RMIT / Duke / ANSYS Contribution to the High-Angle Working Group

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What's next...

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Ansys
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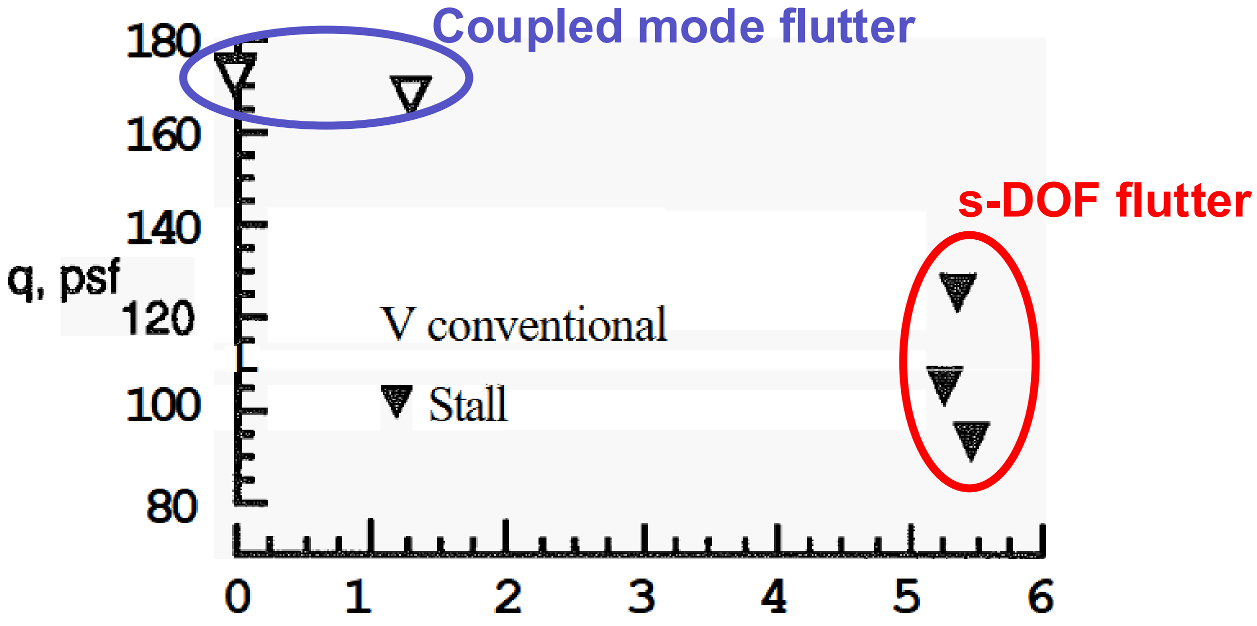
Benchmark Supercritical Wing

- HAWG is concerned with the prediction transonic flutter.
- BSCW has been a test subject in AePW since its inception.

BSCW mounted in TDT at NASA LaRC

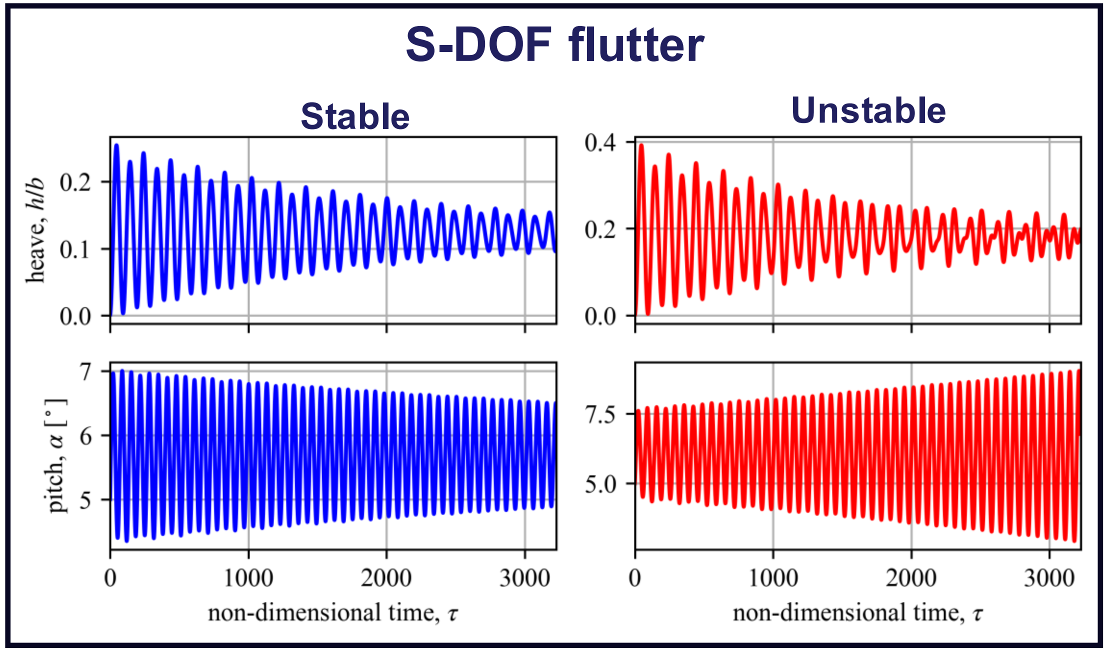


Experimental flutter dynamic pressure versus AOA [2]

[2] Dansberry, B. E., Durham, M. H., Bennett, R. M., Rivera, J. A., Silva, W. A., Wieseman, C. A., and Turnock, D. L., "Experimental Unsteady Pressures at Flutter on the Supercritical Wing Benchmark Model," 34th Structures, Structural Dynamics, and Materials Conference, La Jolla, CA, 1992.

Single-Degree-of-Freedom Flutter

- Coupled-mode flutter is characterized by a loss of stiffness and the coalescence of modes. In the transonic regime:
  - Reasonably well understood.
  - CFD-based linearization codes do well.
- S-DOF flutter is characterized by a loss of aerodynamic damping due to negative aerodynamic damping:
  - Large drop in flutter dynamic pressure.
  - Flutter dynamic pressure can go to zero!
  - Less understood.
  - Very challenging to model.
  - Highly sensitive to treatment of SBLI.



