DREAM MACHINE -- THRUST VECTORING IN THE F-16

TABLE OF CONTENTS

INTRODUCTION

Advances in technology have made aircraft control with thrust vectoring possible. As a result, development of thrust vectoring for fighter aircraft has received considerable attention with a number of systems reaching flight status. To date, there have been 5 aircraft testing thrust vectoring technology --the F-15 STOL/MTD (Short Takeoff and Landing/Maneuvering Technology Demonstrator), the X-31 (Enhanced Fighter Maneuverability demonstrator), the F-18 HARV (High Alpha Research Vehicle), the YF-22 (Advanced Tactical Fighter), and the F-16 MATV (Multi-Axis Thrust Vectoring). The F-15 and YF-22 programs used pitch-only vectoring and were limited in scope with respect to exploring the capabilities of thrust vectoring. The X-31 and F/A-18 programs utilize external paddles - "pitch and yaw vectoring" - which are inefficient vectoring devices. The F-16 MATV system is the only thrust vectoring demonstration system representing an efficient vectoring concept suitable for production implementation. This aspects makes the MATV program unique.

The F-16 MATV program, a joint venture with the USAF, Lockheed Fort Worth Company (LFWC), and General Electric (GE), is a project to designed and build a F-16 thrust vectoring system to demonstrate the concept of post-stall maneuvering. Post-stall maneuvering is the ability to maneuver and control an aerodynamically stalled aircraft. The VISTA (Variable Stability Inflight Simulator) aircraft, a modified F-16D, was designated as the host flight-test airframe for MATV. VISTA is a unique research aircraft that can be programmed to mimic the flying qualities of new aircraft not yet built.

The combat capability of future fighters will rise to incredible levels due to thrust vectoring technology derived from the F-16 MATV. "Dream Machine -- Thrust Vectoring in the F-16" will investigate MATV system operation and performance, flight test results, and test pilot feedback.

MATV SYSTEM DESCRIPTION

- **ENGINE/NOZZLE:**

A production General Electric F-110-GE-100, producing 28,000 pounds of thrust in full afterburner (AB), was chosen for the F-16 MATV due to its incredible performance, operability, and stagnation free operation. The takeoff gross weight of the F-16 MATV is 28,000 pounds with full fuel, wing tip missiles, and two pilots. MATV uses a high tech nozzle first conceived in 1987 by GE. To date, GE's investment to develop their nozzle is $20 million.

GE's Axis-symmetric Vectoring Exhaust Nozzle (AVEN), designed for a simple retrofit to the F-110-GE-100 engine, required no modifications to the airframe and hydraulic system. In order to handle the increased hydraulic flow demand due to the AVEN nozzle, the capacity of the hydraulic pump was increased from 16 to 24 gallons per minute. The new nozzle is very similar to the production F-110 exhaust nozzle and is almost indistinguishable from a production F-16 nozzle. Engine oil powers three actuators, located 120 degrees apart, that in turn drive a vectoring ring. The actuators are independently controlled by the Vectoring Electronic Control (VEC). Since the vectoring ring can be tilted in any direction, vectoring is available in pitch, yaw, or any combination thereof. The AVEN provides up to 17 degrees of thrust vectoring in every direction. Slew rates of the nozzle are 60 deg/sec but limited to 45 deg/sec by the flight control computer software. Figure (1) depicts the major components of the AVEN design.[1] Figure (2) denotes the differences between the production F-16 nozzle and the AVEN nozzle.[2] The proto-type nozzle adds 450 pounds to the engine, however, GE estimates a production nozzle would add only 250 pounds.

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[1]Vickers, J., Capt, USAF, "Propulsion Analysis of the F-16 MATV Aircraft". Presentation to the Fourth NASA High Angle-of-Attack Conference. 13 July 1994. p.2.

[2]Ibid.

The AVEN has two major modes of operation -- "Kill" and "Active". "Kill" enables the pilot to quickly disengage thrust vectoring hydraulics to the nozzle, independent of MATV or AVEN electronics, and return the aircraft to the baseline F-16 flight control laws and non-vectored nozzle condition. "Kill" could be selected by either pilot or automatically by the flight control computer in the event of a failure. "Active" activates the thrust vectoring system by commanding the nozzle control valve in accordance with commands from the VEC.

