Aerodynamic Design of the Lockheed Martin Cooperative Avionics Testbed

(Reference AIAA 2008-0157)

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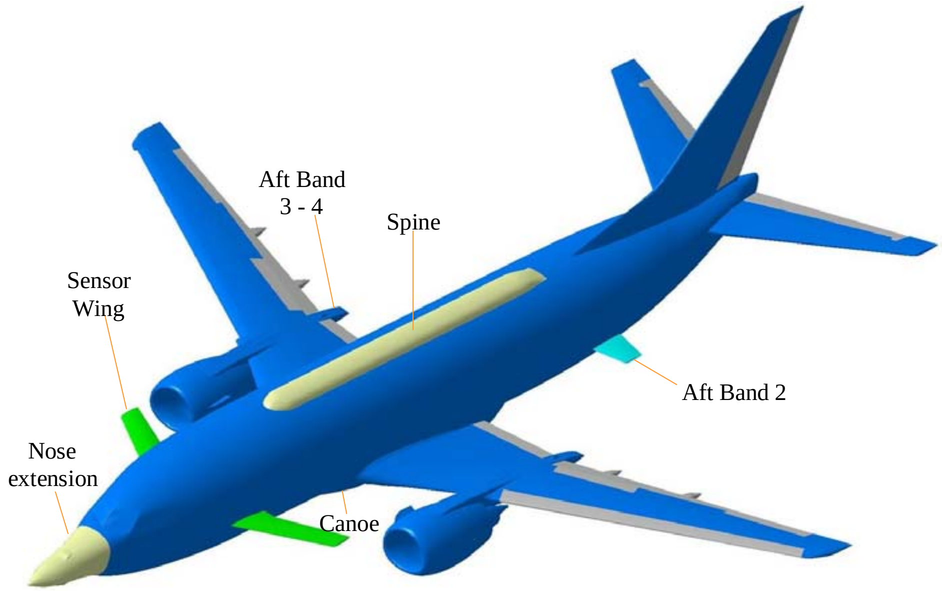
Introduction

- Lockheed Martin Cooperative Avionics Testbed
- (CATBird)
- Heavily modified Boeing 737-300 airplane
- Operated in the Experimental Category
- Testbed for F-35 Joint Strike Fighter (JSF)
  - Sensor operations
  - Data fusion
  - Operational environment
- External modifications to the basic airplane
  - Replacement of the nose radome
  - Sensor wings on the forward fuselage
  - Strake antennas on the aft fuselage
  - Spine and canoe antenna fairings
- Heavily modified internal fuselage
  - Simulated JSF cockpit and
  - Engineering and observer stations



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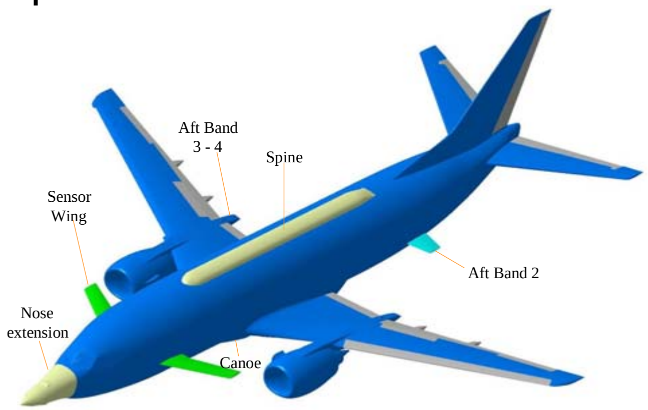
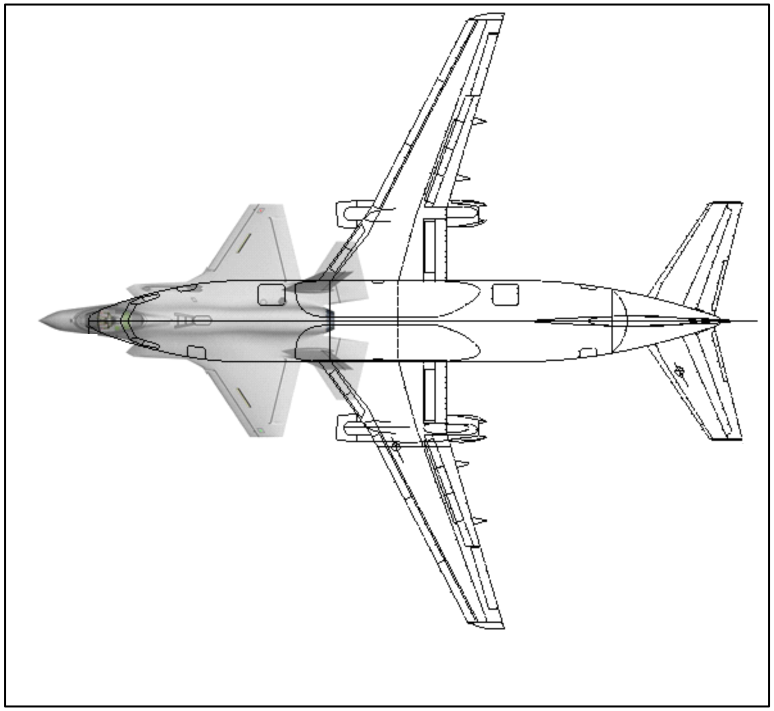
Design and Analysis Approach

- Predict airplane behavior with AMI design and analysis methods and tools
  - MSES, VLAERO, VSAERO, MGAERO, FPI
- Wind tunnel testing
  - Verification and calibration of linear data
  - Non-linear data
- Baseline airplane flight testing
  - Baseline data for further validation
  - Reduces risk that an airframe-specific anomaly is mistaken for a CATBird problem
- Clear CATBird for full operational envelope where possible
  - Reduce risk for flight test expansion
- Primary areas of concern
  - Basic stability and control
  - Air data system effects
  - Stall speeds and handling qualities
  - High speed characteristics
  - Engine inlet flow
  - Design aerodynamic loads
- The airplane is operated in Experimental category
  - Full compliance with CFR14 Part 25 regulations not required
  - Lockheed Martin independent board used as airworthiness authority



Nose Extension and Sensor Wing Design

- Nose extension completely replaced existing radome
  - Minimization of air data system disturbance
- Portions of JSF leading edge mounted to CATBird on ‘sensor wing’
  - JSF relation between radome and LE must be maintained
  - Effect is definitely destabilizing
  - Possible engine inlet effects



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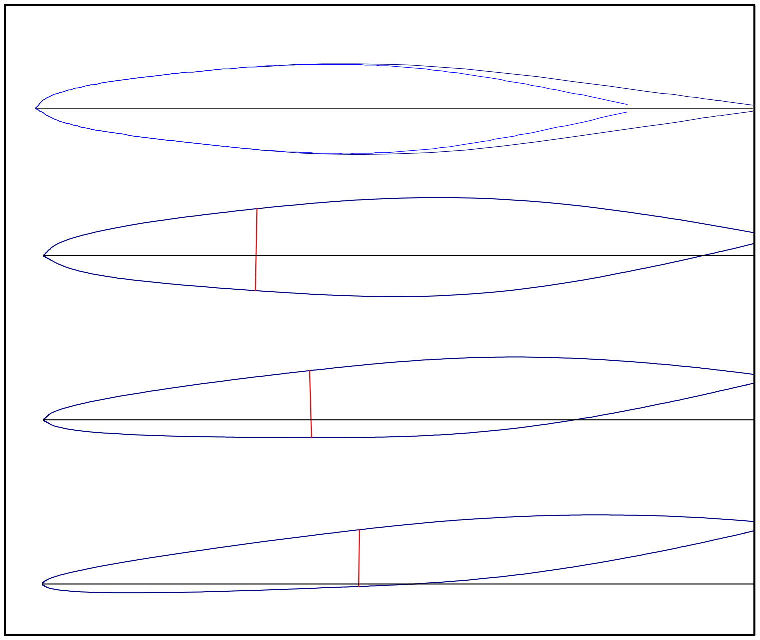
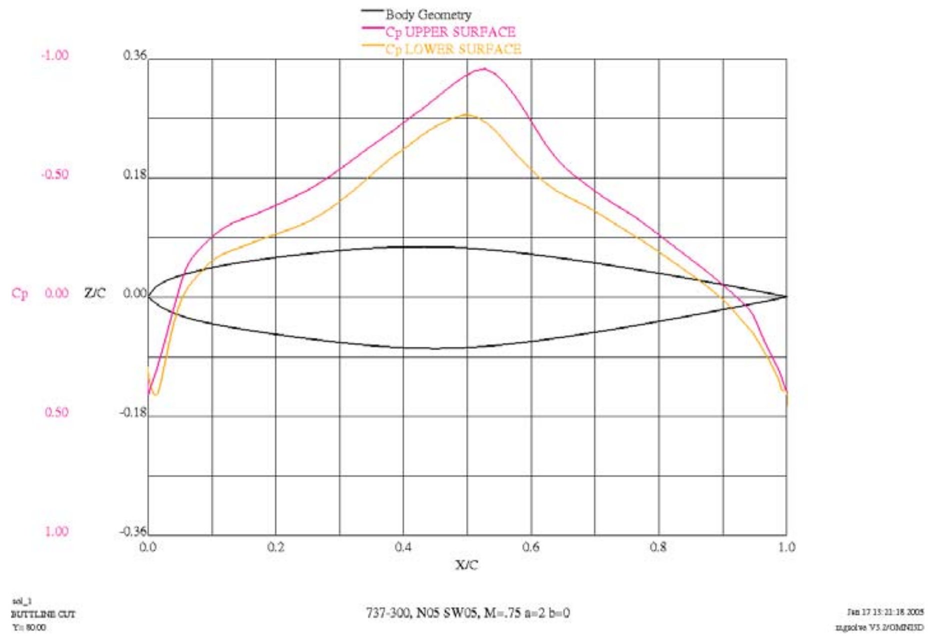
Nose Extension and Sensor Wing Design