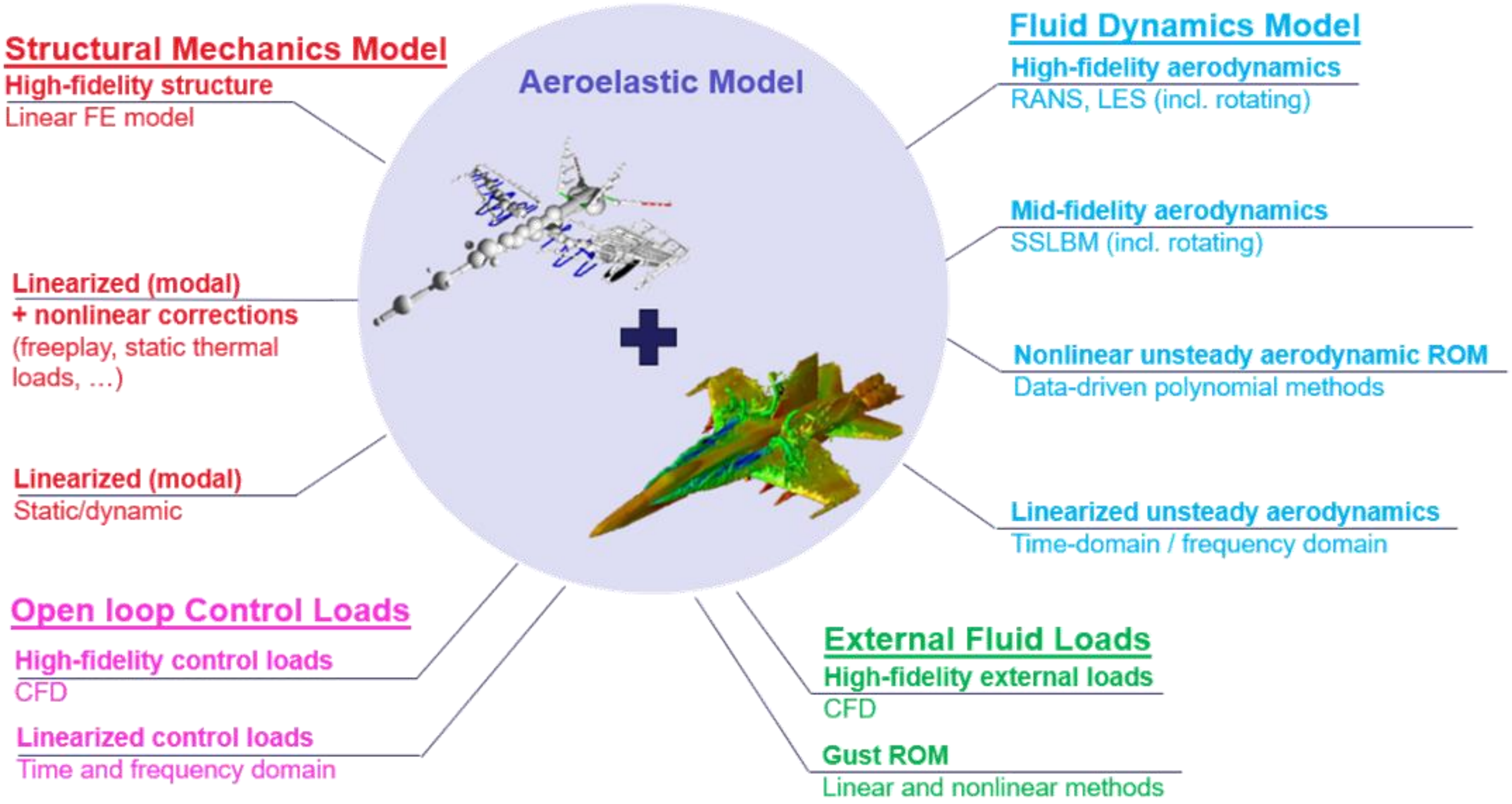
Objectives

- Benchmark RMIT's CFD-based aeroelastic code (PyFSI).
- Benchmark Fluent's Generalized k-ω turbulence for transonic flutter.
  - Is URANS model tuning useful for transonic flutter?

Test Case 1: 3D model, Mach 0.8, AOA, $\alpha_0 = 0° - 6°$.

Test Case 3: 2D model, Mach 0.8, AOA, $\alpha_0 = 0° - 6°$ (limited work, not presented).

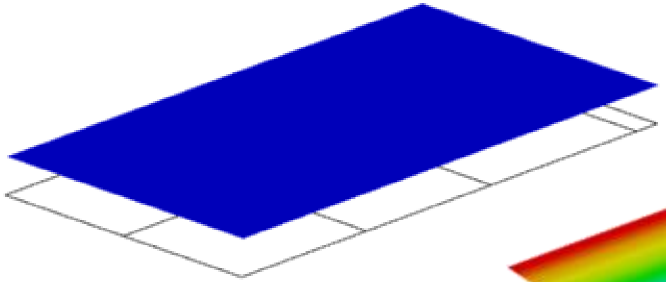
In-House Code (PyFSI)



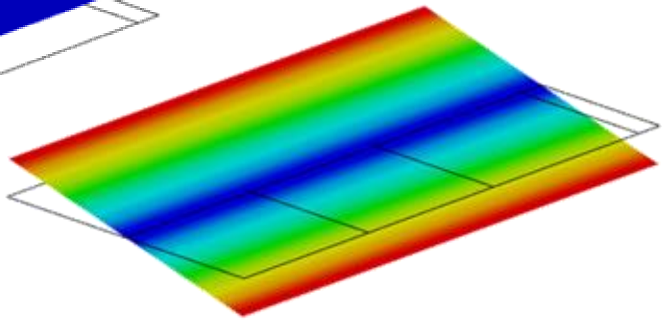
Computational Model

Structural Model

- Modal coordinates.
- Heave and pitch modes only.
- Newmark-Beta time integration.
- Projection using RMIT's MPR algorithm [3].



heave 3.33 Hz



pitch 5.2 Hz

Fluid Model

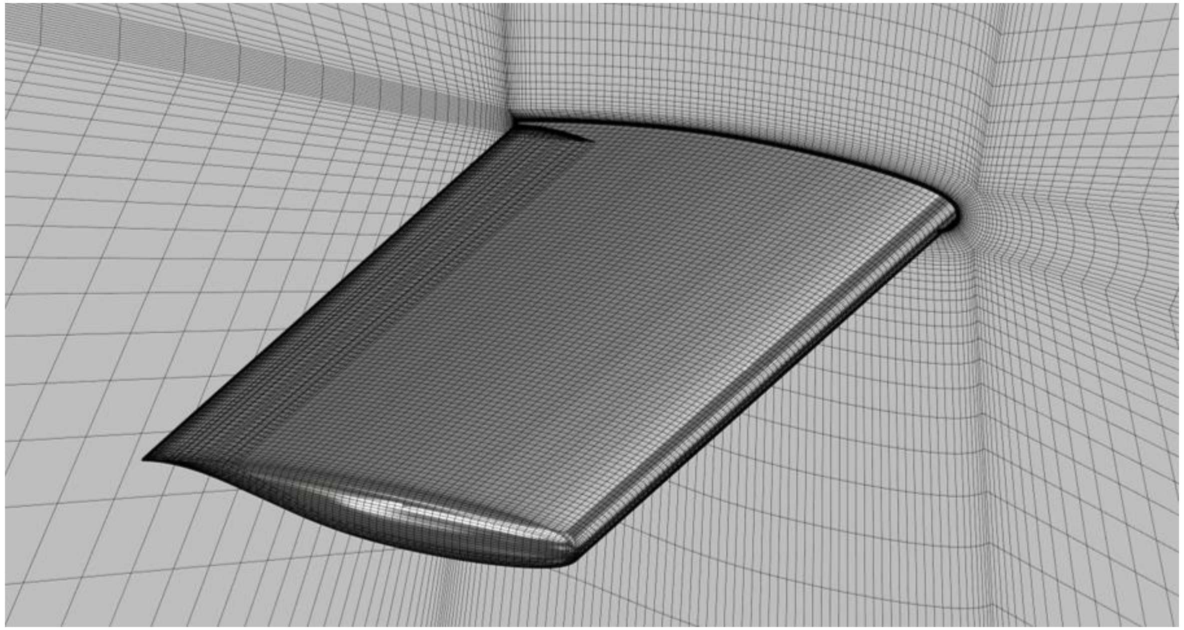
- Fluent 2024 R2 - coupled pressure-based solver
- SST $k-\omega$ turbulence model, CURV, ProdLim.
- Second-order spatial and temporal discretization.

