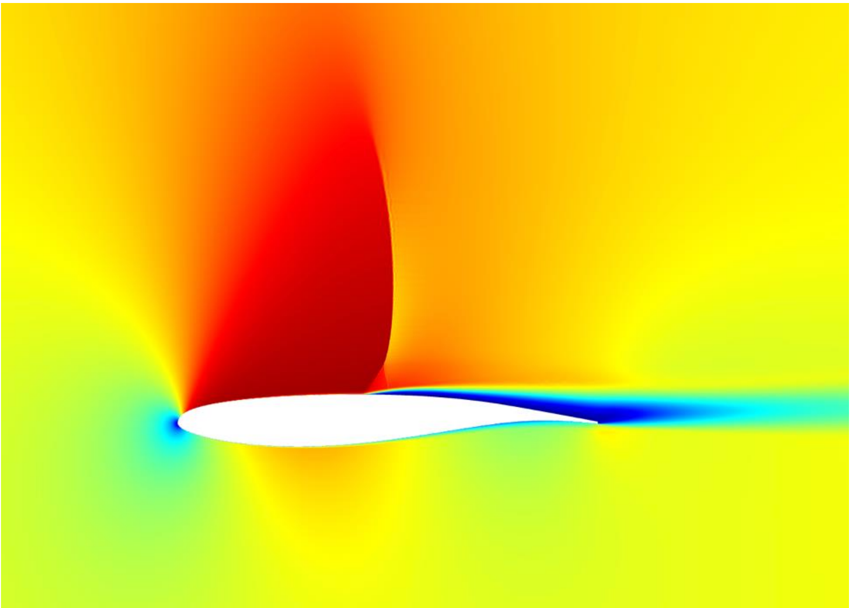

Buffet Onset Prediction with FUN3D's LFD Solver and the Loewner Framework

Kevin Jacobson

Aeroelasticity Branch, NASA Langley Research Center

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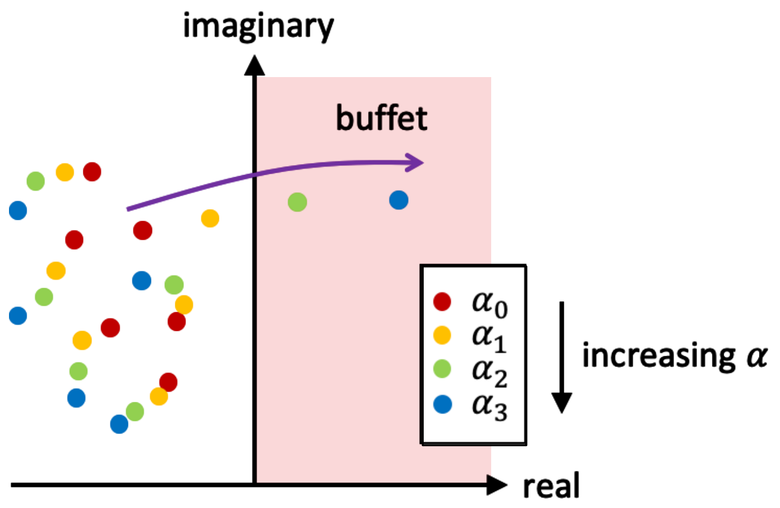
Buffet Onset Prediction

- **Following Crouch et al.[1], the origin of buffet is an aerodynamic linear instability**
- **Buffet onset prediction process:**
  1. Compute a steady flow field
  2. Compute the eigenvalues of the linearized aerodynamic system
     - Crouch et al. perform Global Stability Analysis (GSA)
       - Directly compute the eigenvalues of the full-rank CFD linear operator (the flow solver's Jacobian)
  3. Track the real part of the eigenvalue with changing flow condition
     - Negative real part = stable
     - Positive real part = unstable



Root locus plot

[1]J. Crouch, A. Garbaruk, D. Magidov, A. Travin, "Origin of Transonic Buffet on Aerofoils," *Journal of Fluid Mechanics*, 2009

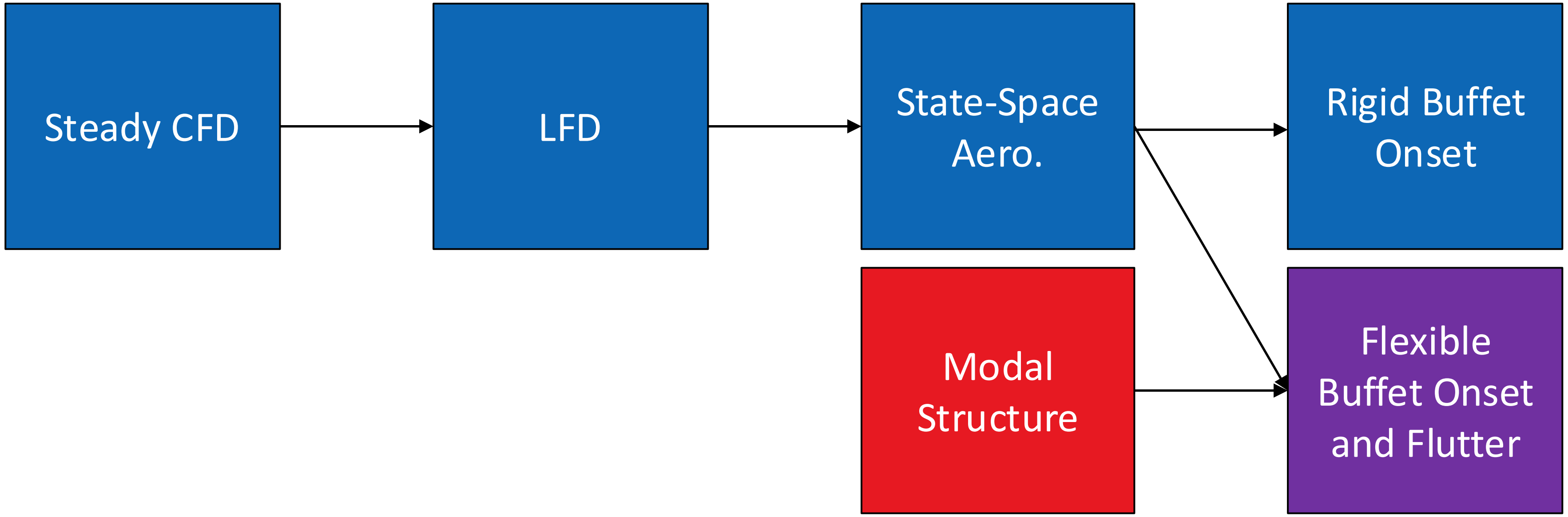
Flutter – Linearized Frequency Domain (LFD)

