Summary of JAXA Studies for the Second AIAA CFD High Lift Prediction Workshop Using Structured and Unstructured Mesh CFD

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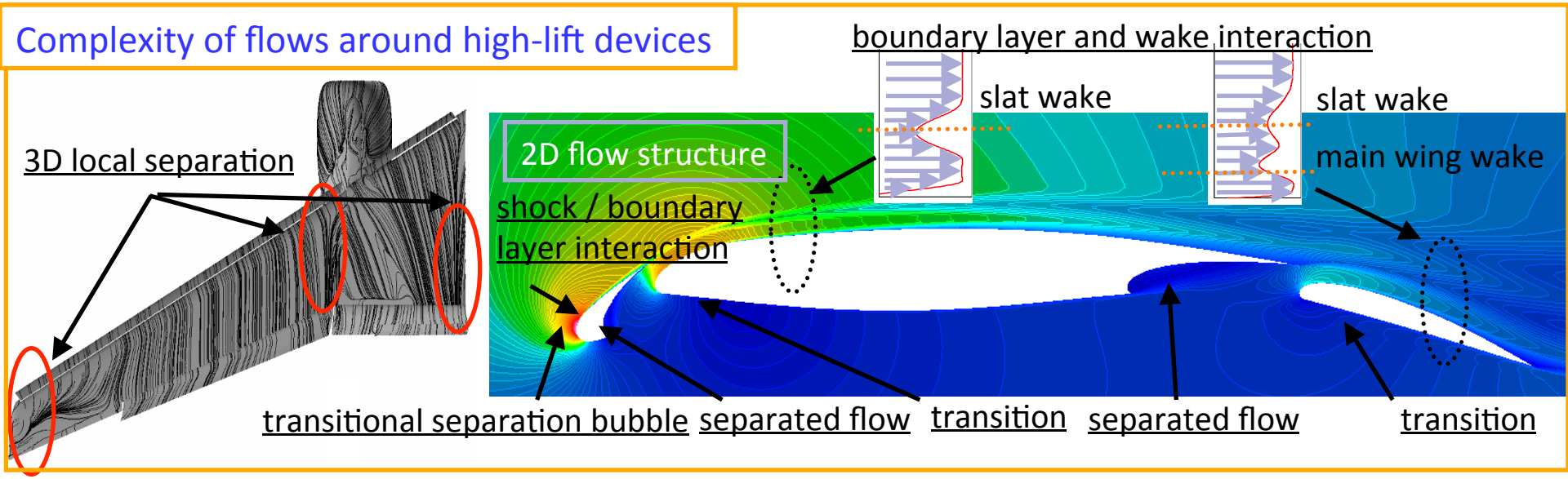
Outline

- Motivations
- Objectives
- Computational Method and Conditions
- Results
  - Grid convergence studies for the SA and SST models
  - Studies on effect of nonlinear Reynolds stress model with Quadratic Constitutive Relation (QCR) including evaluation at higher AoAs
  - Comparison studies using different solvers on different grid systems
- Concluding Remarks

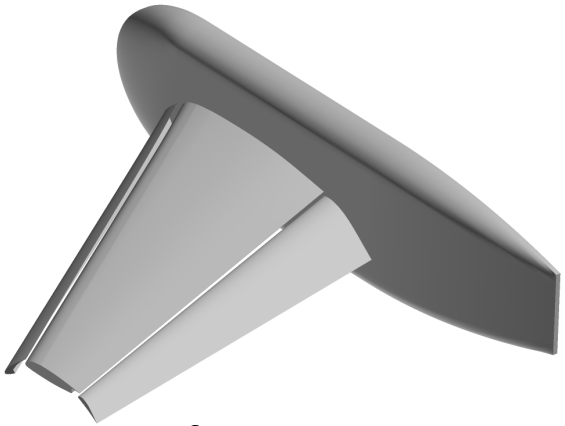
Motivations

- Difficulty in CFD analysis for high-lift devices
  - Mesh generation for complex geometry
  - Complex flow fields
- Efforts to validate and improve CFD for high-lift
  - AIAA CFD High Lift Prediction Workshop (HiLiftPW)
    - HiLiftPW-I: 2010 & HiLiftPW-II: 2013

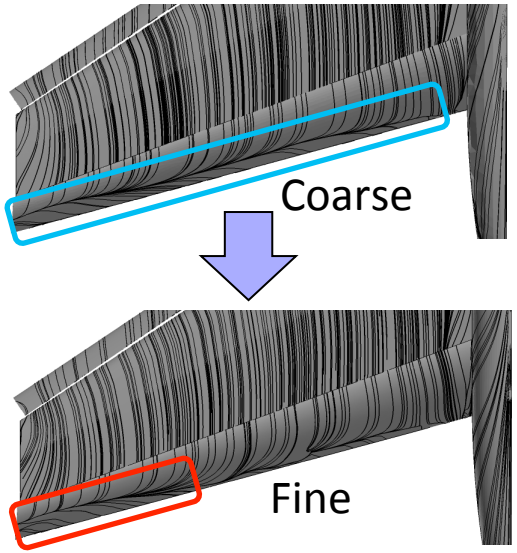


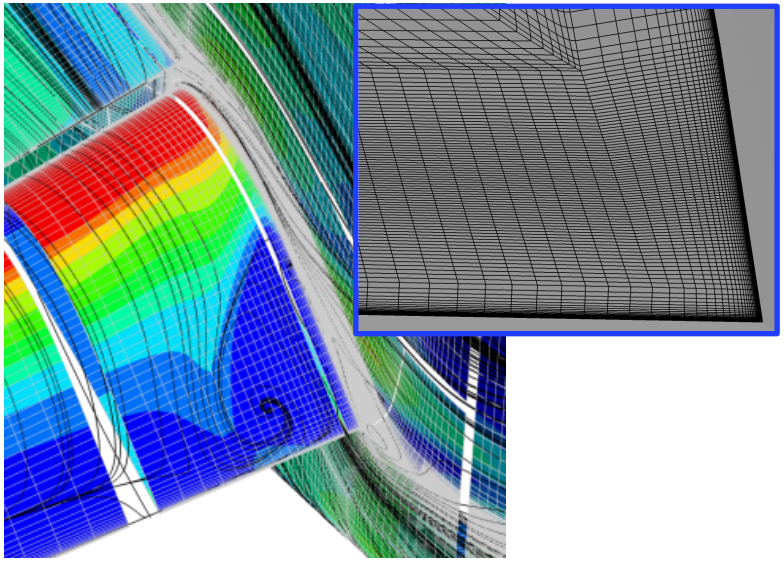
Motivations: JAXA's studies related HiLiftPW-1

- CFD codes
  - Structure grid solver UPACS and unstructured grid solver TAS-code
    - With a variant of Spalart-Allmaras turb. model (SA-noft2-R(Crot=1))
- Comparison studies of several grid systems (2 committee-provided unstr. grids and JAXA-generated 1 str. & 2 unstr. grids)
  - Coarse grid (especially on flap) → earlier flow separation over flap
  - Finer resolution near flap SOB → larger corner flow separation
  - Need of further extensive grid refinement study for tip vortices



HiLiftPW-1:
NASA Trap Wing

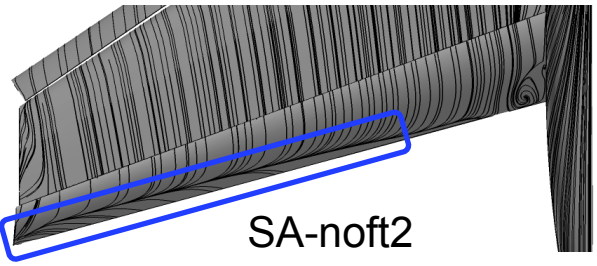


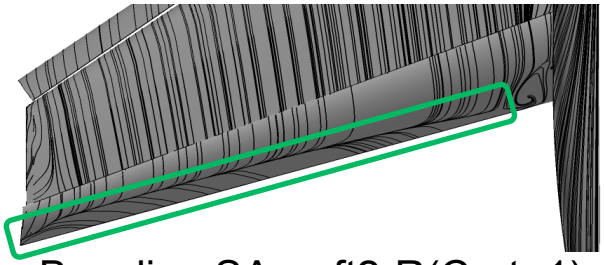


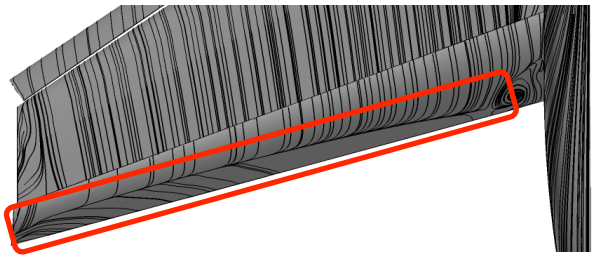
Motivations: JAXA's studies related HiLiftPW-1

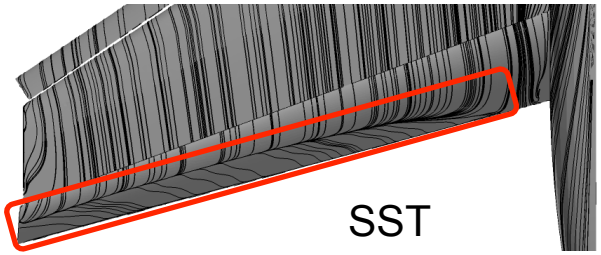
- Evaluations of an e^N-based transition prediction method
- Evaluations of several turbulence models
  - Several studies for selected cases by SST model and other variants of SA model
    - SST model and effect of nonlinear Reynolds stress model with Quadratic Constitutive Relation(QCR) → earlier flap flow separation

However, studies on the grid convergence were not conducted





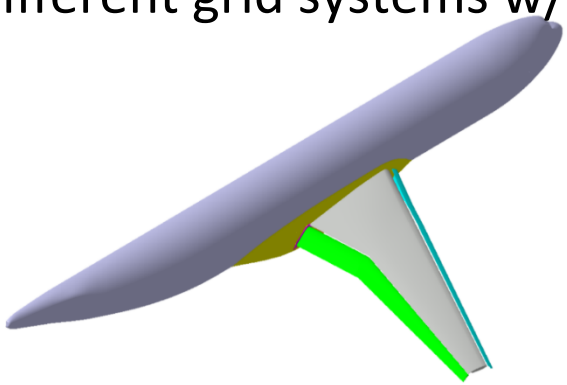




Objectives

- Grid convergence studies of “Case 1” on multi-block structured and unstructured grids provided by the HiLiftPW-2
  - Structure grid solver UPACS and Unstructured grid solver TAS-code

1. Grid convergence studies for the SA and SST models using UPACS
2. Change of grid convergence and predicted flow fields w/ & w/o QCR for the SA and SST using UPACS including evaluation at higher AoAs
   - QCR works well to predict the SOB flow separation at high-speed
     Question: How QCR works for low-speed high-lift flows?
3. Comparison studies using different solvers UPACS and TAS on different grid systems w/ & w/o QCR for the SA model.



HiLiftPW-2 Case 1: DLR-F11 Config 2.
without the slat tracks and flap track fairings

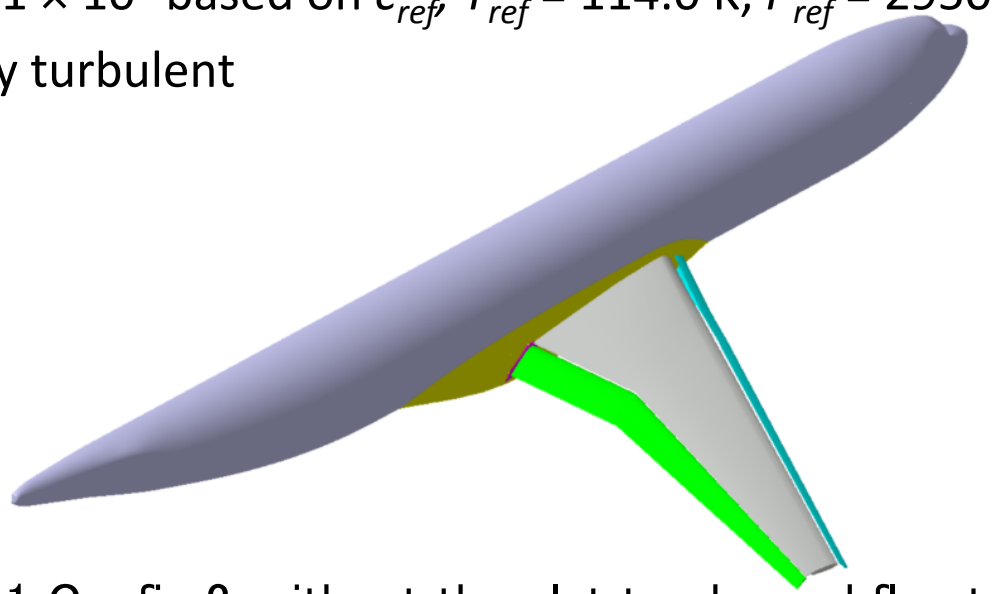
CFD Solver: UPACS and TAS

	UPACS	TAS
Mesh type	Multi-block structured	Unstructured
Equation	Full NS	
Discretization	Cell-centered finite volume	Cell-vertex finite volume
Convection Flux	Roe 3rd-order w/o flux limiter	HLLEW 2nd-order with Venkatakrishnan's limiter
Time integration	Matrix-Free Gauss-Seidel	LU-SGS
Turbulence model	SA-noft2-R(Crot=1) SA-noft2-R(Crot=1)-QCR2000 SST-V SST-V-QCR2000	SA-noft2-R(Crot=1) SA-noft2-R(Crot=1)-QCR2000

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

Cases Tested: UPACS & TAS

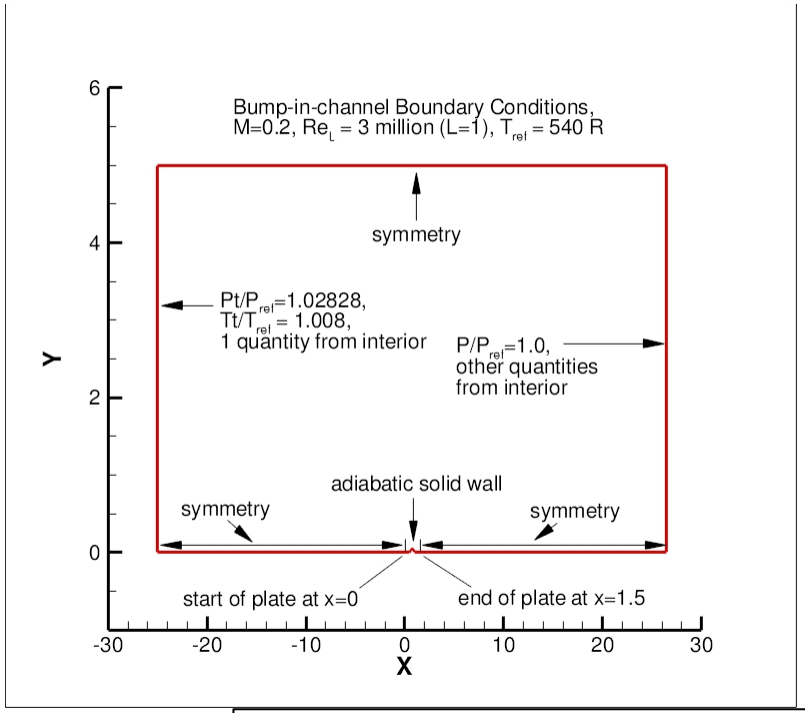
- Case 1 – Grid Convergence Study
  - DLR F11 "Config 2" Wing-body + SOB Flap Seal
    - D_{f_slat} = 26.5° and D_{f_flap} = 32°
  - Flow solutions on the Coarse, Medium, and Fine mesh
    - M_∞ = 0.175
    - α = 7°, 16° (Optional: 18.5°, 20°, 21°, 22.4°)
    - Re = 15.1 × 10^6 based on c_{ref}, T_{ref} = 114.0 K, P_{ref} = 295000 Pa
    - Run fully turbulent

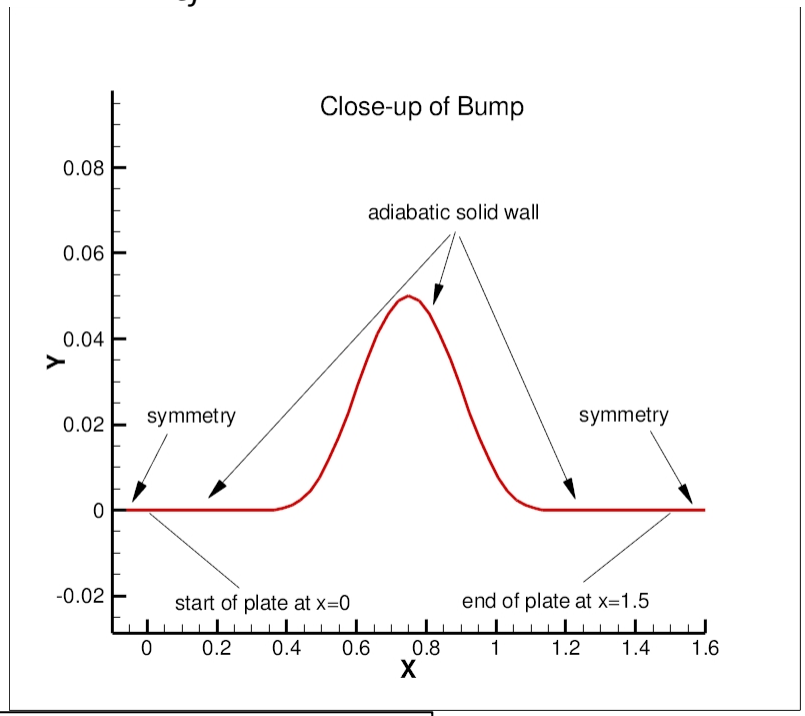


Case 1: DLR-F11 Config 2. without the slat tracks and flap track fairings

Cases Tested: UPACS

- Case 4 – Turbulence Model Grid-Convergence Verification Study
  - 2D Bump case from the Turbulence Modeling Resource website
  - Flow solutions on the finest three supplied grids
    - $M_\infty = 0.2$
    - $Re = 3 \times 10^6$ based on unit length, $T_{ref} = 540$ R



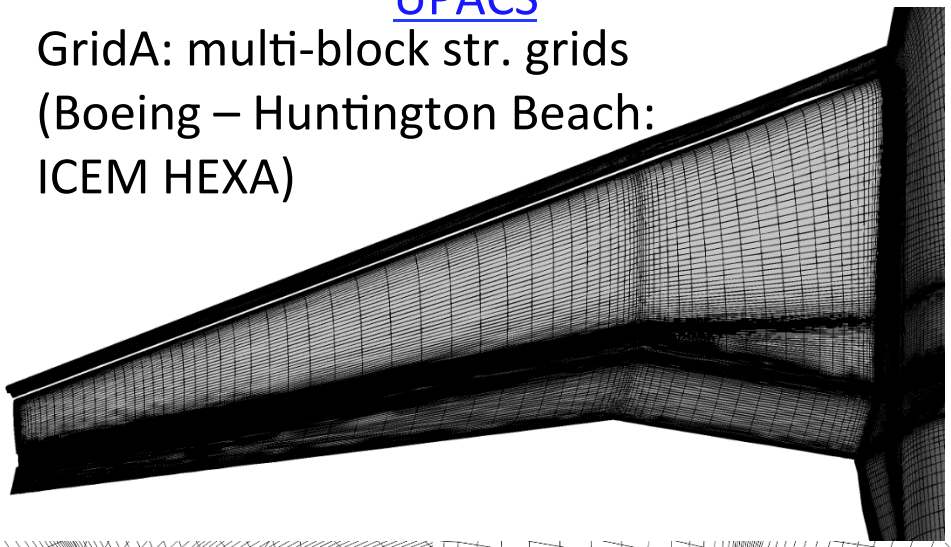


http://turbmodels.larc.nasa.gov/bump.html

Computational grids (GridA & GridD)

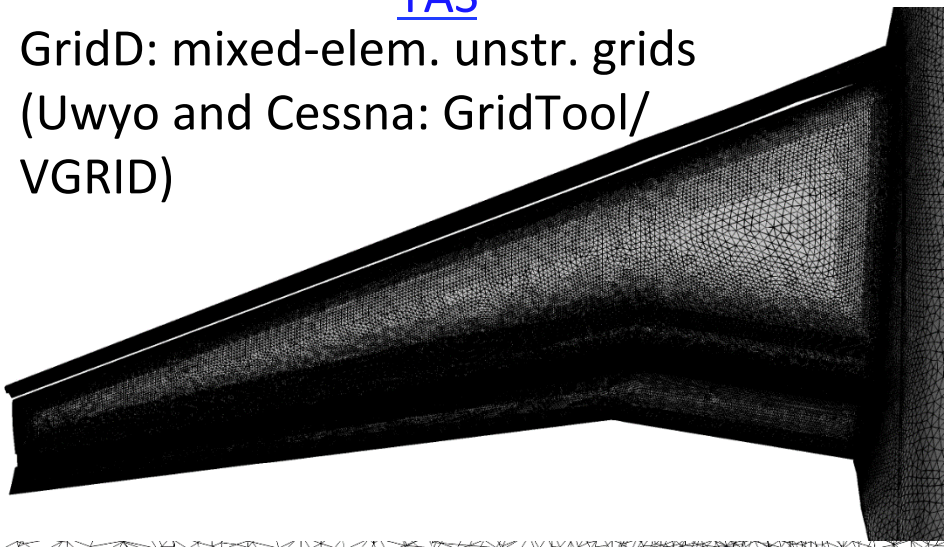
UPACS

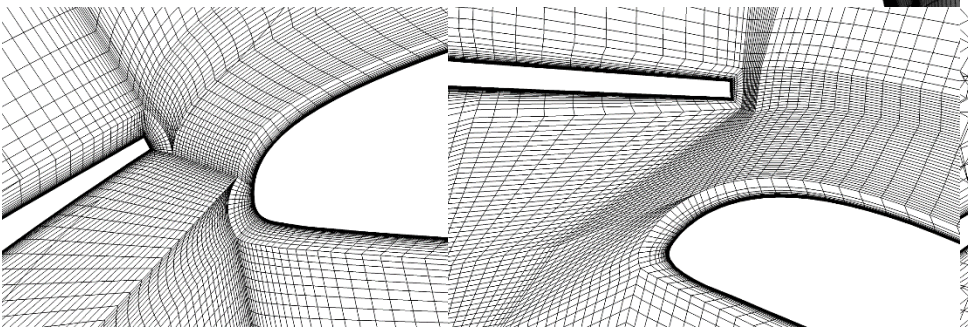
GridA: multi-block str. grids (Boeing – Huntington Beach: ICEM HEXA)

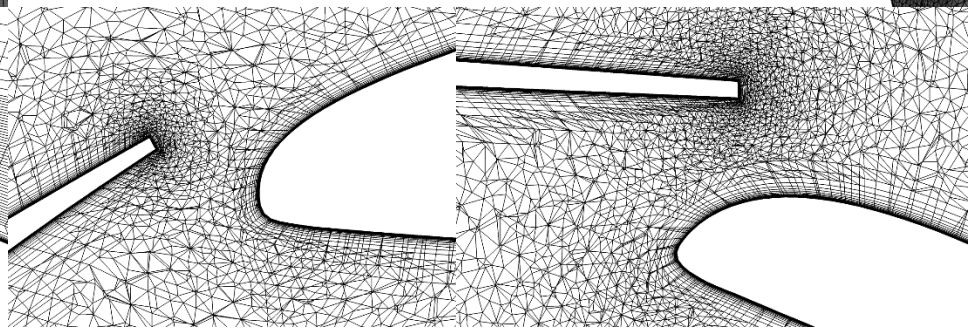


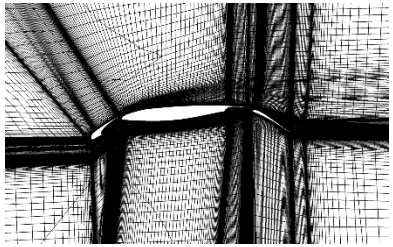
TAS

GridD: mixed-elem. unstr. grids (Uwyo and Cessna: GridTool/ VGRID)

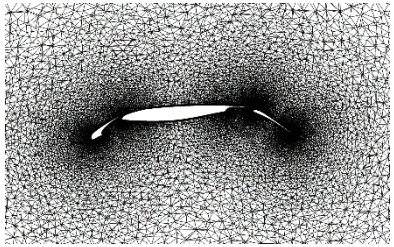








	Grid A (cells x 10^6)	Grid D (nodes x 10^6)
Coarse	9.6	10.2
Medium	32.0	30.8
Fine	100.6	76.0



1. Case4: Turbulence Model Grid-Convergence Verification Study by UPACS

2. Grid convergence studies for the SA and SST models using UPACS

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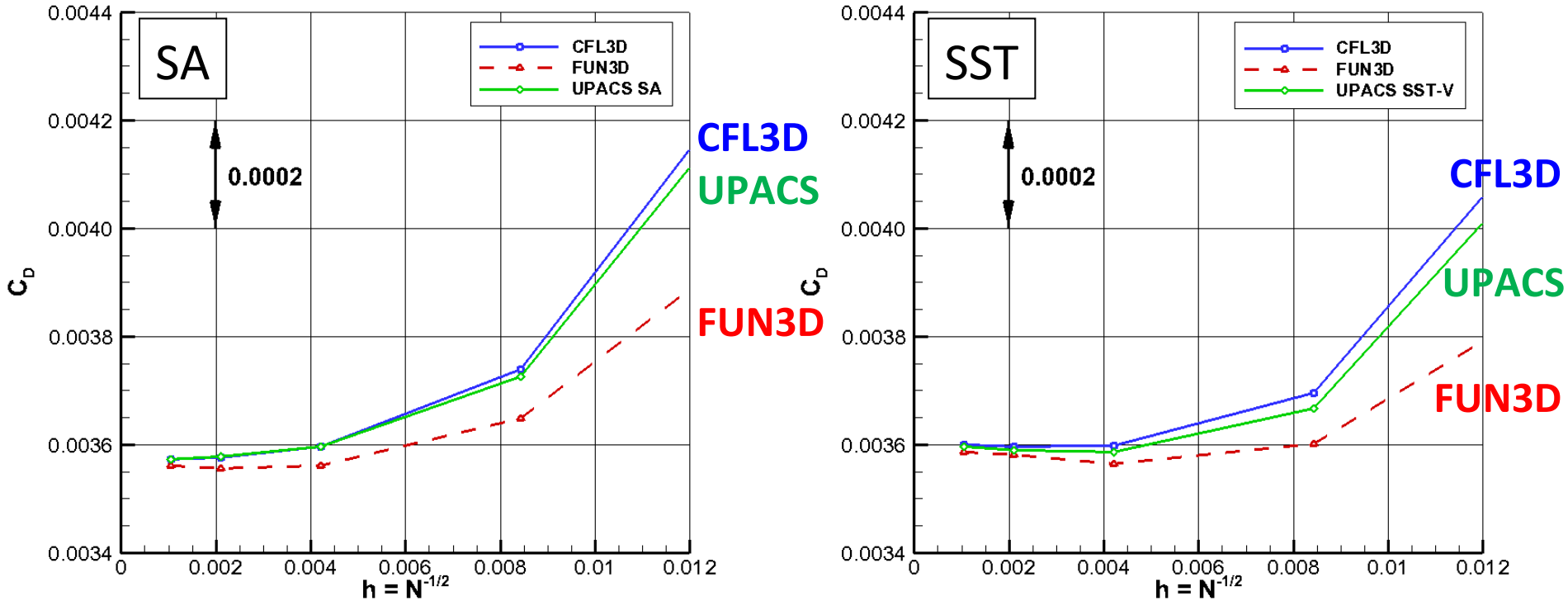
4. Comparison studies using different solvers UPACS and TAS on different grid systems w/ & w/o QCR for the SA model

Case 4: 2D Bump-in-channel: Total drag

- Comparison of grid convergence of C_D with NASA's CFL3D and FUN3D codes is good

Total drag

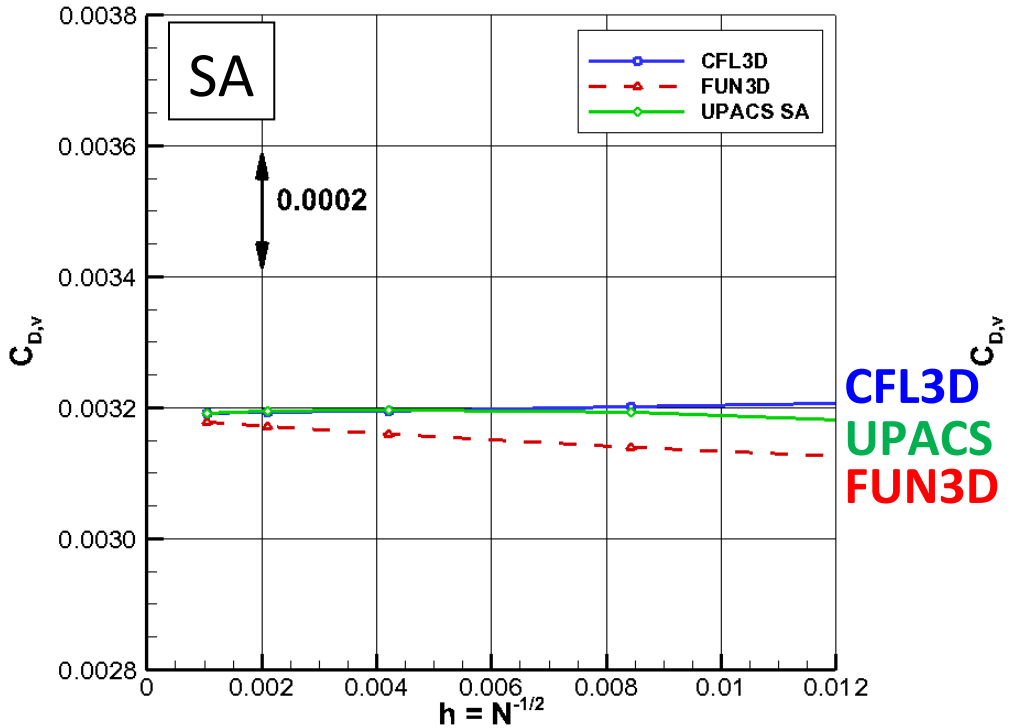


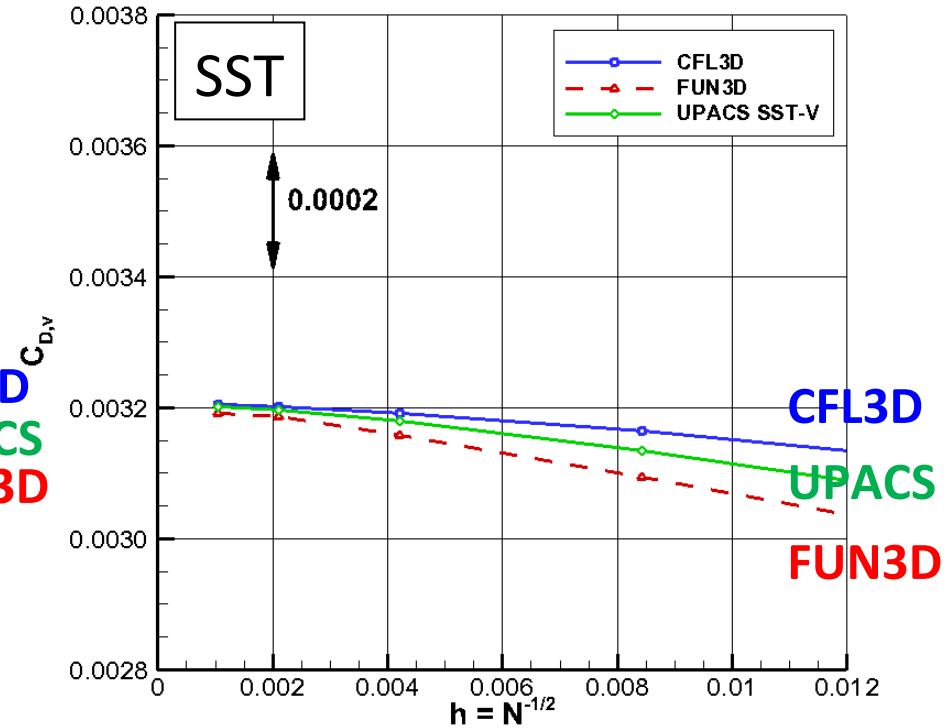
Data of CFL3D & FUN3D http://turbmodels.larc.nasa.gov

Case 4: 2D Bump-in-channel: Friction drag

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

Friction drag





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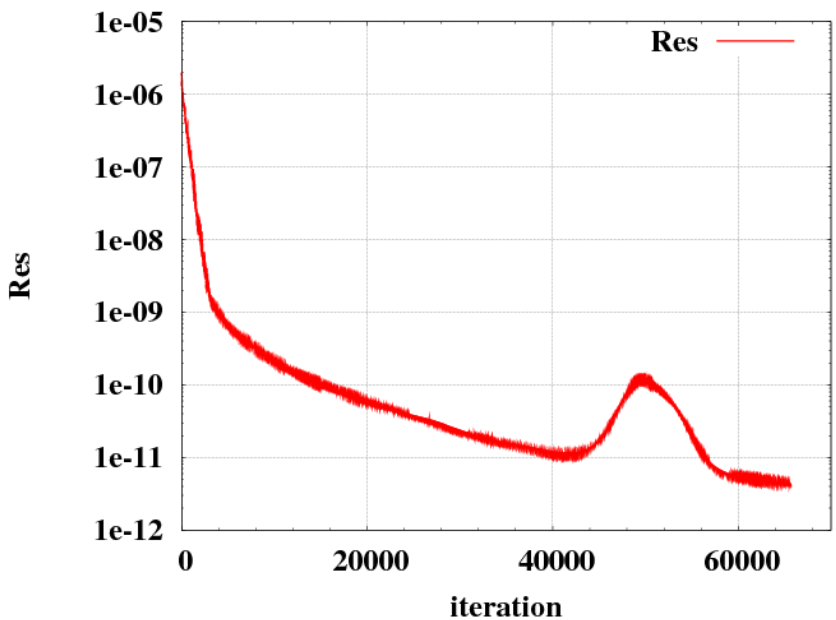
Note.

