TACTICAL UTILITY OF THE X-31A USING POST STALL TECHNOLOGIES

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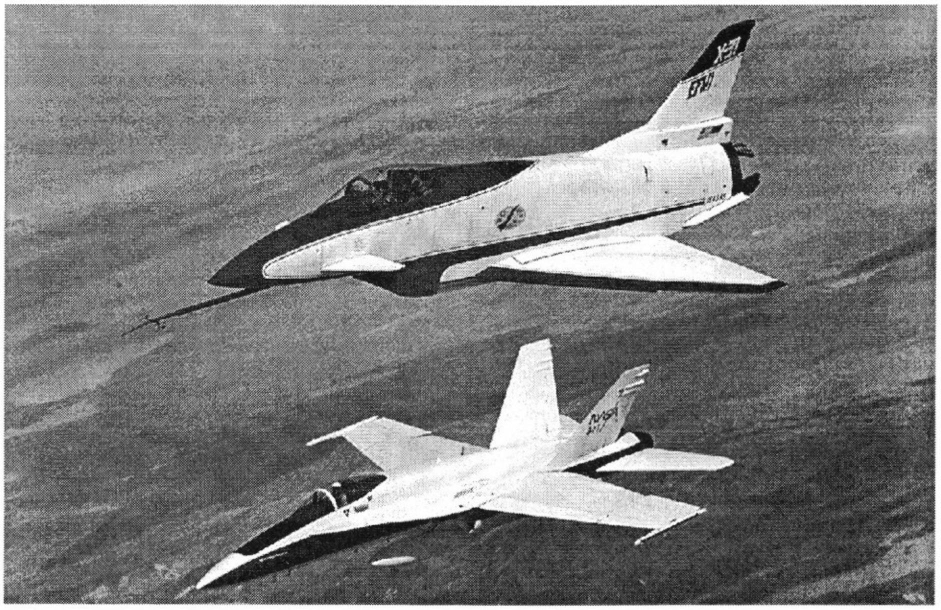

Photo Credit NASA Dryden FRC EC94-42478-08

Figure 1: X-31A with NASA F/A-18 over Edwards AFB, CA

Abstract

The two X-31A jointly built by Daimler-Benz Aerospace AG and Rockwell International were designed to explore the new realm of flight beyond stall employing advanced technologies like thrust vectoring and sophisticated flight control systems. A thrust vectoring system consisting of three aft mounted paddles to deflect the thrust vector in both pitch and yaw axes provided the X-31A in this *'Enhanced Fighter Maneuverability'* program with an agility and maneuverability never seen before. An extensive flight test campaign against various current state-of-the-art fighter aircraft revealed the tactical utility of the X-31A using post stall technologies in a close-in-combat arena. The tremendous tactical advantage of the X-31A during this flight test phase was accompanied by a deepened insight into post stall tactics, its typical maneuvers, impacts on pilot-aircraft interfaces and requirements for future weapons to both engineers and the military community. Some selected aspects of the tactical utility of the X-31A using post stall technologies unveiled by the International Test Organization are presented here.

Nomenclature

AFB	Air Force Base
AGL	Above Ground Level
AoA	Angle of Attack
ARPA	Advanced Research Projects Agency
BVR	Beyond Visual Range
CIC	Close-in-Combat
DLR	Deutsche Forschungsanstalt für Luft- und Raumfahrt

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ECM	Electronic Counter Measures
EF	EuroFighter
EFM	Enhanced Fighter Maneuverability
FMOD	Federal Ministry of Defense
HUD	Head-Up Display
IABG	Industrie- und Anlagenbau Gesell.
IFF	Identification Friend Foe
ITO	International Test Organization
MBB	Messerschmidt Bölkow Blohm
MIL	Milli-Radian
MSL	Mean Sea Level
NASA	National Aeronautics and Space Administration
PST	Post Stall
QT	'Quasi-Tailless'
TES	Test and Evaluation Squadron
TKF	Taktisches Kampfflugzeug
TU	Tactical Utility
USAF	United States Air Force
USN	United States Navy
WTD	Wehrtechnische Dienststelle
WVR	Within Visual Range

C_L	Lift Coefficient
g	Gravitational Acceleration
L	Lift
m	Mass
n_z	Load Factor
P_S	Probability of Survival
r	Turn Radius
S	Wing Surface Area
V	Air Speed
α	Angle of Attack
χ	Heading Angle
ρ	Air Density

Introduction

The X-31 was an experimental aircraft program dedicated to explore the controlled flight beyond stall and enhanced agility (supermaneuverability) [1]. It was the first aircraft using thrust vectoring in both pitch and yaw axes as well as it was the first experimental aircraft in the famous series of X-Planes being developed and tested internationally involving both Germans and Americans [2]. The X-31A aircraft impressively demonstrated the potential of providing means of superior short range air combat capabilities as is described in the following. The tactical utility (TU) flight testing at NASA Dryden Flight Research Center revealed the X-31A being superior to any existing fighter aircraft in terms of the ability to make tight and quick turns and any measures of agility. Most of this unique agility can be attributed to the thrust vectoring system.