- JSF lofts supplemented with chordwise and spanwise fairings
- Conflicting design requirements:
    - Stability impact required minimum area and therefore minimum chord
    - High speed characteristics required low t/c and therefore maximum chord
- Maximum feasible t/c and airfoil curvature used





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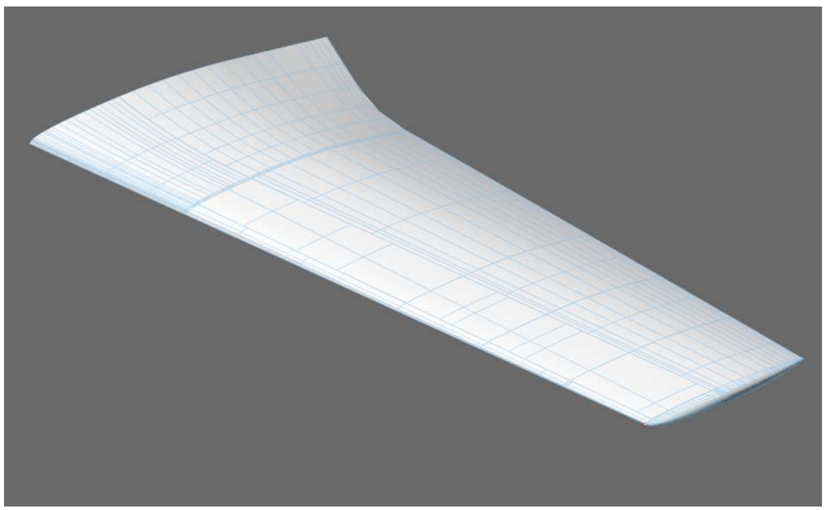
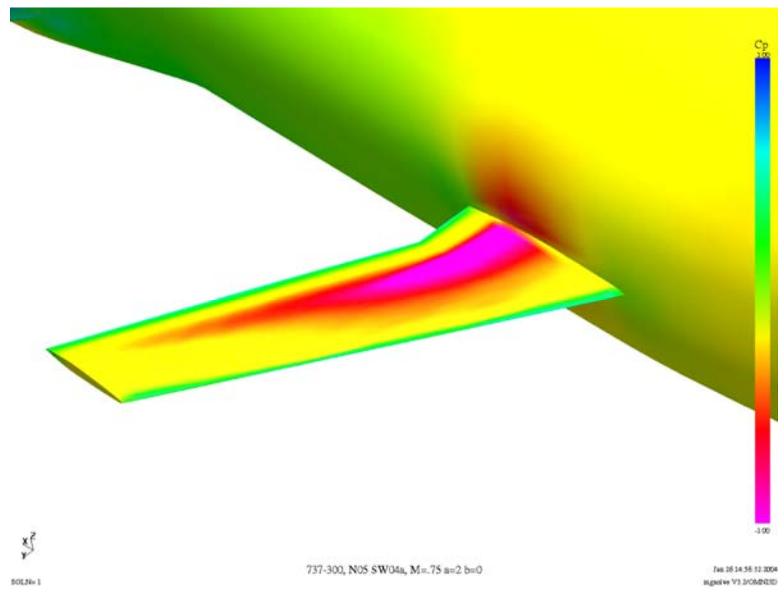
Nose Extension and Sensor Wing Design

- Final loft coordinated with manufacturer
- Flow quality acceptable at design operating Mach numbers
- Airplane stability decrement predicted to be 16% MAC
    - Compensation to be provided by a change to the aft cg limit





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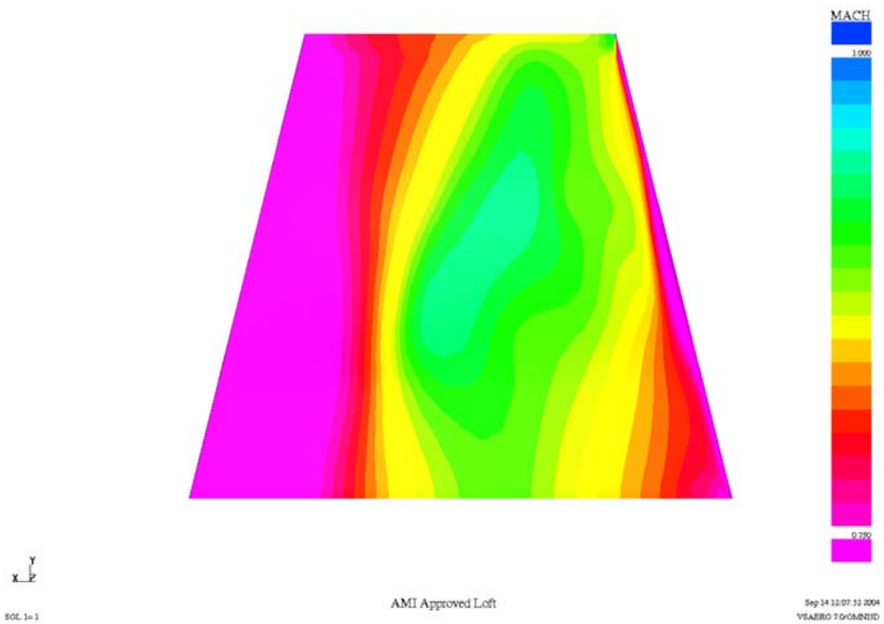
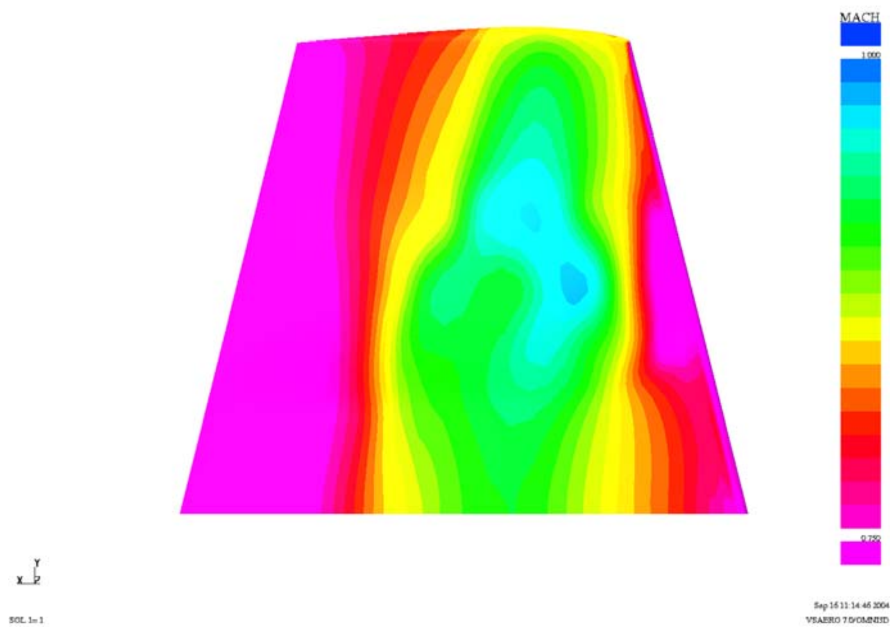
AMI

Aft Band 2 Design

- Portions of JSF horizontal tail mounted on aft fuselage
- Fairing design completed to avoid transonic flow
- Wind tunnel showed no strong impact of planform area on airplane characteristics
- Initial aerodynamic loft was complex and difficult to produce
- A simpler loft was developed with an acceptably small performance penalty





