To the Graduate Council:

I am submitting herewithin a thesis written by David A. Dunaway entitled "Flying Qualities and Performance of the F-16B Airplane". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Aviation Systems.

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We have read this thesis
and recommend its acceptance.

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and Dean of the Graduate School

FLYING QUALITIES AND PERFORMANCE OF THE F-16B AIRPLANE

A Thesis

Presented for the

Master of Science

Degree

The University of Tennessee, Knoxville

David A. Dunaway

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DISCLAIMER

The data included in this thesis are actual flight test data collected during a limited scope flying qualities and performance evaluation of the United States Air Force F-16B airplane. All positive or negative comments concerning the F-16B are the sole opinion of the author and in no way represent the official position of Air Test and Evaluation Squadron Five, Commander Operational Test Force, the Naval Air Test Center or any branch of the Department of the Air Force. Similarly, the recommended corrections to the documented deficiencies are presented by the author for the sole purpose of fulfilling the requirements of this thesis, and are not attributed to any of the aforementioned authorities.

ABSTRACT

Operation Desert Storm illustrated the need for sophisticated military aircraft capable of performing both the power projection and air superiority missions. The F-16 was used extensively to perform self escorted, strike missions in heavily defended areas with good success. However, the airplane demonstrated several shortfalls in capability which affected mission execution and success. These problems prompted further investigation into aircraft deficiencies and modifications which could make the F-16 more successful in the strike fighter mission. A limited, qualitative evaluation of the F-16B airplane for the strike fighter mission was conducted. For the purposes of this test, the performance difference between the F-16A and F-16B were negligible. The evaluation consisted of 2 hours of ground testing and 4 flights totaling 4.0 hours conducted at Edwards Air Force Base. The airplane was tested in a low drag, fighter escort configuration and a high drag strike configuration.

Of the deficiencies found, several were particularly significant and should be corrected in future design modifications. The F100-PW-200 engine has restricted afterburner (AB) operating envelope limitations and was a major deficiency. Loss of rudder authority, angle of attack (AOA) limitations and limited roll performance at high AOA

were all major deficiencies designed into the flight control laws to avoid the aircraft tendency to loose directional stability and depart at high AOA.

The F-16 demonstrated excellent potential for future use as a low cost strike fighter aircraft and will be satisfactory upon correction of the major deficiencies. Addition of an axisymmetric thrust vectoring nozzle as installed on the F100-PW-229 engine has the potential to correct all aircraft deficiencies.

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GLOSSARY OF TERMS

Aerodynamic Center (a.c.)- The point on the cord of an airfoil about which the moment coefficient is practically constant for lower angles of attack.

Afterbody drag- Drag associated with the shape of the aft section of an airplane.

Agility- The ability of an aircraft to generate high and controllable angular rates below corner airspeed.

Angle of Attack (AOA)- The angle between the relative wind and the longitudinal axis of the airplane.

Center of gravity- The point on an airplane about which it will balance.

Center of Pressure (c.p.)- The point on the cord of an airfoil through which all of the aerodynamic forces act.

Chord- The line between the center of the circle forming the leading edge of the wing and trailing edge of an airfoil.

Dynamic Pressure- Defined by the term 1/2(air density)(true velocity)^2

n_z- Normal acceleration of the aircraft.

Strike Fighter Mission- The ability of an aircraft to conduct both the air-to-air and air-to-ground mission on the same or consecutive flights without major reconfiguration of the airframe.

ABBREVIATIONS and SYMBOLS

Afterburner.....AB
Air to Air Infarred Missile.....AIM-9
Alternate Flaps.....ALT FLAPS
Angle of Attack.....AOA
Angle of Attact of the tail.....α_t
Attitud Reference Indicator.....ARI
Area of the tail.....S_t
Center of gravity.....CG
Total pitching moment coefficient about the center of gravity
.....$C_{m_{CG_{total}}}$
Wing contribution to pitching moment coefficient about the center of gravity.....$C_{m_{CG_{wing}}}$
Fuselage contribution to pitching moment coefficient about the center of gravity.....$C_{m_{CG_{fus}}}$
Tail contribution to pitching moment coefficient about the center of gravity.....$C_{m_{CG_{tail}}}$
Power contribution to pitching moment coefficient about the center of gravity.....$C_{m_{CG_{power}}}$
Coefficient of lift with respect to AOA.....a_t
Density.....ρ
Distance from center of gravity to aerodynamic center of the tail.....l_t
Downwash.....ϵ
Flight Control Computer.....FCC
Frequency Operating Band for APG-66.....I/J Band
High Alpha Research Vehicle.....HARV
Heads Up Display.....HUD
Indicated Mach Number.....IMN
Infrared.....IR
Inertial Navigation System.....INS
Kilo Volts Alternating Current .....KVA AC
Leading Edge Extension.....LEX
Load Factor.....g
Mean Aerodynamic Chord.....MAC
Mean Sea Level.....MSL
Moment Coefficient.....C_m
Multi-function Display.....MFD
Normal Acceleration .....n_z
Steady Heading Side Slip.....SHSS
Stores Management Set.....SMS
Specific excess power.....P_s
Tail incidence.....i_t
Tail efficiency factor.....η_t
Tail volume coefficient.....$\bar{V}$
Trailing edge flaps.....TEF
True Air Speed.....TAS
Turn Rate.....w
Turn Radius.....R

US Air Force/McDonnell Douglas STOL/Maneuver Technology Demonstrator.....S/MTD

Variable Inflight Stability Training Aircraft.....VISTA

Wing Area.....S

1. INTRODUCTION

1.1 BACKGROUND

Operation Desert Storm illustrated the need for sophisticated military aircraft capable of performing both the power projection and air superiority missions. The F-16 was used extensively to perform self escorted, strike missions in heavily defended areas with good success. However, the airplane demonstrated some shortfalls in capability which affected safety, mission execution and success. These problems prompted further investigation into aircraft deficiencies and modifications which could make the F-16 more successful in future conflicts as a strike fighter aircraft . The intent of this evaluation was to highlight only major modifications to the existing platform which would most dramatically enhance mission performance of the F-16.

1.2 PURPOSE

The purpose of this evaluation was to conduct a limited scope evaluation of the flying qualities and performance of the F-16B for the strike-fighter mission and to examine potential upgrades to the aircraft which would enhance the ability of the F-16 to conduct the strike fighter mission.

1.3 DESCRIPTION OF TEST AIRPLANE

The F-16B is a tandem, two seat, single engine, supersonic, multi-role (air to ground or air to air) tactical fighter built by general Dynamics. A photograph of the airplane and diagram of the interior cockpit layout is presented in appendix A, figures 1 and 2. Relaxed static stability and fly by wire flight control technology is designed into the aircraft to provide maximum aircraft agility that is easily controlled throughout the flight envelope. Due to relaxed static stability there is a continuous nose up pitching moment which is countered automatically by the flight control system with the horizontal stabilizer. The flight test engine was a Pratt and Whitney F100-PW-200 which is rated at 25,830 lbs of uninstalled static thrust in full afterburner at sea level. There are seven internal fuel tanks which are integral to the structure with a total internal fuel capacity of 5650 $\pm$ 300 lbs. The airplane is also capable of utilizing a 300 gallon centerline tank and two 370 gallon wing tanks. Automatic fuel transfer for center of gravity (CG) control is accomplished primarily via siphoning effect from bleed flow or by electrical and bleed powered fuel pumps. The fuselage is narrow with a single, one piece, bubble canopy. The fuselage and moderately swept wings are smoothly blended together. Wing tip missile launchers, two hard points per wing and a centerline hard point are available for external stores. The thin wings have automatic programming trailing

edge flaperons which are designed to function primarily as ailerons and secondarily as trailing edge flaps (TEF). A single vertical tail is augmented by ventral fins designed to increase directional stability. The all moving horizontal tail exhibits a small amount of negative dihedral and is designed to move differentially for roll commands and symmetrically for pitch commands. An aileron rudder interconnect (ARI) is designed to coordinate rudder for all roll commands. Secondary flight controls include maneuvering leading edge flaps (LEF), the TEF function of the flaperons and two pairs of clam shell speedbrakes located one on either side of the engine nozzle. Speedbrakes are actuated by a switch on the throttle. All primary and secondary flight controls (except speedbrakes) are controlled by a four channel, fly by wire, flight control system. The flight control system also incorporates an automatic pilot, Angle of Attack(AOA) or normal acceleration(n_z) limiter, yaw rate limiter and a roll rate limiter. Two gain schedules, normal gear up (cruise) gains and takeoff/landing gains are used during normal operations as well as one stand by gain for degraded electronic control assembly (ECA) operation. Cruise gains are designed to be n_z command and takeoff gains are designed to be pitch rate command. Both used AOA feedback at higher angles of attack. Trim is also designed to be controlled by the flight control computer. Pitch trim commands n_z in normal cruise gains and in takeoff/landing gains, trim commands pitch rate with a blend of pitch rate

with AOA feedback at higher angles of attack. Roll trim is designed to command roll rate using Aileron, differential stabilizer and rudder via the ARI. Rudder trim commanded the rudder left or right of center to a new neutral position. The control stick is mounted on the right console (side stick controller) and is designed as a force sensor with only 1/4 inch of movement in both pitch and roll. Rudder pedals are also force sensing units which command yaw rate via electrical command. All flight control are operated by two, independent , 3000 pounds per square inch (psi) hydraulic systems. Actuation of the landing gear uses only hydraulic system B and is designed to automatically program the TEF. TEF's are also repositioned with the landing gear up by placing the ALT FLAPS switch to the extend position. Electrical power is supplied by a single 40 KVA AC generator which is backed up by a single 5 KVA generator powered by the external power unit. Dual ejection seats are designed for 0 altitude and 0 airspeed ejection capability. A more detailed description of the test airplane is included in the Operators Manual, reference 1. The test airplanes are representative of production model F-16A's for the purpose of this test.

1.4 DESCRIPTION OF AIRPLANE SYSTEM

The major component of the F-16B airplane system is the Fire Control Computer (FCC) which is the primary bus controller that computes weapons parameters and performs

navigation tasks. An Inertial Navigation System (INS) is used as the primary attitude and heading reference as well as a reference for horizontal velocities, vertical velocities and present position. The Fire Control and Navigation Panel (FCNP) is the pilot interface to the FCC and INS. The Heads Up Display (HUD) displayed attitude, navigation and tactical information as well as computing snap shots weapons solutions and back up missile computations. The Fire Control Radar was the APG-68 multi-purpose, pulse doppler, air to air/air to ground radar which operates in the I/J band. The radar has air to air track and AIM-9 seeker head positioning capability as well as doppler beam sharpening mode for air to ground deliveries. Information from the APG-68 is displayed on the Multi-function Display (MFD). The Stores Management System (SMS) acts as the interface between the pilot and the weapons delivery system. The path for communication of all fire control and navigation elements is the airplane Multiplex Bus (MUX BUS). The MUX BUS acts as a sequencing communications network to coordinate commands from the pilot to each element of the fire control system for the optimum performance. Armament included Aim-9 air to air missiles, internal 20 mm multi-barrel cannon and a multitude of free fall bombs, rockets and guided weapons. Test equipment installed in the F-16B was representative of production models for the purposes of this test. A more detailed description of the airplane systems is contained in the Operators Manual, reference 1.

1.5 SCOPE OF TEST

The limited scope evaluation consisted of ground familiarization and 4 flights totaling 4.0 hours conducted in the Edwards Air Force Base operating complex off of runway 22. All tests were conducted within the limits of the Operators Manual, reference 1. Flight tests covered performance characteristics, flying qualities, formation flying, low level navigation, simulated air to ground ordnance delivery and air to air maneuvering. Flights 1 and 2 were single ship with emphasis on qualitative mission tasks, performance and flying qualities while flight 3 was flown in section with emphasis on air to air aircraft systems and mission utility. Flight 4 was dedicated to air to ground and low level systems and mission utility. The flight envelope is presented in table I .

