National Aeronautics and Space Administration

Joined-Wing Gust Load Alleviation Wind-Tunnel Tests

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2011 Technical Conference
NASA Fundamental Aeronautics Program
Subsonic Fixed Wing Project
Cleveland, OH, March 15 - 17, 2011

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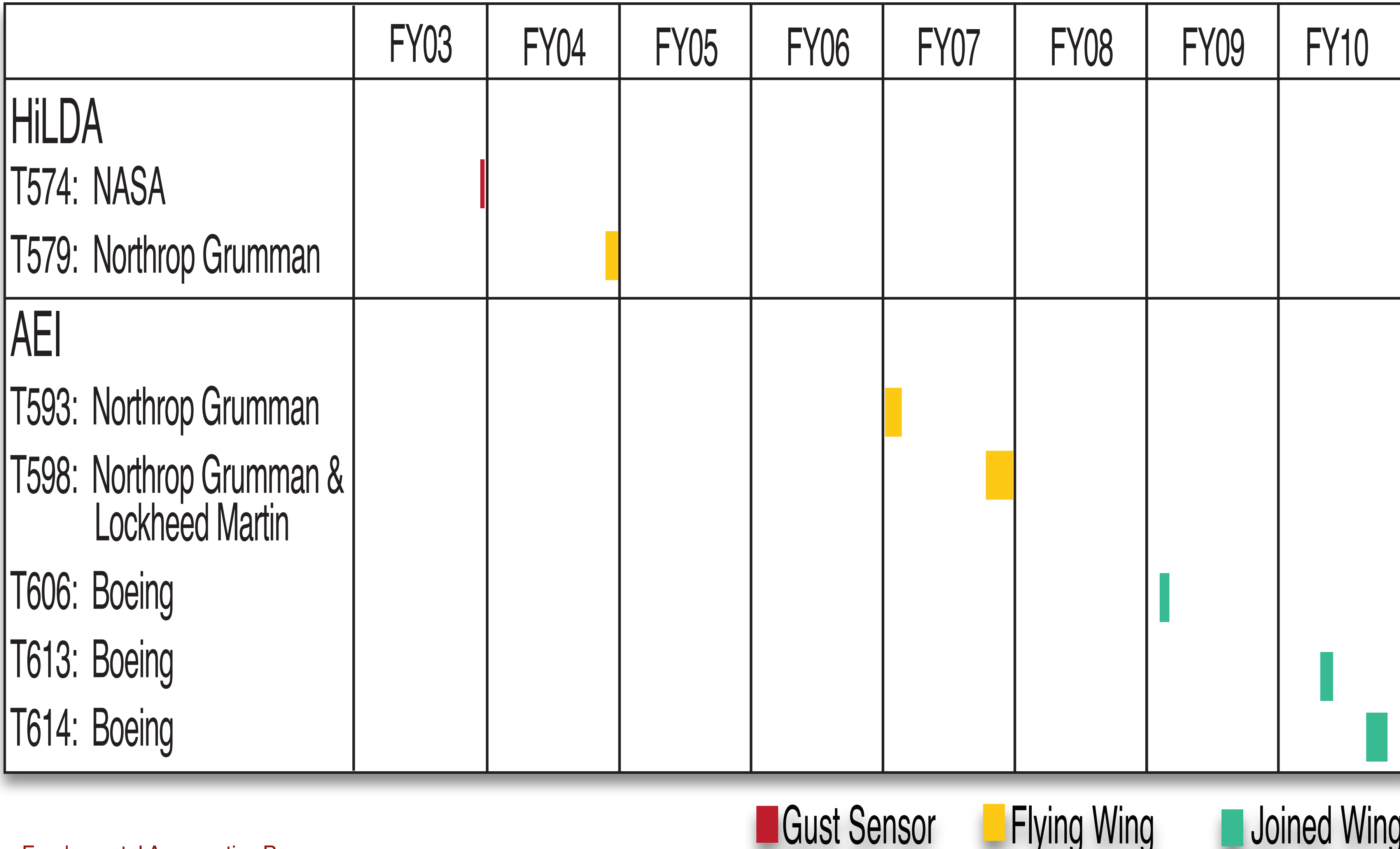
Outline

- SensorCraft TDT Wind-Tunnel Test Summary
- SensorCraft/HALE Technical Challenges
- Test Program Objectives
- TDT and the Airstream Oscillation System
- Flying-Wing Test Summary
- Joined-Wing Tests
  - Model & Support System Description
  - Test Setup
  - Control Systems
  - GLA Results
  - Multisine Parameter ID Results
- Publications
- Concluding Remarks

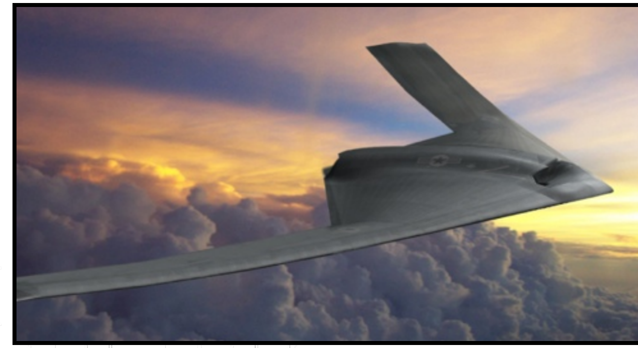
SensorCraft Wind-Tunnel Tests the TDT



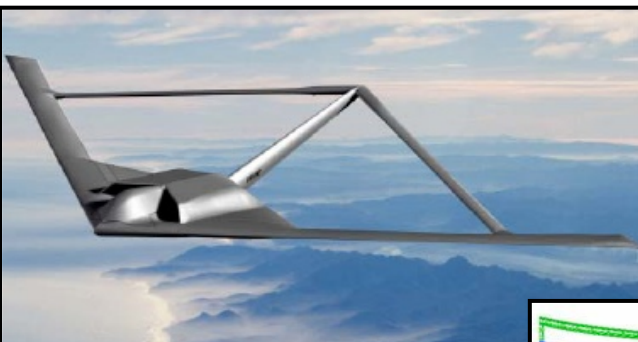
SensorCraft - HALE Vehciles

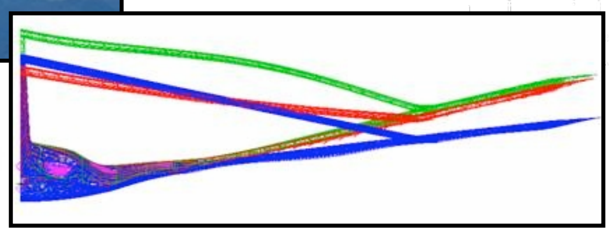
Challenging Persistence Goals and 360 Degree Sensor Field of View Demand:

- *High Aspect Ratio Wings With Embedded Antennas*
- *Inherently Flexible Configurations*
- *Aeroelastic Stability and Gust Loads are Critical Design Issues*

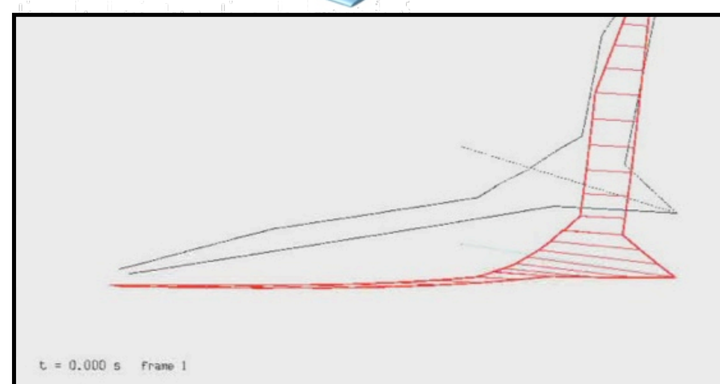


High Aspect Ratio Flying Wings Can Experience Body Freedom Flutter (BFF)





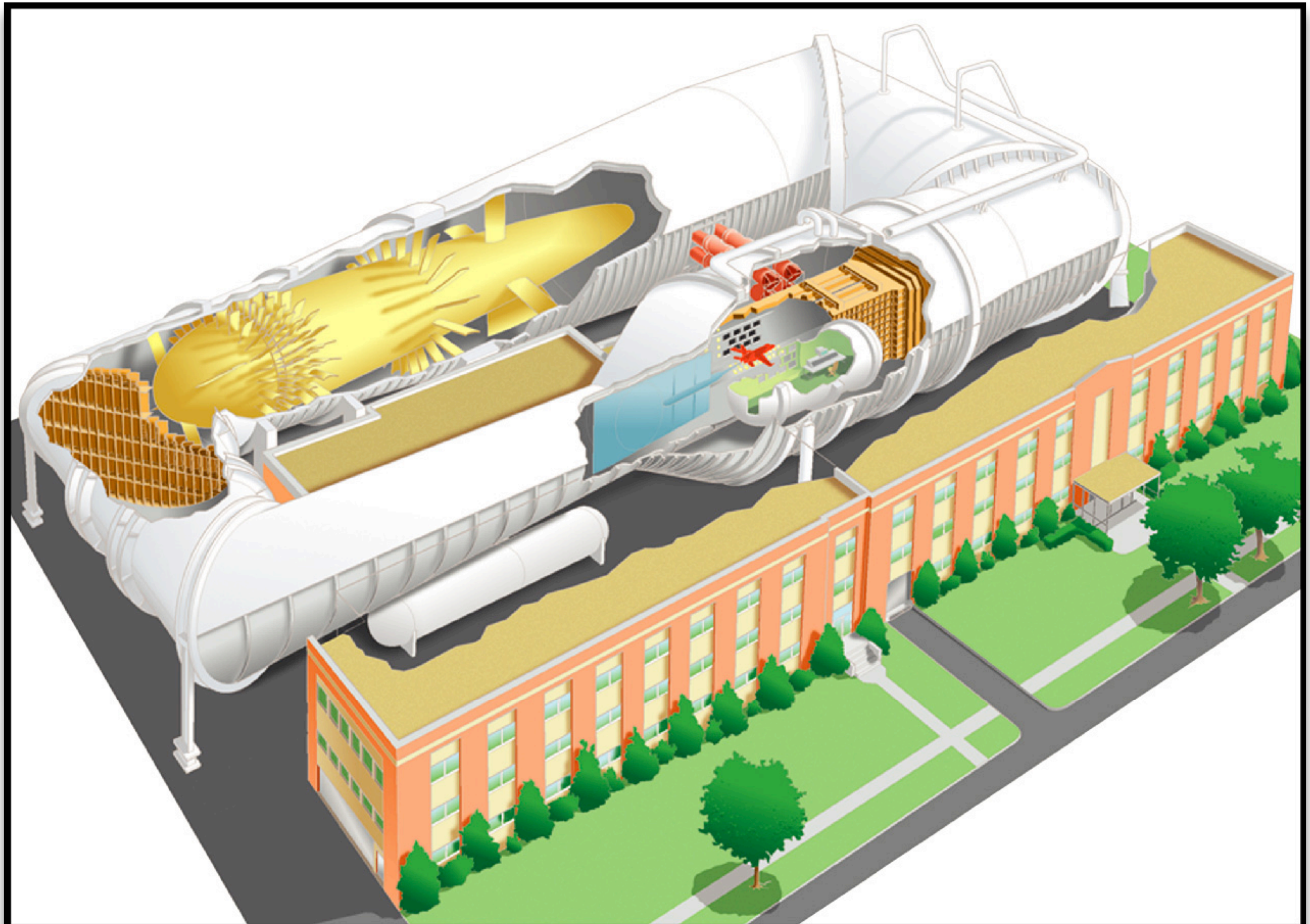
The Joined Wing Configuration Experiences Nonlinear Aeroelastic Deformation