- **FLIGHT CONTROLS:**

The production F-16 Digital Flight Control Computer (DFLCC) is a four channel fly-by-wire system combining pilot inputs along with aircraft motion and flight conditions to command position of the flight control surfaces. The DFLCC provides artificial stability which allows for relaxed static stability thereby increasing performance and maneuverability. Flight control limiters are provided in all three axes to help prevent departure/spins. [3]

The F-16 MATV utilized the production DFLCC computers with changes to the control laws of the software. The engineers designed software to match basic F-16 flight control laws above 350 KCAS, where a "G" command system is used. As airspeed decreased, the pilot would select "Active". In this mode the pitch was converted from a "G" command to a pitch rate command system and the standard flight control limiters were eliminated. As the AOA increased above 20 degrees AOA, nozzle commands were blended in to increase maneuvering performance. Vectoring commands are phased out as aircraft loads increase above 5 "Gs" because there is no need for vector force at conditions producing extreme "G" levels. The normal MATV pitch rate command limit was 30 deg/sec. The "Mongo Mode", selected on the side stick controller by the pilot,

[3] Lockheed Fort Worth Company. F-16 C/D Flight Manual -- T.O. 1F-16CG-1. 24 Jan 1994. p. 6-1.

allowed a pitch rate command of 50 deg/sec. Figure (3) illustrates the MATV area of exploration.[4]

- **PERFORMANCE:**

While the production F-16 is one of the world's most maneuverable fighters, directional stability is lost between 30 and 50 degrees AOA when most of the vertical tail is blocked by the fuselage. (The rudder losses effectiveness at 35 degrees AOA.) Flight control limiters help prevent departure/spins, but restrict commanded AOA to 25.5 degrees--well short of the 32 degrees angle required for maximum lift. With yaw stability provided through thrust vectoring, the 25.5 degree restriction is eliminated maximizing inherent aircraft aerodynamics.

With MATV bringing almost unlimited high angle of attack performance, the jet was able to perform such maneuvers as the "cobra" and "J-turn". Equally important, MATV gives the fighter pilot a jet that is almost impossible to depart from controlled flight--the added safety capability will save aircraft and lives.

FLIGHT TEST RESULTS

The MATV flight test program was conducted in three phases at two locations. Phase I - Functional Check - was conducted at the Lockheed facility in Fort Worth, Texas beginning 2 July 93. Six flights were flown to check basic aircraft systems. Thrust vectoring was not accomplished on these flights. Phase II - Envelope Expansion - and Phase III - Military Utility - were flown at the Air Force Flight Test Center at Edwards AFB, CA. The objective of Phase II, consisting of 48 flights, was to clear an operating envelope for future test flights. The final phase of testing, Phase III, was flown by pilots from the 422nd Test and Evaluation Squadron from Nellis AFB, Nv.

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[4] Ibid., p.5.

- **PHASE 1 & 2 /AIR FORCE FLIGHT TEST CENTER**

The results of the MATV flight test were awesome. Fully controllable, stabilized flight was initially achieved at 86 degrees AOA -- later increased to 90 degrees. Dynamic AOA experienced during maneuvering ranged from positive to negative 180 degrees.

Maneuvering the F-16 MATV above the normal AOA of 25 degrees was effortless. The test pilots had the ability to point the nose in any desired direction during all flight conditions, regardless of airspeed or AOA even while falling flat on their backs at negative 90 degrees AOA. MATV demonstrated that the Russians no longer have a monopoly on the dynamic "cobra" maneuver, which takes a jet from 200 knots level flight to beyond the vertical in about 2 seconds. (A chart of the "cobra" maneuver is provided in Figure (4).[5]) The hammerhead turn, a post-stall loop, was refined during the test. This maneuver allows the aircraft to rotate 270 degrees in pitch while remaining in the same spot in the sky. Transients of 138 degrees AOA were experienced during this maneuver. J-turns, zero airspeed vertical reversals, high AOA offensive spirals, and maximum pitch rate turns were other maneuvers successfully tested by the test pilots.

Flight test demonstrated impressive abilities of the GE engine to operate efficiently throughout the envelope. AB Blowouts and pop stalls were not encountered even while selecting AB at 88 degrees AOA, zero airspeed, and 50 deg/sec yaw rate.

Phase II only investigated benefits of MATV at altitudes of 20,000-33,000 feet. Thrust vectoring would certainly improve low altitude maneuvering as well as takeoff performance.

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[5]North, D.M., "MATV F-16 Displays High Alpha Benefits". Aviation Week and Space Technology. 2 May 94. p. 44.