Table I
FLIGHT TEST ENVELOPE

CONDITION	LIMIT
Altitude	0 to 35000 ft MSL
Airspeed (1)	0 to 600 KIAS below 30000 ft MSL Max 1.6 IMN
Load Factor(1)	0 to +9.33 g

Take off gross weight was between 25000 lbs and 33000 lbs depending on loading. The CG varied between 30.3% and 36.7%

Mean Aerodynamic Chord (MAC) within the manufacturer's limits. The flight test configuration is presented in table II.

Table II
TEST CONFIGURATIONS

Configuration	Symbol	Landing gear	Speedbrakes	Power
Taxi	TX	Down	In	Idle
Takeoff 1	TO1	Down	In	Military
Takeoff 2	TO2	Down	In	Maximum
Cruise	CR	Up	In	TLF (1)
Power	P	Up	In	Military
Combat	CO	Up	In	Maximum
Descent	D	Up	In	Idle
Powered Approach	PA	Down	Out	PNA (2)
Land	L	Down	Out	Idle

Notes: (1) TLF was Thrust for Level Flight.

(2) PNA was Power for Normal Approach

1.6 METHOD OF TEST

The F-16B was evaluated qualitatively and quantitatively throughout the flight test envelope. Specific test techniques were conducted per Flight Test Manual-103 (FTM-103) Aircraft Stability and Control, (FTM-104) Aircraft Performance and the VAX Test Plan references 3,4 and 5 respectively. A complete description of the evaluation conducted on the F-16 is included in reference 2. Takeoff and landing information was estimated using the feet remaining markers on the side of the runway. Stall was defined by the AOA limiter during all tests and operators

manual recovery procedures were used to recover from stall. All sideslip angles were estimated from heading change during SHSS release. All tests were conducted within the limits of the Operators Manual, reference 1. Control forces were estimated qualitatively on all tests. Data were recorded on kneeboard cards, portable voice recorder and HUD video tape. Special instrumentation used was a protractor, and stop watch. All data were reduced by hand to test day conditions and a standard gross weight of 22000 lbs where applicable.

2. RESULTS AND DISCUSSION

2.1 AFTERBURNER OPERATION

The afterburner (AB) was evaluated for selection reliability throughout the flight test envelope and operational utility given the operators manual restrictions found in reference 1 . Afterburner reliability proved to be outstanding during the limited evaluation. All ignition attempts were successful throughout a variety of conditions. However, the operators manual discusses a list of limitations which restrict the aircrew's ability to use AB in some of the most operationally critical situations. The restrictions from reference 1 are shown below in figure 1, but were not tested for safety reasons.

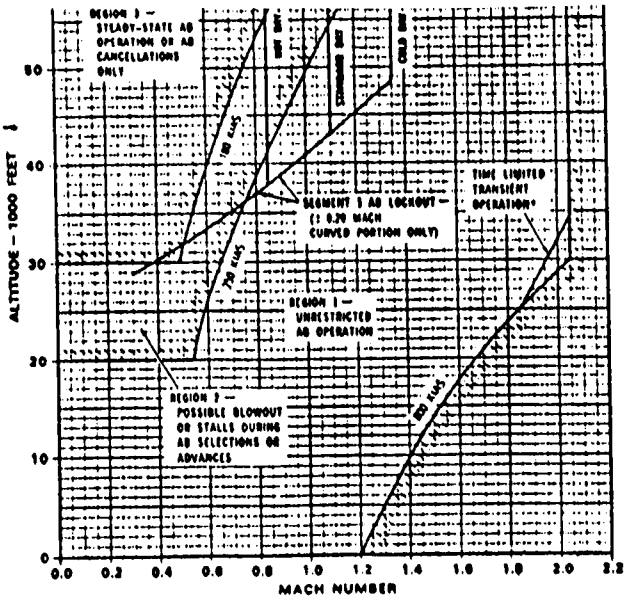


Figure 1
F-16B AFTERBURNER OPERATION ENGINE LIMITS

Operation in region 2 severely limits throttle movements which are normally used during infrared (IR) missile counter measures above 20000 ft Mean Sea Level (MSL). Normal missile defense maneuvers require deselecting of AB several seconds prior to missile intercept followed by immediate selection of AB afterwards to regain airspeed. A missile defense maneuver is accomplished by deselecting AB to reduce IR signature and conducting a hard turn into the missile to create a high angle rate. The result of the maneuver is a high AOA and loss of airspeed. AB limitations described in the operators manual will preclude proper missile defense maneuvers in combat situations and inhibit aircrew from using AB to regain critical airspeed. The AB limitations for the F-16 are unsatisfactory.

2.2 AOA or NORMAL ACCELERATION (n_z) LIMITER

The AOA or n_z limiter was evaluated qualitatively on the first two flights with fighter escort loading. During flight test, the n_z limiter demonstrated some dynamic overshoot of the published 9.0 g limit but remained within the overshoot limit of 9.33 g's. The AOA or n_z limiter was designed to limit n_z available from 9.0 g at 15 degrees AOA to 1.0 g available at slightly over 25 degrees AOA. The purpose of the AOA or n_z limiter was to prevent departures from controlled flight or overstress of the airplane.

Figure 2 from reference 1 shows F-16 AOA limitations.

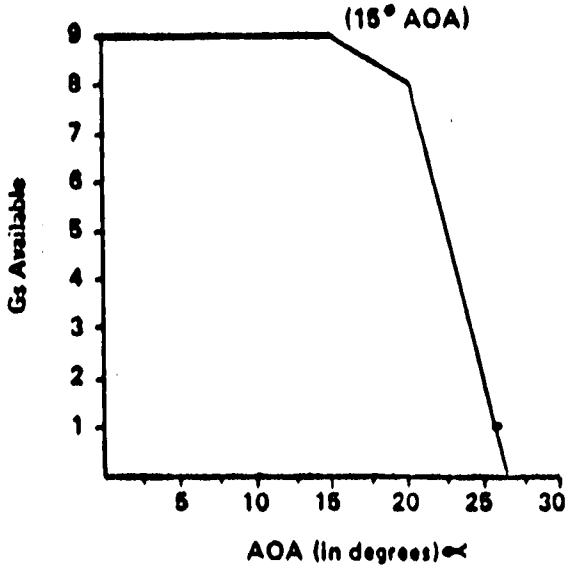


Figure 2
F-16B AOA LIMITER FADE IN

Airplane pitch response below 15 deg AOA was outstanding and in combination with relatively high thrust, the F-16 realizes a sustained pitch rate advantage over most tactical airplanes. As the airplane exceeded 15 degrees AOA, the decrease in available n_z was subtle and difficult to perceive until approximately 18 deg AOA. At 20 deg AOA, available n_z and pitch authority began to decrease noticeably until no further pitch authority was available at approximately 25 deg AOA.

The reason for the limiter as described in reference 1 is two fold. First and foremost is the loss of directional stability and control due to airflow blanking to the vertical stabilizer. The second reason is that at higher AOA (approximately 50 to 60 degrees), nose down pitch authority is lost. To illustrate the longitudinal stability problem

associated with the F-16, a contrasting view of the airflow at 10 and 50 degrees AOA can be used. Figure 3 illustrated flow at 10 degrees AOA. Figures 3 and 4 do not represent actual F-16 data but are visually representative of the phenomenon of interest.

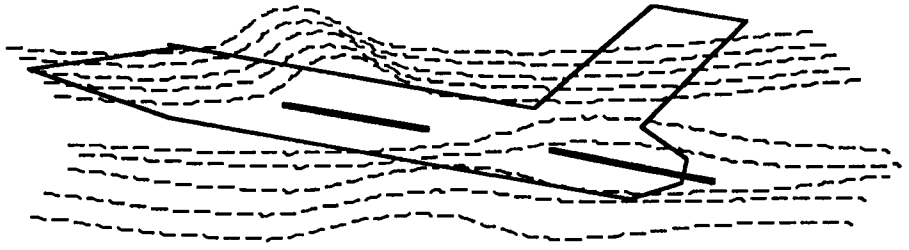
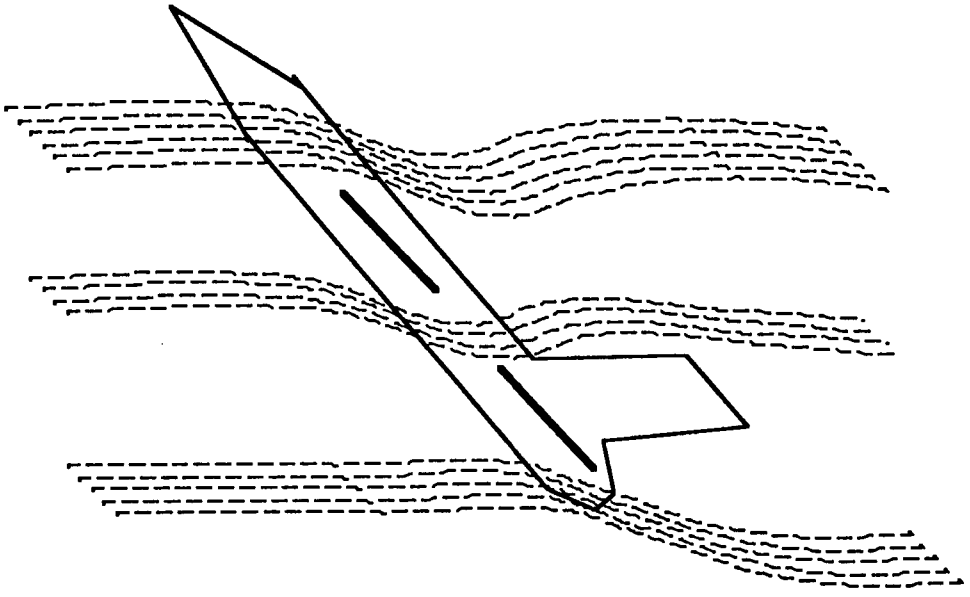


Figure 3

AIRFLOW REPRESENTATION AT 10 DEGREES AOA

In the case of 10 degrees AOA, airflow is influenced by the Leading Edge Extension (LEX), wing and horizontal stabilizer, yet is sufficient to provide positive longitudinal control of the airplane. Also of note is that there is still enough flow over the vertical stabilizer to provide directional stability. On the contrary, at 50 degrees AOA, there are longitudinal and directional stability problems. The most critical problem is that as the fuselage angle to the relative wind approaches 30 degrees, the airflow to the vertical stabilizer is completely blocked by the fuselage causing a loss of directional stability. At approximately 50 degrees AOA the wing is completely stalled. At the same time flow over the horizontal stabilizer is completely stalled. Because of the relaxed static stability of the F-16 and the shape of the fuselage/inlet combination, a nose up pitching

moment occurs which cannot be countered by the stalled horizontal stabilizer. Without the equalizing nose down pitching moment caused by the horizontal stabilizer, the airplane enters an AOA or pitch hang-up. The current AOA limiter is designed to keep the airplane from reaching a critical AOA which will cause directional departures or pitch hang-up. Figure 4 illustrated flow at 50 degrees AOA.



50 Degrees AOA

Figure 4

F-16 AIRFLOW REPRESENTATION AT 50 DEGREES AOA

In tactical situations, nose pointing authority is the most useful tool available to a pilot in the execution of the strike fighter mission. The ability to quickly point the nose at a surface target from any position is critical and in the air to air arena, nose pointing authority equates directly to time to kill. Although sustained turn performance is an excellent tool in tactical employment of

any airplane, agility and the ability to quickly point the nose of the airplane for a quick shot is more frequently the primary factor of success. Limitation of AOA OR pitch authority at higher AOA's severely degrades the ability of the strike fighter pilot to quickly point and shoot at enemy targets and aircraft. AOA OR pitch limitations are a major deficiency.