- **Flutter is an aeroelastic linear instability**
  - Process to solve with LFD:
    1. Solve static (steady) aeroelastic problem
    2. Solve LFD problem: frequency-domain response of the linearized flow due to perturbations of a structural mode shape
       - Solve for perturbations of each mode and a range of frequencies covering the potential flutter frequencies
       - The frequency-domain force responses called Generalized Aerodynamic Forces (GAFs) are a reduced representation of the aerodynamics
    3. Solve the aeroelastic eigenvalue problem using the GAFs as the aerodynamics representation

If we can use LFD aerodynamics to solve for aeroelastic instabilities (flutter), can we also use it for aerodynamic instabilities (buffet onset)?

A Unified Approach for Flutter and Buffet Onset

- **Hypothesis: If the LFD GAFs sufficiently represent the underlying linearized aerodynamic system, we can extract the buffet onset point from LFD GAFs.**
  - Computation of eigenvalues based on the reduced system: the LFD output instead of full CFD Jacobian
- **Approach:**
  - » Create a state-space aerodynamic model from LFD GAFs (~10-100 degrees of freedom)
  - » Eigenvalues of state-space aerodynamic model = rigid buffet onset
  - » Eigenvalues of aeroelastic model (state-space aero. + modal structure) = flexible buffet onset and flutter



State-Space Aerodynamics - The Loewner Framework

- **Building on David Quero et al.'s work with the Loewner Framework[1] for aeroelasticity**
- **Loewner Framework: reduced-order model based on frequency-domain data**
  - Input: LFD GAFs sampled across a frequency range (transfer function samples)
  - Construct rational interpolation matrices (Loewner and shifted Loewner) from those samples
  - Reduce the rank to ~10-100 states via Singular Value Decomposition
  - Output: a state-space linear time-invariant aerodynamic model

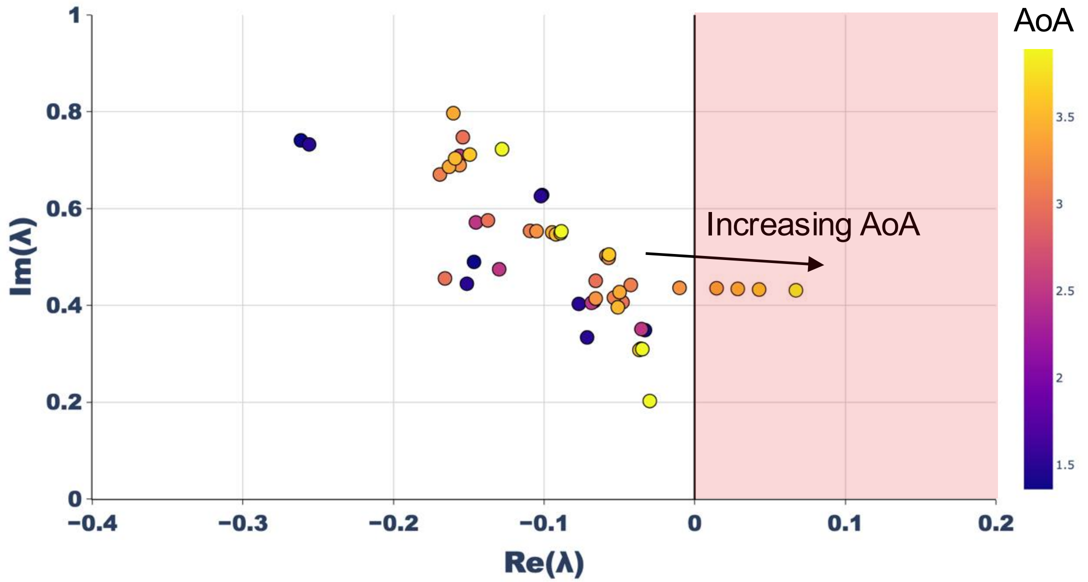
$$\mathbf{E}\dot{x}_a = \mathbf{A}x_a + \mathbf{B}x_s$$

struct. state

$$\mathbf{F}_{as} = \mathbf{C}x_a$$

aero. state

aero. force



Generalized eigenvalue problem with **A** and **E**

[1]D. Quero, P. Vuillemin, C. Poussot-Vassal, "A Generalized State-Space Aeroservoelastic Model Based on Tangential Interpolation," *Aerospace*, 2019

