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FLIGHT TEST RESULTS OF THE F-16 AIRCRAFT MODIFIED WITH THE AXISYMMETRIC VECTORING EXHAUST NOZZLE

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This paper presents the results of the envelope expansion phase of the F-16 Multi-Axis Thrust Vectoring (MATV) program. The objectives and test approach will be presented followed by results of testing with the initial control law configuration. The revised flight control laws will be discussed followed by test results with the revised control laws. Additional testing added to the program, nose-chines, parameter identification maneuvers, and the extended range angle of attack cones will also be briefly discussed.

OVERVIEW

TEST APPROACH

OBJECTIVES

RESULTS OF TESTING WITH INITIAL FLIGHT CONTROL LAWS

REVISION OF THE FLIGHT CONTROL LAWS

RESULTS OF TESTING WITH REVISED CONTROL LAWS

ADDITIONAL TESTING

The flight test program was a three phase effort. Phase I functionally verified the aircraft and systems within the current F-16 Category I angle of attack limitations, Phase II expanded the angle of attack envelope utilizing the thrust vectoring system, and Phase III provided a tactical utility assessment and demonstration of the expanded maneuvering envelope. The program attempted to quickly expand the useable F-16 envelope from the current 25 degrees angle of attack to beyond 80 degrees and attain its final goal of 1 V 1 and 1 V 2 fighter engagement scenarios. Flight testing began in July 1993 and continued through March 1994.

TEST APPROACH

PHASE I - FUCTIONAL CHECK FLIGHTS

- AIRWORTHINESS
- ENGINE OPERABILITY IN STANDBY
- AIRSTARTS
- DEPARTURE RECOVERIES

PHASE II - ENVELOPE EXPANSION

- OPEN LOOP MANEUVERS
- CLOSED LOOP MANEUVERS

PHASE III - TACTICAL UTILITY ASSESSMENT

- FUNCTIONAL MANEUVER DEVELOPEMENT
- OPERATIONAL ASSESSMENT
- FLIGHT DEMONSTRATIONS

The stability and control portion of the F-16 Multi-Axis Thrust Vectoring (MATV) flight test program was designed to achieve the following objectives:

- Clear an expanded maneuvering envelope to enable a meaningful tactical utility assessment
- Assess capability of AVEN/FLCS combination to provide stability and control power in the expanded envelope
- Assess the handling qualities and maneuvering performance of the MATV aircraft in the expanded envelope
- Determine stability derivatives of the MATV aircraft with and without a nose-chine

The most important of these objectives was to provide a maneuvering envelope to be used in the tactical utility assessment as well as VIP demonstrations. In order to achieve this goal, an aggressive yet safe test approach was devised.

OBJECTIVES

CLEAR AN EXPANDED MANEUVERING ENVELOPE TO ENABLE A MEANINGFUL TACTICAL UTILITY ASSESSMENT

ASSESS CAPABILITY OF AVEN/FLCS COMBINATION TO PROVIDE STABILITY AND CONTROL POWER IN THE EXPANDED ENVELOPE

ASSESS THE HANDLING QUALITIES AND MANEUVERING PERFORMANCE OF THE MATV AIRCRAFT IN THE EXPANDED ENVELOPE

DETERMINE STABILITY DERIVATIVES OF THE MATV AIRCRAFT WITH AND WITHOUT A NOSE-CHINE

Envelope expansion maneuvers were conducted between 20,000 and 35,000 feet altitude. In order to achieve the goal of providing a cleared tactical maneuvering envelope for Phase III, this testing attempted to verify that the F-16 MATV aircraft was controllable and the F110 engine was operable throughout the flight regime with no restrictions on pilot control or throttle inputs. If pilot input restrictions were required due to undesirable or uncontrollable aircraft or engine response to specific inputs, those input limitations would be used during Phase III of the program.

The accompanying chart depicts the envelope expansion maneuvers. Testing began at the higher altitude block of 30k-35k feet altitude to allow for sufficient time for recovery if a departure occurred. Open loop maneuvers, defined as test maneuvers designed to assess the airframe and flight control system dynamic response to defined pilot inputs, included stabilizations and doublets. These were initially performed in military power, although this is the area of least control power from thrust vectoring, beginning in military power made sense from a propulsion standpoint due to improved stall margins.