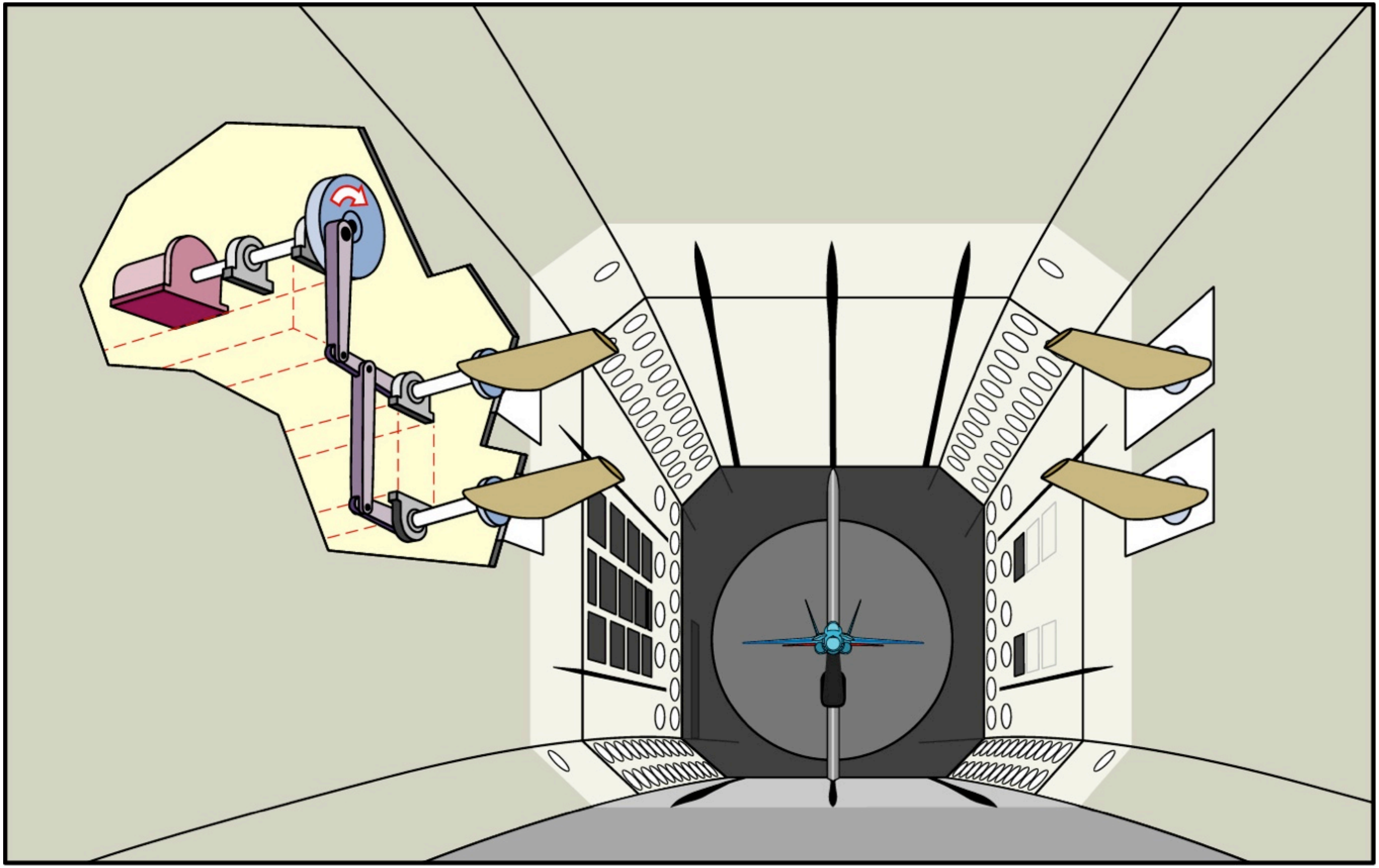
Test Program Objectives

- Demonstrate Enabling Control Technologies HALE Class Vehicles: Joined-Wing SensorCraft
  - Gust Load Alleviation w/ Minimum 6 db of Gain Margin and 30° of Phase Margin
    - Reduction in 1st Flexible Mode Response 50%
    - Reduction in 2nd Flexible Mode Response 20%
  - Reduced Static Margin
    - Stable Flight at -10% MAC
- Wind-Tunnel Test Capabilities
  - Rigid Body Degrees-of-Freedom in Wind Tunnel Environment
    - Sidewall [Flying-Wing SensorCraft] & Tunnel Centerline [Joined-Wing SensorCraft]
  - Enhanced Wind-Tunnel Test Safety
    - WatchDog System
  - Improved System Identification of ASE Systems via Multisine
    - Increased Number of Control Effectors and Frequency Range

