AIAA SciTech Forum 2022

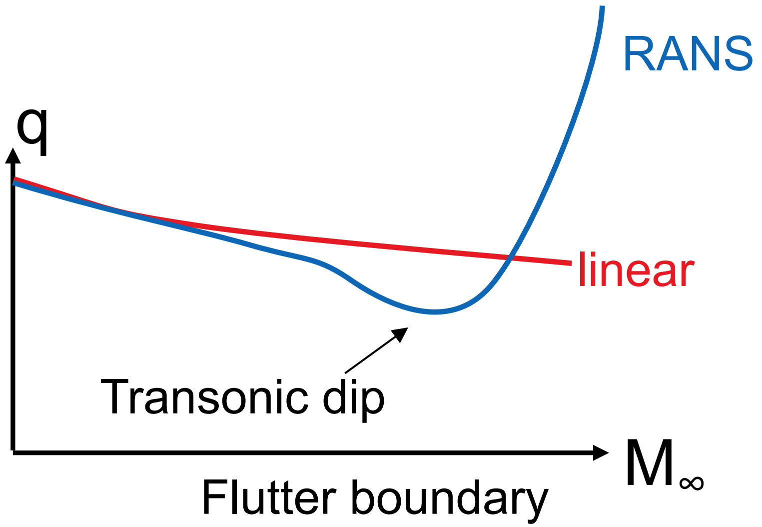
Flutter-Constrained Optimization with the Linearized Frequency-Domain Approach

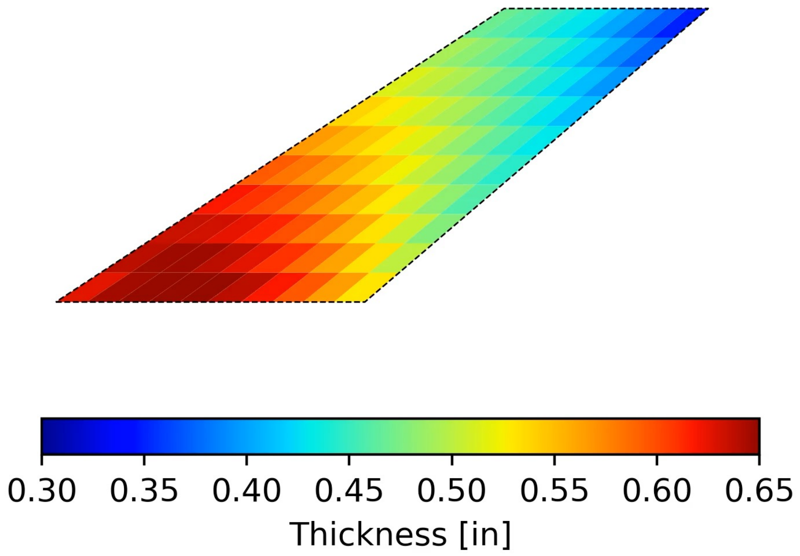
Kevin E. Jacobson* and Bret K. Stanford

NASA Langley Research Center

Background

- **CFD-based aerostructural optimizations produce efficient designs**
  - Typically ignore dynamic aeroelastic constraints
- **Critical flutter conditions are often in the transonic regime**
  - Linear aerodynamic analysis is insufficient
- **The Linearized Frequency-Domain (LFD) method is an approach that reduces the cost of CFD-based flutter analysis**
  - Recently implemented in FUN3D's stabilized finite element solver (FUN3D/SFE) with adjoint-based sensitivities
- **Goal: use LFD to apply CFD-based flutter constraints in multidisciplinary optimizations**
  - Shape optimization of the transonic Isogai airfoil
  - Mass minimization of the AGARD 445.6 wing at a subsonic condition





AGARD 445.6 optimization

Flutter Prediction Approach – p-k Method

- Flutter is a linear stability problem
- Start from linearized aeroelastic governing equation, write in a modally reduced matrix form:

$$\overline{\mathbf{M}}\ddot{\hat{\xi}} + \overline{\mathbf{C}}\dot{\hat{\xi}} + \overline{\mathbf{K}}\hat{\xi} = q_\infty \overline{\mathbf{Q}}\left(i\omega\right)\hat{\xi}$$

Vector of modal displacements from equilibrium

$\overline{\mathbf{Q}}_{m,n}\left(i\omega_k\right)$ GAFs - Generalized Aerodynamic Force on mode m due to harmonic motion of mode n at frequency ω_k

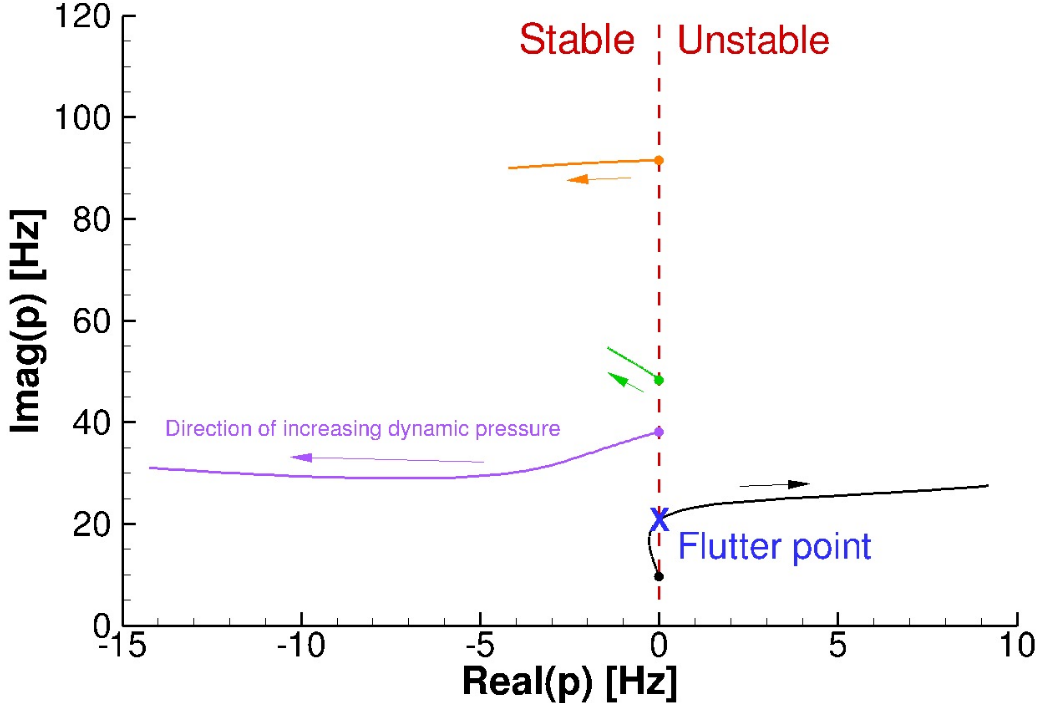
- Convert to an eigenproblem where the eigenvalues are *p*:

$$p = g + ik$$

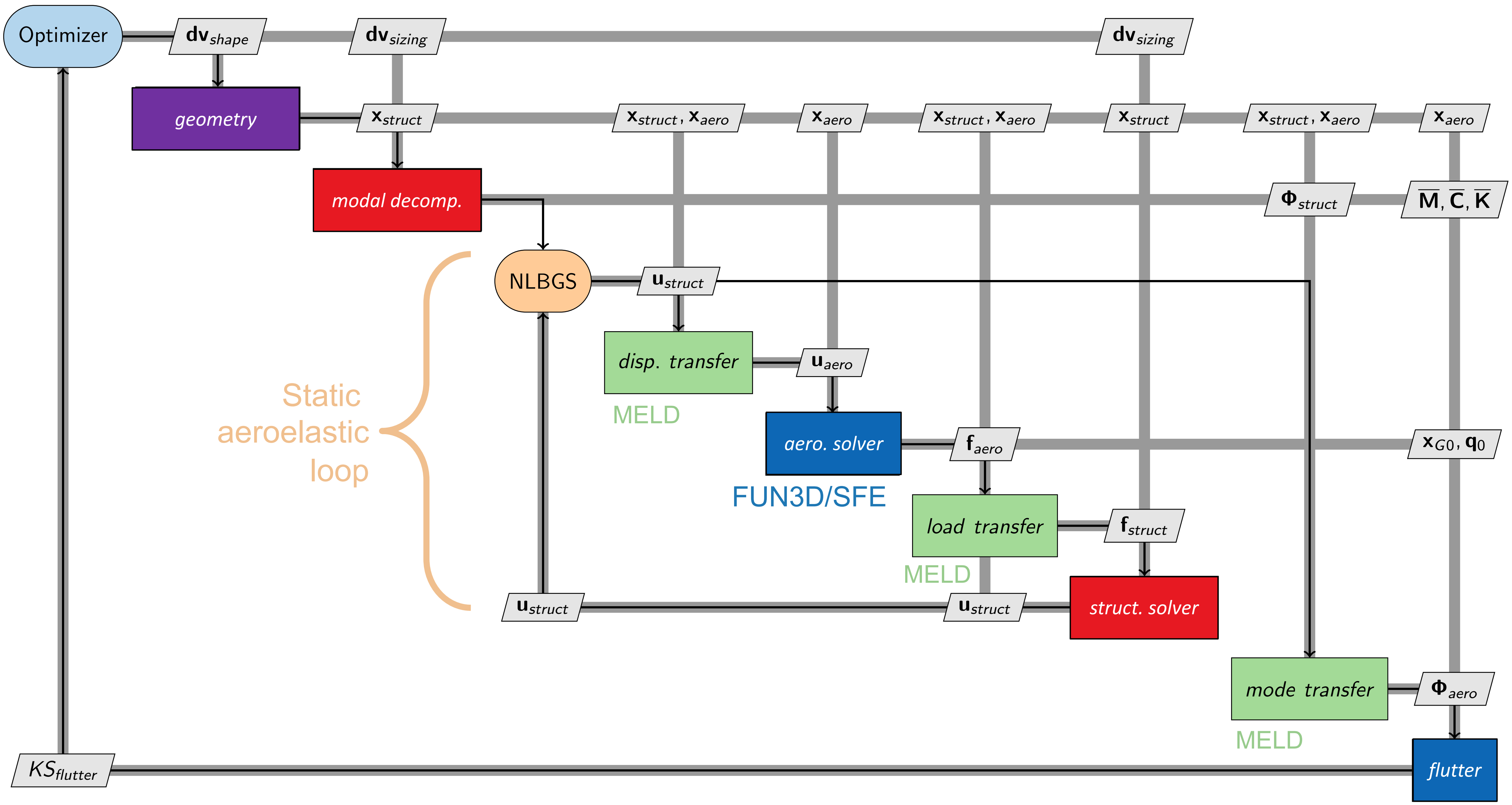
Damping

Frequency: $k = \omega b / U_\infty$

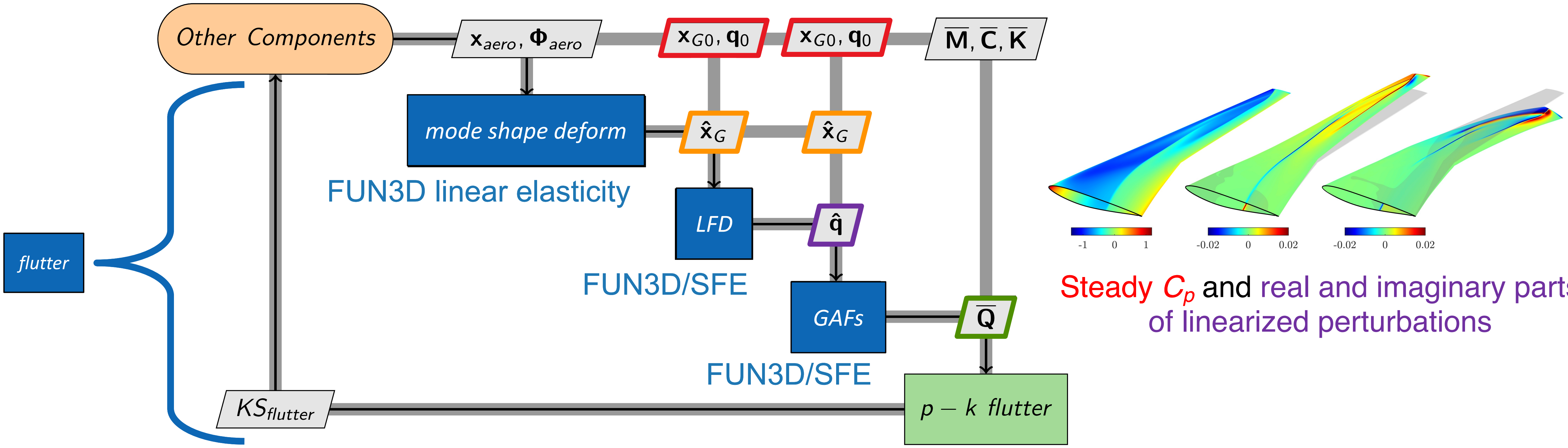
- Sweep over dynamic pressure and track the eigenvalues to find flutter point