Testing then proceeded to maximum afterburner points. This testing included a repeat of the stabilizations and doublets and added pushover/pullups, lateral stick reversals, yaw pedal reversals, 360-degree rolls, both lateral stick and yaw pedal, wind-up turns, and 360-degree rolls at elevated-g, both lateral stick and yaw pedal. This concluded the open loop block maneuvers at the high altitude block and testing proceeded to closed loop maneuvers.

Closed loop maneuvers were defined as test maneuvers designed to assess the aircraft system response to pilot inputs performed as part of a specific mission related task and included maximum pitch rate maneuvers, maximum yaw rate maneuvers, pitch, roll, and yaw capture and tracking maneuvers, and yaw/roll cross control maneuvers all in maximum afterburner. Throttle transients were then performed and concluded the testing at the 30k-35k feet altitude block.

Testing then continued at the lower altitude block of 20k-25k feet and included open loop maneuvers in military power and maximum afterburner, as well as closed loop maneuvers in both military and maximum afterburner. Provisions were made in the test program to allow for one revision to the flight control laws.

ENVELOPE EXPANSION MANEUVERS

OPEN LOOP MANEUVERS

- ANGLE OF ATTACK STABILIZATIONS
- PITCH, ROLL, YAW DOUBLETS
- PUSHOVER / PULLUP
- LATERAL STICK REVERSALS
- YAW PEDAL REVERSALS
- LATERAL STICK 360 DEGREE ROLLS
- YAW PEDAL 360 DEGREE ROLLS
- WIND UP TURNS
- 360 DEGREE LOADED ROLLS

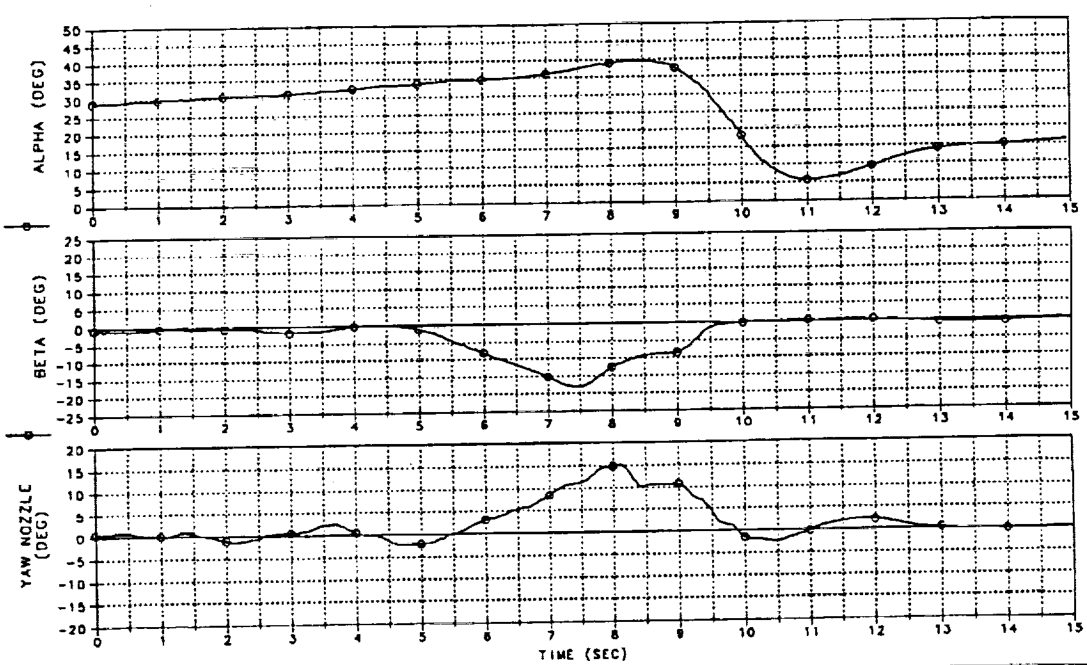
CLOSED LOOP MANEUVERS

- MAXIMUM PITCH RATE
  - HORIZONTAL
  - PULL UP
  - SPLIT S
  - LIMITER TRANSIENT
- MAXIMUM YAW RATE
- VERT PLANE REVERSALS
- HAMMERHEAD TURN
- J TURN
- ROLL/YAW CROSS CONTROL
- PITCH CAPTURES
- BANK ANGLE CAPTURES
- YAW CAPTURES

As planned, envelope expansion testing began at the high altitude block in military power with open loop maneuvers. Stabilizations and doublets were successfully performed from 5 to 30 degrees angle of attack in 5 degree increments with thrust vectoring active. Results from the next point, a 35 degree stabilization were not as favorable. The accompanying figure shows a time history of this maneuver. As angle of attack approaches 35 degrees, a rapid nose-slice of about 18 degrees to the right occurs. This is the classic sideslip departure inherent to the F-16, due to reduced directional stability, with one exception, angle of attack is well contained and the aircraft recovers with a nose-down command. Yaw nozzle saturation in military power was insufficient to oppose this nose-slice tendency.

