National Aeronautics and Space Administration

The Boeing SUGAR Truss-Braced Wing Aircraft: Wind-Tunnel Data and Aeroelastic Analyses

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April 16, 2015

Outline

- Context and objectives
- Wind tunnel testing and validation data
- Analyses
  - Structural Models
  - Aerodynamic Modeling
  - Mode Shape Transfer Between Dissimilar CSD/CFD Models
  - Results
    - Flutter Simulations with Linear Aerodynamics
    - Sensitivity to structural model and angle of attack
- Conclusions

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TBW Context in Fixed Wing Project

Goals Metrics (N+3)	Noise Stage 4 – 52 dB cum	Emissions (LTO) CAEP6 – 80%	Emissions (cruise) 2005 best – 80%	Energy Consumption 2005 best – 60%

Goal-Driven Advanced Concepts (N+3)

Research Theme 2: Higher Aspect Ratio Optimal Wing

Future wings will be of higher aspect ratio, lighter, more flexible, and have varying degrees of laminar flow to reduce drag and improve performance

Technical Challenge 2.1 Higher Aspect Ratio Wing

Enable a 1.5-2X increase in the wing aspect ratio with safe structures and flight control (TRL 3)

FY09	FY10	FY11	FY12	FY13	FY14	FY15	FY16

- Phase I, started April 2008
- Phase II, 4 years
- Truss Braced Wing Concept refinement — Boeing
- FEM / Update FEM — Boeing
- TBW model & TDT test — LaRC, Boeing
- Aero Perf. Test, task ends April 2016 — Boeing

BR&T, BCA, GE, GT, VT, NextGen, MicroCraft

TBW Phase I Findings, Phase II Objectives

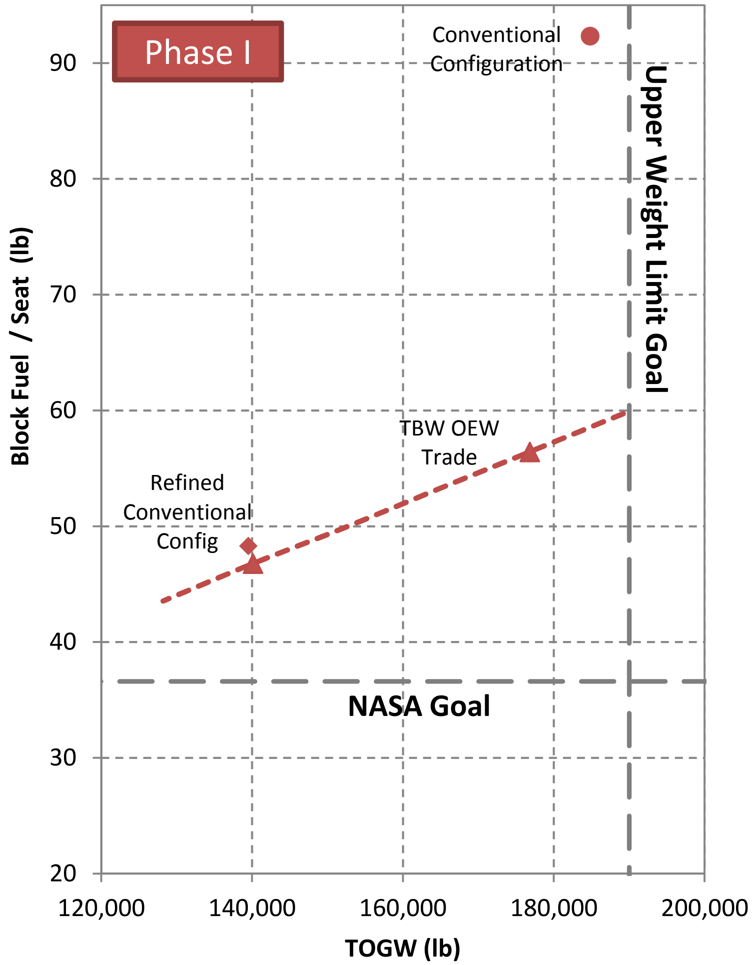
<u>Phase I</u> – Design Study of TBW Configuration

- 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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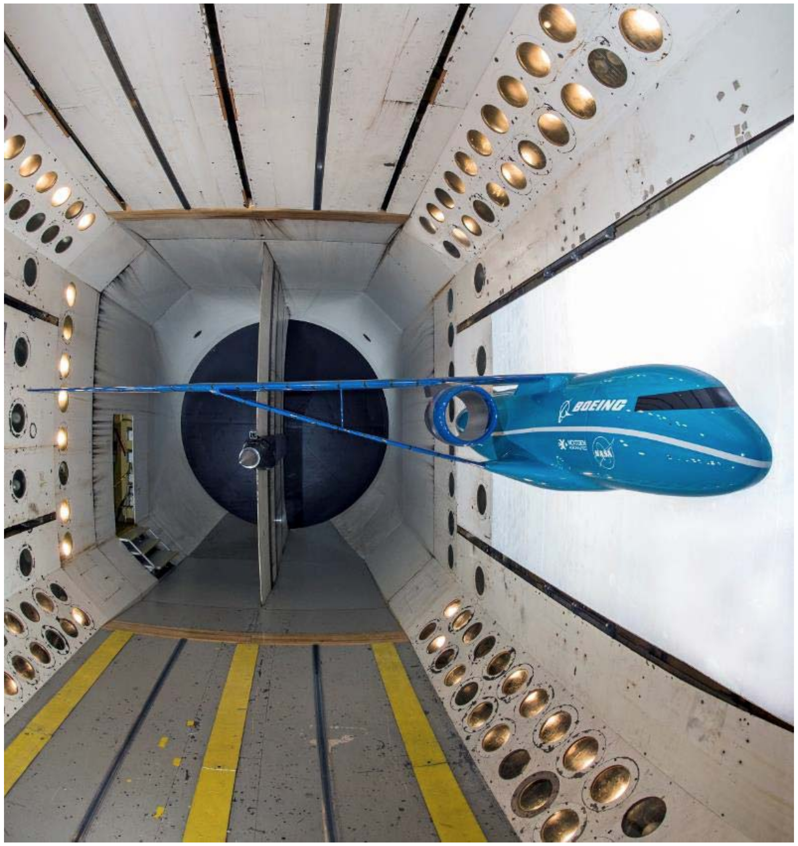
Wind-Tunnel Test Objectives

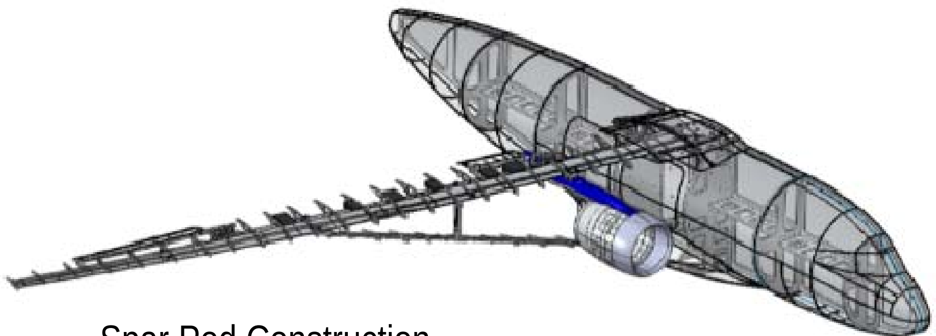
- Determine Experimental Flutter Boundaries

