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X-31 ENHANCED FIGHTER MANEUVERABILITY DEMONSTRATOR: FLIGHT TEST ACHIEVEMENTS

Col. Michael S. Francis
ARPA/ASTO
3701 North Fairfax Drive
Arlington Virginia 22203

E. DeVere Henderson, SRS Technologies

Introduction

The X-31 Enhanced Fighter Maneuverability (EFM) Program was conceived and initiated to demonstrate the feasibility of exploiting several emerging vehicle control technologies to provide greatly enhanced maneuverability and subsequently to assess the tactical value of these capabilities for enhancing close-in air combat effectiveness. Now completing their third full year of flight test, the two demonstration aircraft have achieved virtually all of the program's original objectives, as well as several others introduced as the aircraft matured, culminating in an array of diverse achievements, including several aviation "firsts." This paper focuses on these events and the obstacles which were overcome during the flight test program as well as an assessment of the long-term implications of the results of the effort.

From its inception, the X-31 Program has been both counter-cultural and controversial in its approach to modern air combat. Predicated on the notion that an agile maneuvering capability beyond the "stall boundary" would give a modern fighter a significant advantage in close-in combat (CIC), the program's fundamental basis seemed to ignore two major tenets of aerial warfare as it evolved in the 1980's. First, the basic premise appeared to violate the widely accepted 'sustained energy maneuverability' philosophy which emanated from the post Vietnam era. Second, the program's fundamental presumption of a close-in combat arena was inconsistent with the vision of a legion of stealth advocates — one which emphasized beyond-visual-range (BVR) combat employing long range weapons almost exclusively. Despite this departure from the prevailing view, the continuing march of vehicle and weapons technologies, coupled with the increasingly diverse yet still capable threat, suggests that the capabilities being pioneered in the X-31 Program might yet prove significant for future generations of combat aircraft.

Early studies showed the concept of dynamic, post stall maneuvering to be a promising technique to defeat a 'conventional' adversary in close-in air combat. The hypothesized capability proved extremely effective as verified by the results of literally thousands of simulations — both digital and manned. In fact, these early combat simulation results were key in providing the motivation to conduct the program. The statistical results have been replicated on numerous occasions in other simulation exercises which employed various configurations.[1-6]

Although these revolutionary tactics themselves represented a significant achievement, the ability of an air vehicle to maneuver with agility into this post stall flight regime represented a significant challenge to both the designs and technologies. Breaking the once impenetrable stall boundary had become possible with the emergence of several critical capabilities — (a) high thrust-to-weight aircraft designs to achieve maximum performance; (b) multi-axis thrust vectoring capability for air breathing propulsion systems; and (c) advanced digital flight control schemes which could effectively integrate vehicle and propulsion system controls to achieve 'carefree handling' throughout the expanded flight envelope. These attributes became known as the Enhanced Fighter Maneuverability (EFM) technologies. The capabilities of such a thrust-vectored, high performance aircraft were only beginning to be understood by the visionaries who advocated this technological leap. The X-31 Program has demonstrated a number of the possibilities which exist with the adaptation of these capabilities, and many more may be expected.

The focus of the X-31 Program is as appropriate today as it was at its inception over a decade ago. Despite the gains made in low observables technology, the evolving balance in that technology suggests that close-in combat may again emerge as a significant factor in determining the outcome of the air war in future conflicts. Moreover, the X-31's unique technologies afford an even greater opportunity for improving flight performance and efficiency. Viewed as an alternative to conventional aerodynamically-driven force and moment generation, thrust-vectoring capability of the type employed in the X-31 may prove useful in aircraft stability and control; vectoring in this manner offers the promise of significantly smaller ancillary aerodynamic surfaces, along with concomitant reductions in weight and aerodynamic drag.

The X-31 Aircraft

With a solid basis and rationale provided by the numerous combat simulations, the program's architects understood the characteristics which their hypothesized vehicle would have to possess. The program's philosophy called for a demonstrator design which could not only perform controlled flight and dynamic maneuvers at high angles of attack, but one

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which could also be employed to assess the tactical benefits of the embedded technologies, i.e., a true operational surrogate. In that regard, the vehicle should possess a highly integrated 'pilot friendly' aerodynamic and propulsion flight control system in which complex control interactions would be transparent to the pilot. It must be able to fly into and out of the post stall regime with impunity, and it must have high thrust-to-weight to provide the necessary deceleration and acceleration capability to get in and out of post stall rapidly.

The vehicle design which evolved from early studies resulted in a single seat, single engine, high performance flight demonstrator (Figure 1). The aircraft consists of a slender fuselage containing an F404 turbofan engine fed by a belly-mounted inlet, a cambered and twisted wing mounted on the bottom of the fuselage, a small and aerodynamically decoupled canard forward of the cockpit, a single vertical tail, and its most distinguishing feature — three externally supported thrust vectoring paddles mounted on the aft-most bulkhead. The aircraft has a wing span of 23.8 feet and a length of 43.2 feet. The maximum takeoff gross weight is 16,200 lb., of which approximately 4,000 pounds are fuel. The fuselage contains the flight test instrumentation, the cockpit, the engine inlet and duct, the single cell fuel tank, the F404 engine, the hydraulic and electrical systems, the airframe mounted accessory drive (AMAD), the flight control computers, and the landing gear. The canard consists of left and right panels mounted on a common shaft, and operated thorough electro-hydraulic actuators. Canard deflection angles range from -55 degrees (leading edge down) to +20 degrees. The air data boom is mounted on the underside of the aircraft to counteract effects of this appendage on the lateral-directional characteristics of the aircraft in the post stall regime. A detailed description of the aircraft is available from prior publications.[7-12]

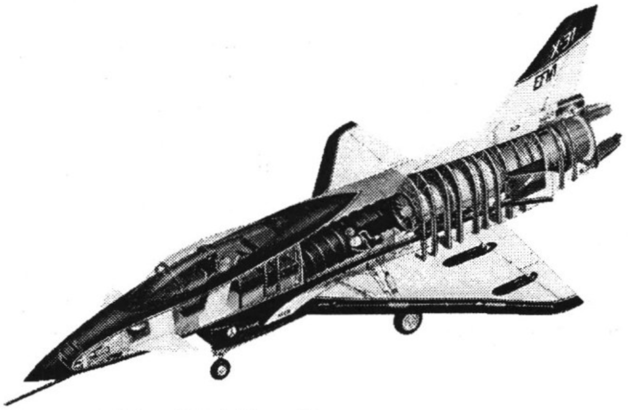


Figure 1. The X-31Aircraft.

Of special significance is the aircraft's thrust vectoring system which consists of three carbon-carbon vanes attached to the aft fuselage structure, each coated with silicon carbide in high temperature regions. These vanes are positioned symmetrically about the engine circumference with vane #1 located just below the vertical tail in the symmetry plane. Each vane is driven by a separate actuator. The vanes can deflect up to 35 degrees into the jet plume. Vanes #2 and #3 located on the lower half of the fuselage can be employed as speed brakes by extending them to their maximum 60 degree outward position. Vane #1 is limited to a 7 degree outward deflection due to its proximity to the spin chute.

