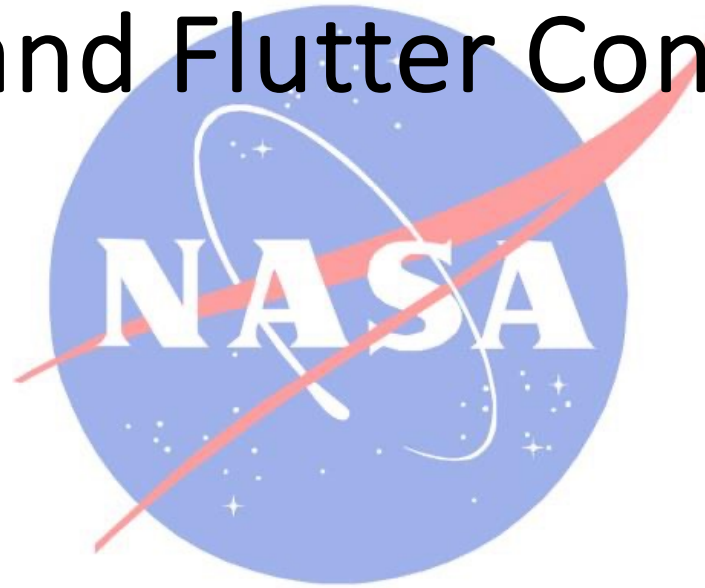


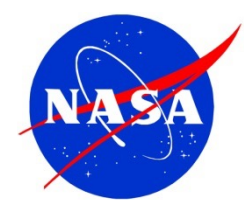


# Gradient-based Optimization of the Common Research Model Wing Subject to CFD-based Gust and Flutter Constraints



Andrew Thelen, Kevin Jacobson, Bret Stanford

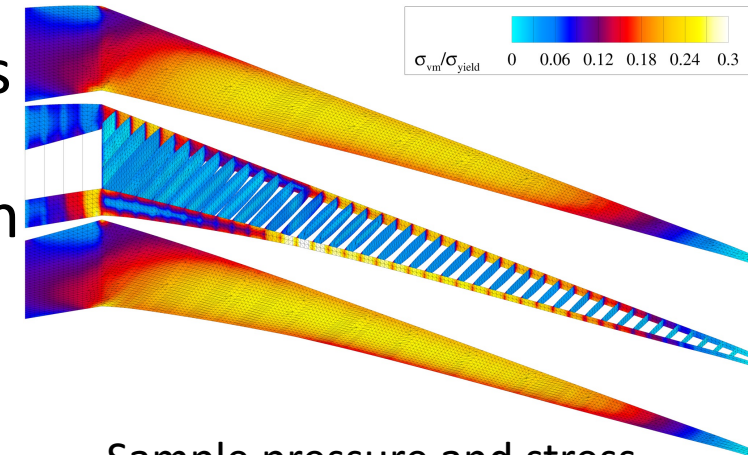
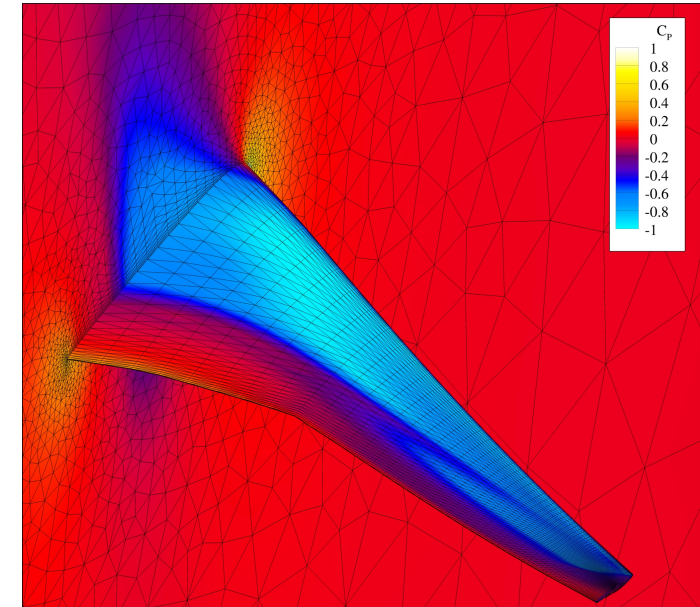
NASA LaRC, Aeroelasticity Branch



# Objective



- Frequency-domain flutter and gust constraints have recently been implemented in OpenMDAO/MPhys
  - Panel-based aerodynamics via Doublet Lattice Method (DLM)
  - CFD-based via FUN3D Linearized Frequency Domain (LFD)
  - Both have analytic derivatives for gradient-based optimization



- Previously, optimization with LFD-based constraints was only demonstrated on the AGARD 445.6 wing
- Current work seeks to demonstrate these constraints on a more industry-relevant design case: the Common Research Model (CRM) wing
  - Prior work at AIAA SciTech 2024 showed only DLM-based constraints

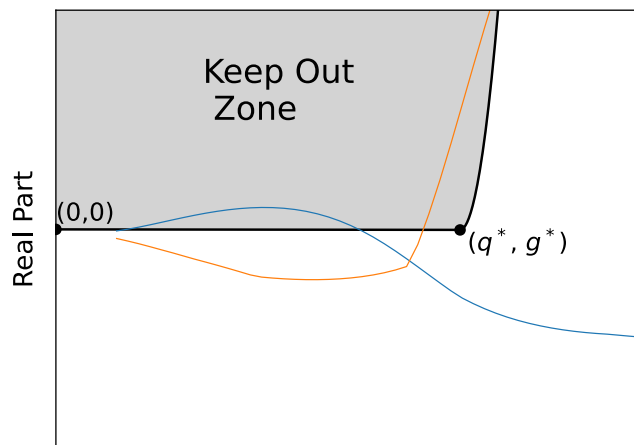
Sample pressure and stress



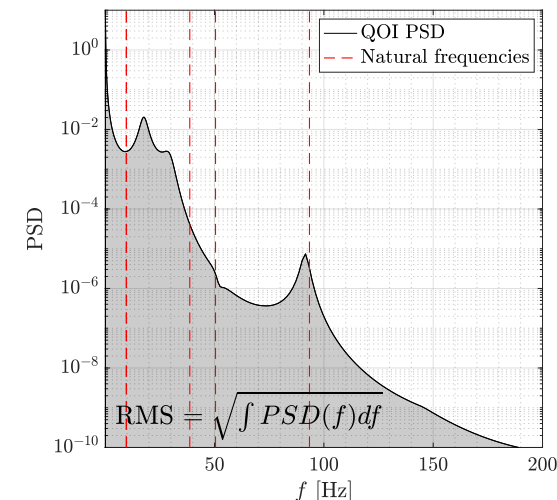
# Flutter and Gust Constraint Formulations



- Flutter is enforced via Kreisselmeier-Steinhauser (KS) damping aggregate
- Gust is enforced via steady root bending moment plus stochastic gust-induced RMS at cruise
  - Dryden gust spectrum to model atmospheric velocity perturbations
  - Step towards enforcing gust-induced stresses, which would require rational function approximation for accurate stresses from modal decomposition
  - Upper limit based on initial load factors and stress KS



Dynamic Pressure  
Notional  $p$ - $k$  damping



Notional PSD due to gust



# CRM Optimization Problem



- Two flight conditions based on CRM literature: 1g cruise, 2.5g pull-up
- One flight condition for transonic flutter: 1g cruise altitude, Mach 0.9
  - Only for FUN3D optimization; DLM-based cases use Mach 0.85 cruise conditions
- **738 design variables:** 720 structural, 14 shape, 3 aerodynamic, 1 fuel scaling
- **12 constraints:** 1 flutter, gust, & stress, 3 load factor, 1 consistency, 5 other geometric/mission
- Present FUN3D case is compared to two DLM-based shown in prior work:

| Description | Steady aerodynamics | Unsteady aerodynamics | Transonic flutter constraints                  |
|-------------|---------------------|-----------------------|------------------------------------------------|
| FUN3D       | FUN3D Euler*        | FUN3D Euler LFD       | Mach 0.9, cruise altitude,<br>load factor of 1 |
| FUN3D+DLM   | FUN3D Euler*        | DLM                   | Mach 0.85                                      |
| VLM+DLM     | VLM                 | DLM                   | Mach 0.85                                      |

