Transonic Buffet and Stall Flutter Predictions with a Tunable Turbulence Model for DPW-8 /AePW-4

Michael Candon, Truman Gerner and Pier Marzocca
RMIT University, Melbourne AU

Luke Munholand and Valerio Viti
ANSYS Inc., Lebanon, NH

Lewis Clark
LEAP Australia, Clayton AU

What's next...

Ansys

RMIT UNIVERSITY

Australian Government
Defence

Sir Lawrence Wackett
Defence & Aerospace Centre

Objectives

Royal Melbourne Institute of Technology (RMIT) team, in collaboration with **Ansys**, are participating in the:

- High-Angle Working Group (HAWG) and
- Buffet Working Group (BWG)

Goals:

- Benchmark RMIT's CFD-based aeroelastic code (PyFSI).
- Assess the efficacy of the tuneable Generalized $k - \omega$ (GEKO) turbulence model for complex transonic unsteady aerodynamic flows.
- Benchmark Ansys Fluent Native GPU solver (in progress for final workshop).

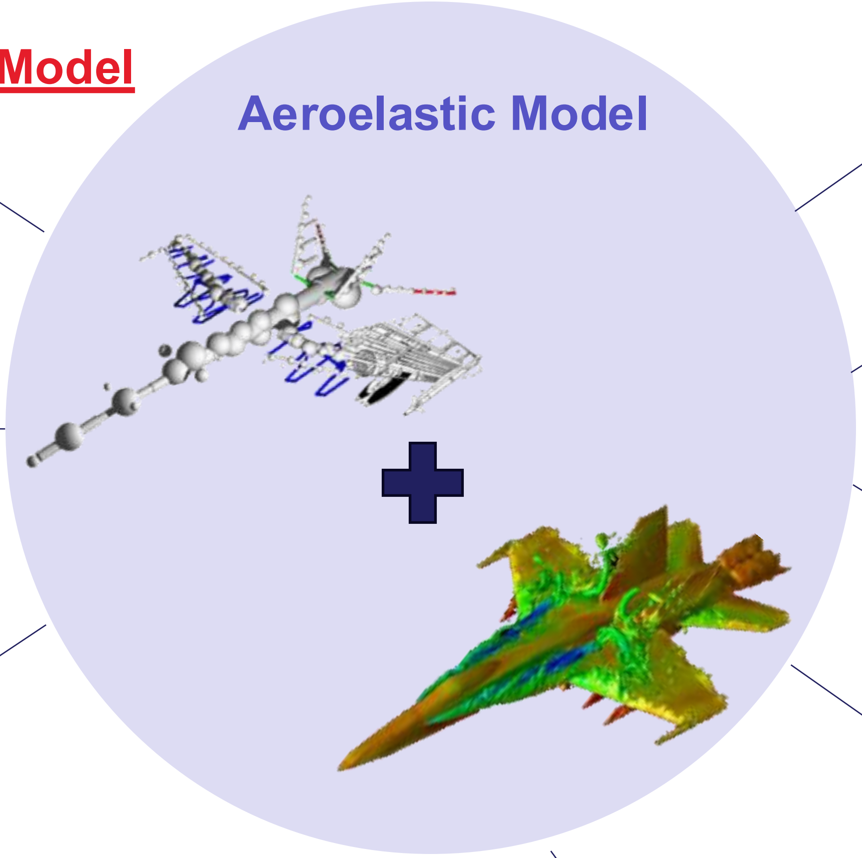
Python Fluid-Structure Interaction (PyFSI)

Structural Mechanics Model

High-fidelity structure
FE model + periodic

Linearized (modal)
w nonlinear corrections (fictitious masses, residual vectors)

Linearized (modal)
Static/dynamic + periodic



Fluid Dynamics Model

High-fidelity aerodynamics
CFD model (incl. periodic)

Mid-fidelity aerodynamics
DUST, SSLBM

Nonlinear unsteady aerodynamic ROM
Data-driven polynomial methods

Linearized unsteady aerodynamics
Time-domain / frequency domain (incl. periodic)

High-dimensionality
High-cost

Low-dimensionality
Low-cost

External Fluid Loads

High-fidelity gust solver
CFD + periodic solver

Gust ROM
Linear and nonlinear methods

Generalized $k-\omega$ (GEKO) Turbulence Model

- GEKO contains free parameters which can be tuned desired performance, including for separation, C_{SEP}, near-wall treatment, C_{NW}, mixing layer, C_{MIX}, jet flow, C_{JET}, among others.
- Free coefficients are implemented through the functions f_1, f_2, f_3 in the turbulence kinetic energy and specific dissipation equations:

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

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

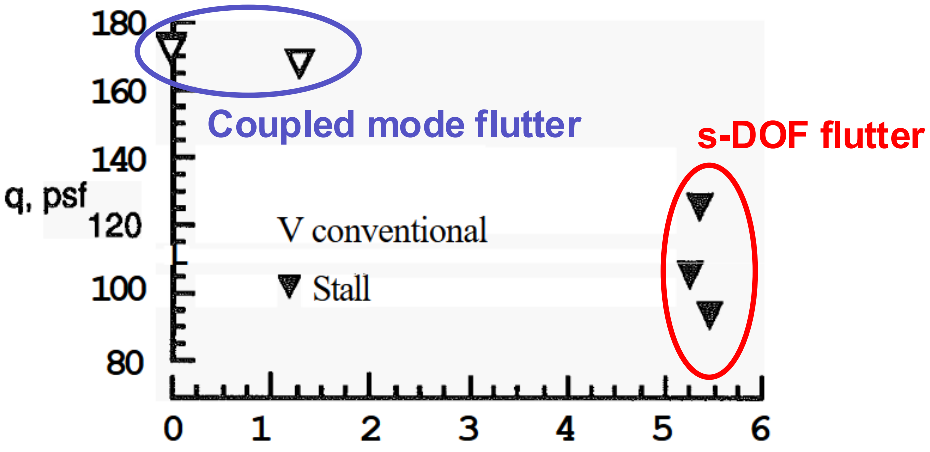
- We are modifying C_{SEP} -> modifies eddy viscosity -> higher values more separation, lower values less separation.

[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.

HAWG – Benchmark Supercritical Wing

- HAWG is concerned with the prediction transonic flutter.
- Benchmark Supercritical Wing (BSCW) is a rigid semi-span model on Pitch and Plunge Apparatus.
- TDT flutter data available from early 1990s [2].
- Mach 0.8, AOA Sweep $0^{o} \leq \alpha_0 \leq 6^{o}$.
- Single-degree-of-freedom (s-DOF) flutter observed, onset appears to be $5^{o} < \alpha_0 < 6^{o}$
- s-DOF flutter -> pitch dominated -> drop in flutter dynamic pressure -> stall for a portion of the pitch cycle.