- Second-order Volterra-based ROM for fast flutter predictions (comprehensively validated) [4].
- New BSCW structural parameters can be run without new CFD.

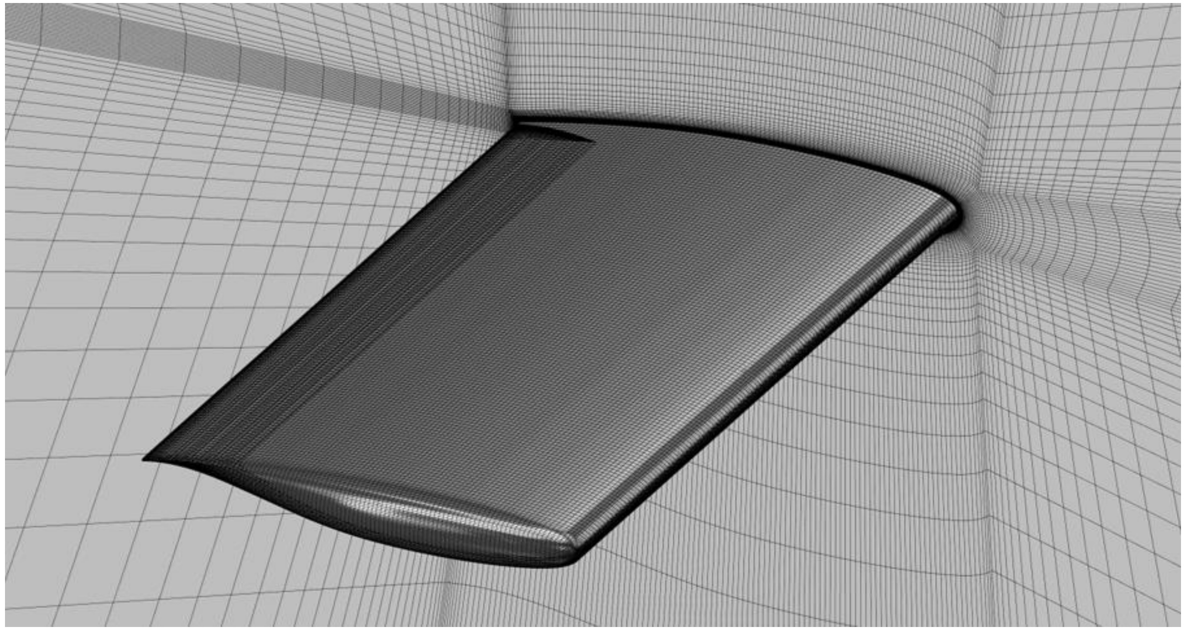
[4] Candon, M., Delgado-Gutierrez, A., Marzocca, P., Balajewicz, M., and Dowell, E. H., "Nonlinear Aeroelastic Reduced Order Modeling with Optimized Sparse Multi-Input Volterra Kernels," AIAA Journal, 2025.

[3] Joseph, N., Carrese, R., and Marzocca, P., "Projection Framework for Interfacial Treatment for Computational Fluid Dynamics/Computational Structural Dynamics Simulations," AIAA Journal,Vol.59,No.6,2021, pp. 2070–2083.

Computational Grids



Medium: 4.5M cells



Fine: 14M cells

Sensitivity to Turbulence Model

Generalized $k-\omega$ (GEKO) Model

- GEKO contains free parameters which can be tuned
- Separation, C_{SEP}, near-wall treatment, C_{NW}, mixing layer, C_{MIX}, jet flow, C_{JET}, among others.
- Implemented through the functions f_1, f_2, f_3 in the TKE and specific dissipation equations:

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho U_j k)}{\partial x_j} = P_k - C_\mu \rho k \omega + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] \qquad (1)$$

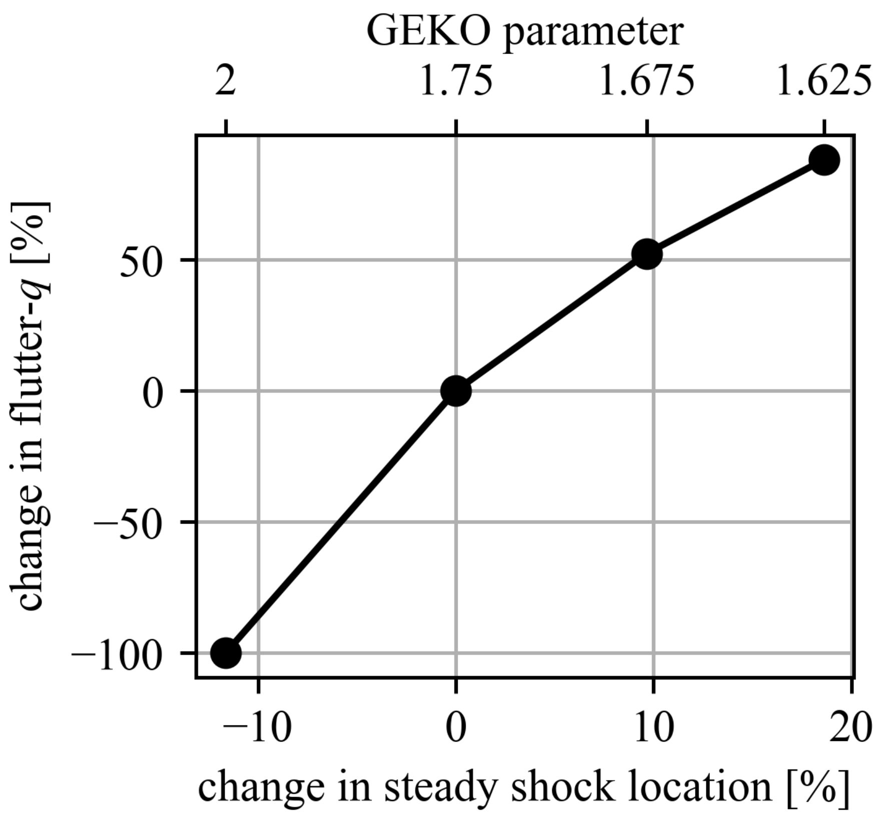
$$\frac{\partial(\rho \omega)}{\partial t} + \frac{\partial(\rho U_j \omega)}{\partial x_j} = C_{\omega 1} f_1 \frac{\omega}{k} P_k - C_{\omega 2} f_2 \rho \omega^2 + \rho f_3 CD + \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\omega}\right)\frac{\partial \omega}{\partial x_j}\right] \qquad (2)$$

