PRELIMINARY VERIFICATION AND VALIDATION OF REYNOLDS STRESS MODELS IN THE CFD SOFTWARE BY ONERA, DLR AND AIRBUS (CODA)

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INTRODUCTION

CODA: NEEDED FOR ENTRY INTO SERVICE (EIS) FOR INDUSTRY

- CODA is the computational fluid dynamics (CFD) software being developed as part of a collaboration between the French Aerospace Lab ONERA, the German Aerospace Centre (DLR), Airbus, and their European research partners. CODA is jointly owned by ONERA, DLR and Airbus.
- **Verification :** To ensure that the RANS model is implemented correctly, i.e., checking of the full behaviour of all the terms in the model.
- **Validation:** To assess the RANS solution by reference to some „ground truth“ – a wind tunnel experiment / DNS / LES.
- **Robustness:** Possibility of convergence of the numerical simulation without crashing
- **Convergence quality:** How can convergence be achieved? Residual convergence to machine accuracy or Cauchy convergence of integral coefficients and surface results but a stall of residual convergence.
- **Best-practice settings:** A unique setting for all flow speeds and flow types that ensure convergence.

SSG/LRR-ln(ω) REYNOLDS STRESS MODEL

- One of the robust models from the RSM family widely used for industrial purposes
- Reynolds stress equations:

$$\frac{\partial(\bar{\rho}\widehat{R_{ij}})}{\partial t} + \frac{\partial(\bar{\rho}U_k\widehat{R_{ij}})}{\partial x_k} = \bar{\rho}P_{ij} + \bar{\rho}\Pi_{ij} - \bar{\rho}\varepsilon_{ij} + \bar{\rho}D_{ij}^{\nu} + \bar{\rho}D_{ij}^{t} + \bar{\rho}D_{ij}^{p}$$

Where, P_{ij} → Production, Π_{ij} → Pressure-strain correlation, ε_{ij} → Dissipation tensor, D_{ij}^{ν} & D_{ij}^{t} viscous and turbulent transport, D_{ij}^{p} transport due to pressure fluctuations.

- We transform the length scale variable as $\widehat{\omega} = \ln \omega$, hence, $\omega = e^{\widehat{\omega}}$

$$\frac{\partial(\bar{\rho}\widehat{\omega})}{\partial t} + \frac{\partial(\bar{\rho}U_k\widehat{\omega})}{\partial x_k} = \frac{\alpha_{\widehat{\omega}}}{k}\frac{\bar{\rho}P_{kk}}{2} - \beta_{\widehat{\omega}}\bar{\rho}e^{\widehat{\omega}} + \frac{\partial}{\partial x_k}\left[\left(\bar{\mu} + \sigma_{\widehat{\omega}}\frac{\bar{\rho}k}{e^{\widehat{\omega}}}\right)\frac{\partial\widehat{\omega}}{\partial x_k}\right]$$

$$+ \sigma_d\frac{\bar{\rho}}{e^{\widehat{\omega}}}\max\left(\frac{\partial k}{\partial x_k}\frac{\partial\widehat{\omega}}{\partial x_k}, 0\right) + \left(\bar{\mu} + \sigma_{\widehat{\omega}}\frac{\overline{\rho k}}{e^{\widehat{\omega}}}\right)\frac{\partial\widehat{\omega}}{\partial x_k}\frac{\partial\widehat{\omega}}{\partial x_k}$$

- Two models for diffusion: Generalized Gradient Diffusion (**GGD**) and Simple Gradient Diffusion (**SD**)

REALIZABILITY CONSTRAINTS

- Non-physical turbulence can arise due to turbulence modelling and discretization errors.
- Problem of non-realizable solutions in RSMs – Schumann
- Possible limits of Reynolds stress values – Lumley
- Constraints derived from these limits – ***Realizability constraints***
- Reynolds stress tensor should be Symmetric Positive Semi Definite (SPSD) tensor which gives rise to the following conditions:

$$R_{ij} \geq 0, \qquad \forall\, i = j$$

$$R_{ij} \leq \sqrt{R_{ii} R_{jj}}, \qquad \forall\, i \neq j$$

- A lesser known constraint is $\det(\mathbf{R}) \geq 0$

METHODS TO ENFORCE REALIZABILITY CONSTRAINTS

- **Clipping approximation**

  The standard approach

- **Blending GGD and SD models**

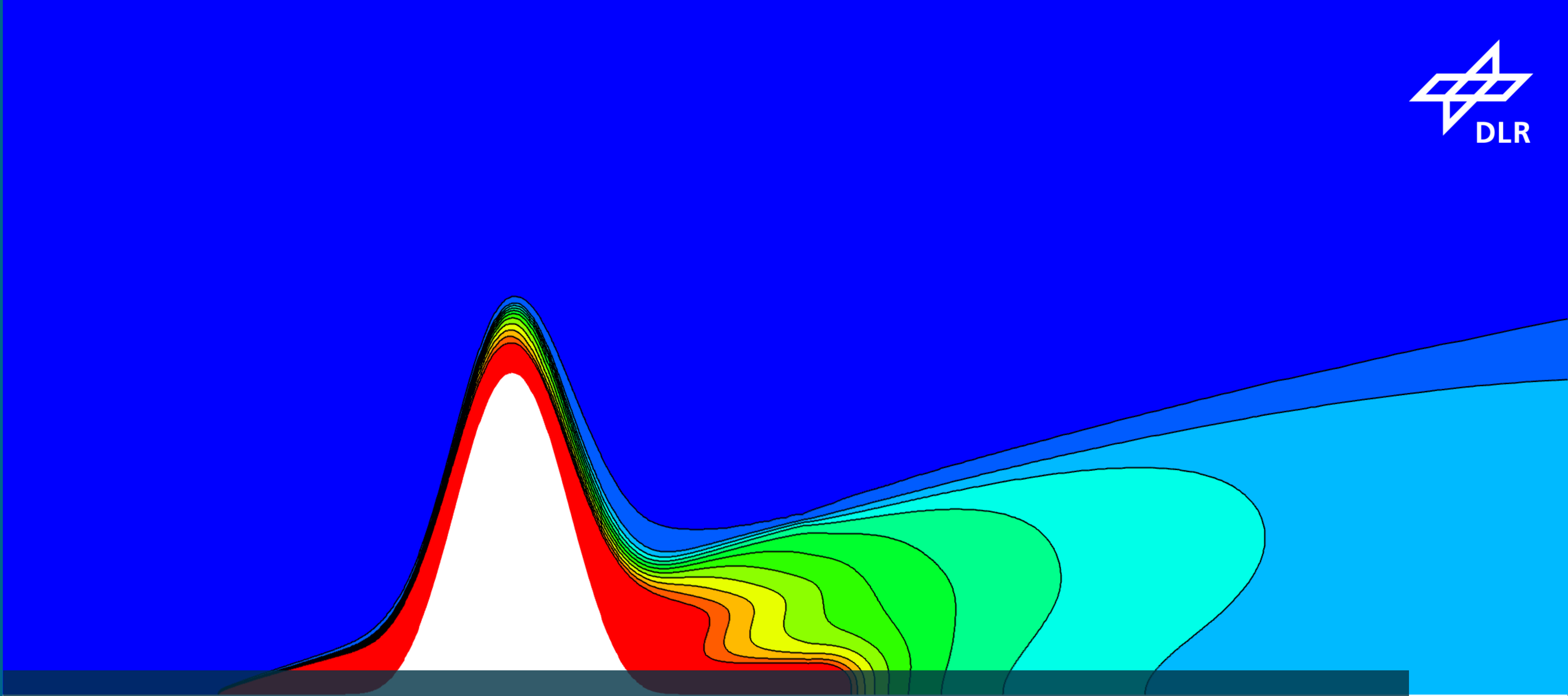
  Combing the diffusion models, i.e. using SD where realizability constraints may not be satisfied.