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



TBW Aeroelastic Wind-Tunnel Model

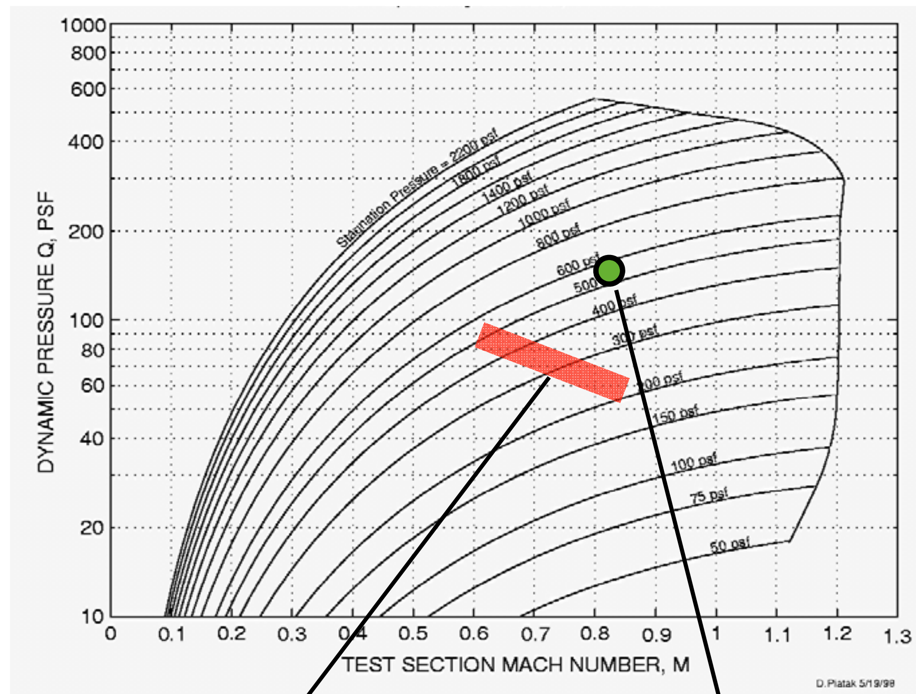
Full-Scale Design Point:
- Mach = 0.82
- Altitude = 15,915 ft
- Span = 170 ft
- Weight = 143,164 lb