MIL POWER STABLILIZATION

35 DEGREES 35,000 FEET

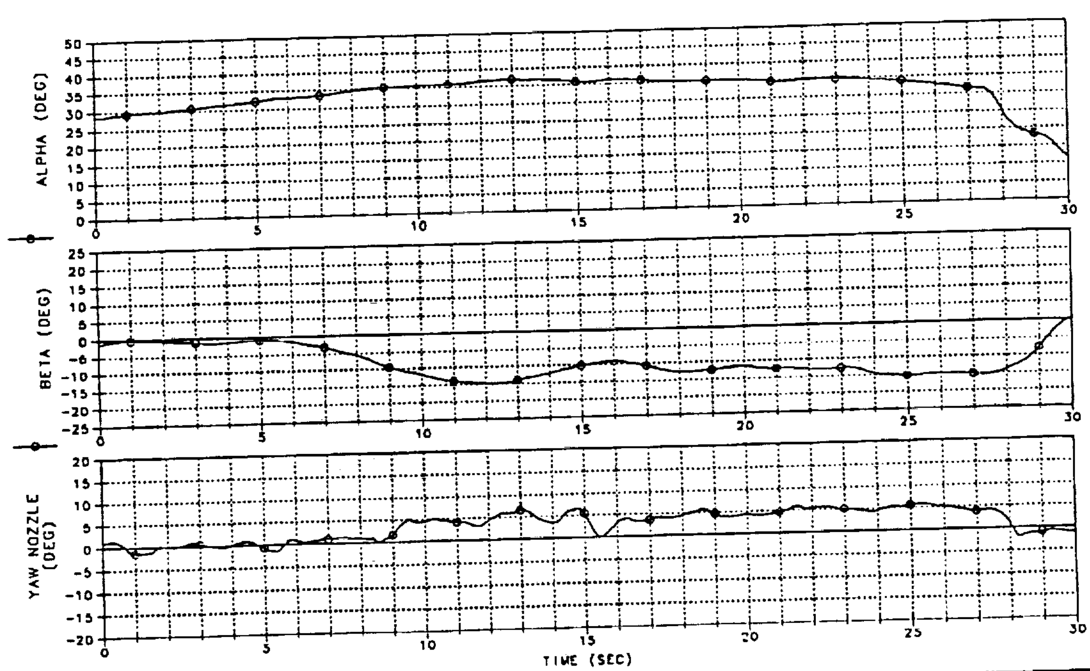


A brief control room discussion resulted in a decision to attempt the same maneuver in maximum afterburner in hopes of reducing the nose-slice with increased yaw control power. The accompanying figure is the time history for this maneuver. Once again the nose-slice was evident at about 35 degrees, but this time sideslip was more contained, between 10 and 15 degrees, and angle of attack was easily controlled. Additional yaw power was available to reduce this sideslip, however due to bias in sideslip measurement and relatively low sideslip feedback gains, the system allowed this sideslip to occur. As a result, the remaining maneuvers in military power at the high altitude block were deleted and testing at this altitude proceeded using maximum afterburner.

Angle of attack stabilizations were performed up to the maximum obtainable, about 70 degrees. Although sideslip oscillations of 10-15 degrees were prevalent at all angles of attack, and these oscillations were less than desireable, the aircraft was controllable and testing proceeded. The rest of the open loop maneuvers were performed per the test plan up to 70 degrees with the exception of the yaw and roll doublets which could not be performed due to the sideslip oscillations.