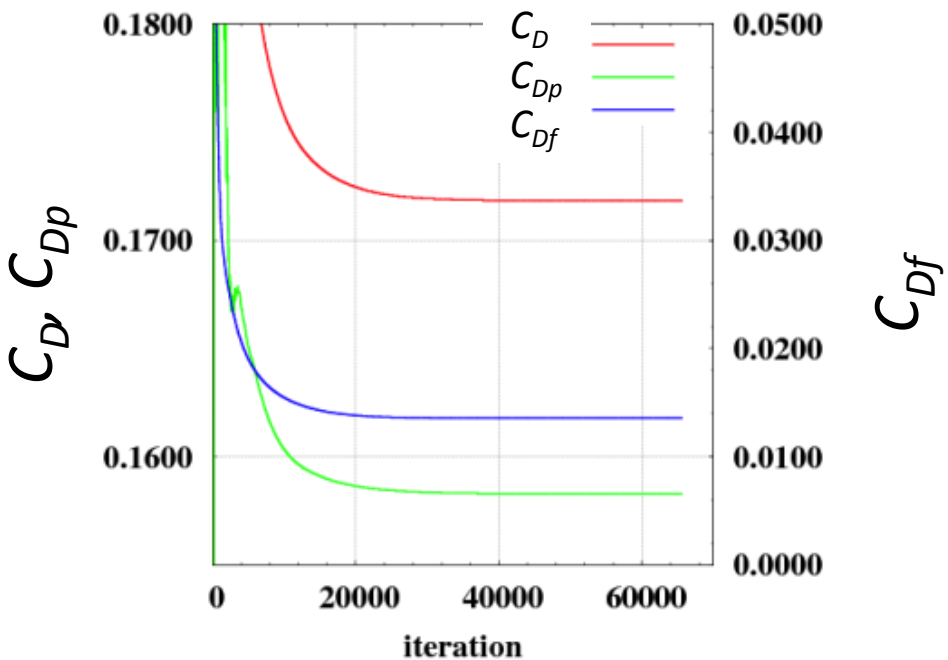
- After the HiLiftPW-2, a wrong post-processing was found to calculate the aerodynamic forces related to C_L

→ The updated aerodynamic forces re-calculated using a corrected post-processing way were re-submitted to the workshop by the deadline of re-submission

Solution convergence history: UPACS
AoA=7,Medium, SA-noft2-R (Crot=1)

- 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)

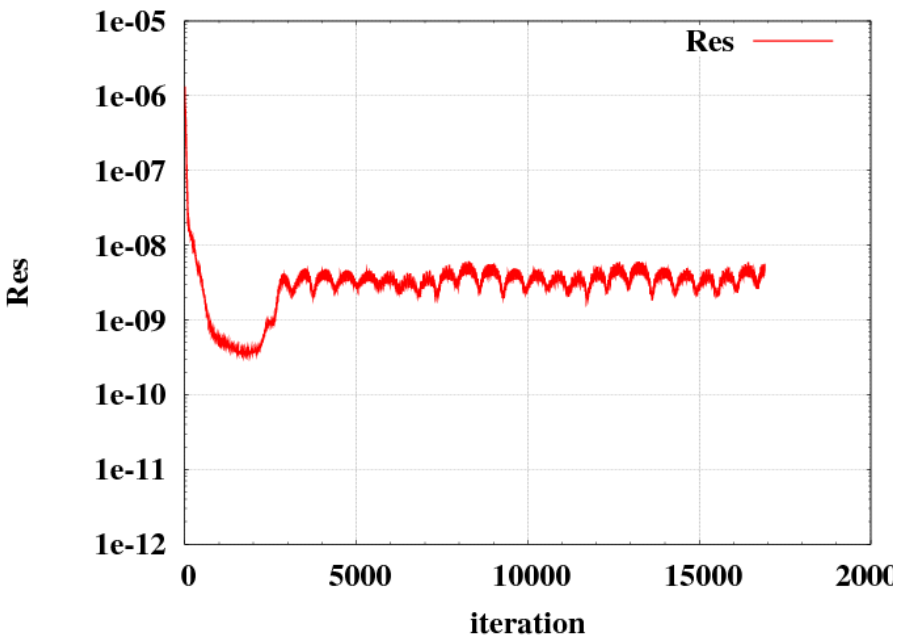


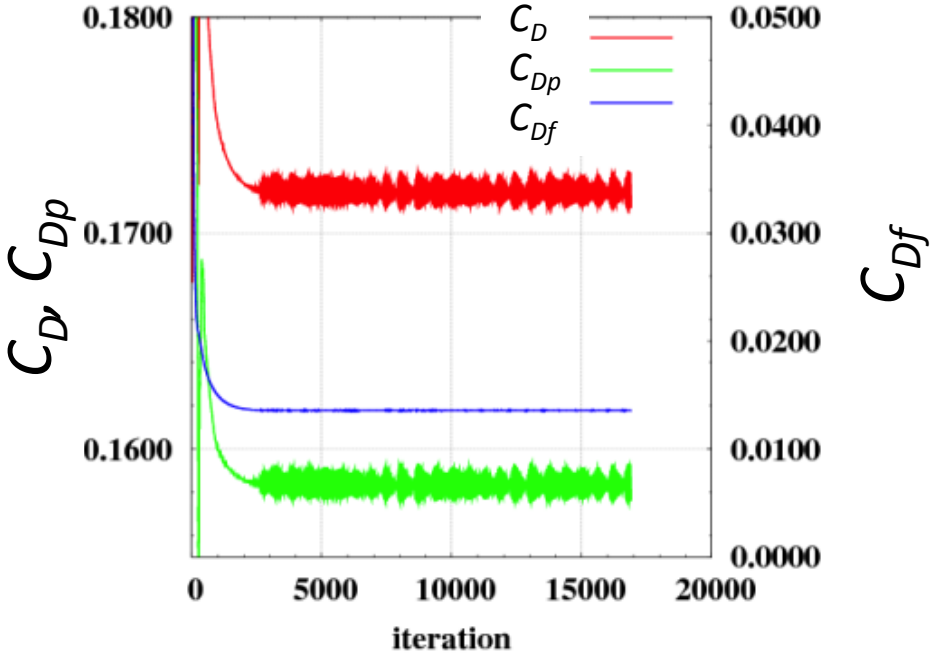


Solution convergence history: UPACS

AoA=7,Medium, SA-noft2-R (Crot=1), w/ Multigrid

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





Solution convergence history: UPACS

AoA=7,Medium, SA-noft2-R (Crot=1), w/ Multigrid

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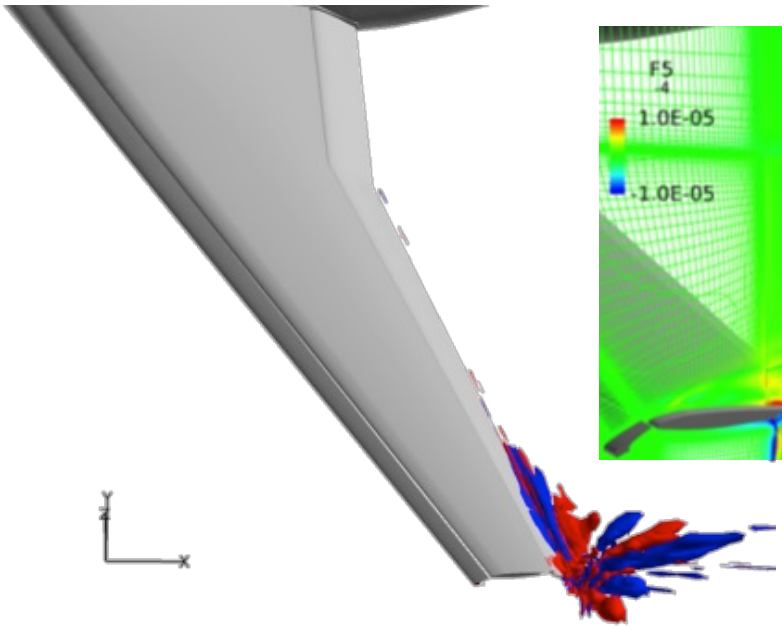
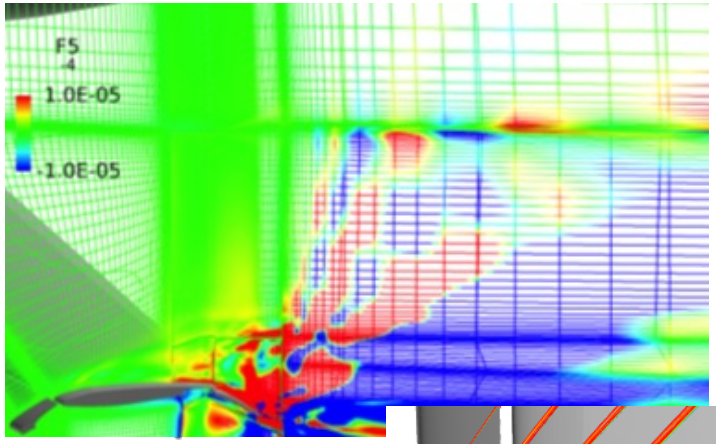
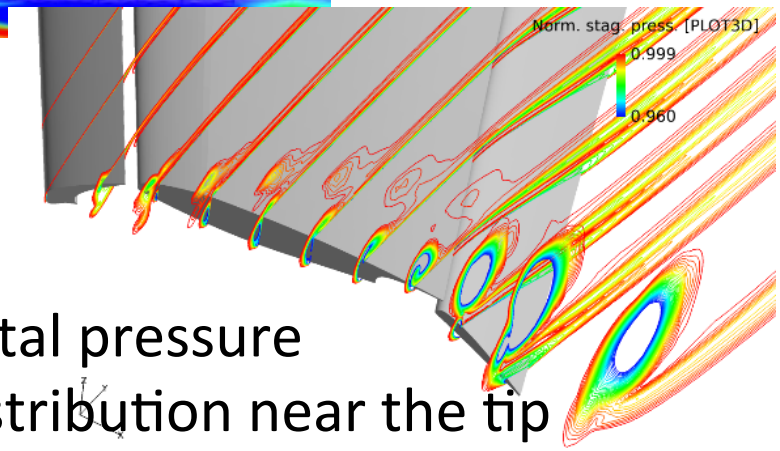
→ Computational results w/o multigrid will be shown hereafter





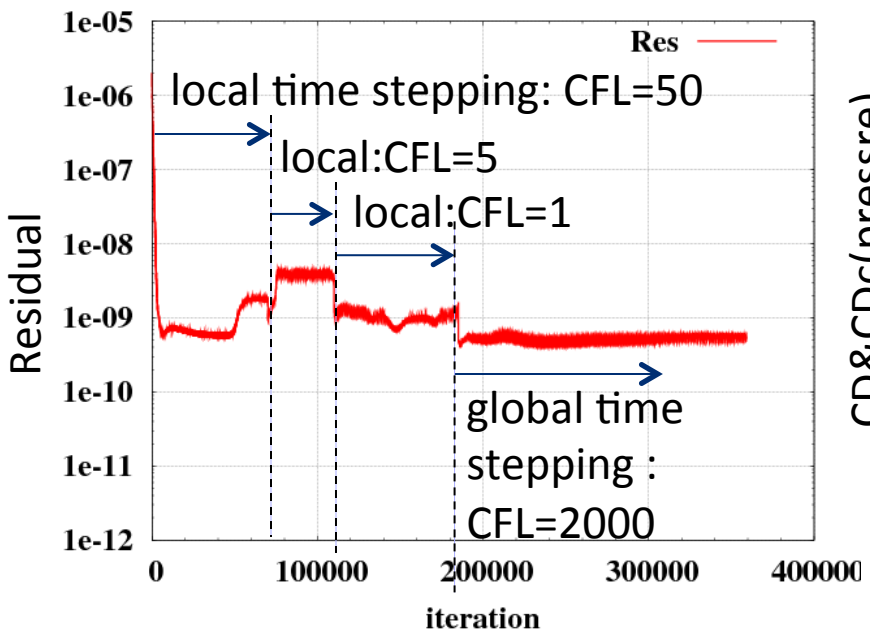
Visualized dQ (Exaggeated)

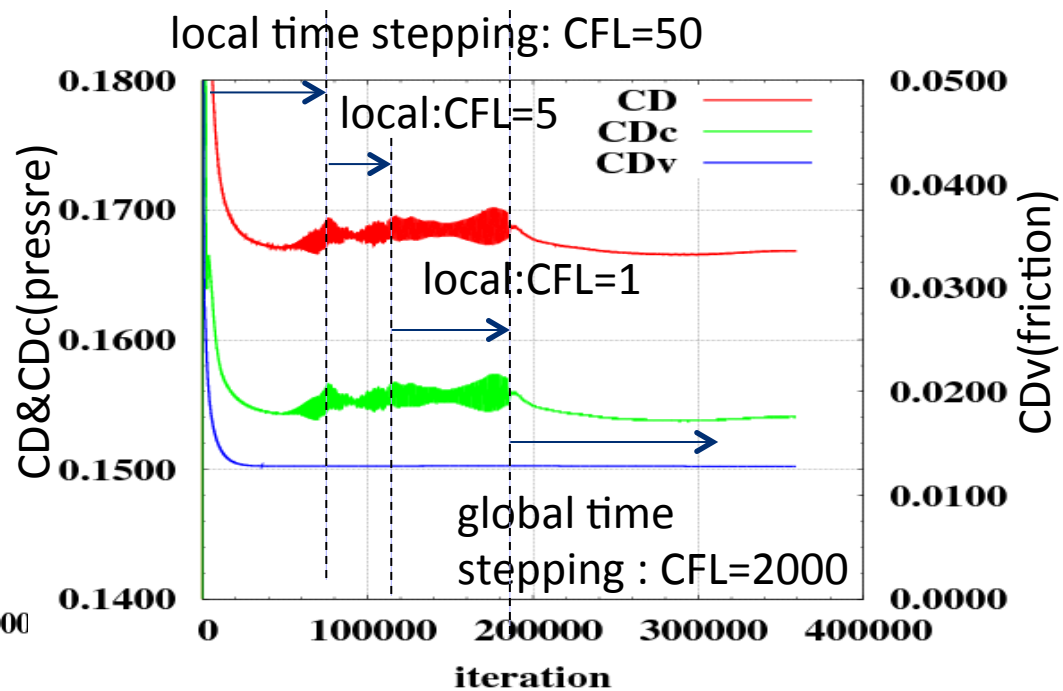


Total pressure distribution near the tip

Solution convergence history: UPACS
AoA=7,Medium, SST-V

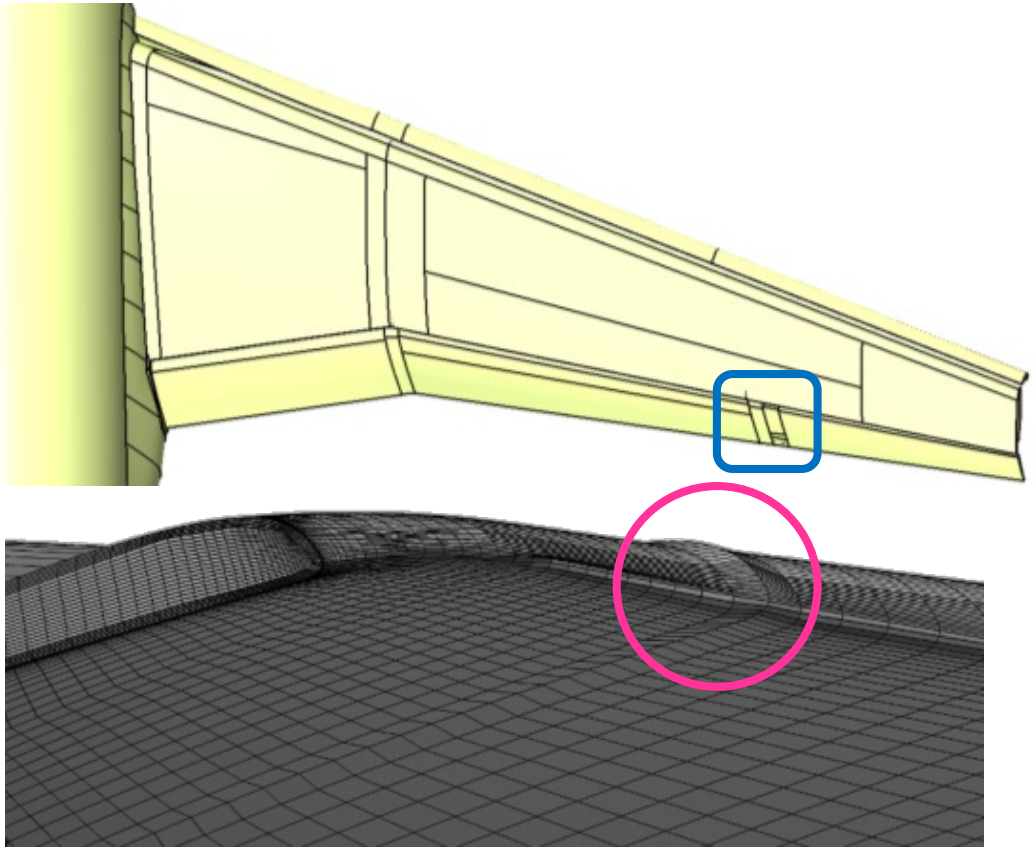
- CFL and local/global time stepping were adjusted to get well converged solution when oscillation of aerodynamic forces were observed for several flow and grid conditions

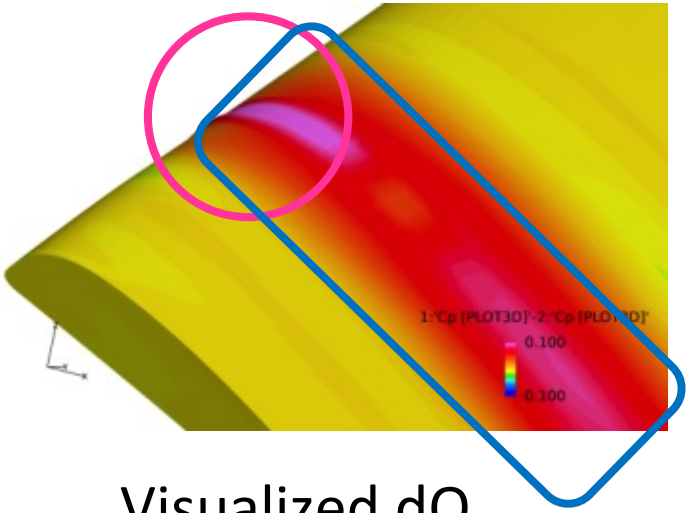




Solution convergence history: UPACS
AoA=7,Medium, SST-V

- The oscillation was found around discontinuous junction between two outer-flaps

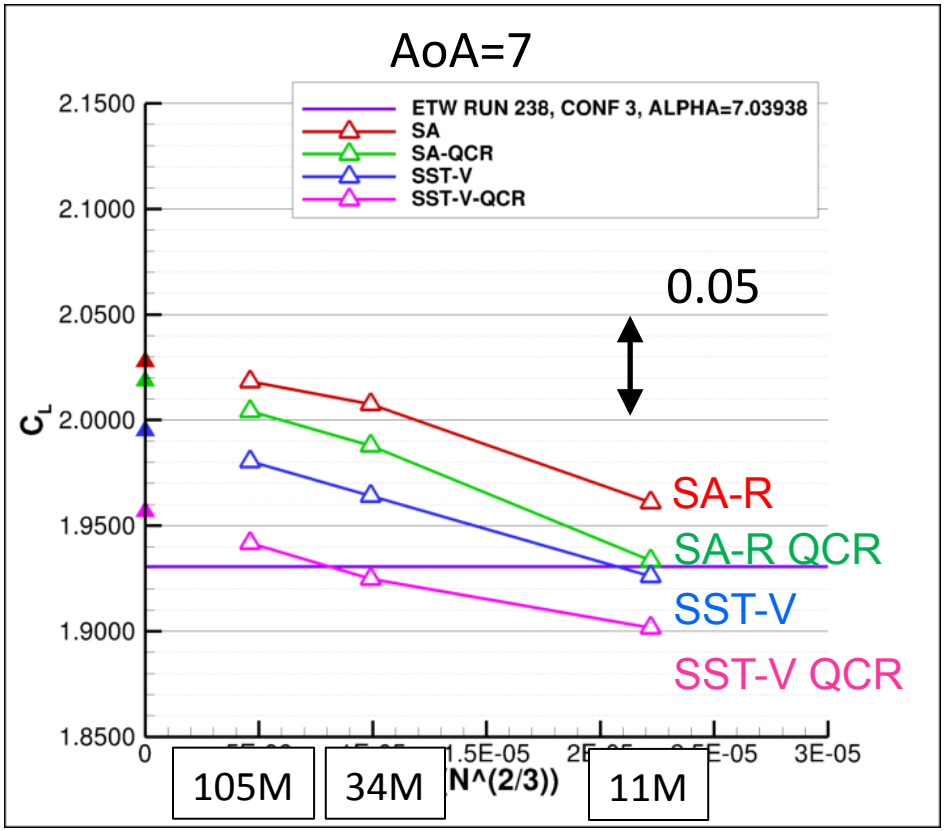


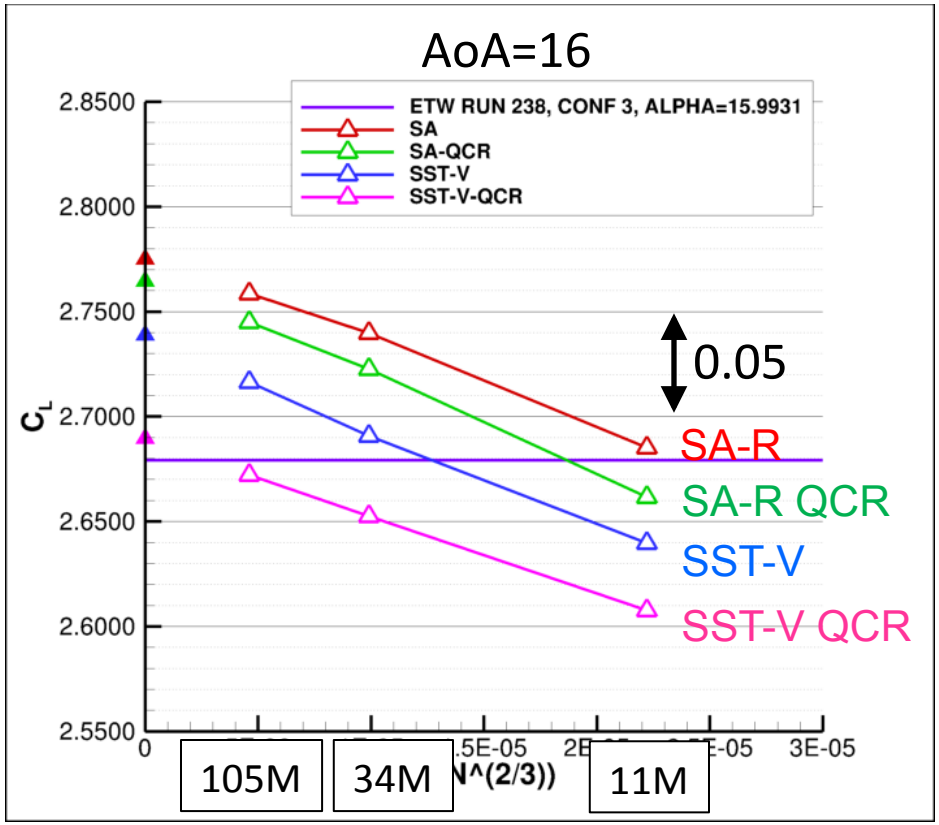


Visualized dQ
(Exaggeated)

Grid convergence of C_L

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

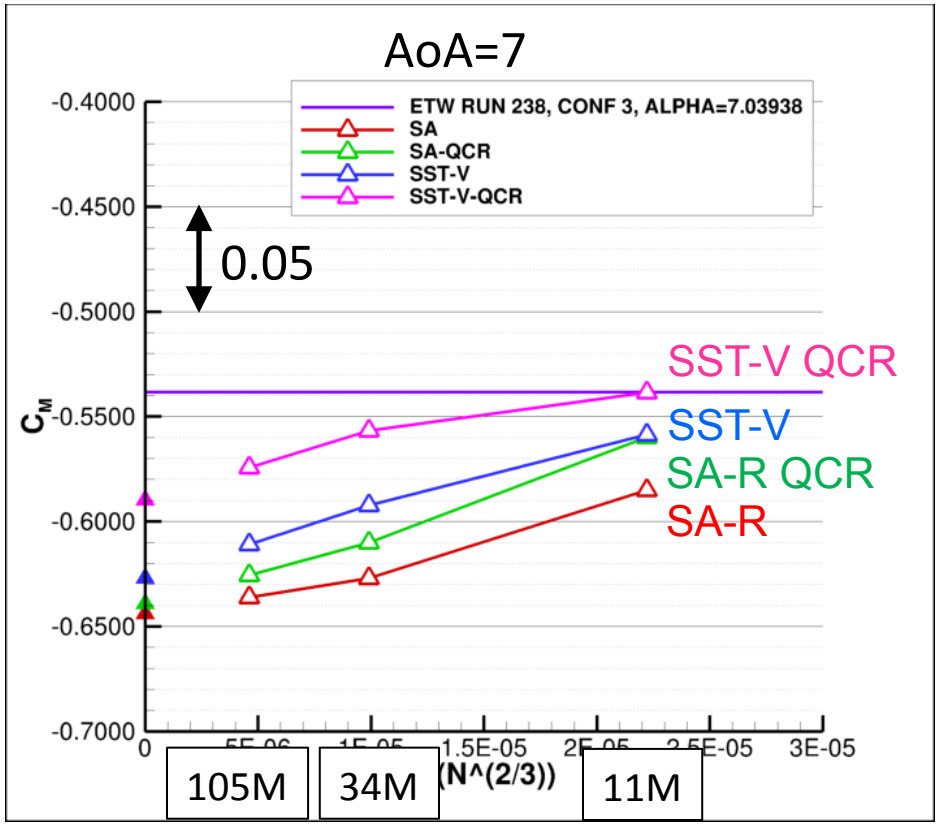


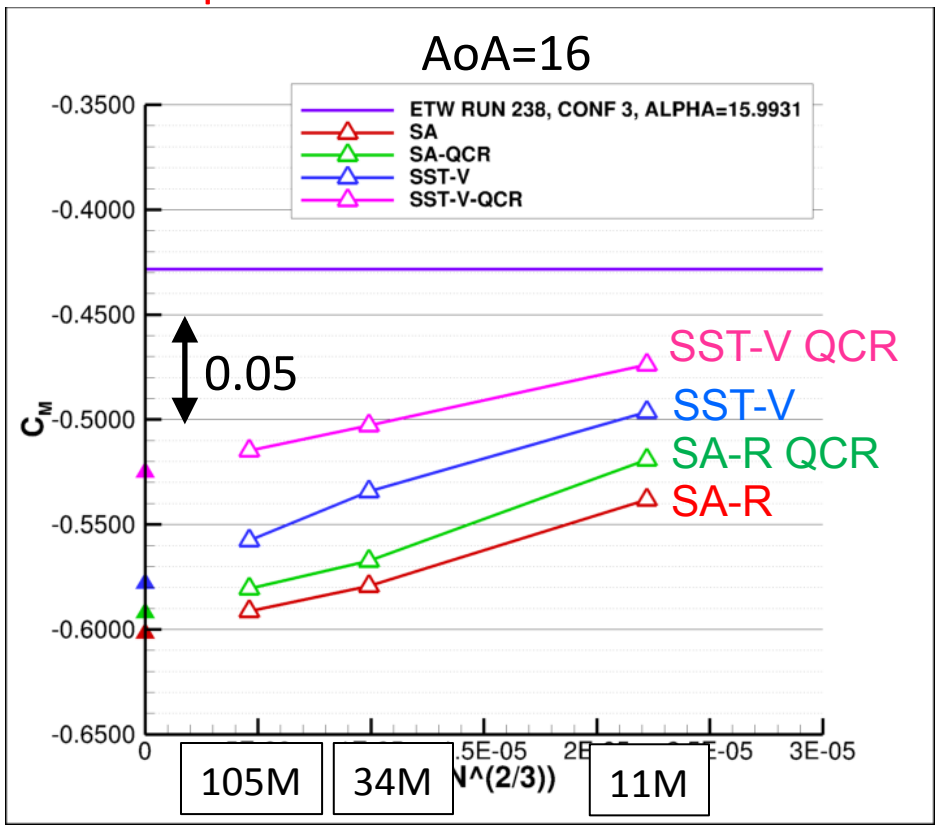


Grid convergence of C_M

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

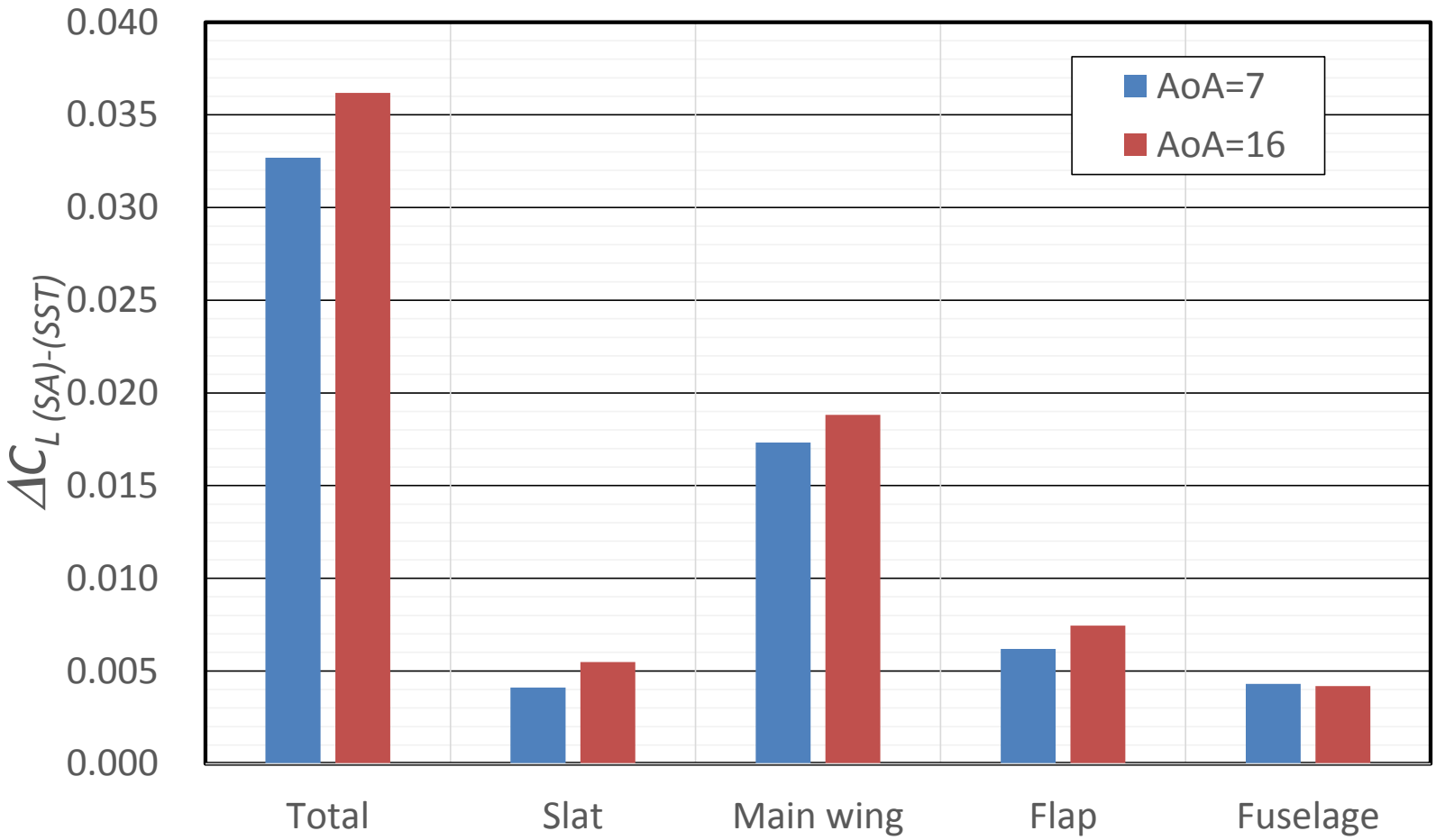
The tendencies of the over-predictions of C_L and pitch-down C_M are reasonable due to lack of the slat and flap brackets





