F-16 Multirole Fighter
MATV PROGRAM

VISTA / F-16 MULTI-AXIS THRUST VECTORING (MATV) CONTROL LAW DESIGN AND EVALUATION

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Lockheed Fort Worth Company

F-16 Multirole Fighter

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The Multi-Axis Thrust Vectoring (MATV) program has been a joint effort by Lockheed Fort Worth Company (LFWC), Wright Laboratory (WL), General Electric (GE), the Air Force Flight Test Center (AFFTC), and the 422nd Test and Evaluation Squadron (TES). The program consisted of integrating a multi-axis thrust vectoring nozzle system with the Variable Stability In-flight Simulator Test Aircraft (VISTA)/F-16 aircraft. The integrated system was used in flight test to demonstrate flight envelope expansion above the normal F-16 angle-of-attack (AOA) limits and to evaluate potential tactical benefits gained by utilizing thrust vectoring in air-to-air combat.

PROGRAM SUMMARY

MATV WAS A COOPERATIVE EFFORT BETWEEN WRIGHT LAB, GENERAL ELECTRIC, AFFTC AND LOCKHEED FORT WORTH

OBJECTIVE: DEMONSTRATE THE TACTICAL UTILITY OF MULTI-AXIS THRUST VECTORING

- Develop Integrated Flight Control / Propulsion System Designed to Expand F-16 AOA Envelope
- Install Vectoring Nozzle (AVEN), Vector Electronic Controller (VEC) and MATV DFLCC OFP on VISTA / F-16 Aircraft
- Perform Aggressive Ground Test and Flight Test Program

The objective of the MATV program was to utilize multi-axis thrust vectoring to expand the F-16 AOA limits into the post-stall regime and to evaluate the tactical benefits gained by utilizing expanded AOA in air-to-air combat. For the MATV program a new control law mode was developed which commands thrust vectoring to augment the aircraft's aerodynamic control power. The additional control power is used to provide high AOA maneuverability. The MATV control laws were primarily developed using LFWC's off-line (non-piloted) and on-line (piloted) handling qualities (HQ) simulation tools. Additionally, the HQ simulator was used to perform an extensive piloted evaluation of the MATV control laws prior to finalizing the flight test control law configuration. This evaluation was an integral part in the development of the initial flight test control laws and flight test maneuvers/techniques.

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CONTROL LAW OBJECTIVES / APPROACH

OBJECTIVES

- Design Control Laws Utilizing Thrust Vectoring to Enable Controlled Flight at AOA Greater than 30 Degrees
- Determine Vectoring Nozzle Requirements
- Determine Military Utility of Thrust Vectoring

APPROACH

- Definitive High AOA Handling Qualities / Agility Metrics Not Available
- Evaluate Different Command Structures in Simulator
- Conduct Piloted Simulations with Operational Pilots to Evaluate Utility

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The figure below illustrates the relationship between the modes and states of operation for the MATV system. The arrows indicate the possible directions from which modes and states can be entered or exited.

The MATV system was designed to provide the pilot with two primary modes of operation: the KILL mode and MATV mode. The pilot toggles between the two modes using the "Kill-Standby" switch on the sidestick controller. With the KILL mode selected the engine hydraulics center the nozzle to zero and baseline F-16 control laws are in place. This is a fail-safe mode used for low altitude operation, in particular for takeoff and landing flight phases. Note that by placing the Kill-Standby switch in the KILL position, the aircraft can be returned to the KILL mode from any one of the states in the MATV mode. This is an important safety feature for the MATV aircraft.

From the KILL mode, the MATV mode is selected by placing the Kill-Standby switch in the Standby position. In the MATV mode, three pilot-selectable states are available. The state which is entered when the MATV mode is first selected is the STANDBY state. In this state the FLCS commands the nozzle to zero and baseline F-16 control laws are used (as in the KILL mode). The pilot can transition to the next state, ACTIVE LIMITER ON, by depressing a button on the multi-function display set (MFDS). The Active Limiter On state is the first FLCS state in which thrust vectoring is utilized. However, this state was primarily provided for potential air-to-ground configuration control law enhancements. The FLCS will only command pitch nozzle to augment the elevator if FLCS AOA limits are exceeded. Otherwise, baseline F-16 control laws are used.

The final MATV state is selected by toggling the "pinky" switch on the sidestick controller. In this state, referred to as ACTIVE LIMITER OFF or MATV LIM OFF, pitch and/or yaw thrust vectoring is used to control the F-16 to very high AOA.