Flutter Analysis in OpenMDAO with Mphys



Flutter Group with LFD-based Aerodynamics



Steady C_p and real and imaginary parts of linearized perturbations

Linearization about static aeroelastic solution to compute GAFs

1. **Compute motion of CFD mesh due to unit displacement of mode n**
2. **Compute linearized flow response due to motion of mode n at frequency ω_k**
3. **Compute $\overline{Q}_{m,n}$: generalized force in mode m due to motion of mode n *at frequency* ω_k**
4. **Solve the p-k eigenvalue problem and compute the flutter constraint**

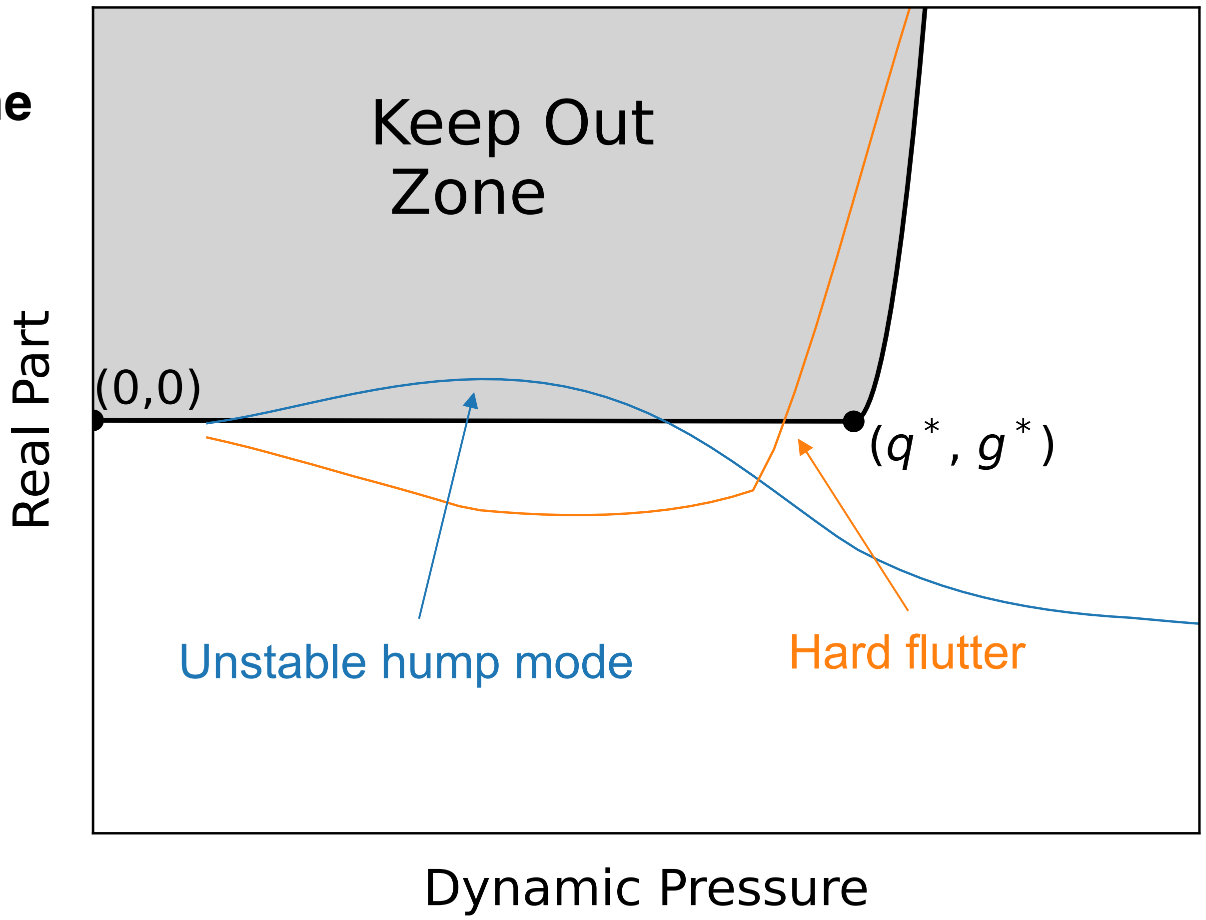
Flutter Constraint Formulation

- **Define a minimum allowable flutter dynamic pressure, *q****
- **Piecewise polynomial forms a "keep out" zone**
  - g^* = failure boundary's damping value at q^*
- **Conceptually we want to constrain that there are no eigenvalues in this region**

$$\max\,(\text{real part} - \text{boundary}) \leq 0$$

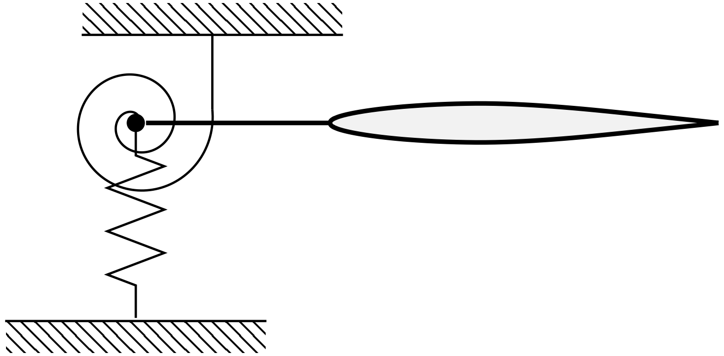
- **Differentiable approximation with Kreisselmeier-Steinhauser (KS) aggregation**

$$KS_{flutter} \leq 0$$



Isogai Airfoil – Optimization Problem

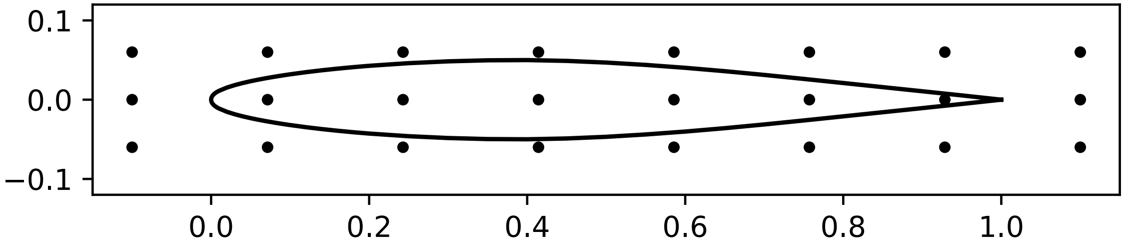
- **NACA64A-010 airfoil with pitch and plunge degrees of freedom**
  - Inviscid analysis at Mach 0.875
  - 24 Free-Form Deformation (FFD) control points