The concept of supermaneuverability was originated about 1978 by the late DR. WOLFGANG B. HERBST of MBB [3]. It was in response to the development of short range air-to-air missiles with all aspect capabilities that a new area of tactics of aerial combat evolved. The ability to successfully launch a missile in almost any clockwise position against an opponent has altered the tactics of air combat and thus the performance requirements of fighter aircraft. It was found in extensive manned and digital air combat simulations that appropriate tactics actually would result in mutual head-on launch opportunities and thus the dilemma of potential mutual kills of almost equal high performance fighters. The analysis of such engagements revealed a new maneuver cycle characterized by dominance of instantaneous maneuvers and a tendency to slow speed. At slow speed V an aircraft can achieve a smaller turn radius r at a given turn rate $\dot{\chi}$ as shown by Equation (1):

$$r = \frac{V}{\dot{\chi}} \qquad (1)$$

The turn radius is proportional to the square of the speed since turn rate can be written in terms of speed and possible load factor n_Z

$$\dot{\chi} = \frac{g}{V} \cdot \sqrt{n_z^2 - 1} \qquad (2)$$

which yields with Equation (1):

$$r = \frac{V^2}{g} \cdot \frac{1}{\sqrt{n_z^2 - 1}} \quad \Rightarrow \quad r \sim V^2 \qquad (3)$$

Obviously, a tighter turn in a developing mutual head-on situation allows for an earlier weapon launch opportunity at any given off-boresight angle. Figure 2 depicts the relationship between turn radii and speed for different load factors.

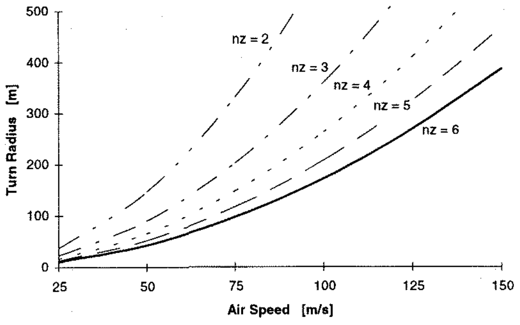

Figure 2: Turn Radii vs. Speed

The evolution of close-in-combat (CIC) tactics as anticipated by SKOW [4] already before the X-31A tactical utility results became public and manifested his conclusions is depicted in Figure 3.

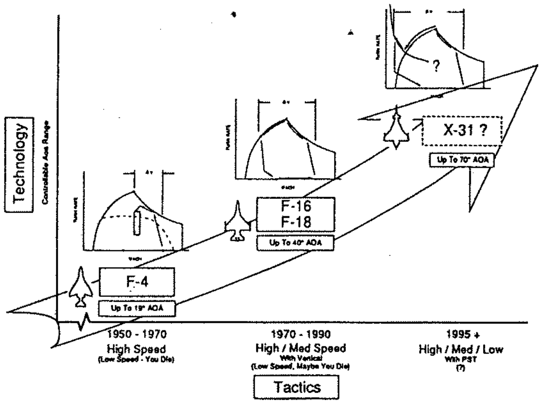

Figure 3: Evolution of CIC Tactics [4]

Aircraft like the F-4 were limited to angles of attack of up to 19°. Flight at higher angles of attack often resulted in departures. Furthermore, due to the high wing loading of the F-4, maneuvering at high angles of attack for prolonged times resulted in a significant loss of energy and placed the pilot in an unfavorable position with limited options. Thus it is easy to understand why phrases like *'Low Speed - You Die'* and *'Speed is Life'* were commonly used to characterize CIC tactics in the period from roughly 1950 to 1970. Modern fighter aircraft like the F-16 and F-18 with angle of attack capabilities of up to 40° allowed to turn at lower speeds as shown by the insets of the doghouse plots (turn rate vs. Mach number) in Figure 3. Fighter pilots started to use the vertical and the old maxims changed to *'Low Speed, Maybe You Die'*. Low wing loading limited the bleeding of energy during aggressive maneuvering and guaranteed a multitude of offensive and defensive options to the pilot. With the advent of deep post stall capabilities by the X-31A again a new area of CIC tactics has begun. Maneuvers can now be performed at extremely low speeds as indicated by the doghouse plot in Figure 3.

