X-48B Preliminary Flight Test Results

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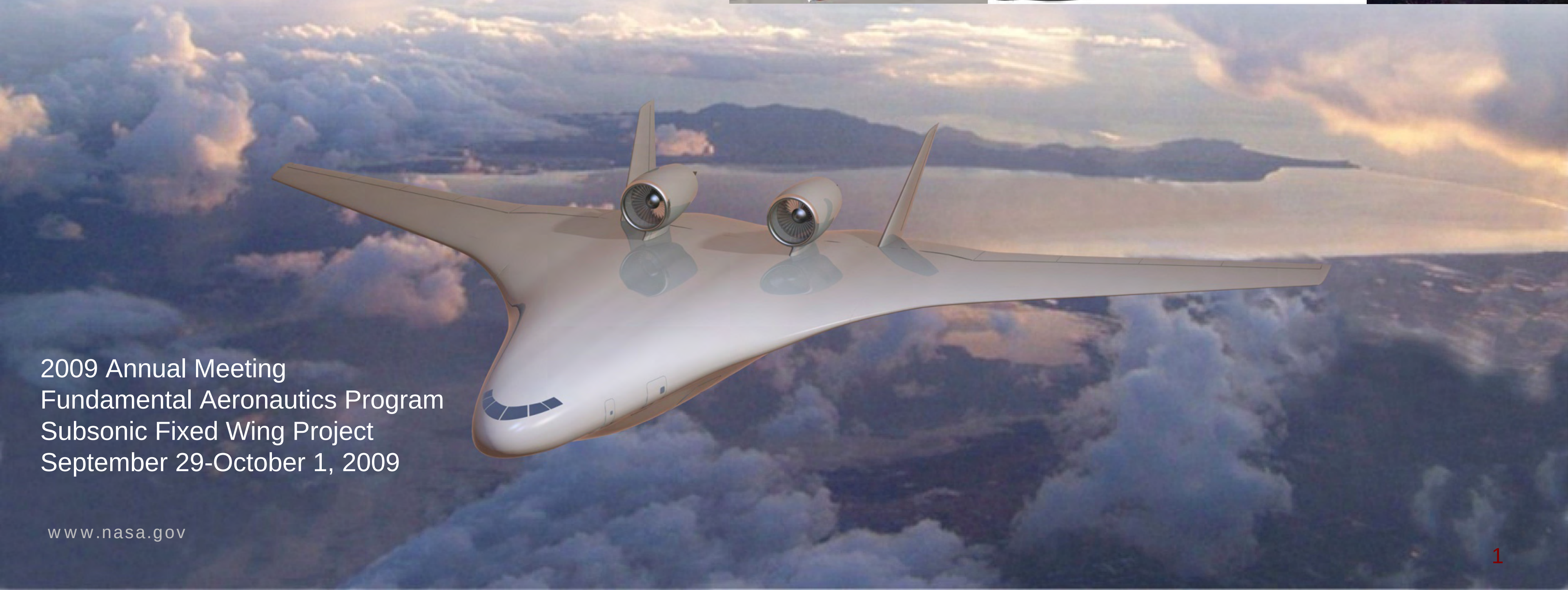

2009 Annual Meeting
Fundamental Aeronautics Program
Subsonic Fixed Wing Project
September 29-October 1, 2009

Outline

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- Flight Research Program Approach
- Flight Status
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  - Intelligent Flight Control and Optimization
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NASA Subsonic Transport System Level Metrics

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

CORNERS OF THE TRADE SPACE	N+1 (2015)*** Technology Benefits Relative to a Single Aisle Reference Configuration	N+2 (2020)*** Technology Benefits Relative to a Large Twin Aisle Reference Configuration	N+3 (2025)*** Technology Benefits
Noise (cum below Stage 4)	- 32 dB	- 42 dB	- 71 dB
LTO NOx Emissions (below CAEP 6)	-60%	-75%	better than -75%
Performance: Aircraft Fuel Burn	-33%**	-40%**	better than -70%
Performance: Field Length	-33%	-50%	exploit metroplex* concepts

*** 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

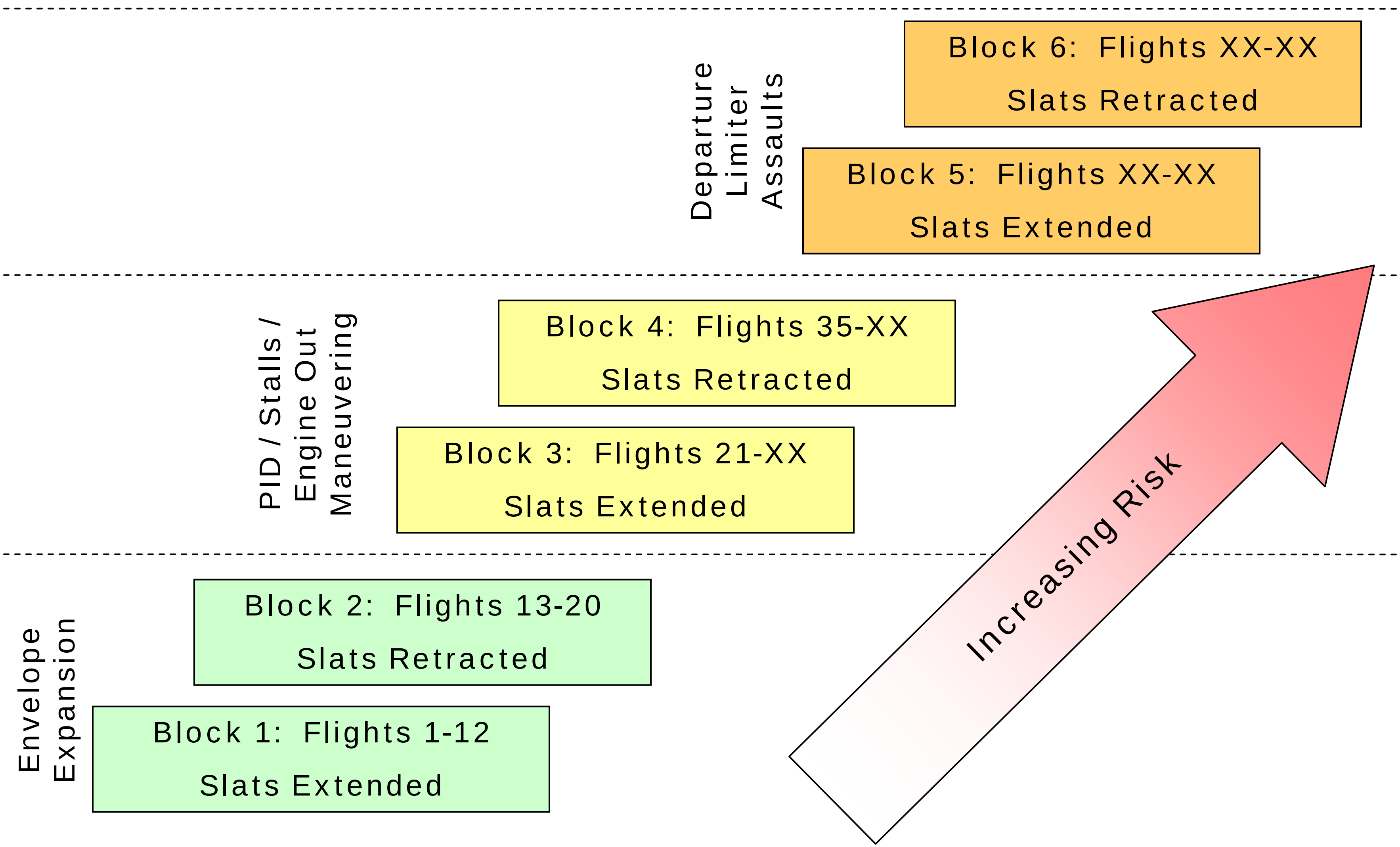
- Reduce Uncertainty in Multi-Disciplinary Design and Analysis Tools and Processes

