JAXA Contribution to HiLiftPW-2 using UPACS

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Computational results by JAXA

- Submitted data by Data Submittal Deadline (May 20)

CFD Code	Grid Type	Grid	Turb. Model	Case	AoA	misc.
UPACS	Point-matched structured grid	Committee provided A_str_1to1_v2, ICEM HEXA	SA-noft2-R (Crot=1)	Case1	7,16	

- Additional evaluations (Not submitted)

CFD Code	Grid Type	Grid	Turb. Model	Case	AoA	misc.
UPACS	Point-matched structured grid	Committee provided A_str_1to1_v2, ICEM HEXA	**SA-noft2-R (Crot=1)w/ QCR**	Case1	7,16	
			SST-V		7,16	
			SST-V w/ QCR		7,16	A part was finished

CFD Code	Grid Type	Grid	Turb. Model	Case	AoA	misc.
UPACS	Point-matched structured grid	Committee provided grids	**SA-noft2-R**	**Case4 Bump**	–	
			SST-V		–	

- Focus of comparisons:
  - Comparison of two turbulence models
    - SA-noft2-R and SST-V
  - Effect of nonlinear Reynolds stress model with Quadratic Constitutive Relation (QCR) for high-lift aerodynamics
    - SA-noft2-R with QCR and SST-V with QCR

CFD Solver: UPACS

UPACS: JAXA's in-house standard CFD code for multi-block structured grids

Computational methods used in HiLiftPW-2

	UPACS
Mesh type	Multi-block structured
Equation	Full NS
Discretization	Cell-centered finite volume
Convection Flux	Roe 3rd-order w/o flux limiter
Time integration	Matrix-Free Gauss-Seidel
Multi-grid	Mostly computed w/o multi-grid
Turbulence model (tested in HiLiftPW-2)	SA-noft2-R (Cvor=1) SA-noft2-R (Cvor=1) w/ QCR SST-V SST-V w/ QCR

- Restart from result at lower α to obtain results at higher α

Effect of nonlinear Reynolds stress model QCR at DPW

Yamamoto et.al AIAA 2012-2895
Murayama,et al AIAA 2013-0049

- JAXA's experiences of predicted size of SOB flow separation for DPW-series when SA model is used with original eddy-viscosity Reynolds stress
  - **Good agreement with WTT** when thin-layer NS and Full NS are solved **on moderate and appropriate corner grid**
  - **Excessively over-predicted** when **Full NS** are solved on **very fine corner grid**

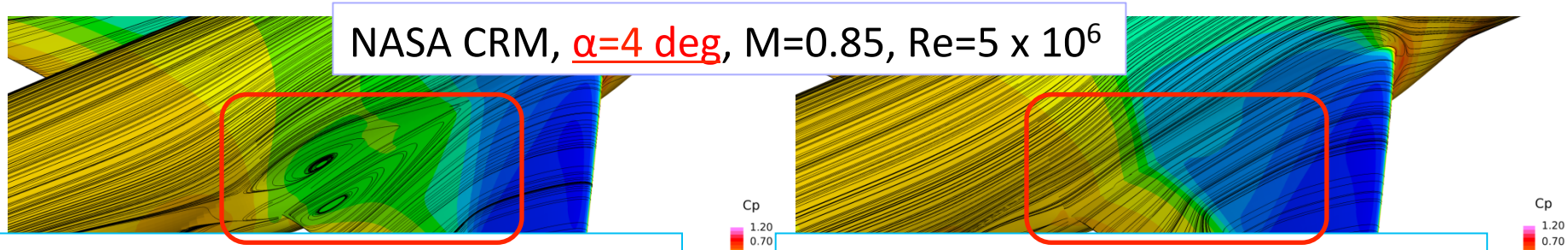
→ Quadratic Constitutive Relation (QCR) P.R. Spalart / Int. J. Heat and Fluid Flow (2000)

$$\tau_{ij} = \bar{\tau}_{ij} - c_{nl1}\left[O_{ik}\bar{\tau}_{jk} + O_{jk}\bar{\tau}_{ik}\right] \quad O_{ik} \equiv \frac{\partial_k U_i - \partial_i U_k}{\sqrt{\partial_n U_m \partial_n U_m}} \text{ (normalised rotation tensor)}, \quad c_{nl1} = 0.3$$

- Capability of capturing the secondary flow
- Applicable to any eddy-viscosity turbulence models (SA, SST, etc.)

  - Results
    - Suppressing spurious SOB flow separation
    - Slight shift of shock to forward

NASA CRM, α=4 deg, M=0.85, Re=5 x 10^6



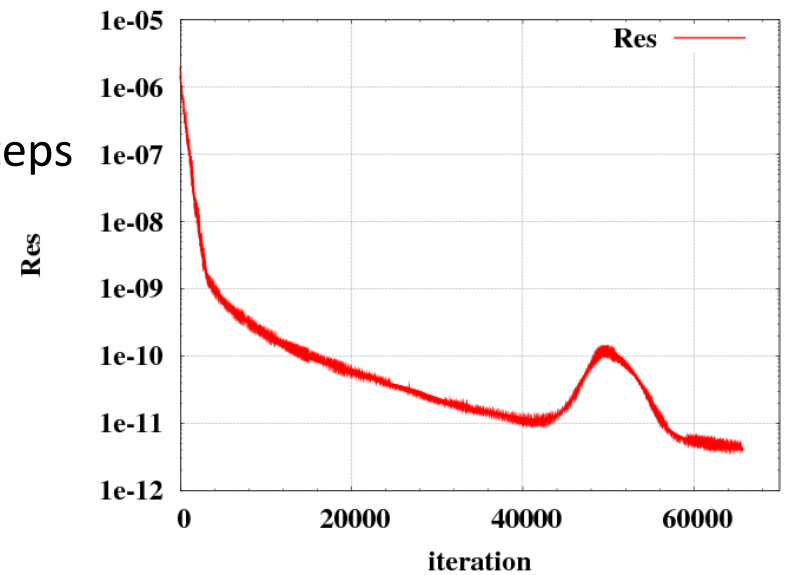
Spalart-Allmaras model
with **original eddy-viscosity Reynolds stress**

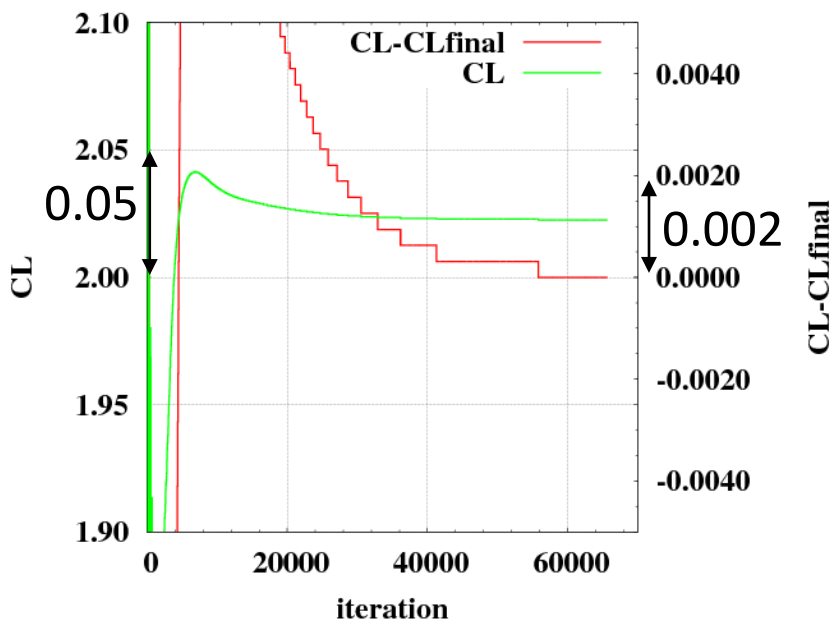
Spalart-Allmaras model
with **a nonlinear Reynolds stress model, QCR**

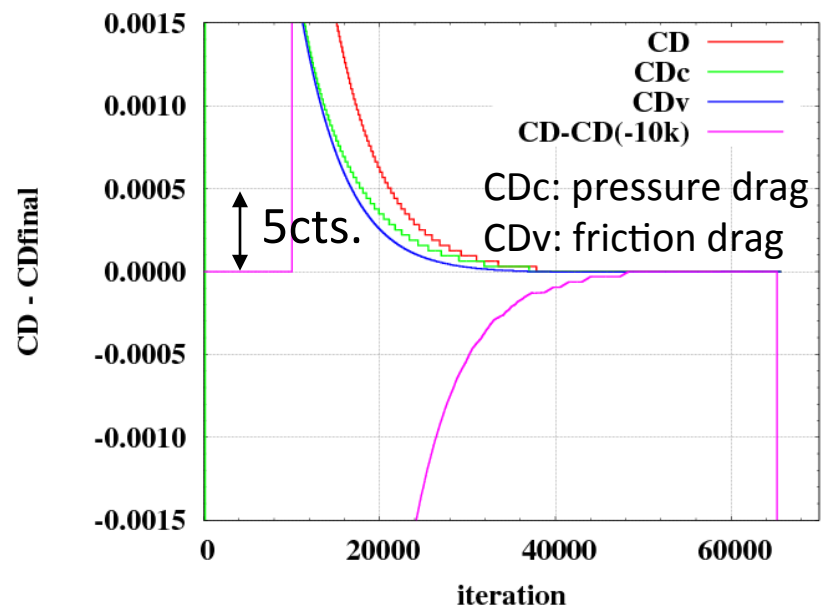
- Case1
  Grid Convergence Study
  - Grid
    - **Committee-provided multi-block structured grid: Grid-A**
  - Flow Conditions
    - M=0.175
    - AoA=7, 16
    - Re=15.1M
    - T=114.0K
    - Ps=295000Pa
    - Fully turbulent
  - **Turbulence models**
    - **SA-noft2-R, SA-noft2-R w/ QCR**
    - **SST-V, SST-V w/ QCR**

Typical solution convergence history(SA,AoA=7,Medium)

- Well converged forces
  - Less than 1 drag count during 10,000steps
- Run Time Wall-Clock
  - 43.08H/45,000steps
    - 92 cores of a PC-cluster
      - Intel Xeon E5-2665 2.4GHz

