Scale-resolving simulations of the CRM high-lift configuration at high angles of attack.

Zauner M., Kojima Y., Sansica A., Hayashi K., and Hashimoto A.
JAXA - Aircraft Lifecycle Innovation Hub

APC-8 Workshop

RANS ~~Scale-resolving~~ simulations of the CRM high-lift configuration at high angles of attack.

M. Zauner, Y. Kojima, A. Sansica, K. Hayashi, and A. Hashimoto
JAXA - Aircraft Lifecycle Innovation Hub

APC-8 Workshop

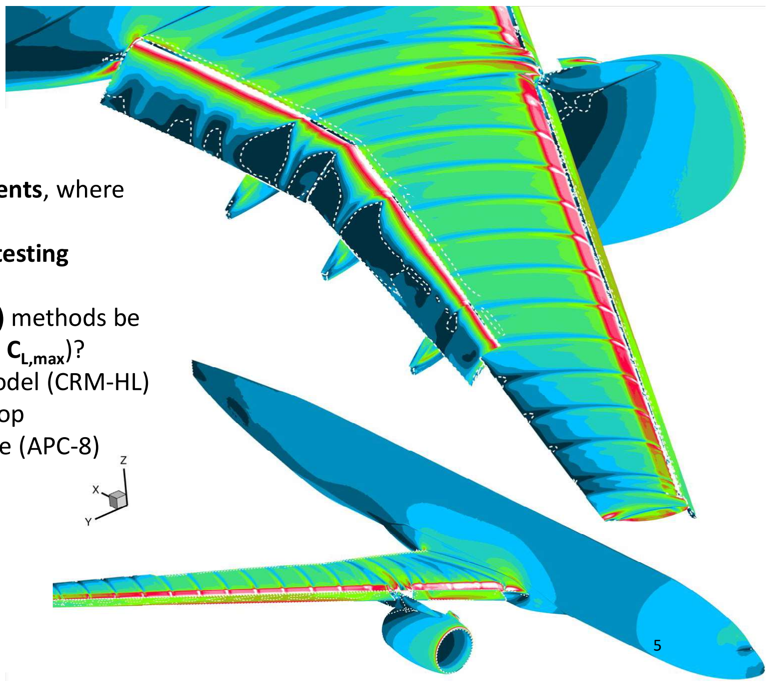
Agenda

- Introduction
- Methods
- Convergence
- Sensitivity of RANS simulations to initial conditions
- Sensitivity of RANS simulations to turbulence model

- Conclusions

4

Introduction



- **Low-speed** flight envelope **critical for safety.**
- More than **50% of commercial airplane accidents**, where high-lift devices are engaged.
- Status: Certification requires **extensive flight testing**
  - ➢ **EXPENSIVE!!!**
- Can **Reynolds-averaged Navier-Stokes (RANS)** methods be used to predict low-speed flight envelope (i.e. $\mathbf{C_{L,max}}$)?
  - ➢ High-lift version of Common Research Model (CRM-HL)
  - ➢ Fourth NASA High-Lift Prediction Workshop
  - ➢ Eighth Aerodynamics Prediction Challenge (APC-8)
- Nominal CRM-HL configuration
  - Flap/Slat angles:
  - AoA: varied
  - M = 0.2
  - Re = 5.5 million

5

Methods

Code: **JAXA's in-house code FaSTAR**

Set-up based on successful contribution to Drag-Prediction Workshop:

- Finite volume, unstructured
- HLLEW for inviscid fluxes
- U-MUSCL reconstruction
- GLSQ for gradient computation
- Limiter: van Leer type Hishida
- LU-SGS for time integration
- Turbulence models:
  - Submitted results: SA-noft2 and SA-noft2-R-QCR2000
  - Additional preliminary results: SA-noft2-R, SA-noft2-QCR2000, SST k-omega variants

6

Convergence Characteristics

Residuals in our case:
1) Compute L2-norm of residuals
2) Pick maximum value of entire domain

In case of no "perfect" convergence (machine-precision zero residuals):
Residuals can depend on numerical schemes and regions with maximum residuals do not necessarily coincide with the those relevant for industrial application. Also, residuals usually only compare two consecutive iterations, which **could understate the total change of results** over longer run times.

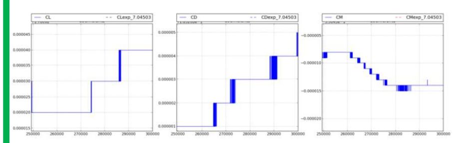
As an **alternative** we propose to assess **fluctuations** of **aerodynamic coefficients**, which are often used for evaluating simulation performances.

Definition of **convergence parameter ConvP**:

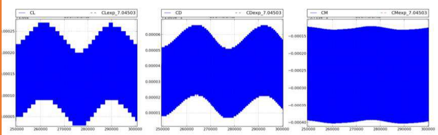
-> Statistics (root-mean-square and time average) of aerodyn. coefficients computed over 50000 iterations

-> ConvP= $\log([(C_{D,rms}/C_{D,avrg})^2 + (C_{L,rms}/C_{L,avrg})^2 + (C_{M,rms}/C_{M,avrg})^{\wedge 2}]^{0.5})$