MAX POWER STABILIZATION

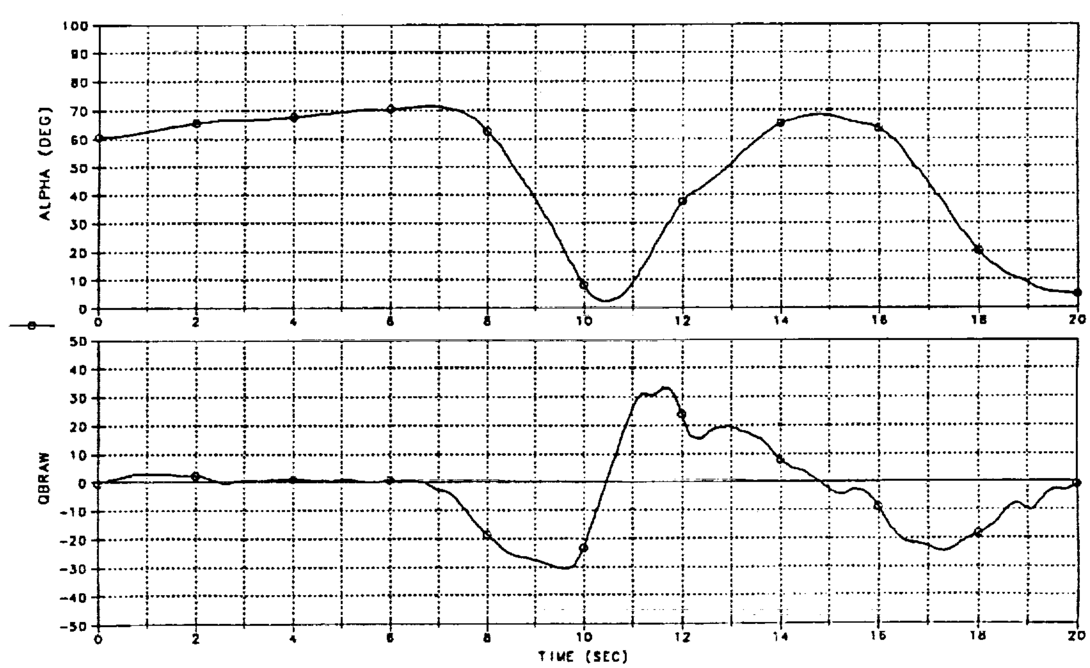
35 DEGREES 35,000 FEET



Pitch response during the push-pull maneuvers was very good with the ability to maintain and capture a given angle of attack precisely. The accompanying figure depicts this capability during a 70 degree push-pull. Control power, limited by control laws and never available power, was more than adequate. Wing rock and nose-oscillations were evident during the pitch maneuvers but did not significantly hinder the completion of the maneuver.