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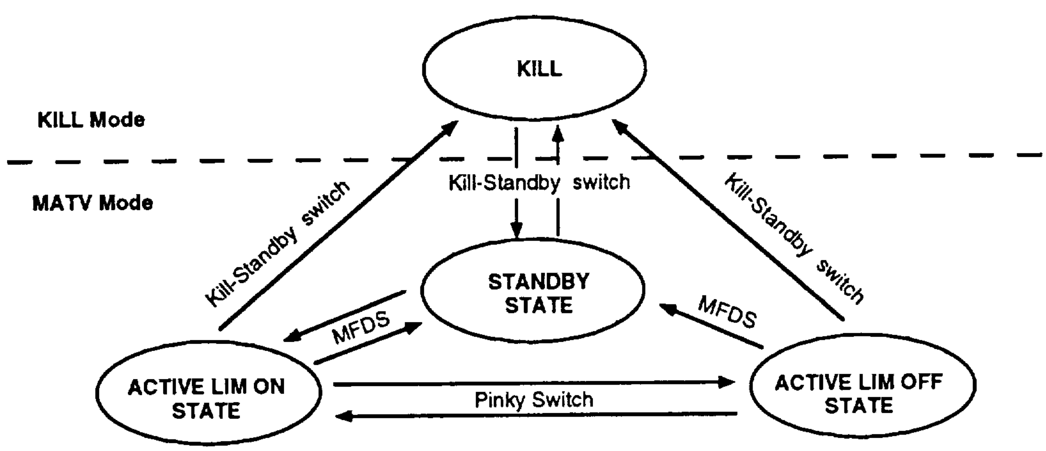
MODES / STATES OF OPERATION



The next two charts describe the LIM OFF state for the pitch axis of the MATV FLCS. The chart on this page gives a functional description of the control laws. A simplified block diagram illustrating the MATV LIM OFF pitch axis control laws is given in the chart on the following page. More specifically, these charts describe the pitch axis for airspeed less than 300 knots. Above 300 knots the flight control laws automatically blend back to the baseline F-16 configuration. This is necessary since load factor limits prevent high AOA maneuvering above 350 knots.

From the block diagram on the following page it can be seen that the pilot's stick force command (in pounds) is converted to a pitch rate command (q, in degrees/sec) and the error signal produced between the pitch rate command and pitch rate feedback is fed to a proportional plus integral element. Some AOA feedback is also present but only enough to slowly decrease AOA when the pilot releases the stick at high AOA. This gives the aircraft's pitch axis a stable feeling at very high AOA flight conditions encountered in this mode. Note also that the pitch axis nozzle command is blended in as a function of airspeed. Above V high (300 knots) only the elevator receives the pitch axis commands. The nozzle command is blended out at the higher airspeed because the elevator alone provides adequate pitch control power above 300 knots. Below V low (100 knots) the pitch nozzle and elevator receive equal commands. This maximizes the use of the available pitch axis control power at very low airspeed. It also allows for a direct comparison between the pitch axis nozzle and elevator actuator dynamic response characteristics at low airspeed since both surfaces are responding to the same command.

(continued on next page)

FUNCTIONAL CONTROL LAW DESCRIPTION
ACT LIM OFF STATE - PITCH AXIS

PITCH RATE COMMAND SYSTEM BELOW 300 KCAS

MINIMUM AMOUNT OF AOA FEEDBACK INTRODUCED ABOVE 20 AOA

PILOT USES MFDS TO SELECT THREE LEVELS OF AOA FEEDBACK

- **No AOA limit**
- **100 Degree AOA Limit**
- **80 Degree AOA Limit**

PADDLE SWITCH DEPRESSED PROVIDES 50% INCREASE IN PITCH RATE COMMAND LIMIT (MONGO MODE)

AT VERY LOW AIRSPEED (< 20 KNOTS) OR VERY HIGH AOA (> 140 DEG), TRANSITION TO PURE PITCH RATE COMMAND SYSTEM OCCURS

(continued from previous page)

The MATV pitch axis contains additional features not shown in the diagram below. One such feature is optional, pilot-selectable AOA limiters. The limiters are selected using the MFDS and provide AOA limiting at either 80 or 100 degrees. They were provided to make it easier for the pilot to adhere to potential AOA restrictions required for stall-free engine operation. Another feature not shown in the simplified block diagram is the pitch axis 'Mongo' mode of operation. The Mongo mode is engaged by depressing the paddle switch on the sidestick controller. When Mongo is engaged the pilot can command an additional 50 percent pitch rate (approximately 45 deg/sec max). In Mongo, precise controllability is sacrificed for gross maneuver capability.