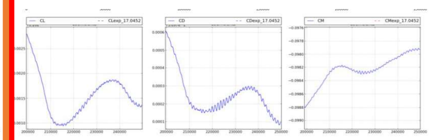
ConvP~-7 CL-jumps of 10-5



ConvP~-6 CL-oscillations of 10-4

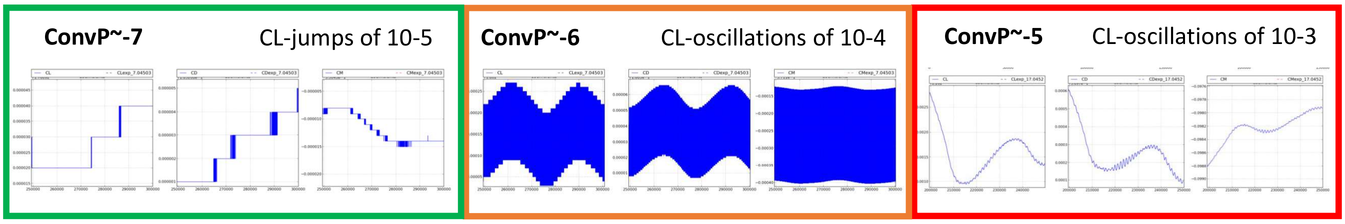


ConvP~-5 CL-oscillations of 10-3



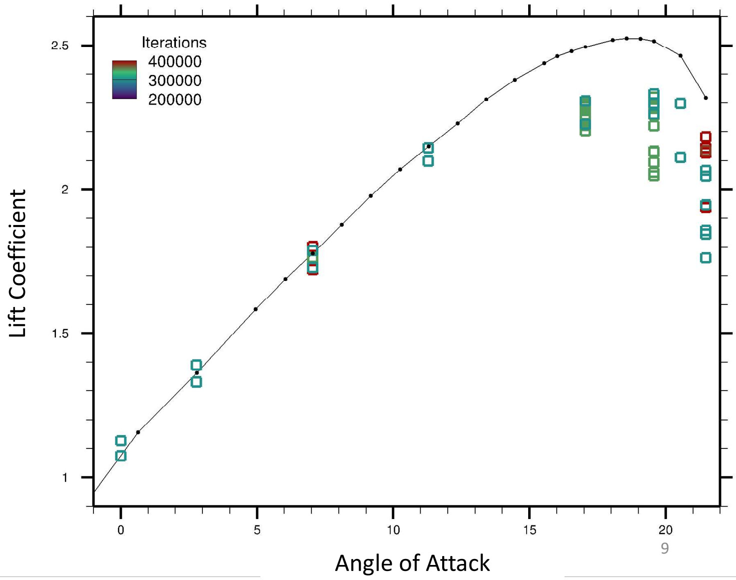
Convergence Characteristics

This convergence parameter allows us for the present test case to
- **separate convergence characteristics** of simulations for the current test case **more clearly**
- **evaluate convergence based on physical quantities**, which are of main interest for practical application



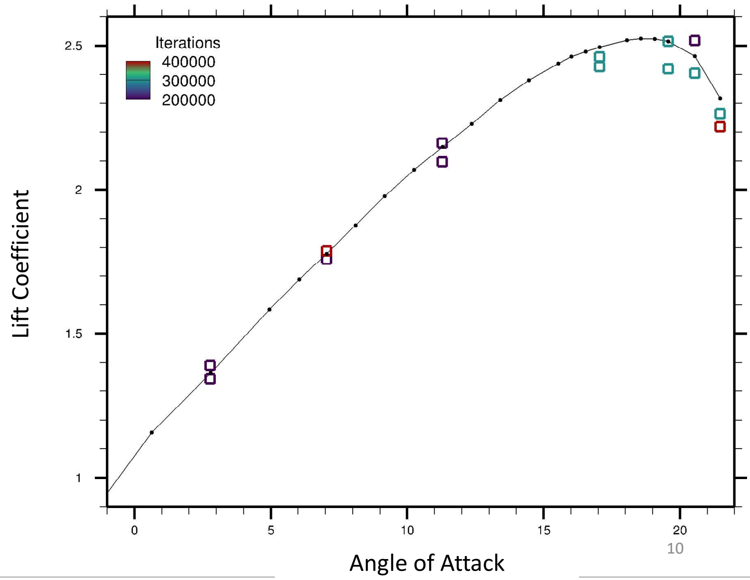
Cold-started RANS simulations

- Testing **different RANS turbulence models** (SA & SST), starting from uniform flow conditions
- **Lift** was significantly **underpredicted** for all simulations **near $C_{L,max}$**.
- **Poor performance** of our simulations compared to HLPW-4 results even at low AoA
- **SST models** show **no improvement**, but are **more expensive**

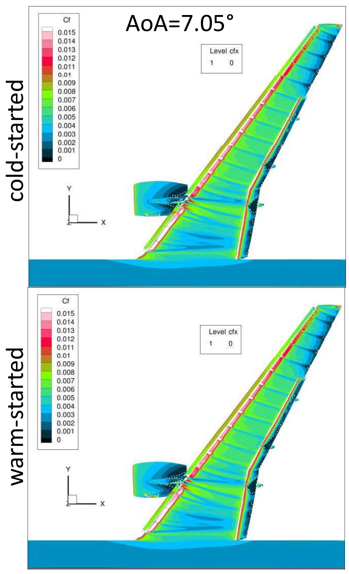


Warm-started RANS simulations

- **Selected RANS SA turbulence models**:
  - SA-noft2
  - SA-noft2-R-QCR2000
- Simulations were **restarted** from a solution obtained at AoA = 0 degrees, run for 10,000 iterations.
- **Significant improvement** compared to cold-started simulations. Results now compare well with HLPW-4 results.



Results for SA-noft2

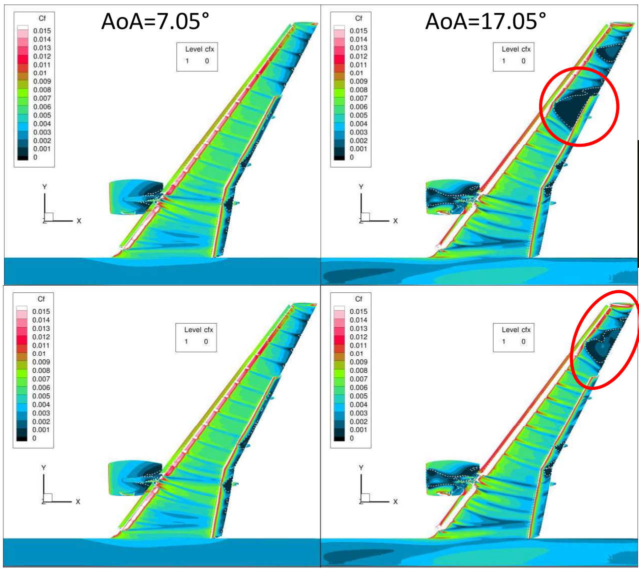


- Showing contours of skin-friction coefficient **Cf** for **cold- and warm-started** solutions using a **SA-noft2** model
- At low angles of attack results look qualitatively similar