- 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



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

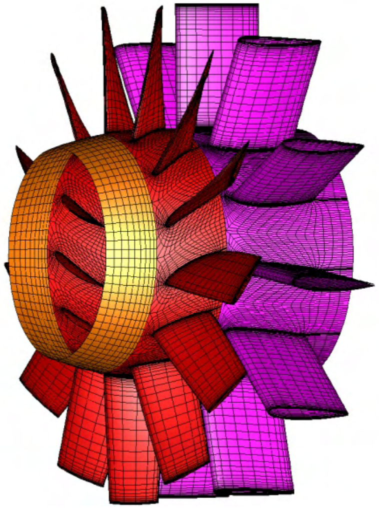
Research Leads

NASA DFRC Lead	Boeing Lead
Real-Time Stability Monitoring	Turbofan Development
Adaptive Flight Control	Envelope Expansion
Intelligent Flight Control and Optimization	Increments to Aero Model (Parameter Estimation)
Airdata Calibration Method Development	Dynamic Departure Limiters
Parameter Estimation Method Development	Stall Characterization

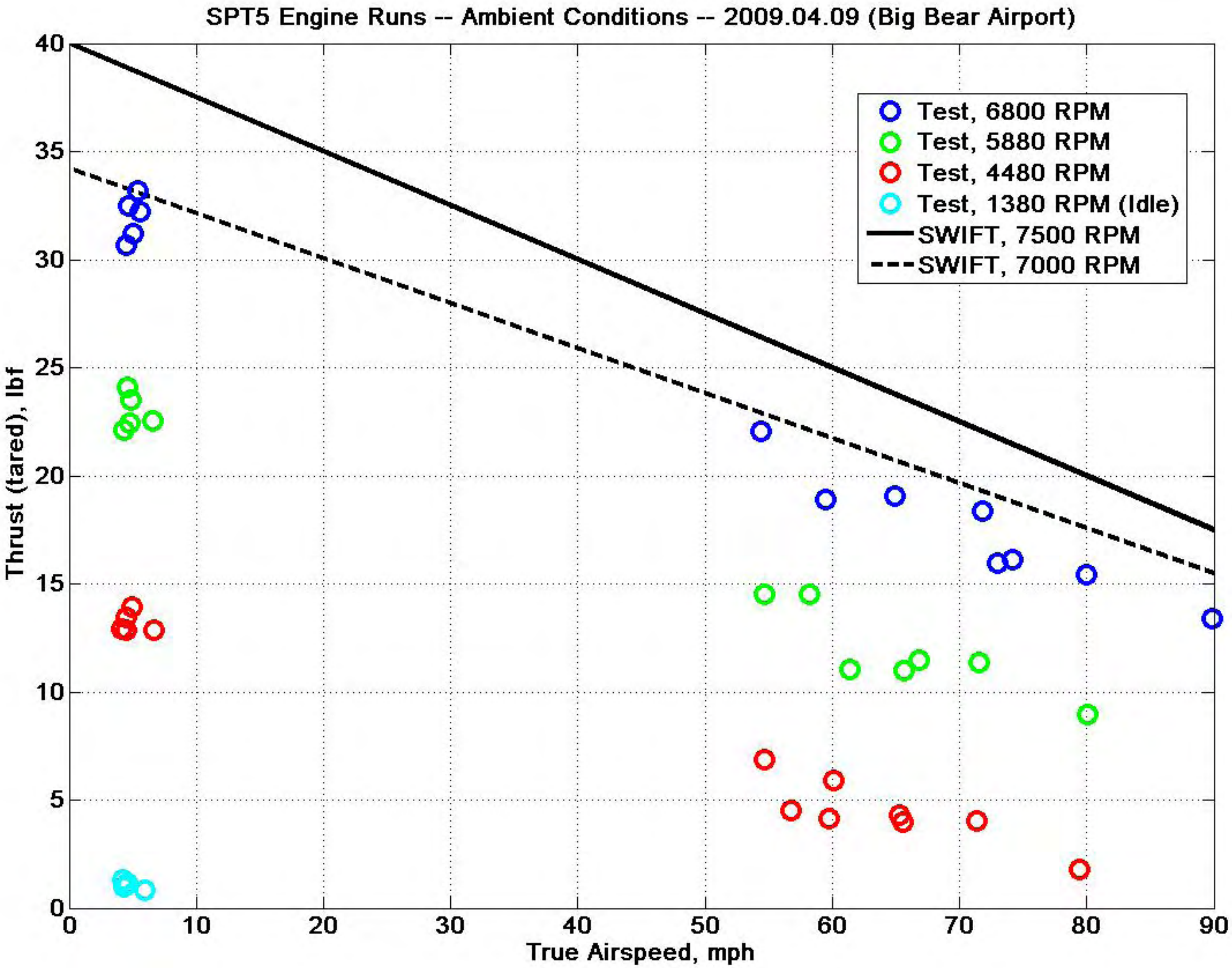
Included in presentation

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



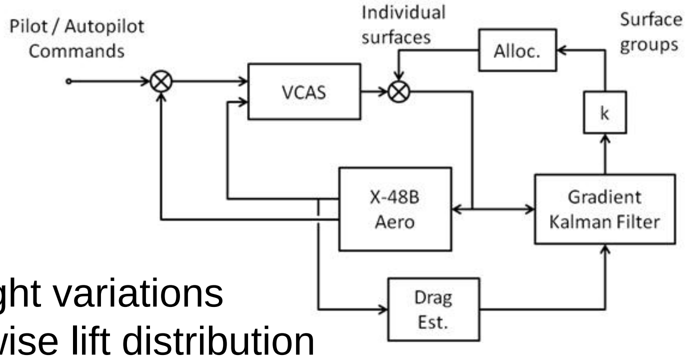
Turbofan Development



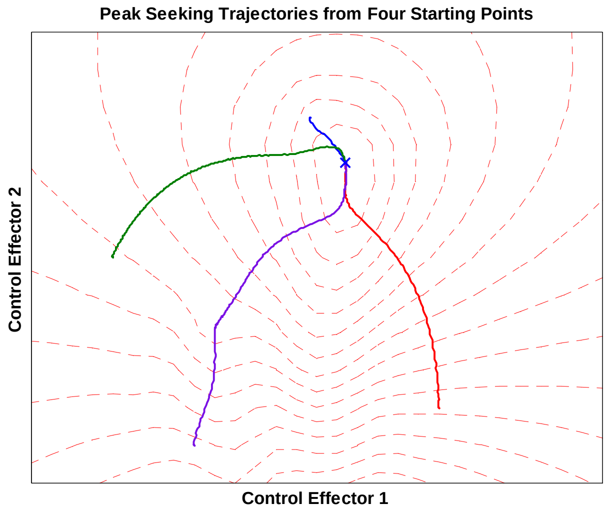
CFD analysis courtesy of Rod Chima, NASA GRC