- **Non-linear positivity filter**

  A smoothed clipping approach to maintain differentiability of the Reynolds stress at the clipped elements.

- **Realizability preserving time stepping**

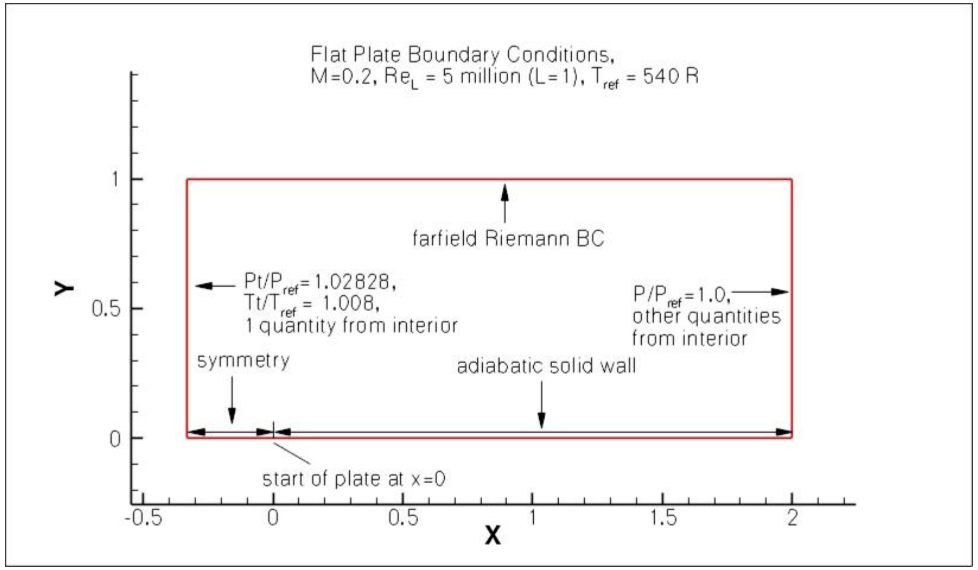
  Source term treatment when considered for the Jacobian by splitting them into explicit/implicit parts.



VERIFICATION TEST CASES

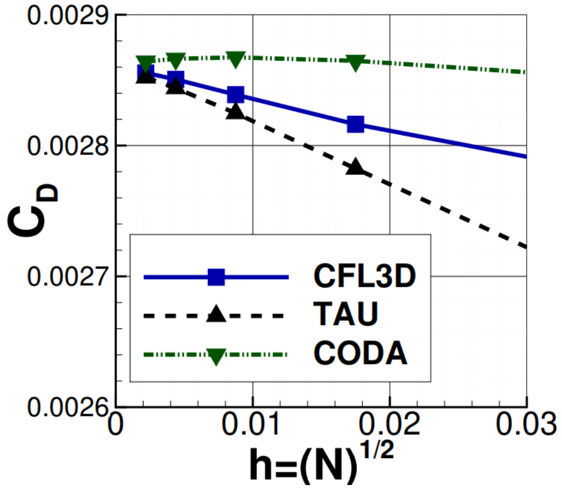
TURBULENT FLAT PLATE (VERIF/2DZP)

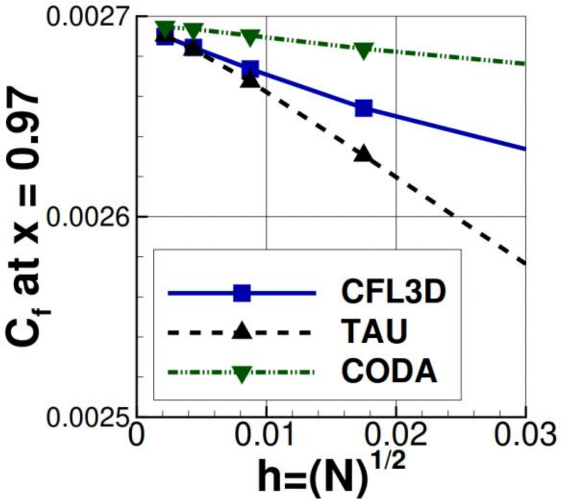
- Mach number $M = 0.2$, Reynolds number $Re = 5 \times 10^6$ based on $L_{Re} = 1$.
- The plate extends from $x = 0$ to $x = 2$ (so $Re = 10 \times 10^6$ at end of grid).
- using the five CGNS "quad" grids
  - 35×25 to 545×385 hexas
- using TAU/CODA turbulence inflow defaults
- CODA and references (TAU/CFL3D) used the Generalized Gradient Diffusion (GGD) model