Transonic Dynamics Tunnel

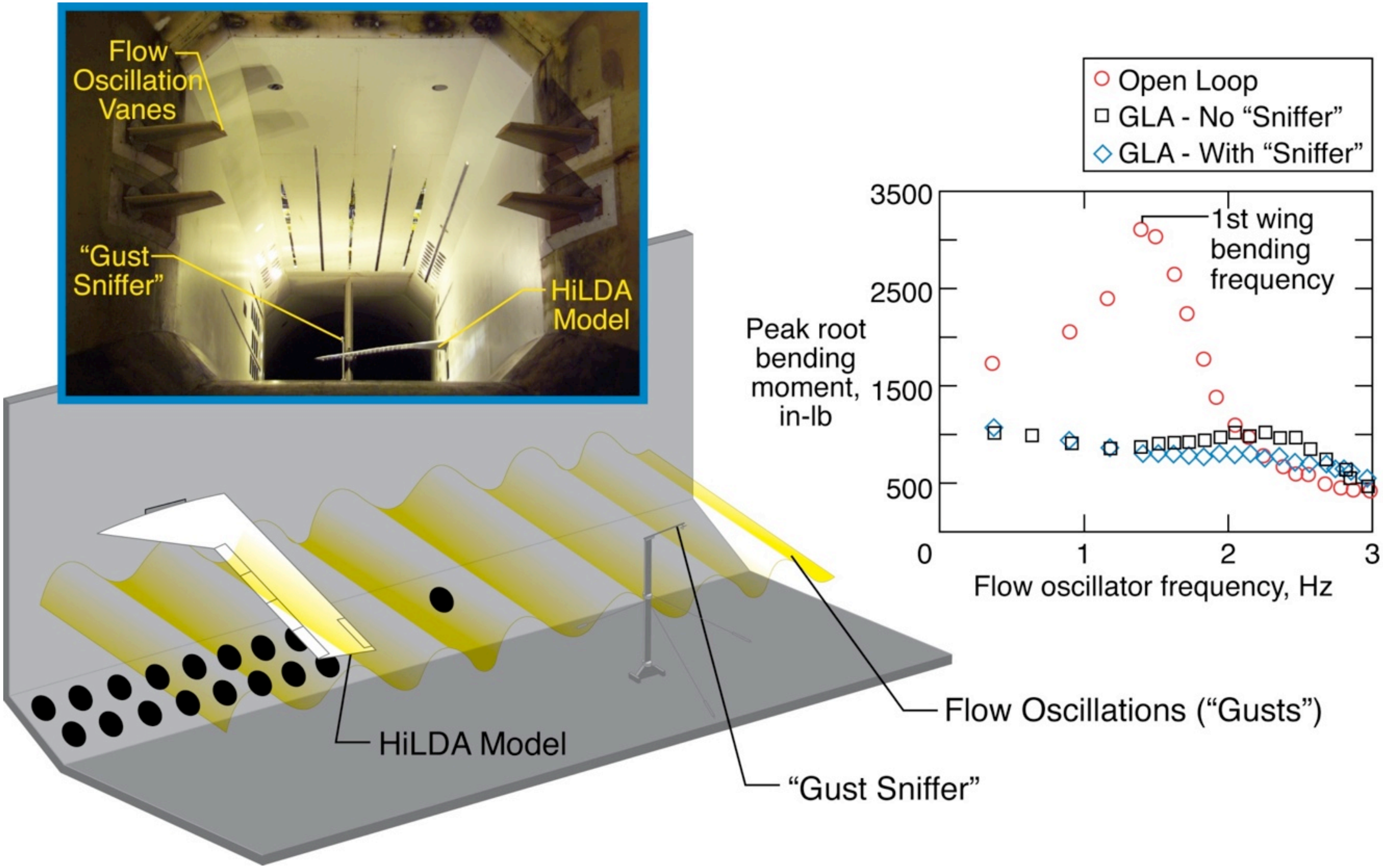


Airstream Oscillating System

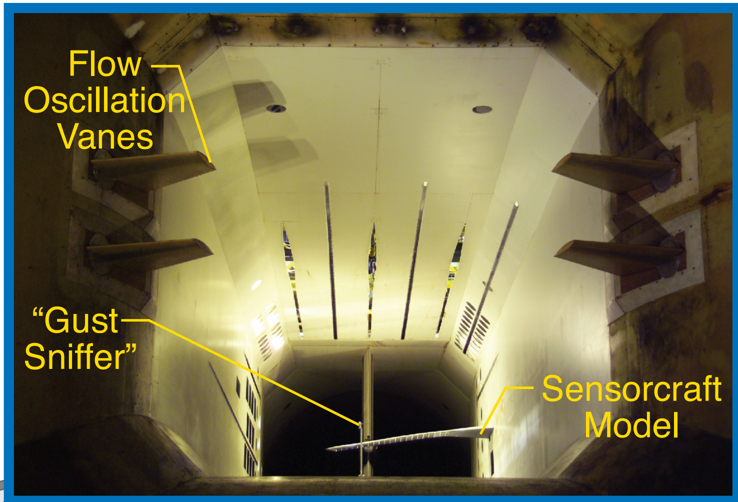


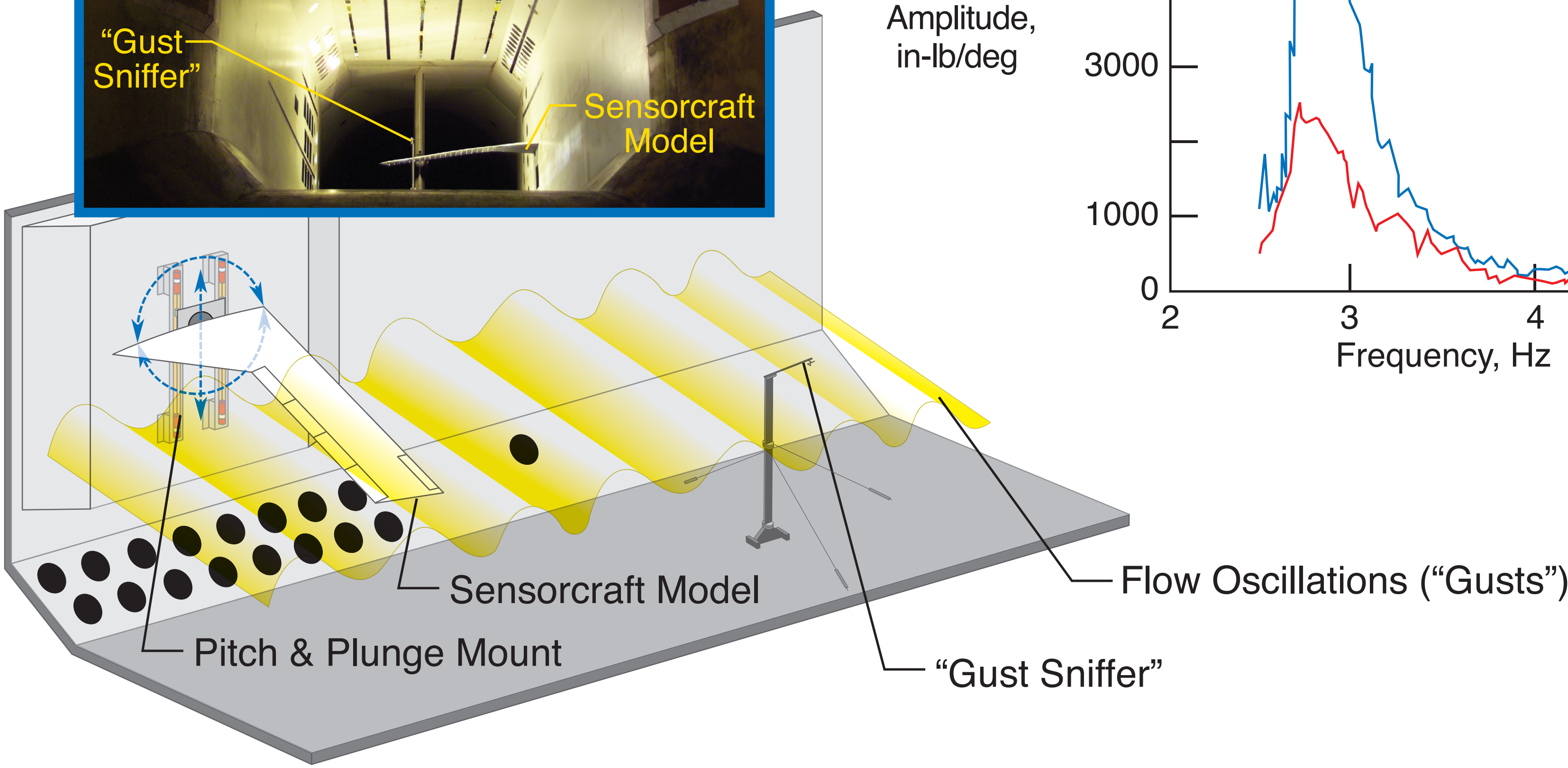
SensorCraft Wind-Tunnel Tests the TDT

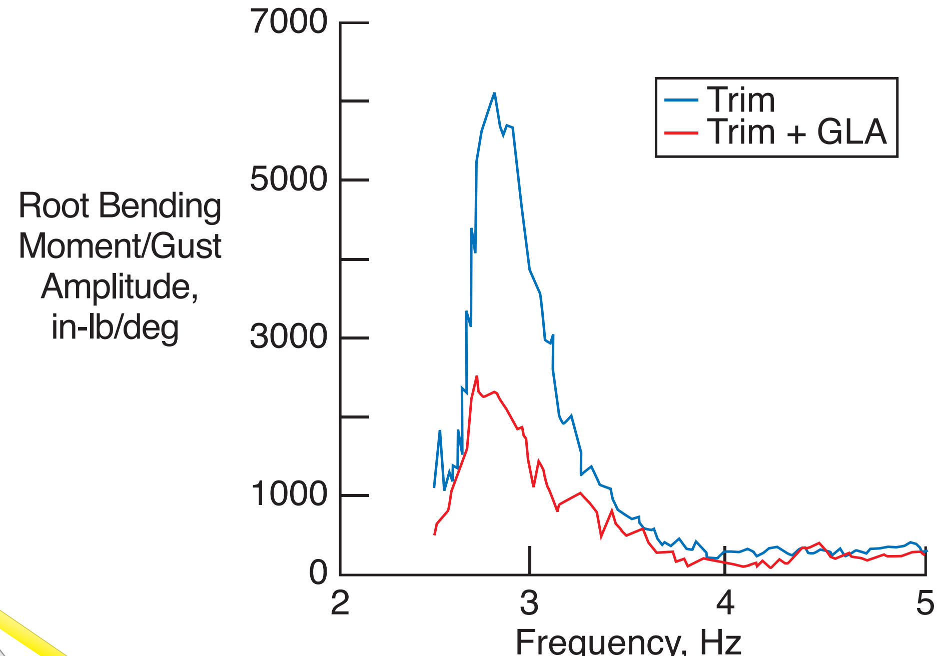
Flying-Wing Model, Cantilevered



Flying-Wing Model, 2 DOF Sidewall Support





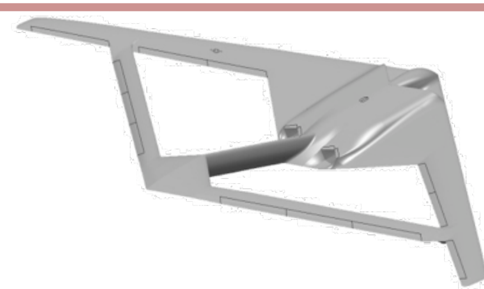


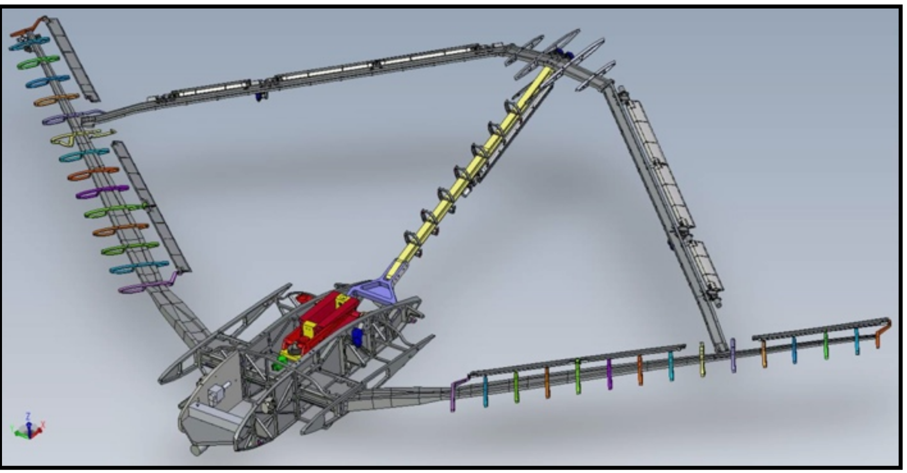
Flying-Wing Model Video

SensorCraft Wind-Tunnel Tests the TDT

Joined-Wing Aeroelastic Wind-Tunnel Model

Full-Scale Design Point:
Mach = 0.3895
Altitude = 5000 ft





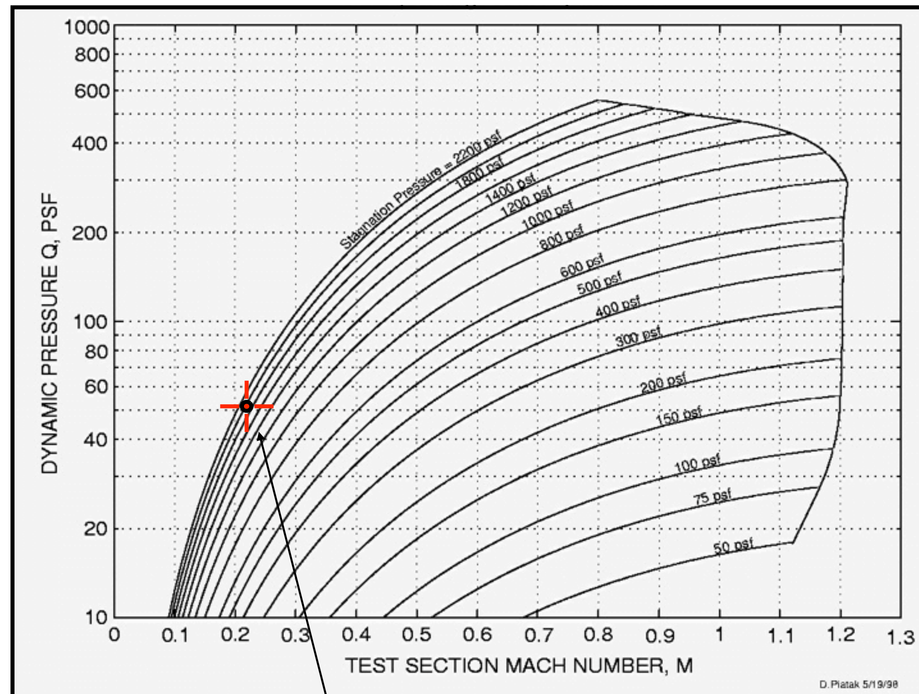
Spar Pod Construction

High Bandwidth Control Surfaces:

12 TE & 1 Rudder

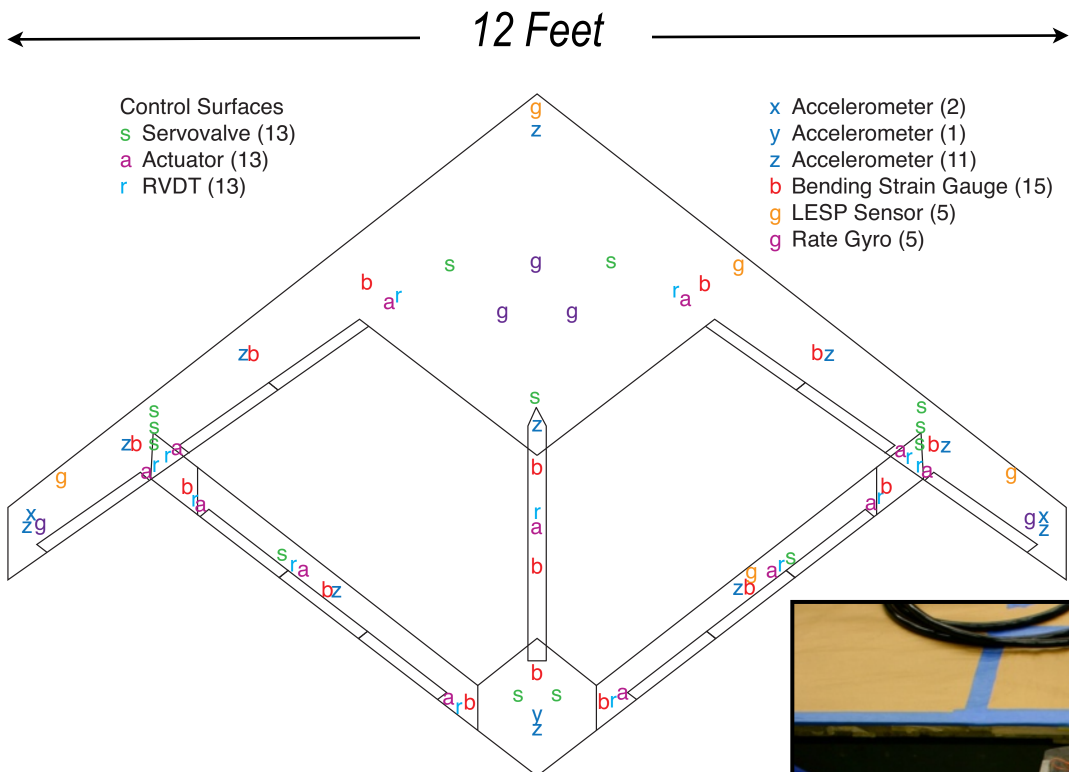
Designed for Sting/Balance & Beam Mounts

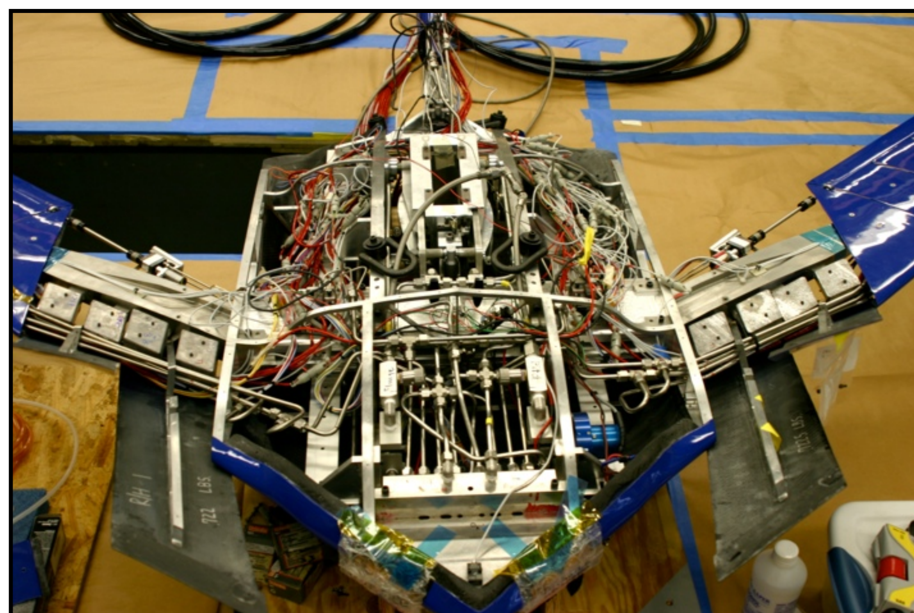
Model Scale Factors:
- Length = 0.08
- Density = 3.4
- Acceleration = 1.0
- Frequency = 3.536



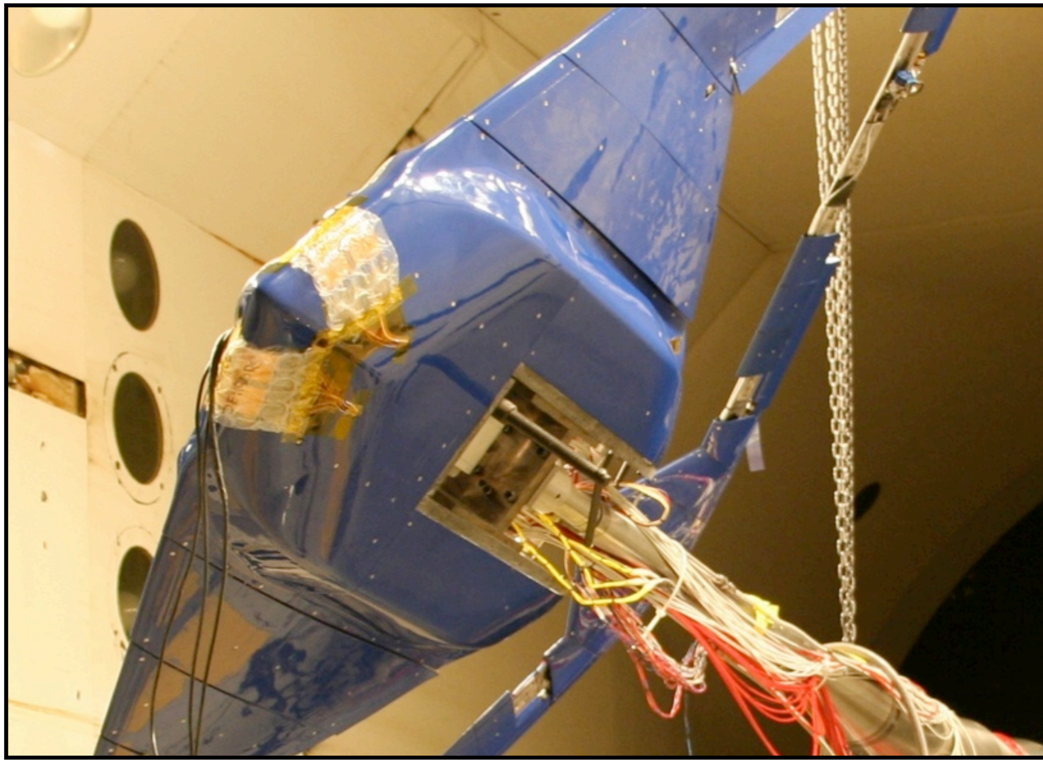
Model Design Point
Gas = R134a
Gross Weight = 243.7 lb
Mach = 0.2240
Q=51 psf

