OVERFLOW Analysis of the DLR F11 Geometry for HiLiftPW-2

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Solution Methods

- Solver: OVERFLOW 2.2e/2.2f
  - RHS: 3rd-order accurate Roe upwind
  - LHS: Scalar pentadiagonal approximate factorization
  - Low-Mach preconditioning
  - Recommended artificial dissipation
  - Grid sequencing and multigrid acceleration
  - Non-time accurate solution
    - Convergence assumed when force/moment limit cycles are reached
- Grids: Committee-provided structured overset grids (series E)
  - Generated by Boeing Huntington Beach
- Hardware
  - DoD HPC machines (AFRL and Navy DSRC Machines)

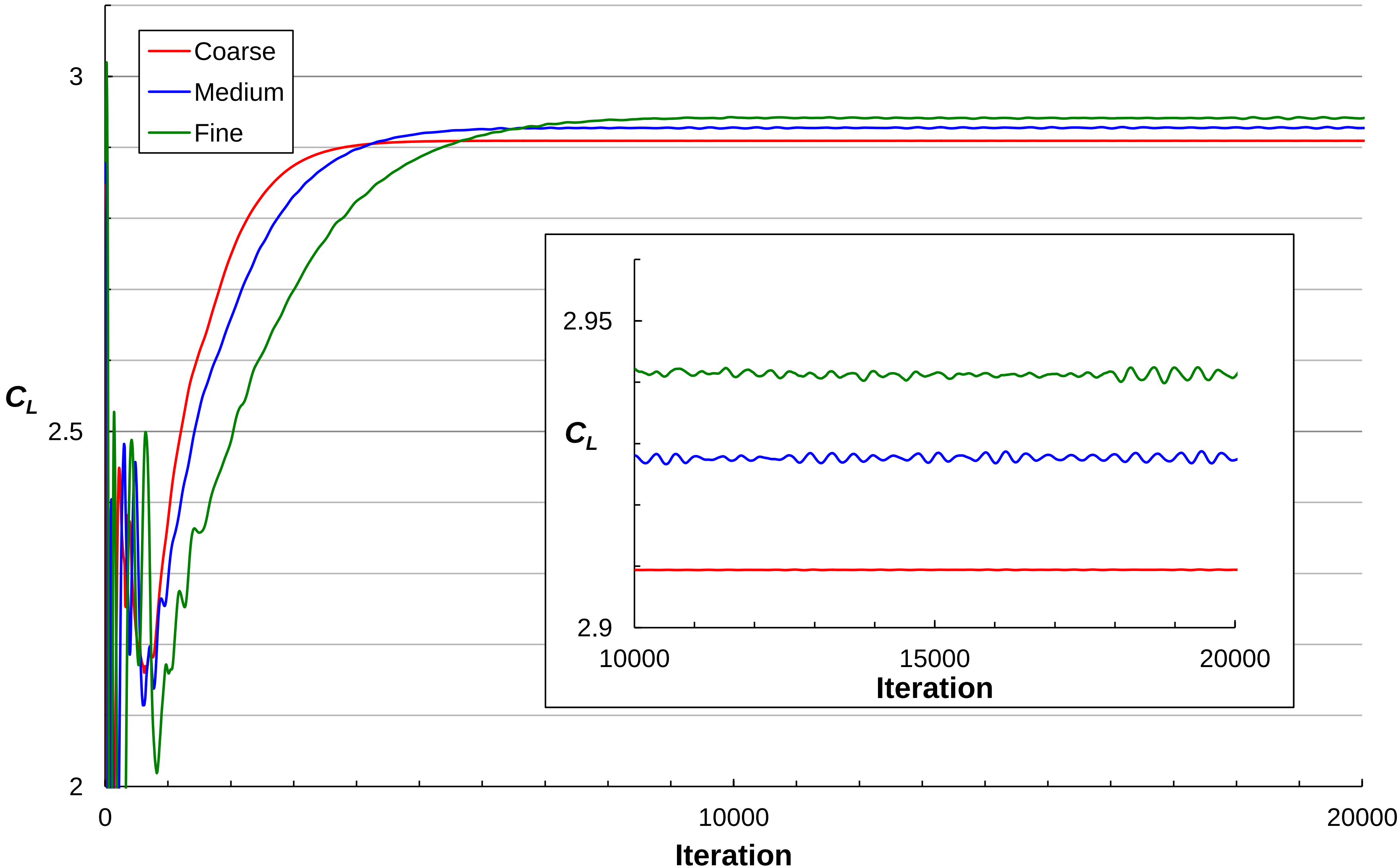
Solution Methods

- Turbulence Modeling
  - SA (Cases 1, 2a, and 2b)
  - SA-RC (Case 1 – Medium, 2a, and 2b)
  - SA-*ñ* (Transition – 2c)
  - SA-QCR2000-*ñ* (Transition – 2c)

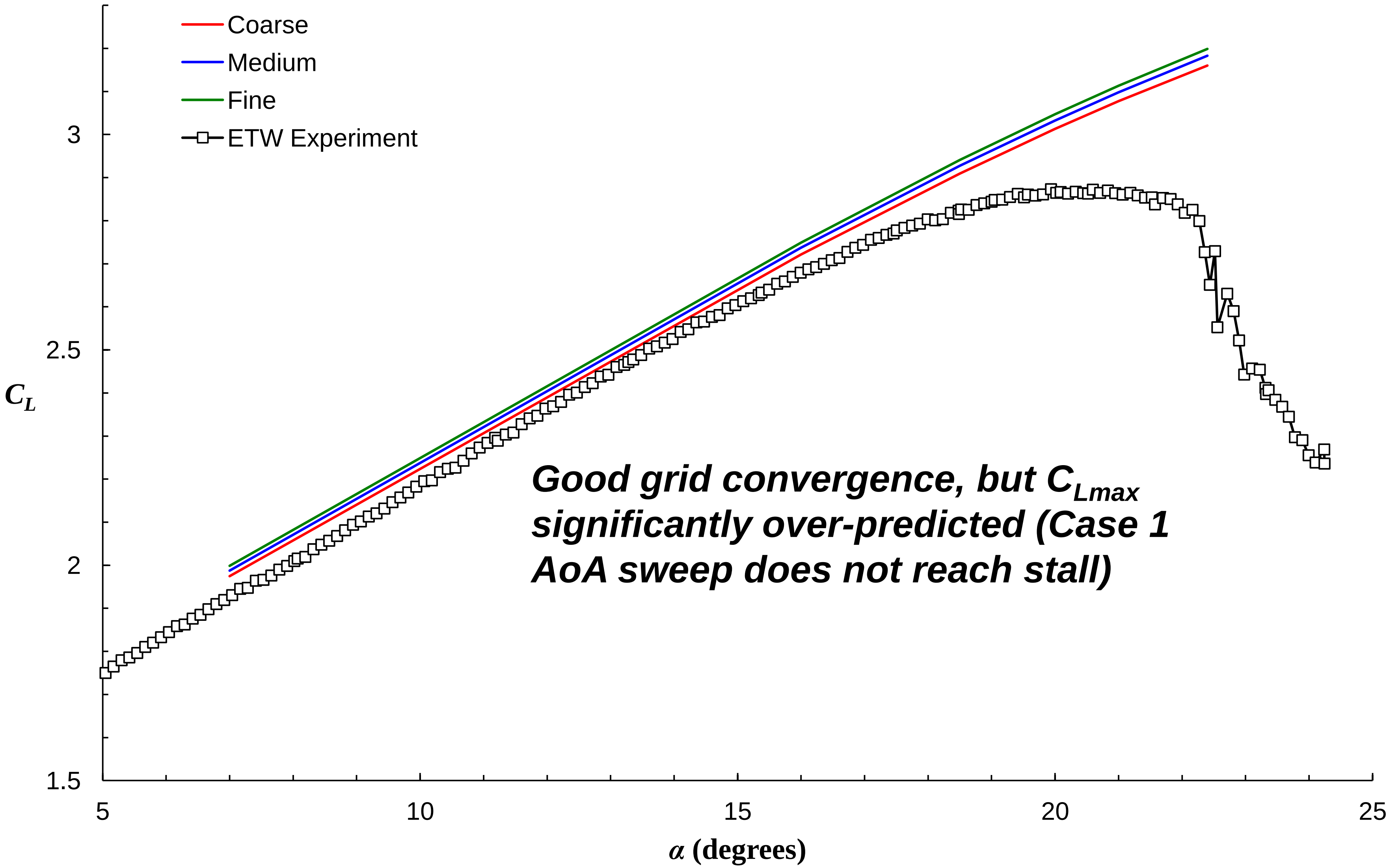
- Turbulence model studies limited by time and available computing resources
  - Originally planned for full studies of SA, SA-RC, SST, and SST-RC for Cases 1, 2a, and 2b
  - Also planned to compare behavior of Langtry-Menter model (both original and applied to the Spalart-Allmaras model) with the Penn State amplification factor transport model

Grid Convergence Study
(*Case 1*)

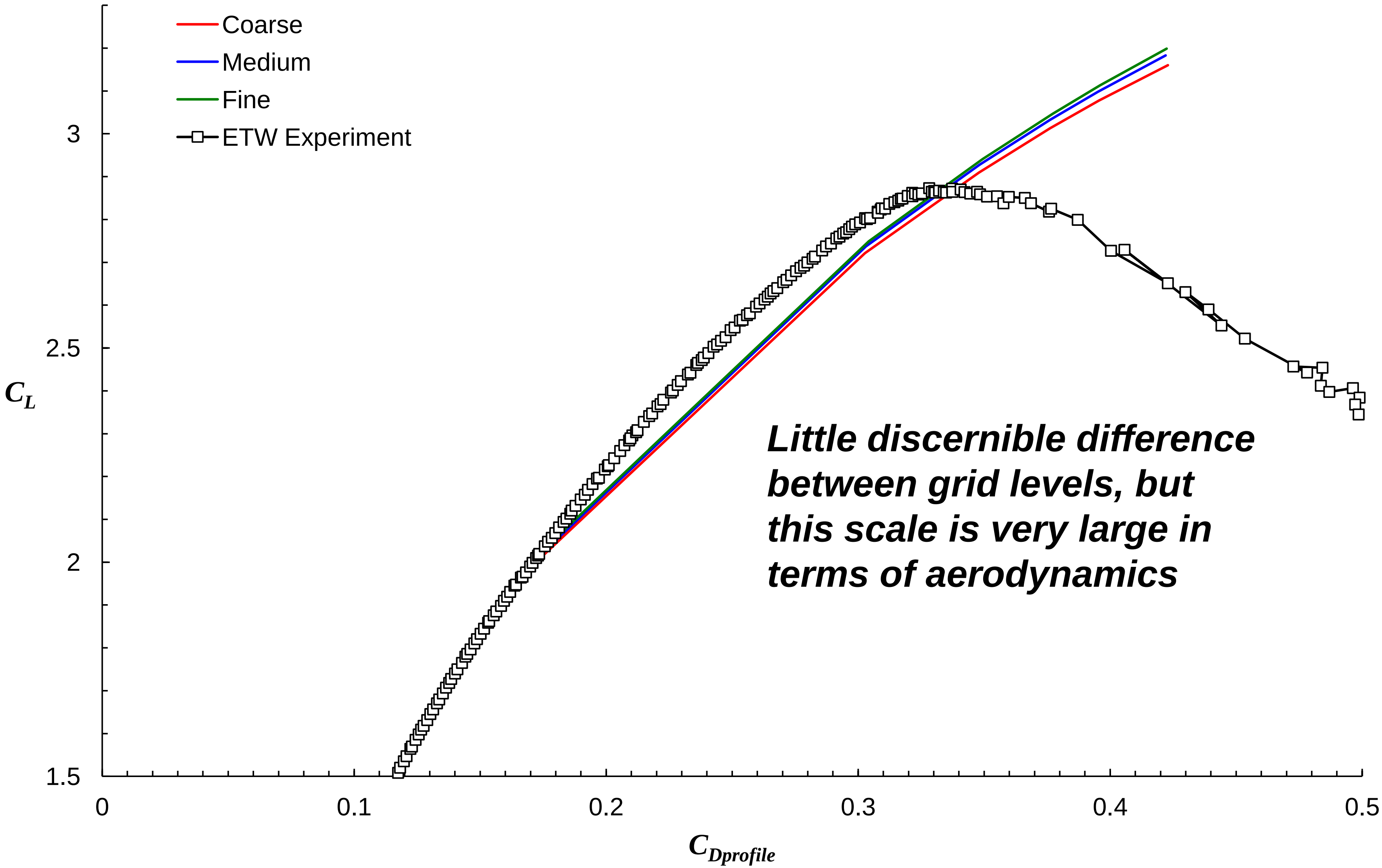
Force/Moment Convergence Behavior



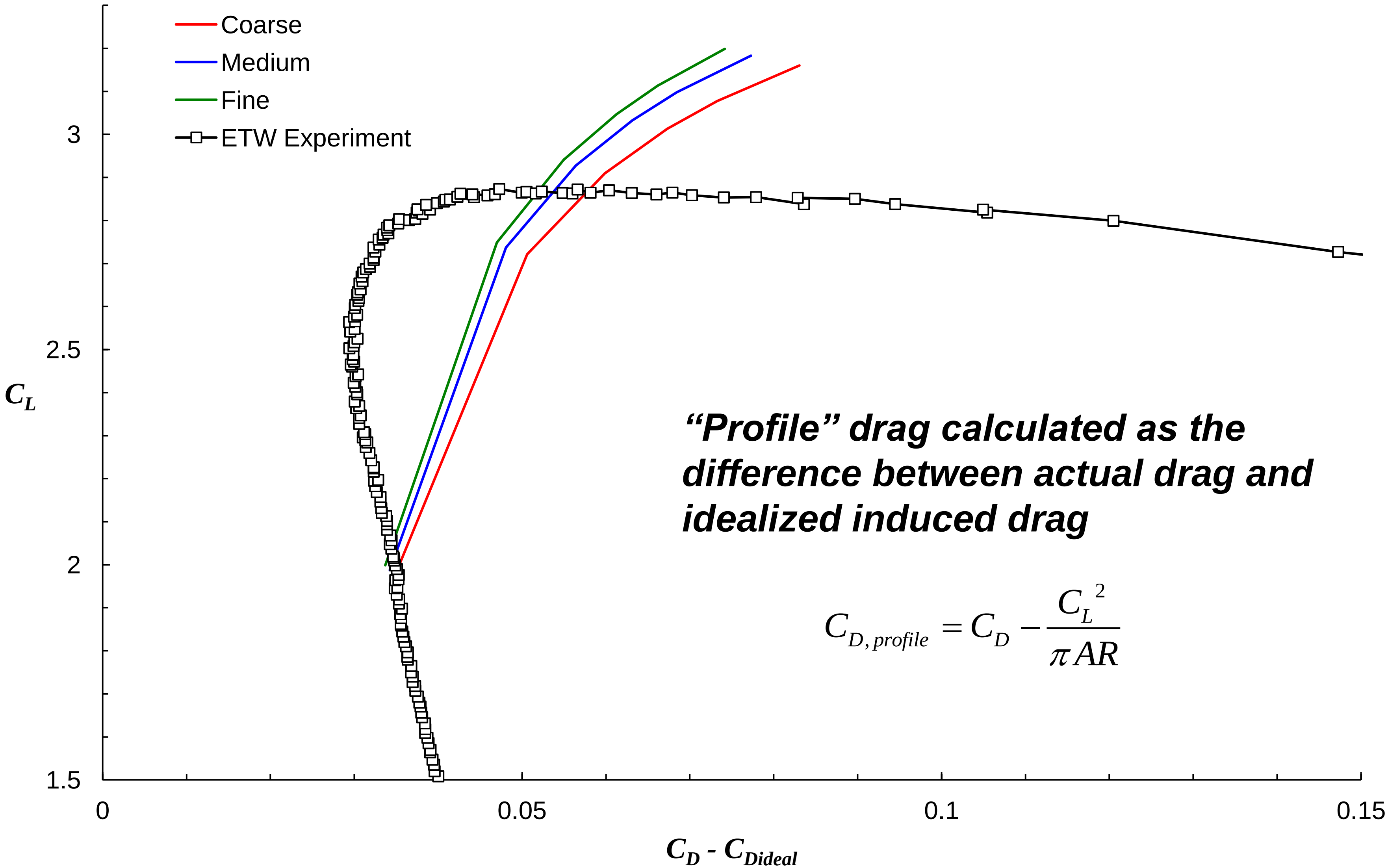
Grid Convergence , R = 15.1 Million : Lift Curve