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



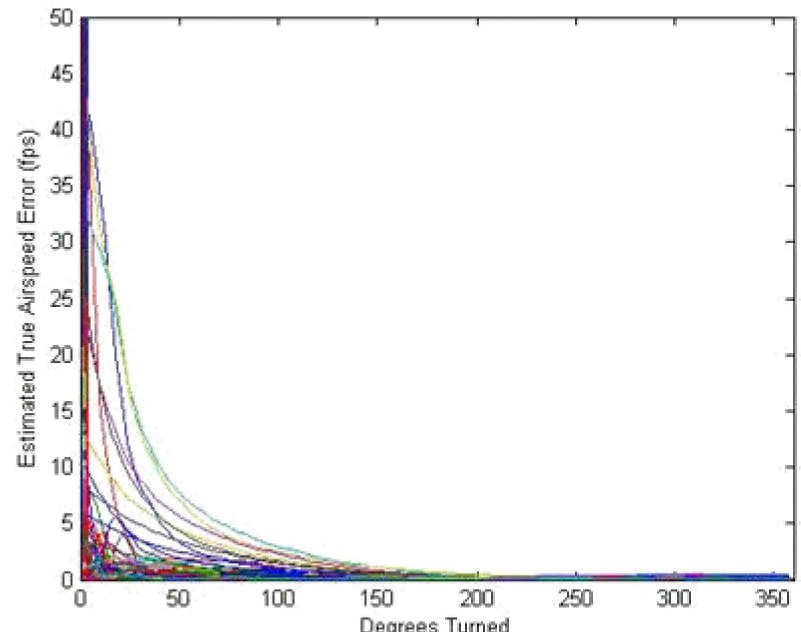
- Status
  - X-48B aero database shows potential for ~5% drag reduction
    - Does not accurately model induced drag effects
    - Likely not representative of real world aerodynamics
    - Provides adequate gradient for testing in simulation
  - X-48B simulation
    - Evaluate sensor and computational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

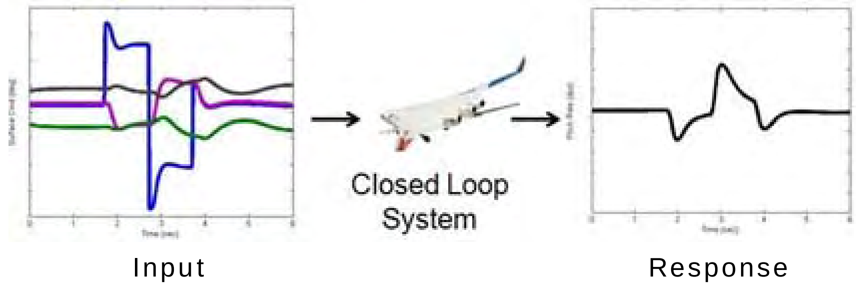
$$\begin{bmatrix} Va \\ VwCos(Xw) \\ VwSin(Xw) \end{bmatrix} = \left(H^T H\right)^{-1} H^T \begin{bmatrix} Vg_{N_1} \\ \vdots \\ Vg_{N_n} \\ Vg_{E_1} \\ \vdots \\ Vg_{E_n} \end{bmatrix} = \Theta$$

$$H = \begin{bmatrix} Cos(\gamma)Cos(\psi)_1 & 1 & 0 \\ \vdots & \vdots & \vdots \\ Cos(\gamma)Cos(\psi)_n & 1 & 0 \\ Cos(\gamma)Sin(\psi)_1 & 0 & 1 \\ \vdots & \vdots & \vdots \\ Cos(\gamma)Sin(\psi)_n & 0 & 1 \end{bmatrix}$$