Flow Solver

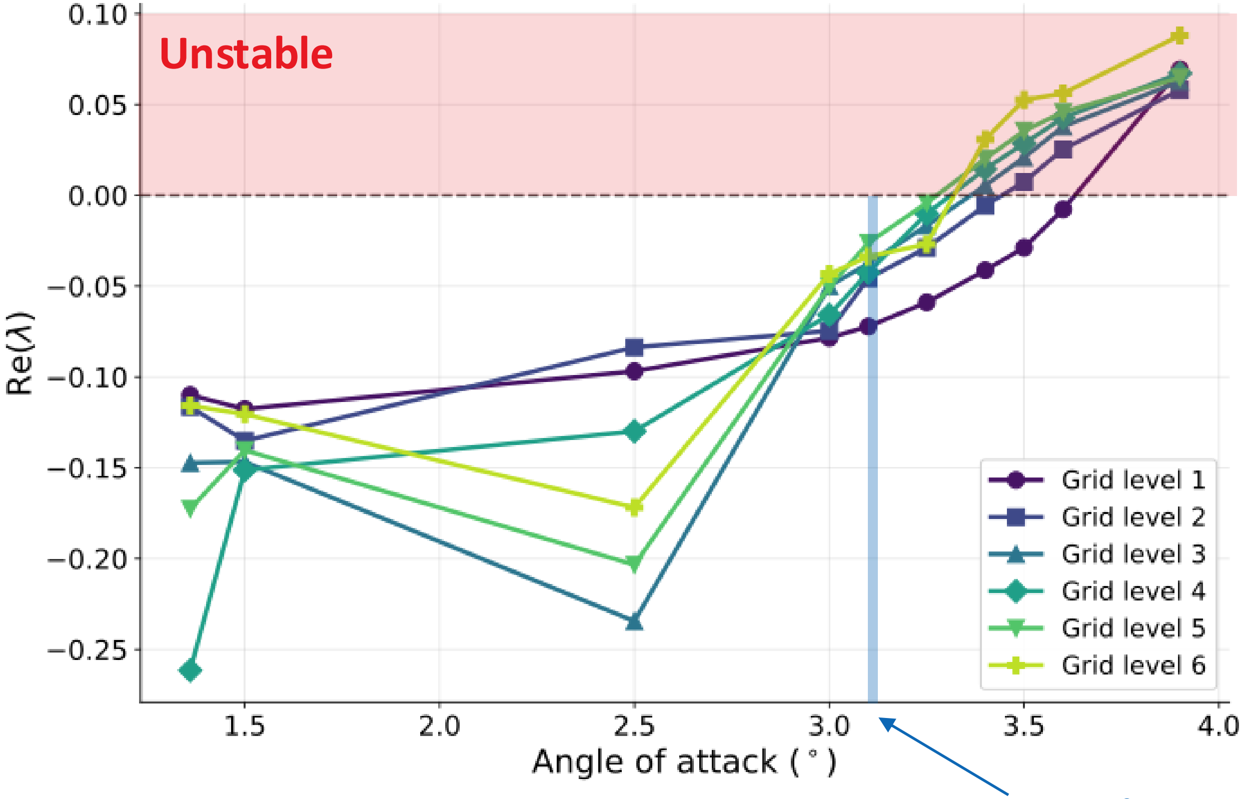
- **FUN3D’s Stabilized Finite-Element solver (FUN3D/SFE)**
  - Continuous Galerkin finite-element solver
  - Streamline Upwind Petrov-Galerkin (SUPG) stabilization
- **ONERA OAT15A simulation settings:**
  - Workshop-provided grids from Cadence Pointwise
  - Turbulence model:
    - » Negative Spalart-Allmaras model with Mixing Layer Compressibility Correction (SA-neg-comp)
  - LFD settings:
    - » Perturbation mode: pitch about 40% chord
    - » 41 frequencies, evenly spaced reduced frequencies k= [0,1]
    - » GMRES + iLU(k) preconditioning

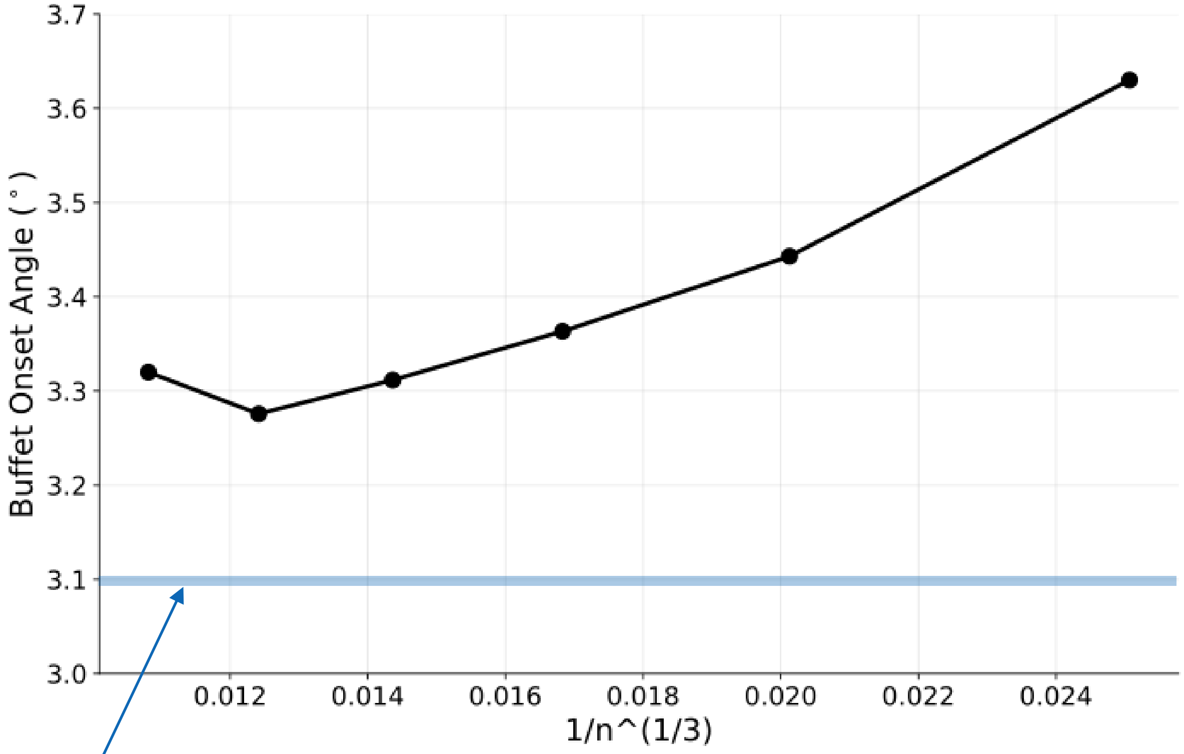
FUN3D
Fully Unstructured Navier-Stokes

Experimental data shows buffet onset is at AoA=3.1°

Mesh Convergence – SA-neg-comp

- **Lack of convergence for LFD on mesh level 6 mesh**
  - Final linear residuals are order 10^{-1} near the buffet frequency
  - Need stronger linear solver + preconditioner