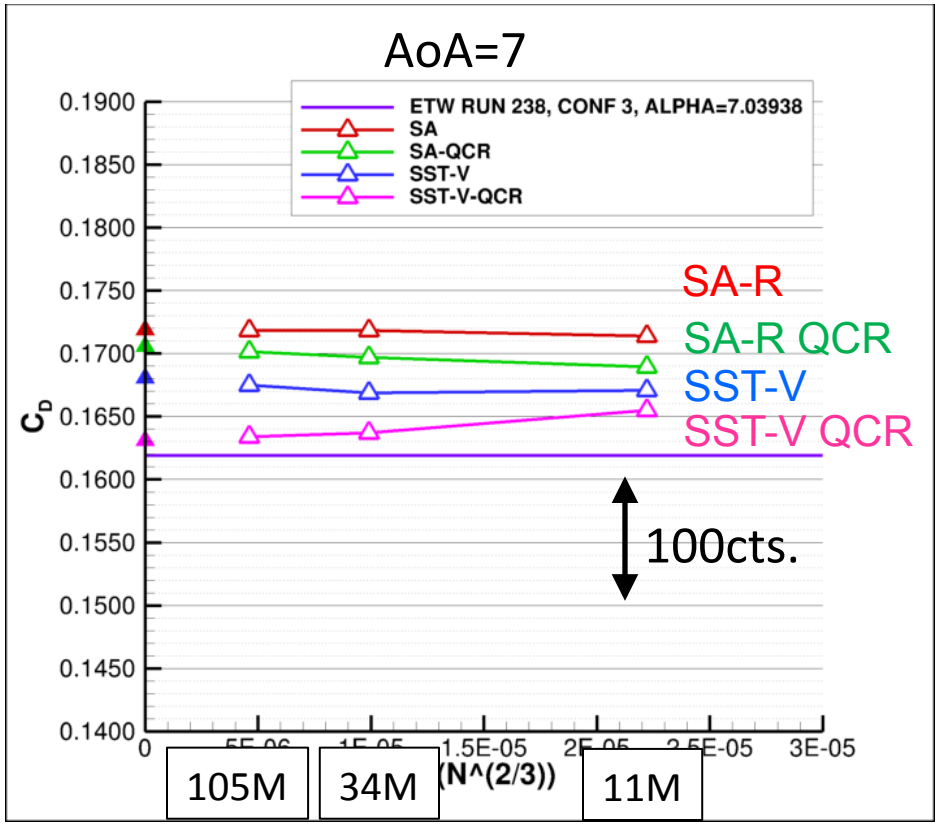
Differences of $C_{L(N\rightarrow\infty)}$ for each component by SA&SST

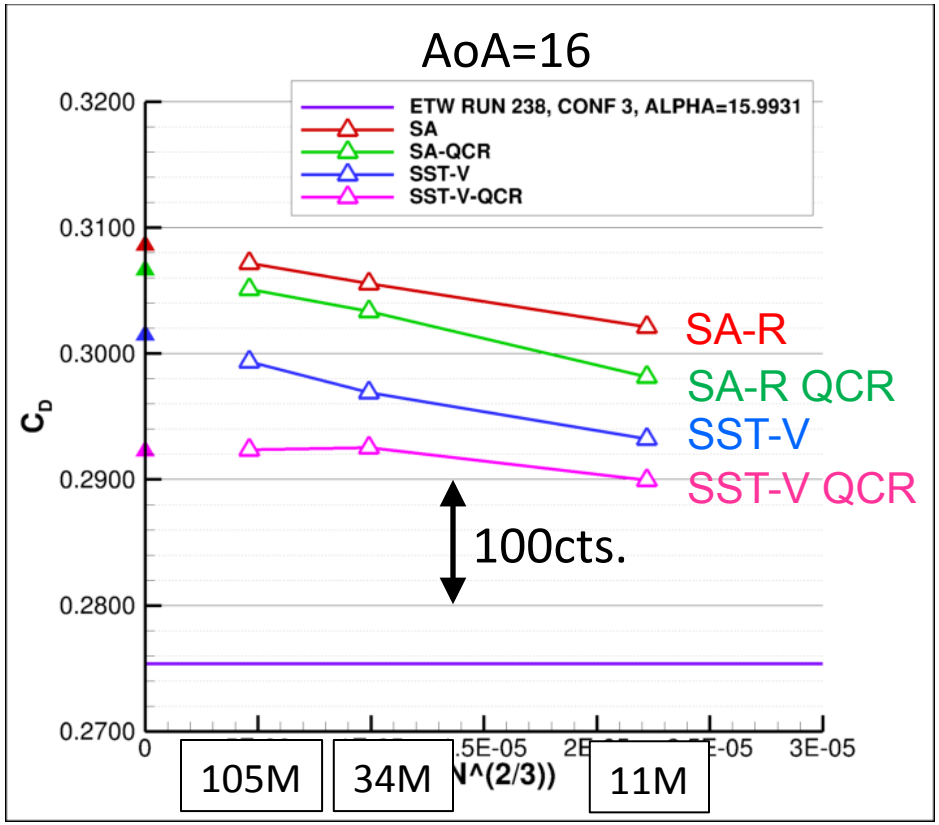
- Main difference derives from the main wing, while other contributions from the slat, flap, and fuselage are the same level



Grid convergence of C_D

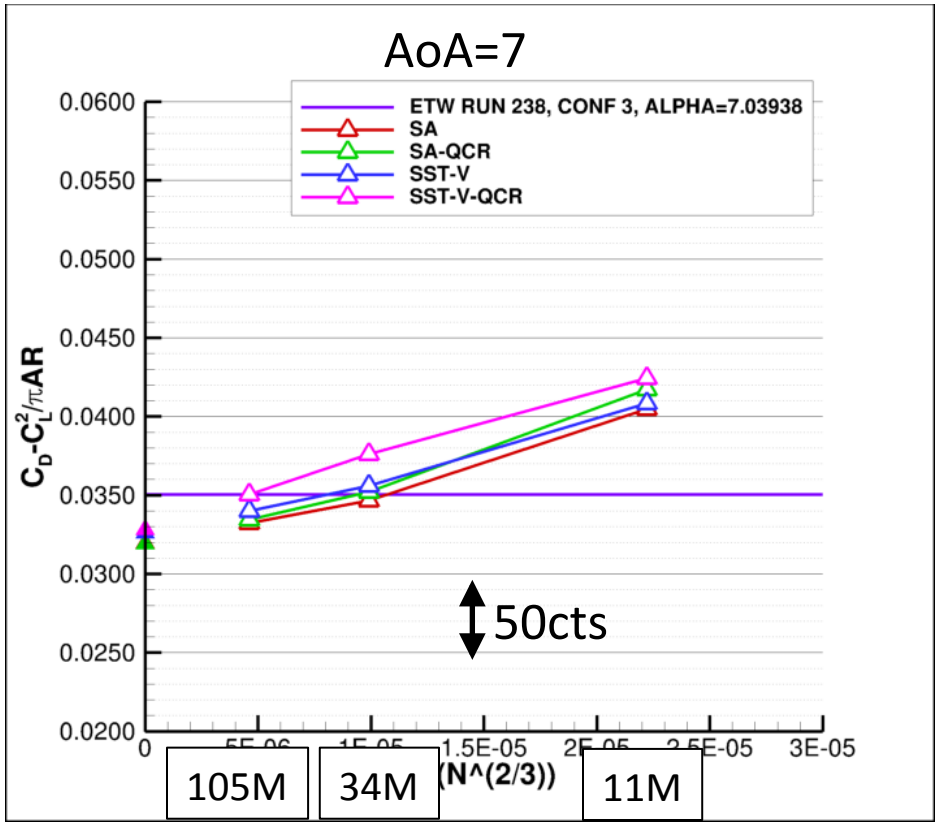
- SA predicts higher C_D than SST
- QCR decreases C_D
- C_D is over-predicted
  - C_D includes influence of induced drag by the difference of lift prediction

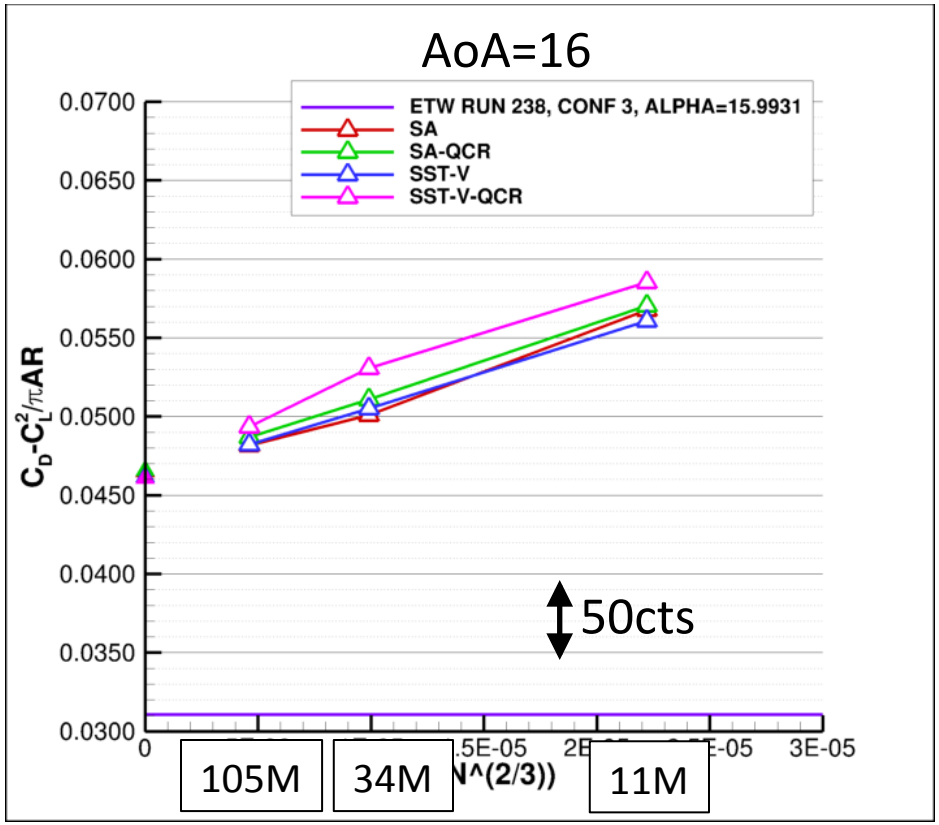




Grid convergence of C_D-$C_{Dinduced}$

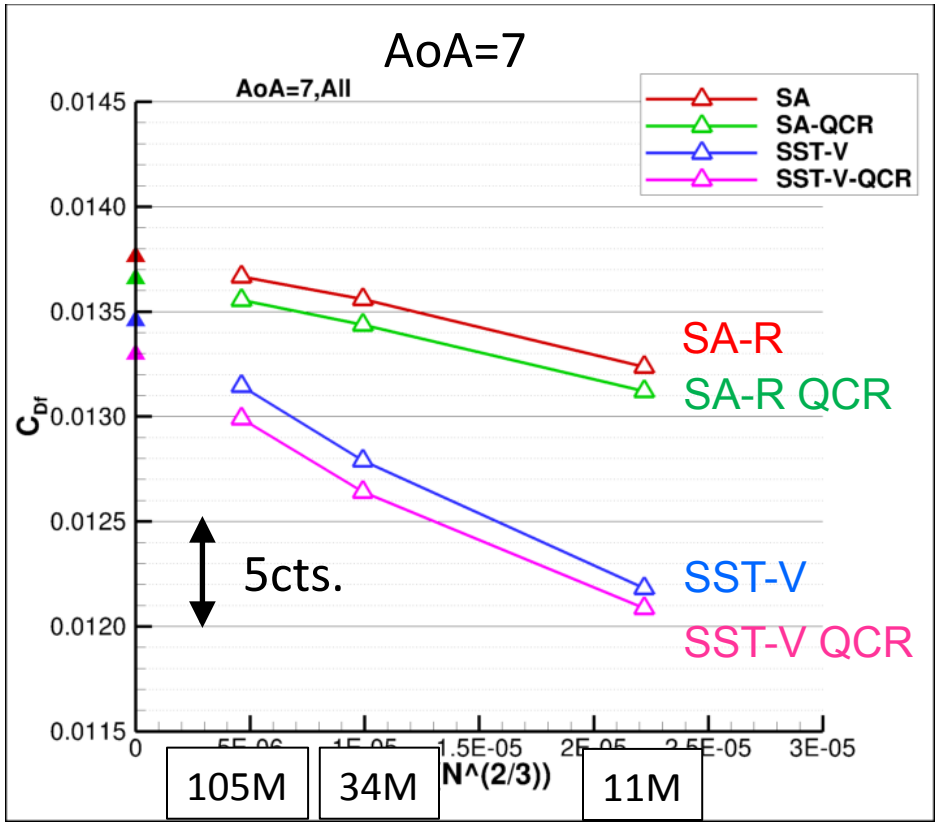
- C_D-$C_{Dinduced}$ is compared
  - Ideal $C_{Dinduced}$ =(C_L*C_L)/(PI*AR)
- Differences of grid converged C_D-$C_{Dinduced}$
  - AoA=7: 10cts.
  - AoA=16: 3cts.

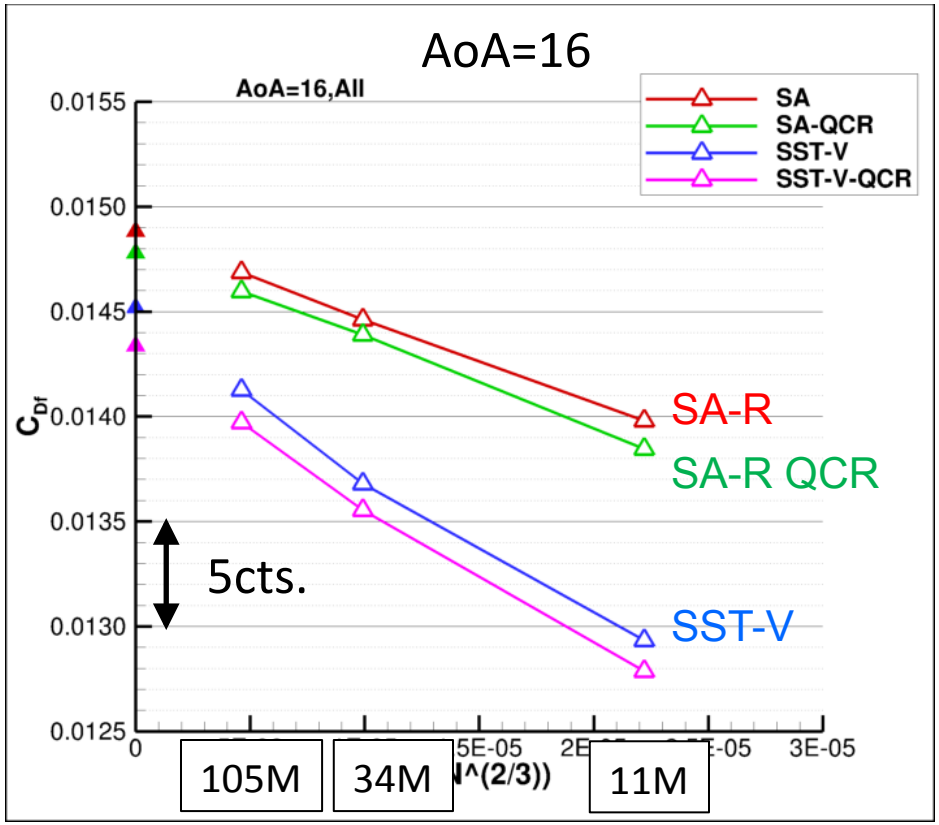




Grid convergence of $C_{Dfriction}$

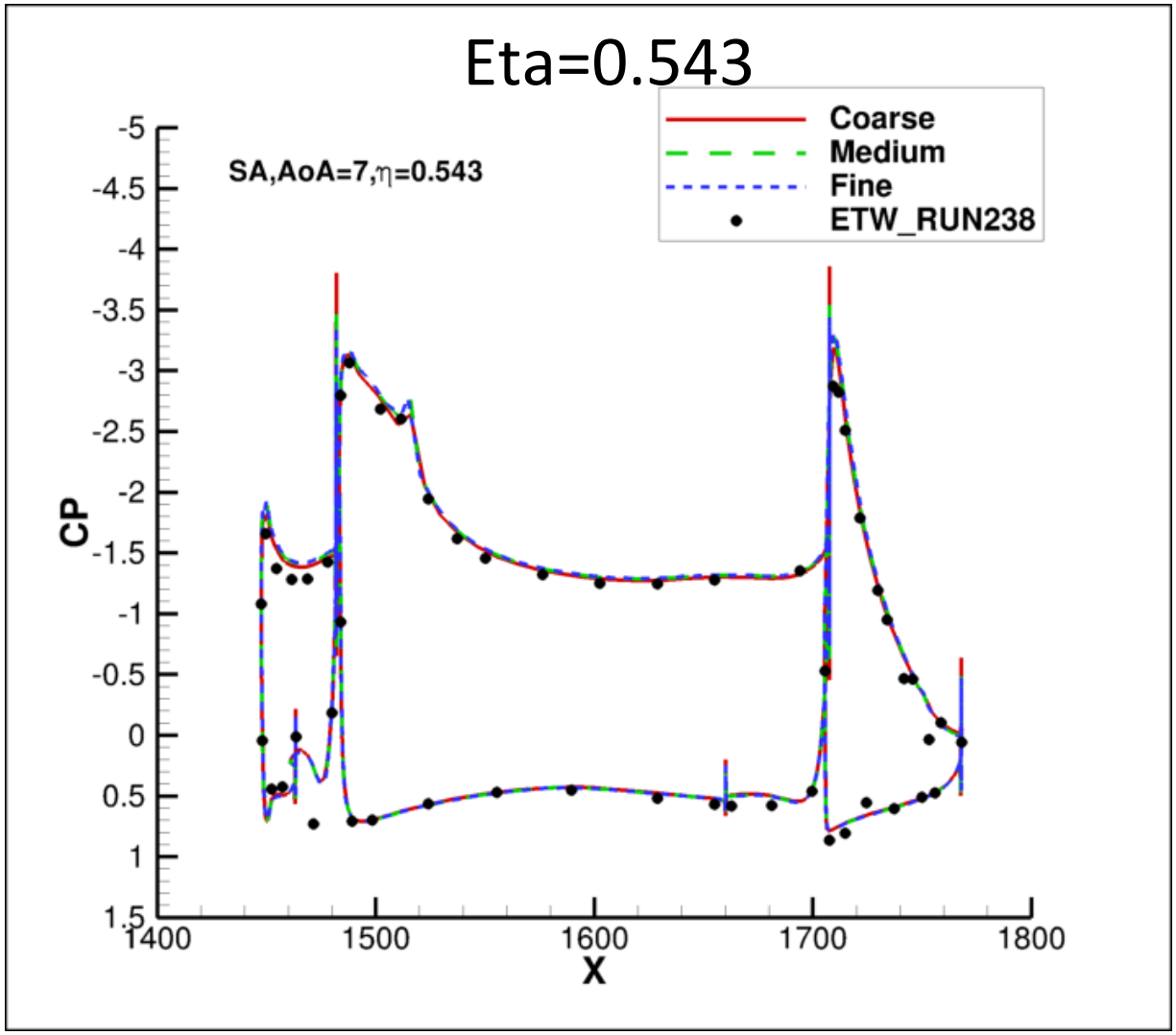
- Grid dependency of skin friction drag by SST is relatively larger
  - Variations by grid density are about 5-10cts. for SA and 15cts. for SST
- $C_{Dfriction}$ of SST is lower than that of SA
- QCR decreases $C_{D\,friction}$ by 1-2 counts for both SA and SST model





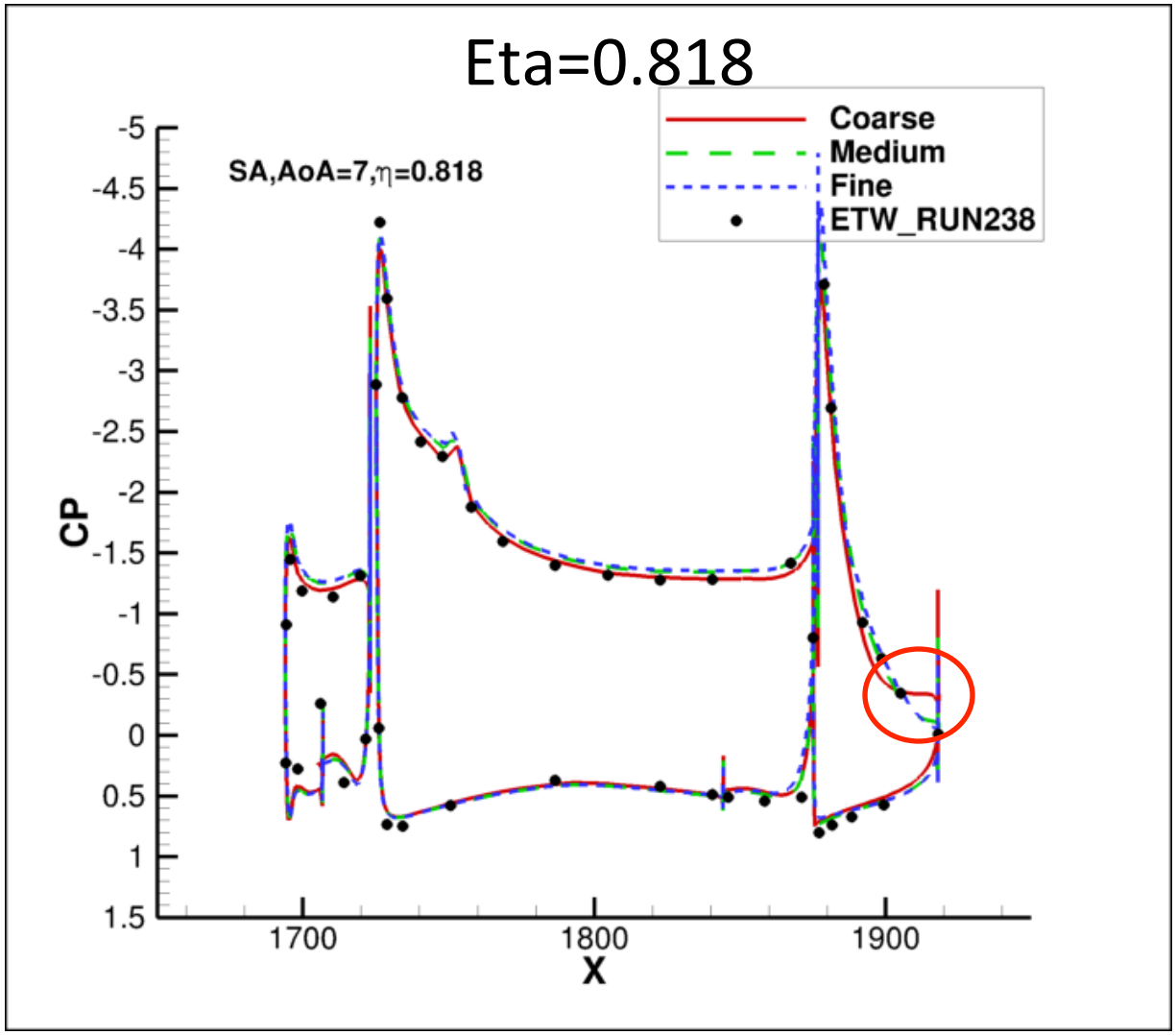
Grid dependency of Cp at AoA=7 (SA-noft2-R)

- At inner section, the differences by the grid density are minor



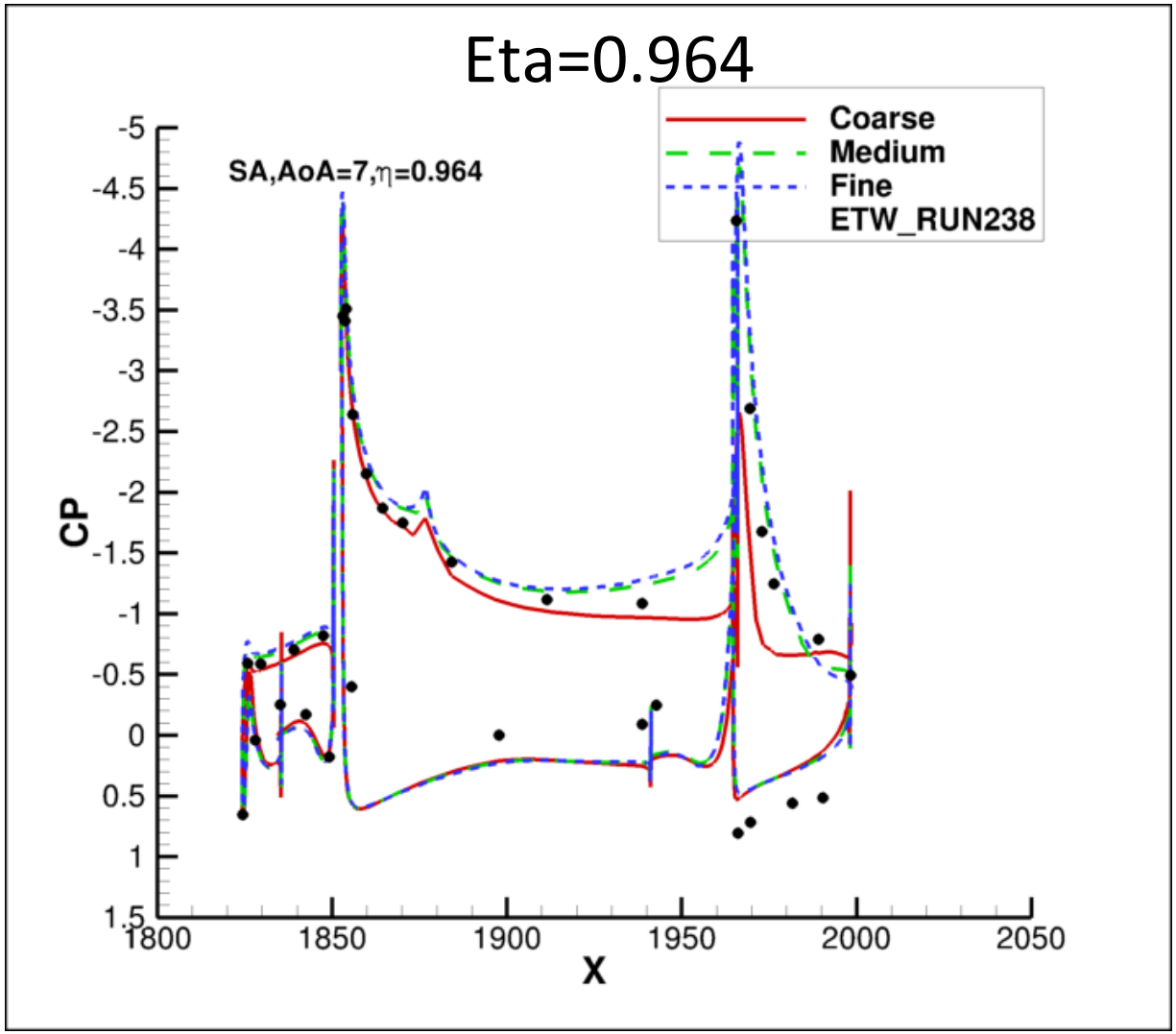
Grid dependency of Cp at AoA=7 (SA-noft2-R)