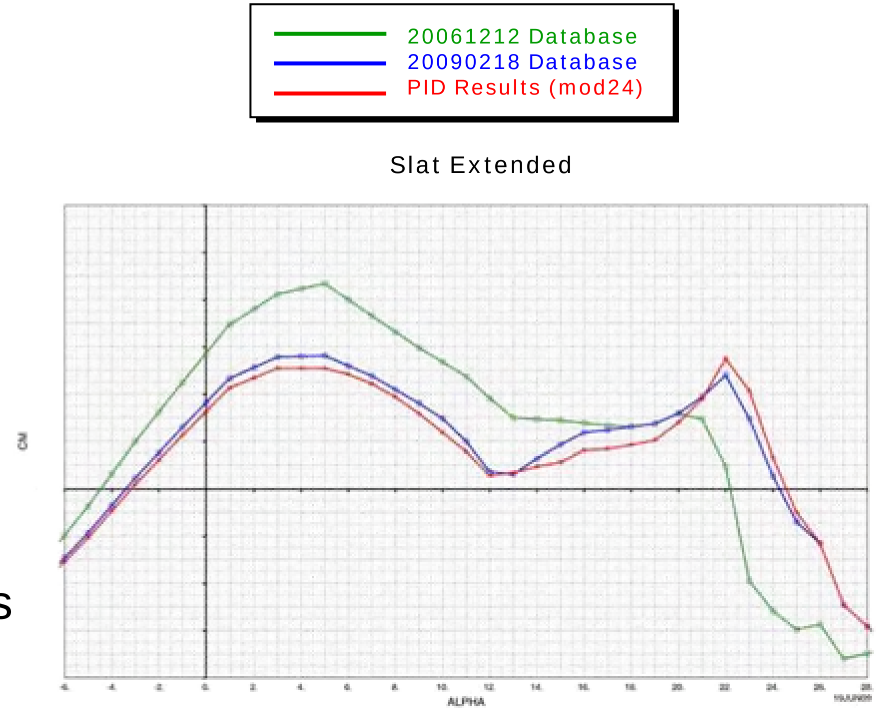
Parameter Identification Background

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

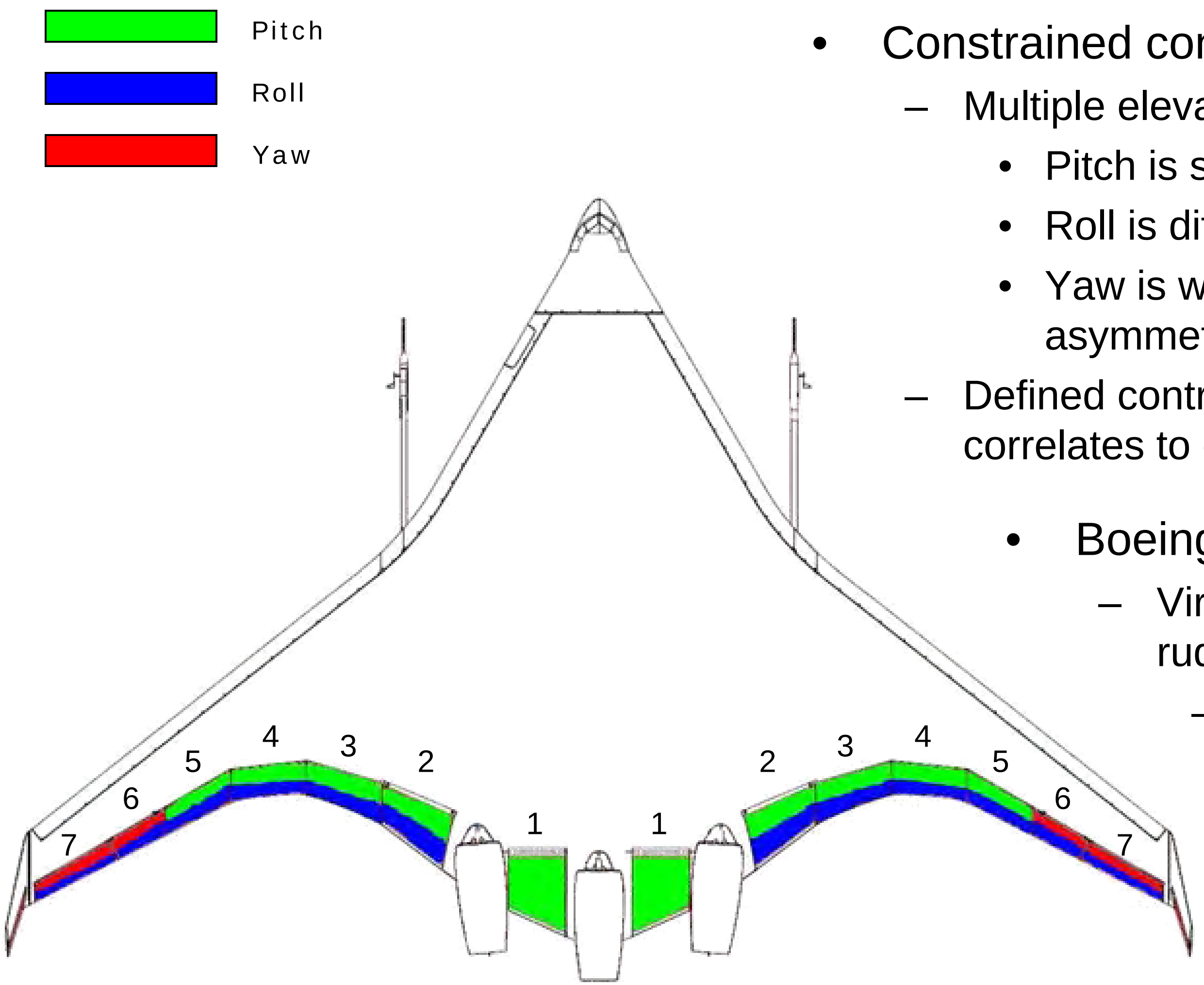
- Validation of parameter identification techniques and methods
  - Tools and methods developed to perform parameter estimation applicable to future vehicles
  - Better flight testing techniques to improve parameter estimation

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



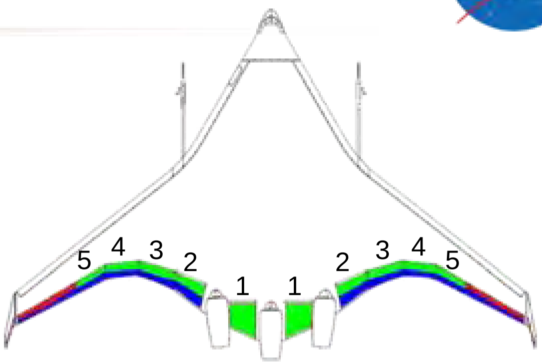
- Constrained control effectiveness
  - Multiple elevators, ailerons, and rudders
    - Pitch is symmetric movement
    - Roll is differential movement
    - Yaw is winglet rudder movement or asymmetric clamshell deployment
  - Defined control surface movement correlates to control allocation architecture

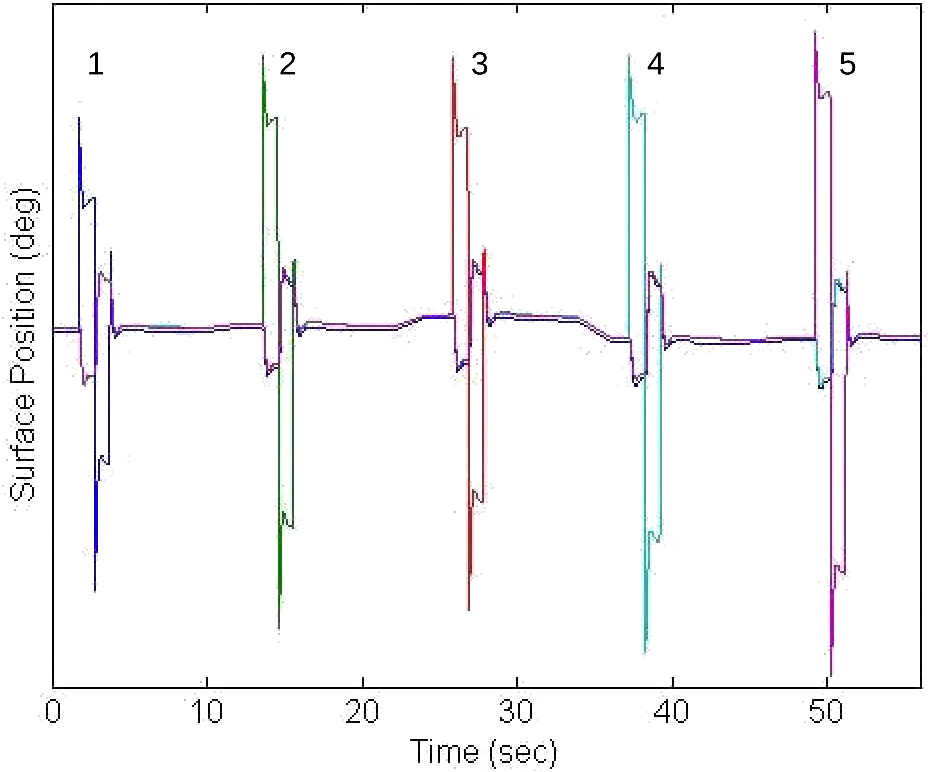
- Boeing gangs control surfaces
  - Virtual elevator, aileron, and rudder
    - Surfaces 1, 2-5, 6, 7, and rudders