MAX POWER PUSHOVER / PULLUP

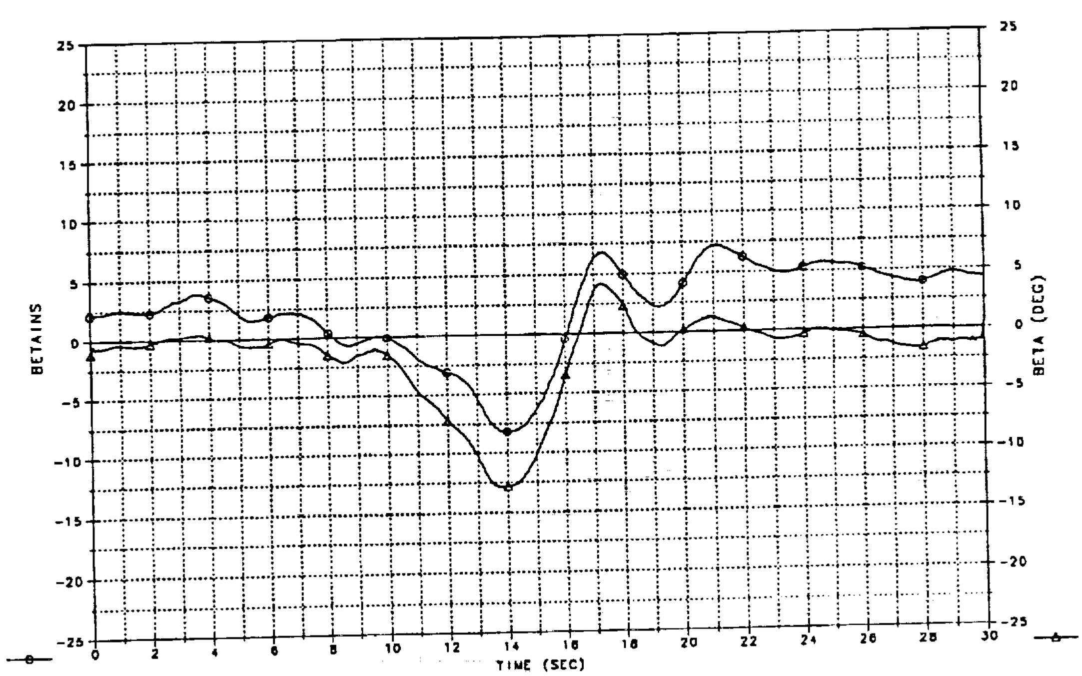
70 DEGREES 35,000 FEET



Results of roll and yaw maneuvers were not as impressive as pitch maneuvers. Lateral stick and yaw pedal reversals (30 to 30 degrees of bank or 90 to 90 degrees of heading) often resulted in overshoots of the intended bank angle or heading change. This was especially evident in the 35-50 degree angle-of-attack range, where aircraft response relied heavily on control authority from the flaperons and rudder. Roll hesitation or reversals were also evident in this angle-of-attack regime. One anomaly noted was a bias between the FLCS sideslip from the INS source as compared to the corrected noseboom sideslip. This is shown during a 35 degree angle of attack stabilization in the accompanying figure. This bias was attributed to the point at which the winds were locked for calculation of INS sideslip and was updated in the revised control laws.

SIDESLIP MEASUREMENT COMPARISON

MAX POWER 35 DEGREE STABILIZATION

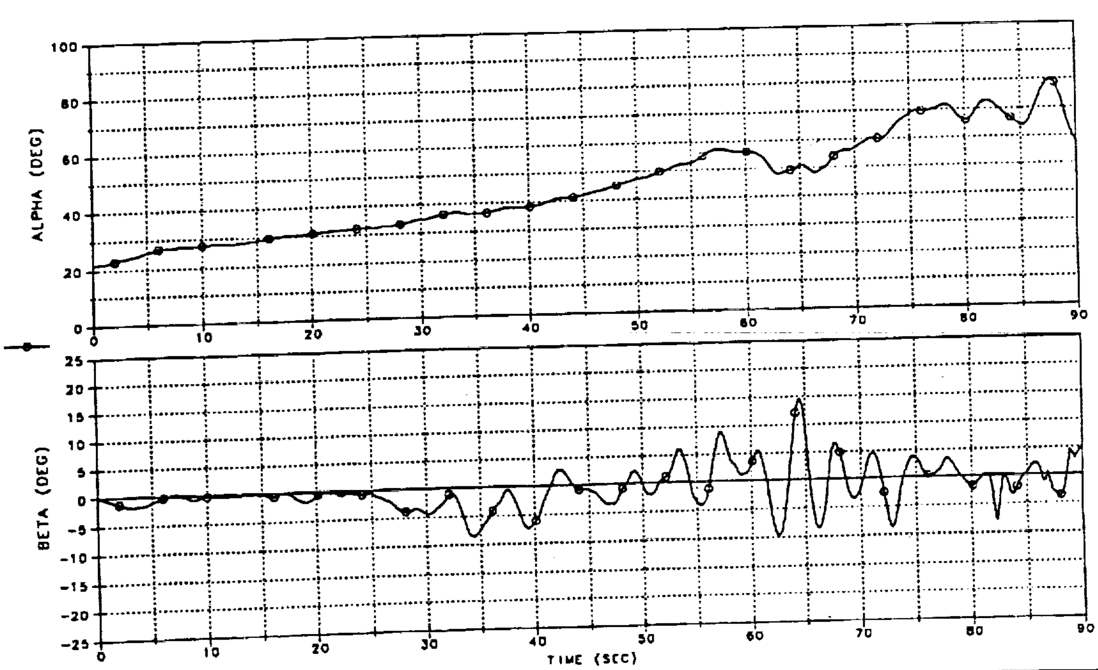


After completion of the planned testing in the 30k-35k feet altitude block, testing progressed to the lower block of 20k-25k feet. It was anticipated that the increase in thrust at this altitude would improve the less than desireable lateral-directional handling qualities observed at the higher altitude. In addition, work was already underway on revisions to the control laws and since the plan was to perform the rest of the test program at 20k-25k feet, it made sense to see the results at this altitude before finalizing any control law changes.