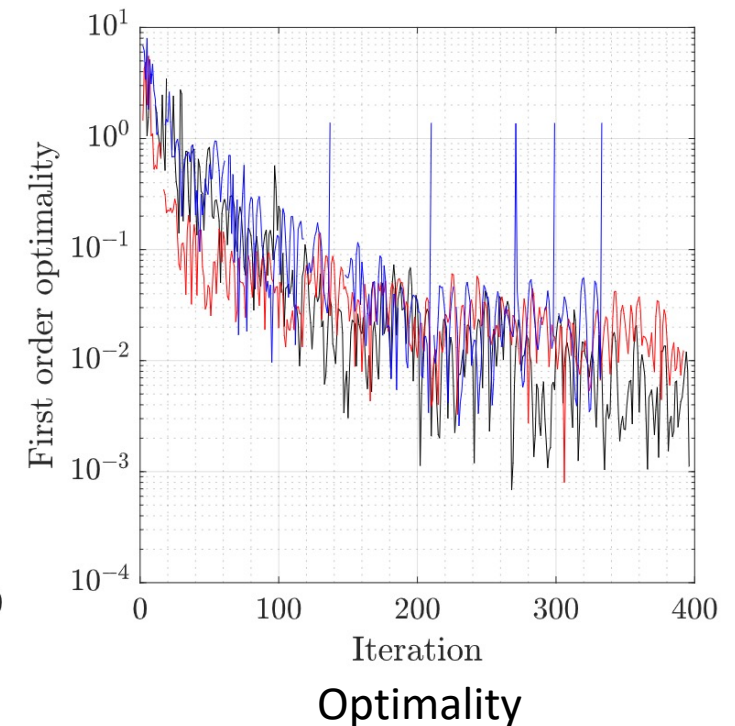
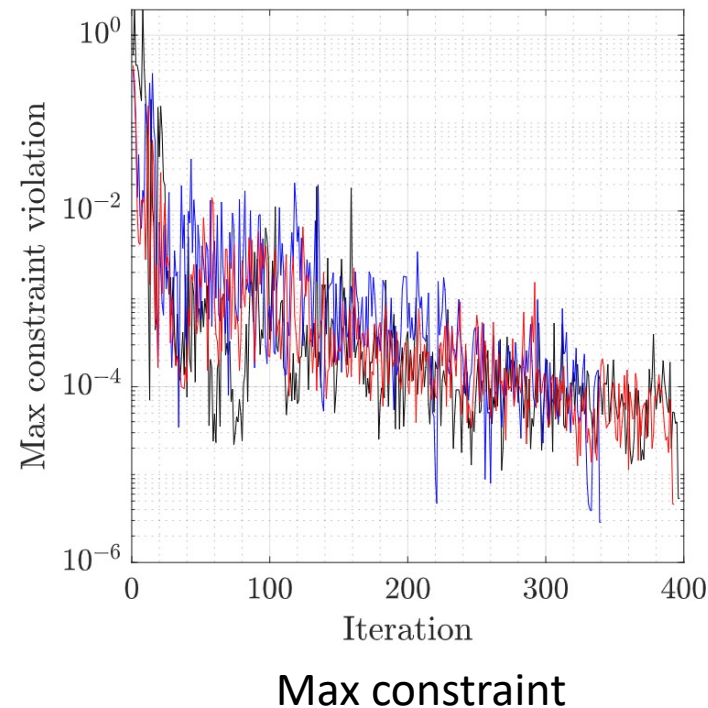
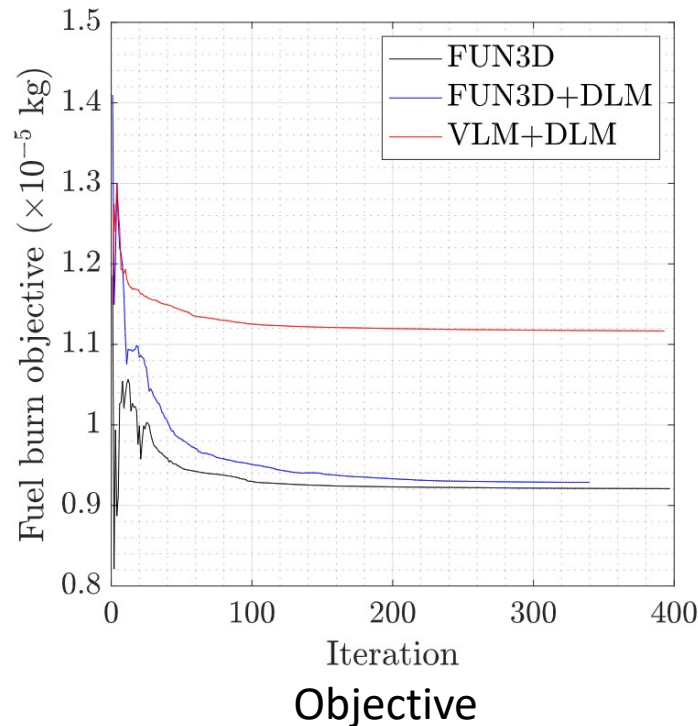
\*augmented with empirical profile drag to approximately account for viscosity



# Optimization Convergence



- FUN3D+DLM optimization started from VLM-based optimum; VLM+DLM and FUN3D started from baseline design
- FUN3D yields lower fuel burn than FUN3D+DLM, in spite of active flutter constraint in FUN3D and not FUN3D+DLM

