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An Analysis of the High Angle of Attack Capabilities of the F/A-18 Hornet and Its Applicability In Modern Air Combat

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

Philip C. Pirozzi
May 1993

DISCLAIMER

The technical data included in this thesis are the result of actual flight test and flight simulator evaluations of the F/A-18 Hornet and the NASA F/A-18 High Angle of Attack Research Vehicle (HARV). All positive or negative comments regarding the F/A-18 are the sole opinion of the author and in no way represent the official position of Air Test and Evaluation Squadron Four, Commander, Operational Test and Evaluation Force or any branch of the United States Navy. Similarly, the recommended corrections to the deficiencies documented by the author should not be attributed to the aforementioned authorities and are for the sole purpose of fulfilling the requirements of this thesis.

ABSTRACT

The development of modern fighter tactics in the last twenty five years has changed dramatically as a result of the increase in the basic flying qualities and performance characteristics of current fighter aircraft and improvements in their associated air-to-air weapons systems. Designers have recently sought to give fighter aircraft the ability to fly at higher angles of attack and slower airspeeds than previous generations of fighter aircraft. These efforts were in response to U.S. fighter aircraft's inferiority in this region of the flight envelope as realized during aerial engagements over Vietnam in the 1960's and early 1970's.

Current fighter aircraft such as the F/A-18 Hornet enjoy excellent controllability up to 30 to 40 degrees angle of attack which is the region in which maximum lift is generated by the aircraft's wing. More recently however, efforts by government and industry have focused on increasing the angle of attack flight capabilities beyond the current 30 to 40 degree region. These efforts have produced aircraft employing technologies which enable controlled flight at stabilized angles of attack up to 70 degrees. The question which arises from these efforts is whether post stall flight can be applied to current fighter tactical doctrine.

This thesis will document the author's experiences in high AOA flight in the production Hornet and in the NASA Langley Research Center F-18 HARV simulation and attempt to present the advantages and disadvantges of post-stall flight within the context of current fighter tactics.

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ABBREVIATIONS and SYMBOLS

AB	Afterburner
ACM	Air Combat Maneuvering
ADC	Air Data Computer
AIM	Air Intercept Missile
Alpha (α)	Angle of Attack
AOA	Angle of Attack
AMRAAM	Advanced Medium Range Air-To-Air Missile
Beta (β)	Sideslipe Angle
BFM	Basic Fighter Maneuvers
CAS	Control Augmentation System
CIC	Close in Combat
CFD	Computational Fluid Dynamics
CG	Center of Gravity
C_L	Lift Coefficient
$C_{m\alpha}$	Pitching Moment Coefficient
CPU	Central Processing Unit
deg	degrees
DEL	Direct Electrical Link
EW	Electronic Warfare
ECM	Electronic Countermeasures
FCC	Flight Control Computer
FCS	Flight Control System
fpm	feet per minute
FSD	Full Scale Development
G (N_Z)	Normal Load Factor
GE	General Electric
HARV	High Angle of Attack Research Vehicle
HATP	High Angle of Attack Technology Program
HUD	Heads Up Display
HMS	Helmet Mounted Sight
INS	Inertial Navigation System
IR	Infrared
LEF	Leading Edge Flap
LEX	Leading Edge Extension
MAC	Mean Aerodynamic Chord
MC	Mission Computer
McAir	McDonnell Aircraft Company
MECH	Mechanical Reversion Mode
mm	millimeter
NASA	National Aeronautics and Space Administration
NATOPS	Naval Air Training and Operational Procedures Standardization
PID	Positive Identification
P_S	Specific Excess Power
PST	Post Stall Technology

RAM	Random Access Memory
RFCS	Research Flight Control System
SETP	Society of Experimental Test Pilots
SMS	Stores Management Set
SRM	Spin Recovery Mode
TEF	Trailing Edge Flaps
TVCS	Thrust Vectoring Control System
WVR	Within Visual Range
RWR	Radar Warning Receiver

1. INTRODUCTION

BACKGROUND

During the last twenty five years, designers of modern jet fighter aircraft have attempted to field operational fighters that have had a capability to fly at slow speeds at high angles of attack (AOA or α). This requirement to fly at slow speeds and at high angles of attack was identified by operational Navy and Air Force fighter pilots of the Vietnam era with combat experience in air combat maneuvering (ACM) within visual range (WVR). These pilots faced an adversary with an advantage in this slow flight arena, the MiG-21 Fishbed. U.S. pilots at this time were flying aircraft that lacked modern day aircraft's agility and possessed no real high AOA capabilities. Examples are the F-4 Phantom, the F-8 Crusader and the F-105 Thunderchief. The MiG-21 was capable of flying at slow speeds and generated impressive sustained and instantaneous turn rates for a fighter of that day. No U.S. fighter was as controllable at slow speeds as was the MiG-21. In response to this threat, pilots formulated high speed "hit and run" tactics that would not let themselves be drawn into slow speed, close-in engagements with the more agile MiG.

In modern day air combat in the close-in visual arena, an aircraft that possess good controllability and agility at high

AOA could have a decisive advantage over an opponent who has limitations to his aircraft's slow flight envelope and many times will be able to maneuver to advantage on the faster flying aircraft by using vertical maneuvers. Additionally, an aircraft that could fly at extremely high AOA as compared to current fighters, would be able to maneuver in various planes and about various aircraft axes in such a way as to turn through a greater number of degrees than an adversary could in the same amount of time. This would result in the more agile aircraft bringing it's nose and weapons systems to bear on an adversary before the adversary could do the same.

Out of all of the fighters in the free world today, the U.S. Navy and Marine Corps F/A-18 Hornet stands out as having the greatest slow speed, high AOA capabilities. The F/A-18 displays good controllability in all axes up to 35 to 40 degrees angle of attack and indicated airspeeds as slow as approximately 70 knots. This basic capability of the production Hornet has been improved upon in a National Aeronautics and Space Administration high angle of attack research program. This program has modified a production F-18's flight control system and added a vectored thrust system in an attempt to produce an airplane, the F/A-18 High Angle of Attach Research Vehicle (F/A-18 HARV), that can trim to 70 degrees angle of attack and demonstrate increased agility over the production airplane.

The objective of this paper is to introduce the reader to the high angle of attack capabilities of the production F/A-18 and NASA F/A-18 HARV and examine the applicability of this extreme high angle of attack capability to modern air warfare.

DESCRIPTION OF THE PRODUCTION F/A-18 HORNET

The F/A-18 Hornet is single seat, twin engine, supersonic, multi-mission aircraft built by the McDonnell Aircraft Corporation (McAir) in service with the United States Navy and Marine Corps, as well as numerous foreign customers. The aircraft has been in service with the fleet since 1982. The Hornet is a strike-fighter aircraft capable of performing both fighter and ground attack missions, designed in the 1970's to replace the aging F-4 Phantoms and A-7E Corsairs. The Hornet is an extremely maneuverable and agile aircraft possessing all of the excellent flying qualities and performance characteristics of a modern fighter.

The heart of the Hornet's weapons system is the multi-mode Hughes APG-65 radar which enables the Hornet to detect, track and employ weapons against both air and surface targets. The aircraft is capable of being configured with air-to-air and air-to-surface ordnance simultaneously which gives military commanders extreme flexibility in assigning the Hornet many diverse missions while airborne. The Hornet is

equipped with nine external carriage stations which can accommodate a wide variety of air and surface weapons. The airplane can carry up to three 330 gallon external fuel tanks.

The airplane is powered by two General Electric F-404 afterburning, turbofan engines providing an installed thrust of 10,700 lbs at military power and 16,000 lbs at maximum power (full afterburner) (NATOPS, 1). The airplane features include a low mounted, swept wing, dual vertical stabilizers, leading edge extension (LEX), retractable tricycle landing gear, nose wheel steering, stowable probe for in-flight refuelling and ejection seat. The twin vertical tails are canted outboard so that they are positioned in the vortex airflow created by the LEX at high AOA. The positioning of the tails in the LEX flow is one of the prime design characteristics which gives the Hornet excellent directional stability at high AOA. Figure 1 depicts the physical layout of the F/A-18.

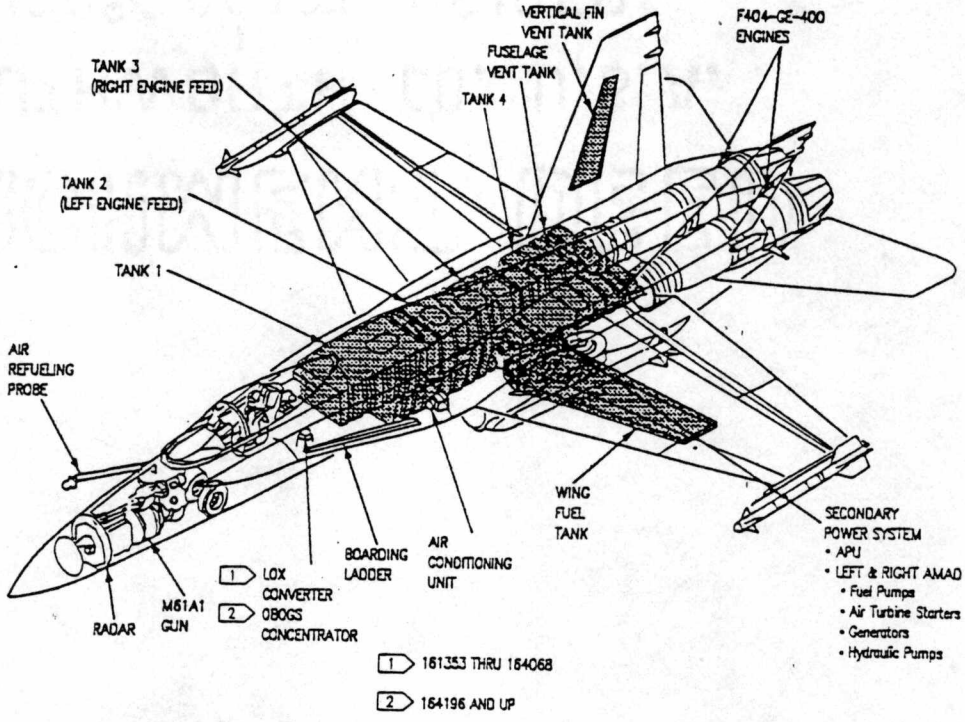


Figure 1. F/A-18 Physical Layout (NATOPS, 1)

The Hornet's primary flight controls consist of irreversible, hydraulically powered ailerons, leading and trailing edge flaps (cruise mode), horizontal stabilizers (stabilators) and rudders. Secondary flight controls include leading and trailing edge flaps (takeoff and landing mode) and a speedbrake mounted on the upper surface of the airplane between the twin vertical tails. Two complete, independent hydraulic power systems simultaneously operate the tandem actuators of the primary and secondary flight control system.