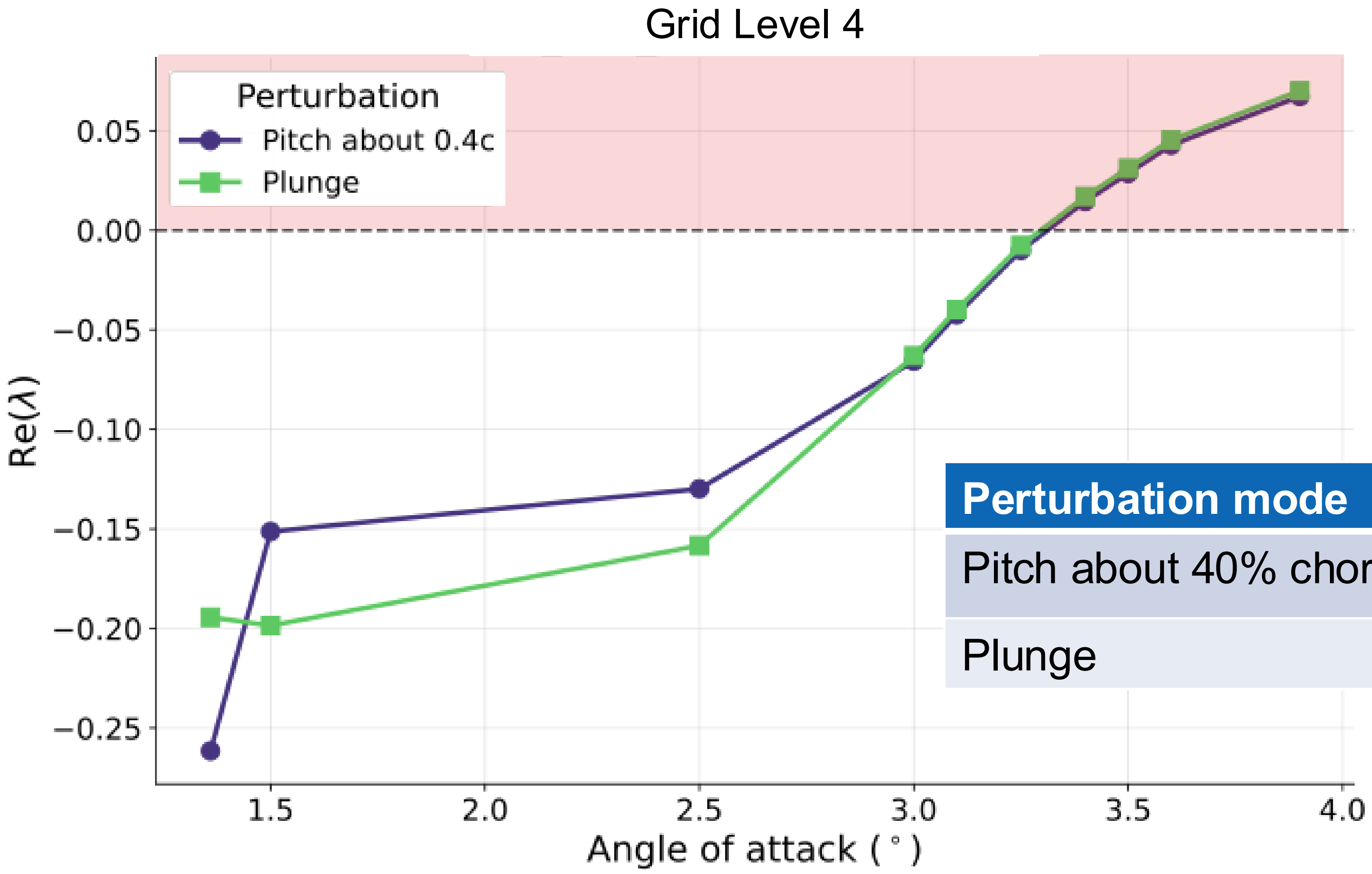
Experimental onset

Angle of attack sweep

Buffet onset convergence

Changing the LFD Perturbation

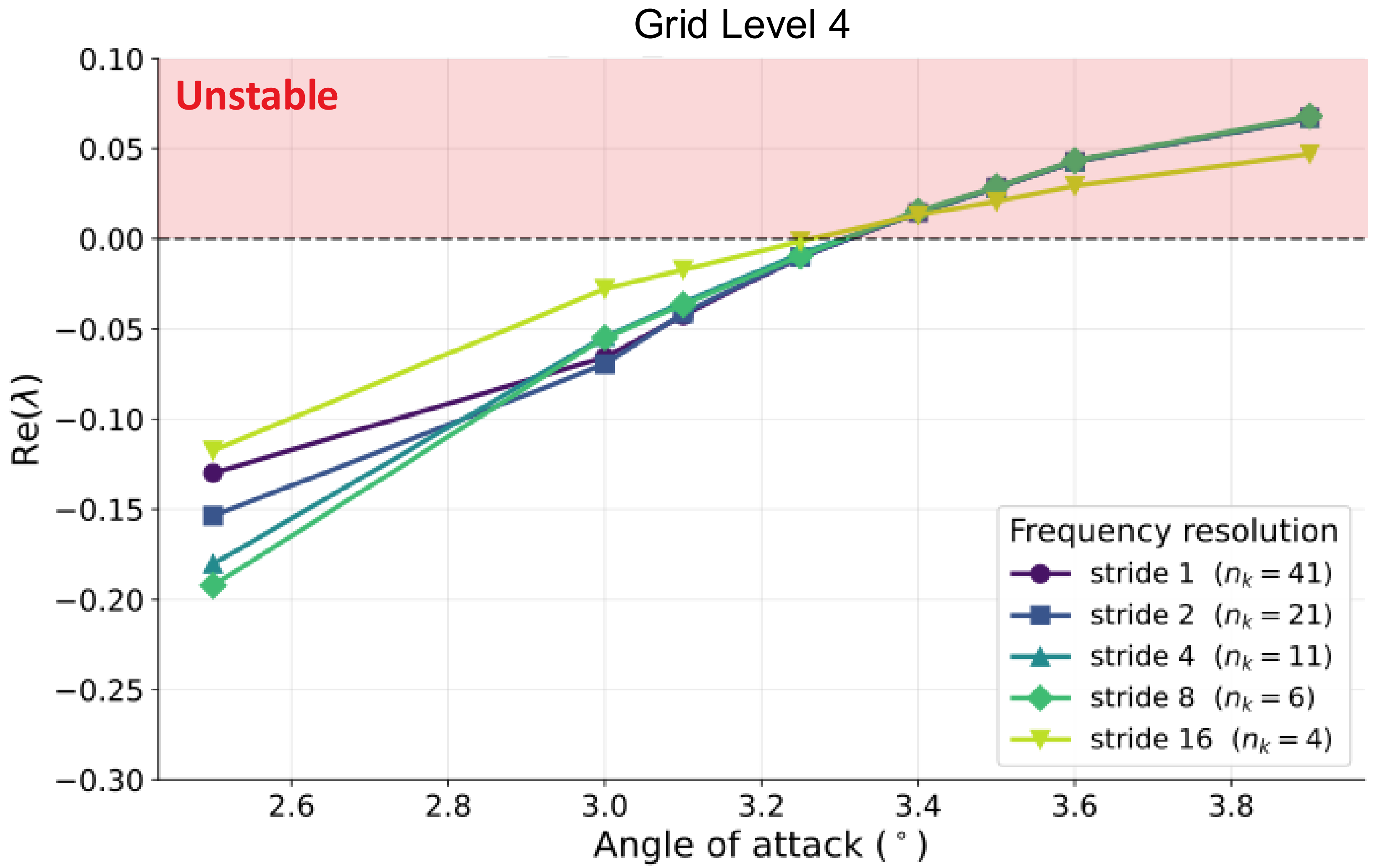
- **The buffet onset eigenvalues should be independent of the LFD perturbation shape**