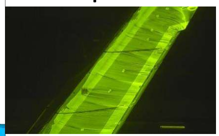
Results for SA-noft2

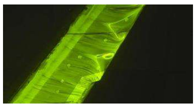
cold-started

warm-started



- Cold-start:
  Two regions of un-physical outboard flow separation





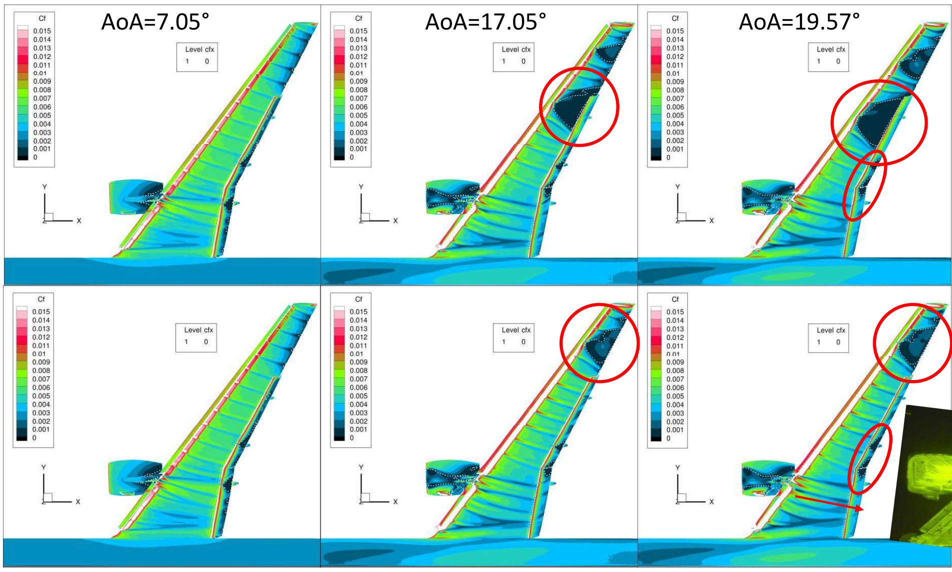
- Un-physical separation region near wing tip larger for warm-started simulation.

12

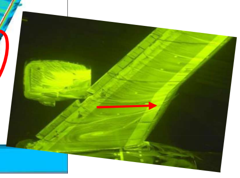
Results for SA-noft2

cold-started

warm-started

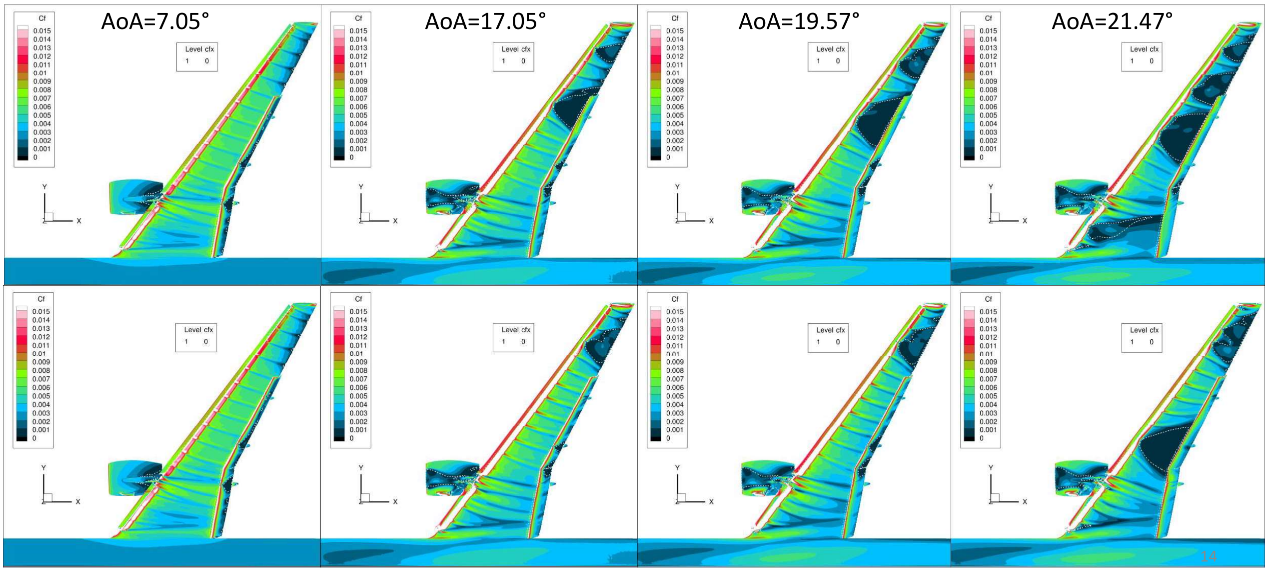


- **Cold-start**: U**n-physical flow separation** grows for further increasing AoA
- **Warm-start**: Out-board flow separation does not change much
- Both cases seem to **over-predict flow separation at the bend** of the wing
- **In-board flow is deflected towards the root**



13

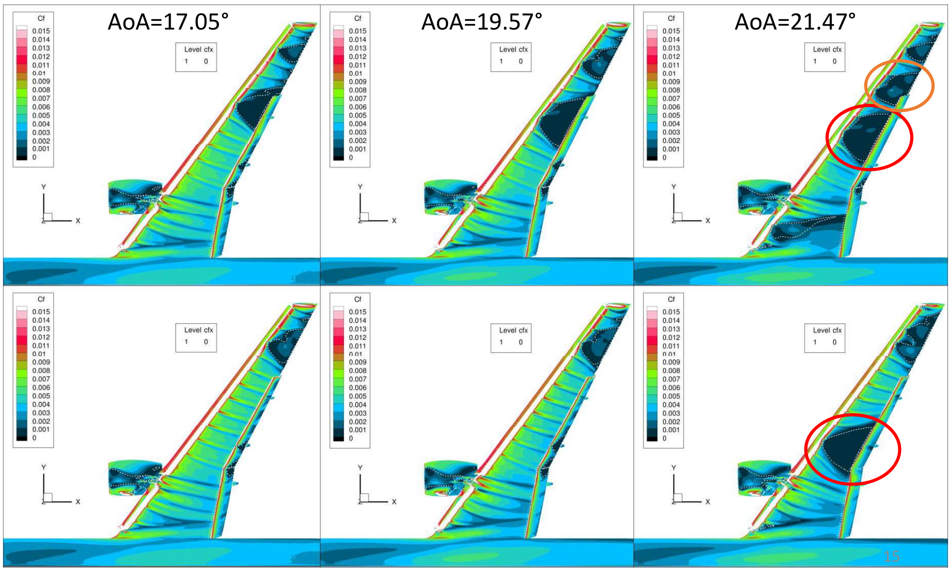
Results for SA-noft2



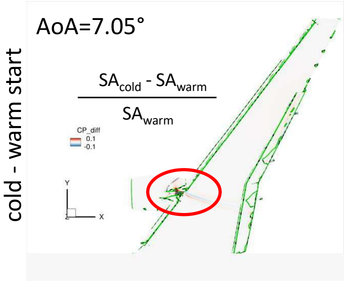
Results for SA-noft2

- **At 21.47°**, also warm-started simulations shows flow separation near bend.
- Large separation regions promote reattachment at the flaps.