PRODUCTION F/A-18 FLIGHT CONTROL SYSTEM

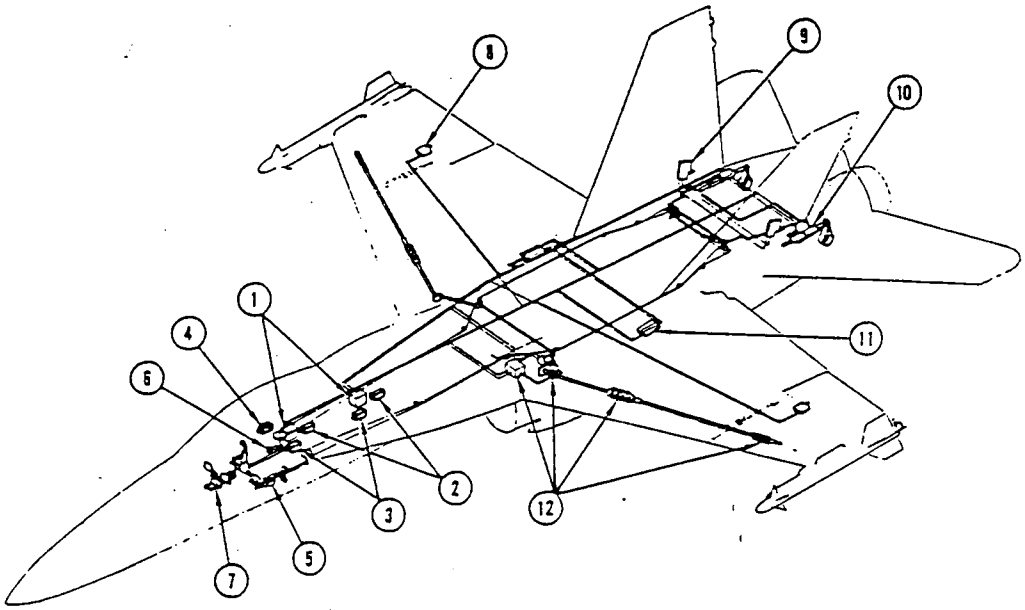
General

The F/A-18 primary flight control system (FCS) is a control augmentation system (CAS) which is accomplished through digital fly-by-wire techniques. All of the computations of the control laws are performed by two flight control computers (FCC A and B) consisting of a quad-redundant, four channel digital architecture. The FCC's are used in concert with redundant electrohydraulic servoactuators and analog sensors to provide a two failure operation of the primary flight controls.

A backup, digital open loop control of the horizontal stabilators, ailerons and rudders, referred to direct electrical link (DEL), is provided for in the event of three similar motion feedback sensor failures. The final backup mode of the flight control system is mechanical control (MECH) of the horizontal stabilator in the event of three digital processor failures or total electrical failure (MDC A7813, 2). MECH provides for longitudinal control with synchronous stabilator deflection as well as roll control with differential stabilator deflection.

Major System Components

The major components of the flight control system consist of the Flight Control Electronic Set, electrohydraulic servoactuators and the mechanical control system. Figure 2 depicts the locations of the main flight control system components.



1. Flight Control Computers
2. Rate Gyros
3. Accelerometers
4. Air Data Sensor
5. Pitch Stick Position Sensor/Feel Spring
6. Roll Stick Position Sensor/Feel Spring
7. Rudder Pedal Force Sensor
8. Aileron Actuator
9. Rudder Actuator
10. Stabilator Actuator
11. Trailing Edge Flap Actuator
12. Leading Edge Flap Actuation System
    - Hydraulic Drive Unit
    - Servovalve Assembly
    - Asymmetry Sensor

Figure 2. F/A-18 Flight Control System (MDC A7813, 2).

The Flight Control Electronic Set consists of two flight control computers (FCC A and B), two rate sensor assemblies containing rate gyros for all axes of motion, two accelerometers and air data pitot-static sensors. These major

components are integrated with other aircraft systems such as the hydraulic and electrical systems, cockpit controls and displays, Mission Computers 1 and 2 (MC 1 and 2), Stores Management Set (SMS), Air Data Computer (ADC), Inertial Navigation Set (INS), AOA sensors and the pitot-static system to provide for the aircraft's complete flight control capability. Figure 3 presents a functional diagram of the F/A-18 FCS.

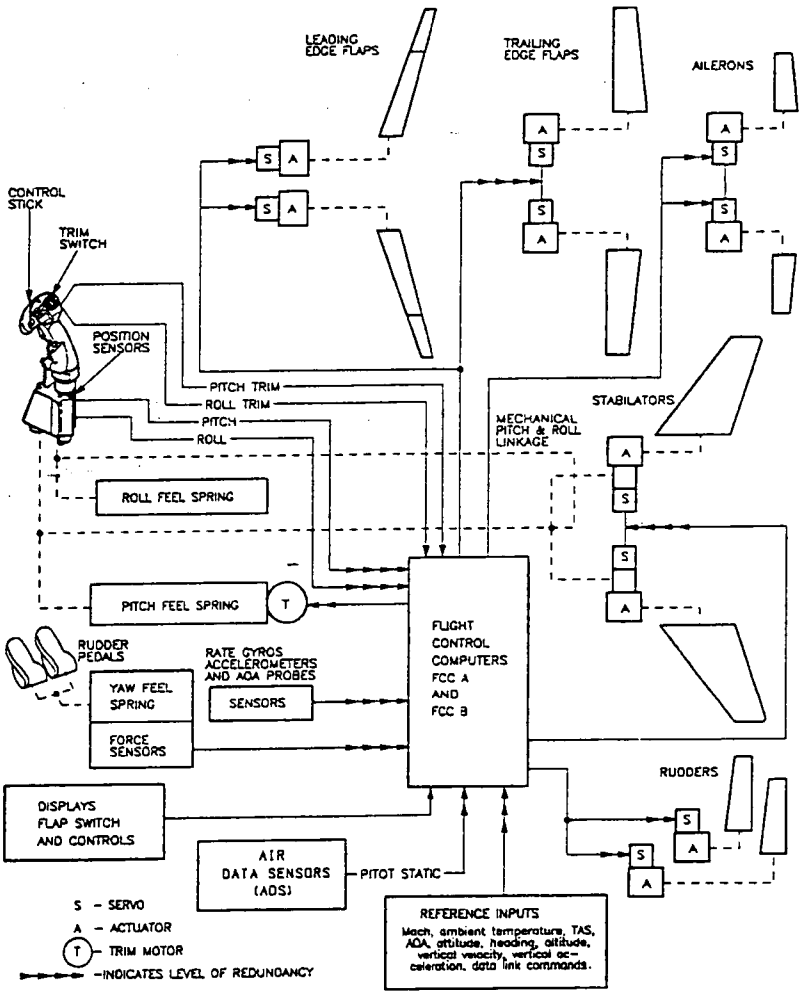


Figure 3. F/A-18 FCS Functional Diagram (NATOPS, 1).

Each flight control surface is driven by a fly-by-wire electrohydraulic servoactuator which is controlled by FCC A or B. If the digital fly-by-wire control has failed, the stabilator servoactuators respond to the mechanical control system in the MECH mode.

The CAS uses gain scheduling and cross axis interconnects to enhance flying qualities, protect the aircraft from overstresses and actively control structural mode oscillations (MDC A7813). AOA and air data computer (ADC) inputs are used for gain scheduling of the control system during various flight conditions. A spin recovery mode of the FCS is provided, for which an out of controlled flight or spin condition is sensed causing the control laws to be reconfigured to facilitate recovery. The spin recovery mode (SRM), when activated, displays proper spin recovery control input directions to the pilot in the form of a spin arrow displayed on both the left and right multi-function displays.

The FCS also provides for pilot relief modes including pitch and roll attitude hold, heading hold, barometric and radar altimeter hold and heading select. There are also coupled data link pilot relief modes which consist of automatic carrier landing mode and vector Link 4 data link mode.

Flight Control Surface Configuration and Limits

There are ten primary flight control surfaces which are part of left/right pairs: stabilators, rudders, ailerons, leading edge flaps (LEF) and trailing edge flaps (TEF). Longitudinal control is accomplished through symmetric deflection of the stabilators, LEF's and TEF's while lateral-directional control is accomplished through differential deflection of the stabilators, ailerons, leading and trailing edge flaps and synchronous deflection of the rudders. The maximum flight control surface deflections are as follows (NATOPS, 1):

Stabilator:	24 deg trailing edge up to 10.5 deg trailing edge down
Aileron:	25 deg trailing edge up to 45 deg trailing edge down
Rudder:	30 deg trailing edge left to 30 deg trailing edge right
TEF:	8 deg trailing edge up to 45 deg trailing edge down
LEF:	3 deg trailing up to 34 deg trailing edge down

PRODUCTION F/A-18 HIGH AOA PERFORMANCE

The F/A-18's high AOA flying qualities and performance are some of the finest ever developed for a fighter aircraft. The flight control system (FCS) was designed to provide controllability, stability and agility throughout the

aircraft's flight envelope. Stability is the measure of the aircraft's resistance to external forces causing disturbances from equilibrium flight conditions (NATOPS, 1). The FCS provides the Hornet pilot with a steady and predictable platform for accomplishing various weapons delivery tasks. Controllability is the measure of ease of changing the aircraft's attitude, flight path, velocity and acceleration. A high degree of controllability in all axes is needed to fly the aircraft aggressively throughout its flight envelope during mission maneuvers. Agility is more specifically, the measure of quickness and adeptness with which an aircraft changes its attitude about all of its axes. An aircraft displaying a high degree of agility could be able to position its nose, where the aircraft's main sensor and target tracking suite is housed, effortlessly in the direction of an enemy air or ground target.