The present paper will now describe the X-31A tactical utility flight test phase highlighting some aspects and results of the X-31A tactical utility using post stall technologies. First however, some conclusive arguments why CIC can still develop in a time of highly sophisticated stealth aircraft and advanced beyond visual range (BVR) weapon systems including both sensors and weapons will be given. The X-31A configuration and its performance capabilities are then briefly introduced including its flight test envelope and head-up display. Main emphasis however is on the tactical utility flight test phase. Its build-up, starting conditions, selected measures of effectiveness are discussed as well as some representative results are presented. Two post stall maneuvers, the clinical 'Herbst Maneuver' and a post stall maneuver resembling a 'fire pole' will be described. For more detailed results of the various phases of the tactical utility flight test program and an extensive collection of post stall maneuver descriptions the reader may refer to various references of different classification levels [5, 6, 7].

CIC in the Air Combat Continuum

An implicit assumption justifying X-31A TU flight testing was that for many reasons future air combat will still develop into CIC and won't be restricted to BVR engagements. Although it will always be desired to engage targets already from BVR, some reasons for the development of CIC are:

- The dynamic merge during prolonged engagements will eventually bring the aircraft close together.
- Measures to enhance low observability may conceal aircraft until they are detected visually in a CIC regime.
- Various optical and electronic counter measures (ECM) can limit sensors in their ability to detect aircraft BVR.
- Limits on number and types of stores carried as well as failed missiles may drive aircraft into a CIC arena.
- Special rules of engagement especially concerning target identification, i.e. identification friend foe (IFF), requirements can make an approach into CIC necessary.
- And last but not least fighting outnumbered, surprised, or having to defend fixed assets on the ground may require to engage into CIC.

These assumptions are tacitly validated by the fact that even the newest air-to-air fighters are all equipped with a gun.

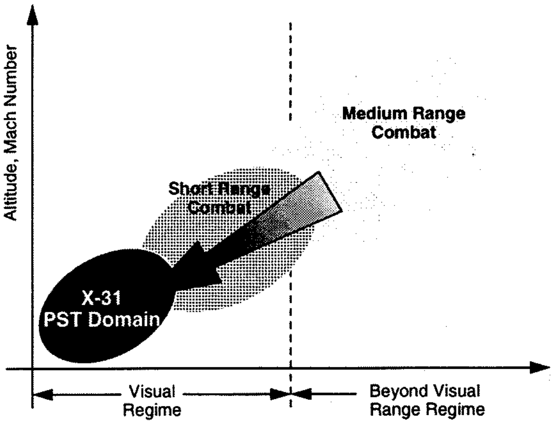

Figure 4: Arenas of Aerial Combat

To retain flexibility and adaptability in combat, fighters must be able to engage at will and dominate across the entire combat continuum as shown in Figure 4. Within visual range (WVR) and CIC engagements should not be favored over BVR, but if forced into CIC, enhanced fighter maneuverability (EFM) provides the necessary potential to effectively and successfully engage. It is here where the X-31A TU flight testing uncovered new dimensions of aerial combat.

X-31A Configuration

Two X-31A aircraft were developed, designed, and built jointly by Rockwell International and Daimler-Benz Aerospace AG.

One of the requirements for the X-31A configuration was that results of the X-31A flight testing are directly transferable to a potential operational aircraft. However, no existing fighter aircraft was suitable to be retrofitted for supermaneuverability. Eventually a derivation of the German TKF (Taktisches Kampfflugzeug), a predecessor of the EF2000, was selected. The X-31A configuration as shown in Figure 5 meets all requirements for enhanced fighter maneuverability.