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



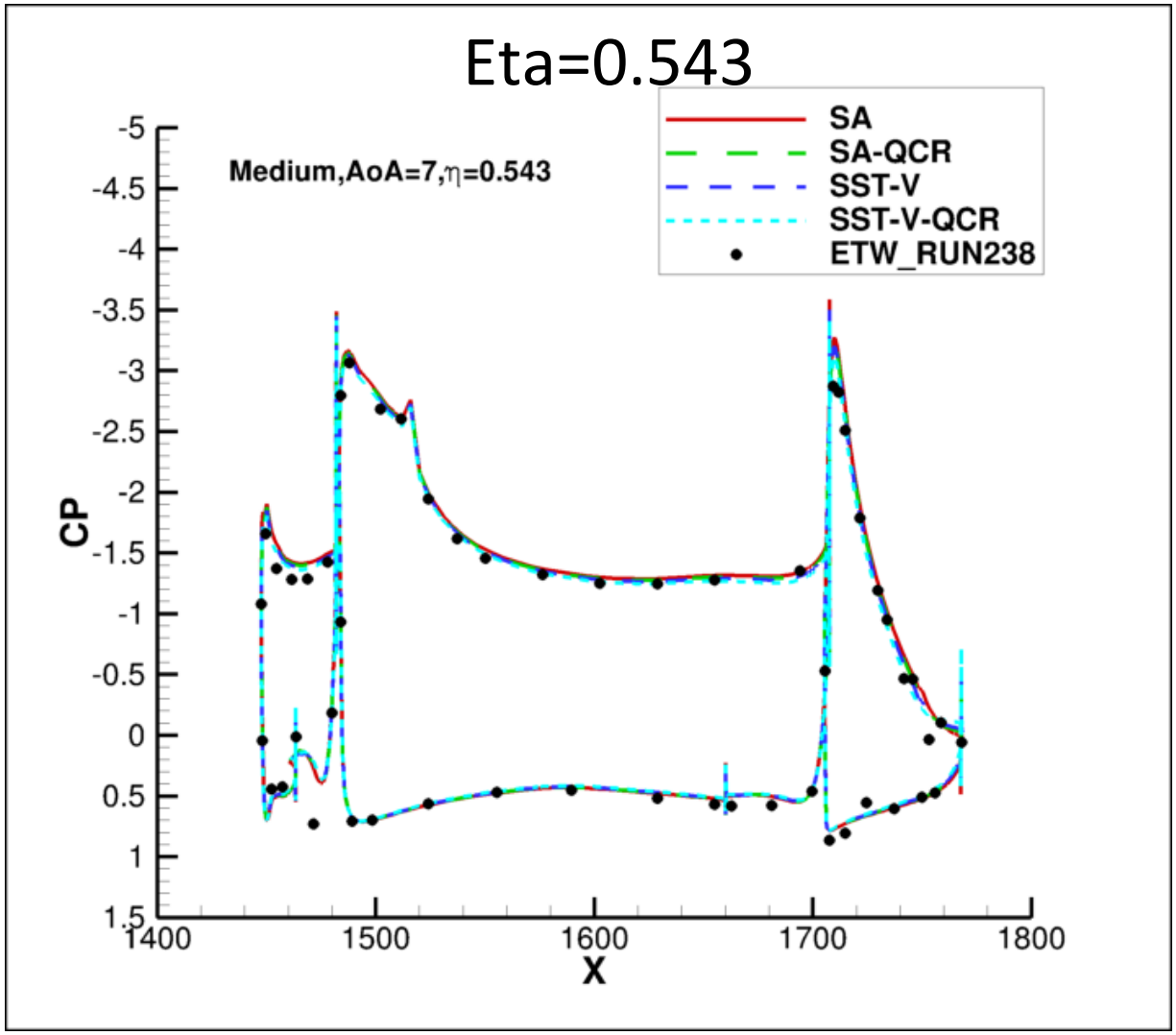
Grid dependency of Cp at AoA=7 (SA-noft2-R)

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



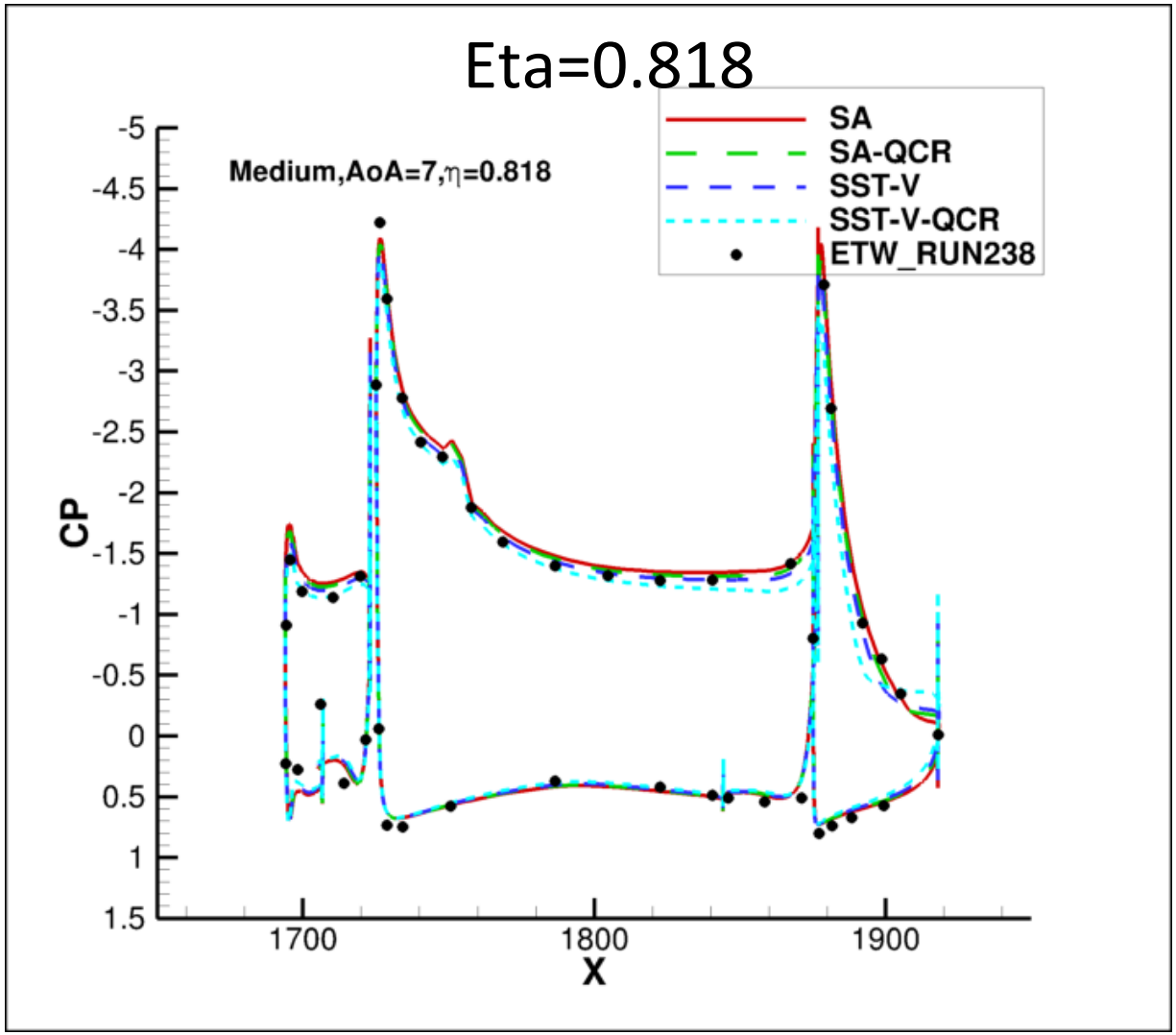
Cp differences by turb. models at AoA=7 (Medium)

- At inner section, the differences by the turbulence models are minor



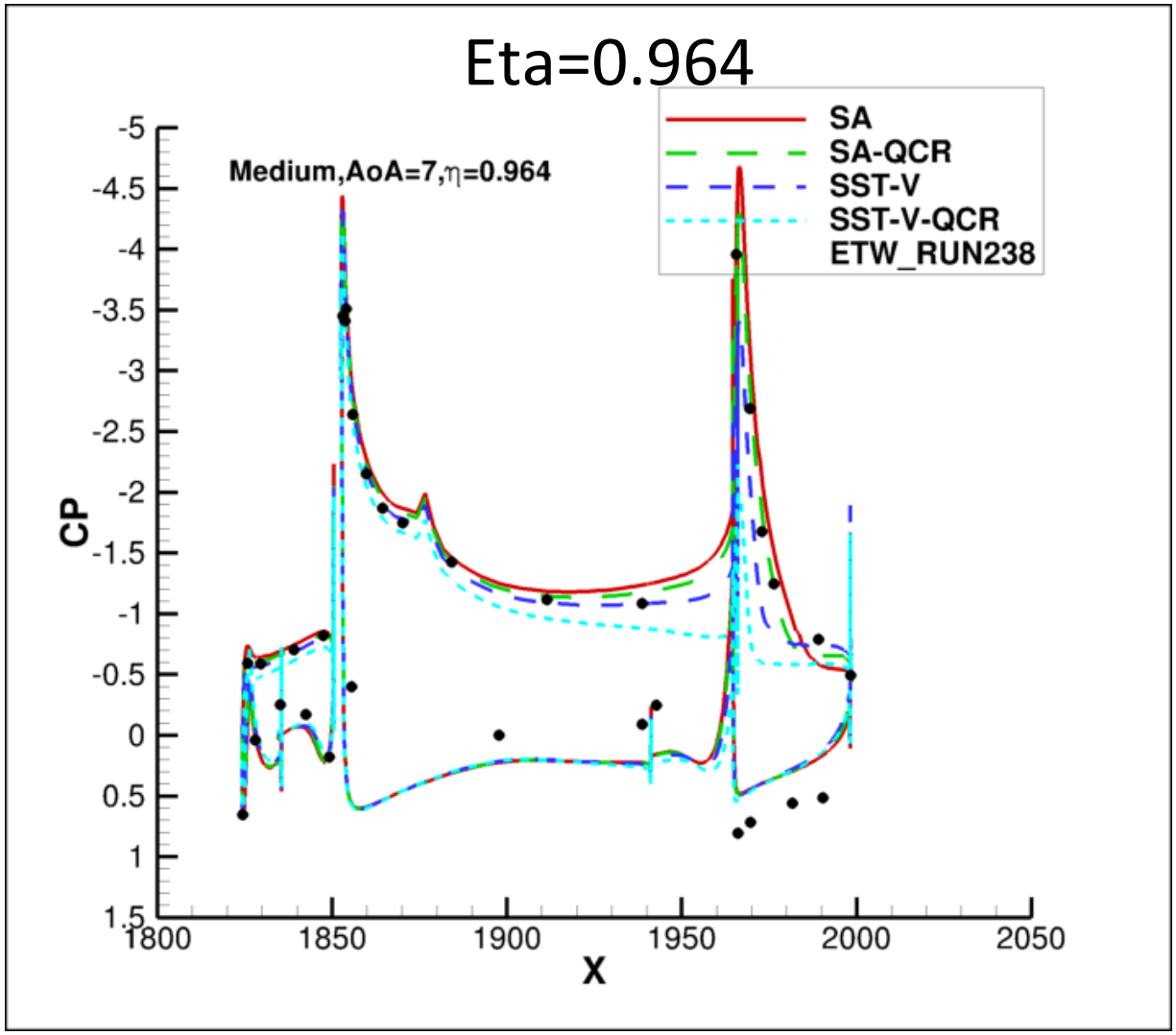
Cp differences by turb. models at AoA=7 (Medium)

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

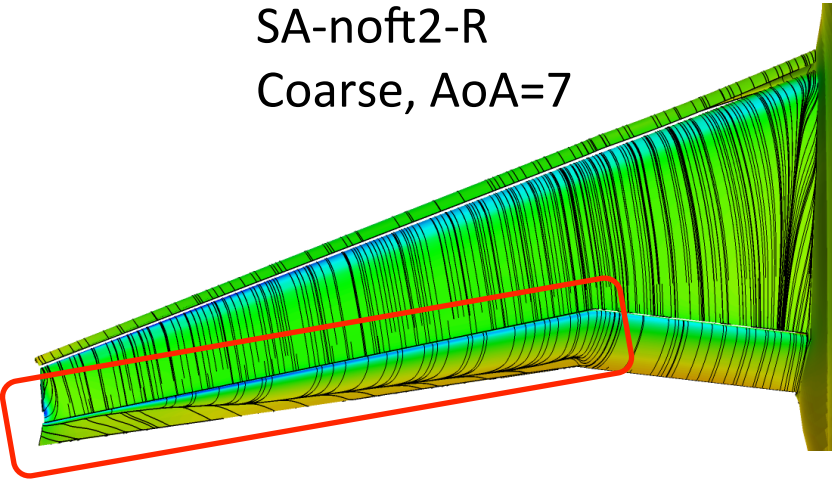


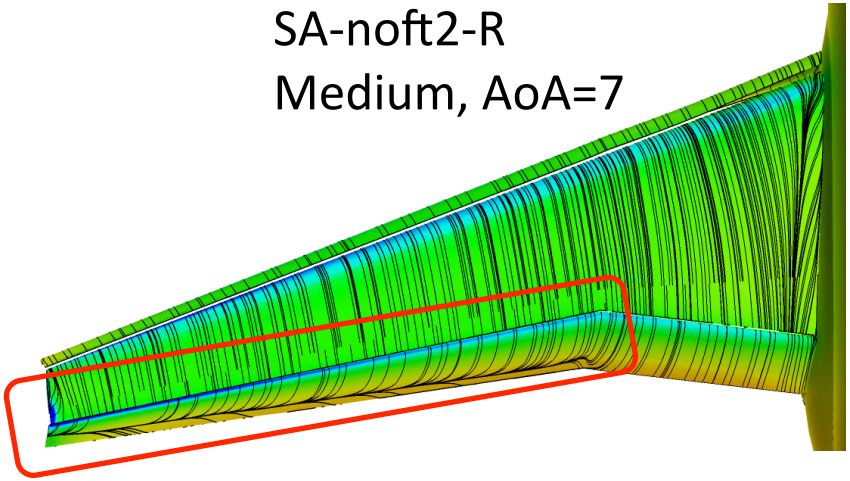
Grid dependency of Cp at AoA=7 (SA-noft2-R)

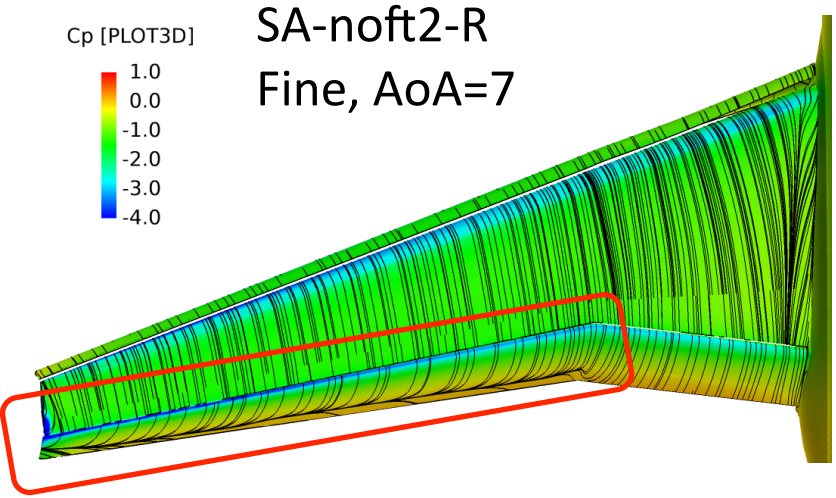
- Major differences are found at outer section
  - Earlier flow separation on the flap by SST especially with QCR



Comparison of surface flow by grid density





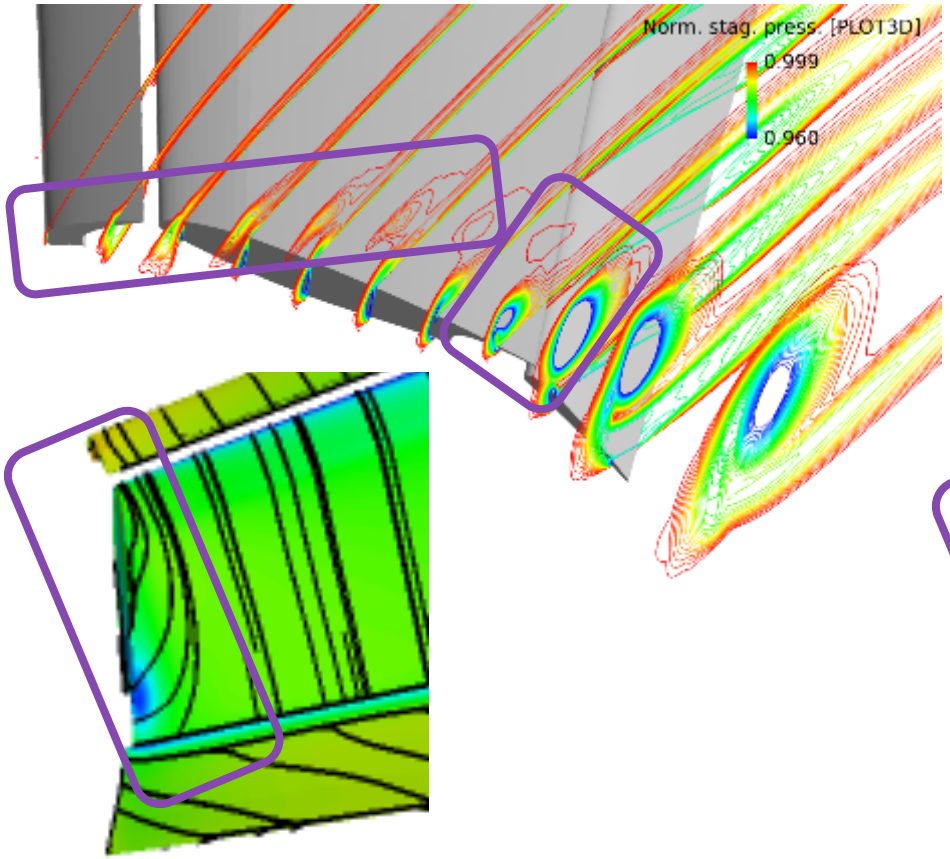


- Flow separation on the flap decreases with increasing grid points (the same tendency for all turb. models)

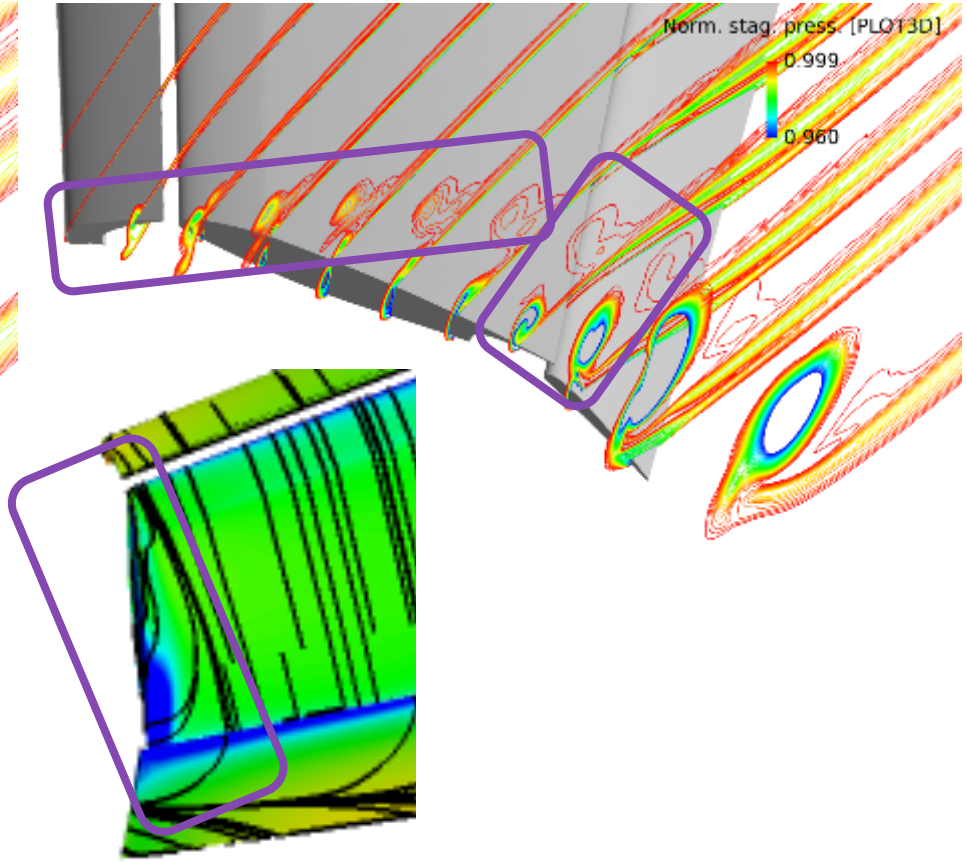
  → C_L increase and pitch-down C_M

Differences of the tip vortices by the grid density

- The vortices rolled-up from the slat side-edge are weaker and rapidly involved by the vortices rolled up from the side-edge of the main wing
  - The differences also contribute to the differences of Cp and flow separation near the wingtip and flap-tip



SA-noft2-R, Coarse, AoA=7

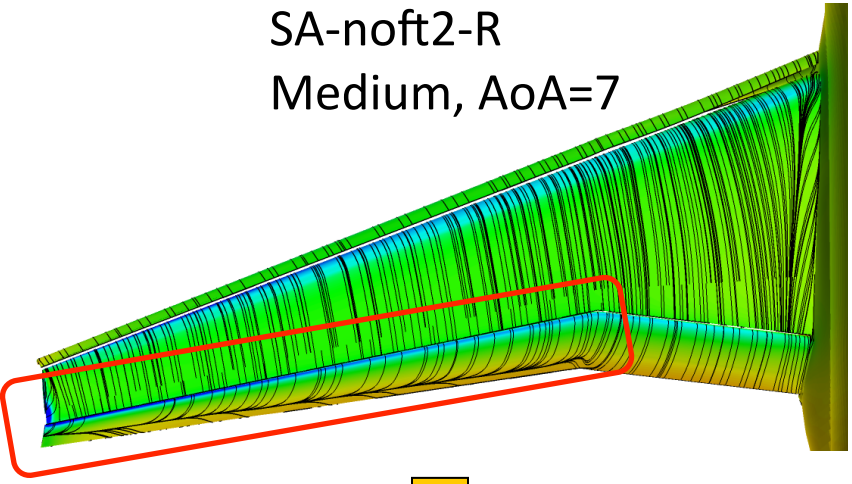


SA-noft2-R, Fine, AoA=7

Comparison of surface flow by turb. model

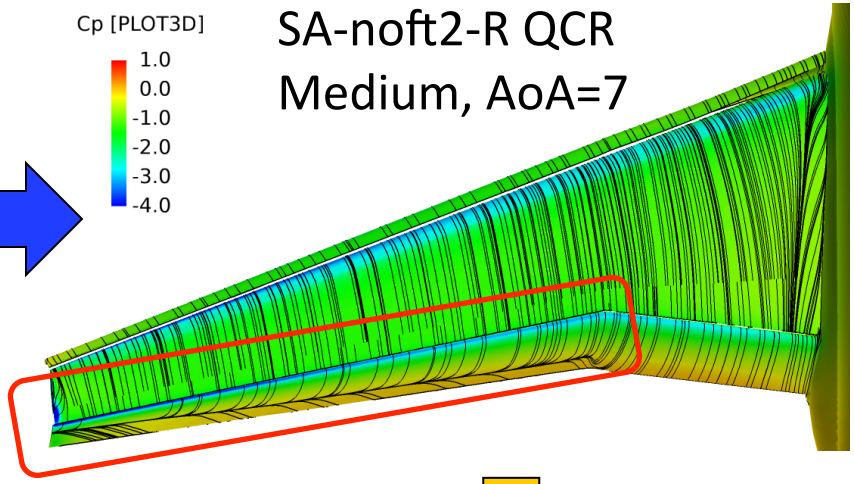
Earlier flow separation with QCR

SA-noft2-R
Medium, AoA=7



Cp [PLOT3D]
1.0
0.0
-1.0
-2.0
-3.0
-4.0

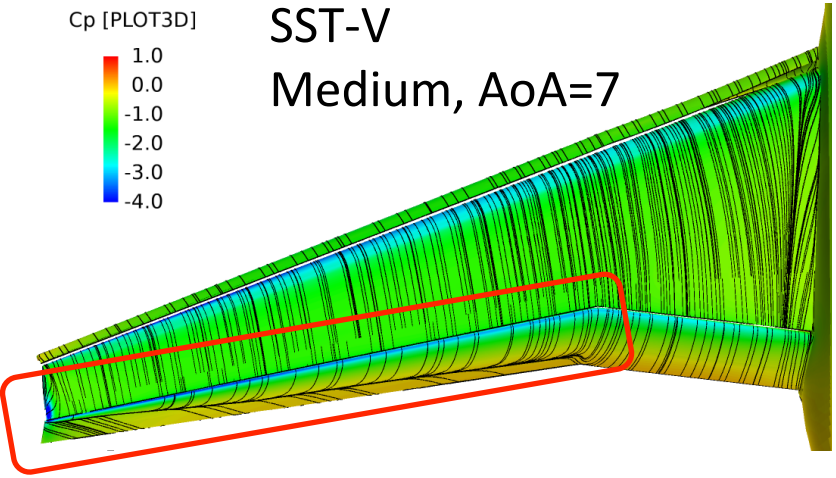
SA-noft2-R QCR
Medium, AoA=7



Earlier flow separation by SST

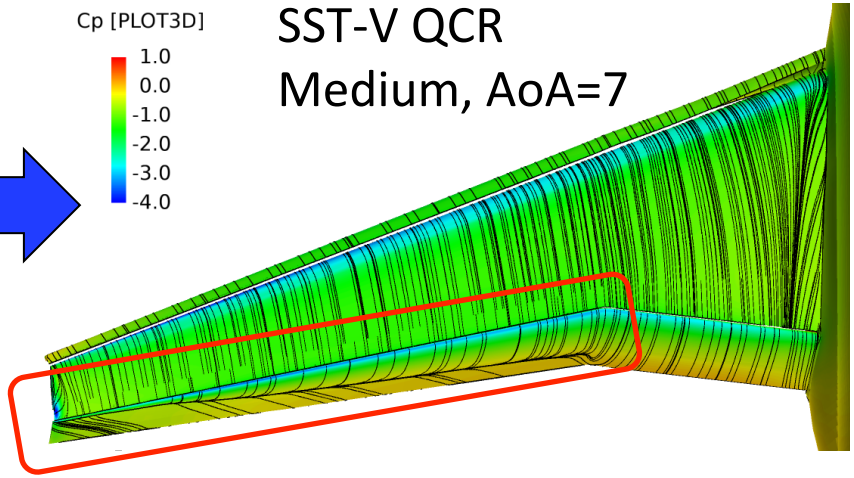
Cp [PLOT3D]
1.0
0.0
-1.0
-2.0
-3.0
-4.0

SST-V
Medium, AoA=7



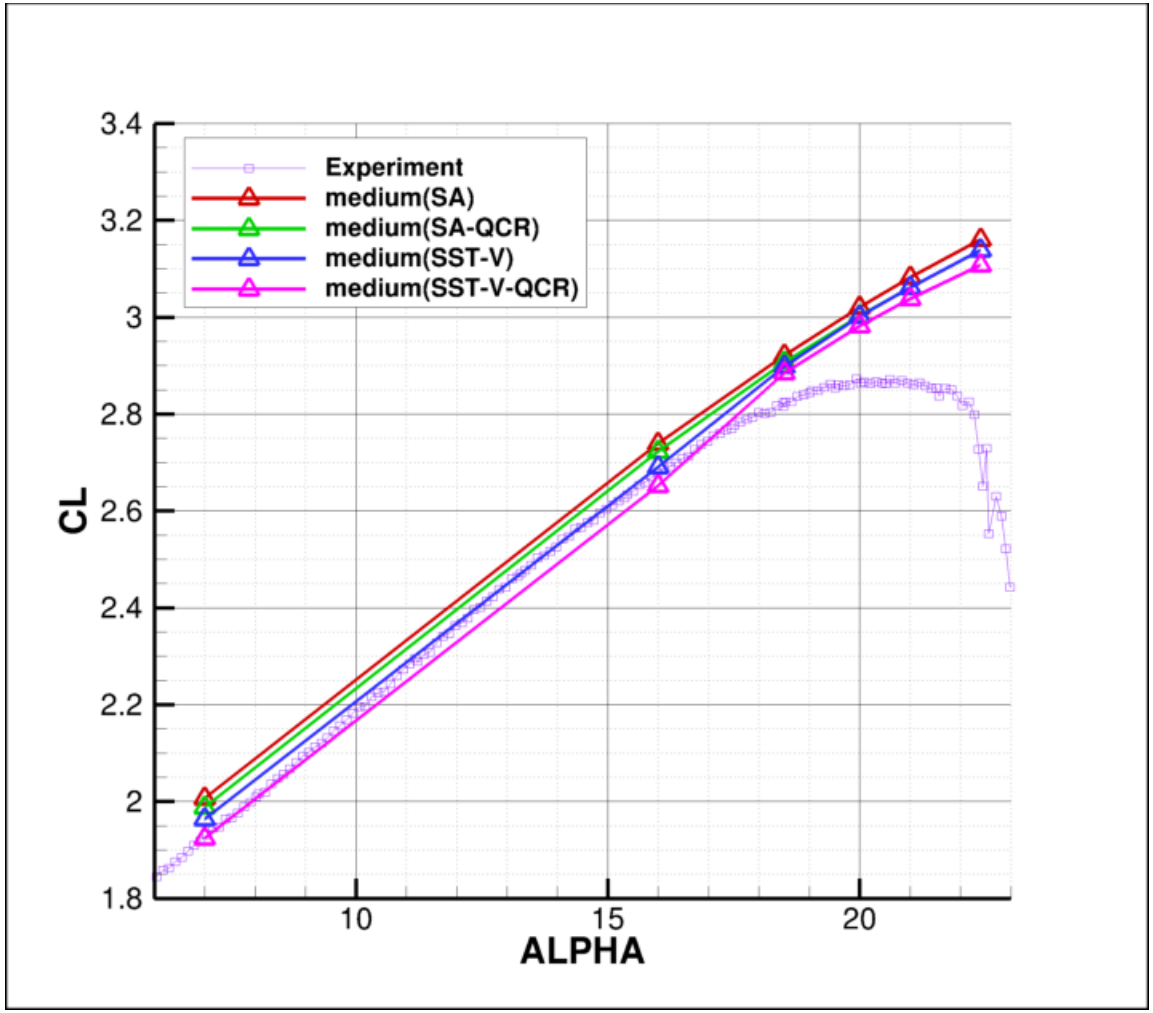
Cp [PLOT3D]
1.0
0.0
-1.0
-2.0
-3.0
-4.0

SST-V QCR
Medium, AoA=7



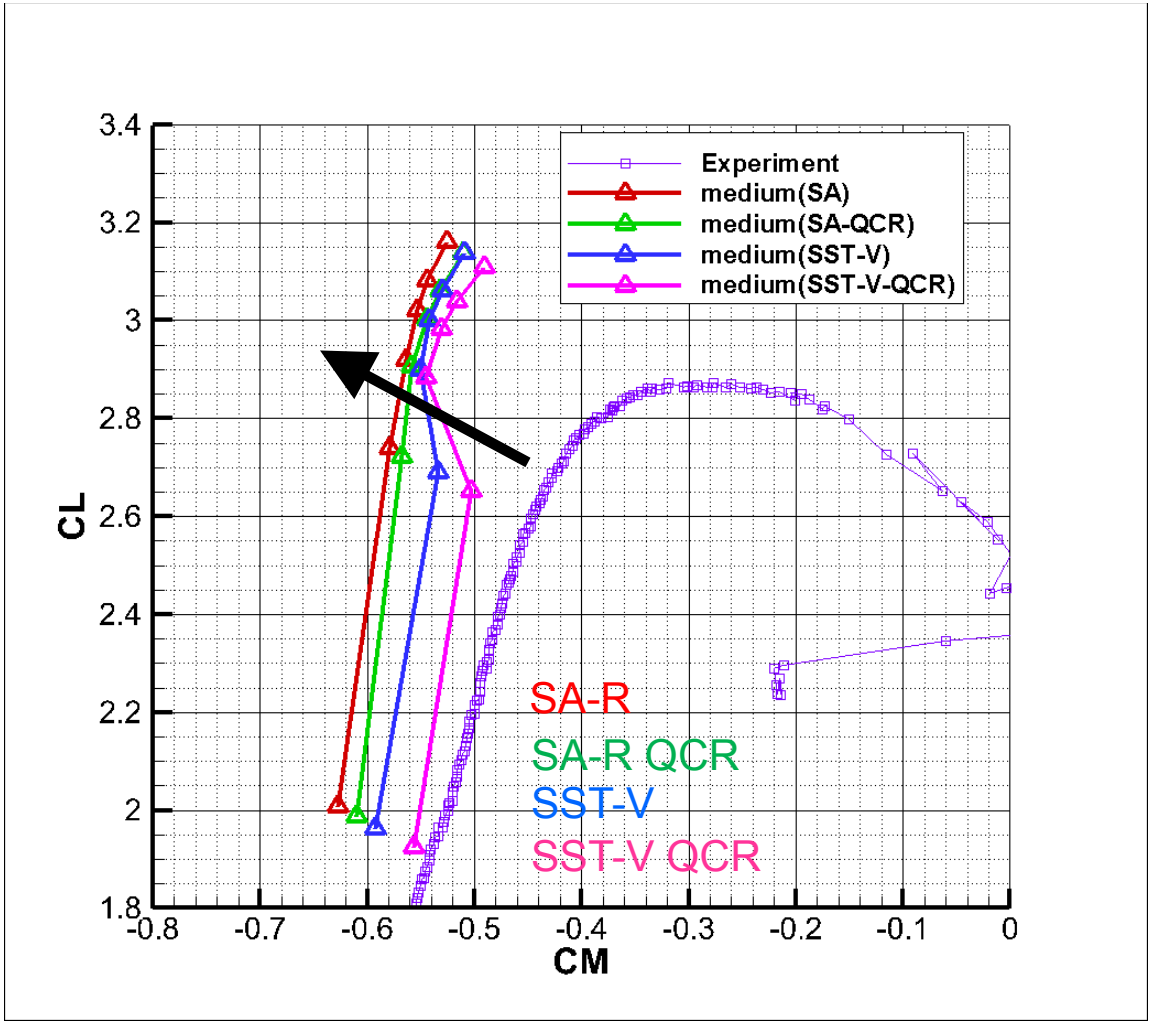
Comparison of α-sweep on medium grid by turb. model