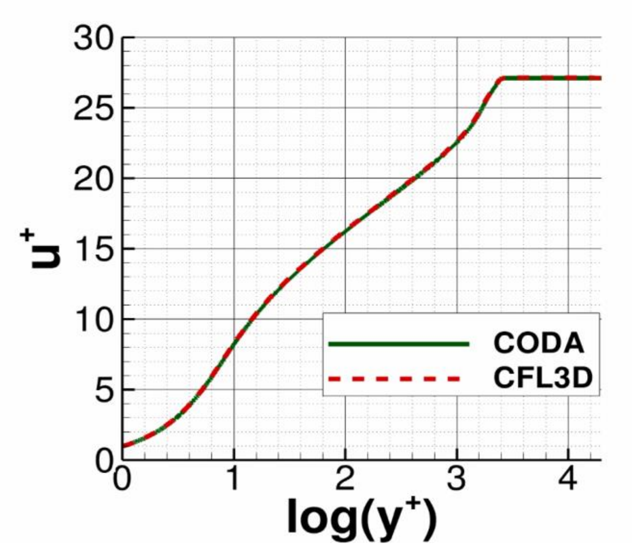


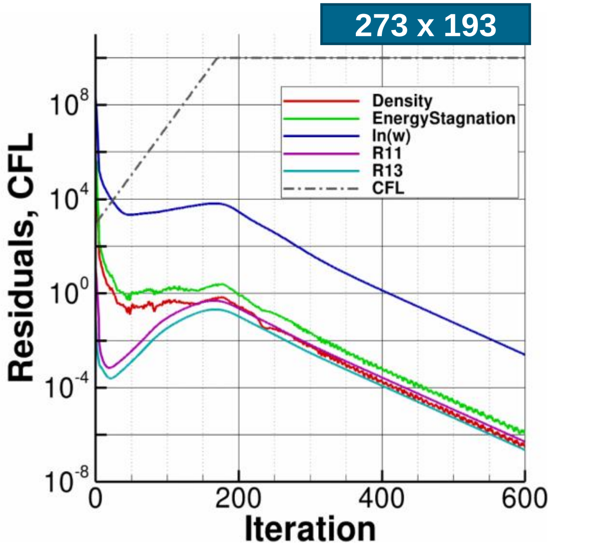
TURBULENT FLAT PLATE (VERIF/2DZP)

- Good convergence obtained without any unphysical Reynolds stresses in the field.
- Better grid convergence for CODA compared to TAU and CFL3D.
- Additional methods to improve robustness and realizability were tested.
    - Initial CFL number and CFL ramping sensitive to the grid size.
    - Realizability preserving time stepping scheme eliminates the CFL sensitivity





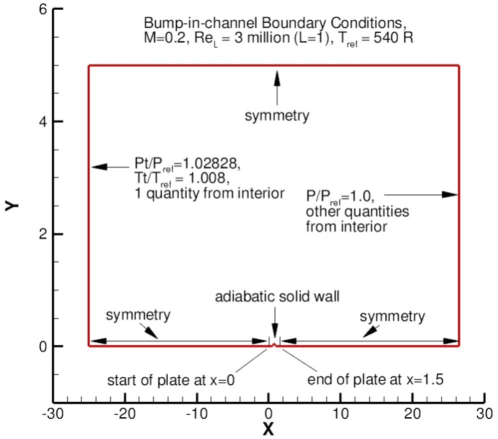


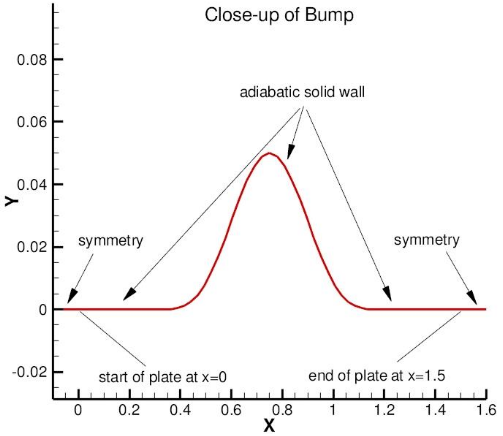


Realizability preserving time stepping scheme

2D BUMP IN CHANNEL (VERIF/2DB)

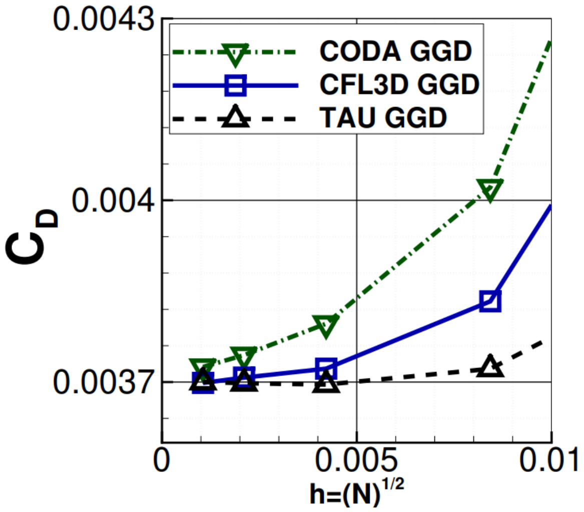
- Mach number $M = 0.2$, Reynolds number $Re = 3 \times 10^6$ based on $L_{Re} = 1$.
- The plate extends from $x = 0$ to $x = 1.5$ (so $Re = 5.5 \times 10^6$ at end of grid).
- using the five CGNS “quad” grids
  - 89×41 to 1409×384 hexas
- using TAU/CODA turbulence inflow defaults
- CODA and references (TAU/CFL3D) used GGD or SD model