- **Cold started** solutions show an **additional** region of out-board **separation.**



Cold vs Warm Start using SA-noft2

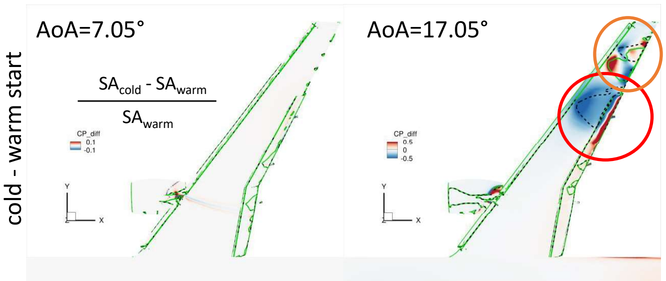


- Plots show relative **differences between Cp contours** of cold- and warm-started RANS simulations:
  - ❖ Blue: Cp of cold-started solutions < Cp of warm-started solution
  - ❖ Red: Cp of cold-started solutions > Cp of warm-started solution
  - ❖ Lower Cp -> increased velocities -> reduced separation
- **Green solid curves: warm-started**
- **Black dashed curves: cold-started**

- Minor differences near nacelle at 7.05°

16

Cold vs Warm Start using SA-noft2

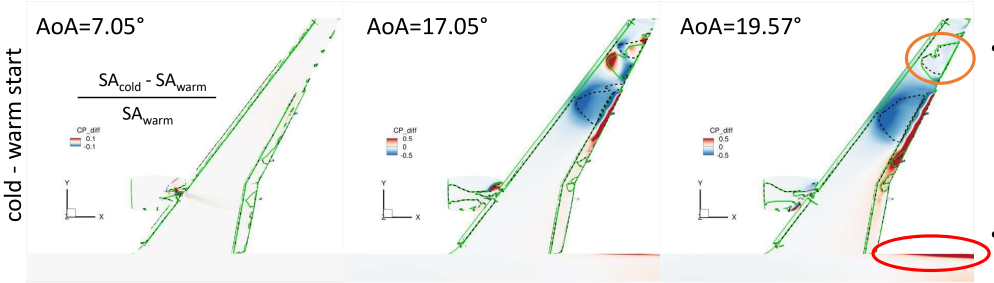


- **Additional separated flow** region for **cold-started** simulation well pronounced.
- Cp on out-board part of flap increased for cold-started case
- Reduced separated flow near wing-tip for cold-started simulation

- **Black dashed curves: cold-started**
- **Green solid curves: warm-started**

17

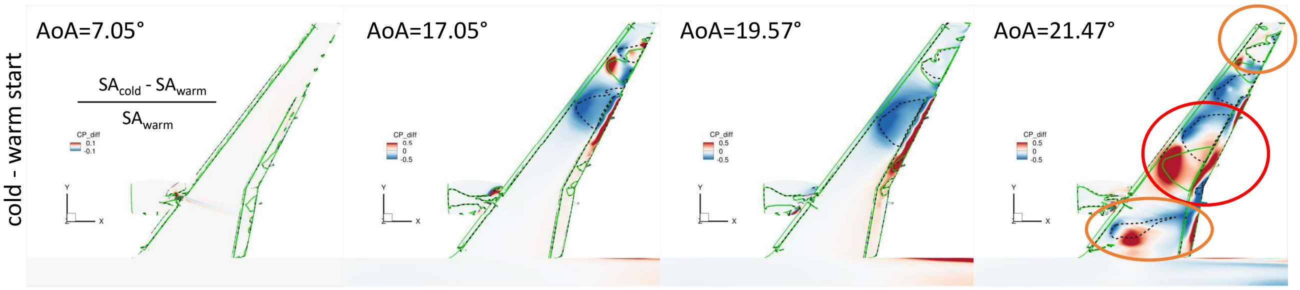
Cold vs Warm Start using SA-noft2



- Out-board region between both approaches similar
- More pronounced difference at fuselage behind the wing

- **Black dashed curves: cold-started**
- **Green solid curves: warm-started**

Cold vs Warm Start using SA-noft2



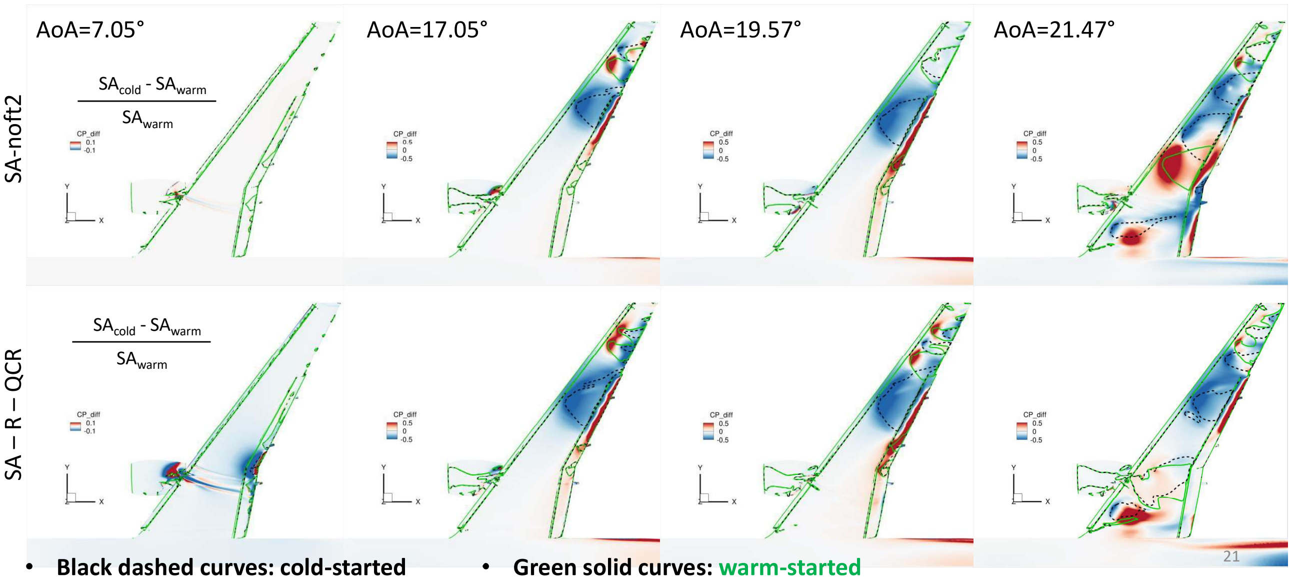
- Mid-span flow separation closer to the bend for warm-started simulation.
- In-board flow separation for cold-started simulation
- Out-board flow separation similar for both

- **Black dashed curves: cold-started**
- **Green solid curves: warm-started**

Cold/Warm start conclusions

- Flow separation tends to occur at lower angles of attack for cold-started simulations
- Is sensitivity to initial condition turbulence-model dependent?

