National Aeronautics and Space Administration

Flutter and Aeroservoelastic Testing of the Boeing SUGAR Truss Braced Wing Aircraft

Presented by Robert Bartels

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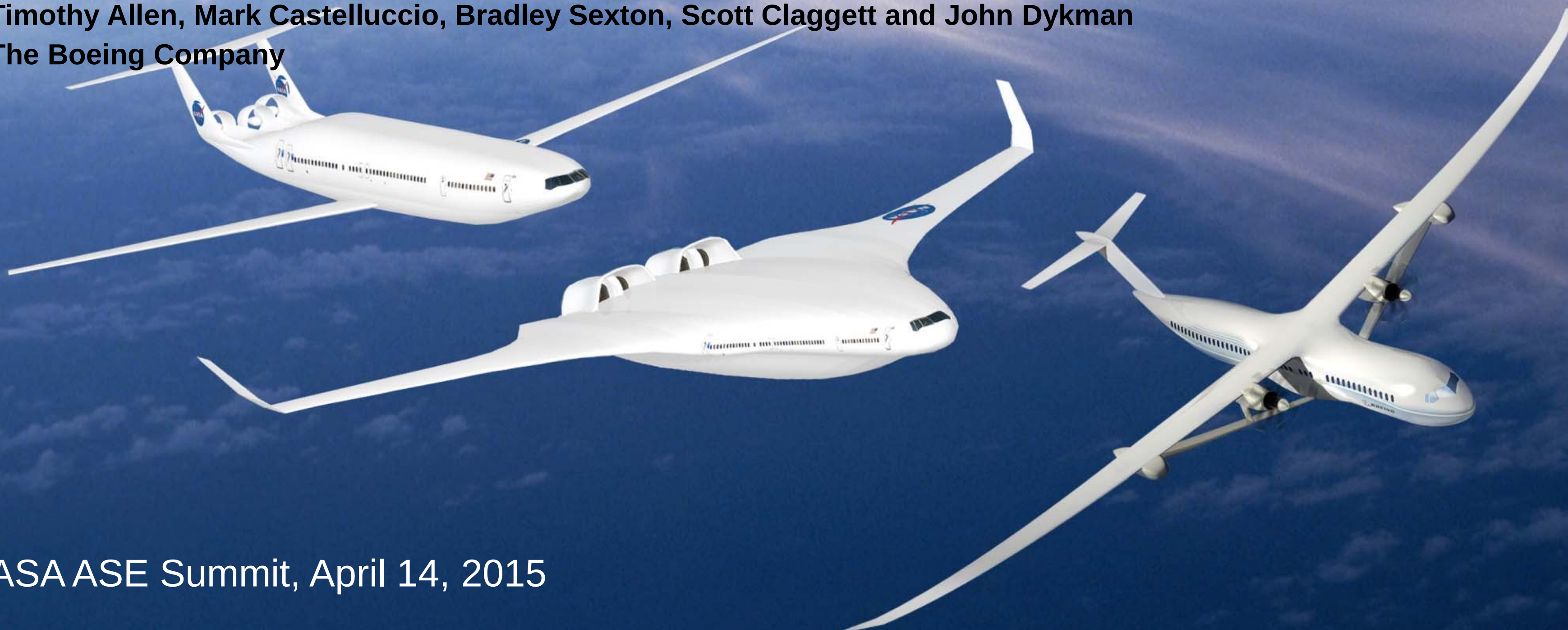

NASA ASE Summit, April 14, 2015

First presented at SD-13/GEPC-05. Special Session: Subsonic Ultra Green Aircraft Research (SUGAR) Truss Braced Wing Aeroelasticity, SciTech 2015

Outline

- Phase I Findings, Phase II Objectives
- Experimental Validation, TDT Test
  - Test Objectives
  - Wind-Tunnel Model Design
  - Transonic Dynamics Tunnel
  - “Configurations” – GVT and FE Analyses
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  - Experimental ASE Results
- Phase II Findings
- Conclusions

TBW Phase I Findings, Phase II Objectives

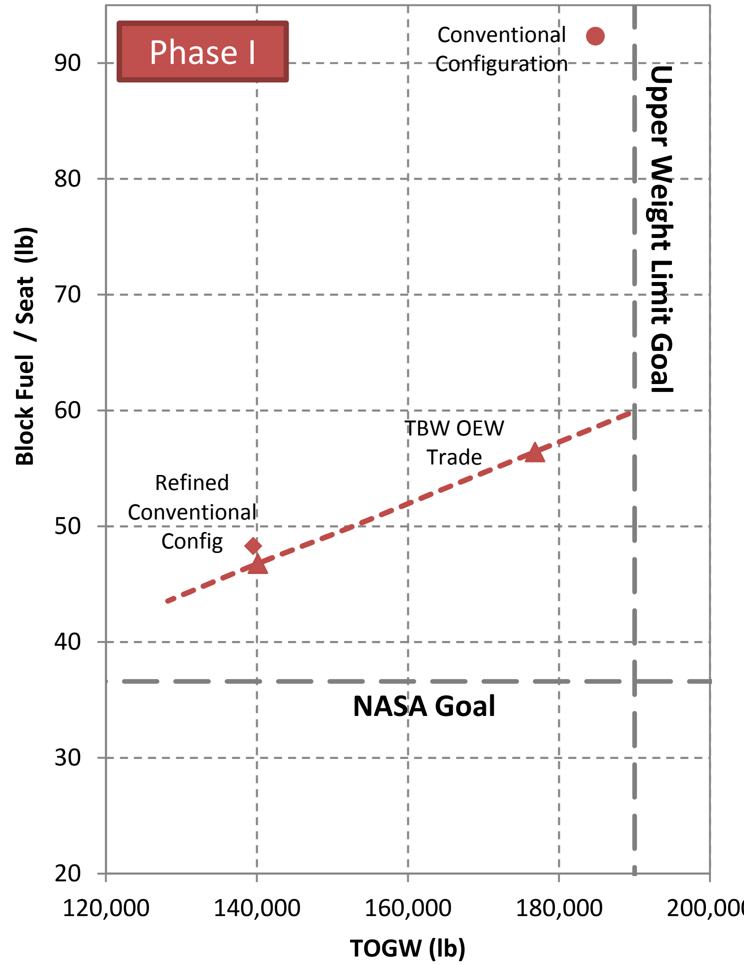
<u>Phase I</u> – Design Study of TBW Configuration

- Large uncertainty in wing weight estimates prevent concluding whether TBW is viable/beneficial concept

Baseline “SUGAR Free” Conventional Configuration

“Refined SUGAR” Conventional Configuration

“SUGAR High” Truss Braced Wing Configuration



<u>Phase II</u> - Includes High Fidelity FEM to Refine Weight Estimate and Experimental Validation via ASE Wind-Tunnel Test in the TDT

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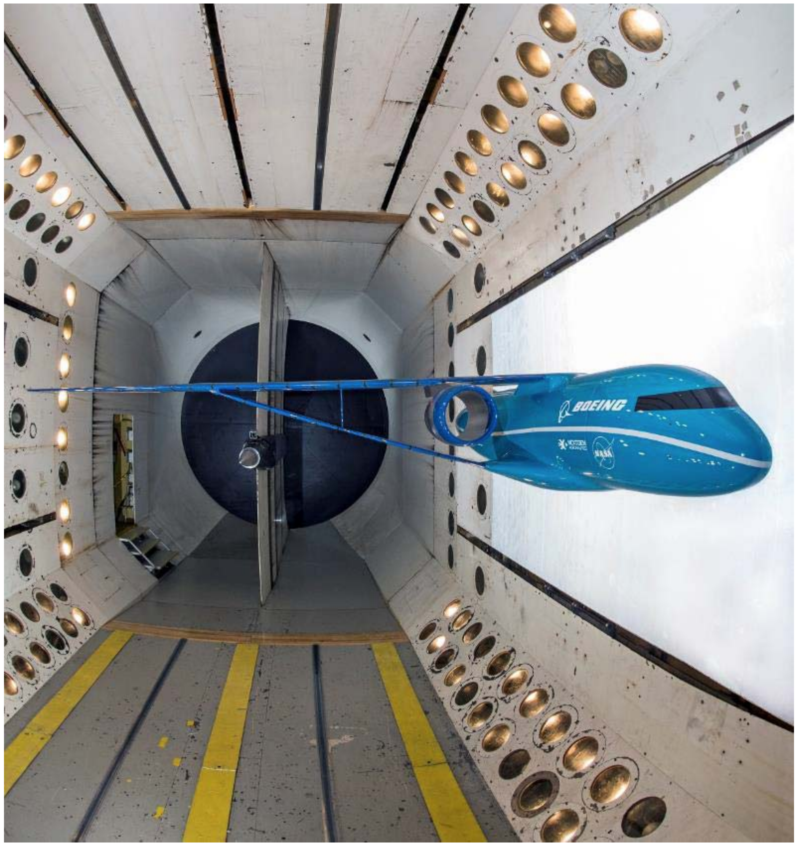
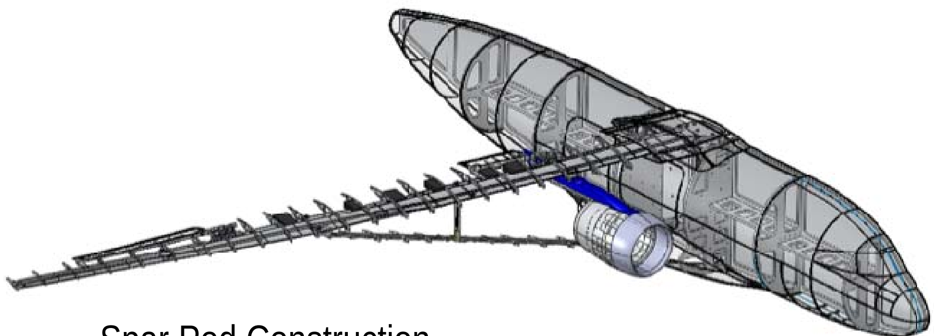
Wind-Tunnel Test Objectives

- Determine Experimental Flutter Boundaries
- Investigate Active Flight Controls
  - System ID
  - Flutter Suppression
  - Assess Effects of FS on Gust Response



TBW Aeroelastic Wind-Tunnel Model

Full-Scale Design Point:
- Mach = 0.82
- Altitude = 15,915 ft
- Span = 170 ft
- Weight = 143,164 lb



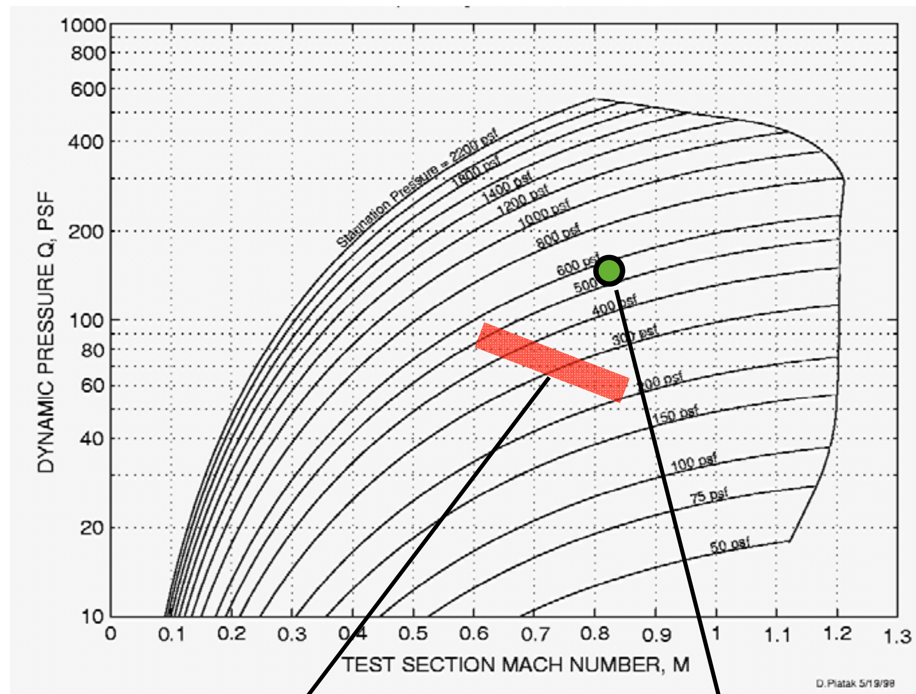
Spar Pod Construction

Wing, Strut, Pylon Scaled

High Bandwidth Control Surfaces:
- 2 Trailing Edge

Designed for Side Wall Mount
- Fuselage 13.4 ft (reduced from 18.7 ft)
- Span = 12.75 ft (to centerline)
- Standoff = 2.25 in
- Weight = 500 lb