Although the Hornet is not completely trouble free in the high AOA regime, it does display a greater degree of controllability, stability and agility than any other production fighter aircraft. Aircraft maneuvering performance and handling qualities are constant up to 22 deg AOA. Up to this point, a light but constant longitudinal stick force of 3.5 to 4.5 lbs per G is provided to the pilot and lateral stick inputs are very effective for roll control (NATOPS, 1). The FCS incorporates AOA feedback above 22 deg AOA. To

increase AOA above the 22 deg point, further aft stick displacement and significant aft stick forces must be applied above the amount of aft stick required for attaining 22 deg AOA. If the aft stick input is released, the FCS will command a nose down pitch moment until the AOA is reduced to below 22 deg where the FCS will again attempt to maintain 1 G, zero pitch rate flight. Above approximately 20 deg AOA, lateral stick inputs as primary roll control drops off in effectiveness quickly but is replaced with good roll control through the use of the rudders. From 20 to 30 deg AOA roll control power from the ailerons and differential stabilators continues to drop while rudder control remains constant (Behm, 3). Longitudinal control effectiveness and pitch damping are good up to 35 deg AOA. The high longitudinal and lateral-directional control power and good aircraft stability in this 20 to 30 deg AOA region provides the Hornet pilot with an effective platform to accomplish high gain tasks such as air-to-air guns tracking of an airborne target. Above 30 deg AOA, rudder control power begins to decrease until it is almost zero in the 40 deg AOA region. In this region, rudder control power is adequate for maintaining wings level flight but large sideslip excursions can occur which can be further aggravated if the aircraft is loaded with a centerline external fuel tank. These sideslip excursions can usually be countered with full deflection rudder inputs. Longitudinal control power for

gross pitch acquisition tasks above approximately 40 deg AOA is very good, but precise AOA control during high gain, gunsight tracking tasks is not possible. The maximum steady state AOA of 55 to 60 deg can be attained with full aft stick input. At these high AOA's, high rates of descent of up to 18,000 fpm cán occur while the aircraft exhibits small, stable pitch and roll oscillations. Above 55 deg AOA, non-divergent yaw rates of up to 35 deg/sec can develop that would engage the spin recovery mode if allowed to continue (NATOPS, 1). If a yaw rate developed in one direction when the aircraft is stabilized in 1 G flight in the 50 to 60 deg region, easing the longitudinal control stick forward of the aft stop should immediately reduce the AOA below 50 deg which should cease the yawing moment.

The Hornet's high AOA performance characteristics mean that up through the AOA for maximum lift (approximately 35 to 40 deg), the aircraft has pitch and roll control sufficient to allow the pilot to employ the aircraft in a visual engagement without fear of nose slices, snap rolls and other forms of departures from controlled flight (Behm, 3). It is also in this region where the benefit of increased maximum lift is realized from the LEX configuration. Figure 4 presents a lift coefficient (C_L) versus AOA curve depicting the AOA region of maximum lift as well as a comparison of maximum lift between

LEX on and off Hornet configurations.

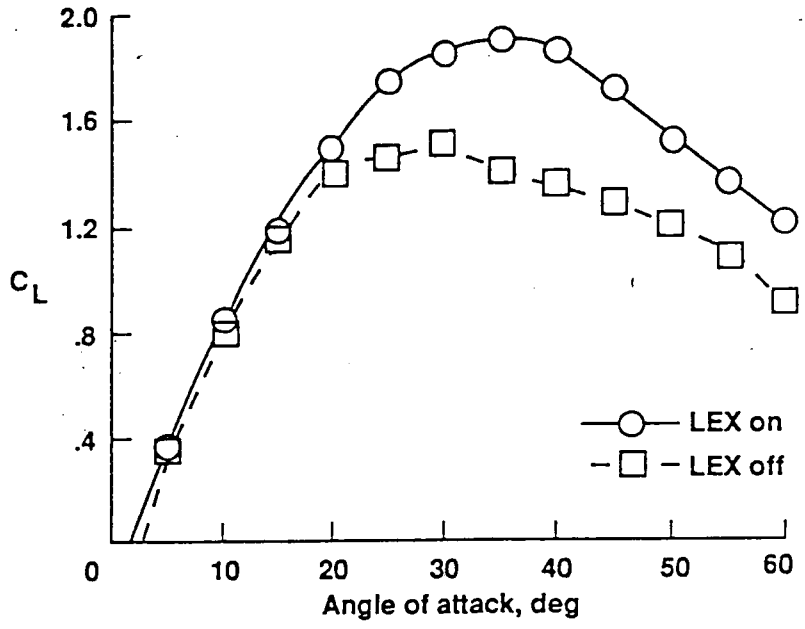


Figure 4. F/A-18 Lift vs. AOA, LEX On and Off (NASA, 5)

Longitudinal stick forces have been designed so that a maximum effort of one hand on the control stick will suffice in producing near maximum lift in the 35 to 45 deg AOA region. Sustained flight above 40 deg AOA requires the pilot to use two hands on the control stick due to high longitudinal stick forces.

McDonnel Douglas, identified three distinct spin modes and two distinct non-spin out-of-control modes. The spin modes were the low rate, oscillatory and flat modes. It is interesting to note that contractor flight testing was unable to achieve an inverted spin. The low rate spin mode exhibited yaw rates of 20 to 45 deg/sec with AOA reaching 50 to 60 degrees. The oscillatory spin mode exhibited yaw rates between 45 to 120 deg/sec with AOA reaching 60 to 80 degrees. The flat spin mode exhibited yaw rates greater that 120 deg/sec with AOA oscillating above 80 degrees (NASA CP-3137, 4). Recovery from all three spin modes was positive and quick. None of these spin modes have ever been experienced by the author in nearly ten years of flying the Hornet operationally. The closest the author has come to spinning a Hornet was the result of low energy, coupled departures from controlled flight, where AOA and yaw rates have sufficiently built up to the point at which the automatic mode of the spin recovery system had been briefly engaged.

The first of the non-spin, out-of-control modes was the AOA hang-up mode, where post-departure, AOA remains in the 45 to 55 deg region. This is the area in the Hornet's flight envelope where maximum nose-down pitching moment is at its minimum. The AOA hang-up mode was characterized by extremely slow response to forward stick inputs. The author, in addition to numerous fleet F/A-18 pilots, has encountered this

mode which is usually attributable to an aircraft center of gravity (CG) which is in the range of 28 to 29 percent mean aerodynamic chord (MAC). This aft CG position can be caused by fuel system transfer anomalies or certain external load configurations. This mode can be entered by causing a high pitch rate overshoot at lower airspeeds that results in the aircraft attaining an AOA between 45 to 60 degrees. As the CG moves aft of 29% MAC, the maximum nose-down pitching moment approaches zero (NASA CP-3137, 4). The second non-spin mode has been called the "falling leaf" mode. This mode exhibited large oscillations in sideslip (β), roll rate and pitch rate. Recovery from this mode requires full forward stick and a great deal of altitude and time. The author experienced this mode during a close-in-combat (CIC) visual engagement in a two seat, trainer version of the Hornet, which is more prone to directional departures from controlled flight. This mode from the pilot's perspective looks like he is sitting on a "falling leaf" in that the aircraft's nose attitude is near the horizon with a mild wing rock occurring of +/- 10 degrees while the aircraft is descending vertically with extremely high rates of descent.

2. F/A-18 HIGH ANGLE OF ATTACK TECHNOLOGY PROGRAM

General

In the early 1980's, NASA conceived the High Angle of Attack Technology Program (HATP) in order to provide in-flight validation of high AOA prediction and analysis methods for aircraft designers and to enable expanded high AOA maneuverability and flight envelope while improving agility at high AOA. The HATP was to be a NASA inter-center effort combining the resources of the NASA Langley, Lewis, Dryden, and Moffett research centers and flight activities. The HATP concentrated on several new Post Stall Technologies (PST) that were thought to offer the potential to avoid the problems that fighter aircraft designers had faced in the past when designing aircraft for maneuvering at high AOA. These technologies included full authority, digital fly-by-wire flight controls, high thrust to weight engines, single or multi axis thrust vectoring, forebody vortex control using mechanical or pneumatic methods, and computational fluid dynamics (CFD) (NASA CP-3137, 4).

The HATP has been carried out in three phases. Phase one centered on an aerodynamic and handling qualities characterization of the production or baseline F-18. Phase two centered on the design and implementation of a thrust vectoring system, expanded flight envelope clearance and

agility and aerodynamic research in the expanded envelope. Phase three will concentrate on advanced aerodynamic controls and maneuver management concepts (NASA CP-3137, 4).

F-18 HIGH ANGLE OF ATTACK RESEARCH VEHICLE

A pre-production F/A-18 which was used by the Navy and McAir for full scale development (FSD) spin and out-of-control flight testing was lent to NASA to become the High Angle of Attack Research Vehicle (HARV). The HARV had been modified by NASA to incorporate a multi-axis, thrust vectoring control system for enhanced maneuverability in the post-stall region. The HARV retained the special in-flight instrumentation package and spin recovery parachute that was used during FSD with the Navy. The Hornet's wing tip missile rails were replaced with instrumentation pods. Five video cameras were installed along with special smoke exhaust ports used for flow visualization. The HARV is noticeably heavier than production F/A-18's primarily due to the thrust vectoring system and the needed counter-weight ballast that was placed in the forward section of the aircraft for CG control. Figure 5 shows the F/A-18 HARV with multi-axis thrust vectoring system installed.