- Results using both turbulence models do not show stall behavior even at AoA=22.4
- Results using SST-V shows a kink of C_L-α curve



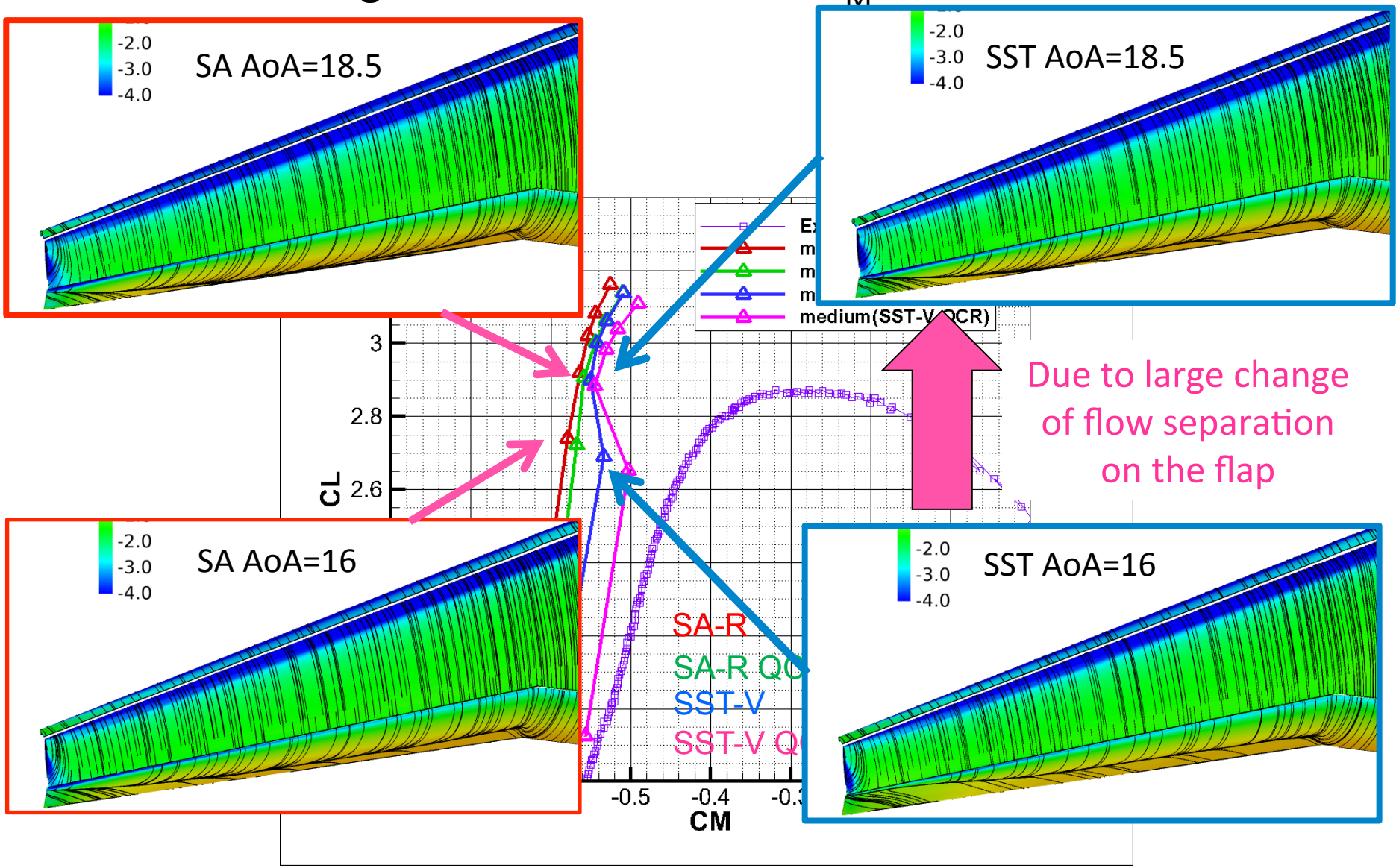
Comparison of α-sweep on medium grid by turb. model

- Results using SST-V shows a kink of C_M



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

- Results using SST-V shows a kink of C_M



1. Case4: Turbulence Model Grid-Convergence Verification Study by UPACS

2. Grid convergence studies for the SA and SST models using UPACS

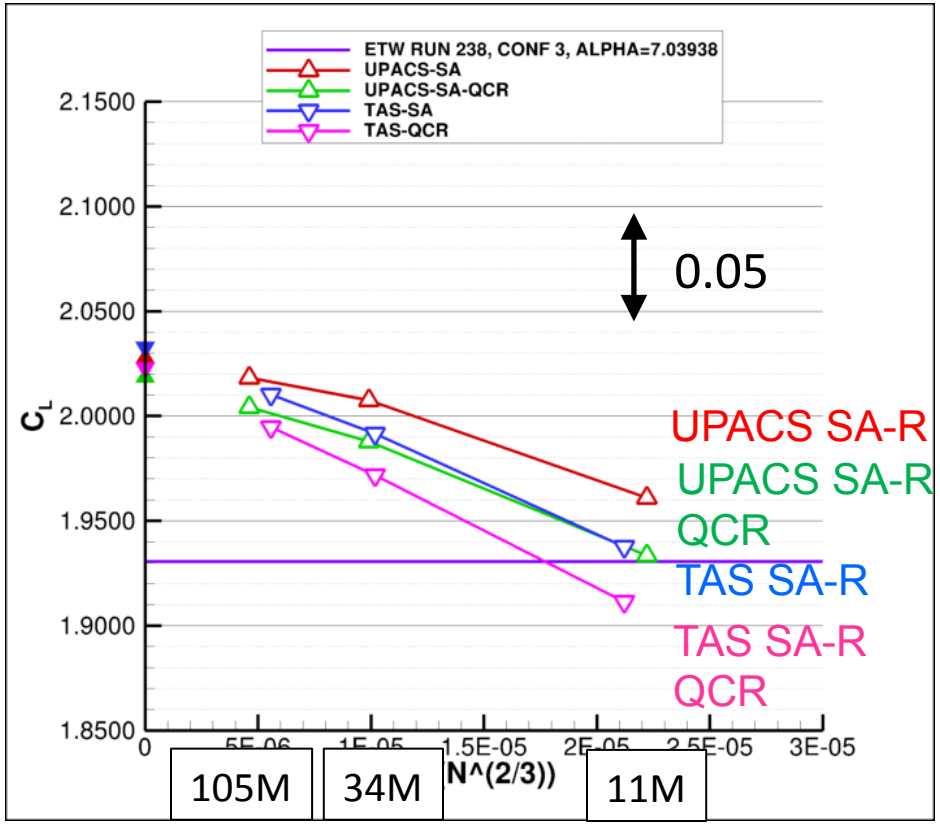
3. Change of grid convergence and predicted flow fields w/ & w/o QCR for the SA and SST using UPACS including evaluation at higher AoAs

4. Comparison studies using different solvers UPACS and TAS on different grid systems w/ & w/o QCR for the SA model

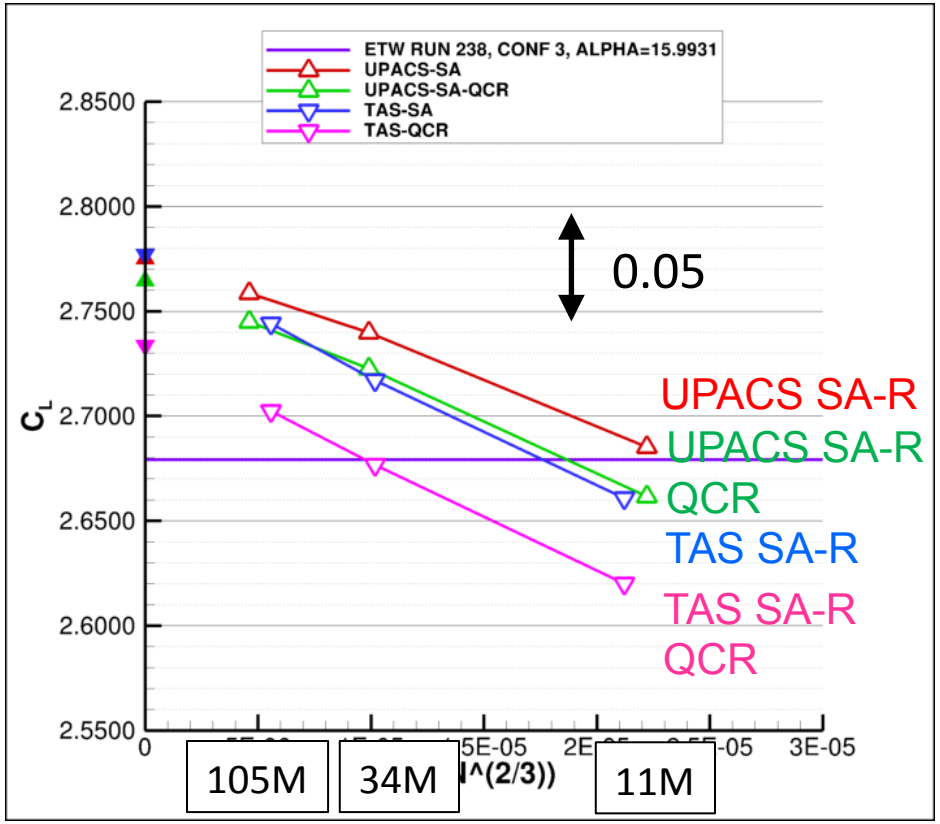
Grid convergence of C_L

- TAS results on GridD tend to show lower C_L, while similar grid converged C_L with UPACS on GridA (except for TAS-QCR AoA=16)
- QCR reduces C_L for both UPACS on GridA and TAS on GridD

AoA=7



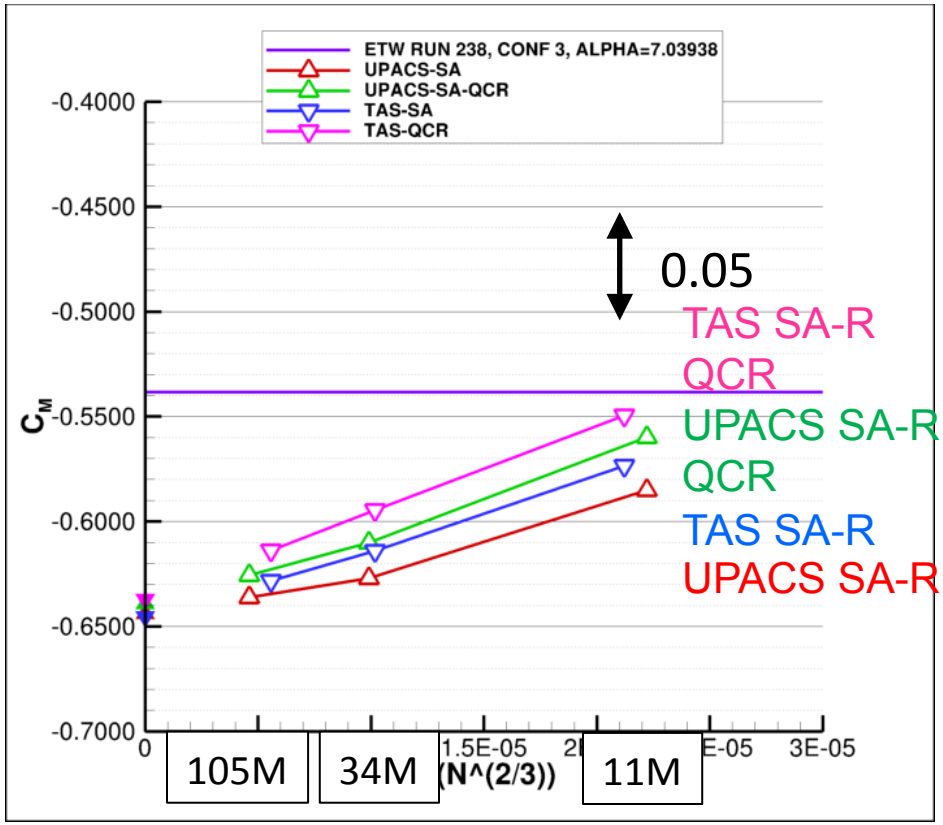
AoA=16



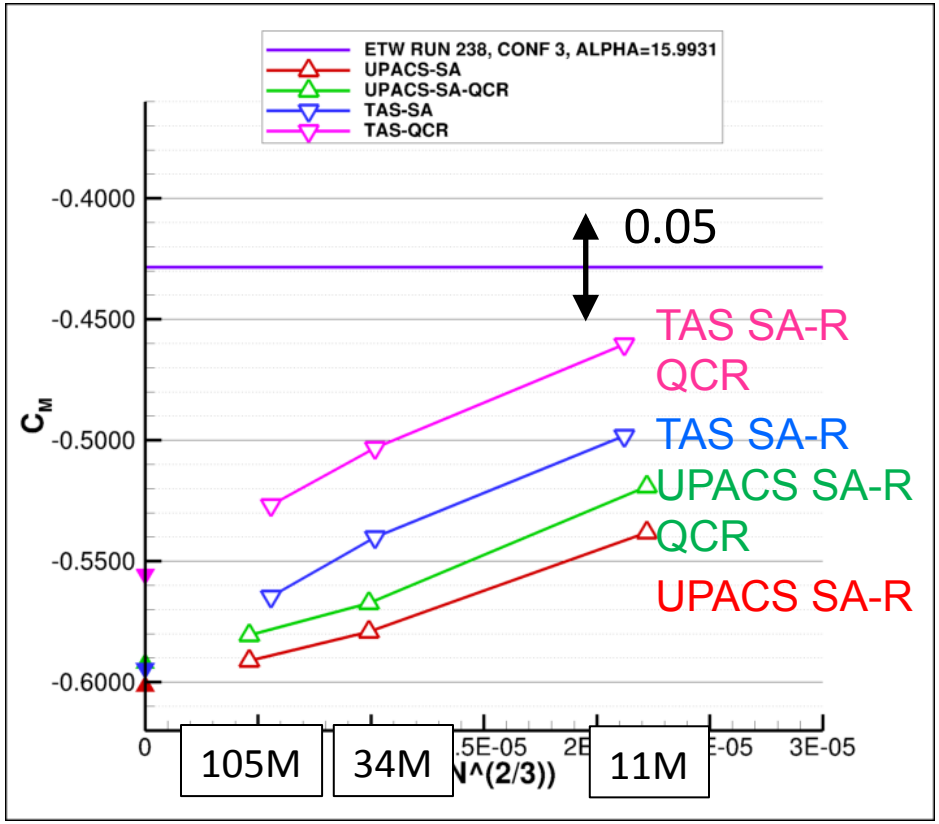
Grid convergence of C_M

- TAS results on GridD tend to show less pitch-down C_M
- Similar grid converged C_M with UPACS
  - Except for TAS-QCR AoA=16
- QCR reduces pitch-down C_M for both UPACS and TAS

AoA=7



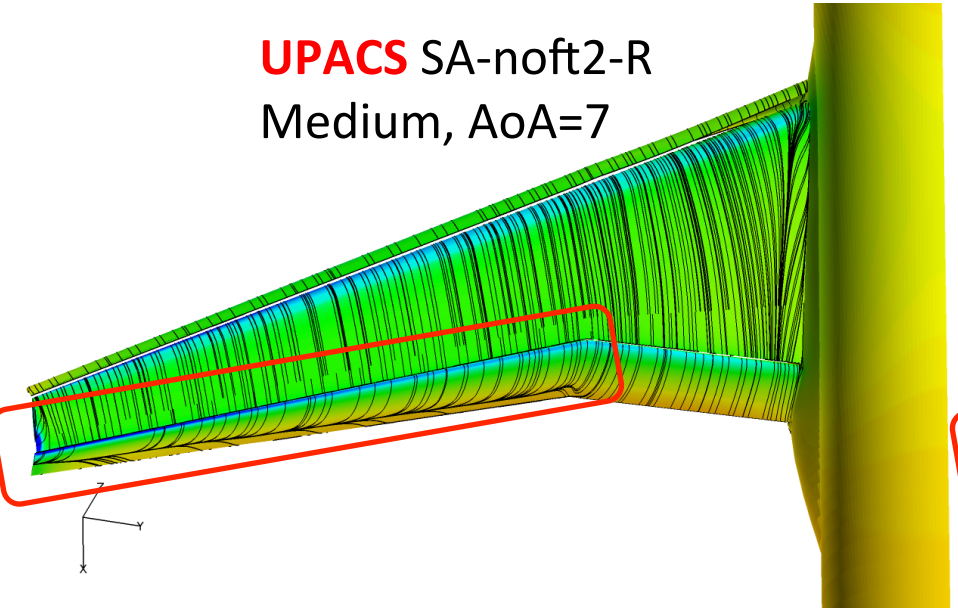
AoA=16

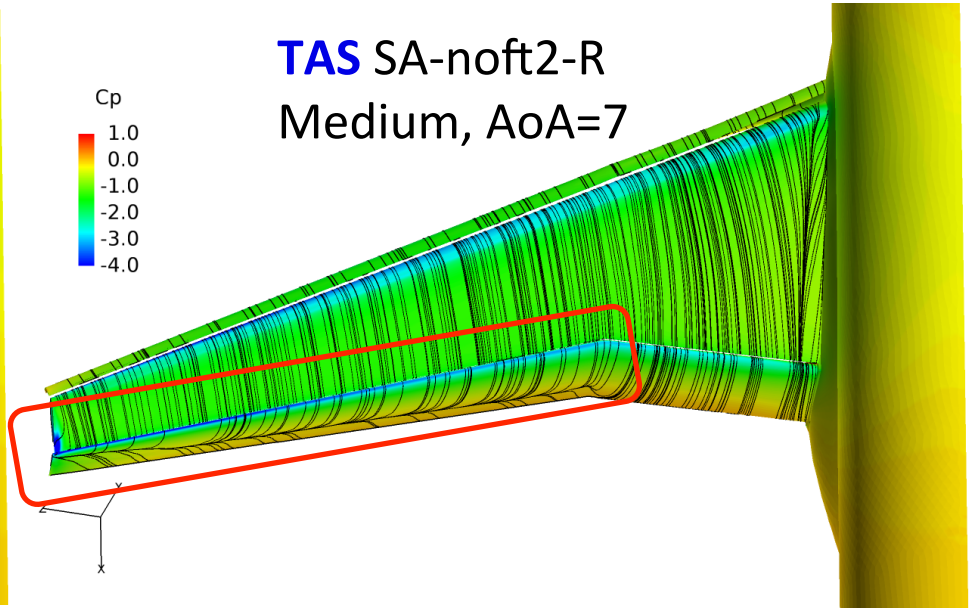


Comparison of surface flow between UPACS and TAS

- Earlier flow separation on the flap than that of UPACS on GridA

  → Lower C_L and less pitch-down C_M





Concluding Remarks

- Two different solvers UPACS and TAS produced similar grid converged aerodynamic forces in most cases even on different grid systems

- Grid convergence study
  - C_L increases and C_M decreases with increasing grid points
  - Flow separation on the flap tends to decrease with increasing grid points
- Comparison of SA and SST
  - SA predicts higher C_L and more pitch-down 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 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

- The above results are consistent with our previous results in HiLiftPW-1 using NASA Trap Wing Model

Backup charts

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**

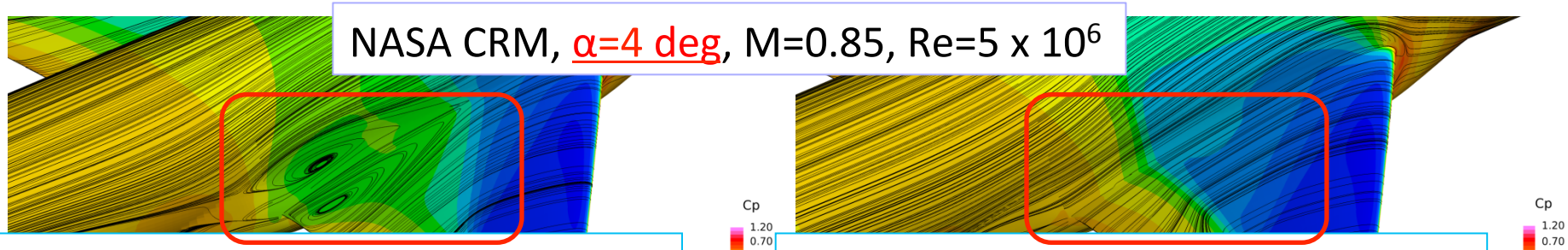
→ Quadratic Constitutive Relation (QCR200) P.R. Spalart / Int. J. Heat and Fluid Flow (2000)

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

- 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

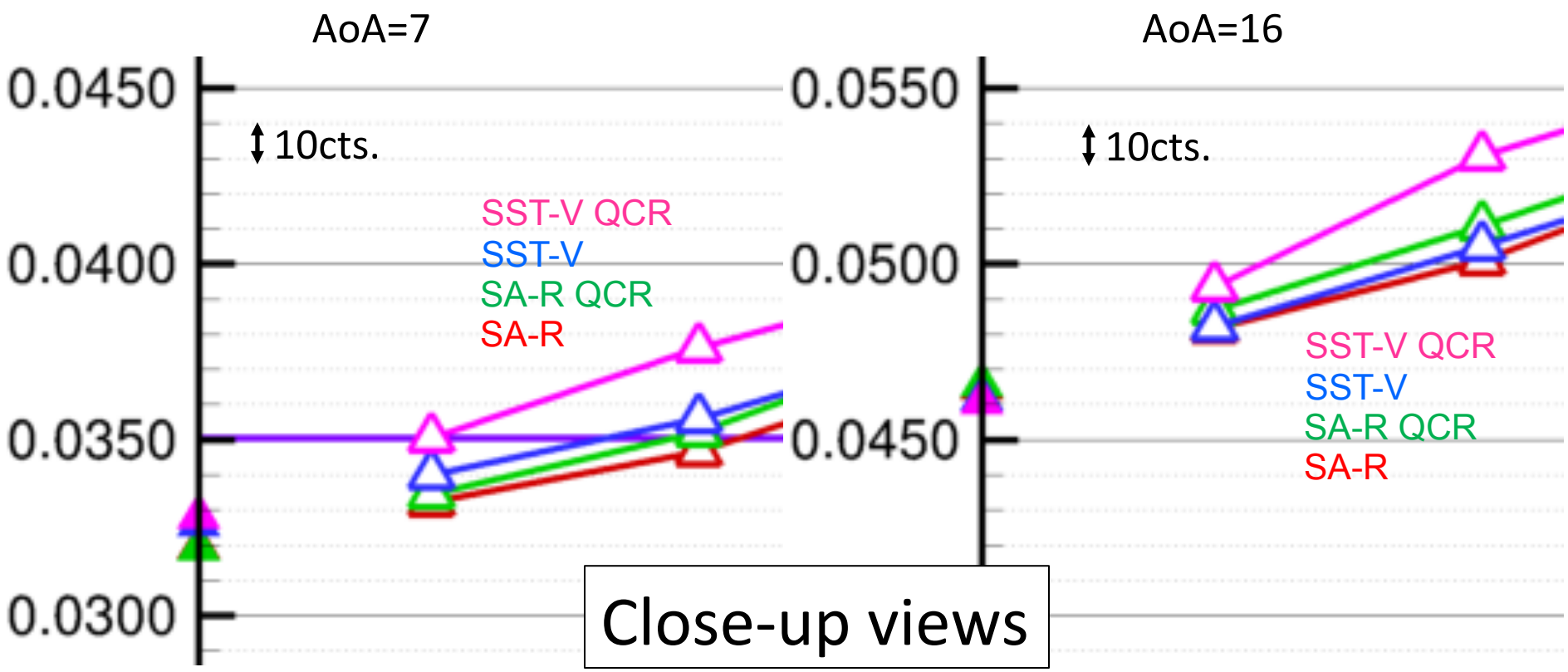


Spalart-Allmaras model
with **original eddy-viscosity Reynolds stress**

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

Grid convergence of C_D-$C_{Dinduced}$

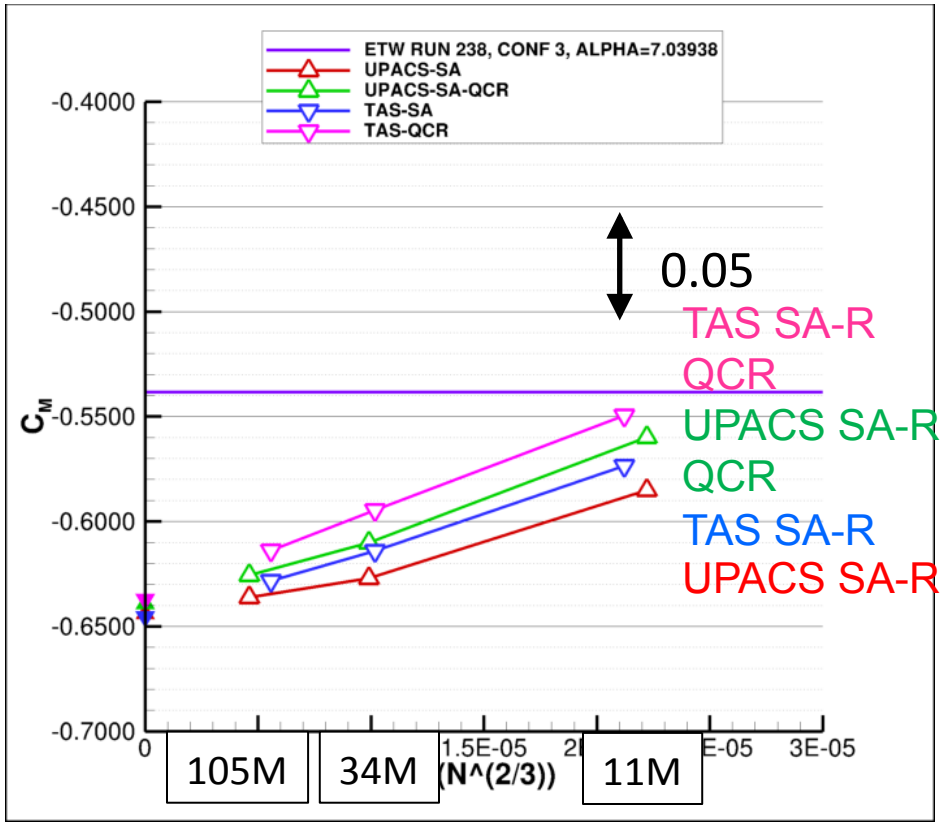
- C_D-$C_{Dinduced}$ is compared
  - Ideal $C_{Dinduced}$ =(C_L*C_L)/(PI*AR)
- Differences of grid converged C_D-$C_{Dinduced}$
  - AoA=7: 10cts.
  - AoA=16: 3cts.