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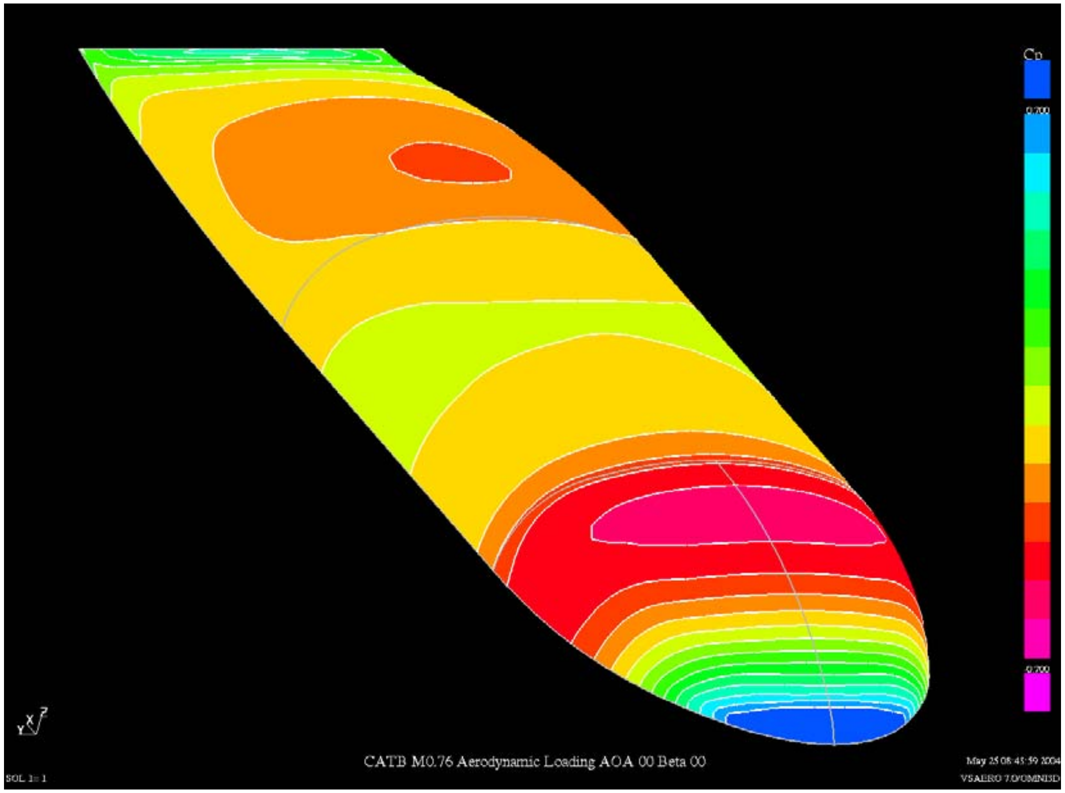
Fuselage Spine and Canoe Fairing Design

- Forward section design to minimize suction peaks under AOA and sideslip
  - Double-elliptical planform with shoulder fullness control
- Constant section used maxim allowable curvature and smooth variation
- Aft section design to minimize pressure recovery gradient



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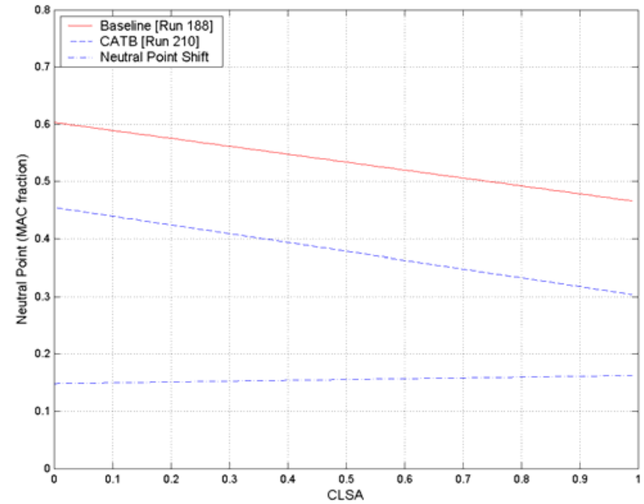
Low-Speed Characteristics

- Testing performed at University of Washington Aeronautical Laboratory’s (UWAL) Kirsten Wind Tunnel in Seattle, WA
    - Closed loop double-return capable dynamic pressure 100 psf
    - 12x8 ft test section
- Wind tunnel model fabricated by Aeronautical Testing Service Inc of Arlington WA
    - Developed from a photogrammetric scan of the baseline airplane
    - 1/12 scale model with full component buildup, control surface and flap deflections
    - All CATBird and baseline 737-300 parts

Low-Speed Characteristics

- Two separate wind tunnel entries
  - 140 hours of testing
  - 780 data runs
  - 112 configurations
  - Component buildups
  - Control effectiveness
  - Flow studies
  - Flaps cruise and deployed
  - In and out of ground effect
- Wind tunnel results verified predicted stability decrement
- Small increase in trimmed C_{LMAX}
- No significant change to control effectiveness or lateral-directional stability
- Data used along with analytical and baseline flight test results to produce an aerodynamic database for further study and analysis



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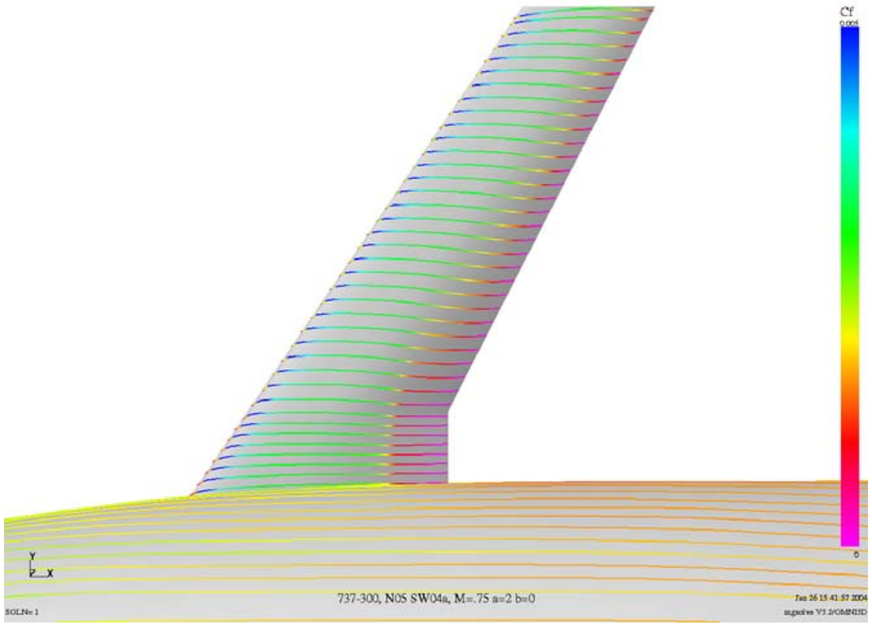
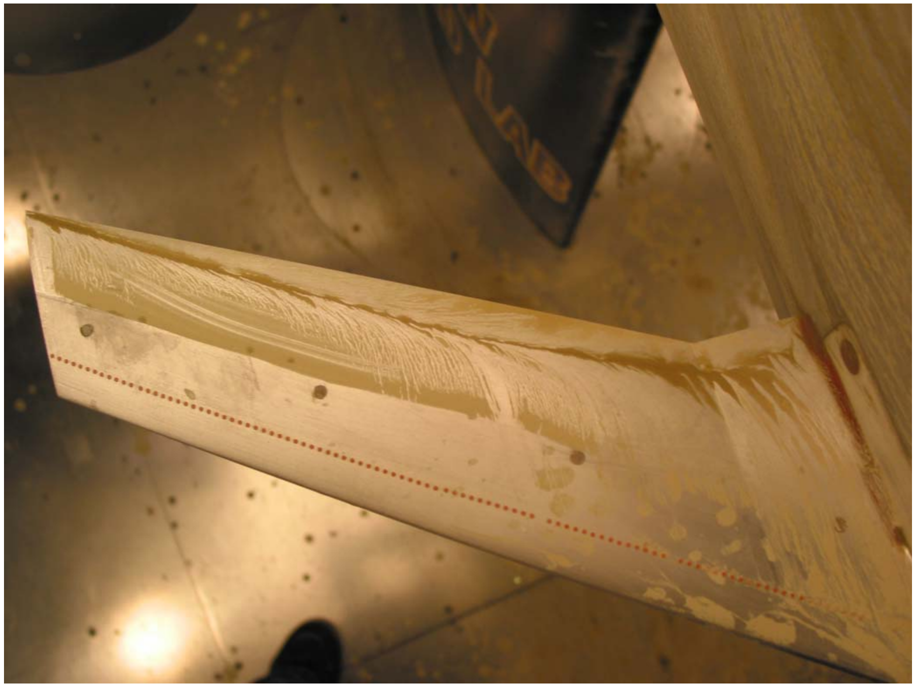
Low-Speed Characteristics

- Basic sensor wing aerodynamic performance verified
  - Stability increment
  - Flow quality over sensor wing
  - Limited study of sensor wing wake trajectories