Perturbation mode	Buffet onset AoA
Pitch about 40% chord	3.31°
Plunge	3.30°

Sensitivity to Frequency Resolution

- **Remove (*k*, GAF) pairs from the original set of 41**
  - Stride N = keep every N^{th} frequency

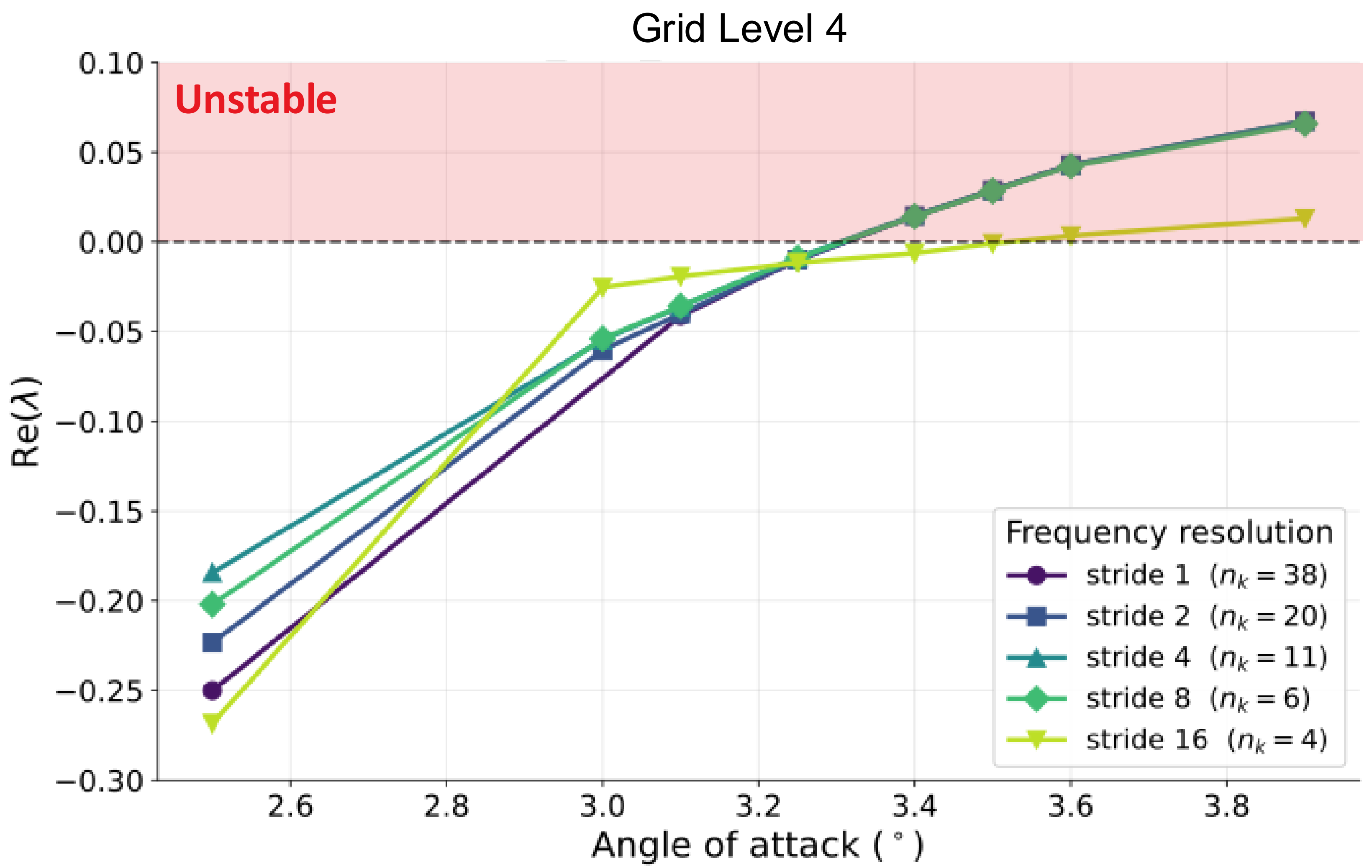


Stride 16:
k = [0, **0.4**, 0.8, 1.0]