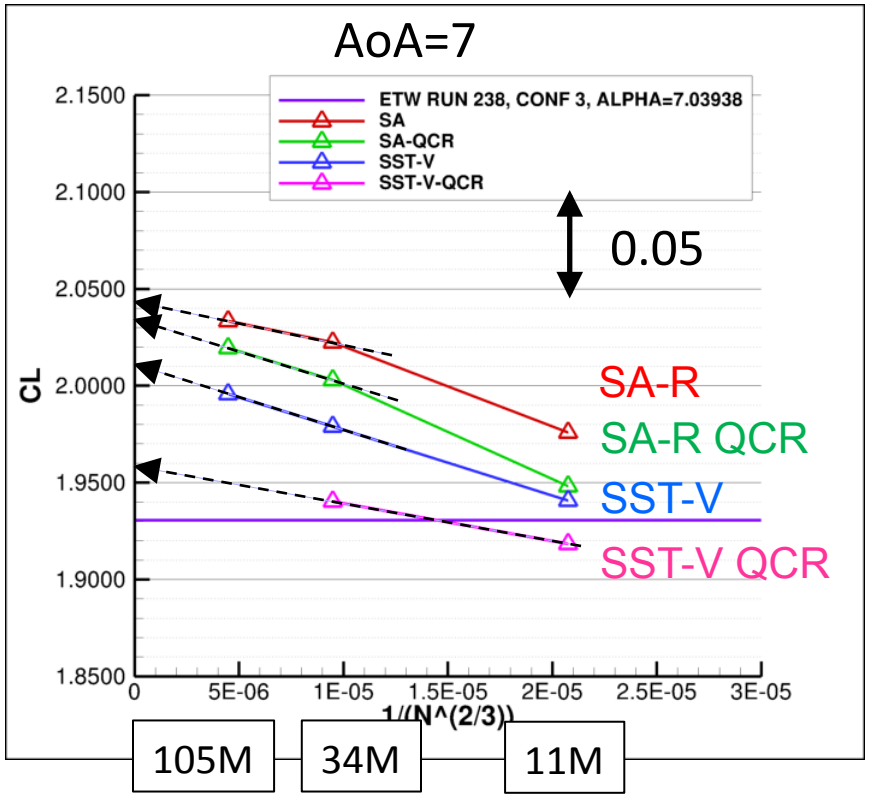


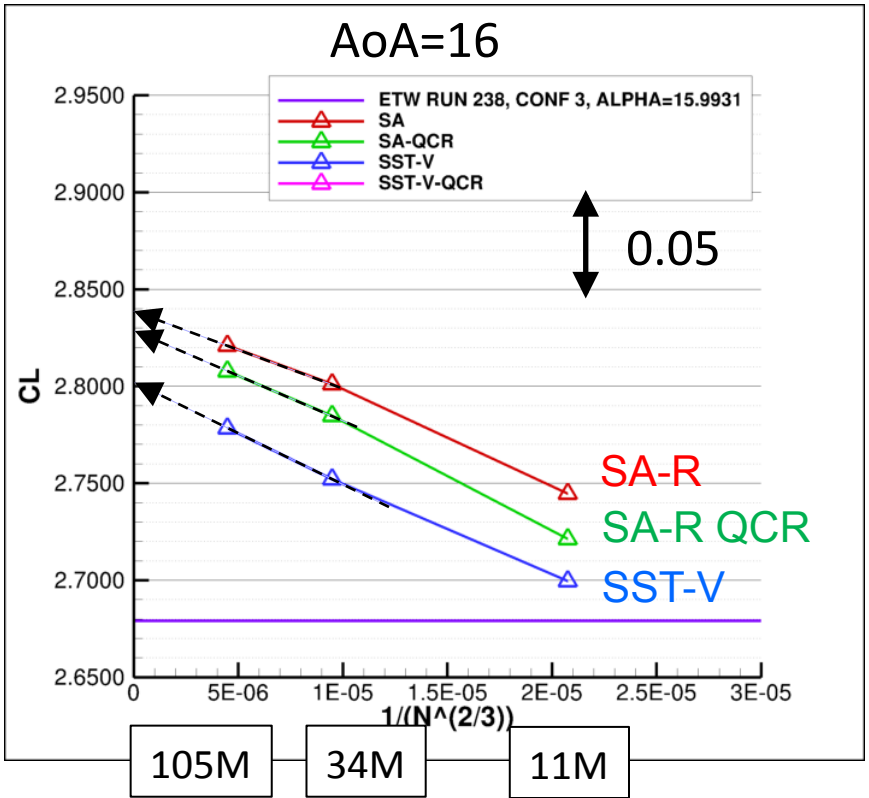




Grid convergence of C_L

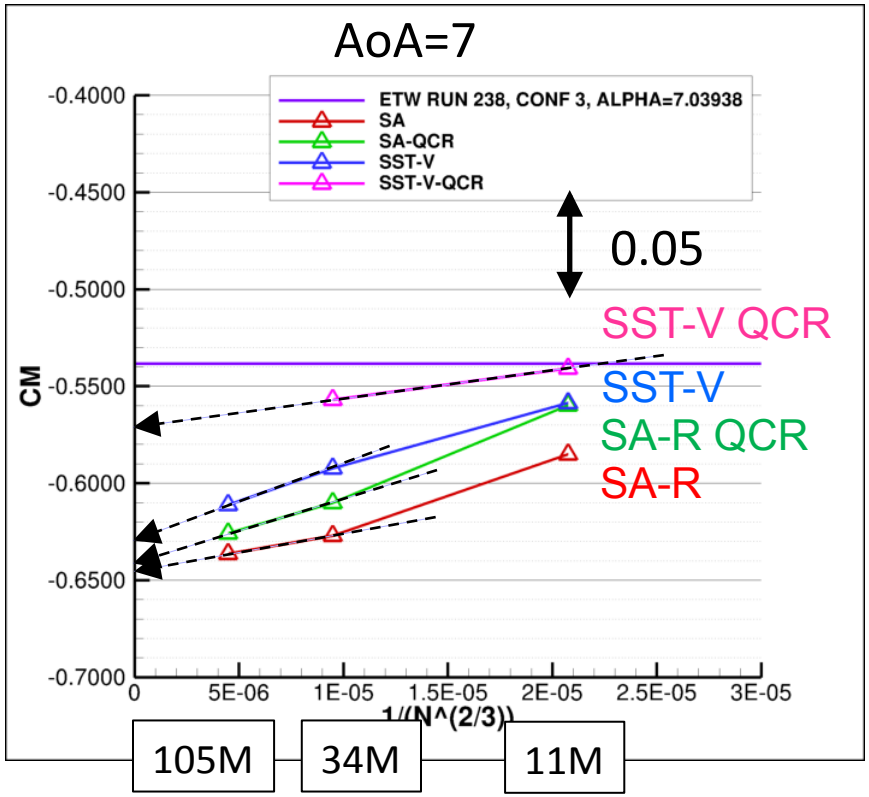
- C_L increases with # of grid points
  - Over-estimation than WTT results
- Different grid converged C_L (expected) by turbulence models
  - SA predicts higher C_L than SST
- QCR reduces C_L

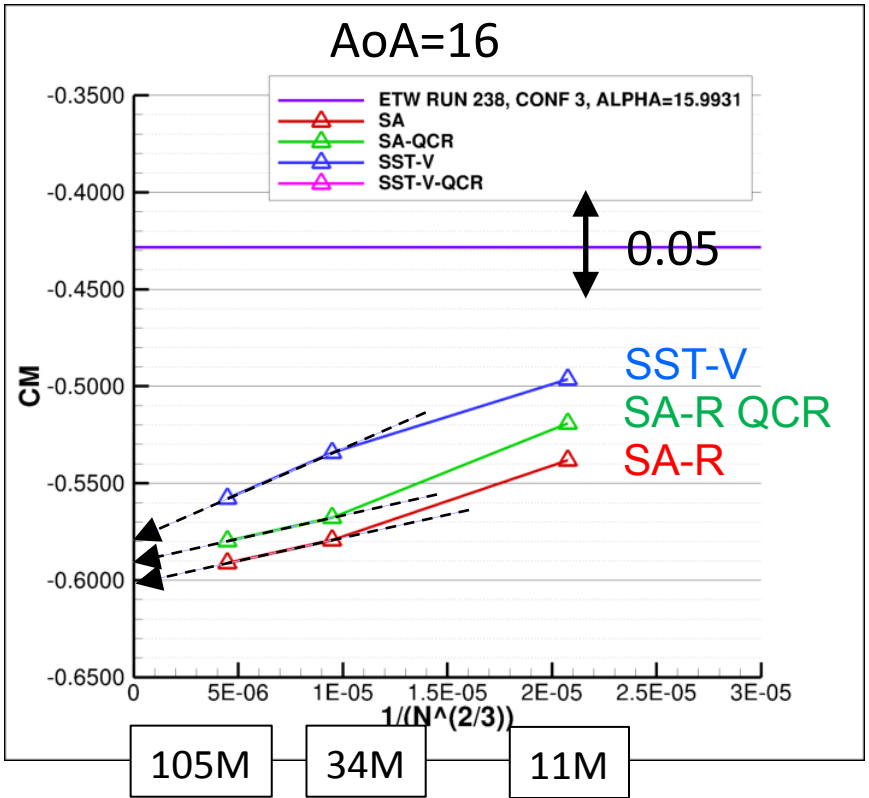




Grid convergence of C_M

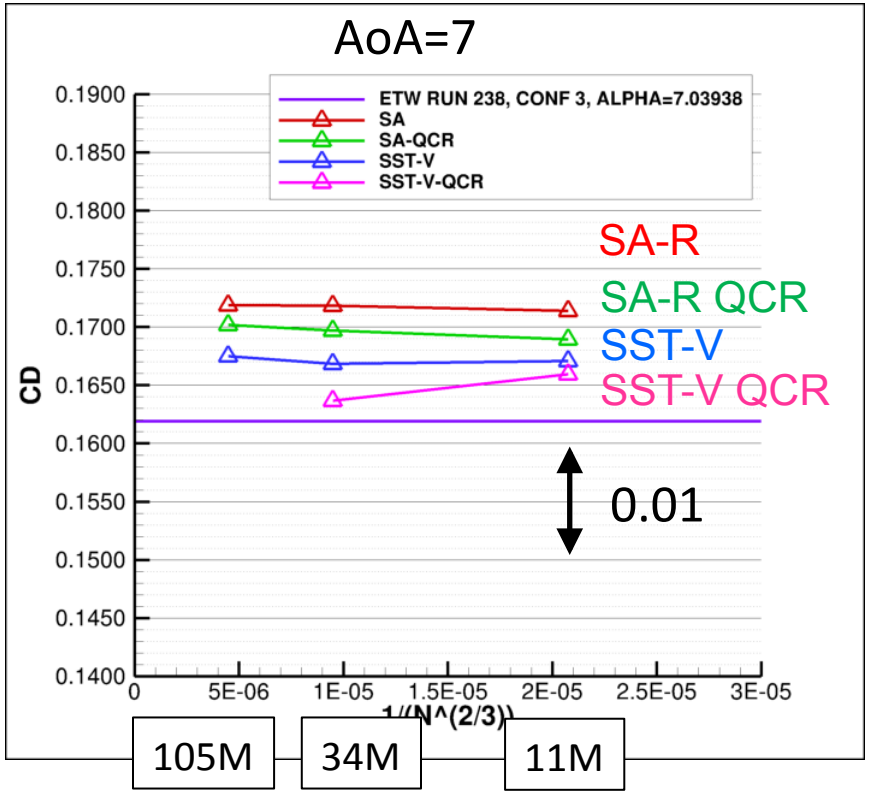
- C_M decreases with # of grid points
  - Over-estimation of Pitch-down than WTT results
- SA predicts lower C_M than SST
- QCR increases C_M

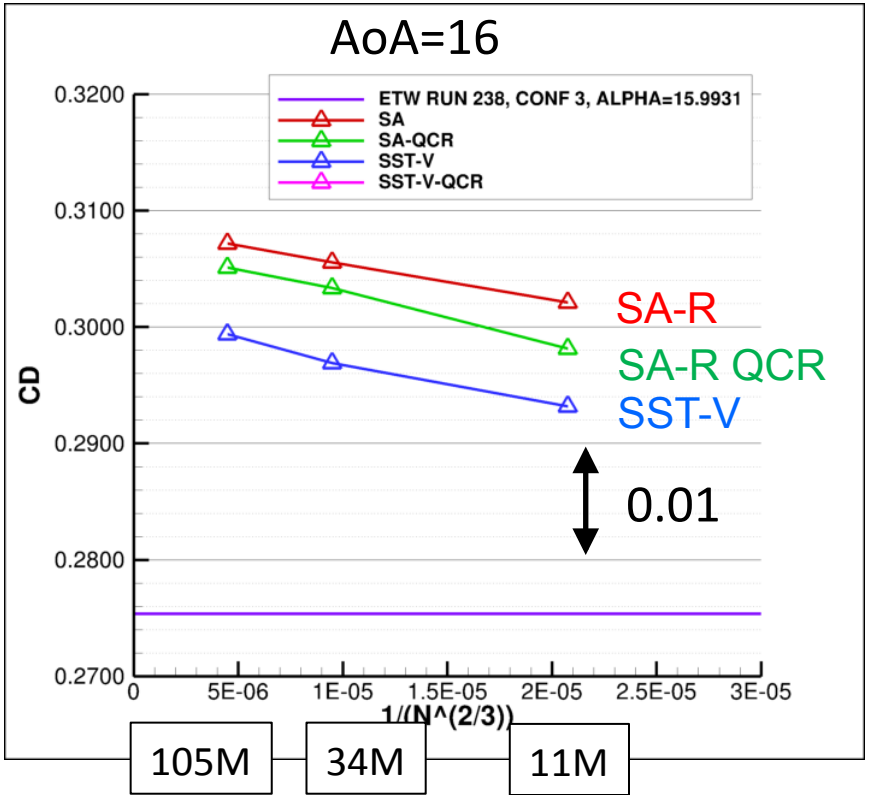




Grid convergence of C_D

- SA predicts higher C_D than SST
- QCR decreases C_D
- C_D is over-predicted
  - C_D includes influence of induced drag by the difference of lift prediction