Grid Convergence, R = 15.1 Million: Drag Polar



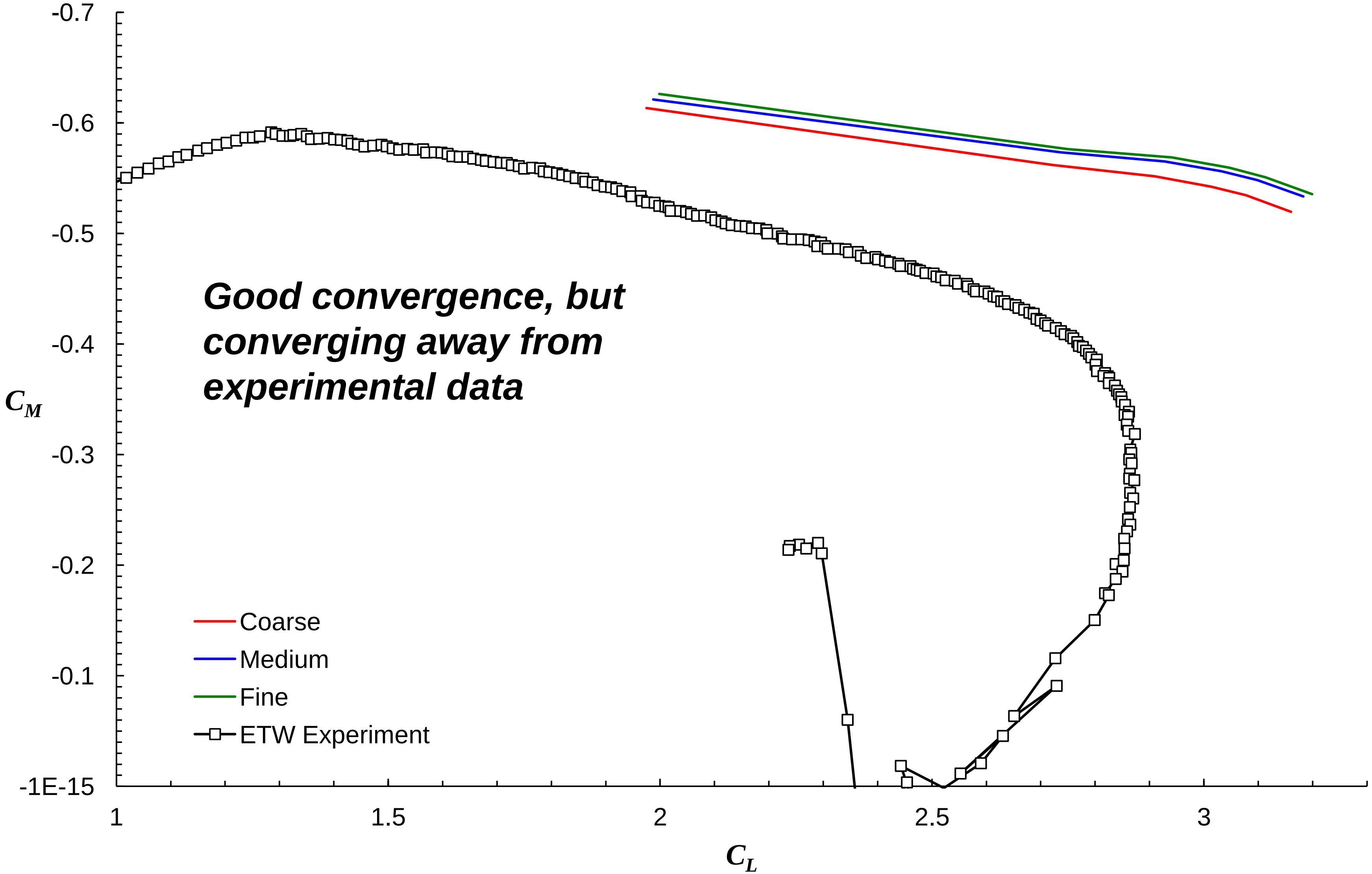
Grid Convergence , R = 15.1 Million : Profile Drag Polar



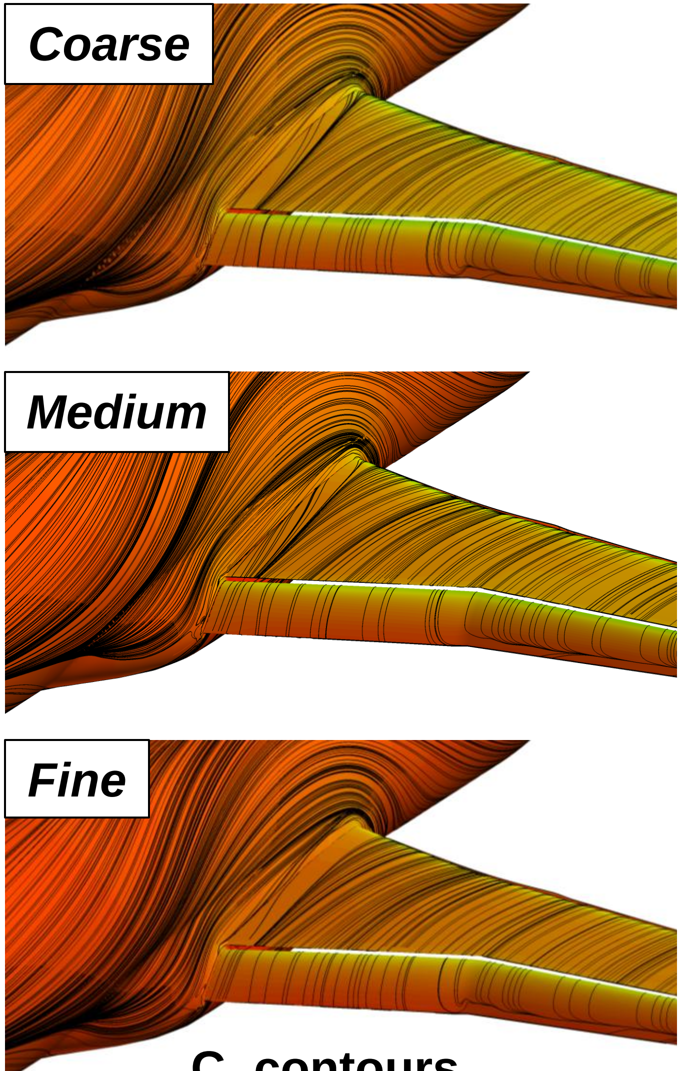
"Profile" drag calculated as the difference between actual drag and idealized induced drag

$$C_{D,profile} = C_D - \frac{C_L^{\ 2}}{\pi AR}$$

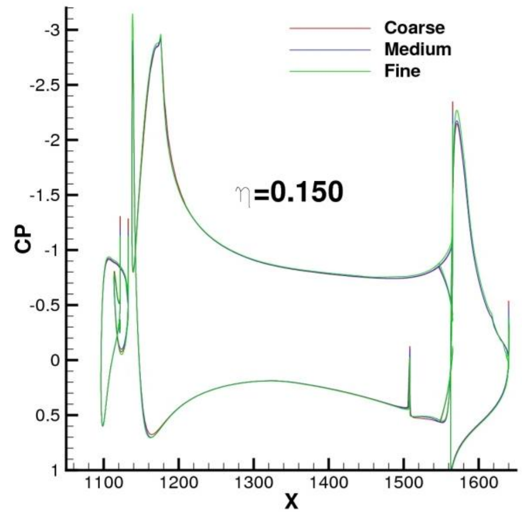
Grid Convergence , R = 15.1 Million : Pitching Moment