2.3 ROLL RATE LIMITER

Maximum roll rate was evaluated on the first two flights with fighter escort loading. The roll rate limiter was designed to limit rates based on AOA, airspeed and horizontal tail deflection. Normal 1 g roll rates were rapid and did not appear to be limited until lower airspeeds/higher AOA. As AOA exceeded 15 degrees, roll performance decreased rapidly. Airplane lateral response became very sluggish above 20 degrees AOA. At 25 degrees AOA, only very slow roll rates could be commanded with maximum lateral control stick deflection. The reason for the roll rate limiter is directly related to the reason discussed in paragraph 2.2 for the pitch limiter. As the AOA increases the airflow is shielded from the vertical stabilizer causing several phenomena. First, as previously mentioned is the loss of directional stability and rudder control power. Second, at higher AOA, the effect of adverse yaw is more pronounced and becomes the dominant effect of aileron

displacement. Because of this the F-16 flight controls phase out aileron deflection as a source of roll command and reverts to rudder displacement which commands roll via the dihedral effect. Since control power of the rudder is diminished as the AOA increases, the ability to command rudder rolls also decreases. The purpose of the limiter is to ensure that roll rates cannot be established via any means which exceed the ability of available dihedral to counter that roll rate. The limiter takes into account the current and predicted amount of airflow over the vertical stabilizer to ensure that it is sufficient to provide the control power necessary to counter the roll via dihedral effect.

Slow roll rates at high AOA severely limit the ability of pilots to conduct the aggressive maneuvers necessary for survival. Although the primary goal of all aircrew is to avoid slow speed maneuvering in combat, there are times when the these types of engagements will be unavoidable. A series of missile defense maneuvers or a late visual acquisition of an enemy aircraft in the rear hemisphere requires aggressive maneuvering that frequently bleeds airspeed and increase AOA to the undesired slow flight regime. Once in the slow flight regime, the goal of the pilot is to defeat the threat as quickly as possible. In the case of surface to air threats, missile engagements often come in a sequence of several missiles. During the first couple of missile defense maneuvers, the energy state is high enough to create sufficient aircraft roll rates to achieve out of plane

maneuvers required to defeat a missile. However, as the airspeed decreases and the roll rate decreases, the ability to create sufficient angle rates to defeat missiles is severely limited by the roll and pitch limiters. In the case of air to air engagements, late acquisition of enemy aircraft in the rear hemisphere requires a maximum rate turn to meet the threat which typically bleeds energy to the point where the F-16 is in the slow speed regime. To quickly reverse the defensive roll to an offensive roll in the air to air case, maximum pitch, roll and yaw rates are required. The ability to avoid being engaged by enemy missiles and to employ offensive weapons on the threat aircraft is severely hampered by the F-16 flight control limiter system. Limited roll performance at high AOA is a major deficiency which should be corrected.

2.4 YAW RATE LIMITER

The yaw rate limiter was evaluated on the first two flights with fighter escort loading. The yaw rate limiter was designed to limit rudder authority form 30 deg to 0 deg at 25 deg AOA. Directional control authority steadily decreased as AOA was increased. At 25 deg AOA, maximum rudder force would command neither yaw or roll. The reason for the yaw rate limiter is predictably related to the loss of directional control authority as were the reasons for the pitch and roll rate limiters. As directional control power

is decreased, less yaw rates can be accepted by the flight control system because less control power is available to counter the yaw rates.

As with the loss of roll performance at high AOA, loss of yaw performance is also important in the defensive arena. For example, in a rolling scissors engagement where two aircraft are in a vertical looping fight, the ability to quickly convert the nose up portion of the loop to the nose down portion of the loop is the single most important factor in winning the engagement. Typically, the conversion from nose up to nose down is conducted at slower airspeeds where pitch performance is limited. Because of the slower pitch response at slower airspeeds, pilots typically use yaw to create a nose slicing maneuver which more quickly converts the nose up portion of the loop to the nose down portion. In the F-16, the loss of yaw authority at the slower airspeeds associated with the top of the looping maneuver virtually eliminates the ability of the pilot to perform a nose slice maneuver in tactical situations. In addition, when a rolling scissors engagement is encountered, the combined effects of pitch, roll and yaw limiting can cause the aircraft to reach an uncontrollable state. The aircrew could easily achieve a nose high position reaching the pitch, roll and yaw limits. In this position the aircrew would be unable to complete a loop before airspeed bleeds all the way to zero causing a ballistic departure which could cause the airplane to exceed the pitch limiter and reach a pitch hang up. Loss of rudder

authority at high AOA will degrade mission performance by precluding the use of nose slicing turns at high AOA for quick kills in air to air engagements and is a major deficiency.

3. ANALYSIS AND DISCUSSION OF POTENTIAL SOLUTIONS

3.1 GENERAL

The F-16 demonstrated excellent potential as a multi mission strike fighter aircraft for current and future threats with the correction of the AB limitations and the flight control limits in the pitch, roll and yaw axis. During testing, many minor deficiencies were manifested as general annoyances which could be worked around through training or pilot compensation and thus are not addressed in this document. However, correction of the major deficiencies is essential to the mission success of the F-16 against future threats. To address the major deficiencies of afterburner limitations and flight control limiters, it is proposed that a new, high performance engine incorporating an axisymmetric thrust vectoring nozzle be installed. The new design should allow for unlimited afterburner operation throughout the flight envelope, higher thrust and most importantly, the thrust vectoring could potentially eliminate the need for multi -axis flight control limiters by providing directional stability and control at higher AOA's.

3.2. F100-PW-229 ENGINE

Engine technology has advanced at a rapid rate in the past several years. The F100-PW-200 engine installed in the flight test article is well behind current technology in

terms of both thrust to weight and reliability. The F100-PW-229 as described in reference 3 is the recommended replacement for the F100-PW-200. It is a 29000 lb class engine which represents an increase in static thrust of 13%. It is a low-bypass, high pressure ratio, dual-spool, afterburning, turbofan engine. It combines a 3-stage axial fan, a 10 stage axial high pressure compressor, an annular combustor, a 2 stage air-cooled high-pressure turbine and a 2-stage uncooled low pressure turbine. The engine is also configured with a full length mixed flow afterburner and a variable area convergent/divergent nozzle which can be replaced with the axisymmetric nozzle used for multi-axis thrust vectoring. A diagram of the engine is shown in figure 5.

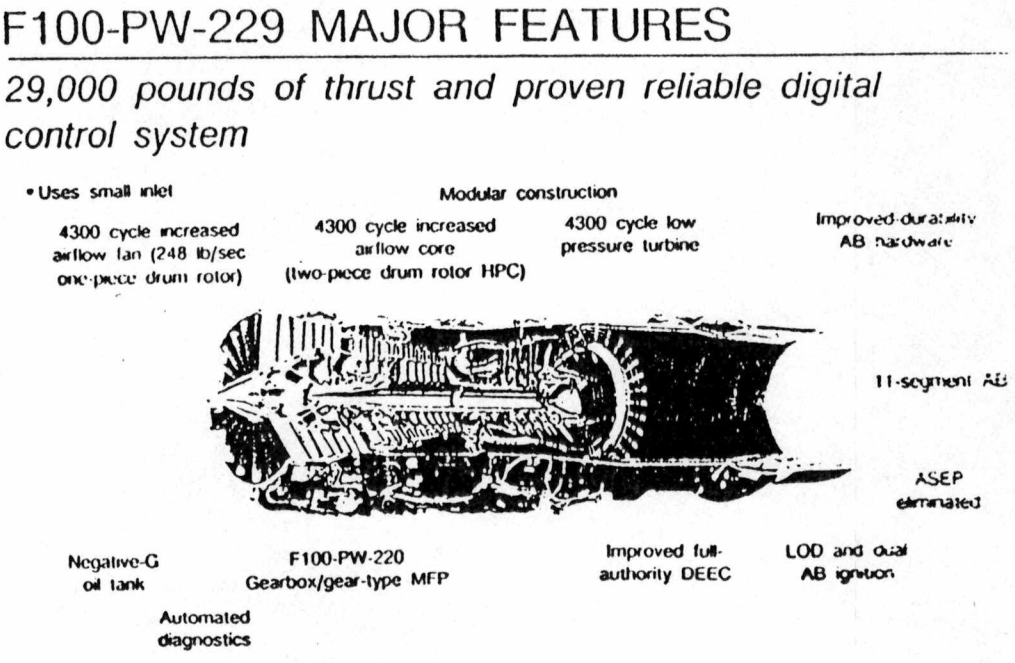


Figure 5
F100-PW-229 MAJOR FEATURES

As discussed in reference 3 the 229 has undergone extensive flight test installed in the F-16 and is cleared throughout the flight test envelope. Essentially, there are no operator limitations since the fuel control system automatically prevents improper operation of the AB as shown in figure 6.

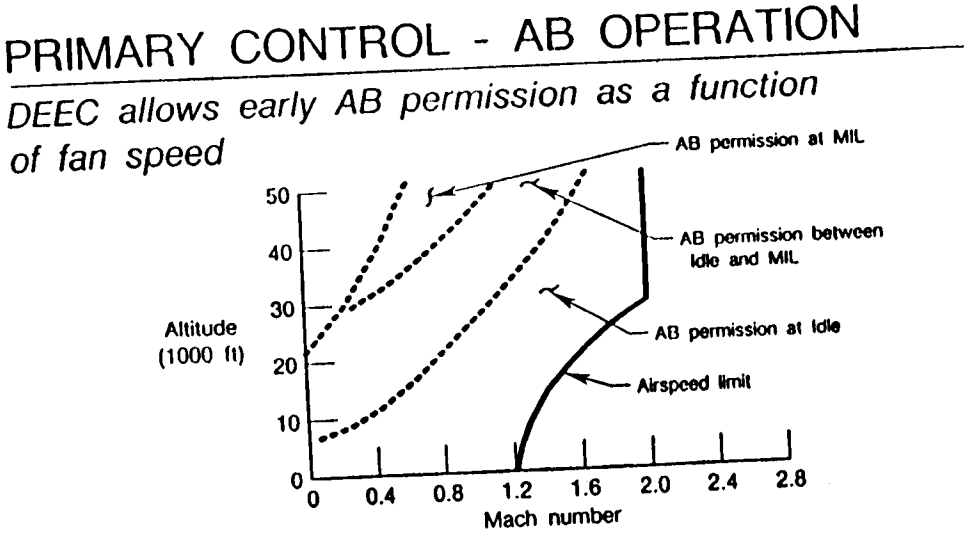


Figure 6

F100-PW-229 AB OPERATING ENVELOPE

In addition to the increased thrust and less restrictive AB operating envelope, the new engine demonstrates much better response times. Some testing has been done on the 229 engine to further increase the static thrust. The test article was called the PW IPE-94 rated at 35000 lbs thrust, representing a 37% increase in thrust and is briefly discussed in reference 4.

Improved response times are shown in figure 7.

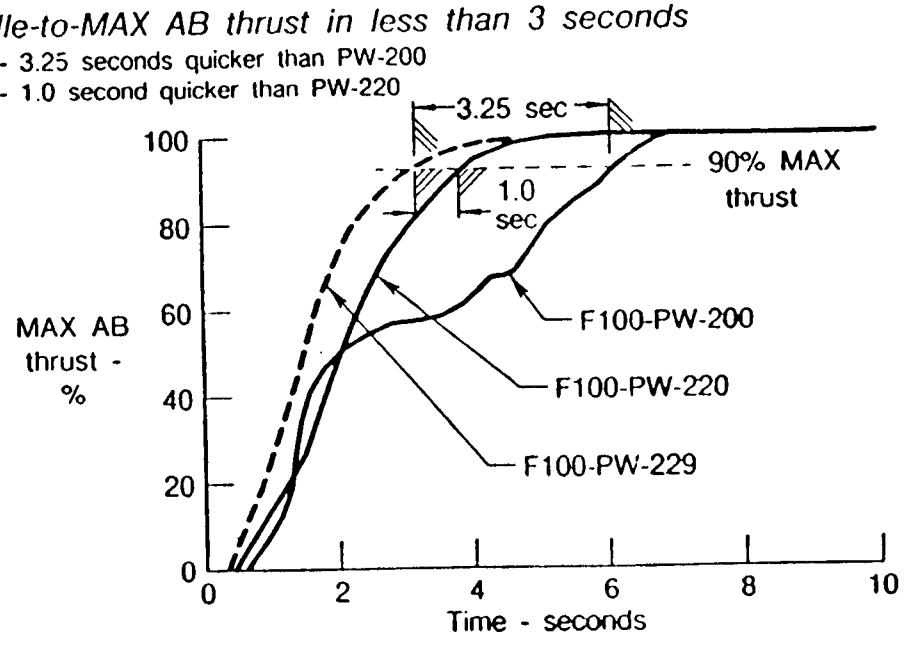


Figure 7

ENGINE TRANSIENT RESPONSE

Figures 6 and 7 were taken from reference 3.