Figure 5. The F/A-18 HARV with Thrust Vectoring Installed. (NASA CP-3137, 4)

F-18 HARV THRUST VECTORING AND RESEARCH FLIGHT CONTROL SYSTEM

The heart of the HARV that differentiates it from fleet F/A-18's is the addition of the Thrust Vectoring Control System (TVCS) and the Research Flight Control System (RFCS). The design philosophy of the RFCS was to develop a system capable of performing both research tasks as well as maneuvers representative of operational air combat at high AOA and slow speeds. The RFCS was designed to be fail-safe with positive reversion to the basic Hornet flight control system in the event of RFCS failure (NASA 104232, 6).

The TVCS was installed in the HARV to provide increased control power essential for stability augmentation and departure resistance in all axes of flight and increased agility in the stall and post-stall region. The TVCS included

the addition of three thrust vectoring vanes located about the center line of each engine and removing the divergent portion of the engine exhaust nozzle and nozzle flaps of the Hornet's GE F-404 engines. Figure 6 depicts the F/A-18 HARV thrust vectoring system.

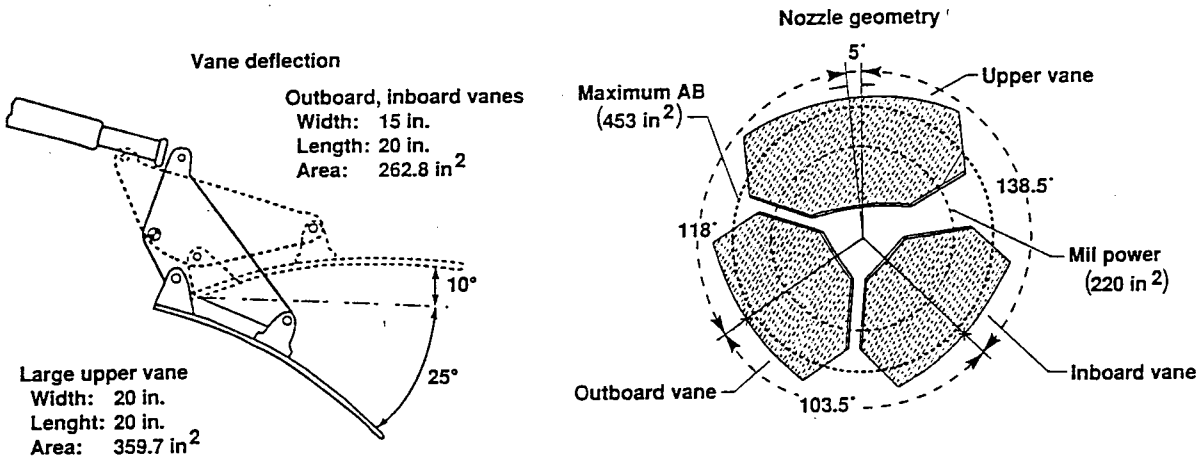


Figure 6. HARV Thrust Vectoring System (NASA 104232, 6)

The HARV flight control design incorporates a dual redundant RFCS in addition to the quad-redundant production F/A-18 FCS. The RFCS provides an embedded research computer that can be engaged by the pilot to exercise full authority of the thrust vectoring system. The production Hornet FCS is used for normal flight and takeoff and landing with the TVCS disengaged. The integration of the RFCS and the production Hornet FCS is shown in figure 7.

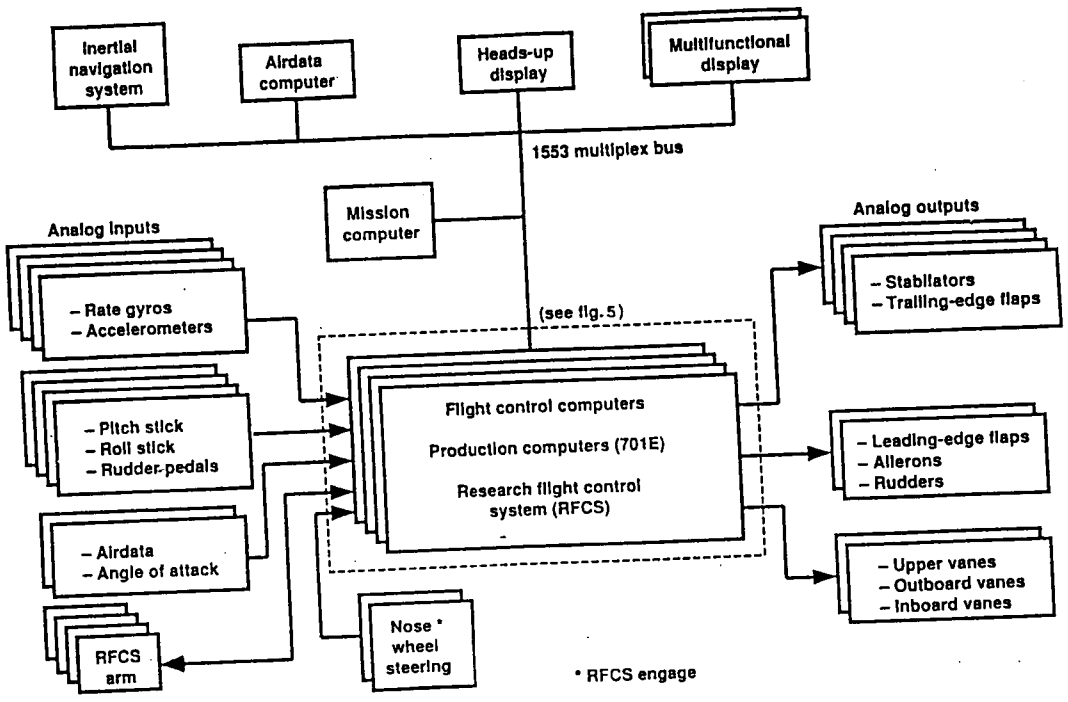


Figure 7. HARV RFCS Integration (NASA CP-3137, 4)

The RFCS processor resides in the same box as the production FCS and operates in parallel with the basic FCS. The RFCS control laws are programmed in ADA, and are independent of the production FCS control laws. The functionality of the basic control laws was left unchanged except when it was needed to incorporate RFCS input-output. All communication to and from the RFCS is handled by the production FCS through dual port random access memory (RAM) to minimize communication delays and isolate the production FCS from any RFCS failures (NASA CP-3149, 5). Sensor inputs, air data parameters and pilot inputs are input to the basic FCS and are compared in the input signal management section of the basic FCS central processor unit (CPU). After signal comparison, a signal is sent to the RFCS and basic control laws where surface position

commands are computed for the basic control surfaces and the thrust vectoring vanes. The output signal management of the basic Hornet FCS was modified to maintain the vanes in a retracted, fixed position of -10 degrees (NASA, 6).

The RFCS longitudinal control is an AOA command system using pilot commanded stick position, AOA, pitch rate and inertial coupling feedback. Inertial coupling feedbacks are employed to counteract undesirable cross-axis motions generated at high angular rates. Stabilator and pitch thrust vectoring are used for rapid pitch commands, but steady-state vectoring is washed out to zero if the stabilator is not saturated. Trimmed flight above 55 deg AOA requires a non-zero, steady-state, pitch thrust vectoring due to stabilator saturation (NASA, 6).

The lateral-directional control laws use stability axis roll and yaw rate, lateral acceleration, sideslip rate and inertial coupling as feedback signals. Aileron, rudder, differential stabilator, differential TEF and yaw vectoring are used for stabilization, coordination of maneuvers and maneuvering flight (NASA, 6).

F-18 HARV HIGH AOA PERFORMANCE

As mentioned in a previous section, the maximum steady-state AOA the production F/A-18 can achieve is approximately 55 degrees. Very early in the HARV flight test program during

phase two (TVCS operations), the F/A-18 HARV achieved one of it's design goals of controlled flight at a sustained AOA of 70 degrees. Figure 8 shows the F/A-18 HARV AOA and sideslip envelopes with the TVCS engaged.

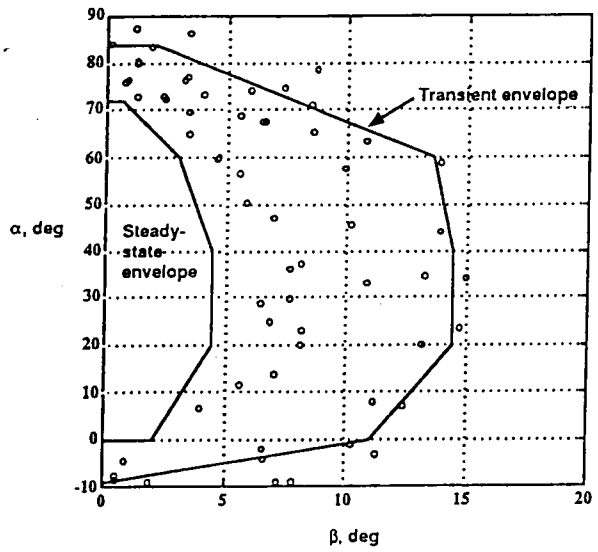


Figure 8. HARV AOA and Sideslip Envelope with TVCS (NASA CP-3137, 4)

The Thrust Vectoring Control System allows steady-state flight at an AOA of 70 deg with very little or no later stick inputs. Approximately 60 to 65 deg is the highest useable AOA range, in that this is the range at which lateral stick inputs do not cause significant pitch down moments (NASA 3137, 4). The highest steady-state side-slip is approximately 4 degrees. As figure 8 depicts, the transient AOA and side-slip envelopes are significantly larger than the steady-state envelopes and therefore become important in the applications of this post-

stall technology to air combat tactics. Transient AOA's and side-slips up to 80 and 14 degrees respectively, can be achieved.

The production F/A-18 experiences wing rock in the 35 to 50 deg AOA region. Aircraft motion is characterized by low frequency, moderate amplitude perturbations in angle of bank and side-slip. Figure 9 shows a comparison of wing rock at 40 deg AOA between the HARV with RFCS/TVCS off and on.