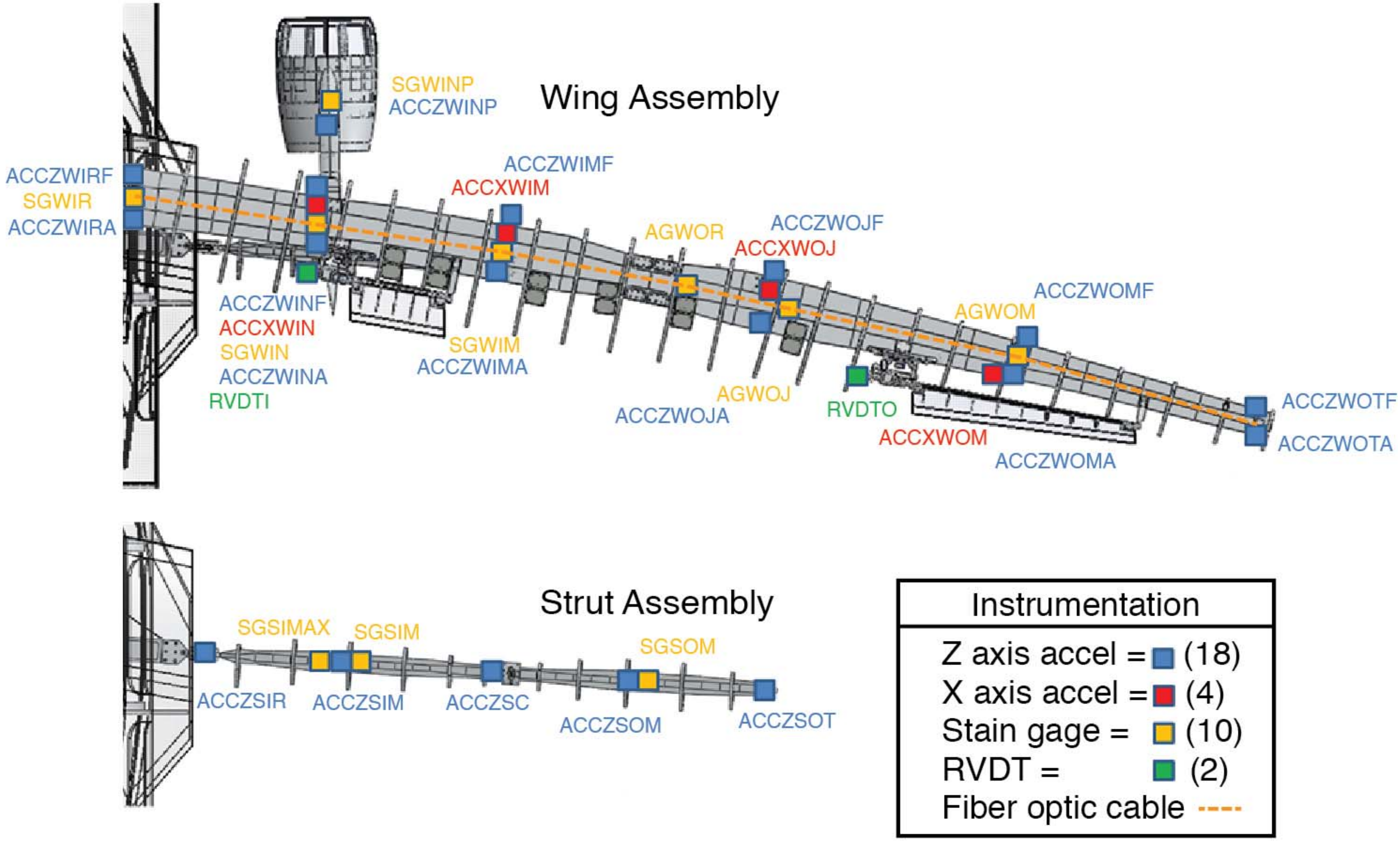
Model Scale Factors:
- Length = 0.15
- Frequency = 3.470



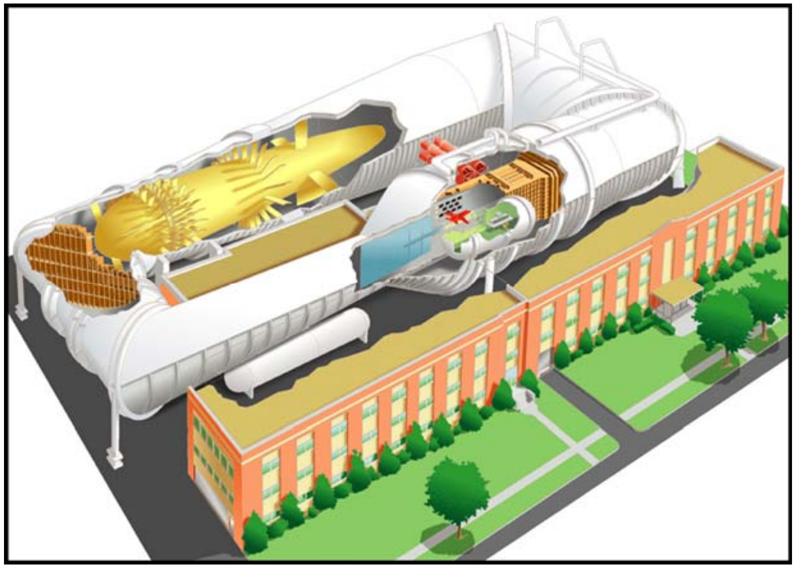
Predicted Flutter Boundary

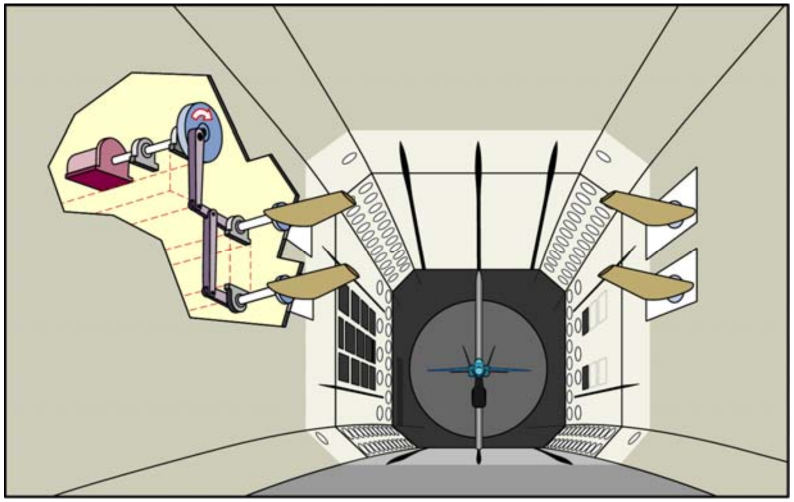
Model Design Point
- Gas = R134a
- Scaled Weight = 109.63 lb
- Mach = 0.82
- Q=162 psf