Buffet frequency k=0.41

Sensitivity to Frequency Resolution

- **Remove all frequencies between 0.38 and 0.45 before striding**

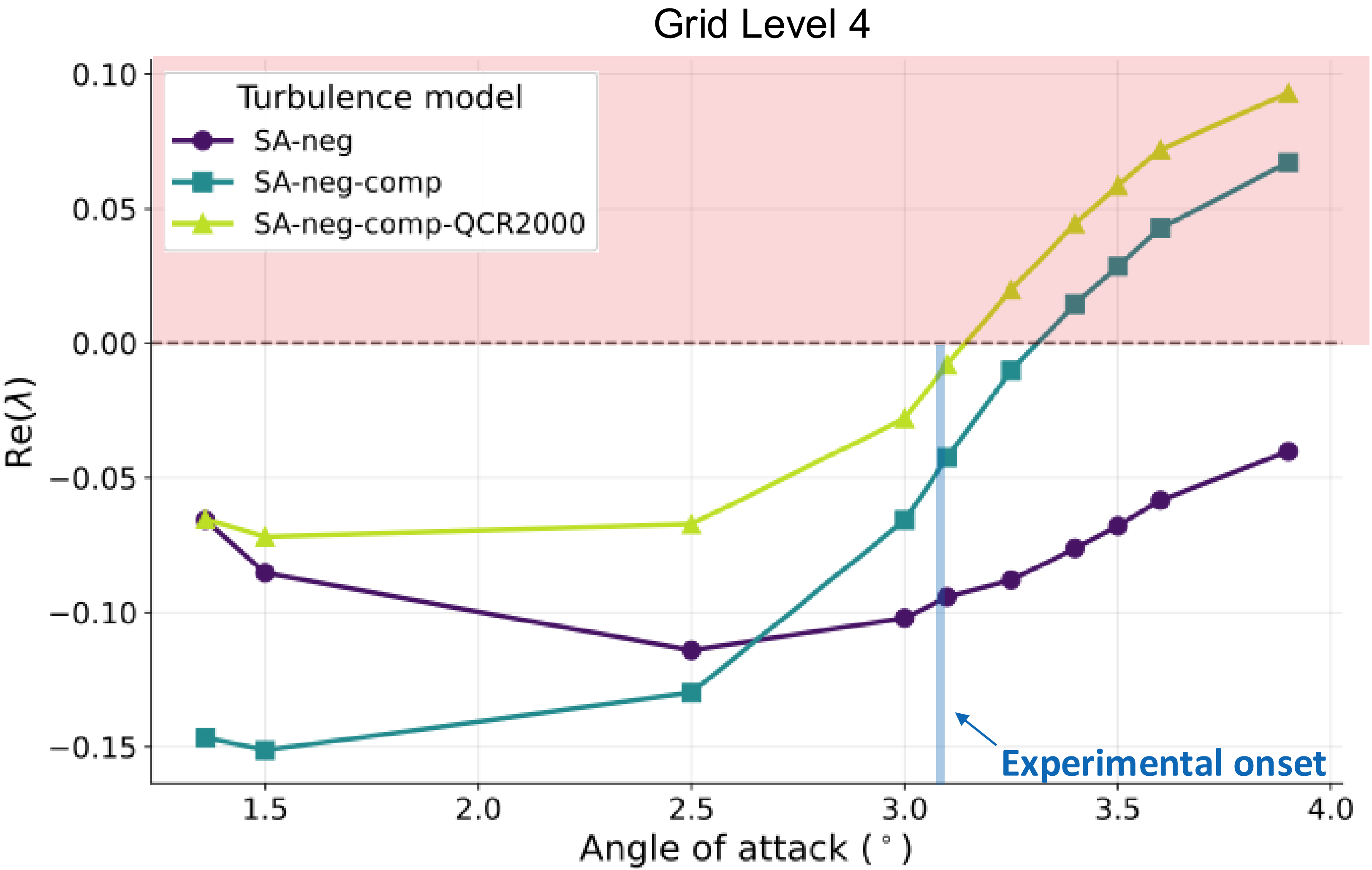


Stride 16:
k = [0.0, 0.475, 0.875, 1.0]