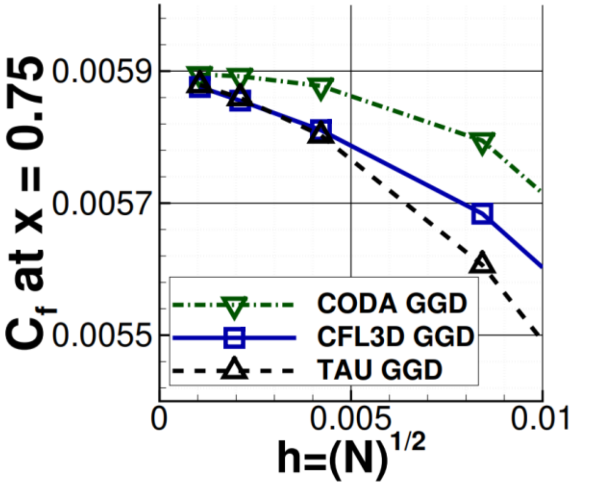


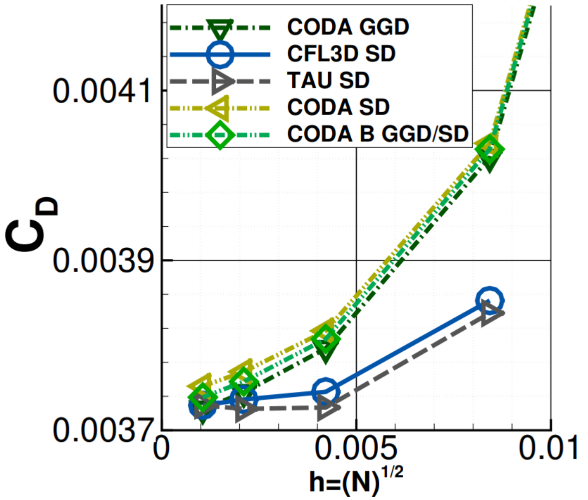


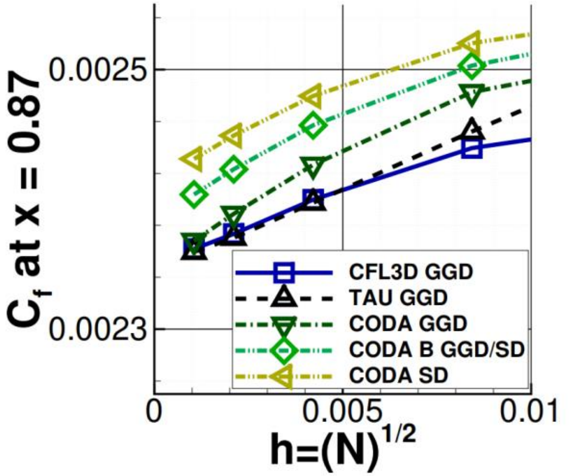
2D BUMP IN CHANNEL (VERIF/2DB)

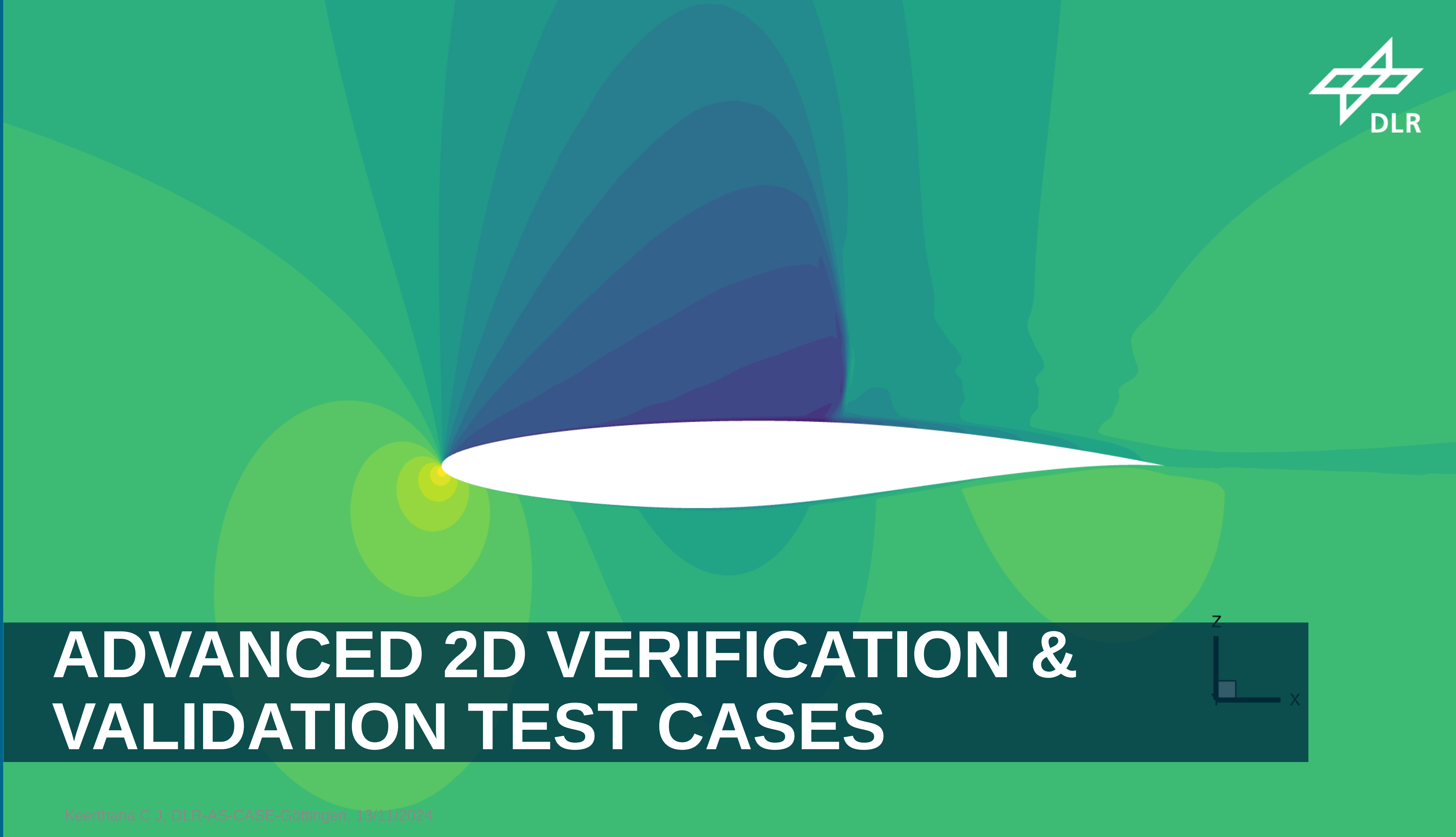
- SD model converged while GGD did not converge.
- Unrealizable Reynolds stresses in a few elements are cause for the convergence issues
- With different strategies to enforce the realizability constraints, integral coffecients convergence through Cauchy criteria was possible. Residual convergence is still not possible.