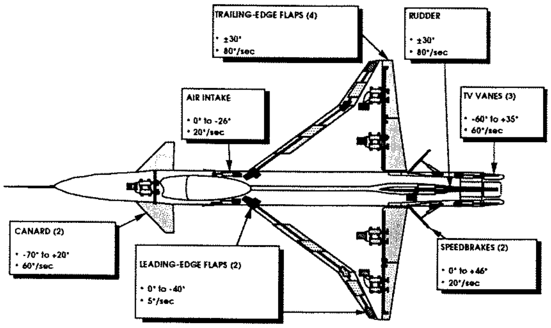

Figure 5: X-31A Configuration With Its Effectors

The single-seat fighter-type X-31A is a delta-wing configuration with a long-coupled canard. Its take-off weight is little over 16 000 lbs. The X-31A is powered by a single General Electric F404 engine with some 17 000 lbs thrust wet. In order to reduce trim drag in supersonic flight the X-31A was designed with a center of gravity aft of the subsonic center of lift which makes it aerodynamically unstable. As the canard is commanded downward into the wind with increasing angle of attack it always maintains its control effectiveness (see [8] for selected aerodynamic identification results) and can be utilized for longitudinal control throughout the flight envelope. It especially guarantees adequate pitch-down control power in PST flight. Other control surfaces of the X-31A include a rudder and ailerons, i.e. trailing edge flaps which can be used both as elevator and ailerons. Unique feature of the X-31A are its three aft mounted paddles around the exhaust nozzle of the engine. These carbon-carbon paddles allow a deflection of the thrust vector in both pitch and yaw axis thus providing means of enhanced longitudinal and lateral/directional control independent from dynamic pressure and angle of attack as compared to the conventional aerodynamic control surfaces [9].

Summarizing the features of the X-31A configuration it is clear that the requirements for an aircraft with supermaneuverability were met:

- The thrust-to-weight ratio was in excess of 1.
- The air intake allowed full power engine operation at up to 70° angle of attack by a movable intake lip.
- Aerodynamic characteristics were tailored to enable a smooth transition into the PST regime.
- Thrust vectoring in pitch and yaw added a vast amount of control power in those axes while the X-31A was still trimable by conventional aerodynamic control surfaces even at PST angles of attack. Thus the thrust vectoring system was no safety critical item in terms of recovery from a possible spin entry.
- To control the X-31A a full authority, triplex, digital fly-by-wire flight control system was developed by Dasa [10]. It included mechanization of lateral stick inputs to roll the aircraft around the flight path at zero sideslip rather than around the familiar aircraft body axes. Thus, the so-called 'velocity vector roll' is a coordinated yaw and roll maneuver in terms of body axes. The longitudinal control featured angle of attack command at slow speeds and load factor command at higher speeds. One of the main tasks of the flight control system was the scheduling of control surfaces and thrust vector blend-in dependent on their control effectiveness as a function of flight condition.

Head-Up Display

The X-31A was equipped with a head-up display (HUD). Its symbology is shown in Figure 6. Explaining most of the indicators and dials on the HUD, the unique performance features of the X-31A are illustrated again.

On the left hand side is an angle of attack ladder and a digital display. Range of values of the AoA ladder is -20° ... 90° while the maximum AoA which can be commanded at lower dynamic pressures is 70°. Inboard of the AoA ladder is a load factor ladder with an additional digital display. At higher dynamic pressures n_z is commanded by the pilot instead of α.

Maneuvers in deep post stall are maneuvers at extremely low speed and thus the load factor during those maneuvers is moderate. In the upper right-hand corner altitude above ground as well as rate of climb / descent are displayed digitally. All TU flight testing at Edwards AFB was performed in designated spin areas above 13 000 ft MSL respectively some 3 200 m above ground level (AGL). The rules of engagements called for an immediate 'Knock it off' command by either the control room or any of the pilots in case of an altitude violation.

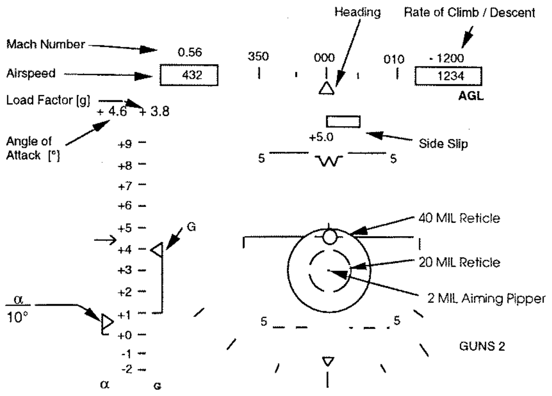

Figure 6: HUD of the X-31A

Although a hypothetical sideslip angle of 5.0° is indicated in Figure 6 digitally and by a bar in the middle of the HUD, the X-31A flew without any major sideslip thanks to its control law design except during cross wind landings and deliberate sideslip maneuvers. There is no need to use the pedals for any but those two reasons. Two reticles of 40 and 20 MIL and a 2 MIL gun aiming pipper formed the center of the HUD. The gun aiming line was depressed by 2° from the aircraft's center line. Video footage of the HUD camera provided valuable information for post flight analyses of the CIC engagements.

