X-48B Preliminary Flight Test Results

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Subsonic Fixed Wing Project
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Outline

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- Flight Research Program Approach
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## NASA Subsonic Transport System Level Metrics

*... technology for dramatically improving noise, emissions, & performance*

### CORNERS OF THE TRADE SPACE

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<thead>
<tr>
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<tbody>
<tr>
<td>Noise</td>
<td>- 32 dB</td>
<td>- 42 dB</td>
<td>- 71 dB</td>
</tr>
<tr>
<td>LTO NOx Emissions</td>
<td>-60%</td>
<td>-75%</td>
<td>better than -75%</td>
</tr>
<tr>
<td>(below CAEP 6)</td>
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<td></td>
<td></td>
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<tr>
<td>Performance: Aircraft</td>
<td>-33%**</td>
<td>-40%**</td>
<td>better than -70%</td>
</tr>
<tr>
<td>Fuel Burn</td>
<td></td>
<td></td>
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<tr>
<td>Performance: Field</td>
<td>-33%</td>
<td>-50%</td>
<td>exploit metroplex* concepts</td>
</tr>
<tr>
<td>Length</td>
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*** Technology Readiness Level for key technologies = 4-6

** Additional gains may be possible through operational improvements

* Concepts that enable optimal use of runways at multiple airports within the metropolitan areas

### SFW Approach

- Conduct Discipline-based Foundational Research
- Investigate Advanced Multi-Discipline Based Concepts and Technologies
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes
- Enable Major Changes in Engine Cycle/Airframe Configurations
X-48B Background

- Research partnership of Boeing, NASA, and AFRL
  - Design and fabrication contracted to Cranfield Aerospace

- Purpose
  - Evaluate low speed stability and control of hybrid wing body configuration in free-flight
  - Evaluate flight control algorithms
  - Evaluate prediction and test methods for hybrid wing body class vehicles

- Airframe
  - Remotely piloted from ground control station
  - 8.5% dynamically scaled (rigid body)
    - Wingspan: 20.4 ft
    - Weight: 525 lbf
    - Thrust: 54 lbf each (3 JetCat turbojets)
  - 20 control surfaces
    - 10 elevons
    - 8 split ailerons (4 clamshell pairs)
    - 2 winglet rudders
Flight Research Program Approach

Block 1: Flights 1-12
Slats Extended

Block 2: Flights 13-20
Slats Retracted

Block 3: Flights 21-XX
Slats Extended

Block 4: Flights 35-XX
Slats Retracted

Block 5: Flights XX-XX
Slats Extended

Block 6: Flights XX-XX
Slats Retracted

PID / Stalls / Engine Out Maneuvering

Departure Limiter Assaults

Envelope Expansion

Increasing Risk

Increasing Risk
Flight Status

• 58 flights completed as of the end of August

• Initial envelope expansion complete
  – Angle of attack up to 23 degrees
  – Angle of sideslip up to 20 degrees

• PID and approaches to stall have been performed
  – Slats extended and retracted
  – Forward and aft C.G.

• Stalls performed at forward C.G., slats extended and retracted

• Regression testing of software update in preparation for departure limiter assaults in work
## Research Leads

<table>
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<tr>
<th>NASA DFRC Lead</th>
<th>Boeing Lead</th>
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<tr>
<td>Real-Time Stability Monitoring</td>
<td>Turbofan Development</td>
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<tr>
<td>Adaptive Flight Control</td>
<td>Envelope Expansion</td>
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<tr>
<td>Intelligent Flight Control and Optimization</td>
<td>Increments to Aero Model (Parameter Estimation)</td>
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<tr>
<td>Airdata Calibration Method Development</td>
<td>Dynamic Departure Limiters</td>
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<tr>
<td>Parameter Estimation Method Development</td>
<td>Stall Characterization</td>
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*Included in presentation*
Turbofan Development

• Objectives
  – Gain engine development experience
  – Increase flight time
    • From 35 to 60 minutes