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

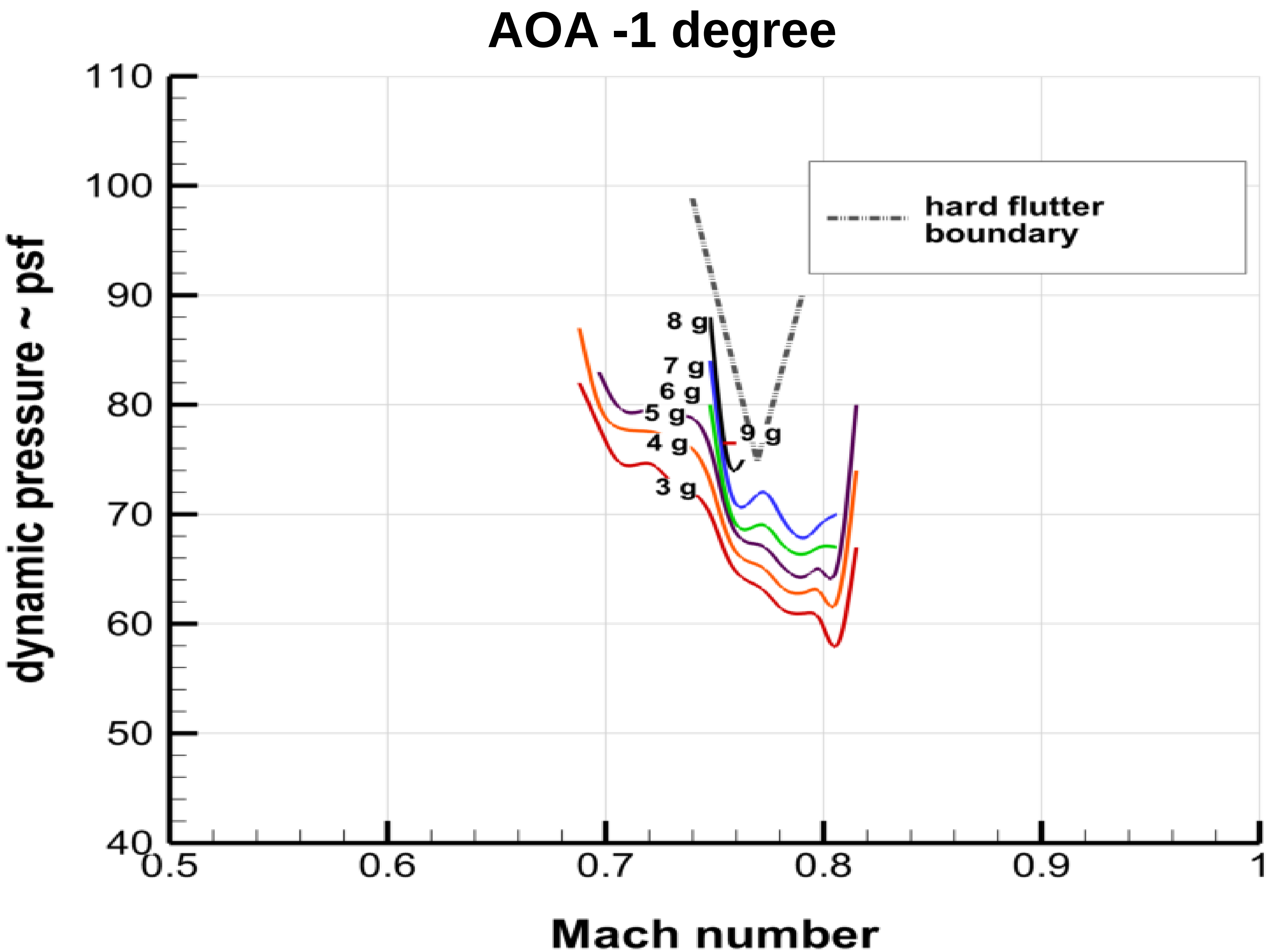


Predicted Flutter Boundary

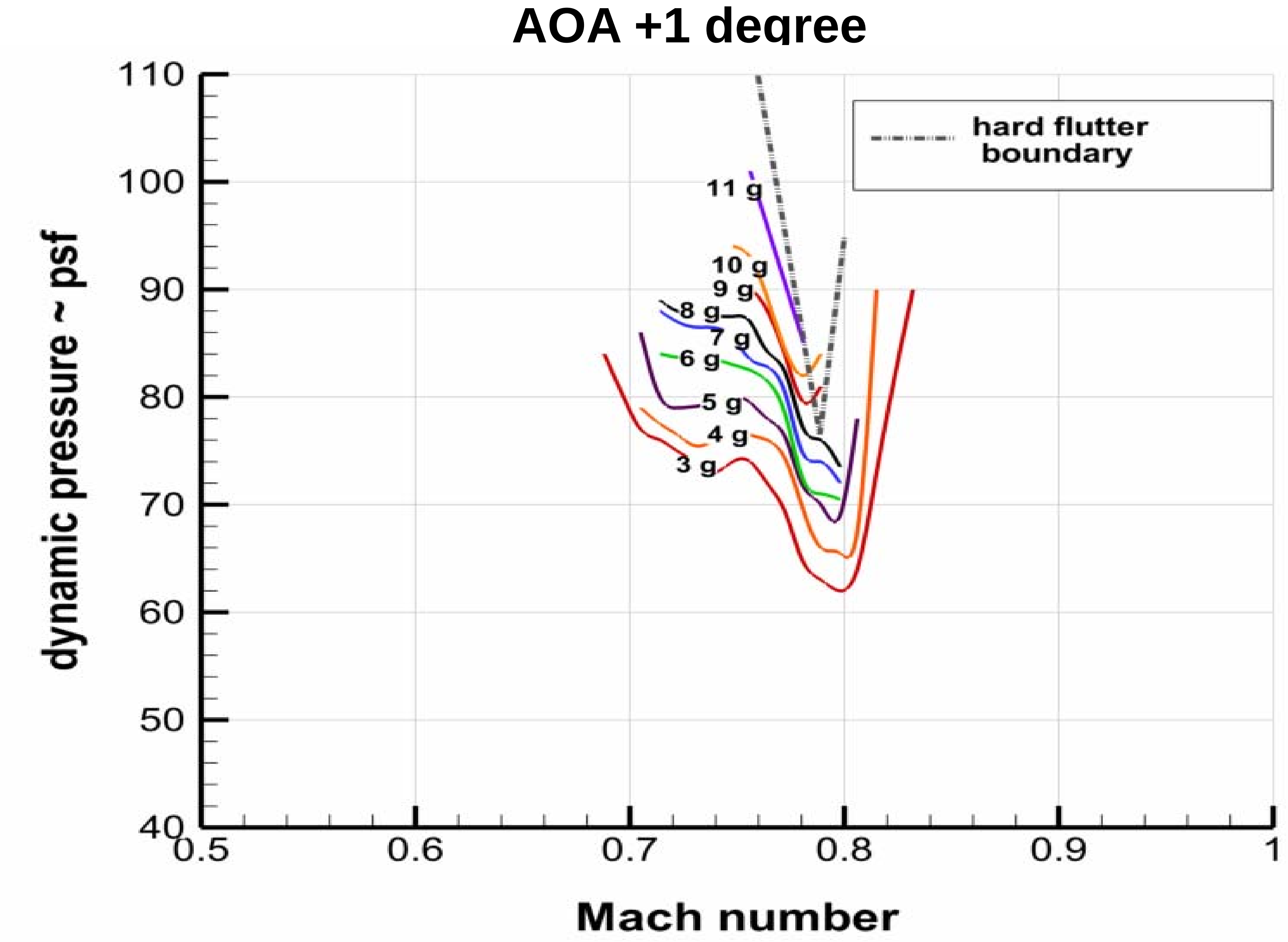
Model Design Point
- Gas = R134a
- Scaled Weight = 109.63 lb
- Mach = 0.82
- Q=162 psf

NextGen Aeronautics

TBW Wind-Tunnel Model Wing Tip Accelerations



TBW Wind-Tunnel Model Wing Tip Accelerations



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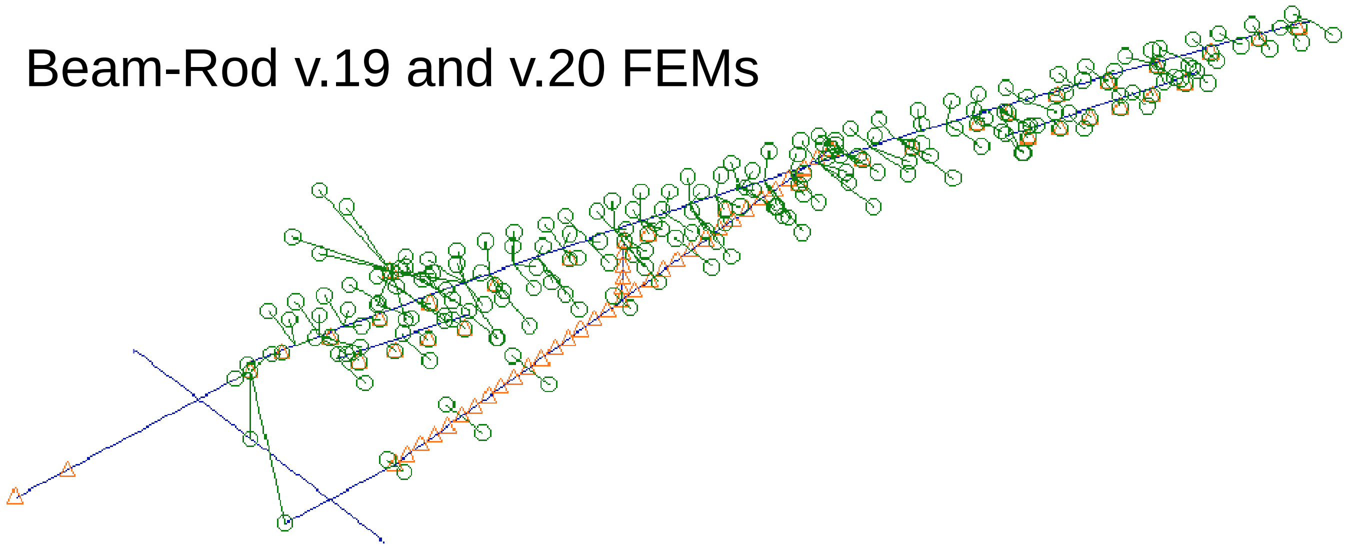
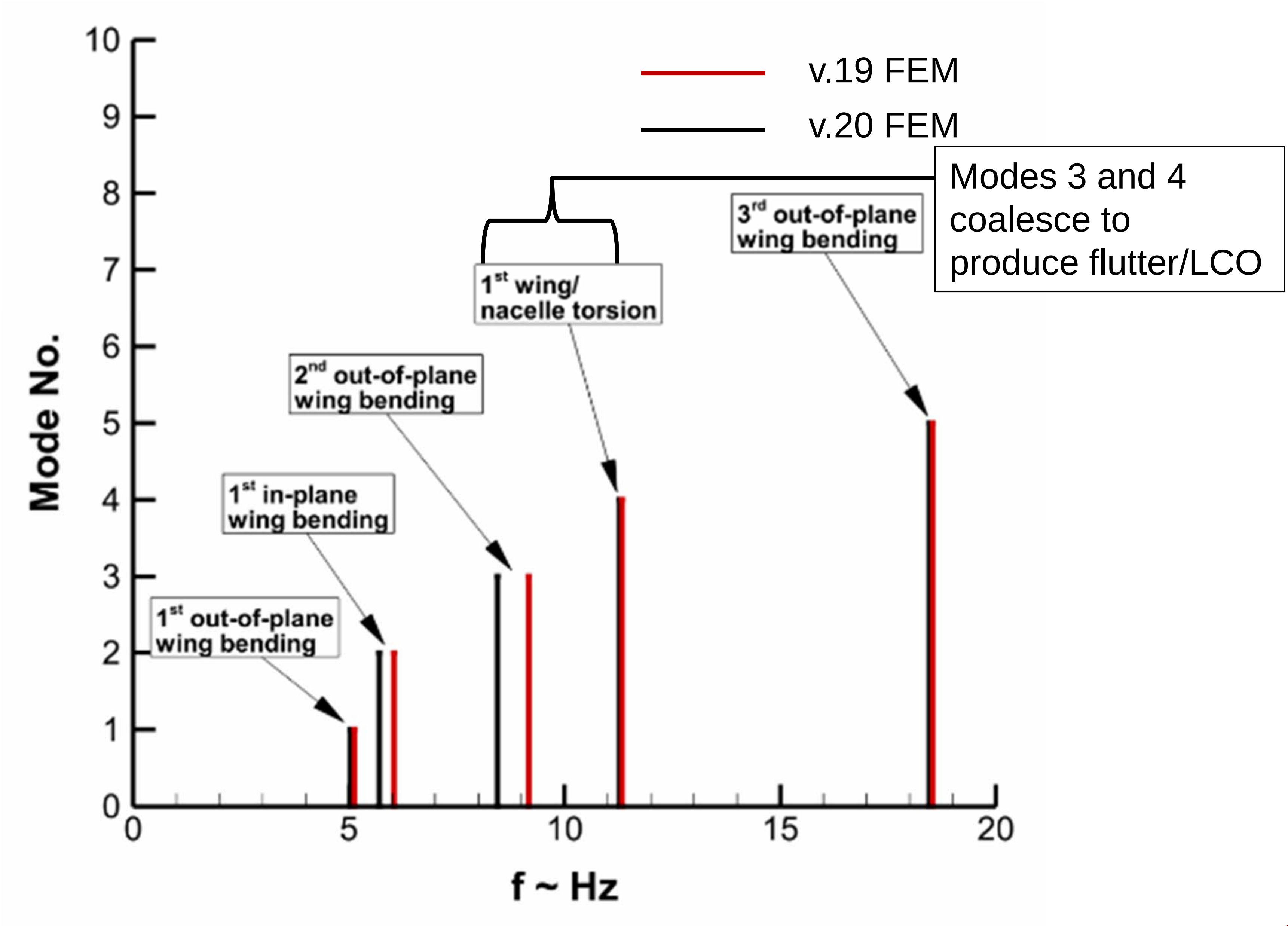
Structural Models

