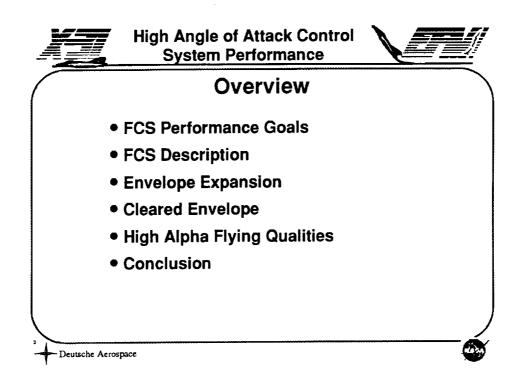# X-31 High Angle of Attack Control System Performance

By:

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X-31 Flight Controls Engineer**

Overview

- ● **FCS Performance Goals**
- ● **FCS Description**
- ● **Envelope Expansion**
- ● **Cleared Envelope**
- ● **High Alpha Flying Qualities**
- ● **Conclusion**

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The design goals for the X-31 flight control system were:

- Level I handling qualities during post-stall maneuvering (30 to 70 Degrees angle-of-atttack).

- Thrust vectoring to enhance performance across the flight envelope.

- Adequate pitch-down authority at high angle-of-attack.
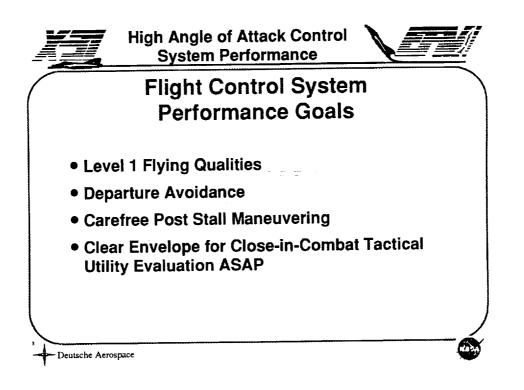
Additional performance goals are discussed.

A description of the flight control system will be presented, highlighting flight control system features in the pitch and roll axes, and X-31 thrust vectoring characteristics.

The high angle-of-attack envelope clearance approach will be described, including a brief explanation of analysis techniques and tools. Also, problems encountered during envelope expansion will be discussed.

This presentation emphasizes control system solutions to problems encountered in envelope expansion. Other papers discuss in detail the aerodynamic fixes that were used in conjunction with the control system fixes to achieve the program goals.

An essentially "care-free" envelope was cleared for the close-in-combat demonstration phase.

High angle-of-attack flying qualities maneuvers are currently being flown and evaluated. These results are compared with pilot opinions expressed during the close-in-combat program, and with results obtained from the F-18 HARV for identical maneuvers. The status and preliminary results of these tests will be discussed.

Flight Control System
Performance Goals

- **Level 1 Flying Qualities**
- **Departure Avoidance**
- **Carefree Post Stall Maneuvering**
- **Clear Envelope for Close-in-Combat Tactical
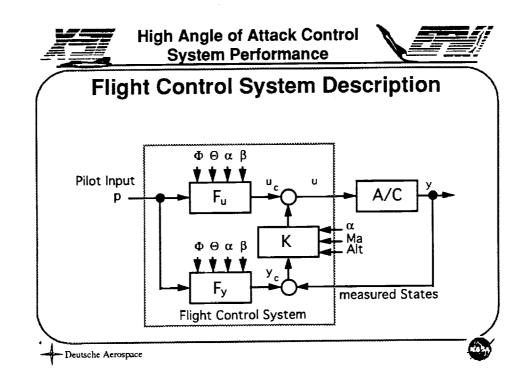 Utility Evaluation ASAP**

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Original performance goals included achieving Level 1 flying qualities throughout the flight envelope.

Other goals emerged with initial envelope expansion and insight into aircraft aerodynamic characteristics as a result of NASA Langley Research Center drop model tests. A spin mode found in these tests and re-discovered in Langley's wind tunnel and free-to-roll tests made engineers cautiously approach high angle-of-attack envelope clearance.