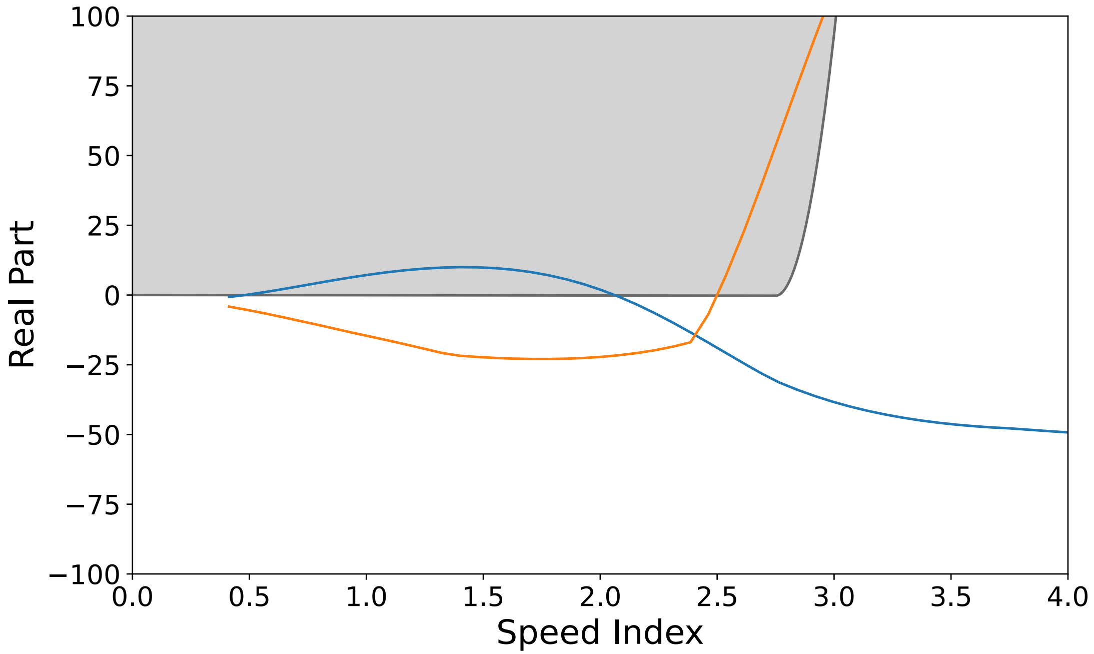
Pitch-plunge model

$$\min_{\Delta \mathbf{x}, \Delta \mathbf{y}} \quad \sum_{i=1}^{24} \sqrt{\Delta x_i^2 + \Delta y_i^2}$$