Beam-Rod v.19 and v.20 FEMs



- V.19 FEM was updated with *before-test* ground vibration test (GVT) data.
- V.20 FEM was updated with *after-test* GVT data.
  1. Correlation of mode 3 was improved by decreasing bending stiffness on the strut attachment beam and on certain wing elements.
  2. Correlation of mode 4 was improved by adjusting torsional stiffness on inner wing elements.

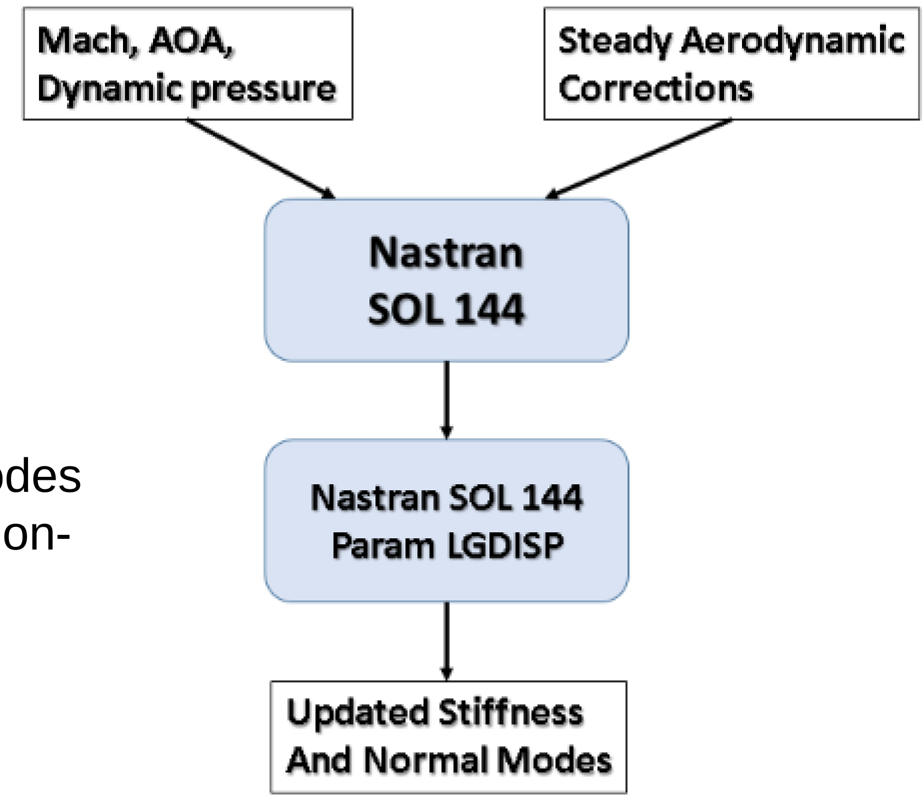
Structural Models



Structural Models

- Cases at zero degrees AoA use unloaded structural modes.

- Cases at +1 and -1 degree AoA use structural modes derived from a nonlinear loaded static solution. i.e., modes derived from a geometrically non-linear structure.