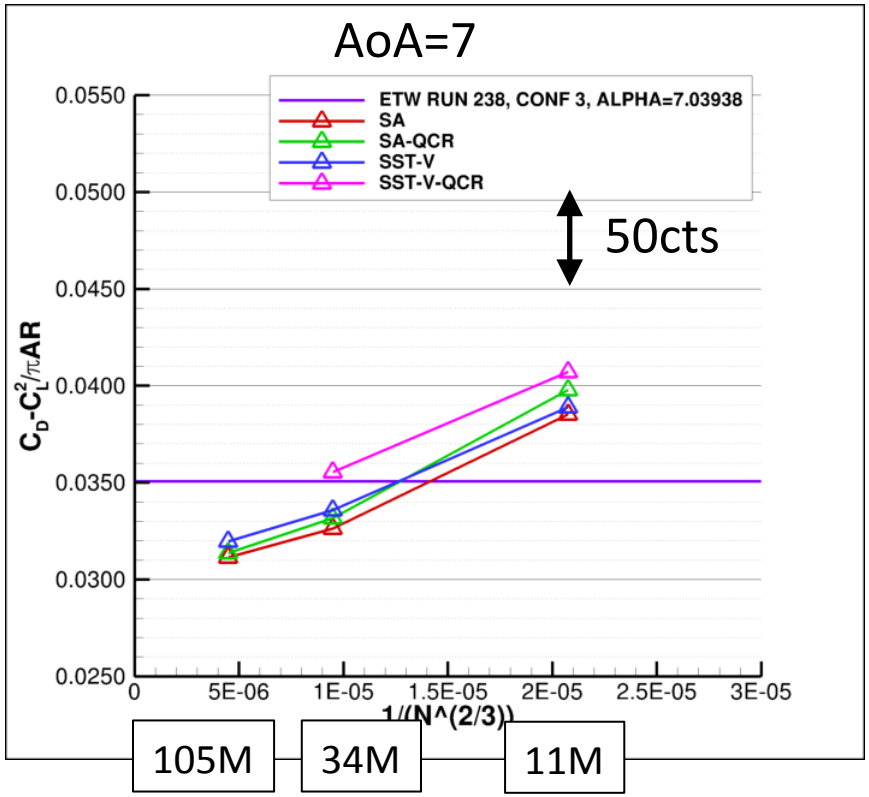


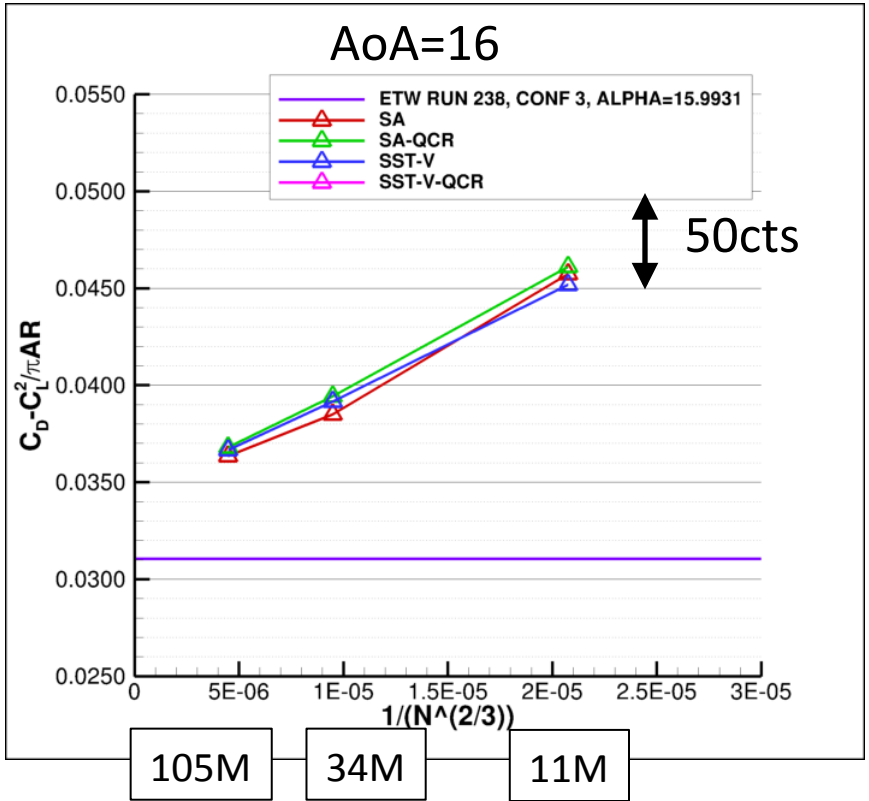


Grid convergence of C_D-$C_{Dinduced}$

- C_D-$C_{Dinduced}$ is compared
  - Ideal $C_{Dinduced}$ =(C_L*C_L)/(PI*AR)

Total C_D
AoA= 7:1620cts.-1720cts.
AoA=16:2920cts.-3080cts.

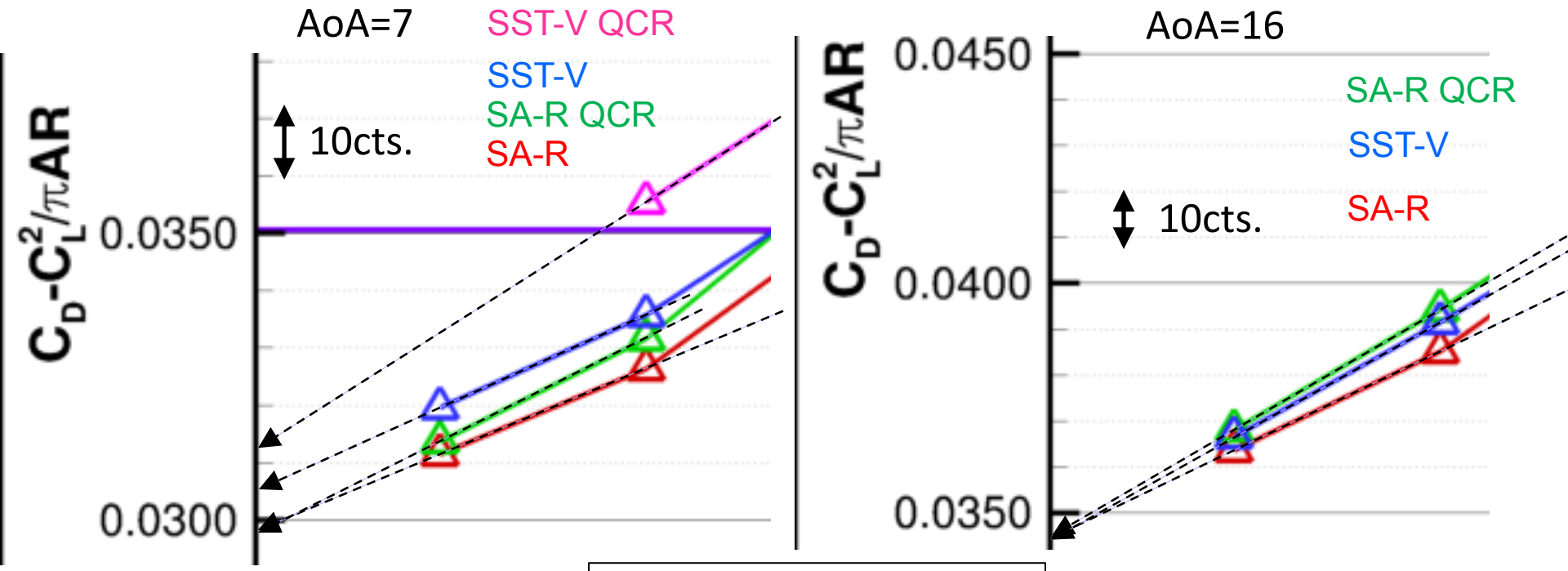




Grid convergence of C_D-$C_{Dinduced}$

- C_D-$C_{Dinduced}$ is compared
  - Ideal $C_{Dinduced}$ =(C_L*C_L)/(PI*AR)
- Differences of grid converged C_D-$C_{Dinduced}$
  - AoA=7: 10-15cts.
  - AoA=16: 2-3cts.

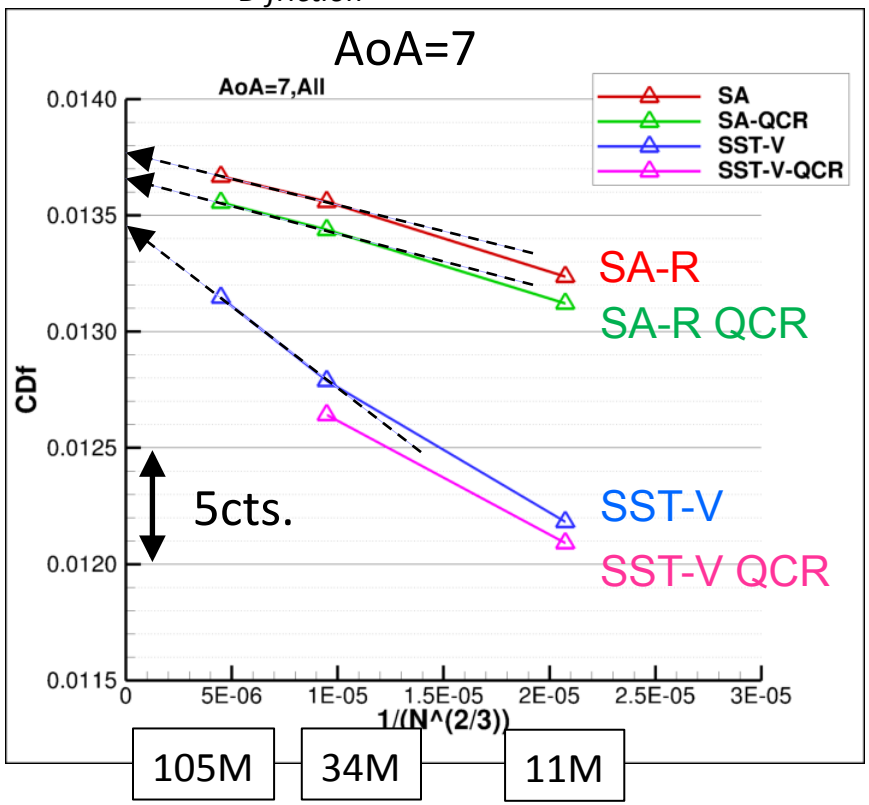
Total C_D
AoA= 7:1620cts.-1720cts.
AoA=16:2920cts.-3080cts.

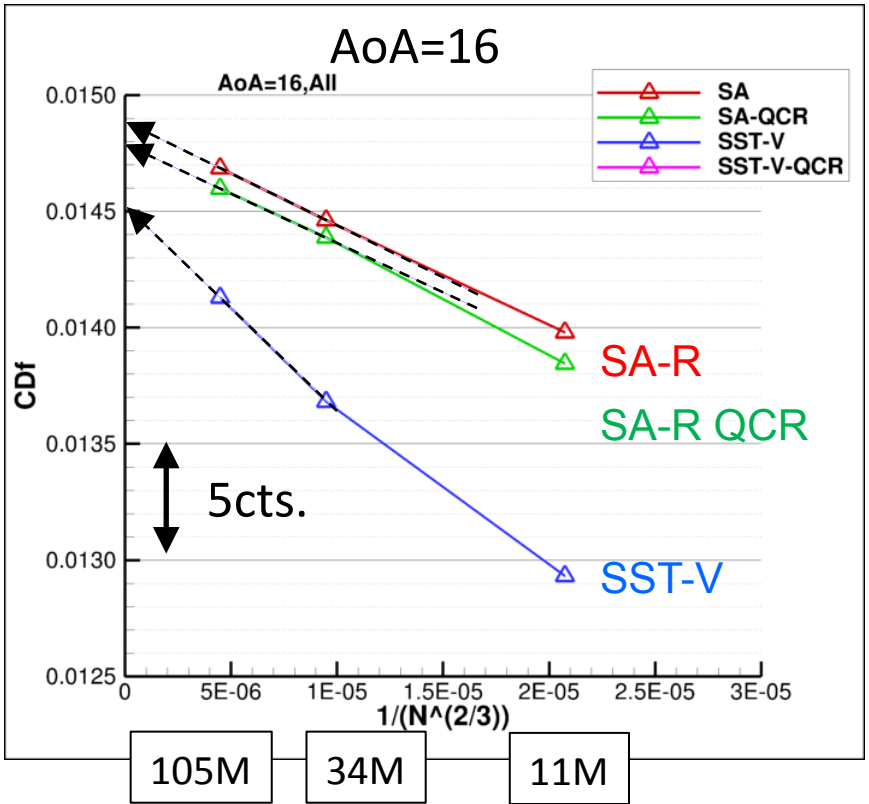


Close-up views

Grid convergence of $C_{Dfriction}$

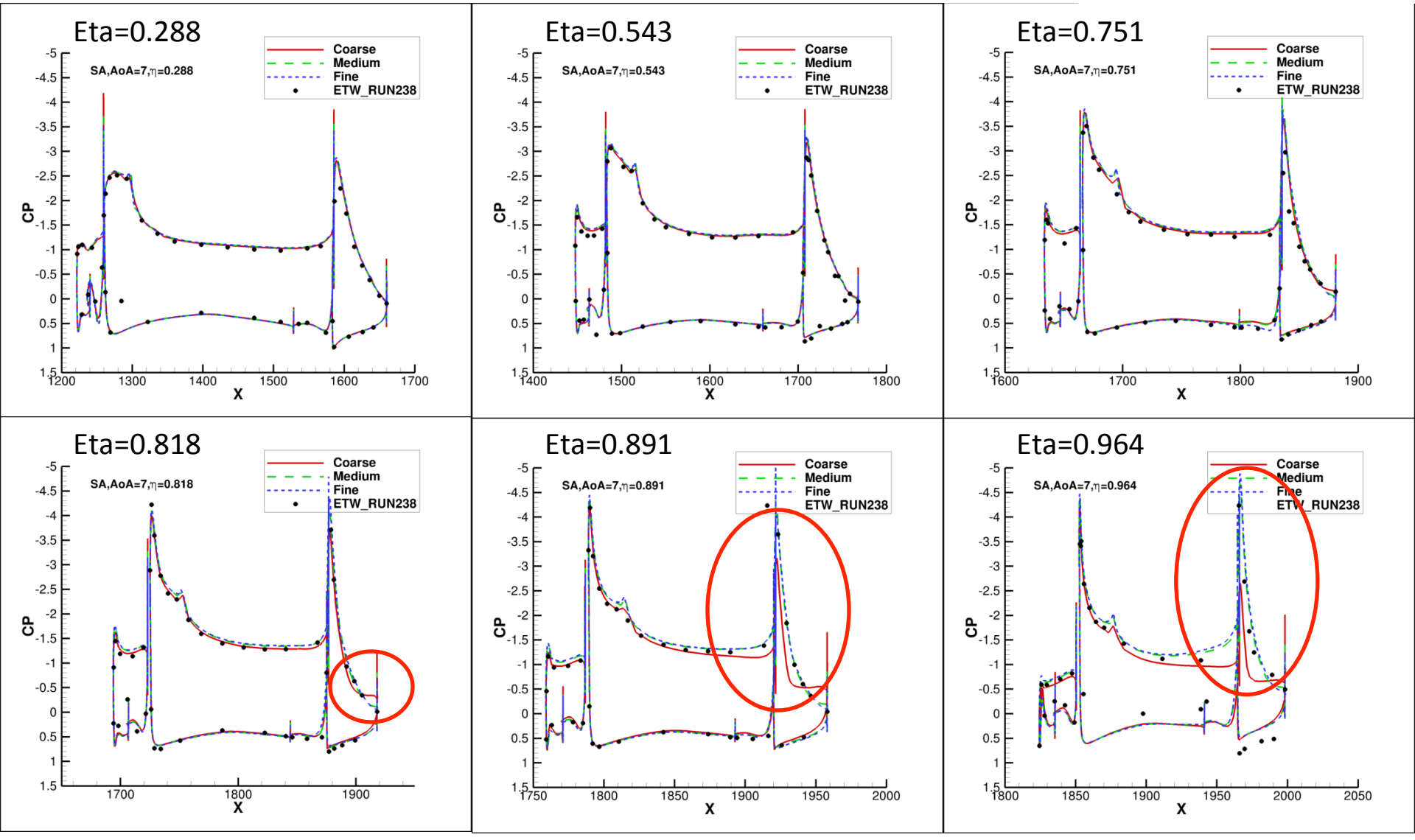
- Grid dependency of skin friction drag by SST is relatively larger.
  - SST needs more grid density in viscous sub-layer than SA
  - Variations by grid density are about 5-10cts. for SA and 15cts. for SST
- $C_{Dfriction}$ of SST is lower than that of SA
- Influence w/ and w/o QCR model is almost constant shift for both SA and SST model. Due to QCR,
  - $C_{D\ friction}$ decreases by 1-2 counts