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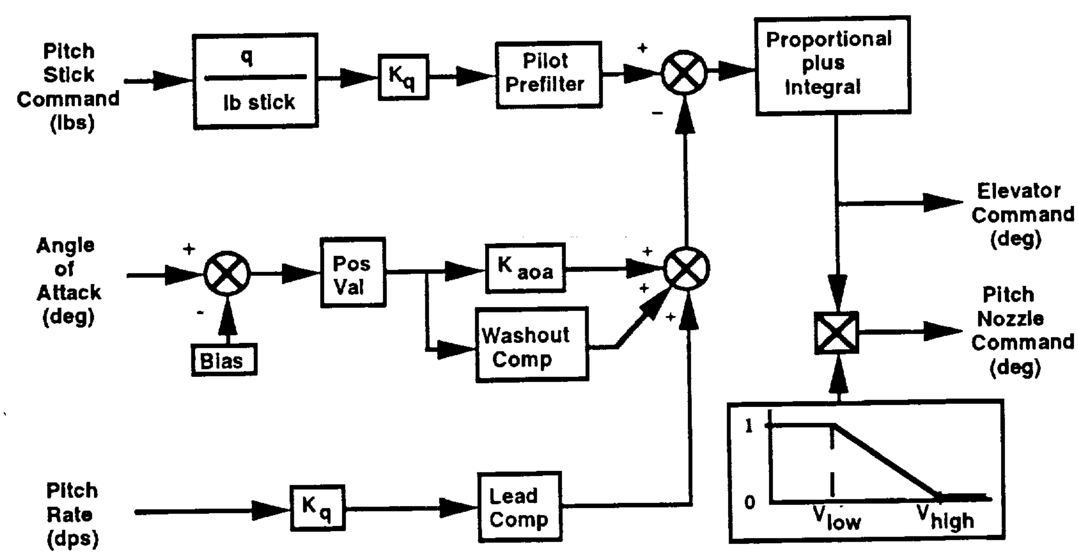
SIMPLIFIED PITCH AXIS BLOCK DIAGRAM

ACT LIM OFF STATE



The next two charts describe the LIM OFF state for the roll axis of the MATV FLCS. The chart on this page gives a functional description of the control laws. A simplified block diagram illustrating the MATV LIM OFF lateral axis control laws is given in the chart on the following page. The control laws shown are only applicable for AOA greater than 25 degrees. Below 25 degrees AOA the MATV lateral control law blends back to the baseline F-16 configuration. Also note that starting at 45 degrees AOA ($\alpha_{blend} = 0$) and up to 60 degrees AOA ($\alpha_{blend} = 1$) the roll stick command to the roll control surfaces is faded out and sent to the yaw axis instead. This command is summed in with the rudder pedal command in the yaw axis. Therefore, the MATV pilot can use the roll stick to control the yaw axis at AOA's greater than 60 degrees. Since the rudder pedals can perform the same function, the pilot can choose between the rudder pedal and roll stick for yaw control above 60 degrees AOA.

The simplified block diagram on the following page illustrates that the MATV lateral axis is a stability axis roll rate command system. The difference between the roll stick command and stability axis roll rate feedback is sent to the roll surface command mixer. The roll surface mixer performs the following functions:

1. Calculates the aileron-to-rudder and aileron-to-yaw nozzle interconnect gains.
2. Distributes the roll command to the appropriate control surfaces: flaperon, differential tail, rudder, and yaw nozzle.
3. Limits the surface commands based upon the available roll and yaw control power.

The roll surface command mixer outputs are then sent to the surface actuators.

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FUNCTIONAL CONTROL LAW DESCRIPTION