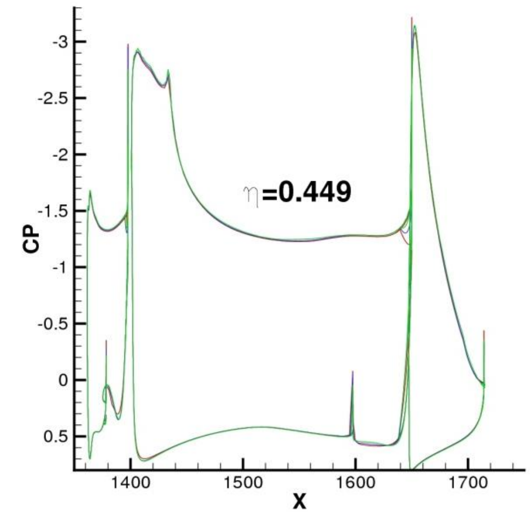


High Re Grid Convergence Study

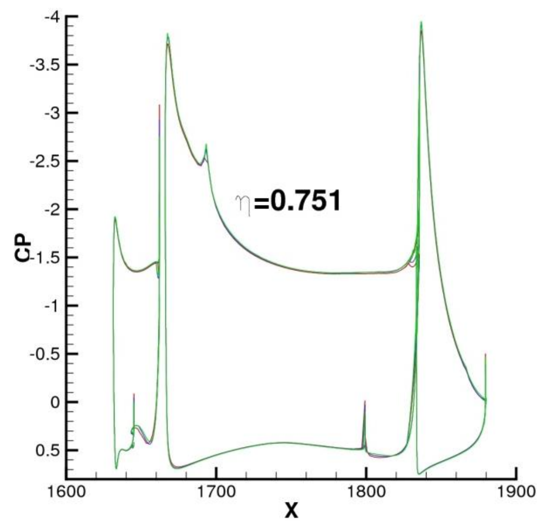


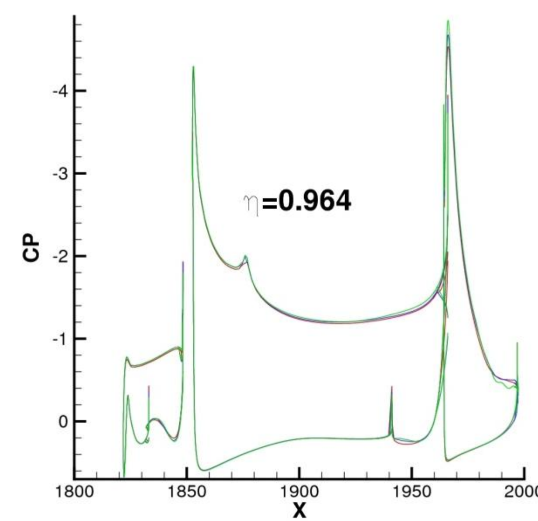
C_p contours



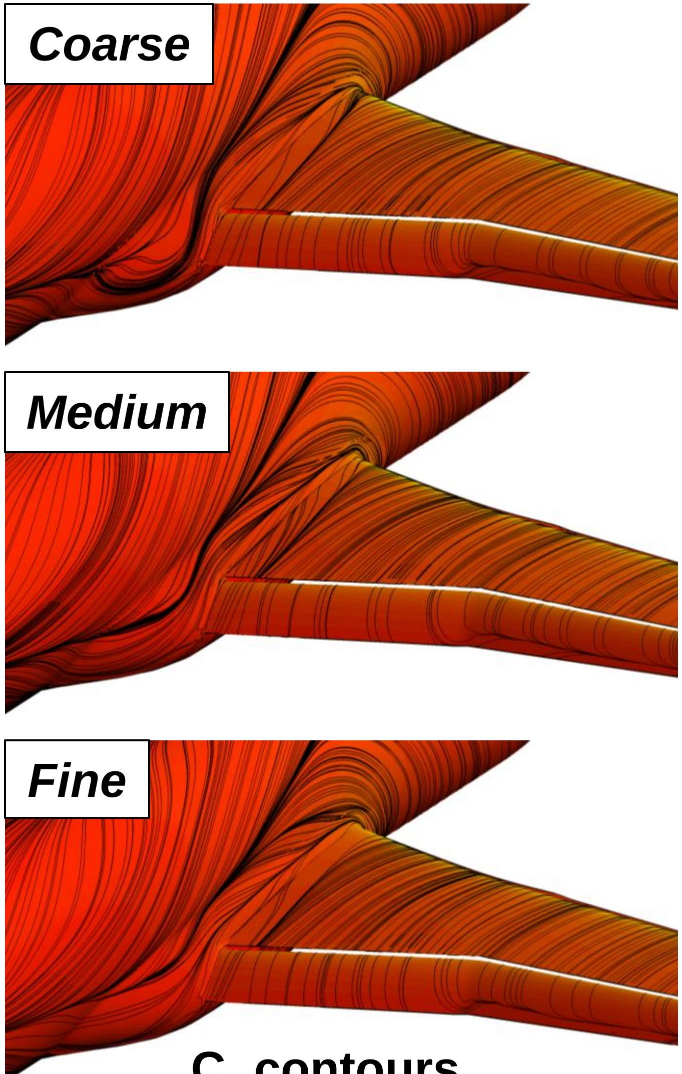


R = 15.1e6, α = 7°

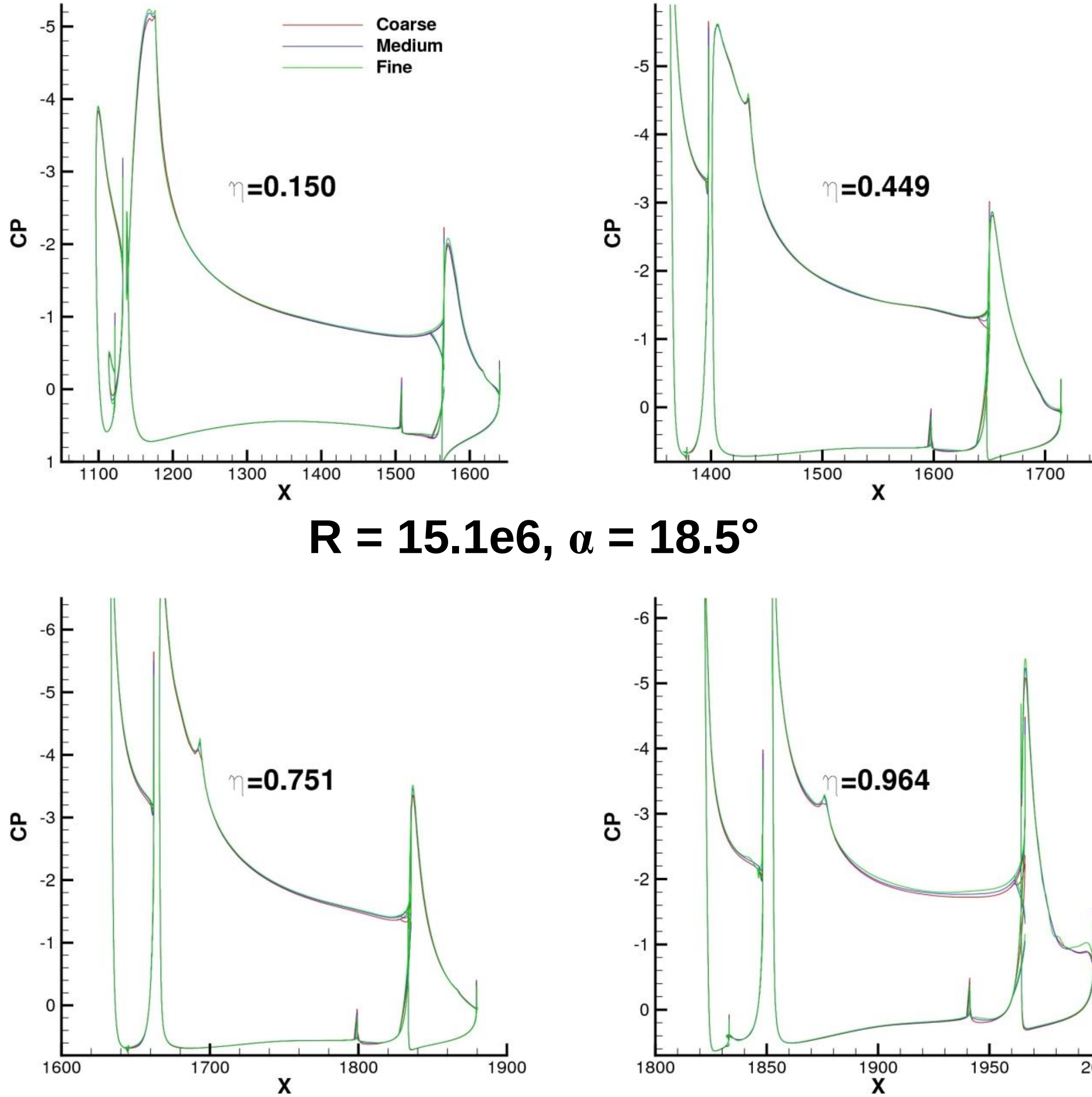




High Re Grid Convergence Study

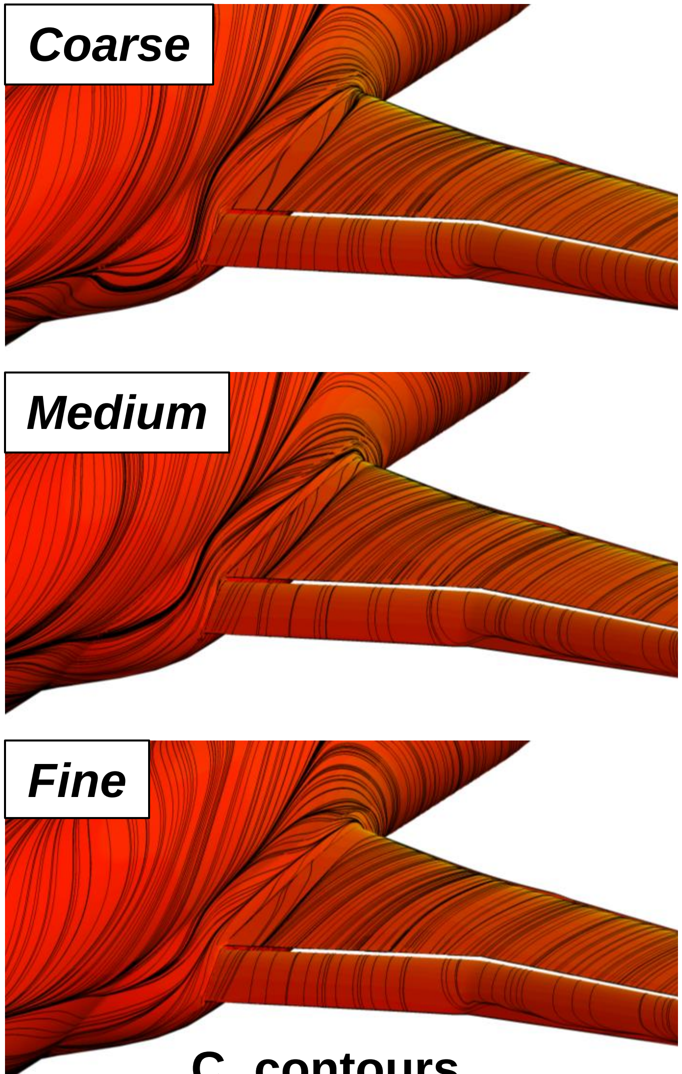


C_p contours

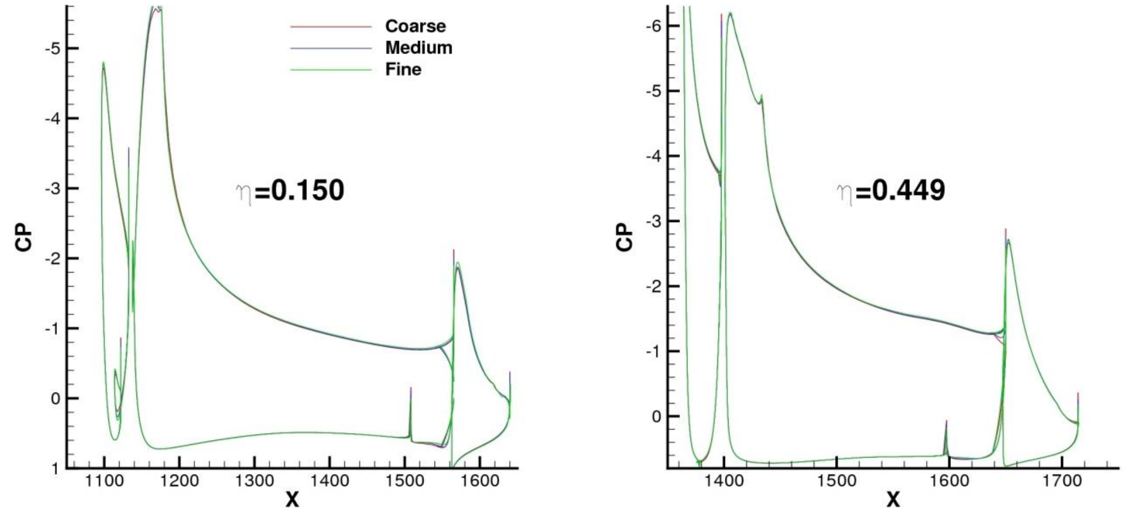


R = 15.1e6, α = 18.5°

High Re Grid Convergence Study



C_p contours



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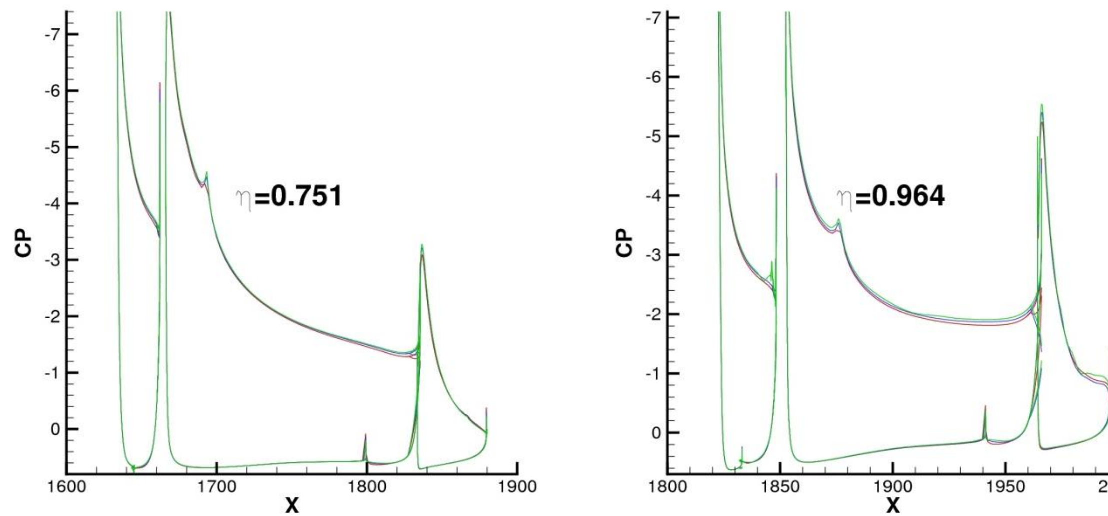
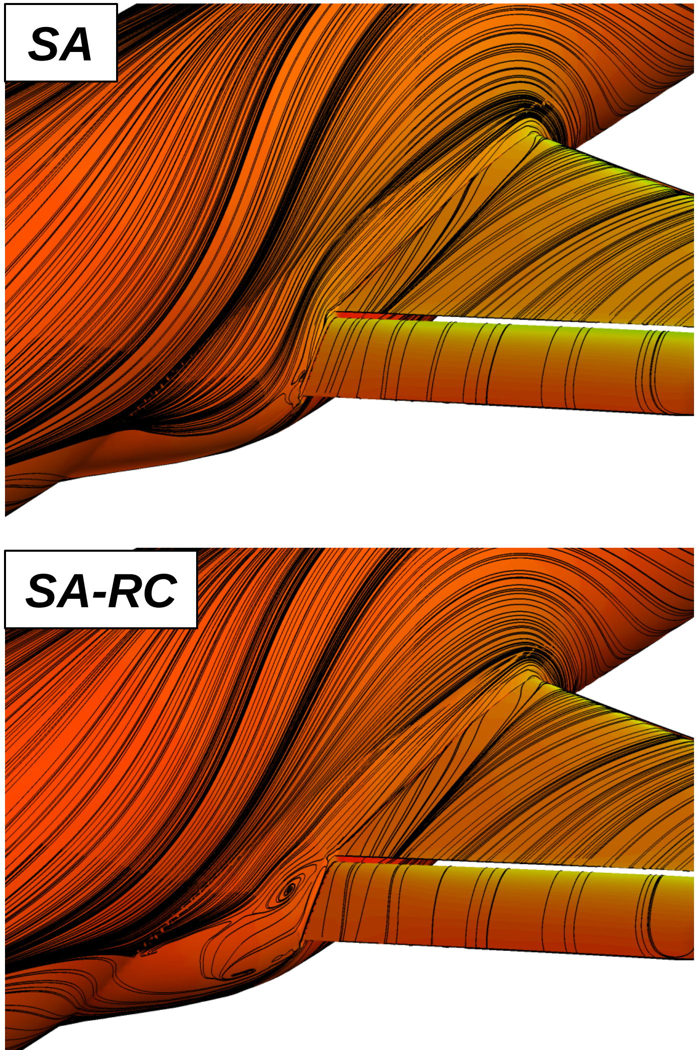
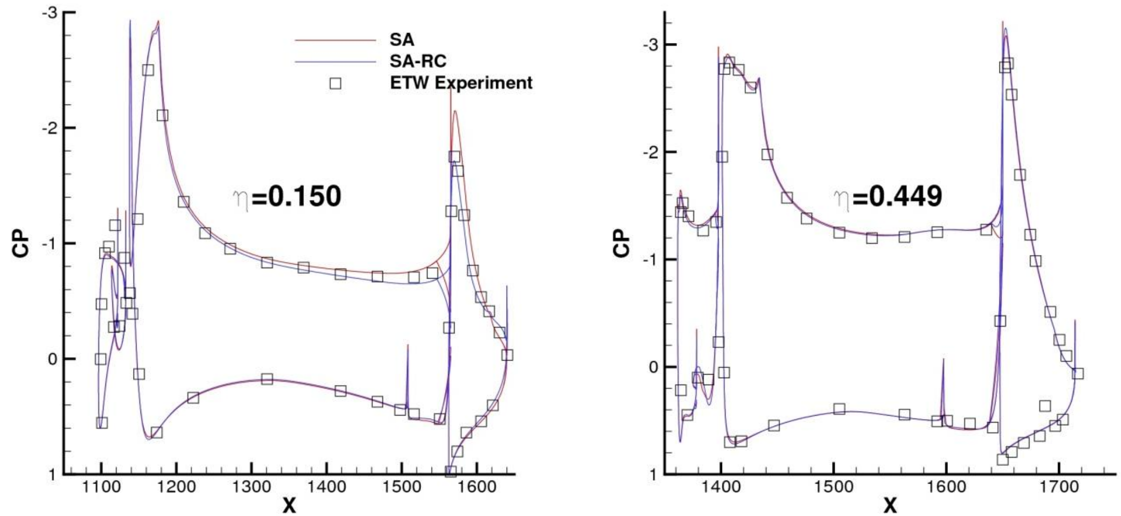


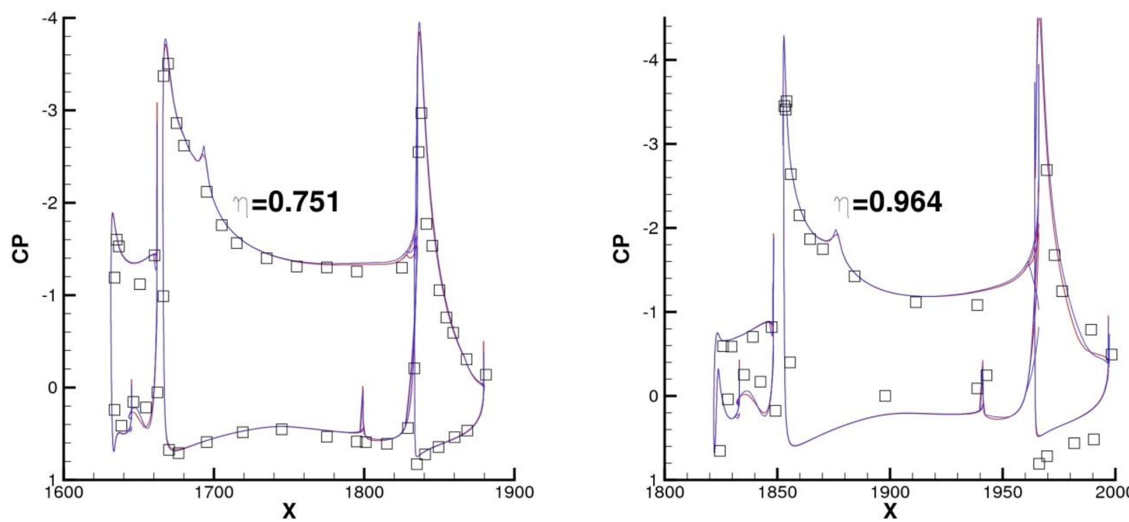
RC Correction, No Tracks, R = 15.1 Million



C_p contours

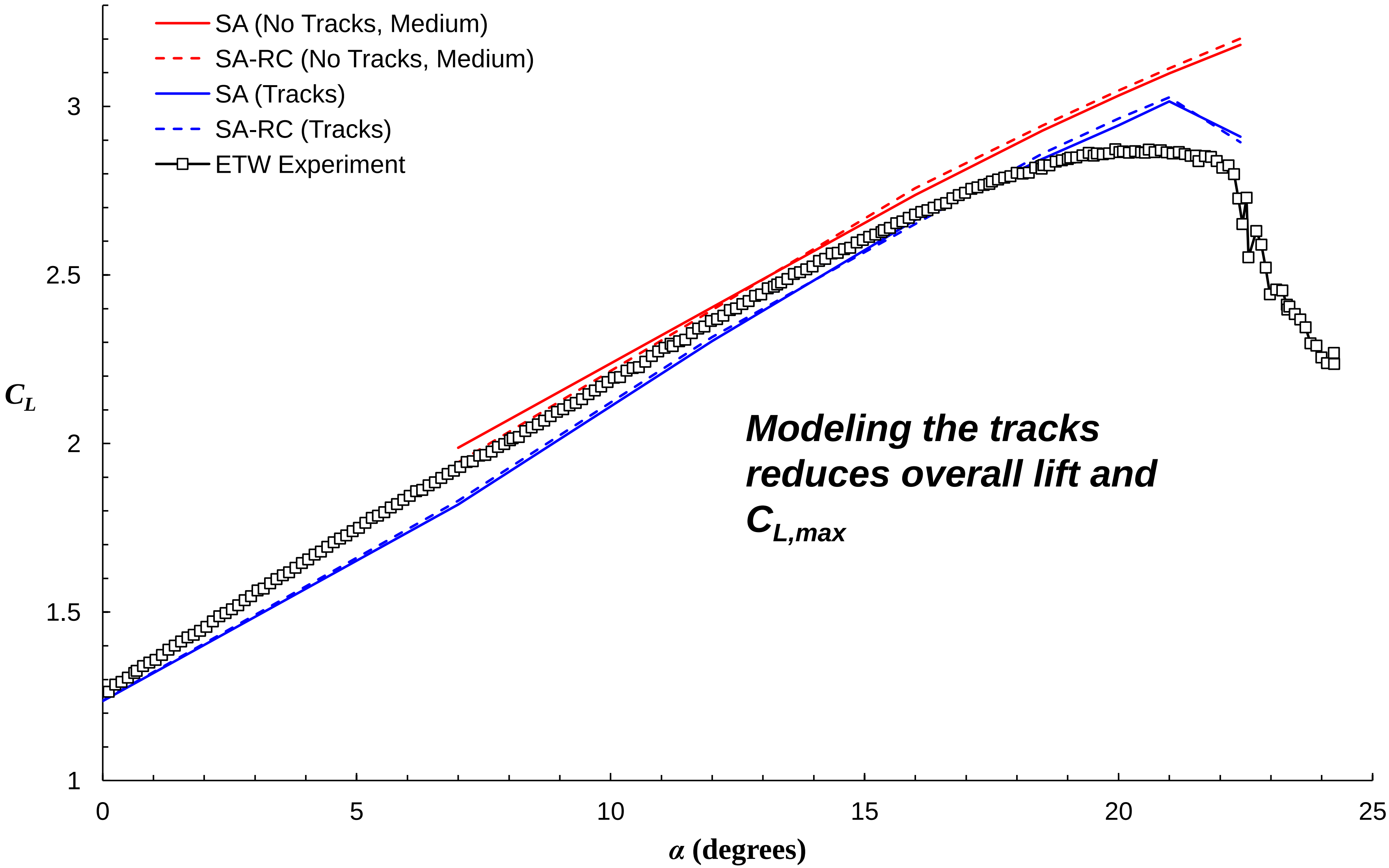


R = 15.1e6, α = 7°



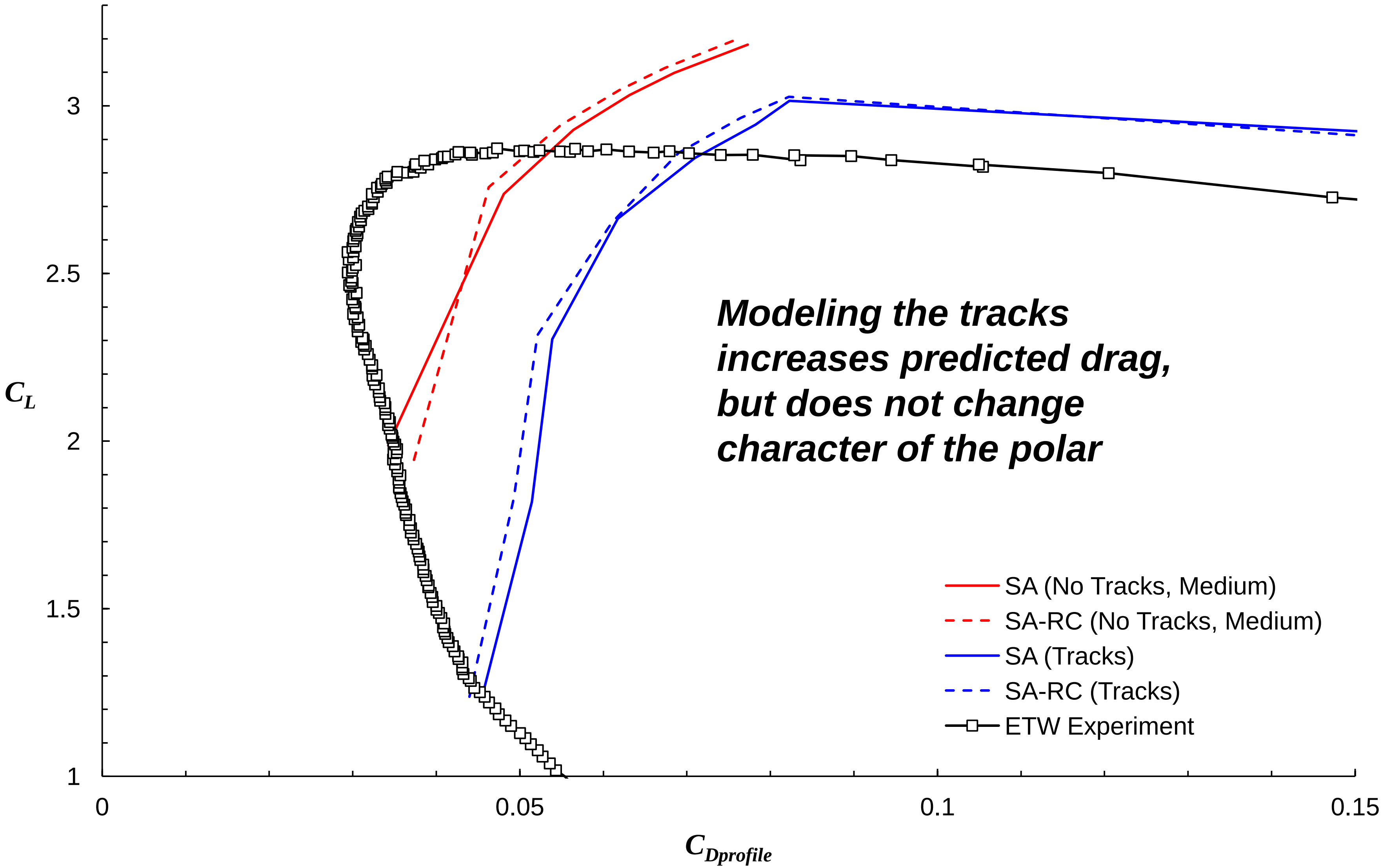
Effect of Slat Tracks and Flap Track Fairings (*Cases 1 and 2b*)