Testing at the lower altitude began using military power. As was expected, the aircraft response was similar to the results of the 30k-35k maneuvers in maximum afterburner, since engine thrust is comparable at these conditions. Testing progressed to maximum afterburner maneuvers, the accompanying figure is a time history of an angle of attack sweep. The increased thrust and control power became evident at these conditions. The initial nose-slice as angle of attack approaches 35 degrees was reduced to about 8 degrees compared to over 15 degrees in military power.

MAX POWER AOA SWEEP

25,000 FEET



Numerous modifications were made in the revised flight control laws to improve handling qualities with emphasis on the lateral-directional axes in the 35 to 55 degree angle of attack region. Two types of modifications were included. First, any change that would definitely result in improved handling qualities was fixed in the new software, such as the calculation of INS angle of attack and sideslip and the normalization of gain schedules with thrust. Second, were modifications that allowed for changes to be pilot selectable in flight, such as the multiplier on the sideslip feedback gain and eliminating lateral stick inputs at high angles of attack. The accompanying chart lists the revised flight control law modifications.

REVISED FLIGHT CONTROL LAWS

MODIFICATIONS FIXED IN REVISED OFP

IMPROVEMENTS TO INS ALPHA / BETA ESTIMATOR

NORMALIZING GAIN SCHEDULES WITH THRUST

INCREASED AILERON-RUDDER INTERCONNECT GAIN

IN FLIGHT PILOT SELECTABLE MODIFICATIONS

REDUCED ROLL STICK GRADIENT

AOA LIMITER OF 80 DEGREES

DIFFERENTIAL FLAP UP ONLY FOR ROLL CONTROL

NO LATERAL STICK COMMAND AT HIGH AOA

NO RUDDER COMMAND AT HIGH AOA

ADJUSTABLE BREAK POINT FOR CONVENTIONAL TO BODY-AXIS YAW-RATE COMMAND

ADJUSTABLE GAIN MULTIPLIERS FOR

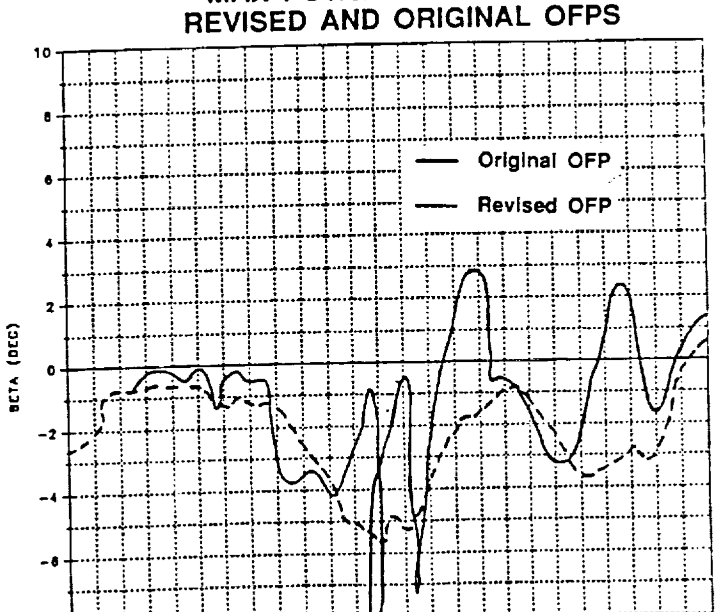
- SIDESLIP FEEDBACK
- SIDESLIP RATE FEEDBACK
- ROLL RATE FEEDBACK
- YAW RATE FEEDBACK

A slow angle of attack sweep, pitch roll, and yaw doublets as well as lateral stick and yaw pedal reversal were performed as abaseline with the revised flight control laws at 20k-25k feet altitude. The accompanying figure shows a comparison of sideslip versus angle of attack for the original and revised flight control laws. This data was obtained from maximum afterburner slow angle of attack sweeps. Note that not only was the magnitude of the nose-right excursion between 35 and 40 degrees reduced by about 35 percent, but also the random nose-wandering was eliminated.

Optimization of the control laws then proceeded evaluating yaw response at the higher angles of attack and roll response at the mid angles of attack utilizing open loop maneuvers. Compromises were required to gain a balance in aircraft response in these two regions, but satisfactory results were achieved and testing proceeded to closed loop maneuvering. Only one change was made to the options during this testing for satisfactory aircraft response. The accompanying two figures are time histories for a cobra, J-turn, helicopter, and a hammerhead. These type of maneuvers were considered the building blocks of post-stall tactical maneuvering. At this point, the envelope-expansion was considered complete and the aircraft was ready for the tactical utility assessment.