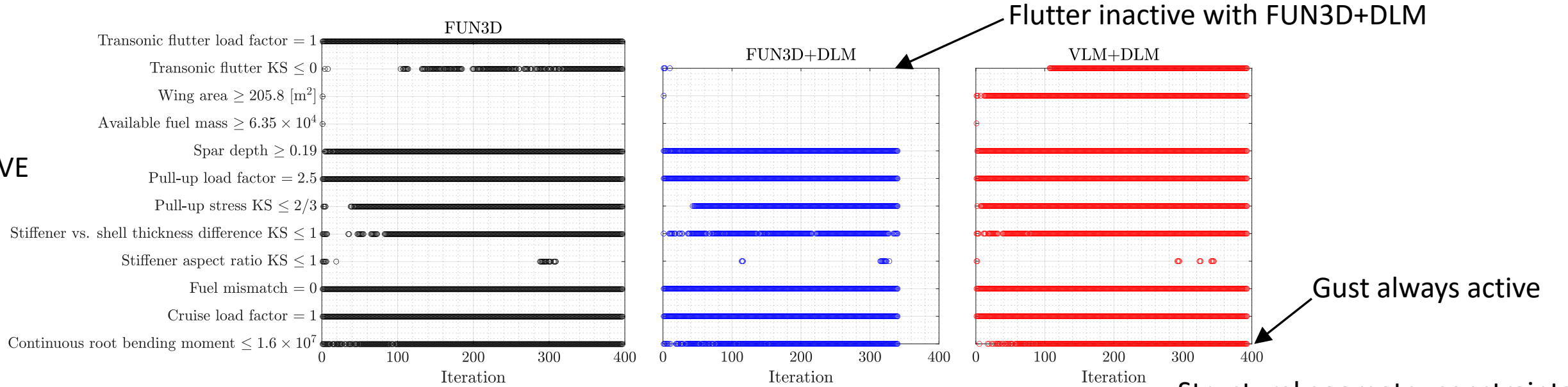




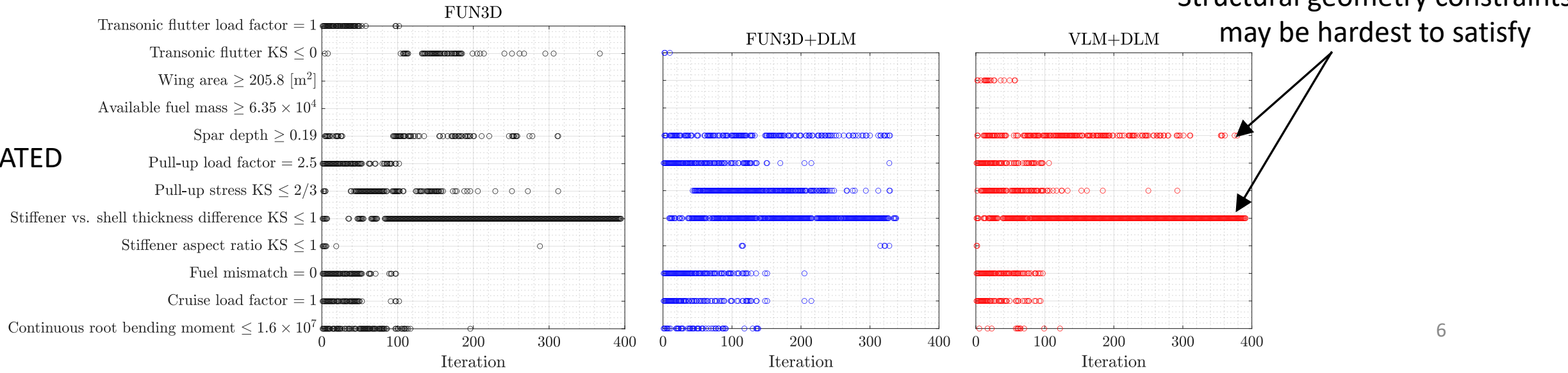
# Categorizing Constraint Convergence



ACTIVE



VIOLATED

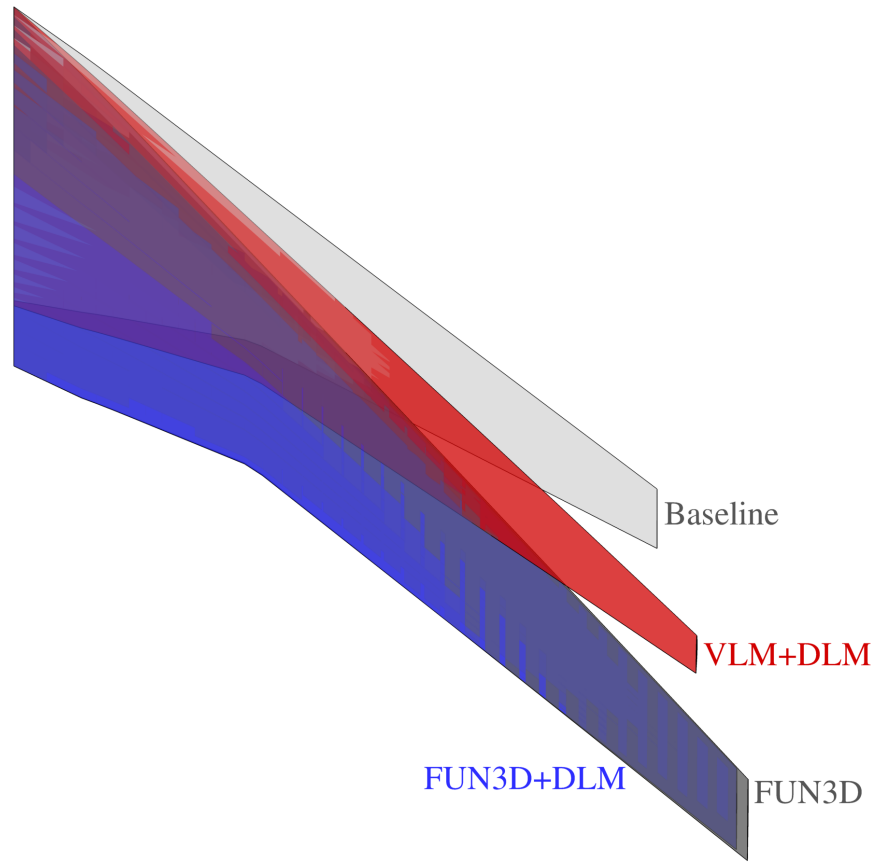




# Resulting planform shapes

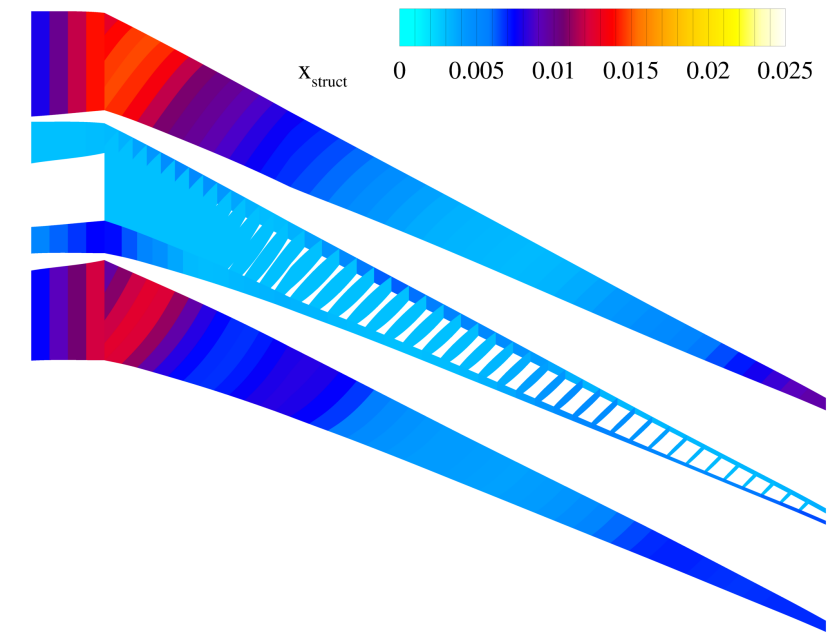


- FUN3D-based cases yield similar designs; longer, more swept wings
- Tip chord increase likely due to optimizer taking advantage of the low-fidelity of empirical profile drag