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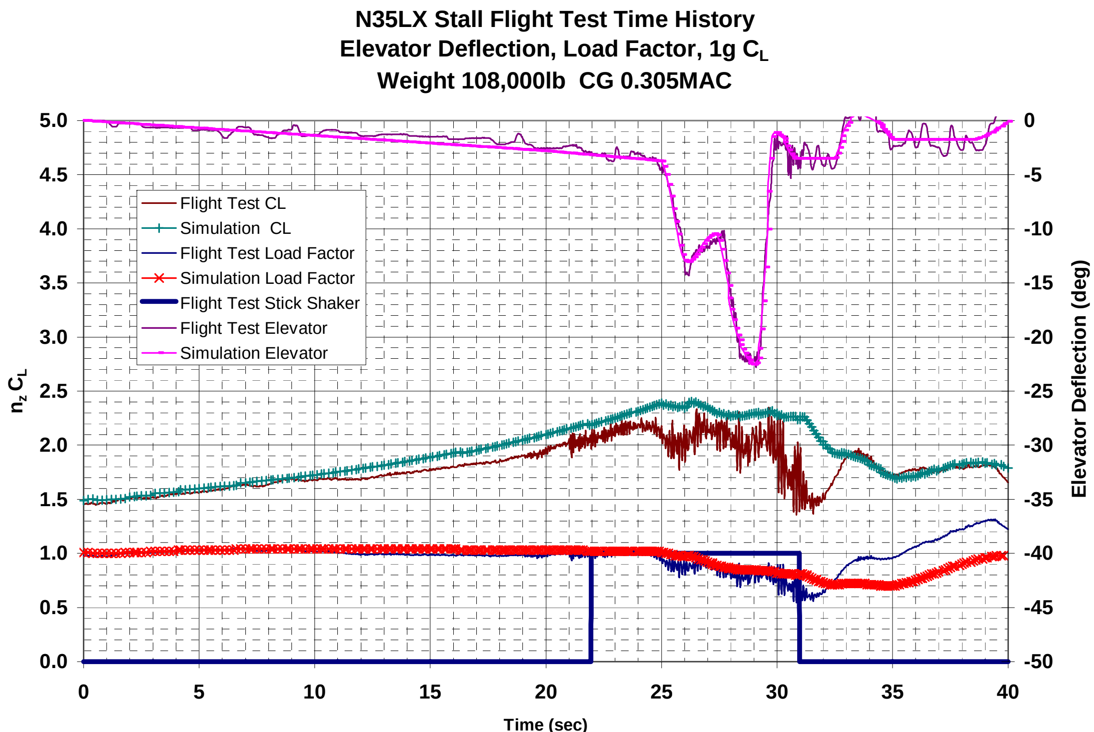
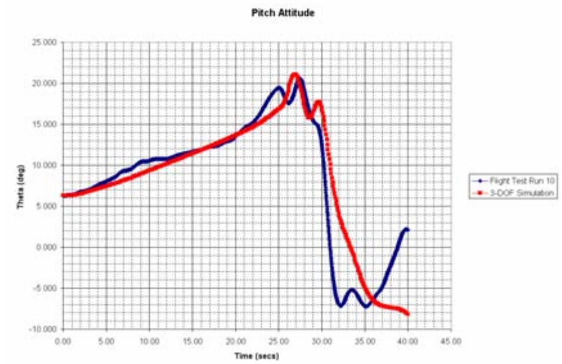
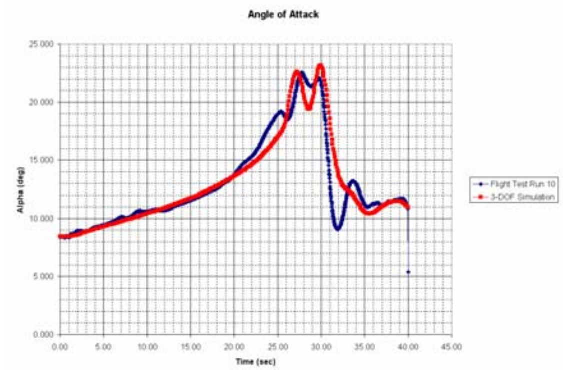
Low-Speed Characteristics

- Stall maneuvers simulated with 3 DOF program
- Focus on pitchup and pitchdown at stall
- Program calibrated by reproducing baseline stall using full nonlinear wind tunnel data and flight test control input
- Results showed good agreement with flight test results
- Increased confidence in CATBird simulations







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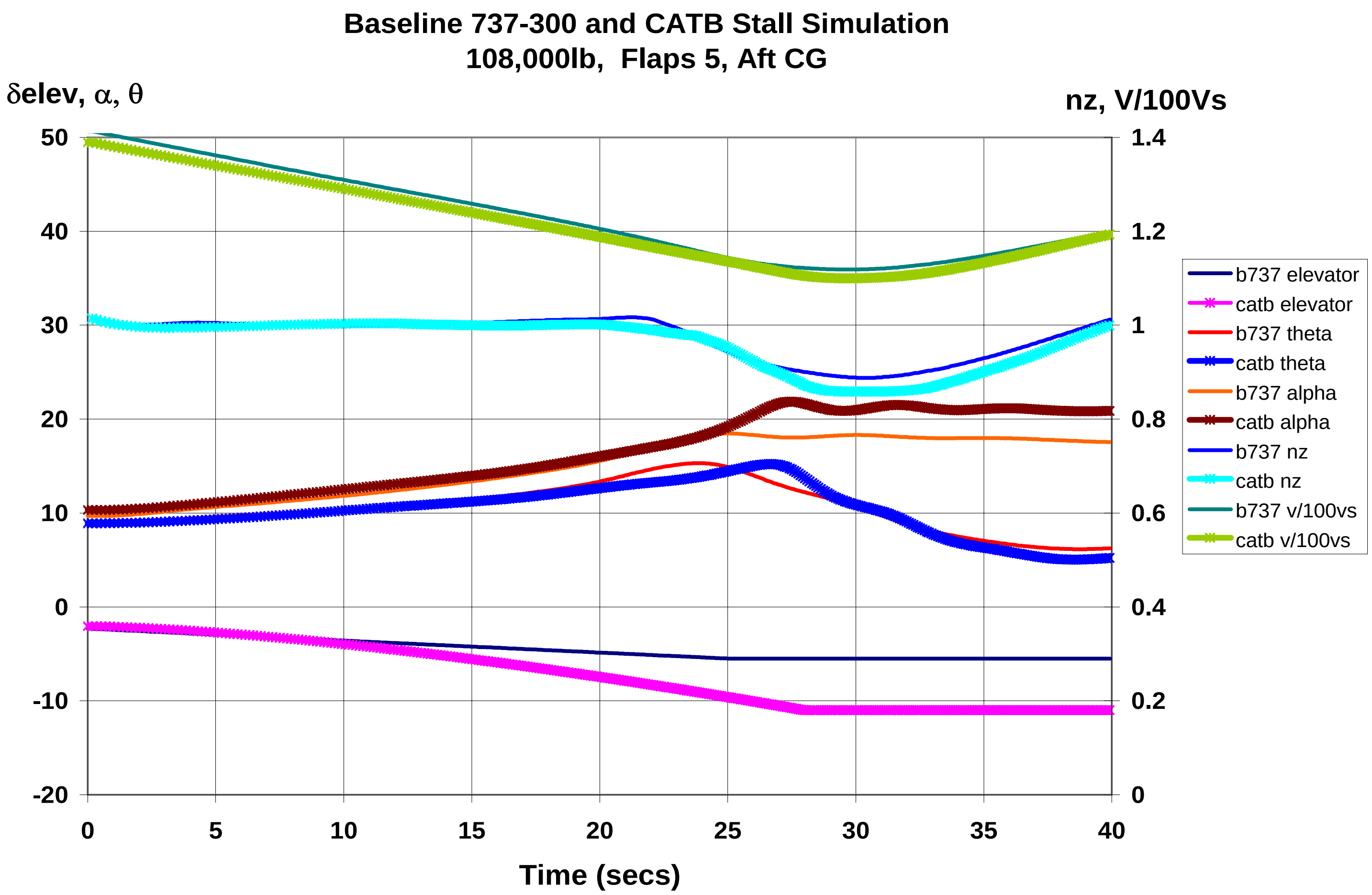
Low-Speed Characteristics

- CATBird simulations showed no appreciable decrement in behavior



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Air Data

- Effect of chined radome on air data examined
  - China clay and minituft flow visualization to track vortex
  - Mini pitot probes to track blanking
- No CATBird effects found