ACT LIM OFF STATE - ROLL AXIS

STANDARD F-16 CONTROL LAWS BELOW 25 AOA

BLEND TO PERFECT ROLL COORDINATION SCHEME (ZERO SIDESLIP) BETWEEN 35 AND 45 AOA

- **Yaw Nozzle and Rudder Used to Coordinate Roll Control**

ROLL STICK COMMANDS BODY AXIS YAW RATE ABOVE 60 AOA

See word description on previous page

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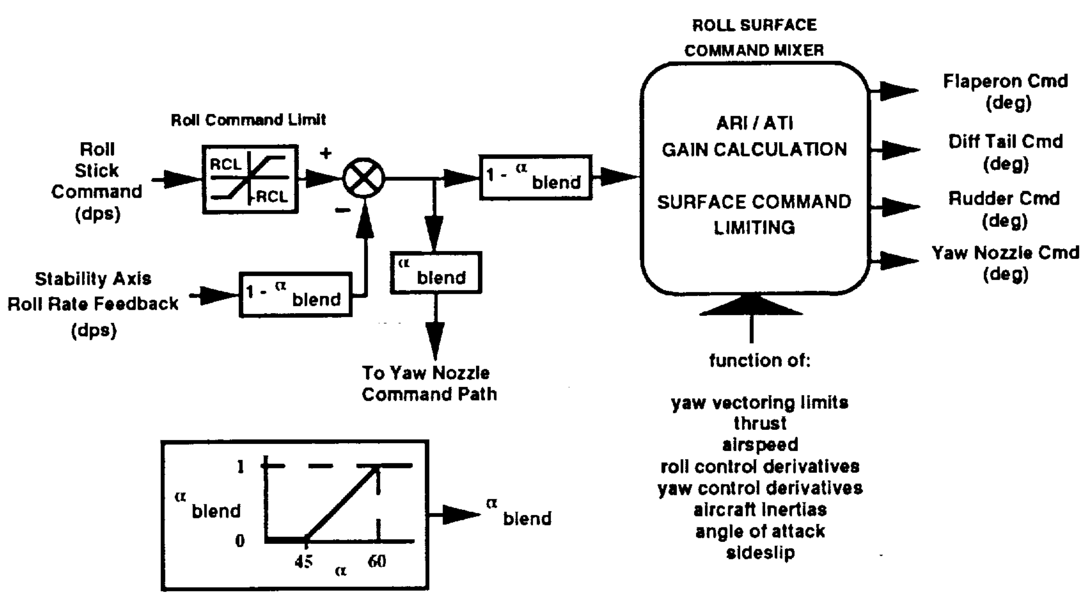
SIMPLIFIED ROLL AXIS BLOCK DIAGRAM

ACT LIM OFF STATE - A0A > 35 DEG



A functional description of the MATV directional axis control laws is given in the figure below. The control laws are described for three AOA regions: AOA less than 45 degrees, AOA between 45 and 60 degrees, and AOA greater than 60 degrees. Note that the yaw axis control laws between 45 and 60 degrees are blended as a function of AOA between those described for less than 45 degrees AOA and greater than 60 degrees AOA. For AOA less than 45 degrees, three features of the MATV LIM OFF yaw axis are described. First, the rudder pedal command is not faded above 15 degrees AOA as is done for the baseline F-16 control laws. Secondly, the rudder pedal commands both yaw nozzle and rudder below 250 knots. These two features give the pilot control of the yaw axis at low airspeed below 45 degrees AOA. Finally, sideslip feedback to the rudder and yaw nozzle is introduced above 25 degrees AOA. The sideslip feedback augments the directional stability of the F-16 in a region where the free airframe directional stability is low or even unstable. It also counters the buildup of large steady-state sideslips during high AOA rolling maneuvers, thereby preventing adverse rolling moments due to the powerful dihedral effect.

Above 60 degrees AOA, the rudder pedals command yaw nozzle only. In this region, the rudder is ineffective and therefore is not used. Also, for AOA greater than 60 degrees, the directional axis has blended to a body axis yaw rate command system. Finally, the sideslip feedback introduced above 25 degrees has been faded out at 60 degrees. This is accomplished since the F-16 directional stability improves above 60 degrees AOA and the accuracy of the sideslip feedback source is questionable at very high AOA's.

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FUNCTIONAL CONTROL LAW DESCRIPTION

ACT LIM OFF STATE - YAW AXIS

AOA<45	45<AOA<60	AOA>60
• Rudder Pedal Command Not Faded Above 15 AOA • Rudder Pedal Commands Rudder and Yaw Nozzle Below 250 KCAS • Sideslip Feedback Above 25 AOA	B L E N D	• Rudder Pedal Commands Yaw Nozzle Only • Body Axis Yaw Rate Command System • No Sideslip Feedback

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For the MATV program, an inertially based AOA and sideslip estimator was synthesized to provide sideslip and AOA feedback outside the current range of the hardware AOA and sideslip sensors. A functional description of the estimator is given in the Figure below.