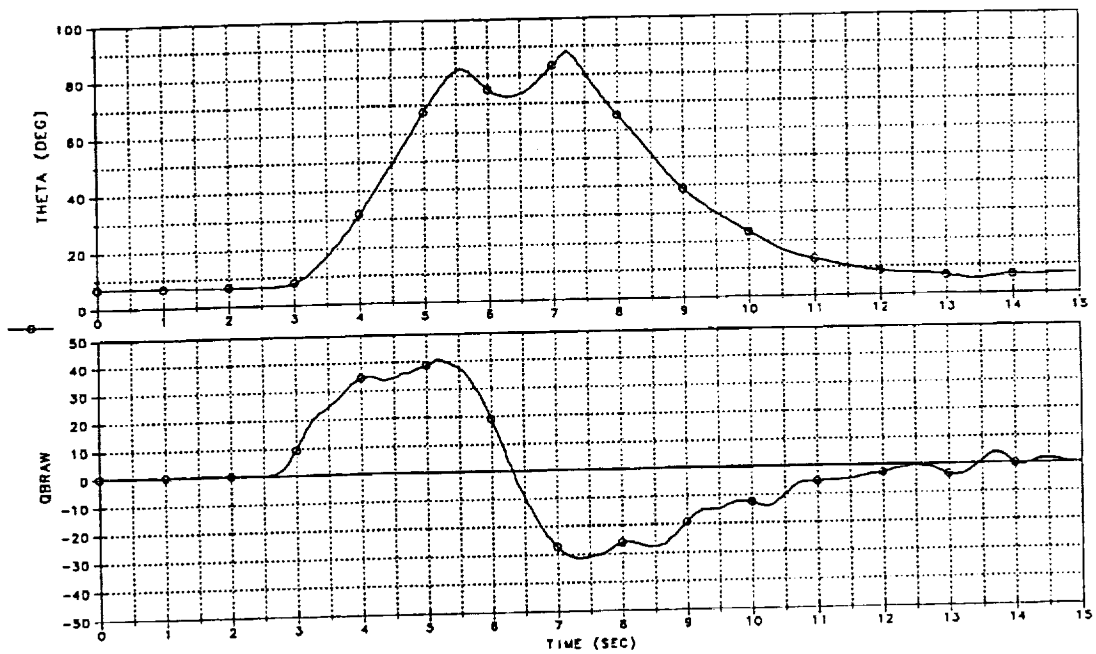
SIDESLIP COMPARISON

MAX POWER AOA SWEEPS
REVISED AND ORIGINAL OFPS



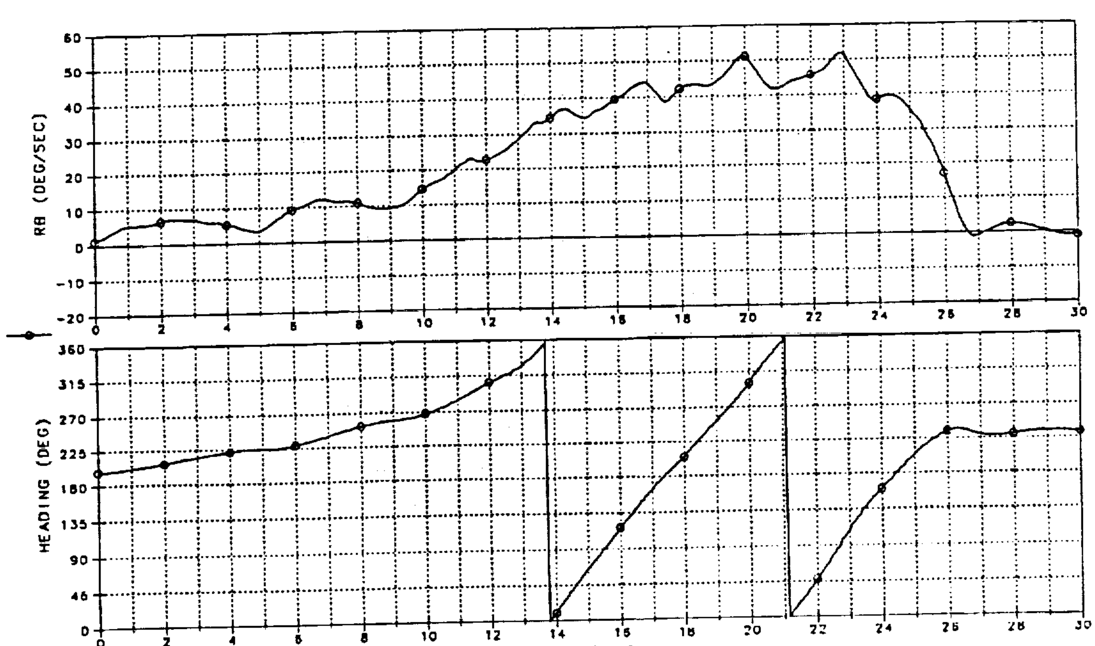
COBRA MANEUVER

MAX POWER 20,0000 FEET



HELICOPTER MANEUVER

MAX POWER 25,000 FEET



The unique capabilities of the MATV aircraft presented the opportunity to flight test potential improvements for high angle of attack flight. Although not part of the original test plan, several flights were allocated to test a nose-chine designed by Wright Laboratory and perform maneuvers designed to allow for parameter identification with and without the nose-chine in an effort to improve the F-16 simulation database. In addition, an extended range angle of attack cone was designed to evaluate its capabilities.

Wind tunnel data suggested a potential improvement in directional stability in the 30 to 40 degree angle of attack region. Although flight test results were not very encouraging, data was collected for parameter identification. This data as well as additional data from the program is being analyzed under a separate contract for Wright Laboratory in an effort to improve the high angle of attack data base for the F-16.

The additional testing with the extended range angle of attack cone did not require any dedicated flights. The standard angle of attack cones for the F-16 have a local flow angle range of -30 to 70 degrees while the extended range cones have a range of -180 to 180 degrees. Limited analysis of this data indicates that the extended range cones have good potential to be utilized up to moderately high angles of attack with no degradation in the normal flight envelope.

ADDITIONAL TESTING

NOSE-CHINE DESIGNED BY WRIGHT LABORATORY

- WIND-TUNNEL DATA SUGGESTED LATERAL-DIRECTIONAL IMPROVEMENTS
- FLIGHT TEST DATA HAS BEEN COLLECTED

PARAMETER IDENTIFICATION MANEUVERS

- WITH NOSE-CHINE
- WITHOUT NOSE-CHINE

EXTENDED AOA RANGE CONE

- POTENTIAL FOR MODERATELY HIGH AOA USAGE