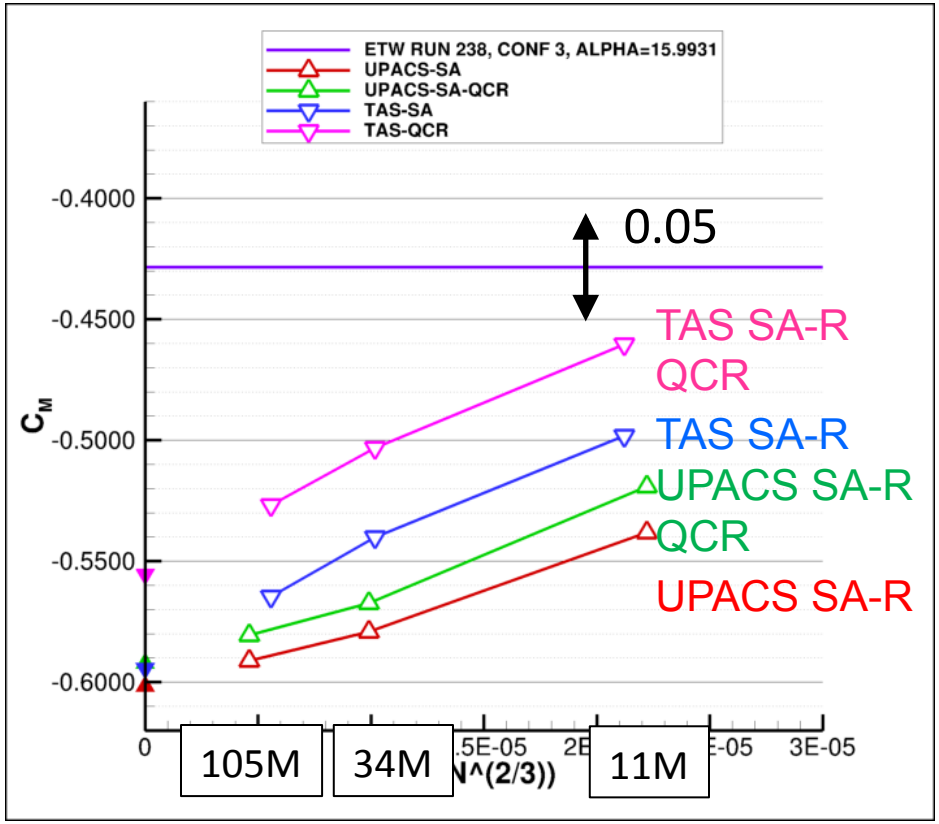
Grid convergence of C_M

- TAS results on GridD tend to show less pitch-down C_M
- QCR reduces pitch-down C_M for both UPACS and TAS

AoA=7



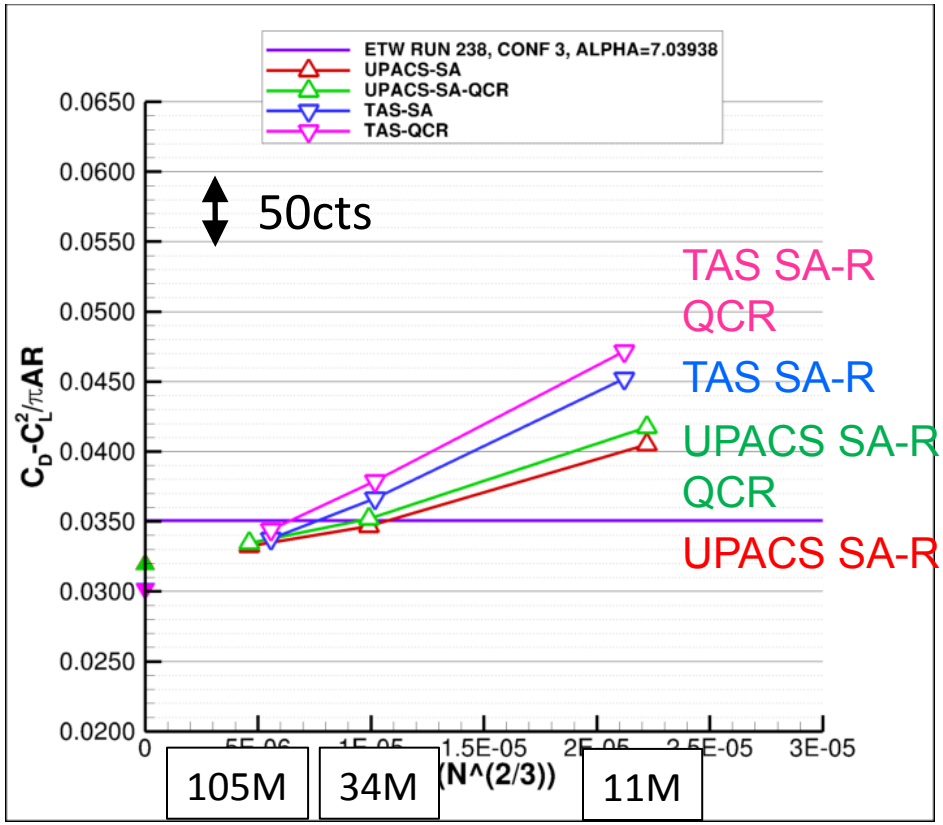
AoA=16



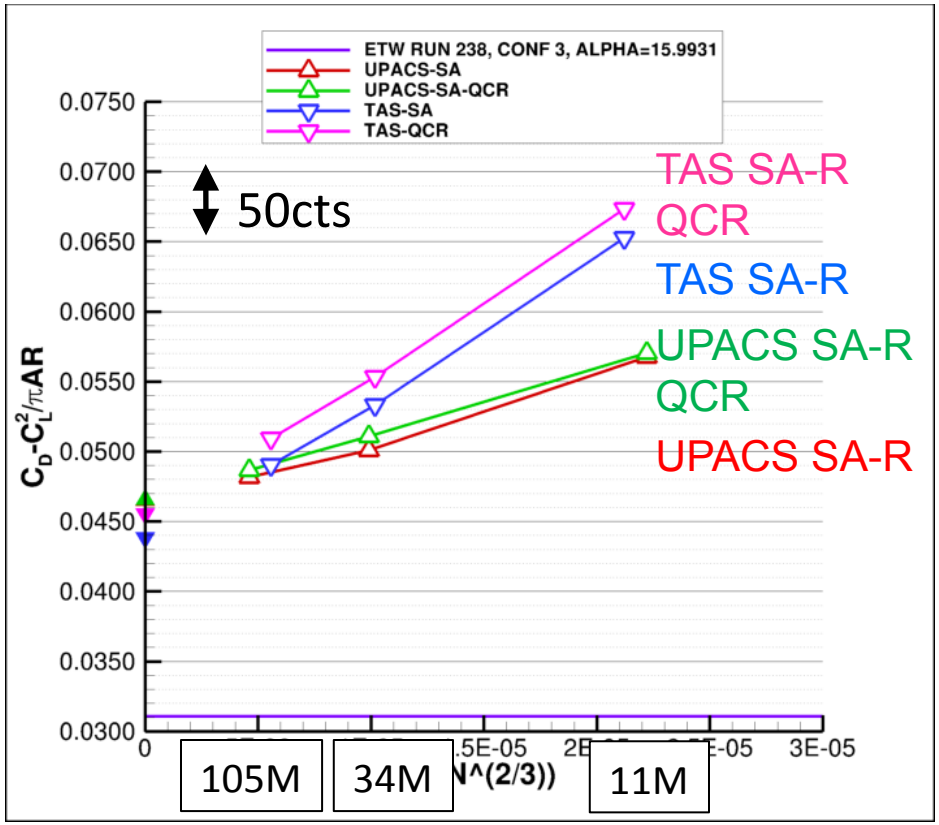
Grid convergence of C_D-$C_{Dinduced}$

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

AoA=7

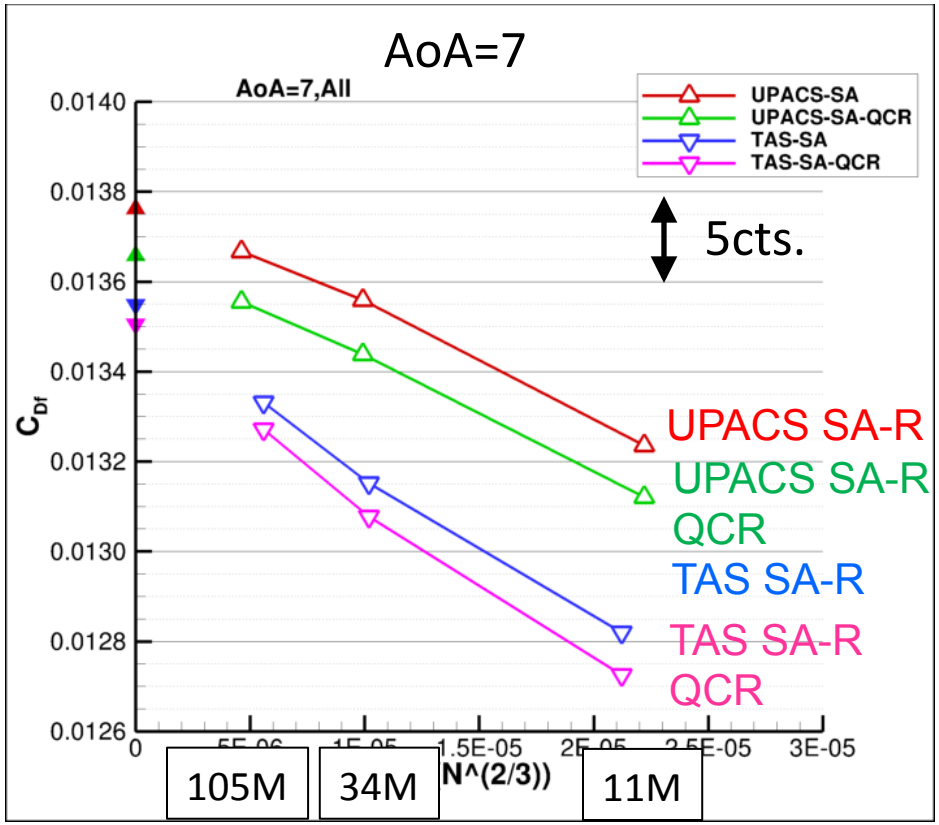


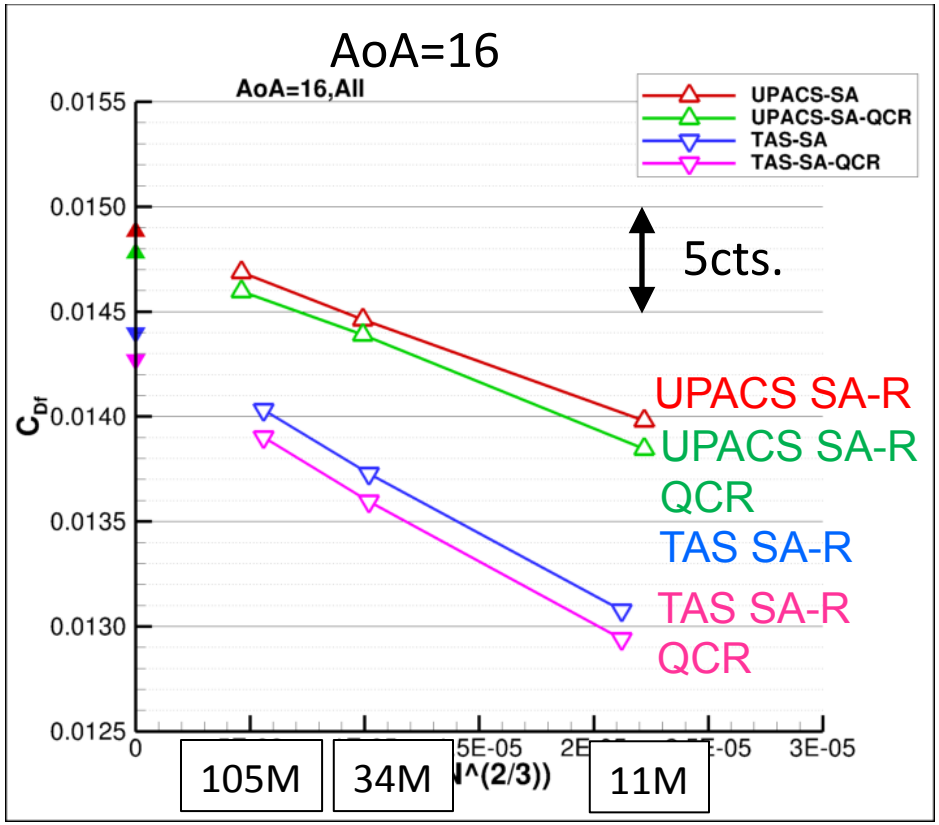
AoA=16



Grid convergence of $C_{Dfriction}$

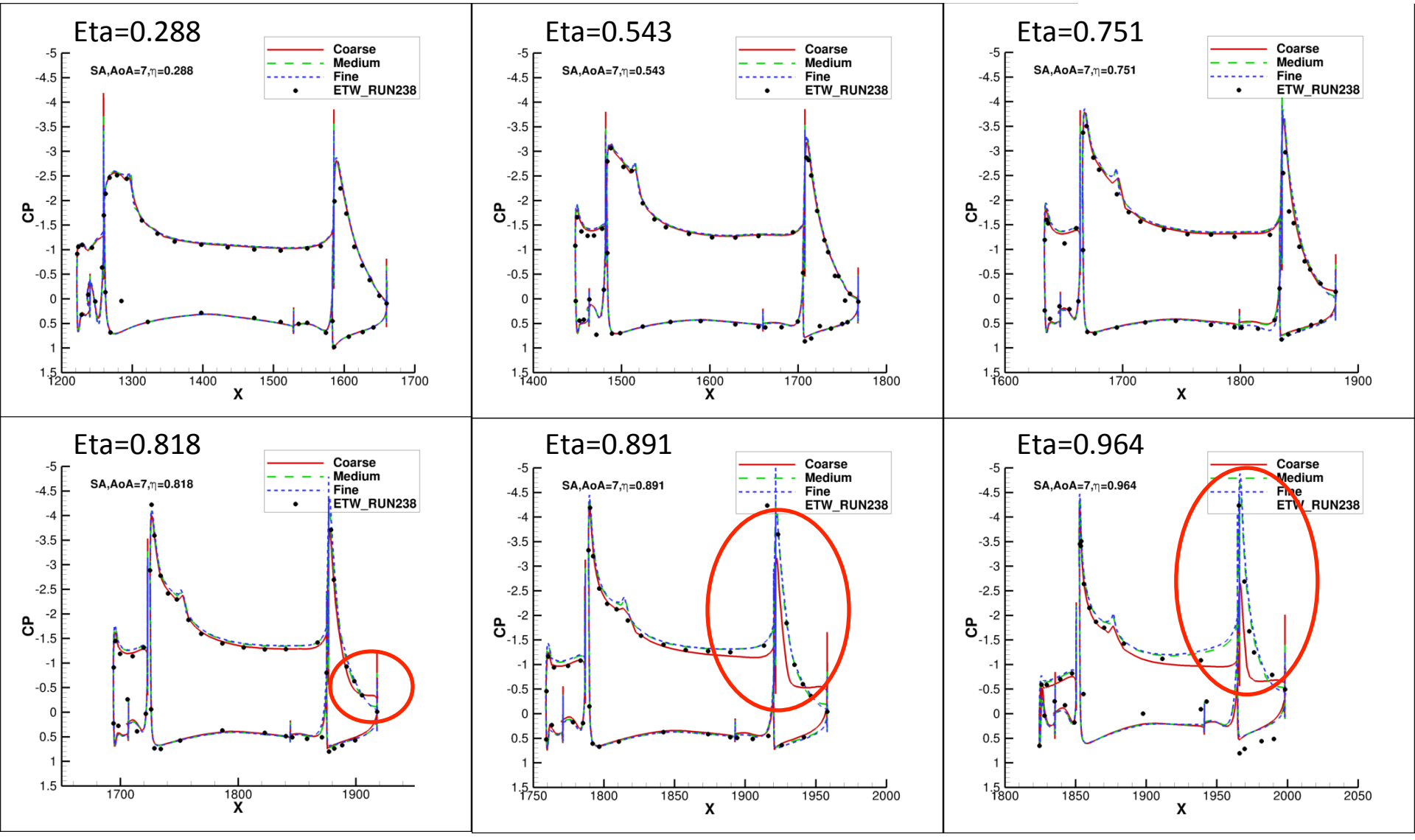
- Variations between UPACS on GridA and TAS on GridD are about 5-7cts.
- Influence w/ and w/o QCR model is almost constant shift for both UPACS on GridA and TAS on GridD. Due to QCR,
  - $C_{D\ friction}$ decreases by 1-2 counts





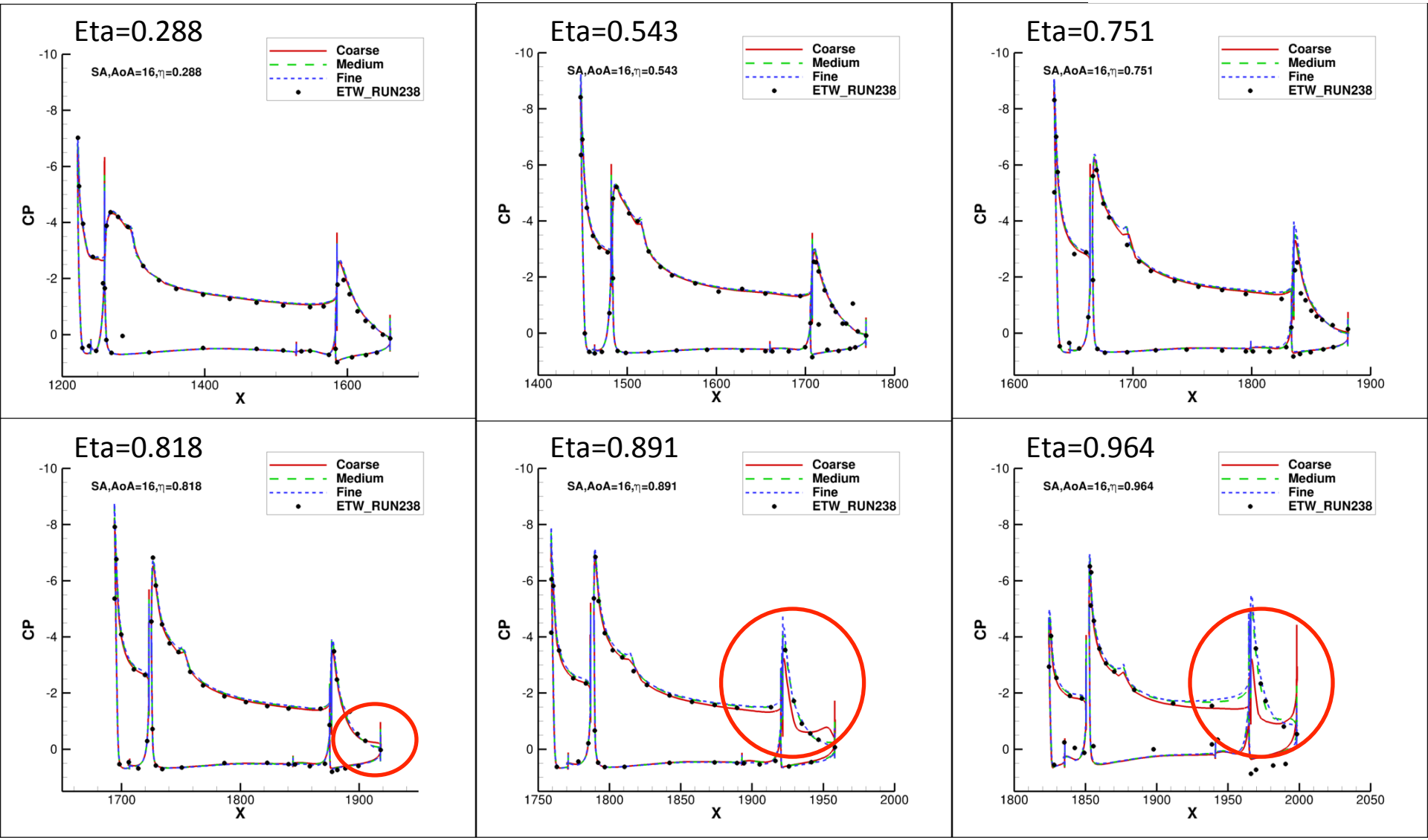
Grid dependency of Cp at AoA=7 (SA-noft2-R)

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



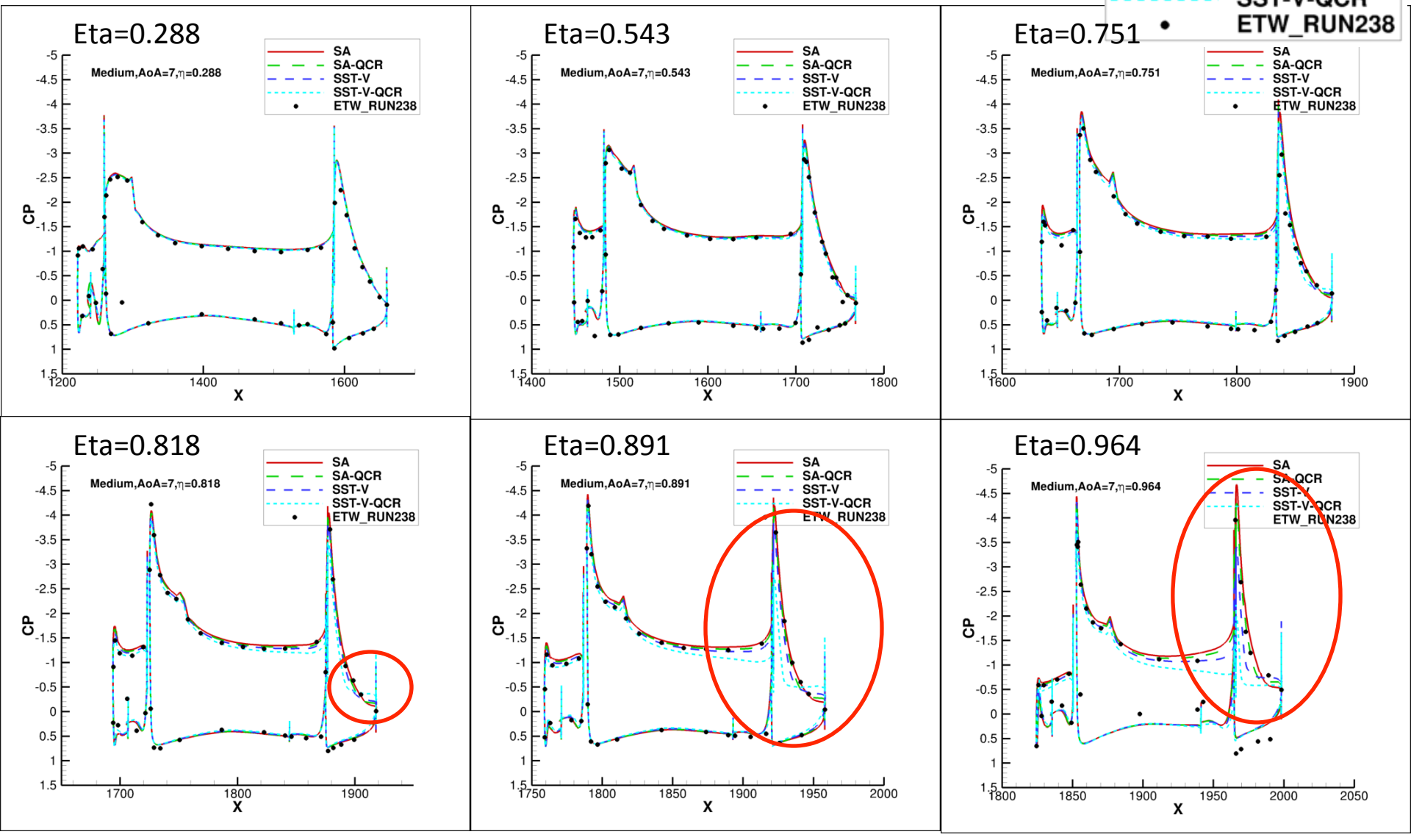
Grid dependency of Cp at AoA=16 (SA-noft2-R)

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



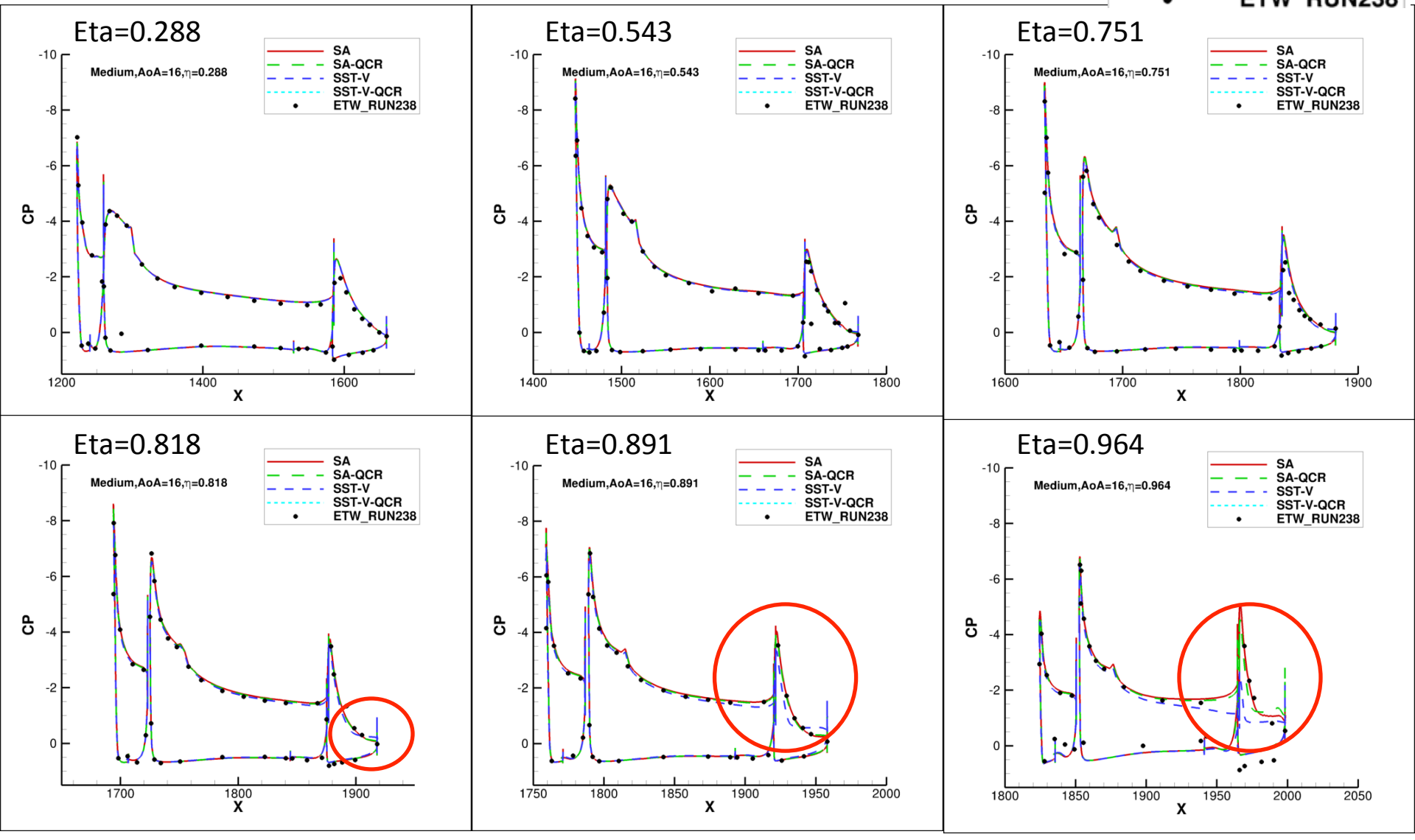
Cp differences by turb. models at AoA=7 (Medium)

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



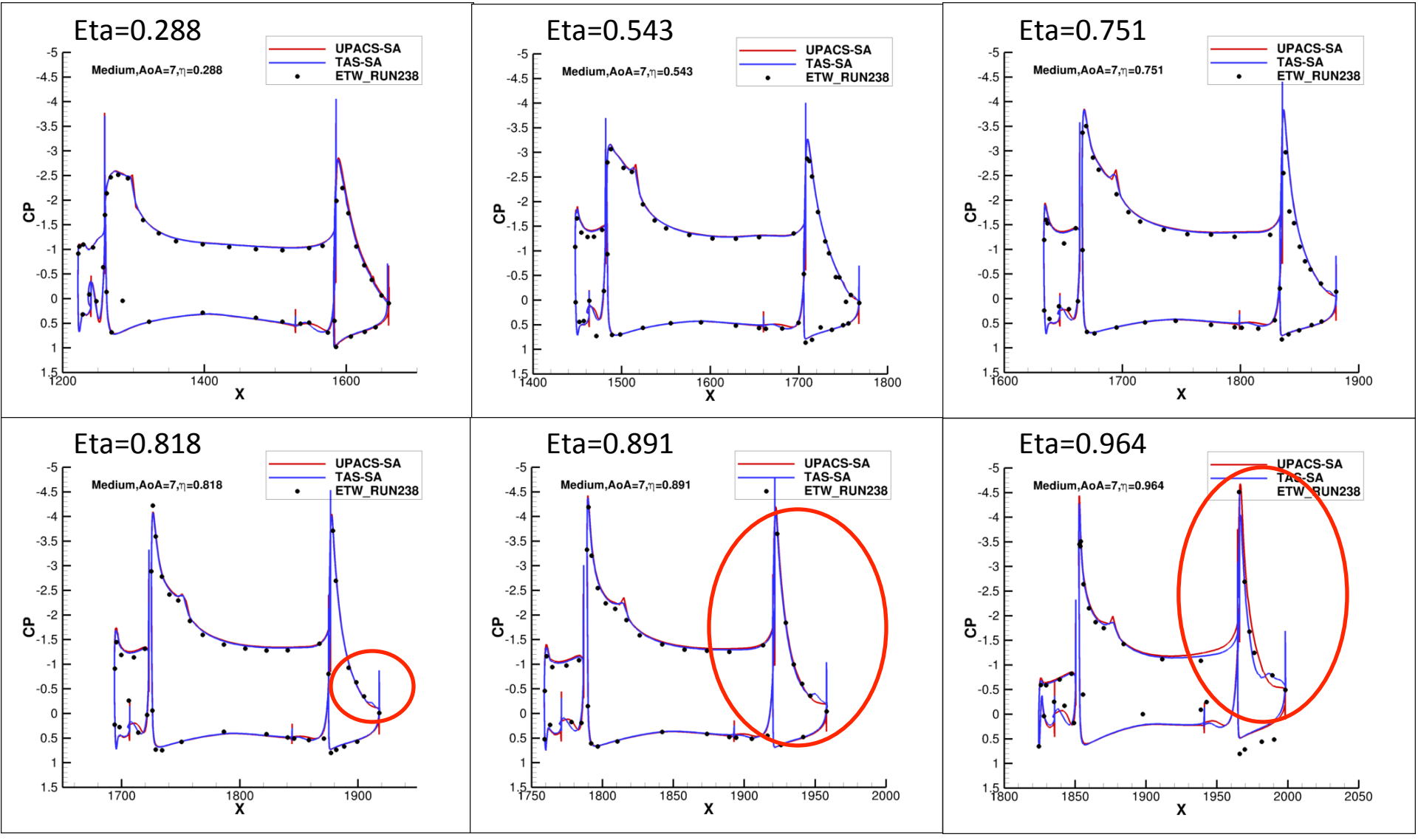
Cp differences by turb. models at AoA=16 (Medium)