BSCW mounted in TDT at NASA LaRC



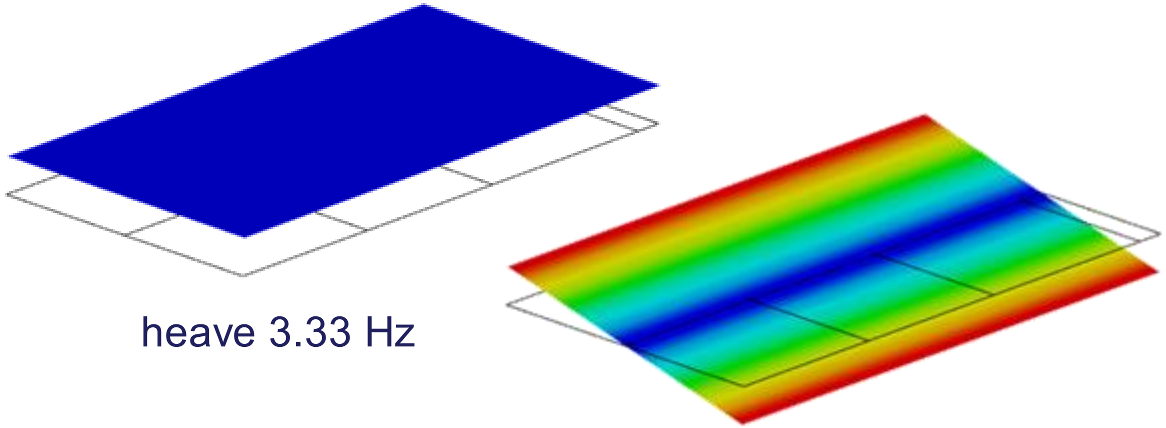
Experimental flutter dynamic pressure versus AOA [2]

[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.

HAWG – Computational Model

Structural Model

- Modal coordinates
- Heave and pitch modes only (wing body assumed to be rigid)
- Newmark-Beta time integration
- Projection using RMIT's MPR algorithm [3].

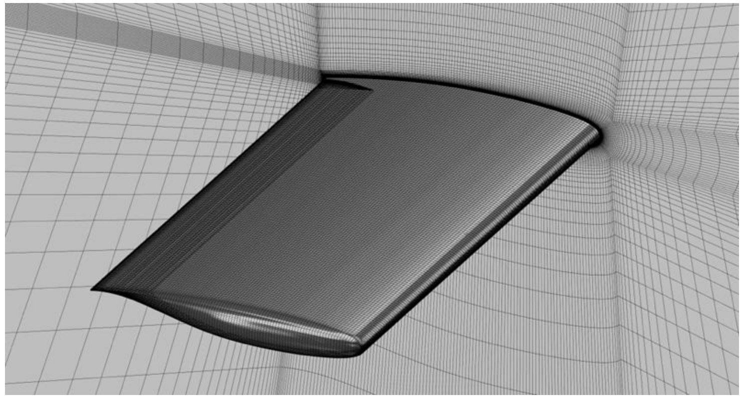


heave 3.33 Hz

pitch 5.2 Hz

Fluid Model

- Fluent 2024 R2 - coupled pressure-based solver
- SST $k-\omega$ and GEKO models
- Second-order spatial and temporal discretization
- CFD model used to train a nonlinear Volterra ROM for rapid flutter predictions (comprehensively validated) [4].



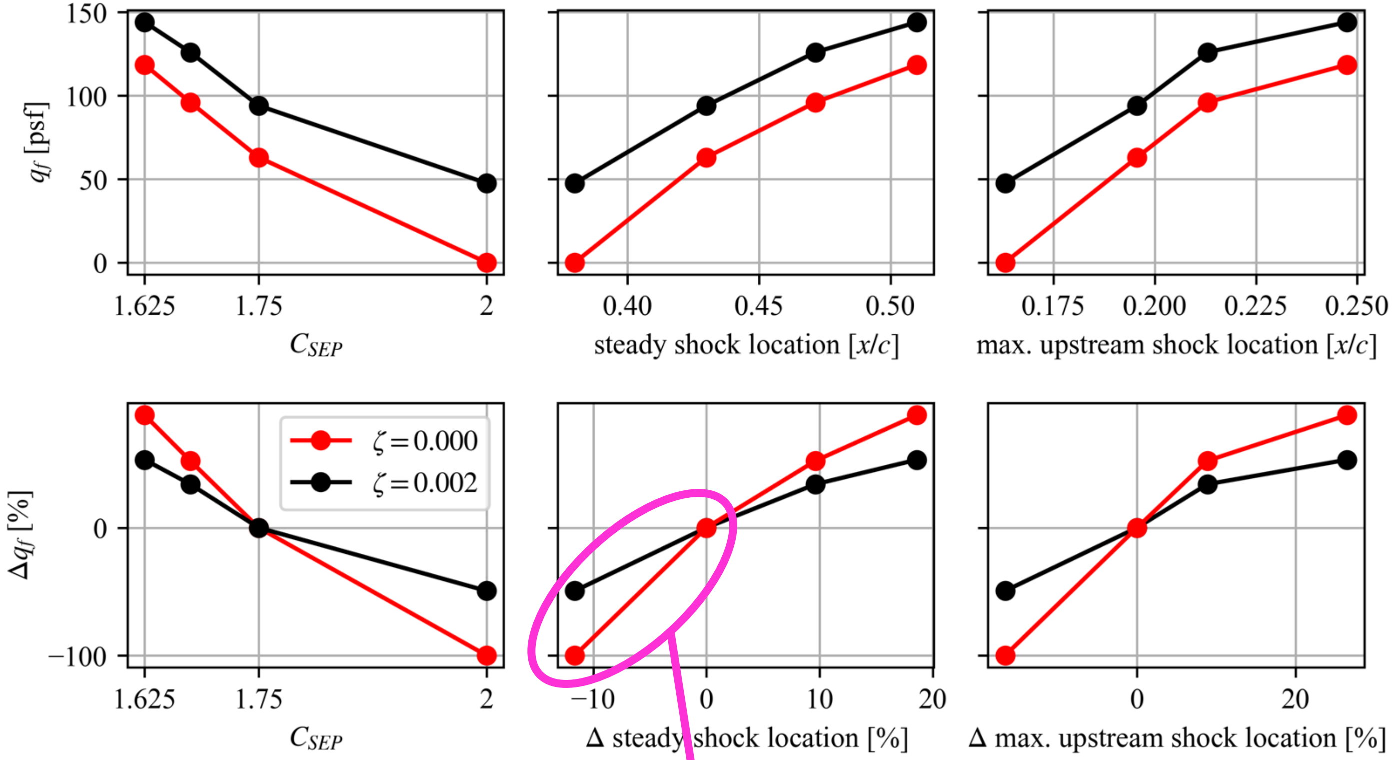
Fine: 13.7M cells (grids generated by ANSYS Germany as part of AePW I)