Tracks/Fairings Effects, R = 15.1 Million: Lift Curve

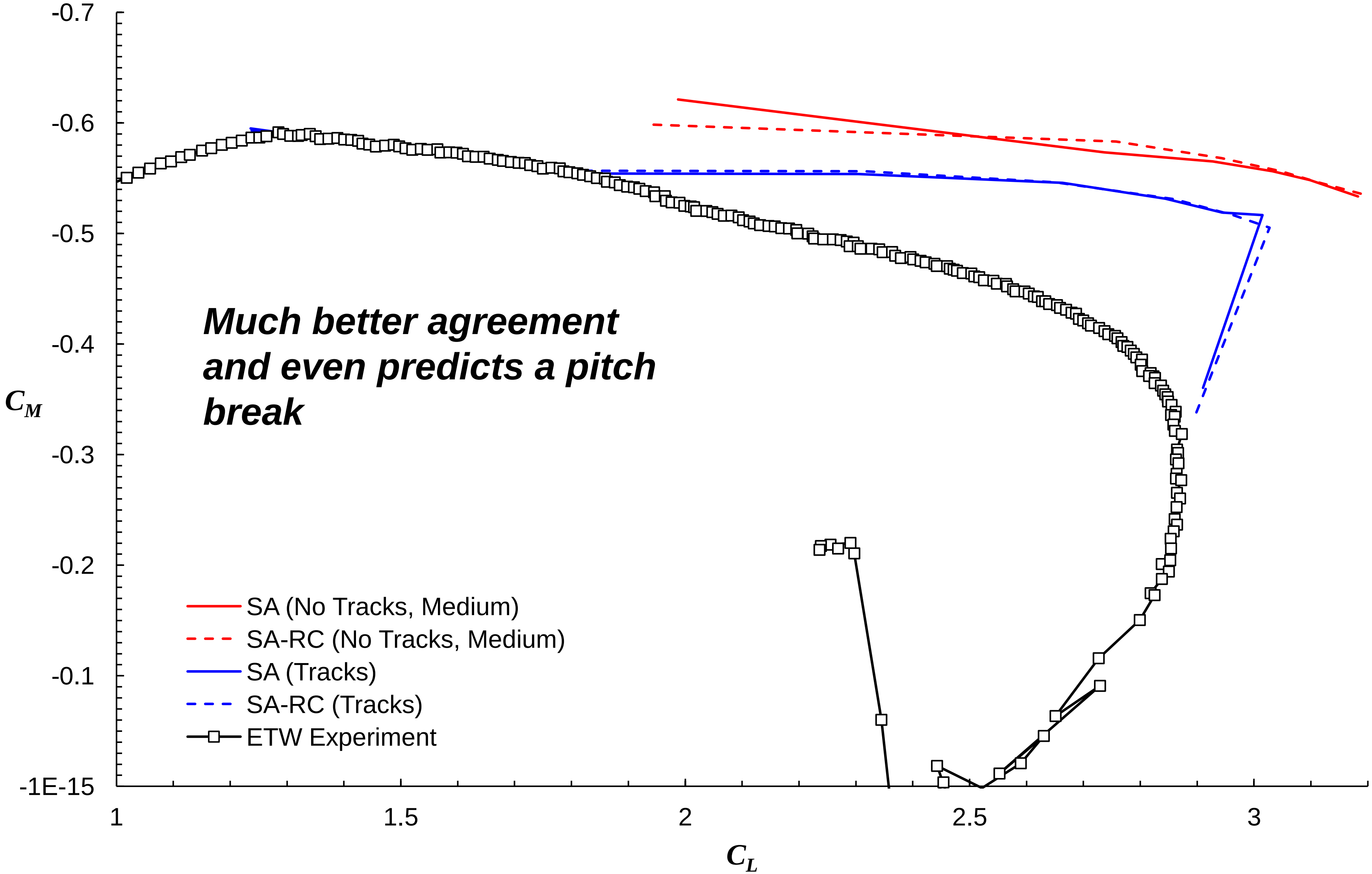


Modeling the tracks reduces overall lift and $C_{L,max}$

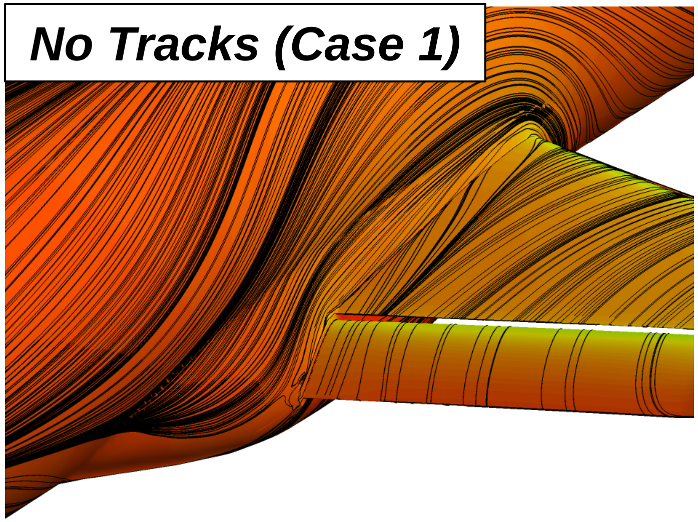
Tracks/Fairings Effects, R = 15.1 Million: Drag Polar

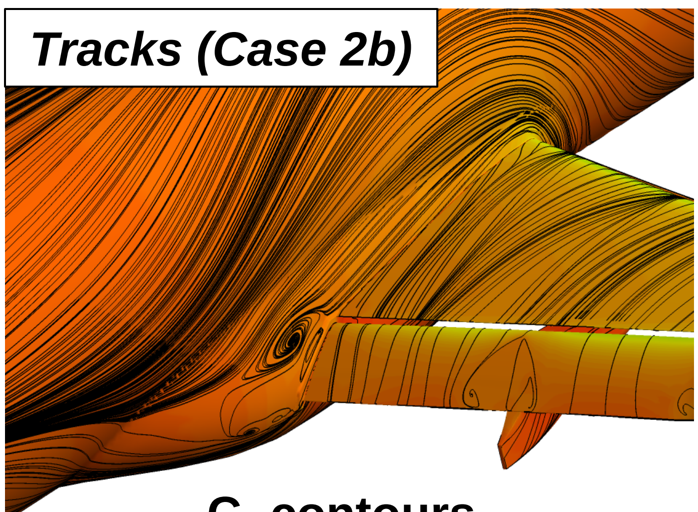


Tracks/Fairings Effects, R = 15.1 Million: Pitching Moment

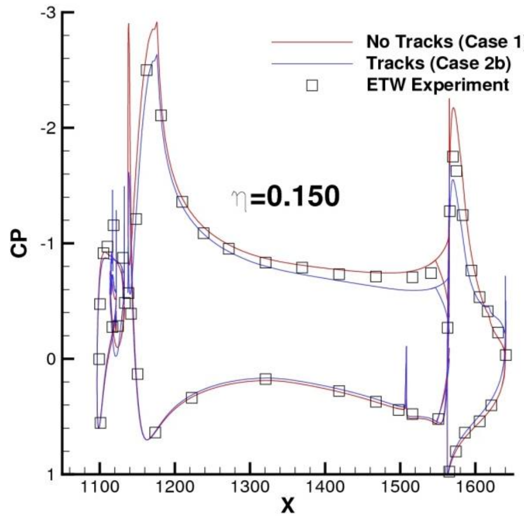


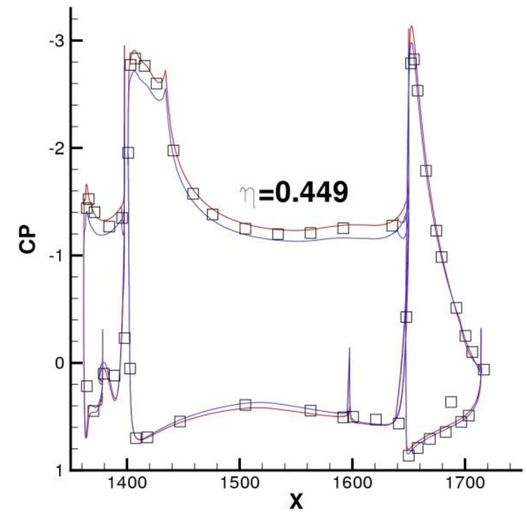
Effect of Slat and Flap Tracks, R = 15.1 Million