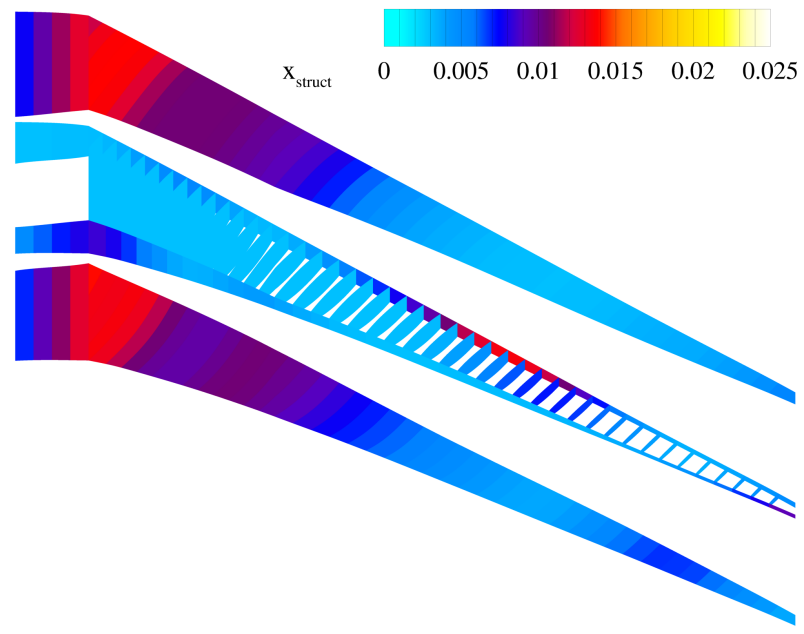




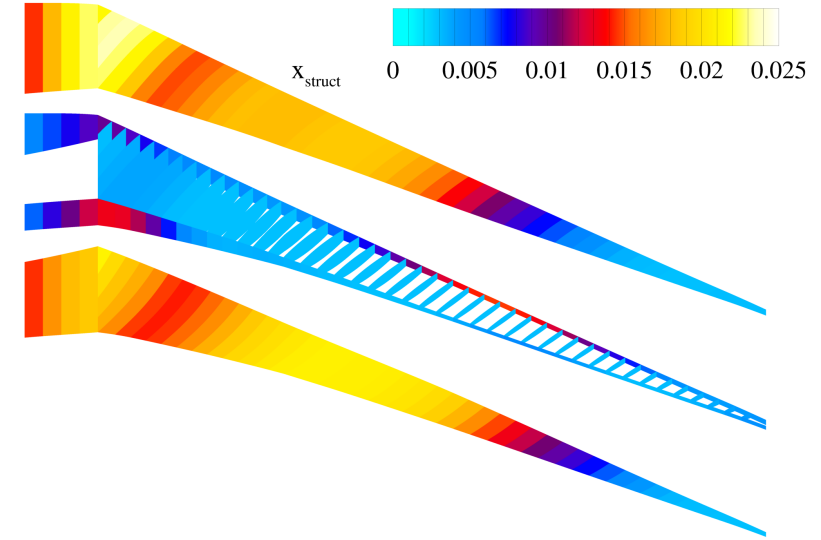
# Resulting Shell Thicknesses



FUN3D



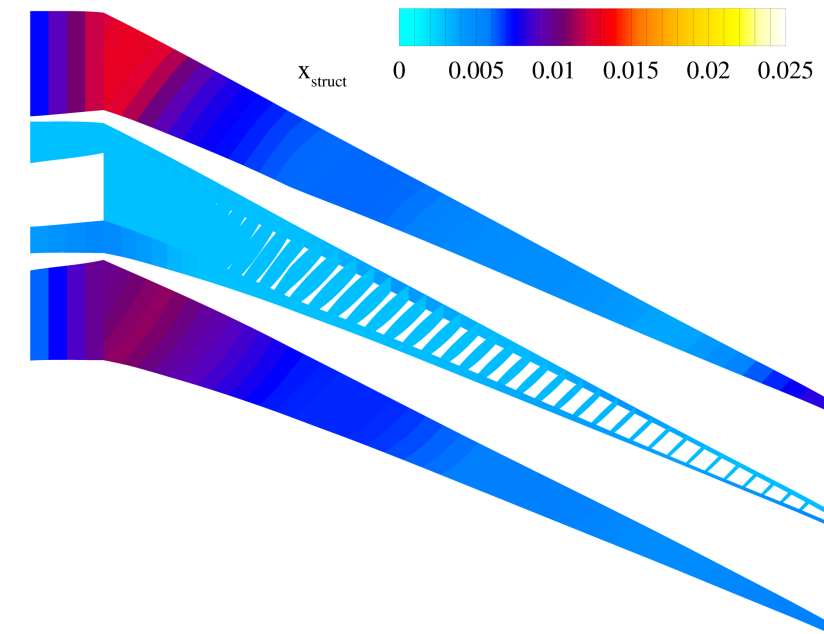
FUN3D+DLM



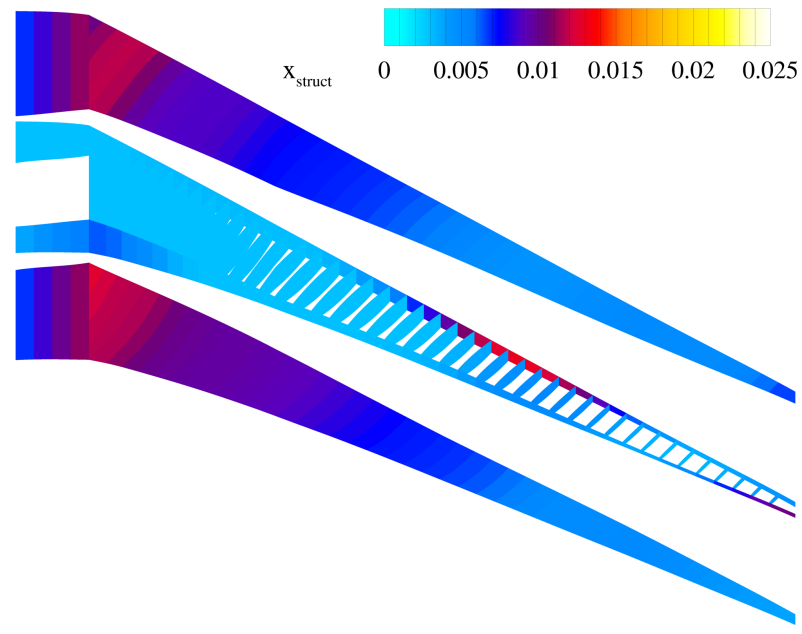
VLM+DLM



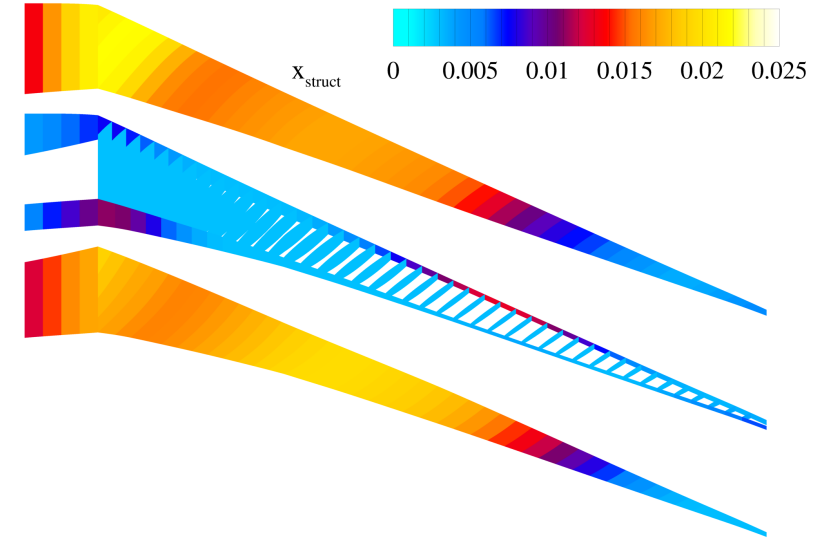
# Resulting Stiffener Thicknesses



FUN3D



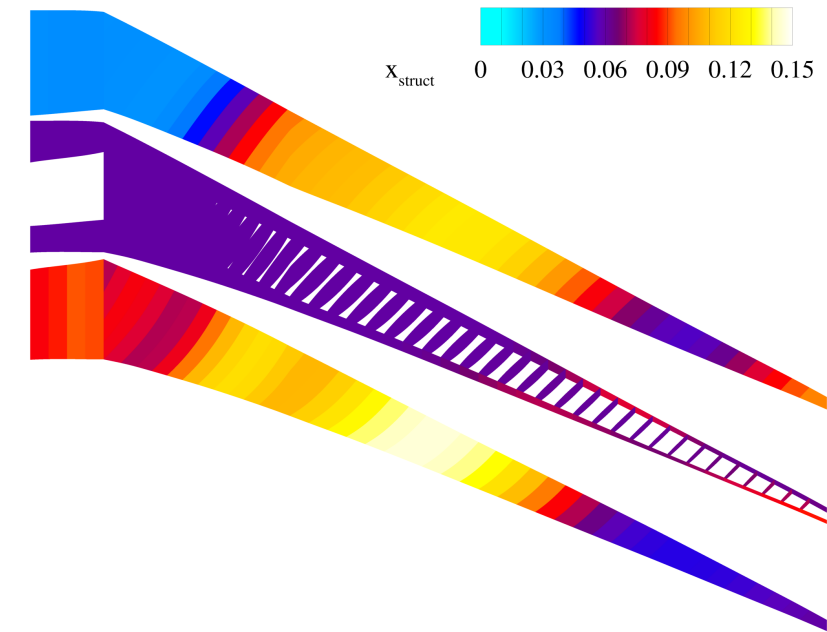
FUN3D+DLM



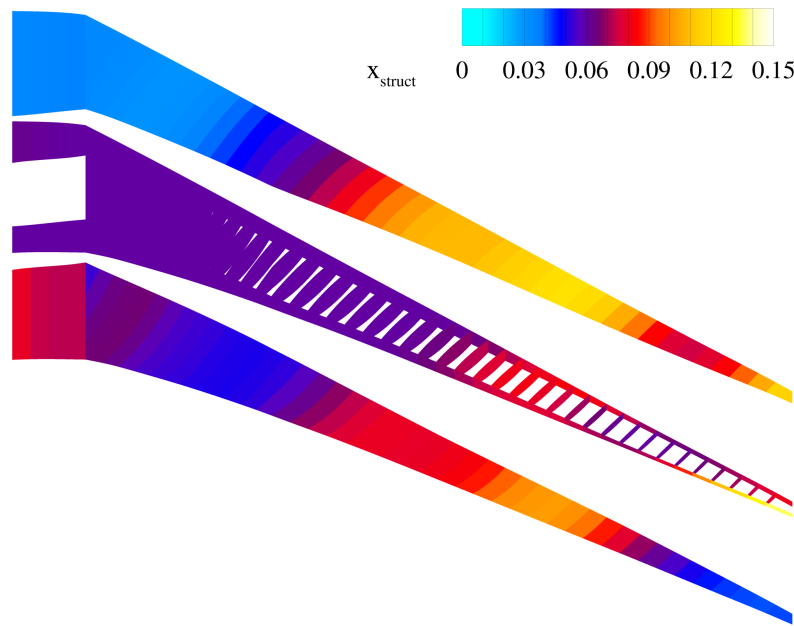
VLM+DLM



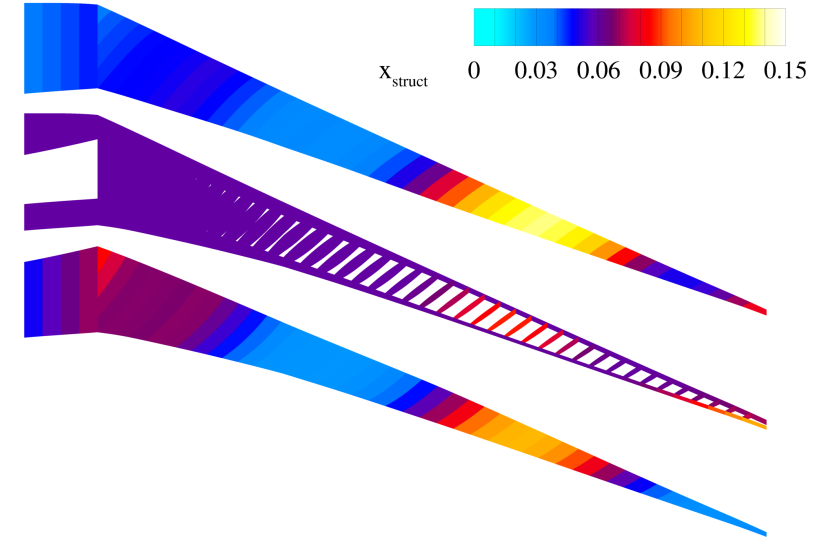
# Resulting Stiffener Heights



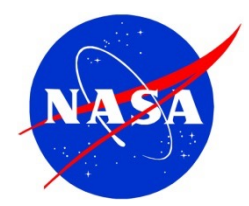
FUN3D



FUN3D+DLM



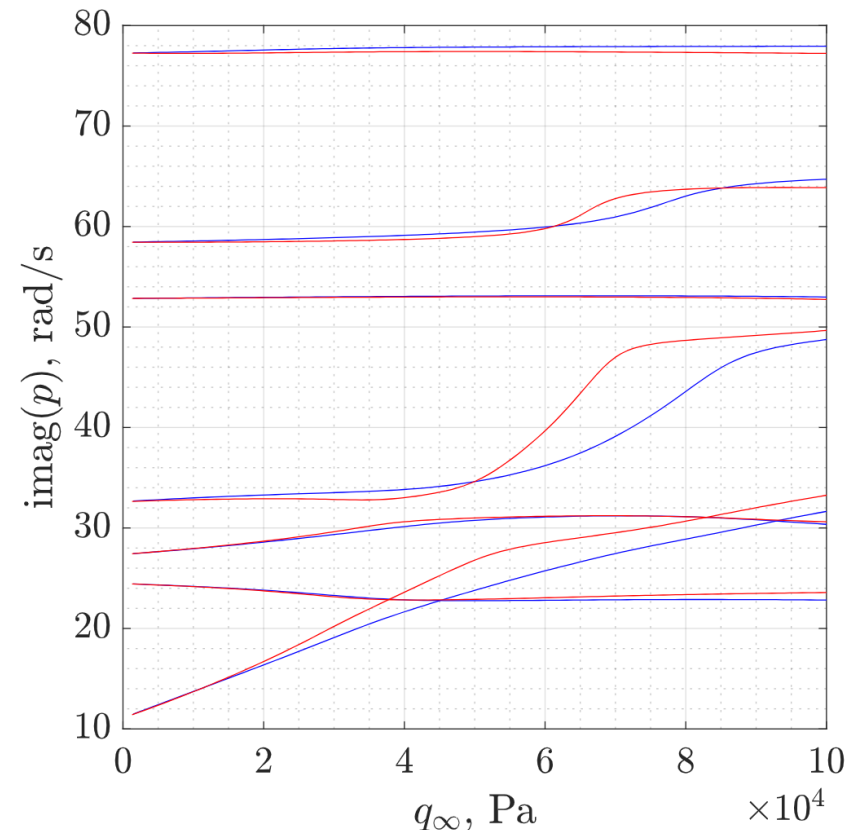