The figure below illustrates how the aircraft inertial velocities and attitudes are first used to compute the earth axis wind velocities for a region where the AOA cone and sideslip measurement is valid. These wind velocities are then held constant when AOA or sideslip is outside of the valid AOA cone and sideslip measurement range. While the winds are held constant, the aircraft's velocities and attitudes are used to compute the extended AOA and sideslip feedback signals necessary to control the F-16 at very high AOA's.

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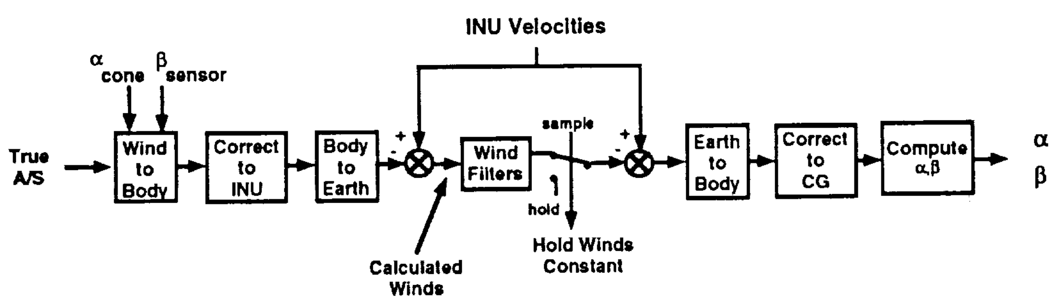
FUNCTIONAL CONTROL LAW DESCRIPTION

AOA/SIDESLIP ESTIMATOR - SIMPLIFIED BLOCK DIAGRAM



<u>HOLD WINDS CONSTANT</u> IF ANY OF THE FOLLOWING CONDITIONS EXITS:

- AOA CONE OUTSIDE OF CONE RANGE
- SIDESLIP OUTSIDE OF SENSOR RANGE
- SIGNIFICANT A/C BODY AXIS RATES
- LOW AIRSPEED
- SIGNIFICANT PILOT LATERAL-DIRECTIONAL INPUTS

A concentrated piloted evaluation was flown in the HQ simulator during the months of October and November 1992. The primary objective of this evaluation was to assess potential areas of improvement within the MATV control laws that could be incorporated prior to first flight.

Test maneuvers used during the piloted simulation were adopted from a preliminary flight test plan. Using planned flight test maneuvers during the evaluation provided additional pilot training and further aided in the development of the final flight test plan. Maneuver entry conditions, realizable parameter capture and tracking envelopes, and maximum expected aircraft angles and rates were identified.

The maneuvers were flown at 25K and 35K feet altitude in MIL and MAX A/B power. The altitudes were consistent with the actual flight test altitude blocks. The power settings were limited to MIL power and above because that was a restriction for the flight program.

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SIMULATION -
PILOTED EVALUATION TEST MANEUVERS

Axis	Test Maneuver
Longitudinal	Angle of Attack Stabilizations Throttle Transients Angle of Attack Captures Pitch Attitude Captures/Tracking Zero Airspeed Pull/Pushes
Lateral-Directional	Bank Angle Reversals Heading Angle Reversals Steady Sideslip/Yaw Heading Angle Captures Zero Airspeed Roll/Yaw
Combined	Target Acquisition

Longitudinal results of the piloted simulation exercise are summarized in the chart below. The pitch rate/AOA response deficiencies were primarily due to varying pitch rate command limits with airspeed and direction (nose up versus nose down). The command limits were modified to provide a more consistent pitch rate response (30 deg/sec in the normal mode, 45 deg/sec in the 'Mongo' mode) over a wider range of velocities. An additional schedule was introduced as a function of load factor that prevented load factor excursions above the specified limit. The negative pitch rate command limit was increased to match the nose up authority at very low speeds.

Pitch attitude/AOA capture difficulties were attributed to the varying pitch rate and a lack of sufficient pilot cueing. The AOA indication on the HUD did not provide a means for the pilot to identify the target AOA. The HUD was modified so that the pilot could designate a target AOA using a staple alongside the AOA ladder. All the pitch attitude captures were performed using a target. The limited vertical field of view in the simulator resulted in the target being outside the pilot's field of view at the initiation of the pull.

The pitch tracking tasks were modified during the evaluation to force the pilot to track the target aircraft at AOA's between 30 and 80 degrees. These modifications primarily consisted of adjusting the relative airspeeds between the test and target aircraft.