Joined Wing Planform & Internal View



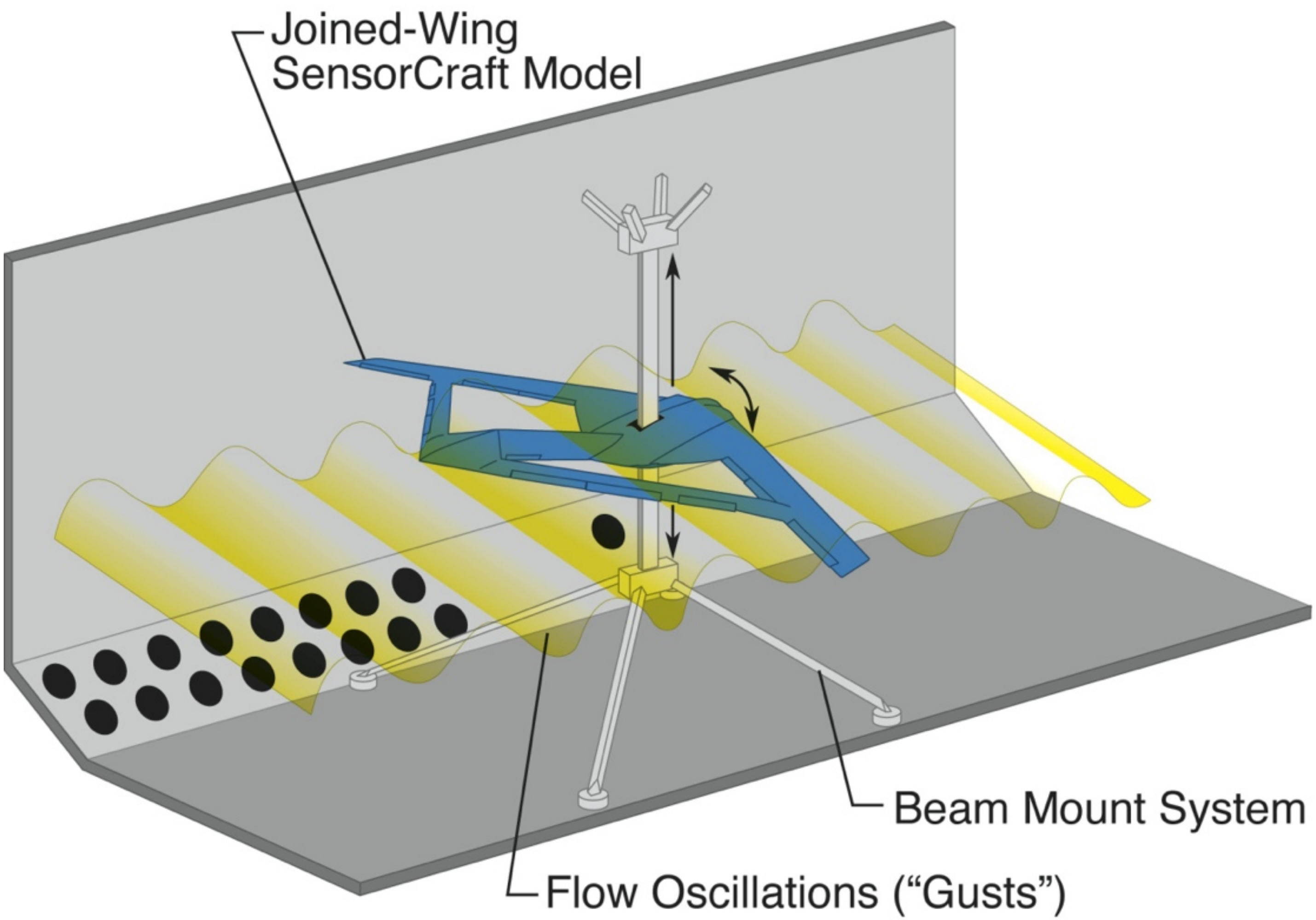


Steady Aerodynamic Testing

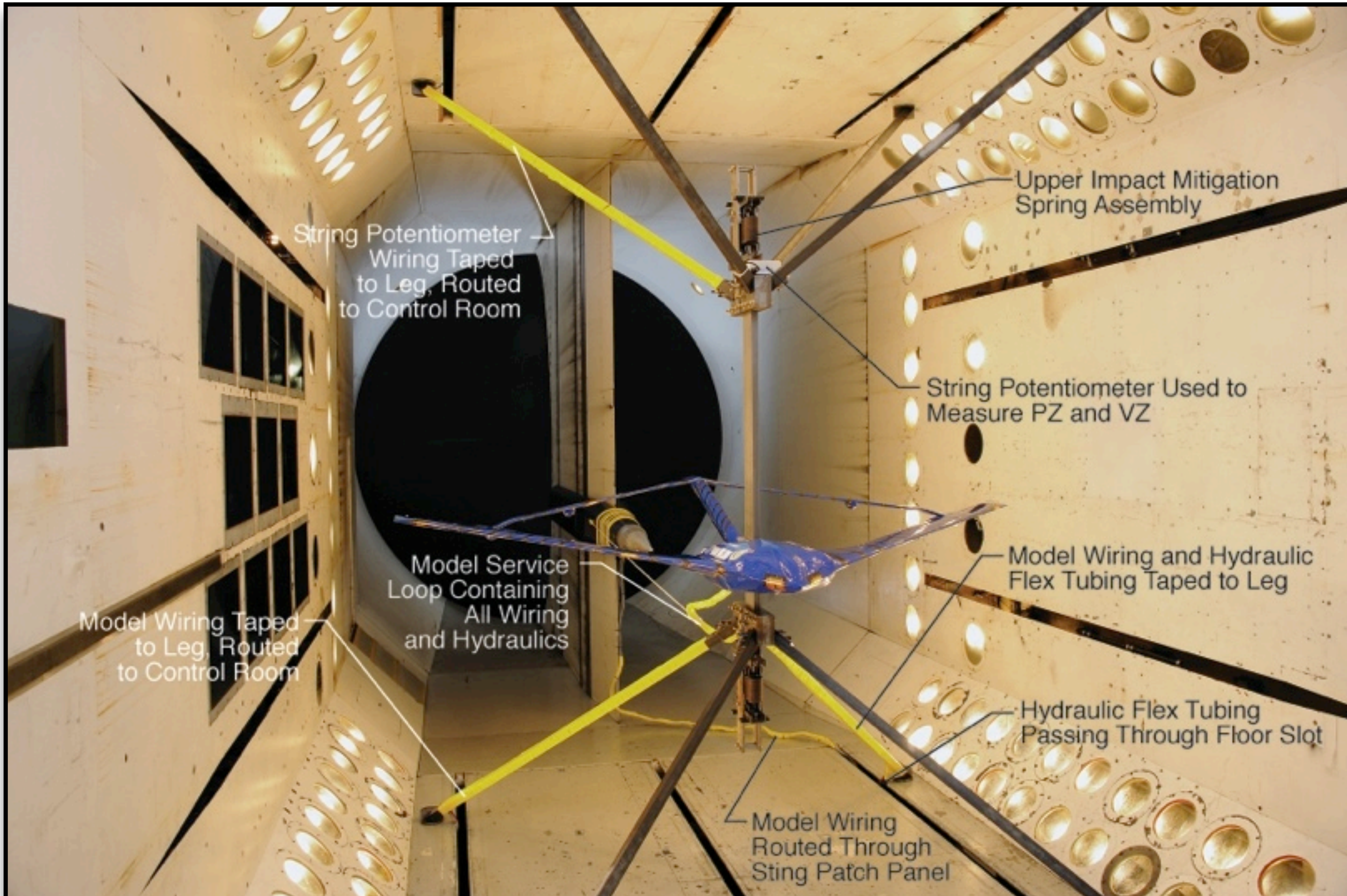


Force/Moment Balance Data:
- *Update Analytical ASE Models*
- *Neutral Point Determination/Verification*

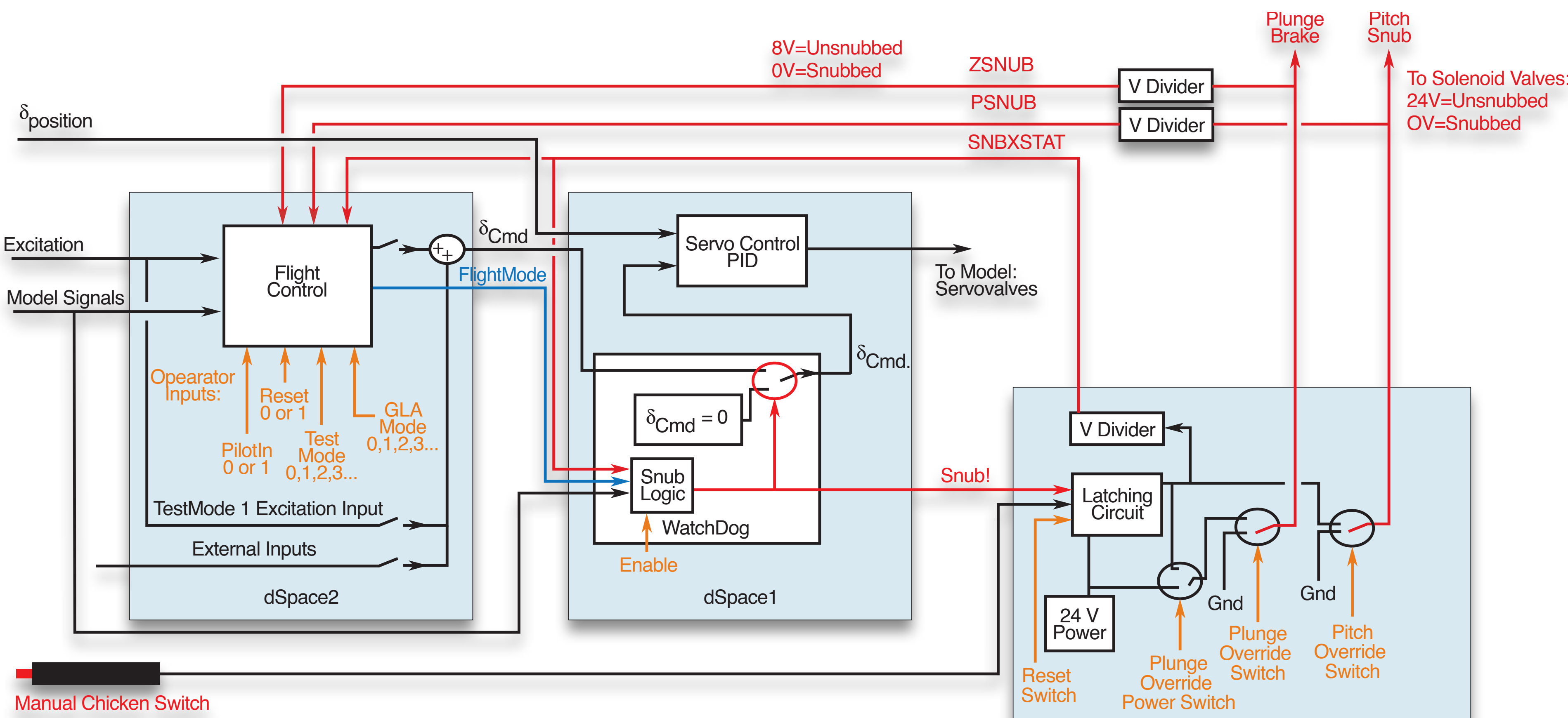
Joined-Wing ASE Wind-Tunnel Model



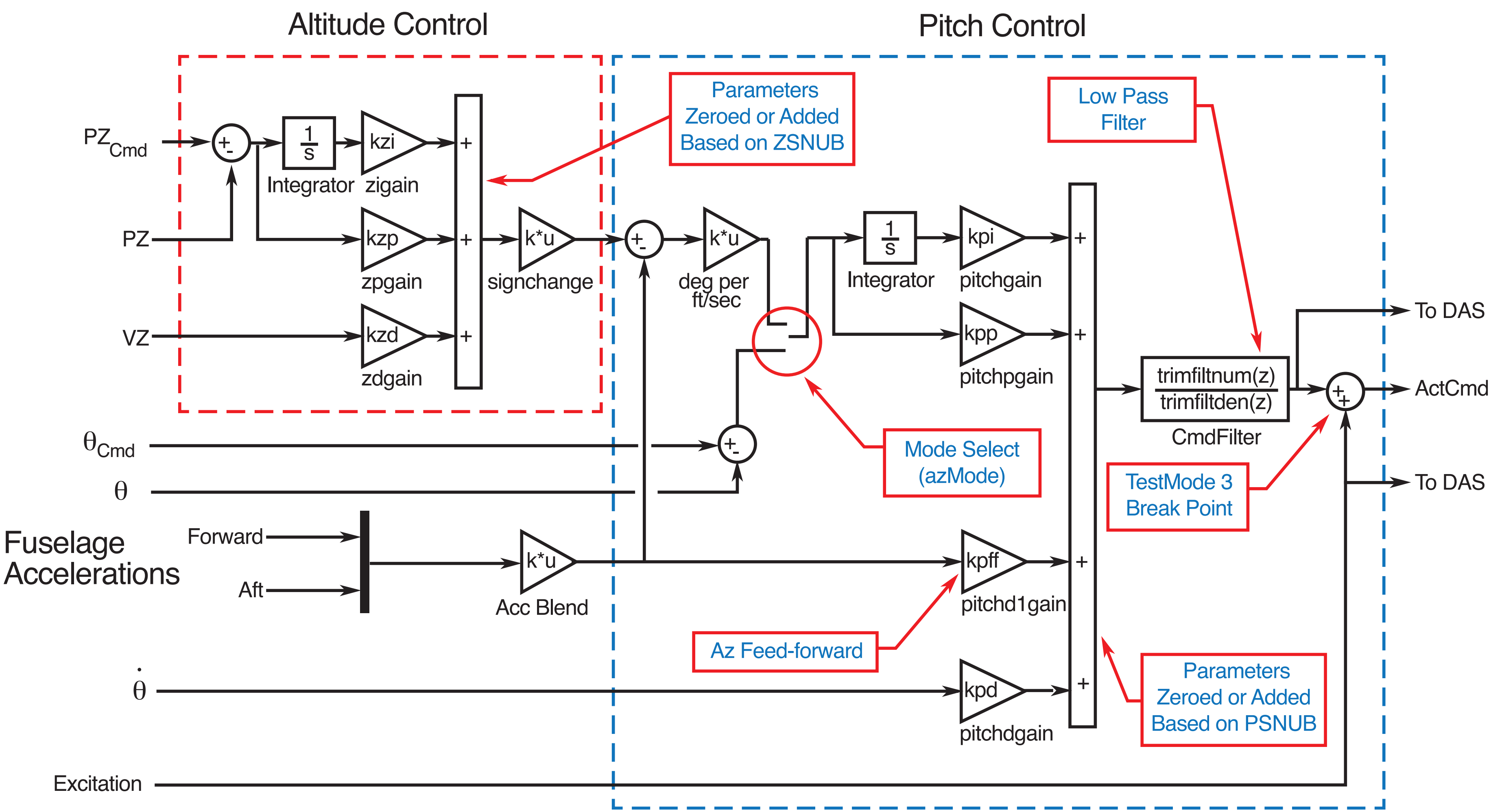
Joined-Wing Model on Beam Support



Control and Safety Systems



Trim Control Controller (Baseline)



