F-35A High Angle-of-Attack Testing

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Lockheed Martin's Joint Strike Fighter (JSF) is the latest 5th generation fighter to be incorporated into the Air Force, Navy, and Marine services with an operational goal of 2016. Since the legacy platforms the JSF will replace were put into production, there have been significant strides in increasing the maneuverability of aircraft. Modern fighters have the ability to maneuver in the post stall region, giving these planes a significant advantage in air-to-air combat. JSF continues this trend, using an advanced control system to provide maneuverability well into the post stall angle of attack region. The Air Force variant of the JSF, the F-35A, is currently undergoing high angle-of-attack testing at Edwards Air Force Base, CA. With diligent planning and a complete understanding of the system, the Integrated Test Force (ITF) took the F-35A from its first high angle-of-attack test point to the aircraft angle-of-attack limit in four missions. This paper outlines the efforts by the ITF team to safely and efficiently complete high angle-of-attack (AoA) testing, starting from the planning process going through flight test execution and exploring the challenges that have been encountered along the way.

Nomenclature

ADA	=	Air Data Application
AoA	=	Angle of Attack
AoS	=	Angle of Sideslip
APR	=	Automatic Pitch Rocking
ATA	=	Air to Air
CG	=	Center of Gravity
CLAW	=	Control Law
DHS	=	Symmetric Horizontal Tail Deflection
EAFB	=	Edwards Air Force Base
EB	=	Effector Blender
EOM	=	Equations of Motion
FTCC	=	Flight Test Continuation Criteria
HT	=	Horizontal Tail
ITF	=	Integrated Test Force
JSF	=	Joint Strike Fighter
MPR	=	Manual Pitch Rocking
NDI	=	Non-linear Dynamic Inversion
Q_b	=	Body Axis Pitch Rate
R_b	=	Body Axis Yaw Rate
SRC	=	Spin Recovery Chute
TV	=	Thurst Vectoring

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I. Introduction

SINCE World War I, air-to-air combat has been an integral part of air warfare and from that have arisen techniques and maneuvers to best take advantage of one's own fighter to gain the upper hand on the opponent. These maneuvers have generally fallen within the pre-stall envelope of the aircraft in terms of sustained turn rate, instantaneous turn rates, and the excess power that the engine produces to gain energy. A low angle of attack allows

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the fighter to maintain lift over the wing and its control surfaces, which maintains their effectiveness. Once the plane exceeds its stall angle-of-attack, drag increases rapidly while the surfaces effectiveness diminishes. For many years pilots were taught that exceeding the stall angle-of-attack of the aircraft could put them in a precarious situation during combat; the enemy pilot could take advantage of the low energy state (or loss of control) to orient for a kill shot.

With the advent of Thrust Vectoring (TV), much more research has been done into the area of post stall maneuvering. One example is the X-31A, which conducted mock air-to-air combat scenarios against an F/A-18 with and without thrust vectoring/post stall maneuvering.[1] Without TV and post stall maneuvering the X-31 would only win about half of the engagements. When TV and post stall maneuvering were enabled, a win/loss ratio of 32:1 was attained. This combat advantage hasn't gone unnoticed by the United States Air Force, and it was first integrated into the design of the F-22, the world's first 5th generation air superiority fighter. As a 5th generation multirole strike fighter, the F-35 is designed to complement the F-22. While still possessing many of the advantages that its big brother has such as stealth, advanced avionics, and post stall maneuvering, the F-35 lacks TV to save on cost and weight. In the absence of TV, the ability to control an aircraft at high angles of attack would normally be incredibly challenging, but with the use of an advanced control system, the F-35 overcomes this challenge.

II. Background

The control architecture used in the F-35 is a departure from the classic control law used in previous fighter programs. In older systems, control gains were scheduled for different flight conditions (ex. Angle-of-attack, Mach, V_{EAS}, etc). These gain schedules are then adjusted and/or updated based upon flight test results. To handle the multiple JSF variants (A, B, C) with the same control strategy, Nonlinear Dynamic Inversion (NDI) was chosen to be the control architecture for the F-35.

