. Results indicated that the model with the two-place canopy addition exhibited slightly better longitudinal stability over the single place canopy and that the departure resistance was slightly degraded below 36 deg AOA. During this test, the departure resistance was improved at higher AOA with the larger two-seat canopy (ref 14).

During Hornet FSD flight test limited evaluations of the two-seat aircraft were performed in the high AOA region. The most significant finding was that the two-seat aircraft was less departure resistant than the single seat aircraft in the 30 to 40 deg AOA and high subsonic Mach number region. Nose slice departures were seen at 0.9 Mach number in the clean two-seat aircraft and at 0.7 and 0.8 Mach number with three external fuel tanks loaded (ref 12). At that time, recommendations were made to further investigate the two-seat departure and OCF characteristics. During the BIS trials, with version 8.2.1 flight control software (with nose slice fixes incorporated) the two-seat aircraft was found to be satisfactory for the trainer mission when symmetrically loaded (ref 13). Departure resistance testing at 0.7, 0.8 and 0.9 Mach number did not depart from controlled flight as had been seen during NTE testing and the documented flight test conclusion was that the two-seat symmetric AOA and Mach number restrictions could be removed.

In 1985, during acceptance tests for a fleet trainer aircraft that had exhibited a roll-off tendency, a number of high AOA flight test points were flown to evaluate high

AOA flying qualities. This testing concluded that the two-seat aircraft was less departure resistant and more prone to spin entry than the single seat aircraft. However, it recommended that the AOA limitations for the two-seat aircraft with less than 6000 ft-lbs asymmetry at high subsonic Mach number be changed to –6 deg to 15 deg above 0.8M (ref 17). It also recommended further testing for the symmetric and asymmetric store configurations.

Additional departure resistance flight test of the F/A-18B aircraft was performed by the Navy, in cooperation with McDonnell Douglas, in 1986 resulting in qualitative comparisons of the clean and centerline tank loaded configurations, documented in ref 15. The specific two-seat, clean flying qualities above 30 deg AOA were deemed satisfactory for the strike-fighter mission. The two-seat aircraft without stores loaded "will be able to aggressively maneuver during BFM/ACM using both lateral and directional controls throughout the airspeed envelope above 30 deg AOA without loss of control," (ref 16). During low AOA (below 10 deg) departure resistance testing in the two-seat clean configuration no departures were seen, however on maneuvers that generated large sideslip values the aircraft was slow to recover when control inputs were released. At low AOA there appeared to be less aircraft restoring moment with the two-seat canopy.

Despite the results documented and listed above, the basic conclusions of the flight test effort (ref 13) were that the two-seat aircraft was more departure prone in flight regimes encountered during air combat maneuvering (ACM), seriously degrading the Hornet's capability as a trainer aircraft. The Part 1 deficiencies cited were based on lateral weight asymmetry configurations and centerline tank loaded configurations.

There appears to be no explanation for the conclusion of acceptable departure resistance in the clean configuration and then the recommended restrictions, except for the addition of stores. NAVAIR headquarters did not accept all of the recommendations from the flight test effort due to the "limited scope of the … flight test program, and the conflicts in analysis of the test results by [McDonnell Douglas] and NATC…," ref 3. A flight test effort was planned for 1988 to resolve conflicting departure resistance results and explore additional asymmetry effects, but was never completed.

The results from the above wind tunnel test efforts were used to evaluate departure resistance. $Cn_{\beta dynamic}$ plots (Figure 10) for various Mach numbers show the two-seat canopy increment on departure resistance. The region of low stability seen at approximately 25 deg AOA and high subsonic Mach number was evident in the flight test

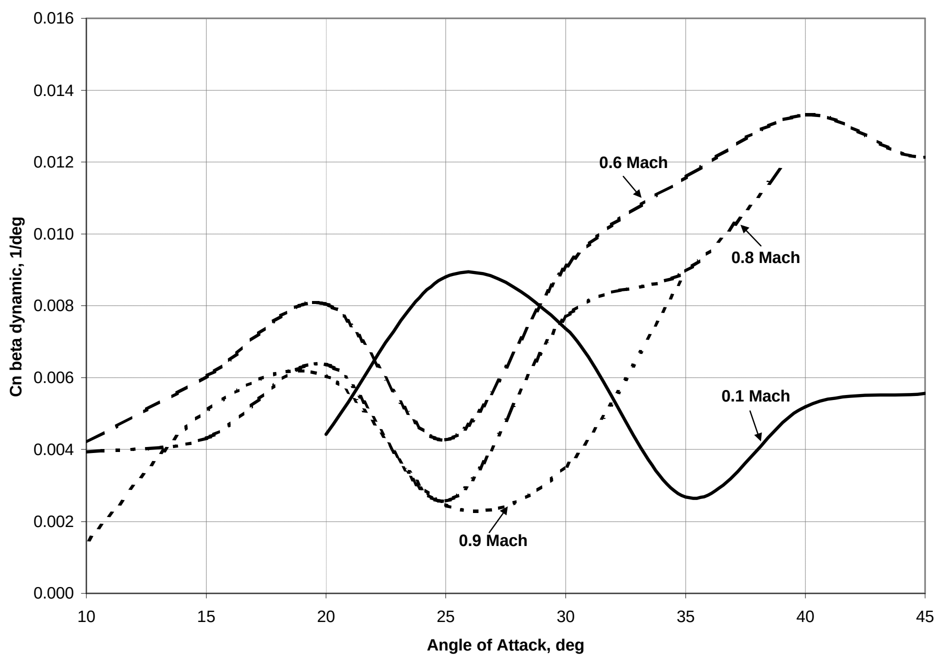

Figure 10 – Departure resistance of the two-seat Hornet at various Mach numbers

results. Though the aircraft does show slightly decreased departure resistance with the two-seat canopy, the high AOA aerodynamic data and flying qualities flight test results indicate that the departure susceptibility of the two-seat aircraft with the centerline tank was more likely the reason behind the Navy aircraft and flight test incidents.

CENTERLINE TANK

A majority of the fleet departures in the early to mid 1980's had the common link of the two-place canopy with the centerline tank configuration. Today a large percentage of the departures leading to OCF in the two-place aircraft loaded are with the centerline tank. Documentation of departure susceptibility investigations (ref 7-13) indicates that the two-seat canopy was only a minor contributor to the departure susceptibility. The more conclusive factor was the reduction in the lateral and directional stability of the F/A-18 due to the addition of the centerline tank and its pylon. Early FSD testing (ref 12) of the Hornet concluded that the "centerline tank had the most destabilizing effect of all stores tested on lateral-directional stability, particularly at high subsonic Mach number". The Hornet flight manual (NATOPS) still limits the operational use of the two-seat aircraft, not specifically in combination with the centerline tank, even though the areas of departure susceptibility are listed with the centerline tank loaded (Figure 11).

The aforementioned investigation into the two-seat departure characteristics pointed to a major contributor to departure susceptibility at high AOA – the centerline tank. The 1984 LSWT test (ref 14) revealed that the centerline tank had little effect on longitudinal stability below 40 deg AOA, but departure resistance was significantly reduced, particularly lateral-directional stability in the 36 to 40 deg AOA region. The

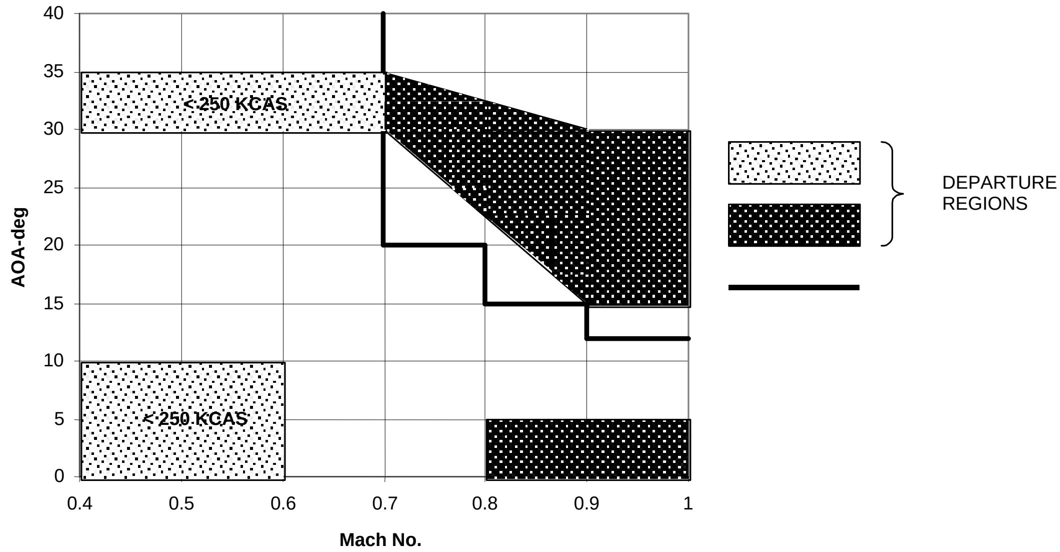

Figure 11 – F/A-18 Departure Susceptibility Regions (Two-Seat with Centerline Tank)

combination of the two-place canopy and the centerline tank drove the directional stability even more negative, though the combination was not simply aerodynamically additive.

The results from the 1986 F/A-18B flight test program revealed similar pilot handling qualities results. Of the three Part 1 deficiencies noted, two were found with centerline tank loadings: 1) inadequate departure resistance for centerline tank loadings below 0.7 Mach number in the 30 to 35 deg AOA region; and 2) inadequate departure resistance in the centerline tank loadings at slow airspeed in the AOA region below 10 deg, (ref 16). The results from the two-seat with centerline tank configuration departure resistance testing are echoed in the final conclusions of the test report as "departure from controlled flight will seriously limit training effectiveness, as well as impact safety of flight". During ACM tests a single seat aircraft loaded with a centerline tank and a two-seat aircraft loaded with a centerline tank and pylons were flown. Reference 16 states that, at high angles of attack the "single seat FA-18A airplane did not exhibit the hesitation and subsequent nose slice reversal demonstrated by the two seat FA-18B above 30 deg AOA". The results showed that the combination of the centerline tank and the two-seat canopy did have a departure resistance degradation over the single seat aircraft.