Buffet frequency k=0.41

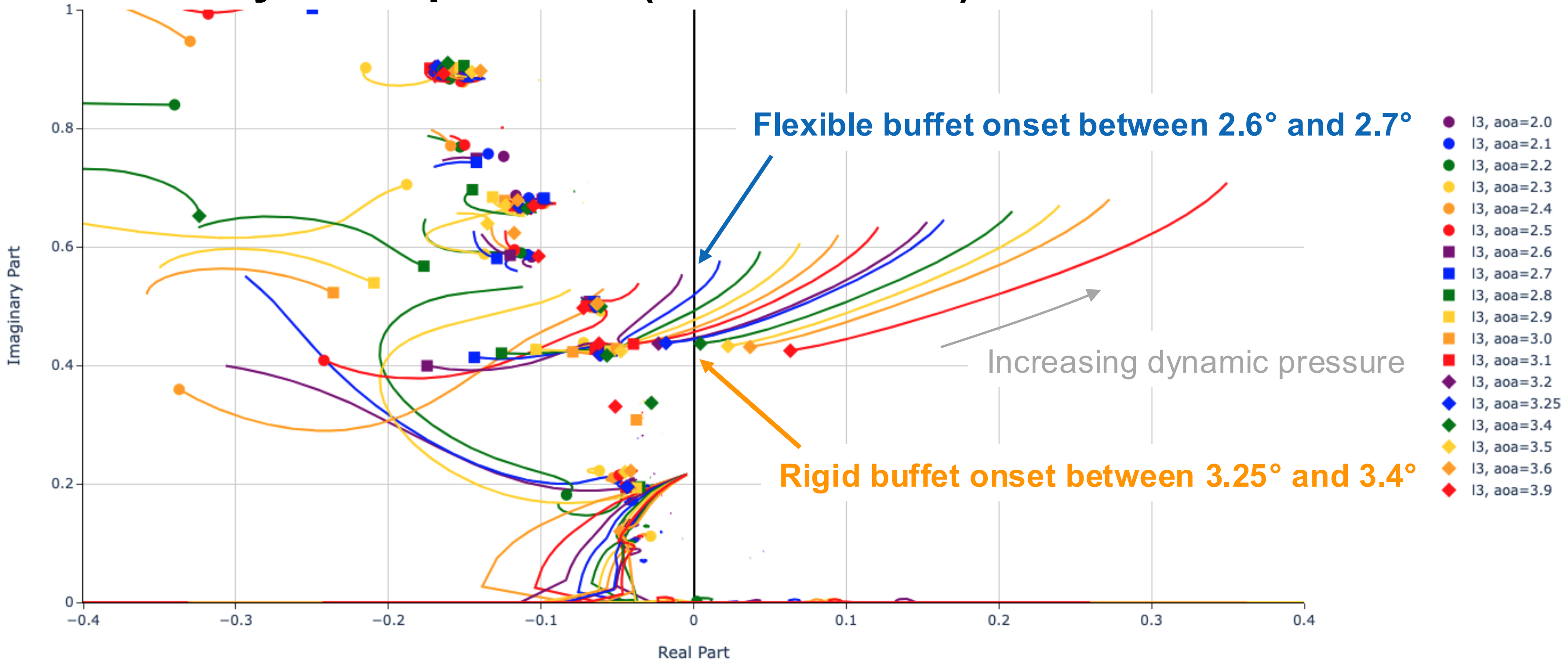
Turbulence Model

- **Mixing Layer Compressibility Correction (comp) required to get SA model to buffet**
- **QCR2000 shifts the buffet onset earlier**



Flexible Buffet Onset

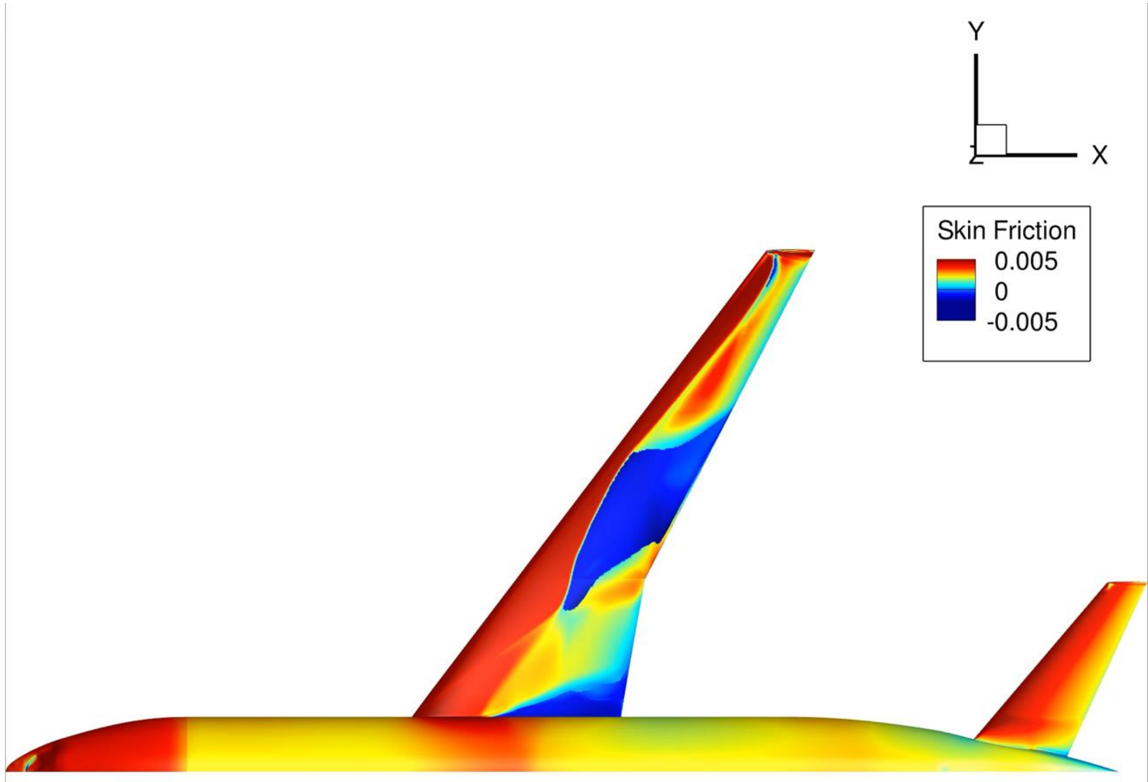
- **Pitch degree of freedom about 40% chord**
  - Compare to time-domain computations of Giannelis[1]
    - » Rigid buffet onset at 3.5° and flexible buffet onset at 2.5°
- **Symbols are zero dynamic pressure eigenvalues (rigid buffet)**
- **End of line = the total dynamic pressure (flexible buffet)**



[1]N. Giannelis "Transonic Aeroelastic Limit Cycles and Their Dependence on Freestream Conditions" IFASD 2024