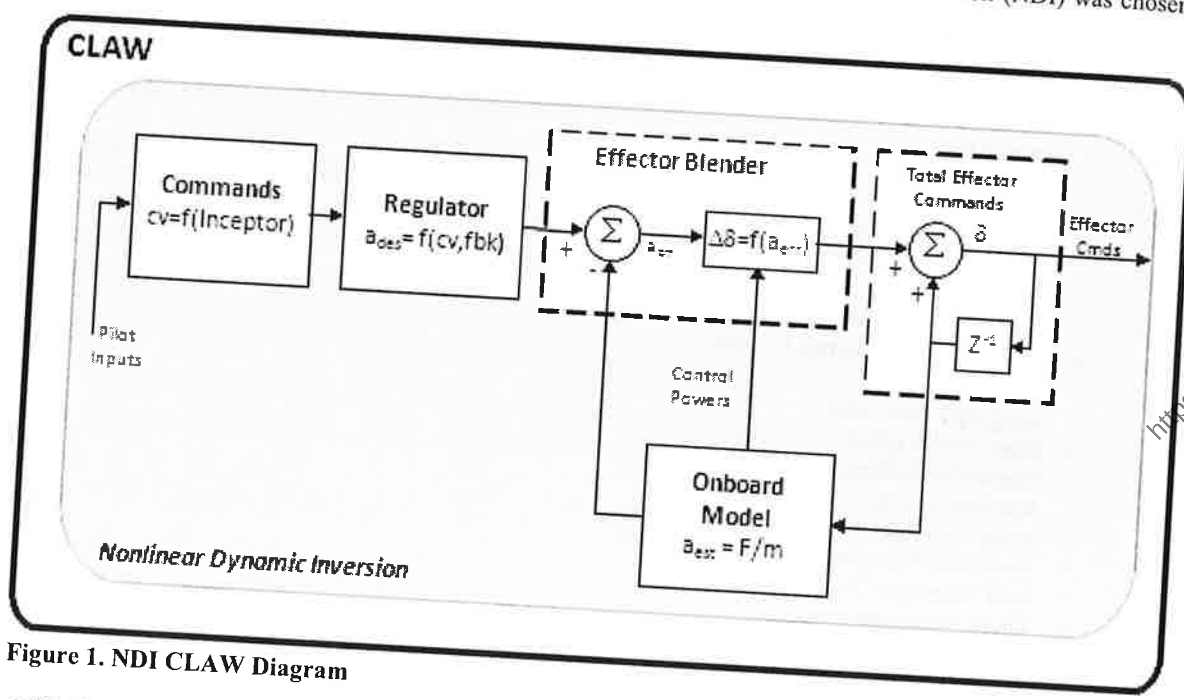

Figure 1. NDI CLAW Diagram

NDI allows the team to design directly to the desired criteria and share that design across variants with the intent that only the Onboard Model (OBM) inside the NDI architecture needs to be changed to match the variant. The OBM houses information on control power effectiveness for that particular aircraft variant at all flight conditions throughout its envelope. Inputs are sent to the control law (CLAW), which then takes the commands and sends them

through the Effector Blender (EB). The EB uses the EOM and the information from the OBM to solve for a control position in response to a given command by moving surfaces in the most effective way.[2] For example, the CLAW will command asymmetric flap deflection to generate a roll rate while the same command at a different condition may use asymmetric tail. A diagram of this can be seen in Fig. 1. This type of flexibility is important to high AoA flight, as the effectiveness of the surfaces changes considerably at AoAs near wing stall and beyond. In addition, it alleviates pilot workload by keeping inceptor commands consistent across various flight regimes.

Such a system requires a rather sophisticated and refined OBM and an accurate Air Data Application (ADA). Incorrect information such as control power available or the current state parameters (ex. AoA) of the aircraft can lead to poor handling qualities. Unlike the CLAW and its flexibility to convert to different modes, the ADA uses hardware that cannot alter its orientation to the wind vector. The system first transitions to high AoA logic before blending to inertial AoA and angle of sideslip (AoS) near the maximum AoA. The aerodynamic data gathered from wind tunnel tests were used to originally develop the OBM and ADA that is routinely verified and updated from flight test throughout the envelope. The intent of high angle-of-attack testing is to verify and update the OBM, CLAW performance, and ADA at angles of attack above 20°.

III. High AoA Logic and Recovery Modes

Once within the high angle-of-attack regime, the control law is optimized to allow the maximum commanded rates while preventing departures. The maximum AoA limit for the F-35 is 50° in an air-to-air (ATA) configuration. Below 20° angle of attack, the jet performs as legacy fighters do: the pedals command sideslip, while the stick commands roll rate and Nz/pitch rate. As the F-35 travels above 20° AoA, the control law transitions into high angle-of-attack logic. Commands in the roll axis are stability axis roll rate in both the high angle-of-attack and low angle-of-attack logic. The rudder pedals transition from sideslip command to body-axis yaw rate command with large pedal deflections. The maximum yaw rate depends on AoA and dynamic pressure. The pilot can also command a sideslip by applying roll stick and pedal in opposite directions.