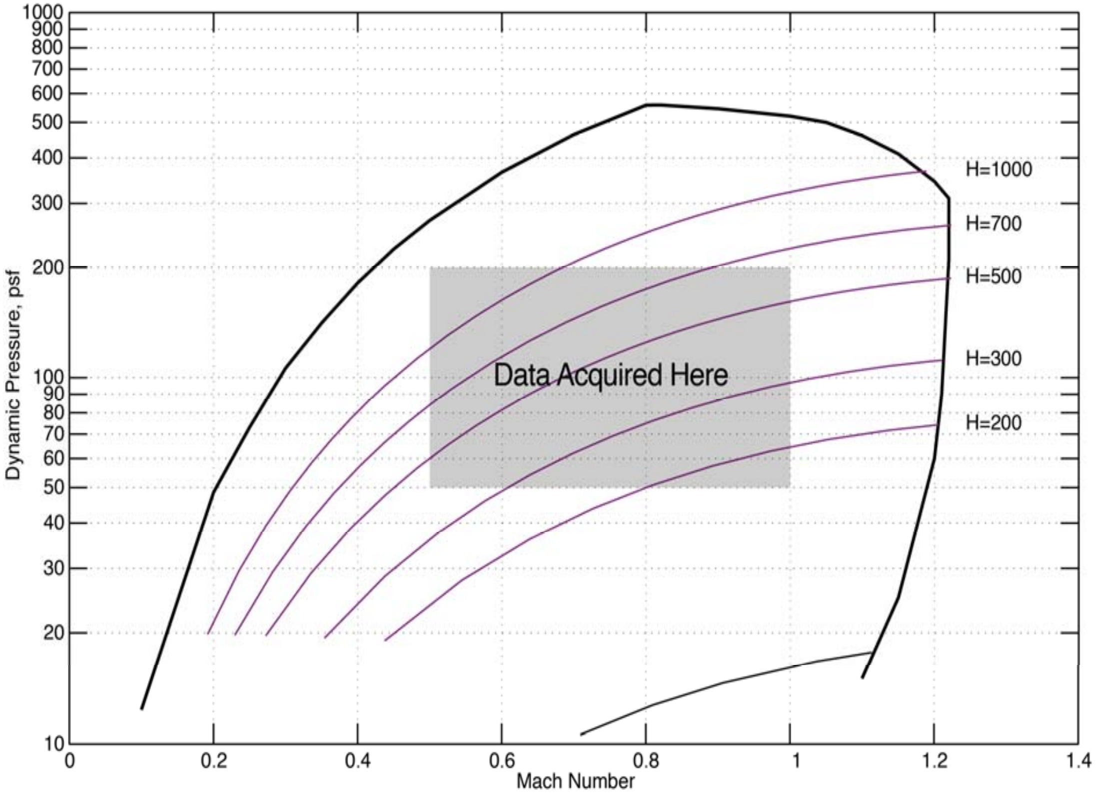
TBW Model Instrumentation



Transonic Dynamics Tunnel

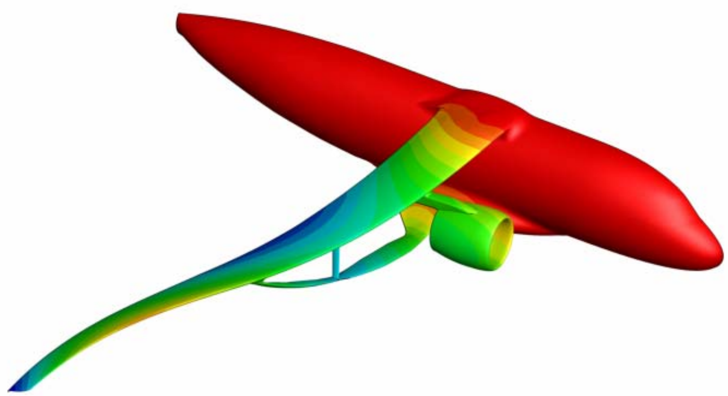




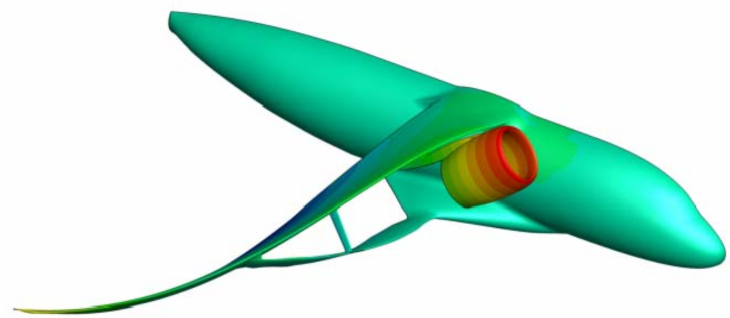


TBW Modes and Frequencies

Wing 2nd out-of-plane bending mode

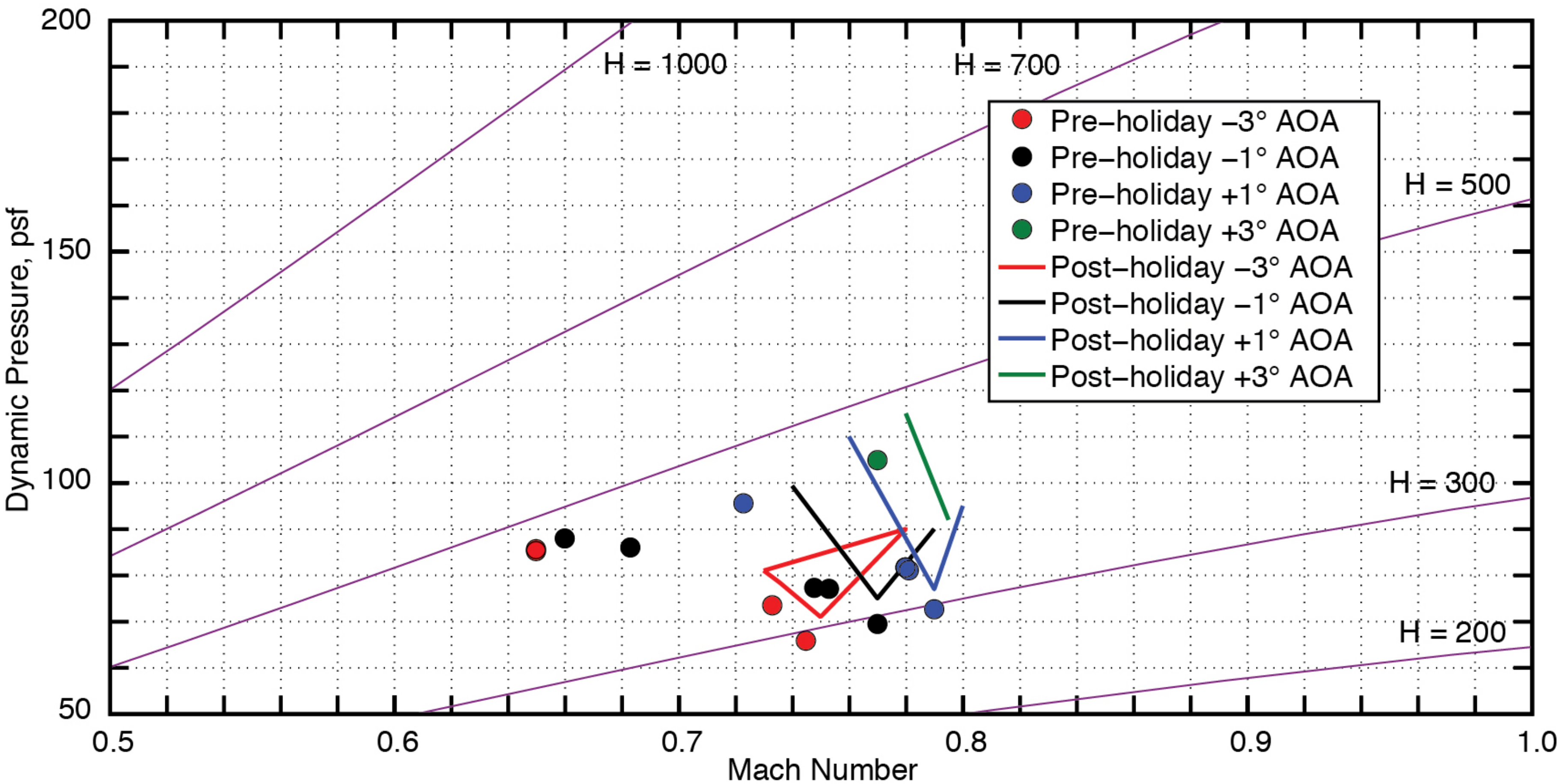


Wing 1st torsion mode

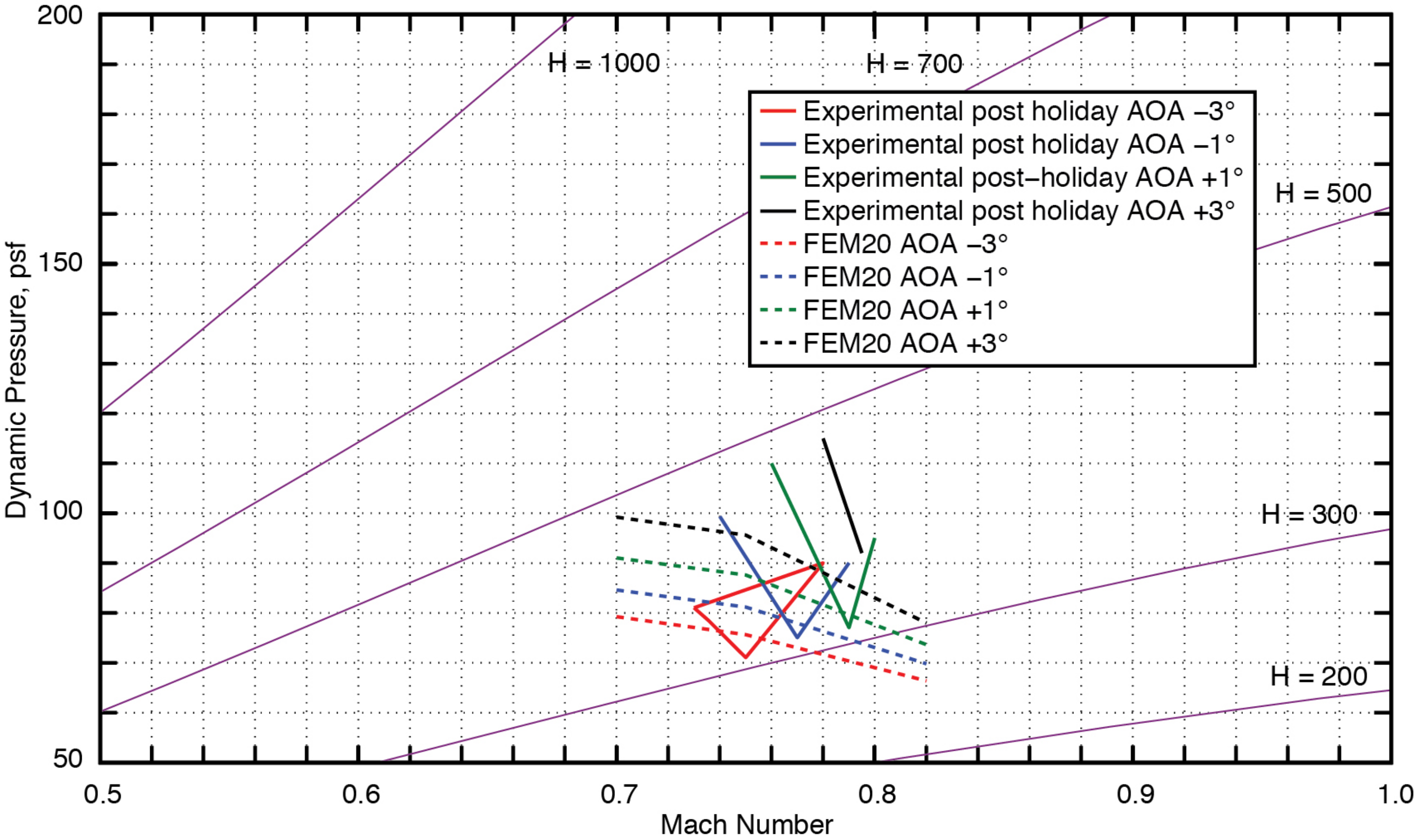


	Pre-Holiday (Hz)		Post-Holiday (Hz)		Description
Mode	GVT	FEM19	GVT	FEM20	
1	5.20	5.12	5.08	5.04	1^{st} out-of-plane wing bending
3	9.08	9.17	8.43	8.44	2^{st} out-of-plane wing bending
4	11.35	11.34	11.14	11.28	1^{st} wing/nacelle torsion
5	19.56	18.53	18.62	18.46	wing bending
7	28.44	27.44	27.57	27.13	wing/nacelle torsion/bending

Flutter Boundary Summary



Analysis/Test Comparison



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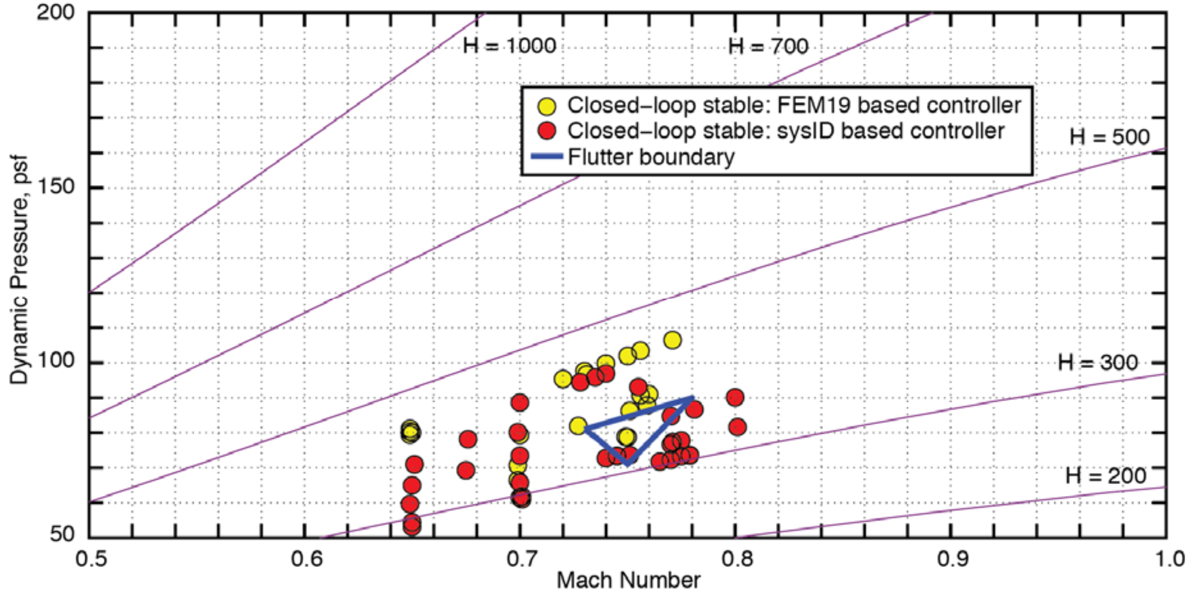
ASE and CL Testing