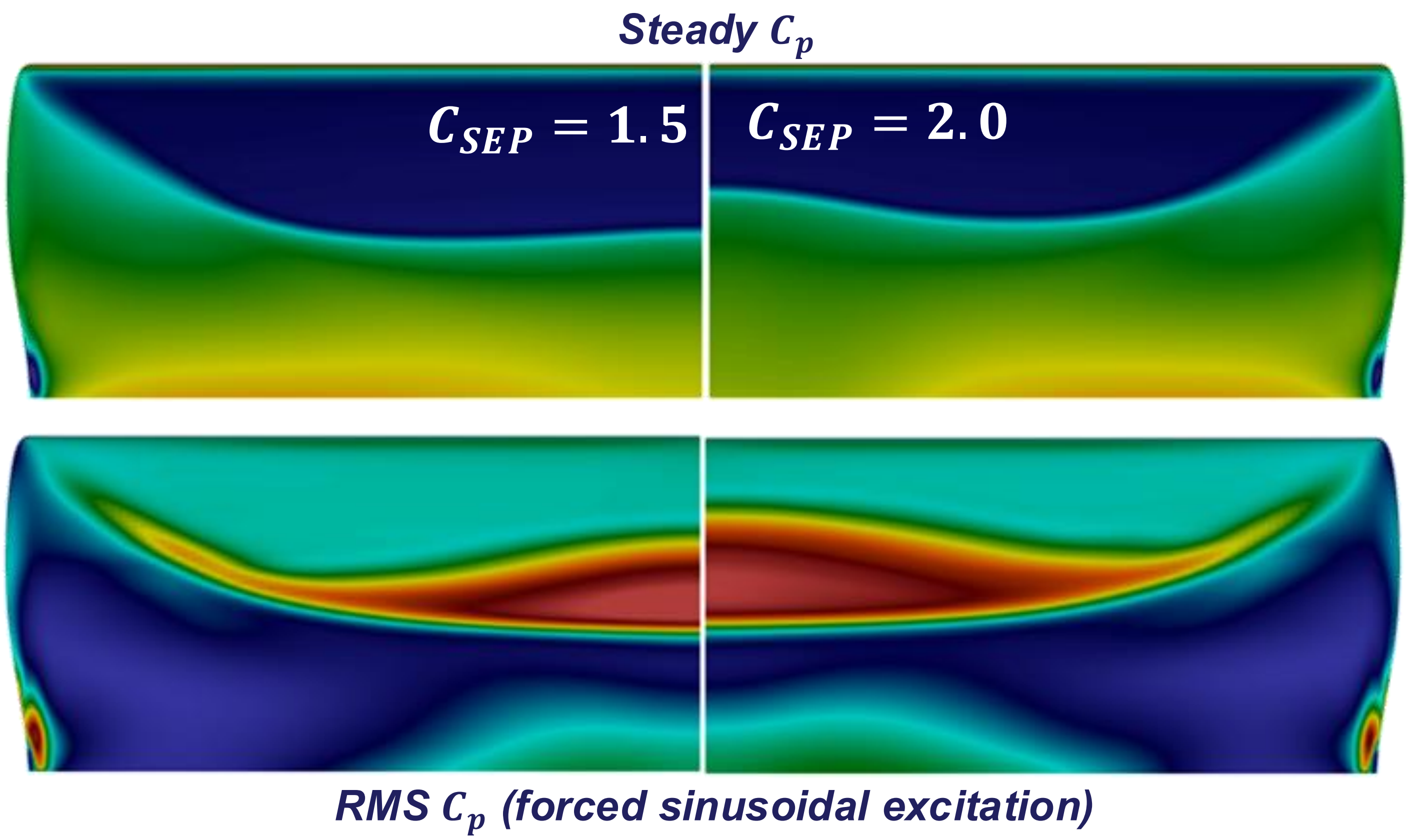
- C_{SEP} modifies eddy viscosity -> higher values more separation, lower values less separation.

[1] Menter, F. R., Lechner, R., and Matyushenko, A., Best Practice: Generalized k-ω (GEKO) Two-Equation Turbulence Modeling in Ansys CFD, ANSYS Academic Research, 2021.

Sensitivity to Turbulence Model

Mach 0.8, AOA = 5deg

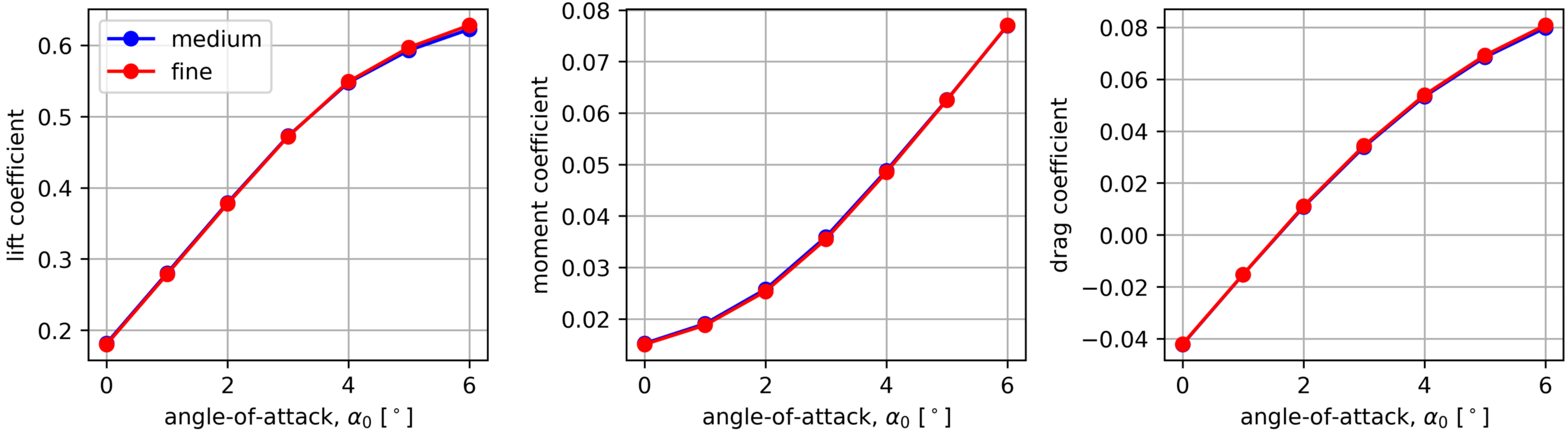




[5] Candon, M., Balajewicz, M., Delgado-Gutierrez, A., Marzocca, P., Thomas, J., and Dowell, E. H., "Stall Flutter of the Benchmark Supercritical Wing Using Aeroelastic Model Reduction and Tunable Turbulence Parameters," 66th Structures, Structural Dynamics, and Materials Conference, 2024.