$$\text{subject to:} \quad KS_{flutter} \leq 0$$

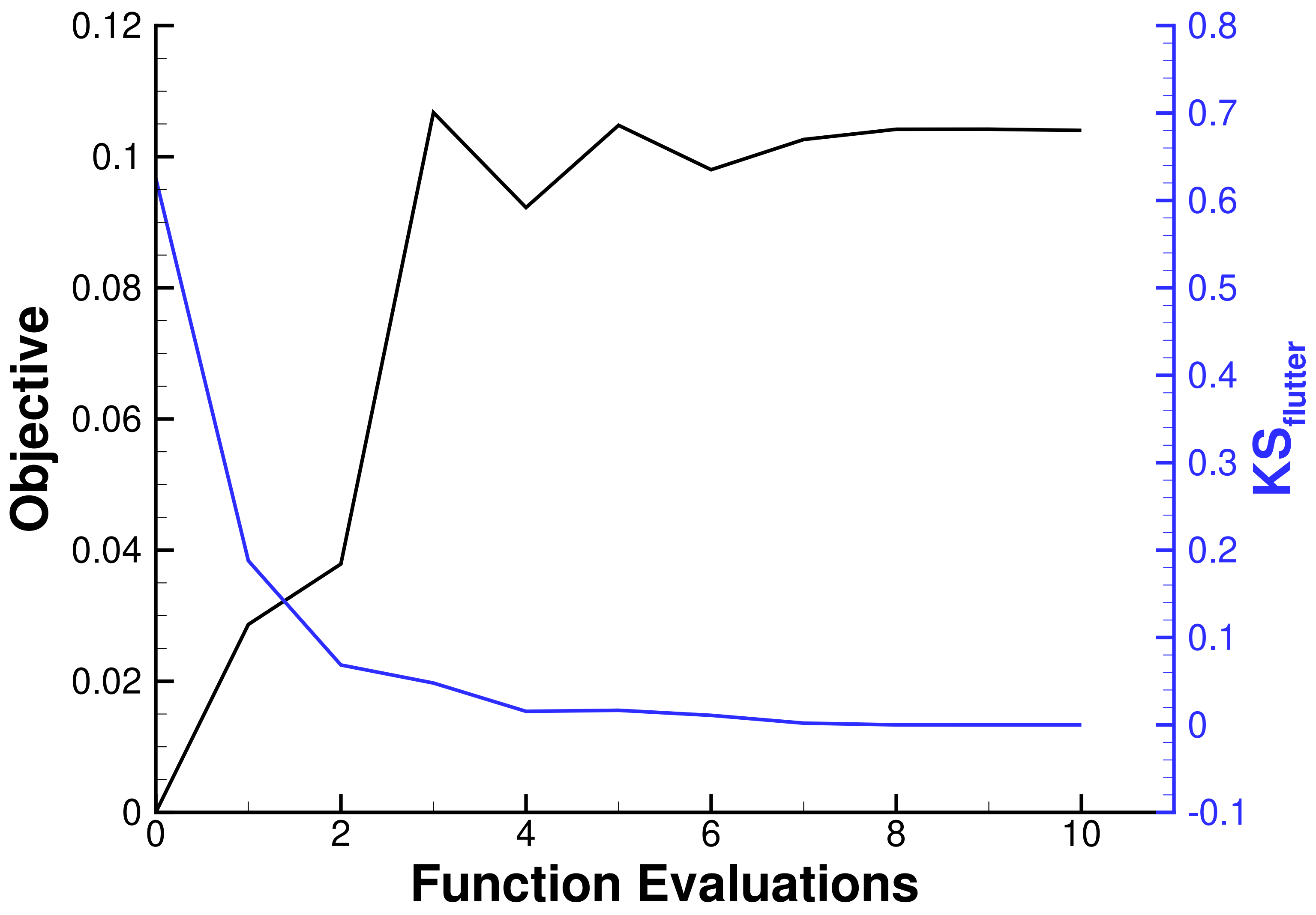


FFD control points



Initial flutter response

Isogai Airfoil – Optimization History

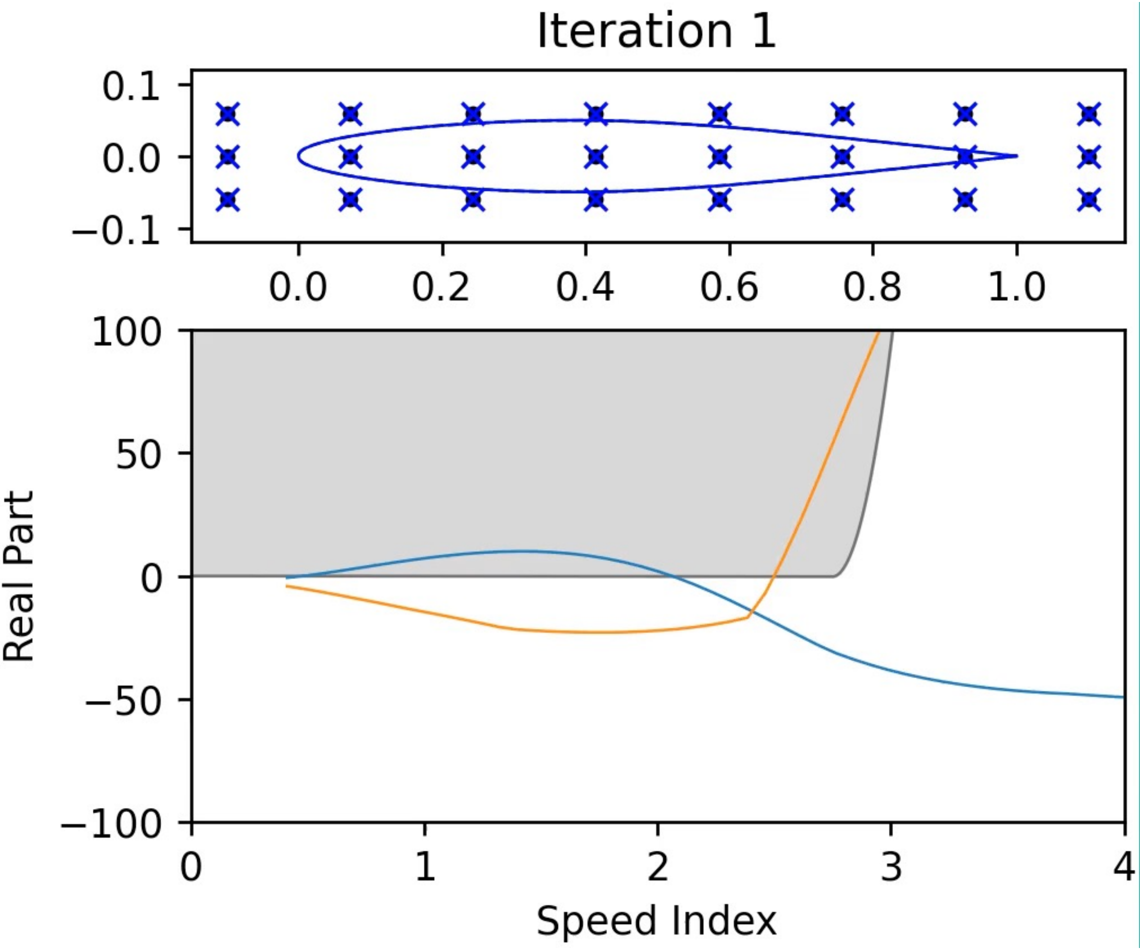


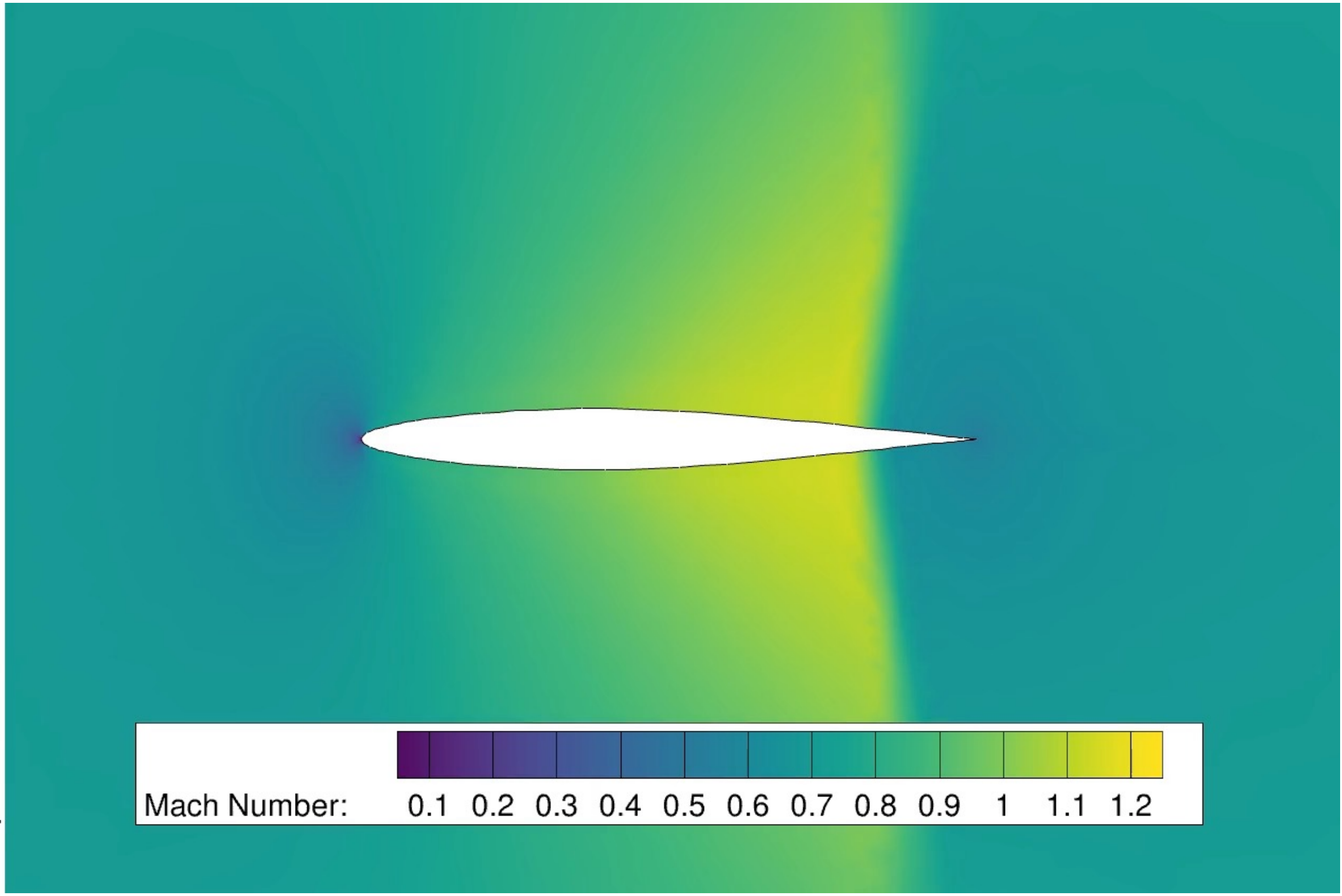
Computational cost

- **129.26 min. on a dual socket Intel Skylake node (40 cores)**
  - 15,854 nodes in CFD mesh
  - 14 LFD frequencies
  - 2 structural modes
  - 11 function evaluations