The pilot could select various levels of declutter of the HUD as desired. In addition to the HUD, a helmet mounted display was investigated [11].

Tactical Utility Evaluation

TU Envelope

Figure 7 shows the flight envelope of the X-31A used during the tactical utility evaluation phase. It is a subset of the cleared flight envelope which also includes supersonic flight regimes and higher post stall entry speeds.

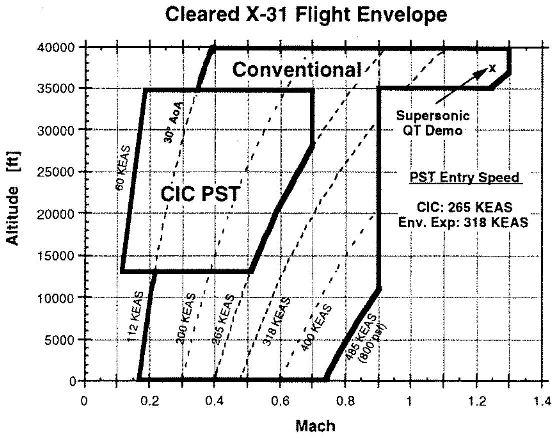

Figure 7: X-31A Envelope for CIC

It is noteworthy that the flight control system of the X-31A provides carefree handling qualities throughout the flight envelope [12, 13]. Thus, the pilots weren't exposed to any additional workloads especially in post stall concerning possible departures and spin entries.

Measures of Effectiveness

It is very difficult to conclusively describe the agility of the X-31A and its tactical implication on the outcome of CIC. Looking at a definition of agility by SKOW [4] it becomes obvious that no known metrics cover the entire weapon system in all aspects: *'Agility is an attribute of a fighter aircraft that measures the ability of the entire weapon system to minimize the time delay between target acquisition and target destruction.'*

Although a multitude of primary and secondary measures of effectiveness were evaluated during the X-31A TU flight testing, only selected results of two primary measures are given in this paper.

The exchange ratio is defined as the ratio of adversary losses divided by the number of own losses.

$$\text{Exchange Ratio} = \frac{\text{Number of Adversary Losses}}{\text{Number of Own Losses}} \qquad (4)$$
$$\text{Exchange Ratio} \in [0, \infty]$$

The range of values of the exchange ratio is from 0 to infinity indicating a superior adversary and own superiority, respectively. An exchange ratio of 1.0 or 1:1 as the fractions sometimes aren't simplified represents an equal number of adversary losses and own losses.

The S Factor is calculated from the probability of survival of the adversary and one's own.

$$\begin{aligned} &\text{S Factor} = 0.5+0.5\left(P_{S_{Own}} - P_{S_{Adversary}}\right) \\ &\text{S Factor} \in [0,1] \end{aligned} \qquad (5)$$

The probability of survival is defined by

$$P_S = \frac{\text{Number of Engagements Survived}}{\text{Total Number of Engagements}} \qquad (6)$$

Thus an S Factor of 0 represents 100% own losses while all adversary aircraft survive. An S Factor of 0.5 is equivalent to an exchange ratio of 1:1.

A compilation of various measures of effectiveness and agility metrics is given in [14], a comprehensive description of mathematical methods including measures of effectiveness in defense analyses in [15].

Starting Conditions

In order to efficiently perform TU flight testing, a set of starting conditions was selected. They were chosen to maximize the results by guaranteeing easy repeatability and by quickly forcing the engagements into CIC, the objective of all X-31A TU flight tests. Only by this way could the most be gained from a limited number of sorties.

The starting conditions investigated included defensive, offensive, and various types of neutral set-ups. All starting conditions are depicted in Figure 8.

While the defensive, offensive, and line-abreast starting conditions were also investigated in simulation studies [16], the butterfly set-up was introduced by USAF and USN guest pilots during a special TU flight test campaign.

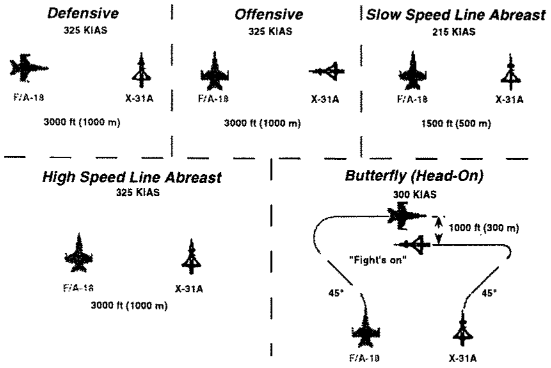

Figure 8: Starting Conditions

Tactical Utility Flight Testing

As one of the main X-31 EFM Program objectives a tactical utility evaluation phase was conducted between October 1991 and October 1995. Leading the way to TU flight testing were two X-31 EFM simulation campaign conducted at the IABG facility in Ottobrunn, Germany, between October 1991 and April 1993 [16]. These simulation campaigns were used to define test methods and baseline expectations in a phased build-up approach. An initial flight test envelope expansion was accomplished so that the pilots could refine clinical PST maneuvers derived from simulation.