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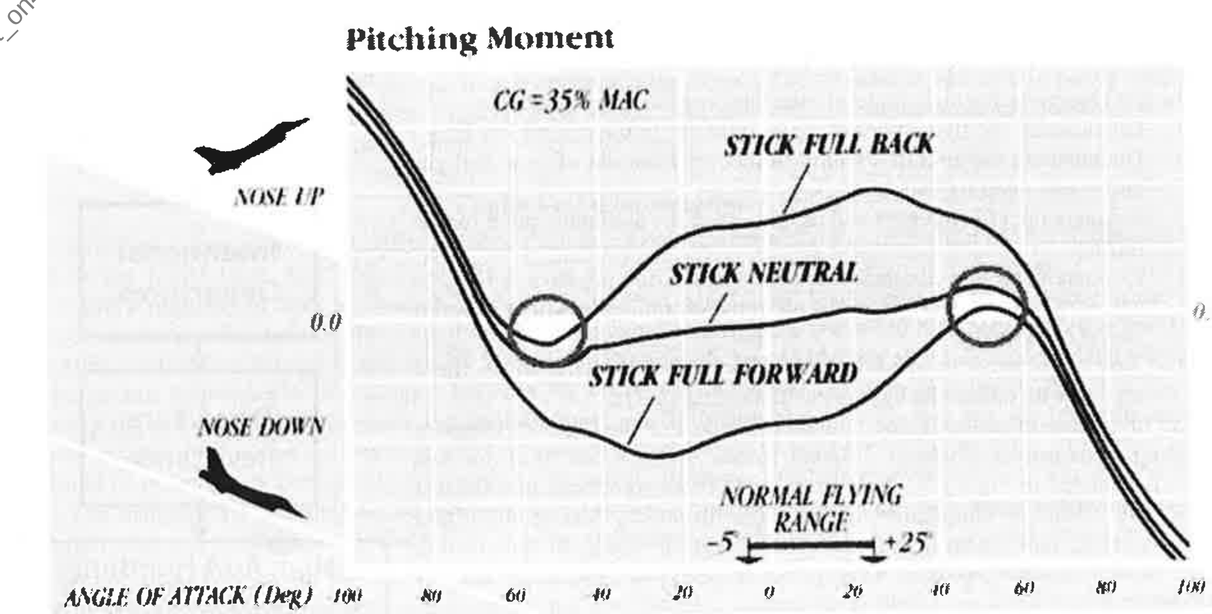

Figure 2. F-16 Pitching Moment Curve with Deep Stalls[3]

While the control law should keep the JSF within controlled flight, manual and automatic recovery modes are included to recover from spins or deep stalls. A spin is defined as a sustained body axis yaw rate while above the current AoA limit of the aircraft. A deep stall is when the aircraft has departed controlled flight above the AoA limiter and is unable to generate a nose down pitch rate to recover with the horizontal tail full trailing edge down. Figure 2 shows a CG condition for the F-16 that has an upright deep stall at 50° AoA where full forward stick alone will not recover the jet. The stick full forward and full aft translate into full trailing edge down and up, respectively, for the horizontal tails. The recovery modes that can be activated (manually or automatically) to bring the aircraft back to controlled flight are spin recovery mode, APR, and manual pitch rocking (MPR).

The spin recovery logic automatically engages when the body axis yaw rate exceeds a scheduled value based on dynamic pressure and AoA. Once activated, the CLAW no longer gives priority to the pitch axis; instead, the CLAW uses all possible control power to arrest the spin rate. While this mode is engaged, any pilot inputs in the direction of the spin are ignored. Once the airplane's yaw rate has been reduced to near zero, the CLAW will exit spin mode. At this point, if still departed, the pitch recovery logic can be used.