Vehicle control of the X–31 aircraft is achieved through pilot "commanded", computer-implemented flight control laws which select the appropriate mix of control effectors to match the desired flight condition. This unique control strategy may involve any of a multitude of combinations of aerodynamic surfaces, i.e., wing leading and trailing edge flaps (inboard or outboard) and canard, as well as the position of the three thrust vector vanes. Although designed to be employed as a maneuvering aide in various flight control strategies, the canard has been employed only as an aerodynamic 'recovery' device, to date. By remaining unloaded (or nearly so) in post stall flight, the weathervaned canard can effectively provide restoring moments in the unforeseen event of loss of control. Engine throttle control is maintained as a separate, independent pilot-selectable function. The system is automated to the extent that the control effector combination commanded is generally transparent to the pilot.

The X-31's digital fly-by-wire multi-variable feedback system affords exceptional flexibility for configurational changes. Although a classical quadruplex hardware concept was proposed early in design, budget and schedule constraints dictated a somewhat different approach based on three dedicated flight control computers and a fourth computer to serve as a so-called "tie breaker." Figure 2 illustrates the concept and ancillary components. This new FCS hardware architecture required the development of a complex redundancy management concept. In order to fulfill the "fail-safe" requirements, some of the redundancy man-

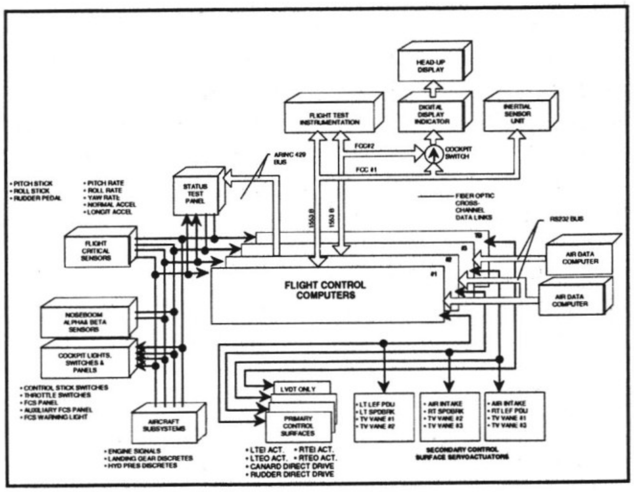


Figure 2. Flight Control System Architecture

agement logic functions had to be integrated into the control law structure and increased the control law design effort considerably. Loss of essential feedback signals could only be compensated by reconfiguration of the basic control mode, which led to the implementation of degraded (reversionary) control modes.[13]

Flight Test Program

The focus of the X-31 Program was on flight demonstration. To achieve the program's diverse objectives, a three phase flight test program was created. These three major phases can be defined as 1) conventional envelope definition; 2) post-stall envelope expansion; and 3) tactical evaluation.

Conventional Envelope Definition

The first of these segments was conducted with two objectives in mind. First, since the X-31 was a new design, it was important to demonstrate its performance, reliability and overall flight worthiness. Second, a comprehensive examination of the conventional (below stall) flight regime was necessary to conduct safely the mock combat exercises to be flown as part of the tactical evaluation.

During the conventional envelope expansion process, the two aircraft completed 102 sorties over an approximately 14 month period. The aircraft were flown to a Mach number of 0.92, achieved 40,000 feet altitude and demonstrated 7.2g (positive-g load factor) conventional turns. This envelope was entirely adequate for the tactical close-in engagements planned for the final flight test phase. During these flights the vehicle's handling qualities, structural loads, flutter characteristics and flight control system behavior were assessed. A summary of conditions flown in the conventional envelope is depicted in Figure 3. Formation flight and other tasks in the conventional mode which require precise flying were accomplished without difficulty.

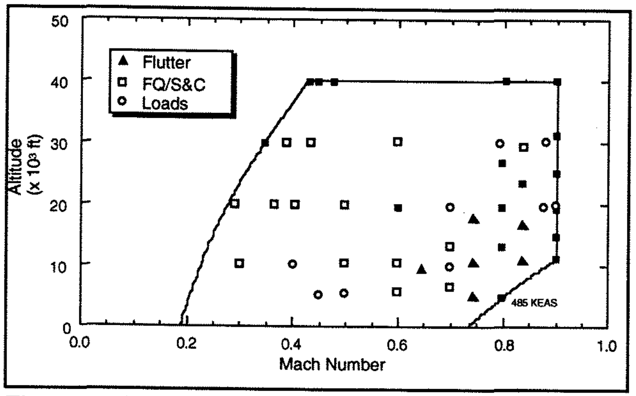


Figure 3. Conventional Flight Test Conditions

The thrust vectoring system was initially calibrated in the conventional flight mode. Its operation in flight has been verified as being transparent to the pilot. Identical flying qualities are evident with thrust vectoring on or off (as designed). A compilation of thrust vectoring calibration test points accumulated over the conventional envelope is depicted in Figure 4. A detailed assessment of conventional performance and handling qualities can be found in prior publications. This first phase of the flight test program was concluded in the fall of 1991.[10,13]

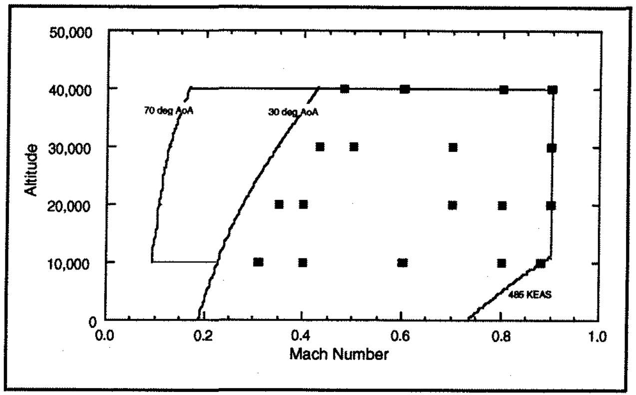


Figure 4. Thrust Vectoring Vane Calibration Points

Post Stall Envelope Expansion

In December 1991, the X-31 aircraft and the flight test program were relocated from Rockwell's Palmdale flight facility to the NASA Dryden Flight Research Center. With the addition of NASA personnel and facilities, as well as U.S. Air Force Flight Test Center participation, the program was poised to begin its most challenging phase. The post-stall envelope expansion was the lengthiest and most demanding phase of the flight test effort. It embodied the greatest number of unknowns, so the schedule was adjusted to allow for this pioneering activity.

The post-stall regime has been defined as any flight condition in which the angle of attack exceeds 30 degrees. Expanding the post-stall envelope, however, involved significantly more than reaching the limiting values of this parameter. Because the X-31 is designed to fly aggressively into and out of the post stall arena to facilitate extremely rapid turning and pointing, the coupling of multi-axis high levels of agility within the high angle-of-attack regime necessitated a broader view of the envelope expansion process. The potential number of test variable combinations increases dramatically when dynamic rate parameters in all six degrees of freedom are introduced. The desire to explore this expanded new envelope comprehensively and investigate new 'discoveries', such as unique aerodynamic phenomena, was clearly at odds with the available resources and schedule.