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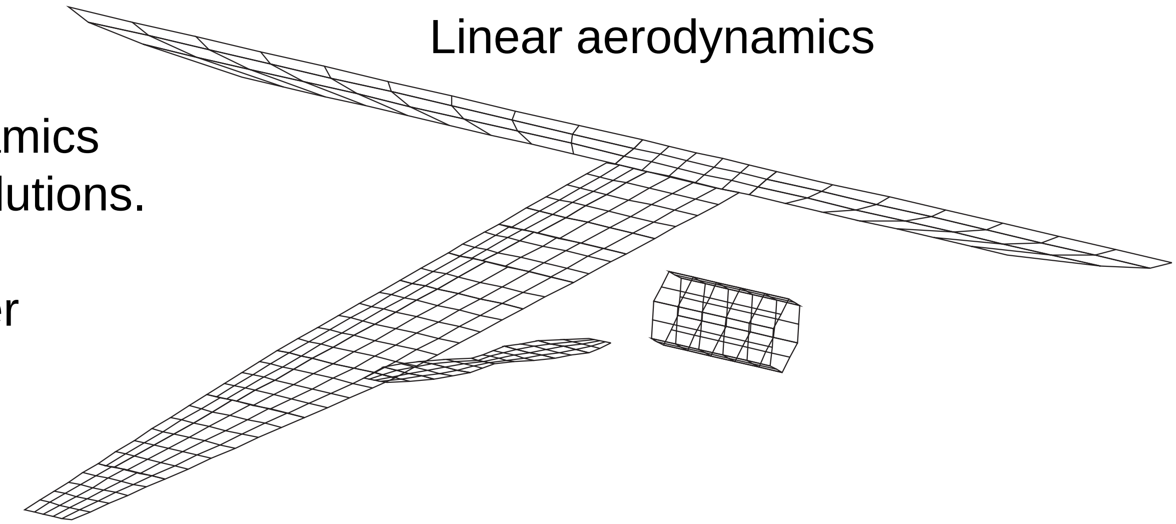
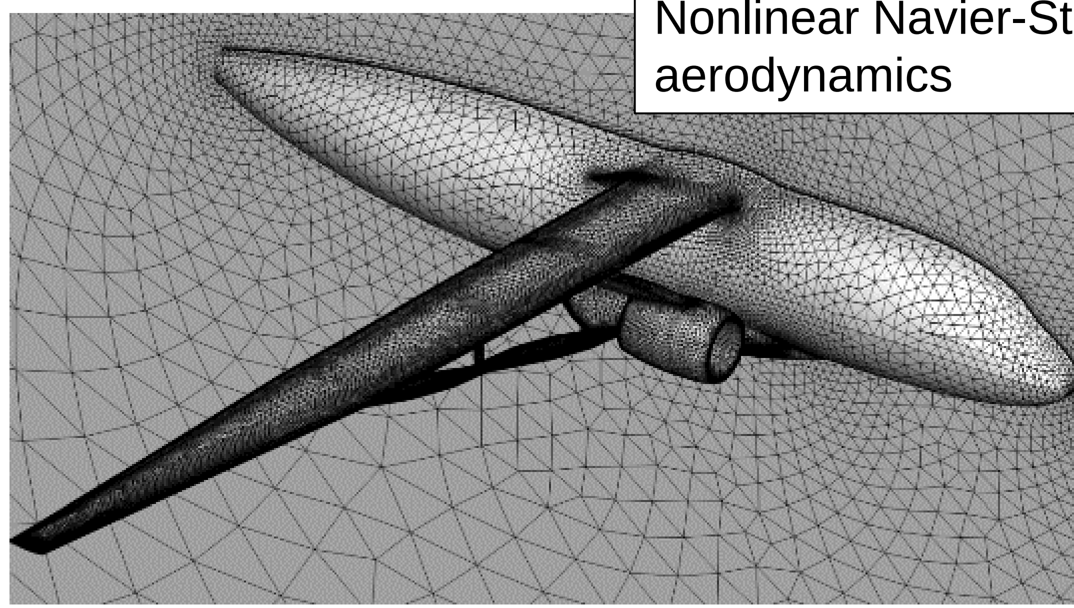
Aerodynamic Modeling

Linear aerodynamics



- Vortex-lattice aerodynamics for static aeroelastic solutions.
- Doublet-lattice for flutter solutions.

Nonlinear Navier-Stokes aerodynamics



- The Navier-Stokes grid has 4.5 million nodes.
- The wind-tunnel wall is treated as a symmetry plane.

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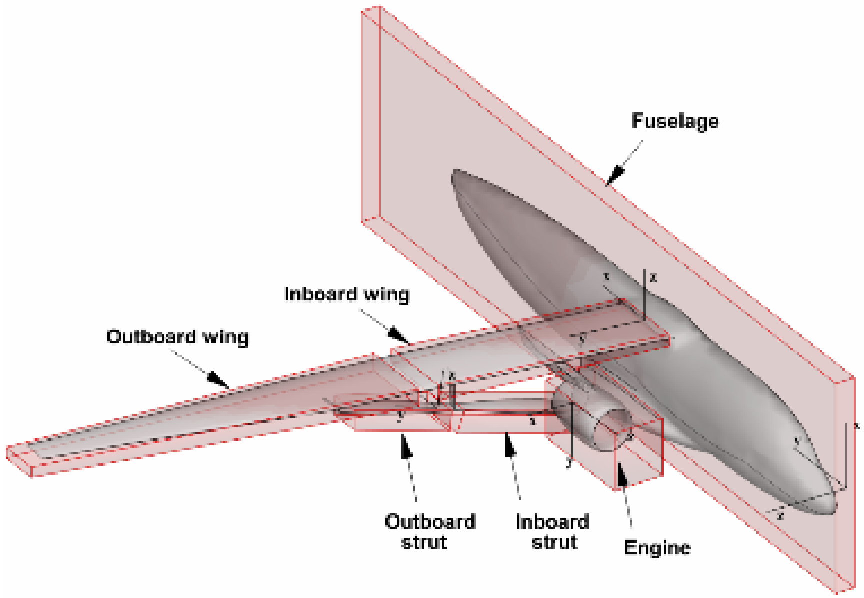
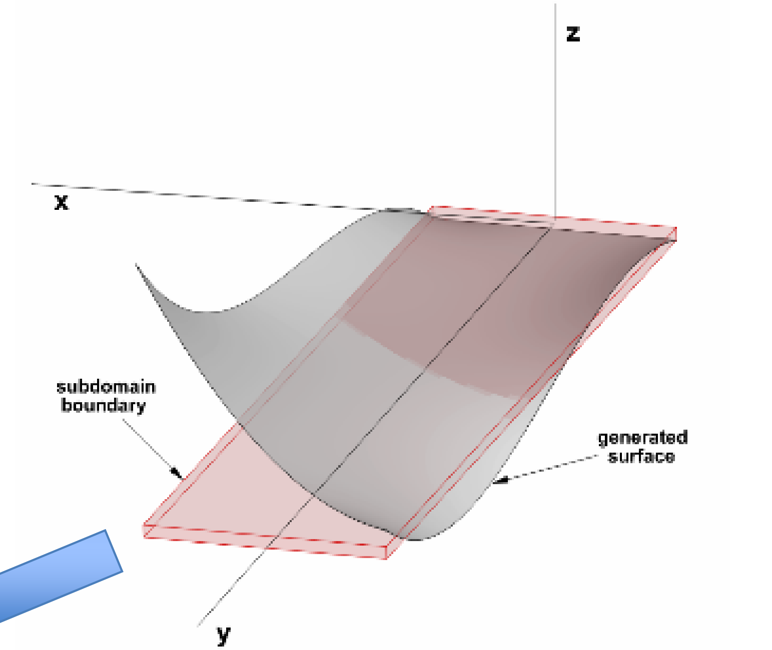
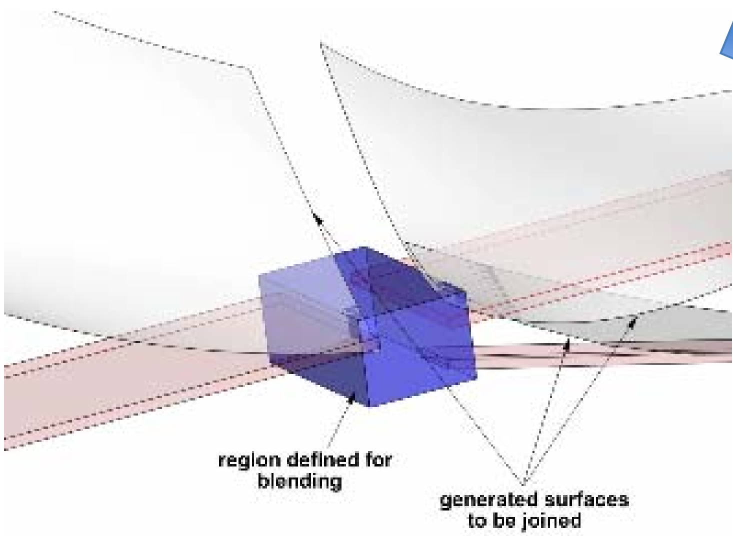
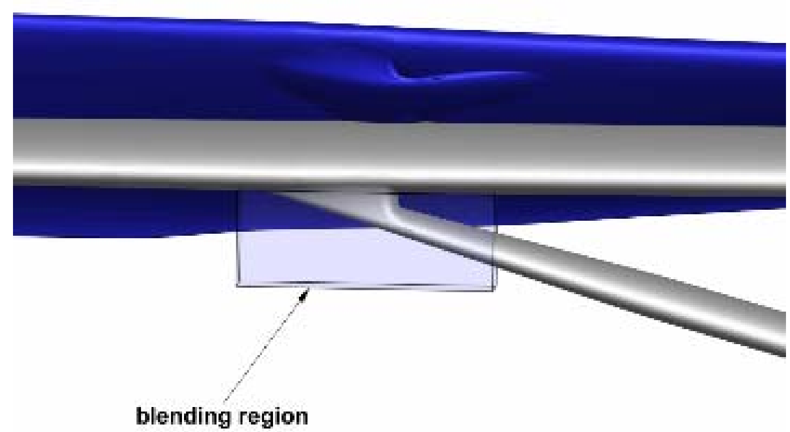
Mode Shape Transfer Between Dissimilar CSD/CFD Models