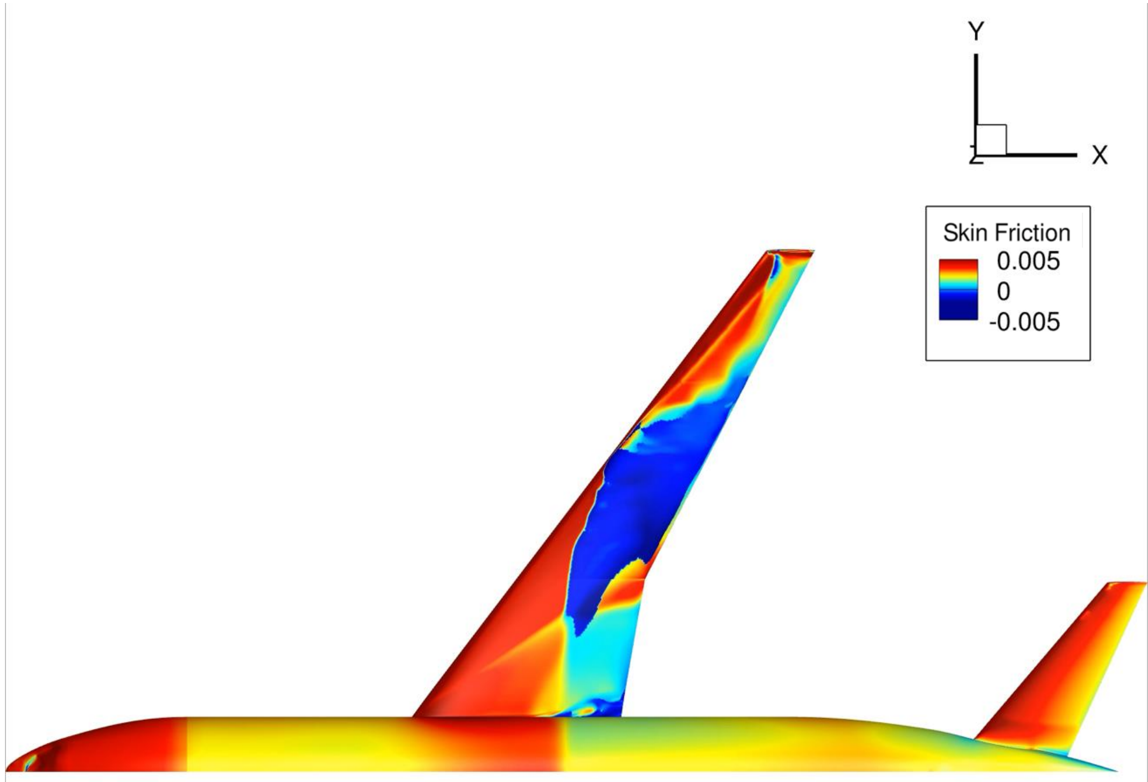
Case 2: In Progress

- **FUN3D/SFE solver in the time domain**
  - SA-neg-comp-R-QCR2000
- **AOA 4.84 °**
  - Grid: HeldenMesh L3 and L4
  - BDF2 temporal integration with 100 steps/CTU
  - Status:
    - » Side of body = buffeting
    - » Outboard mode = stabilizing after initial perturbation



Case 2: In Progress

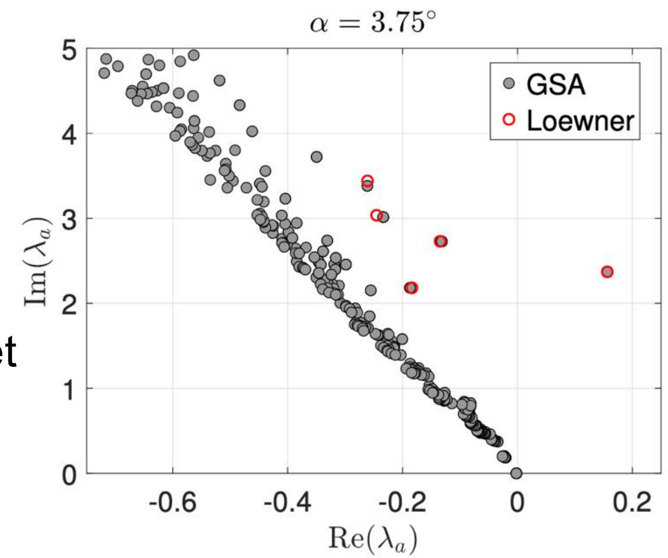
- **AOA 5.89°**
  - Grid: HeldenMesh L3
  - BDF2 temporal integration with 100 steps/CTU
  - Status:
    - » Side of body = buffeting
    - » Outboard mode = buffeting



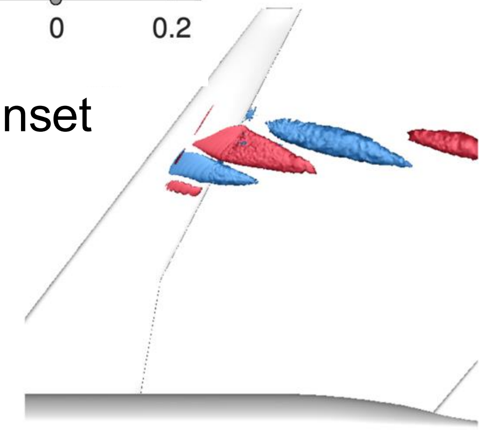
Summary

Buffet onset prediction of the ONERA OAT15a

- FUN3D/SFE's LFD + Loewner framework
- Insensitive to frequency resolution and perturbation mode
- LFD + Loewner framework looks like a promising path for a unified workflow for flutter, rigid buffet onset, and flexible buffet onset



CRM buffet onset



Our paper[1] at IFASD next week has more details:

- About the LFD + Loewner method
- Application to the CRM (Non-DPW JAXA case)
- Reconstruction of buffet modes using Proper Orthogonal Decomposition (POD)

Acknowledgments:

- David Quero, Christoph Kaiser, Sebastian Timme, and Bret Stanford:
  Collaborators on the development of the LFD + Loewner buffet onset prediction approach

[1]D. Quero, C. Kaiser, S. Timme, K. Jacobson, B. Stanford, "Buffet Onset Prediction with the Linearized Frequency Domain Method," International Forum on Aeroelasticity and Structural Dynamics (IFASD) 2026