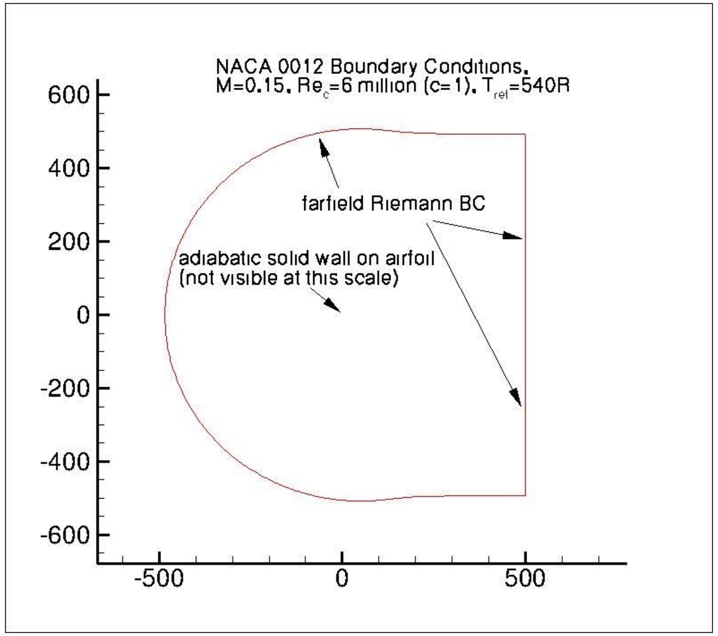


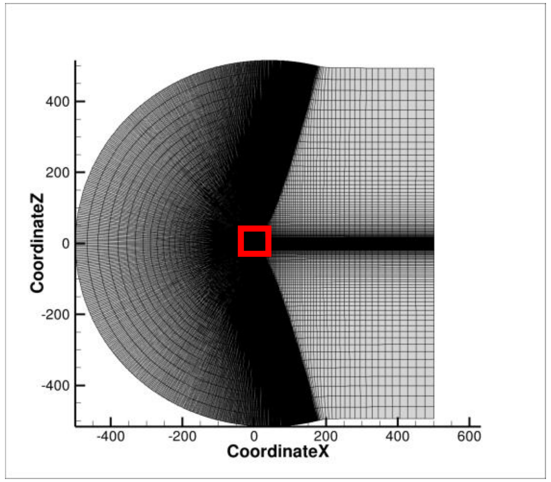


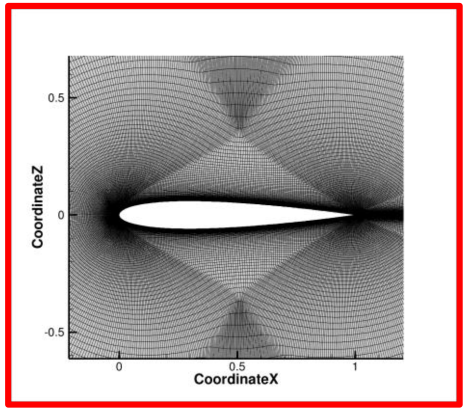
ADVANCED 2D VERIFICATION & VALIDATION TEST CASES

2D NACA0012 AIRFOIL

- Mach number $M = 0.15$, Reynolds number $Re = 6 \times 10^6$ based on $L_{Re} = 1$.
- using the five unstructured CGNS quad grids
  - 113×33 to 1793×513 hexas
  - Results from CFL3D available for 897×257 grid
- Experimental data available AoA, $\alpha = 0^\circ\ to\ 15^\circ$, CFL3D data available $\alpha = 0^\circ, 10^\circ, 15^\circ$
- using CODA turbulence inflow defaults
- CODA and references (CFL3D) used the GGD model.

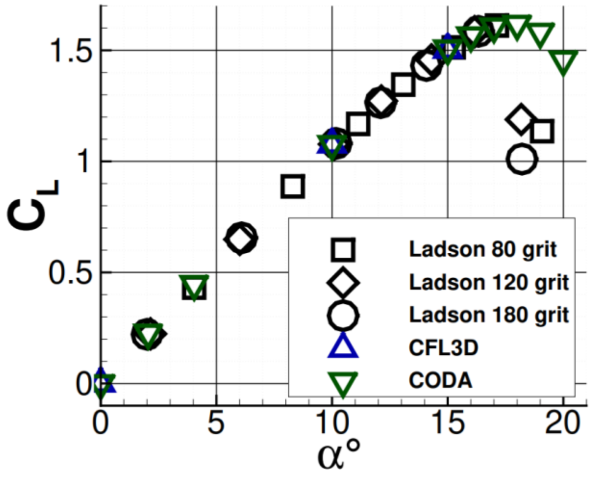


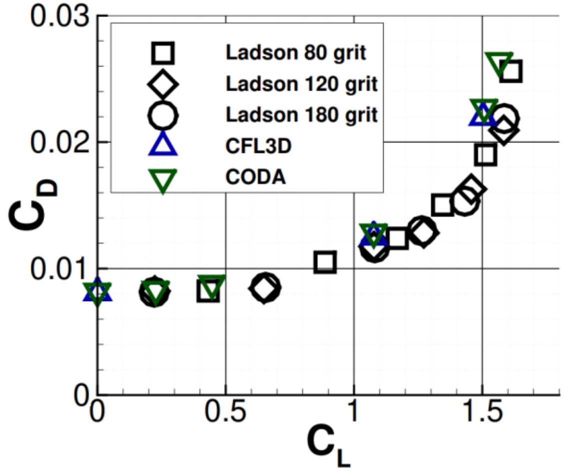


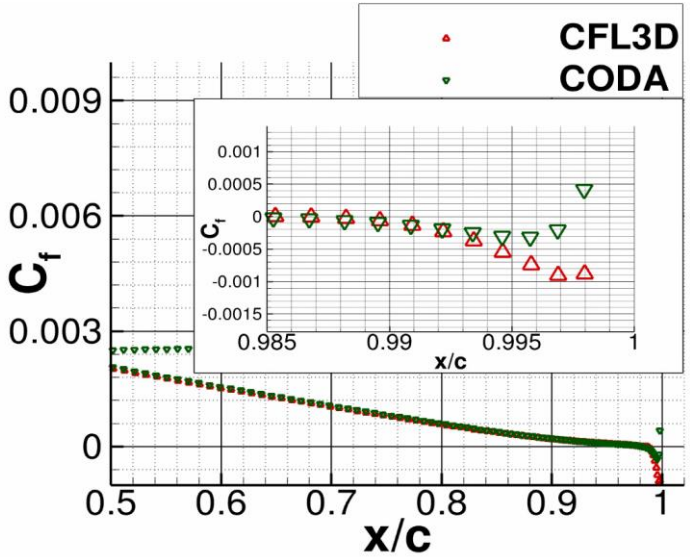


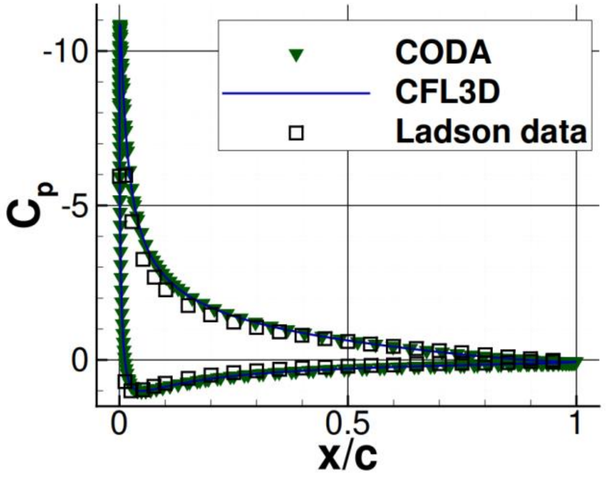
2D NACA0012 AIRFOIL

- Residuals stall when realizability constraints are imposed. When realizability is removed, a few cells close to the trailing edge where separation occurs violate realizability. (next slide)
- Slight discrepancy with CFL3D results in the separation region where the drop in C_f for CFL3D is higher than CODA.