Final (blue) and initial (gray) surfaces

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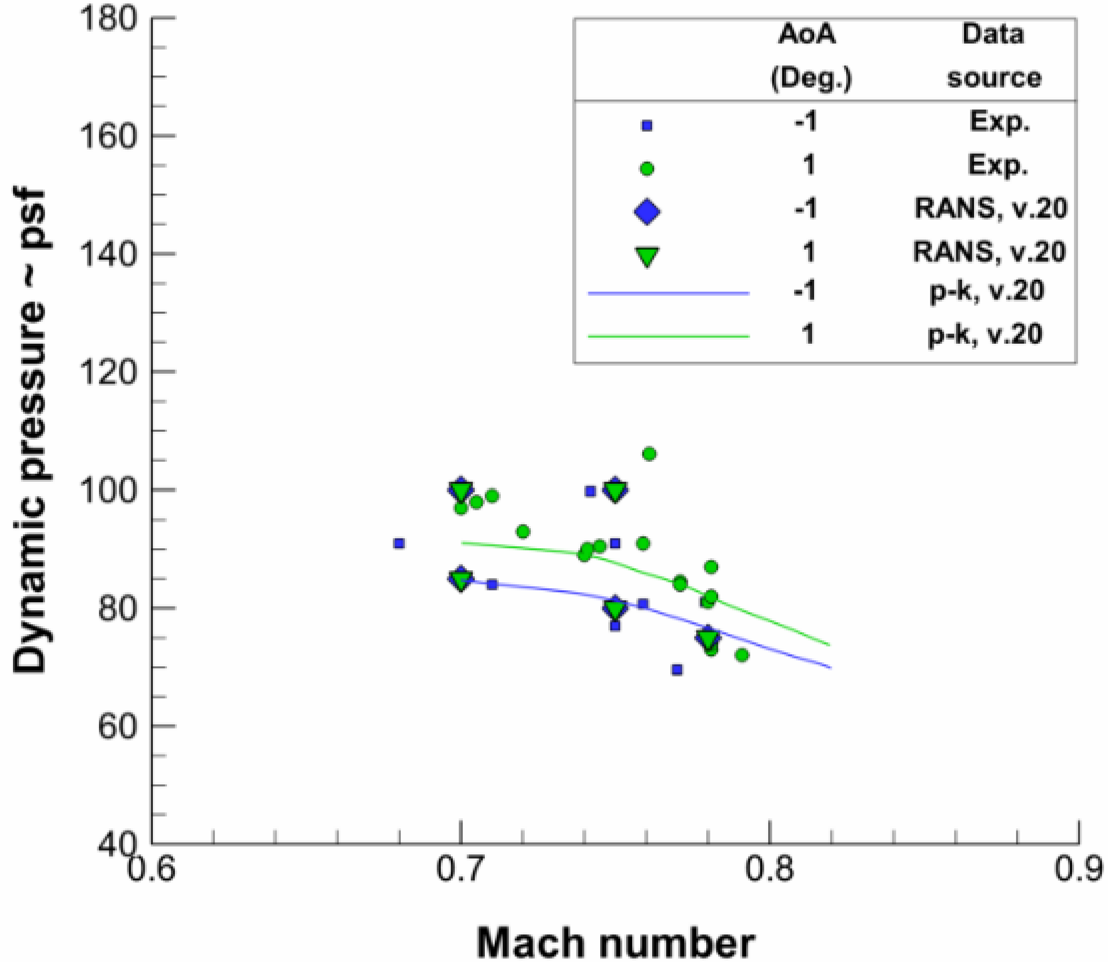
Results – Linear Aerodynamics

- Flutter simulations with linear aerodynamics
- Conditions at which Navier-Stokes simulations are performed
- All conditions in this figure are at -1 or +1 degree AoA.
- Static wing and strut loading influences the dynamic pressure at which flutter occurs.
- Note that experimental conditions are also included for reference.



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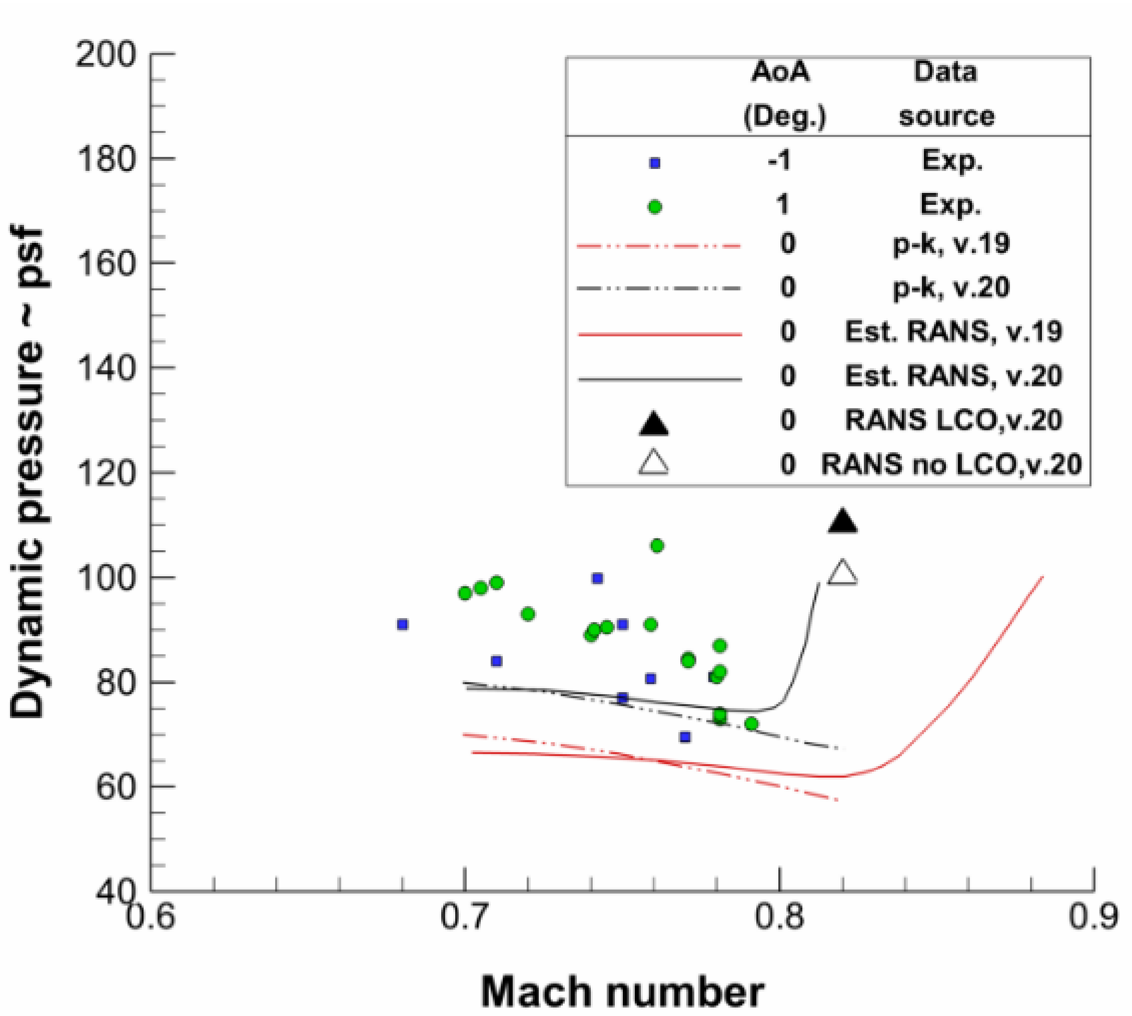
Results – Comparison of v.19 and v.20 FEM