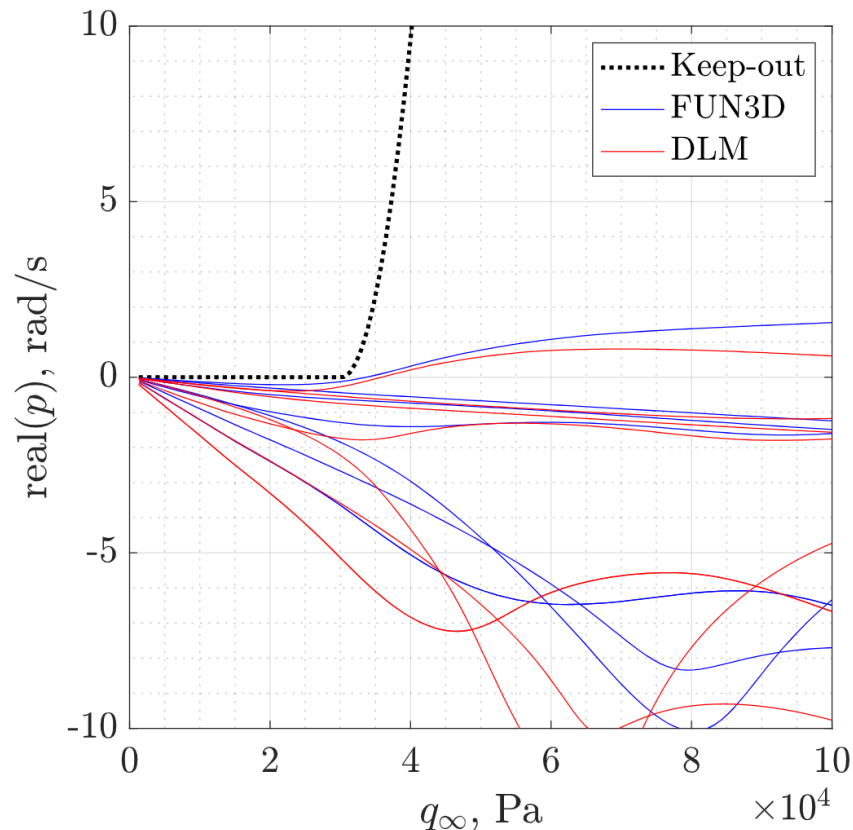
VLM+DLM



# Baseline Flutter Results, DLM vs. LFD



- DLM and LFD flutter are fairly similar, in spite of the transonic Mach number (0.9)
- Existing literature suggests transonic effects not huge driver for CRM

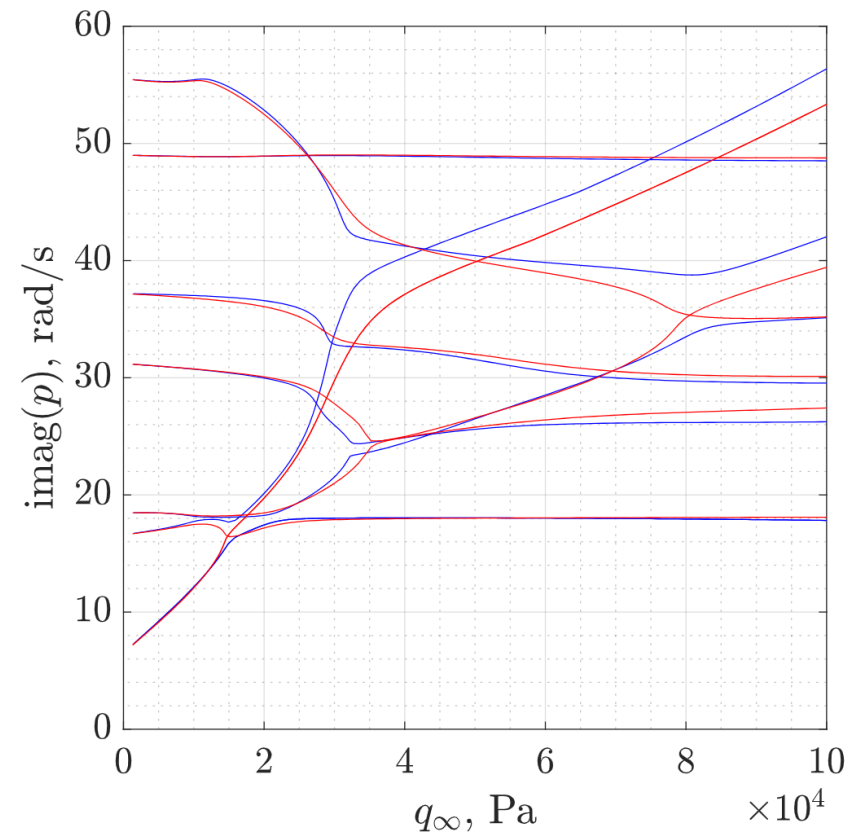
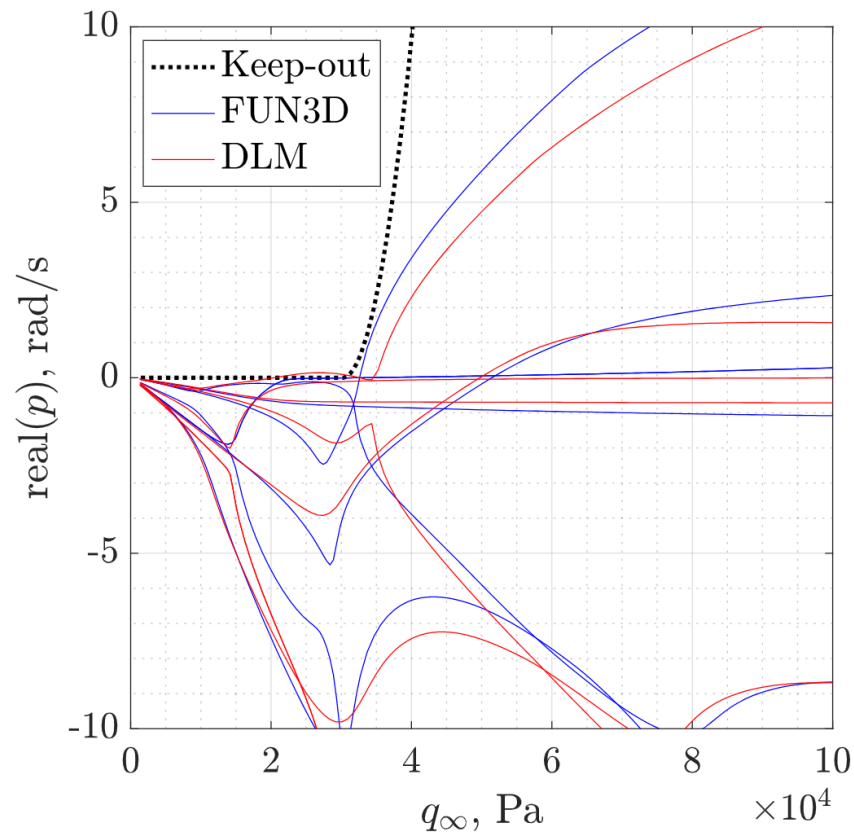




# Flutter at FUN3D Optimum, DLM vs. LFD



- LFD predicts hard flutter at lower dynamic pressure, as expected
- DLM predicts hump mode before hard flutter, leading to violated KS constraint ( $0.147$  vs.  $-3 \times 10^{-9}$ )