To achieve a reasonable compromise on these issues, the concept of "maneuver milestones" was created. This idea permitted the selection of a small set of stressing maneuvers which could form a building block approach to expand aircraft performance sequentially in the dynamic post stall regime. To this end, a set of four maneuver milestones was identified:

1) Trimmed, stable flight at a maximum angle of attack of 70 degrees;

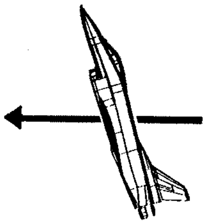
2) Full deflection, 1g, velocity vector rolls at 70 degrees AoA;

3) Dynamic, level turn entry to post stall conditions from corner speed with maximum AoA less than or equal to 70 degrees; and

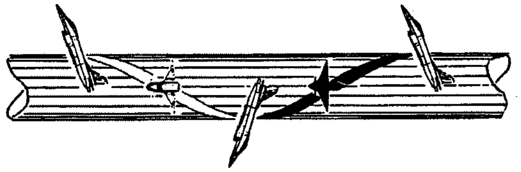
4) Turn-optimized, gravity-assisted post stall maneuver with a 180 degree heading change at minimum radius and maximum rate.

The first three are graphically depicted in Figure 5. The fourth maneuver (Figure 6) is sometimes referred to as the "clinical" or "Herbst" maneuver, after the originator of the concept. This maneuver is analogous to a classic wing over, but it incorporates the vehicle agility and high AoA characteristics embedded in the X-31 philosophy, i.e. high entry speed, rapid deceleration to deep post stall conditions, rapid roll around the velocity vector at high AoA, and subsequent rapid acceleration back to high speed conditions with concomitant return to low (conventional) AoA.

(a) Steady State Flight (70° AoA)



(b) Velocity Vector Roll (70° AoA)



(c) Dynamic Entry (70° AoA)

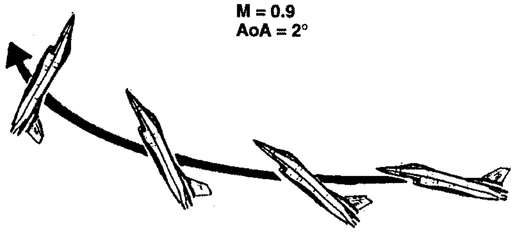


Figure 5. Maneuver Milestones.

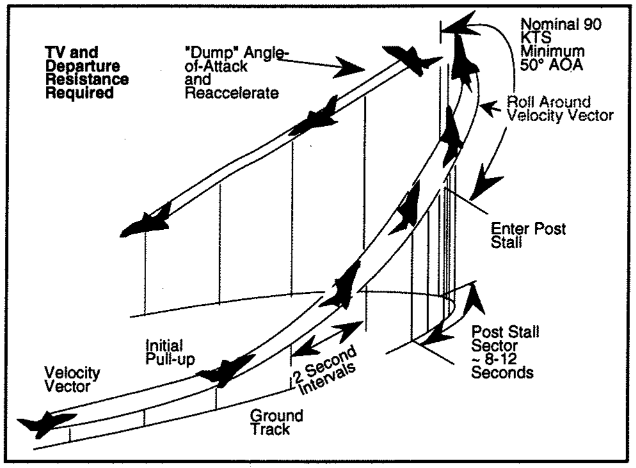


Figure 6. Clinical Post Stall Maneuver.

Collectively, this set of maneuvers embodies virtually all of the agility characteristics and performance attributes desired of the vehicle. While none of these maneuvers was developed uniquely for combat purposes, they illustrate the desirable properties of the vehicle in a way understandable to combat pilots and tacticians.

The string of significant achievements in post stall flight began in September of 1992 when Navy test pilot Al Groves achieved sustained 70 degree AoA flight for 45 seconds at 35,000 feet altitude. Prior to this flight, numerous tests were conducted in the 30-70 degree AoA range during gentle (1g) deceleration. Pitch and roll doublets were employed to assess handling characteristics and aerodynamic issues.

In the post stall mode with vectored thrust enabled, the X-31 has continuously demonstrated adequate pitch-up authority and a repeatable, authoritative response to control input. However, the aircraft has exhibited less of a nose-down pitching moment than predicted. This was found to be due to changes in the external lines of the aircraft. The original X-31 configuration featured external structural booms to hold the thrust vectoring paddles in place. These were later incorporated into the structure so that the aft end of the fuselage presented a smooth, unbroken contour. The aerodynamic database used for control system development was based on the original configuration with the exposed booms. No significant difference between the predicted and the experienced aerodynamics was noted until angles of attack of 52 degrees and greater were reached. The deviation between prediction and experience increased as lateral maneuvers were introduced. As a result, small aft strakes were added to the aircraft's tail region (Figure 7a). The strakes are oriented 11 degrees, nose down, to provide the requisite effect.

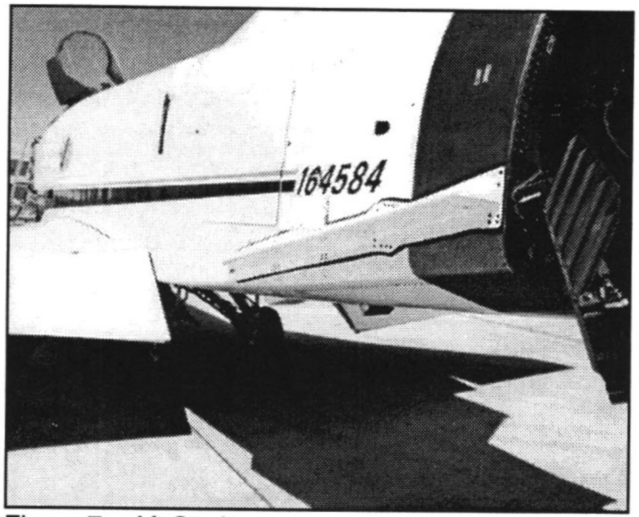


Figure 7a. Aft Strake.

During this phase of testing, "agility" at high angles of attack was a major area of program focus. The velocity vector roll response and controllability at high AoA were employed as principal metrics in this regard. As angle-of-attack expansion was occurring, full stick input bank-to-bank and 360 degree velocity vector rolls were also being attempted. At this same time, asymmetries in vehicle response to control inputs were observed as were differences between simulator and actual fight parameters. These anomalies created considerable attention and concern.

Initially, the velocity vector roll response was observed to be rather sluggish when compared to conventional mode maneuvers. However, even these initial tests revealed response significantly better than any current aircraft. (Full stick rolls under post stall conditions in most conventional modern conventional aircraft are likely to result in a departure.)

The initial segment of the post stall envelope expansion was completed on November 6, 1992, when Aircraft # 2 successfully completed Maneuver Milestones 1 and 2, both on the same day. Sustained 1g deceleration to 70 degrees AoA at 20,000 ft (msl), the lowest altitude required for official completion of the milestone, was achieved by DASA test pilot Dietrich Seeck. On the very next flight, Rockwell pilot Fred Knox successfully completed 360 degree velocity vector rolls at 70 degree AoA to both the left and right. This too was accomplished at 20,000 feet nominal altitude.

The principal issues encountered during this early flight test effort were in two areas: (1) sub-optimal handling qualities due to excessive stick forces, and (2) lateral asymmetries resulting from unusual aerodynamic phenomena.