3.3 VECTORED THRUST TECHNOLOGY

Vectored thrust for enhanced maneuvering is a new technology recently introduced in flight test by the US Air Force/McDonnell Douglas STOL/Maneuver Technology Demonstrator (S/MTD) F-15, the F-22, the FA-18 High Alpha Research Vehicle (HARV) and the X-31 agility demonstrator. The F-15 S/MTD and the F-22 platforms have demonstrated the ability to integrate digital flight controls with a pitch vectoring nozzle in an effort to enhance longitudinal pitch performance and to decrease takeoff and landing distances as described in reference 5. The fundamental premise behind the vectored thrust nozzle is the application of an additional pitching or

yawing moment at the exhaust nozzle caused by redirecting engine exhaust. Because of the large moment arm between the nozzle exit area and the aircraft body center of rotation (in both pitch and yaw axis) combined with the high thrust output of modern engines, large pitching and yawing moments can be expected from thrust vectoring. The increased pitching or yawing moment imparted by the thrust vectoring is independent of aircraft velocity and control authority which makes it all the more attractive. Traditional aerodynamic limits which in the past have limited aircraft angular rate performance can be overcome by the addition of vectored thrust moments. Limitations for consideration are the possibility of compressor stall of the engine at high AOA, increased weight, afterbody interference drag and reliability.

3.3.1 PITCH VECTORED THRUST OF THE S/MTD TO DATE

Pitch vectored thrust has demonstrated excellent potential for operational production in flight testing to date. Unfortunately, the utility of S/MTD data for the F-16 is limited because it is in the pitch axis only. The two test platforms currently utilizing the pitch vectored thrust nozzle are the F-15 and the F-22, both of which have twin vertical stabilizers which are not blanked at high AOA and provide some directional stability which eliminates the need for yaw thrust vectoring. As previously discussed, the F-16 does not demonstrate acceptable pitch authority or directional stability at high AOA due to blanking of the

single vertical stabilizer. Thus the recommendation for pitch/yaw vectored thrust. All information concerning the performance of pitch vectored thrust for the S/MTD was taken from reference 5 and from an interview with project pilot Major Michael Costigan (USAF). The aircraft used was an F-15B modified with a four channel, digital, fly-by-wire flight control system. The aircraft was powered by two F100-PW-220 turbofan engines with two dimensional nozzles capable of thrust vectoring and thrust reversing. The nozzles were capable of 20 degrees of deflection and the vanes were capable of 135 degrees of deflection for thrust reversing. A diagram of the nozzles in shown in figure 8.

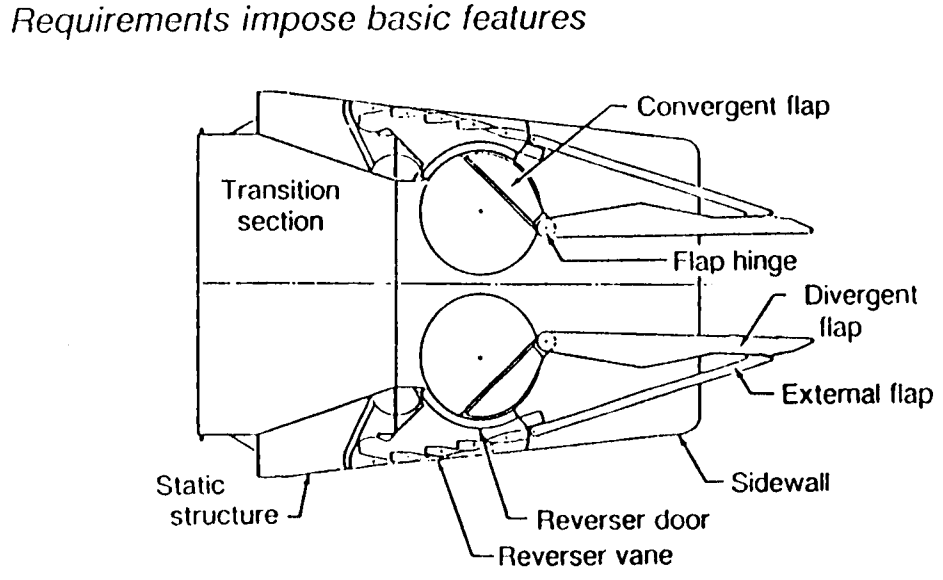


Figure 8

S/MTD VECTORED THRUST NOZZLE

The engine and nozzles were each controlled by an independent digital electronic engine control (DEEC) processor and the nozzle controller. Flight control laws were completely different in the S/MTD than the conventional F-15 and had three up and away modes as well as three landing modes. The up and away modes were CRUISE (thrust vectoring optimized for cruise), COMBAT (thrust vectoring optimized for aggressive maneuvering) and CONV (no thrust vectoring). Landing modes were STOL (thrust vectoring for landing), SLAND (constant airspeed using thrust reversing for speed control and thrust vectoring) and CONV (no thrust vectoring). Close-coupled canards were installed forward of the cockpit with 20 degrees of negative dihedral. Canards operated differentially for lateral-directional control and symmetrically for pitch control.

3.3.1.1 After Body Drag

After body drag is the disturbance of airflow as it passes over the aft portion of the airplane, namely the nozzles. As per reference 6, the rectangular design used for pitch only vectoring demonstrated approximately an 8% decrease in drag over conventional axisymmetric nozzles. This decrease was not quantified as a comparison to the conventional F-15 during S/MTD flight test since it was not a primary objective. However, the project pilot qualitatively

confirmed a perceptible increase in level acceleration performance in the S/MTD.

3.3.1.2 Takeoff and Landing Performance

Takeoff performance was not significantly improved over the conventional F-15. However, the ability to rotate the nose of the aircraft at lower airspeeds was 27% (33 kts) better than conventional F-15 aircraft. Average rotation was 84 KCAS vice 115 KCAS for conventional airplanes. Unlike takeoff, the combination of thrust vectoring and thrust reversing had a dramatic effect on landing distance. Slower approach speeds coupled with thrust reversing on touchdown decreased landing distance form 3400 ft to 1428 ft on dry runways (58% reduction)

3.3.1.3 Turn Performance

Sustained turning performance was performed at 30000 ft at Ps=0 in maximum power. Conventional sustained g was 3.55 g's while 3.65 g's were maintained in COMBAT configuration for an increase of 2.8%. Due to unknown thermal effects on nozzles and unknown choking effects with nozzle deflection, significant losses of power were experienced when AB was selected in the thrust vectoring mode. Qualitatively, pitch authority was significantly higher in the COMBAT mode. Instantaneous turn performance at slow airspeeds was not tested since it was not a primary objective of the test.

3.3.1.4 Flying Qualities

During personal interviews with test aircrew, pilots uniformly agreed that flying qualities of the S/MTD airplane were far superior to the conventional F-15. Pilots were especially impressed with the potential for substantial advances in air combat maneuvering capability during slow speed, high AOA maneuvering. In the landing configuration, slower approach speeds combined with thrust vectoring dramatically improved flying qualities. Pilots were exceptionally pleased with the ability to rapidly and precisely maneuver the airplane in the landing configuration

3.3.2 HARV PITCH/YAW VECTORED THRUST TO DATE

NASA has equipped an FA-18 with pitch and yaw vectored thrust paddles, High Alpha Research Vehicle (HARV) as discussed in reference 7. The system is currently operational at Edwards Airforce base in an effort to evaluate the high AOA regime of flight. The primary objective of HARV testing is to investigate the feasibility of incorporating a thrust vectoring control system into tactical aircraft in order to exploit the high AOA regime of flight. Unlike the S/MTD system, the HARV system was primarily designed for low cost research and not operational deployment. A photograph of the HARV is included in appendix A, figure 3 illustrating the bulky external structures and spin chute installed for

flight test purposes. In addition to increases parasite drag, the system added nearly 900 lbs of thrust vectoring equipment and 200 lbs of nose ballast/peripheral equipment to maintain the approximately 27% CG. The HARV configuration includes three paddles per engine, each operated by an FA-18 aileron hydraulic actuator. Paddles are deflected into the exhaust stream to create the thrust vectoring effect and can operate up to approximately 100 deg/sec deflection rate and 25 degrees of actual deflection. Both the flight control system and the engine fuel control were modified to compensate for the effects on the new nozzles. A diagram of the aft body design is shown in figure 9.

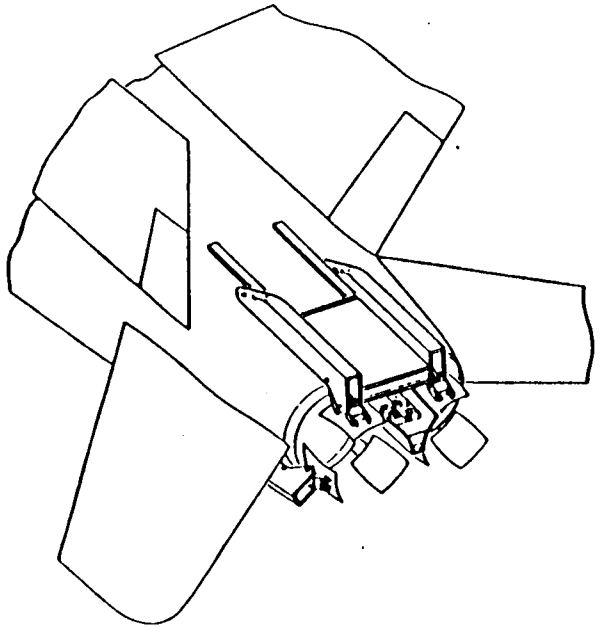


Figure 9

HARV VECTORED THRUST NOZZLE

3.3.2.1 After Body Drag

The after body drag of the HARV aircraft was exceptionally higher than the conventional FA-18 due to the external configuration of the actuators for the paddles and the noncontinuous nature of paddles. Approximately 90 counts of drag were added due to the thrust vectoring modification. As previously mentioned, the purpose of this test was not to assess the tactical performance capability of the airplane but to investigate agility and the high AOA regime of flight. The net propulsive force was decreased approximately 5% due to the paddles nozzle configuration.

3.3.2.2 Pitch/Yaw Performance

The HARV was designed to have a capability of achieving 70 degrees AOA with a desired pitch rate of 26.5 degrees per second and a desired yaw rate of 18.55 degrees per second. To date, 70 deg AOA has been achieved for one 4 second test point. Pitch and yaw rate data has not been reduced, but qualitative assessment by NASA pilot, Mr. Ed Schneider, is that pitch rates at high AOA exceed that of conventional FA-18 aircraft. Because testing is still in progress, the only data available to date on HARV is analytical predictions. HARV has demonstrated a significant increase in maximum pitch trim capability.

Figure 10 shows maximum pitch trim capabilities.

