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
• Flight Status
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  – Intelligent Flight Control and Optimization
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    • Background
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    • Approach and Methods
    • Preliminary Results
    • Future Research and Improvements

• Future Efforts
### NASA Subsonic Transport System Level Metrics

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

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

Increasing Risk

Envelope Expansion

Fundamental Aeronautics Program
Subsonic Fixed Wing Project
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

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<th>NASA DFRC Lead</th>
<th>Boeing Lead</th>
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<td>Turbofan Development</td>
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<td>Envelope Expansion</td>
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<td>Intelligent Flight Control and Optimization</td>
<td>Increments to Aero Model (Parameter Estimation)</td>
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<td>Airdata Calibration Method Development</td>
<td>Dynamic Departure Limiters</td>
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<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

\[ \begin{bmatrix} V_a \\ V_{w \cdot \cos(X_w)} \\ V_{w \cdot \sin(X_w)} \end{bmatrix} = \left( H^T \cdot H \right)^{-1} \cdot H^T \begin{bmatrix} V_{g_n} \\ \vdots \\ V_{g_{n+1}} \\ \vdots \\ V_{g_{n+k}} \end{bmatrix} = \Theta \]

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

\[ C_m = C_{m_0} + C_{m_\alpha} \alpha + C_{m_q} \frac{q_c}{2V} + C_{m_{\delta_1}} \delta_1 + C_{m_{\delta_2}} \delta_2 + \ldots \]
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 Reynold’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:**
- Finite Differences on Aero Model
  - True Parameter Value
- Open Loop System + Controller
- Parameter Estimation from Input and Response
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

Output Error Closed Loop Super Maneuver Time History Response

![Graph showing pitch rate over time with measured and computed data]

![Scatter plot comparing Cm percent error from aero model]
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

Output Error Flight Super Maneuver Time History Response

![Graph showing time history response with measured and computed data](image)

![Scatter plot showing Cm percent difference from aero model](image)
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

- Graph showing roll rate (deg/s) over time (sec)
- Graph showing percentage difference from the model
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