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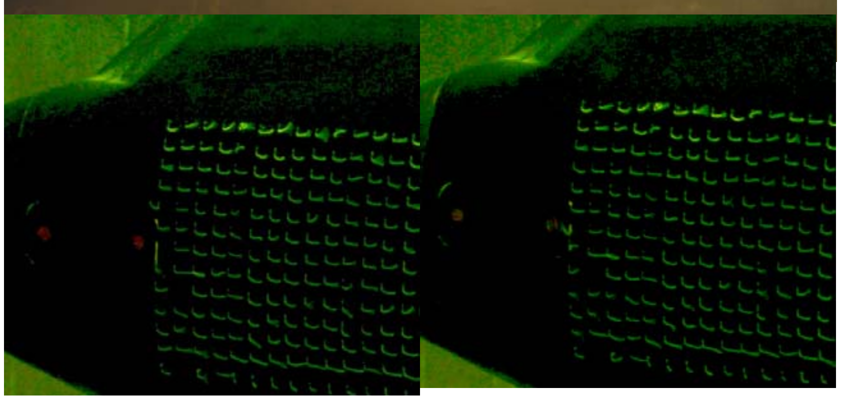
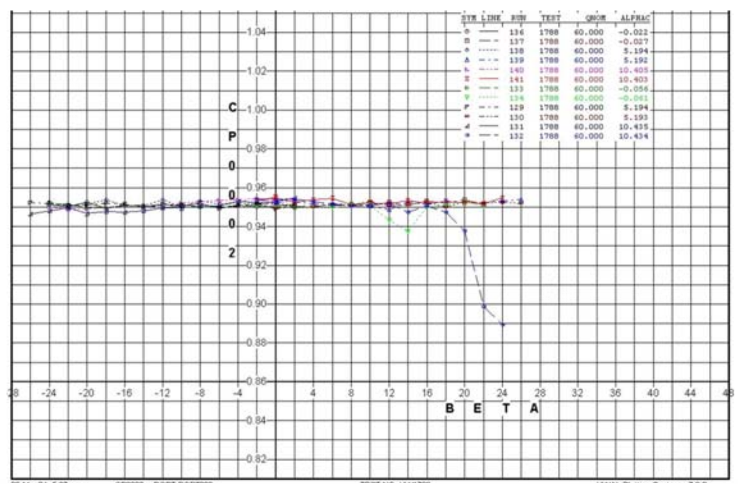
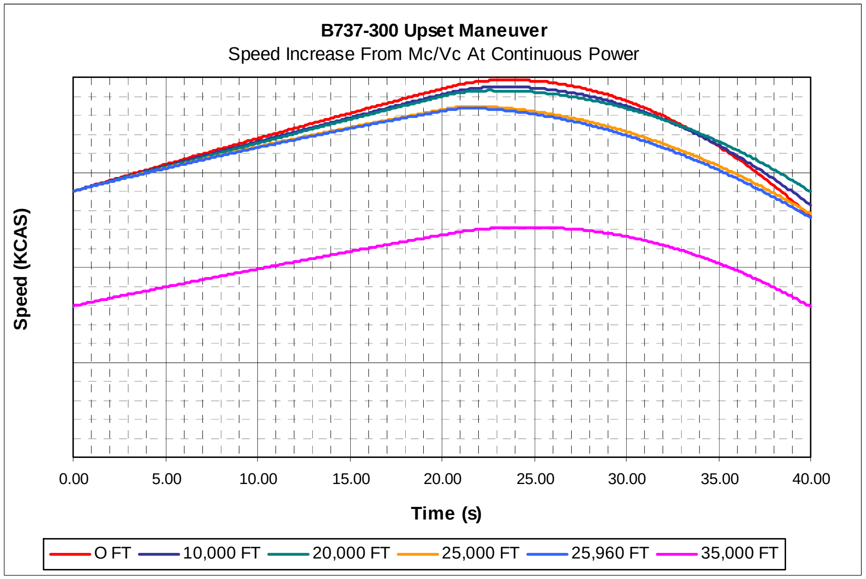
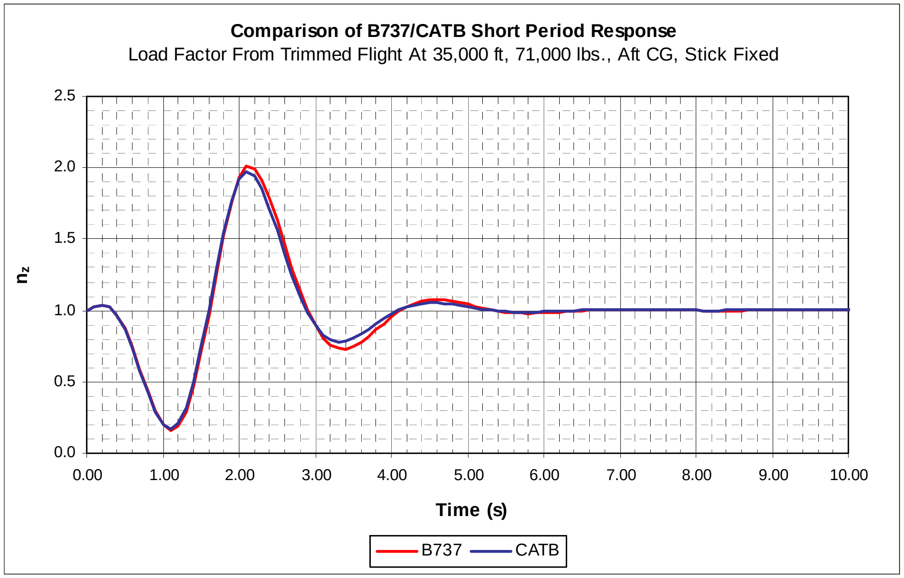




High Speed Analysis

- High speed analysis used overall aerodynamic database
- Efforts focused on dynamic stability, trim runaway, and upset recovery
- No problems or significant CATBird effects found
- Airplane cleared for flight testing





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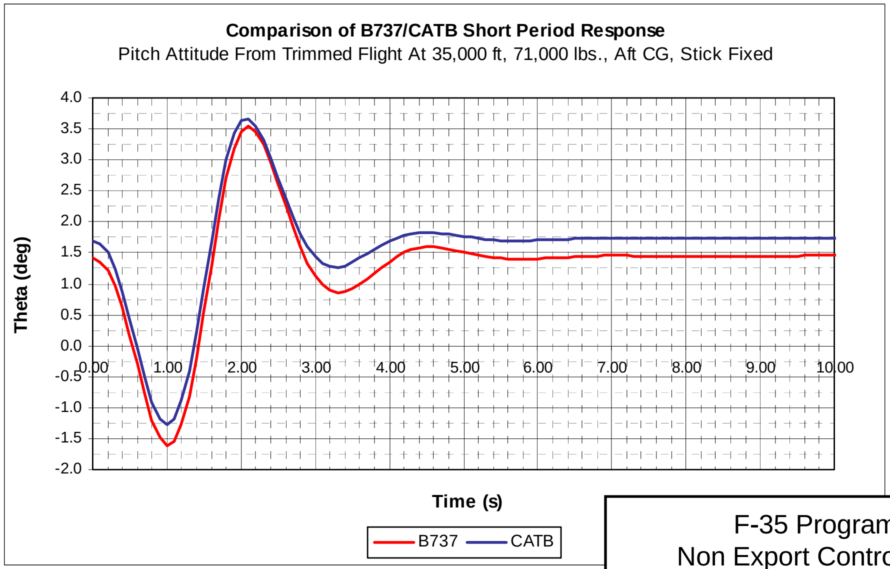
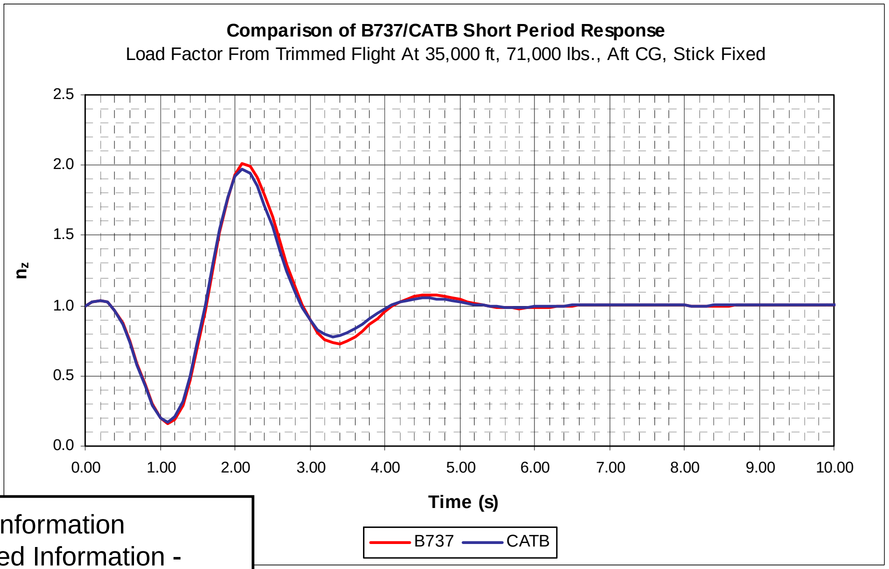
High Speed Analysis