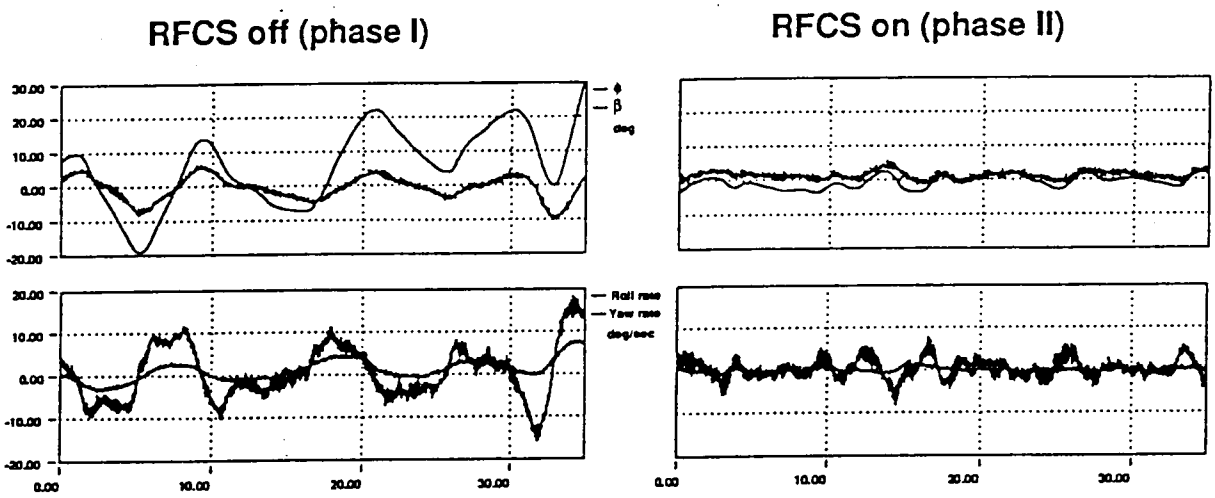


Figure 9. HARV Wing Rock with RFCS/TVCS On/Off (NASA CP-3137, 4)

The RFCS off data are representative of classic Hornet wing rock as experienced by the author and numerous fleet pilots. The RFCS off maneuver was flown without any attempt to counter the wing rock oscillations with opposing lateral stick inputs. The RFCS on maneuver was also flown without any lateral control inputs, but it must be noted however, that the RFCS on maneuver did not require any lateral stick inputs. Pilot

comments during these maneuvers indicate that the aircraft was "easy to control in the wing rock region" and that "no evidence of oscillations in bank angle and sideslip" were present (NASA CP-3137, 4).

Maximum roll rate capability was greatly increased at high AOA with the RFCS/TVCS engaged. Figure 10 shows a plot of roll rate (non-dimensional) versus AOA.

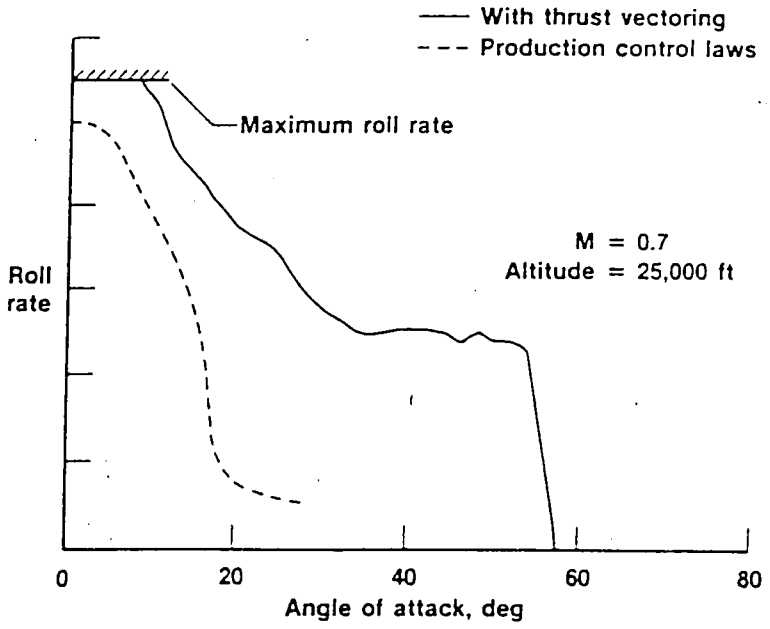


Figure 10. Maximum Roll Rate (SETP, 7)

As figure 10 shows, the maximum roll rate capability of the HARV with RFCS on is greatly increased throughout the range of AOA from 15 to 55 degrees over the production Hornet control laws. The production Hornet suffers a degradation of roll rate capability at moderate AOA's in the 15 to 35 degree region, which is restored with the HARV RFCS configuration.

Benefits of high AOA maneuverability have been demonstrated not only at AOA's at or above maximum lift, but also at moderate AOA's.

Equally as important as nose up pitching capabilities and sustained high AOA flight, is the ability of an aircraft to generate sufficient nose down pitching moments to recover from a sustained or transient high AOA maneuver. The production F/A-18 suffers from a weakness in nose down pitch control power while in the 30 to 50 deg AOA region. Figure 11 shows a comparison of the nose down authority at high AOA between the production F/A-18 and the HARV with RFCS engaged.

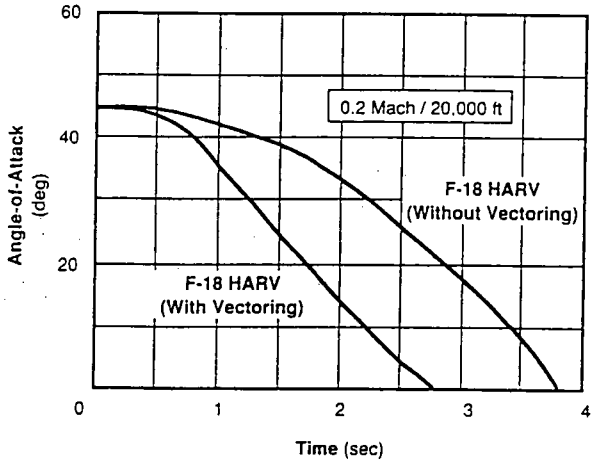


Figure 11. Nose Down Authority Comparison (Rietz, 8)

Throughout most of the AOA envelope, the RFCS HARV has a distinct advantage over the production F/A-18 in nose down pitching moment. The pitch thrust vectoring provides the necessary longitudinal control power to quickly get the nose of the aircraft back down from a high AOA maneuver. This

increased nose down pitching capability is of critical importance during air combat maneuvering (ACM) at high AOA's. The author has experienced transient and sustained flight in the production Hornet at the 35 to 45 deg region during ACM, and found it very difficult to rapidly "unload" the Hornet and reduce the AOA in order to point and shoot an airborne adversary that might have been made to overshoot during a high AOA maneuver.

Additional comments of pilots flying the HARV have included that once engaged, the RFCS/TVCS is transparent to the pilot and that it provides "near carefree maneuverability to the Hornet" (McAir, 8). With RFCS engaged, the aircraft (and simulation) can be flown in an aggressive and precise manner such that AOA can be easily maintained to within 1 deg of AOA in a wings level attitude. Full stick pitching maneuvers have resulted in pitch rates of 55 deg per second and pitch accelerations of 80 deg per second^2. During the flight test program, 360 deg, full lateral stick deflection, velocity vector rolls have been accomplished at 65 deg AOA. At lower AOA, a lateral stick input produces a rolling moment about the longitudinal axis of the aircraft. However, once an aircraft is operating in the high AOA regime, lateral stick inputs produce a rolling moment about the wind axis or velocity vector of the aircraft which is offset (depressed)

from the longitudinal axis of the aircraft in the amount of degrees of AOA that the aircraft is experiencing. This velocity vector roll appears to the pilot as a yawing motion that looks like a heading change rather than a bank angle change. This maneuver has very important applications in air combat as pilots of aircraft visually engaged with an enemy are concerned with turning or pitching his aircraft's nose through the greatest heading change in the shortest amount of time.

The final phase of the HARV flight test program, phase 3, will attempt to improve aircraft agility and control at high AOA by exerting forces on the forward section, or forebody, of the aircraft. Two techniques that are currently planned for investigation during flight test are the use of forebody mounted strakes; while the other involves the blowing of a sheet of high velocity air through a thin slot along the forebody of the aircraft. Figure 12 shows four possible methods of increasing yaw control at high AOA.

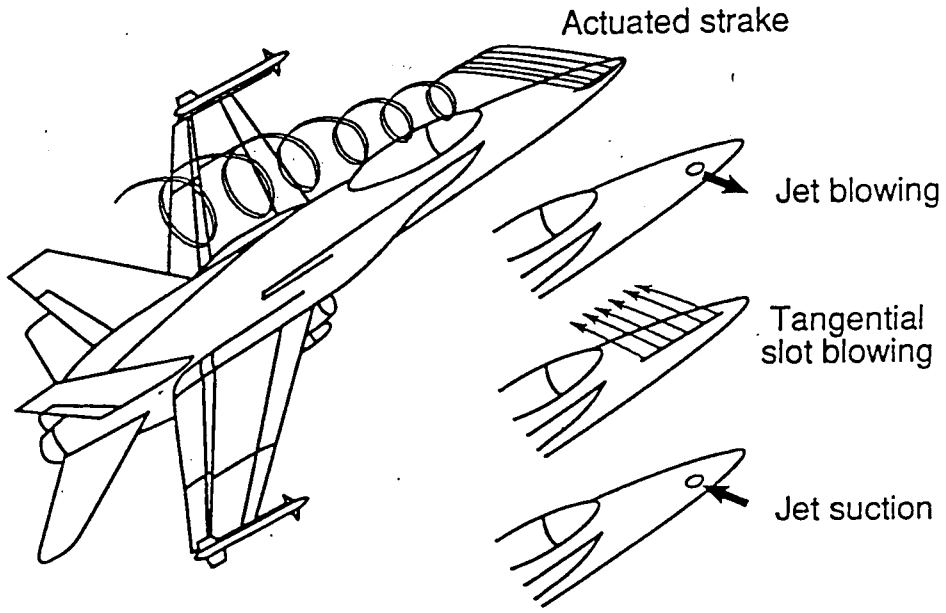


Figure 12. Forebody Flow Control Methods (NASA CP-3137, 4)

In each of the methods of controlling the flow around the forebody of an aircraft presented in figure 12, an attempt is made to produce a side force on the forebody which would result in a yawing moment in the opposite direction. It is thought that the control of forebody flow and generation of forebody forces will produce greater yaw control power at high AOA and therefore greater agility and maneuverability.