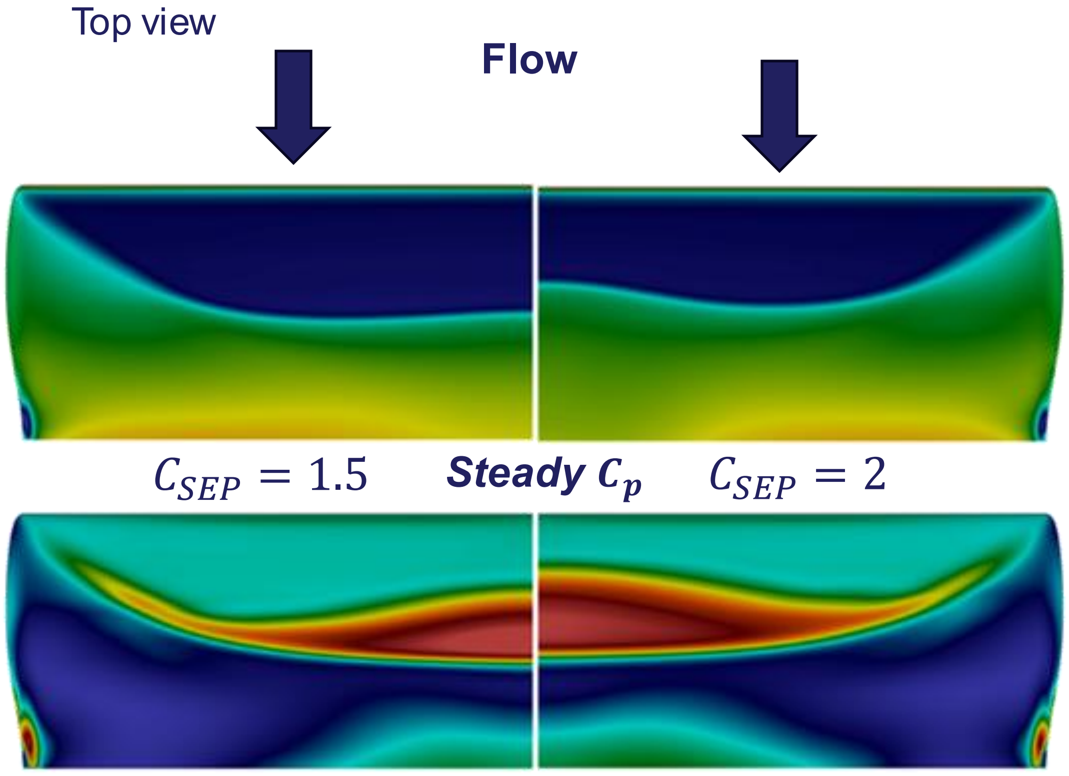
[3] Joseph, N., Carrese, R., and Marzocca, P., "Projection Framework for Interfacial Treatment for Computational Fluid Dynamics/Computational Structural Dynamics Simulations," AIAA Journal,Vol.59,No.6,2021, pp. 2070–2083.

[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, Available Online, 2025.

HAWG – Influence of $C_{SEP}@\ \alpha_0 = 5^{\circ}$

Flutter dynamic pressure versus shock statistics for different C_{SEP}





RMS C_p (forced sinusoidal excitation)

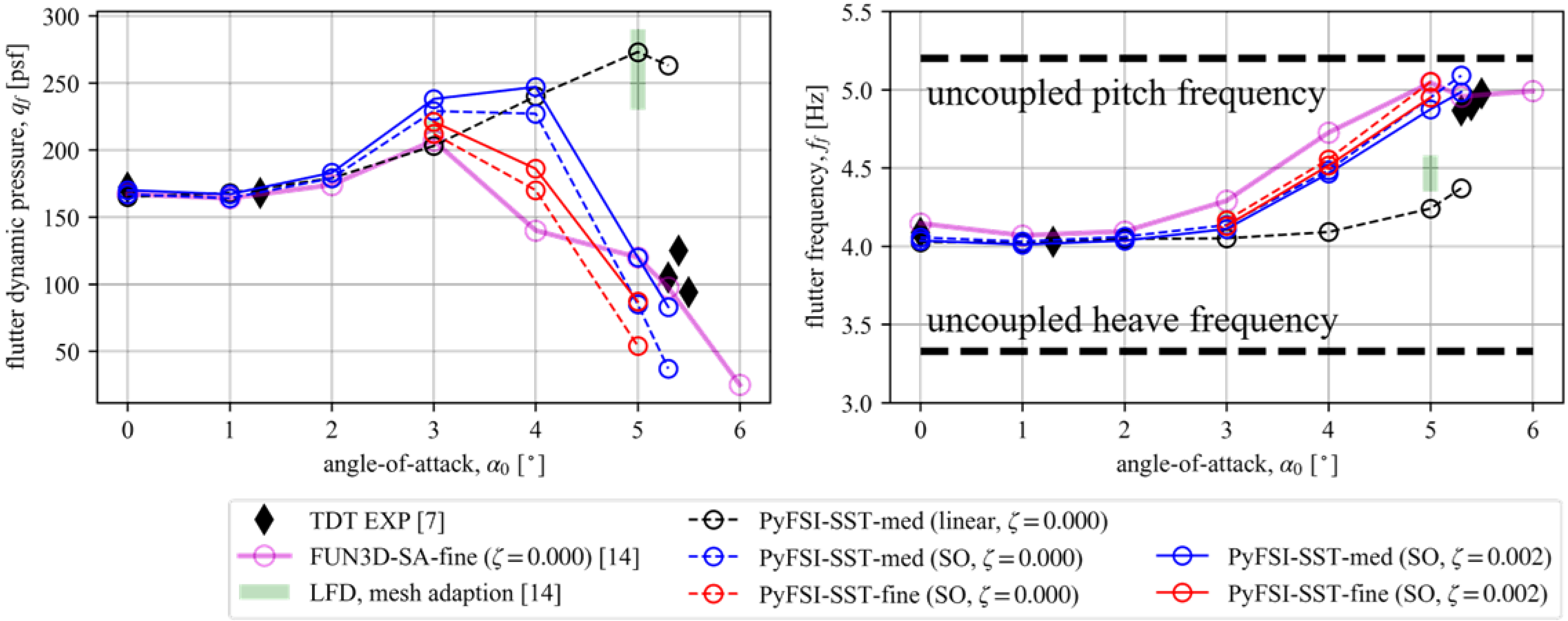
10% change in the RANS-predicted steady-state shock location correlates to a 50% - 100% change in predicted flutter dynamic pressure!!