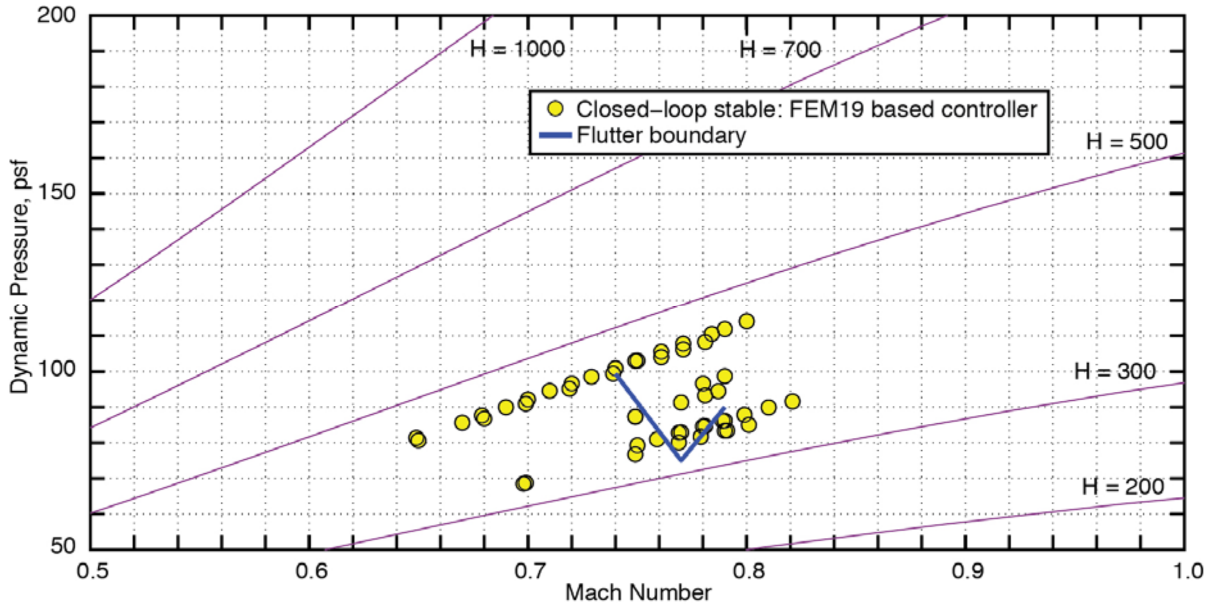
- Open Loop System ID
  - Sine sweeps to control surfaces for ASE model verification and system ID
  - Dwell/Decay for estimating modal damping
- Flutter Suppression Control Laws
  - LQR based control law for each ASE model
  - System ID based control law (2)
    - Derived from two experimental data points
      - Linear sine sweeps to each surface at two stable tunnel conditions
      - AOA = -3°
  - FEM 19 based control laws (18)
    - ASE models derived from version 19 of NASTRAN FEM
    - 18 ASE models used, including OL stable and unstable
  - Control laws were scheduled based on Mach and dynamic pressure
- Gust Response
  - Back to back OL and CL data points acquired with AOS frequency sweep