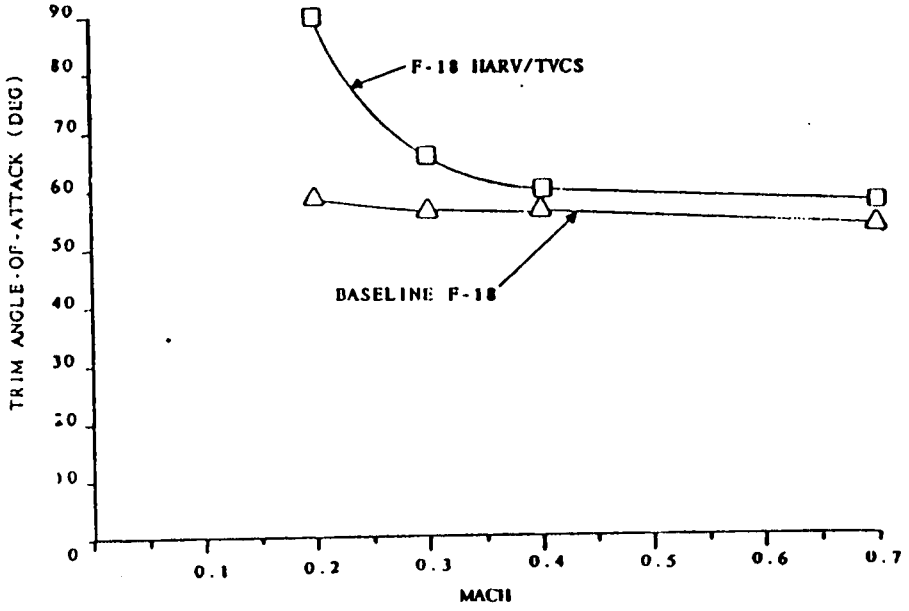


Figure 10

HARV MAXIMUM PITCH TRIM DRAG

The tactical advantage of maintaining controlled flight at such high AOA's is the ability of aircrew to be able to point the nose of the aircraft quickly to employ weapons before threat aircraft can respond. Maximum predicted roll performance was also analyzed for two mach numbers. Inflight evaluation of roll performance has been limited due to aircraft modifications and maintenance. However, the qualitative assessment by the mission pilot was that roll performance significantly improved. The increase in roll rate at 0.2 IMN as described in reference 7 was primarily due to increased capability to negate inertial coupling effects through the use of the thrust vectoring nozzle. By negating coupling effects, full control power could be applied to roll performance. At 0.7 IMN improved performance was also observed because of the ability to use thrust vectoring in

the flight control laws to coordinate aircraft axes. Maximum roll rate capability is shown in figure 11.

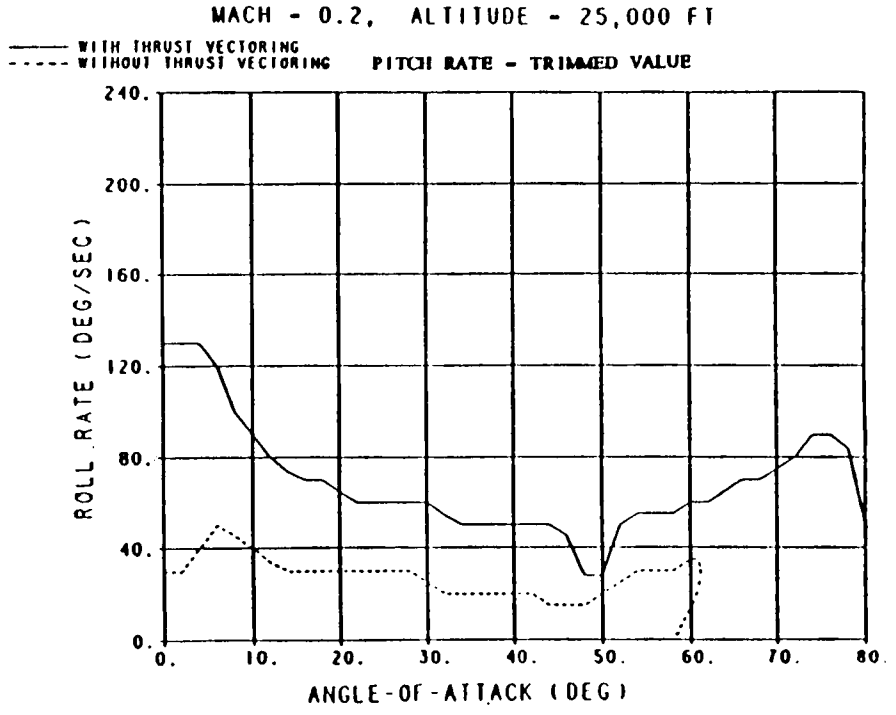


Figure 11

HARV MAXIMUM ROLL RATE CAPABILITY

3.3.3 AXISYMMETRIC VECTORED THRUST

Given the demonstrated capabilities to date in the S/MTD and HARV programs, it is apparent that incorporation of an axisymmetric thrust vectoring nozzle is technologically possible and effective. Thrust vectoring can be utilized to provide additional pitching and yawing moments to provide stability and control beyond the conventional aerodynamic limit of the aircraft. In the case of the F-16, some

technical information was recently released by GE and PW in reference 4 with regards to their version of the pitch/yaw vectoring nozzle. The only performance information available is uninstalled static information from the test stand and analytical predictions supplied by PW. Flight test on an Israel F-16 may be conducted in 1993. The total increase in weight associated with the new nozzles is between 200 and 300 lbs. As mentioned before, the effect of the nozzles is most prominent in the slow speed/high AOA regime because thrust vectoring can provide pitching and yawing moments independent of speed. A schematic of the axisymmetric design used by PW and GD shown in figure 12.

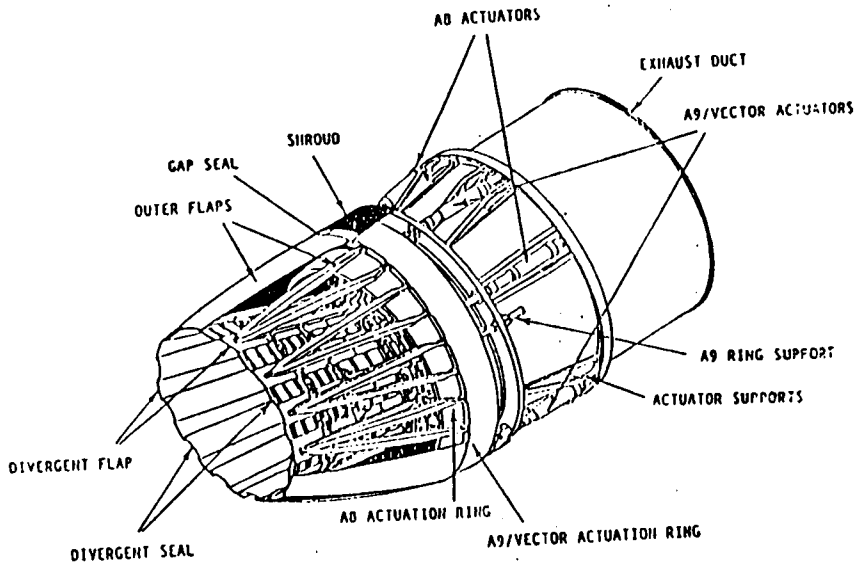


Figure 12

AXISYMMETRIC VECTORING EXHAUST NOZZLE

The current nozzle design by GE has demonstrated 45 deg/sec articulation rates and up to 17 degrees of deflection on the

GE-F110 engine with unlimited throttle transients. Although tests to date have been promising, there are many questions to be answered before complete integration can be expected. Dynamic actuation performance including transient response and actuation system loads, hydraulic system design, aero-mechanical stability and flutter, extended thermal stress effects and lastly, actuation/response rates in the 2 Hz range are all issues which must be investigated prior to installation in an F-16 for flight test. Actuation rates of 2 Hz on a continuing basis is considered the maximum rate required to maintain directional stability at high AOA. The axisymmetric nozzle used for pitch/yaw vectoring demonstrates afterbody drag characteristics similar to that of current nozzle designs in conventional use. However, there will be some incremental increase in interference drag when nozzles are deflected to higher angles. Fortunately, by design, thrust vectoring is most frequently used in the slow airspeed/high AOA regime where the impact of interference drag will be minimal. Further discussion of axisymmetric nozzles was derived from reference 8.

3.3.3.1 Digital Flight Controls

The installation of a thrust vectoring system is completely dependent upon the ability of the digital flight control system to coordinate the aerodynamic effect of flight controls and thrust vectoring effect from the new nozzle to create controlled flight throughout an expanded flight

envelope. Digital Electronic Flight Controls (DFCS) have been installed in all block 40 F-16 aircraft. Previous blocks incorporated analog electronic flight controls. The flight control system provides the means for both stability and control throughout the flight regime by commanding flight control surface movement in response to pilot force commands on the control stick. The step to digital technology has provided the F-16 with the ability to optimize control laws in an effort to gain maximum performance out of the F-16 without increasing the likelihood of departure. DFCS is easily reprogrammable and can even be reprogrammed airborne to help maximize flight testing as is the case with the USAF, Variable Inflight Stability Training Aircraft (VISTA) F-16 inflight simulator. During the incorporation of the axisymmetric thrust vectoring nozzle, the use of the VISTA F-16 will be critical in determining the proper combination of thrust vectoring and conventional F-16 aerodynamics for maximum performance. Higher fidelity and reliability associated with digital technology allows for much more precise input in an effort to extract maximum performance. Current F-16 flight control laws discussed in references 1 and 13 have been designed to maximize the performance of the aircraft while still maintaining a sufficient safety margin for flight. Some testing is currently being conducted to investigate methods of controlling excessive body rates which in the past have overshot previously mentioned aircraft limiters. In any case, new modifications to the currently

configured F-16 would likely further limit maneuverability to increase safety margins, not increase performance. The feature attraction of the system for the purposes of this report is that all flight control laws can easily be modified to accommodate another advanced technology such as vectored thrust.

The proper combination of aerodynamic control and thrust vectoring will vary widely depending upon the flight conditions. Current predictions indicate that there is little advantage to thrust vectoring at higher airspeeds because flight controls provide sufficient control. However, at slow airspeeds where dynamic pressure over the control surfaces are low, parasitic drag is low and flow disturbance is low, the effectiveness of thrust vectoring will be much greater. Although much of the testing can be conducted in wind tunnel testing, the use of the VISTA F-16 promises to be the most efficient means of determining the optimum utilization of the digital flight control, nozzle combination.

3.3.3.2 Tactical Application of Turning Performance

In the air-to-air arena, there are essentially two longitudinal characteristics of an airplane which are most useful in the pursuit of an enemy aircraft. Those two characteristics are sustained turn performance and instantaneous turn performance. Both of these

characteristics are useful at different times during an engagement and are equally important to mission success. The key elements of both sustained and instantaneous turn performance are turn radius and turn rate. When one aircraft demonstrates a smaller turn radius and or higher turn rate than an adversary, that airplane is at a distinct advantage in an air to air engagement. Both of these elements equate to a quicker ability of an airplane to bring weapons to bear on an enemy airplane. The following equations taken out of reference 9 describe turn rate and radius for an airplane:

$$\text{Turn Radius} = R = \frac{V_T^2 \quad (\text{fps})}{g\sqrt{N_z^2 - 1}} \tag{3.1}$$

$$\text{Turn Rate} = \frac{g\sqrt{N_z^2 - 1}}{V_T} \tag{3.2}$$

Figure 13 is a representative V-n diagram utilized by tactical pilots to determind tactical advantage.