- Time step and sub-iterative convergence of RANS solutions was studied in Bartels et al. (2014)

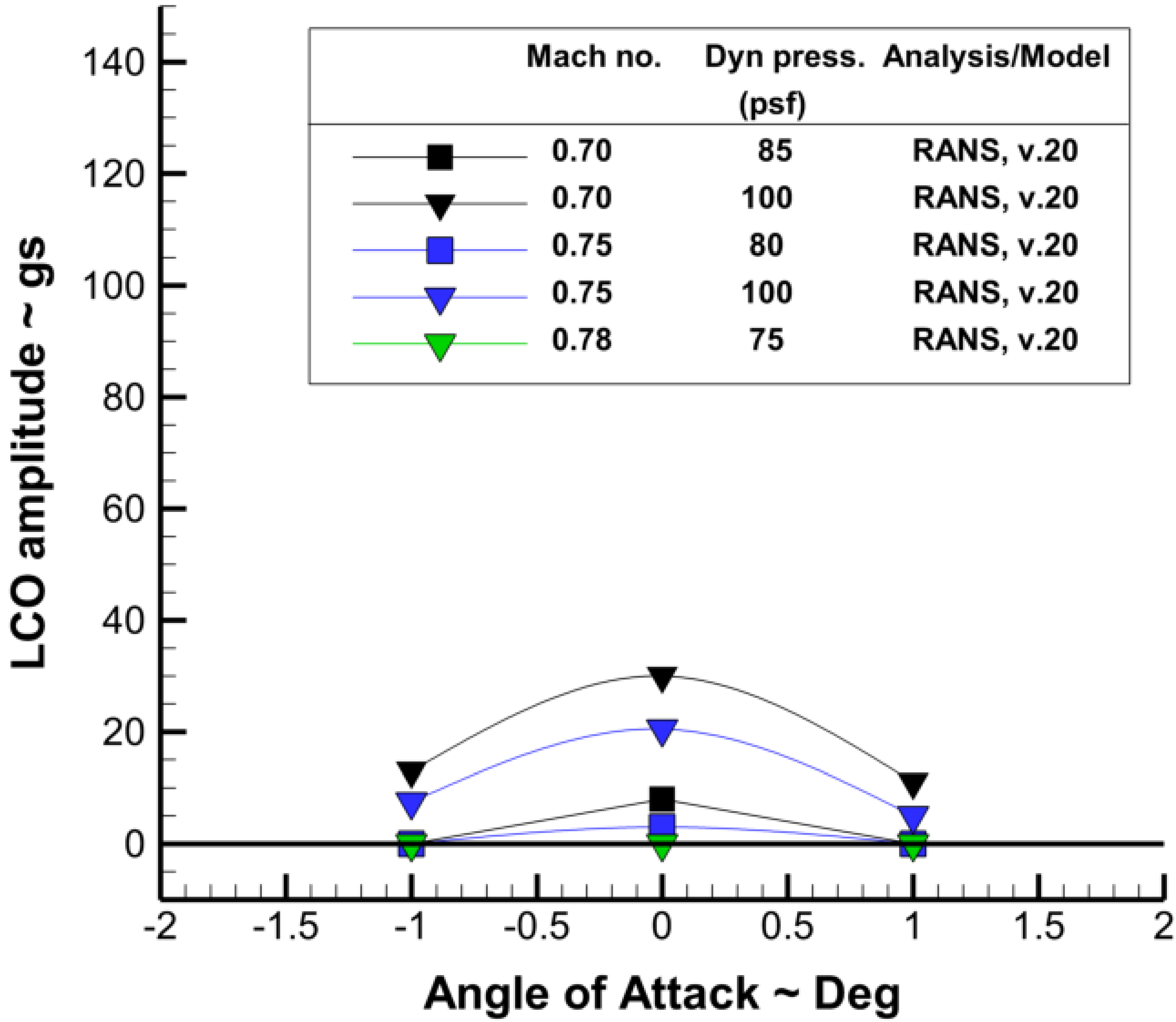
- Comparison is made between the v.19 and v.20 TBW FEMs at 0 AoA.

- Flutter occurs for the v.20 FEM at a higher dynamic pressure due to larger separation of mode 3 and 4 frequencies.