The handling qualities in the post stall regime were sub-optimal due to the substantial pitch stick forces required for control. Overly high levels of pilot concentration were required to stabilize the vehicle and sustain exact test conditions due to stick forces ranging from 15 to 22 1/2 pounds in the PST mode. Furthermore, the stick travel "alpha" command schedule was such that one millimeter of stick travel was nominally equivalent to one degree angle of attack. Loads of this magnitude, coupled with command schedule sensitivity required both hands on the stick and intense focused attention. Constant-angle-of-attack rolls were even more difficult. Despite excessive forces and other negative aspects of the pitch axis control scheme system, the pilots unanimously believed that the system would be satisfactory for performing the maneuvers anticipated during the tactical evaluation phase of the flight test program.

The lateral asymmetries experienced in sustained 1g deceleration maneuvers at high angle of attack are believed to be caused by the behavior of longitudinal vortex pairs generated on the nose of the vehicle. The asymmetric behavior was most intense in the 45-55 degree AoA range, with extreme sensitivity to minor irregularities in nose geometry. The resultant influence of these vortices led to a build-up of yaw angle ('beta' build-up) and an eventual inability of the control system to generate sufficient control power to resolve the problem. Several aerodynamic solutions were attempted. Sandpaper-like 'grit strips' were fabricated and attached in various areas of the nose in an attempt to spread spectral energy in the nose vortices and force a higher degree of symmetry. These devices worked with mixed success.

While these aerodynamic questions persisted, the task of envelope expansion continued. The most difficult of the maneuver milestones turned out to be the high speed 'dynamic entry'. As in other cases, a building process was used employing sequentially larger entry velocities coupled with higher terminal angles of attack. Pilots also progressed from gradual to more abrupt stick pulls to control entry rate. The maneuver was also attempted from an inverted position (following a split - S from higher speed) for added safety and controllability.

On the third attempt at a dynamic entry from Mach 0.50, Air Force pilot Lt. Col. Jim Wisneski abruptly pulled the nose to a terminal angle of 60 degrees. After momentary stabilization, the X-31 departed controlled flight and entered a one revolution spin before a full aerodynamic recovery was effected by the pilot implementing spin control inputs. This departure on 25 November 1992 is the only instance in which the X-31 has been out of control during its flight history.

After analysis of flight test data, the culprit was again identified as lateral aerodynamic asymmetries coupled with insufficient control power to overcome the resulting forces. The magnitude of the forces and the time delay strongly suggest the influence of an energetic unsteady aerodynamic phenomenon. Subsequently, an error in the control algorithm was found, suggesting that the vectoring vanes were not properly commanded during the resulting rapid 'beta' build-up.

Solutions to these problems came through modifications to flight control software which corrected the algorithm and provided greater control authority — achieved by increasing the inward thrust vector vane travel from 26 degrees to 35 degrees. The original vane travel limit was derived as the maximum deflection which geometrically prevented collision of the vanes. The additional requirement for vectoring control authority necessitated a removal of this constraint and the incorporation of a new flight control algorithm to prevent vane collision.

In addition, a set of small strakes (Figure 7b) was added in the nose region extending rearward from its apex along the half-breadth line, extending outward and perpendicular to the surface. These 0.6 inch wide by 20 inch long additions were incorporated to broaden the spectral content of the turbulence generated from the nose vortices, decreasing the probability and severity of any asymmetric forces. Based on wind tunnel test data which indicated nose apex radius also influences vortex behavior, the nose radius was increased slightly from less than 0.1 inch to approximately 0.58 inch to achieve similar results.

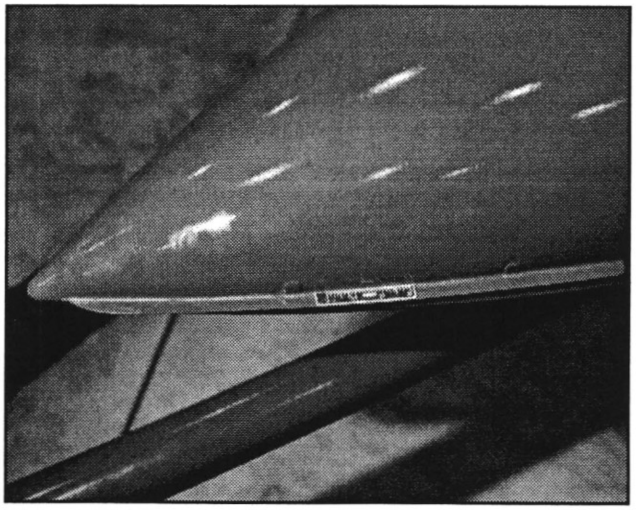


Figure 7b. Nose Strake.

On 9 February 1993, Lt. Col. Wisneski re-flew the departure-inducing maneuvers on Aircraft #1 with the new changes to vehicle hardware and software. He successfully completed Maneuver Milestone 3 by achieving a dynamic entry from Mach 0.6 to a terminal angle-of-attack of 70 degrees. Again, this maneuver was completed from the inverted position following an initial split-S maneuver. The sensed rotation rate was 37 degrees per second, with the aircraft sustaining 2.3 g's during the pitch-up portion of the maneuver.

Although the dynamic entry maneuver was successful, the lack of 'margin' experienced during the process provided the most limiting characteristic in the aircraft's dynamic maneuver envelope. Full travel, abrupt stick pulls to maximum AoA were limited to 185 knots (approximately Mach 0.40) yielding an almost 4g pull-up load. Additional control law modifications soon increased this limit to 225 knots (Mach 0.6) and an approximately 5.2g pull up load. In comparing this capability with the many combat simulations, it was estimated that over 85% of combat applications of post stall maneuvering would occur inside of this limitation. It should also be noted that pitch up to lower maximum AoA values permits higher initial entry speeds. Since that time, the envelope has been expanded to allow a 265 knot entry.

Upon completion of Maneuver Milestone 3, efforts were immediately focused on Maneuver Milestone 4 — the so-called J-turn with a 180 degree change in flight path direction. This "Herbst maneuver" combined all the essential elements of the first three milestones. To begin, a dynamic entry was initiated to a maximum angle-of-attack condition (70 degrees AoA). The aircraft acts as its own speed brake as it pancakes into the relative wind. As the vehicle decelerates, the pilot begins to rotate the aircraft about the velocity vector — all the while precessing the flight path direction until a 180 degree heading change is realized. With the aircraft nose and flight path oriented opposite to the initial direction, the high thrust-to-weight capability of the X-31 is used to accelerate back to high speed as the aircraft is 'unloaded'. Accomplished at high altitude and with a requirement to reach 70 degree AoA, an altitude loss of approximately 2500 feet results. If initiated from lower altitudes and taken to lower maximum angles of attack, the maneuver can actually result in a slight altitude gain.

On 25 February 1993, German Government test pilot Karl Lang was the first pilot to successfully complete the full Herbst maneuver. Entry began at 30,000 feet, at Mach 0.4. The resulting deceleration and turn took approximately 11 seconds for the vehicle to achieve the 180 degree nose heading change. Acceleration and recovery to level flight required an additional 32 seconds. The resulting turn radius was 475 feet (compared to an equivalent conventional turn of approximately 2500 feet).

The final segment of high alpha envelope expansion involved several characterization activities such as loads evaluations and flying qualities assessments. The most critical flights were those directed at evaluating the aircraft's departure resistance under post stall conditions to assure that pilots could confidently operate the X-31 under mock combat conditions without concern for loss of control. To accomplish this, combinations of abrupt, full-stick, diagonal stick motions were input in an attempt to induce loss of control. Eight flights were employed to assure program and safety officials that the aircraft possessed true carefree handling.