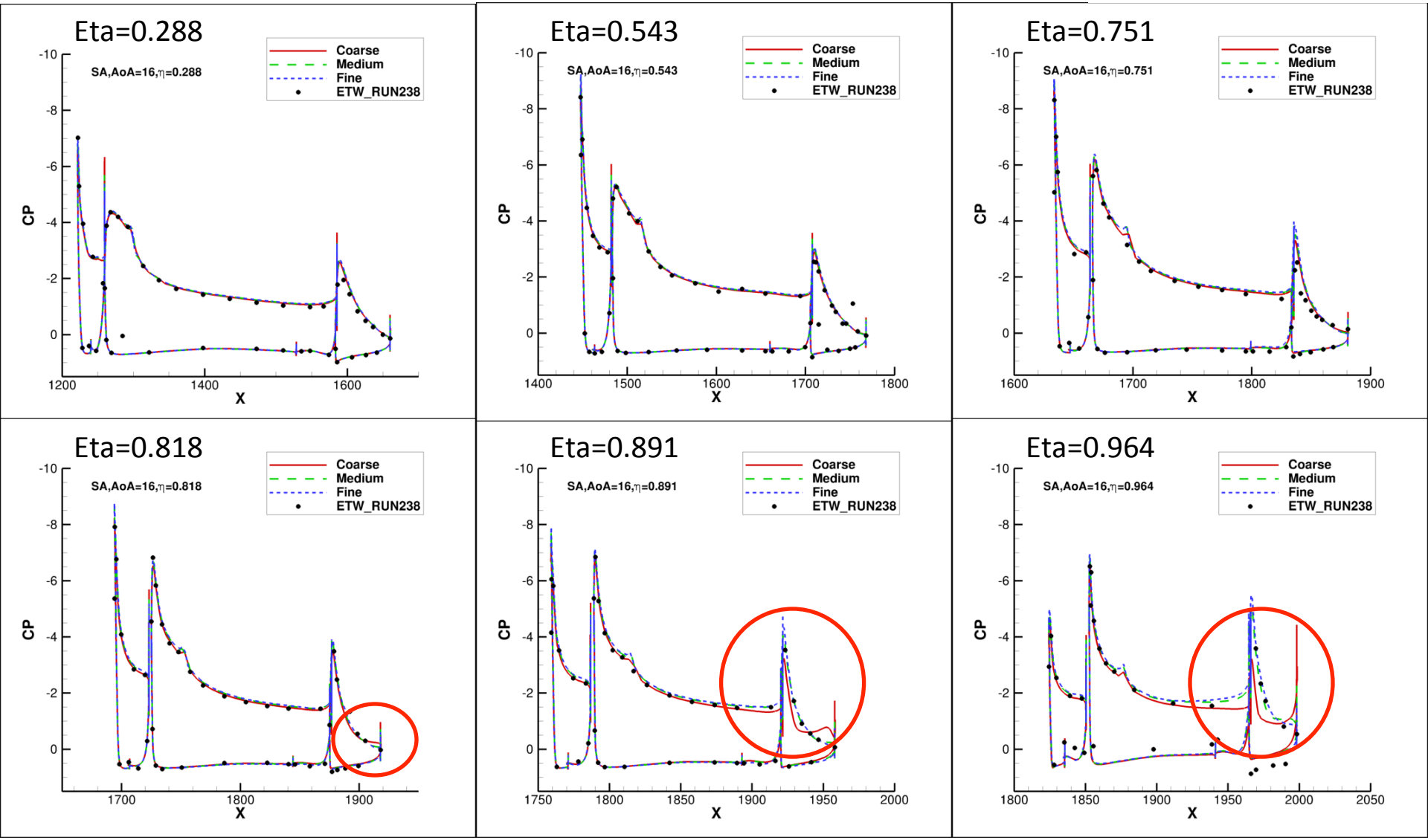
Grid dependency of Cp at AoA=7 (SA-noft2-R)

- Major differences are found on the coarse grid at outer section
  - Earlier flow separation on the flap



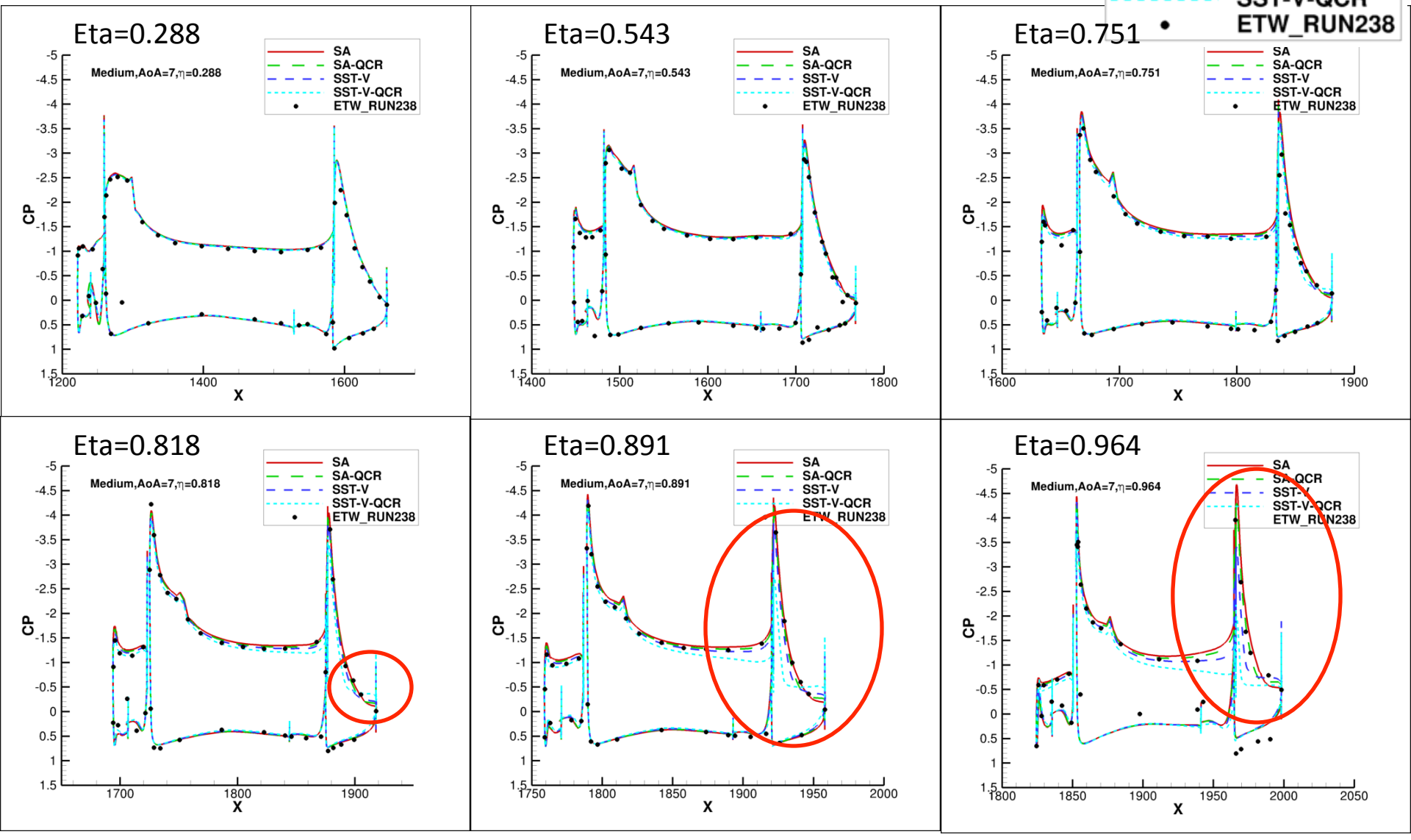
Grid dependency of Cp at AoA=16 (SA-noft2-R)

- Major differences are found on the coarse grid at outer section
  - Earlier flow separation on the flap



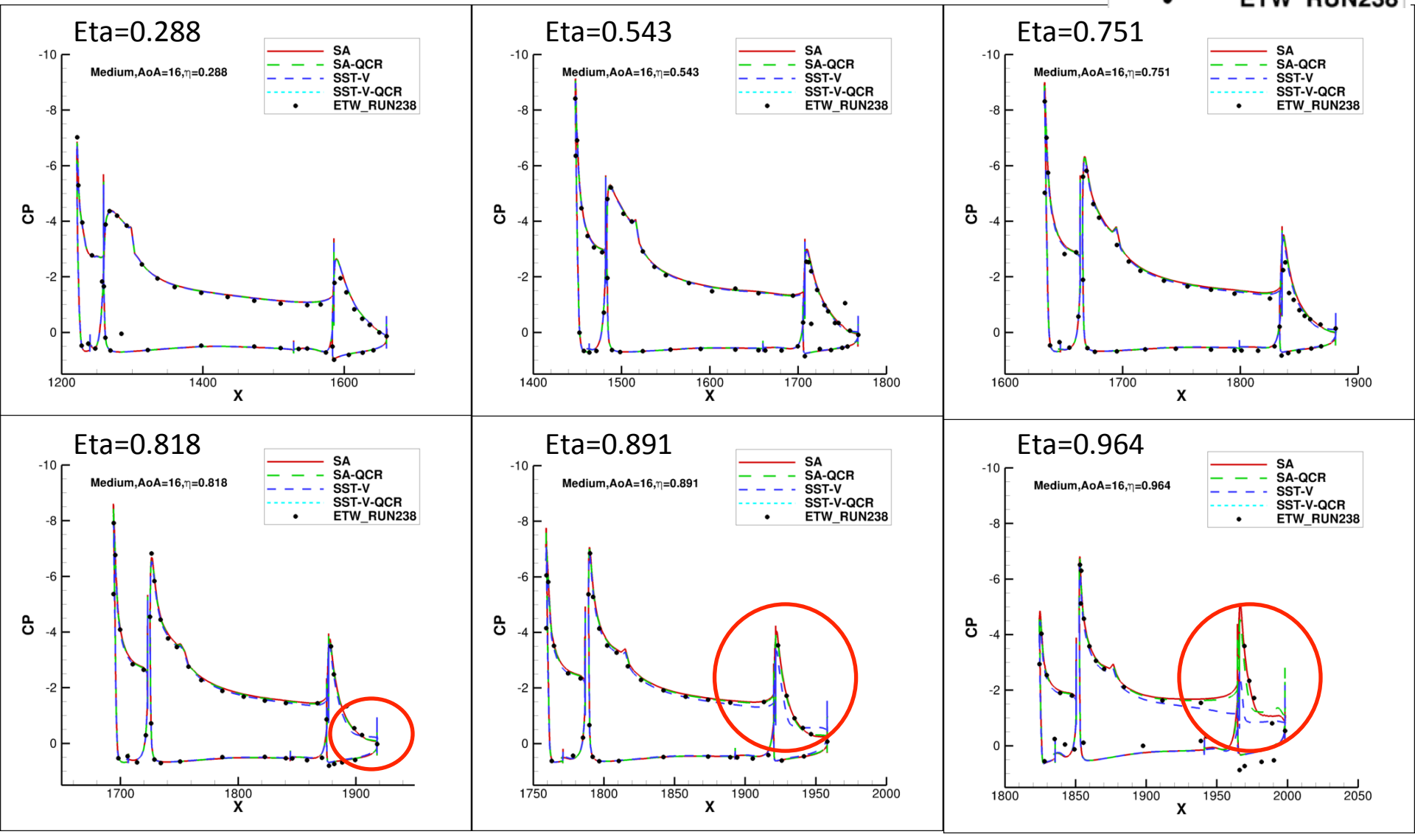
Cp differences by turb. models at AoA=7 (Medium)