Various efforts were performed to analyze flight test data and compare it to wind tunnel data throughout the 1980's and quantify the effects of configuration on departure resistance. Most of these analyses concluded similarly to the wind tunnel and flight test results with respect to the departure resistance decrement with the carriage of the centerline tank. The departure resistance plots (Figure 12 and 13) show the effect of the

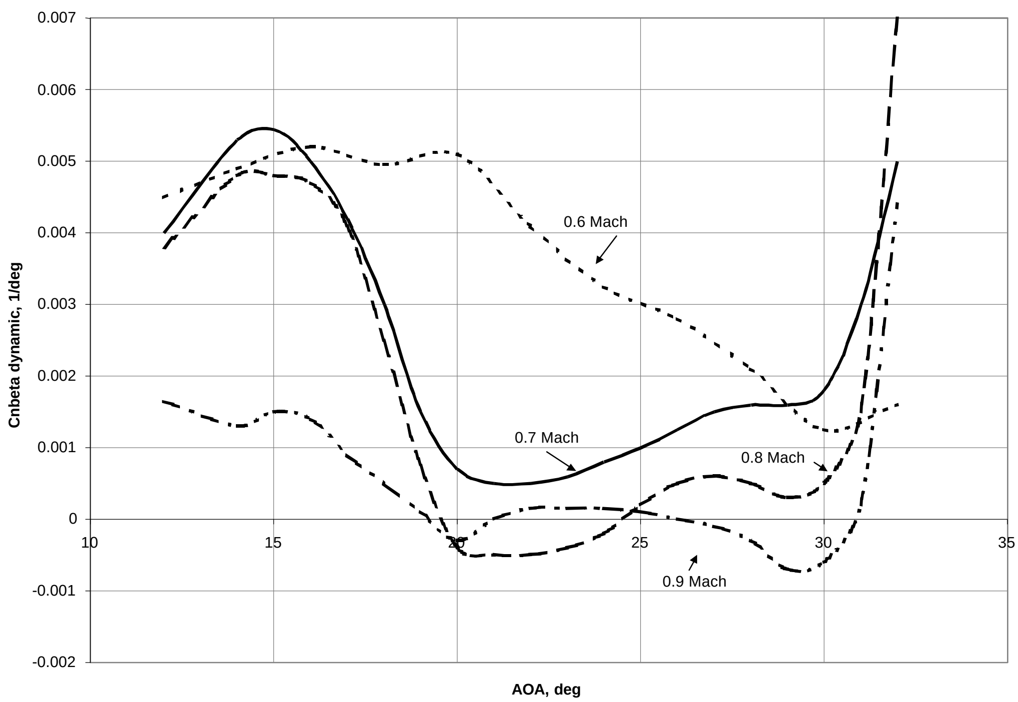

Figure 12 - Departure resistance of the single seat aircraft with the centerline tank, at various Mach numbers

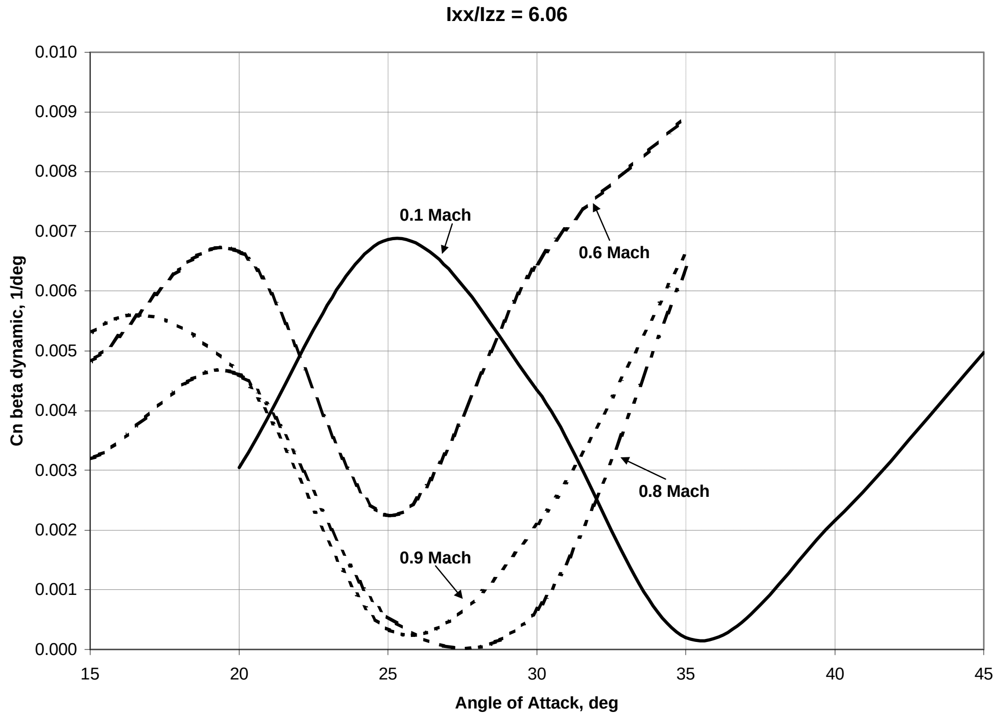

Figure 13 – Departure resistance of the two seat aircraft with centerline tank at various Mach numbers

centerline tank on the single and two-seat aircraft for varying Mach numbers. Reference 25 states that the centerline tank and centerline pylon "reduce both the lateral and directional static stability in the F/A-18. The addition of inboard pylons or the addition of the remaining stores necessary for to configure the F/A-18 for its interdiction configuration all tend to partially reduce the lateral static stability loss experience by the presence of the centerline tank". It continues to state that the additional stores and pylons have only a marginally stabilizing effect on the directional stability of the aircraft. In addition, this and other studies confirm the loss of stability due to centerline tank combined with the loss in static stability that the basic airframe experiences as Mach number increases leads the Hornet to be departure prone in high subsonic speed region of the flight envelope.

PYLONS AND EJECTOR RACKS

The addition of pylons and vertical ejector racks (VERS) to the wing of the Hornet has a slight impact on the high AOA flying qualities. Some difficulty exists in determining precise affects on departure resistance due to the combination of pylons and VERS with other store configurations for a significant amount of the Hornet test history. Some wind tunnel test and minimal flight test data has been collected during various test programs to support the conclusion that pylons and ejector racks only slightly add or detract from the departure resistance of the aircraft.

Low speed wind tunnel data from a recent 16% scale model test with four pylons mounted on the inboard and outboard wing stations indicates that the aircraft is more stable with pylons than without pylons. Limited low speed results in the 30 to 50 deg AOA range show approximately a 15 % increase in departure resistance with carriage of four pylons when compared to the clean aircraft. Higher speed data (0.6 Mach number), collected with the 6% scale two-seat F/A-18 model, indicates that two inboard pylons maintain similar stability levels as the clean aircraft until 35 deg AOA. Above 35 deg AOA the departure resistance drops below the clean aircraft levels and between 40 and 45 deg AOA are approximately the same as the two-tank configured aircraft. Low speed wind tunnel data from a 1984 test with the 16% scale F/A-18 model in the 20 to 45 deg AOA region shows the aircraft loaded with two outboard pylons has approximately the same departure resistance levels as the clean aircraft. There is a slight reduction in stability between 24 and 30 deg AOA and a slight increase in stability from 35 to 45 deg AOA compared to the clean aircraft.

Flight test in1982 (ref 27) included high AOA flying qualities and departure resistance testing in the attack training configuration (wingtip stores, pylons and VERs on four wing stations, fuselage missiles and a centerline fuel tank). Results from this testing were that “defensive high g barrel rolls [in the attack training configuration] were easily performed with no problem controlling yaw rate. Sideslip excursions were small in comparison to similar maneuvers in the FE or FCL loading”. The report goes on to detail that the resistance to directional divergence with the pylons and VERs appeared stronger than the centerline tank configuration, particularly during ACM in the 30 to 35 deg AOA region. One sideslip excursion was noted at 0.9 Mach number during a loaded deceleration maneuver in the known area of directional departure tendency for the aircraft loaded with a centerline tank.

FUSELAGE MOUNTED STORES

The Hornet has two fuselage store stations, on each side outboard of the centerline tank that are typically loaded with missiles or pods (AIM-7s, AIM-120s, FLIR pods, etc). The effect of missiles and pods on these stations has historically been considered to have minimal impact on departure resistance by the Navy and Boeing (successor of McDonnell Douglas). Limited wind tunnel data and quick look flying qualities flight test on the Hornet revealed no impact to high AOA characteristics with fuselage-mounted pods. However, in recent years the larger pods have been seen to cause some degradation in departure resistance at high AOAs and cause a roll-off phenomenon at high speeds.

In July 2002 data from a fleet F/A-18D was evaluated that revealed an uncommanded roll-off encountered during flight between 30 and 35 deg AOA with carriage of symmetric or asymmetric fuselage pods. The pods under investigation were the Targeting FLIR pod (TFLIR), Navigation FLIR pod (NAVFLIR) and the Laser Designator Pod (LDT). The largest of the three pods is the LDT pod, which is carried almost exclusively by Marine Corps F/A-18 squadrons. Limited data from 1g stalls, accelerated stalls, steady heading sideslips and high AOA rolls indicated that there was a significant roll off (up to two inches of lateral stick required to maintain wings level) accompanied by a sideforce buildup from 30 to 35 deg AOA. The worst case was seen with the LDT pod only, with the FLIR pod only and symmetric FLIR pods decreasing in roll-off and sideforce buildup (respectively). NAVAIR engineering concluded that asymmetric fuselage pod carriage, particularly the LDT pod, did increase the departure susceptibility of the Hornet in the 30-35 deg AOA region. Below 30 deg and above 35 deg the pod carriage did not appear to affect flying qualities.

WINGTIP STORES

Wingtip missiles and launchers have also historically been considered to have minimal impact on high AOA flying qualities. Launchers typically weigh less than 100 lbs and wingtip missiles weigh around 200 lbs. The small size and weight have led to considering the wingtip store as negligible to the overall configuration when addressing flight envelope. McDonnell Douglas FSD test results showed that the aerodynamic affects of a wingtip AIM-9 missile counteract the weight asymmetry (approx. 4000 ft-lbs). Due to this finding the weight of wingtip missiles is not used when calculating lateral weight asymmetries of a specific weapon configuration (ref 12).

The LSWT test of 1984 (ref 14) also investigated the effect of wingtip missiles and launcher rails on the Hornet high AOA stability. Results indicated that removing wingtip missiles and launchers slightly reduced longitudinal stability and lateral stability below 42 deg AOA. Data from runs with an asymmetric wingtip missile and launcher loaded indicated that the aerodynamic rolling moment above 32 deg AOA exceeds the weight moment of the store. Below 32 deg AOA the rolling moment is slightly less than the weight moment. 32 deg AOA is approximately stall AOA, indicating that above stall the aircraft will tend to roll away from the single wingtip store and below stall the aircraft will tend to roll into the single wingtip store. Limited departure resistance data from the wind tunnel results is shown in Figure 14. The asymmetric wingtip missile configuration at extremely low airspeed was shown to be departure prone between 30 and 40 deg AOA.

Hornet FSD flight test investigated the affects of carriage of a single wingtip missile on asymmetric configuration (ref 8). It was determined that the aerodynamic asymmetry from one tip missile off gives results in an apparent weight asymmetry. “For some loadings this aerodynamic effect is in the same direction as the weight asymmetry and, hence, increases the apparent total asymmetry. For other loadings it cancels some of the weight asymmetry” (ref 8). During 1 g stalls, accelerated stalls and aggravated inputs with the single wingtip missile canceling the weight asymmetry, results showed almost no departure tendencies for asymmetries less than 10000 ft-lbs.