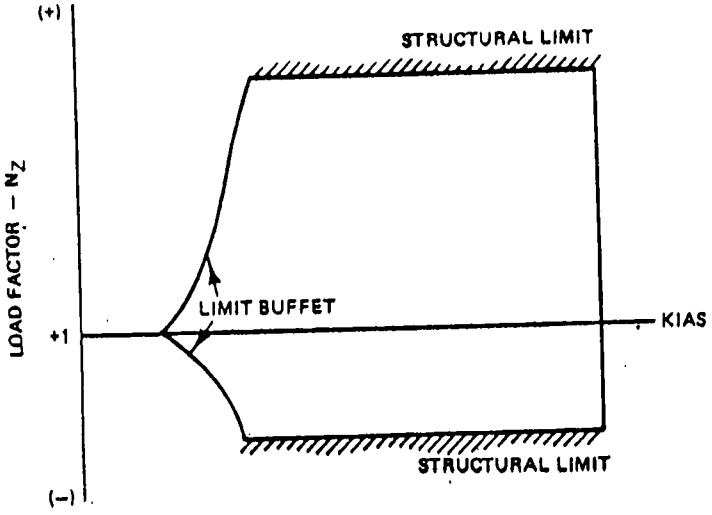


Figure 13

REPRESENTATIVE V-N DIAGRAM

Ideally, maximum sustained turn performance would occur at the lowest airspeed at which an airplane may achieve its maximum available n_z without loosing energy. This condition is dependent upon thrust available, altitude and gross weight of the airplane and may not be attainable. For a given altitude and gross weight condition, maximum sustained turn performance occurs at the n_z where the specific excess power (P_S) of the airplane equates to zero. This allows pilots to have the maximum turn rate and smallest turn radius possible while still maintaining enough energy and speed to provide tactical flexibility. Tactical flexibility is the choice of either disengaging or conducting a maximum instantaneous turn to point and shoot at the adversary. In the case of the F-16, the high thrust to weight and 9g limit equate to an excellent sustained turn performance. Maximum instantaneous turning performance is defined where n_z on the airplane is increased to the point where either the maximum load factor of the airplane, maximum lift (C_{Lmax}) or longitudinal control limit is reached. For the purposes of this evaluation, the maximum load factor for the F-16 is 9.0 g's, C_{Lmax} occurs at approximately 35 degrees AOA and longitudinal control limit is defined as the point where the aircraft could not maintain an air-to-air guns tracking solution on another airplane for 2 seconds. The tactical application of instantaneous turn performance is the ability to quickly point the nose or create high pitch rates without the requirement of

maintaining P_s= 0. Instantaneous turn performance is useful in defeating surface to air missiles which are fired at the aircraft and is also the tool used in quickly point the nose of the airplane at enemy targets to employ weapons. As discussed in reference 8, the limiting factor to instantaneous turning performance above corner airspeed was the maximum load factor of the airplane. However, below corner airspeed, the limiting factor to the F-16 instantaneous turning performance was the 25 degree AOA limiter. This 25 degree limitation severely degrades the ability of the F-16 to quickly point and shoot at enemy aircraft under all conditions.

3.3.3.3 Conventional Approach to Increased F-16 Agility

In the air-to-air arena, higher instantaneous turn performance is directly related to time to kill. Assuming there is no lift due to thrust, maximum instantaneous turn performance is defined by the equation shown below from reference 9:

$$L_{max}=(W)(N_{z_{max}})=1/2\ rho V_t^2 (C_{Lmax}) S \qquad (3.3)$$

L_{max}= Maximum lift of the airplane
W= Gross weight of the airplane
$N_{z_{max}}$= Maximum load factor at the given flight conditions
rho= Atmospheric density
V_t= True airspeed
C_{Lmax}= Maximum lifting coefficient
S= Lifting surface area

The equation for maximum instantaneous turn performance is shown below:

$$n_{z\ \text{inst}}^{\text{avail}} = \frac{C_{L_{max}} \rho V_T^2}{2\,(W/S)} \qquad (3.4)$$

Therefore at any given airspeed and altitude, instantaneous n_z available is a function of C_{Lmax} and wing loading (W/S) of the airplane. In the case of the F-16 where conventional post stall performance may be unrecoverable due to loss of directional stability and pitch hang up, a limiter is required to keep the airplane from ever reaching C_{Lmax} which by default eliminates the potential for conventional flight beyond C_{Lmax}. The pitch limiter in the F-16 limits pitch to 25 degrees AOA and C_{Lmax} of the wing does not occur until approximately 35 degrees AOA. Therefore a conventional aerodynamics approach to increasing agility by increasing C_{Lmax} will not work. In fact, automatic programming leading and trailing edge flaps which are a common mechanism for increasing C_{Lmax} are already in use and do increase C_{Lmax}. Still, the complete benefit of these high lift devices cannot be utilized because AOA is limited well below 35 degrees AOA due to loss of directional stability and pitch hang up. Another conventional approach to eliminating the need for the AOA OR pitch limiter and increasing $n_{z_{max\ inst}}$ which might be derived from equation 3.4 would be to decrease wing loading. This could be accomplished by either decreasing the gross weight of the airplane or increasing the planform area

of the wing. The possibility of decreasing gross weight enough to appreciably decrease wing loading is very unlikely in the case of a mature airplane like the F-16 which has been streamlined for years. The conventional approach to increasing the planform area of the wing without adversely affecting the other performance characteristics of the airplane is most easily accomplished once again by the use of leading and trailing edge flap which are already incorporated in the F-16. Once again however, neither of these methods addresses the overriding limiting factor which is the loss of directional stability due to vertical tail blanking and pitch hang up, not limited aerodynamic lift. Since conventional use of aerodynamic lift to improve agility is not practicable, an alternative method of increasing instantaneous turn performance below corner airspeed is desired. An analysis of the directional and longitudinal moments experienced by the F-16 which provide directional and pitch stability and control is required.

3.3.3.4 Alternative Analysis for F-16 Increased Agility

The pitch, yaw and roll performance limitations of the F-16 observed during flight test are self imposed limitations and do not actually approach C_{Lmax}. Instead of the conventional approaches discussed above which addressed the symptoms of the underlying deficiency, a new and innovative approach is required to address the core of the problem. The

challenge of maintaining directional stability on a single engine airplane without the use of the vertical stabilizer is a different proposition. For the purpose of clarification, the body axis system shown in figure 14 will be utilized in further discussion.

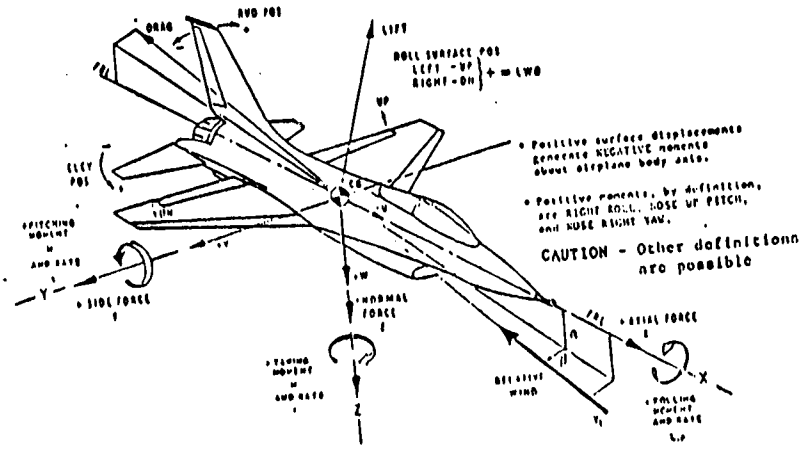


Figure 14

BODY AXIS REFERENCE DIAGRAM

Since conventional aerodynamic modifications alone cannot supply an adequate yawing moment to control directional stability, another source of the yawing moment is required. Addition of an axisymmetric thrust vectoring nozzle has the potential to not only address directional stability but can also greatly enhance the agility of the airplane.

3.3.4.1 Directional Yawing Moments

Directional stability for the F-16 is maintained largely by rudder deflections which create yawing moments. For the

purposes of this explanation adverse yaw, fuselage contribution to directional stability, or rolling moments and sideforces developed by rudder deflection will not be considered since the yawing moment from the rudder is by far the major contributing factor in yaw control (reference phone conversation with Doyle Jansen, F-16 Combined Test Force). When the rudder is deflected, a sideforce is generated on the vertical stabilizer which affectively creates a sideforce in the Y axis on the tail of the airplane causing a yaw moment as shown in figure 15.

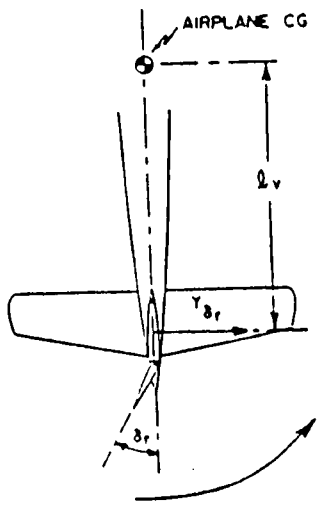


Figure 15

YAWING MOMENT DUE TO RUDDER DEFLECTION

It is easily understood that as the tail is blanked at high AOA, the ability of the rudder to generate directionally stabilizing force decreases. Potential solutions for loss of directional stability and control are to either redirect airflow over the vertical stabilizer or to find another means of providing a yawing moment. To redirect airflow in a manner which provides enough dynamic pressure over the

vertical stabilizer is likely to be impractical and costly in the case of the F-16 where the single vertical tail runs along the fuselage axis. Another aircraft which operates at high AOA without directional stability problems is the twin tailed FA-18. The reason for the FA-18's ability to operate at high AOA is due to the fact that a vortex is produced by the leading edge extension of the airplane which flows over the outwardly canted vertical stabilizer. The flow from the vortex provides enough dynamic pressure on the control surface to provide sufficient directional control power at higher AOA. Any effort to design twin canted tails or redirect the F-16 vortices straight back down the fuselage would likely be extremely expensive.

However, using a vectored thrust nozzle as an alternate means of providing an additional yawing moment to the airplane may be more practical and it is the exact effect of the axisymmetric thrust vectoring nozzle. As shown in the calculation below, 17 degrees of thrust vectoring provides a substantial yawing moment.

Yawing moment due to vectored thrust=
Trust x sin(thrust vector angle) x moment arm= (3.5)
29000 lbs (sin 17 degrees)(22.6 ft)=191620 ft lbs

Neglecting the loss of thrust due to deflection of the nozzle and effects on afterbody drag, a yawing moment of 191620 ft lbs can be generated. The large yawing moment combined with

the exceptionally high articulation rate of the nozzle (45 deg/sec) has the potential to provide more than adequate directional control to provide stability for the F-16 when the tail is completely blanked based upon predicted modeling to date.

3.3.3.4.2 Longitudinal Pitching Moments

When the problem of directional stability is resolved by the use of vectored thrust, the door to unsurpassed agility in the pitch axis is opened for the F-16. Since the nozzle can deflect in both pitch and yaw, the increased performance in the pitch axis at slow speeds could be exceptional. Unlike directional control where rudder control power was the dominate factor in maintaining control, in the longitudinal axis the wing, fuselage, tail and thrust effects all have a considerable effect in maintaining longitudinal stability and control as described in reference 10. The effects of each contributor are summed as shown in the equation below:

$$C_{m_{CG_{total}}} = C_{m_{CG_{wing}}} + C_{m_{CG_{fus}}} + C_{m_{CG_{tail}}} + C_{m_{CG_{power}}} \qquad (3.6)$$

$C_{m_{CG_{total}}}$ = total pitching moment coefficient about the center of gravity

$C_{m_{CG_{wing}}}$ = wing contribution to pitching moment coefficient about the center of gravity

$C_{m_{CG_{fus}}}$ =

fuselage contribution to pitching moment coefficient about the center of gravity

$C_{m_{CG_{tail}}}$ =

tail contribution to pitching moment coefficient about the center of gravity

$C_{m_{CG_{power}}}$ =

power contribution to pitching moment coefficient about the center of gravity

Given that directional stability is no longer a problem for the F-16 at high AOA, an analysis of each contributor to longitudinal stability and control can be conducted to determine how pitch performance can be optimized to provide maximum agility. Equations for each term were derived in reference 3.