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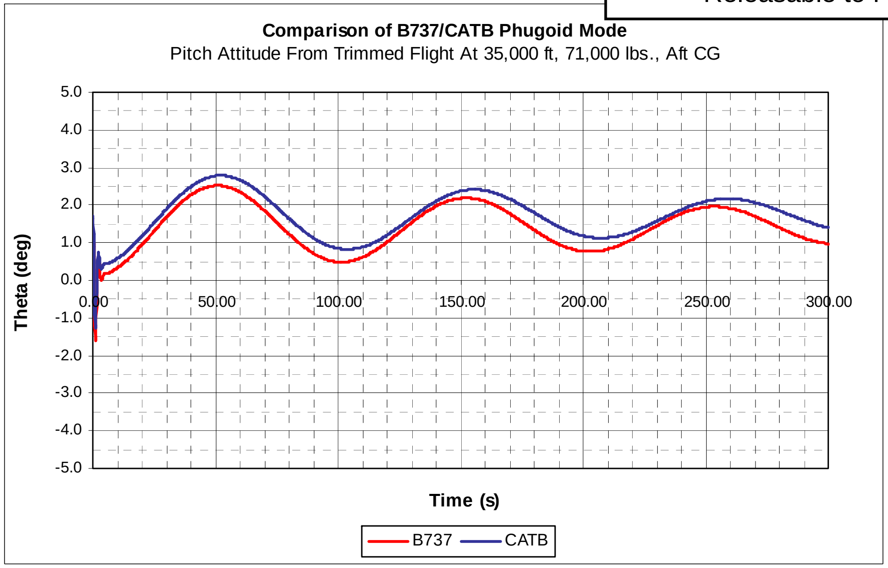
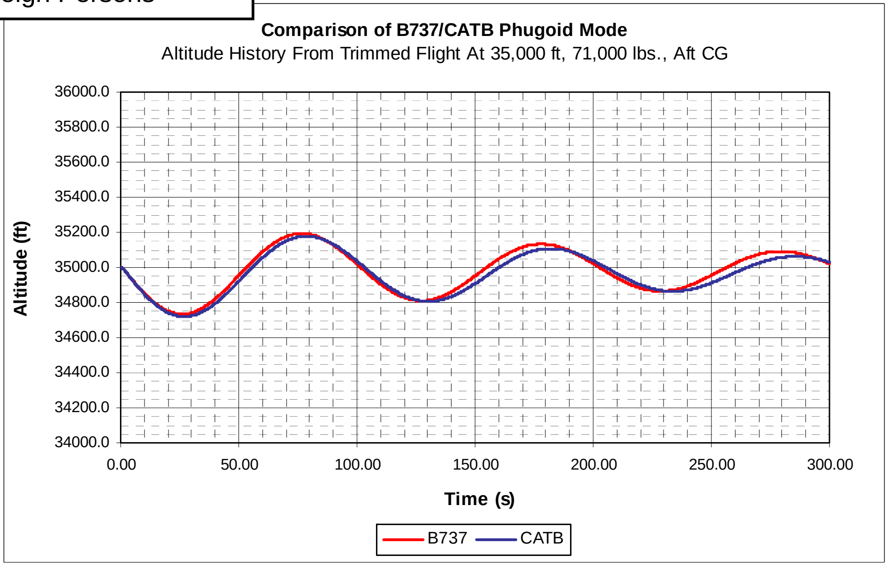
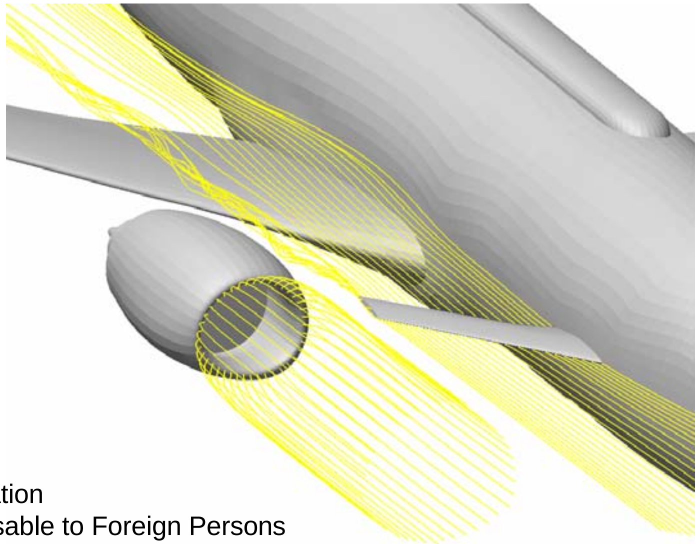




Sensor Wing and Engine Inlet Interaction

- Areas of concern were engine ingestion of wake and/or vorticity
- Sensor wing wake trajectory study performed using VSAERO
  - Sensor wing wake streamlines traced aft
  - Engine highlight streamlines traced forward
  - Engine mass flow effects included
- Wake ingestion classified as 'None', 'Possible', and 'Definite'



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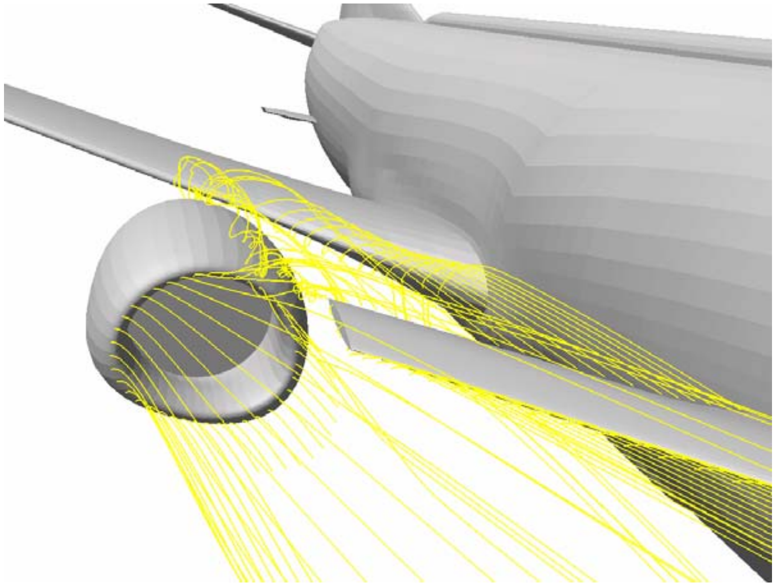
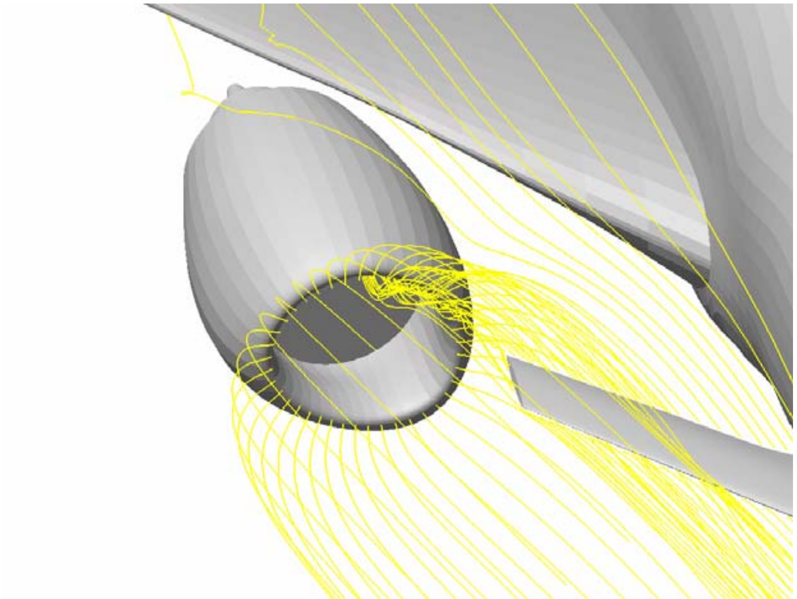
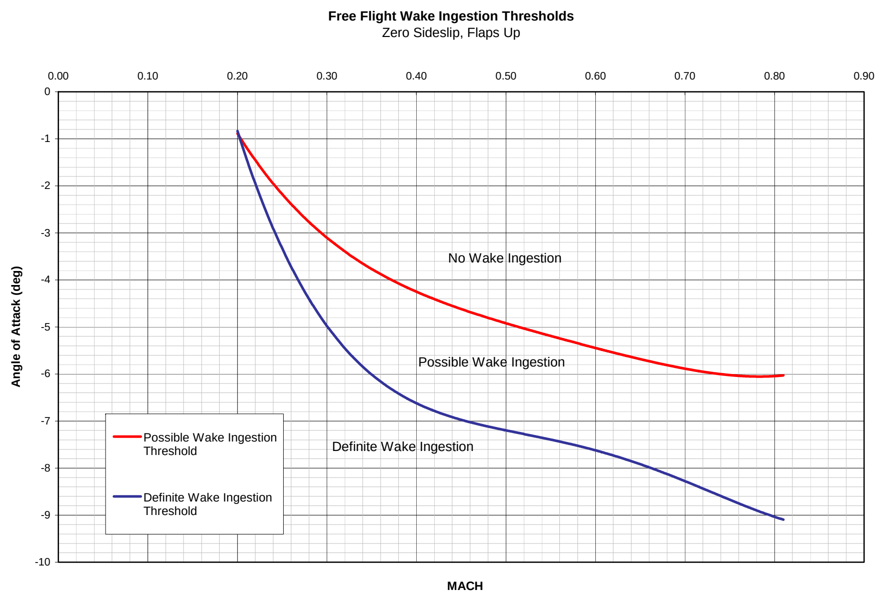
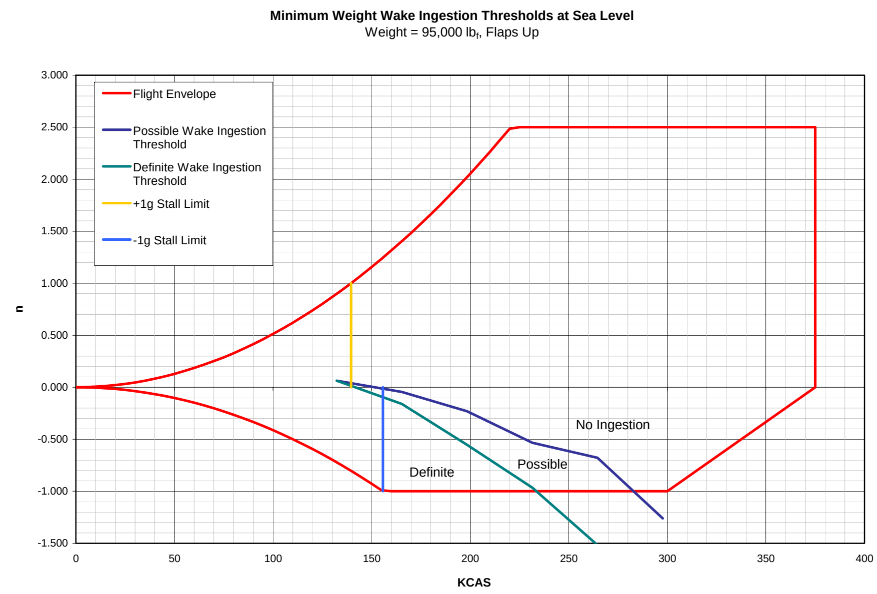