• Approach
  – Initial development of 50 lb thrust direct replacement followed by 80 lb thrust to reduce number of engines from 3 to 2
  – Build turbofan around existing engine core and gear reduction set
  – Initial fan geometry scaled existing open rotor helicopter fans
    • Analyze fan performance using CFD (SWIFT)
      – 3-D multiblock Navier-Stokes turbomachinery analysis code
    • Results of testing and analysis used to develop improved fan

• Status
  – Currently performing static and dynamic thrust testing at DFRC
  – Planned installation on X-48C if flight tested
Turbofan Development

SPT5 Engine Runs -- Ambient Conditions -- 2009.04.09 (Big Bear Airport)

CFD analysis courtesy of Rod Chima, NASA GRC
Intelligent Flight Control and Optimization

- **Objective**
  - Demonstrate real-time drag minimization

- **Benefits**
  - Operable over a wide range of flight conditions and weight variations
  - HWB trailing edge control surfaces allow tailoring spanwise lift distribution

- **Approach**
  - Estimation of local performance index gradient
    - Kalman filter
    - Control surface positions as controls
  - Define optimal control surface trim positions

- **Status**
  - X-48B aero database shows potential for ~5% drag reduction
    - Does not accurately model induced drag effects
    - Likely not representative of real world aerodynamics
    - Provides adequate gradient for testing in simulation
  - X-48B simulation
    - Evaluate sensor and computational requirements
Airdata Calibration

• Objective
  – Reduce flight time required to evaluate air data calibration

• Approach
  – Fly “wind circle” maneuvers via autopilot
    • Constant airspeed and bank angle
  – Estimate vehicle states with linear regression
    • Time history of groundspeed, flight path angle, and heading
    • Estimated true airspeed, wind speed, and wind direction

• Results
  – True airspeed estimation converges well after 180° heading change
  – Reduced time to verify airdata calibration from 6 minutes to 1 minute

\[
\begin{bmatrix}
V_a \\
V_w \cos(X_w) \\
V_w \sin(X_w)
\end{bmatrix} = (H^T H)^{-1} H^T
\begin{bmatrix}
V_{g, N_1} \\
\vdots \\
V_{g, N_n} \\
V_{g, E_1} \\
\vdots \\
V_{g, E_n}
\end{bmatrix} = \Theta
\]

\[
H = \begin{bmatrix}
\cos(\gamma) \cos(\psi) & 1 & 0 \\
\vdots & \vdots & \vdots \\
\cos(\gamma) \cos(\psi) & 1 & 0 \\
\cos(\gamma) \sin(\psi) & 0 & 1 \\
\vdots & \vdots & \vdots \\
\cos(\gamma) \sin(\psi) & 0 & 1
\end{bmatrix}
\]
Parameter Identification Background

Determination of the parameters of a mathematical model of a system based on observation of the system inputs and response

- Value of in-flight parameter estimation
  - Risk reduction during envelope expansion
  - Comparison to predictive results
    - Wind tunnel
    - Analytic
  - Control law refinement
    - Dynamic analysis
    - Validation of advanced techniques

- Focus on rigid body dynamics with an emphasis on control surface effectiveness
X-48B Parameter Estimation Benefits

- X-48B provides unique opportunity to validate test methods to address identification issues associated with HWB configurations

- Validation of parameter identification techniques and methods
  - Tools and methods developed to perform parameter estimation applicable to future vehicles
  - Better flight testing techniques to improve parameter estimation
HWB Unique Challenges

- HWB
  - Control surfaces
    - Adjacent control surfaces have similar response (nearly coplanar)
    - Adjacent control surfaces influence each other
    - Allocation of control effectiveness utilizes common surfaces for control of multiple dynamic modes
  - Unstable in large regions of the flight envelope
    - Closed-loop flight control responds to excitations as disturbances

- X-48B
  - Susceptible to turbulence
    - Low wing loading (~5 psf)
    - Low Reynold’s number
  - Airdata system in significant local flow
  - Control surface positions inferred from actuator position
Constraints Used in Parameter Estimation