$C_{m_{CGwing}}$ is defined by the following equation and figure 16:

$$C_{m_{CGwing}} = C_{m_{ac}} + \left(\frac{X_{CG}}{\bar{c}} - \frac{X_{ac}}{\bar{c}} \right) C_{L_w} \qquad (3.7)$$

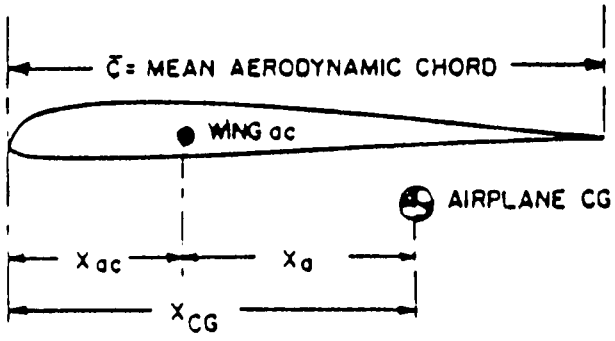


Figure 16

ILLUSTRATION OF WING LOCATIONS

With an operating center of gravity greater than 30% aft along the wing chord during normal flight and assuming that the aerodynamic center is approximately 25 % aft along the wing chord, the wing already provides a large nose up pitching moment. Although destabilizing in nature, large nose up pitching moments are useful in providing higher pitch rates and thus greater agility. Further expansion of the wings contribution to pitching moment does not address the underlying problems of lost directional stability and control or pitch hangup. In fact, although the current configuration greatly enhances the F-16 pitch rates below 15 degrees AOA and decreases trim drag, the wing actually stalls at about 32 degrees AOA and is one of the major contributing factors to the pitch hang up phenomenon demonstrated by the F-16 at about 50 degrees AOA. The goal of optimizing agility would not likely be accomplished by increasing the relative effect of $C_{m_{CGwing}}$.

$C_{m_{CGfus}}$ is also destabilizing in nature on the F-16 as it is on most airplanes. An accepted equation for the fuselage contribution to pitching moment is shown below:

$$C_{m_{CGfus}} = C_{m_{CG}}\Big|_{\substack{FUS \\ C_{L_w} = 0}} + \left(\frac{dC_m}{dC_L}\right)_{FUS} C_{L_w} \qquad (3.8)$$

Reference3 discusses fuselage shape and mating of the wing to the fuselage as key areas that contribute to the fuselage contribution. Because of the leading edge extension, the blended wing/fuselage design and the inlet below the

fuselage the nose up pitching moment caused by the fuselage is likely to be especially high in the case of the F-16. As is the case with the wing contribution to pitching moments, any modification to the fuselage nose up pitching moment does not address the fundamental problem of lost directional stability and control. In fact, it is the fuselage itself which blanks airflow over the vertical stabilizer. It is likely that little optimization of agility could be accomplished by reshaping the fuselage to increase the contribution to pitching moment.

In the case of the tail contribution, $C_{m_{CGtail}}$ provides the only nose down pitching moment on the airplane since the effect of power on the pitching moment of the conventional F-16 is zero. The contribution of the tail is described by the equation shown below from reference3.

$$C_{m_{CGtail}} = - a_t \ (\alpha_{w_o} - i_w) \ \eta_t \ \overline{V} + {}^{C_m}{}_{i_t} \ i_t + \left[- \frac{a_t}{a_w} \left(1 - \frac{d\varepsilon}{a\alpha}\right) \eta_t \ \overline{V} \right] \ C_{L_w}$$

The tail provides both stability and control of the longitudinal axis of the F-16. The tail acts much the same as a conventional wing, however there are several terms in the equation which are unique to the horizontal stabilizer. The additional considerations accounted for in the tails contribution are due to disturbed flow of the air coming from the wing which effects the angle of attack of the airflow as it hits the tail. The efficiency factor and downwash angle, are a factor of where the tail is mounted on the fuselage and

how the airflow deflected by the wing hits the control surface. Another major factor in the tail contribution is the length of the moment arm from the center of pressure on the tail to the center of gravity of the airplane. Any significant improvement in longitudinal stability and control achieved by modifying the horizontal tail would likely be very small and not cost effective.

The $C_{m_{CGpower}}$ contribution to pitching moment by power on the conventional F-16 is essentially zero since the engine lies directly along the longitudinal axis. However, the contribution could be greatly enhanced with the addition of an axisymmetric thrust vectoring nozzle. The nozzle would provide another strong influence to the pitch axis of the airplane. At slower airspeeds where the decrease in dynamic pressure over the tail of the airplane decreased the tail effectiveness, pitch vectored power could add up to 191620 ft lbs of pitching moment with 29000 lbs of thrust deflected 17 degrees as shown in the calculation below.

Pitching moment due to vectored thrust=

Trust x sin(thrust vector angle) x moment arm= (3.9)

29000 lbs (sin 17 degrees)(22.6 ft)=191620 ft lbs

Assuming that the engine could fly at high AOA without power restrictions and that the thrust lost due to the deflected nozzle were minimal, the new nozzle has the potential to dramatically improve the pitch performance characteristics of the airplane. With the current conventional configuration,

the AOA hang-up which occurs at approximately 50 degrees AOA is just strong enough that the tail cannot pitch the nose out of the deep stall. The current procedure to break the high AOA hang-up is to override the pitch limiter (which prevents trailing edge up slab deflections) and then rocking in pitch. Using thrust vectoring could completely eliminate the AOA hang up phenomenon by providing a strong and controllable pitching moment to maintain control independent of airspeed and AOA. Another major attraction of the axisymmetric thrust vectoring nozzle is the fact that there would be no aerodynamic modifications to the airplane and that all existing F-16s could be retrofited to the new configuration.

3.3.3.5 Tactical Applications to Axisymmetric Thrust Vectoring

Aside from virtually eliminating stability and control problems at high AOAs, thrust vectoring has tremendous tactical applications. The flight envelope has the potential of being greatly expanded. As discussed earlier, the ability to pitch the nose quickly is directly tied to time to kill and is essential to survival. Any small improvement in these tactical areas geatly enhances the ability of the F-16 to perform the strike fighter mission.

Figure 17 from reference 10 illustrates the potential expanded flight envelope using thrust vectoring.

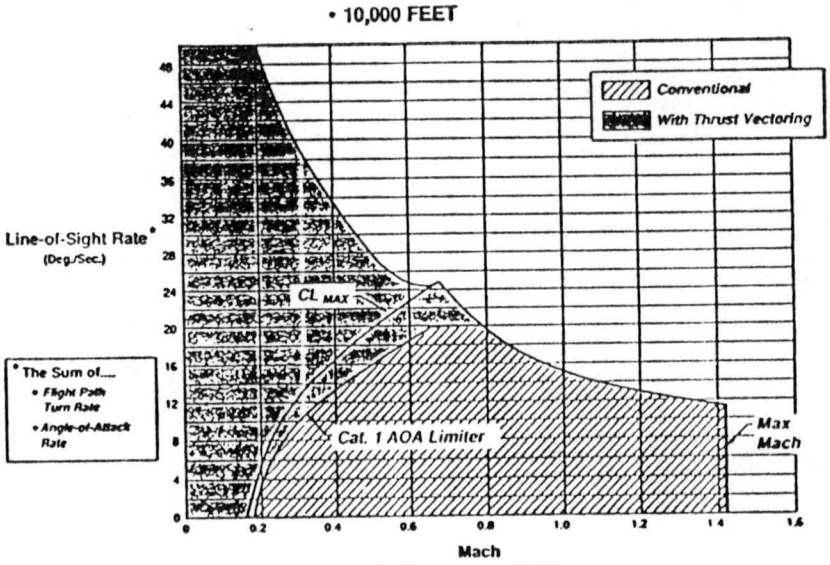


Figure 17

EXPANDED FLIGHT ENVELOPE WITH THRUST VECTORING

Figure 18 from reference 10 illustrated the potential effects of thrust vectoring on nose pointing authority.

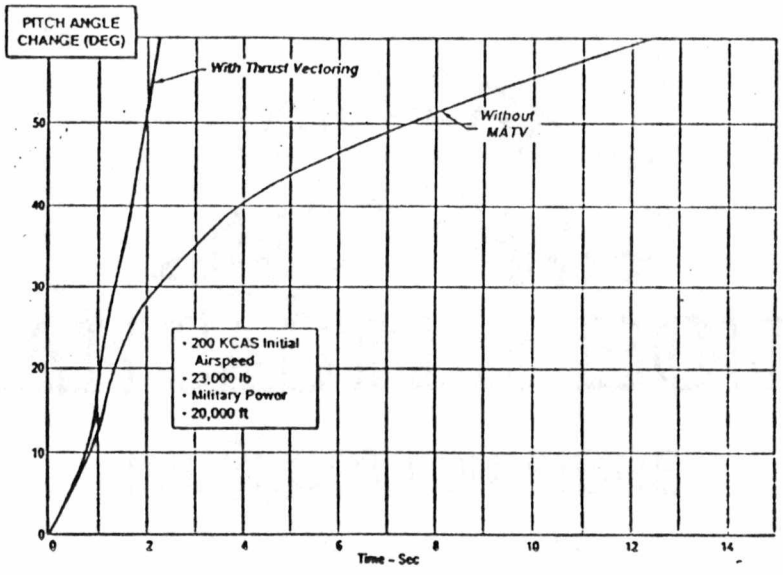


Figure 18

THRUST VECTORING EFFECTS ON NOSE POINTING

Figure 19 form reference 10 illustrates the potential decrease in time to kill using thrust vectoring.

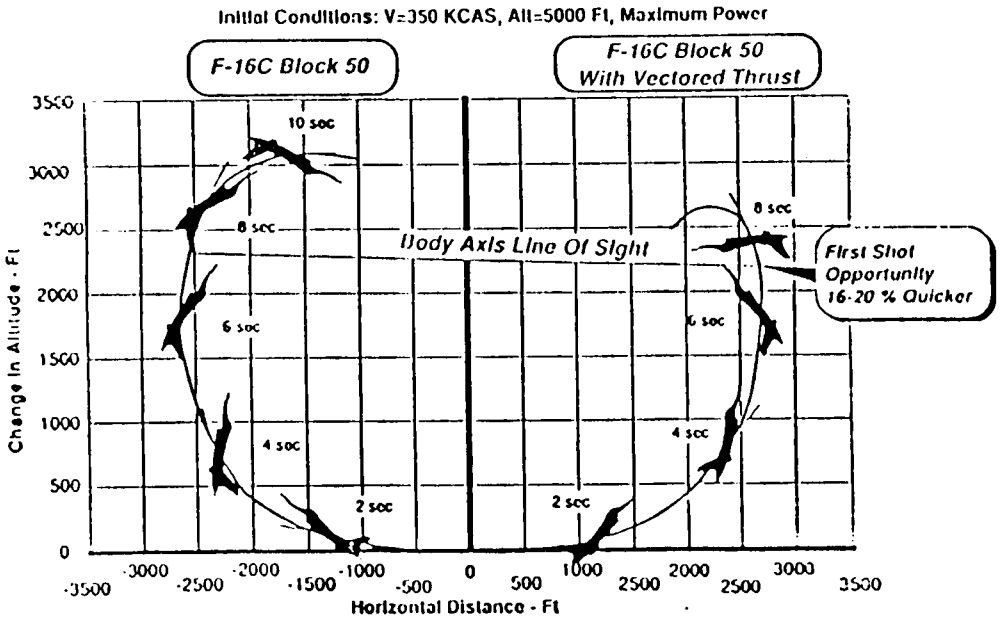


Figure 19

TIME TO KILL

Multi-axis thrust vectoring represents a 16 to 20% decrease in time to first shot over the conventional F-16. The shape of a loop performed by an aircraft employing thrust vectoring illustrates the potential advantage at high AOA or slow airspeed. The top of the loop is more of a teardrop shape because of the increased pitching moment introduced by the nozzle. This type of agility is currently unknown in aviation and would easily take the F-16 into the 21st century. An illustration of the advantage gained by multi-

axis thrust vectoring in a loop compared to a conventional F-16 is shown in figure 20.