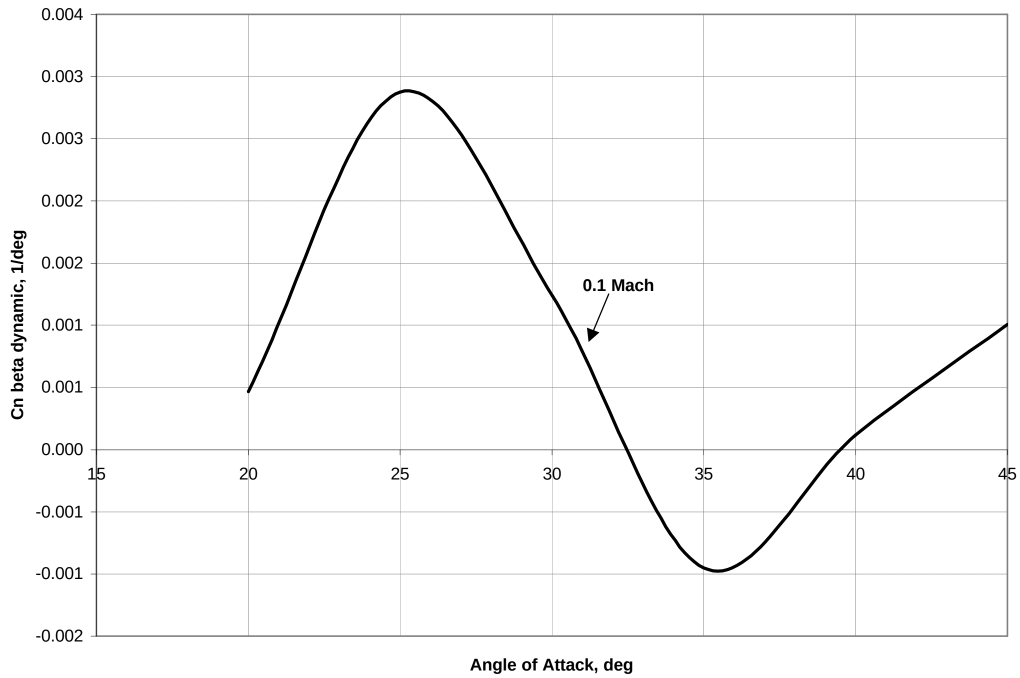

Figure 14 – Departure resistance of the two seat aircraft with asymmetric wingtip missile loaded (left wingtip)

INBOARD STORES

A significant amount of the wind tunnel and flight test work to define the high AOA flying qualities and departure resistance of the Hornet with stores loaded on the inboard wing station was conducted with external 330-gallon fuel tanks. Characteristics were evaluated with two external wing tanks only (wingtip and fuselage stores optional) or with the two external wing tanks and a centerline tank loaded, cited as fighter escort overload (FEO). The FEO configuration was often plagued by increased departure susceptibility due to the centerline tank effects.

The Hornet loaded with two external wing tanks and no centerline tank is limited to 35 deg AOA with CG's at or forward of 24% m.a.c. and 25 deg AOA at more aft CG locations. Low speed wind tunnel testing data was gathered for configuration development using the 12% scale F/A-18 model, including the two wing tank configuration. Results show that at 0.2 Mach number (low airspeed), the two wing tank configuration remains more stable than the centerline tank loaded aircraft up through 35 deg AOA. Additional data from 6% scale F/A-18 two-seat model testing shows that above 35 deg AOA, as Mach number increases, the stability levels of the two wing tank configuration decrease to levels comparable to the centerline tank loaded aircraft. Figure 15 shows representative wind tunnel data results.

Flight derived basic airframe data from FSD Hornet flight test shows similar results, documented in ref 11. FE plus two wing tank loaded aircraft was more departure resistant (higher positive value of $Cn_{\beta dynamic}$) than the centerline tank only configuration up to approximately 25 deg AOA at 0.7 Mach number, and up to approximately 32 deg AOA at 0.8 Mach number. At 0.9 Mach number the FE plus two wing tank loading was only slightly more departure resistant than the centerline tank only configuration.

A common configuration for Navy F/A-18 aircraft is to carry a centerline fuel tank and one external wing fuel tank on an inboard station, nicknamed the Goofy gas configuration. The single external wing tank is typically balanced by a weapon on the opposite inboard wing station for takeoff, but once the weapon has been released the aircraft is left with an asymmetric wing tank. Very little wind tunnel and flight test data exists in this configuration. Limited moderate to high subsonic Mach number data

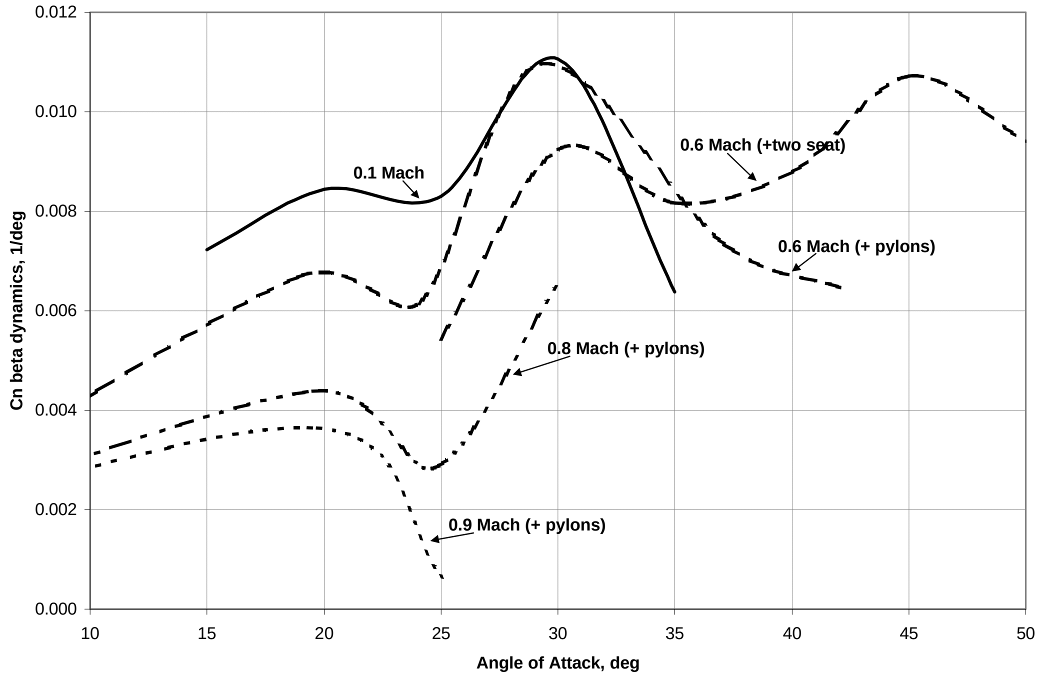

Figure 15 – Departure resistance with two wing fuel tanks

indicates that the Goofy gas configuration with pylons has similar departure resistance as the centerline tank only configuration at 0.6 Mach number, and slightly increased departure resistance over the centerline tank only configuration at 0.8 and 0.9 Mach number. This data covers only the 16-20 deg AOA range and is not necessarily representative of the high AOA flight region that is of most concern for low airspeed departures.

Carriage of two external wing fuel tanks and a centerline fuel tank (FEO configuration) is limited to 25 deg AOA for nose-down pitch restoring capability and departure resistance. The FEO configuration exhibits weak departure resistance at 0.7 Mach number and above (ref 12). The CG that results in static (unrecoverable at 50 deg

AOA) AOA Hang-up for this configuration is 25.5% m.a.c., far further forward than the centerline tank loaded aircraft. The increased susceptibility of a departure entering Falling Leaf motion or a static AOA Hang-up was a significant factor in the current AOA limitation of 25 deg AOA for all CG. locations. Additionally, FSD flight test results showed that above 25 deg AOA, high subsonic roll maneuvers in FEO resulted in yaw rates in excess of 40 deg/sec (ref 11). Remaining below 25 deg AOA with three external fuel tanks, regardless of airspeed, is recommended to preclude a departure and the possibility of an extended OCF situation.

OUTBOARD STORES

The outboard wing station of the Hornet is utilized for carriage of weapons, either loaded on pylons or ejector racks. The current operating limitations with carriage of an outboard store (with or without the centerline tank) is –6 to 25 deg AOA. Wind tunnel and flight test data for outboard store carriage has been specific to individual stores, but will be generalized for this document based on a variety of Navy bombs.

Low speed wind tunnel data with the 12% scale F/A-18 model indicates t that carriage of outboard stores with a centerline tank is significantly less departure resistant from 20 to 30 deg AOA than the centerline tank only configuration (ref 26). Above 30 deg AOA limited data that indicates similar levels of departure resistance for the carriage of outboard stores that exists for the centerline tank only configuration. Low speed wind tunnel data with the 16% scale F/A-18 model with weapons loaded on the outboard wing stations showed overall reductions in directional stability but an increase in lateral stability. The limited data indicated that the there were no significant reductions in departure resistance compared to the centerline tank loaded aircraft at high AOA. Flight test data taken with outboard stores loaded (no inboard stores, with a centerline tank) indicates that roll response at high subsonic Mach number and high AOA can be significantly decreased (ref 28) . In addition, data showed that yaw rates in excess of 25 deg/sec were easily obtained during roll maneuvers at high speeds.

INBOARD AND OUTBOARD STORES

The F/A-18 is often loaded with inboard tanks or weapons and outboard weapons for the attack mission. Wind tunnel and flight test data has been gathered over many years for various weapons and combinations of weapons with and without a centerline tank. In general, wind tunnel results have shown decreased levels of departure resistance of the F/A-18 FCL with inboard and outboard weapons loaded compared to the centerline tank (FCL) only configuration. Flight test results support this conclusion, citing high subsonic roll maneuvers at approximately 20 deg AOA that saw rapid AOA increases and yaw rate excursions above 25 deg/sec.

The interdiction loading is a mission representative configuration that includes wing and centerline fuel tanks, 2 stores loaded on ejector racks on each outboard station, wing tip missiles and fuselage stores. It is considered a “worst case” symmetric loading for wind tunnel and flight test efforts, and is limited to 20 deg AOA for all CG locations, throughout the envelope. Below 20 deg AOA at low speeds, the interdiction aircraft is a stable, maneuverable aircraft and this loading is considered more departure resistant than the centerline tank loading. FSD flight test results showed that above 25 deg AOA, high

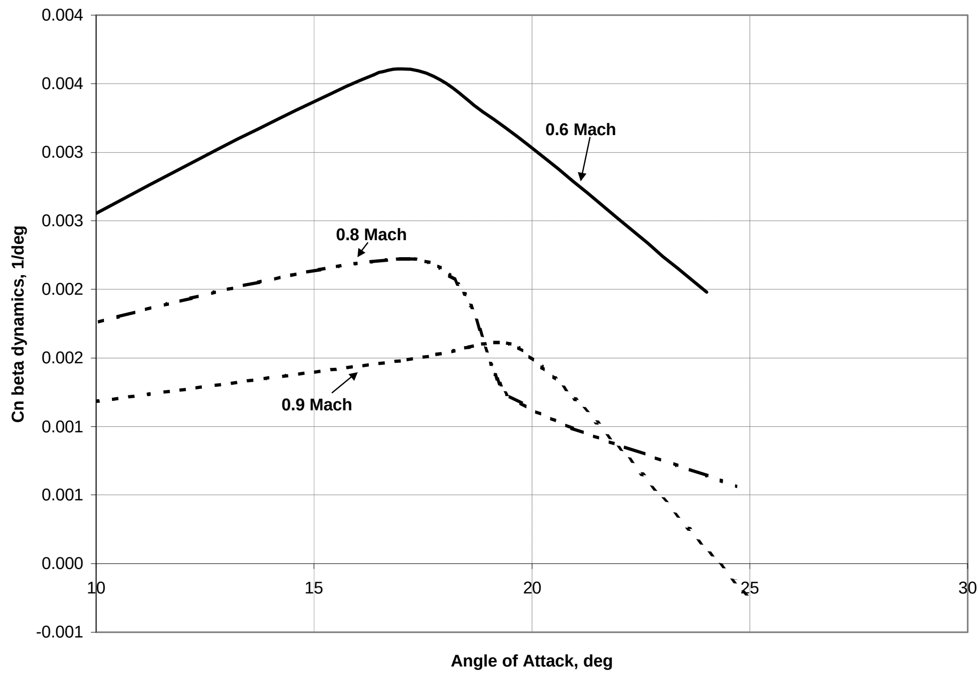

Figure 16 – Departure resistance of the single seat aircraft with Interdiction loading

subsonic roll maneuvers in FEO resulted in yaw rates in excess of 40 deg/sec (ref 11). Also, at high subsonic Mach number (between 0.8 and 0.9 Mach number) and 20 to 30 deg AOA region the interdiction loaded aircraft was found in flight test to be as departure prone as the centerline tank loaded aircraft (ref 12). Figure 16 shows the decrease in departure resistance as AOA increases above 20 deg, seen in representative wind tunnel test data.