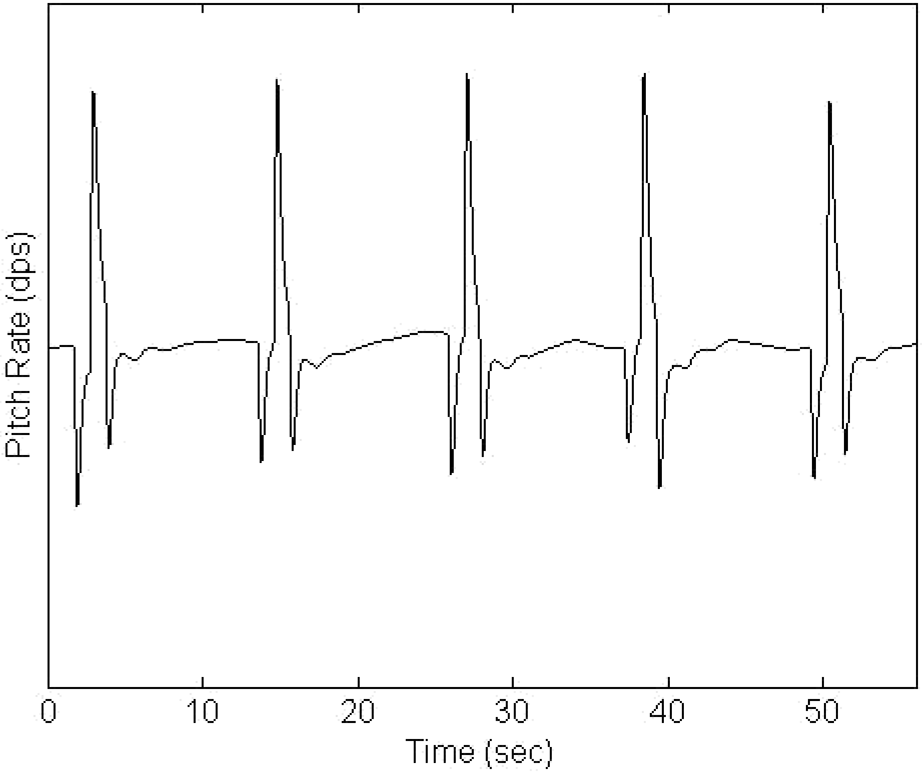
Treating Identifiability – Super Maneuvers

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

$$Cm = Cm_0 + Cm_\alpha \alpha + Cm_q \frac{qc}{2V} + Cm_{\delta e1}\delta e1 + Cm_{\delta e2}\delta e2 + \ldots$$