[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.

HAWG – AoA Sweep with SST vs Exp

BSCW: AOA Sweep using SST $k-\omega$ with medium and fine grids.

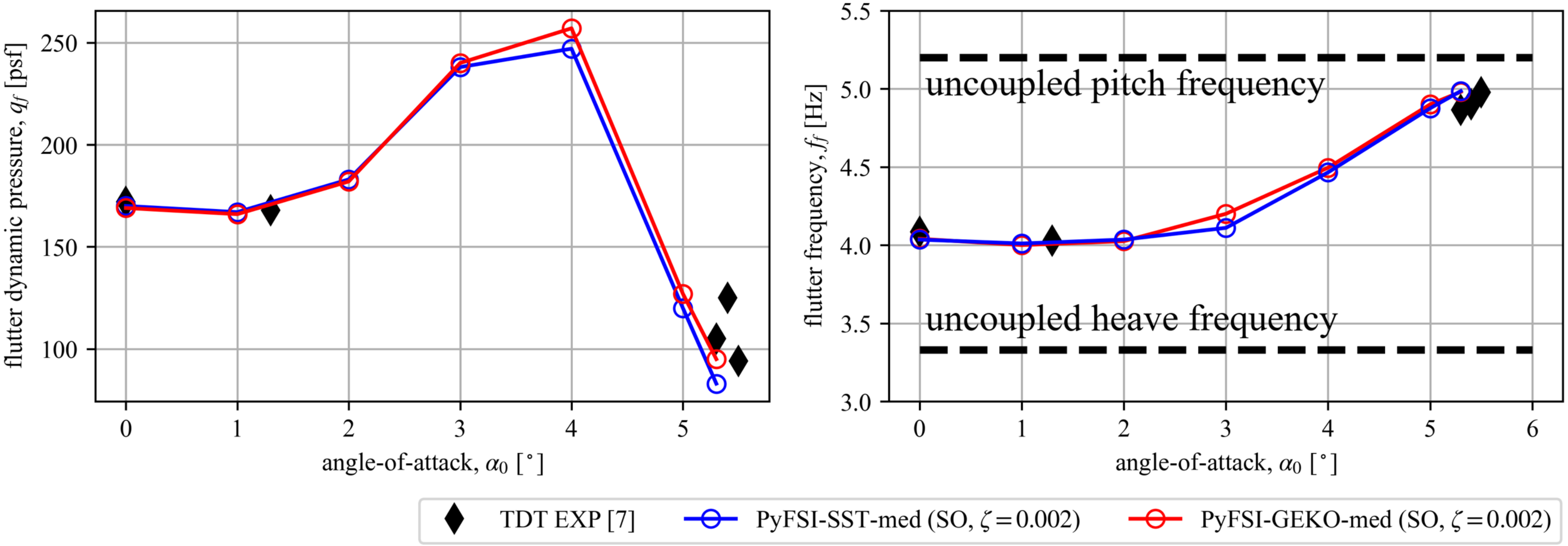
[6] Stanford, B., Chwalowski, P., and Jacobson, K., "Transonic Limit Cycle Oscillations of the Benchmark Supercritical Wing, "International Forum on Aeroelasticity and Structural Dynamics, The Hague, The Netherlands, 2024.



- Comparing to experimental data and the FUN3D results of Stanford et al. [6]
- Grid convergence not yet observed.
- Good agreement for frequencies.
- Structural damping becomes more influential deeper into stall flutter region, must recompute with $\zeta = 0.001$ (recent discussions with Pawel et al.)
- Linear model cannot predict stall flutter, similar to NASA LFD result.

HAWG – AoA Sweep, GEKO vs SST

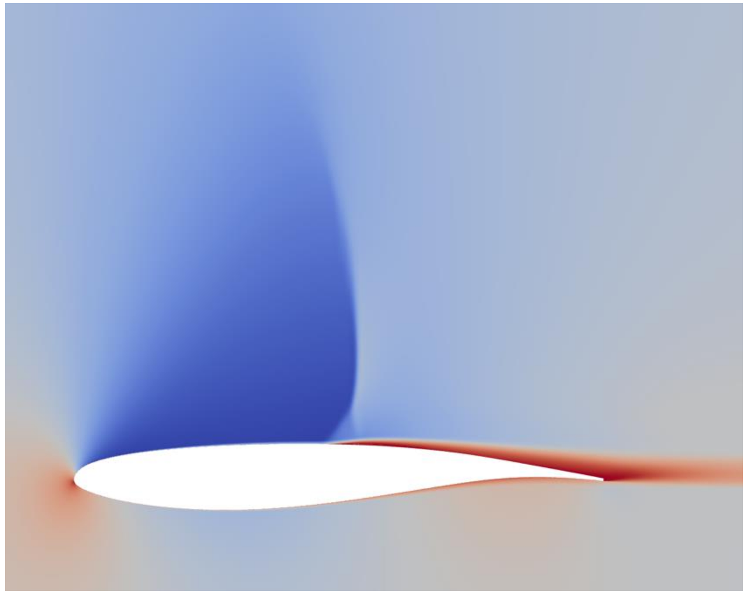
- GEKO model only tuned using medium mesh, C_SEP = 1.675.
- We can tune the GEKO model to match flutter-q at high AOA, does not influence flutter-q at low AOA.
- We need to re-tune the model using the fine mesh.



Medium grid.