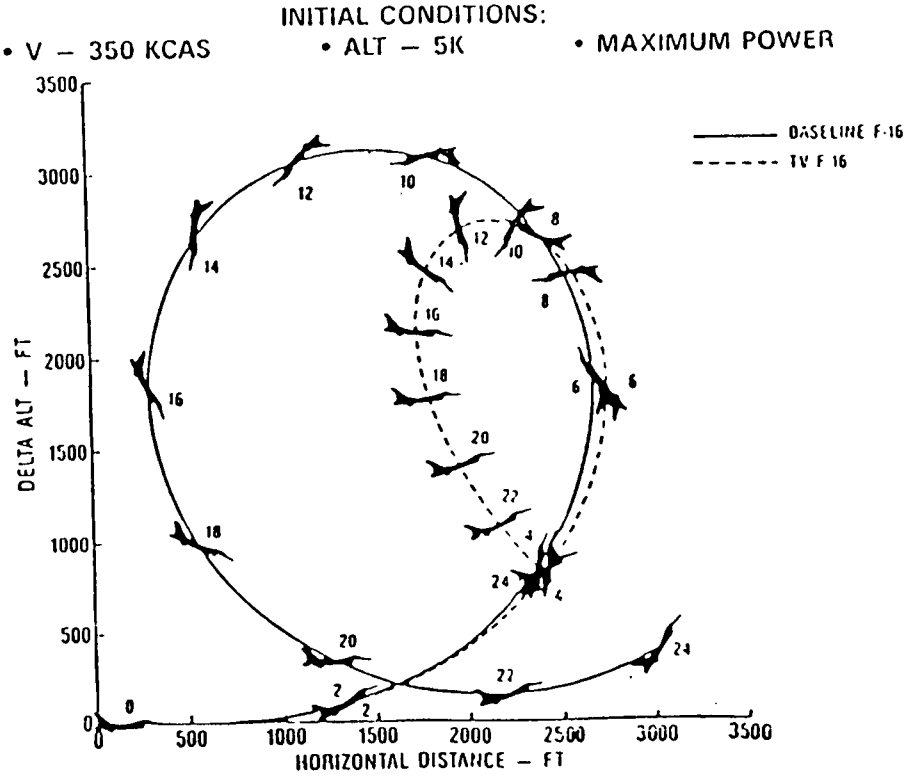


Figure 20

CONVENTIONAL VS THRUST VECTORING LOOP

4. CONCLUSIONS AND RECOMMENDATIONS

4.1 GENERAL

Although adequate for current air warfare requirements, the F-16 has demonstrated several deficiencies which will preclude effective mission performance in future conflicts. With the correction of these major deficiencies, the F-16 has excellent potential for use as a multi-mission strike fighter aircraft well into the 21st century.

4.2 SUMMARY OF CONCLUSIONS AND RECOMMENDATIONS

A. The current AB limitations for the F-16 are unsatisfactory. Installation of the new F100-PW-229 engine will virtually eliminate any AB restrictions while increasing thrust by approximately 13%. In testing to date the 229 engine has demonstrated a full throttle transient capability throughout the flight envelope without compressor stall or AB blowout.

B. Loss of directional stability and control above 25 degrees AOA as well as pitch hang up at higher AOA has perpetuated the need for pitch, yaw and roll rate limiters and is unsatisfactory. Integration of the fully articulated pitch/yaw thrust vectoring nozzles designed by GW or PW as installed on the F100-PW-229 has the potential to eliminate the loss of directional stability and control due to vertical stabilizer blanking by providing a pitching and yawing moment

independent of airspeed and AOA. Due to the critical nature of the proposed modification, a triple redundant hydraulic actuation system with integrated switching valves between systems is recommended to avoid the possibility of system failure due to a single or dual point failure. The primary design concern should be reliability followed by performance. Integration of the nozzle should be fully automatic and transparent to the aircrew. Additional research is required to define the testing requirements for thrust vectoring.

REFERENCES

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3. Brief prepared by F-16 Combined Test Force on the F-100-PW-229 Engine.Effects at Speeds up to Mach 2.0, dated February 1992.

4. Aviation Week and Space Technology, March 1992, artical on "Axisummetric Thrust Vectoring Nozzles for Fighters", p. 44.

5. Major M. Costigan, STOL/Maneuver Technology Demonstrator Final Report, dated December 1991.

6. NASA Technical Note, NASA TN D-8449, Performance of Twin Two-Dimensional Wedge Nozzles Including Thrust Vectoring and Reversing Effect at Speeds Up to Mach 2.20, NASA TN D-8449, July 1977.

7. NAS2-12661, Briefing slides from NASA High Alpha Research Vehicle Thrust Vectoring COntrol System Preliminary Design Review, dated 31 March 1988.

8. Brief prepared by F-16 Combined Test Force on Multi Axis Thrust Vectoring, dated March 1992.

9. Naval Test Pilot School Flight Test Manual, Performance, USNTPS-FTM-No. 103, dated 1 January 1977.

10. Naval Test Pilot School Flight Test Manual, Fixed Wing Stability and Control, USNTPS-FTM-No. 104, dated 1 January 1977.

APPENDICIES

Appendix A- Illustrations

1. F-16 Airplane
2. F-16 Cockpit
3. HARV FA-18

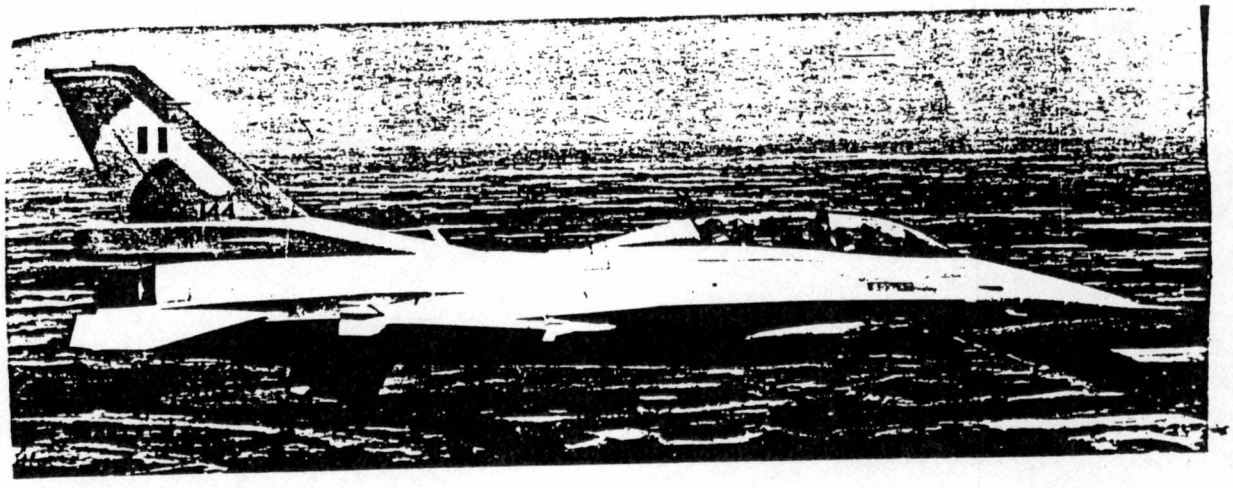
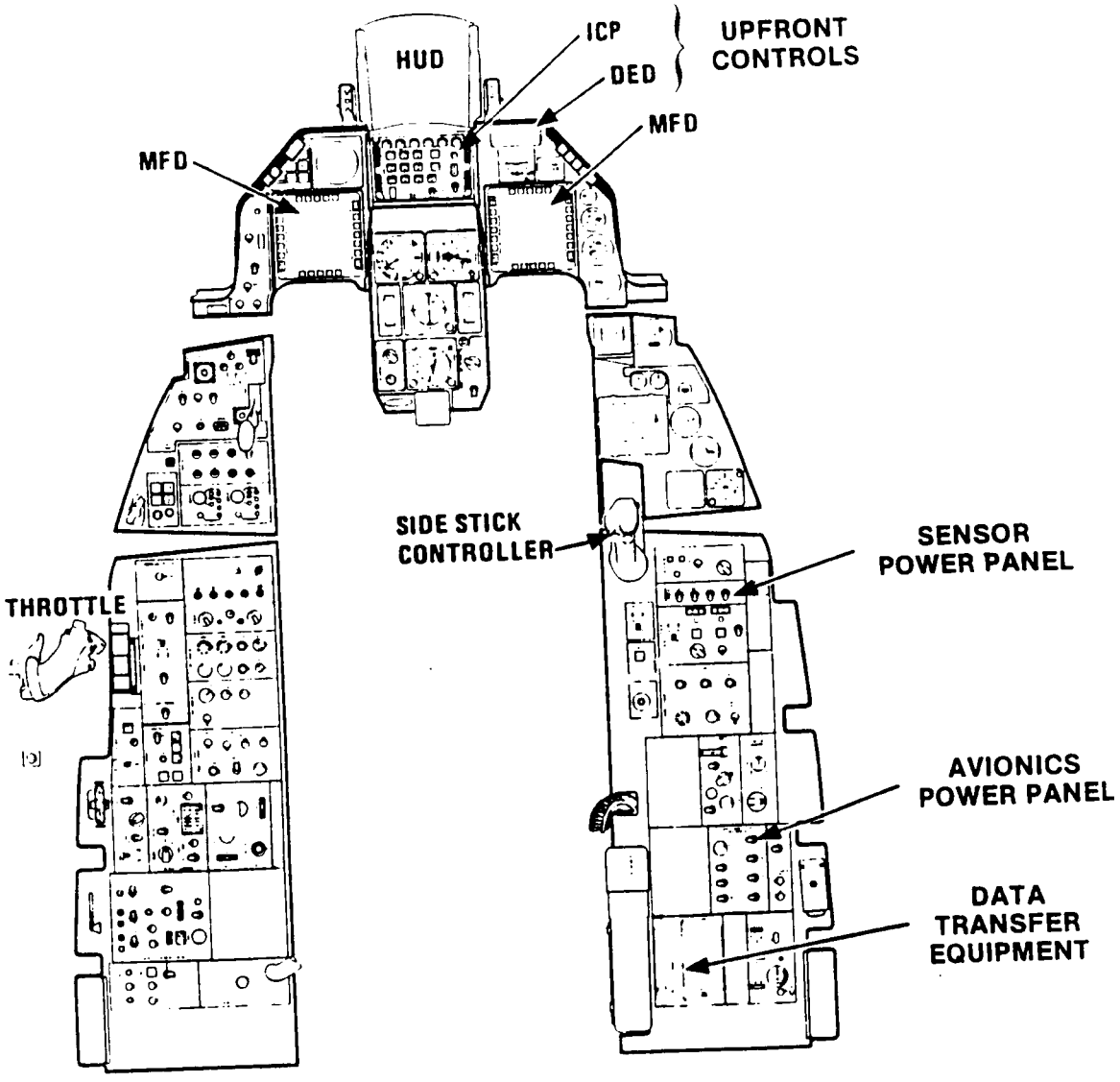


Figure 1
F-16B AIRPLANE

APPENDIX A


HUD
ICP
DED
UPFRONT CONTROLS
MFD
MFD
SIDE STICK CONTROLLER
SENSOR POWER PANEL
THROTTLE
AVIONICS POWER PANEL
DATA TRANSFER EQUIPMENT

ANNEX A

ANNEX A

VITA

LCDR David A Dunaway was born in El Paso, Texas in June 13, 1960. He attended elementary schools in the El Paso Independent School District and graduated from W. H. Burgess High School in 1978. The following July he reported to the United States Naval Academy and graduated with a Bachelor of Science in Mechanical Engineering. He was selected for flight training and received his wings in March 1984. Since becoming a qualified naval aviator he has been assigned to VT-9 as a flight instructor, VFA-151 as an operational fleet aviator, U. S. Naval Test Pilot School for instruction as a test pilot and to Air Test and Evaluation Squadron Five as a Test Pilot.