ASYMMETRIES

Lateral weight asymmetries evaluated throughout the life of the Hornet program have been a combination of wing stores asymmetries, forced fuel asymmetries, and wingtip missile asymmetry. Maneuvering with any lateral weight asymmetry at high

AOA (greater than 25 deg) and below 0.7 Mach number the aircraft tends to yaw and roll into the light wing (ref 12). High AOA flying qualities degrade as lateral weight asymmetries increase, leading to nose-slice departures. At higher Mach numbers, these departure tendencies are more pronounced and violent departures have been encountered.

Unlike the symmetrically loaded aircraft, with lateral weight asymmetries greater than 6000 ft-lbs the aircraft will easily enter a spin from a stalled condition. The aircraft can generate a low yaw rate spin of 30 to 40 deg/sec yaw rate by simply maintaining AOA above 30 deg. Increasing yaw rate is generated with increasing lateral weight asymmetry (ref 12). At higher subsonic Mach number (>0.8 Mach number) the asymmetric aircraft is more likely to depart at AOAs above 15 deg. The two-seat aircraft with asymmetries at or greater than 6000 ft-lbs can violently depart at high subsonic Mach number, and is more likely to enter a spin following a departure (ref 13). Departures seen during FSD testing of the two-seat aircraft with approximately 6000 ft-lbs at 0.9M and 15 to 20 deg AOA were characterized by sharp increases in sideslip and sideslip rate followed by rapid yaw rate increase and a sharp nose slice at 30 deg AOA.

As lateral weight asymmetries increase above 12000 ft-lbs the aircraft becomes less stable in pitch and sees increased roll/yaw divergence tendencies at high AOA. Figure 17 shows the decreasing departure resistance above 15 to 20 deg AOA for a 17000 ft-lb asymmetric configuration at high subsonic Mach numbers. Flight test results indicate that rolls into the heavy wing generates lower yaw rates than rolls away from the heavy wing. High yaw rates and sideslips have been seen during slow speed maneuvering flight with asymmetries between 12000 and 22000 ft-lbs. During

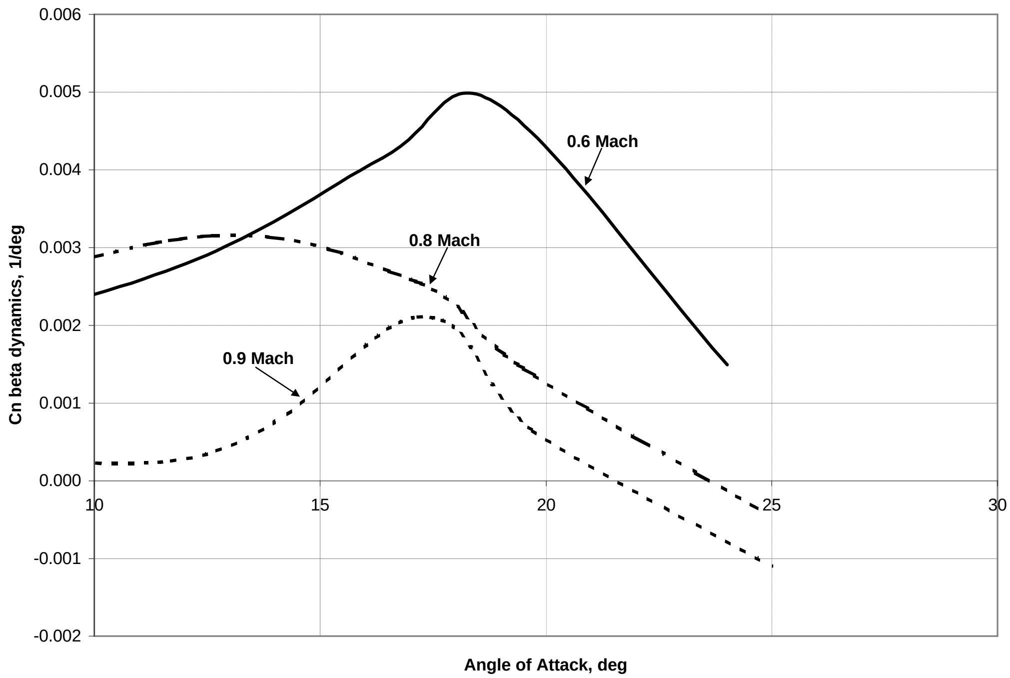

Figure 17 – Departure resistance with stores representing 17,000 ft-lbs asymmetry

maneuvering flight in the high subsonic Mach number region and at approximately 15 deg AOA, roll and yaw departures are likely. Aggravated flight control inputs (cross control, forward corner, etc.) can lead to violent departures from controlled flight in this region.

High lateral weight asymmetries (greater than 22000 ft-lbs) can generate significant yawing moment and sideslip at AOAs above 12 deg. This sideslip may not be accompanied by sideforce cues to the pilot. Flight test of lateral weight asymmetries up to 25900 ft-lbs exhibited moderate airframe buffet combined with small pitch and roll excursions, beginning at 10 deg AOA (ref 29). Testing at higher dynamic pressures led to more pronounced excursions and increased use of cross control lateral stick was required to counter the natural tendency to roll into the heavy wing. Maneuvering flight at high lateral weight asymmetries requires significant pilot attention to sideslip, translating into increased attention to the slip indicator ball in the cockpit.

ANTENNAE AND OTHER OUTER MOLDLINE CHANGE EFFECTS

Various external antennas, sensors, and camera mounts have been explored as systems with outer moldline changes during the life of the Hornet. Two of significance, which initially raised concern with respect to flying qualities and departure resistance, are the CIT antenna array and the Reconnaissance (RECCE) modification. Both are modifications to a section of the Hornet radome, which, as previously discussed, can be very sensitive to incongruities at high AOA. Neither was located near the tip of the radome, but was still considered significant moldline changes that could affect the flying qualities of the aircraft.

Combined Interrogator Transponder (CIT) Antennas

The F/A-18 Positive Identification System (PIDS) incorporates the Combined Interrogator Transponder (CIT) five blade antenna array on the upper surface of the radome, just forward of the aircraft windscreen. The blade antenna array is currently installed on a majority of the fleet aircraft. It was part of the production versions of the aircraft after 1995 and has been available for retrofit on earlier Hornets. The CIT antenna array was flown in flight test in 1995 during Boeing's basic acceptance regression testing and to understand any impacts on air data sensors. No significant flying qualities issues were noted, though no dedicated high AOA flight test was performed at that time.

The CIT antenna array was used as the baseline configuration during flight test of an F/A-18E/F antenna system in 1999. During this testing some high AOA data was collected that indicated that there were no basic instabilities due to the CIT antenna array, ref 30. No yawing tendencies were noted during 1 g and loaded deceleration maneuvers to full aft stick (40-50 deg AOA). Rolls at 25 and 35 deg AOA generated less than 5 deg of sideslip and less than 20 deg/sec yaw rate. The aircraft was described by the test pilots as "very stable" and no flying qualities concerns were raised.

RECCE

The Advanced Tactical Air Reconnaissance System (ATARS or RECCE configuration) was developed for implementation in the F/A-18D aircraft and resulted in a significant change to the moldline of the aircraft forward fuselage, Figure 18. Wind tunnel and flight test data support that there is a minimal reduction in stability and departure resistance and overall no degradation in the handing qualities of RECCE configured F/A-18D aircraft as opposed to non-RECCE two-place F/A-18s. McDonnell Douglas Corporation performed wind tunnel tests of the two-place RECCE configuration to investigate stability characteristics and departure resistance, as shown in Figure 19. Test conditions ranged from 0.6 to 1.6 Mach number and –5 to +20 degrees AOA, 0.20 Mach number and –5 to +35 degrees AOA, and were performed with fighter escort (FE)

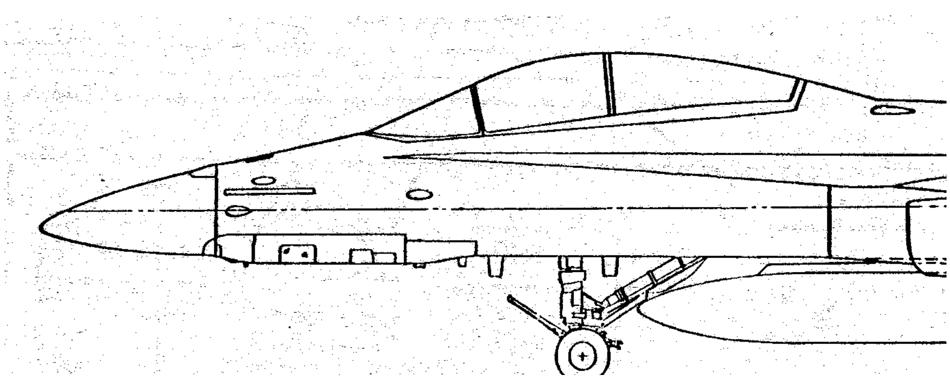

Figure 18 – RECCE outer moldline

and centerline tank only (FCL) configurations (Ref 31, 32). As stated ref 31, "minimal changes in TF/A-18 longitudinal and lateral-directional stability characteristics were measured with the RECCE nose installed."