Closed Loop Results, AOA < 0

AOA -3

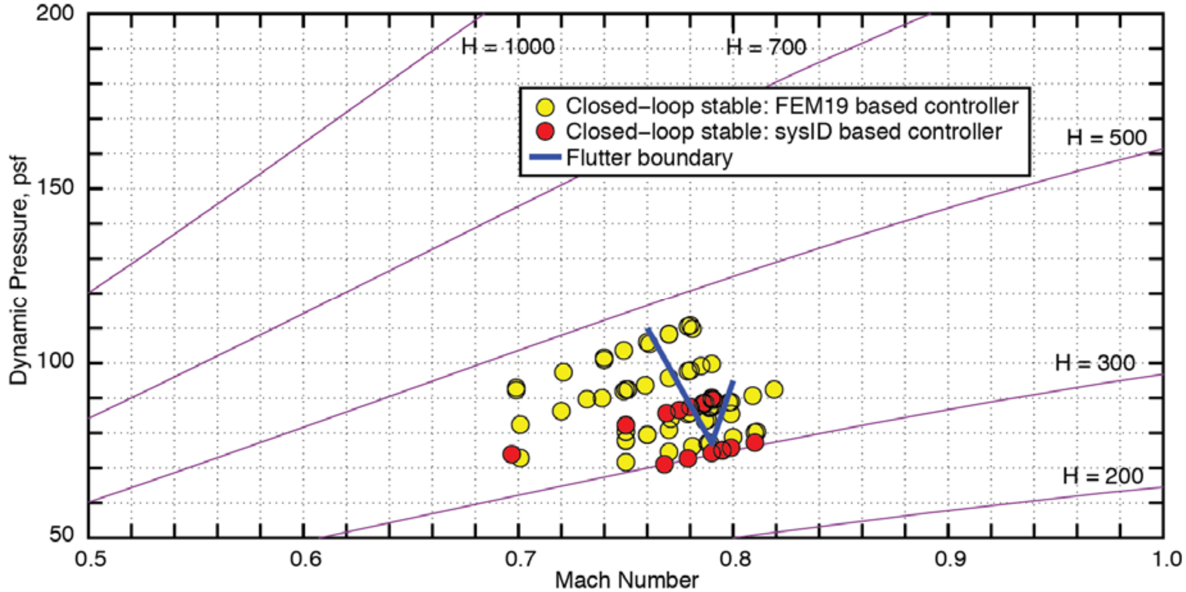


AOA -1

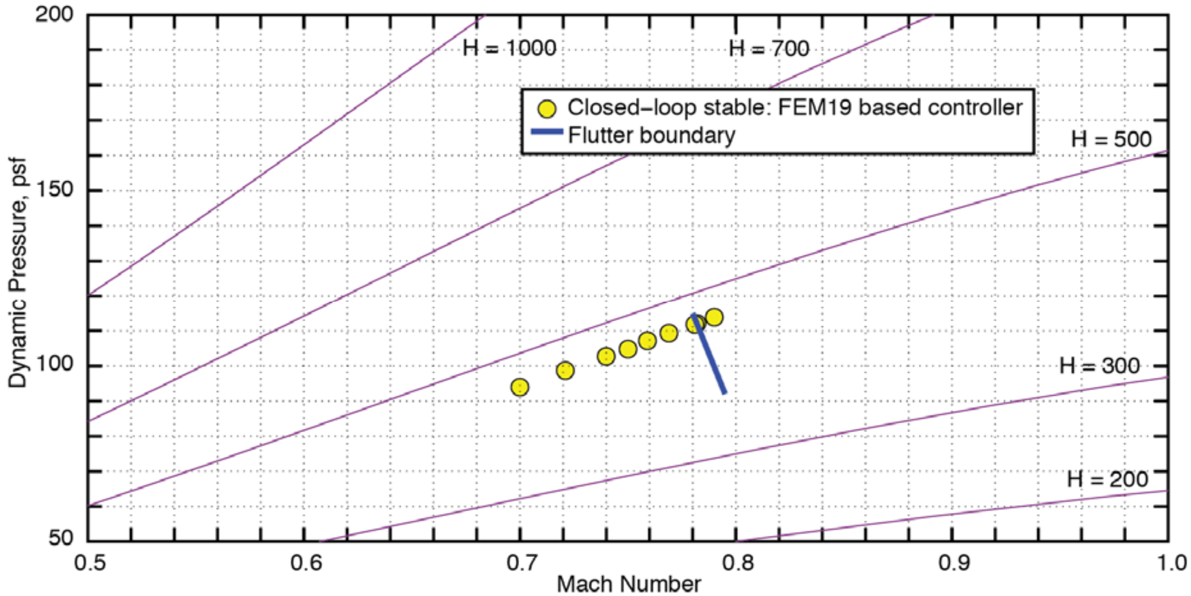


Closed Loop Results, AOA > 0

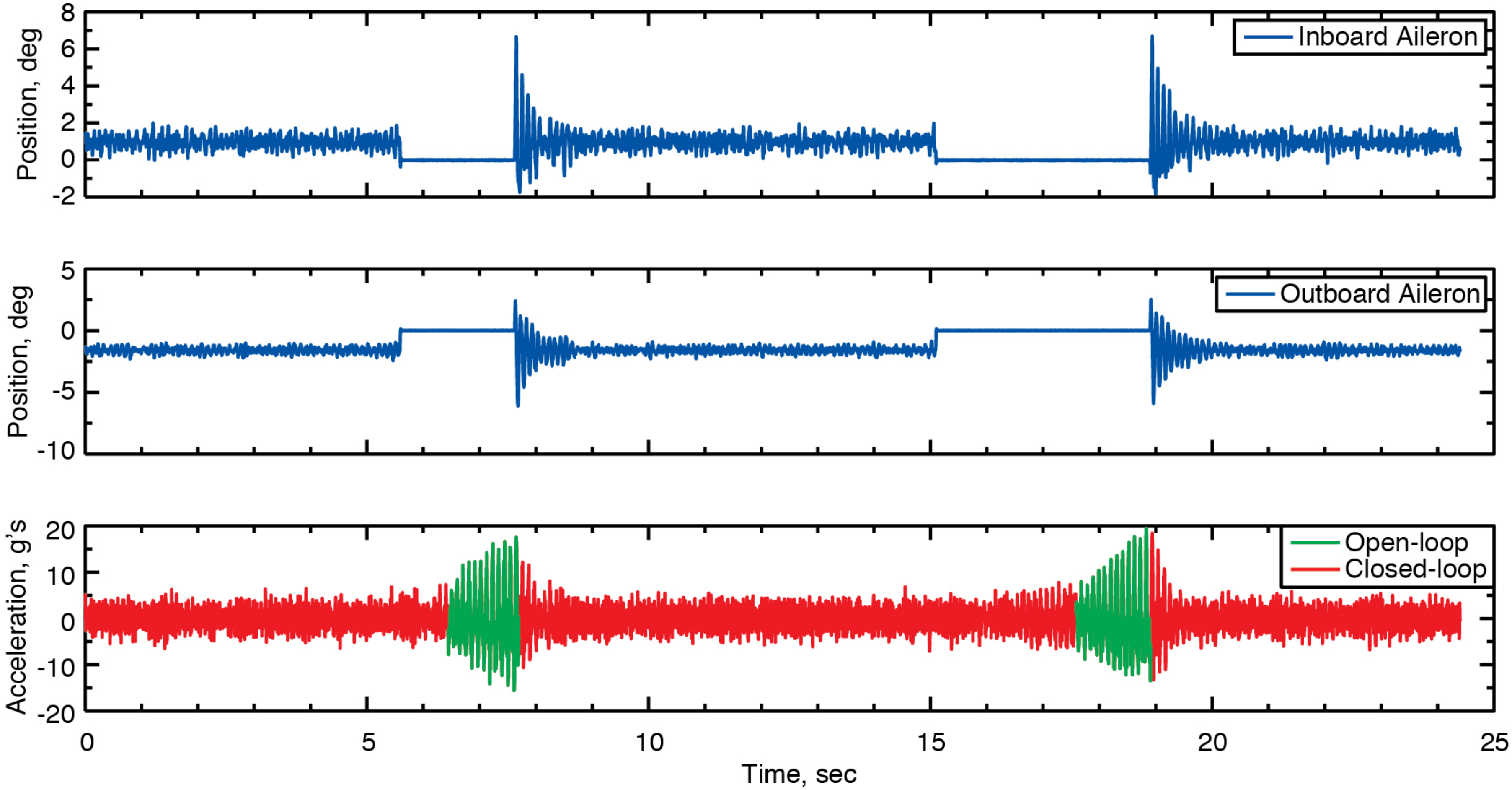
AOA +1



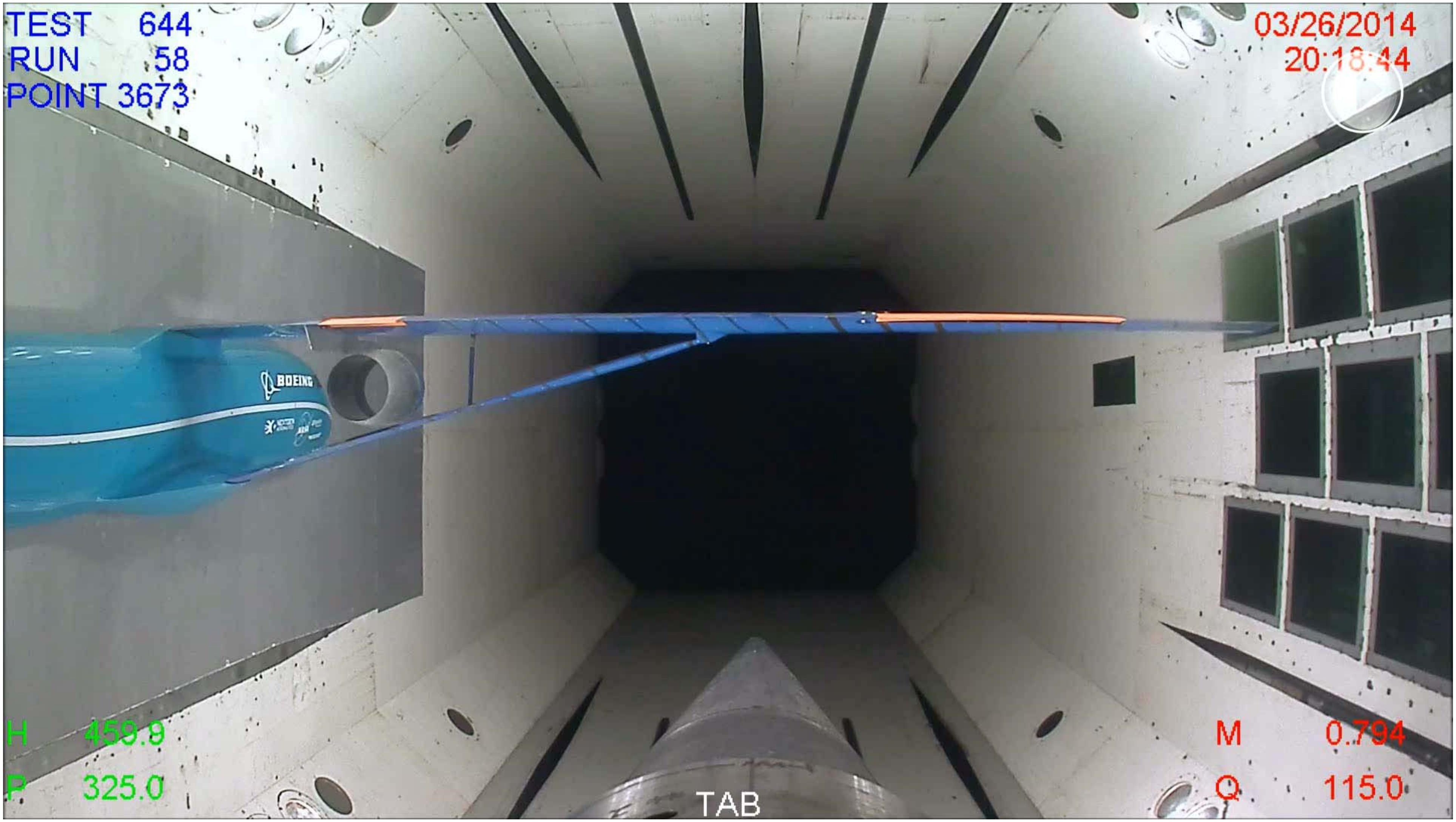
AOA +3



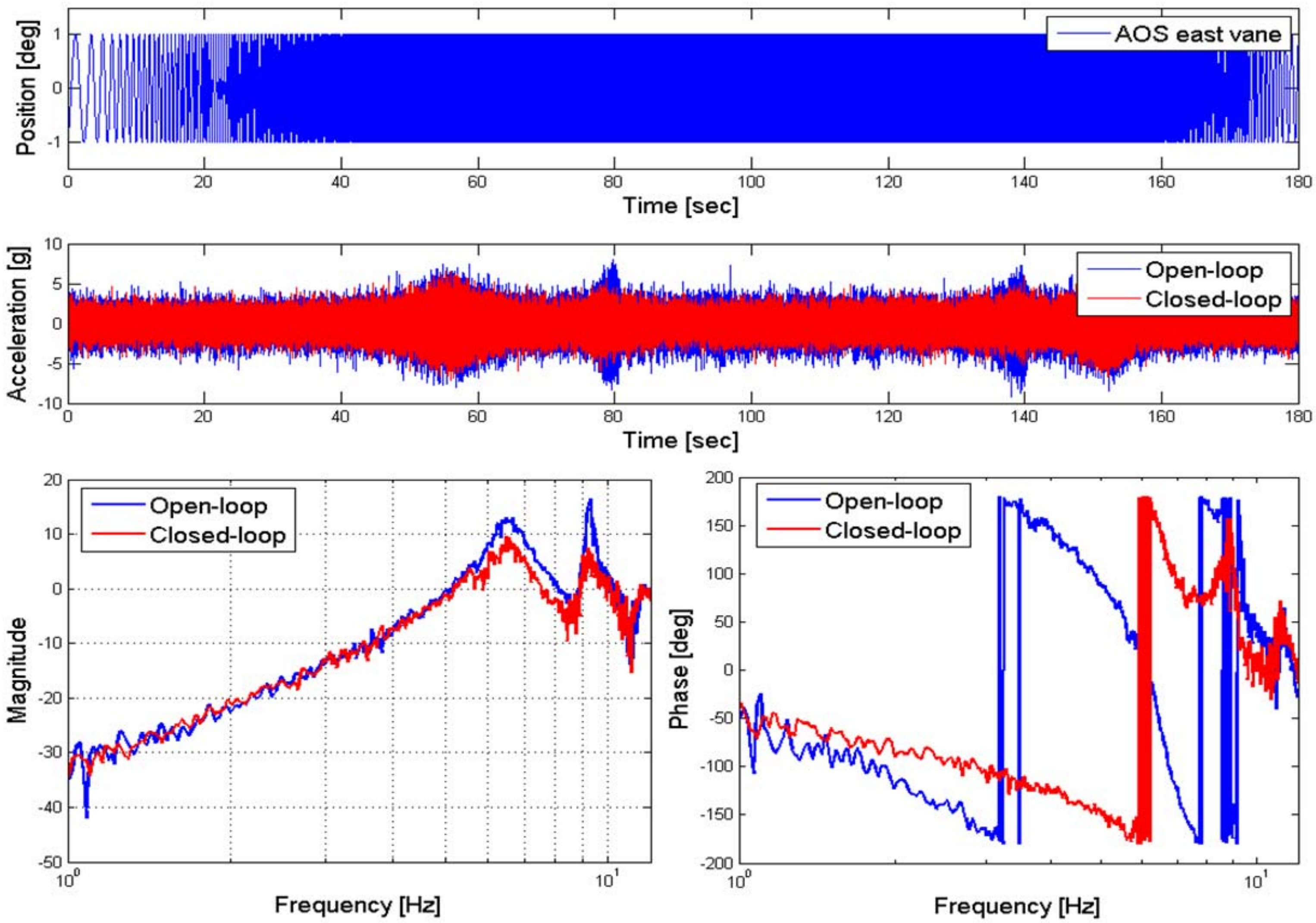
FEM19 Controller OL/CL @ Unstable Condition



Flutter Suppression



OL/CL Gust Response, FEM19 Based Control



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Conclusions

- Open-Loop Flutter Boundaries Established
  - Flutter Boundaries a Function of Aerodynamic Loading (Angle of Attack)
  - Boeing NASTRAN/MDO Approach Validated/Improved
    - Importance of Static Nonlinear Effects Established
    - The TBW Configuration Remains A Viable Concept For Reducing Transport Aircraft Energy Consumption
- Flutter Suppression Control Laws Designed & Demonstrated
  - Control Laws Designed using ASE Models Derived From Both Open-Loop Experimental Data and the NASTRAN FEM
  - Close Loop Dynamic Pressures of at Least 25% Above the Open Loop Boundary Were Demonstrated
  - Viability of Flutter Suppression for TBW N+3 Concept Established
  - Flutter Suppression Controllers Provide Small Gust Load Alleviation Benefit
- Model Status
  - Survived Several Hard Flutter Points
  - NASA Retained Ownership, Available for Future Testing
- Documentation
  - SciTech 2014 (2)
  - Contractor Reports (2)
  - SciTech 2915 Special Session
  - Aviation 2015 (1)

NASA

Backup Slides

Truss-Braced Wing: Wing Weight Uncertainty

PROBLEM

Conceptual design of Truss-Braced Wing (TBW) configuration during the N+3 phase 1 study showed significant potential of this technology to contribute to meeting NASA N+3 goals, but also highlighted a significant uncertainty in the wing weight estimate.

OBJECTIVE

Refine the TBW configuration and reduce the uncertainty in the potential benefits with specific focus on reducing the uncertainty of the wing weight.

APPROACH

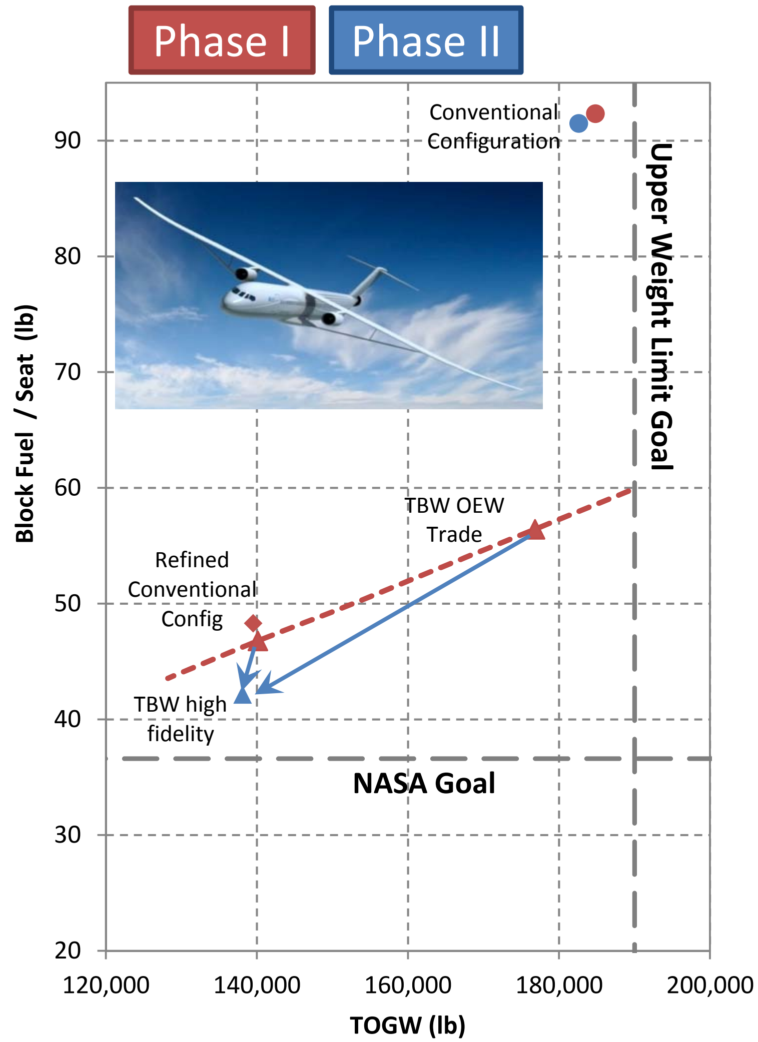
Create a detailed finite element model (FEM) of the TBW configuration to provide a higher fidelity weight estimate of the concept; validate the FEM via a transonic aeroservoelastic (ASE) test in the NASA Transonic Dynamics Tunnel (TDT).

RESULTS

A high fidelity weight estimate was completed which showed favorable wing weights and significant improvement in fuel burn. The ASE test was used to validate and update the wing weight estimate which increased 463 lbs (12,577 lb wing).

SIGNIFICANCE

The TBW configuration remains a viable concept for reducing transport aircraft energy consumption. The validated detailed FEM enables credible weight and fuel burn estimates that justify further investigations of the TBW concept. Based on these results, an aerodynamic performance test and evaluation is going forward that will show that high-order aerodynamic design and analysis tools can be used to predict the performance of a low-interference truss braced wing.