  - 9 gradient evaluations

Isogai Airfoil – Optimization

- **Asymmetric final airfoil leads to nonzero static aeroelastic motion**



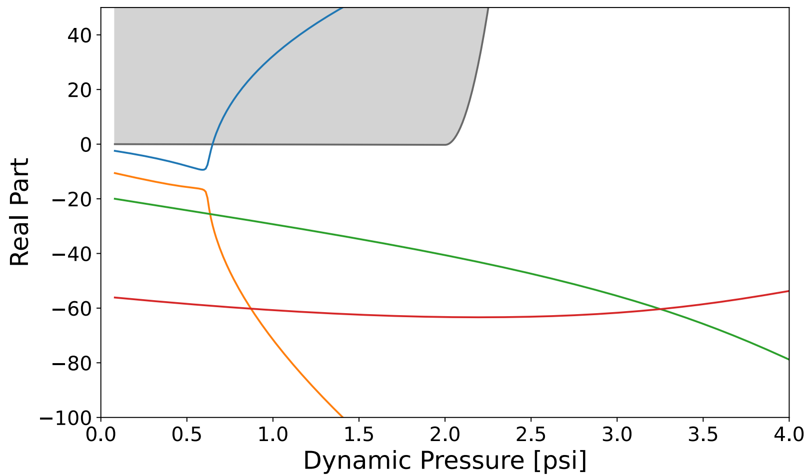


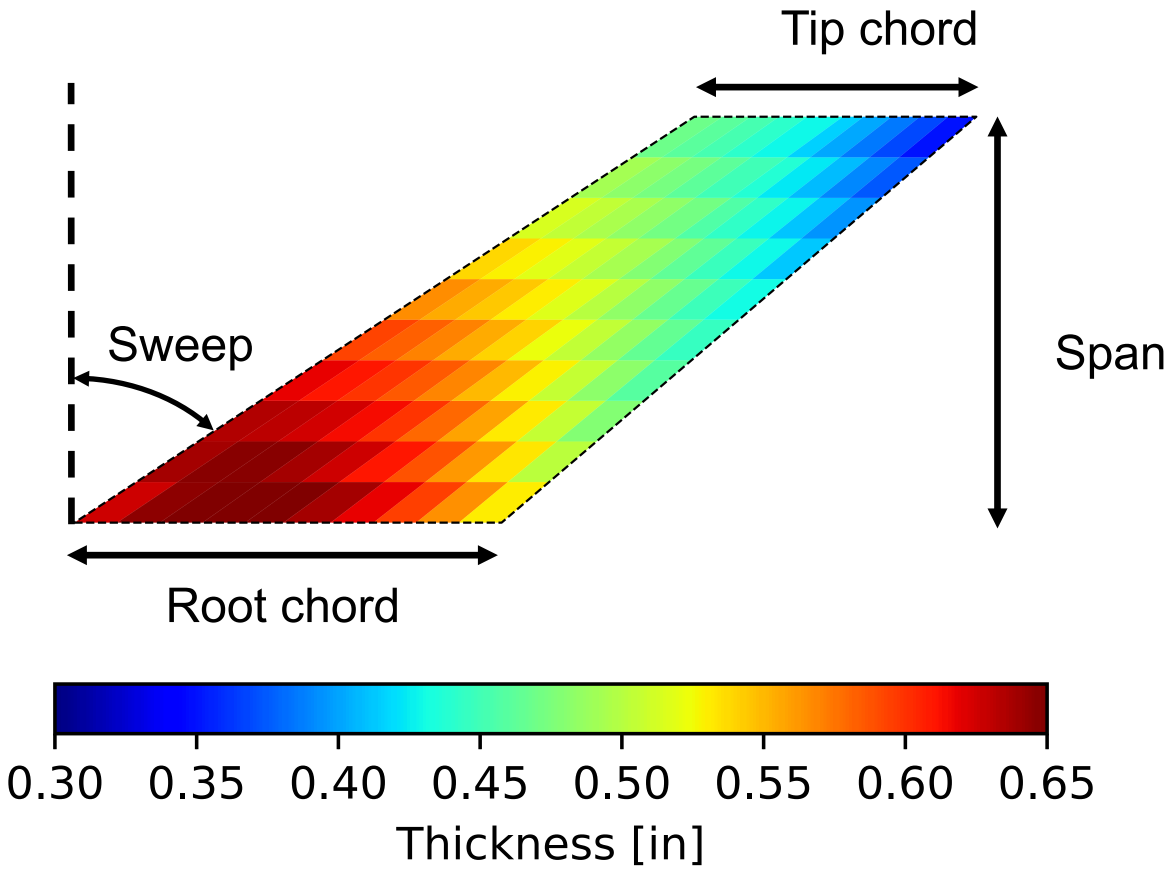
AGARD 445.6 Wing – Optimization Problem

- **Inviscid, symmetric wing at Mach 0.5**
  - Performed with LFD and Doublet Lattice Method (DLM) flutter analysis
- **Minimize the mass subject to flutter constraint and fixed planform area**