The High Incidence Kinetic Roll (HIKR) mode is a roll-dominated spin mode, rarely seen in spin testing. Free-to- roll tests indicated that both high alpha and high sideslip values along with unstable C_{lp} trigger the mode. Therefore, a departure resistant aircraft was an important flight control system performance goal.

Providing a carefree post-stall maneuvering envelope for the close-in combat tactical utility evaluation as soon as possible was the primary project goal. Both aerodynamic and flight control system solutions were applied to problems discovered during envelope expansion, a timely and cost-effective approach.
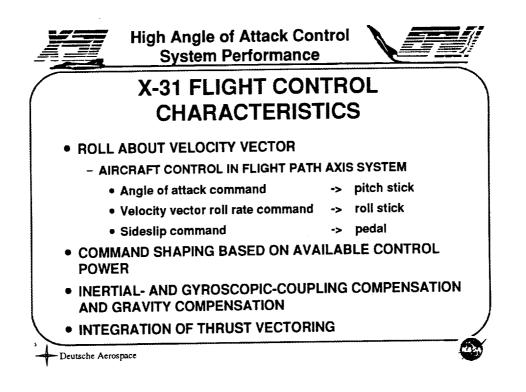
Flight Control System Description

Flight Control System

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The three main external control system interfaces are the pilot command vector (stick, pedal), the sensed feedback vector (α, q, β, p, r) and the actuation command vector (canard, symmetrical and differential trailing edge flap, rudder, and thrust deflection in pitch and yaw).

The control law blocks consist of a linear feedback Matrix K and the nonlinear feedforward Matrices F_u and F_y. The feedback gains are calculated by using the optimal linear digital regulator design.

There is an additional integral feedback of angle-of-attack, as well as an integral feedback of wind axis roll rate and sideslip above 30° angle of attack.

Additional elements are the inertial and engine gyroscopic coupling compensation and the gravity effect compensation.
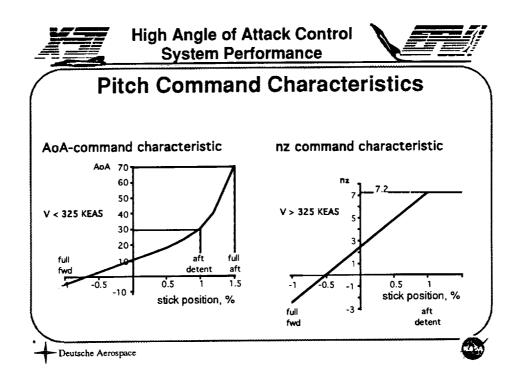
X-31 FLIGHT CONTROL CHARACTERISTICS

- **ROLL ABOUT VELOCITY VECTOR**
  - **AIRCRAFT CONTROL IN FLIGHT PATH AXIS SYSTEM**
    - Angle of attack command   ->   pitch stick
    - Velocity vector roll rate command   ->   roll stick
    - Sideslip command   ->   pedal
- **COMMAND SHAPING BASED ON AVAILABLE CONTROL POWER**
- **INERTIAL- AND GYROSCOPIC-COUPLING COMPENSATION AND GRAVITY COMPENSATION**
- **INTEGRATION OF THRUST VECTORING**

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The X-31 design was oriented towards aircraft control at high angles-of-attack from the beginning, therefore a unique approach was chosen - aircraft control in the flight path axis system.

The pilot input is translated into an angle-of-attack command or load factor command at high dynamic pressure (pitch stick), wind axis roll rate command (roll stick) and sideslip command (pedal).
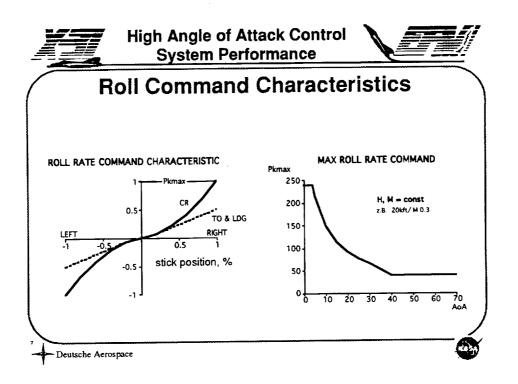
In order to achieve carefree maneuvering and departure resistance the maximum possible command is based on the available control power. In addition inertial and engine-gyroscopic coupling compensation, as well as gravity compensation has been included.