APR and MPR are similar in nature to the techniques used to recover the F-16 from a deep stall. Once in the deep stall, the F-16 pilot is required to manually generate an oscillation by pitching, or, rocking the plane up and down to develop rates large enough to drive the aircraft back down into the nominal angle-of-attack envelope. For the F-35, the horizontal tails will automatically attempt to pitch the aircraft back into the allowable flying envelope once departed, ignoring pilot inputs to the contrary. This will recover the jet when a deep stall condition is not present. When in a deep stall, the pilot can override this action by depressing a switch after meeting the airspeed and AoA required for MPR mode. When activated, MPR mode gives the pilot direct authority over the symmetric horizontal tail to generate the pitch rate necessary to recover from a deep stall. For purposes of testing, the MPR switch is used to defeat the AoA limiter to characterize the aerodynamics and recovery from the departure region. When the F-35 becomes operational, the MPR mode is expected to be removed from the aircraft and replaced with APR.

As the production solution, APR is designed to recognize a deep stall and recover the aircraft without any pilot input, whether the F-35 has departed upright or inverted. When APR is engaged, the pilot's pitch commands are ignored, but lateral directional inputs are not. The pilot can use yaw pedals, for example, to keep the aircraft from developing a spin while APR is active so spin mode does not engage. The CLAW will recognize once the aircraft has recovered and disengage APR mode. Both the nominal high AoA logic and the recovery logic are tested as part of the overall high AoA test plan.

IV. Test Objectives and Phases

The test objectives for high angle-of-attack testing are as follows:

1) Characterize the flyqualities at AoAs from 20° to the control law limit
2) Demonstrate the aircraft's ability to recover from out of control flight and assess deep stall susceptibility
3) Evaluate the effectiveness and usefulness of the automatic pitch rocker (APR)
4) Evaluate departure resistance at both positive and negative AoA with center of gravity (CG) positions up to the aft limit and with maximum lateral asymmetry.
5) Assess the handling qualities of the aircraft in the High AoA flight regime with operationally representative maneuvers.

The first phase of testing is the initial expansion into the high AoA region, consisting of maneuver blocks at different AoAs. A flow chart of all the test phases is depicted in Figure 3. These maneuver blocks were built into the test plan to safely build up and explore higher angles of attack, starting at 26° and 30° AoA before moving up in increments of 5° to 50° AoA. At each testing block, an AoA limiter was used to keep the aircraft at the specified AoA for both data quality and safety.

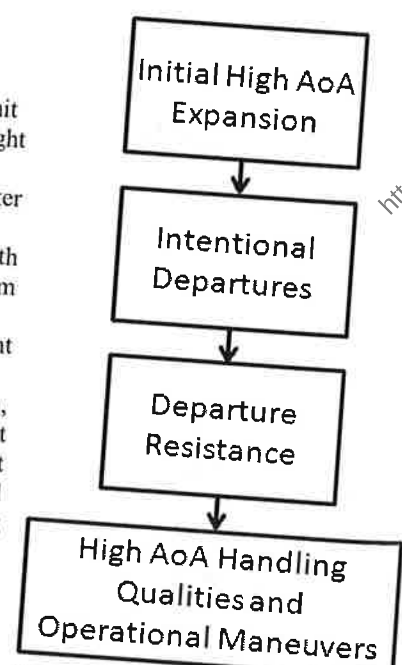

Figure 3. Test Phases

Once the first phase of testing is complete, intentional departures can begin. The purpose of this testing is to verify the pitching moment curves past the AoA limiter with different tail deflections, as shown in Figure 2, by using MPR to overcome the AoA limiter. In addition to exploring the aerodynamics past the limiter, the intentional departure phase is used to verify that the pitch recovery and the spin recovery systems

work appropriately. Once the recovery modes have been evaluated and been determined to work satisfactorily, testing moves into departure resistance.

Departure resistance consists of maneuvers designed to stress the AoA and yaw rate limiters with cross coupled inputs, high energy states, and aircraft lateral/longitudinal CG locations which could lead to out of control conditions. Testing will conclude with pilots evaluating handling qualities during operationally representative maneuvers throughout the high AoA regime.

Before the testing phases begin, the spin recovery chute (SRC) had to be installed and tested.

V. Spin Recovery Chute

The SRC is a parachute attached to the aft section of the aircraft via a quadrapod. It is designed to be deployed if the jet is unable to recover on its own. Once launched, the drag from the chute will stabilize the aircraft in a nose down, low yaw rate, orientation. The pilot can then jettison to return to controlled flight. A schematic of the SRC can be seen in Fig. 4.