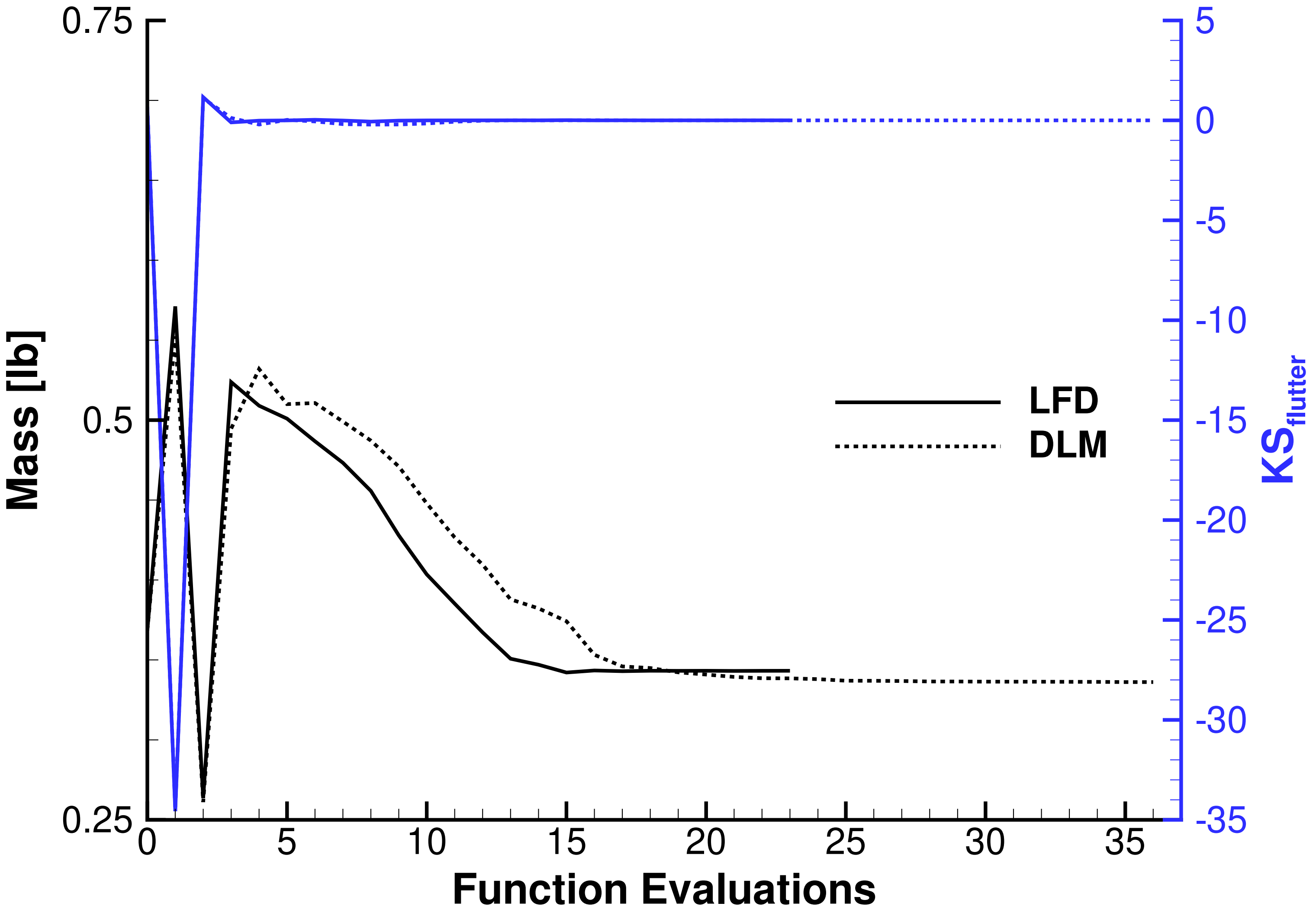
$$\begin{aligned} \min \quad & mass \\ \text{subject to:} \quad & KS_{flutter} \leq 0 \\ & A = A_0 \end{aligned}$$

- **104 design variables**
  - 100 structural thicknesses
  - 4 geometric (affect aero. and struct. meshes)





AGARD 445.6 – Optimization History



LFD computational cost

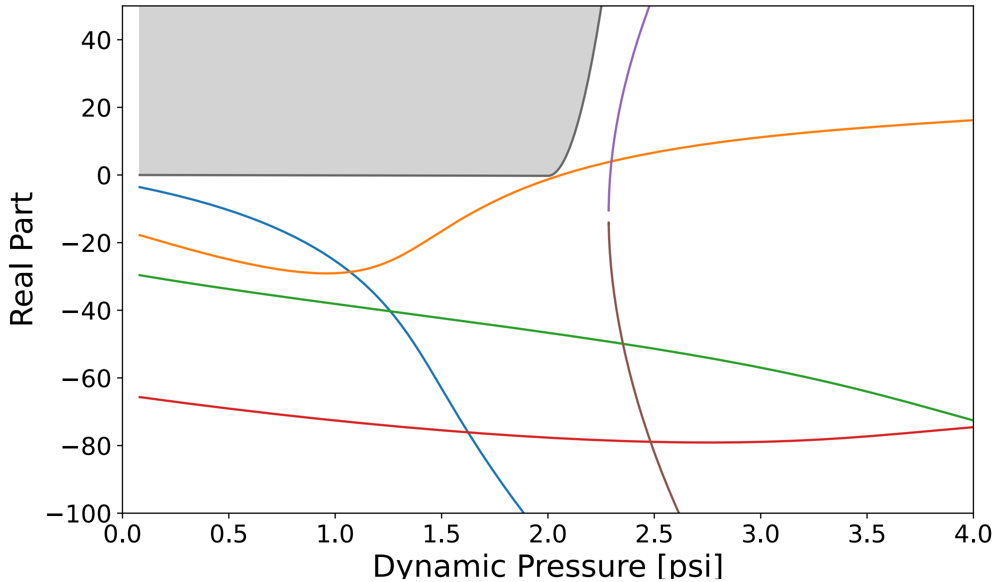
- **33.1 hours on 2 dual socket Intel Skylake nodes (80 cores)**
  - 145,118 nodes in CFD mesh
  - 11 LFD frequencies
  - 6 structural modes
  - 24 function evaluations
  - 19 gradient evaluations