Gust Load Alleviation Controller

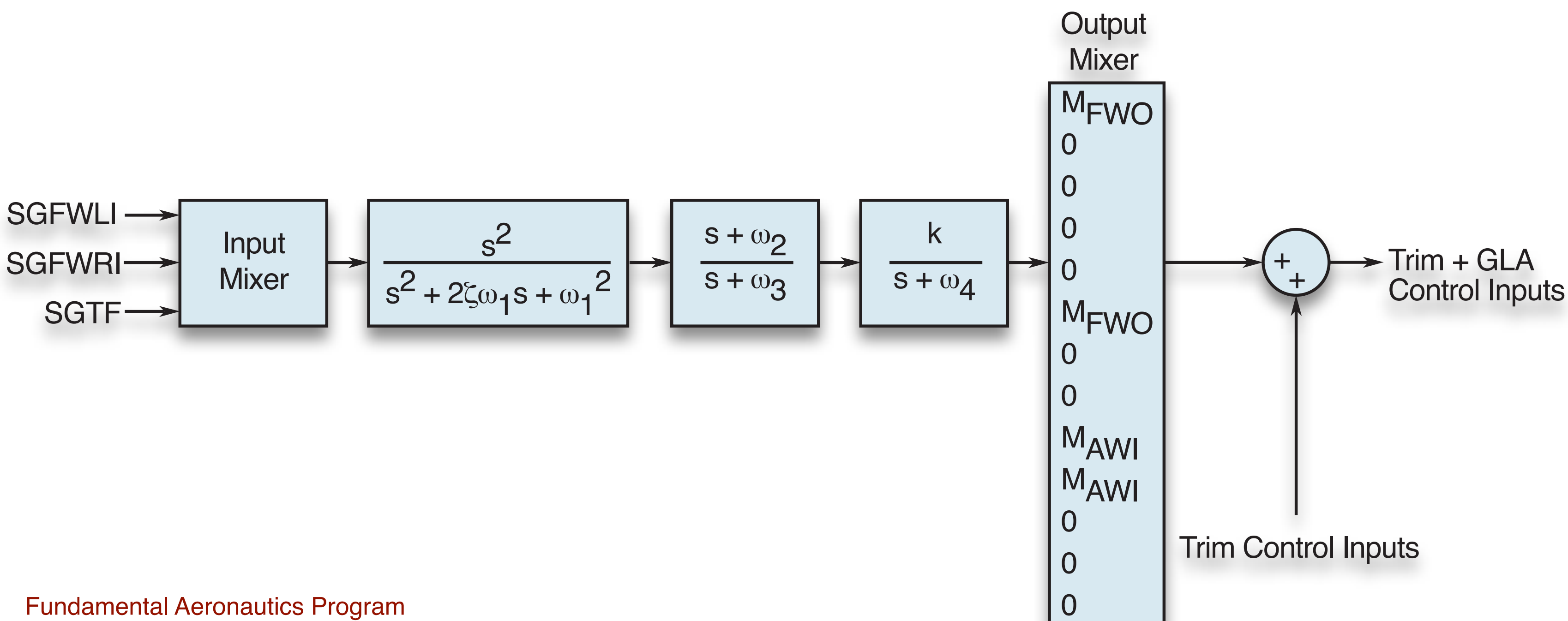
GLA Controller Signals Added to Trim Controller

TDT Schedule & Gas Processing Requirements Allowed Slow Pace of Testing

- *Multiple Parameter ID, ASE Model Refinement, Trim & GLA Controller Redesign Cycles*
- *Improved Testing Procedures: Model Trim Optimization and WatchDog Limit Expansion*

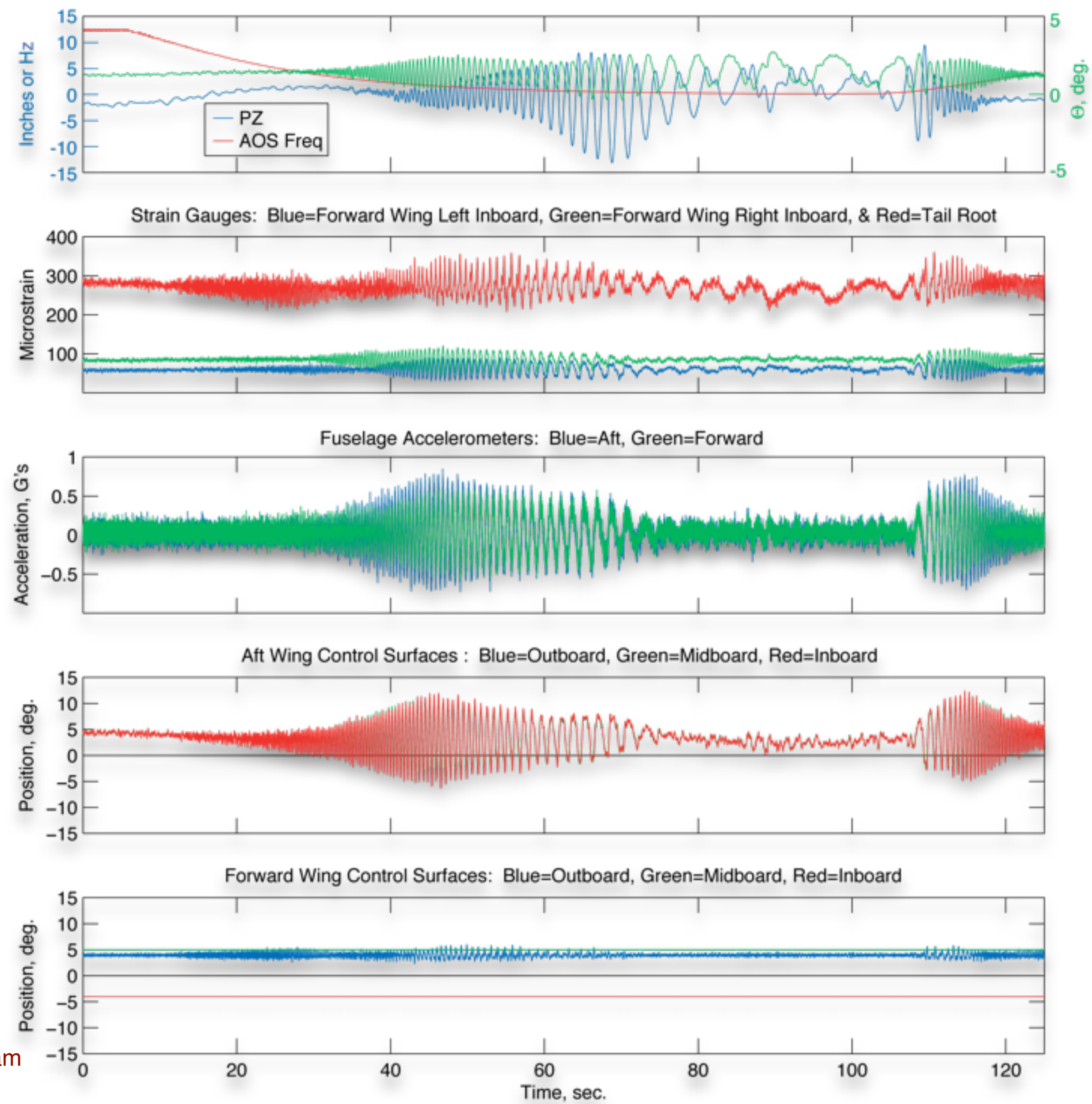
14 Controllers Tested Over 6 Week Period

- *Final, Most Successful Control Law Used FWI and Tail Strain Gauges & AWI and FWO Control Surfaces*



Launch, AOS, Snub, & Recovery

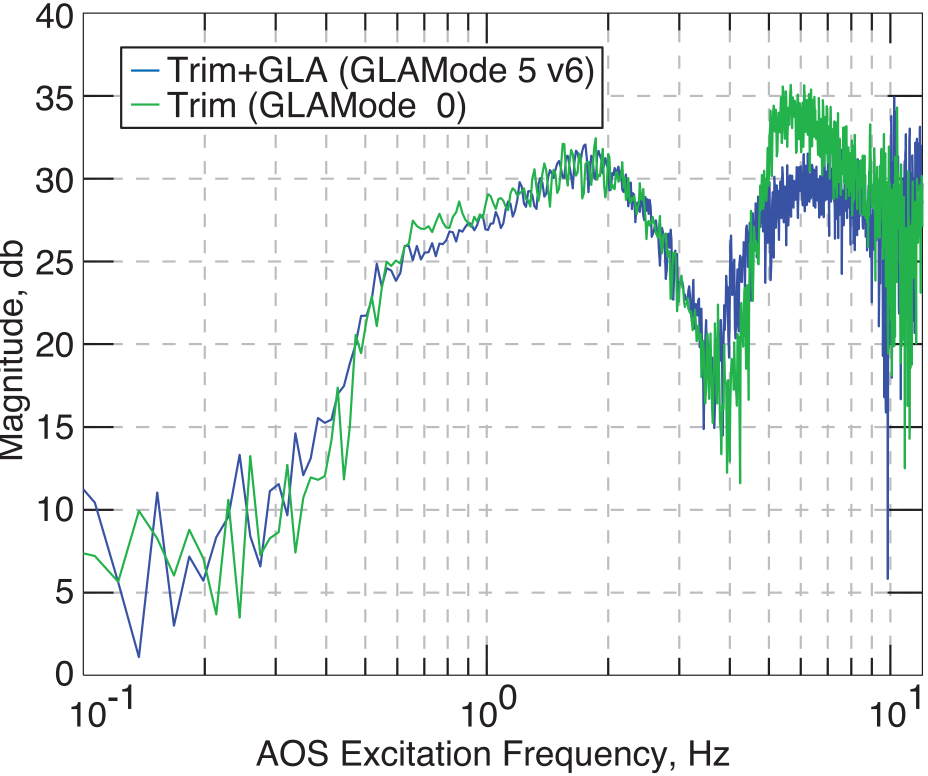
Example Time History: Trim+GLA



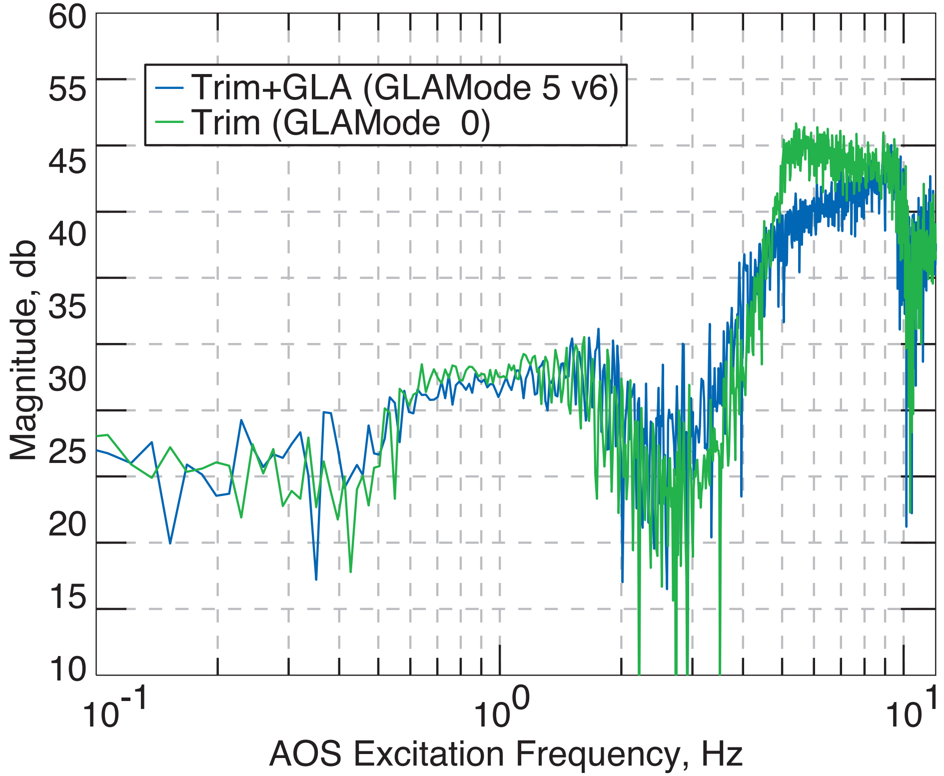
Gust Load Alleviation: 5 to 6 db Reduction