Documentation

Contractor Final Reports

1. Bradley, M. K. and Droney, C. K., "Subsonic Ultra Green Aircraft Research: Truss Braced Wing Design Exploration," Contractor report, The Boeing Company, June 2014.
2. Bradley, M. K., Droney, C. K., and Allen, T. J., "Subsonic Ultra Green Aircraft Research: Truss Braced Wing Aeroelastic Test Report," Contractor report, The Boeing Company, June 2014

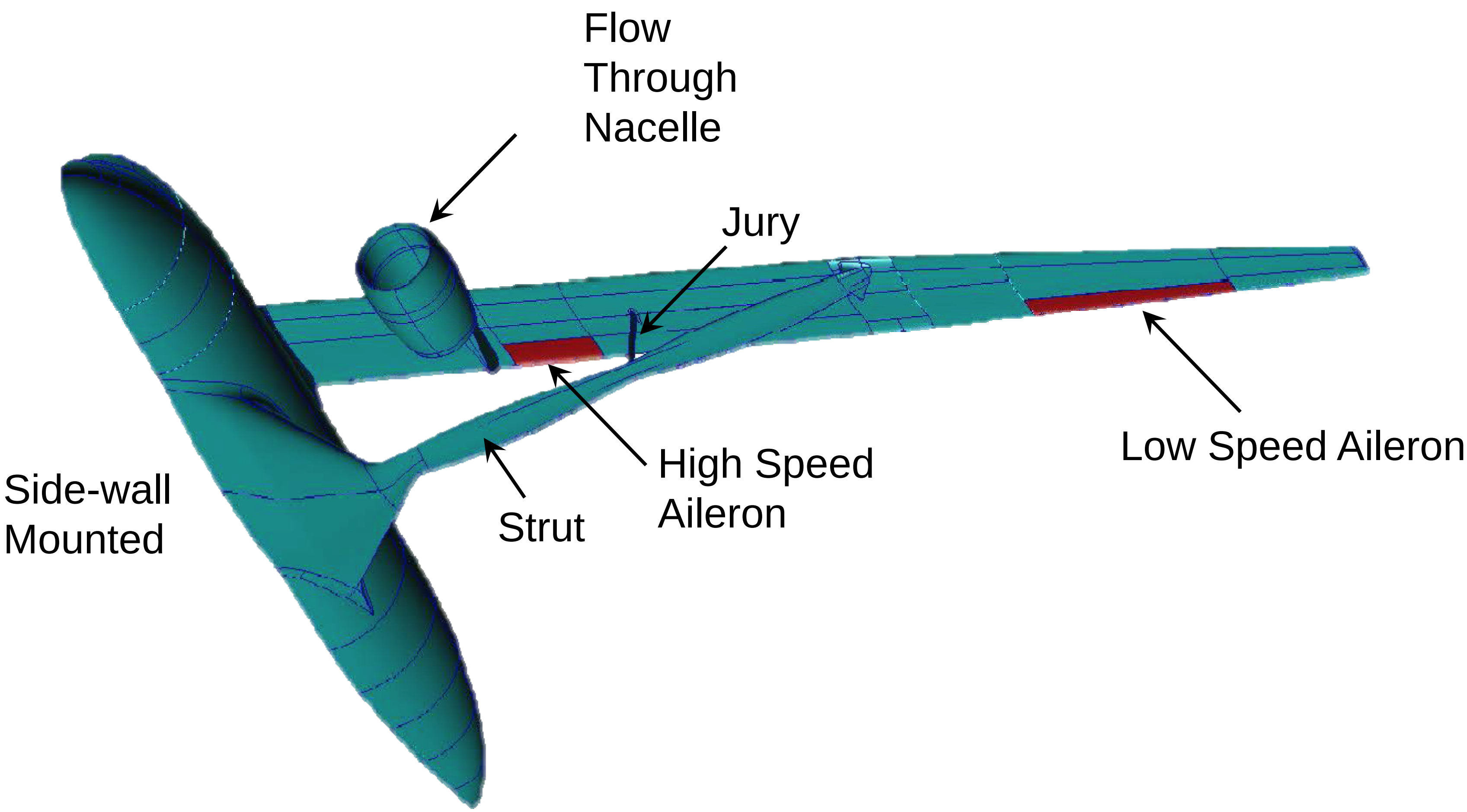
AIAA Conference papers

1. Coggin, J., Kapania, R., et. al., "Nonlinear Aeroelastic Analysis of a Truss Braced Wing Aircraft", SciTech, No. AIAA-2014-0335, National Harbor, Maryland, January 2014.
2. Bartels, R. E., Scott, R. C., Allen, T., Sexton, B., and Funk, C., "Computed and Experimental Flutter/LCO Onset for the Boeing Truss-Braced Wing Wind-Tunnel Model," 32nd AIAA Applied Aerodynamics Conference, No. AIAA-2014-2446, Atlanta, GA, June 2014.

FY15 Documentation

- Contractor Final Report -> submit for publication as a NASA CR
- AIAA SciTech, January 2015
  - Bradley, M., “Final Results of the Subsonic Ultra Green Aircraft Research (SUGAR) Study”
  - Special Session Sponsored by SDTC & GEPC
    1. Allen, Timothy J. [The Boeing Company], "SUGAR Truss Braced Wing Full Scale Aeroelastic Analysis and Dynamically Scaled Wind Tunnel Model Development”
    2. Scott, Robert C. [NASA], "Aeroservoelastic Wind-Tunnel Test of the SUGAR Truss Braced Wing Wind-Tunnel Model”
    3. Bartels, Robert E. [NASA], "Nonlinear Aeroelastic Analysis of SUGAR Truss-Braced Wing Wind-Tunnel Model Using FUN3D”
    4. Zhao, Wei [Virginia Tech], "Nonlinear Aeroelastic Analysis of SUGAR Truss-Braced Wing (TBW) Wind-Tunnel Model (WTM) under In-plane Load”
    5. Mallik, Wrik [Virginia Tech], "Aeroelastic Analysis and Optimization of Truss-Braced Wing Aircraft with Novel Control Effectors”
    6. Chen, P. C. [ZONA], "Low-Weight Low-Drag Truss-Braced Wing Design using Variable Camber Continuous Trailing Edge Flaps”
- AIAA Aviation, June 2015
  - Bartels, R., Scott, R., and Funk, C. “Analysis of Limit Cycle Oscillation Data from the Aeroelastic Test of the Boeing SUGAR Vehicle”

Flow Through Nacelle and Active Control Surfaces



Boeing Weight Results with Resized FEM

		Pre Test		Post Test	
	Config 1	Config 1	Delta	Config 1	Delta
	No Flutter	1.15VD		1.15VD	
Skins	5557.8	5689.1	131.3	6030.9	473.1
Spars	765.8	828.4	62.6	814.1	48.3
Ribs	705.4	718.3	12.9	724.2	18.8
Spar Caps	229.6	250.0	20.4	230.3	0.7
Rib Caps	160.9	174.2	13.3	170.1	9.2
Strut	787.1	889.6	102.5	1031.6	244.5
Jury	21.4	24.0	2.6	35.7	14.2
Gear Pylon 2D	3415.2	3415.2	0.0	3415.2	0.0
Gear Pylon 1D	125.2	125.2	0.0	125.2	0.0
Total	11768.4	12114.0	345.6	12577.3	808.9

Updated flutter penalty increases to 809 lb

Dynamically Scaled Model

Full-Scale Data - Full Span Values				
Weight (lb)	Span (ft)		Mach	Vel (KEAS)
143164	170		0.82	400

Full-Scale Data - Half Span Values							
Weight (lb)	Span (ft)	Mach	Altitude (ft)	Dyn Pres (psf)	Density (s/cf)	Velocity (fps)	Re
29530	85	0.8200	15915.36	542.47	0.001451	864.56	4.35E+07

Basic Scale Factors			Derived Scale Factors					
Length	Density	Velocity	Mass	Acceleration	Force	Stiffness	Frequency	Dyn Pres
0.150	1.1000	0.5211	0.003713	1.8103	0.006721	1.5122E-04	3.4740	0.2987

R134a

Model-Scale Data						
Weight (lb)	Span (ft)	Mach	n Pres (psf)	Density (s/cf)	Velocity (fps)	Re
109.63	12.75	0.820	162.03	0.001597	450.52	5.07E+06