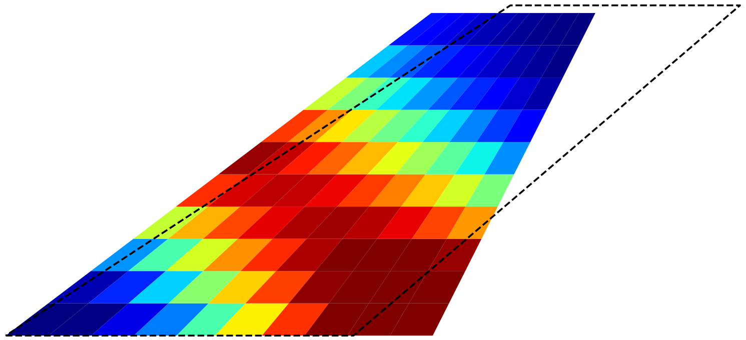
DLM computational cost

- **43.5 min. with 1 core of Intel Skylake CPU**
  - 37 function evaluations
  - 34 gradient evaluations

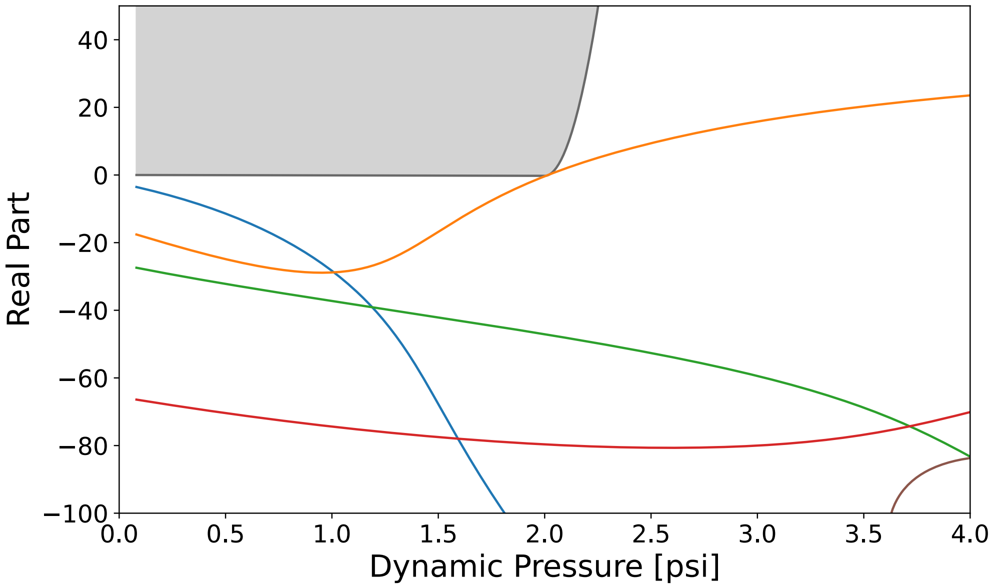
AGARD 445.6 – Optimized Designs

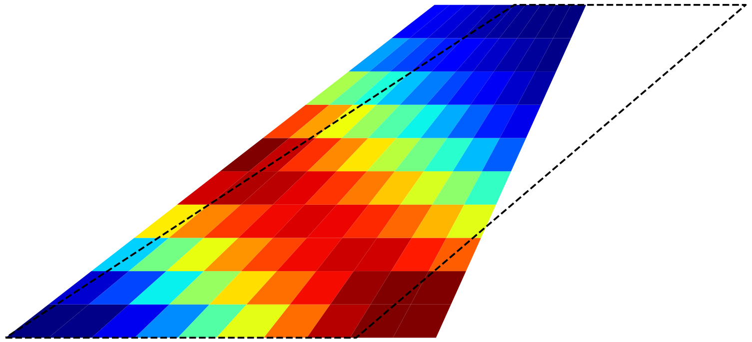
LFD

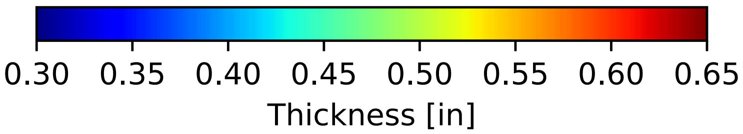




DLM



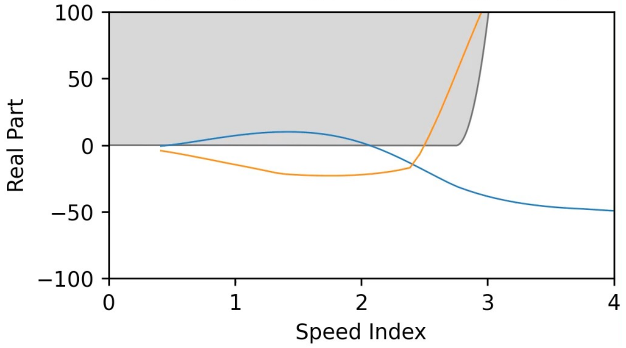




Conclusions

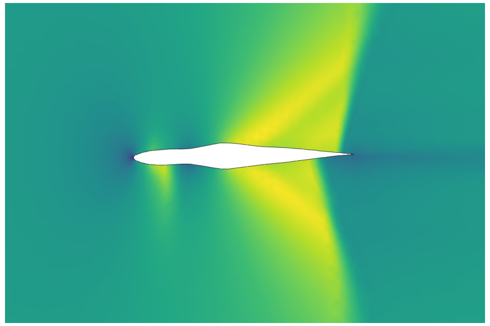
Implemented LFD-based flutter constraints with FUN3D/SFE using OpenMDAO

- GAF-based analysis avoids focusing on a single flutter mechanism
- OpenMDAO creates modularity and automates the coupled sensitivity computation



Results

- Isogai airfoil: successfully applied flutter constraint at a transonic condition
- AGARD 445.6: optimized design comparable to DLM at subsonic condition



Future Work

- Reduce computational cost of LFD analysis and sensitivities in OpenMDAO
- Multifidelity optimization

Acknowledgments

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