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SIMULATION -
PILOTED EVALUATION RESULTS (LONGITUDINAL)

Area of Improvement	Characterized By:	Corrections Made:
Pitch Rate/AOA Rate	- Sluggish at 250 KCAS when Compared to 150 KCAS - Sluggish Nose Down with Pitch Hesitations - Significant Increase in Commanded Rate as Airspeed Bleeds Off	- Decreased Command Limit Sensitivity to Airspeed - Increased Nose Down Authority
Pitch Attitude/AOA Captures/Track	- Excessive Overshoots - Pitch Oscillations due to Nozzle Limiting	- Improved Consistency Between Nose Up/Down - Improved AOA Cuing on HUD - Refined Test Maneuvers to Minimize Tracking Near Nozzle Limits

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Lateral-directional results of the piloted simulation exercise are summarized in the chart below. The roll rates generated during the roll reversals and the bank-to-bank maneuvers were considered good for the AOA's being evaluated. The difficulties with these maneuvers centered on the inability to precisely stop or reverse the roll. Furthermore, there were a number of roll hesitations due to adverse sideslip and the pitch axis using the nozzle to counter AOA excursions.

The ability to stop and reverse the roll was improved by introducing a stability axis roll rate feedback to the lateral axis. The forward loop path gain was also increased to provide higher initial roll accelerations. The nozzle priority between the pitch and yaw axis was adjusted to give equal priority between the axes, thus, reducing the roll hesitations identified.

The aircraft's response to pedal inputs typically resulted in pedal rolls in the mid-AOA range (30 to 50 degrees) and pure yawing maneuvers above 60 degrees AOA. The yaw response exhibited hesitations due to the pitch axis using the nozzle to counter AOA excursions. The priority modification noted above provided a smoother more consistent yaw rate. Another potential problem identified for the yaw axis was that both the lateral stick and the rudder pedals both commanded body-axis yaw rate above 60 degrees AOA. If the pilot used the lateral stick to correct body axis roll variations during a yawing maneuver, he could potentially cancel the yaw rate commanded by the pedals.

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SIMULATION - PILOTED EVALUATION RESULTS (LATERAL-DIRECTIONAL)

Area of Improvement	Characterized By:	Corrections Made:
Roll Response	- Sluggish Roll Acceleration - Roll Hesitations	- Increased Roll Loop Gain - Increased Yaw Nozzle Priority
Roll Reversals/Bank Angle Captures	- Inability to Precisely Stop or Reverse Roll	- Introduced Stability-axis Roll Rate Feedback - Increased Yaw Nozzle Priority
Yaw Response	- Yaw Hesitations - Partial Cancellation of Pedal Commands with Lateral Stick Inputs	- Increased Yaw Nozzle Priority - Cut Out Lateral Stick Commands Above 60 deg AOA (not implemented)

Flight test of the MATV system was conducted from July, 1993 to March, 1994. The first flight test phase consisted of functional check flights in Fort Worth and at Edwards Air Force Base (EAFB). The functional check flights verified safe non-vectoring aircraft operation. Phase II was the envelope clearance portion of the program. The objective for Phase II was to define an aircraft operational envelope for the tactical evaluation phase. The final phase of the flight test program was a tactical evaluation of the MATV capability by operational F-16 pilots from the 422nd Test and Evaluation Squadron. The purpose of the tactical evaluation was to collect data on the benefits of post-stall maneuvering.

Initial MATV flight test results demonstrated pitch axis handling qualities similar to those noted in the simulator and considered good. The lateral-directional handling qualities in the 35 to 45 degree AOA region were poor. However, the pilots were able to control the aircraft through this AOA region and even perform some limited maneuvering.

Above 45 degrees, the aircraft exhibited higher levels of lateral-directional stability and, consequently, better handling qualities. A nose right yawing tendency at these elevated AOA's resulted in an asymmetric yaw response to pedal commands. The general consensus from the flight test team was that the limited capability to maneuver in the 35 to 45 degree AOA region could potentially interfere with the tactical evaluation of the system.

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FLIGHT TEST -
RESULTS PRIOR TO OFP UPDATE

Angle of Attack Range	Longitudinal	Lateral-Directional
30 to 55 degrees	**Correlated Well with Simulator Predictions**	**Sideslip Excursions out to +/-15 Degrees Resulting in Inability to Roll Smoothly and Precisely**
55 to Max degrees	**Correlated Well with Simulator Predictions**	**Nose Right Yawing Tendency Resulting in AsymmetricYaw Response**

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Because of poor lateral-directional flying qualities in the 35 to 45 degree AOA region, Lockheed chose to update the flight control laws in the middle of the flight test program. The traditional approach for this task consists of first updating the simulation aero data base to match flight test results. Then the updated sim is used to design the control law mods necessary to improve the flying qualities. Time and budgetary constraints on the MATV program disallowed this procedure. Therefore, Lockheed chose to pursue a 'dial-a-gain' approach to the control law update.