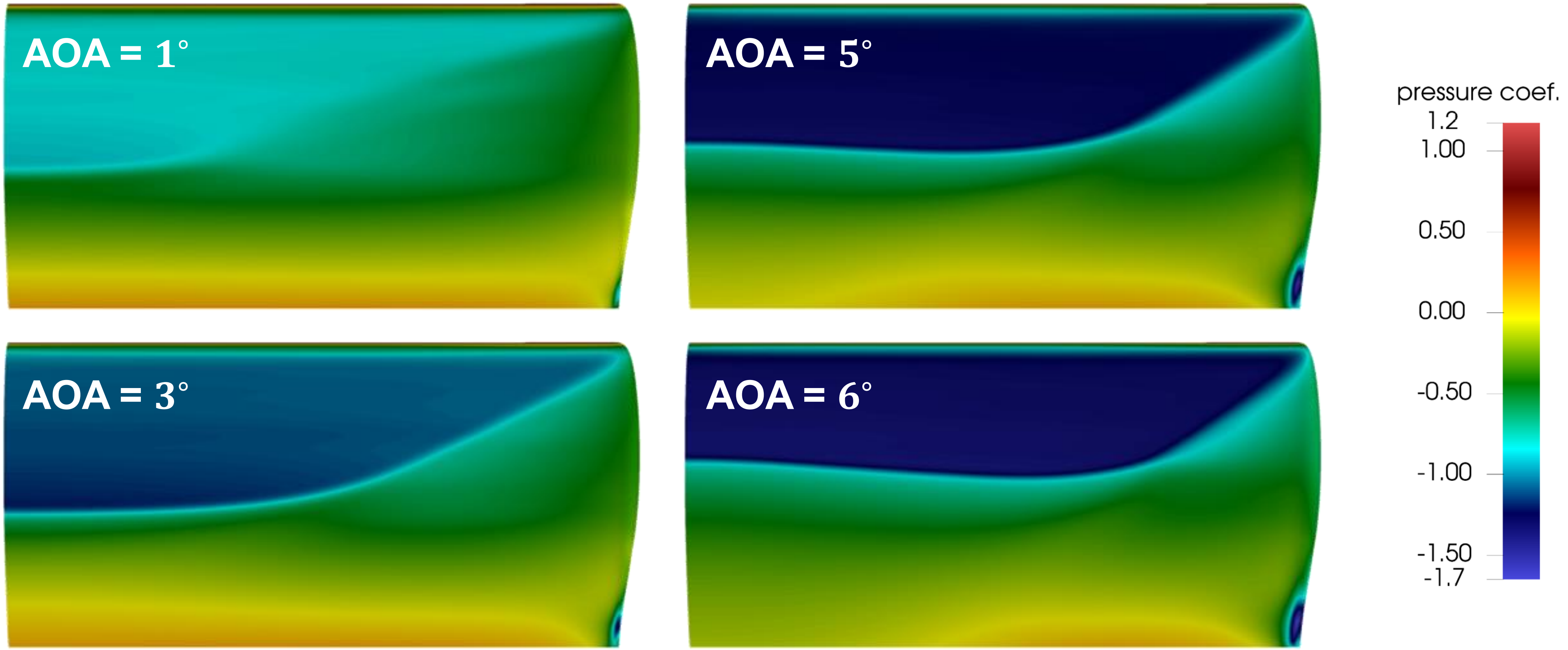
Steady State Forces

SST $k-\omega$, medium and fine grids



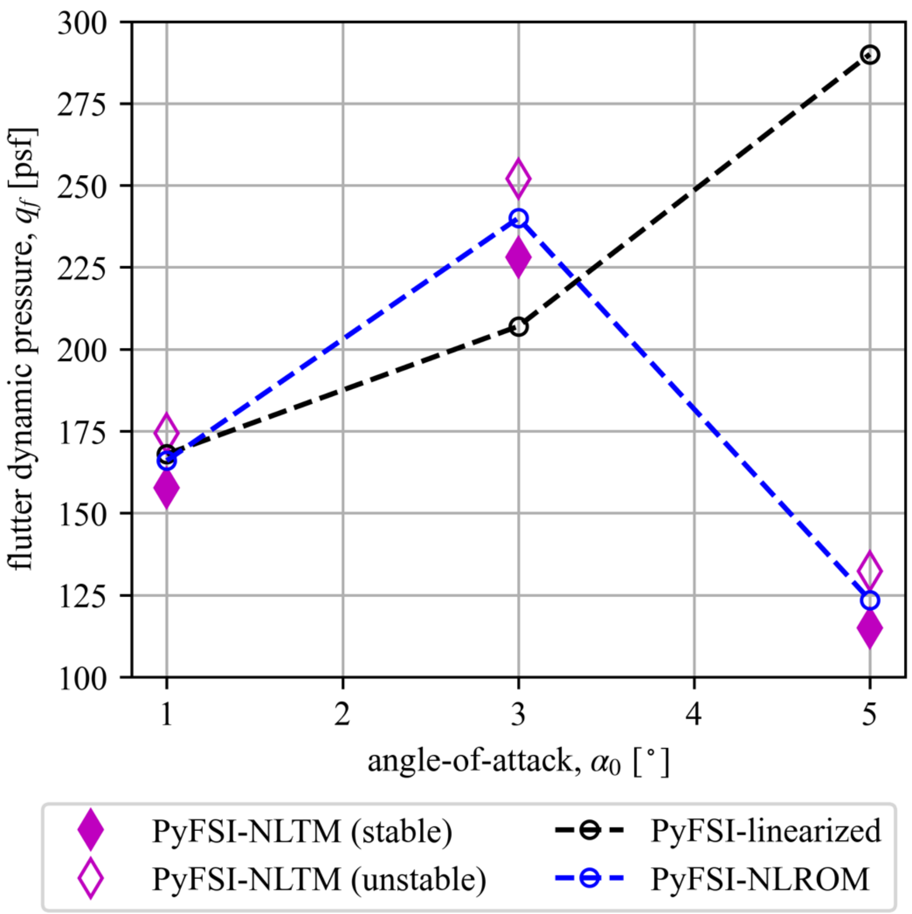
Steady State Pressure Coefficient

SST $k-\omega$, fine grid (upper surface)