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



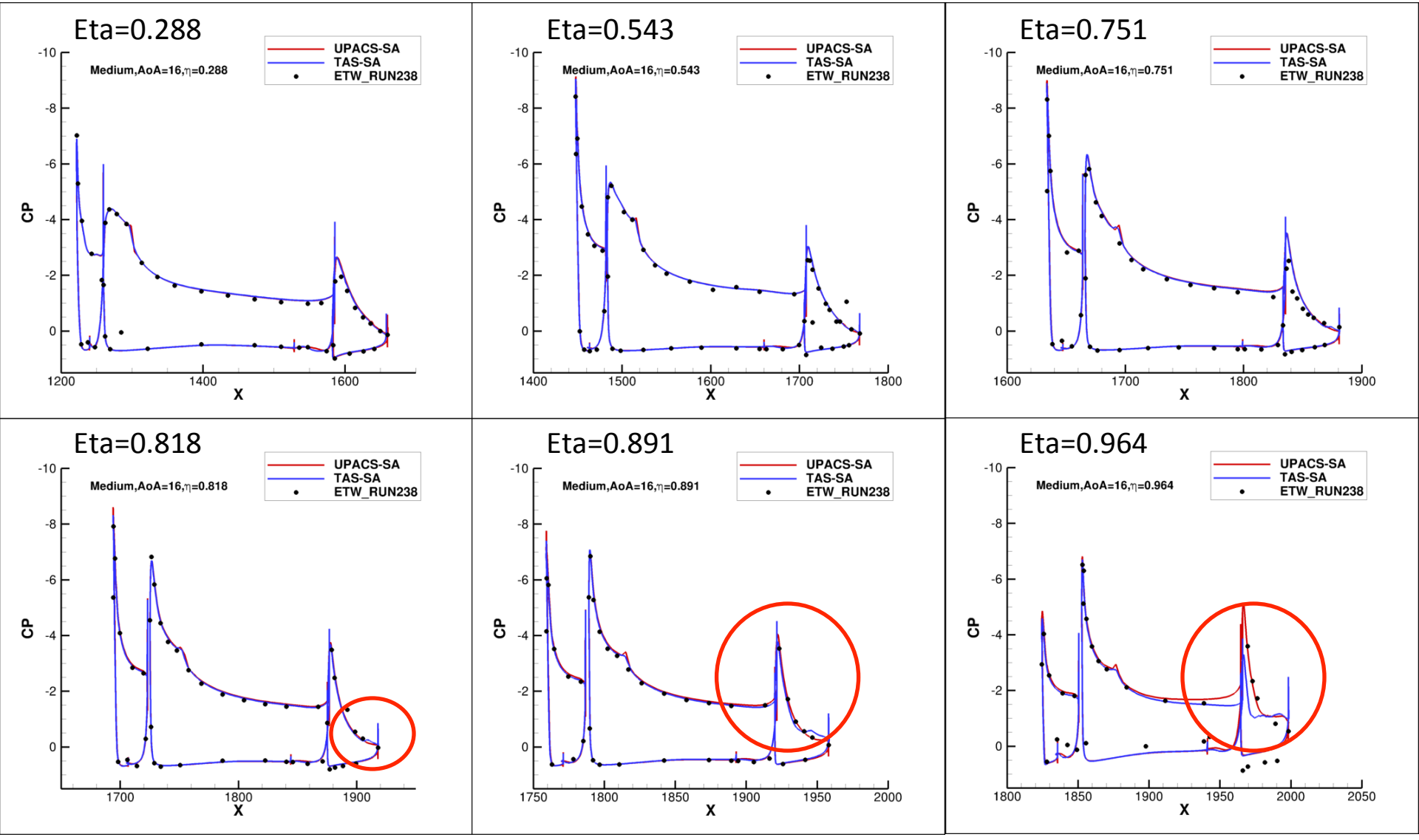
Cp differences between UPACS and TAS at AoA=7 (Medium)

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

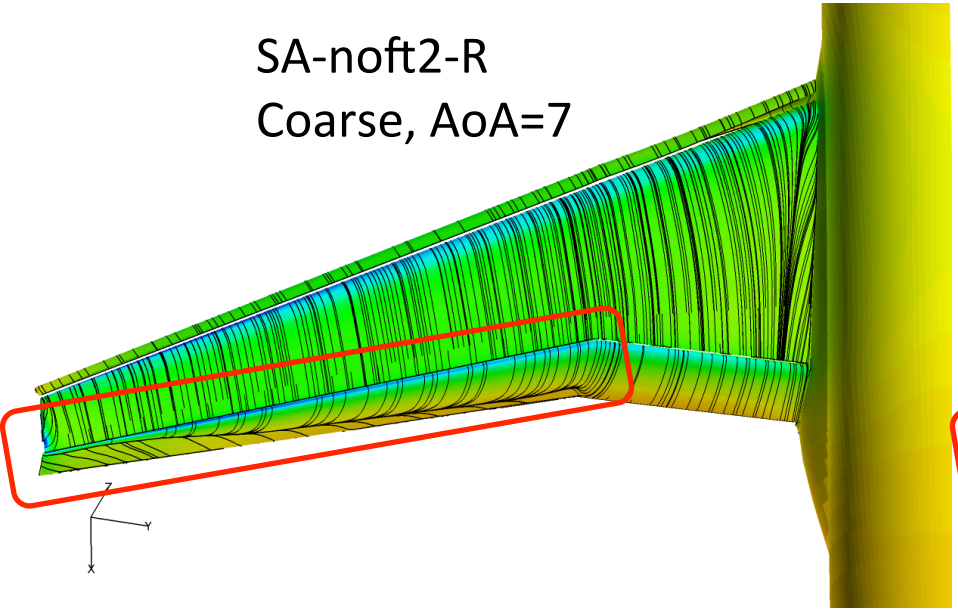


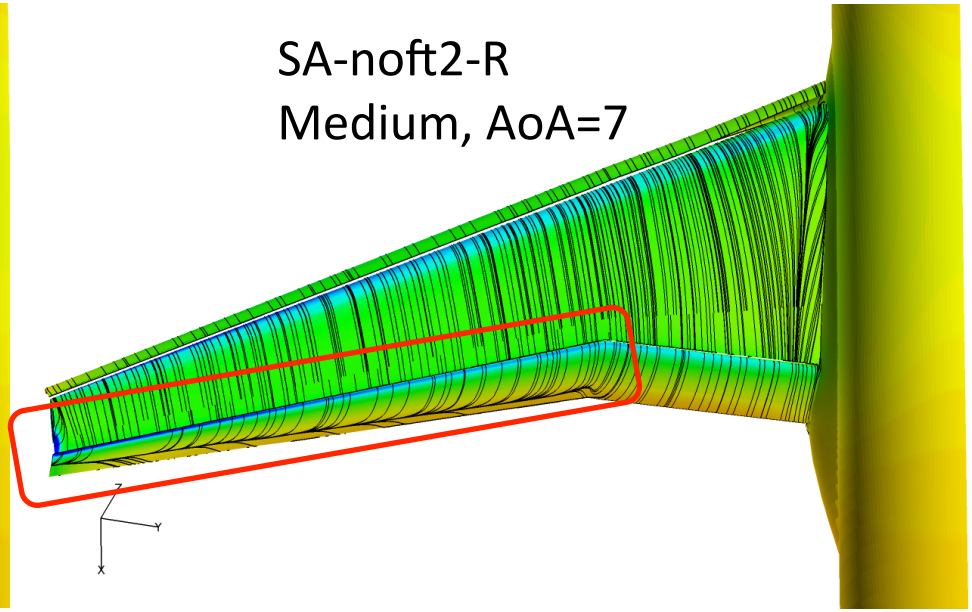
Cp differences between UPACS and TAS at AoA=16 (Medium)

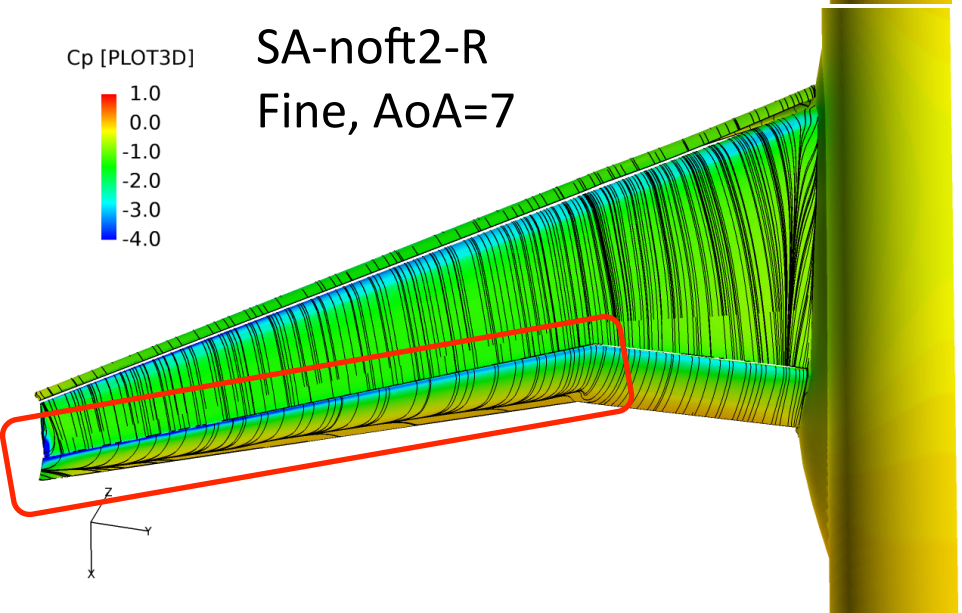
- Major differences are found at outer section
  - Earlier flow separation on the flap by TAS



Comparison of surface oil flow



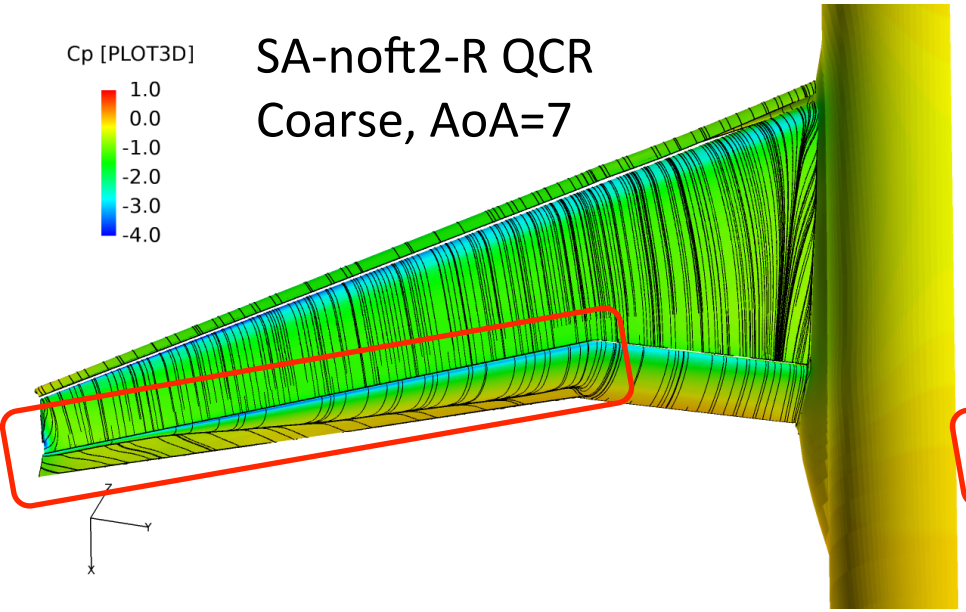


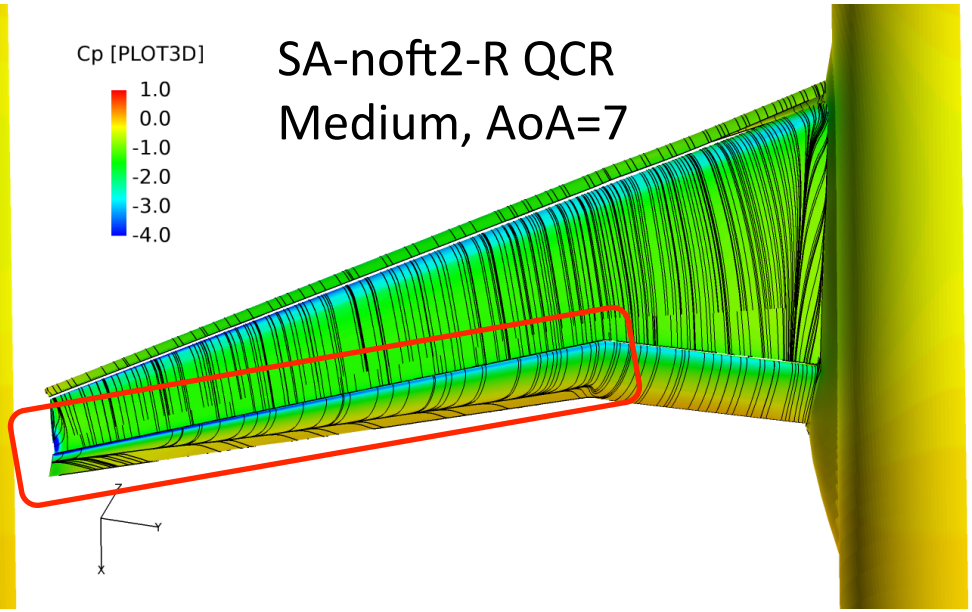


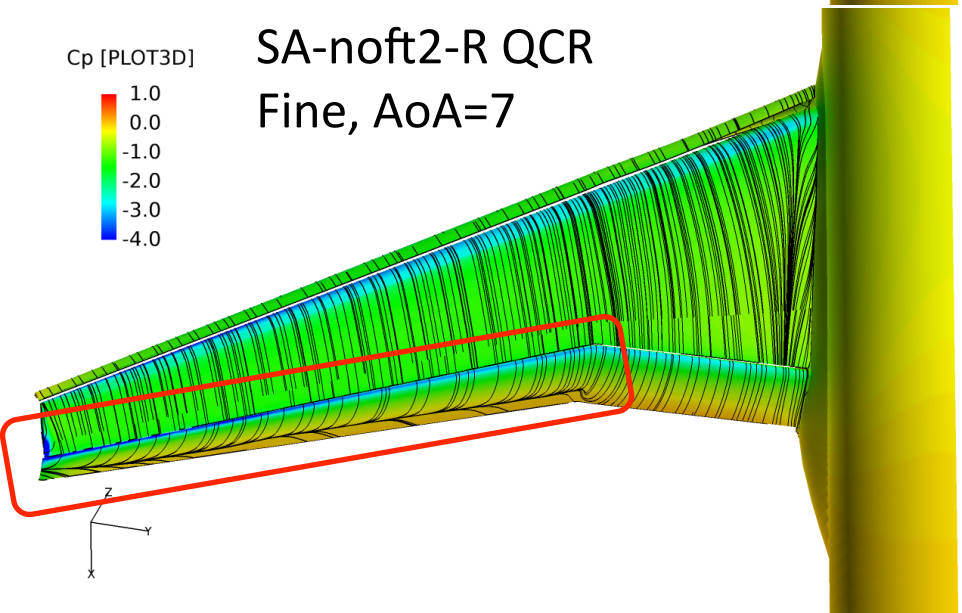
- Flow separation on the flap decreases with increasing grid points

  → C_L increase and Pitch-down C_M

Comparison of surface oil flow

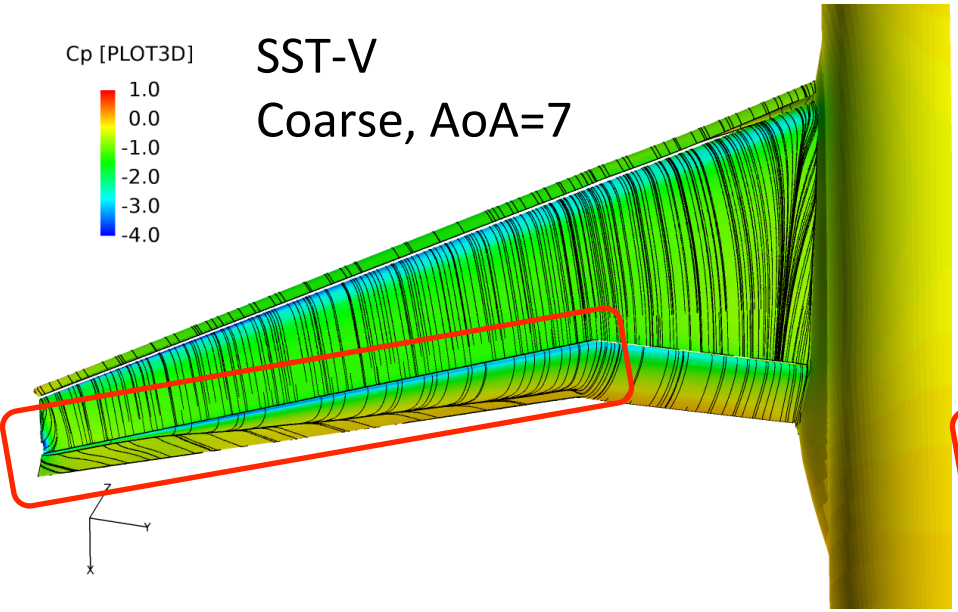


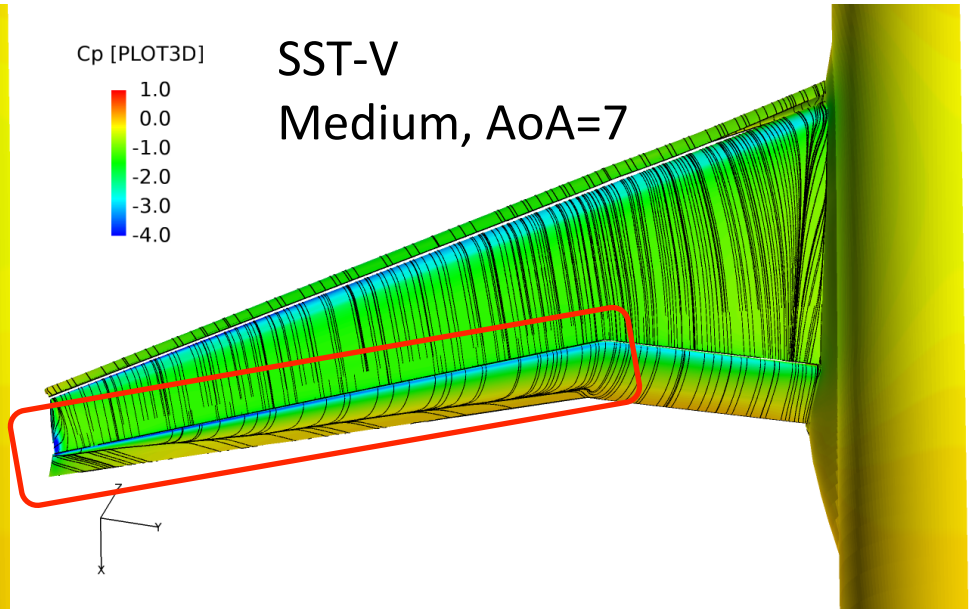


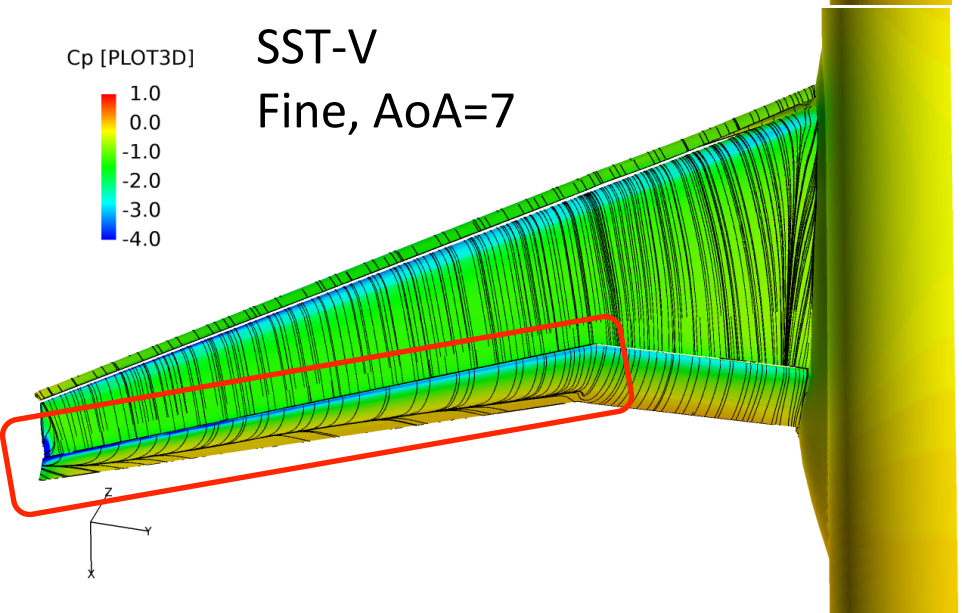


- Flow separation on the flap decreases with increasing grid points
  - Same trend bewteen w/ & w/o QCR
- Earlier flow separation with QCR

Comparison of surface oil flow

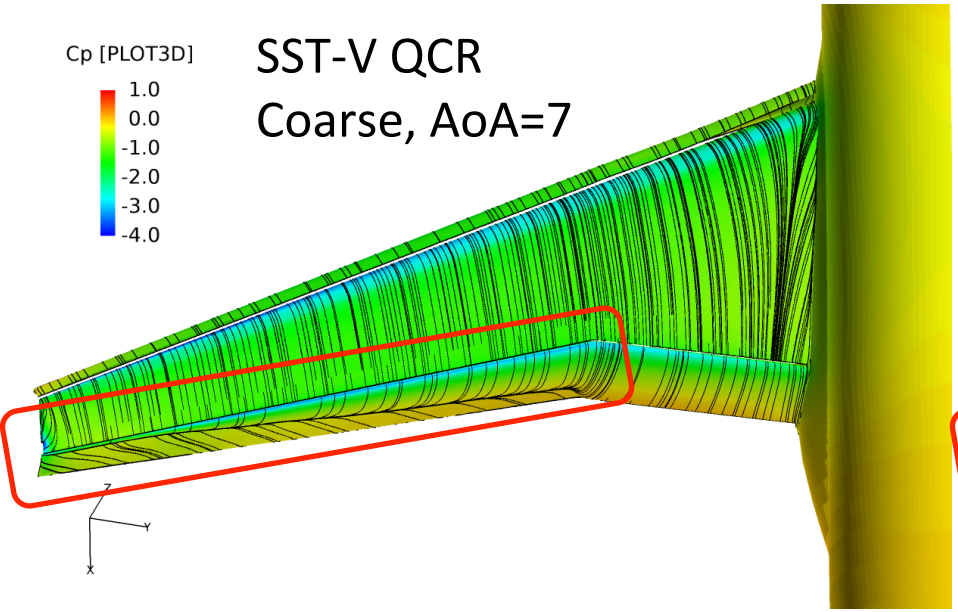


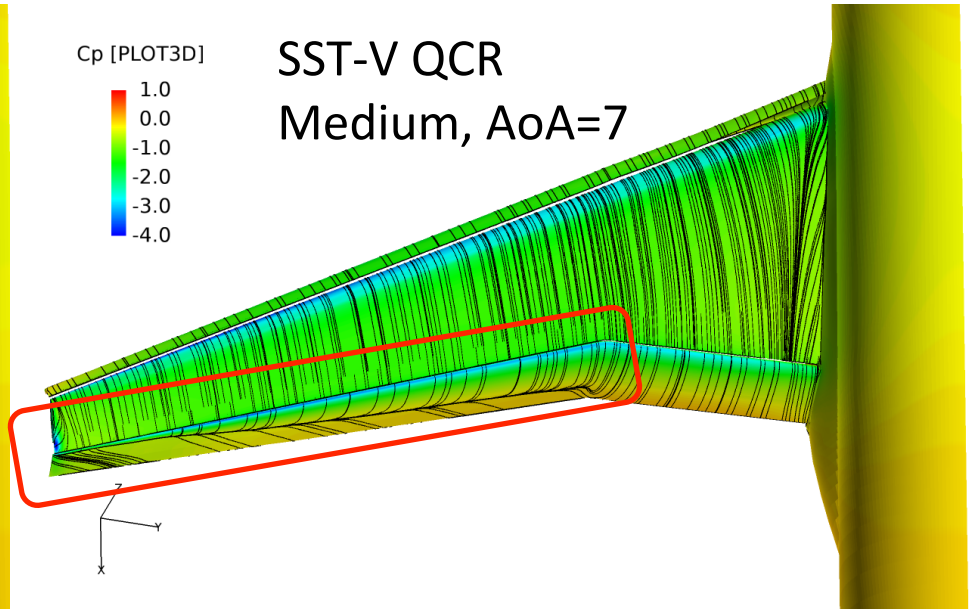


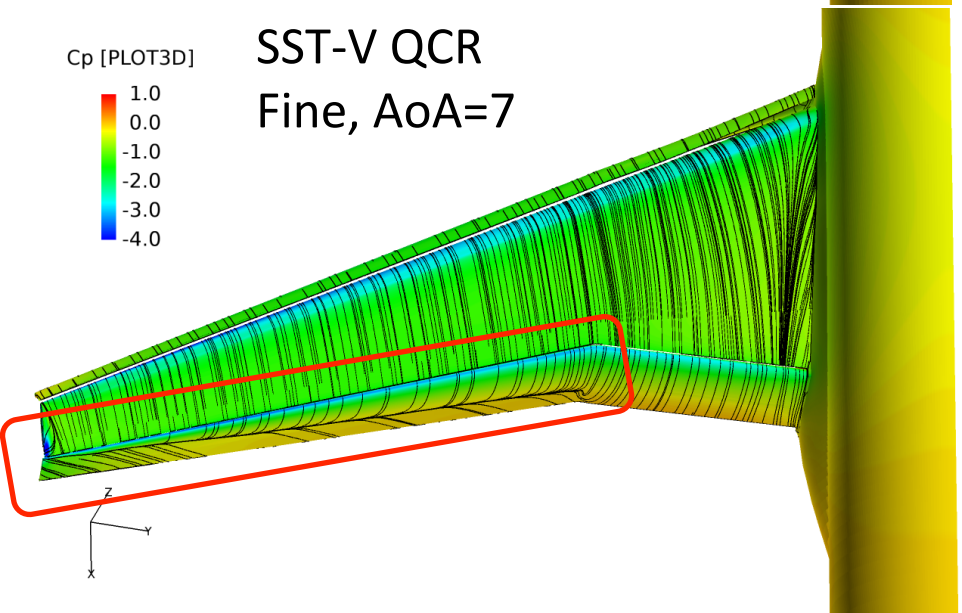


- Flow separation on the flap decreases with increasing grid points
  - Same trend bewteen SA & SST
- Earlier flow separation by SST

Comparison of surface oil flow



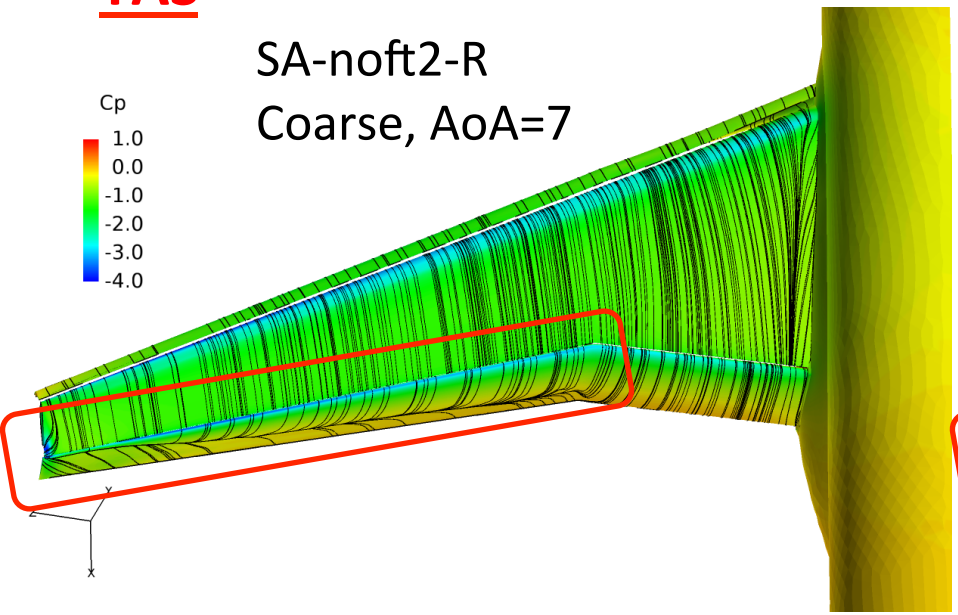


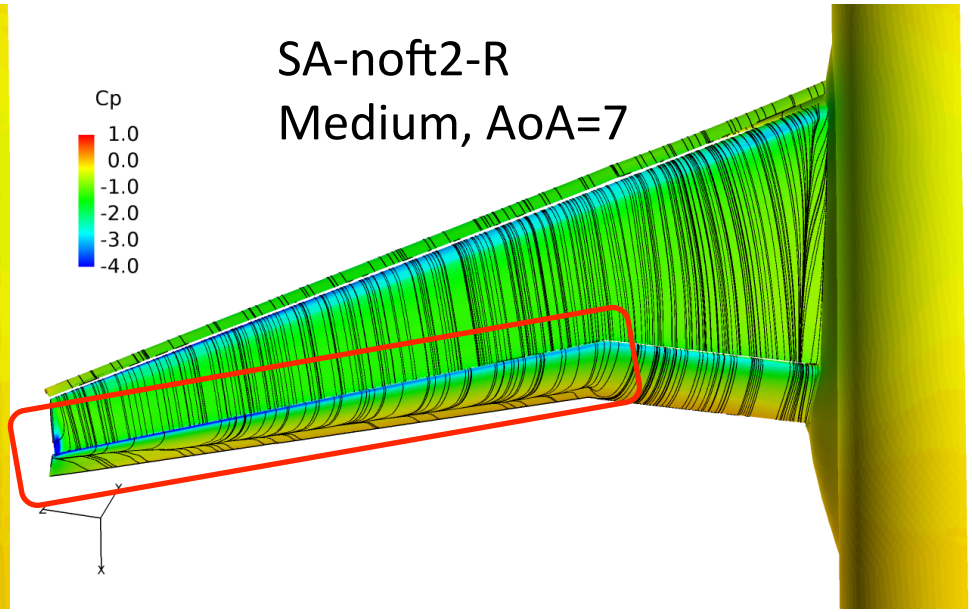


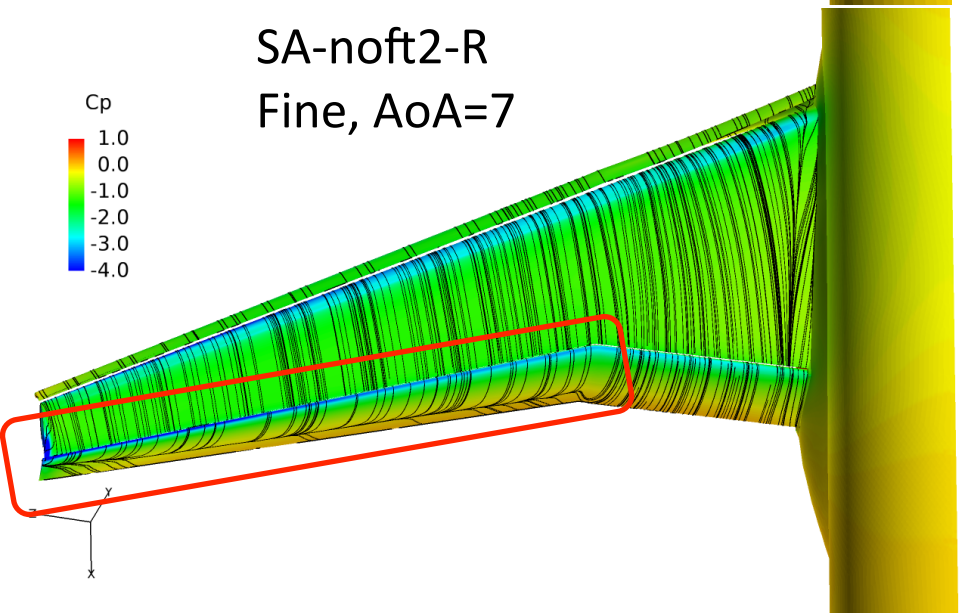
- Earlier flow separation on the flap with QCR