Truss-Braced Wing: Wing Weight Uncertainty

Phase I Findings

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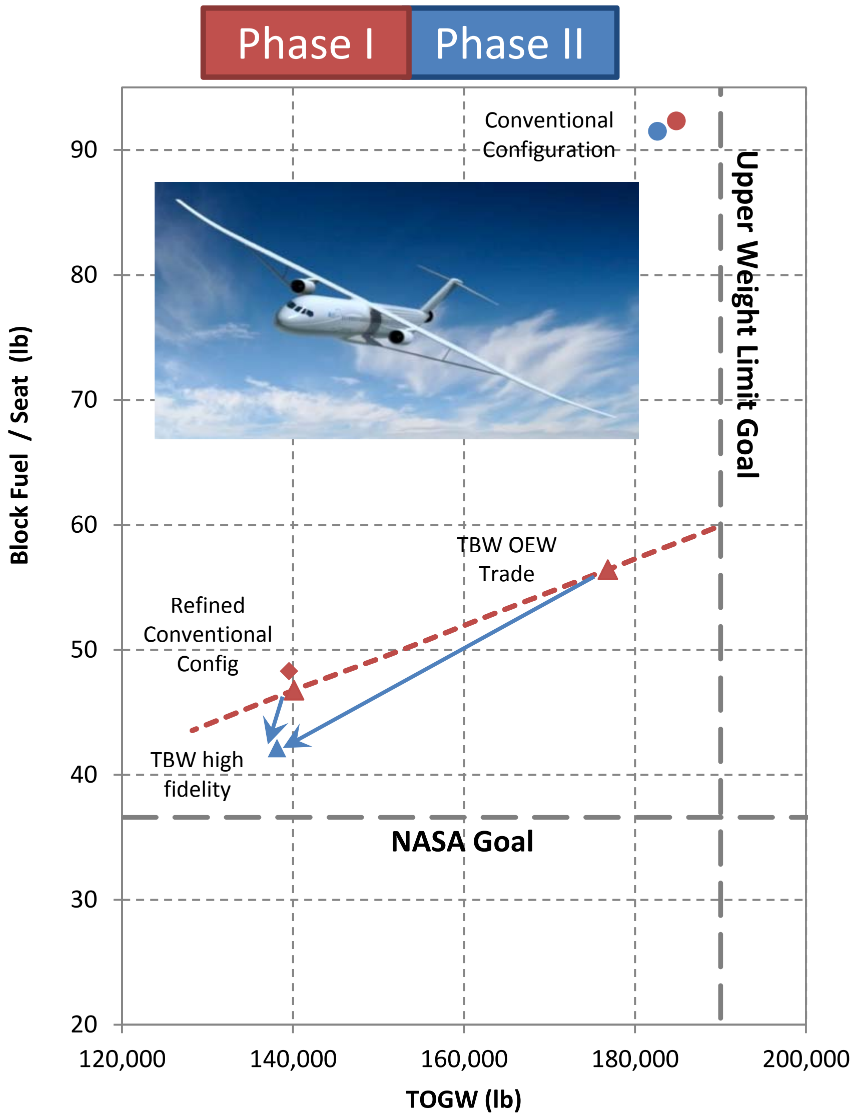
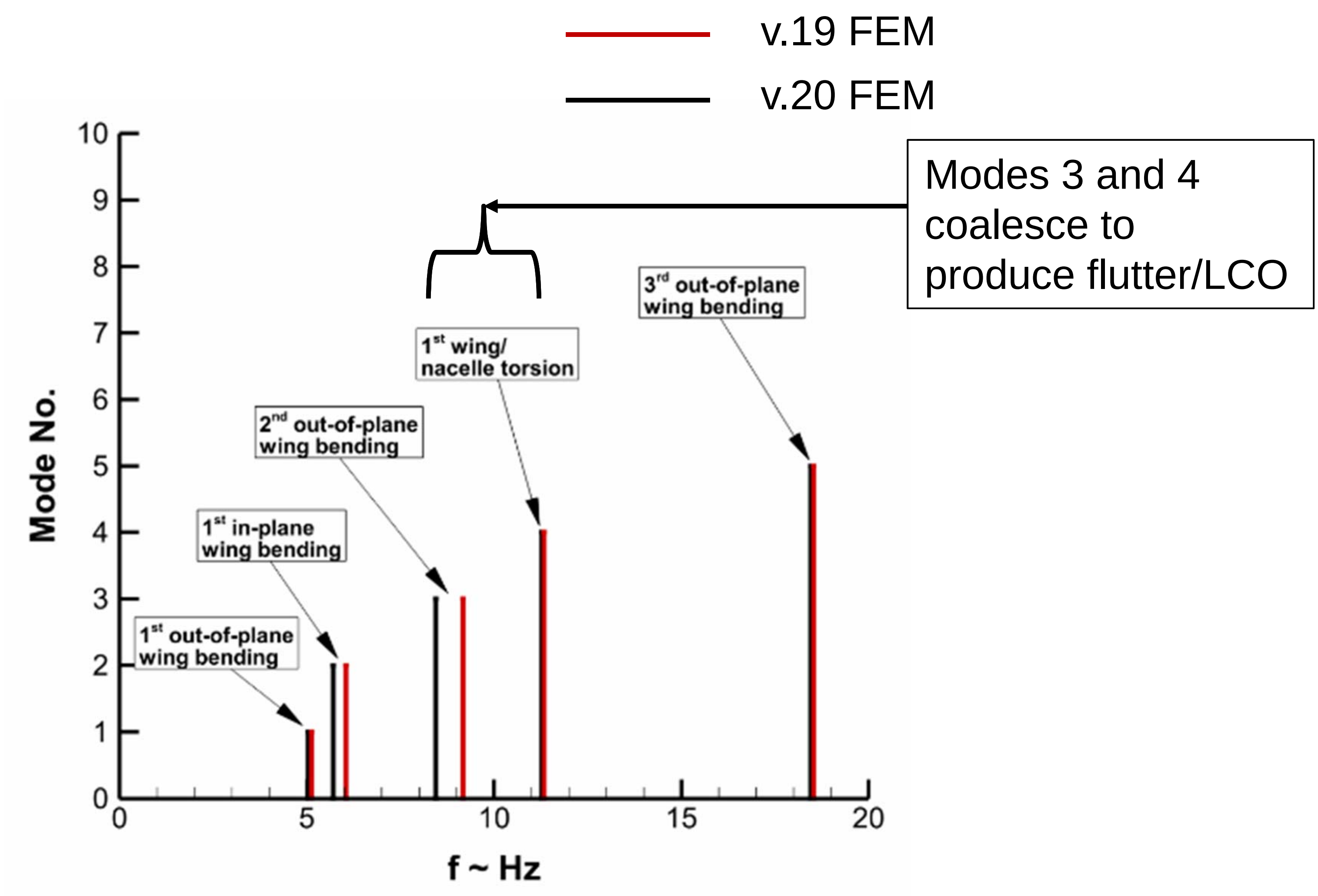
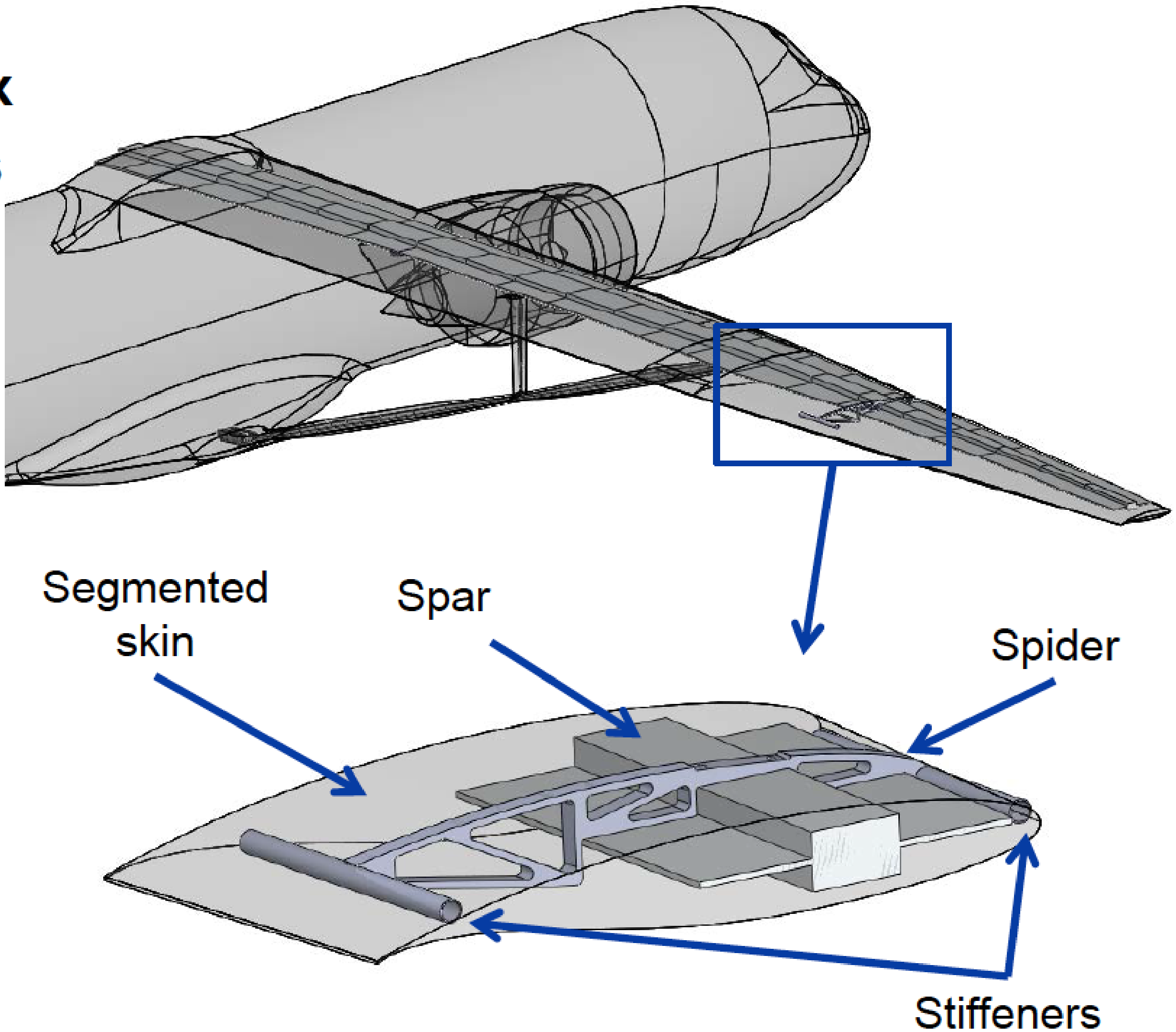


FEM 19 and FEM 20 Differences

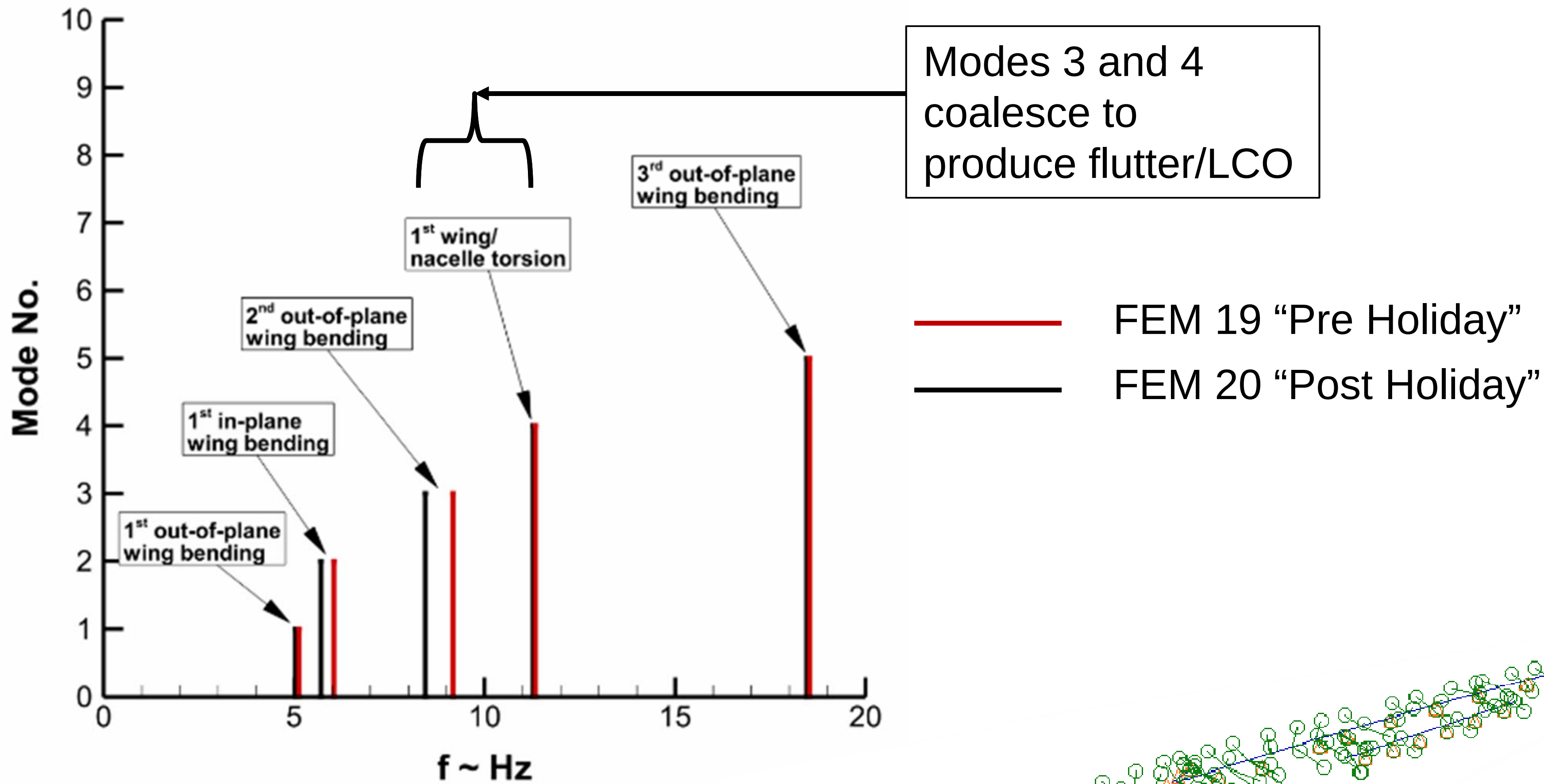


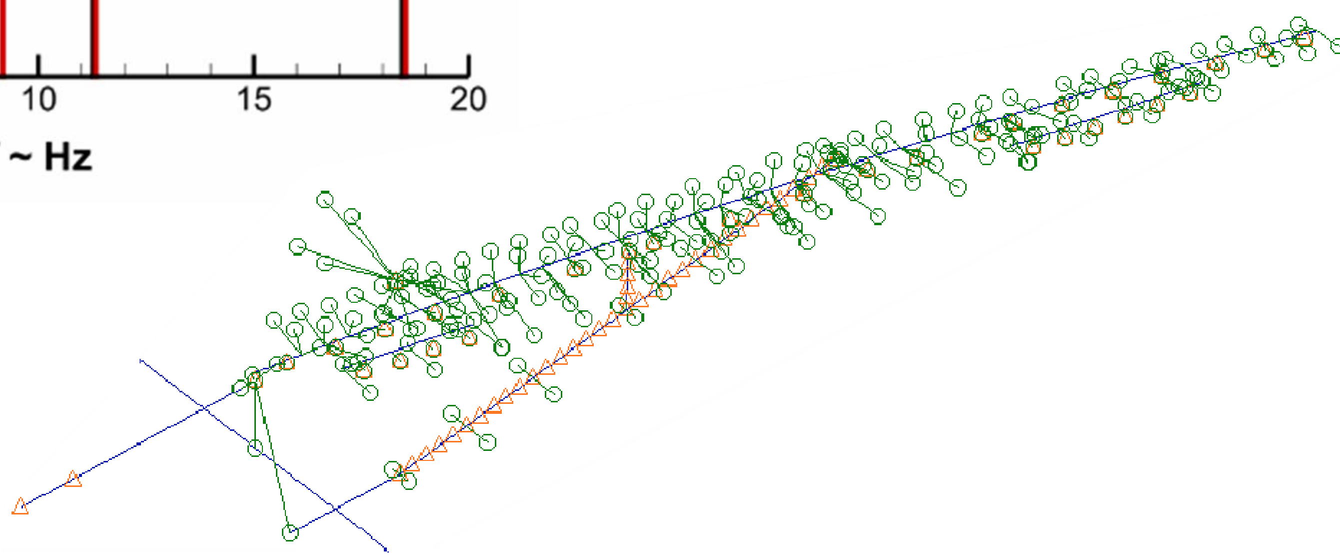
Skin / Pod Design

- Skin created from carbon \ epoxy matrix
- Segmented into pods to prevent stiffness addition to spar
- Attached to spar via ribs, which provide support along the entire chord
- Additional optional skin reinforcement provided by stiffener tubes, located at leading and trailing edges