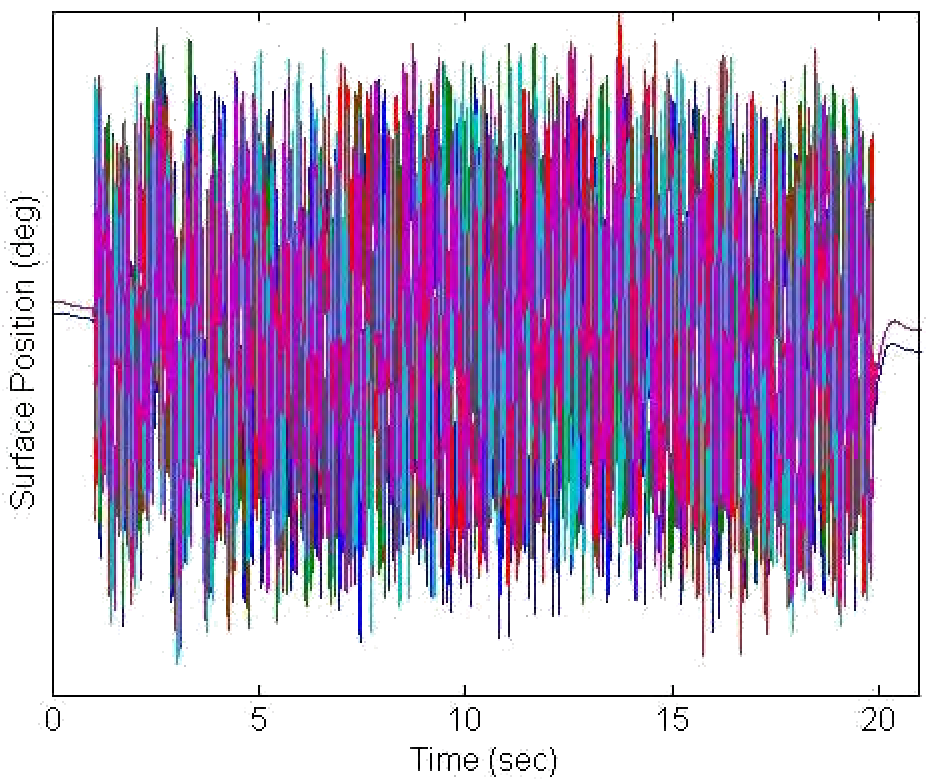


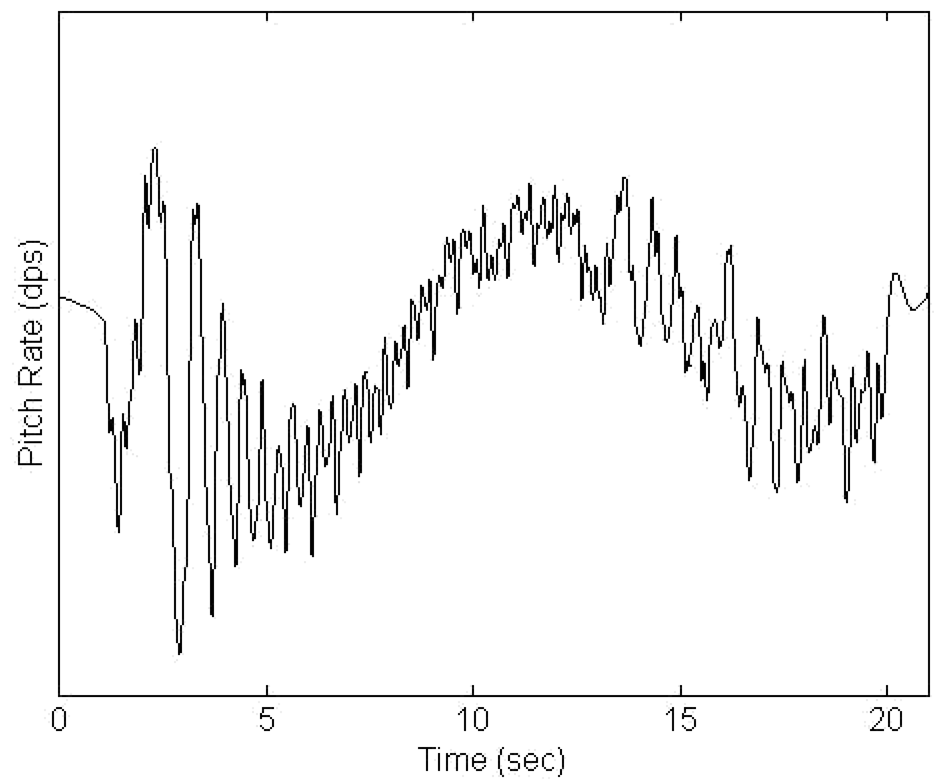




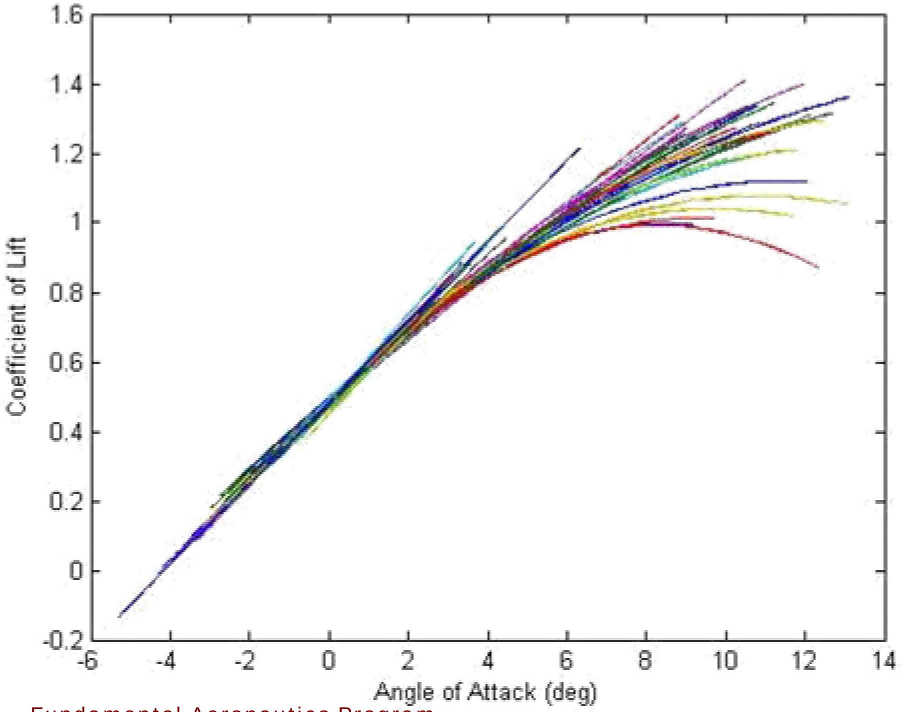
Treating Identifiability – Multisines

- Multisines
  - Excitation of surfaces simultaneously at different frequencies
  - Combinations for symmetric, anti-symmetric, clamshell, and fully independent





Method Validation with TG-14A



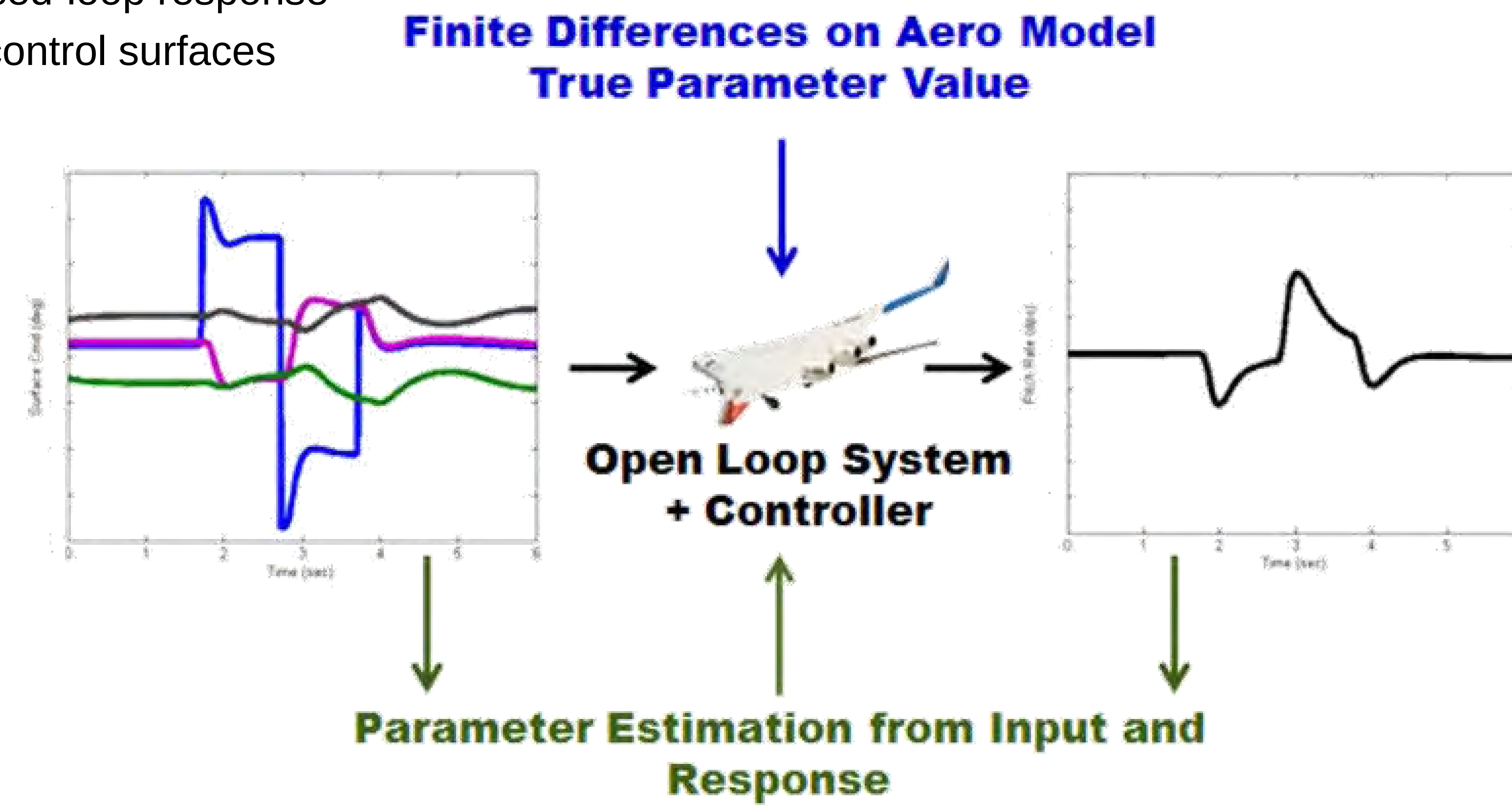
- TG-14A parameter estimation
  - Low wing loading at low Reynold's number
  - Airdata in significant local flow
  - Open-loop response
  - Traditional control surfaces

- Flight data
  - Hand flown doublets
  - Airspeed: 60 – 80 knots
- CLα
  - Analytic: 0.1097
  - Estimated: 0.1025

- Verified output error technique for low Reynolds number, low wing loading aircraft