Thrust vectoring has been integrated as a control effector, equivalent to aerodynamic control surfaces.

Pitch Command Characteristics

AoA-command characteristic

AoA

V < 325 KEAS

70
60
50
40
30
20
10
-10

full
fwd

aft
detent

full
aft

-0.5   0.5   1   1.5

stick position, %

nz command characteristic

nz

V > 325 KEAS

7.2
7
5
3
1
-1
-3

-1   -0.5   0.5   1

full
fwd

aft
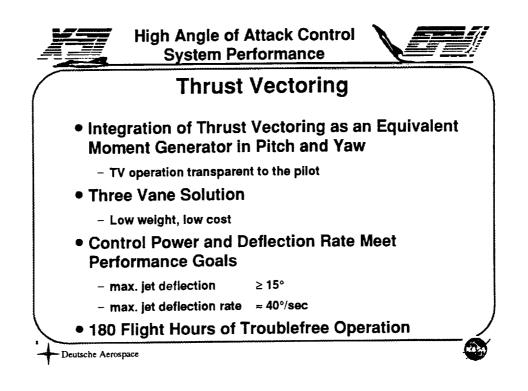detent

stick position, %

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The X-31 flight control system is an angle-of-attack command system, changing to an nz-command system above the corner speed. Corner speed as defined in this context is the airspeed where limit load factor is reached at 30 degrees angle-of-attack.

In addition to the angle-of-attack command generation which is based on the pitch stick position a steady state pitch rate command is calculated based on the actual flight condition.

Roll Command Characteristics

ROLL RATE COMMAND CHARACTERISTIC

MAX ROLL RATE COMMAND

Pkmax

1 — Pkmax

CR

0.5

TO & LDG

LEFT

RIGHT

-1   -0.5   0.5   1

-0.5   stick position, %

-1

Pkmax

250

200   H, M = const
z.B. 20kft/ M 0.3

150

100

50

0
0   10   20   30   40   50   60   70
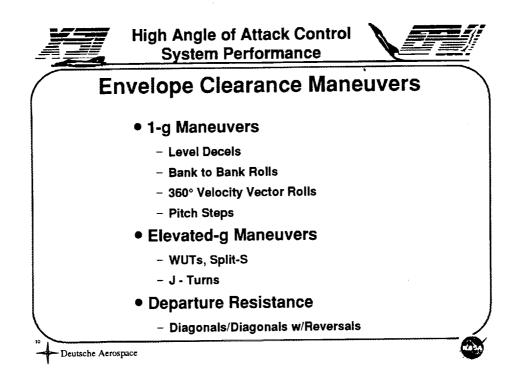AoA

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Lateral stick position commands roll rate about the velocity vector, also referred to as the wind axis. The maximum possible roll rate command depends on the available control power at the actual flight condition, i.e. it is a function of altitude, Mach number, dynamic pressure and angle-of-attack.

Thrust Vectoring

- **Integration of Thrust Vectoring as an Equivalent Moment Generator in Pitch and Yaw**

    - TV operation transparent to the pilot

- **Three Vane Solution**

    - Low weight, low cost

- **Control Power and Deflection Rate Meet Performance Goals**

    - max. jet deflection $\geq 15°$
    - max. jet deflection rate $\approx 40°/sec$

- **180 Flight Hours of Troublefree Operation**

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One of the unique features of the X-31 control law is that thrust vectoring is integrated as a moment generator in pitch and yaw equivalent to aerodynamic control surfaces. This means that the aerodynamic surfaces and thrust vectoring can be blended in and out without changing the aircraft behavior as long as the aerodynamic surfaces are effective. Thrust vectoring is used for yaw control at high angles-of-attack where the rudder is ineffective.