- Major differences are found at outer section
  - Earlier flow separation on the flap by SST especially with QCR

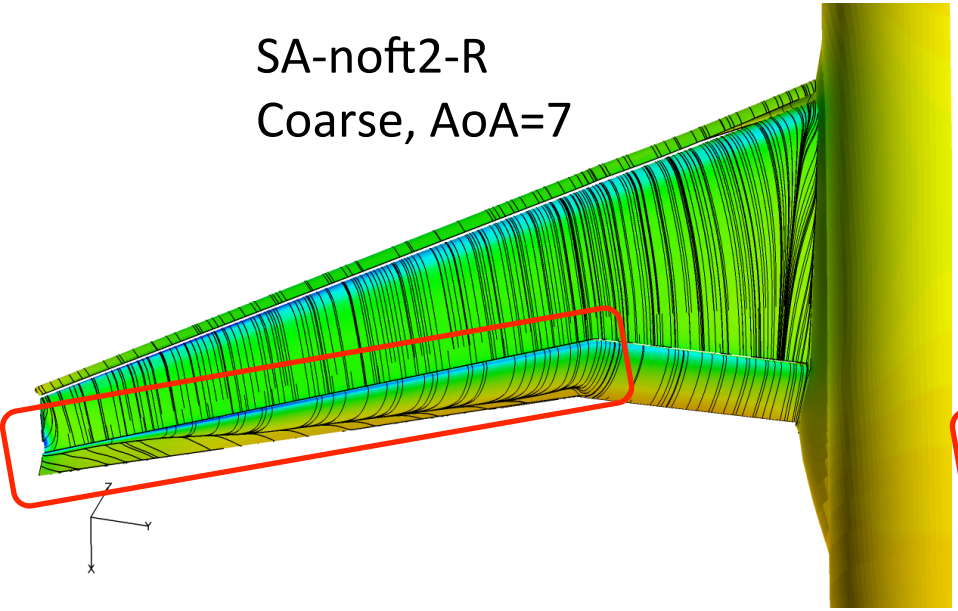


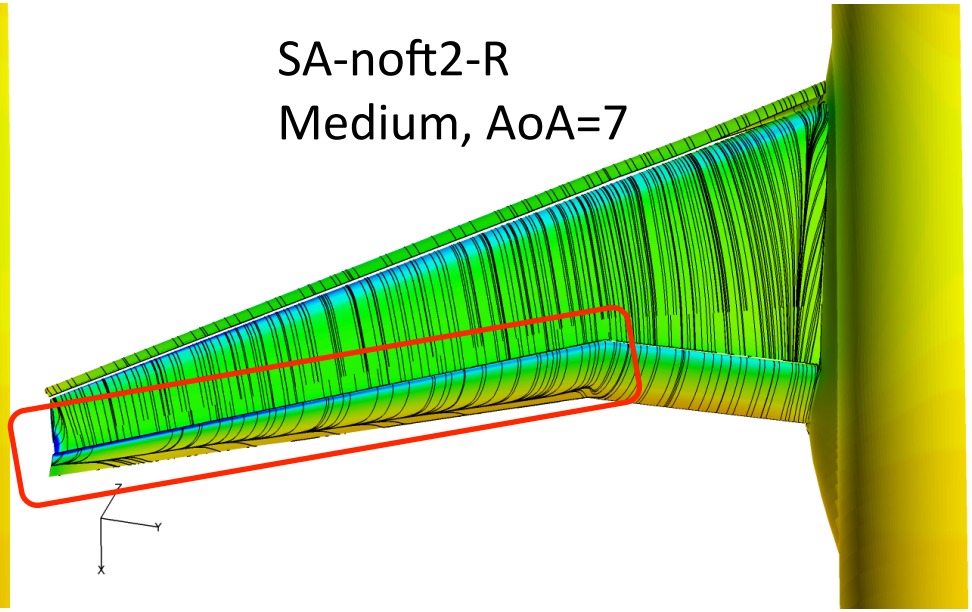
Cp differences by turb. models at AoA=16 (Medium)

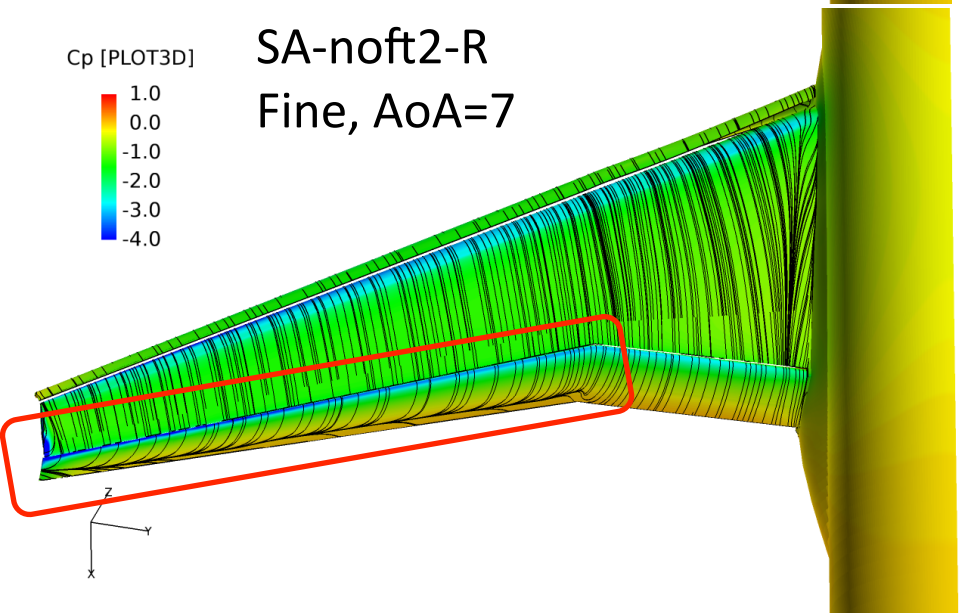
- Major differences are found at outer section
  - Earlier flow separation on the flap by SST



Comparison of surface oil flow



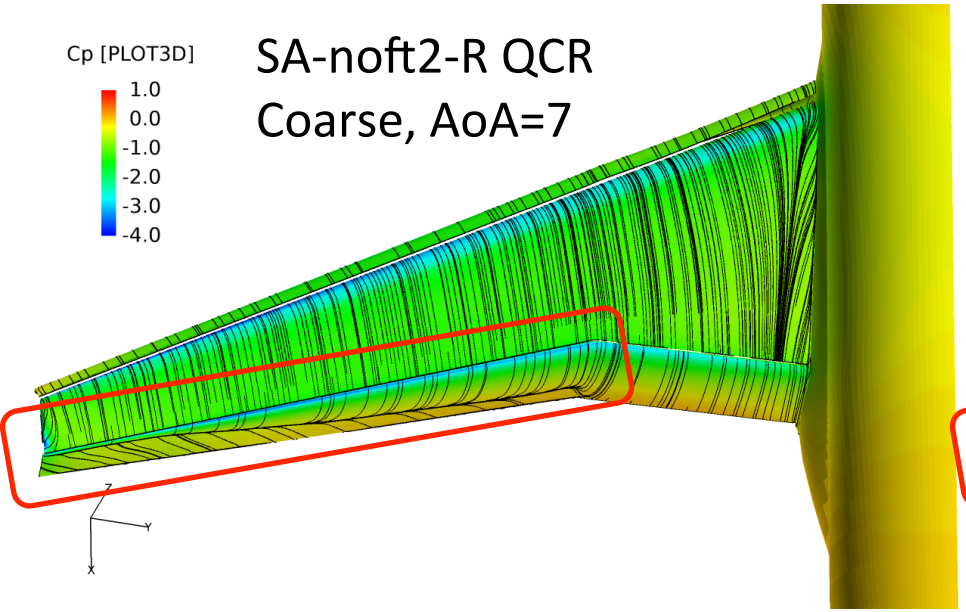


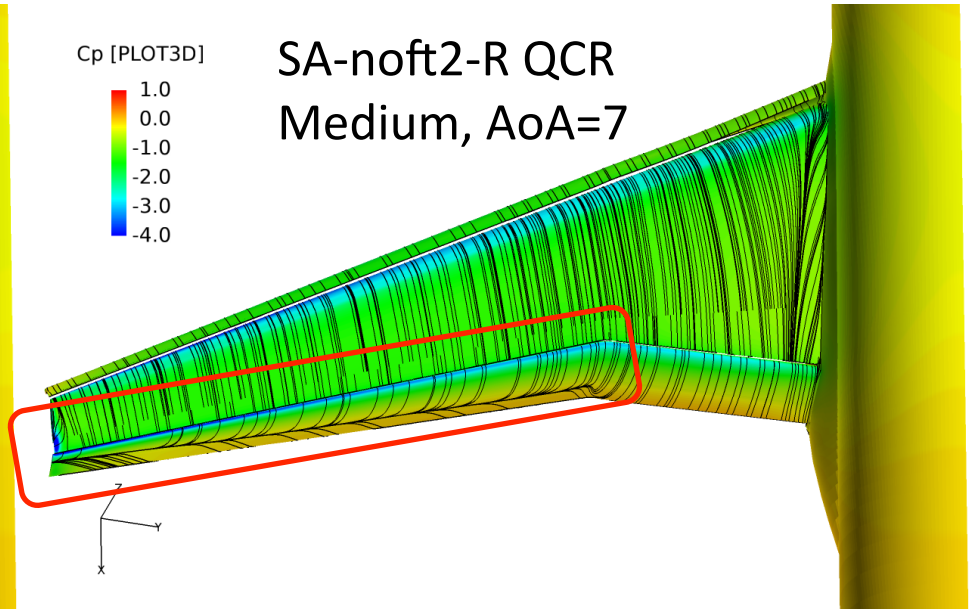


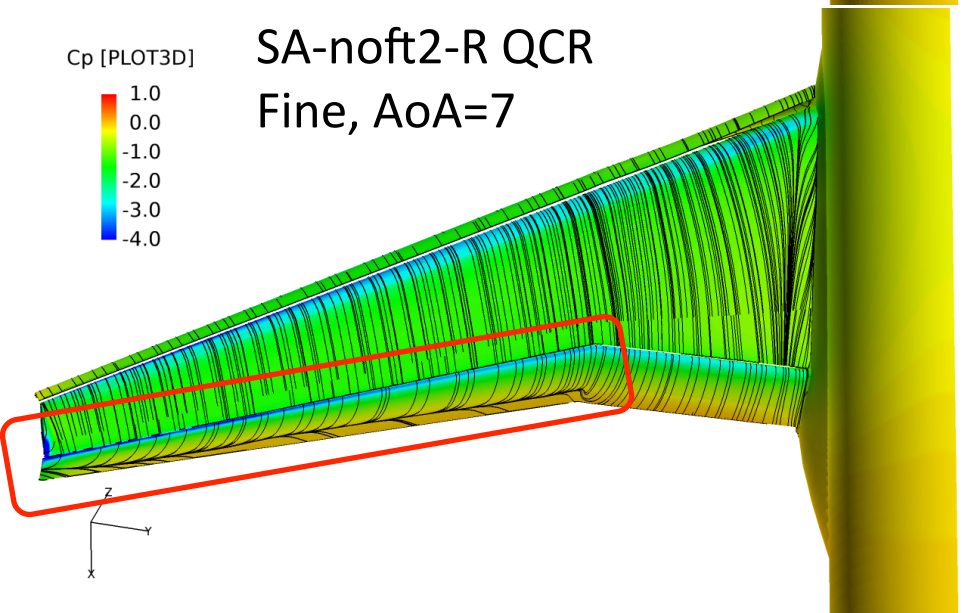
- Flow separation on the flap decreases with increasing grid points