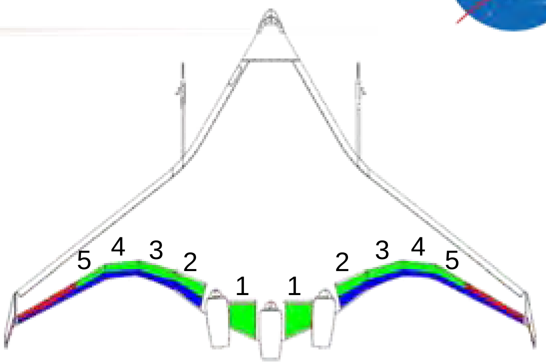
Method Validation with Simulation

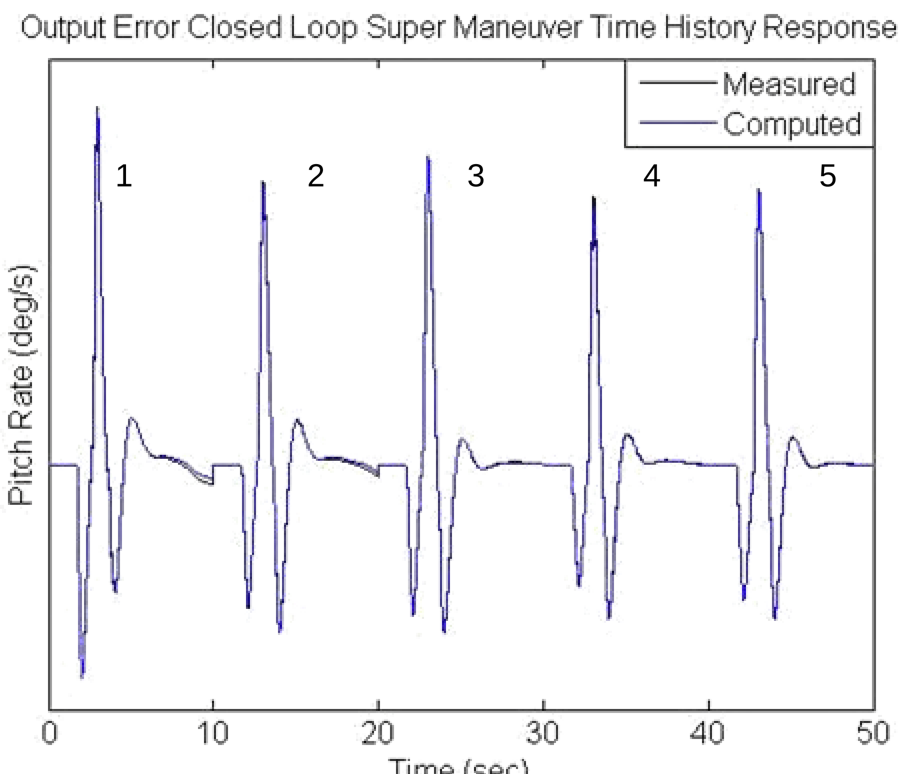
- X-48B simulation
  - Known environment
    - Airdata and turbulence models
  - Closed-loop response
  - 20 control surfaces