The Navy, in cooperation with McDonnell Douglas, evaluated departure resistance and the flying qualities associated with the RECCE configuration in flight test. RECCE departure resistance and flying qualities evaluations were primarily performed in the FE, FCL, and FCL + pylons loadings with some flying qualities testing performed in a three tank interdiction (INT) loading. Mission tasks included takeoff, erobatics/basic fighter maneuvers, air-to-air and air-to-ground tracking, formation flight, and in-flight refueling. The results are documented in ref 33, stating that "the flight characteristics of

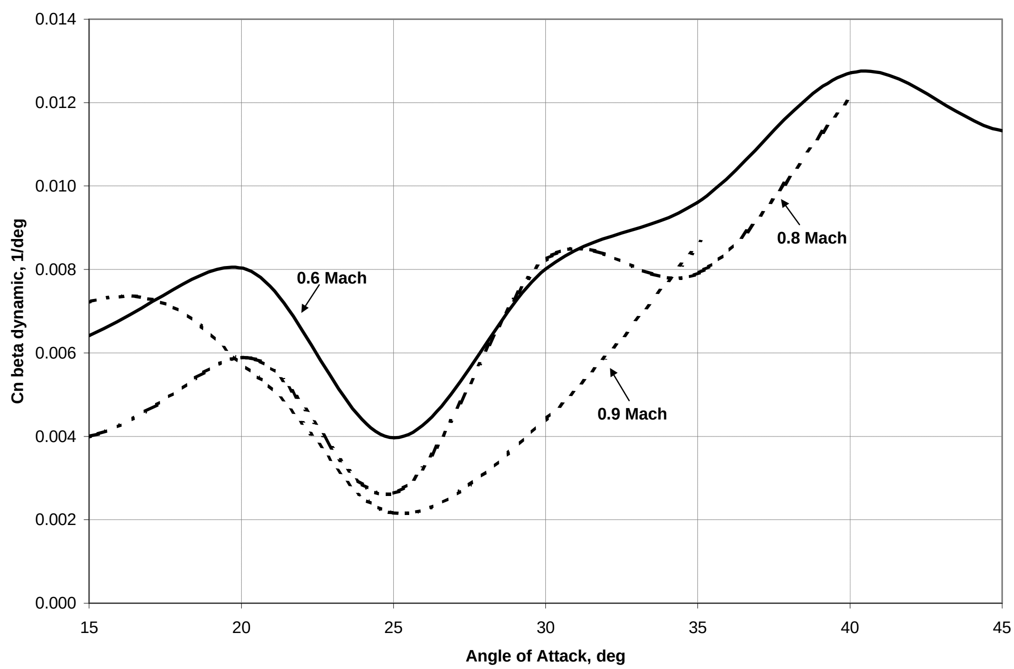

Figure 19 – Departure resistance of the two seat aircraft with the RECCE nose

the reconnaissance F/A-18D airplane are equivalent to those of baseline production aircraft without the reconnaissance door kit installed and are satisfactory" for the intended missions.

CONFIGURATION SUMMARY

Departure resistance comparisons of the external configuration data at each Mach number are shown to summarize the conclusions of each individual section.

At extremely low airspeeds, represented by 0.1 Mach number wind tunnel data in Figure 20, the degradation in departure resistance due to the centerline tank is clearly seen. The two place canopy is slightly less departure resistant from 20 to 35 deg AOA, but actually

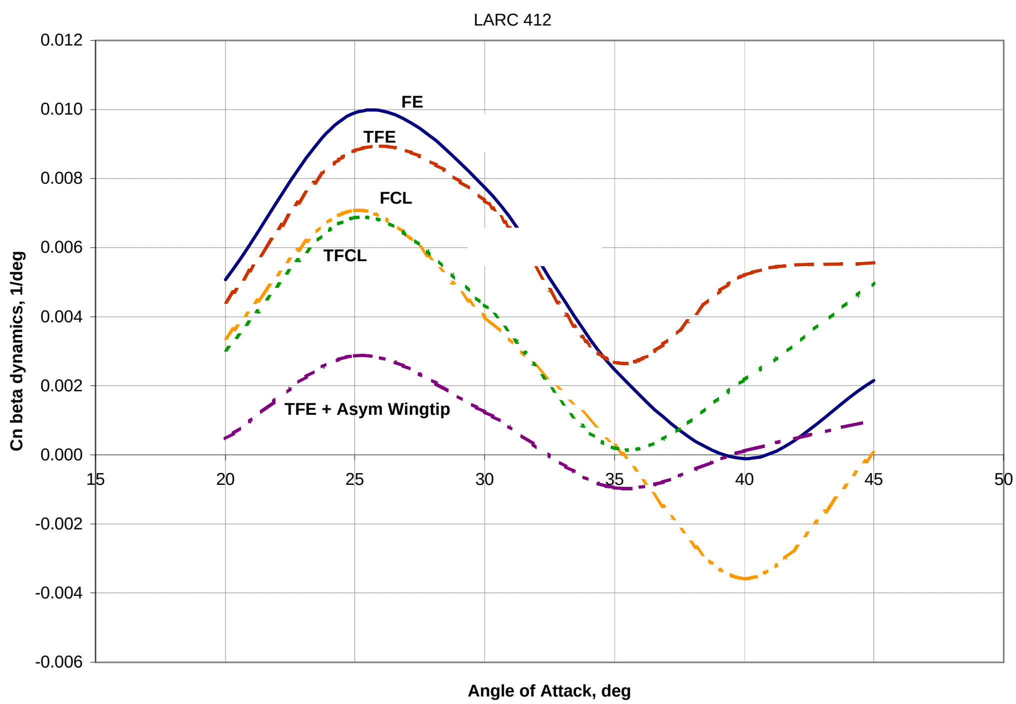

Figure 20 – Departure resistance summary at 0.1 Mach number

increases departure resistance above 35 deg AOA. The two seat aircraft with asymmetric wingtip store is significantly degraded over both the two seat canopy and the centerline tank loadings, though this was not seen in the limited flight test results discussed above. The 0.1 Mach number data clearly shows the basic aircraft has lower stability from 35 to 40 deg AOA. This correlates to the known degradations in roll performance above 35 deg AOA (in general) and the slow speed nose-slice departures that are common to the Hornet at high AOA with sideslip buildup.

At low airspeeds, represented by 0.2 Mach number wind tunnel data shown in Figure 21, the degradation in departure resistance due to centerline tank is again seen from 15 to 35 deg AOA. Also seen is an increase in departure resistance up to 30 deg

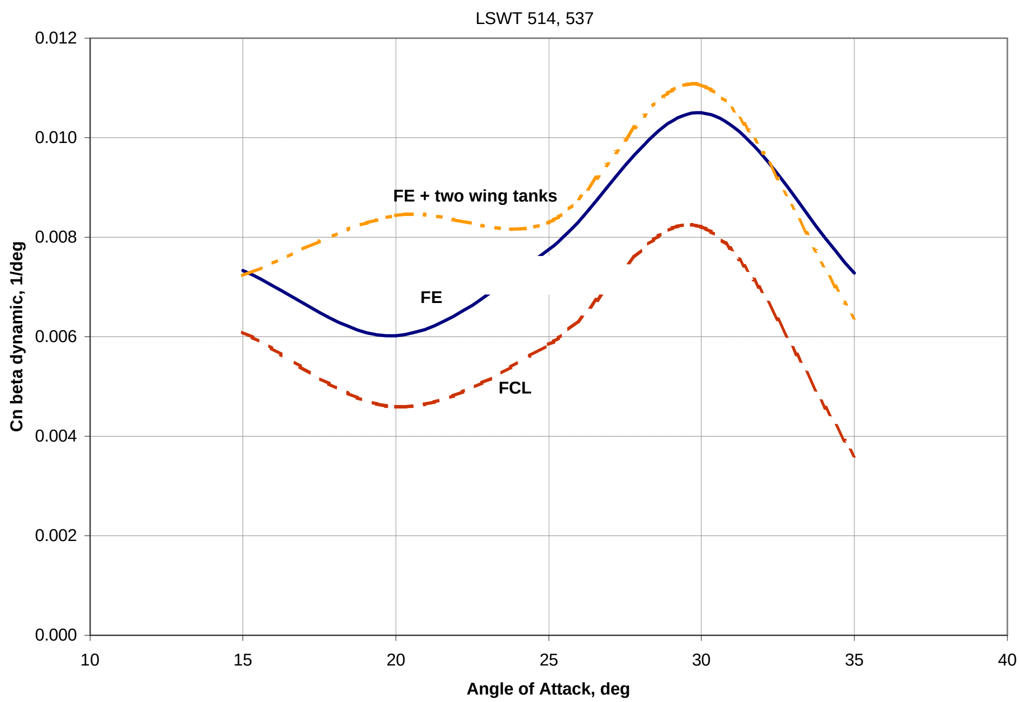

Figure 21 – Departure resistance summary at 0.2 Mach number

AOA with the addition of two wing tanks. This is accounted for by the increased lateral stability from 15 to 25 deg AOA and slightly increased directional stability. It is misleading, however, to assume that the aircraft loaded with two wing tanks is more departure resistant than even the FE configuration. The data presented only goes as high as 35 deg AOA and the trend above 30 deg AOA is a distinct drop in departure resistance. The configuration remains limited in AOA due to departure tendencies and nose-down pitching moment considerations.

At moderate airspeeds, represented by 0.6 Mach number wind tunnel data shown in Figure 22, the effect of configuration on departure resistance becomes less clear. The overall aircraft stability in this moderate speed range is good. From 20 to 30 deg AOA

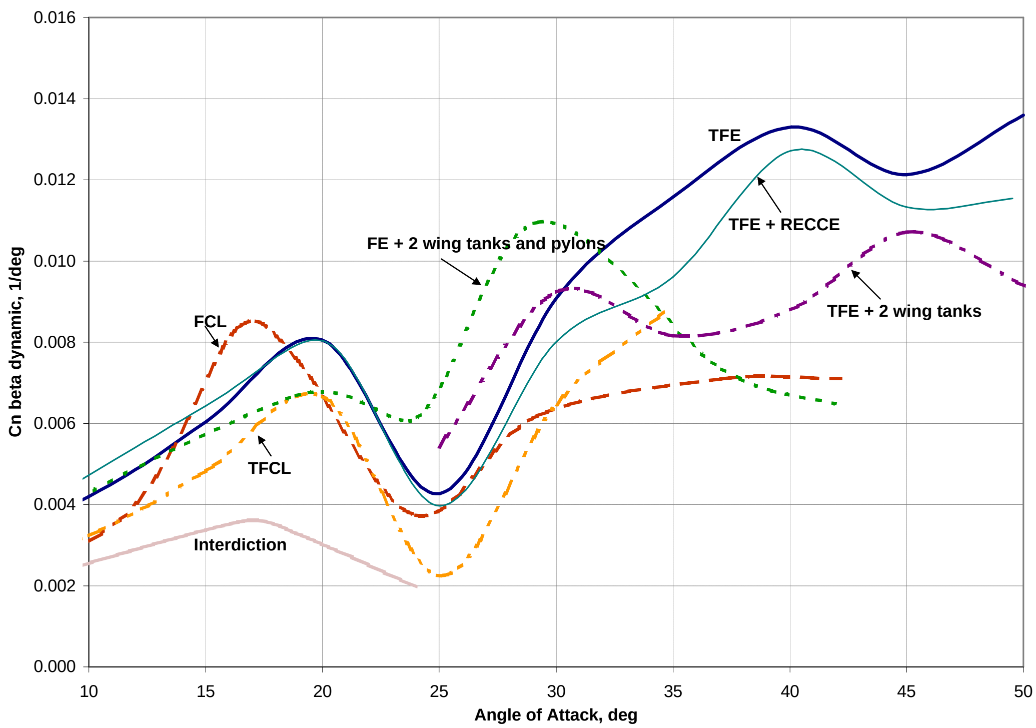

Figure 22 – Departure resistance summary at 0.6 Mach number

the Interdiction loading is the least departure resistant, with the two seat centerline tank (TFCL) configuration slightly better. The centerline tank (FCL) configuration, two seat canopy (TFE), and two seat with RECCE configuration have higher levels of departure resistance in this AOA region. The two external fuel tank configurations are the most departure resistant loadings in the 20 to 30 deg AOA region. Above 30 deg AOA most configurations show good levels of departure resistance. The FCL loading is the least departure resistant configuration tested, followed by TFCL due to the two seat canopy increased lateral stability around 35 deg AOA. The two wing tank loadings show decreased levels of departure resistance. The TFE and TFE + RECCE configurations exhibit the most departure resistant characteristics. Above 30 deg AOA there is no representative Interdiction data.