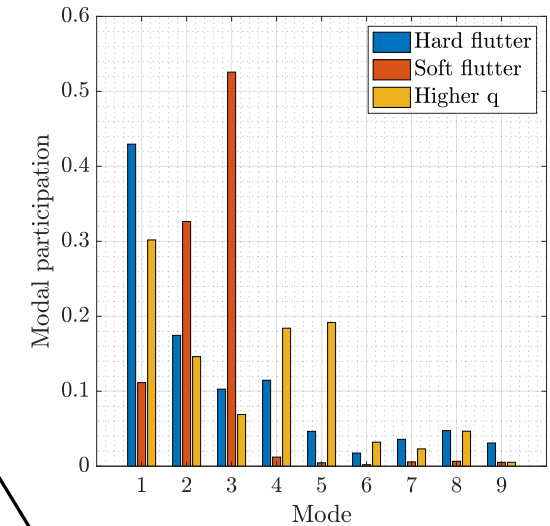
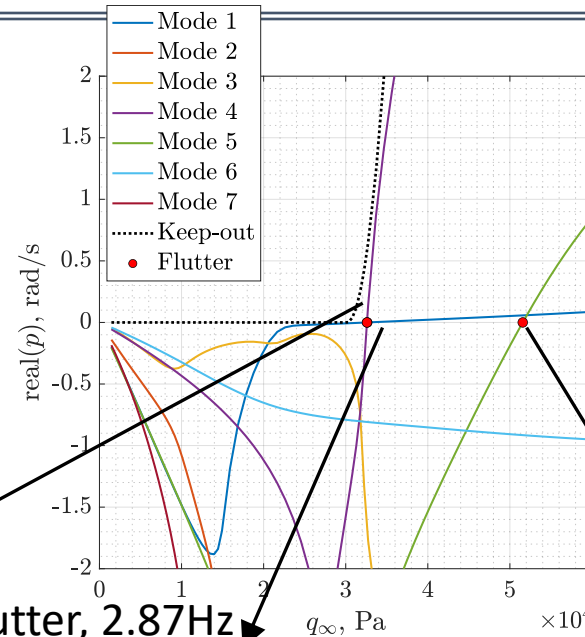




# Flutter Modes at the FUN3D Optimum



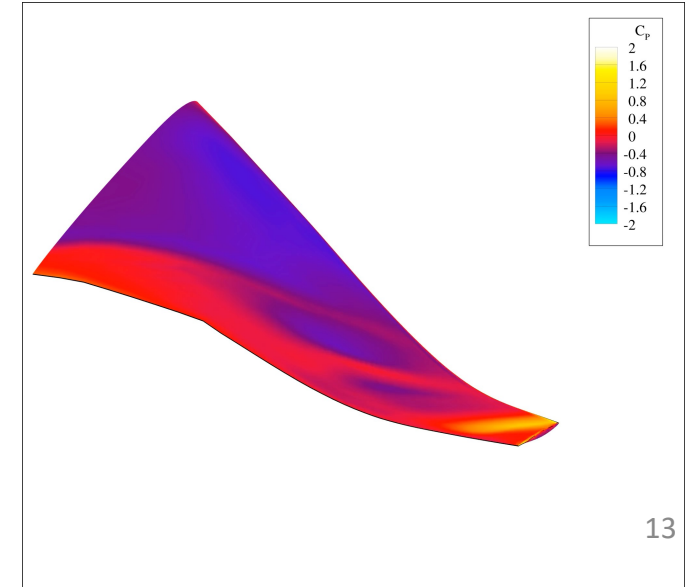
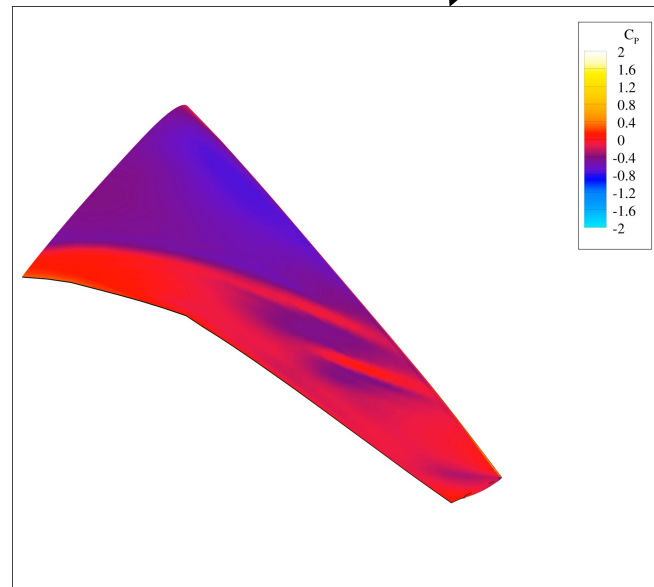
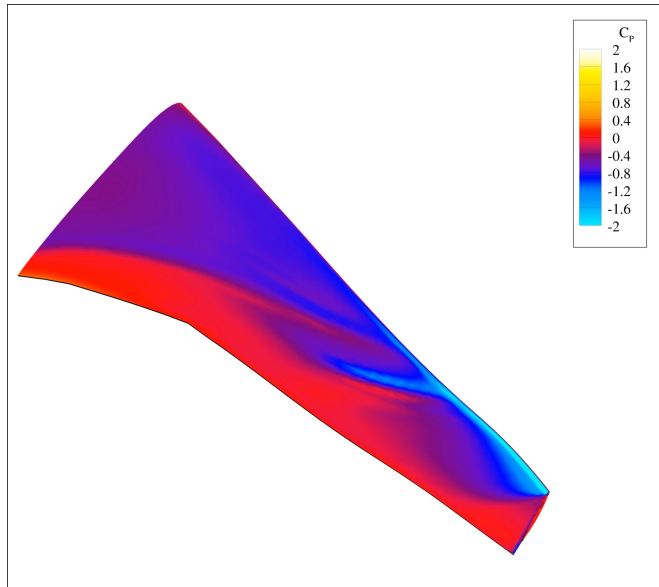
- Modal,  $C_p$  oscillations amplified by 100x
- Slowed down by 10x
- Mode number does not mean highest participation



Hard flutter, 3.88Hz

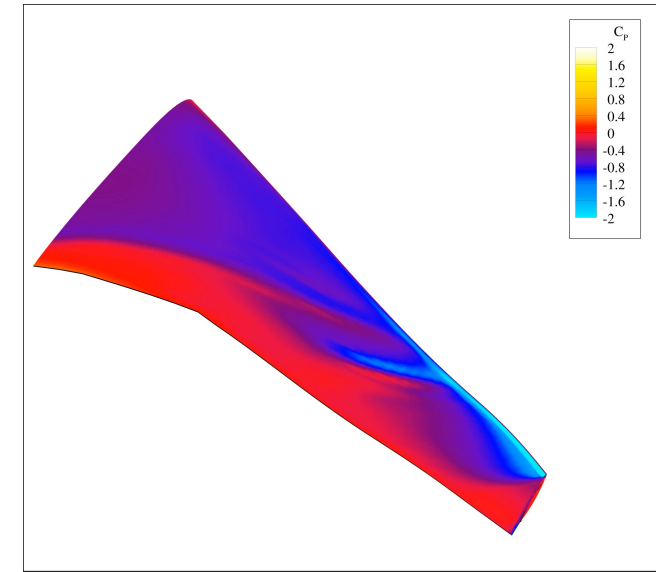
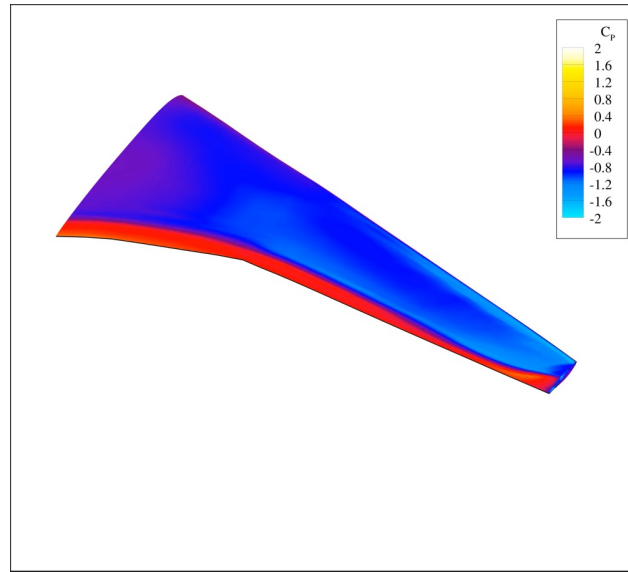
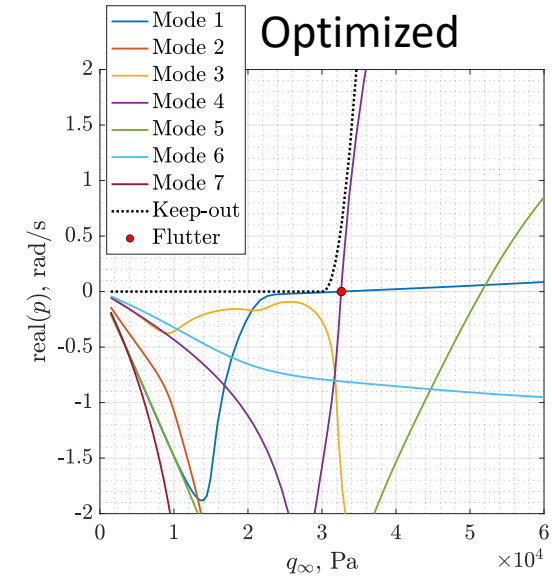
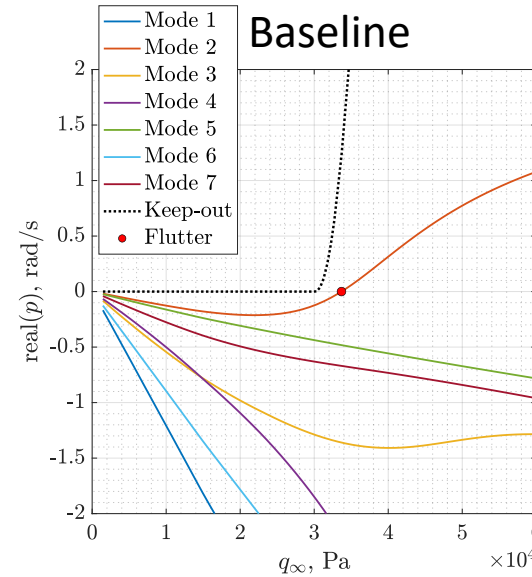
Soft flutter, 2.87Hz