  → C_L increase and Pitch-down C_M

Comparison of surface oil flow

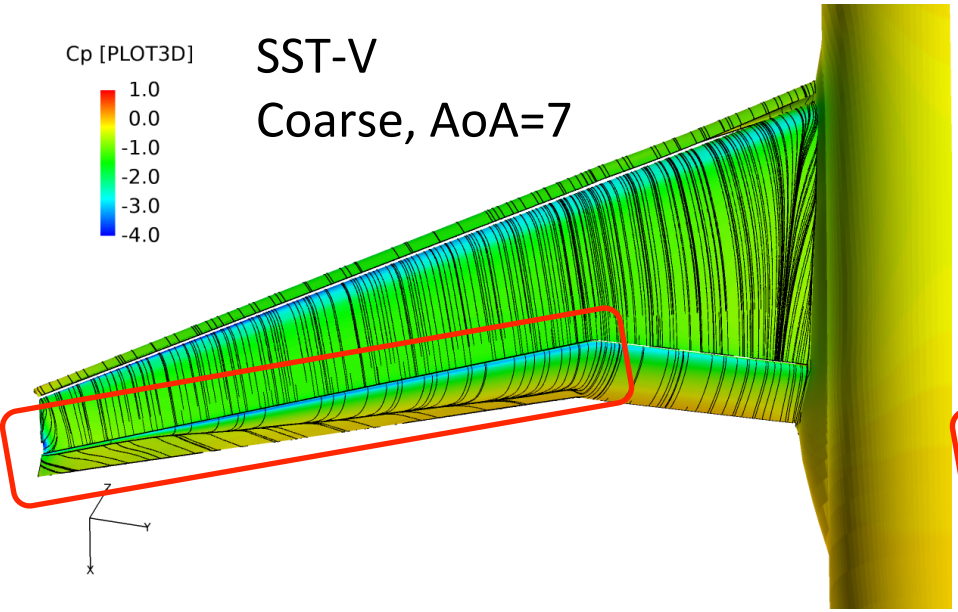


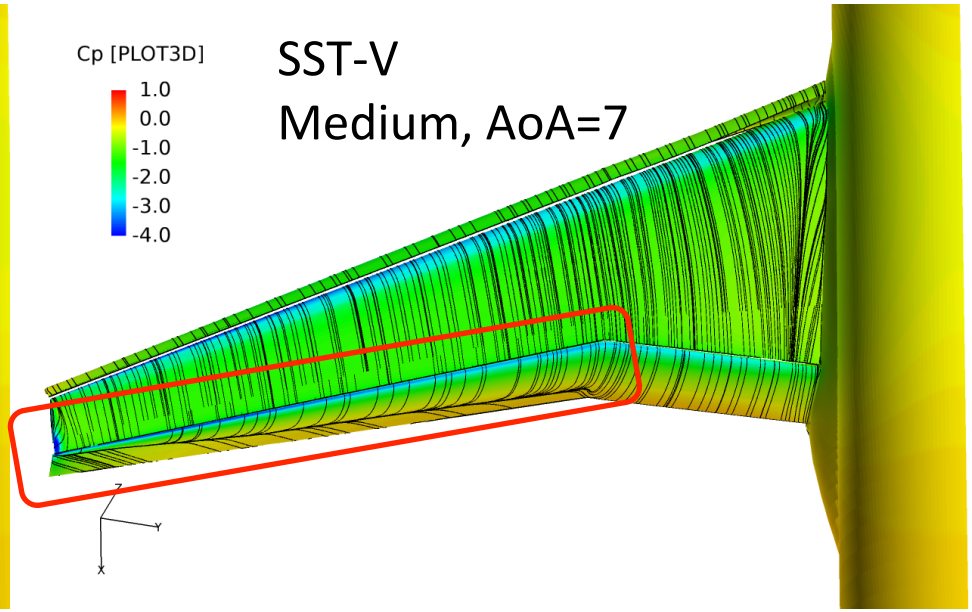


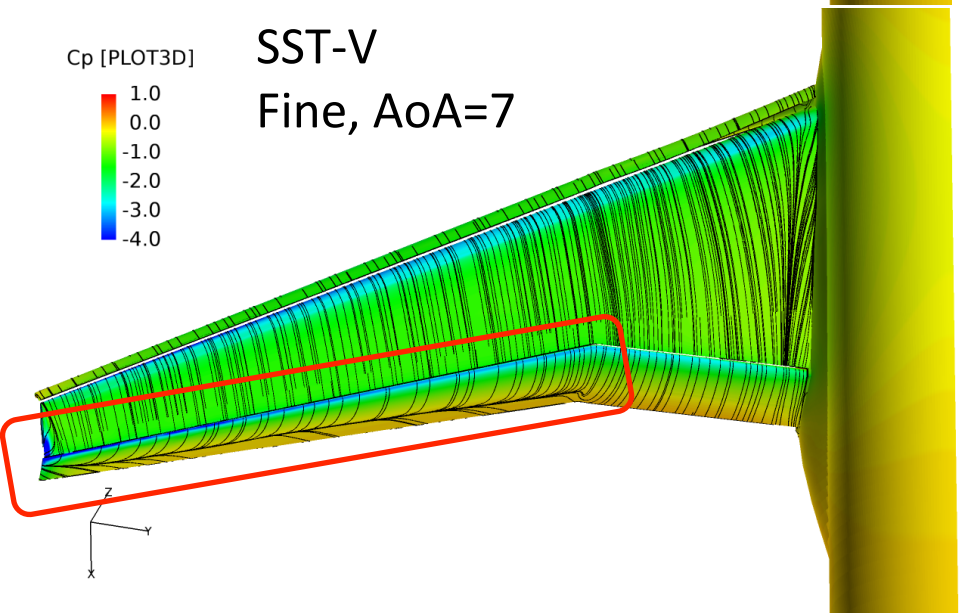


- Flow separation on the flap decreases with increasing grid points
  - Same trend bewteen w/ & w/o QCR
- Earlier flow separation with QCR

Comparison of surface oil flow

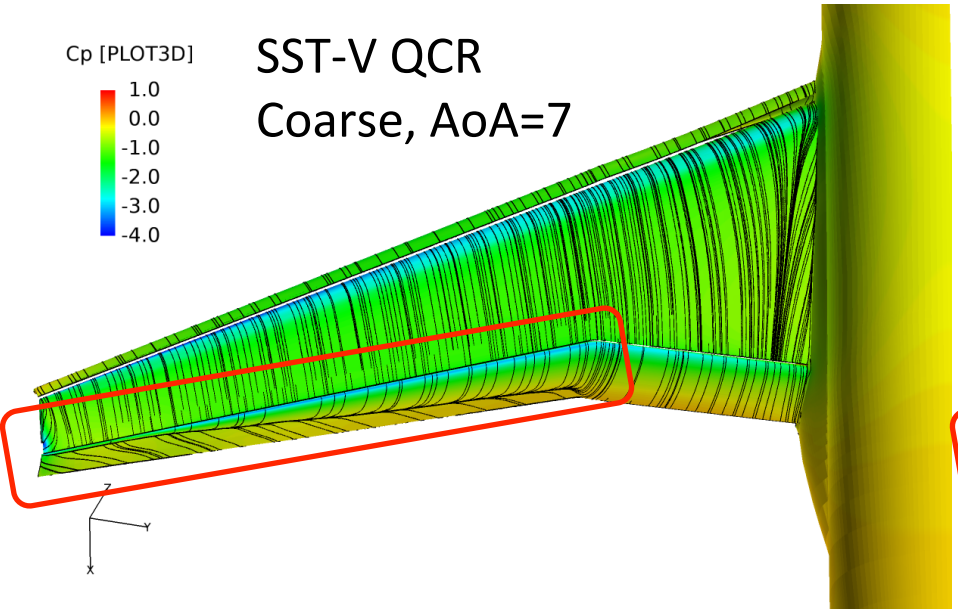


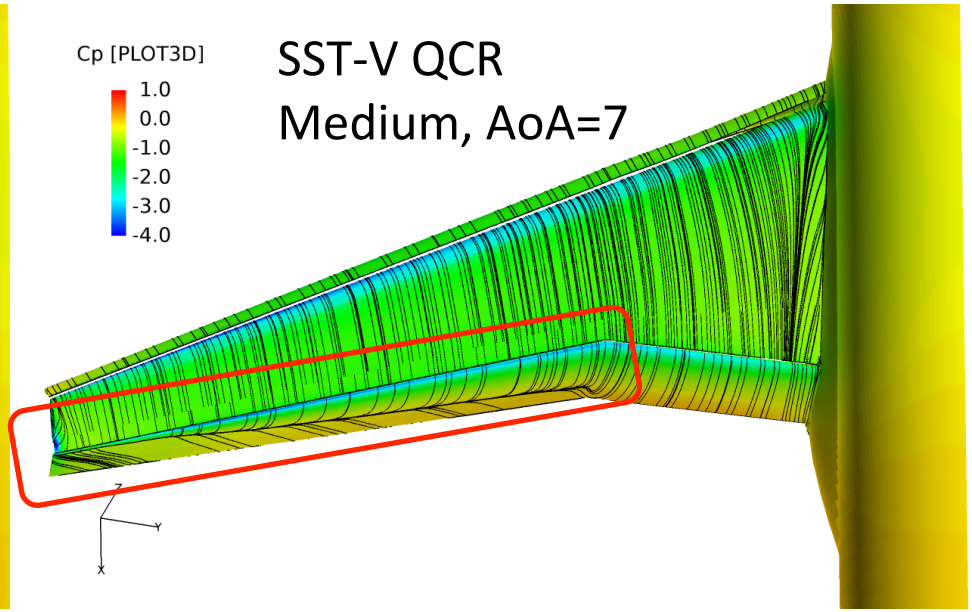




- Flow separation on the flap decreases with increasing grid points
  - Same trend bewteen SA & SST
- Earlier flow separation by SST

Comparison of surface oil flow



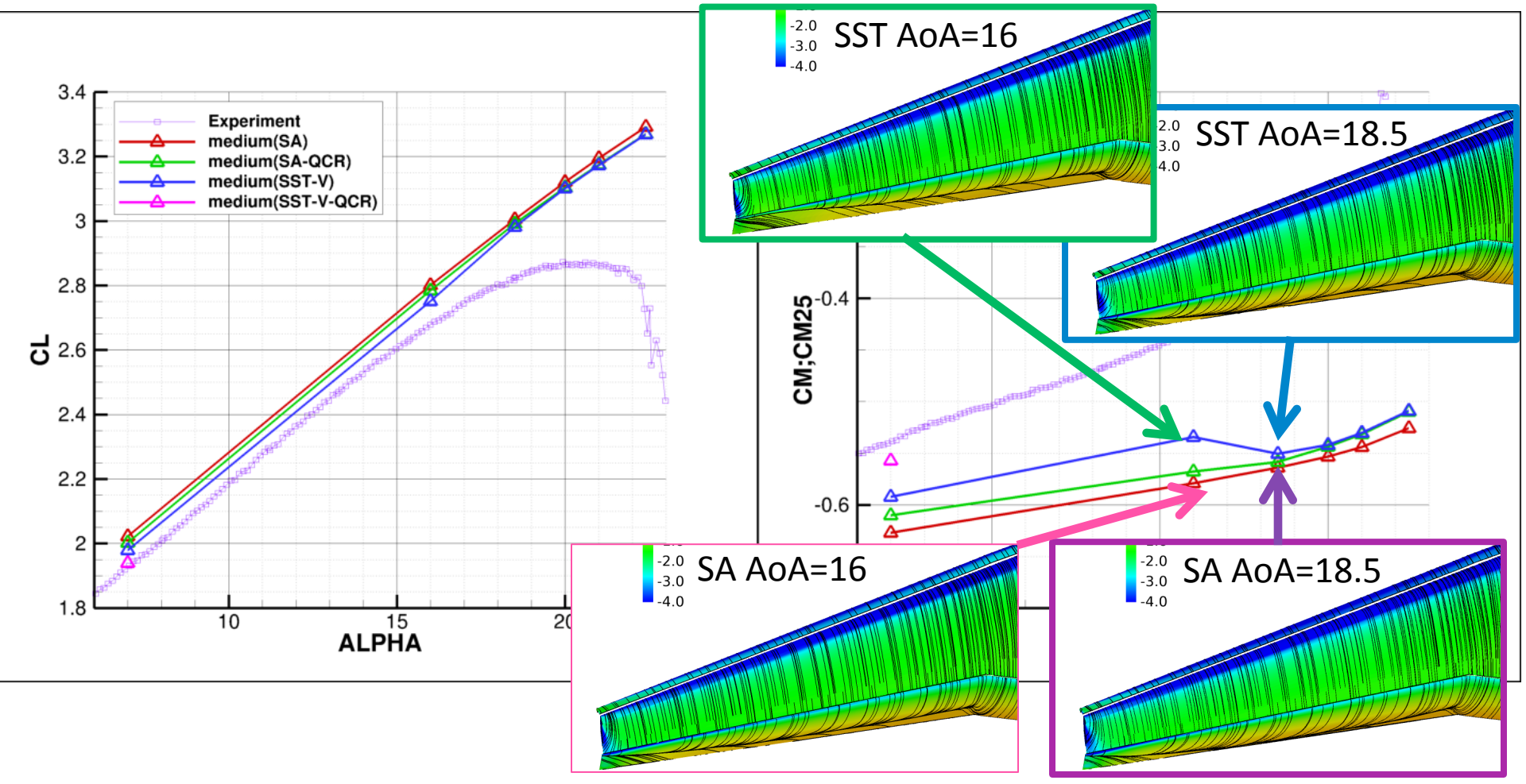


- Earlier flow separation on the flap with QCR

- Some additional notes

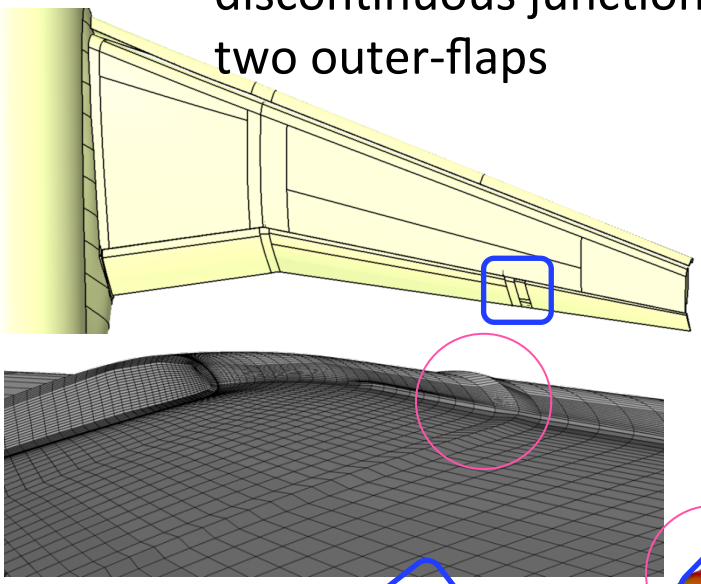
Comparison of α-sweep on medium grid by turb. model