As airspeed enters the high subsonic Mach number region, represented by the 0.8 Mach number wind tunnel data shown in Figure 23, the AOA range evaluated for multiple configurations has decreased. In the 20 to 30 deg AOA region, the centerline tank configurations (FCL and TFCL) and the Interdiction loading are the least departure resistant. Clean (FE and TFE), two wing tanks and RECCE configurations are all moderately departure resistant. In this region the FE loading data is the most departure resistant. Above 30 deg AOA the wind tunnel data becomes more limited, but the TFCL loading remains the least departure resistant configuration. The data shows the departure resistance of all loadings increasing above 30 deg AOA. These results correspond fairly well to the increased departure tendencies seen in flight at high subsonic Mach number and high AOA. Reaching high AOA conditions can be difficult due to the bleed off of airspeed. Even with the departure resistance levels reaching close to zero, the aircraft

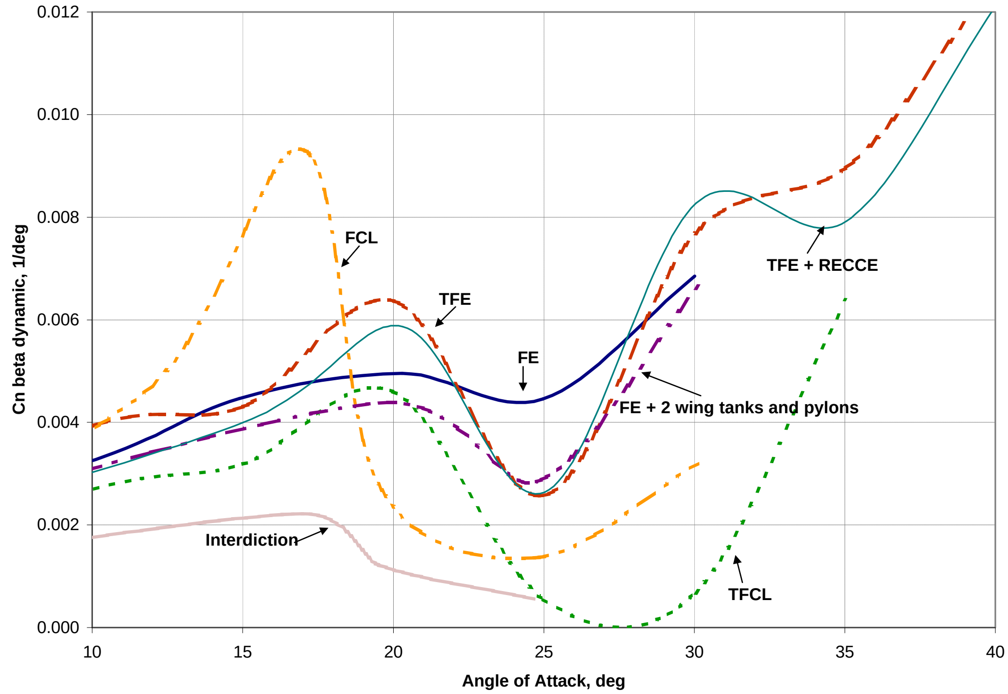

Figure 23 – Departure resistance summary at 0.8 Mach number

can be flown safely. Flight data has shown that aggressive rolling maneuvers or aggravated control inputs are the cause of violent departures in the high subsonic airspeed region.

High subsonic Mach number (0.9 Mach number) wind tunnel data shows a general decrease in departure resistance and more limited data sampling (Figure 24). From 20 to 25 deg AOA the Interdiction and FCL loadings exhibit the least departure resistance. The FE configuration shows moderate and fairly constant levels of departure resistance. TFE and RECCE configurations show similar decreasing but moderate levels of departure resistance. Above 25 deg AOA limited data shows the departure resistance of the two seat and RECCE configurations steadily increasing. At these airspeeds the aircraft has difficulty maintaining flight conditions and will see excessive airspeed bleed

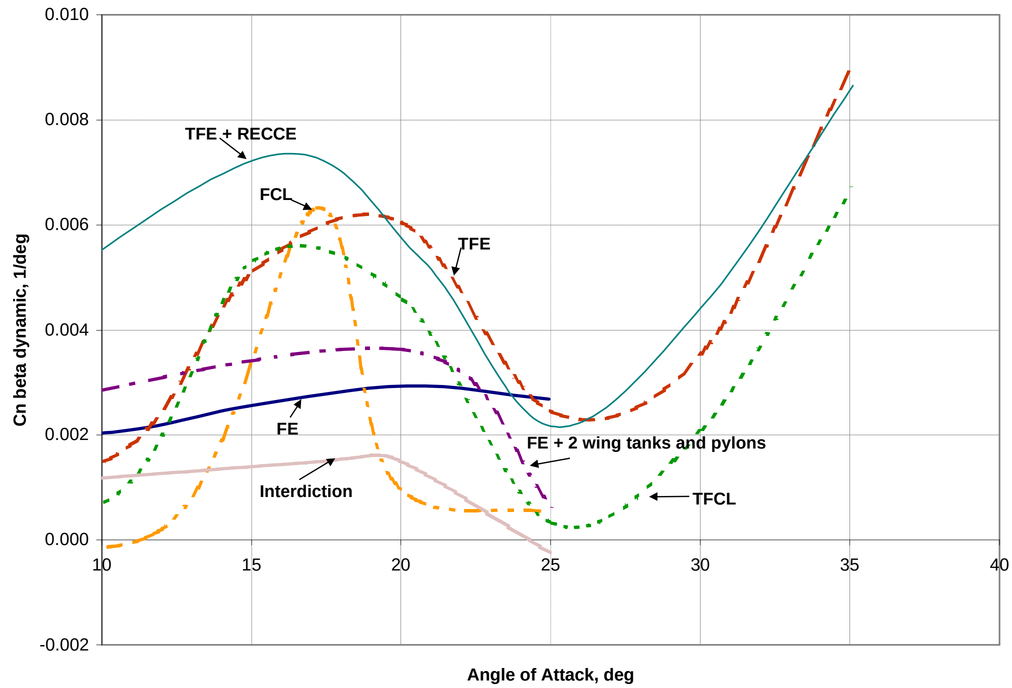

Figure 24 – Departure resistance summary at 0.9 Mach number

off at high AOA. Flight data indicates that high AOA rolling maneuvers and aggravated control inputs at 0.9 Mach number can result rapid sideforce buildup and violent departures from controlled flight.

The most departure resistance regions of the flight envelope are as expected, at moderate airspeed levels. Configuration effects at all of the speed ranges are fairly similar. The Interdiction loading exhibits the lowest levels of stability for most cases. In general, the clean FE loading exhibits the highest departure resistance levels. For other configurations, airspeed and AOA range can play a large role in the departure resistance level that the aircraft will experience. A configuration that is more departure resistant at low speed and moderately high AOA may be much less departure resistant at high speed or very high AOA.

CHAPTER 6

FLIGHT CONTROL SOFTWARE UPGRADE

DEPARTURE RESISTANCE/ENHANCED MANEUVERABILITY

The long history of the F/A-18 Hornet departure susceptibility in certain areas of the flight envelope has been a continual source of concern for the engineering community. In the late 1980's and early 1990's efforts to develop more departure resistant flight control laws were explored, but met with budget constraints and significant user concerns about possible reductions in maneuvering capability. In addition, a great deal of effort was being devoted to the development of the F/A-18E/F aircraft. Due to the lessons learned from the A/B/C/D departures and OCF, the E/F flight control design utilized technological advances in software to increase departure resistance while maintaining excellent maneuverability. The F/A-18E/F enabled considerable resources including a dedicated high AOA designer, months of dedicated design time, a dedicated spin aircraft complete with emergency recovery provisions, a dedicated test plan consisting of 215 flights, and the opportunity to fine tune the design over six flight software versions. The F/A-18E/F design provided invaluable lessons for F/A-18A/B/C/D upgrade that would not have been realized if the program started from scratch in the early 1990s.

Utilizing calculated sideslip and sideslip rate, along with improvements in flight controls allocation and spin recovery mode, the E/F aircraft saw improved departure resistance, damped motion after aircraft departure and significant maneuverability enhancements at high AOA. In addition, inertial coupling logic was added to improve resistance to departures due to aggravated or multi-axis control inputs. Flight test and further engineering development proved the design worked and was a great success.

Due to the success and refinement of F/A-18E/F high angle of attack flight control software, the aging F/A-18A/B/C/D fleet had an opportunity for a low risk safety upgrade. The flight control implementation was not an exact match due to minor limitations in the A/B/C/D control surfaces and sensors, but the departure resistance improvements could be realized with a flight control software upgrade. The engineering effort began in 1999 and the new flight control software began flight test in May of 2002.

CURRENT FLIGHT TEST RESULTS

The production flight control software upgrade, version 10.7, is currently finishing flight test at NAWC-AD. A full departure resistance and spin flight test investigation was performed that showed extremely good results. Though designing a departure-free aircraft is never a possibility, the Hornet software upgrade will increase the departure resistance in the high AOA region greatly, while also preventing the aircraft from entering fully developed Falling Leaf motion. In addition, maneuverability enhancements make the high AOA maneuverability more predictable and controllable. All indications from the flight test effort are that the older A/B/C/D fleet will be a much safer aircraft during maneuvering flight.

One of the more significant accomplishments of the software upgrade will be the removal of the current flight limitations with the two-seat canopy. The improvements in departure resistance and recoverability have been proven to remove any differences in the flying qualities and departure resistance between the single and two-seat aircraft. In fact, preliminary flight test results are that most minor degradations in departure resistance (areas of uncommanded yaw rate at high AOA due to antennas, fuselage pods, etc.) are negligible with the upgraded flight control software. The software has given the Hornet an opportunity to see increase levels of safety and performance for it’s remaining years of service.

CHAPTER 7

CONCLUSIONS

The effects of external configuration on departure resistance at high AOA have been explored in many wind tunnel tests, analytical studies and flight test efforts throughout the life of the F/A-18 Hornet. Changes in aircraft moldline, stores configurations, and flight control software can have a significant effect on high AOA flying qualities and departure resistance. Even though the aircraft has been in service for twenty years, there continue to be modifications and new configurations that require high AOA investigation.

Flight accident and incident data supports the overarching results from years of wind tunnel and flight test efforts. The two-seat aircraft loaded with the centerline tank (TFCL) is the most departure prone configuration that currently has no AOA limitation (forward of 23.5% m.a.c.). This configuration is the most common (with or without pylons) utilized in the training flights, where the odds of an inexperienced pilot at the controls are high. Utilizing other stores configurations can be beneficial in some regions of the flight envelope, however, caution should be used in evaluating the departure resistance of a configuration across the Mach number and AOA ranges. A configuration that is more departure resistant at low speed and moderately high AOA may be much less departure resistant at high speed or very high AOA.

Flight with lateral weight asymmetry or heavy stores and tanks will significantly increase susceptibility to departure and OCF or spin entry. Though the Hornet is designated as a fighter and attack aircraft, performing fighter maneuvering with an attack configuration can lead to OCF. The limitations that are currently in place for the aircraft should be honored to maintain adequate longitudinal and lateral-directional stability, resulting in flying qualities sufficient for each aircraft mission.