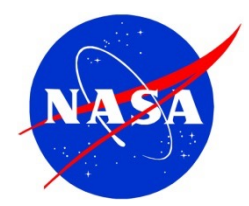
Higher q flutter, 4.99Hz



# Baseline and Optimized Flutter Modes

- Different modes (2, 4) cross x-axis, but visually similar flutter modes
- No in-plane modes seen at baseline, unlike optimum

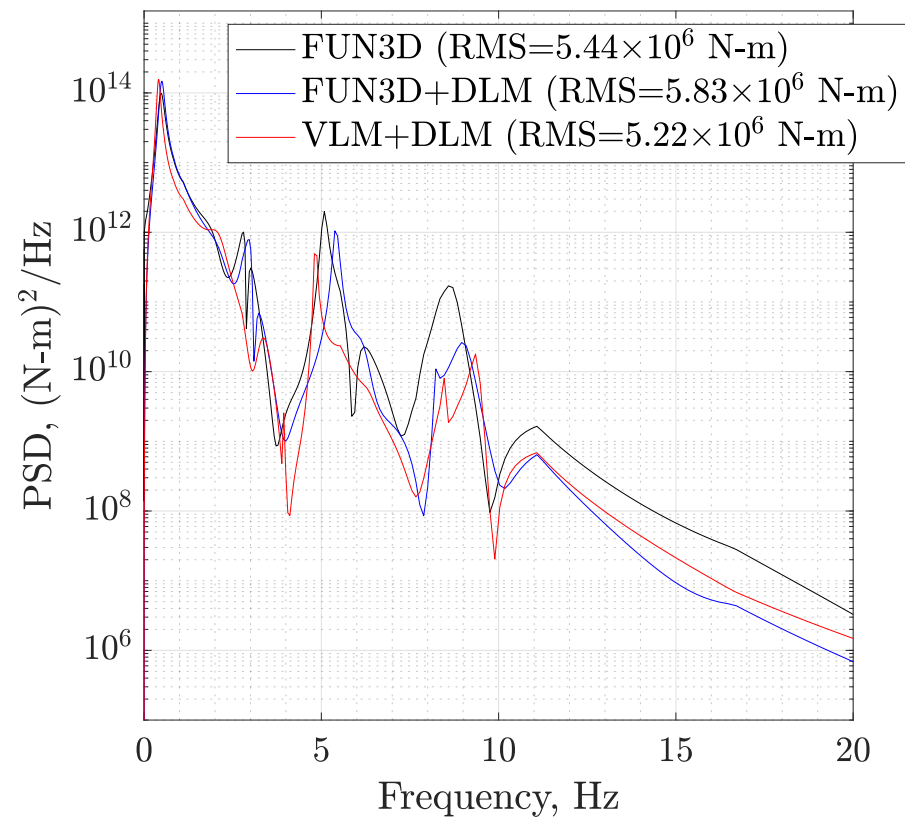




# Gust Results at the Optima



- Differences at larger frequencies are relatively unimportant to RMS
- Peak at  $\sim 0.5\text{Hz}$ , driven by rigid body motion and first flexible mode, is main driver

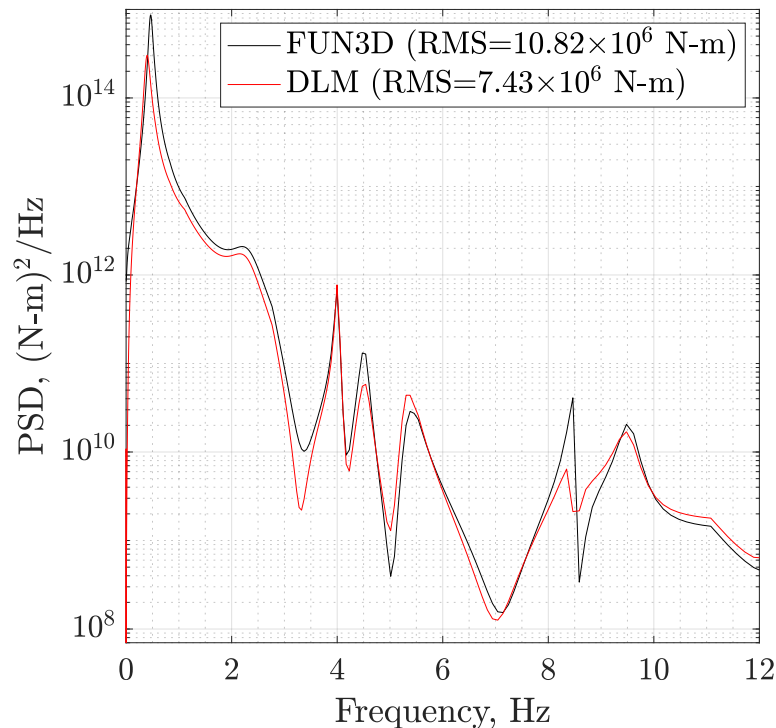




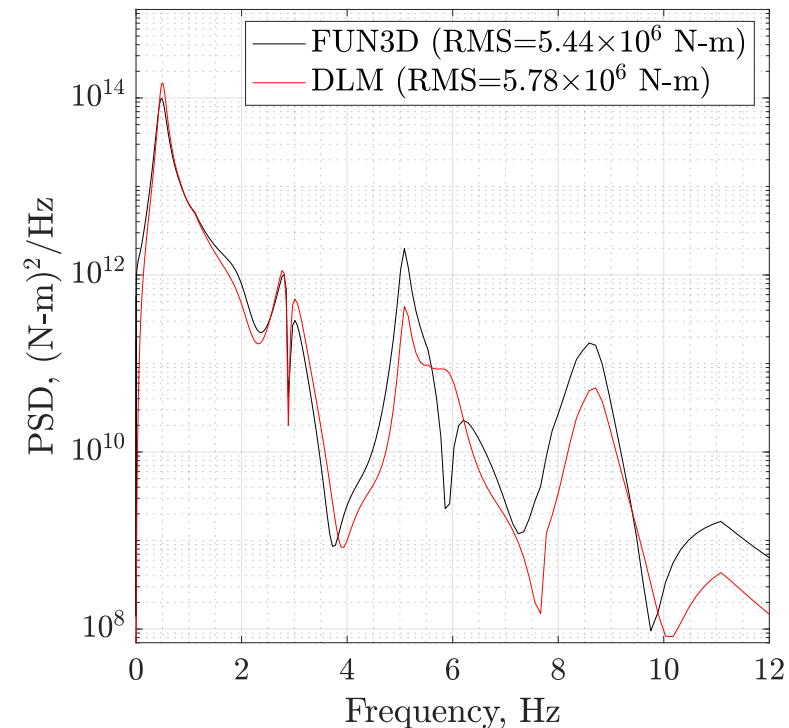
# Initial and Opt. Gust Results, DLM vs. LFD



- Due to peak at  $\sim 0.5\text{Hz}$ , LFD RMS significantly larger than DLM at baseline
- LFD RMS smaller at optimum; DLM more restrictive, leading to larger fuel burn with FUN3D+DLM when compared to FUN3D