3. HIGH AOA CAPABILITIES APPLIED TO AIR COMBAT

Air Combat Phases of Engagement

Analysis of modern fighter tactical doctrine can be separated into two, distinct categories within which, there are many sub-categories. The two categories or zones of engagement defining the requirements of a fighter aircraft are the beyond visual range (BVR) and within visual range (WVR) zones.

The long range, BVR engagement has many phases which include; search, detect, sort, track, and target enemy aircraft. The predominating factor is an aircraft's ability to successfully engage and kill an adversary in the BVR scenario is the fighter's weapons control system and avionics suite. Current fighters must have the following attributes to succeed in the BVR engagement; long range radar and associated sensors, positive identification (PID) systems, radar or electronic warfare (EW) warning systems, electronic counter-measures (ECM) suites and medium and long range, all-aspect, look-down, shoot-down radar and infrared (IR) missiles. The fighter must also have an airframe and engine combination which allows it to fly at supersonic speeds and generate high normal load factors (G's) in order to quickly change flight paths during forward hemisphere offensive maneuvers as well as during all aspect radar and IR missile defense maneuvers.

It would be valuable at this point to differentiate between maneuverability and agility. Maneuverability is the ability of an aircraft to change the direction of it's velocity vector, or flight path and therefore change it's position in space. Agility in contrast, is the ability of an aircraft to change it's attitude about one or all of it's axes without regard to it's velocity vector or flight path.

It is now quite apparent that nowhere in the BVR engagement zone is there a requirement for a highly agile fighter aircraft that is capable of post-stall maneuvering at high AOA flight. The author concludes that high AOA capabilities can and should only be exploited by a fighter in the WVR zone of air combat.

The WVR engagement zone encompasses two sub-zones, the transition zone and the close-in-combat (CIC) zone. The transition phase between the beginning of the WVR zone and the close-in combat zone requires the successful fighter to possess the following attributes; small visual signature, point and shoot weapons system and missile, superior specific excess power (P_s) and superior maneuverability (Whiteford, 9).

The CIC zone requires the fighter to possess the following attributes; good sustained maximum turn performance, superior maneuverability, superior thrust-to-weight ratio, a short range launch and leave missile, a gun, and superior

agility (Whiteford, 9). The objective of a fighter in the CIC zone is to kill, as quickly as possible, an adversary aircraft by pointing it's nose at the adversary and employing a radar or IR missile or gun. The need for an expeditious kill is especially amplified if the fighter is in an arena where there are multiple and possibly unseen adversaries.

ANALYSIS OF HIGH AOA IN WVR ENGAGEMENTS

General

Assuming two conventional fighters survive the BVR engagement and meet each other 180 degrees out of phase at a merge (nose to nose), they usually turn toward each other employing a nose low, energy sustaining turn, flown at the airspeed at which the fighter can generate it's maximum sustained turn rate, also known as the aircraft's corner speed. As the fighters meet at this 180 deg pass, they have the option of turning in the same or opposite directions. The various geometries which could result are shown in figures 13 and 14.

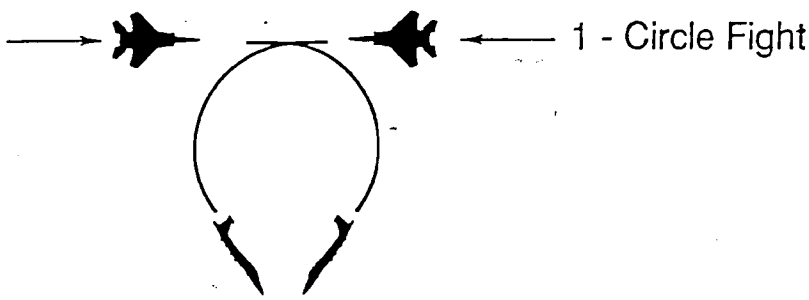


Figure 13. 1 Circle Fight (Whiteford, 10)

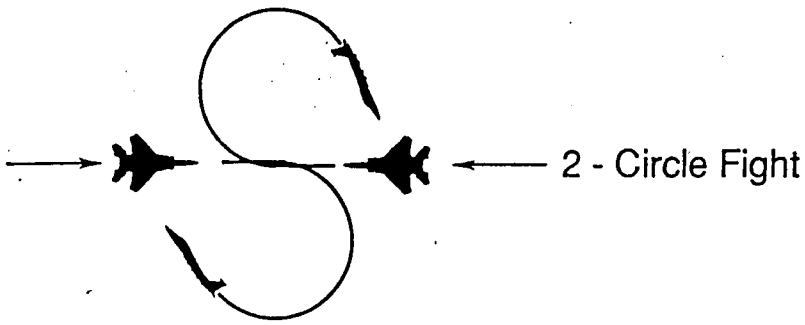


Figure 14. 2 Circle Fight (Whiteford, 10)

If the fighters turn in the same direction they would generate a two circle geometry as opposed to a one circle geometry if they turned in opposite directions. The outcome of these engagements is a result of the separation between the fighters, the maneuverability and energy management of the fighters, and the weapons systems and comparative agility of the fighters. Generally, the aircraft that is endowed with the better sustained turn rate will employ a rate fight and eventually turn through a greater heading change in a given period of time than his adversary and will therefore bring his nose and lethal weapons systems to bear on his adversary before the adversary can do the same. As figure 15 shows, an aircraft in a one circle fight might be able to bring it's nose to bear more quickly than the adversary, but if there is not sufficient separation between the aircraft such that the adversary is outside the minimum range of his weapons system,

he might not have a viable weapons solution on his adversary.

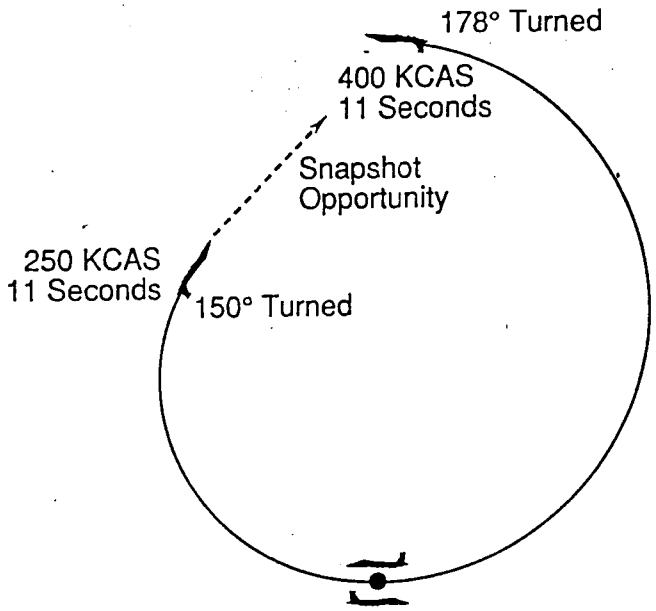


Figure 15. 1 Circle Fight Geometry (Whiteford, 10)

Turn rate is normally considered by fighter pilots as the most important attribute of maneuverability in the CIC. The contributions of a small turn radius is less well understood, but as important to the outcome of the fight. The fighter flying slower, with a smaller turn radius is able to achieve an offensive position sooner, thereby possibly employing his gun in a snap-shot. Figure 16 shows a comparison of the turn radii of two fighters in a one circle fight.

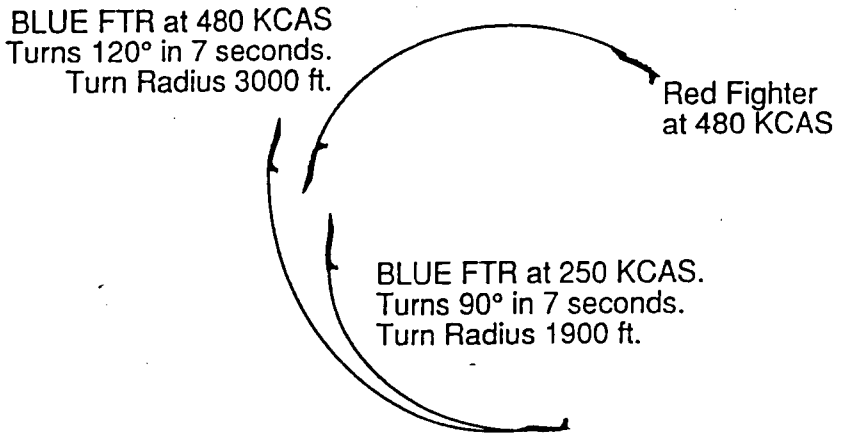


Figure 16. Turn Radius in 1 Circle Fight (Whiteford, 10)

It is in this arena of comparative turn radii, where the high AOA capabilities of the HARV with thrust vectoring can be successfully employed. The primary advantage of a PST fighter is it's ability to maneuver inside the minimum turn radius of his adversary and to enjoy a very high nose pointing rates in addition to high roll rates at an extremely high AOA. Once inside the minimum turn radius arc of the adversary, the adversary cannot point at the PST fighter.

Pitch Rate Reserve

If a fighter is turning at it's maximum rate (maximum lift coefficient), it usually can increase AOA by 5 to 10 degrees. This increase in AOA and associated pitch attitude will cause a decrease in the fighter's energy state and turn

rate but can be the extra pitch rate needed to cause an overshoot of an attacking adversary or give the fighter the ability to point and position the nose for a snap-gun shot. If a fighter has pitch thrust vectoring such as the HARV, this pitch rate reserve becomes an extremely important tactical option (Whiteford, 9). Figure 17 demonstrates the pitch rate reserve and it's employment.