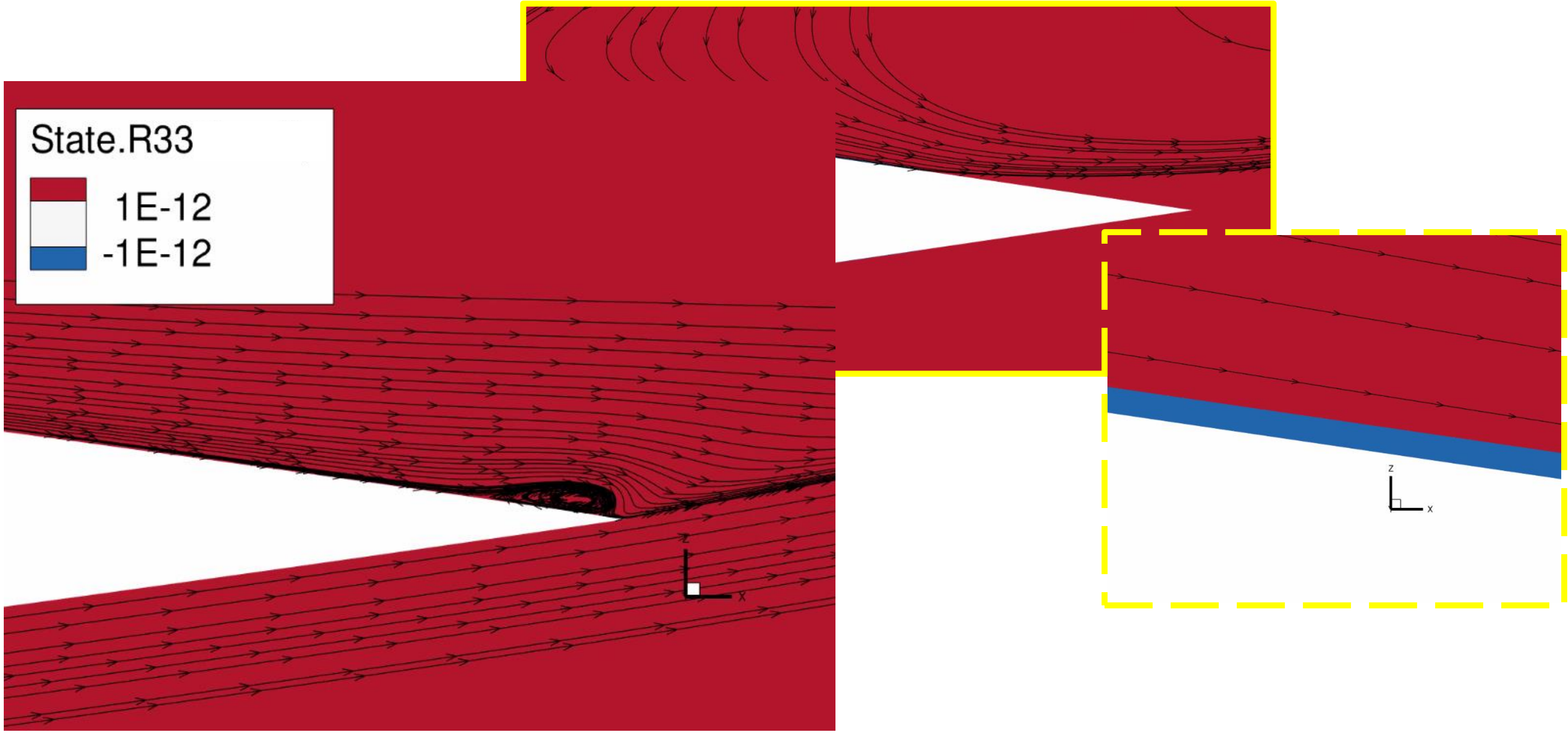






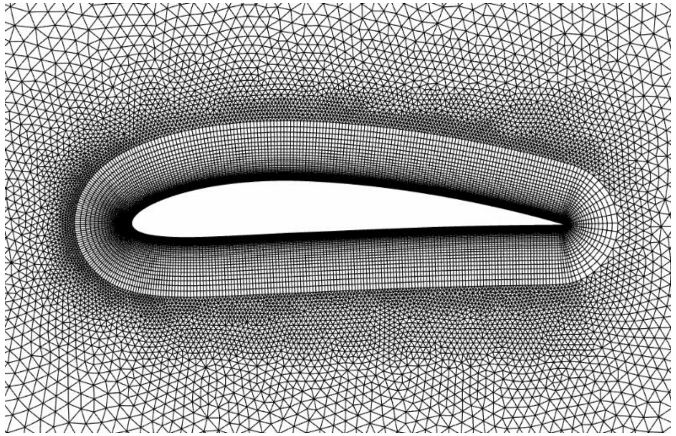


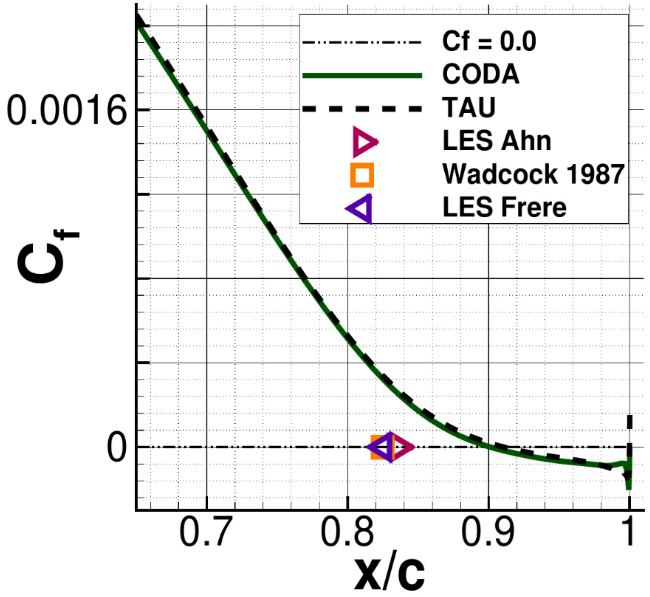
2D NACA0012 AIRFOIL
REALIZABILITY VIOLATION