Transfer Function Estimates: Strain Response/AOS

Forward Wing Inboard Strain

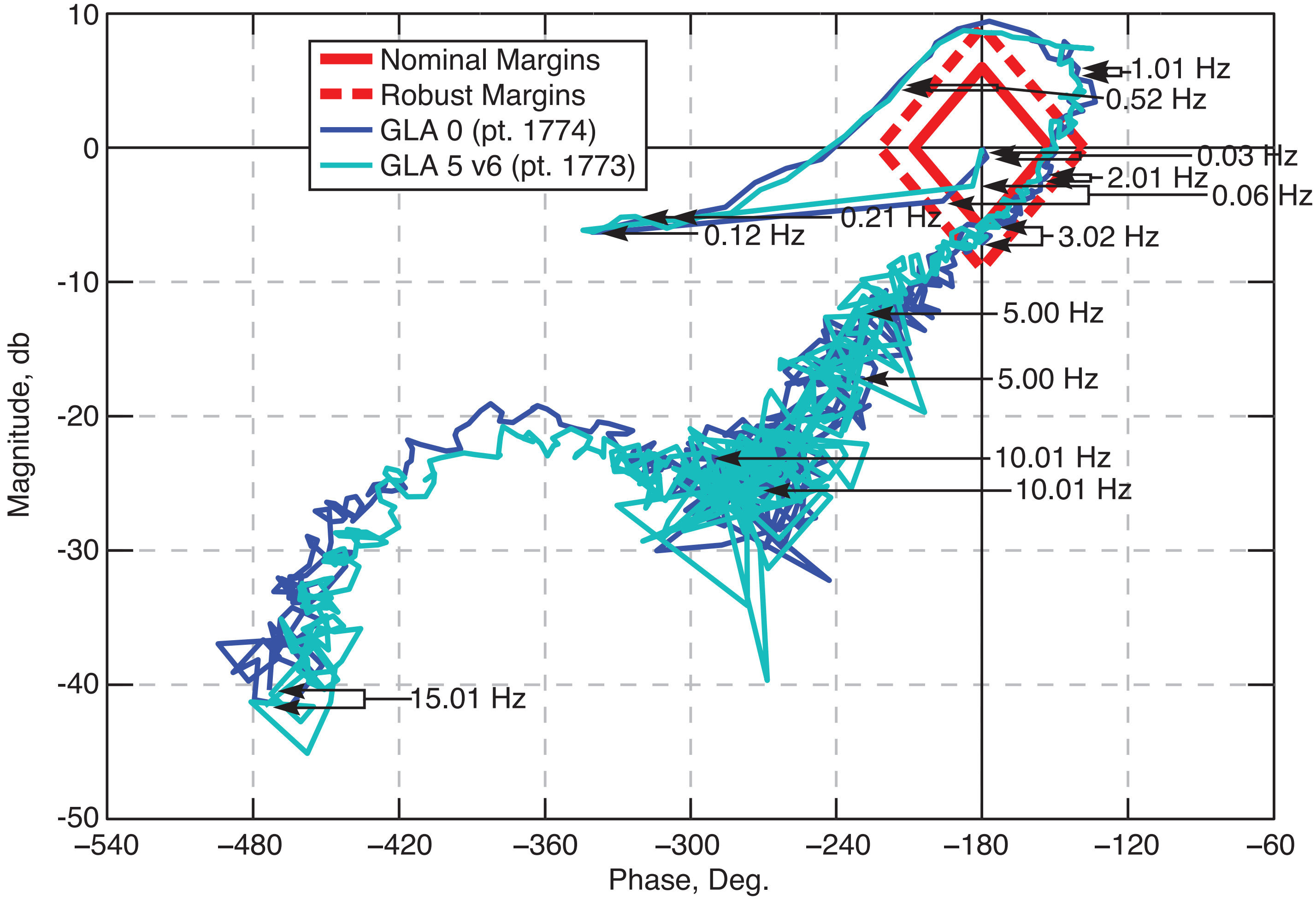


Tail Root Strain



Experimental Stability Margins

Final Versions of Trim and Trim+GLA Both Provide 6 db of Gain Margin and 30° of Phase Margin



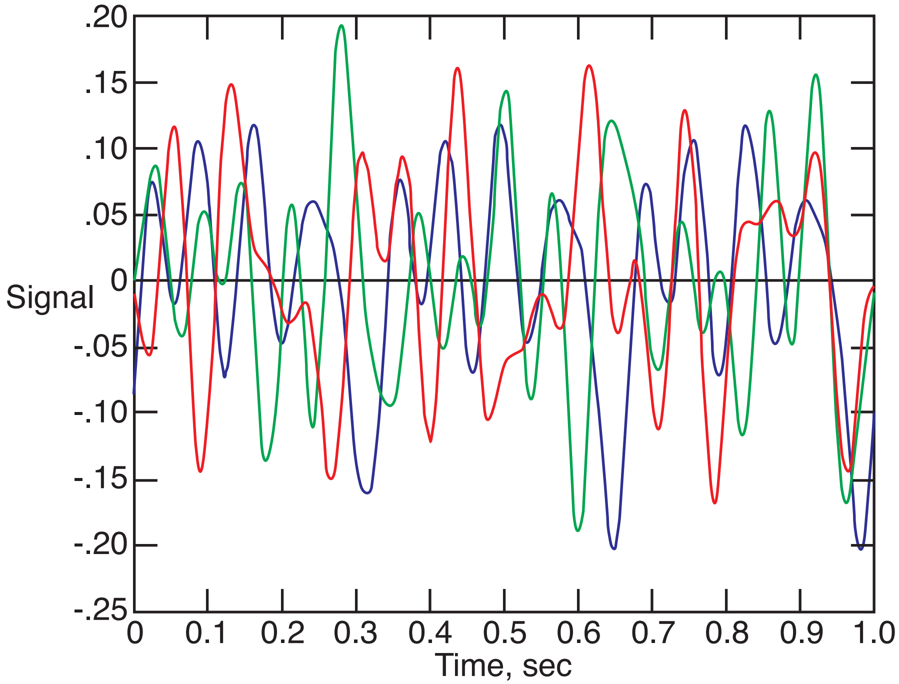
Multisine Orthogonal Excitation Signals

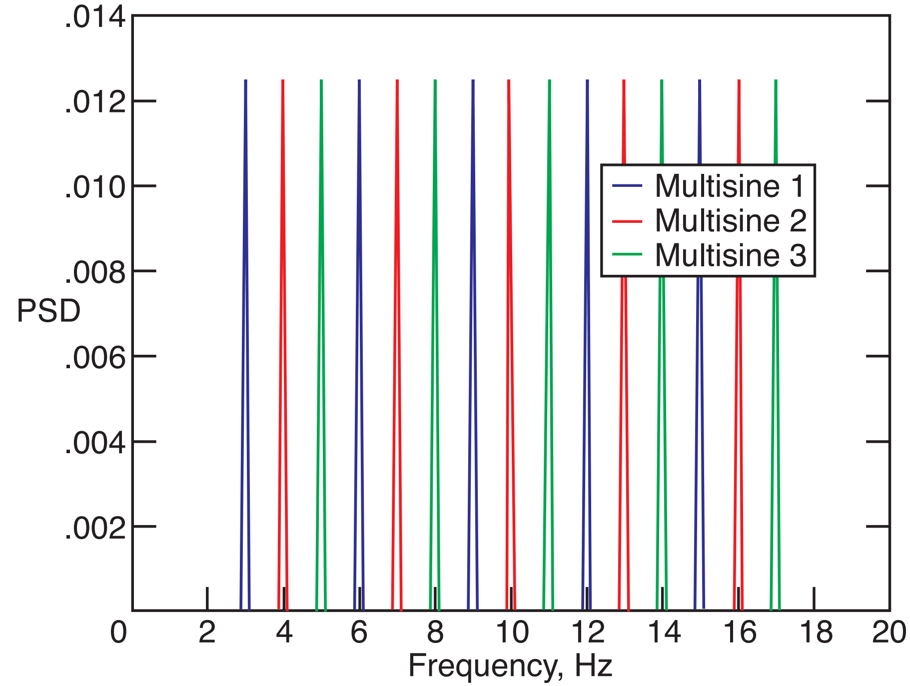
$$u_j(t)=A_i \sin(2\pi f_i t + \varphi_i)$$