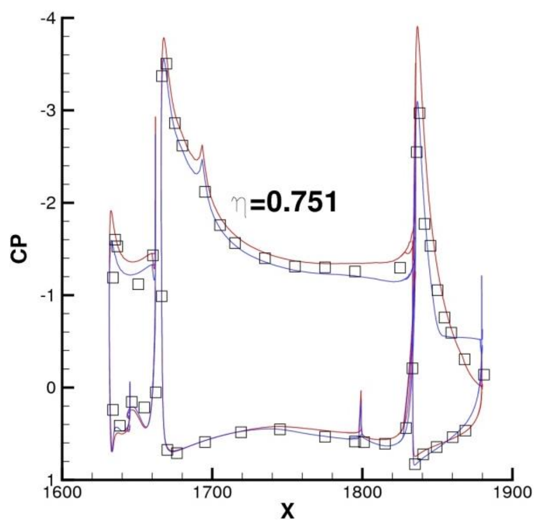


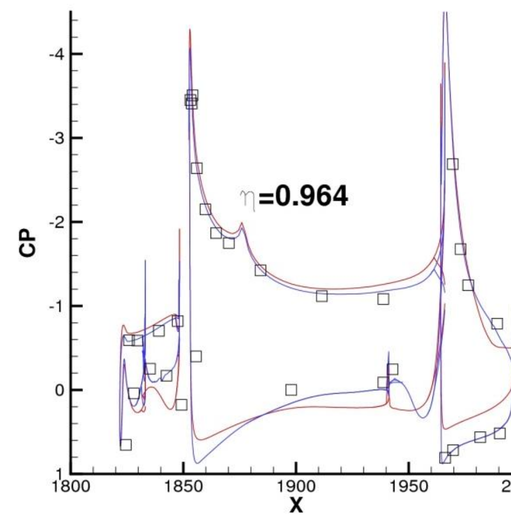
C_p contours



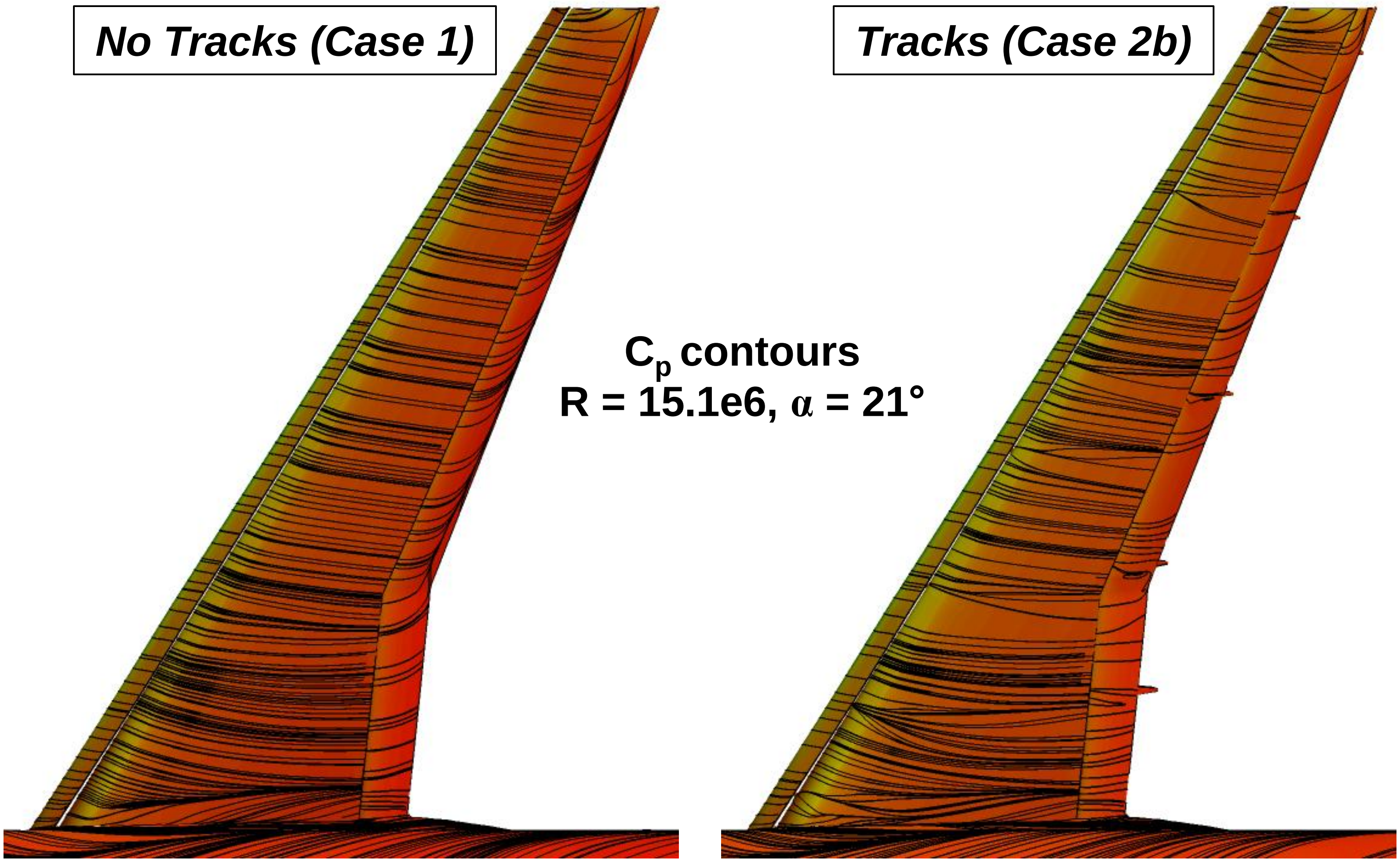


R = 15.1e6, α = 7°



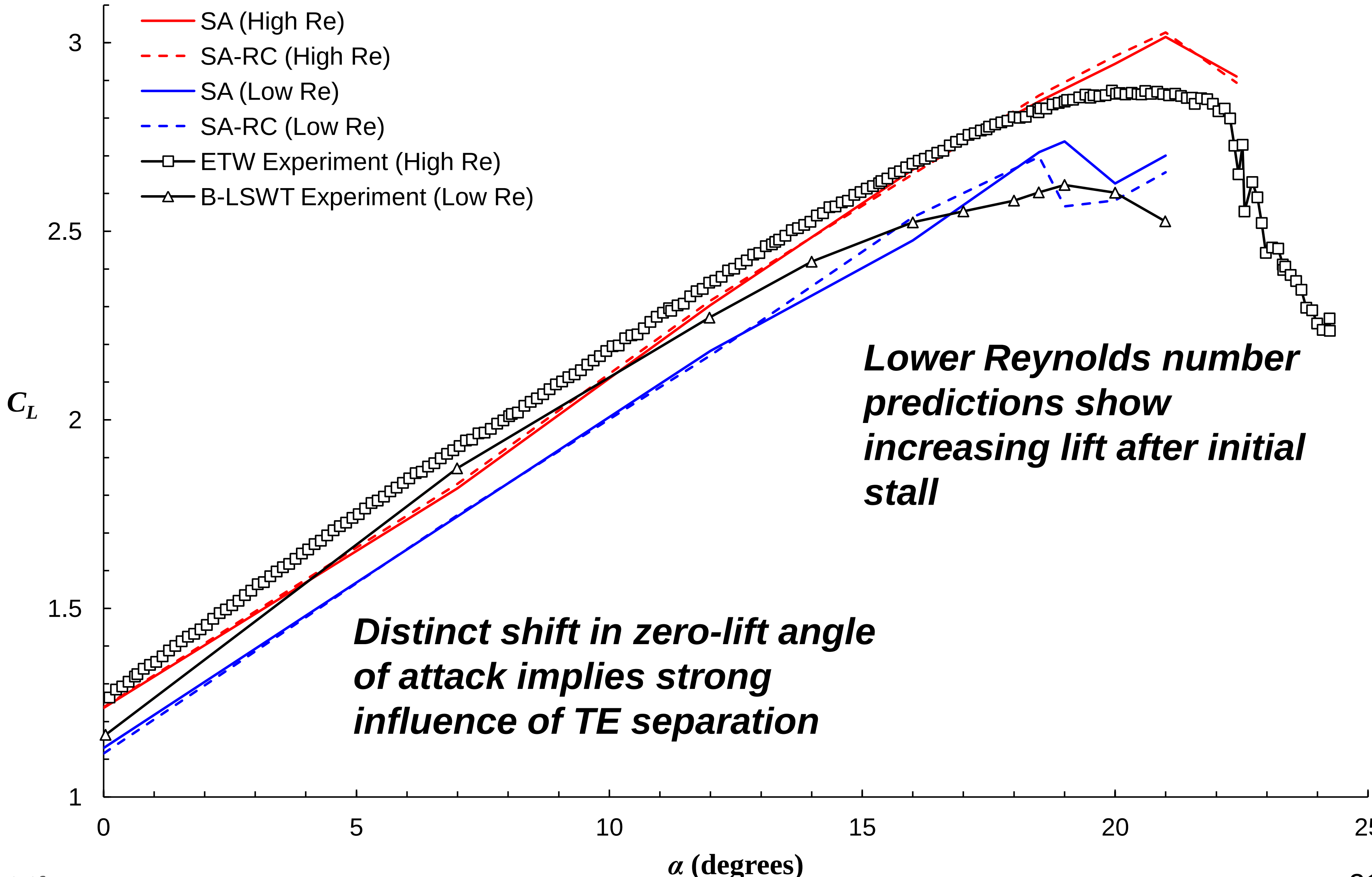


Effect of Slat and Flap Tracks, R = 15.1 Million



Reynolds Number Study
(*Cases 2a and 2b*)

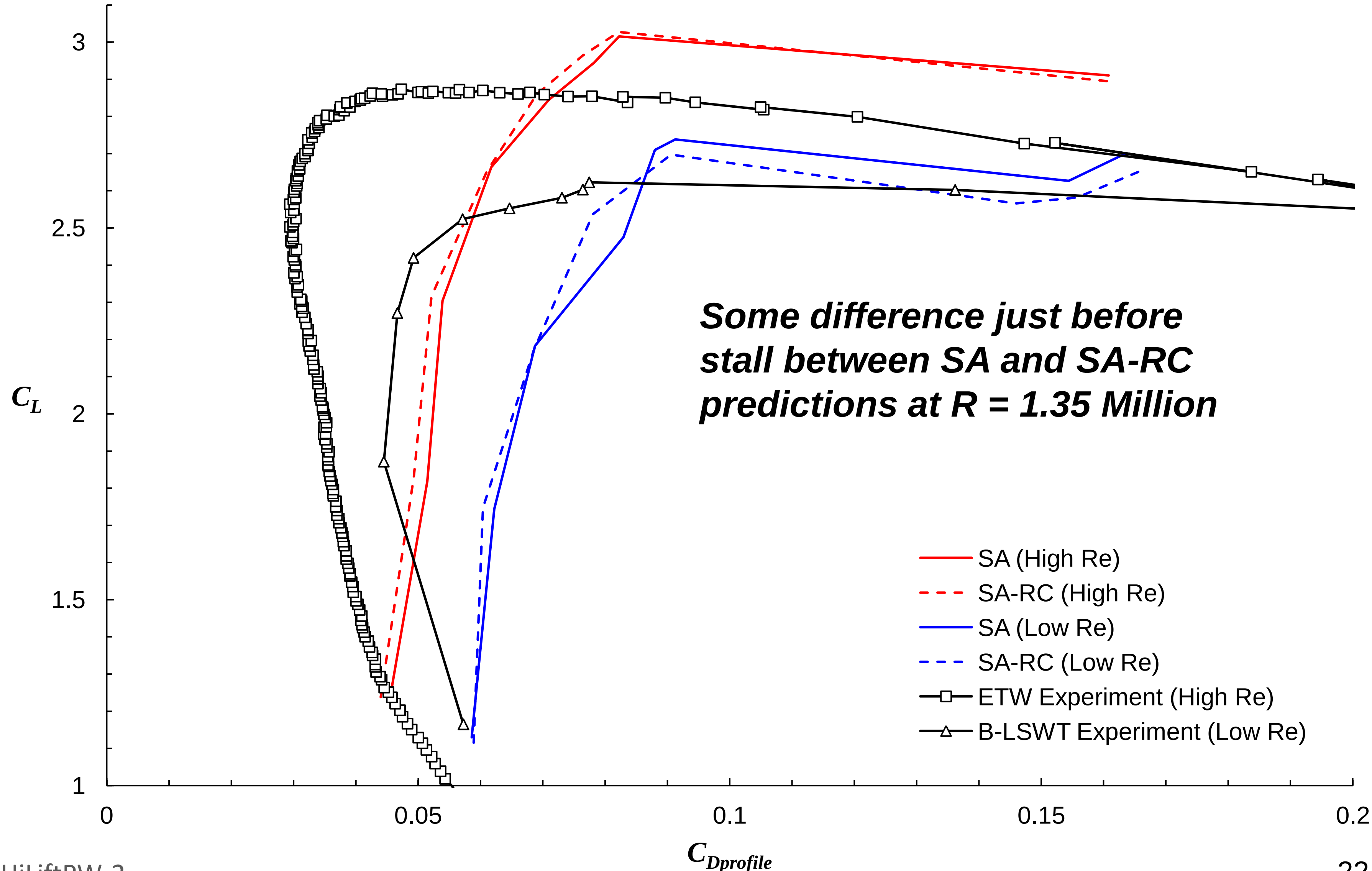
Reynolds Number Study: Lift Curve



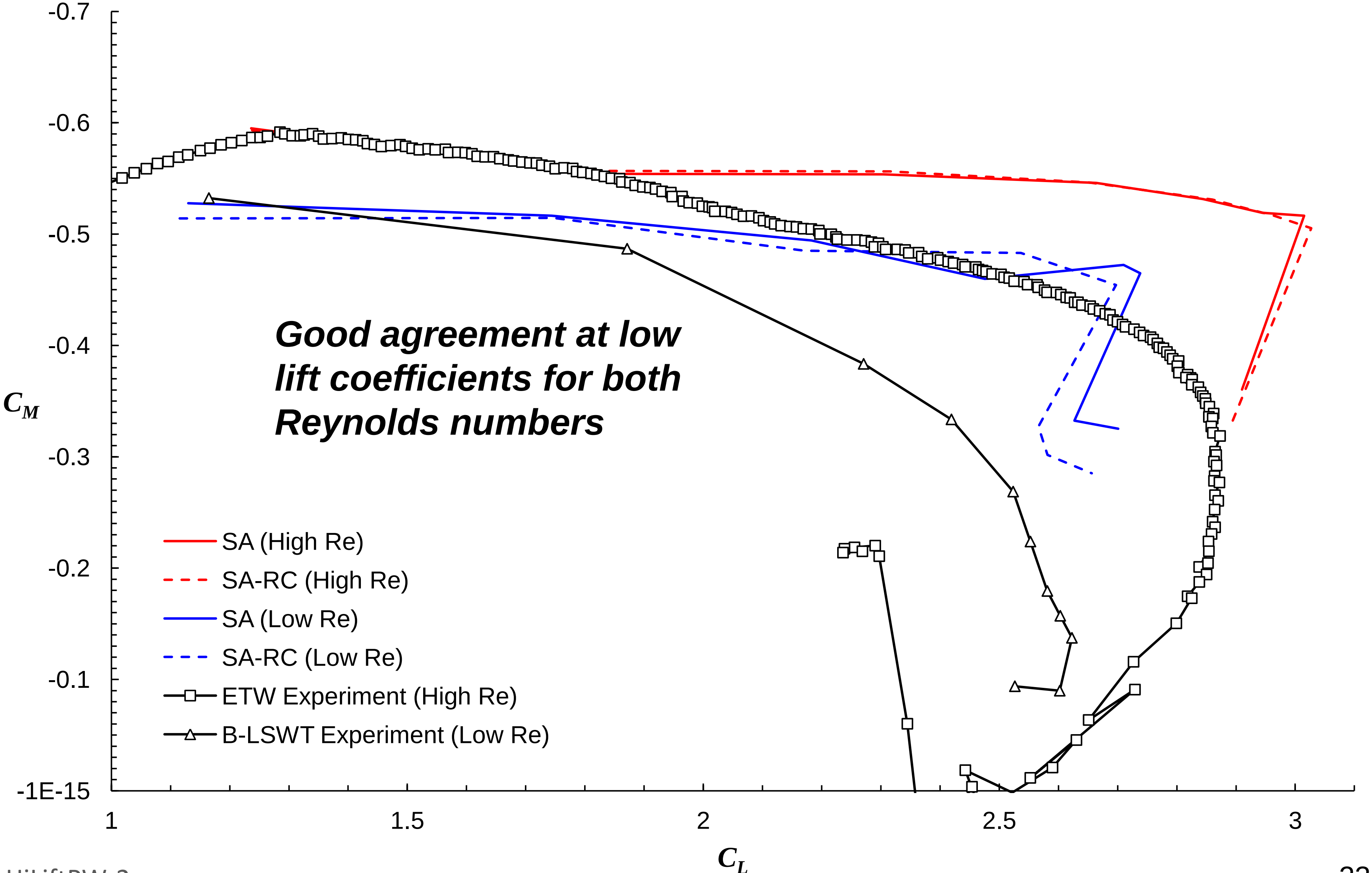
Lower Reynolds number predictions show increasing lift after initial stall

Distinct shift in zero-lift angle of attack implies strong influence of TE separation

Reynolds Number Study: Drag Polar

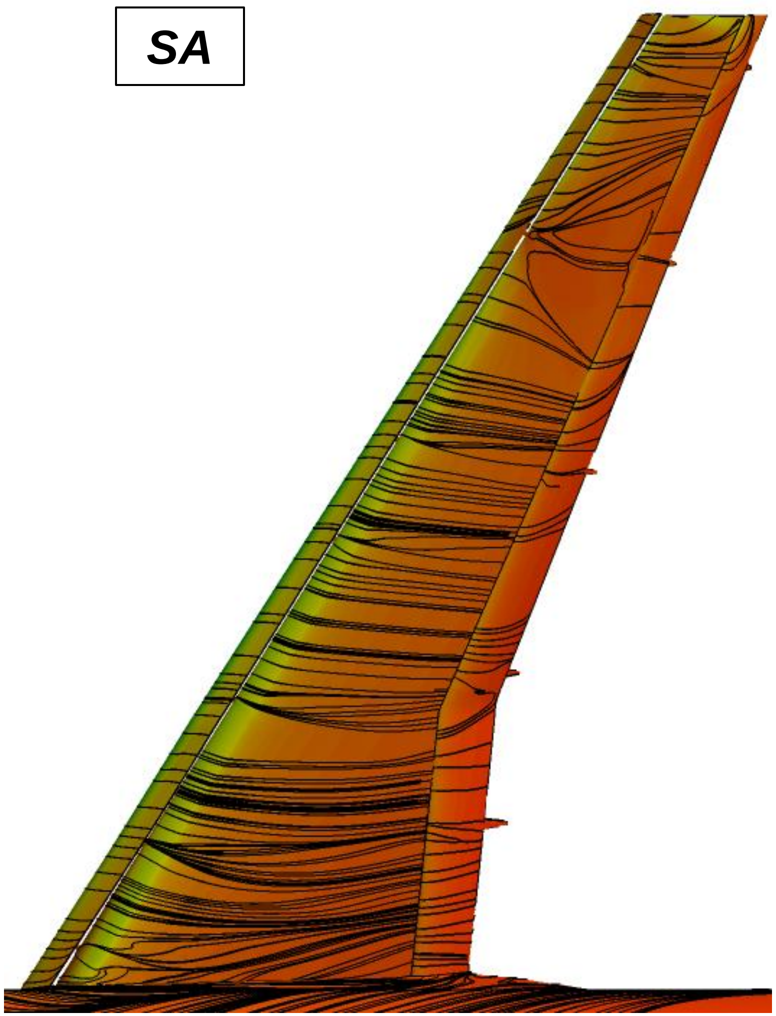


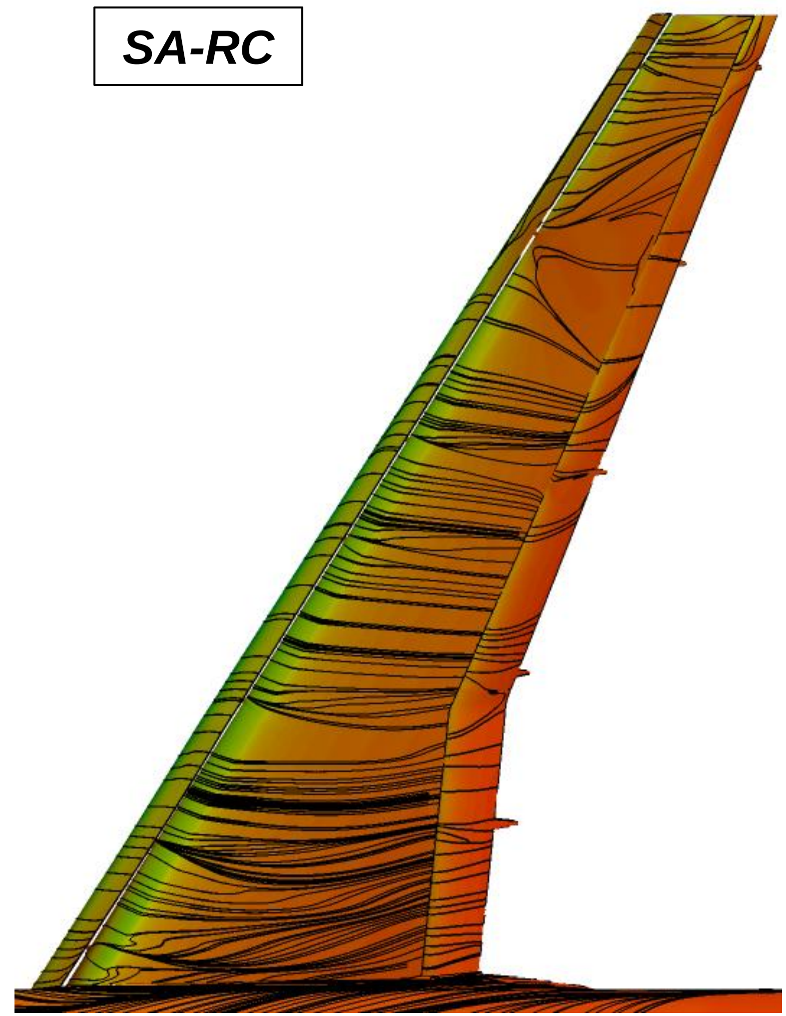
Reynolds Number Study: Pitching Moment



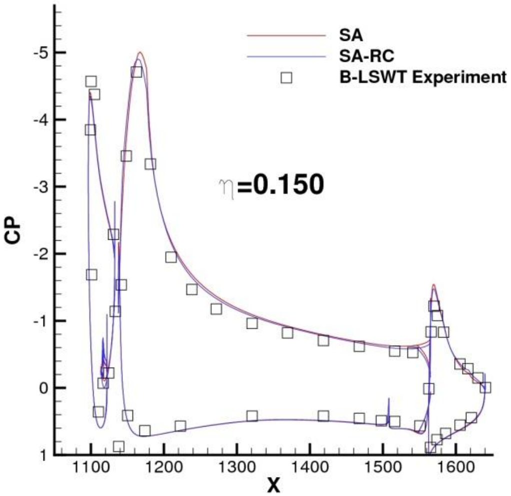
Good agreement at low lift coefficients for both Reynolds numbers