Full envelope expansion, a necessary prerequisite for tactical evaluations, was completed in July 1993.

The Tactical Evaluation

Preparations

Early in the development of the plan to evaluate the tactical benefits of vectored thrust, it was recognized that, without onboard sensors and other fire control elements on the X-31, it would be necessary to estimate the effectiveness of various firing conditions and related parameters. To develop this understanding and to train pilots in judging the conditions for success, a simulation campaign was conducted at the German IABG facilities in Ottobrunn in April 1991. From the many one-vs-one combat simulations which occurred, a set of various combat "rules of thumb" (ROT) was created. A second, intense three week campaign, named Pinball I, conducted in October 1991, sought to further develop and refine the ROT for use in the flight test program.

During that latter campaign effort, a set of twelve engagement starting conditions was employed. Observations suggested that set-ups at longer ranges and larger heading-crossing angles resulted in stalemates or mutual kills, substantiating results from previous operational analysis and unmanned simulations. Therefore, the twelve initial conditions which were used at the outset were reduced to a meaningful set of four. Final preparations for flight test were completed during a third simulation exercise in October, 1993. The starting conditions which were used are shown in Figure 8.

Exchange ratios achieved during these simulation campaigns were consistent with earlier simulation exercises having the same objectives and constraints. The X-31 achieved, on average, an approximate 3-to-1 advantage over an otherwise equal conventional opponent. However, there were some significant differences in the detailed metrics. For example, the original hypothesis was to employ thrust vectoring capability in post stall flight to achieve rapid flight path 'bending' — to decelerate rapidly, precess the velocity vector in post stall, and use the inherently high thrust-to-weight to rapidly accelerate in the new direction of flight. However, the simulations instead revealed that pilots em-

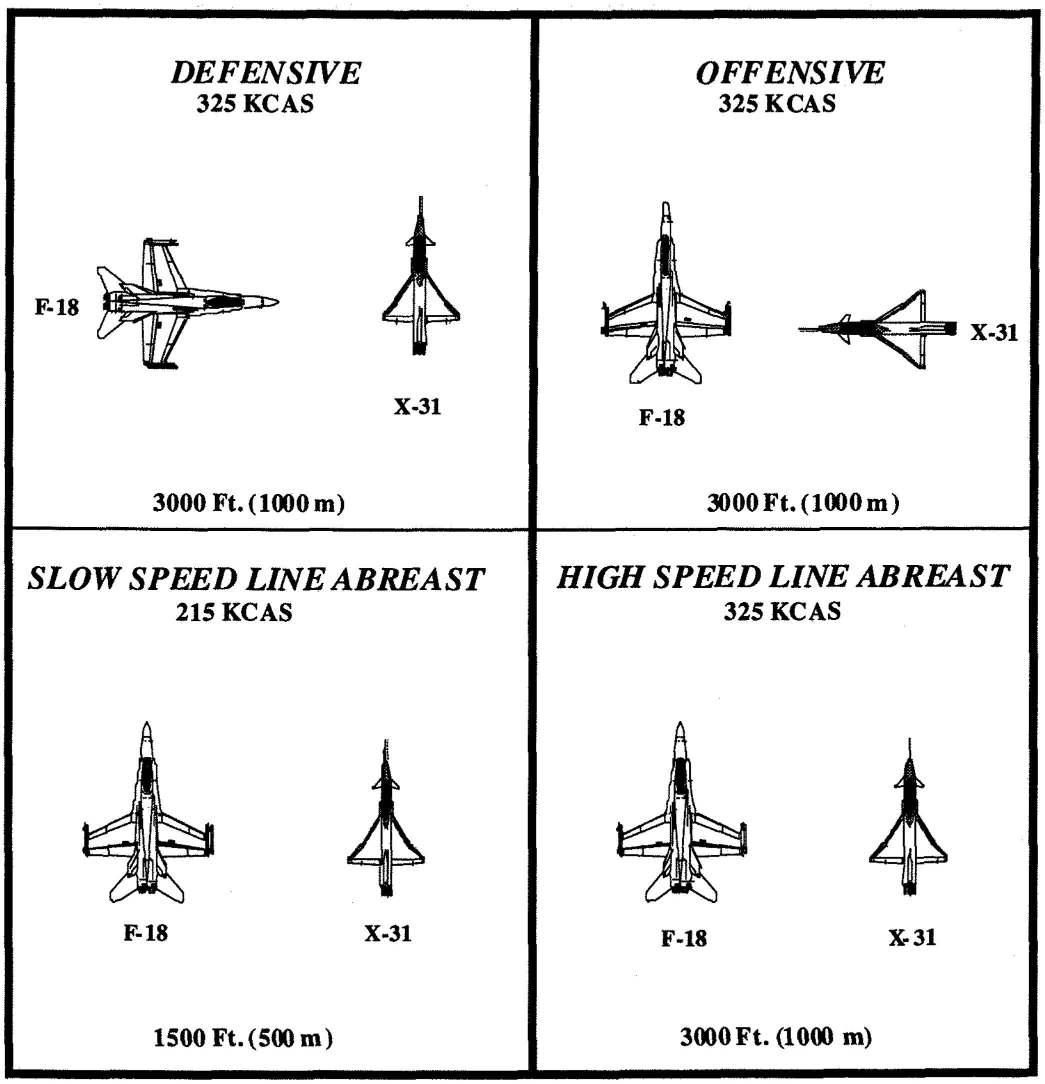


Figure 8. Starting Conditions for Tactical Utility.

ployed the vectored thrust capability in a different manner — namely to dissociate the aircraft's longitudinal body-fixed axis from the velocity vector for pointing or tracking snap gunshots.

This is probably attributable to several factors associated with the 'as built' X-31 aircraft. First, the X-31's actual thrust-to-weight ratio was not as high as anticipated in design due to small weight growth during development. Second, engagement initial conditions constrained both proximity and speed to avoid aircraft post stall dynamic entry limitations, and thus inhibited the exploitation of higher speed agility metrics. Other factors include limitations in assumed missile weapons which precluded the X-31 from fully exploiting the high alpha envelope for weapons release, and, the limitations on visual acuity available from domed simulators which alter the pilot's natural sensory inputs.

Although the overall statistical results were comparable to prior simulation efforts, the mechanics and tactics which produced those results were markedly different.

In-Flight Tactical Evaluation Summary

While much of the flight test program was focused on demonstrating agility in the post stall regime, the ultimate measure of success for the X-31 would be the value of these capabilities in close-in combat. Mock combat engagements were employed to validate the tactics and trends observed in simulations, but the actual outcome was more than could have been expected.

The CIC evaluation was conducted at NASA Dryden between November 1993 and February 1994. The X-31 utilized its full post-stall capabilities in 21 sorties which encompassed 93 scored engagements. Five of the six program pilots participated in these tests. Three NASA pilots (one of whom was also an X-31 pilot), highly experienced in fighter aircraft, performed the role of adversary pilot for all of the CIC engagements.[14]

The results of the engagements were dramatic. A majority of the setups were flown with neutral initial conditions. In these cases, the post stall capable aircraft won 64 out of 66 engagements, yielding a 32:1 exchange ratio. Considering all the post-stall X-31 engagements, there were only four that ended in a draw. (A draw occurred when either 90 seconds expired without a winner or one of the aircraft descended below the 13,000 ft. soft deck). Even for the defensive setups, the X-31 won a majority of the time — a factor which has surprised many analysts. In these situations, knowledgeable pilots take advantage of the aircraft's inherent quickness to avoid an initial shot, maneuver into position, and accomplish a 'kill' — all in just over a minute, on average.