Buffetting WG – ONERA OAT15A

- BWG is concerned with the prediction of transonic shock buffet.
- Test Case 1: 2D ONERA OAT15A airfoil model [7].
- $M_\infty = 0.73$, $p = 71{,}800$ Pa, $Re_c \approx 3M$
- $\alpha_0 = 3.1^\circ, 3.25^\circ, 3.4^\circ, 3.5^\circ, 3.6^\circ\ 3.9^\circ$

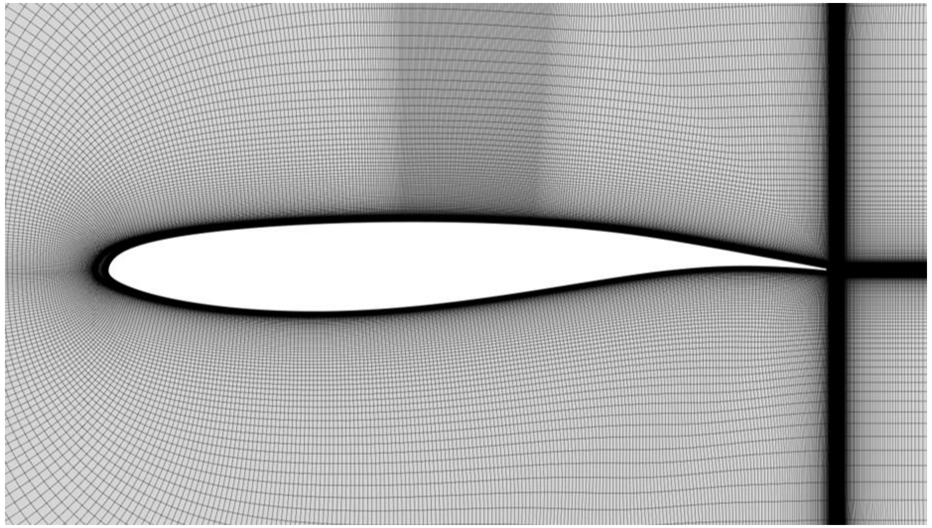


OAT15A: Steady Mach number contours at $M_\infty = 0.73$, $\alpha_0 = 3.1^\circ$

[7] Jacquin, L., Molton, P., Deck, S., Maury, B., and Soulevant, D., "Experimental Study of Shock Oscillation over a Transonic Supercritical Profile," AIAA Journal, Vol. 92, No. 9, 2009, pp. 1985–1994.

BWG – Computational Model

- Using Fluent 2024 R2
  - Coupled pressure-based solver
  - Second-order upwind spatial discretization.
  - Bounded 2nd-order implicit time discretization
  - $\Delta t = 5 \times 10^{-6}$ s -> 200 timesteps per CTU.
- Four levels of grid refinement
  - Supplied by organizing committee
- Compariong 3 TMs
  - GEKO
  - Spalart-Allmaras
  - SST $k - \omega$ turbulence models.

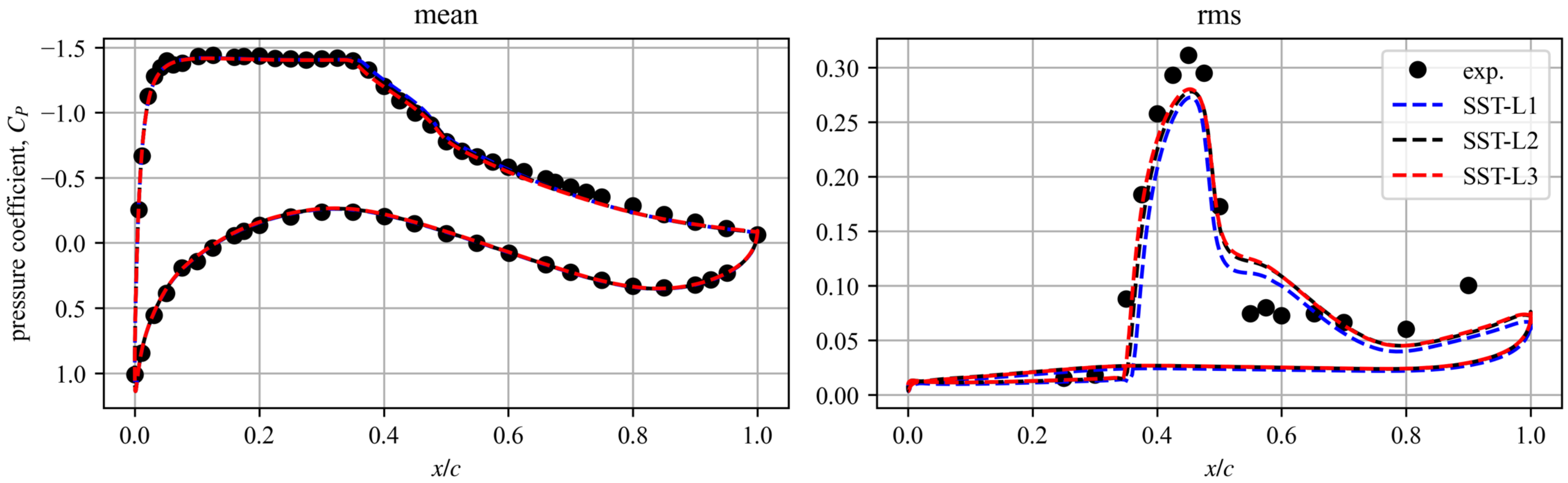


OAT15A Grid Level 3 (medium)

Can a tuned GEKO model provide superior performance to conventional RANS turbulence models?

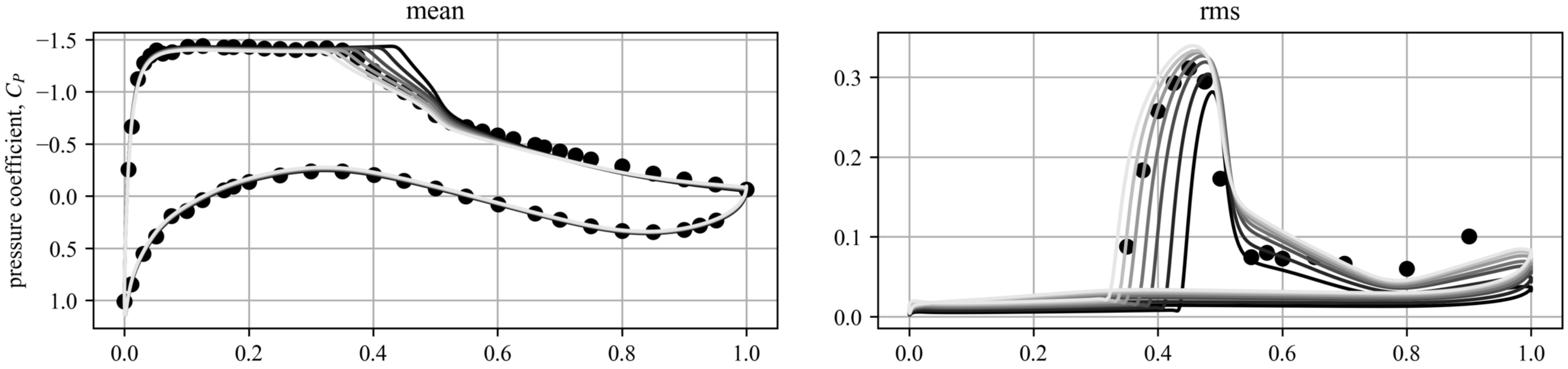
BWG – Grid Refinement @ $\alpha_0 = 3.5^{\circ}$

- Convergence observed between L2 and L3
- Proceed with L3 based on requirement of committee.
- Reasonably good agreement with experiment.