A three-vane thrust vectoring configuration was chosen as a low weight, low cost solution at a time when an engine with a swivelling nozzle was still unavailable.

Envelope Clearance Maneuvers

- **1-g Maneuvers**
  - Level Decels
  - Bank to Bank Rolls
  - 360° Velocity Vector Rolls
  - Pitch Steps
- **Elevated-g Maneuvers**
  - WUTs, Split-S
  - J - Turns
- **Departure Resistance**
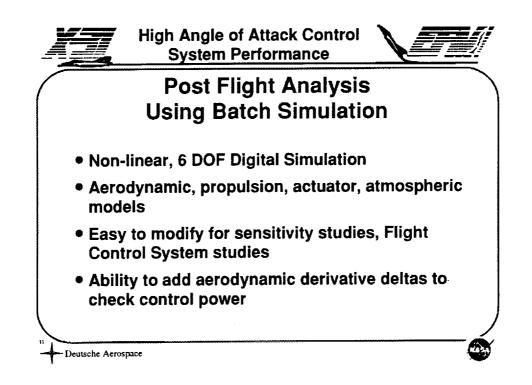 - Diagonals/Diagonals w/Reversals

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Envelope expansion began at high altitude (35,000 feet MSL), proceeded out in airspeed (Mach 0.3 - 0.7 in tenth increments) and down in altitude (20,000 then 13,000 feet MSL), increasing dynamic pressure and post-stall entry condition g's. Alpha values were increased in five-degree increments, from 30 to 70°, increasing to 10° increments as system confidence increased.

Initial 1-g maneuvers included level decelerations to show any large asymmetries in yaw and/or roll, half and full-stick bank-to-bank rolls, 360° velocity vector rolls both to the left and right. The velocity vector rolls gave indications on how well inertial and gyroscopic coupling compensation worked, and if there were any roll command overshoots. Abrupt pitch steps were performed to assess any pitch rate or alpha dot effects on flying qualities.

More dynamic maneuvers followed the 1-g phase, beginning with symmetric pulls (wind-up turns, split-S) and proceeding to more dynamic maneuvers (J-turns).

If aircraft performance was satisfactory through the 1-g and elevated-g flight phases, departure resistance maneuvers were flown. The diagonals and diagonals with reversals were the last expansion maneuvers to be flown before the envelope was cleared for tactical utility.

Post Flight Analysis
Using Batch Simulation

- **Non-linear, 6 DOF Digital Simulation**

- **Aerodynamic, propulsion, actuator, atmospheric models**

- **Easy to modify for sensitivity studies, Flight Control System studies**

- **Ability to add aerodynamic derivative deltas to check control power**
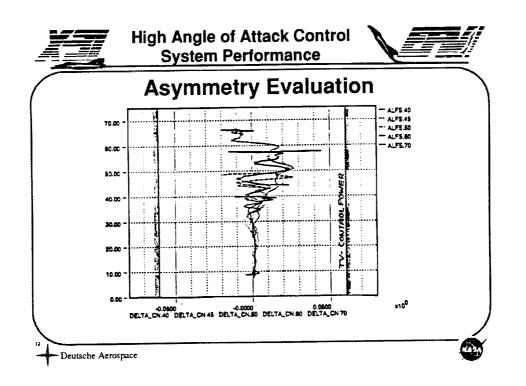
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Satisfactory flying quality performance was judged in two parts: 1) Control room pilot/near real-time assessment and, 2) Post-flight analysis.

A vital analysis tool was the X-31 batch/real-time simulation, a non-linear six degree-of-freedom FORTRAN simulation containing aerodynamic, propulsion, control system, atmospheric and actuator models.