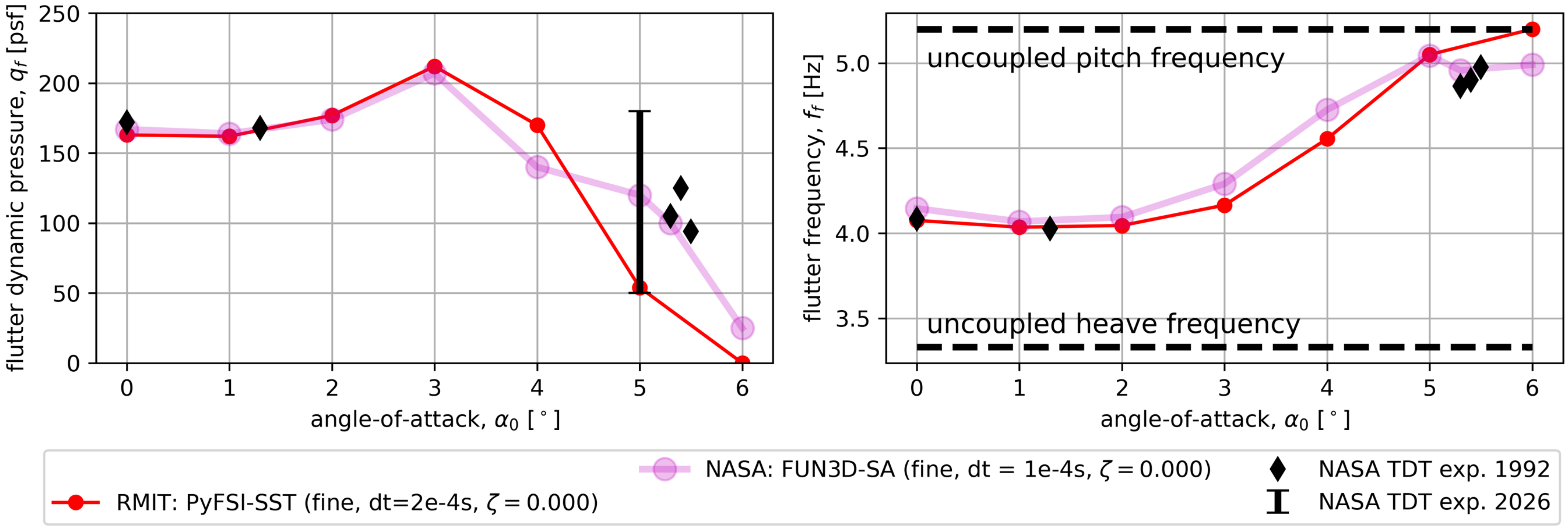
ROM Verification

- Nonlinear Time Marching (NLTM) solution run at ±5% the flutter dynamic pressure computed by the second-order model.
- Nonlinear ROM (NLROM) solution within ±5% of NLTM predictions. This is very conservative.



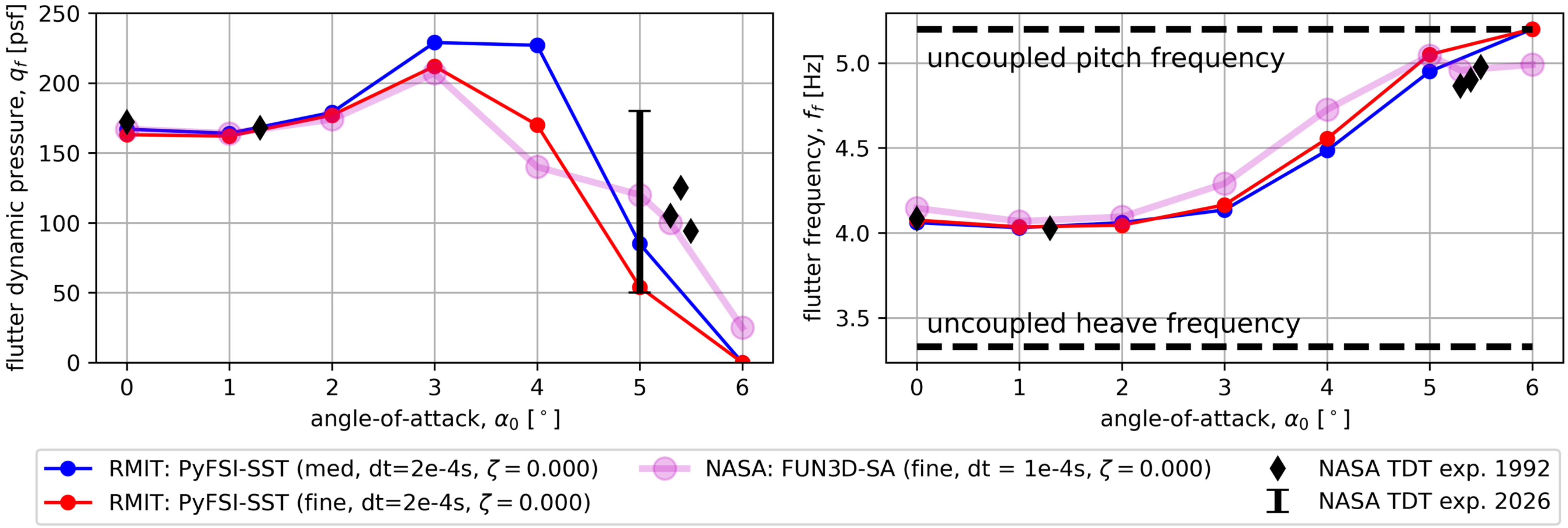
Baseline Results

- Perturbation: GVEL = 1
- Comparing to experimental data and the FUN3D results of NASA LaRC.
- These results will be shown on every slide.