Comparison of surface oil flow

TAS





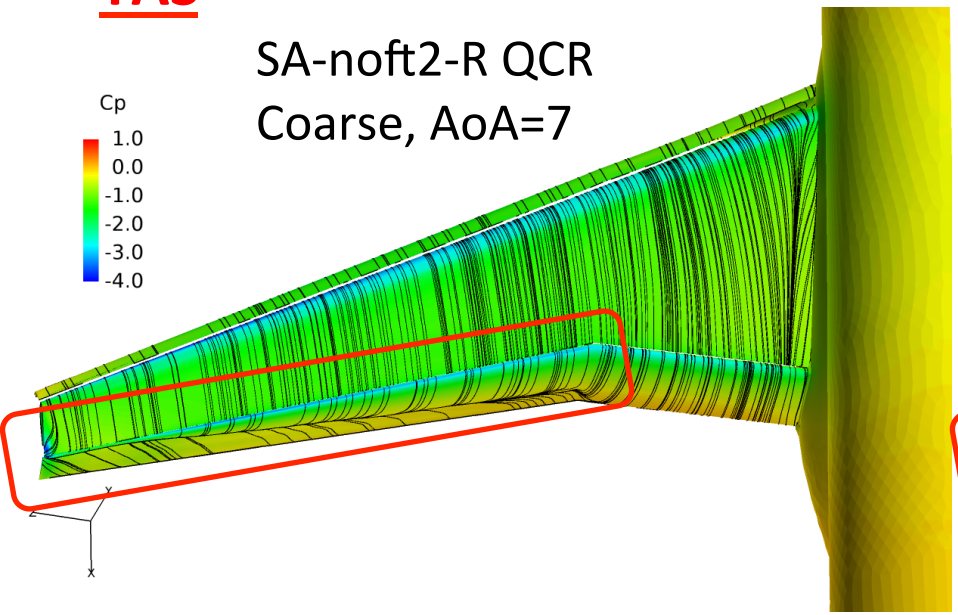


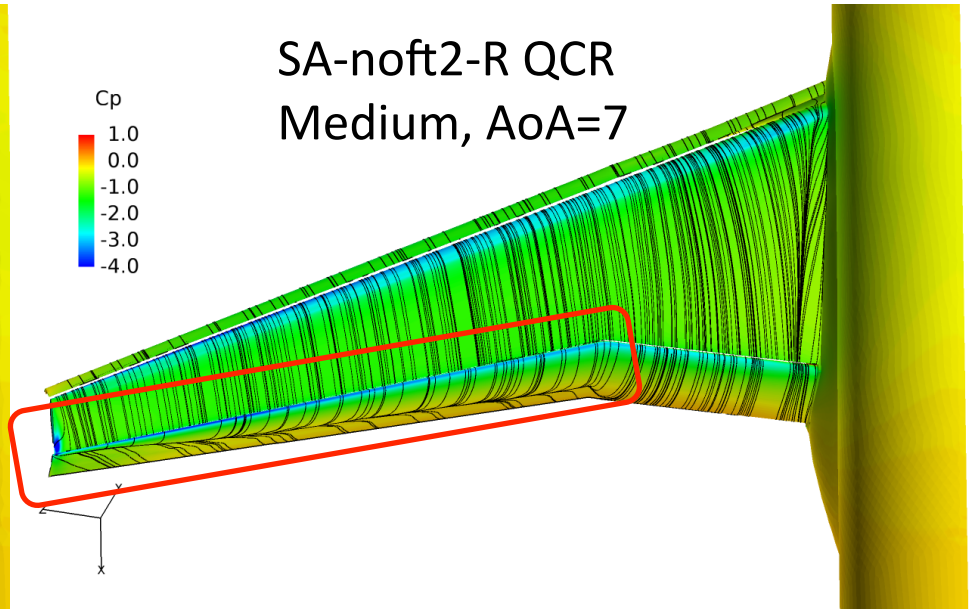
- Flow separation on the flap decreases with increasing grid points
  - Same trend bewteen UPACS on Grid A and TAS on Grid B
- Earlier flow separation on the flap than that of UPACS on Grid A

  → Lower C_L and Lower Pitch-down C_M

Comparison of surface oil flow

TAS



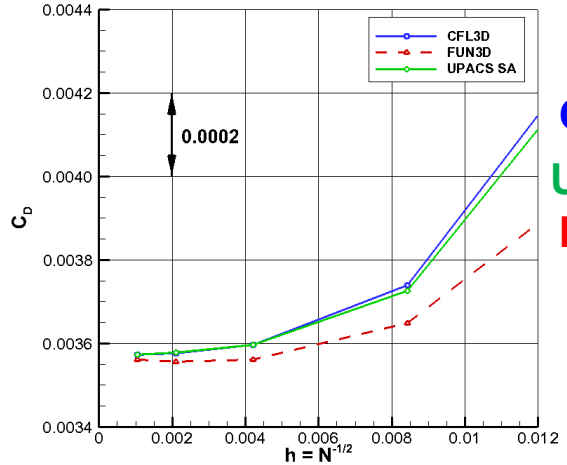


- Earlier flow separation on the flap with QCR
  - Same trend bewteen UPACS on Grid A and TAS on Grid B

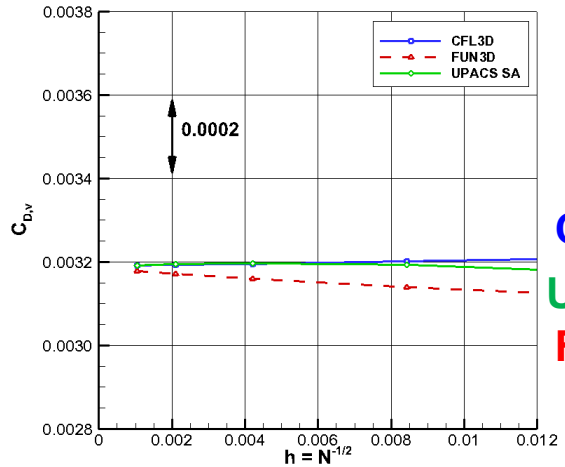
Case 4: 2D Bump-in-channel

- 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

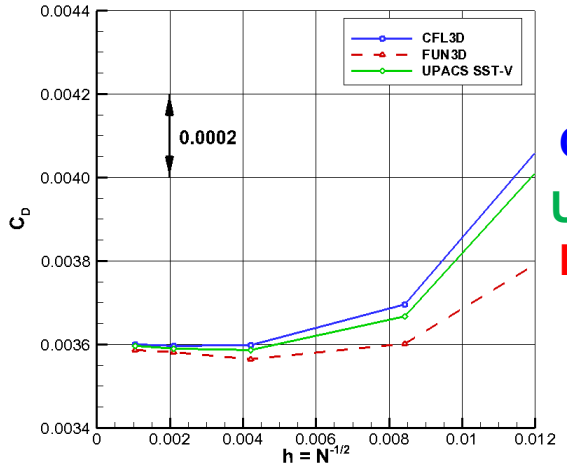


CFL3D
UPACS
FUN3D

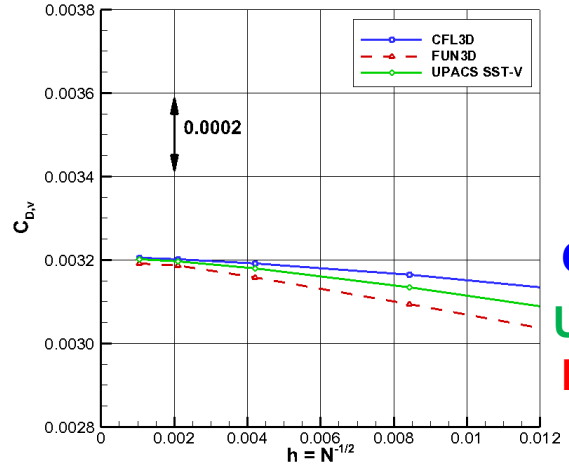


CFL3D
UPACS
FUN3D

SST



CFL3D
UPACS
FUN3D



CFL3D
UPACS
FUN3D

Total drag

Friction drag

http://turbmodels.larc.nasa.gov/bump.html

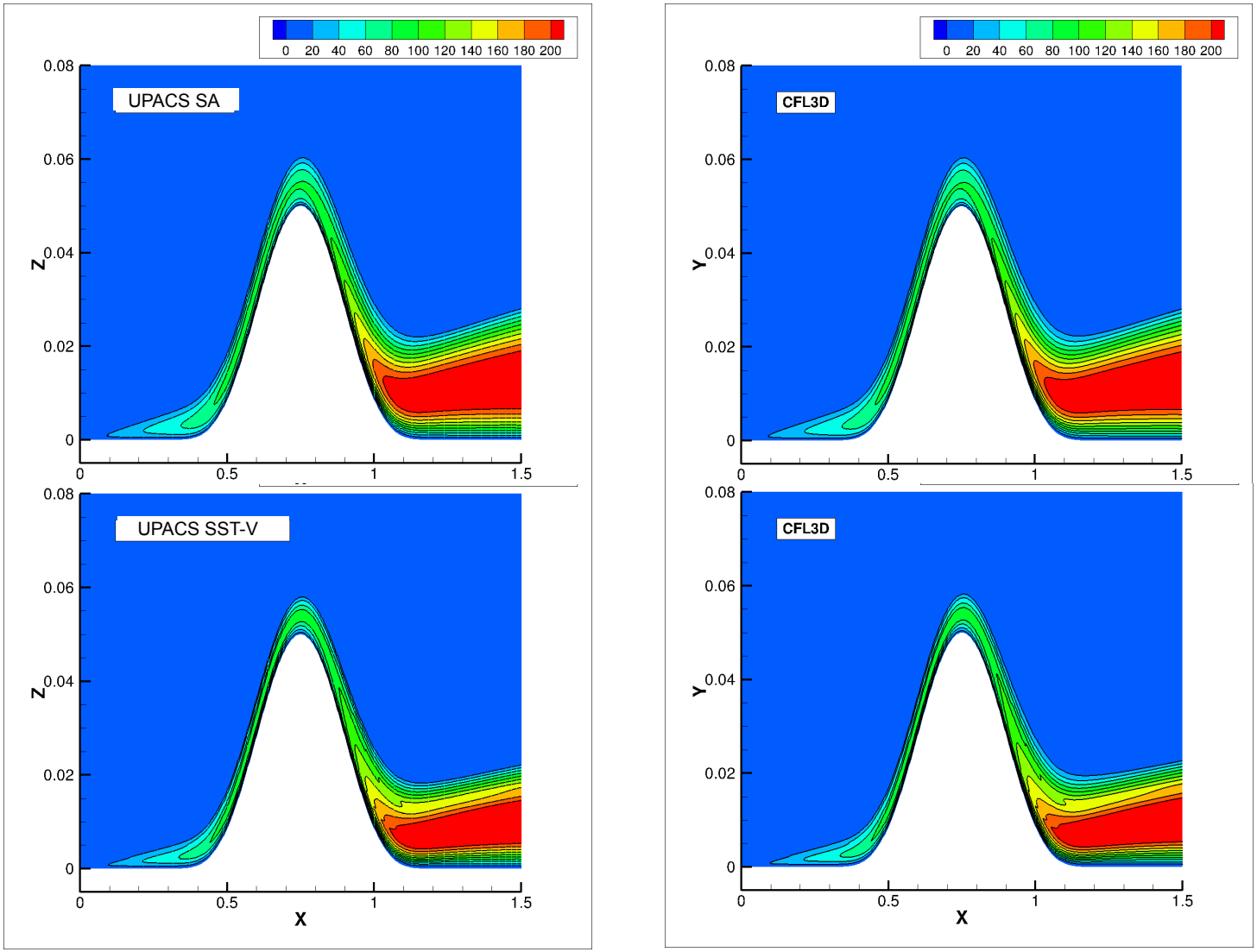
Case 4: 2D Bump-in-channel

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

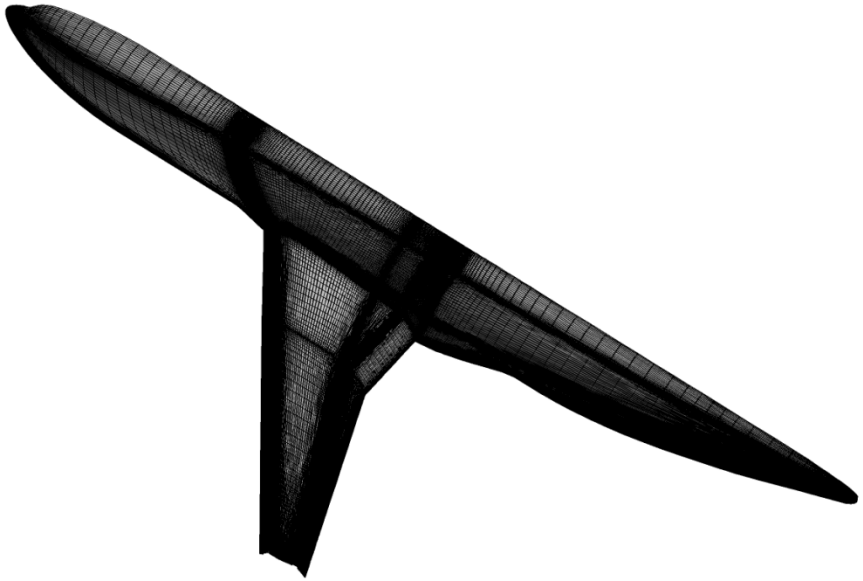
http://turbmodels.larc.nasa.gov/bump.html

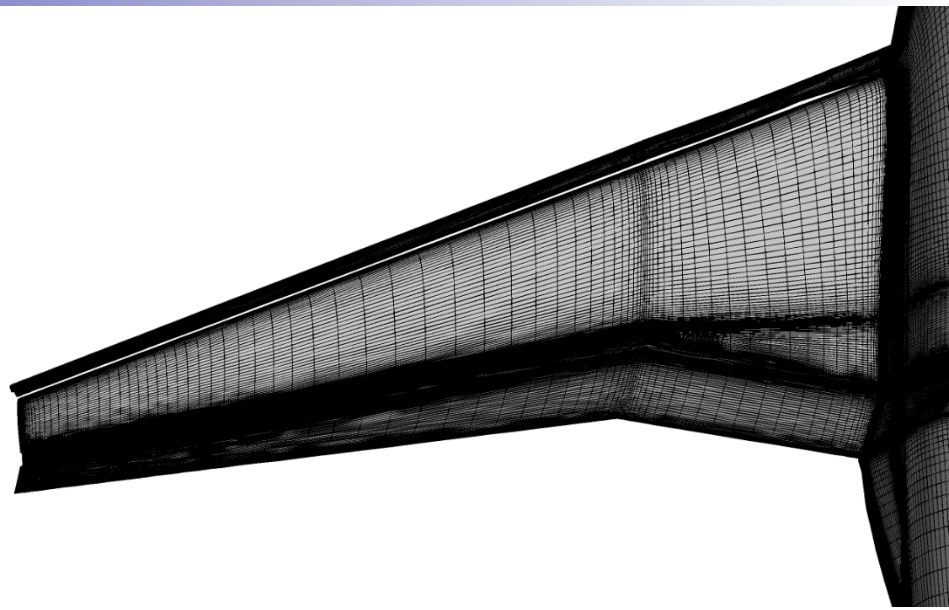
SA

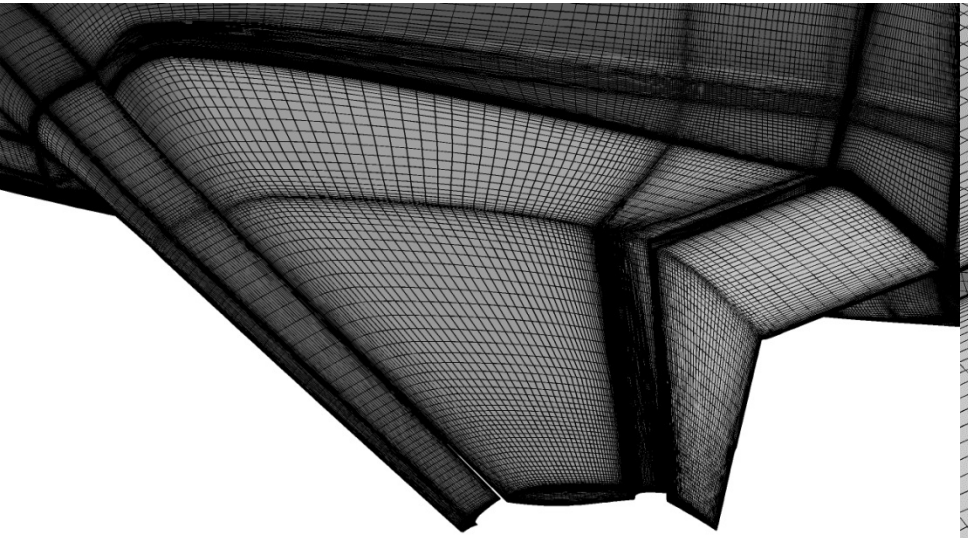
SST

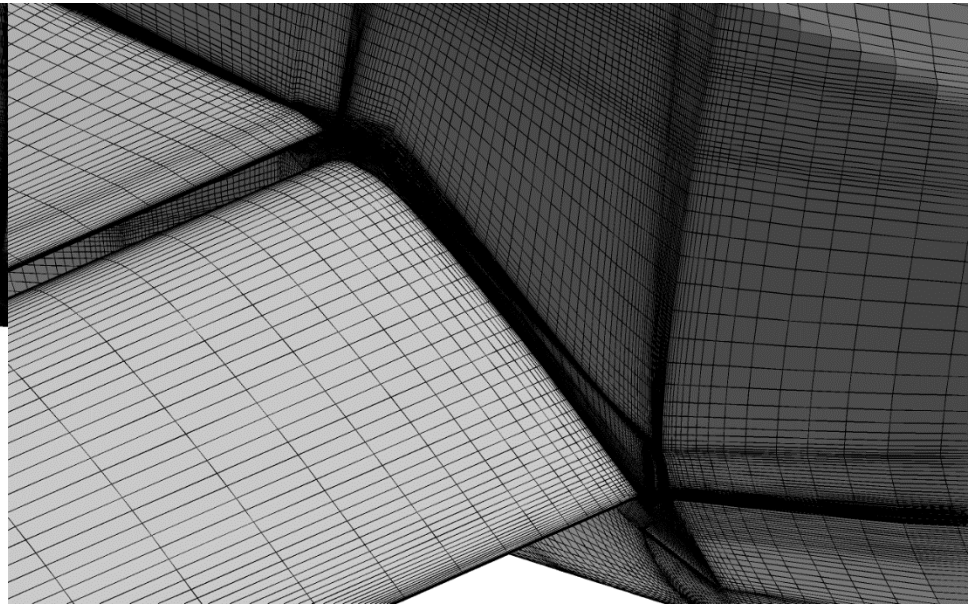


gridA（medium）

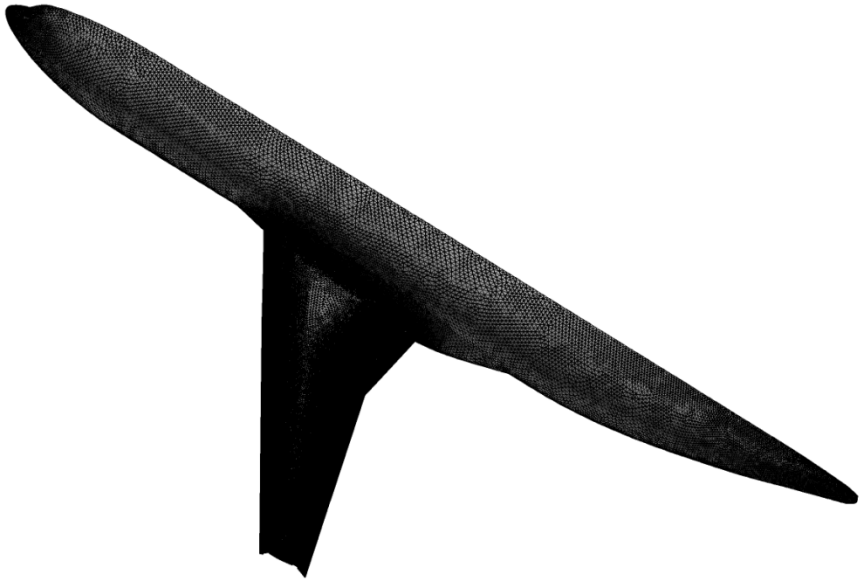


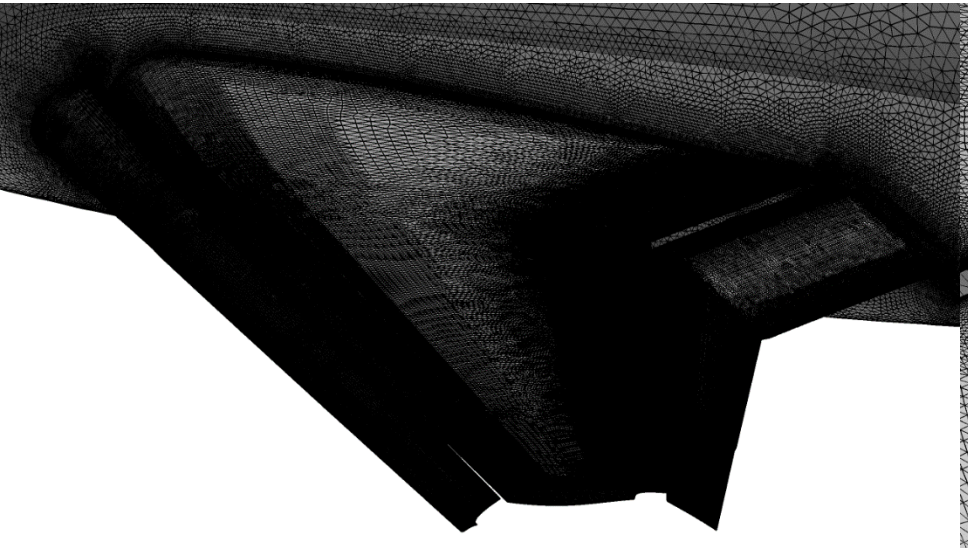


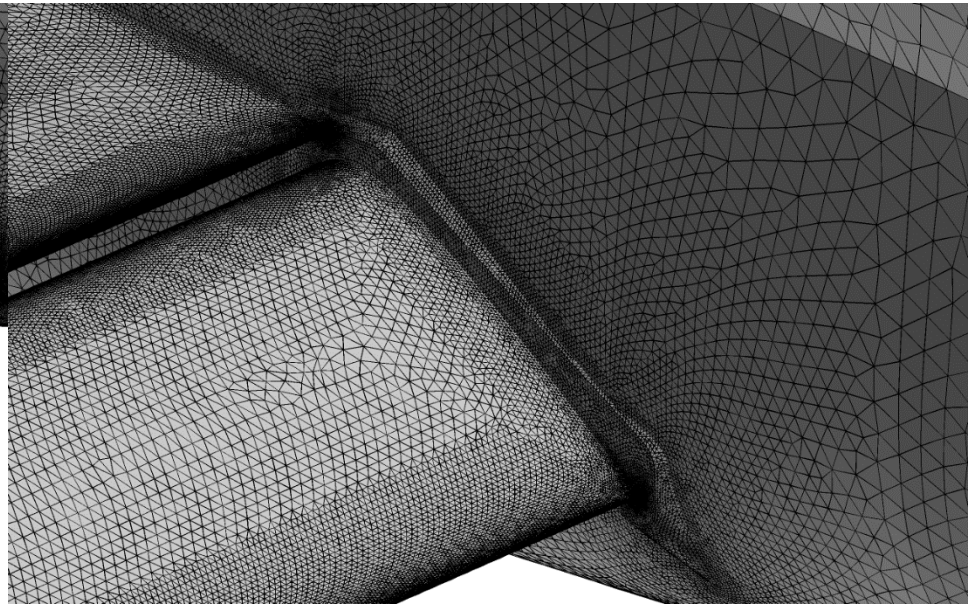




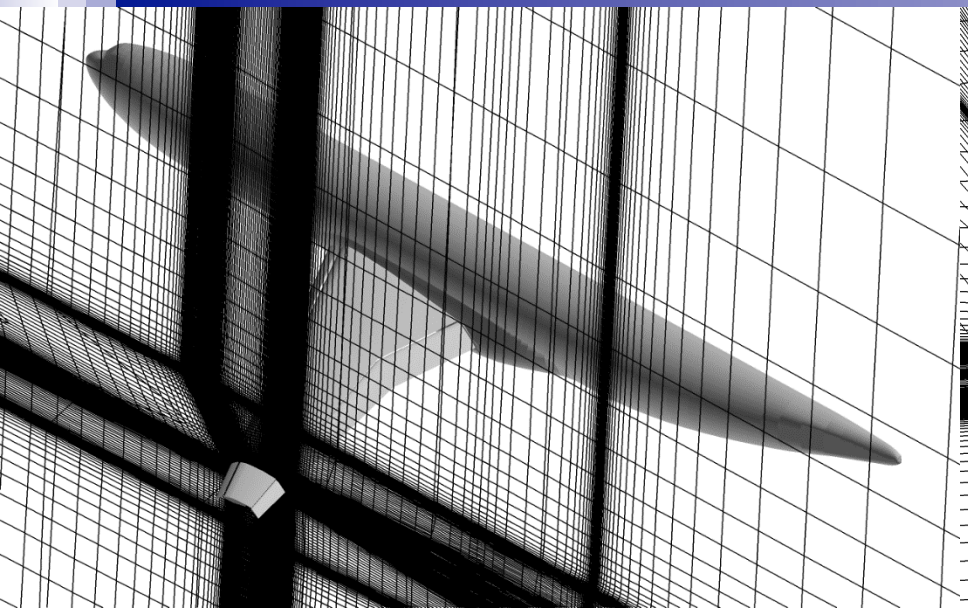
gridD（medium）

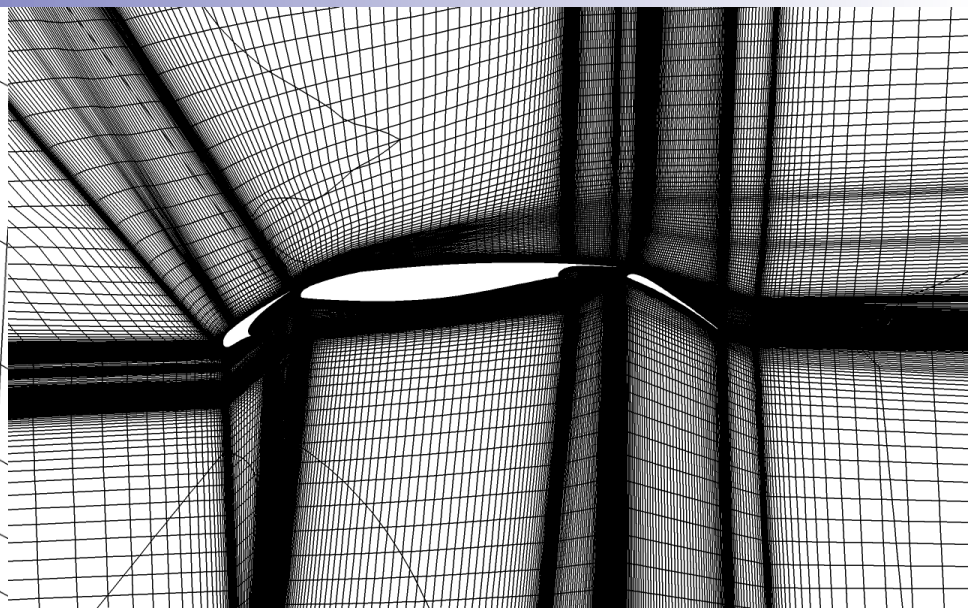


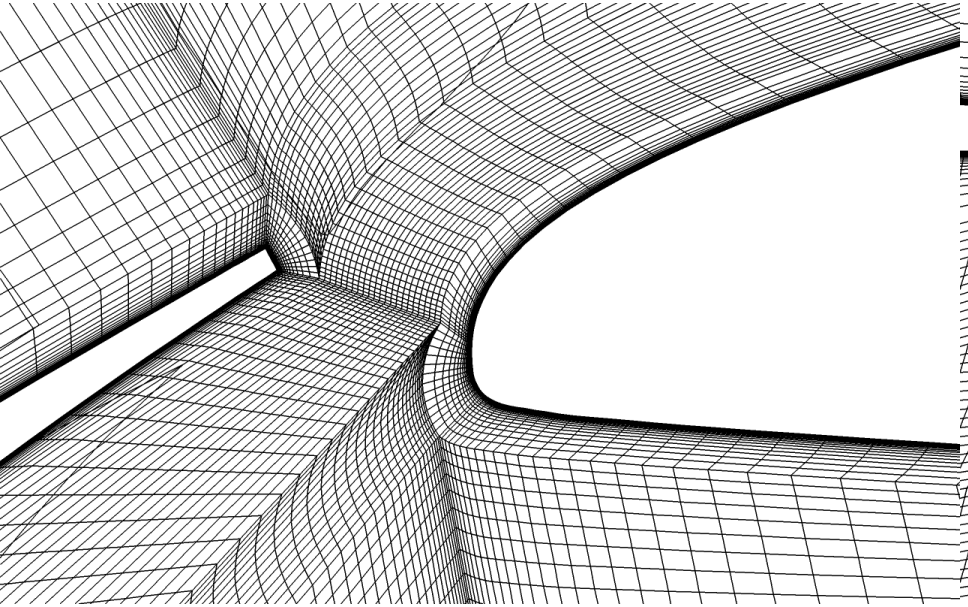


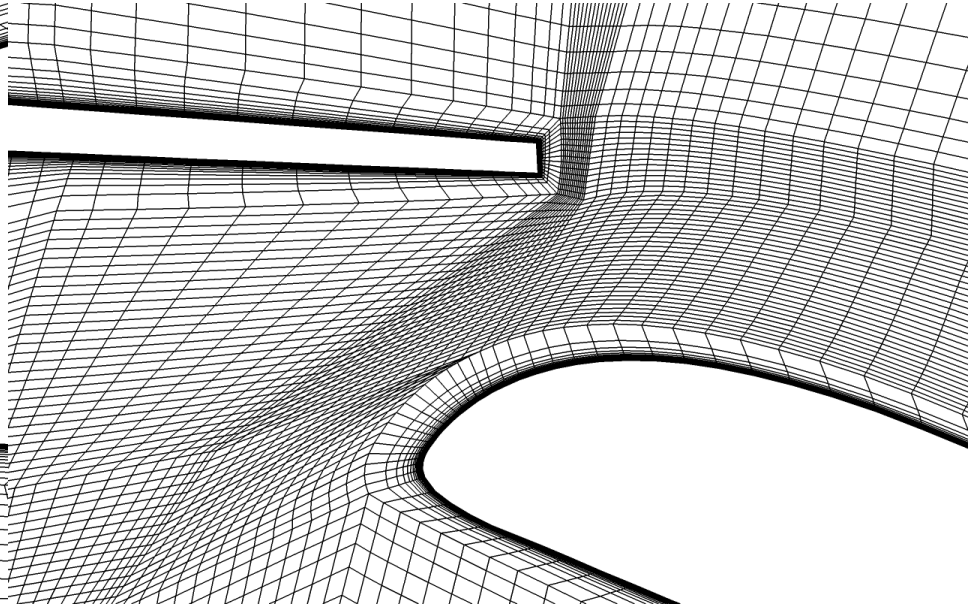


gridA（medium）









gridD（medium）