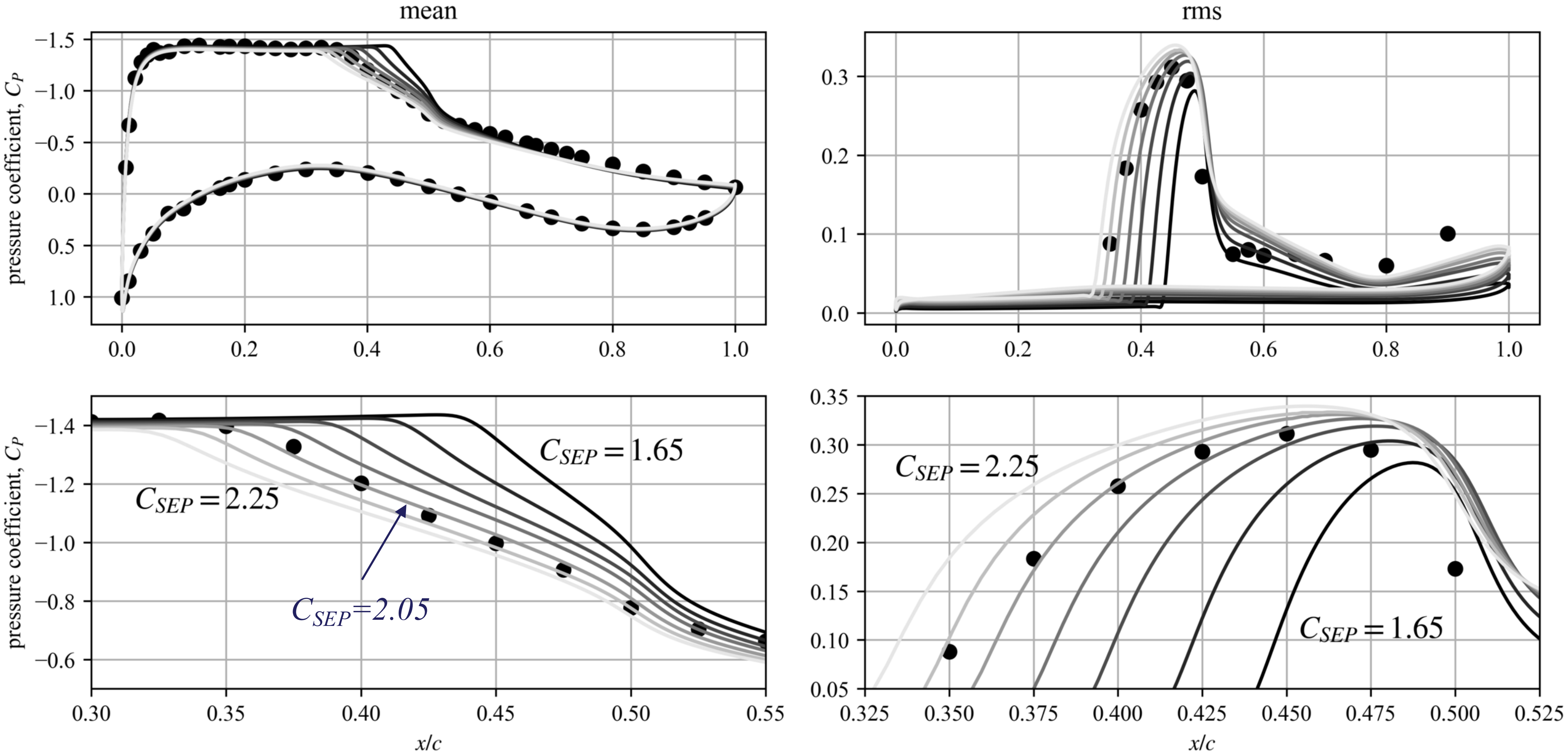
OAT15A: Grid convergence study of surface pressure.

BWG – GEKO Model Tuning @ $\alpha_0 = 3.5^{\circ}$



OAT15A: GEKO model tuning at $\alpha_0 = 3.5^{\circ}$ with grid L3.

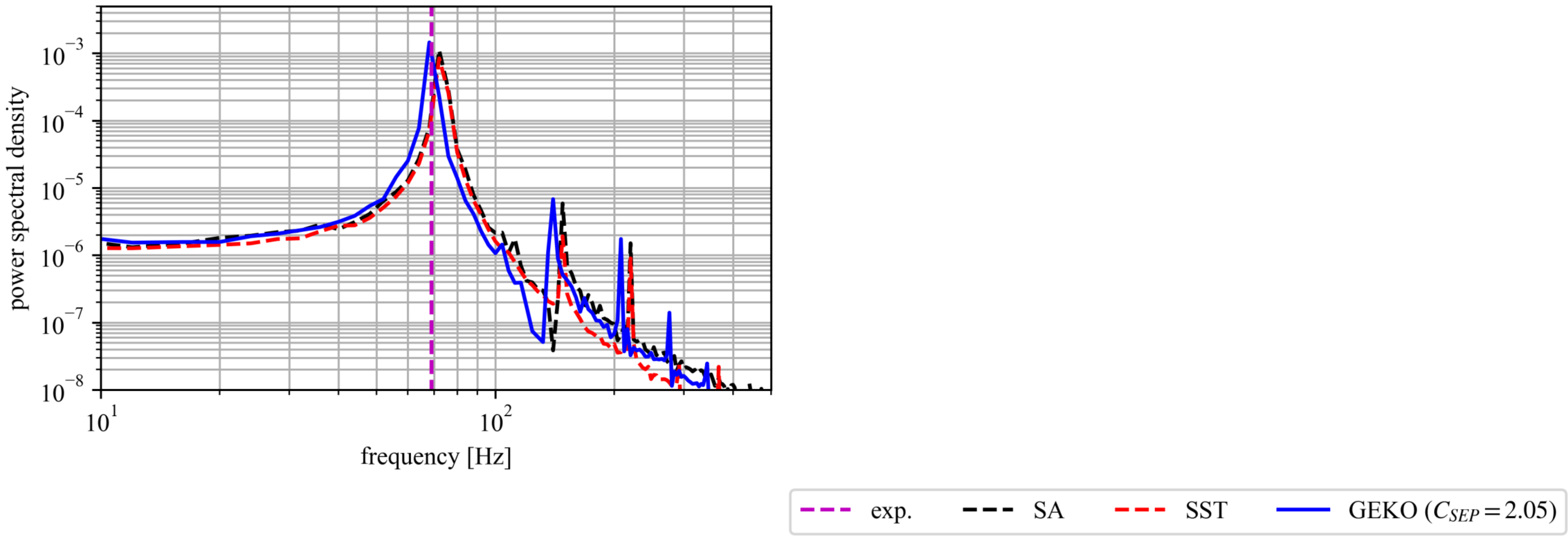
BWG – GEKO Model Tuning @ $\alpha_0 = 3.5^{\circ}$