To assure that a competitive conventional advantage had not somehow accrued to the X-31, 28 engagements (7 sorties, all six program pilots) were flown with the X-31 limited to its conventional performance, i.e. no thrust vectoring and 30° maximum AoA. When the X–31 was constrained to its conventional mode against the F/A–18 from neutral starting conditions (HSLA and SSLA), the F/A–18 won 12 out of 16 engagements, for a 1:3 X-31 exchange ratio. Ten engagements ended in a draw when the X-31 was limited to its conventional envelope.

In addition to quantitative results, the flight evaluation provided additional insights into the nature of close-in combat using post stall tactics (PST). PST should be employed for either positioning or pointing. In either case, the capability must be applied selectively, and sparingly. In a neutral situation, PST can be effective for gaining an advantage. However, PST should not be used for extended periods, due to the concomitant high energy loss and eventual negative consequences.

Pointing with PST should only be used when ready to employ a weapon or to force the adversary to a desired move. Since energy loss occurs, the pilot should assure that the energy loss is traded for a kill.

Ancillary EFM Technologies

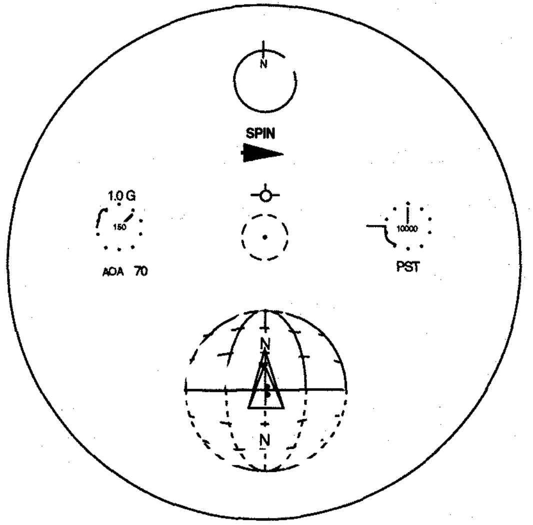
Crew Support Initiatives

During the formulation of the X–31 experimental test program, it was anticipated that the execution of post-stall maneuvers might induce physical and cognitive stresses quite unlike those experienced in conventional flight. Accordingly, crew support technologies were identified as one of the key areas which could enhance operations in the post stall regime, and a set of related development initiatives was implemented. These included investigation of anti-g and situational awareness-related devices. Due to programmatic constraints, these initiatives were deferred shortly after the program was initiated. However, with schedule slips in the X-31 flight test program and subsequent breakthroughs in helmet-mounted display technologies as well as audio techniques, it became feasible to incorporate some of these ideas into the X-31 flight test program.

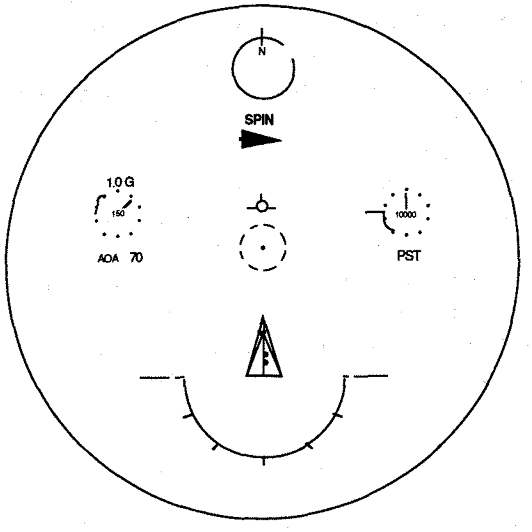
Based on the availability of a capable helmet-mounted display (HMD) system, program officials decided in early 1993 to investigate the values and effectiveness of several unique visual display formats for improving pilot situation awareness in the dynamic, post stall environment. To further enhance this capability, a spatially three-dimensional (3-D) audio system would be integrated with the visual format. The evaluation of these capabilities was led by the U.S. Air Force Joint Cockpit Office. Their involvement also permitted comparison of results with related F-22 data points. A secondary objective was to obtain data for off-line agile aircraft/agile weapons analysis, including an assessment of the feasibility of using the helmet-mounted displays for aiming high alpha weapons during PST combat maneuvering.

The helmet with display hardware used in the X-31 Program is designated as the "Viper," and is manufactured by GEC-Marconi Avionics. It is comprised of a standard (Navy) Gentex helmet with additional, specialized optics. Viper uses a miniature cathode ray tube (CRT) to generate a monocular image of the symbology which is presented to the pilot directly on his helmet visor. The HMD system, which includes a Polhemus head tracker, is fully integrated and operational on the X–31. Pilot response to the system has been very positive. The X-31 Helmet-Mounted Display was initially flown in December 1993. This event represents the first usage of such a device on a highly-agile demonstrator aircraft with key instrument data display. This format allows the pilot to monitor critical aircraft data while remaining "heads-up" throughout dynamic air-to-air engagements. No matter where the pilot looks, his display is always in view, increasing the pilot's level of tactical and spatial awareness, thereby enabling the pilot to optimally utilize the aircraft's unique capabilities. The HMD has been flown as part of the X-31 close-in combat tactical evaluation to assess the utility of two unique attitude display formats developed by the US Air Force and Deutsche Aerospace of Germany. The two formats, known as THETA and Arc-Segmented Attitude Reference (ASAR), respectively, are illustrated in Figure 9.

The 3-D audio system was designed and developed by the Air Force's Armstong Laboratory to provide complementary, useful sound cues to the pilot and to declutter the visual system. The spatial resolution capability was believed to add a level of added fidelity in this regard. Sound cues generated by a 3-D Audio Localization Cue Synthesizer (ALCS) have been used to provide navigation and targeting information to pilots flying AV-8B aircraft. Equipment limitations would preclude the evaluation of this capability during the flight test program.



FULL THETA SYMBOLOGY



FULL ASAR SYMBOLOGY

Figure 9. Helmet Mounted Display Symbologies.

During initial ground evaluation, three different sound cueing formats were evaluated in the manned simulator. In the first, a tone that varied in frequency and pulse rate cued AoA. For AoA less than 20 degrees, no cue was provided; for angles between 20 and 27 degrees, a 400 Hz tone was presented and the pulse rate varied linearly from 1.6 to 6 Hz. For AoA between 27 and 33 degrees, a 900 Hz steady tone was provided. Finally, at AoA between 33 and 45 degrees, a 1600 Hz tone with linearly increasing 1.5 to 9.6 Hz pulse was provided. For this "non-localized" or "1-D" format, the sound cue was not localized in space but was, instead, presented monaurally to the left and right earcups. In the second format - a "localized" or "3-D" format, a low frequency tone was presented when AoA was less than or equal to 30 degrees. For AoA above 30 degrees, a medium frequency tone was presented. The pulse rate for the tones in this format varied linearly, so that at 70 degrees AoA, the pulse rate reached 10 Hz maximum. In this display, the sound cues were localized in space, so that changes in angle resulted in a re-positioning of the sound cues presented to the pilot. Finally, a third audio format provided 3-D sound cues at a constant frequency and pulse rate that were correlated with true North heading.