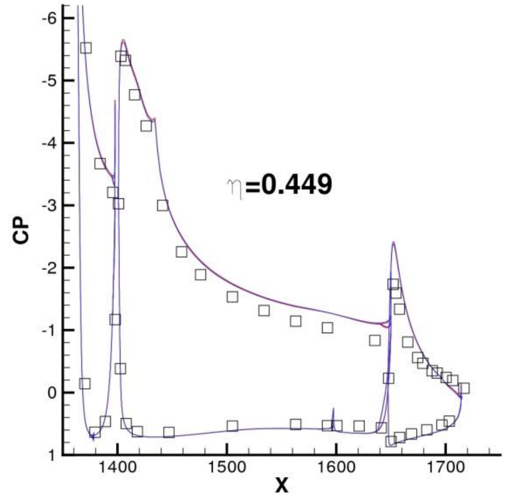
Effect of RC Correction, Tracks/Fairings On, R = 1.35 Million

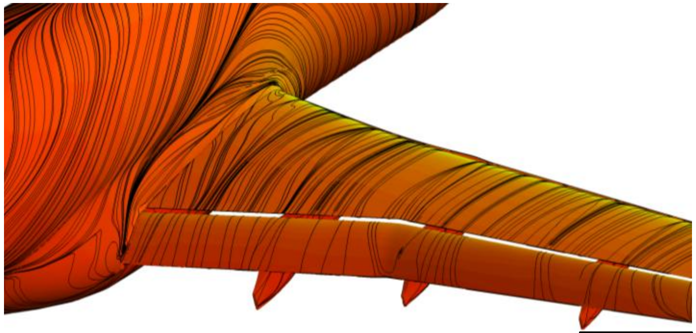




Effect of RC Correction, Tracks/Fairings On, R = 1.35 Million

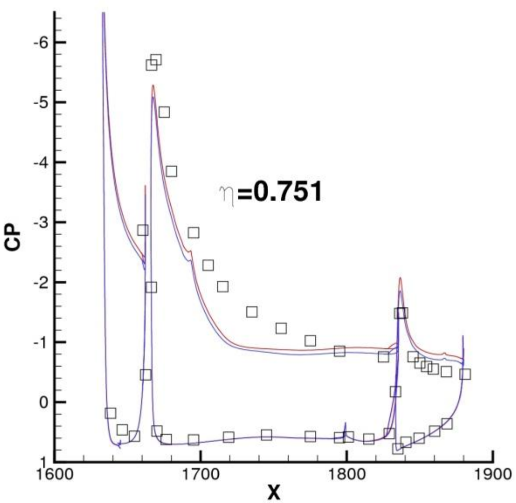


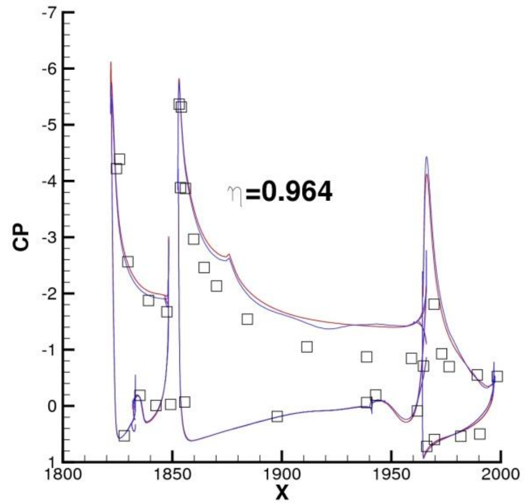


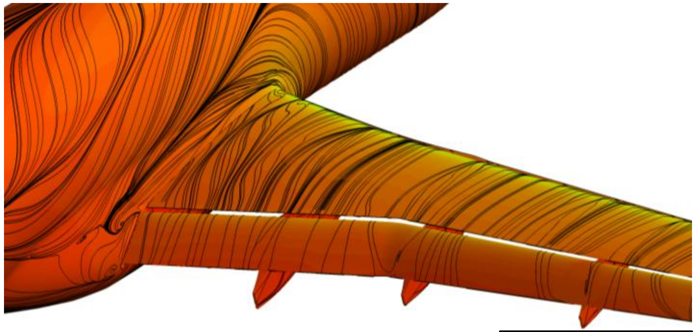


SA

R = 1.35e6, α = 21°







SA-RC

C_p contours

Transitional Flow Effects
(*Case 2c*)

Transition Modeling

- Amplification Factor Transport Equation (AIAA 2013-0253)

$$\frac{\partial(\rho\tilde{n})}{\partial t}+\frac{\partial(\rho u_j\tilde{n})}{\partial x_j}=\rho\Omega F_{crit}F_{growth}+\frac{\partial}{\partial x_j}\left[\sigma_n(\mu+\mu_t)\frac{\partial\tilde{n}}{\partial x_j}\right]$$

  - Predictive model based on the approximate envelope method of Drela and Giles
    - Models Tollmien-Schlichting transition
  - Uses local flow variables and wall distance to estimate the boundary-layer shape factor
    - Parallelizable (no integration paths)
    - Requires free-stream conditions to be available at every grid point
  - Insensitive to domain size
    - Transition criterion set critical amplification factor
  - Shows improvement over local-correlation methods for predicting flow around airfoils (including multi-element airfoils)

Transition Modeling

- Applied to the Spalart-Allmaras eddy-viscosity model

$$\frac{D\tilde{\nu}}{Dt} = c_{b1}\left(1 - f_{t2,mod}\right)\tilde{S}\tilde{\nu} - \left[c_{w1} f_w - \frac{c_{b1}}{\kappa^2} f_{t2,mod}\right]\left(\frac{\tilde{\nu}}{d}\right)^2 + \frac{1}{\sigma}\left[\frac{\partial}{\partial x_j}\left(\left(\nu + \tilde{\nu}\right)\frac{\partial \tilde{\nu}}{\partial x_j}\right) + c_{b2}\frac{\partial \tilde{\nu}}{\partial x_j}\frac{\partial \tilde{\nu}}{\partial x_j}\right]$$

  – where the f_{t2} function is modified to

$$f_{t2,mod} = c_{t3}\left[1 - \exp\left(2\left(\tilde{n} - N_{crit}\right)\right)\right]\exp\left(-c_{t4}\left(\frac{\tilde{\nu}}{\nu}\right)^2\right)$$

with c_{t3} = 1.2 and c_{t4} = 0.05

- N_{crit} set to 8.15 for Case 2c
  – Based on reported B-LSWT turbulence levels and Mack's relationship

Quadratic Constitutive Relation (QCR)

- Non-linear extension to the Boussinesq eddy-viscosity hypothesis proposed by Spalart
  - Original (QCR2000) version implemented into OVERFLOW 2.2f

$$\tau_{ij,QCR} = 2\mu_t \left[S_{ij} - c_{nl1} \left(O_{ik} S_{jk} + O_{jk} S_{ik} \right) \right]$$

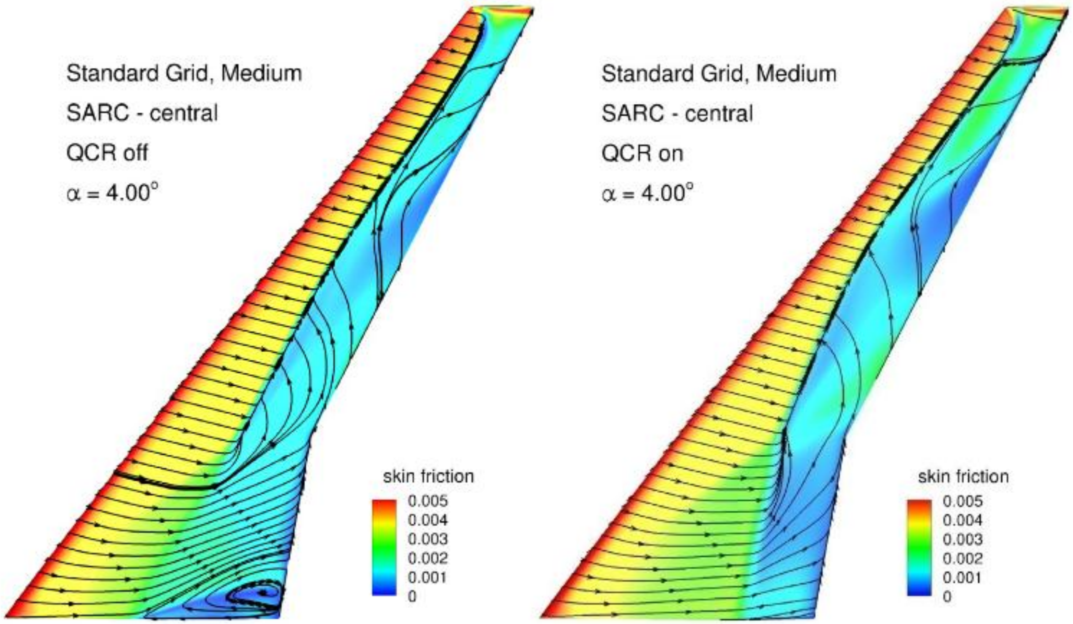
  - where c_{nl1} = 0.3 and

$$O_{ik} = \frac{\dfrac{\partial u_i}{\partial x_k} - \dfrac{\partial u_k}{\partial x_i}}{\sqrt{\dfrac{\partial u_m}{\partial x_n} \dfrac{\partial u_m}{\partial x_n}}}$$

- Higher-order terms demonstrated to improve predictions for corner flows

Quadratic Constitutive Relation (QCR)

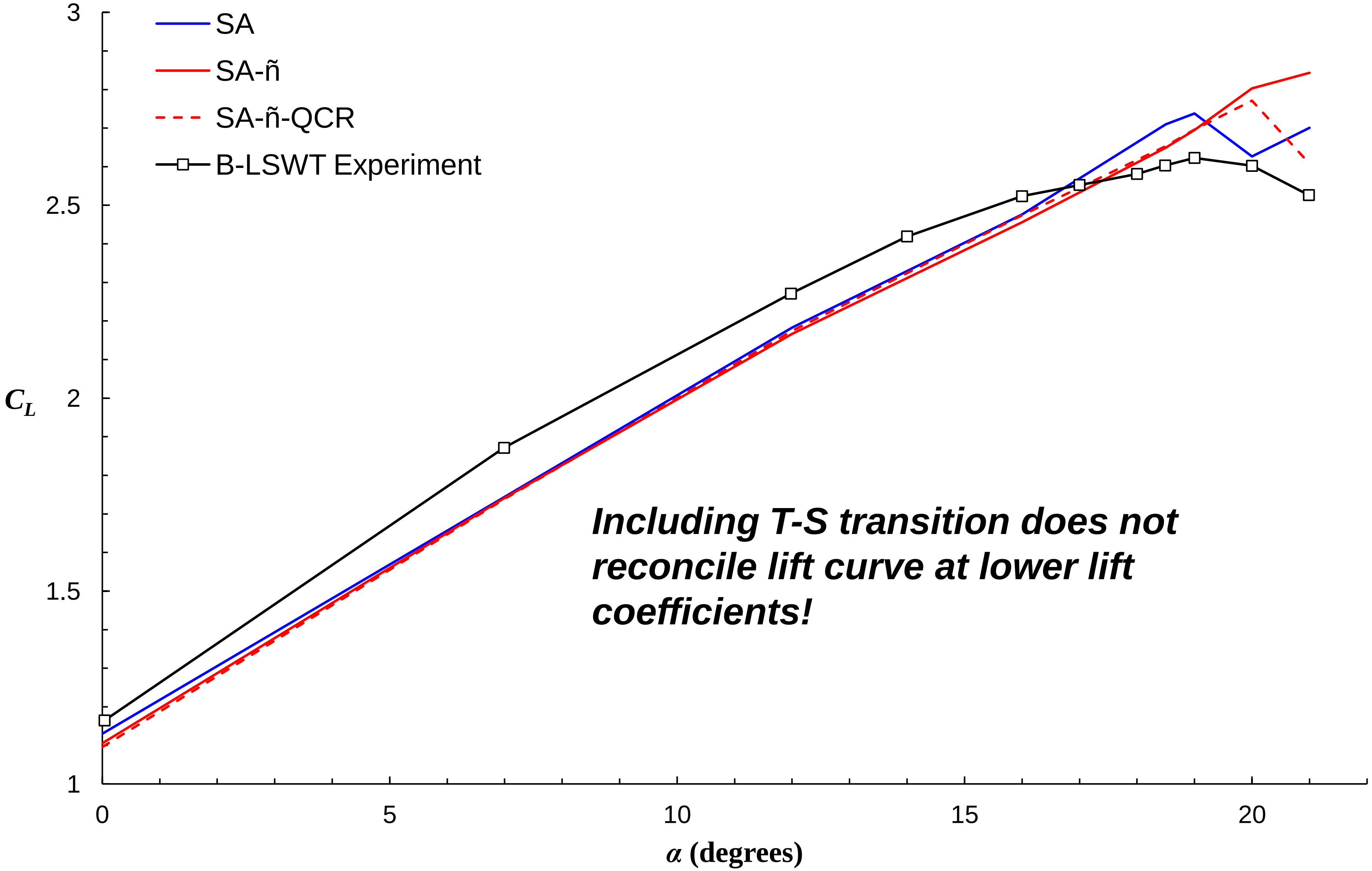
- SA-QCR predicts significantly reduced SOB separation on the CRM wing used for DPW-V



From Sclafani, et al. (AIAA 2013-0048)

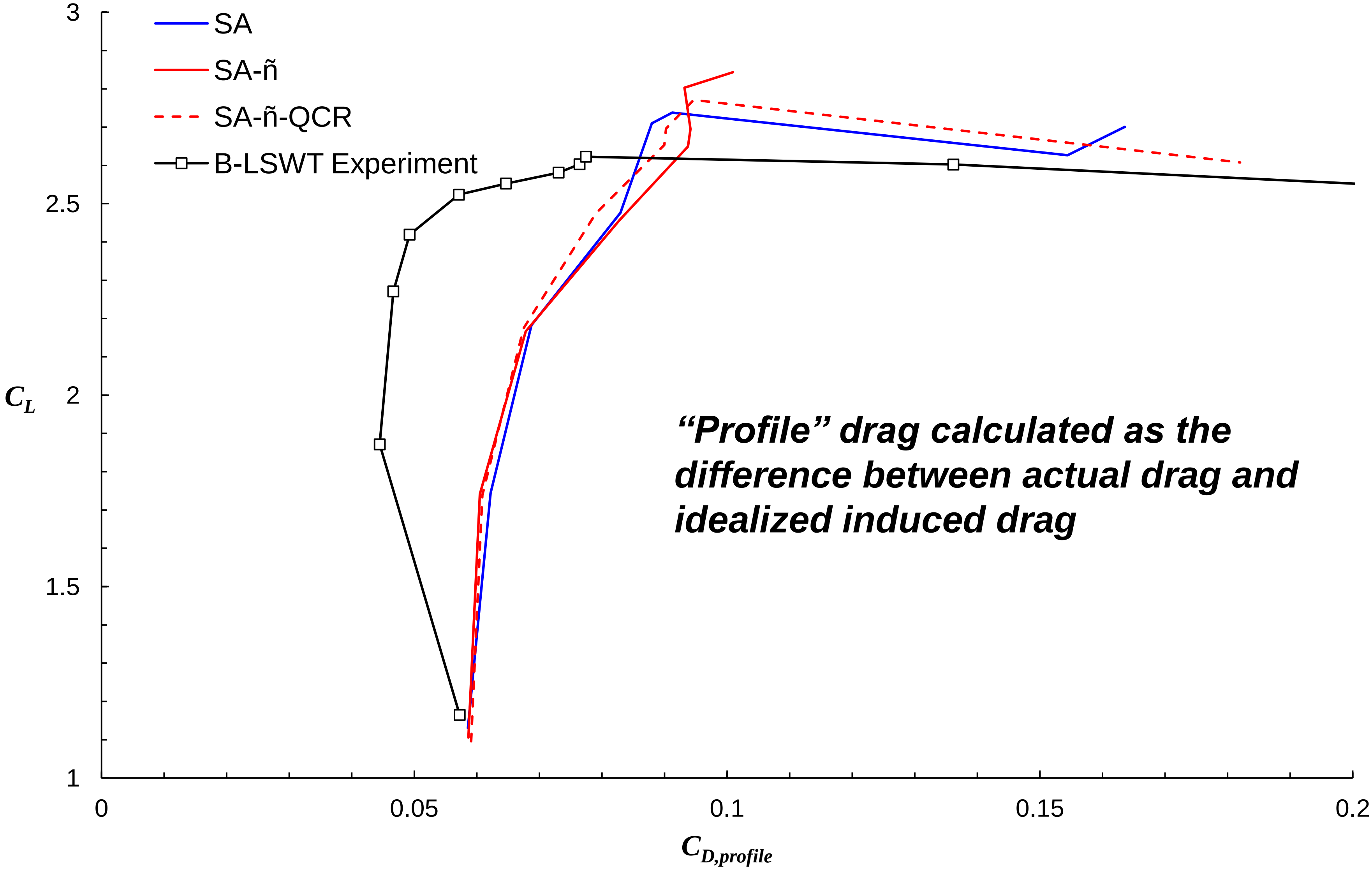
- Of great interest for HiLiftPW-2 simulations, but only applied to transitional data due to time constraints