This versatile tool was used in many ways. Simulating envelope expansion points gave pilots and engineers an expectation of aircraft response, and thus the ability to respond quickly to unexpected aircraft behaviour during the flight. The simulation was used to check control surface activity as a function of sensor noise. Effects on flying qualities of wake or jet wash encounters were also simulated. Flight control system changes e.g. fader time constants, or integrator surface authority could be quickly checked in the simulation, making it an invaluable tool for trouble-shooting, or bounding problem areas.
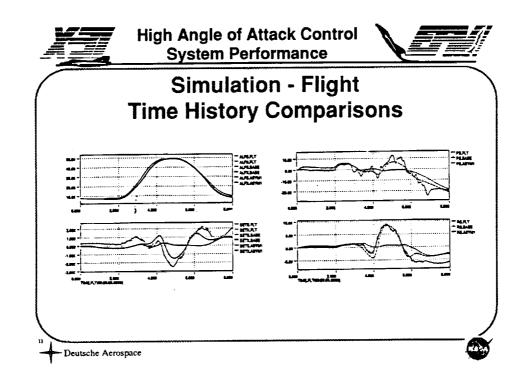
The simulation could be driven by pilot/flight control system inputs from flight data. The response was plotted against the measured aircraft response. Differences in rates, motions, surface deflections were assigned to unmodelled or mismodelled aerodynamic derivatives in the simulation. Called "deltas", these aerodynamic derivative differences between baseline simulation and flight data could be added to the simulation.

Adding C_{no} and C_{lo} deltas derived from flight data to the baseline simulation provided insight into control power limitations and aircraft motion in the presence of large yawing and/or rolling asymmetries.

Asymmetry Evaluation

	— ALFS.40
	— ALFS.45
	-- ALFS.50
	— ALFS.60
	— ALFS.70

70.00

60.00

50.00

40.00

30.00

20.00

10.00

0.00

TV- CONTROL POWER

-0.0600   -0.0000   0.0600   x10⁰
DELTA_CN.40   DELTA_CN.45   DELTA_CN.50   DELTA_CN.60   DELTA_CN.70
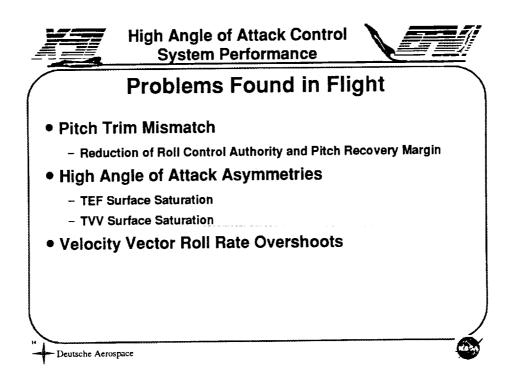
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The control derivatives were assumed to be modelled correctly in the simulation. These effects were subtracted out from the total yawing and rolling moment coefficients, C_n and C_l. For most flight cases where large yawing and rolling moments were encountered, roll rate, yaw rate and sideslip values were small, hence moments were assumed to be static asymmetries.

The graphic shows an overlay plot of five pullups to different target-alphas, delta-c_{no} versus angle of attack in comparison to TV control power available at that flight condition. The largest asymmetries occur around 50°.
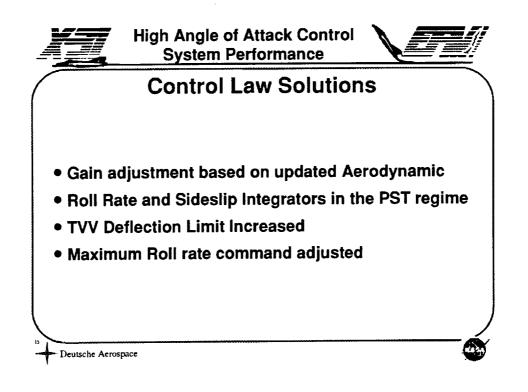
Simulation - Flight
Time History Comparisons

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Time history comparisons of baseline simulation, C_{n0}, C_{l0} deltas added to the baseline simulation and flight data indicate a better match with the asymmetry deltas added to the baseline simulation.