Sensor Wing and Engine Inlet Interaction

- Results tabulated as functions of airplane Mach number, AOA, and C_L
- No ingestion for positive airplane C_L at cruise
- Wake ingestion boundaries developed as a function of airplane normal load factor for various weights and altitudes
- Information used in test planning and flight manual supplement development





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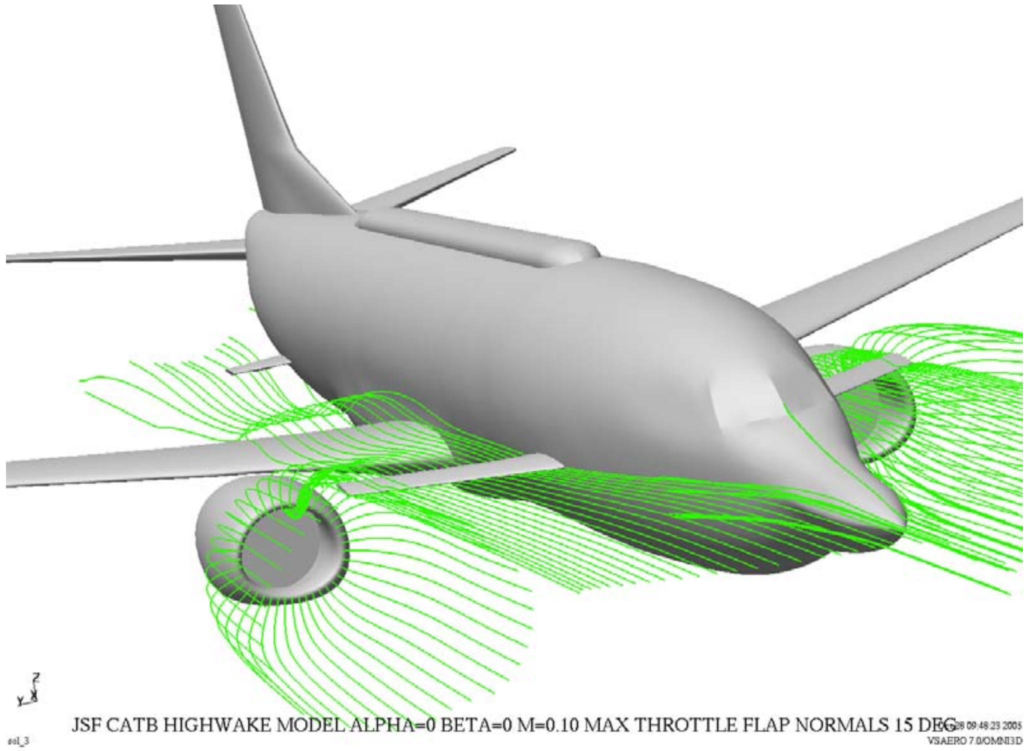
Sensor Wing and Engine Inlet Interaction

- Large engine streamline during takeoff roll engulfs sensor wing
- Ingestion was predicted to cease before rotation speeds
- Flight test group advised that any adverse engine effects would be noticed before rotation and the takeoff could be aborted if needed



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Design Loads and Flight Loads Clearance

- Design aerodynamic loads calculated for new external parts
- CFR14 Part 25 load cases formulated as a linear matrix of quasi-steady state conditions
- Airplane flight condition and resulting sensor wing and aft band air loads calculated
- Results surveyed to find critical cases for design
- Aerodynamic model used to produce distributed airloads
  - Design airloads for critical cases
  - Loads for flight test structural monitoring during envelope expansion

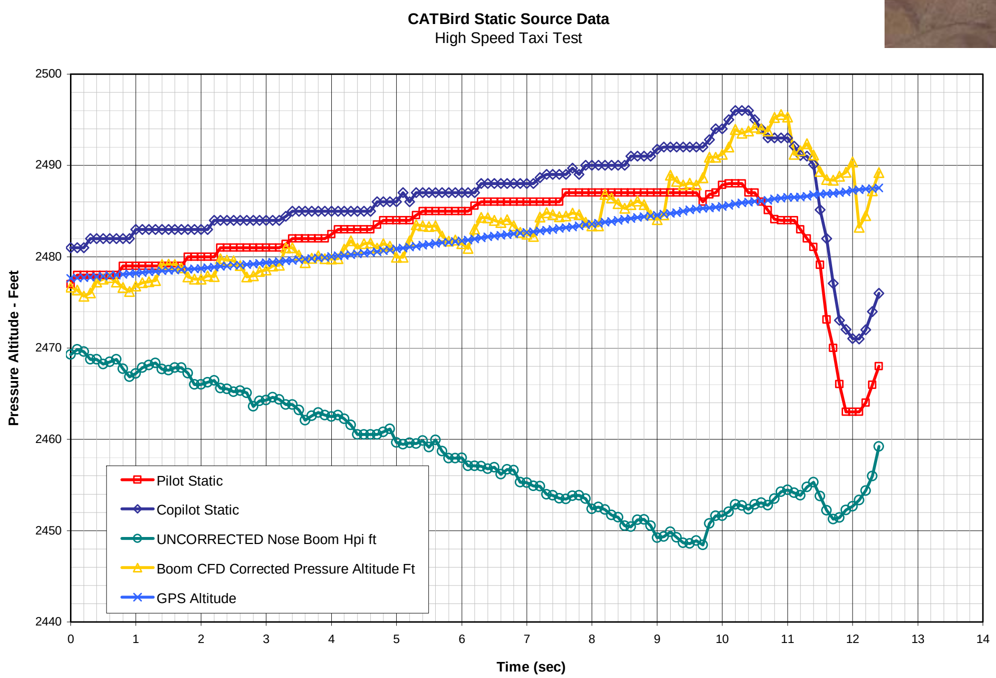
FAR 25 Section	U	n_Y	N_Z	β	P	Q	$\ddot{\phi}$	$\ddot{\theta}$	$\ddot{\psi}$	δ_e	δ_R	δ_A
331 b)	All	0	1	0	0	0	0	0	0	A/R	0	0
331 b)	All	0	$\pm n_{LIMIT}$	0	0	$\frac{57.3(n_z-1)}{U}$	0	0	0	A/R	0	0
331 c) 1)	V_A	0	1 (see note 8)	0	0	0	0	A/C	0	$-\delta_{eMAX}$	0	0
331 c) 2) Pitch Up	All	0	1	0	0	$\frac{57.3(n_z-1)}{U}$	0	$\frac{39n_z(n_z-1.5)}{V}$	0	A/R	0	0
331 c) 2) Pitch Down	All	0	$+n_{LIMIT}$	0	0	0	0	$\frac{-26n_z(n_z-1.5)}{V}$	0	A/R	0	0
331 (d), 341	V_C, V_D	0	$1 \pm \frac{K_g U_{de} V C_{Z\alpha}}{498(W/S)}$	0	0	0	0	A/C	0	331 b)	0	0
349 a) 2)	V_A	0	2/3($+n_{LIMIT}$) & 0	0	A/C (9)	0	(9)	0	0	A/R	0	δ_{AMAX}
349 a) 3)	V_C	0	2/3($+n_{LIMIT}$) & 0	0	455a)2)i) (note 9)	0	(9)	0	0	A/R	0	A/R
349 a) 4)	V_D	0	2/3($+n_{LIMIT}$) & 0	0	$\frac{445a)2)i)}{3}$ (note 9)	0	(9)	0	0	A/R	0	A/R
351 a) 1)	V_A - V_D	A/C	1	0	0	0	A/C	0	A/C	331 b)	δ_{RMAX}	0
351 a) 2)	V_A - V_D	A/C	1	β_{MAX}	0	0	A/C	0	A/C	331 b)	δ_{RMAX}	A/R
351 a) 3)	V_A - V_D	A/C	1	β_{MAX}	0	0	A/C	0	A/C	331 b)	0	0
351 b)	All	A/C	1	$K_{gt} U_{de}$	0	0	A/C	0	A/C	421a)	0	0