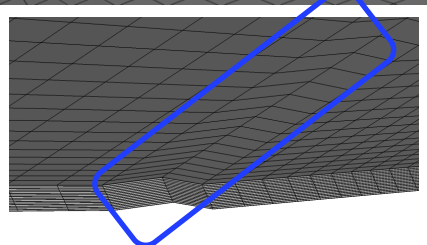
- Results using both turbulence models do not show stall behavior even at AoA=22.4
- Result using SST-V shows a kink of C_M
  - Due to large change of flow separation on the flap



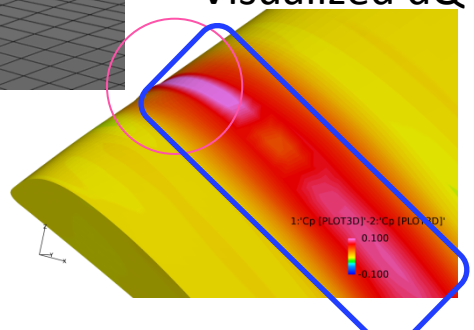
Solution convergence (Medium, SST-V, AoA=7, w/o MG)

- Medium, SST-V, AoA=7
  - CFL and local/global time stepping were adjusted to get well converged solution
  - The oscillation was found around discontinuous junction between two outer-flaps

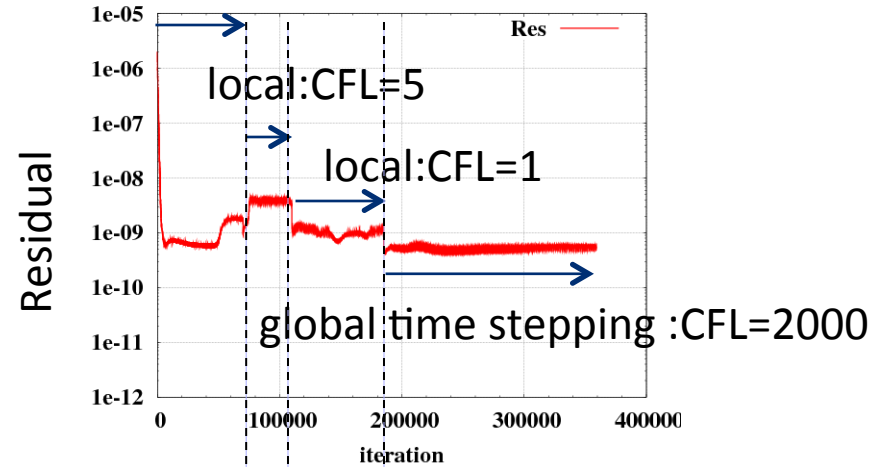


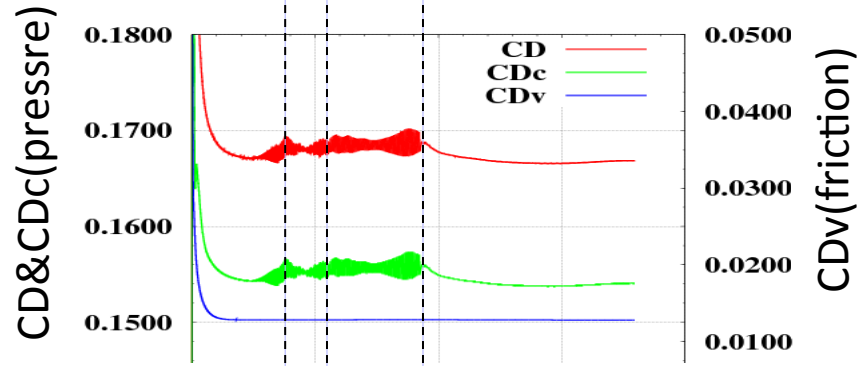


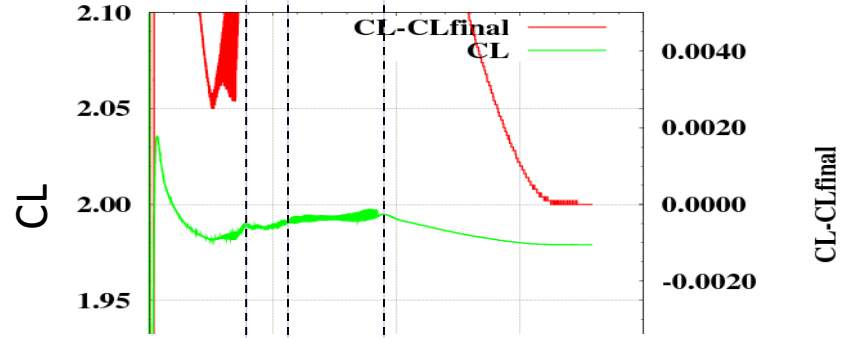
Visualized dQ



local time stepping: CFL=50

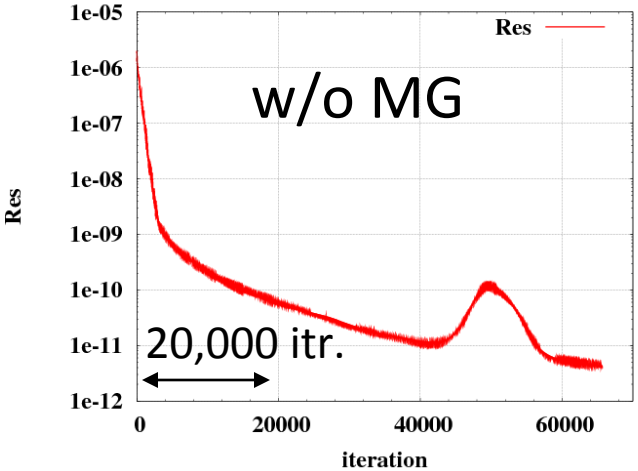


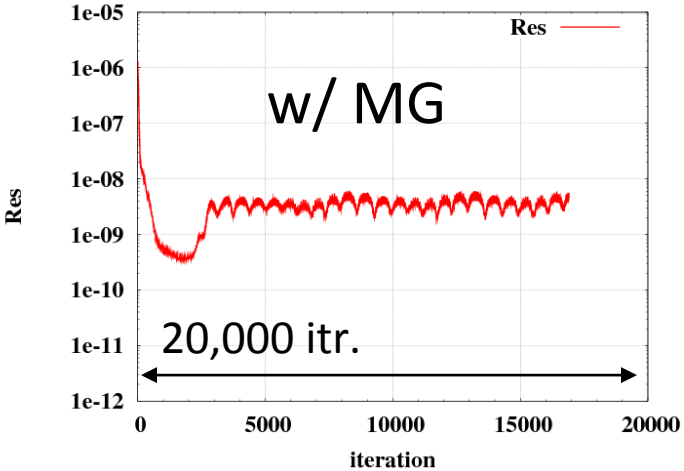


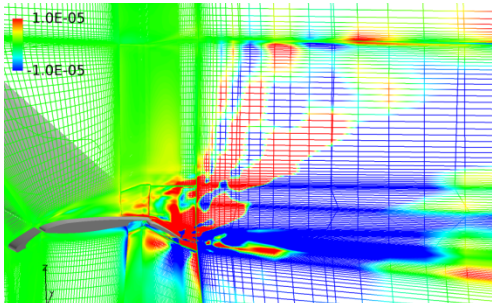


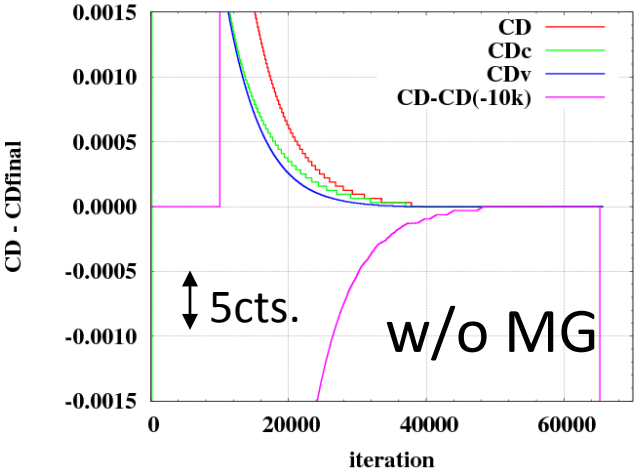
Solution convergence (Medium, SA-R, AoA=7, w/o&w/ MG)

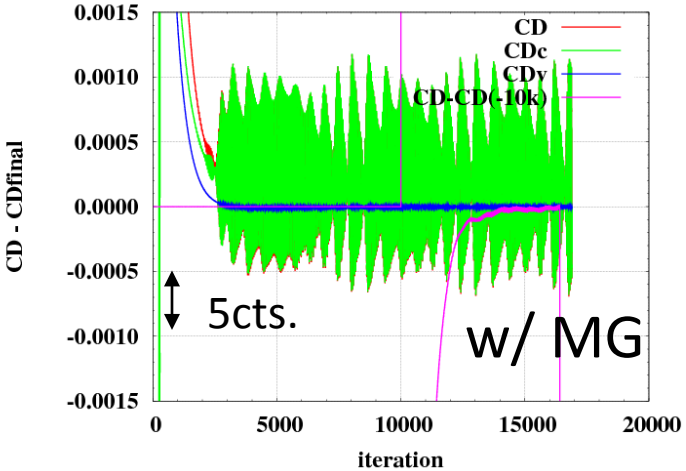
- Multi-grid(MG) (3-level V/W cycles) accelerates solution convergence but remains a slight convergence oscillation