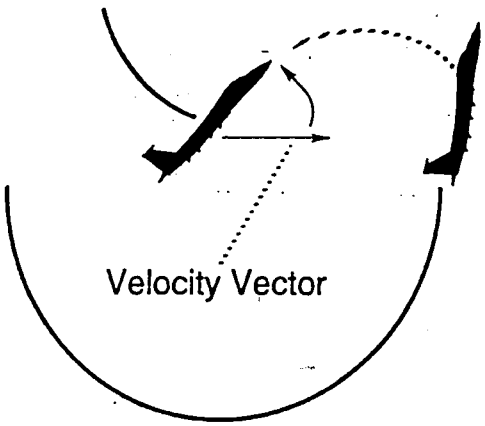


Figure 17. Pitch Rate Reserve (Whiteford, 10)

As can be seen in figure 17, the offensive fighter to the left increases pitch rate by increasing AOA to the 50 to 70 deg region and is in a position to take advantage of a gun shot opportunity since the conventional adversary cannot accomplish this PST maneuver.

Hammerhead Turn

The hammerhead turn illustrated in figure 18 is a maneuver in which the PST fighter uses pitch thrust vectoring

to initiate and recover from the turn.

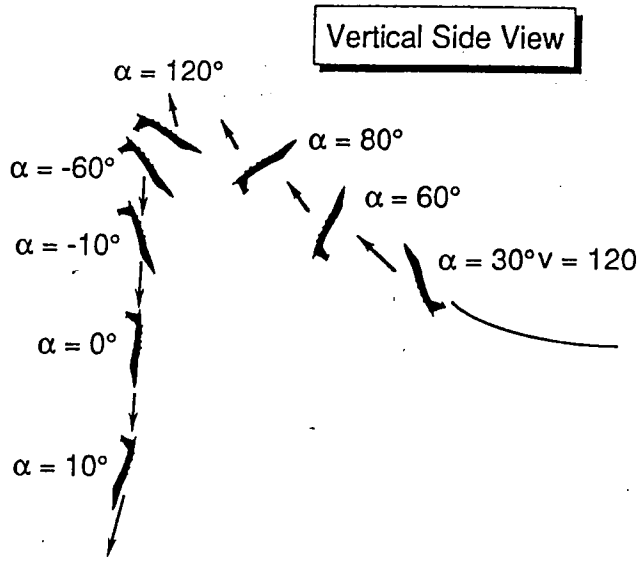


Figure 18. High AOA Hammerhead Turn (Whiteford, 9)

The fighter is rapidly maneuvered into the vertical, increasing both pitch rate and AOA. The fighter then continues to rate the nose through the vertical until it is pointing straight down. This hammerhead turn could be employed to very quickly reverse the PST fighter's flight path in the vertical against an adversary that has extended in a vertical, nose low turn in order to gain weapons separation.

J Turn

The J-turn is essentially a hammerhead turn with a 180 deg roll which accomplishes the heading change instead of a continuous pull through the vertical. Figure 19 illustrates the J-turn.

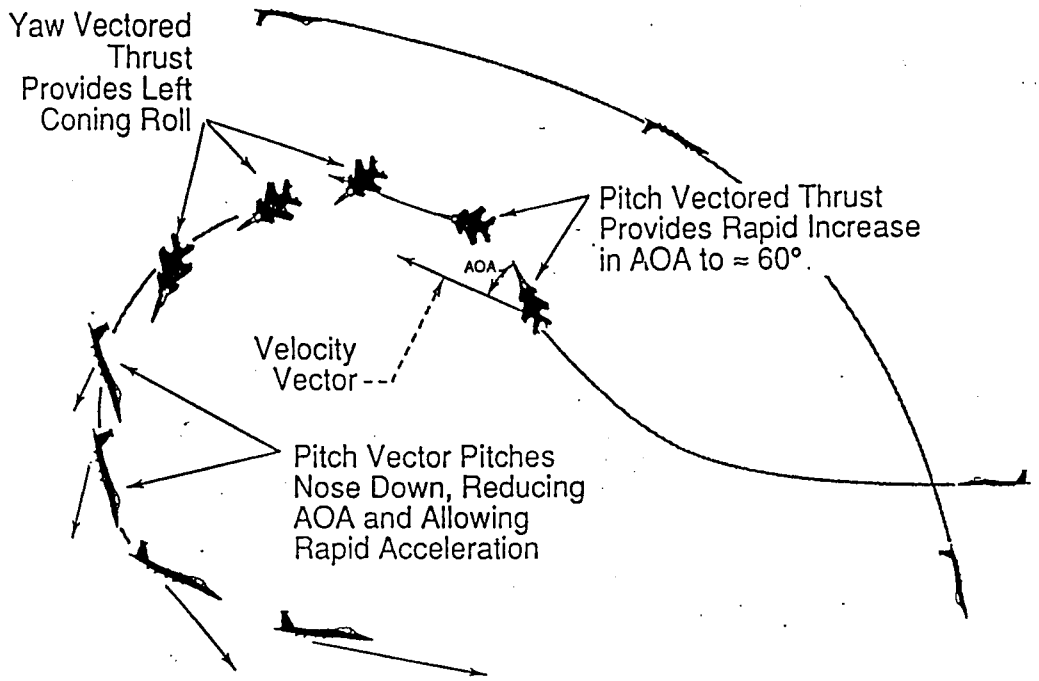


Figure 19. J-Turn (NASA CP-3149, 5)

The J-Turn is commenced by a rapid pitch rate to 50 to 80 deg AOA, followed by a roll about the fighter's velocity vector. The author executed many J-Turns while flying the Langley HARV simulation and found the maneuver easy to accomplish. Full lateral stick inputs after attaining 50 to 80 deg AOA produced a crisp, RFCS thrust vectoring, conical roll about the velocity vector. During numerous simulator engagements, the HARV employing the J-turn completed a 180 deg heading reversal well before the simulator adversary (a production Hornet) was able to complete the same turn.

Helicopter Gun Attack

The Helicopter Gun Attack illustrated in figure 20 is

primarily a guns tracking maneuver but can also be used to bring the PST fighter's nose across the horizon to aim and lock an IR missile to an adversary that has a high line of sight rate change with respect to the PST fighter but is outside of gun employment range.

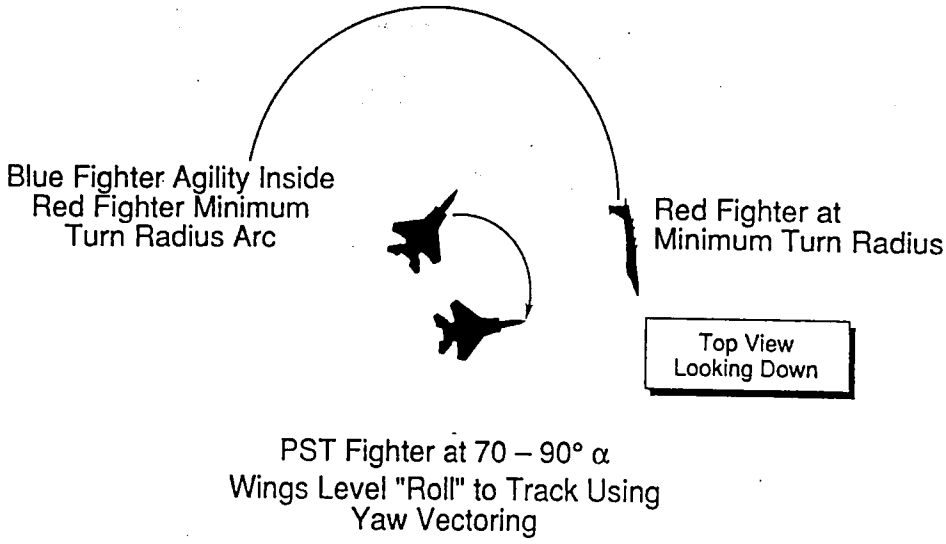


Figure 20. Helicopter Gun Attack (NASA CP-3149, 5)

The maneuver derives its name from the fact that the PST fighter when employing this maneuver, tracks across the horizon, in a wings level yawing motion, in the manner that a helicopter would accomplish a "pedal turn". The maneuver is entered by increasing pitch rate to establish a very high AOA while commanding lateral control inputs to generate a velocity vector roll. The velocity vector roll at very high AOA will appear as a yawing motion, during which an adversary can be

tracked for a gun shot or missile launch.

General PST Maneuvering Considerations

Both the Hammerhead Turn and the J-Turn are PST turns or reversals that are used as lead turns in order to gain a positional advantage over an adversary which can then be exploited for a missile or gun attack. The Helicopter Gun Attack and the Pitch Rate Reserve are PST maneuvers which exploit a positional advantage that has already been achieved.

PST turns usually begin with the PST fighter pulling up into the vertical in order to trade some airspeed for altitude and decelerate to an airspeed range that is optimized for a PST reversal. Since PST turns were created for the slow speed regime, entry into a PST at too high of an airspeed will degrade turning performance. The general philosophy with which PST maneuvers should be employed should be one in which the PST fighter transitions rapidly to high AOA, turns in the shortest direction to the adversary, shoots and then recovers from the PST maneuver by unloading the aircraft at zero G to facilitate rapid re-acceleration.

During the author's HARV simulated engagements as well as interviews with pilots of the HARV, PST maneuvers appeared to be most beneficial when the adversary was below the PST fighter. Conventional, basic fighter maneuvers (BFM) were employed to force the adversary into a vertical fight after

which the PST fighter could then employ a J-Turn or Hammerhead Turn. After completion of the PST maneuver, the PST fighter would be in a nose low attitude which would facilitate rapid regaining of energy lost during the maneuver. This was in contrast to PST maneuvers initiated in a nose low attitude which ended in a nose high attitude from which the PST fighter would have a more difficult time of regaining lost energy. Generally, PST maneuvers were most successful when the PST fighter forced a one circle engagement after the initial merge, thereby taking advantage of an expected smaller turn radius and not giving the adversary weapons separation range.

Both the Pitch Rate Reserve maneuver and the Hammerhead Turn were very successful in forcing an overshoot of an adversary who was offensive and within guns employment range of the PST fighter. However, if the previously mentioned PST maneuvers were initiated when the adversary was farther away than lethal gun range, as with any "last ditch" guns defense maneuver, the PST maneuver was unsuccessful in forcing an overshoot and "flushing out" the adversary.