Flight Test

- Flight testing performed by AeroTEC of Seattle, WA
  - Detailed test planning with inputs and reviews from all team members
  - Daily pre- and post-flight briefings
  - Rapid data release to engineers
- Baseline flight tests before modification
  - Confirmed basic performance and handling of this airframe
  - Produced data for validation and calibration of analytical models
  - Reduced risk of an airframe-specific anomaly mistaken for CATBird problem
  - Airplane was flown to dive speed and Mach number
- Modified airplane flight tests
  - All external shape and structural modifications completed
  - Substantiated compliance with CFR14 Part 25 airworthiness criteria
  - Validated the effect of the external modifications
    - Airplane aerodynamics
    - Air data
    - Handling qualities
  - Validated flutter and other structural margins
  - Provided performance and flying qualities information for the CATBird Aircraft Flight Manual Supplement.

Air Data Boom

- JSF air data boom used on JSF radome for convenience
- Boom not long enough for CATBird installation
- Significant effect on error at static source



- VSAERO used to provide local CP and data correction
- Results verified by flight test

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Stability and Control Flight Test Results

- Stabilizer to trim measured for a range of speeds at several weights and cg locations
  - Measured during hands-free trim and steady maneuvers
- Elevator position measured and effect accounted for
- Resulting corrected stabilizer angle is a roughly linear function of trimmed C_L.
  - Slope proportional to airplane static margin
  - Intercept proportional to zero lift pitching moment
- Results validated stability increment prediction

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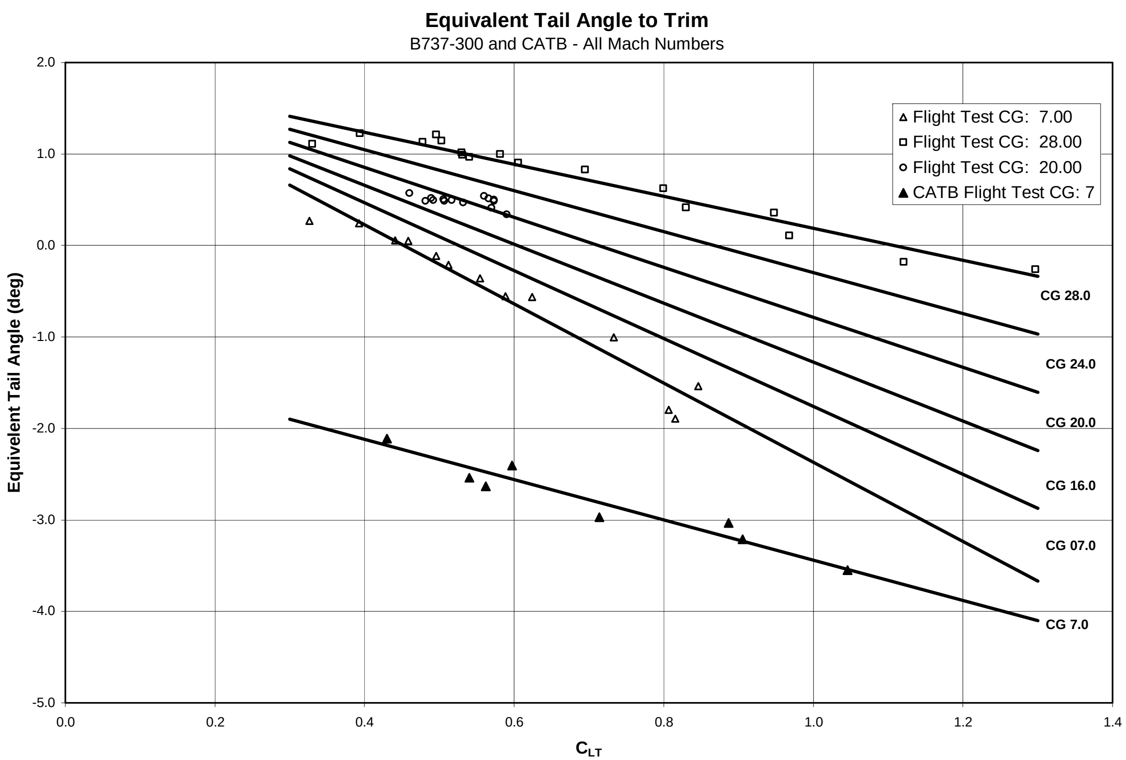
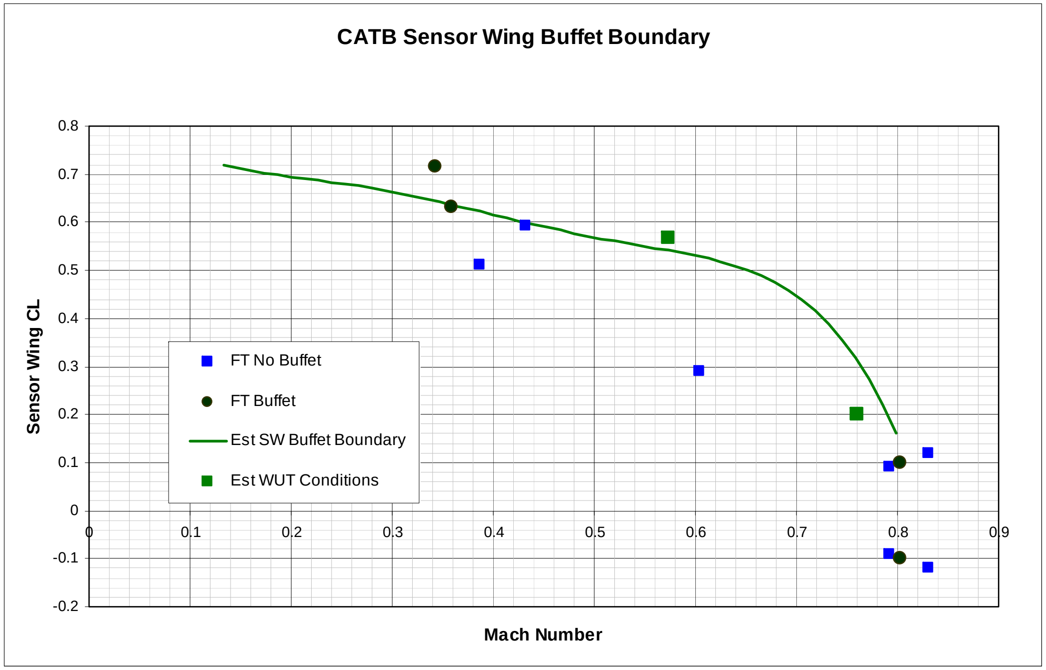


Buffet Flight Test Results

- Flight test did not produce any unacceptable low or high speed buffet or vibrations
- Sensor wing buffeting was observed
  - High angle of attack conditions – wind up turns
  - Mach numbers above CATBird VMO/MMO during the flutter clearance flights
  - Neither produced any discernable airframe response
- Buffet characteristics of the CATBird were determined to be satisfactory
- Flight test results showed good correlation with predicted buffet boundary



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Summary

- Successful development and test program
- In depth analyses
  - Multiple reviews by experienced engineers
  - Realistic assessments of tool capabilities
- Recognition of tool limitations
- Mitigations and conservatism applied where uncertainty existed
- Open interchange and participation of engineers
  - Customer
  - Contractor engineering
  - Airworthiness authority
  - Flight test teams
- Robust design and well-planned test process
- Risks eliminated or reduced
  - Design and analysis
  - Planned envelope expansion flight tests
  - Concurrent data review and analysis.
- Testbed was successfully demonstrated
  - Mission performance
  - Compliance with the appropriate CFR14 Part 25 airworthiness requirements