Problems Found in Flight

- **Pitch Trim Mismatch**
  - Reduction of Roll Control Authority and Pitch Recovery Margin
- **High Angle of Attack Asymmetries**
  - TEF Surface Saturation
  - TVV Surface Saturation
- **Velocity Vector Roll Rate Overshoots**

Envelope expansion flights were halted periodically by problems encountered during expansion into higher dynamic pressure maneuvers. Primary problems were trailing edge flap and thrust vector vane surface saturation caused by large rolling and yawing moments. Roll rate command overshoots were also of concern.

Trailing edge flaps served dual-duty as moment generators in pitch and roll. Differential trailing edge flap was the only roll moment generator. Close watch was kept on the trailing edge flap deflection and roll rate command; saturation of the trailing edge flaps would effect the ability to recover from high alpha.

Thrust vector vane saturation was also of concern as it controls yawing moments above 45 degrees alpha.

Control Law Solutions

- **Gain adjustment based on updated Aerodynamic**
- **Roll Rate and Sideslip Integrators in the PST regime**
- **TVV Deflection Limit Increased**
- **Maximum Roll rate command adjusted**

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In order to achieve carefree PST maneuvering control surface saturation must be avoided. Both aerodynamic and control law changes were used.
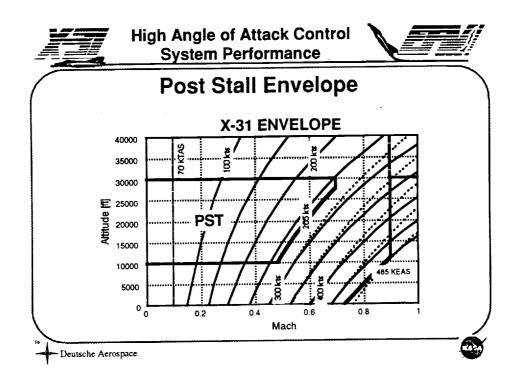
Aerodynamic changes to the aircraft included aft and forebody strakes and nose blunting to regain the desired trailing edge pitch trim position, and to reduce high angle-of-attack asymmetries.

Control law changes were aimed at retaining tight control and increasing yaw control power.

Gain adjustments were made based on updated high angle of attack aerodynamic derivative data. In addition integrators were added to the roll rate and sideslip feedback to achieve tighter control of sideslip and velocity vector roll rate in the presence of aerodynamic asymmetries.
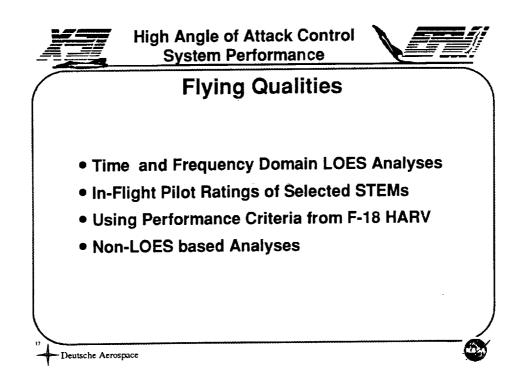
Increasing the thrust vector vane maximum deflection limit from 26 degrees to 35 degrees improved yaw control power.

Limiting wind axis roll rate command in the post-stall regime proved to be an acceptable compromise of roll performance and controllability.

Post Stall Envelope
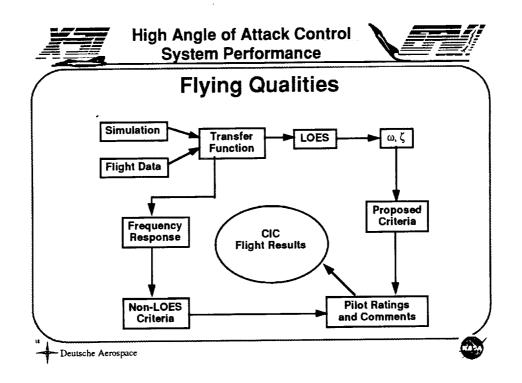
X-31 ENVELOPE

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The aircraft was finally cleared for essentially carefree PST maneuvering between 13,000 feet and 30,000 feet, reaching from a 6g PST entry at 265 KEAS, Mach 0.7 down to 70 KTAS.