Integration of lessons learned from other current high AOA and super maneuverability flight test programs (X-29, X-31, and F-18 HARV) were used to improve Phase I and II test flights. Figure (5) depicts comparison data between the X-31, F-18 HARV, and the F-16 MATV. [6]

- **PHASE 3 / 422nd Test and Evaluation Squadron**

The tactical evaluation phase of the program began 10 Nov 93 by the 422nd Test and Evaluation Squadron from Nellis AFB, Nv. The 422nd test and develops tactics for new equipment and systems for operational F-16, F-15, A-10, and F-4G squadrons. Weapons simulated during the evaluation were the F-16's standard gun with increased range PGU-28 bullets, AIM-9Ms (infrared guided missile) and AIM-120s (radar guided missile). 175 tactical one-vs-one and one-vs-two engagements were flown against USAF Fighter Weapons School F-16s and NASA F/A-18s. Approximately 15 engagements were flown against the F/A-18s in one-vs-one set-ups only. The engagements started from offensive and defensive perches -- positions in trail or lead of the bandit -- as well as from neutral or head-on passes. Engagements were flown at tactically representative airspeeds of 435 knots to 250 knots, with separations varying from 3000 to 9000 feet. Neutral engagements were entered from a "Butterfly" set-up maneuver, typical of operational training sorties. Shot validity criteria were the same as those employed by operational fighter units for training sorties.

The results of the operational test were equally impressed. The MATV pilot could take advantage of the F-16s maximum turn capability improving the ability to kill and survive. From an offensive position, thrust vectoring allowed the pilot to get a quicker kill. Common mistakes such as overshooting or getting stuck in lag (a situation in which the aircraft can't quite get its nose onto the bandit because of the flight control

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[6] Dornheim, M. "X-31, F-16 MATV, F/A-18 HARV Explore Diverse Missions". Aviation Week and Space Technology. 18 Apr 94. p 47.

limiters) were eliminated by thrust vectoring. During defensive maneuvering, thrust vectoring increased the survivability of the F-16 MATV due to the ability to use post-stall maneuvering. Post-stall maneuvering caused the attacking pilot to feel defensive and thereby modify his tactics to guard against the thrust vectoring jet. A graphic depiction of a post-stall maneuver during a one-vs-one high aspect single circle engagement is provided in Figure (6).[7]

MATV and the ability to post-stall maneuver provides an evolutionary enhancement in tactical capabilities, provides offensive options, reduces the impact of mistakes, and increases defensive survivability. The pilots adapted quickly to post-stall maneuvering and were able to exploit its advantages after only minimal practice.

TEST PILOT FEEDBACK

" The bandits were leery about pointing at MATV since my post-stall "bat turn" and rudder gun attack generally killed them." -- Major Jay Pearsall, 422nd Test and Eval Squadron.[8]

"The bottom line: you have a greatly increase capability to survive and kill with this system."-- Capt Jim Henderson, 422nd Test and Eval Squadron.[9]

" Very impressive. The combined ability to expand the usable flight envelope to CLmax (maximum lift) and to reduce any departure tendency for both air-to-air and air-to-ground loadings could increase military utility and safety." -- Brig. Gen. Rich Engel, commander of the Air Force Flight Test Center at Edwards AFB.[10]

"The performance of the MATV aircraft was very impressive. Handling qualities were good. I found it valuable to see the MATV utilize many of the maneuvers and

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[7]Sergeant, J., "Thrust Vectoring in the real world". Code-one. July 1994. p 8.
[8]Ibid.
[9]Ibid., p 10.
[10]Sweeney, J.E., "Flying Beyond the Limiter". Code-one. July 1994. p 3.

control schemes conceived in the YF-22 and planned for the F-22." -- Jon Beesley, Lockheed F-16, YF-22, and F-22 test pilot.[11]

"MATV opens up a new era of fighter tactics. Let's hope we see it in the operational fleet soon." -- Gen. Ron Yates, Head of the USAF Material Command, Wright-Patterson AFB, Ohio.[12]

CONCLUSION

The debate over thrust vectoring has moved from the chalkboard to the cockpit. The MATV program proved that effective thrust vectoring was not aircraft, engine, or technology limited, but budget limited. This new technology is a reliable and highly effective means of control for tactical jet aircraft and significantly enhanced the combat capability of the F-16. Thrust vectoring can be integrated economically - approximately $1 million - into the F-16. The capability designed for the F-22 may well find its way into existing and future versions of the well-fielded F-16. The pilots who have witnessed this capability first-hand have been very impressed and the data collected will alone revolutionize future fighter research and development.

[11]Ibid., p. 5.
[12]Sergeant. "Thrust Vectoring in the real world". p. 8.

LIST OF ABBREVIATIONS AND SYMBOLS

AB	Afterburner
AFB	Air Force Base
AOA	Angle-of-Attack
AVEN	Axisymetric Vectoring Exhaust Nozzle
DEG	Degrees
DFLCC	Digital Flight Control Computer
HARV	High Alpha Research Vehicle
KCAS	Knots Calibrated Airspeed
MATV	Multi-Axis Thrust Vectoring
SEC	Second
VEC	Vector Electronic Control
VISTA	Variable Stability Inflight Simulator

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