Disadvantages of PST Maneuvers

A general axiom among fighter pilots executing current tactics is that a visual engagement is the result of a poorly executed BVR radar intercept. In other words, it is much better to detect, identify and kill an adversary at BVR ranges

than it is to get "tangled up" in a "phone booth" during a WVR engagement with one or more adversaries. It has been shown throughout the development of sophisticated, forward quarter radar tactics as well as CIC tactics that as the time a fighter spends in an engagement (time-to-kill) increases, the probability that he will be killed by an unseen, un-targeted adversary increases. The fact that a fighter is in a position to employ a PST maneuver is in itself, a very serious situation since the fighter's adversaries survived the BVR phase of engagement.

A general disadvantage of any PST maneuver lies in the fact that the PST fighter during any PST maneuver has probably selected full afterburner and presents a very high IR signature for an unseen adversary. The geometry of a properly executed PST maneuver places the PST fighter in a position above the adversary and gives the adversary (and his IR missile) against which the maneuver is being performed, as well as other adversaries, a clear, "blue sky", look-up aspect towards the PST fighter's engine exhaust which is free from ground IR clutter. The PST fighter has also visually separated his aircraft from the normal horizontal planes of BFM and would be more easily acquired visually, than a fighter turning nose low against the earth as a background.

Another disadvantage of PST maneuvers is that unlike other basic fighter maneuvers, PST maneuvers force the fighter

into a slow speed regime in which maneuverability (ability to change flight path) has been sacrificed for agility (ability to change attitude about velocity vector). This is a serious situation since all aspect missile defense maneuvers require the fighter to possess a high energy state (airspeed and altitude) to defeat an observed missile guiding to him by the execution of properly timed, very high G maneuvers which cause changes in the fighter's flight path into the missile, to force a missile overshoot. The PST fighter when executing a high AOA maneuver will be very vulnerable to missile attack and will be unable to execute a missile defense maneuver.

Weapons Employment in High AOA Regime

The employment of weapons during high AOA flight places demands on a missile that exceeds their current capabilities. A current limitation of modern air-to-air missiles lies in their inability to be successfully locked onto, and launched at targets from an aircarft in a high AOA environment. This is primarily due to the fact that current missiles do not possess a seeker head gimbal assembly that will allow the missile to be slewed to high off-boresight angles (after seeker head lock-on). A high off-boresight angle gimbal is required of a missile to be launched at high AOA since a missile tends to fair into the relative wind after leaving the aircraft's missile rails. Current missiles would "break lock"

on a target if launched at high AOA as they faired into the relative wind.

Another limitation of current missile systems is their inability to execute very high G, high angle turns immediately after launch. Since many PST maneuvers are attempting to place a fighter inside the turn radius of an adversary, the fighter must be able to shoot a missile at shorter ranges and with higher line of sight rates than current WVR tactics dictate. PST fighters therefore require a missile with thrust vectoring control capable of turning 90 deg off the missile rail, to fully take advantage of the small turn radii the PST maneuvers produce.

During simulated CIC engagements, the author executed numerous PST maneuvers which resulted in an offensive position pointing at the adversary while at 50 to 70 deg AOA and being unable to launch a missile due to the previously mentioned missile limitations. The pilot of a PST fighter in this position would have to achieve seeker head lock-on while pointing at the target at high AOA and then reduce the AOA to a level where he could then fire a missile. This would give the adversary time to counter the PST fighter's offensive position.

The same problem that affects missile employment at high AOA plagues gun employment at high AOA. The current 20mm guns employed by fighter aircraft fire rounds at too low of a

muzzle velocity which results in the rounds experiencing a large "tragectory drop" as they exit the gun barrel at high AOA. This requires the fighter to pull too much of a "lead" solution to the target for current gun systems. Additionally, current lead computing gunsights and heads up displays (HUD) cannot display proper firing solutions at high AOA due to display and gunsight computer limitations. Employment of higher velocity guns would allow the pilot of a PST fighter to more accurately shoot an adversary at high AOA and at longer ranges than current fighter gun systems.

Another requirement of a fighter operating in the high AOA regime is that of possessing a fast, short time of flight missile. Figure 21 illustrates the exchange of missiles between a PST fighter and a conventional adversary in a two circle fight.

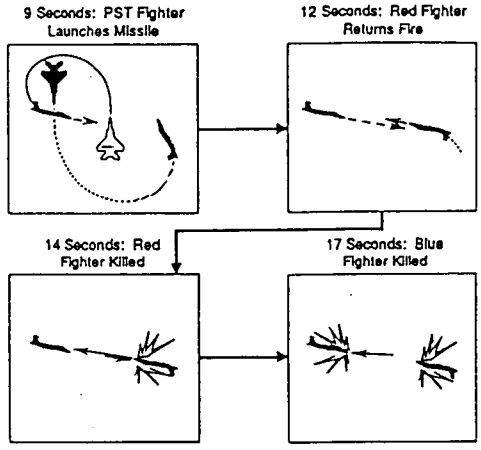


Figure 21. Effect of Missile Time Of Flight (Whiteford, 10)

As figure 21 shows, the PST fighter is able to position his

nose on the adversary to achieve a missile shot first, but in a two circle fight, as the PST fighter's missile is guiding to the adversary, the adversary still has time to launch a missile at the PST fighter just before he is killed. Since both missiles in this scenario are launch and leave weapons such as the AIM-9M Sidewinder of AIM-120 AMRAAM, the adversary's missile will continue to guide after he is killed. This scenario underscores the requirement for a missile with a large enough of a propulsive section to produce greatly shortened times of flight as compared to current missiles.

A helmet mounted sight (HMS) which could point the missile's seeker head at the target well before the PST fighter pointed at the adversary would have allowed the fighter in the figure 21, to fire upon and kill the adversary before the adversary achieved a firing nose position. This has been demonstrated repeatedly during simulations as well as actual ACM engagements using prototype HMS's. Employment of HMS's during simulated CIC has both negated the PST fighter's advantage when employed by an adversary, and greatly increased the advantage and lethality the PST fighter enjoys over and adversary without an HMS. The author has concluded that a PST fighter employing a HMS in conjunction with a high off-boresight capable, thrust vectored missile could not be defeated during one versus one CIC engagements.

4. CONCLUSIONS AND RECOMMENDATIONS

Although today's fighter tactics and weapons systems procurement plans center on giving the fighter pilot the most lethal BVR system possible, it has been proven repeatedly that visual engagements between fighter aircraft still have a very high probability of occurring in any of the world's potential wartime theaters of operations. This, in addition to the increased capabilities of potential U.S. adversary's all-aspect IR missiles, places an increased emphasis on the maneuverability and agility requirements of modern fighter aircraft.

PST maneuvering capabilities of the F/A-18 HARV give a fighter the ability to execute small radius turns, increased pitch, roll and yaw control power at high AOA and greatly increased resistance to departures from controlled flight. These capabilities result in a fighter that can turn inside an adversary's turn radius and can generate moments about all axes to point at an adversary regardless of airspeed and flight path considerations. PST maneuvering also gives the pilot an aircraft with near-carefree flying qualities at high AOA and slow speeds.

Some specific conclusions and recommendations include:

A. The employment of PST maneuvers has no tactical utility in BVR engagement phases. The BVR axiom that "speed is life"

for forward quarter maneuverability and missile defense considerations still holds true.

B. PST maneuvers should be limited to very short durations. Slow speed, high AOA flight, although very offensive against a seen adversary (referred to as a "bogey" by fighter pliots), puts the fighter in a very vulnerable position to acquisition and attack from an unseen, untargeted bogey.

C. PST capable fighters should attempt to force a one circle fight in order to take advantage of a smaller turn radius over an adversary and not give the adversary weapons separation created from a two circle fight.

D. The PST fighter should execute conventional BFM to force the adversary into a vertical or oblique fight at which point the PST fighter will employ a PST maneuver from a low to high pitch-up, staying above the adversary thereby more easily gaining back the energy lost during a PST maneuver at its conclusion.

E. The HARV pilot should only employ a PST maneuver in a multi-adversary engagement when the fighter has awareness or sight of all bogies and a quick kill can be achieved. In any case, the PST fighter should attempt to stay close to, and inside the turn radii of all bogies and not give any bogey weapons separation.

F. The PST fighter must have a high off-boresight acquisition, increased gimbal angle, thrust vectored, IR

missile to fully exploit the advantages of increased high AOA agility.

G. The PST fighter must have a HMS for increased off-boresight sensor and missile acquisition capability.

H. The PST fighter should have a high impulse, short time of flight missile.

I. As in any ACM engagement, the PST fighter must properly assess the energy state of an adversary in order to properly time the execution of a PST maneuver.

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VITA

Philip C. Pirozzi was born May 11, 1957 in New York City, N.Y. where he was raised. He graduated from the United States Naval Academy in 1979 with a Bachelor of Science degree in Aerospace Engineering and was subsequently commissioned as an Ensign in the U.S. Navy. Philip was sent to Pensacola, Florida to attend Naval Flight Training in 1980, and completed training, receiving his "wings" in 1982. After graduating from flight training he was assigned to fly the A-7E Corsair Light Attack aircraft for a deployment assigned to the USS Coral Sea. After this tour he was selected to transition to the F/A-18 Hornet and become part of the initial cadre of the first east coast fleet Hornet Carrier Air Wing. During this tour he participated in the Operations in the Vicinity of Libya (OVAL) during the winter of 1985 to 1986 and the bombing raids of Libya in April, 1986. After this tour Philip was selected to attend the U.S. Naval Test Pilot School. Upon graduation from test pilot school in July 1989, he was assigned to his current assignment as a Navy Test Pilot and F/A-18 Department Head of Air Test and Evaluation Squadron Four, NAS Pt. Mugu, California. He has flown the F/A-18 Hornet operationally in the fleet and in the flight test community for over nine years. He is a member of the Society of Expermimental Test Pilots.