OAT15A: GEKO model tuning at $\alpha_0 = 3.5^{\circ}$ with grid L3.

BWG – Lift Power Spectra @ $\alpha_0 = 3.5^\circ$

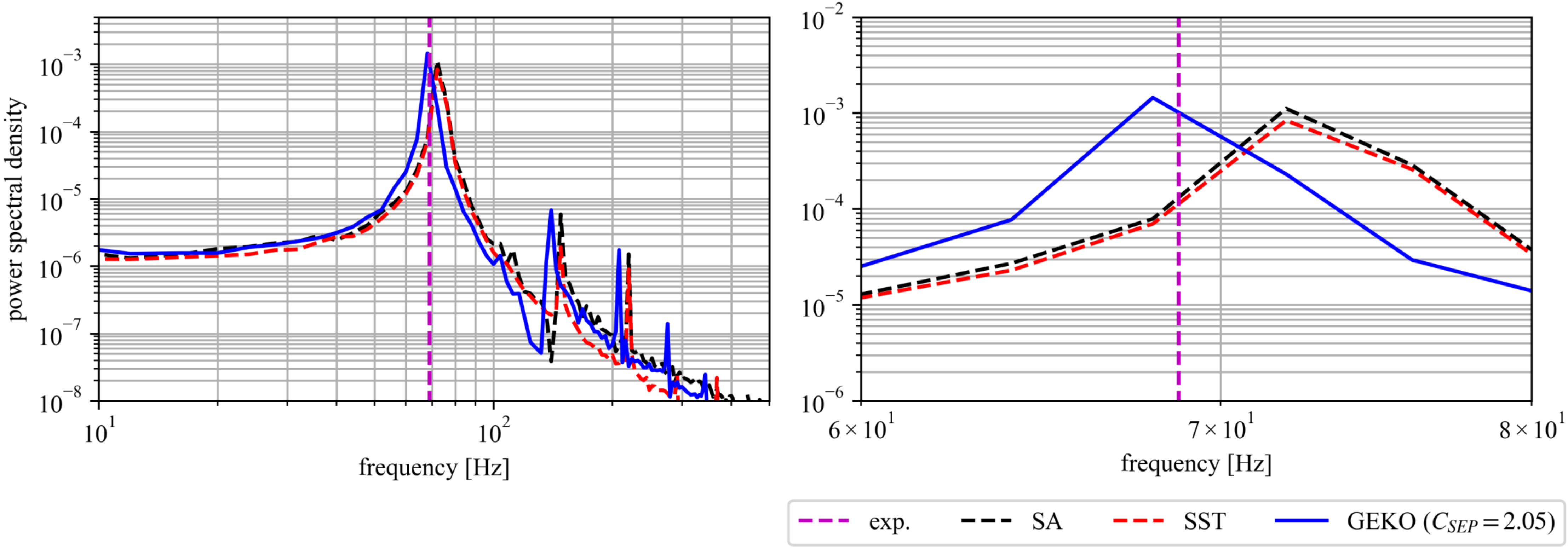
- The tuned model improves the prediction of buffet frequency substantially.



OAT15A: Lift PSD for different turbulence models at $\alpha_0 = 3.5^\circ$ with grid L3.

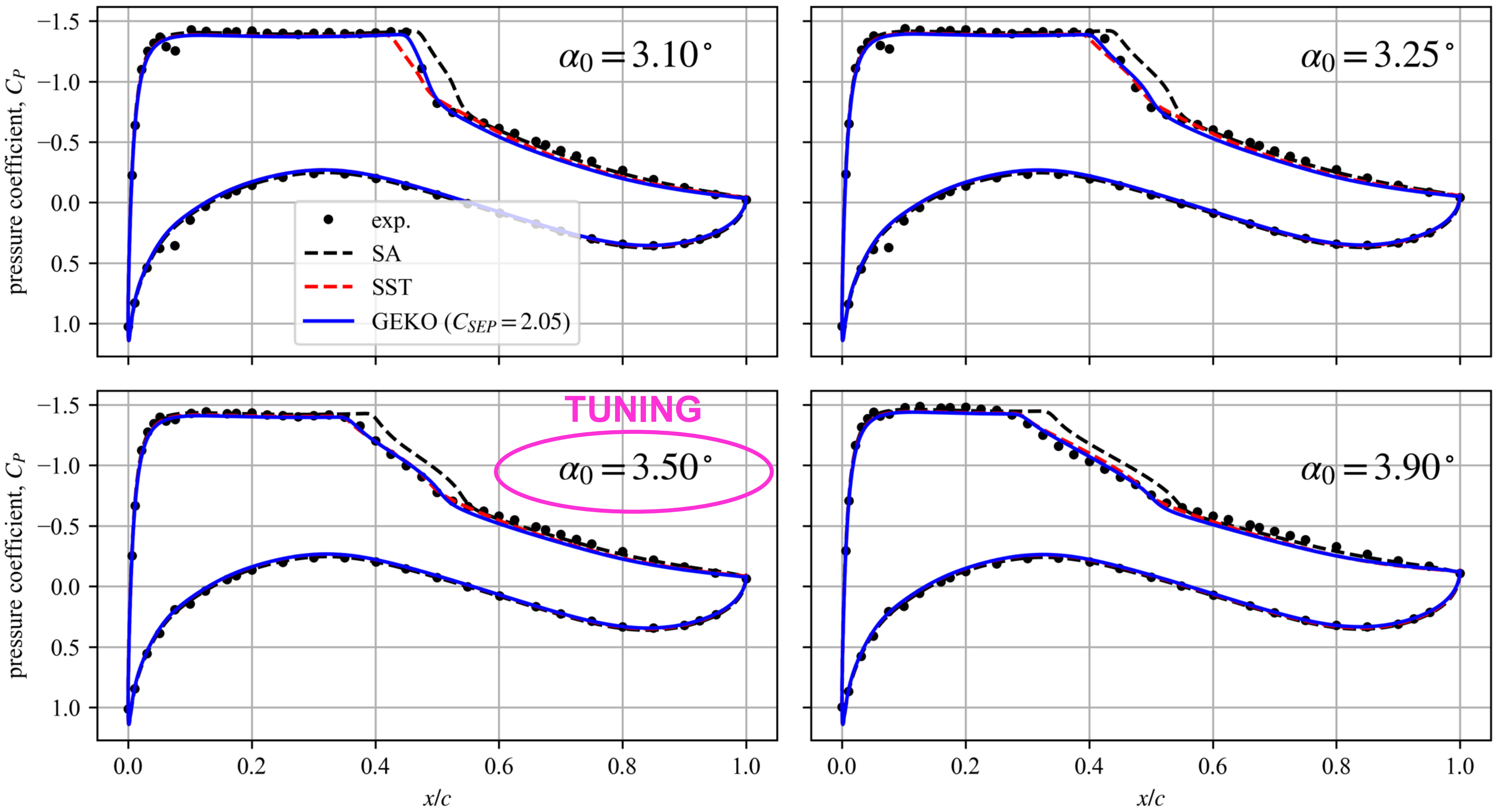
BWG – Lift Power Spectra @ $\alpha_0 = 3.5^{\circ}$