The envelope expansion phase of the MATV flight test program was very successful with an unrestricted envelope for use in the tactical utility assessment provided in a minimum amount of time. The envelope was cleared in only six weeks and 20 flights with the original flight control configuration. Revised flight control laws were available within a month and these control laws were optimized and the envelope cleared within two weeks and only ten flights.

Several factors were key to achieving these results. Extensive flight simulations in a high fidelity handling qualities simulator were performed. This allowed for optimization of control laws and provided insight into the development of effective maneuver definitions and the unique flight test techniques required to evaluate thrust vectoring technology. Lessons learned from other high angle of attack programs were solicited and provided valuable information. The flight test team was a small integrated team with all parties in agreement from the beginning to be a team committed to common goals and objectives. The acceptability of flight test results were based upon real-time data analysis by the team and qualitative assessment by the pilots as opposed to correlation with predicted results. The use of in-flight pilot selectable control law options provided an extremely efficient means of optimizing handling qualities. The use of a time-proven airframe was indispensable, at any time the pilots could revert back to a known configuration. These factors provided for an efficient and effective envelope expansion phase and allowed the program to proceed to its primary goal of evaluating the tactical utility of thrust vectoring.

SUMMARY

EXPANDED ANGLE OF ATTACK ENVELOPE

CLEARED IN ONLY 20 FLIGHTS AND 6 WEEKS

REVISED CONTROL LAWS AVAILABLE WITHIN ONE MONTH

CONTROL LAWS OPTIMIZED IN 10 FLIGHTS AND 2 WEEKS

KEY FACTORS IN SUCCESS

EXTENSIVE SIMULATION

LESSONS LEARNED FROM OTHER PROGRAMS

SMALL INTEGRATED TEST TEAM

REAL-TIME DECISIONS ON ACCEPTABILITY OF RESULTS

IN-FLIGHT PILOT SELECTABLE CONTROL LAW OPTIONS

TIME PROVEN AIRFRAME