Baseline



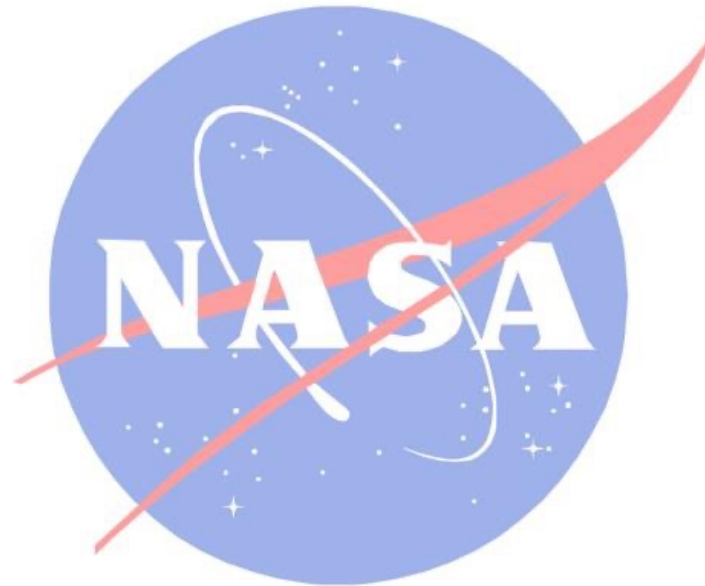
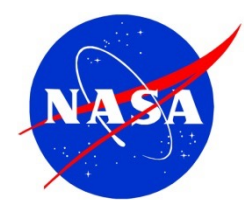
FUN3D optimum



# Conclusions and Future Work



- CRM optimization with flutter and stochastic gust constraints has been demonstrated
  - Fully panel-based, panel- and CFD-based, fully CFD-based
- Baseline and optimized gust and flutter responses have been compared
- Several areas of growth in MPhys-based analysis chain:
  - Add more flutter and gust constraints throughout flight envelope, using DLM in subsonic regime
  - Use RANS aerodynamics rather than coarse Euler augmented with empirical profile drag
  - Constrain gust-induced stresses rather than root bending moment
  - Model wing-body-tail rather than wing-only
  - Include structural damping and rigid body modes in flutter analysis
  - Include control surface modeling for gust and maneuver load alleviation



[andrew.s.thelen@nasa.gov](mailto:andrew.s.thelen@nasa.gov)



# CRM Optimization Problem



- Two flight conditions based on CRM literature: 1g cruise, 2.5g pull-up
- Additional flight condition for transonic flutter: 1g cruise altitude, Mach 0.9
- **738 design variables:** 720 structural, 14 shape, 3 aerodynamic, 1 fuel scaling
- **12 constraints:** 1 flutter, gust, & stress, 3 load factor, 1 consistency, 5 other geometric/mission

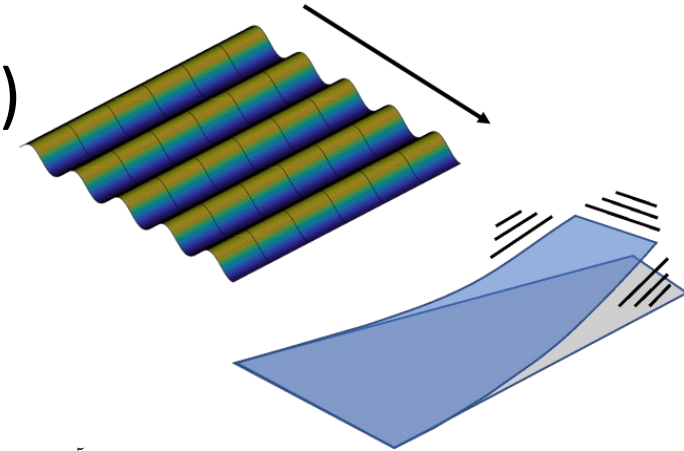
|                  | Description                   | Specification                         | Quantity   |
|------------------|-------------------------------|---------------------------------------|------------|
| minimize:        | Cruise fuel burn              |                                       |            |
| with respect to: | Root chord differential       | $\in [-3, 3] \text{ m}$               | 1          |
|                  | Tip chord differential        | $\in [-1, 1] \text{ m}$               | 1          |
|                  | Span differential             | $\in [-10, 10] \text{ m}$             | 1          |
|                  | Sweep differential            | $\in [-10, 10] \text{ deg}$           | 1          |
|                  | Wing thickness                | $t_{wing} \geq 0.5 \times t_{wing,0}$ | 5          |
|                  | Wing twist differential       | $\in [-10, 10] \text{ deg}$           | 5          |
|                  | Fuel scaler                   | $\in [0, 1]$                          | 1          |
|                  | Shell thickness               | $\in [0.003, 0.03] \text{ m}$         | 240        |
|                  | Stiffener thickness           | $\in [0.003, 0.03] \text{ m}$         | 240        |
|                  | Stiffener height              | $\in [0.03, 0.15] \text{ m}$          | 240        |
|                  | Static angle of attack        | $\in [-10, 10] \text{ deg}$           | 3          |
|                  | <b>Total</b>                  |                                       | <b>738</b> |
| subject to:      | Fuel mismatch                 | $= 0$                                 | 1          |
|                  | Static load factor            | $\eta = [1, 2.5, 1]^T$                | 3          |
|                  | Wing area                     | $A \geq 205.8 \text{ m}^2$            | 1          |
|                  | Available fuel mass           | $\geq 63,464.28$                      | 1          |
|                  | Trailing edge spar depth      | $\geq 0.19 \text{ m}$                 | 1          |
|                  | Stiffener aspect ratio        | $KS_{AR} \leq 1$                      | 1          |
|                  | Stiffener vs. shell thickness | $KS_{t/t_s} \leq 1$                   | 1          |
|                  | Pull-up stress                | $1.5KS_{\sigma} \leq 1$               | 1          |
|                  | Transonic flutter             | $KS_{fl} \leq 0$                      | 1          |
|                  | Cruise gust                   | $\leq 1.6 \times 10^7 \text{ N-m}$    | 1          |
|                  | <b>Total</b>                  |                                       | <b>12</b>  |

| Description | Steady aerodynamics | Unsteady aerodynamics | Transonic flutter constraints               |
|-------------|---------------------|-----------------------|---------------------------------------------|
| FUN3D       | FUN3D Euler*        | FUN3D Euler LFD       | Mach 0.9, cruise altitude, load factor of 1 |
| FUN3D+DLM   | FUN3D Euler*        | DLM                   | Mach 0.85                                   |
| VLM+DLM     | VLM                 | DLM                   | Mach 0.85                                   |

\*augmented with empirical profile drag to approximately account for viscosity

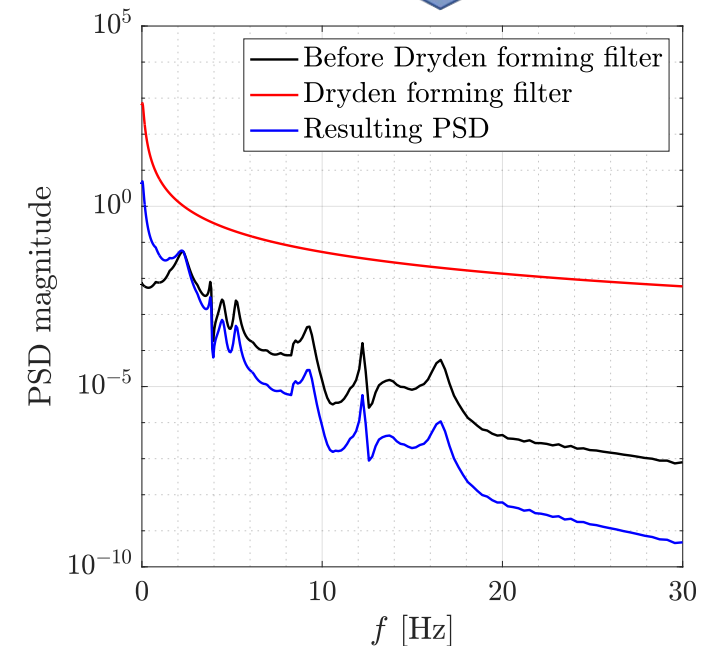
- Structure-on-structure and gust-on-structure GAFs ( $\mathbf{Q}$ ) may be computed by either DLM or FUN3D SFE/LFD:

$$\left( -\omega^2 [\bar{\mathbf{M}}] + i\omega [\bar{\mathbf{C}}] + [\bar{\mathbf{K}}] - q_\infty [\bar{\mathbf{Q}}_{ss}] \right) \{\boldsymbol{\eta}\} = q_\infty \{\bar{\mathbf{Q}}_{gs}\}$$



- Gust PSD of a quantity of interest (QOI) is found via
  - $\mathbf{S}$  – QOI induced by unit modal displacements
  - $\boldsymbol{\eta}$  – Complex generalized displacements
  - $f$  – Dryden model of atmospheric velocity perturbations

$$PSD(\omega) = |\{\mathbf{S}\}^T \{\boldsymbol{\eta}\}|^2 f_{atm}(\omega)$$





# Resulting planform shapes



- FUN3D cases without empirical profile drag (red and green) show similar result: gust/flutter constraints reduce wing span
- Adding empirical drag (purple) increases tip chord length