f_i Frequencies are determined and distributed based on problem definition

φ_i Phase angles are randomly assigned to each sinusoid

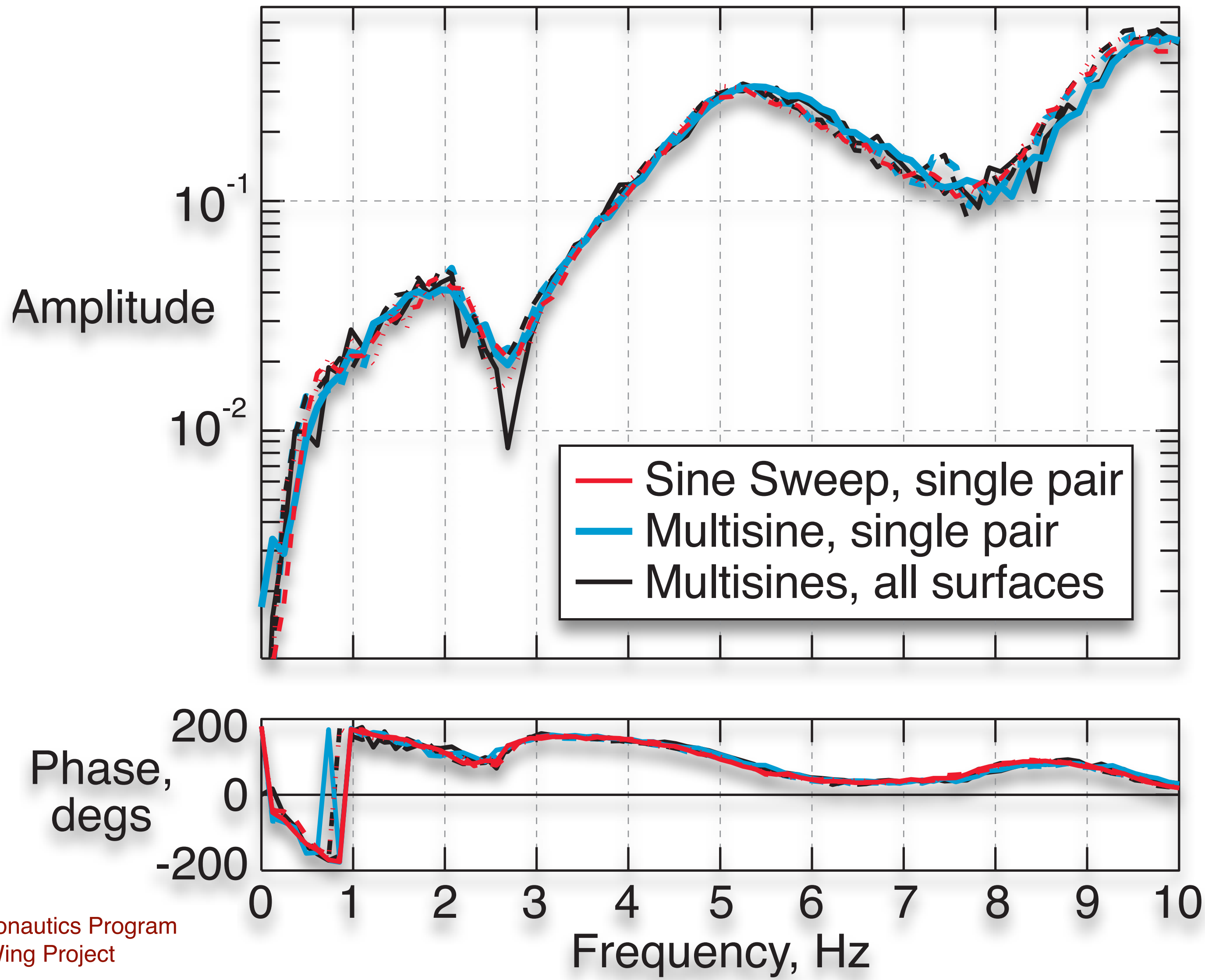
A_i Amplitude is tailored based on desired energy distribution





Multisine Experimental Results

Transfer Function Estimates: FW-Acceleration/FWO-CS-Position



Flying-Wing Publications

- Vartio, E., Shimko, A., Tilmann, C. P., and Flick, P. M., “Structural Modal Control and Gust Load Alleviation for a SensorCraft Concept,” 46th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference , No. AIAA-2008-7185, Austin, Texas, April 2005.
- Silva, W., Vartio, E., Shimko, A., Kvaternik, R. G., Eure, K. W., and Scott, R. C., “Development of Aeroservoelastic Analytical Models and Gust Load Alleviation Control Laws of a SensorCraft Wind-Tunnel Model Using Measured Data,” 47th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference , No. AIAA- 2006-1935, Newport, Rhode Island, May 2006.
- Martinez, J., “An overview of SensorCraft capabilities and key enabling technologies,” 26th AIAA Applied Aerodynamics Conference , No. AIAA-2008-7185, Honolulu, Hawaii, Aug. 2008.
- Scott, R. C., Vetter, T. K., Penning, K., B., Coulson, D. A., and Heeg, J., “Aeroservoelastic Testing of a Sidewall Mounted Free Flying Wind0tunnel Model,” 26th AIAA Applied Aerodynamics Conference , No. AIAA-2008-7186, Honolulu, Hawaii, Aug. 2008.
- Penning, K., Zink, P. S., Wei, P., De La Garza, A. P., and Love, M. H., “GLA and Flutter Suppression for a SensorCraft Class Concept Using System Identification,” 26th AIAA Applied Aerodynamics Conference , No. AIAA-2008-7188, Honolulu, Hawaii, Aug. 2008.
- Vartio, E., Shaw, E., and Vetter, T.,”Gust Load Alleviation Flight Control System Design for a SensorCraft Vehicle,” 26th AIAA Applied Aerodynamics Conference , No. AIAA-2008-7192, Honolulu, Hawaii, Aug. 2008.
- Penning, K. B., Zink, P. S., Wei, P., De La Garza, A. P., and Love, M. H., “Aeroservoelastic Analysis of a SensorCraft Vehicle and Comparison with Wind Tunnel Data.” 50th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, No. AIAA-2009-2405, Palm Springs, California, May 2009.

Joined-Wing Publications

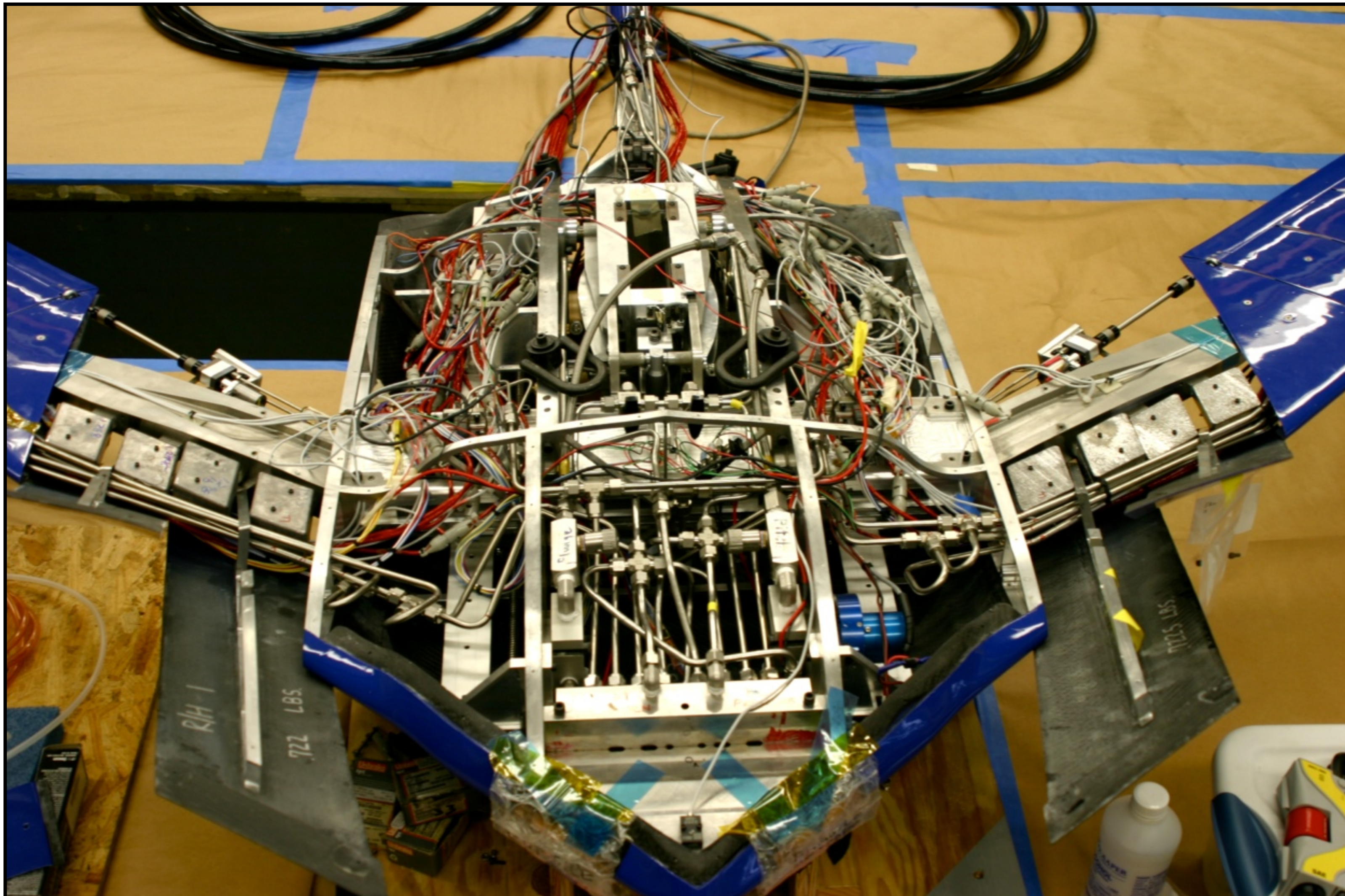
- Reichenbach,E. Aeroservoelastic Design and Test Valida- tion of the Joined Wing Sensorcraft, 26thAIAAAppliedAero- dynamics Conference, No. AIAA-2008-7189, Honolulu, Hawaii, Aug. 2008.
- Reichenbach, E., Castelluccio, M., Sexton, B., and Scott, R., "Aerodynamic Efficiency Improvement Final Report Volume 2: Aeroservoelastic Test Program," AFRL Contractor Report FA8650-05-C-3500, Boeing Research and Technology Computational Sciences, 2010.
- Reichenbach, E. and Sexton, B., "Joined-Wing SensorCraft Aeroservoelastic Wind Tunnel Test Program," *52nd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics and Materials Conference*, Denver Colorado, April 2011, Submitted for Publication.
- Scott, M. J., Enke, A., and Flanagan, J., "SensorCraft Free-Flying Aeroservoelastic Model: Design and Fabrication," *52nd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics and Materials Conference*, Denver Colorado, April 2011, Submitted for Publication.
- Sharma, V. and Reichenbach, E., "Development of an Innovative Support System for SensorCraft Model," *52nd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics and Materials Conference*, Denver Colorado, April 2011, Sub- mitted for Publication.
- Scott, R., Castelluccio, M., Coulson, D., and Heeg, J., "Aeroservoelastic Wind-Tunnel Tests of a Free-Flying, Joined- Wing SensorCraft Model for Gust Load Alleviation," *52nd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics and Materials Conference*, Denver Colorado, April 2011, Submitted for Publication.
- Heeg, J. and Morelli, G., "Avaluation of simultaneous multi-sine excitation of the Joined Wing aeroelastic wind tunnel model," *52nd AIAA/ASME/ASCE/ASC Structures, Structural Dynamics and Materials Conference*, Denver Colorado, April 2011, Submitted for Publication.

Concluding Remarks

- Joined-Wing Gust Load Alleviation at -10% Static Margin
  - Tail Boom Root Strain Response Reduced 50%
  - Forward Wing Inboard Strain Response Reduced 44%
  - Phase and Gain Margin Requirements Met
- Wind-Tunnel Test Capabilities
  - Two ASE Wind-Tunnel Models Available for Future Work
    - Models Valued at Over $2M Transferred to NASA
  - New Model Supports Provide Rigid-Body Degrees-of-Freedom in Wind-Tunnel Environment
    - Sidewall & Tunnel Centerline Support Systems
    - High Risk Tests Accomplished Safely via New WatchDog Capability
    - Strut-Braced Wing Test Program Plans to New Support
  - Demonstrated System Identification of ASE Systems via Multisine
    - Demonstrated for a 6 Control Effector System
    - Expanded Frequency Range Over Previous Applications
    - Wind-Tunnel [and Flight] Test Time Savings Can Be Achieved

Extra Images

Joined-Wing Internal View



Joined-Wing Model on Beam Support