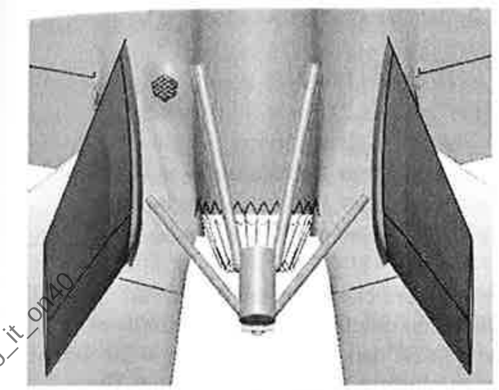
Figure 4. Spin Recovery Chute

Until the recovery modes have been properly tested and verified to work in the intentional departure phase of testing, the SRC will remain on. Once the recovery system has been proven, the SRC will be removed. Since the aerodynamic effects from the SRC may have some effect on the controllability of the aircraft,, most of the departure resistance testing will be done with the SRC removed. Before high angle of attack testing with the SRC, a ground deployment was performed to ensure the deploy and release mechanisms worked properly.

As the SRC was being installed and prepared for its functional check, the test team was simultaneously planning for the initial expansion of the high angle-of-attack region. With limited ability during a mission to analyze the response of the aircraft, the team had to have a way to see if the F-35 was roughly matching the expected aerodynamics and control power modeled in the OBM. Flight Test Continuation Criteria (FTCC) was developed so the engineers in the control room could determine if the jet was performing within an acceptable margin.

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VI. Flight Test Continuation Criteria

FTCC was created from uncertainty analysis run using maneuver simulations of the test blocks at different AoAs from the Initial High AoA Expansion phase. The blocks consisted of basic maneuvers, designed to explore the aircraft's response in both the longitudinal and lateral/directional axes. While post flight analysis can derive the coefficients and determine if the aircraft was meeting expectations, there needed to be a way to do this real time so testing could move efficiently and safely. The goal of the analysis was to identify an easily recognizable response of the aircraft that indicated a mismatch between the OBM and the actual flight characteristics; the most important being the plane's pitching moment and the horizontal tail (HT) control power. Simply put, the test team needed a way to identify if the jet was running short on control power before moving further up in AoA. If it was, the F-35 could be in danger of losing control, departing, and potentially being unable to recover.

The maneuvers established in the test plan to test the HT control power and pitching moment were a trim at the target AoA and an abrupt push. For the uncertainty analysis, the coefficients $C_{m_{\delta h}}$ and C_{m_q} were scaled by about +/- 50% at all the trims up to 50° AOA. Then simulations of the push overs were run using these same uncertainties. With the data from the trims and push overs created, they could be used to identify responses that would stand out.

For the trim FTCC, comparisons of the normal trim data compared to the decreased HT control power and altered pitching moment gave way to a continuation criteria that allowed an acceptable delta in HT trim position from predicted.

The push over criteria was a little bit more difficult to derive as nothing immediately distinguishable fell out in terms surface responses. This would pose troubles for a quick identification in the control room, hindering efficient testing. By taking the filtered derivative of pitch rate (Q_b), pitch acceleration ($\dot{Q}_b$), in the first part of the abrupt push, an estimation of control power was available. From that, it was determined that as long as the aircraft met a certain percentage of the predicated $\dot{Q}_b$, then the team was safe to continue on with testing.

The FTCCs for lateral directional maneuvers were done in a similar fashion. Simulations were run of the lateral directional maneuvers with alterations to control power and $C_{n\beta}$. Comparisons between the runs led to the FTCCs being related to how long the surfaces were on their limits for, along with no saturation of the horizontal tail.

For Air Data at nominal AoAs, a noseboom is used as a "truth source" for the aircraft state parameters from which their FTCCs are derived. A delta between the "true" aircraft states and the ADA values was picked to ensure safe operation and that the updates to the OBM accurately represent the flight condition. However, in high AoA testing, the noseboom has been removed to be more production representative. An alternate method to obtain truth data had to be developed, so a truth table was created. Before initiating maneuvers, the pilot would fly the F-35 through the test altitude band to gather wind data recorded in the control room and used to create a wind table. This table was then used in conjunction with the aircraft inertial data to compute truth air data parameters which could be compared against those used on the aircraft, which in some cases relied on latched winds.

With these guidelines established, expanding the F-35A envelope up to 50° could begin.