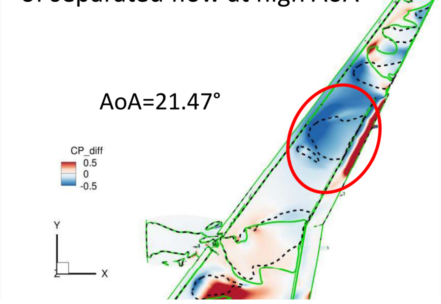
Cold vs Warm start for SA-noft2 and with R-QCR corrections

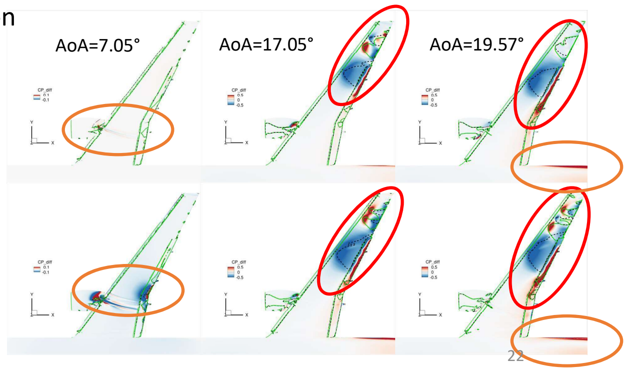


- **Black dashed curves: cold-started**
- **Green solid curves: warm-started**

Cold/Warm start conclusions

- Flow separation tends to occur at lower angles of attack for cold-started simulations
- Is sensitivity to initial condition turbulence-model dependent?
  - This question is hard to answer at the time being. However, there seems to be a trend.
  - Cold-started simulations seem to be less sensitive to turbulence-model effects.
  - R-QCR correction seems to have larger effects on warm-started simulations, as it prevents parts of separated flow at high AoA

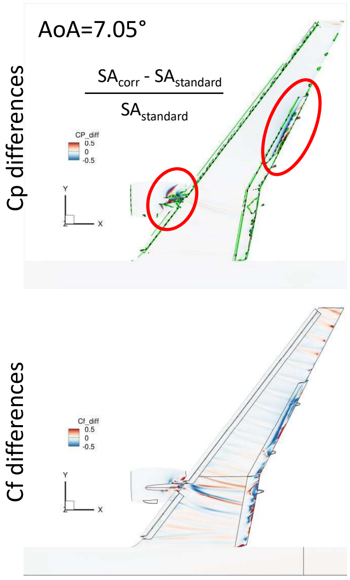




Now, comparing **only warm-started** solutions using

SA-noft2 and **SA-R-QCR**

Comparing warm-started SA-noft2 and SA-R-QCR



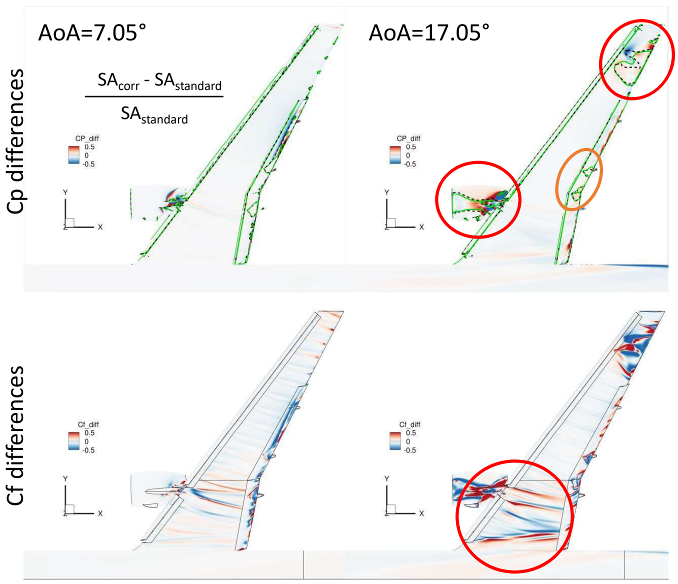
- Plots show relative **differences between Cp contours** of SA with R-QCR correction and SA-noft2 RANS simulations:
  - ❖ Blue: Cp of corrected SA solutions < SA-noft2 solution
  - ❖ Red: Cp of corrected SA solutions > SA-noft2 solution
- **Green solid curves:** SA-noft2
- **Black dashed curves: SA R-QCR corrected**

- Minor influence of turbulence model on flow over flaps and nacelle

- Plots show relative **differences between Cf contours** of SA with R-QCR correction and SA-noft2 RANS simulations:
  - ❖ Blue: Cf of corrected SA solutions < SA-noft2 solution
  - ❖ Red: Cf of corrected SA solutions > SA-noft2 solution

24

Comparing warm-started SA-noft2 and SA-R-QCR

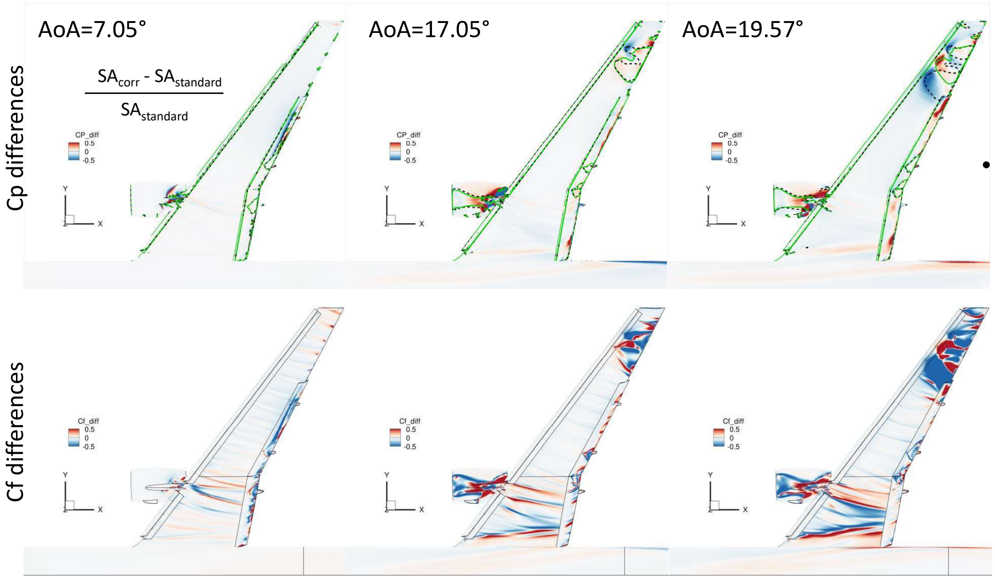


- Differences in Cp mainly near wing-tip and nacelle
- Localized pockets of flow separation for both turbulence models