For the dial-a-gain approach, a set of critical flight control law feedback gains and paths could be varied by the pilot through the MFDS (as shown in the figure below). The gains included the beta and beta dot feedback gains, the yaw rate feedback gain at very high AOA and the stability axis roll rate feedback gain. The gains were varied over a range large enough to bound the flying qualities problem but yet small enough to preserve rigid body and structural mode stability margins. Paths that could optionally be left in or taken out included the lateral stick command to yaw nozzle at very high AOA's (above 60 degrees) and the rudder command path above 30 degrees AOA. The AOA range for which the directional axis transitioned from beta/beta dot feedback to yaw rate feedback could also be varied. Additionally, an option existed for using trailing-edge-flap only in the trailing edge up direction to roll the aircraft above 30 degrees AOA. The idea was that it is more efficient to 'kill' lift over a wing at high AOA than to generate lift.

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FLIGHT TEST -

CONTROL LAW 'DIAL-A-GAIN' OFP UPDATE

CONTROL LAW OPTION (CLAW'OPT)	TRIM DISC	AOA FEEDBACK (AOA'FB'LEV)	CONTROL LAW SETTING (CLAW'SET)	BETA MULT (B'MULT)	BETA DOT MULT (BDT'MULT)	STAB ROLL MULT (PS'MULT)	DIFF SURF OPT (OPT'DIFF)	YAW RATE MULT (YR'MULT)	YAW CMD BREAK (YC'BRK)	NO HI AOA ROLL OPT (OPT'NHAR)	NO RUDDER OPT (OPT'NR)
1	NORM	NORM	0 (NORM)	1.0							
			1	0.0							
			2	0.5							
			3	1.5							
			4	2.0							
2		LEV1	0 (NORM)		1.0						
			1		0.0						
			2		0.5						
			3		1.5						
			4		2.0						
3		LEV2	0 (NORM)			1.0	0				
			1			0.0	0				
			2			0.0	0				
			3			0.0	1				
			4			0.0	2				
4	DISC	NORM	0 (NORM)					1.0			
			1					0.5			
			2					1.5			
			3					1.0			
			4					1.5			
5		LEV1	0 (NORM)						40		
			1						35		
			2						45		
			3						50		
			4						55		
6		LEV2	0 (NORM)							0	0
			1							1	0
			2							0	1
			3							1	1
			4							1	1

ADDITIONAL PVI NOTES:

TRIM DISC switch in the NORM position selects a reduced/less sensitive roll stick command gradient (for AOA > 25 degrees only)
TRIM DISC switch in the DISC position selects the original (MATV first flight) roll stick command gradient

AOA FEEDBACK in NORM --> VERY HIGH AOA LIMITER not selected and "TRAILING-EDGE-FLAP UP ONLY" option not selected
AOA FEEDBACK in LEV1 --> VERY HIGH AOA LIMITER not selected and "TRAILING-EDGE-FLAP UP ONLY" option selected
AOA FEEDBACK in LEV2 --> 80 DEGREE AOA LIMITER selected and "TRAILING-EDGE-FLAP UP ONLY" option selected

The chart below summarizes the flight test results achieved following the control law OFP update.

First, a smooth, predictable roll response to lateral stick inputs was achieved in the 30 to 50 degree AOA region by optimizing the beta/beta-dot feedback gains. Second, the yaw rate feedback gains were selected based on heading angle captures performed at AOA's between 70 and 80 degrees. The nose right yawing tendency exhibited during the early flights was replaced by a slight nose left yaw tendency the was easily countered with pedal inputs. The final yaw response at the elevated AOA's was consistent for both left and right yaw commands.

The roll oscillations occurring around 55 degrees AOA were stabilized with the beta/beta-dot feedbacks. However, using beta and beta-dot feedback in the 55 to 60 degree AOA region degraded the yaw response to pedal inputs. Furthermore, the accuracy of the sideslip feedback source at the very high AOA's was questionable.