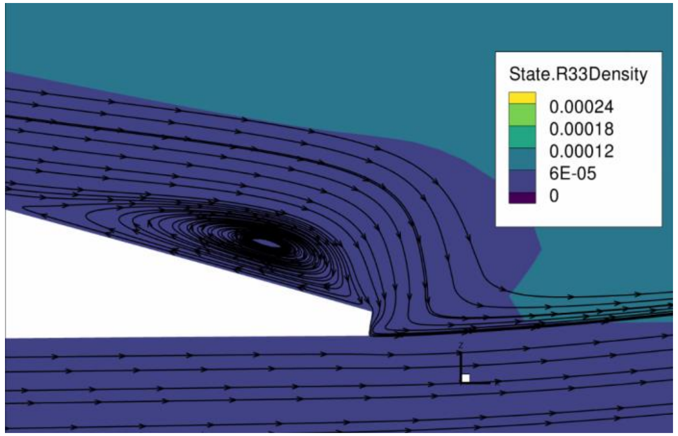


2D NACA4412 AIRFOIL

- Centaur mesh with ~80000 nodes
- Validation with Wadcock (1987) data.
- Experimental conditions - Mach number $M = 0.085$, Reynolds number $Re = 1.64 \times 10^6$, angle of attack $\alpha = 12^{\circ}$ based on $L_{Re} = 1$.
- Steady state solution obtained from TAU for verification
- No stalling of residuals and no violation of realizability constraints after removal of non-linear positivity filter.

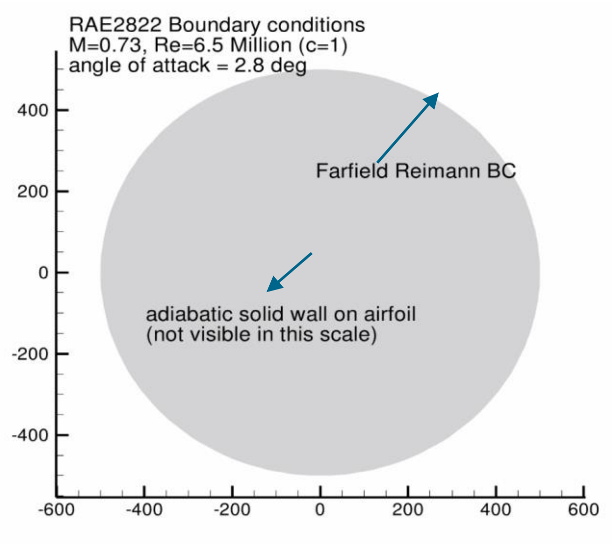


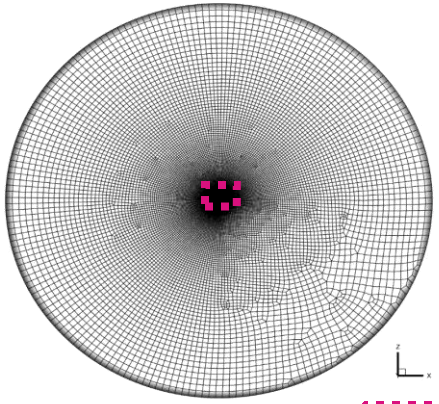


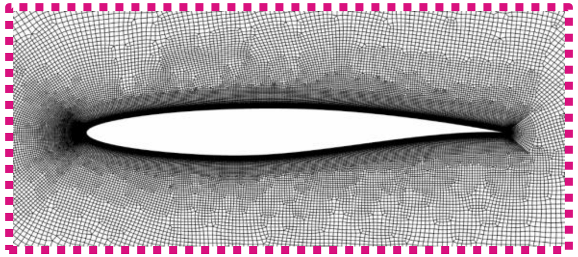


RAE2822 AIRFOIL – Case 9

- Mach number $M = 0.73$, Reynolds number $Re = 6.5 \times 10^6$, angle of attack $\alpha = 2.8^\circ$ based on $L_{Re} = 1$.
- 254252 nodes, 126698 hexas hybrid ANSA mesh.
- Experimental data available $\alpha = 2.8^\circ$ (Cook et al), using TAU/CODA turbulence inflow defaults
- CODA and references (TAU) used the GGD model.