The introduction of new flight control software in the future may improve on the F/A-18 Hornets high AOA flying qualities and departure resistance significantly. However, maneuvering at the edge of the flight envelope will always increase the risk of departure and OCF. Knowing the effects that external configuration have on departure resistance will help determine where the edges are for each aircraft and mission.

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APPENDICES

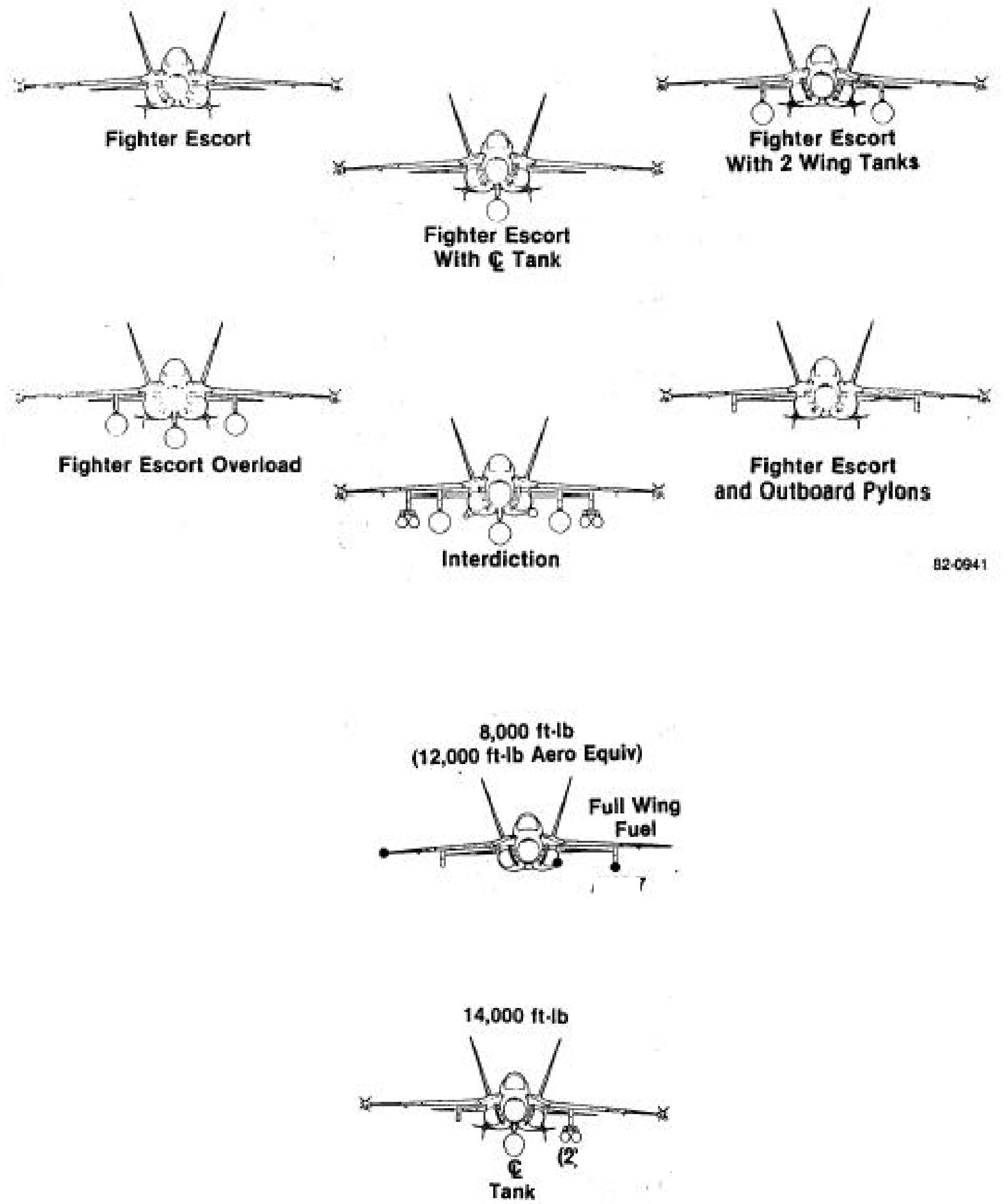

Figure A1 - F/A-18A/B/C/D Configuration Examples

APPENDIX B – Past F/A-18 Flight Control Law Developments for High AOA

Table B1 - Departure Resistance Flight Control Law Modifications

Flight Control PROM Version	Timeframe	Change Description
3.X (7 total versions)	Nov 1978 – Dec 1979	Improved Handling Qualities ❑ Added roll prefilter in Up/Auto flaps ❑ Incorporated sideslip rate feedback Improved Carrier Suitability ❑ Lead-lag prefilter in pitch ❑ Scheduled rudder-toe-in ❑ Added full time AOA feedback
4.X (26 total versions)	Jan 1980 – Nov 1981	Reduce Time Delays Improve Handling Qualities ❑ Modified longitudinal and lateral stick force gradients ❑ Modified Nz feedback filter ❑ Added full time pitch rate feedback at low speed conditions ❑ Redesigned control stick sensor to eliminate stick torqueing ❑ Scheduled leading edge flaps with AOA in approach configuration Added RSRI vice SRI Spin Mode Improvements Roll Modifications
6.X (4 total versions)	Nov 1981	Reduce Time Delays Modified long. and lat. stick gradients and utilized forward path gain scheduling to optimize handling qualities Modified AOA feedback schedules and forward path integrator logic to improve maneuvering characteristics Position vice Force Sensors Autopilot Modes Incorporated
7.X (22 total versions)	Mar 1983, Jun 1983-Nov 1983	Revised Spin Logic Improved Directional Stability Active Oscillation Control (AOC) Initial G-limiter Development
8.X (11 total versions)	July 1982, Nov 1983-1985	Throttle Sensitivity Autopilot/APC/ACLS Improvements Refinement of G-limiter Longitudinal PIO Fix in Approach Config Refinement of AOC Filter

HANDLING QUALITIES RATING

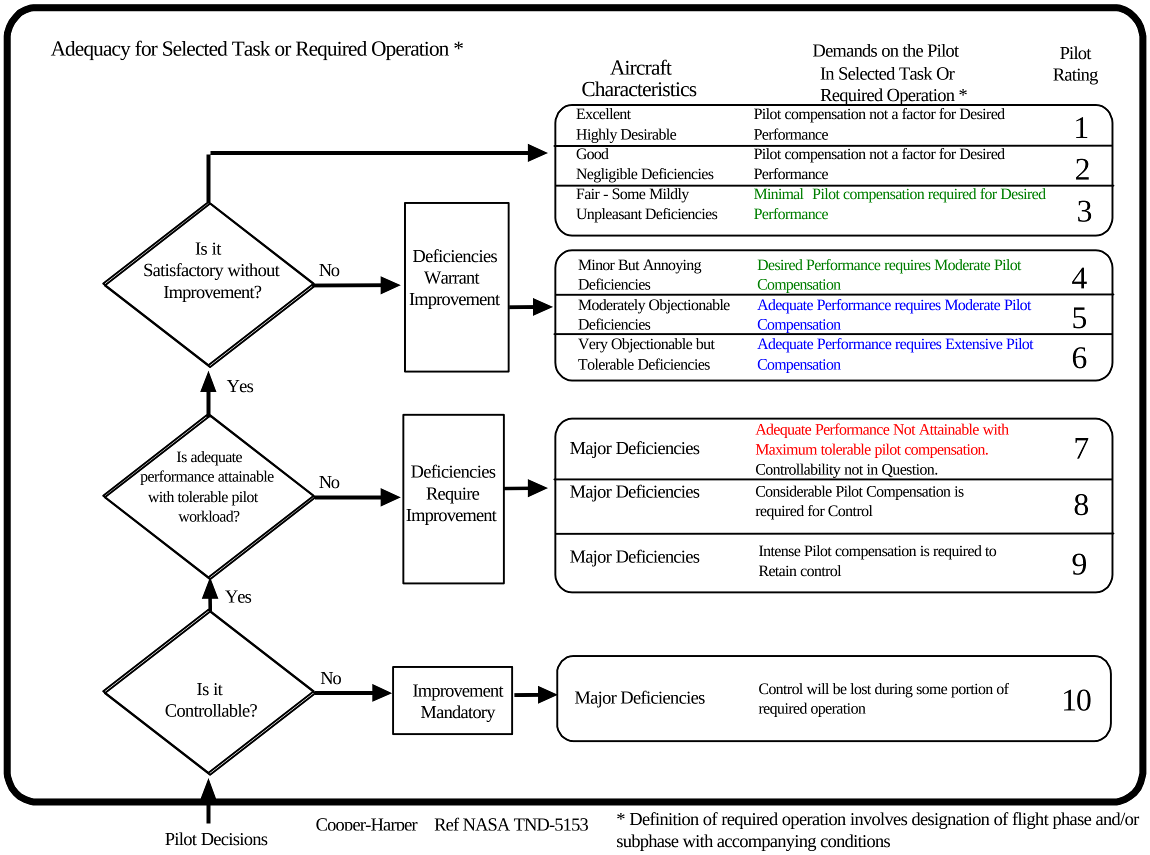

Figure C1 – Pilot Handling Qualities Rating Scale (HQRs)

Deficiency	Description
Part I	Indicates a deficiency, the correction of which is necessary because it adversely affects: 1) airworthiness of the aircraft or system, 2) the capability of the aircraft or system to accomplish its primary or secondary mission, 3) the safety of the crew or the integrity of an essential subsystem (real likelihood of injury or damage).
Part II	Indicates a deficiency of a lesser severity than a Part I which does not substantially reduce the ability of the aircraft or system to accomplish its primary or secondary mission, but the correction of which will result in significant improvement in the operational cost, effectiveness, reliability, maintainability, or safety of the aircraft or system, or required significant operator compensation to achieve the desired level of performance.
Part III	Indicates a deficiency which is minor or that appears too impractical or costly to correct in this model, but which should be avoided in future designs.