In general, the pilots found the 3-D audio system to have limited value. Among several limitations, it was difficult to distinguish audio cues with 30°. It was also difficult to distinguish spatially in some areas, as, for example, between a cue at the 12 o'clock position from one at 6 o'clock. In contrast, the 1-D cueing scheme was effective for alerting pilots to critical angles of attack. After significant testing in the simulator, only the 1-D audio system was installed in the aircraft.

Combined Visual/Audio Cue Flight Test Results

Data collected over 35 flights included pilots' responses to the post-flight questionnaire, test observers comments, pilot in-flight and post-flight interviews, and selected periods of down-linked and on-board recording of the actual time dependent display data. Data were collected on the operation of the HMD helmet and symbology, physical characteristics of the HMD helmet, effectiveness of both the ASAR and THETA display formats and suggested format improvements.

After a short familiarization period, the pilots encountered no difficulties operating the equipment suite. The aiming reticle on the HMD was used for tracking and targeting tasks on several of the flights. On other flights, the HUD reticle, rather than the HMD reticle, was used for these tasks. Furthermore, because the HUD has no declutter functions, whenever the HUD was on, the full HUD symbology set was presented. The simultaneous use of both HMD and HUD symbology required a certain amount of accommodation for some of the pilots. However, pilots found that during CIC, they were so focused on target tracking that the relatively cluttered FOV containing HMD and HUD symbols was not distracting. Overall the combination of the visual and 1-D sound cues were found to contribute positively to situation awareness and aircraft control. Additional tests of display variants were also planned for later flights.

The Quasi-Tailless Flights

Although the initial focus of the X-31 Program was on close-in air combat involving relatively slow speeds (by modern jet standards), it became apparent that the aircraft's key enabling technologies might also provide significant enhancements in other areas of the flight envelope. In particular, it appeared possible to use the multi-axis thrust vectoring capability to stabilize and trim the vehicle and perhaps even provide maneuvering control — at supersonic speeds. Employed for these purposes on a conventionally designed aircraft, the thrust vector control scheme provides a form of true 'functional' redundancy — an attribute which both enhances safety as well as inherently improving combat survivability. However, if exploited in a new vehicle design, this capability affords an opportunity for an entirely new control strategy permitting reduction or possibly even removal of the empennage.

To investigate this notion, a unique experiment was conceived which tested the hypothesis without physically altering the airframe. In this "quasi-tailless" experiment, as it came to be known, the conventional aerodynamic control surfaces are employed pro-actively to reduce or eliminate the stabilizing influences of the vertical stabilizer. Destabilization is accomplished by counteracting the vertical stabilizer's normally positive influence using the rudder in a manner opposite to normal use. The resulting sideslip, or "beta," generates an aerodynamic coupling in roll and yaw which requires a second order correction to counteract these tendencies. This is accomplished by "corrections" to the yaw rate and roll rate feedback signals to the ailerons and rudder. Restabilization is then mechanized by a redistribution of the required control power using the thrust vectoring system. This quasi-tailless experiment is depicted schematically in Fig. 10.

The potential to create this unusual capability is a by-product of the aircraft's fully digital flight control system. Vehicle destabilization is accomplished by a software "overlay" to the conventional flight control system rudder and aileron gains (beta, yaw rate, and roll rate) to obtain the desired lateral/directional qualities of a reduced tail, or even tailless aircraft. The actual gains required for destabilization are depicted in Figures 11a and 11b, as a function of fraction of tail stabilization decrease, or, equivalently, per-

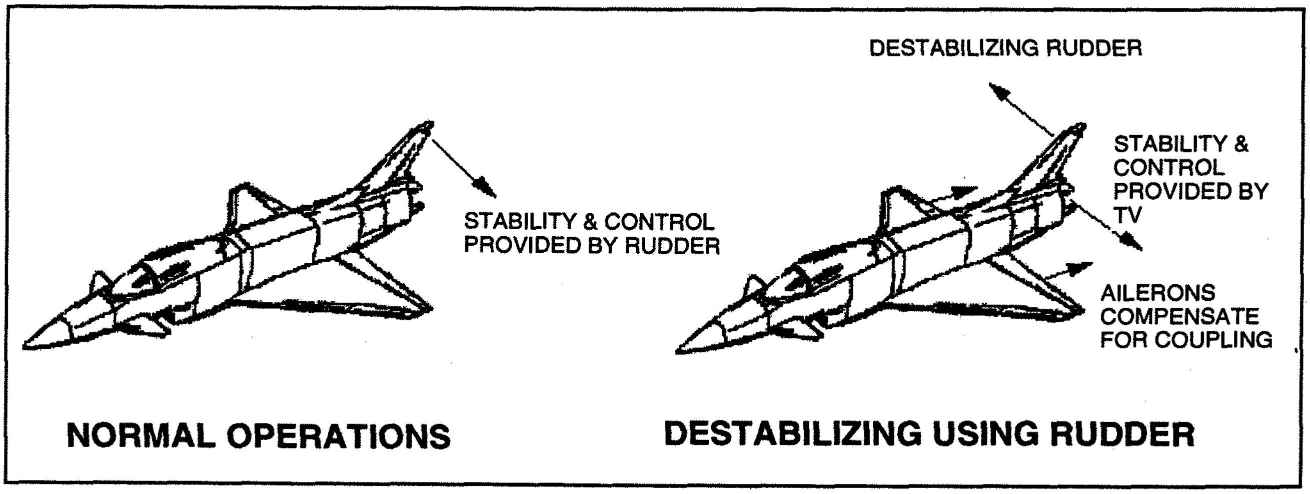


Figure 10. Quasi-Tailless Demonstration.

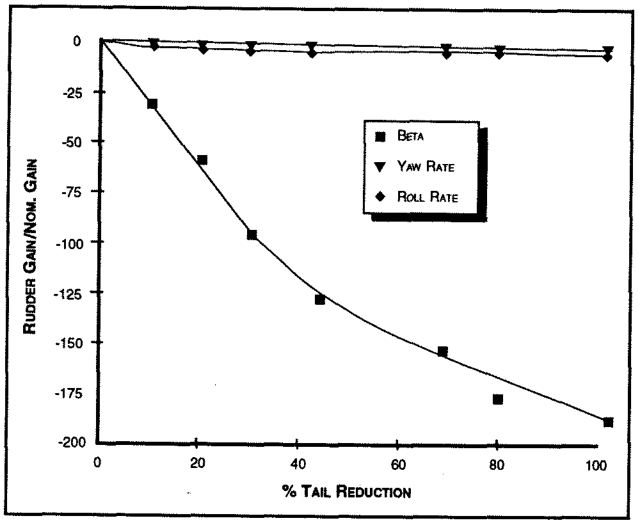


Figure 11a. Rudder Gain Schedule(M=1.2, 37.5 Kft).