- Differences in Cf near the wing root become more pronounced with increasing AoA

25

Comparing warm-started SA-noft2 and SA-R-QCR

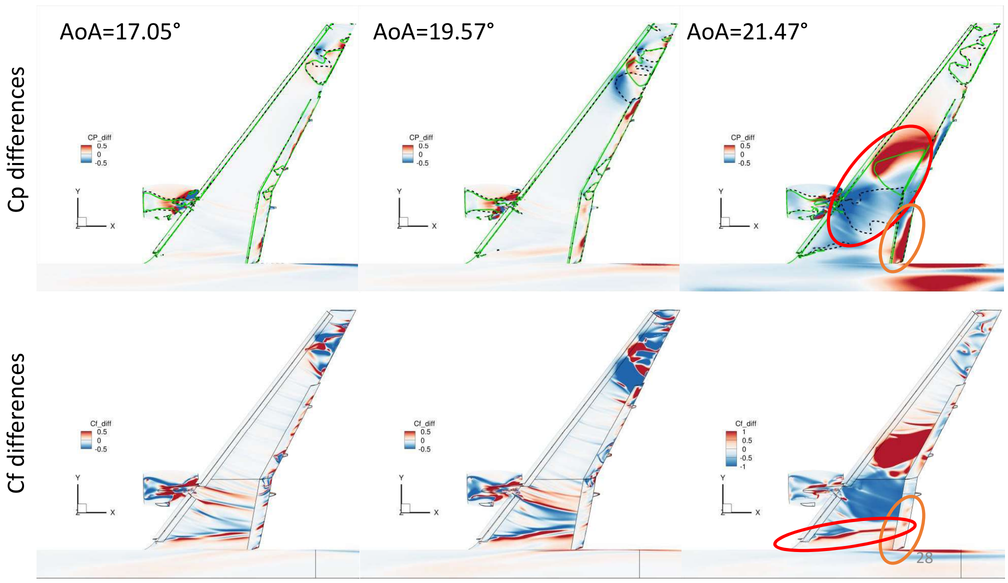


- Trends continue for increasing AoA to 19.57°

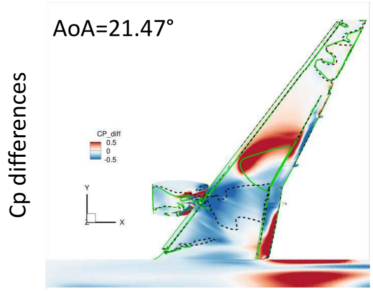
26

Comparing warm-started SA-noft2 and SA-R-QCR

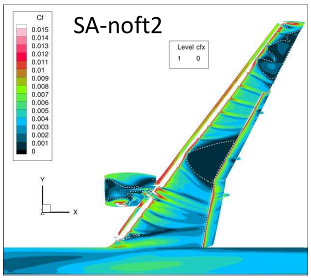
- Solutions at 21.47° fundamentally different.
- Main flow separation for SA-R-QCR behind the nacelle.
- Increase pressure recovery over the in-board flaps for SA-R-QCR, despite minor differences in Cf.
- SA-R-QCR: flow separation originating from the slats is more pronounce.

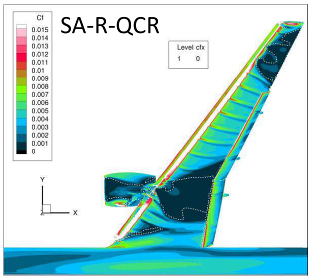


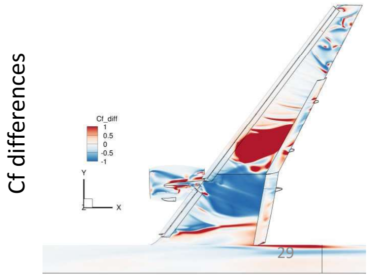
Comparing warm-started noFt2 SA and SA-R-QCR



- To confirm observations, here Cf_x plots for each simulation







Turbulence model conclusions

- R-QCR correction seems to suppress flow-separation near wing bend, but promotes separation behind the nacelle at high AoA.
- Flow around sharp corners and edges of slats or flaps seem to be sensitive to the choice of turbulence model
- More detailed studies required

Conclusions for <u>CRM-HL</u>

- **No tested RANS turbulence model suitable for <u>accurate</u> $C_{L,max}$ predictions.**
- **Cold started RANS simulations should be avoided!**
- **Experiment-based error** for warm-started simulations at lower angles of attack **within 5%**
- Significant **convergence problems** make purely RANS-based **conclusions** and comparisons **difficult.**
- Presented **RANS** simulations **<u>on their own</u>** seem **not reliable** for complex configurations like CRM-HL, even at moderate angles of attack (~7 degrees)

Conclusions for <u>CRM-HL</u> & Outlook

- **No tested RANS turbulence model suitable for <u>accurate</u> $C_{L,max}$ predictions.**
- **Cold started RANS simulations should be avoided!**
- **Experiment-based error** for warm-started simulations at lower angles of attack **within 5%**
- Significant **convergence problems** make purely RANS-based **conclusions** and comparisons **difficult.**
- Presented **RANS** simulations **<u>on their own</u>** seem **not reliable** for complex configurations like CRM-HL, even at moderate angles of attack (~7 degrees)

→ **Combinations or assimilations** of lower fidelity (e.g. RANS), higher-fidelity methods (e.g. WM-LES), and experiments may be required.

→ **Global stability analysis and reduced order models (e.g. ML/AI-based)**

ご清聴ありがとうございました

Any questions?

(Personal) open questions

- What do we expect from RANS? What can we expect from RANS?
- Why are we systematically underpredicting lift, but overpredicting drag and pitch? (I.e. Large regions of un-physical flow separation)
- Why do SA models perform better than SST models? (How important is Boussinesq)
- How do SST models perform for warm starts?
- Why do we have convergence problems:
  - Aerodynamic instabilities -> Would RANS "mimic" URANS?
  - Due to flow separation effects
  - Grid
- How can we improve the convergence characteristics? (e.g. selective frequency damping, GMRES)
- Can we use Global Stability Analysis (GSA) to extend the application of RANS (e.g. predicting onset of numerical instabilities + selective frequency damping)?
- Would conclusions change when using different grids or adaptive mesh refinement (AMR)?
- Can URANS simulations improve accuracy (SA and SST)?