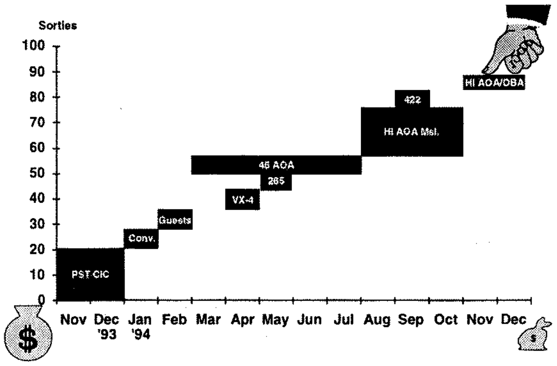

Figure 9: Tactical Utility Flight Testing Events

Once pilots had achieved sufficient proficiency in PST maneuvering, unscripted CIC testing was accomplished in test blocks. These blocks were defined by parametric changes to baseline weapons and PST maneuver limits as well as adversary aircraft capabilities and are shown in Figure 9.

Tactical Utility Evaluation Events

As already shown in Figure 9, the major X-31A tactical utility evaluation events were PST CIC, conventional CIC, guest pilots and guest adversary aircraft evaluation, as well as parametric changes in AoA limit to 45°, PST entry speed limit to 265 kts, and various missile launch envelopes (high AoA missile only limited to the launch platform's AoA limit and high off-boresight missile launches).

Due to classification issues quantitative results of all TU evaluation phases cannot be presented here (see [5]), some qualitative remarks however can be given.

USAF and USN 'guest' pilots confirmed results demonstrated by X-31A cadre pilots and demonstrated that combat-ready fliers could use PST effectively in CIC without extensive training.

Pilots from VX-4 (the USN West coast operational evaluation squadron based at Point Mugu NAS, CA) with F-14B/D and F/A-18C aircraft and pilots of the 422 TES (the USAF operational test and evaluation squadron from Nellis AFB, NV) with F-15C and Block 52 F-16C flew against the X-31A and yielded considerable insight into both the value and limitations of PST capabilities in CIC. Thus they helped to isolate critical EFM design parameters.

Limiting the X-31A to 45° AoA isolated effects of velocity-vector roll capabilities from high AoA capabilities so that relative contributions of each to CIC effectiveness could be studied. In general, the X-31A derived significant combat advantage by using thrust vectoring to retain considerable lateral and directional control at PST AoA. Velocity vector roll rate and high AoA capabilities are complimentary. Since technical requirements and associated costs are the same for 45° and 70° PST maneuvering, and the benefits of 70° AoA capabilities are higher, no sensible design trade exists on AoA limit beyond stall.

Advanced missile capabilities were simulated by permitting missile launches at high AoA and high off-boresight. The helmet-mounted display used for some of these tests enhanced pilot awareness of weapon envelopes, which increased CIC effectiveness.

Conventional versus PST CIC

As some data of conventional CIC of the X-31A versus an X-31A with full PST capabilities is unclassified it enables a comparison here.

Figure 10 depicts the tremendous advantage of the X-31A using PST. The X-31A exploiting its full PST capabilities is significantly superior in CIC against an F/A-18 degraded to resemble the X-31A in conventional performance. That this goal of equal conventional performance wasn't quite achieved is visible in the left-hand side of Figure 10. The X-31A won only 15% while the degraded F/A-18 scored 46% of all 28 engagements thus no perfect equality was established.

However looking at the right-hand side of Figure 10 the X-31A using its unique PST capabilities won 91% of all engagements from neutral, line-abreast starting conditions. This is an improvement in combat outcome by more than a factor of 6 as compared to the case of the X-31A restricted to conventional flight, i.e. limited to 30° AoA.