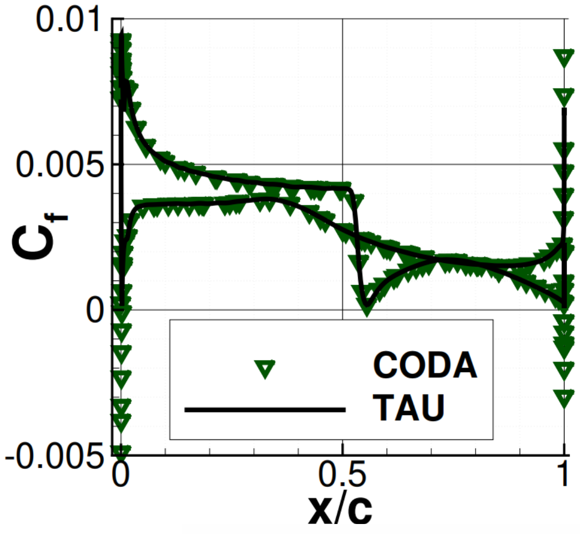


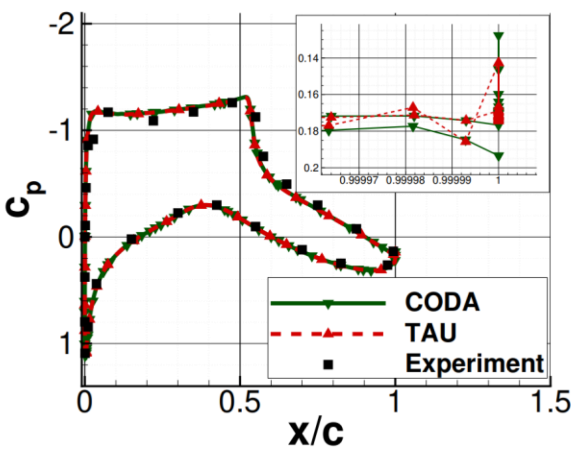


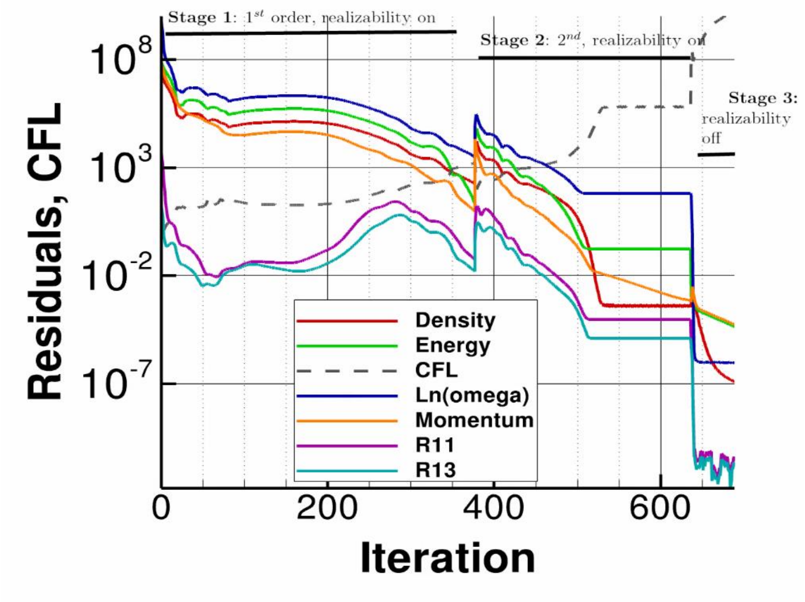


RAE2822 AIRFOIL – Case 9

- Good agreement with TAU and experimental results.
- Very slight variantion in the C_f at the trailing edge compared to TAU result
- Stalling of residuals when realizability constraints are enforced. No violation of realizability when constraints are removed. It is note that this case does not have separation.
  - No shock induced separation.
  - No trailing edge separation.







CONCLUSION

- First results from verification of the SSG/LRR-ln(ω) RSM model in CODA
- Interplay between numerics and realizability constraints within the transient phase of the solution has been described.
- Non-linear positivity filter has provided the best improvement until now.
- Realizability constraints have to be enforced during the transient phase and then deactivated later due to residual stall.
- Suitable treatment of source terms as implicit/explicit in the Jacobian can enhance robustness
- A Cauchy convergence of lift, drag and momentum may be achieved even if the residuals stall.

FUTURE WORK

- Verification and validation of 3D complex aircraft configurations.
- A deeper analysis of the role of realizability constraints and its interplay with the numerical stability.

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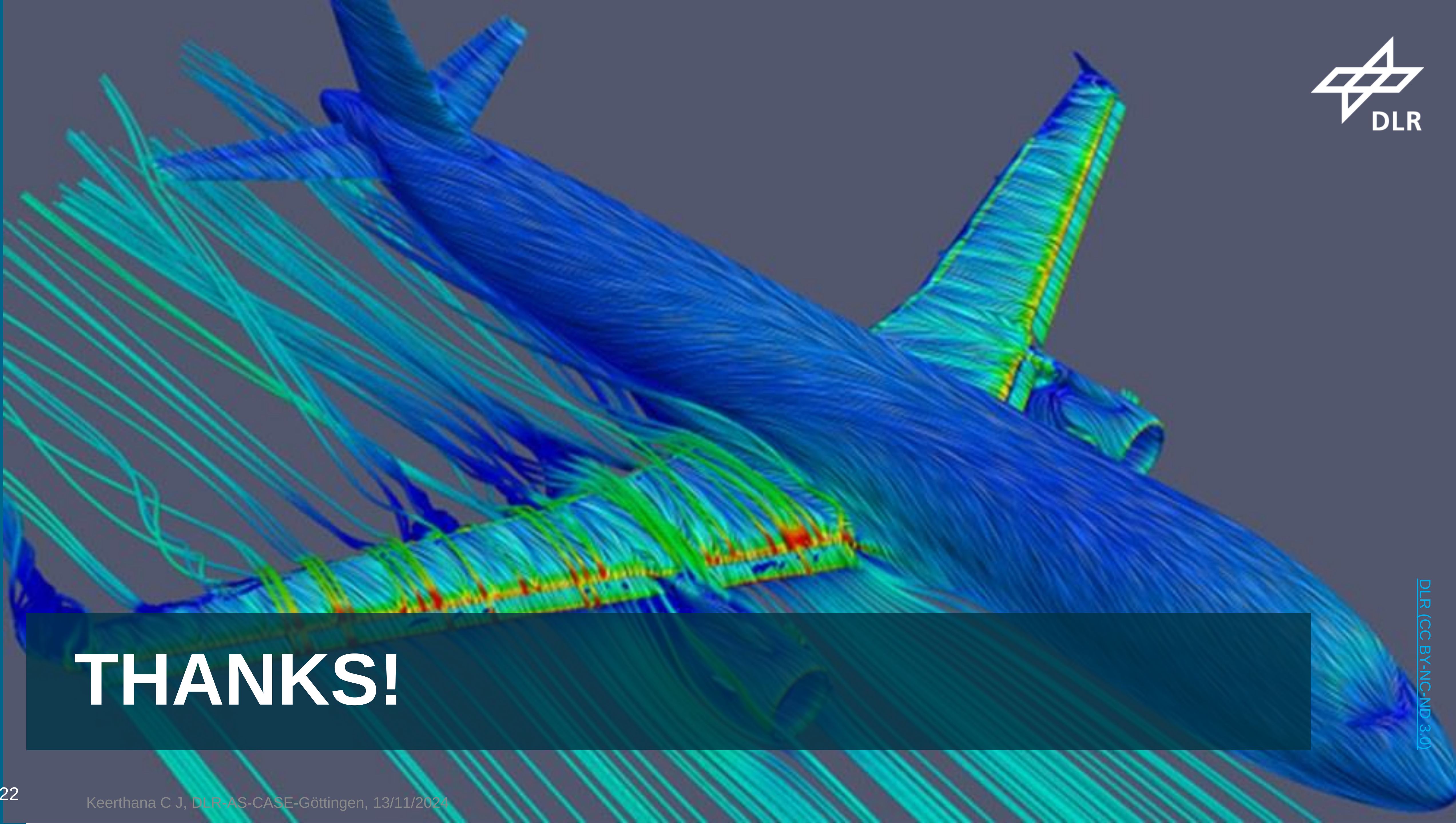

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