VII. Flight Test

The testing began on October 29, 2012 with a trim and push over from 26° and 30° AoA to ensure the aircraft had the control power to begin testing at 26° AoA. After that, the team was able to explore the lateral directional maneuvers, knowing that if AoA limiter could not hold the jet during a maneuver, the control power to push the nose down and recover was available.

As the team moved up the AoA blocks, one of the coordinated maneuvers exceeded the FTCC for the delta between predicted DHS deflection and actual deflection. With the continuation criteria exceeded, generally the team cannot continue on with testing along the same path. However, the team knew that from the push over the aircraft had more than enough control power in the horizontal tails to move up safely in AoA. As such, that test flight was able to continue, moving up in AoA while holding off on the coordinated maneuvers until the data could be reviewed. After the flight, coordination with the Flying Qualities Subject Matter Experts (SMEs) using the flight test data allowed the team to open up the FTCC for coordinated maneuvers. Smartly making use of the information in the control room allowed the team to quickly and safely work up to the aircraft limit in four sorties, reaching 50° AoA on November 1st, 2012.

While the jet remained in its pneumatic envelope, the aircraft response matched predictions fairly well. Once the angle of attack crossed into the inertial envelope, sensitivity to the errors between the true sideslip on the jet and the inertial value used began to show itself in the behavior of maneuvers and even trims. On one of the coordinated maneuvers, the yaw rate passed the trip level for anti-spin engagement. As the team wasn't expecting to see anti-spin until the dedicated test block after intentional upright departures, testing was terminated for data review and a path forward was coordinated with the SMEs.

When the aircraft's air data system went inertial, the winds were latched so they could be used to calculate the angle-of-attack and beta. It was determined that these errors caused the CLAW to incorrectly know how much control power to use to reach the intended yaw rate, resulting in an overshoot of command and an anti-spin engagement. The team quickly learned that the winds could be "gamed" in a way to minimize the beta error generated as the F-35 fell through the wind gradient. Instead, the wind error appeared in angle-of-attack where the sensitivity to that error was much less. While this works for testing where a control room is available to give headings and altitudes for high angle-of-attack maneuvering, it would not work in an operational setting: the pilot could potentially have to maneuver at high angle-of-attack in many different wind gradients and through many different altitudes. The solution, however, arose from the data gathered from flight testing: the probes and flush ports were still usable in calculating pneumatic sideslip throughout the flight envelope.

With the envelope expanded up to 50° AoA, the next phase of testing could begin: intentional departures. Trim settings were used to put the tails at fixed tail deflections to see what angle of attack the aircraft trimmed at. For the first exploration into the departure region, the aircraft center of gravity was set so there would be no deep stall condition, eventually building up to that case. The same was true for inverted departures. Exploration into the

upright departure region went smoothly, with the aircraft settling out at the predicted AoA for set tail positions. However, once the team moved into the inverted departures, a roadblock was hit.

During the first inverted departure, a flow phenomenon over the air data probes caused a significant change in the static pressure being used to calculate air speed, which, in turn, feeds into the recovery logic. In this situation, MPR disabled because the reported airspeed exceeded the maximum allowable value for this mode. Fortunately, the jet was able to recover naturally because the forward CG ensured there was no deep stall. While in the previous sideslip problem the team was able to come up with a workaround, this issue halted departure testing due to the potential for more aft CGs to get into an out of control situation with an incorrect airspeed reading, disabling all recovery logic. Then, the only solution would be to use the SRC. An operational pilot will not have the same luxury, highlighting the importance of thorough testing. A software update was quickly developed and delivered, allowing the team to continue intentional departures.

Along with intentional departures, the recovery logic was tested. At the most aft CG conditions, the APR system was used as the recovery method rather than MPR. APR recovered the jet every time, and pilots called the system, "brisk" and "confidence inspiring." Similarly, the anti-spin logic was deliberately tested using a flight test aid that disabled the anti-spin logic. The pilot could then generate a yaw rate to exceed the anti-spin logic limit before disengaging the flight test aid, thereby engaging anti-spin. Intentional departure testing culminated with vertical climbs, driving the aircraft straight up until it runs out of airspeed. At this point, the low airspeeds could cause the jet to depart upright, inverted, or allow the nose to slice off. No matter the direction, the jet recovered with no issue.

With intentional departure testing wrapped up, the team will soon move into departure resistance and plan to remove the SRC now that these systems have been verified. In this phase of testing, the jet will test the CLAW limiters with much higher energy and rates than previous testing, fleshing out and correcting areas that may be departure prone. Lastly, select operational maneuvers, such as a slow down turn and a Split-S, will be used to gather handling qualities data on high AoA maneuvers. With the completion of this phase, the F-35 will be released for initial operational capability in the high AoA region.