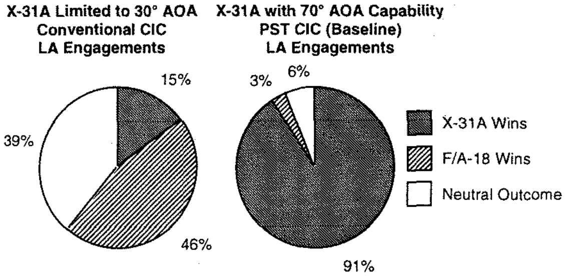

Figure 10: Conventional vs. 70° AoA CIC

Using Equations (4) and (5) and flight test data primary measures of effectiveness could be calculated (Figure 11):

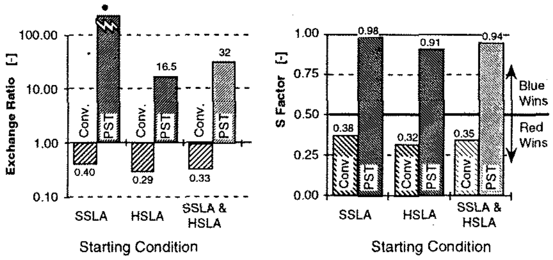

Figure 11: Conventional vs. 70° AoA CIC

Post Stall Maneuvers

The flight regime beyond stall houses several unique types of maneuvers of which two will be described here. Not being limited to the maximum aerodynamic lift during heading changes as in conventional flight (see Equation 8) PST maneuvers are characterized by extremely small turn radii.

Substituting the load factor in Equation (3) by

$$n_z = \frac{L}{mg} \qquad (7)$$

yields with the lift coefficient C_L an expression for the minimum turn radius r_{min}:

$$r_{\min} = \frac{V^2}{g} \cdot \frac{1}{\sqrt{\left(\frac{C_{L_{\max}} \frac{\rho}{2} V^2 S}{mg} \right)^2 - 1}} \qquad (8)$$

A considerable contribution by the thrust vector to balance the weight, i.e. an increase of the denominator, allows for smaller turn radii.

The clinical 'Herbst Maneuver' and a maneuver resembling a 'funnel' or a 'fire pole' belong to the typical PST maneuvers.

'Herbst Maneuver'

The 'Herbst Maneuver' developed by and named after Dr. Wolfgang B. Herbst [3] is a very tight 180° heading change. It is depicted in Figure 12.

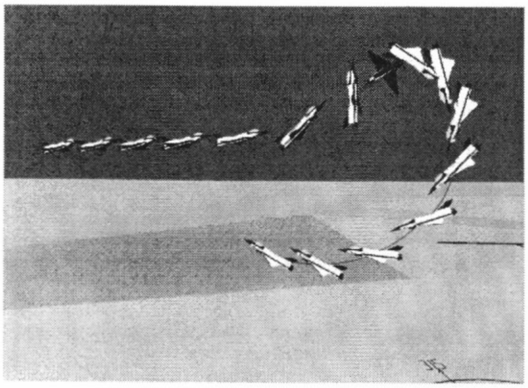

Figure 12: Herbst Maneuver

The 'Herbst Maneuver' is characterized by the following phases: The X-31A enters the maneuver at high speed. A rapid deceleration while increasing angle of attack exceeds the conventional aerodynamics limit (stall) reaching an angle of attack of 70°. In this PST flight condition the X-31A performs a velocity vector roll, i.e. a coordinated body axis roll and yaw maneuver. With this 'coning' motion a new flight direction, i.e. a heading change, is achieved. Unloading and decreasing the angle of attack the X-31A terminates the 'Herbst Maneuver' in an accelerating fashion.

'Fire Pole'

A PST maneuver with an even greater impact on tactical utility is shown in Figure 13.

Closing in onto the adversary both aircraft try to establish a gun tracking solution. While the adversary's turn radius (refer Equation 8) is limited by its maximum possible load factor, i.e. maximum lift, the X-31A can exploit its PST capabilities. The adversary aircraft (solid aircraft in Figure 13) bleeds off speed to achieve smaller turn radii and to establish a gun tracking solution. Having reached its minimum turn radius, the adversary aircraft is restrained to circling at this turn radius. Thus its flight path describes the surface of a 'funnel' with a cylindrical lower part. The X-31A however slides down a 'fire pole'. With its extremely tight turn radii and its aircraft reference line decoupled from its flight path, the X-31A can permanently threaten the adversary. The X-31A's motion along is referred to as 'Helicopter Gun Attack' maneuver since the X-31A can turn its nose and thus its gun aiming line like a helicopter.