Back-up slides

- Convergence

- 7deg:
- 17deg
- 19deg
- 21deg

35

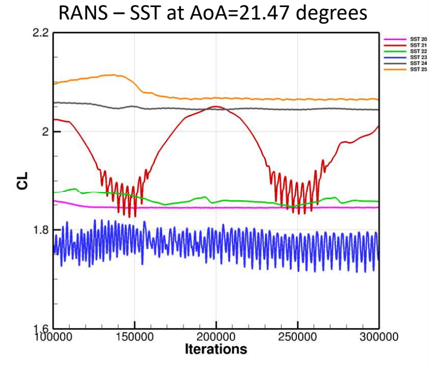
Comments on convergence characteristics

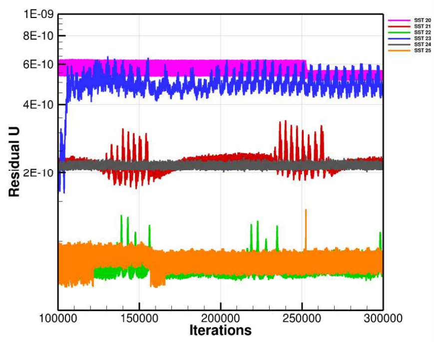
Convergence at off-design conditions with **significantly separated flow** can be **problematic.**

Residuals can depend on numerical schemes and regions with maximum residuals do not necessarily coincide with the those relevant for industrial application. Also, residuals usually only compare two consecutive iterations, which **could understate the total change of results** over longer run times.

Note that
- All residuals are for all cases of the same order of magnitude
- Pink and grey curves show reasonably steady CL
- Blue and red curves show significant lift fluctuations
- **BUT** pink/blue and grey/red curves have <u>similar residuals</u>

RANS – SST at AoA=21.47 degrees



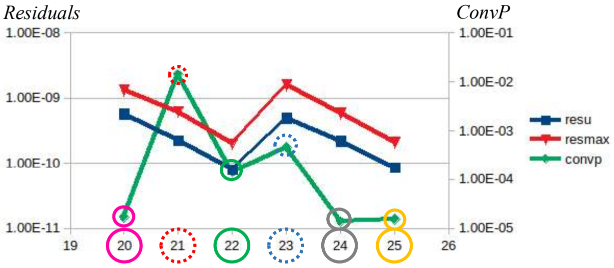


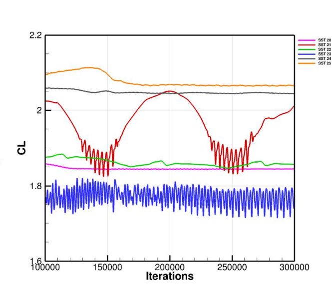
As an **alternative** we propose to assess **fluctuations** of **aerodynamic coefficients**, which are often used for evaluating simulation performances.

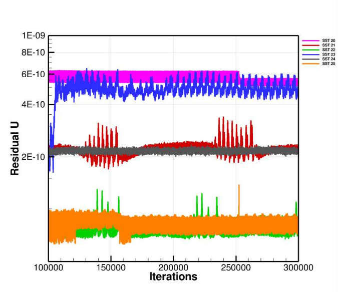
Definition of **convergence parameter ConP**:

-> Statistics (root-mean-square and time average) of aerodyn. coefficients computed over 50000 iterations

-> ConvP= log([(CDrms/CDavrg)^2 + (CLrms/CLavrg)^2 + (CMrms/CMavrg)^2]^0.5)



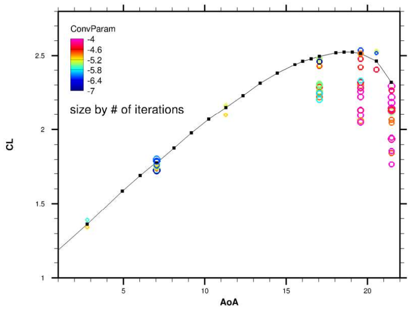


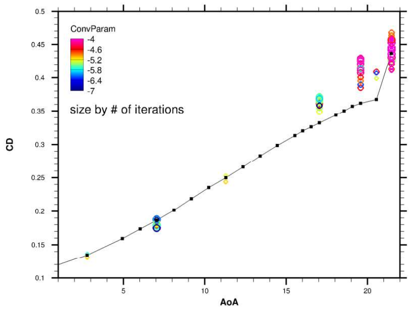


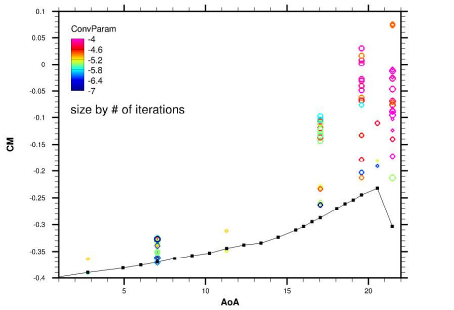
This convergence parameter allows us to

- **separate convergence characteristics** of simulations for the current test case **more clearly**
- **evaluate convergence based on physical quantities**, which are of main interest for practical application

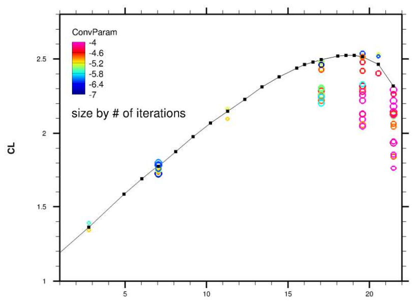
Simulation results with respect to convergence





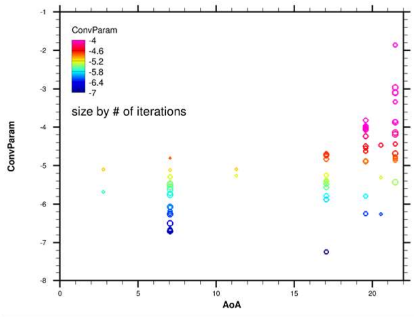


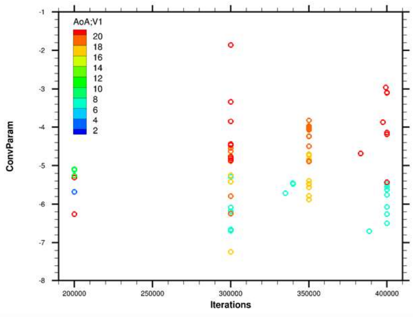
- Using **different turbulence models**, we observe a **significant spread** of **RANS results**, particularly at increased AoA.
- Lift is mostly underpredicted and drag overpredicted.
- **Momentum coefficient** is most **critical** and even at moderate AoA not sufficiently well predicted.
- **SST models** show **no significant improvement** and are much more expensive.
- **Convergence** is **insufficient** near $C_{L,max}$.