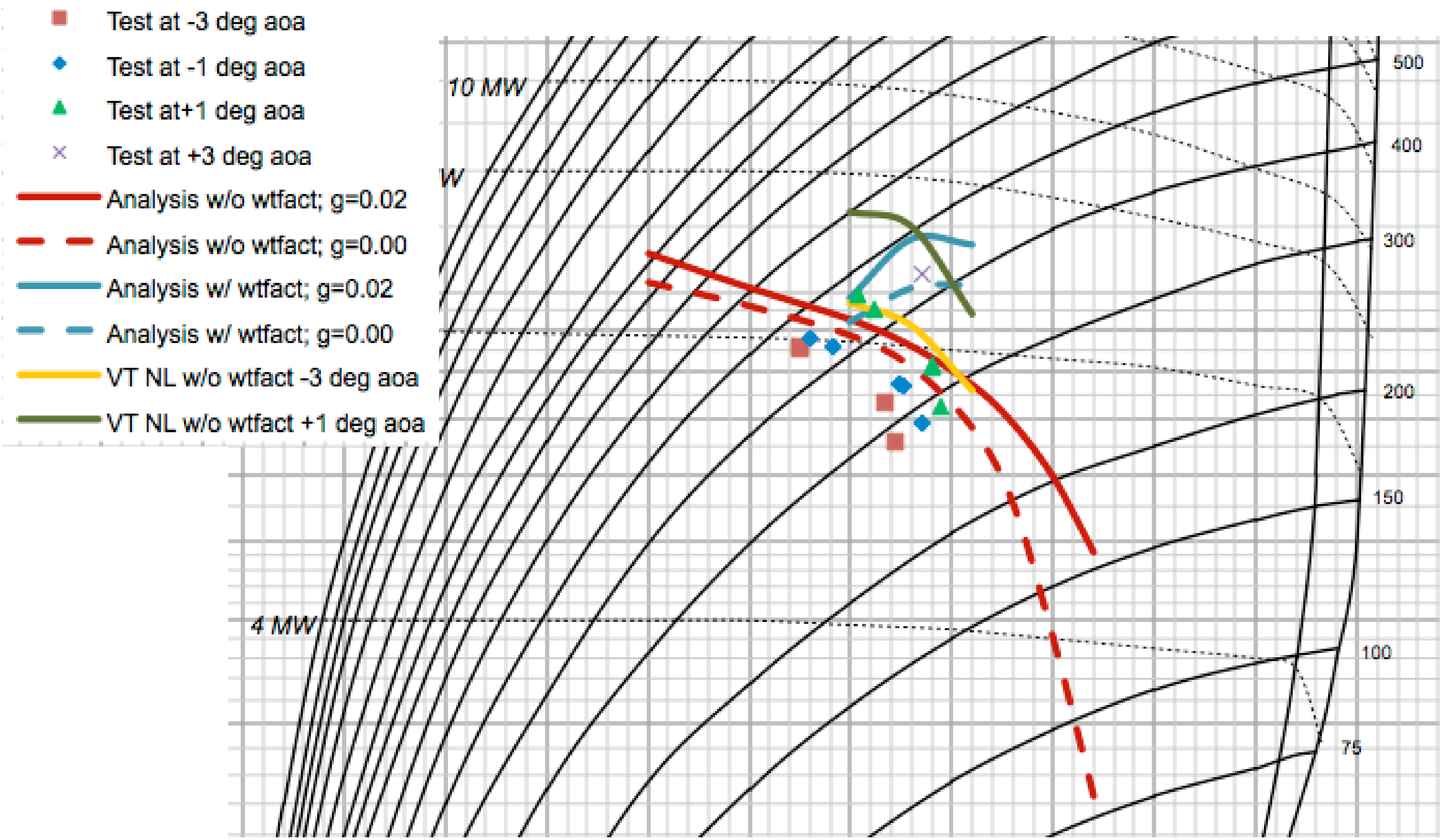


Wind-TunModel FEMs

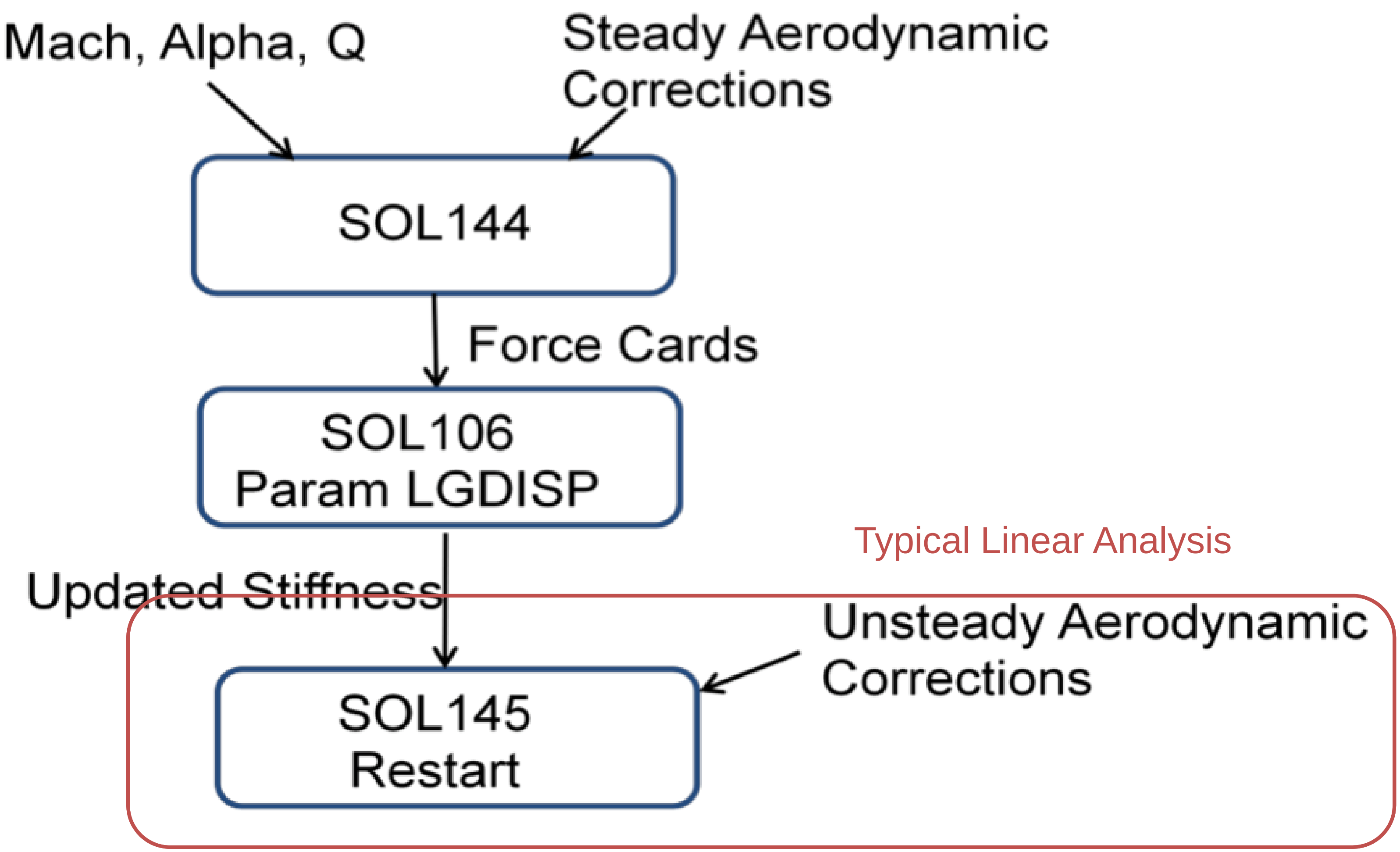




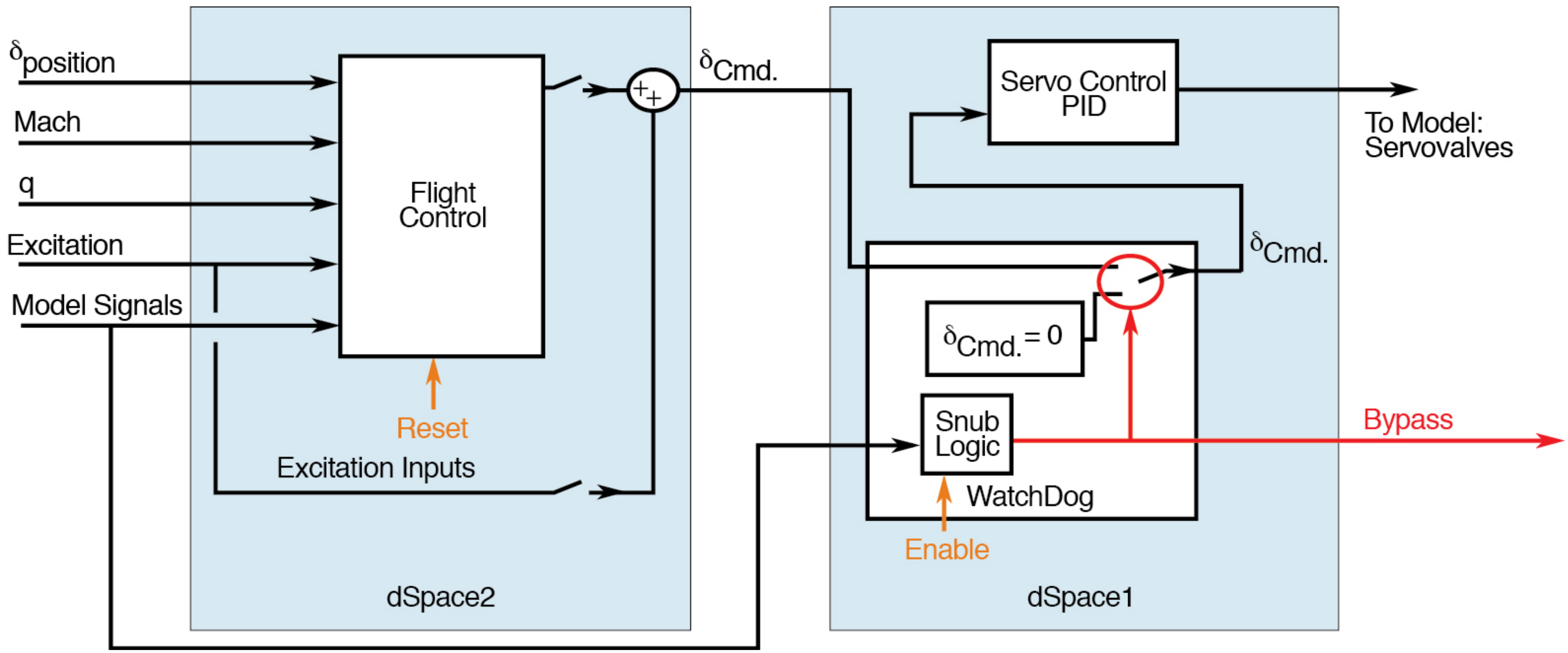
Pre-Holiday Flutter w/ NASTRAN Analyses



NASTRAN Flutter Analysis



Control Systems



Control Law Design Block Diagram