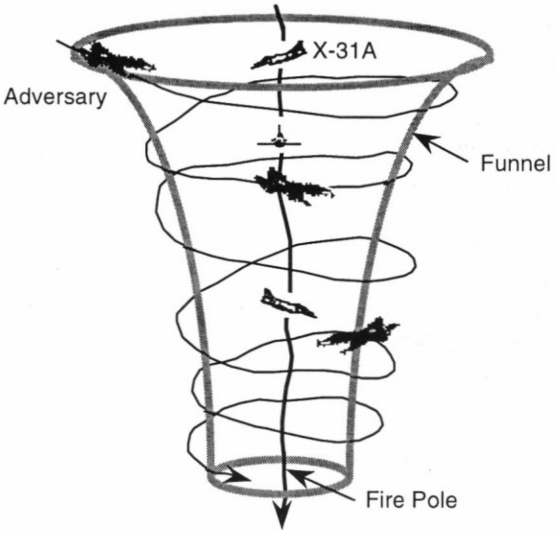

Figure 13: 'Fire Pole'

Conclusions

As no aircraft before the X-31A has demonstrated post stall capabilities up to 70° angle of attack. The X-31A using post stall technologies including a thrust vectoring system was significantly superior in CIC to various state of the art fighter aircraft. Improvement in CIC effectiveness was not only a mere few percent but changed by almost an order of magnitude.

Even though the X-31A was a low cost demonstrator and thus aerodynamically anything but optimized, it was perfectly suitable to evaluate the tactical utility of aircraft with post stall capabilities. The delta-canard configured single engine X-31A has flown a total of 580 flight during its flight test program. The joint efforts of the International Test Organization as it united various international partners from Germany and the USA including the two main industry contractors Daimler-Benz Aerospace AG and Rockwell International enabled a timely and cost-efficient experimental program.

The X-31A aircraft with its thrust vector control in both pitch and yaw axes in conjunction with a highly sophisticated flight control system experienced a maneuverability and agility never seen before. The technical feasibility and tactical utility of post stall capabilities have impressively been proven as described qualitatively and quantitatively in this paper. Maxims of aerial combat like '*Speed is Life*' have been rendered obsolete as with the X-31A and its capabilities came the dawn of a new area of CIC tactics. Various maneuvers unique to the post stall arena like the 'Herbst Maneuver', an extremely tight heading change, and maneuvers with phases of decoupled fuselage reference line from the flight path like in a 'Helicopter Gun Attack' have been demonstrated by the X-31A and are presented here.

Given sufficient thrust-to-weight ratio, thrust vectoring provides not only post stall maneuvering capabilities through the additional control power by the thrust vector but also superior conventional performance for smaller turn radii, higher turn rates, higher pitch rates, etc. as described analytically here.

This enhanced fighter maneuverability in turn assured superior weapon pointing and velocity vector roll capabilities at slow speed and high angle of attack, as well as departure resistance for carefree handling. All are essentials for success in CIC. Proper and timely employment of post stall maneuvering in CIC significantly improves the combat effectiveness not only in offensive and neutral starting conditions but also in defensive maneuvering.

Various tactical utility flight testing phases unveiled several sensitivity parameters to CIC effectiveness (see [5] for details). Qualitatively it can be stated that thrust vector control and supporting enhanced fighter maneuverability technologies provide tremendous airframe growth potential and might even be suitable not only for future fighter aircraft design but also for mission-enhancement upgrades to current fighters.

Besides its almost 400 CIC engagements guaranteeing statistical significance the X-31A aircraft have set several records for flight test efficiency and productivity. The benefits of thrust vectoring and enhanced fighter maneuverability were clearly and convincingly demonstrated, not only by the tactical utility evaluation but also by X-31A flight test initiatives. These include the X-31 Quasi-Tailless (QT) demonstrations [17] and the Low Altitude PST Envelope Expansion conducted in preparation for the Paris Air Show in 1995. The attendant risk of incorporating enhanced fighter maneuverability technologies has been reduced significantly.

Acknowledgment

The authors would like to express their deep appreciation for all the support granted to them during the X-31A TU flight test campaigns. Without all eight major partners from US and German government agencies and US and German contractors (including various subcontractors like Honeywell, GEC Marconi, the German Aerospace Research Establishment DLR, and WTD-61 to name a few) united in the International Test Organization (ITO) the X-31 program couldn't have been as successful as it was. The players in the X-31 program under a Memorandum of Agreement and an Associate Contractor Agreement were ARPA and FMOD, the German Ministry of Defense, as well as the US Air Force and US Navy, the German Luftwaffe, NASA, and the two industry partners Rockwell International and Daimler-Benz Aerospace AG. All their logos are included in the ITO logo as shown in the Figure 14.

Figure 14: ITO Logo

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