To date, pilot inputs during CIC are less severe than departure resistance maneuvers flown during envelope clearance.

Flying Qualities

- Time and Frequency Domain LOES Analyses
- In-Flight Pilot Ratings of Selected STEMs
- Using Performance Criteria from F-18 HARV
- Non-LOES based Analyses

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Throughout the envelope expansion time domain LOES analysis was performed to confirm that conventional Level 1 Flying Quality Requirements were met. However, above 45° alpha the data scatter increases significantly and alternative ways have to be considered.
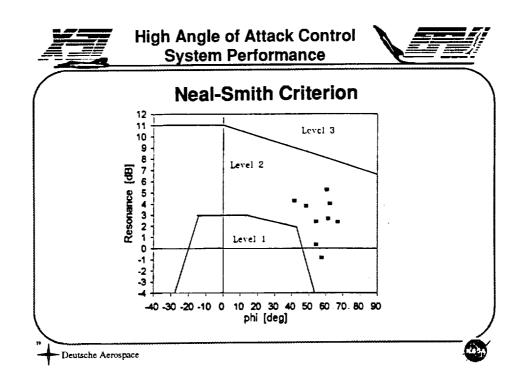
The X-31 is flying selected maneuvers from the Standard Evaluation Maneuver Set (STEMS) and collecting in-flight pilot comments and Cooper-Harper ratings. Initial flights use performance criteria established by the F-18 HARV. Ratings from the X-31 will be correlated with close-in-combat data, a unique data resource for high alpha flying qualities analysis. F-18 HARV and X-31 ratings and comments for the same STEM will also be compared.

Flying Qualities

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Flying qualities analyses focus on tying the STEMS Cooper-Harper ratings to criteria historically used in the conventional envelope, e.g. Neal-Smith, and Smith-Geddes. Additionally, flying qualities predictions based on lower order equivalent system (LOES) models, both in the time and frequency domain, will be compared with the actual pilot ratings.
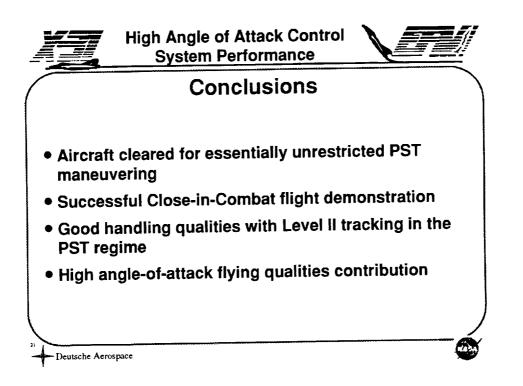
Pilot comments and Cooper-Harper ratings from the STEMs will be compared with the pilot opinions expressed during X-31 CIC. This will give confidence that the STEMs can be used to predict the suitability of flying qualities for high angle-of-attack close-in-combat.

The correlation of handling quality ratings with LOES predictions will be compared with the same correlation done for the HARV.

Neal-Smith Criterion

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Criteria used for conventional alpha handling qualities predictions were checked with high angle-of-attack flight data.

The Neal-Smith plot shows tracking task Cooper-Harper pilot ratings. Note that the high angle-of-attack flight data indicates Level II flying qualities.

Conclusions

- Aircraft cleared for essentially unrestricted PST maneuvering

- Successful Close-in-Combat flight demonstration

- Good handling qualities with Level II tracking in the PST regime

- High angle-of-attack flying qualities contribution

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In summary, the X-31 has met its flight control system performance goals, delivering the desired close-in-combat envelope, enabling the completion of over 200 successful close-in-combat engagements, and making a unique and significant contribution to understanding high angle-of-attack flying qualities.