The decision was made to fade from the beta/beta-dot feedback to the yaw rate feedback between 50 and 60 degrees AOA. This fade region provided the best handling qualities improvements between 30 to 45 degree AOA region (CL_{max}) and above 60 degrees AOA (yaw tracking using pedals). Flight in the 50 to 55 degree AOA regime typically occurred only as a transition from the CLmax region to a yaw tracking region.

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FLIGHT TEST -
RESULTS AFTER THE OFP UPDATE

AOA Range	Longitudinal	Lateral-Directional
30 to 50 degrees	Correlated Well with Simulator Predictions	Sideslip Excursions Typically Within +/-5 Degrees. Smooth and Predictable Roll Response.
50 to 60 degrees	Correlated Well with Simulator Predictions	Slight Wing Rock (+/-10 Deg.) at 55 Degrees AOA. Wing Rock Damped out at 60 Degrees AOA.
60 to Max degrees	Correlated Well with Simulator Predictions	Slight Nose Left Yawing Tendency That Was Easily Controlled. Smooth, Predictable Yaw Response to both Left and Right Pedal Inputs.

The tactical evaluation phase of the program was flown by pilots from the 422nd Tactical Evaluation Squadron stationed at Nellis Air Force Base. This evaluation consisted of 1V1 and 1V2 engagements between the MATV aircraft and two F-16's provided by the 422nd squadron. A limited number of 1V1 engagements against dissimilar aircraft (NASA F-18's) were also flown.

No control input (other than remaining between MIL and MAX power), aircraft rate, or aircraft attitude limitations were placed on the pilots during the tactical evaluation phase of the program. The pilots were able to maneuver the MATV aircraft without fear of aircraft departure. This ability to maneuver without fear of aircraft departure allowed the pilots to focus more on the tactical utility of the aircraft.

The handling qualities of the MATV system were not an issue during the tactical evaluation phase of the program. The pitch axis handling qualities were good. Lateral-directional flying qualities were adequate, requiring some pilot compensation to control the roll axis between 35 and 45 degrees AOA. Comprehensive results of the MATV tactical evaluation are classified and therefore are not covered in the contents of this presentation.

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FLIGHT TEST -
TACTICAL EVALUATION PHASE

Tactical Evaluation Flown by Pilots from the 422nd Test and Evaluation Squadron Stationed at Nellis Air Force Base.

- **1V1 and 1V2 Engagements**
- **Similar (F-16) and Dissimilar (F-18) Aircraft Engagements**

Standard Tactical Setups and Rules of Engagement Used... Bandits Allowed to Fly Their Best Fight.

No Control Input, Throttle Movement, Aircraft Rate, or Aircraft Attitude Limitations Imposed. Pilots Able to Maneuver Without Fear of Aircraft Departure.

For the MATV program, a new control law was developed using multi-axis thrust vectoring to augment the aircraft's aerodynamic control power to provide maneuverability above the normal F-16 AOA limit. The control law architecture was developed using Lockheed Fort Worth's offline and piloted simulation capabilities. The final flight control laws were used in flight test to demonstrate tactical benefits gained by using thrust vectoring in air-to-air combat.

Differences between the simulator aero data base and the actual aircraft aerodynamics led to significantly different lateral-directional flying qualities during the flight test program than those identified during piloted simulation. Because of time and budgetary constraints, a 'dial-a-gain' flight test control law update was performed in the middle of the flight test program. This approach allowed for inflight optimization of the aircraft's flying qualities. While this approach is not preferred over updating the simulator aerodynamic data base and then updating the control laws, the final selected gain set did provide adequate lateral-directional flying qualities over the MATV flight envelope. The resulting handling qualities and the departure resistance of the aircraft allowed the 422nd pilots to focus entirely on evaluating the aircraft's tactical utility.

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CONCLUSIONS AND RECOMMENDATIONS

Multi-Axis Thrust Vectoring Was Successfully Utilized to Augment the Aircraft's Aerodynamic Control Power to Provide Maneuverability Above the Normal F-16 AOA Limit.

Extensive Use of Piloted Simulation was Critical in the Development of the MATV Control Laws and the Refinement of Test Maneuvers.

The Ability to "Dial-a-Gain" in Flight Provided Acceptable Handling Qualities in the Presence of Extremely Tight Scheduling Constraints and Relatively Large Aerodynamic Uncertainties.

The Ability to Maneuver Without Control Input, Throttle Movement, Aircraft Rate, or Aircraft Attitude Limitations Allowed the 422nd Pilots to Successfully Evaluate the Tactical Utility of the System in a Relatively Short Time.