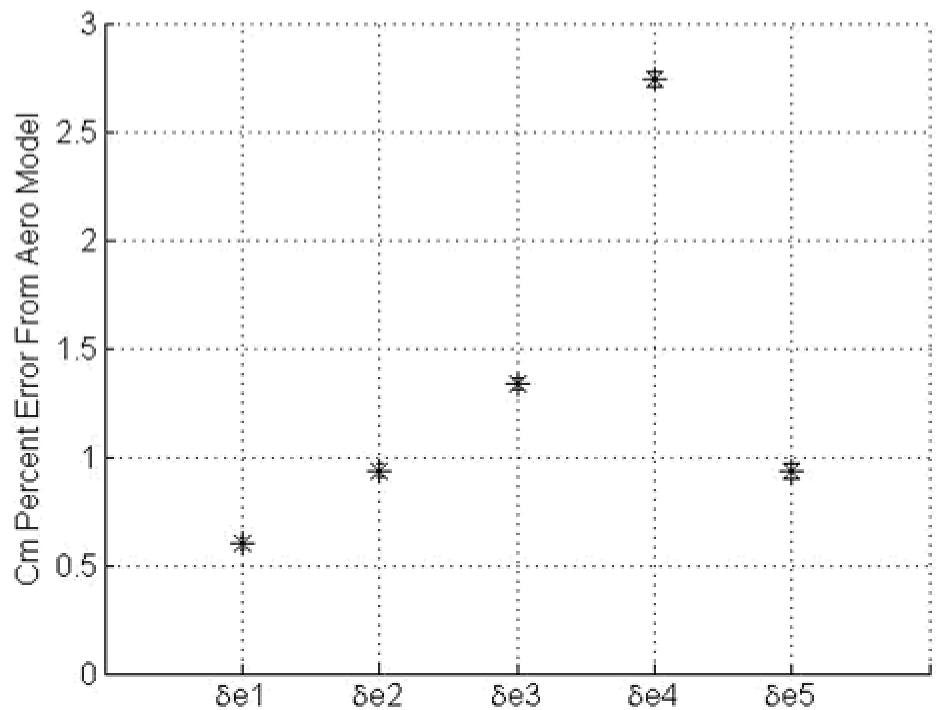


Method Validation with Simulation Results

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

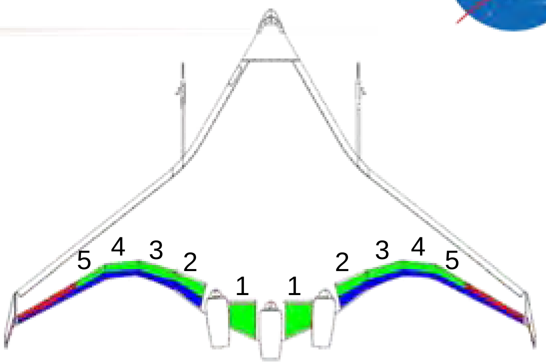


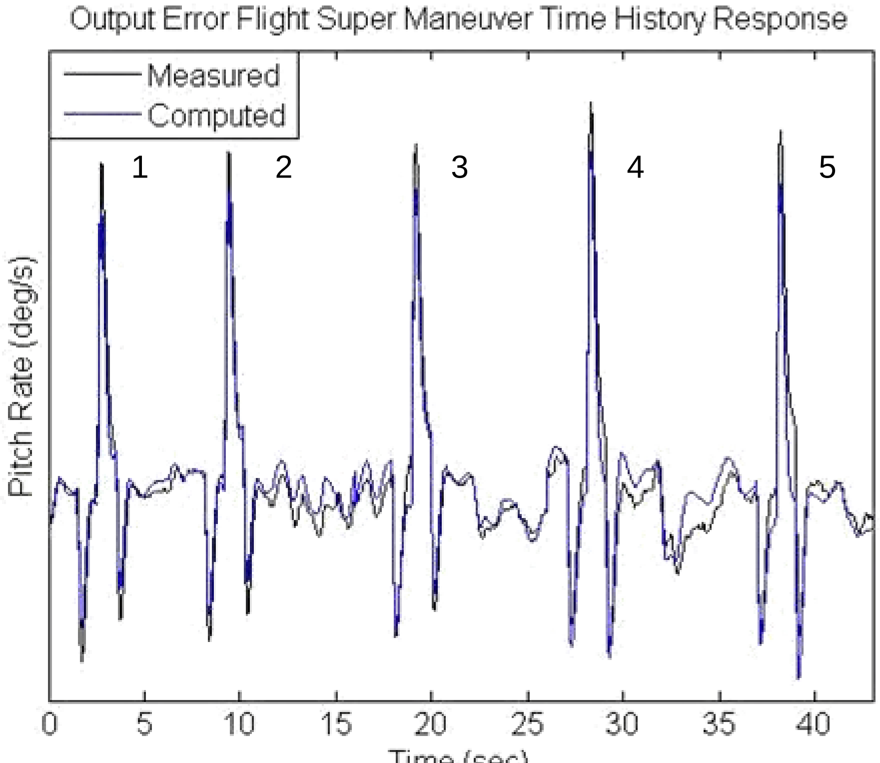


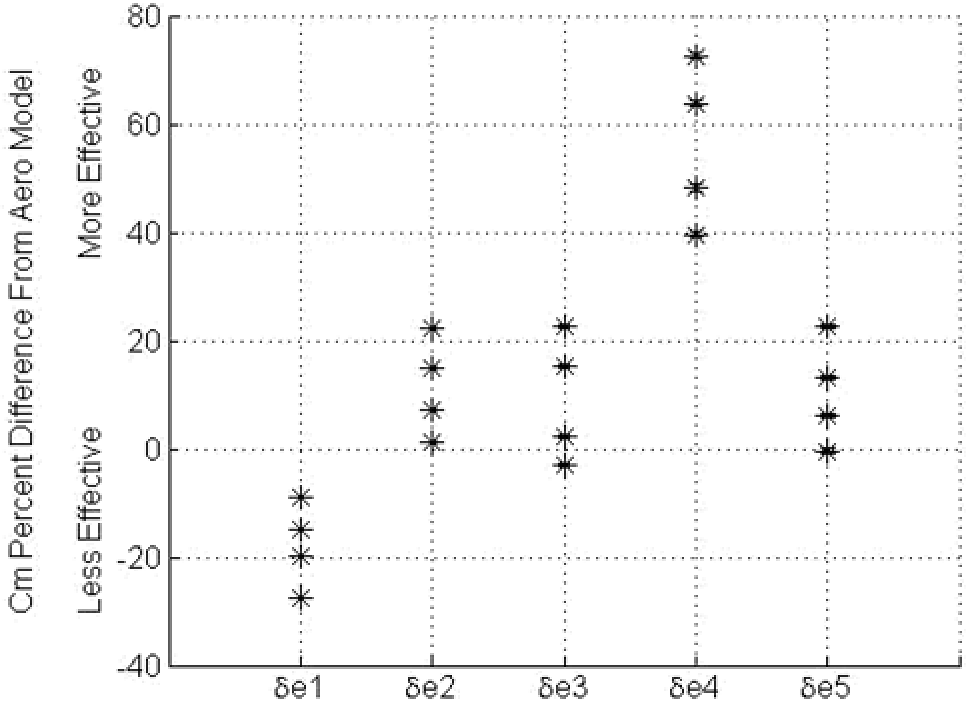


Preliminary Flight Results

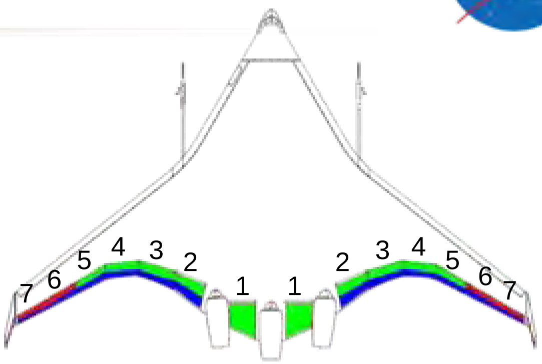
- Surface pair symmetric doublets
  - Data collected during 1 flight
  - 10 degrees angle of attack
  - Slats extended, aft CG
  - 5 repeats of each doublet



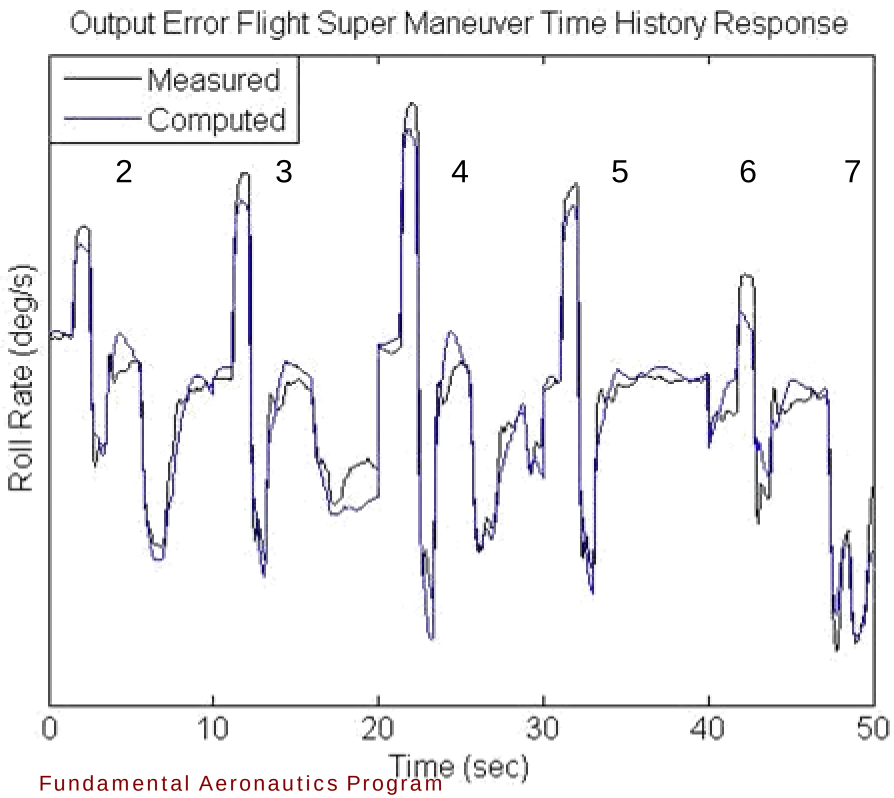


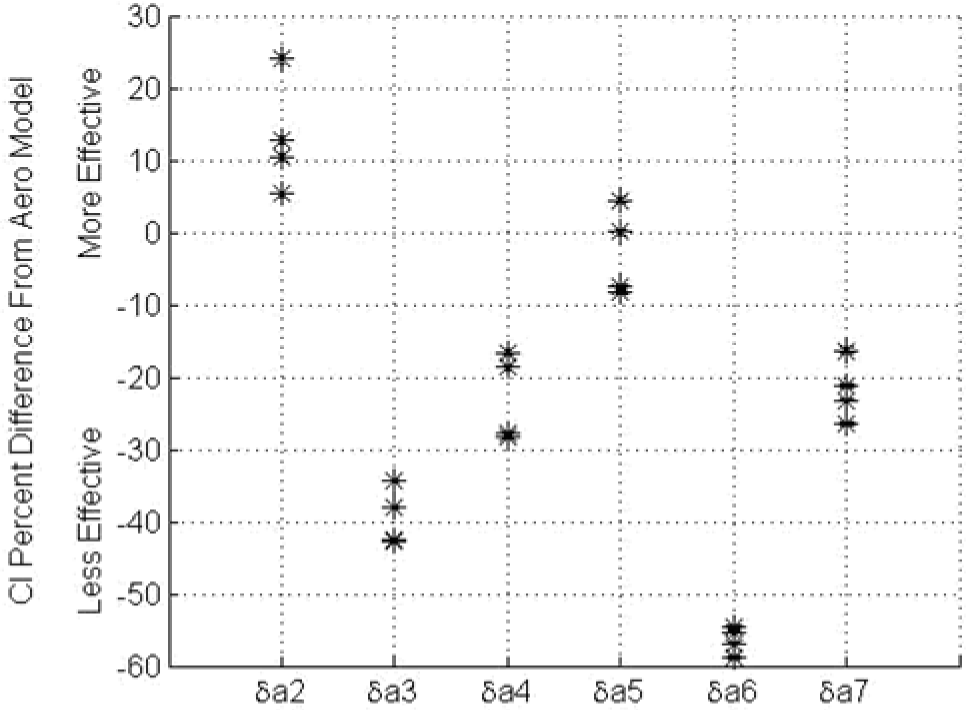


Preliminary Flight Results



- 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





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

NASA