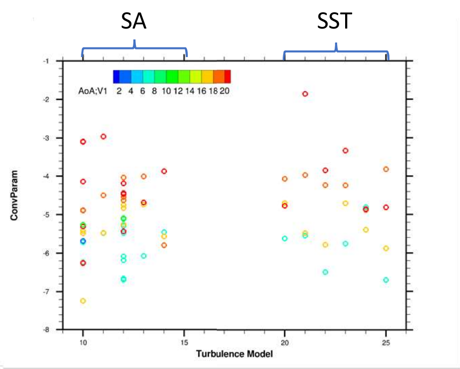


Number of iterations and convergence of Simulations

- **Convergence** is **insufficient** near $C_{L,max}$.
- All simulations were run for at least 200,000 iterations.
- SST models were limited to 300,000 due to computational expenses.





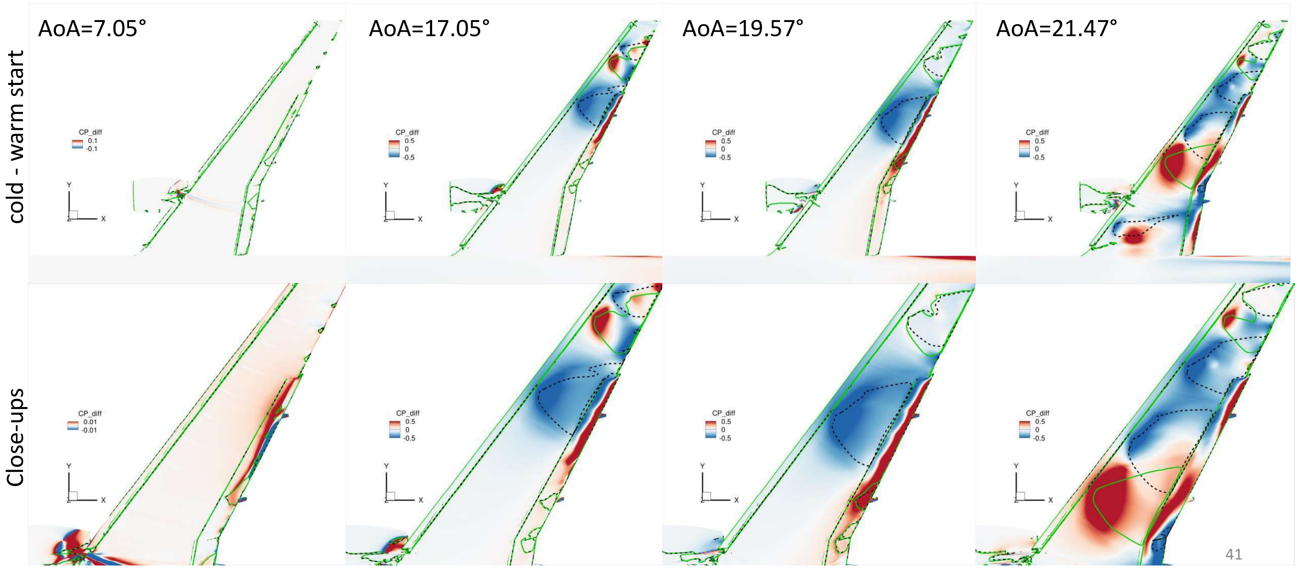


Back-up slides

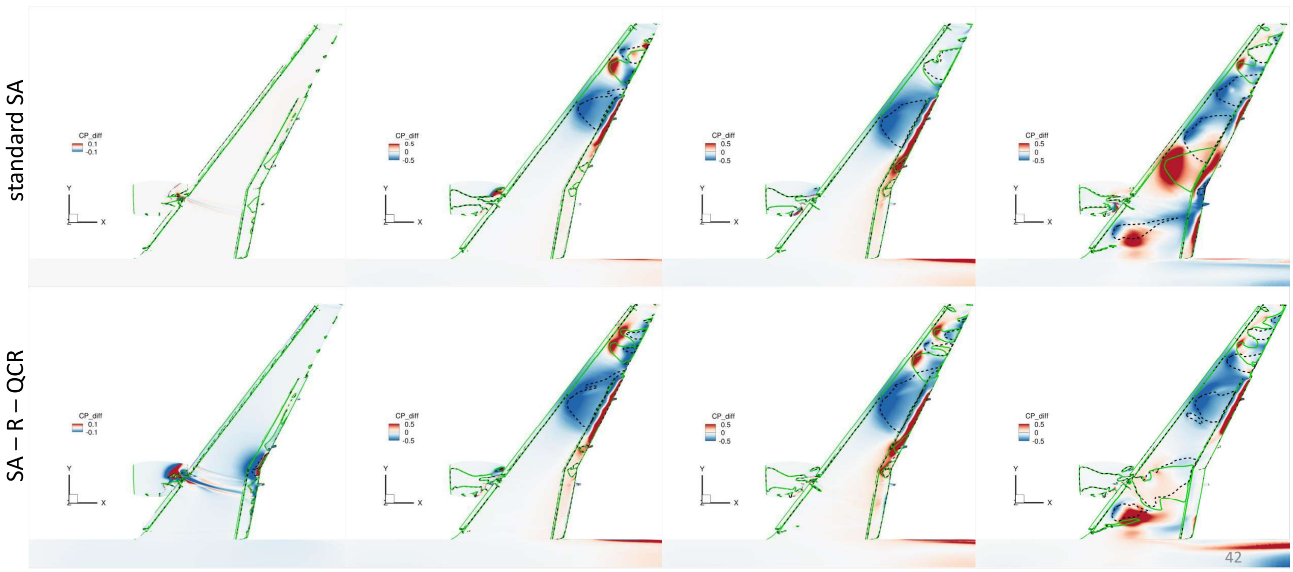
- Comparison cold vs warm start using different SA models

40

Cold vs Warm Start using SA-noft2



Cold vs Warm Start for SA-noft2 and with rotation and QCR corrections



Back-up slides

- Simulation costs

Simulation costs

	Standard FaSTAR	Tuned FaSTAR
SA (standard)	96000 coreh/300000 iterations	50000 coreh/300000 iterations
SST	115000 coreh/300000 iterations	65000 coreh/300000 iterations

- SST about 30% more expensive than SA
- Tuned FaSTAR almost twice as fast as standard FaSTAR