Transition Study, R = 1.35 Million: Lift Curve



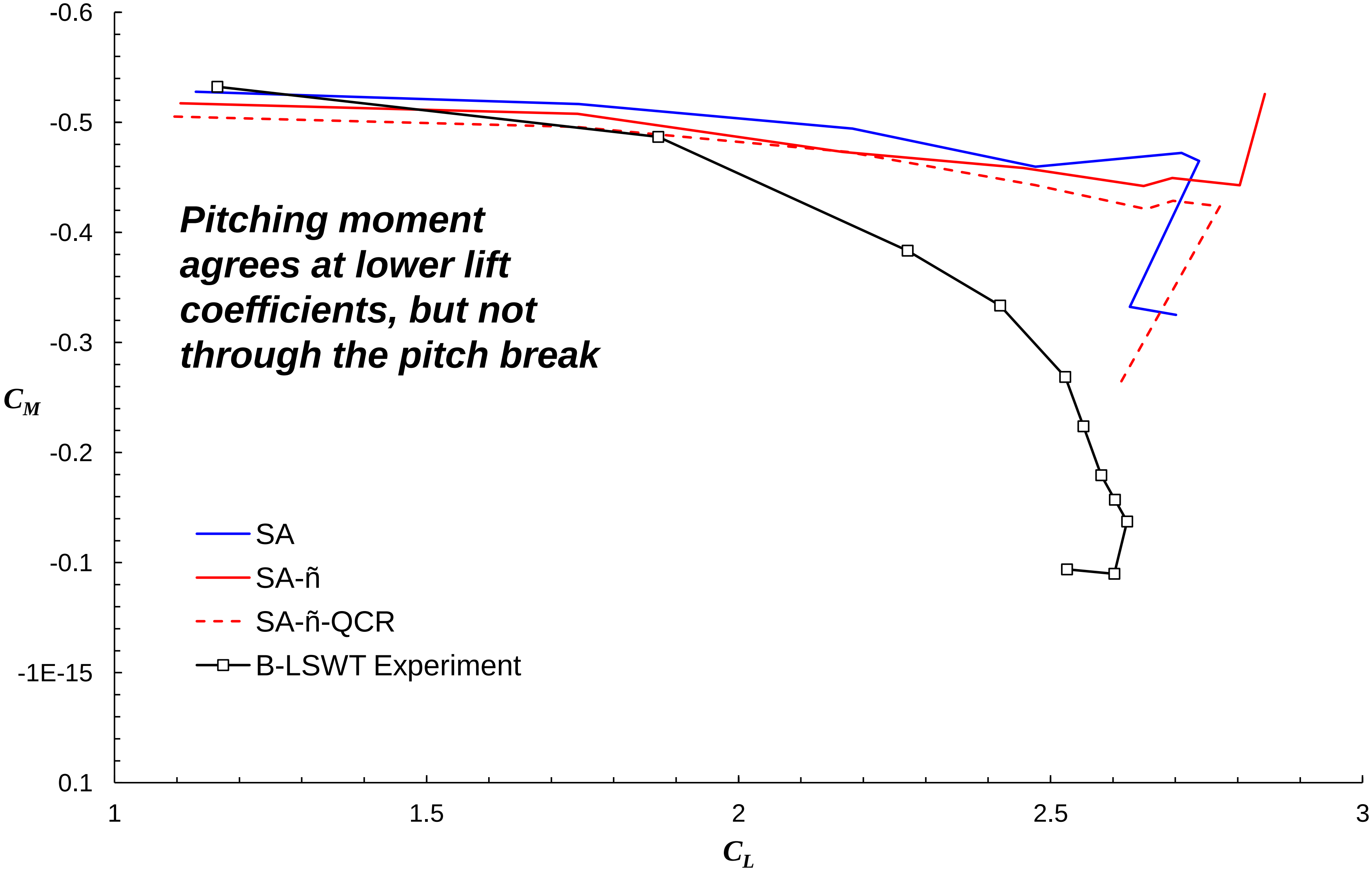
Including T-S transition does not reconcile lift curve at lower lift coefficients!

Transition Study, R = 1.35 Million : Drag Polar



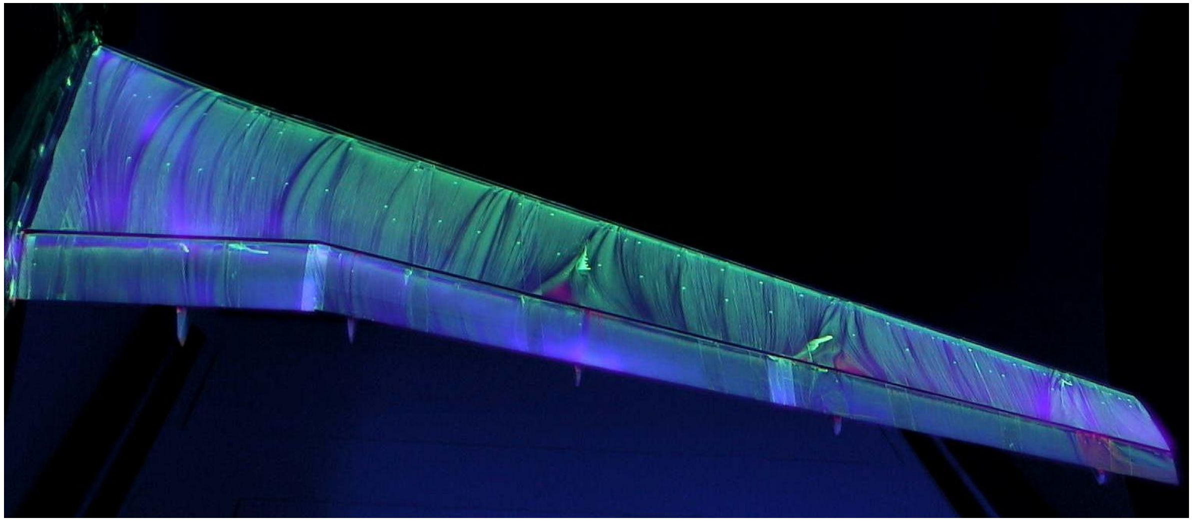
"Profile" drag calculated as the difference between actual drag and idealized induced drag

Transition Study, R = 1.35 Million : Pitching Moment

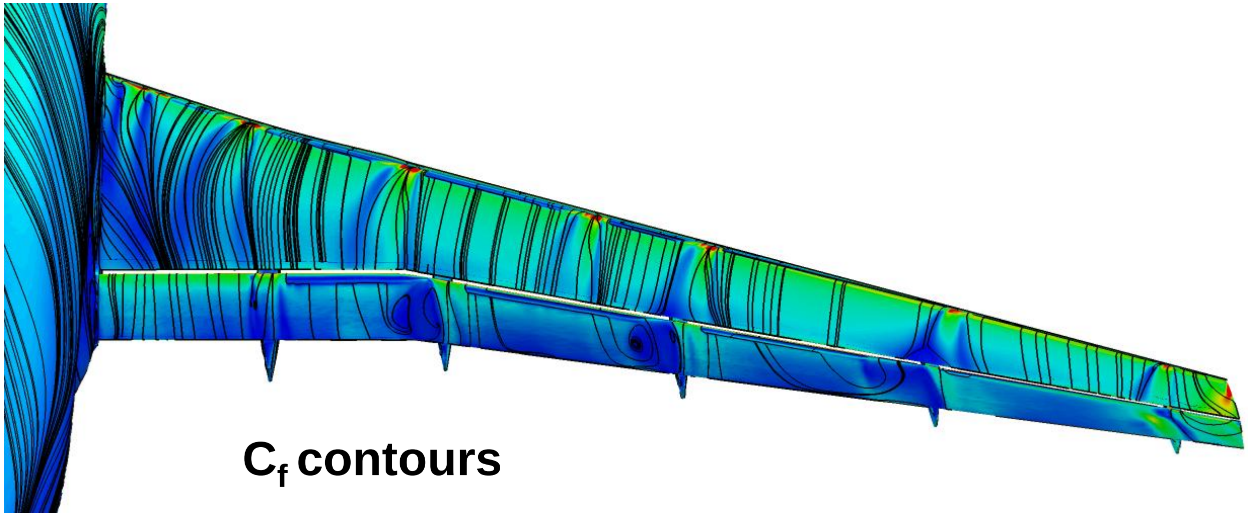


Pitching moment agrees at lower lift coefficients, but not through the pitch break

Surface Streamlines vs. QCR/Transition: α = 18.5°



Experiment shows separation onset on the main element at ~50% and ~75% semispan locations



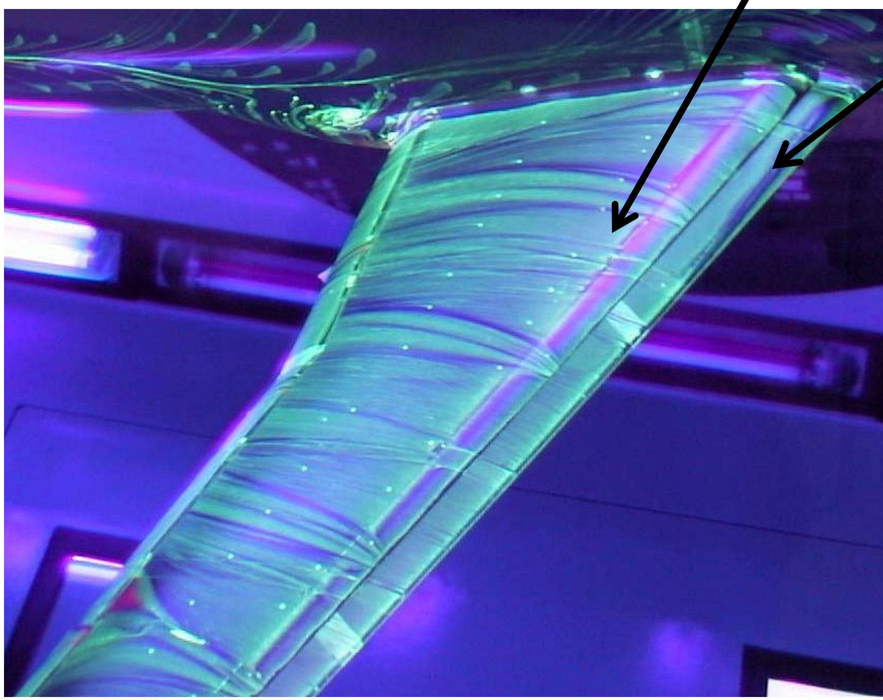
C_f contours

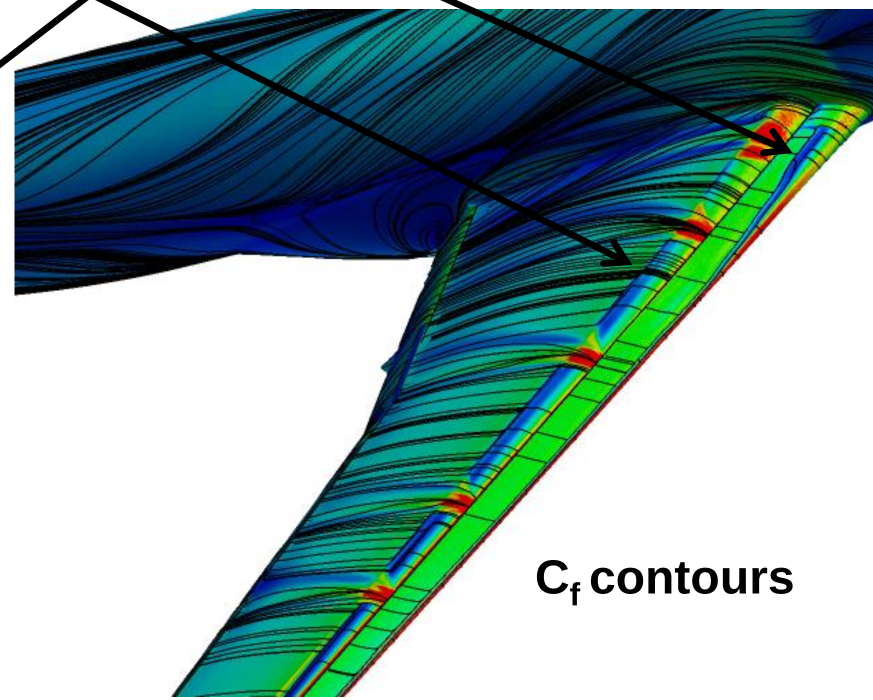
OVERFLOW predicts onset of separation at 75%, but not at 50%.

Separation on flap appears to be more prominent

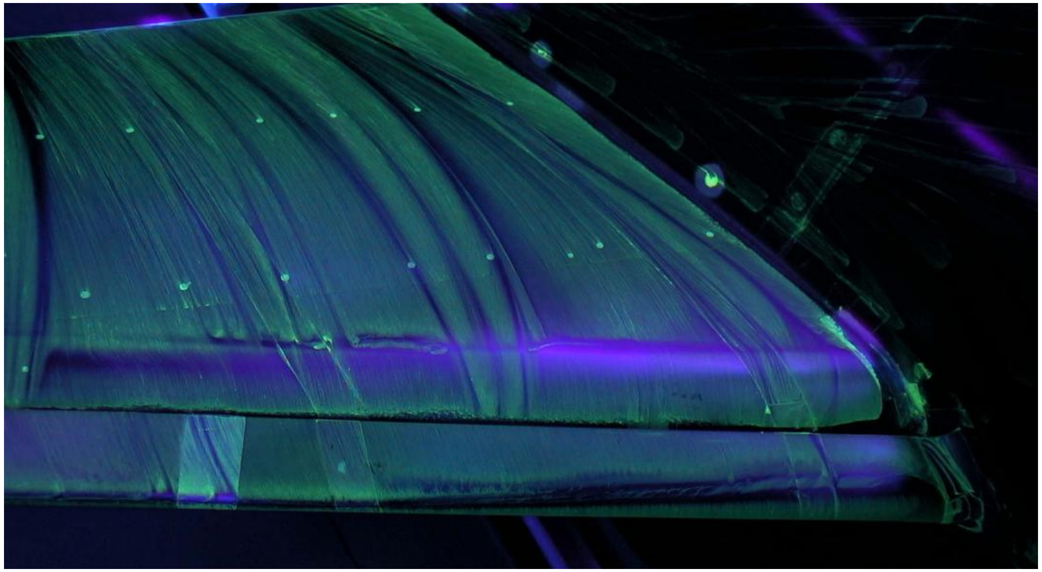
Surface Streamlines vs. QCR/Transition : α = 18.5°

Good agreement for laminar-separation bubble patterns





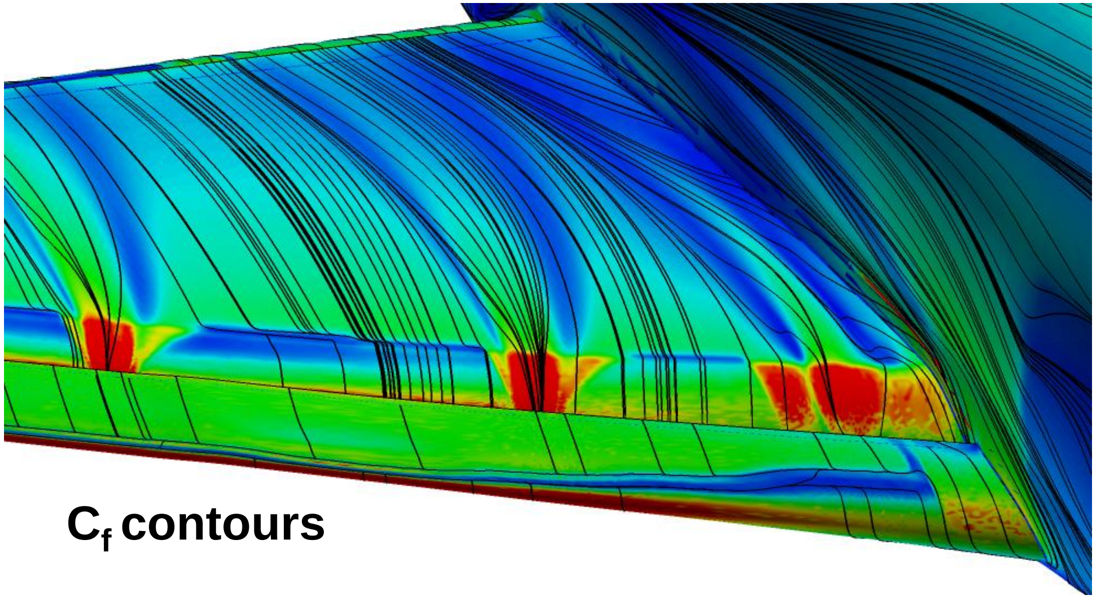
Surface Streamlines vs. QCR/Transition : α = 18.5°