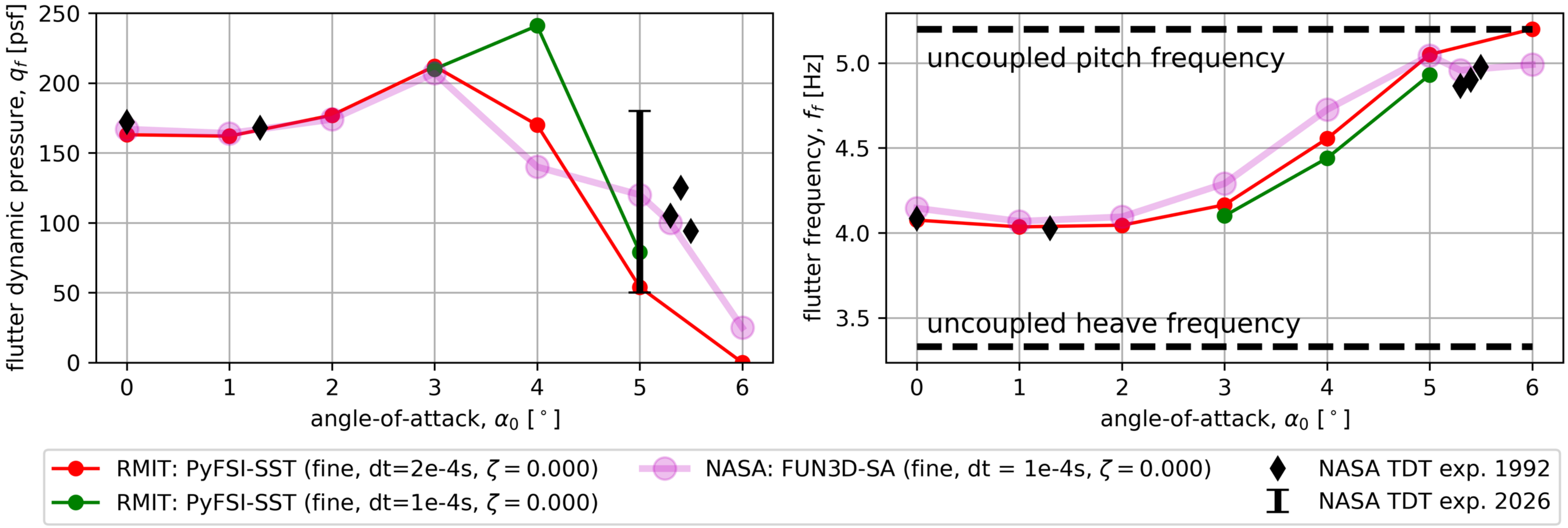
Grid Refinement

- Perturbation: GVEL = 1
- Grid convergence for lower AOA.
- Grid convergence is slower for higher AOA (unsurprising).



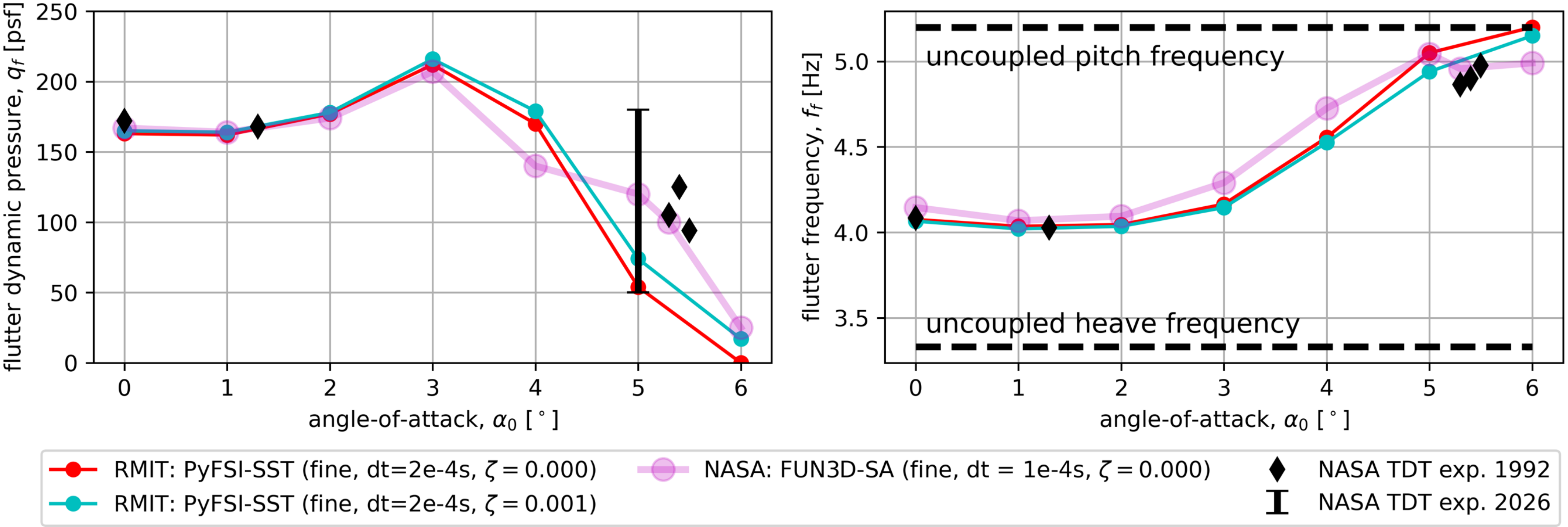
Temporal Refinement (incomplete)

- Perturbation: GVEL = 1
- Temporal convergence for lower AOA (?)
- Temporal convergence is slower for higher AOA (unsurprising).



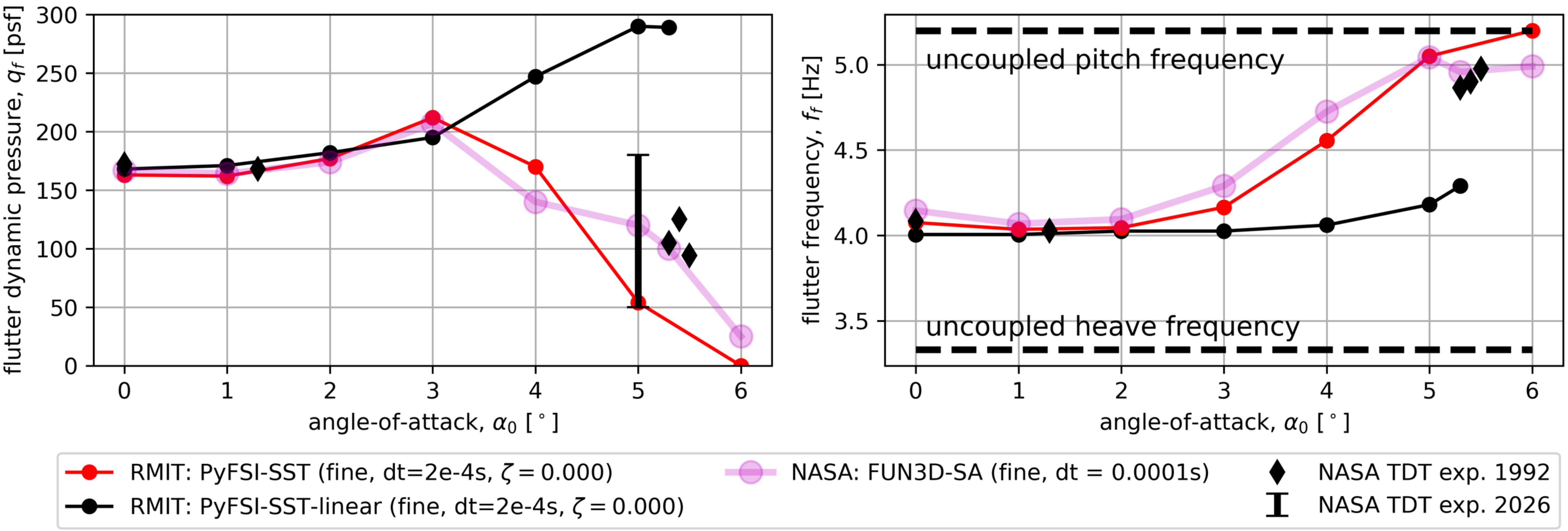
Structural Damping

- Perturbation: GVEL = 1
- Structural damping has little influence on coupled mode flutter.
- Structural damping has a significant influence on s-DOF flutter.