Figure C2 – Deficiency Classifications

APPENDIX D – F/A-18 Departure and OCF Event Summaries

Table D1 – F/A-18 Aircraft Out-of-Control Flight Mishap Summary

Date	**Aircraft**	**Configuration**	**Comments**
14 Nov 80	F/A-18A		FSD Operational Evaluation – identified a previously unknown low yaw rate spin mode
09 May 89	F/A-18C	FCL St 1: Wingtip Missile St 2: Clean St 3: Clean St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Clean St 9: Wingtip Missile	Departure during ACM engagement
23 Feb 90	F/A-18C	5470 Asym/FCL St 1: Clean St 2: AIM9 Missile St 3: Clean St 4: AIM7 Missile St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Clean St 9: Clean	Departure during ACM engagement – vertical maneuvering with low airspeed
14 Aug 90	F/A-18D	FCL St 1: Wingtip Missile St 2: Clean St 3: Clean St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Clean St 9: Wingtip Missile	Departure during BFM training at low altitude

Table D1 – Continued

Date	Aircraft	Configuration	Comments
04 Dec 91	F/A-18C	3 External Tanks (FEO) St 1: Wingtip Missile St 2: Pylon St 3: Wing Fuel Tank St 4: FLIR Pod St 5: Centerline Fuel Tank St 6: Clean St 7: Wing Fuel Tank St 8: Pylon St 9: Clean	Departure during Air Intercept Training (AIC) at low altitude
15 May 92	F/A-18D	FCL St 1: Wingtip Missile St 2: Clean St 3: Clean St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Clean St 9: Wingtip Missile	Departure during BFM, attempted brief full afterburner and full forward stick that were unsuccessful for recovery
21 May 93	F/A-18C		Departure during ACM engagement in the vertical
MAG-42	F/A-18A	FCL St 1: Wingtip Missile St 2: Clean St 3: Clean St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Clean St 9: Clean	MSRM selected after ASRM engagement, Centerline Tank jettisoned during recovery
03 Apr 96	F/A-18C	FCL St 1: Clean St 2: Pylon St 3: Pylon St 4: FLIR Pod St 5: Centerline Fuel Tank St 6: Clean St 7: Pylon St 8: Pylon St 9: Wingtip Missile	Departure during ACM maneuvering

Table D1 – Continued

Date	Aircraft	Configuration	Comments
25 Sep 98	F/A-18C	<u>3 External Tanks (FEO)</u> St 1: Wingtip Missile St 2: Pylon St 3: Wing Fuel Tank St 4: FLIR Pod St 5: Centerline Fuel Tank St 6: Clean St 7: Wing Fuel Tank St 8: Pylon St 9: Clean	Departure during BFM, low airspeed and high AOA. Entered Falling Leaf motion.
16 Jun 99	F/A-18D	FCL St 1: Wingtip Missile St 2: Clean St 3: Pylon St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Pylon St 8: Clean St 9: Data Pod	Departure during BFM at low altitude. Entered Falling Leaf motion. One fatality.
3 Dec 99	F/A-18A	FE St 1: Wingtip Missile St 2: Clean St 3: Pylon St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Pylon St 8: Clean St 9: Clean	Departure during ACM/BFM, delayed recognition of departure and controls released.
10 Jan 00	F/A-18D	FCL St 1: Wingtip Missile St 2: Pylon St 3: Pylon St 4: FLIR pod St 5: Centerline Fuel Tank St 6: FLIR pod St 7: Pylon St 8: Pylon St 9: Data Pod	Departure during ACM/BFM – appears to redepart after a period of PDGs and Full Fwd Stick input.

Table D1 – Continued

Date	Aircraft	Configuration	Comments
07 Jul 00	F/A-18D	FCL St 1: Wingtip Missile St 2: Clean St 3: Pylon St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Pylon St 8: Clean St 9: Data Pod	Departure during ACM/BFM
22 Aug 01	F/A-18A+		LEF failure, continued maneuvering flight above 20 deg AOA
15 Mar 02	F/A-18A	FE	Departure during ACM engagement, entered OCF at low altitude
Jun 02	F/A-18A	FE	Departure during ACM engagement at aft cg condition
Nov 02	F/A-18D		
Feb 03	F/A-18C	FE + 2 Tanks	Departure during maneuvering flight

Table D2 - Hazard Report List (recoveries from OCF flight)

Date	Aircraft	Configuration	Comments
03 Jun 85	F/A-18B	FCL St 1: Clean St 2: Clean St 3: Pylon St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Pylon St 8: Clean St 9: Clean	Departure during ACM/BFM flight, cross control inputs with forward stick
10 Aug 88	F/A-18A	Asym St 1: Clean St 2: Pylon St 3: Clean St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Pylon/AGM88 Missile St 9: Clean	Departure during maneuvering flight – high subsonic departure due to slice turn with asymmetry
26 Mar 91	F/A-18B		Departure during high AOA maneuvering at moderate to high subsonic airspeed
25 Jun 91	F/A-18D		Departure during BFM engagement – high AOA low airspeed, aft corner with pedal input
30 Oct 91	F/A-18B	FCL St 1: Clean St 2: Clean St 3: Clean St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Clean St 9: Clean	Departure during supersonic roll, centerline tank and pylon separated from aircraft and damaged wing/wingtip

Table D2 - Continued

Date	Aircraft	Configuration	Comments
26 Apr 93	F/A-18A	FCL St 1: Clean St 2: Pylon St 3: Pylon St 4: Clean St 5: Centerline Fuel Tank St 6: LDT pod St 7: Pylon St 8: Pylon St 9: Wingtip Missile	Departure during maneuvering flight in the vertical
07 Jun 93	F/A-18C		Departure during BFM engagement (rolling maneuver)
06 Jul 93	F/A-18C		Departure from low airspeed, high AOA maneuvering flight
03 Mar 94	F/A-18D		Departure during maneuvering flight with low airspeed
20 May 94	F/A-18C		Departure during guns defense maneuvering, high AOA and low airspeed
12 Jul 95	F/A-18D	FCL St 1: Clean St 2: Pylon St 3: Clean St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Pylon St 9: Clean	Departure during BFM engagement, high AOA and low airspeed
29 Jul 95	F/A-18C	6720 ft-lbs Asym St 1: Clean St 2: AIM7 Missile St 3: Clean St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Pylon St 9: Wingtip Missile	Departure during AIC flight, high subsonic airspeed and high AOA

Table D2 – Continued

Date	Aircraft	Configuration	Comments
03 Sep 95	F/A-18C	6700 ft-lbs Asym St 1: Clean St 2: Missile St 3: Clean St 4: FLIR pod St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Clean St 9: Wingtip Missile	Departure during AIC flight
23 Oct 95	F/A-18A	FCL St 1: Clean St 2: Clean St 3: Pylon St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Pylon St 8: Clean St 9: Wingtip Missile	Uncommanded roll and pitch during maneuvering flight (loaded roll)
07 Nov 95	F/A-18D	FCL St 1: Clean St 2: Pylon St 3: Clean St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Pylon St 9: Clean	Departure during BFM engagement, entered Falling Leaf
23 Jul 96	F/A-18B		Departure during BFM engagement, low airspeed and high AOA. Entered Falling Leaf motion.
04 Feb 97	F/A-18C		Departure during BFM engagement, low airspeed and high AOA. Tailslide motion followed by gyrations.

Table D2 - Continued

Date	Aircraft	Configuration	Comments
11 Dec 97	F/A-18D	FCL St 1: Wingtip Missile St 2: Clean St 3: Pylon St 4: FLIR pod St 5: Centerline Fuel Tank St 6: LST pod St 7: Pylon St 8: Clean St 9: Wingtip Missile	Departure during ACM engagement, high AOA and low airspeed. Entered Falling Leaf motion.
28 Feb 98	F/A-18C		Departure during defensive maneuvering
02 Mar 98	F/A-18D	FE + 2 Tanks St 1: Wingtip Missile St 2: Pylon St 3: Wing Fuel Tank St 4: Clean St 5: Clean St 6: Clean St 7: Wing Fuel Tank St 8: Pylon St 9: Clean	Departure during ACM engagement, low airspeed and high AOA (within NATOPS limits, but close to aft CG.)
08 Mar 99	F/A-18C		Departure during ACM engagement, high AOA and low airspeed
21 May 99	F/A-18A		Departure during ACM engagement, high AOA and low airspeed
09 Jul 99	F/A-18D		Departure during aggressive maneuvering
22 Dec 99	F/A-18C	FCL St 1: Clean St 2: Clean St 3: Pylon St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Pylon St 8: Clean St 9: Wingtip Missile	Leading Edge Flap Failure during ACM led to departure

Table D2 - Continued

Date	Aircraft	Configuration	Comments
20 Jun 00	F/A-18D	FCL St 1: Wingtip Missile St 2: Clean St 3: Pylon St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Pylon St 8: Clean St 9: Data Pod	Departure during BFM/ACM flight
07 Sep 00	F/A-18C	FCL St 1: Clean St 2: Clean St 3: Clean St 4: Clean St 5: Centerline Fuel Tank St 6: Clean St 7: Clean St 8: Clean St 9: Wingtip Missile	Supersonic high altitude departure, centerline tank and pylon separated from aircraft and damaged right wing
23 Jan 01	F/A-18C	16000 ft-lbs Asym St 1: Clean St 2: Pylon St 3: 1000 lb bomb St 4: FLIR pod St 5: Centerline Fuel Tank St 6: Fuselage Missile St 7: Wing Fuel Tank St 8: Clean St 9: Wingtip Missile	Maneuvering with lateral weight asymmetry (uncoordinated)

APPENDIX E – Early Two-Seat Hornet Departures

Table E1 – F/A-18B Fleet Departures 1983-1986 (ref 17)

Aircraft[1]	Year	FCC PROM[2]	Configuration	Condition/ Maneuver
TF-10	1983	V8.2.2	FE + Centerline Tank + Outboard Pylons + AIM-7 on station 8	Low Speed Barrel Roll at approximately 30 deg AOA (Lateral Weight Asymmetry was approx. 6000 ft-lbs)
TF-14	1983	V8.2.2	Centerline Tank + Inboard Pylons + Asymmetric Wing Tip AIM-9 Missile	Low Speed Barrel Roll at approximately 30 deg AOA (Lateral Weight Asymmetry was approx. 3600 ft-lbs)
TF-17	1984	V8.2.2	Centerline Tank (elliptical) + Inboard Pylons + 2 Wing Tip AIM-9 Missiles	Asymmetric Thrust
TF-7	1984	V5.3.1	Centerline Tank + Inboard Pylons	Low Speed Pushover
TF-7	1984	V5.3.1	Centerline Tank + Inboard Pylons	Rudder Roll at approximately Zero deg AOA
CF-2B	1985	V8.3.3	Centerline Tank	Rudder Roll at approximately 30 deg AOA
TF-29	1985	V8.3.3	Centerline Tank	Rudder Roll at approximately Zero deg AOA
TF-13	1986	V8.3.3	Centerline Tank + Inboard Pylons	Barrel Roll at approximately 30 deg AOA, Underneath to Over-the-Top

NOTES: 1. TF = Two seat aircraft, CF = Canadian Air Force two seat aircraft
2. FCC PROM = Flight Control Computer Programmable Read-Only Memory

VITA

Jessica Aileen Wilt was born in Leonardtown, Maryland on May 22, 1974. Her family resided in California, Maryland beginning in 1974 and remains there today. Jessica graduated from Great Mills High School in 1992. She graduated from Virginia Polytechnic Institute and State University in Blacksburg, Virginia with a Bachelor's Degree in Aerospace Engineering in 1996.

Jessica began her career with the Naval Air Systems Command in 1996 working for the Flight Dynamics Branch of the Air Vehicle Engineering Department's Aeromechanics division. She initially worked on the F/A-18E/F Engineering and Manufacturing Development program, including a work assignment rotation as a member of the integrated test team focusing on the high angle of attack and spin flight test efforts. Jessica was accepted to the United States Naval Test Pilot School in 1997 and began the fixed wing curriculum as an engineer with Class 114 in January of 1998. She completed the course logging over 130 flight hours in 18 different aircraft, graduating in December of 1998. Jessica returned to the Flight Dynamics branch and has been working flying qualities and stability and control issues for Navy fixed wing aircraft programs ever since. Programs have included X-31 Extremely Short Takeoff and Landing (ESTOL), F-14, E-2C, C-2, T-45, and the P-3. She is currently the lead Flight Dynamics engineer for the F/A-18A/B/C/D program.