OVERFLOW solution shows contamination on the slat and main element near the root

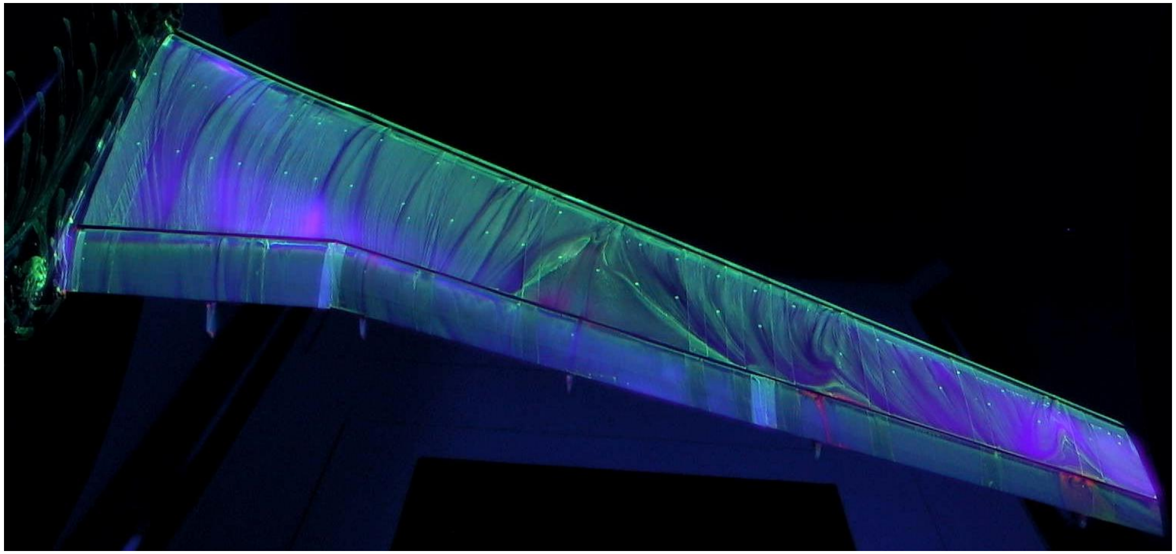
This behavior for the slat seems to agree with experiment

Laminar-separation patterns are well-predicted outboard of the contaminated region

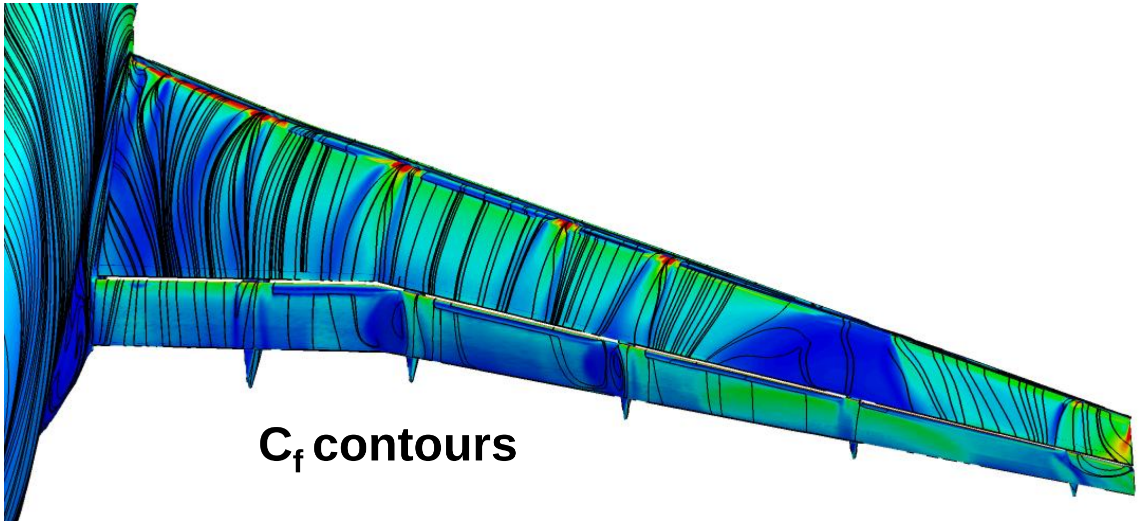


C_f contours

Surface Streamlines vs. QCR/Transition : α = 21°

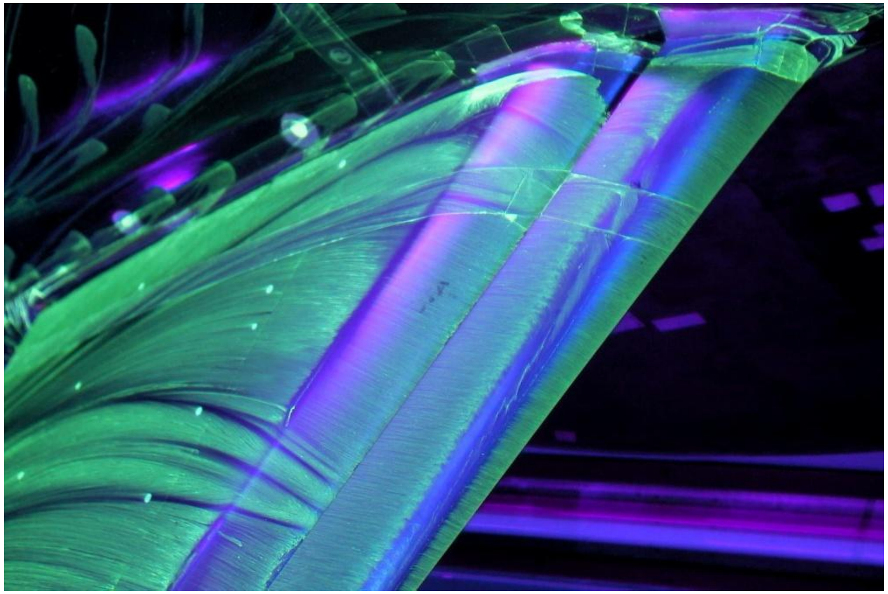


Experiment shows large separated region mid-span causing wing stall



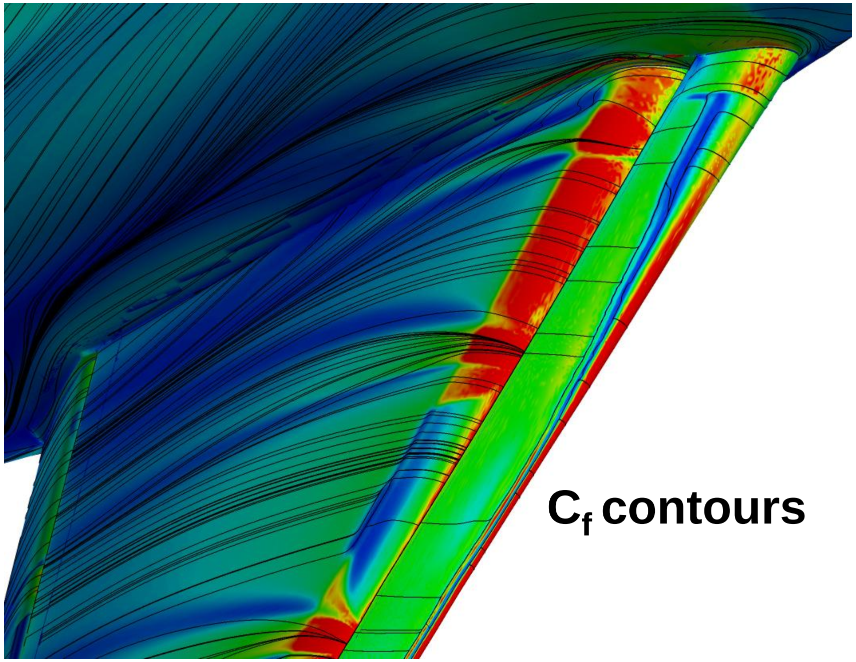
OVERFLOW predicts stall-causing separation farther outboard

Surface Streamlines vs. QCR/Transition: α = 21°



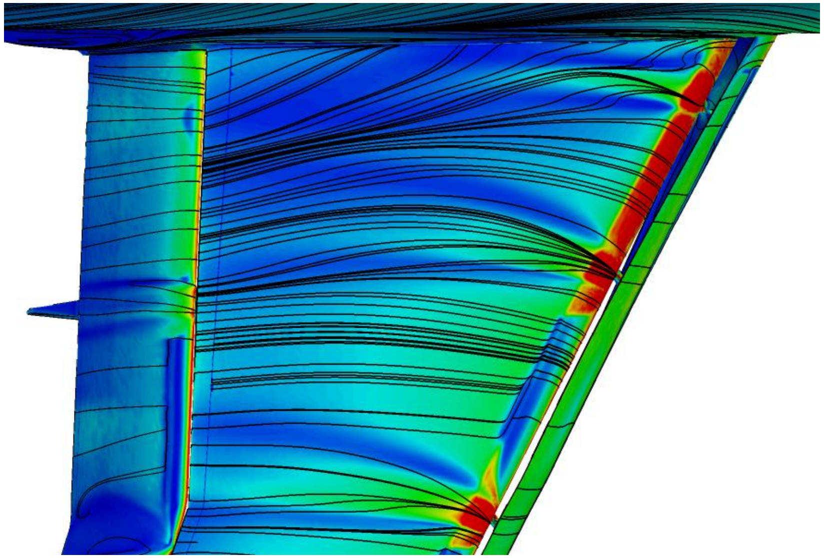
Root contamination on the main element is more prominent, but still contained on slat

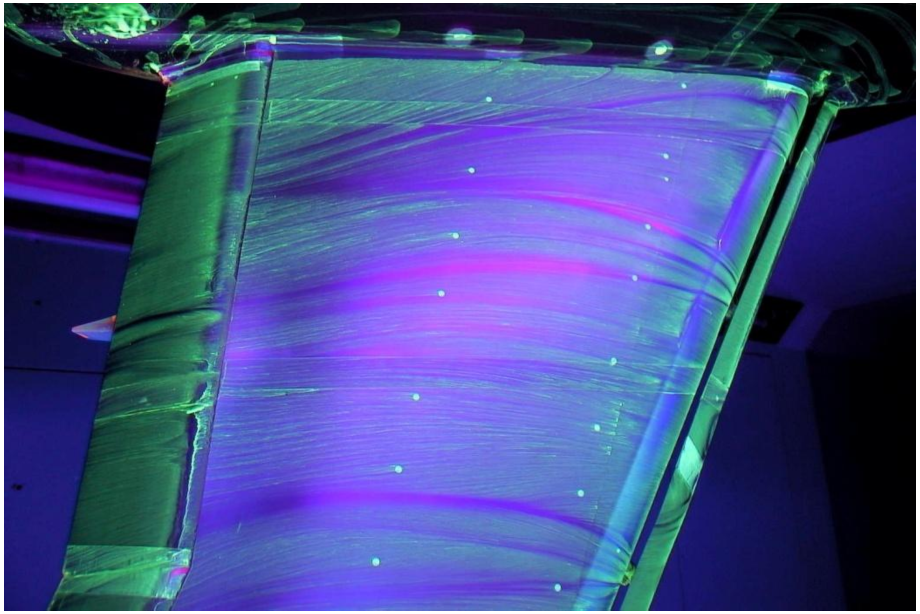
Seems to be the result of slat wake contamination (essentially bypass transition) rather than leading-edge contamination



Surface Streamlines vs. QCR/Transition : α = 21°

Contamination occurs on the flap as well near the root





Preliminary studies indicate it being a result of excessive eddy-viscosity production

More investigation required into this behavior

Some Conclusions and Future Work

- Behavior dominated by trailing-edge separation
  - Shift in zero-lift angle of attack
  - Relatively soft stall behavior
  - Choice of turbulence model has strong influence

- OVERFLOW failed to predict spanwise location of upper-surface separation wedge
  - Experiment showed $\eta \approx 50\%$
  - OVERFLOW predicted $\eta \approx 75\%$

- Transition modeling had little effect on the predictions
  - Slight reduction in profile drag
  - Not enough to reconcile CFD predictions with experiment
  - More transition models need to be explored!

Acknowledgments

- HiLiftPW-2 Organizing Committee
- Boeing Research & Technology, Huntington Beach
- Professor Mark Maughmer, Penn State University
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Thank you for your time

Questions?

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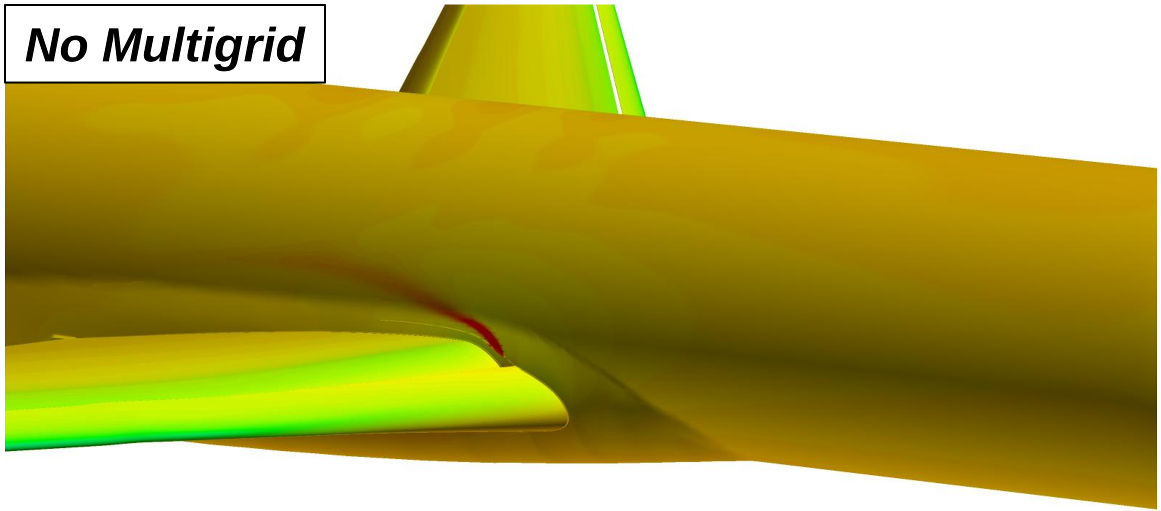
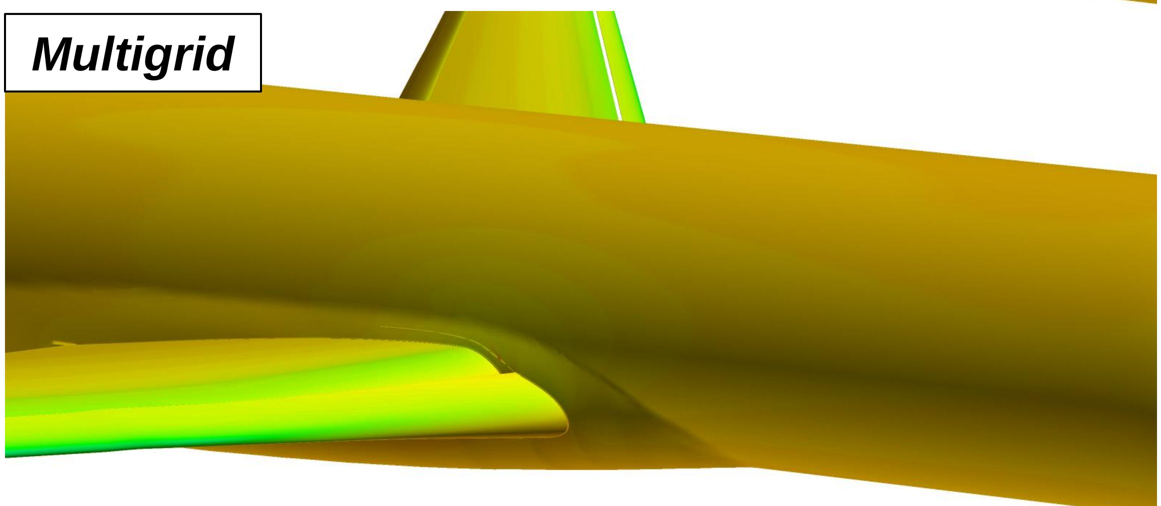


Without multigrid acceleration, solution locally destabilized on the medium grid but produced reasonable forces/moments



Multigrid stabilized the solution, but barely affected the lift, drag, and pitching moment in comparison

Density contours, R = 15.1e6, α = 18.5°