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VIII. Operational

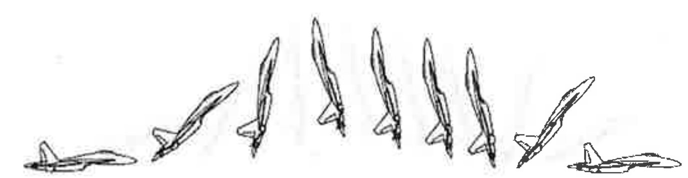

Figure 5. Pugachev's Cobra[4]

While the flight test team will explore legacy high AoA maneuvers for handling qualities, it will be the Operational Test and Evaluation team that will truly develop high AoA maneuvers for the F-35. In the operational world, a pilot should rarely be taking the F-35 into the high angle-of-attack regime, but the ability to do so could make the difference between being the victor or the victim in air-to-air combat, several of which are mentioned below.

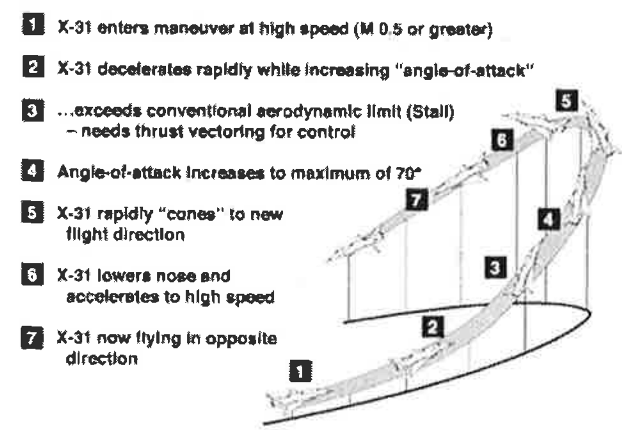

Figure 6. X-31 Performing a J-Turn[5]

If being tailed by an enemy fighter, a pilot can rapidly slow his aircraft by pulling back on the stick to rapidly increase AoA and, by extension, drag on the aircraft causing the pursuer to quickly become out front and vulnerable. At this point, the previously pursued pilot can pitch his nose down and get a shot off to take out the enemy. A similar maneuver called the "Pugachev's Cobra" can be seen in Fig. 5. While this puts the jet in a low energy state, it now has the advantage.

Similar to other high AoA platforms, the ability to generate yaw rates at high AoA allows the pilot to change his heading quickly through a high yaw rate rather than a sustained or instantaneous G turn. The J-Turn, or Herbst maneuver, represents this ability by using a high angle of attack with a body axis yaw rate, as seen in Fig. 6.

Circle flow combat is one of the basic fighter maneuvers where two pilots engage in a sustained or instantaneous turn towards or away from one another. In this fight, the first pilot to get his aircraft's nose on the enemy will get the first shot off. In Fig. 7 is a combat scenario where both the aircraft turn towards one another. Here the friendly fighter has high AoA capability, allowing him, with proper timing, to pitch his nose up to get line of sight first on the enemy.

Used properly, high angle-of-attack capability can be the "gold nugget" that determines whether or not the F-35 comes out the victor in air combat. When combined with an already impressive arsenal of weapons, sensors, and stealth, the JSF will be a formidable foe in the air.

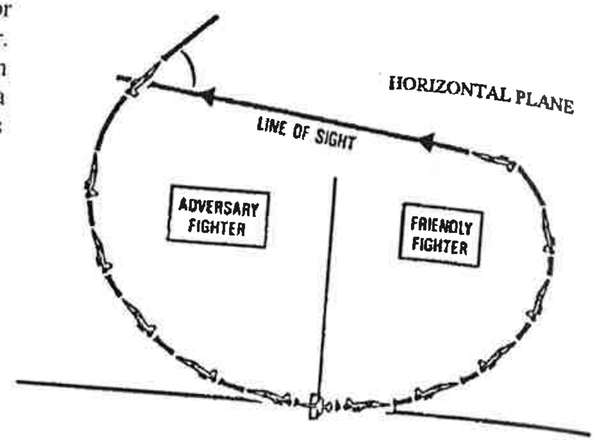

Figure 7. High AoA Advantage in Circle Flow Combat[1]

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