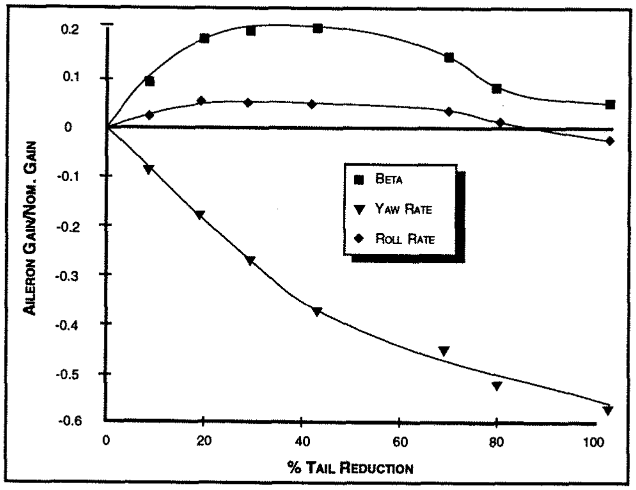


Figure 11b. Aileron Gain Schedule(M=1.2, 37.5 Kft).

cent of tail 'removed'. In the figures, the required gains have been normalized with respect to the nominal gains employed in otherwise conventional flight. (The system gains represent a ratio of the required aircraft motion to the required control surface output. For example, the rudder beta gain represents the desired aircraft yaw displacement to the required rudder deflection.) The negative value for the rudder 'beta' gain indicates that the rudder acts opposite to its conventional displacement during the quasi-tailless experiment. The magnitude of this parameter suggests that it dominates other terms in providing destabilization. The dominant parameter governing the aileron motion and used to compensate for the moving rudder, is the yaw rate gain. The other gains in the system are necessary to further compensate for the mode coupling alluded to above.

The actual degree of net stability provided by the tail can be preselected or even "dialed-in" using the proper adjustments. Once the degree of destabilization is selected, a separate control algorithm can be used to provide stabilization, trim, and even limited pitch and yaw control through the thrust vector vanes.

The system was mechanized to revert back to normal conventional flight if certain parametric criteria were not met. If any component of the thrust vectoring system failed to engage, or if any event caused the flight control redundancy management system to request one of the reversionary modes of the basic flight control system, the system would exit the destabilized/quasi-tailless mode.

A major concern in implementing the quasi-tailless control capability rested in the adequacy of the thrust vector vane (TVV) actuators to respond to perturbations in this high speed regime. Digital simulations indicated that an actuator response capability approaching 60 degrees per second would be required at Mach 1.2. The X-31's TVV actuators are capable of producing up to 60 degrees per second, including the response of the sensor-flight control computer elements of the control system. This capability is more than adequate to provide the requisite performance.

To minimize the cost and schedule impact of this "add-on" capability (it was not a programmed or funded requirement), the initial set of tests focused on a single flight condition — Mach 1.25 at 37,500 feet altitude. In November, 1993, the X-31 was flown to supersonic speeds (M=1.28) for the first time, and, on a series of four flights, cleared the envelope for the quasi-tailless experiments.

Prior to the X-31's historic flight, a plume tracking test was conducted from Mach 0.9 to 1.25 to confirm predicted thrust vector effectiveness at these higher Mach numbers. A series of four test flights was then conducted for the quasi-tailless experiment. Roll doublets were performed in the destabilization mode up to an effective tail reduction of 20%. Maneuvers in the thrust vectored quasi-tailless mode included roll doublets, bank-to-bank rolls, and 2G turns up to 100% tail reduction and yaw doublets up to 40% tail reduction. Control inputs were limited to one-half lateral stick with no abrupt maneuvers. Conventional speed brakes were not used nor were the thrust vectoring vanes used as speed brakes in this experiment.

The quasi-tailless experiment was successfully completed in the four dedicated test flights. The thrust vector effectiveness exceeded all expectations, even compensating for an over destabilization that occurred at higher tail reductions due to a higher than expected rudder effectiveness. Achieving these results in only four flights, three of which occurred on the same day, was clearly a significant engineering accomplishment.

Summary

The X-31 Program has achieved all of its original goals related to low cost demonstrator development and dynamics post stall flight. The tactical utility results achieved with the EFM technologies in close-in combat are staggering by any measure and speak for themselves. The X-31 has successfully demonstrated the potential of vectored thrust for achieving stabilization and control of atmospheric flight vehicles at high speeds. The implications of this capability are profound — offering the potential to reduce or eliminate the ancillary aerodynamic surfaces associated with the tail region of the aircraft. The concomitant potential to reduce aircraft weight, aerodynamic drag and related 'observable' has yet to be fully assessed or exploited, but the potential gains are known to be significant. Further investigation, for application to both civil and military air vehicles is clearly warranted.

References

1. Herbst, W.B., *Dynamics of Air Combat,* Journal of Aircraft, Volume 20, July 1983.

2. Ross, H., *Tahtische Auswertung von PST - Manover im Luftkampf,* MBB Report ETL 1977, 1.SS-1.

3. Haiplik, R., Eberle, *Bemannte Simulation - 1979,* MBB Report TKF/STY/0071.

4. Herbst, W.B., *Future Fighter Technologies,* Journal of Aircraft, Volume 17, August 1980.

5. Herbst, W.B., *Supermaneuverability,* Joint Automatic Control Conference, University of Virginia, Charlottesville, June 17-19, 1981.

6. Doave, P.M., Gay, C.H., Fligg, J.A., et.al., *Multi-System Integrated Control (MuSIC Program),* McDonnell Aircraft Company, June 1990, WRDC Technical Report 90-6001, Restricted by Arms Export Control Act.

7. Powers, S. and Schellenger, H., *The X-31: High Performance at Low Cost,* AIAA-89-2122, Presented at the AIAA/AHS/ASEE Aircraft Design, Systems, and Operations Conference, Seattle, WA, July 31 - August 2, 1989.

8. Powers, S.A., *The Design and Manufacturing Approach to the X-31A,* AIAA 91-3150, Presented at the AIAA Aircraft Design, Systems, and Operations Meeting, Baltimore , MD, September 23-25, 1991.

9. Robinson, M.R., and Herbst, Dr. W.B., *The X-31A and (sic) Advanced Highly Maneuverable Aircraft,* ICAS-90-04, Presented at the ICAS meeting in Stockholm, Sweden, September 9-14, 1990.

10. Hoerter, G.J., Powers, S.A., and Robinson, M.R., *The Development and Progress of Enhanced Fighter Maneuverability on the X-31,* SAE-90-91, presented at the SAE Atlantic Meeting, Dayton, OH April 22-26, 1991.

11. Bayati, J.E., and Lum, E.L., *Control Design for the X-31 Aircraft,* Presented at the 1991 American Control Conference, Chicago, IL, June 24, 1992.

12. Lang, J.D. and Francis, M.S., *Unsteady Aerodynamics and Dynamic Aircraft Maneuverability,* Unsteady Aerodynamics - Fundamentals and Applications to Aircraft Dynamics, AGARD-CP-386, April 1985.

13. Francis, M. S., Henderson, E. D., Kunz, E., Powers, S., & Richter, H. *X-31 Demonstration of Integrated Flight and Propulation Control For Effective Combat At Extreme Angles of Attack,* Combat Automation for Airborne Weapons Systems: Man/Machine Interface Trends and Technologies, AGARD -CP-520, April 1993.

14. Canter, D. and Groves, A. *X-31 Post-Stall Envelope Expansion and Tactical Utility Testing,* Naval Air Warfare Center-Aircraft Division, NAS Patuxent River, MD, 7th Biennial AIAA Flight Test Conference, Colorado Springs, CO, June 20-23, 1994.