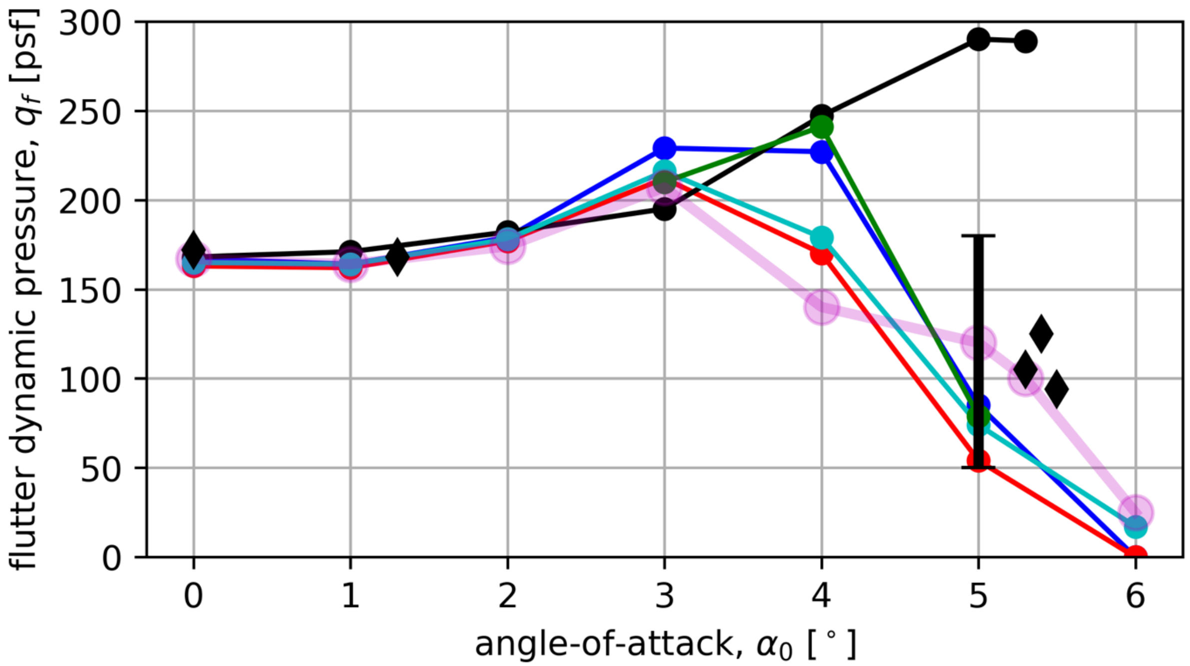
Linearization

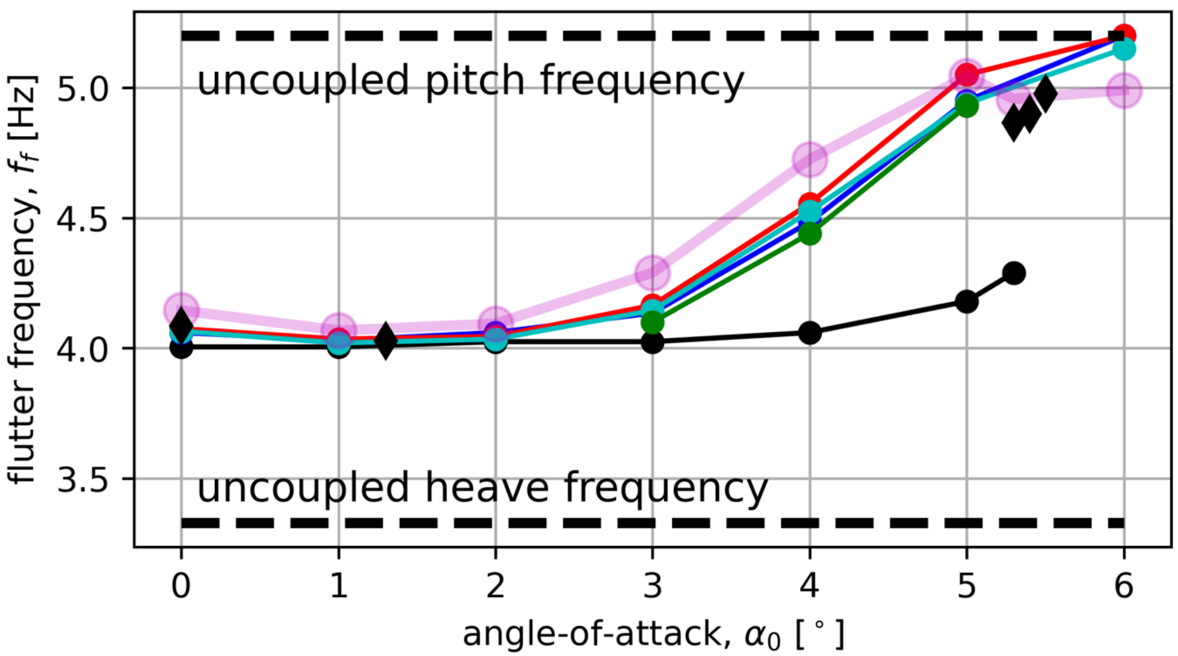
- Perturbation: GVEL = 1
- The linear and nonlinear models are in strong agreement up to AOA = ~3deg.
- Linear model does not predict the sDOF flutter.



All Results and Scatter

- Perturbation: GVEL = 1
- Scatter is most significant at AOA = 4deg.





GVEL (subcriticality)

- Generalized velocity (GVEL) perturbation not properly investigated yet.
- Have seen some subcritical behavior at AOA = 4deg:
  - GVEL = 1 -> q-flutter = 241psf
  - GVEL= 5 -> q-flutter = 223psf
- However, GVEL = 2 – 3 kicks the model beyond training data range.
- Predictions becomes unreliable above GVEL = 3
- Will try to do a dedicated study of this for SciTech 2027.

Final Remarks

- Transition from coupled-mode to s-DOF flutter captured using a simple nonlinear ROM.
- Reasonable agreement with NASA and experiment.
- More work is needed for mesh and time-step refinement.
- More work is needed to assess the subcriticality of the response at higher AOA.
    - Would like to use NASA “fine” grid for this.
- Can re-run with new structural parameters.