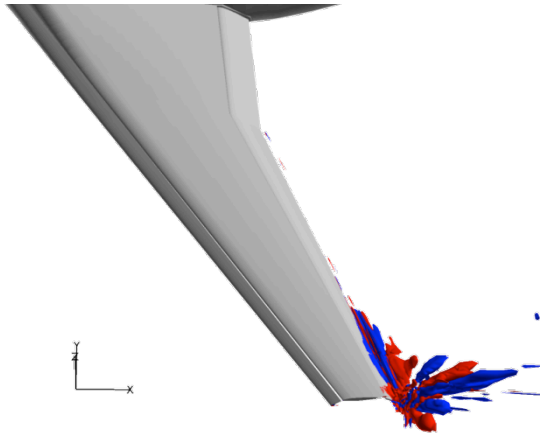










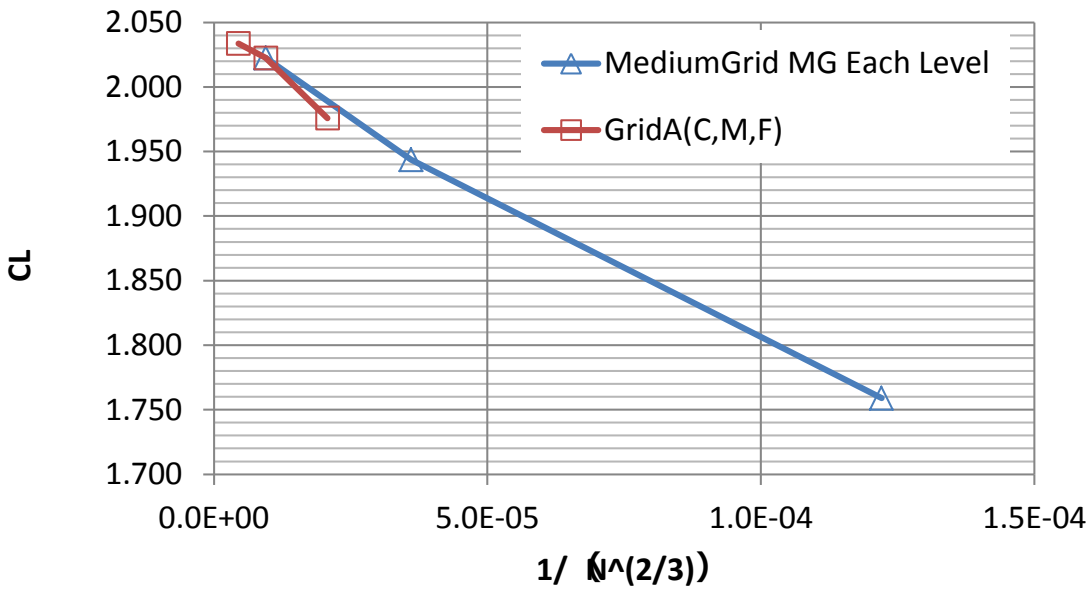


Visualized dQ

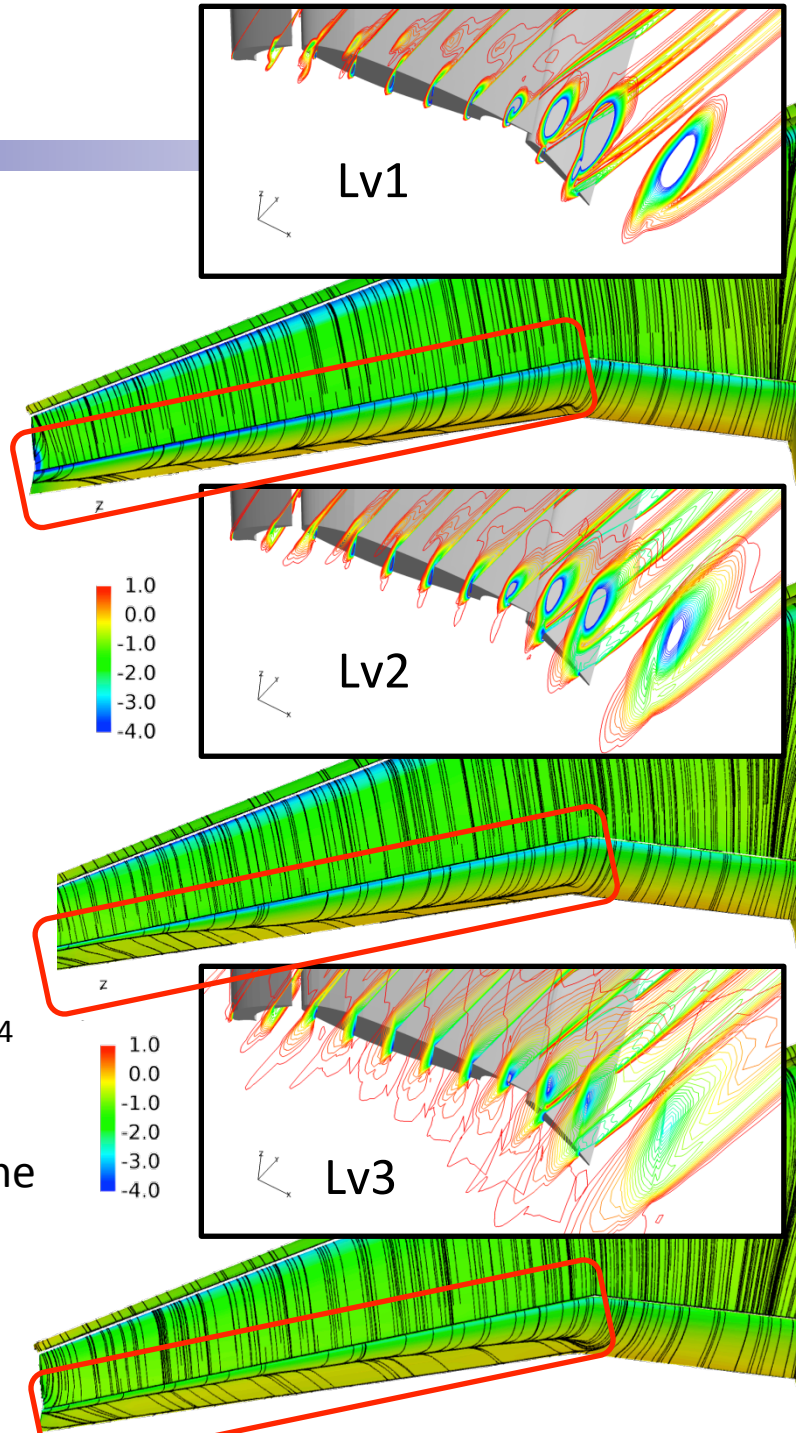
Ref. Results on each level grid of MG

- 3-level multi-grid of medium grid
  - # of grid points:
    Lv1=34M, Lv2=4.6M, Lv3=0.7M

Computations are run on each level grid w/o multi-grid acceleration



- Large differences of flow separation on the flap and wing-tip vortices between each level grid

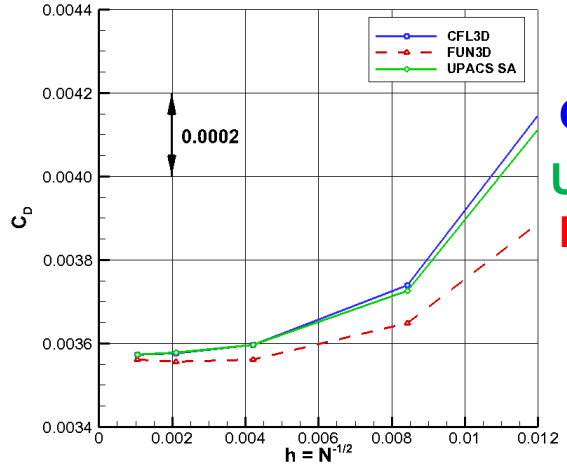


- Case4
  Turbulence Model Grid-Convergence Verification Study
  - 2-D bump

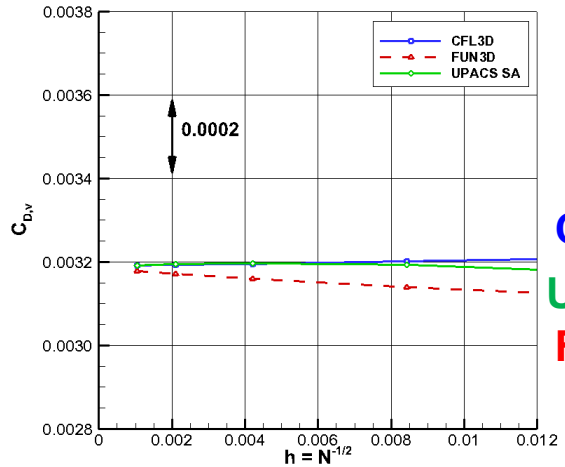
Case 4: 2D Bump-in-channel

- Comparison with NASA's CFL3D and FUN3D codes is good for grid convergence of C_D and C_{Df}.
- SA: C_{Df} is less sensitive to # of grid points.
- SST: All solvers show that C_{Df} is increasing with # of grid points

SA

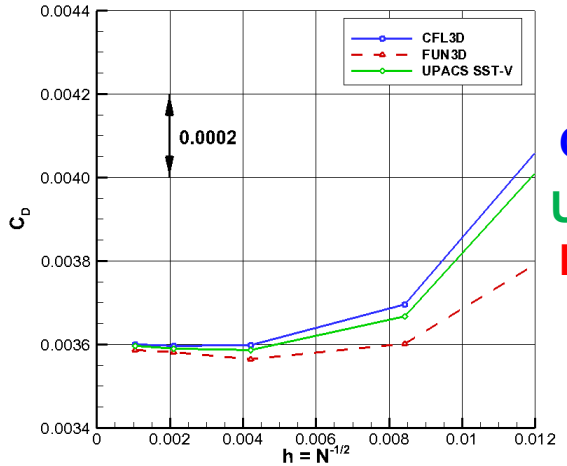


CFL3D
UPACS
FUN3D

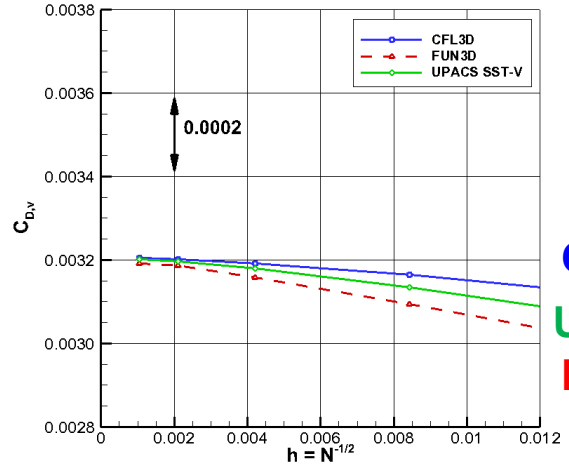


CFL3D
UPACS
FUN3D

SST



CFL3D
UPACS
FUN3D



CFL3D
UPACS
FUN3D

Total drag

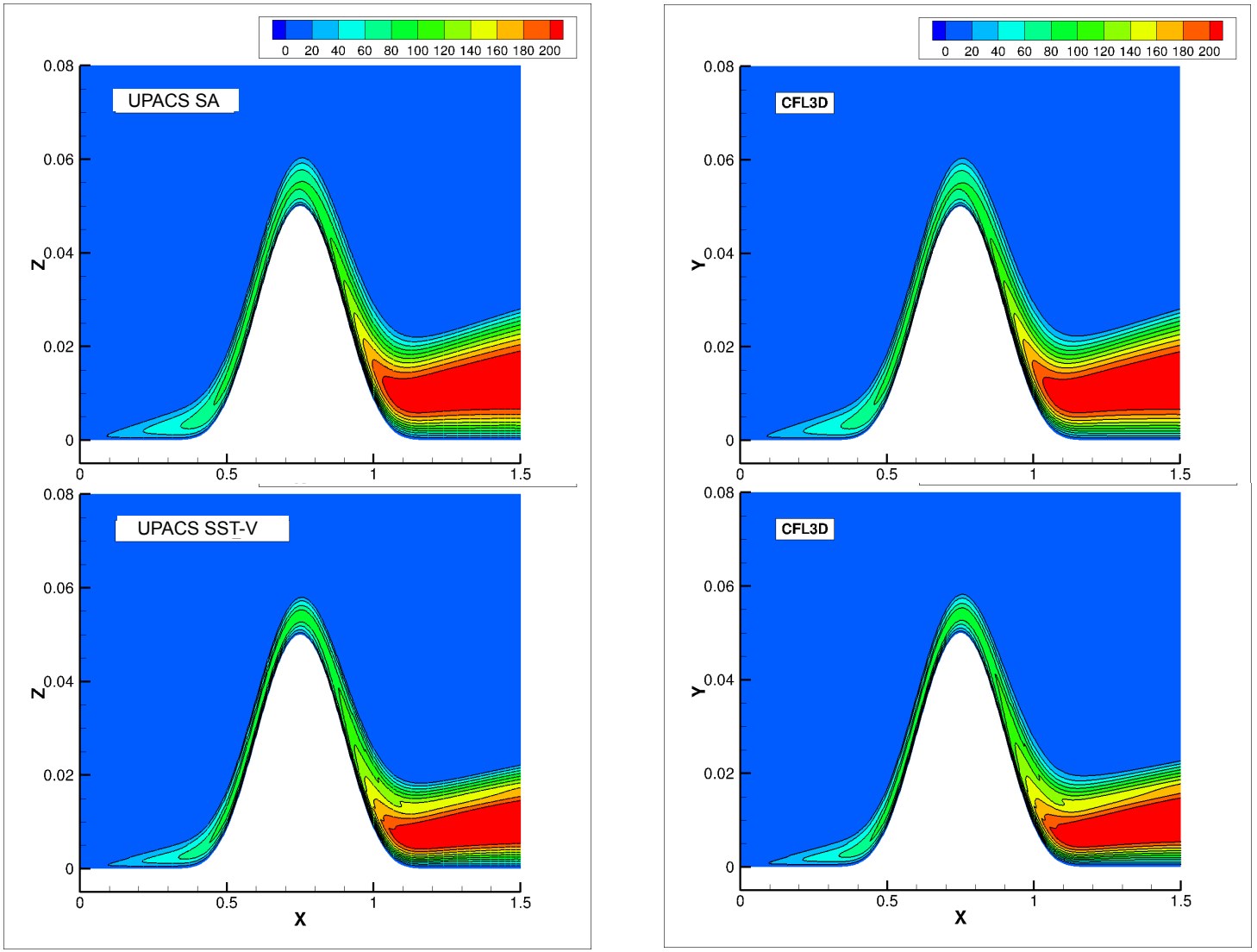
Friction drag

Case 4: 2D Bump-in-channel

- Comparison of μ_t/μ_{ref} contours between UPACS and CFL3D

SA

SST



Summary

- Case 1
  - C_L increases and C_M decreases with increasing grid points
    - Flow separation on the flap decreases with increasing grid points
  - Comparison of SA and SST
    - SA predicts higher C_L and lower C_M than SST due to less flap flow separation
    - Variation of skin friction drag with grid resolution by SST is relatively larger
    - SST gives lower friction drag
  - QCR
    - QCR reduces C_L and increases pitch-down C_M due to more flap flow separation
      - Earlier flow separation on the flap by SST especially with QCR
    - Due to QCR, $C_{D\,friction}$ shifts by -1 to -2 counts
- Case 4
  - UPACS shows consistent results with NASA codes.
  - C_{Df} by SA is less sensitive to # of grid points than those by SST

- Backup slides