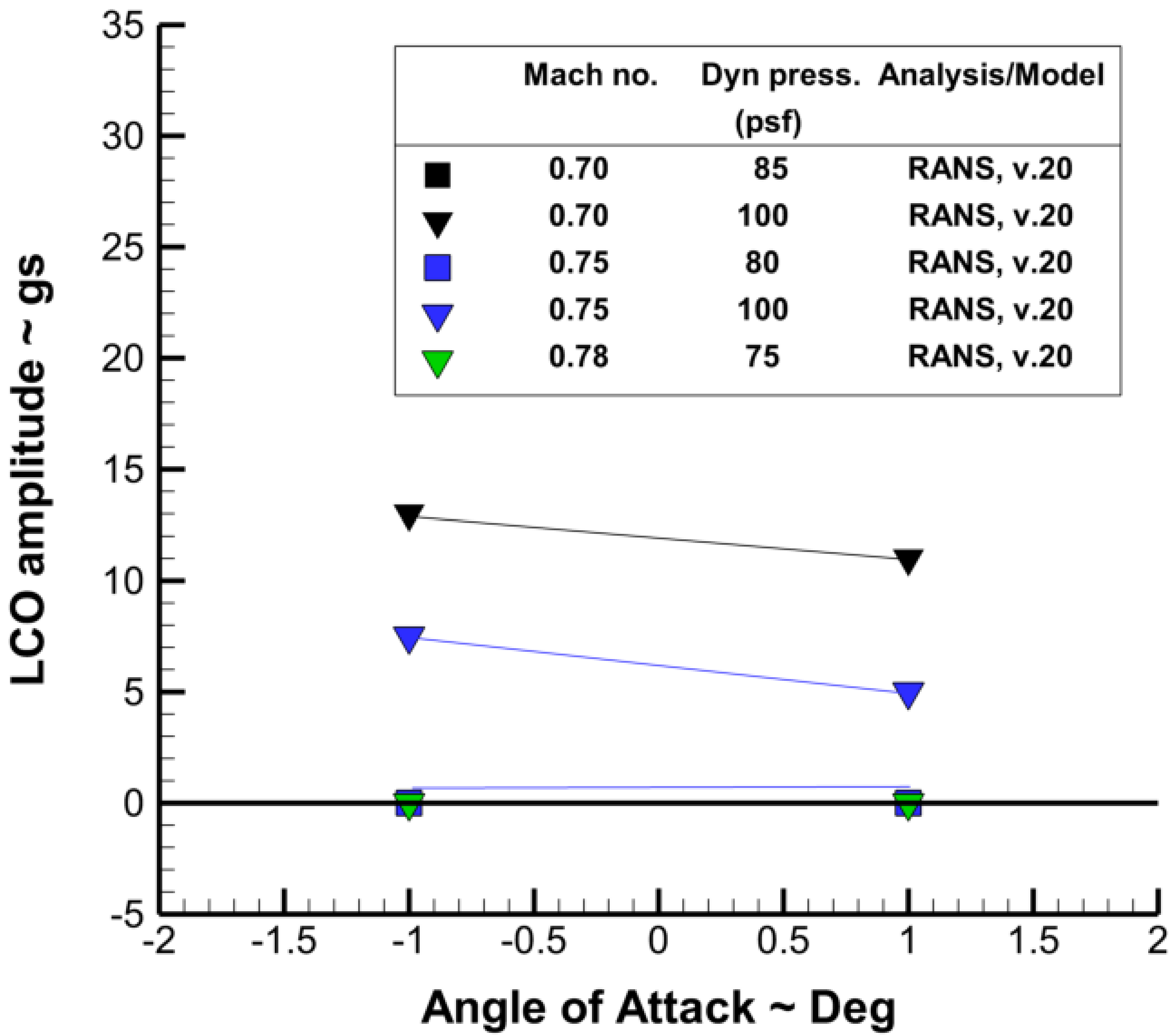
- The shape of the v.20 flutter onset above Mach 0.80 is different than the v.19 FEM flutter onset.



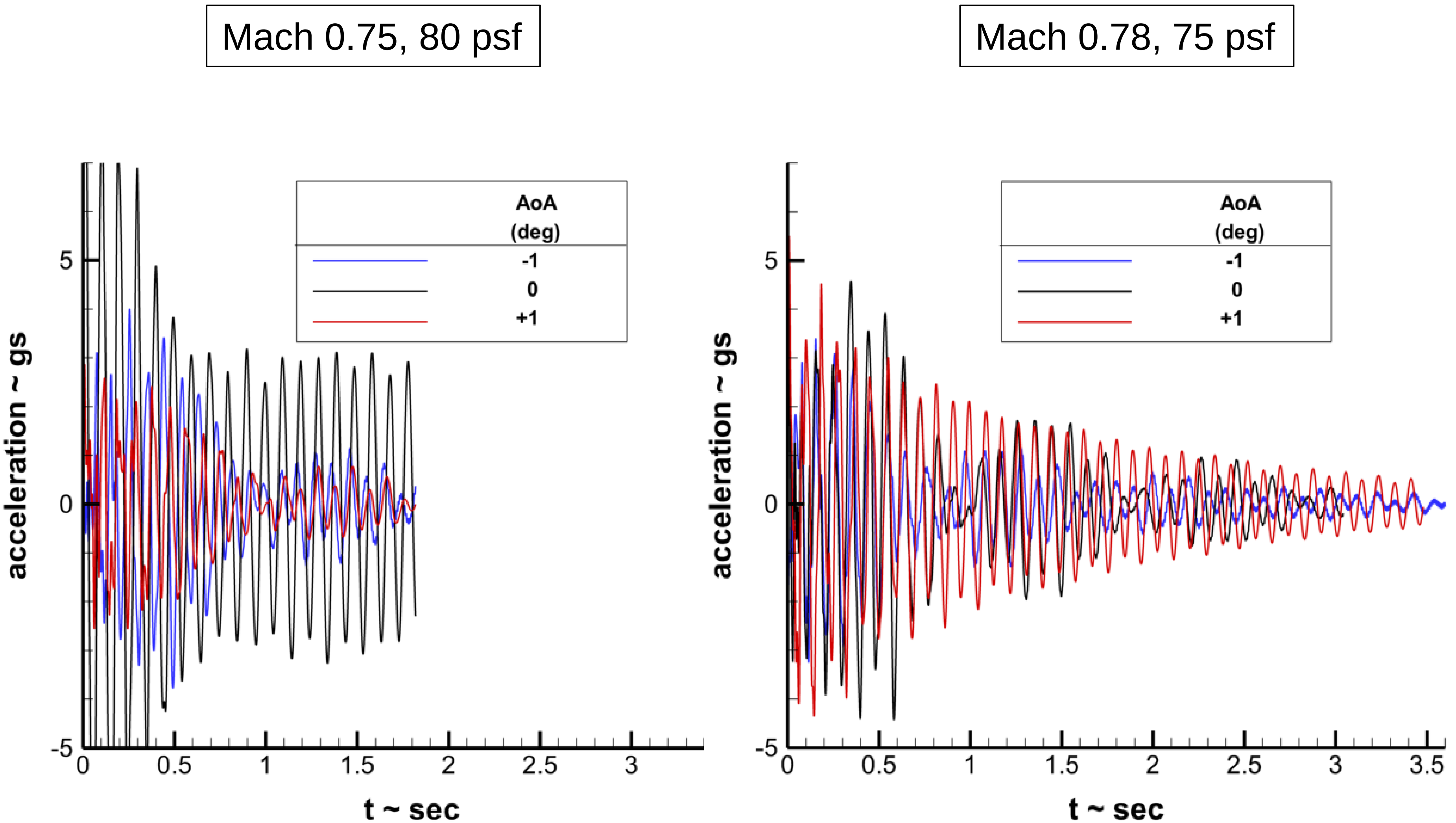
Results – Comparison, AoA -1, 0 and +1 deg



Results – Comparison, AoA -1 and +1 deg



Results – Comparison, AoA -1 and +1 deg



Conclusions

- Conclusions that can be clearly made:

  1. Angle of attack and model sensitivity is predicted well with linear aerodynamics and a static nonlinear structural model.
  2. LCO is predicted with nonlinear aerodynamics (Navier-Stokes) and linear dynamic structural model
  3. Flutter and LCO onset are quite sensitive to the mass and/or stiffness distribution of the wing.
  4. Force/displacement transfer between fluid and structure meshes requires algorithms that can accommodate complex beam structures models and fine CFD mesh spacing.

- Somewhat tentative conclusions:

  1. A better refined CFD mesh may enable better correlation of simulated LCO onset with experiment.

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