- The tuned model improves the prediction of buffet frequency substantially.



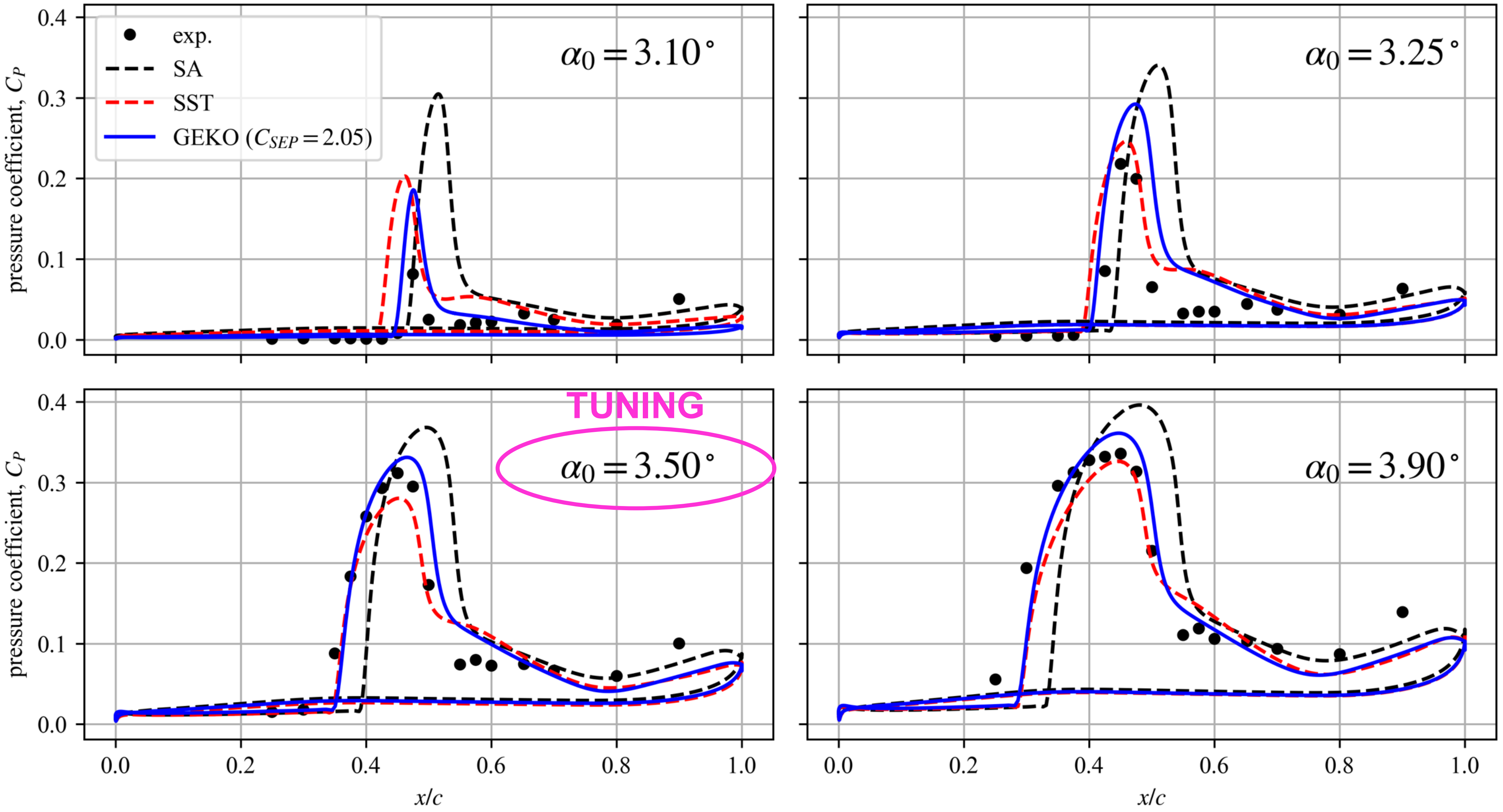
OAT15A: Lift PSD for different turbulence models at $\alpha_0 = 3.5^{\circ}$ with grid L3.

BWG – AOA Sweep (mean C_p)



OAT15A: Mean pressure coefficient comparing different turbulence models for AOA sweep

BWG – AOA Sweep (RMS C_p)



OAT15A: RMS pressure coefficient comparing different turbulence models for AOA sweep

Conclusions and Ongoing Work

The GEKO turbulence model can be tuned to provide superior performance to conventional RANS turbulence models for complex transonic unsteady aerodynamic problems, ongoing work includes:

High Angle Work Group (HAWG):

- Complete spatial and temporal convergence studies, re-tune the GEKO model on a converged grid.

Buffet Work Group (BWG):

- Test Case 2: NASA CRM using Fluent Native GPU solver. Run LES, too.
- Test Case 3: NASA CRM with structural model will be run using PyFSI.