- Constrained control effectiveness
  - Multiple elevators, ailerons, and rudders
    - Pitch is symmetric movement
    - Roll is differential movement
    - Yaw is winglet rudder movement or asymmetric clamshell deployment
  - Defined control surface movement correlates to control allocation architecture

- Boeing gangs control surfaces
  - Virtual elevator, aileron, and rudder
    - Surfaces 1, 2-5, 6, 7, and rudders
Treating Identifiability – Super Maneuvers

- Super Maneuver
  - Combines individual surface excitations
  - Enables identification of coplanar control derivatives

\[ Cm = Cm_0 + Cm_\alpha \alpha + Cm_q \frac{\frac{q}{2}}{V} + Cm_{\delta_1} \delta_1 + Cm_{\delta_2} \delta_2 + \ldots \]
Treating Identifiability – Multisines

- Multisines
  - Excitation of surfaces simultaneously at different frequencies
  - Combinations for symmetric, anti-symmetric, clamshell, and fully independent
Method Validation with TG-14A

- TG-14A parameter estimation
  - Low wing loading at low Reynolds’s number
  - Airdata in significant local flow
  - Open-loop response
  - Traditional control surfaces

- Flight data
  - Hand flown doublets
  - Airspeed: 60 – 80 knots

- $CL_\alpha$
  - Analytic: 0.1097
  - Estimated: 0.1025

- Verified output error technique for low Reynolds number, low wing loading aircraft
Method Validation with Simulation

- X-48B simulation
  - Known environment
    - Airdata and turbulence models
  - Closed-loop response
  - 20 control surfaces

![Diagram showing Finite Differences on Aero Model, True Parameter Value, and Parameter Estimation from Input and Response.](image)
Method Validation with Simulation Results

- Surface pair symmetric doublets
  - Same initial conditions as longitudinal flight data
    - 10 degrees angle of attack
    - Slats extended, aft CG
Preliminary Flight Results

- Surface pair symmetric doublets
  - Data collected during 1 flight
  - 10 degrees angle of attack
  - Slats extended, aft CG
  - 5 repeats of each doublet
Preliminary Flight Results

- Surface pair anti-symmetric doublets
  - Data collected during 3 flights
  - 10 degrees angle of attack
  - Slats extended, forward & aft CG
  - 5 repeats of each doublet

Output Error Flight Super Maneuver Time History Response

<table>
<thead>
<tr>
<th>Roll Rate (deg/s)</th>
<th>Time (sec)</th>
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<tbody>
<tr>
<td></td>
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<table>
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<tr>
<th>CI Percent Difference From Aero Model</th>
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<tbody>
<tr>
<td>More Effective</td>
</tr>
<tr>
<td>Less Effective</td>
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<tr>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
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Future PID Research and Improvements

• Flight conditions of interest and doublet sequences defined for super maneuvers

• Multisine control surface excitations
  – Evaluation with X-48B simulation has started
  – Validate against aero model
  – An upgraded flight computer will provide the capability for performing multisine maneuvers in flight

• Measure control surface position
  – Currently deduced from actuator position
  – Linkage slop and bending could introduce significant and unknown errors

• Inertia swings
  – Aircraft inertia directly correlated to moment parameters
  – Parameter estimation only as accurate as the aircraft inertia
    • Roll/yaw coupling could have higher error
      – Trade between kinematics and aerodynamics
Future Efforts

• X-48C wind tunnel testing
  – Increments to aero table
• X-48B limiter assaults
• NASA DFRC research flights
  – Parameter estimation
    • Continue method development
      – Super maneuvers, multisines
    • Investigate non-linear control surface effectiveness
      – Effect of surface deflection and influence of adjacent surfaces
  – Intelligent control
    • Definition of necessary hardware upgrades for flight testing
• Research Opportunities
  – Tufting to investigate boundary layer
  – Improved control allocation
    • Reduced actuator requirements
      – Large potential for reduction in aircraft weight