Stanford University

Recent Developments of Hybrid RANS/LES in SU2

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4th Annual SU2 Developers Meeting

Outline

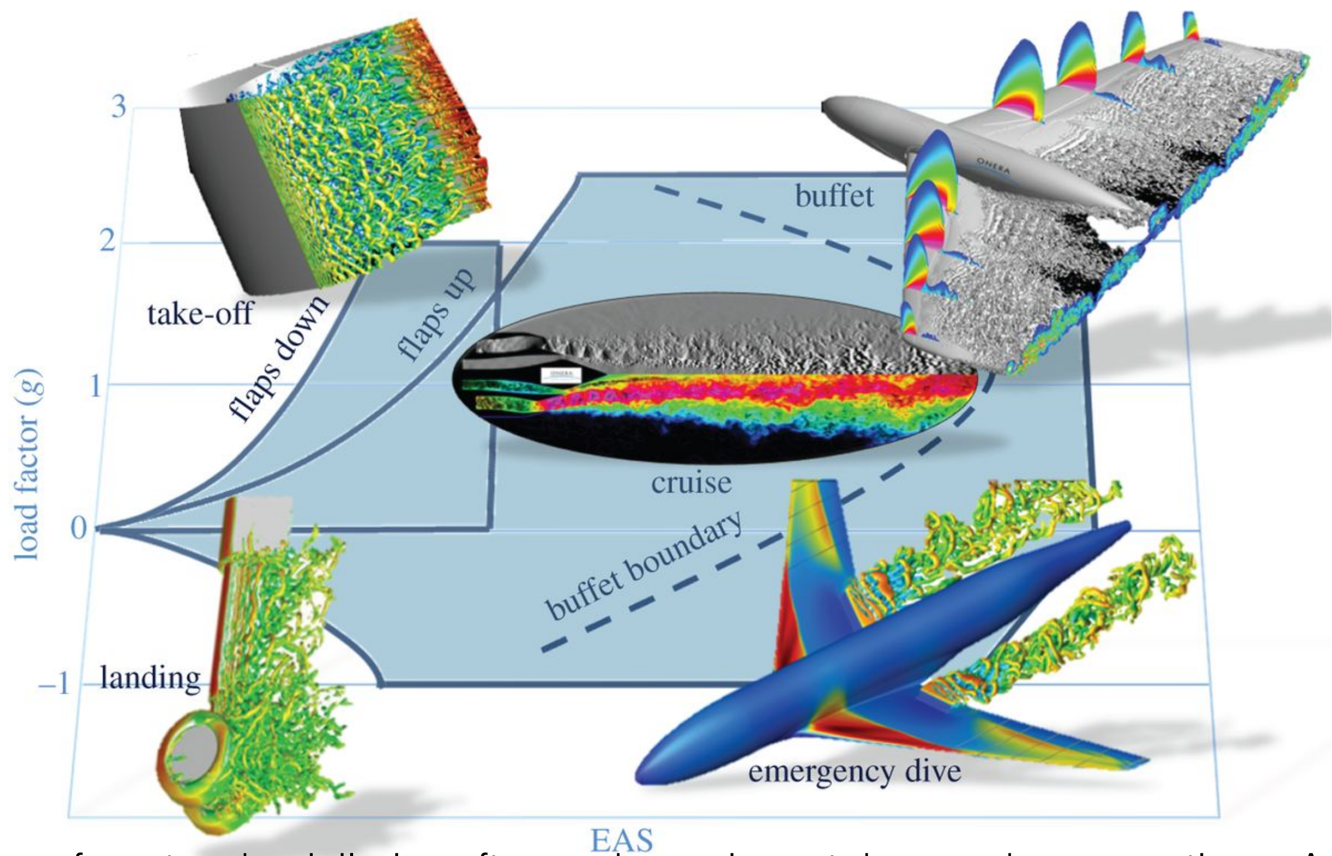
- Motivation
- Numerical Methods
- Past Test Cases
- Ongoing Test Cases
- Future Implementations

Motivation (1)

1. Implement, verify and validate the Delayed Detached Eddy Simulation (DDES) approach with methods to accelerate the RANS to LES transition.

2. Implement low-dissipation and low-dispersion convective schemes that are needed to successfully resolve vortex dominated flows.

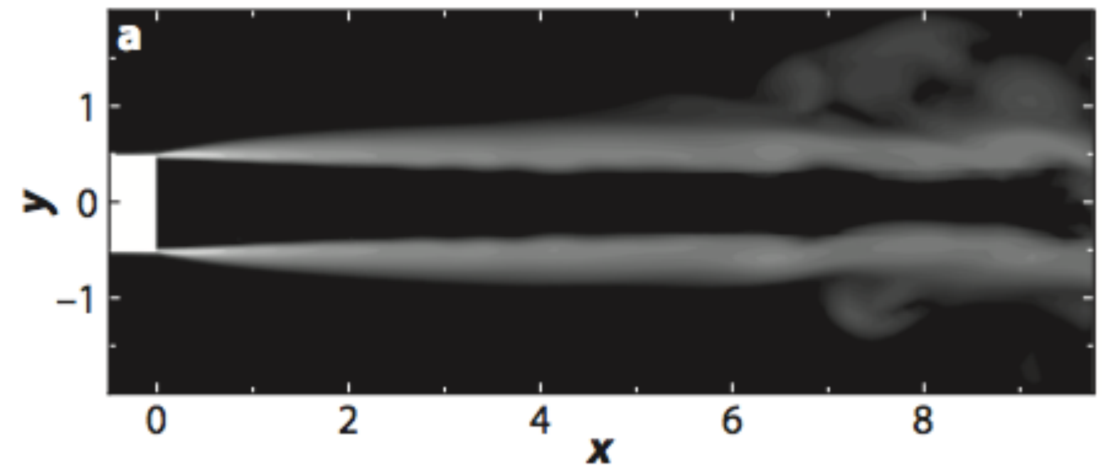
3. Provide to the community an open-source framework for further improvement of hybrid RANS/LES models, extending the applicability to new industrial needs in aerodynamics and optimization concerns.



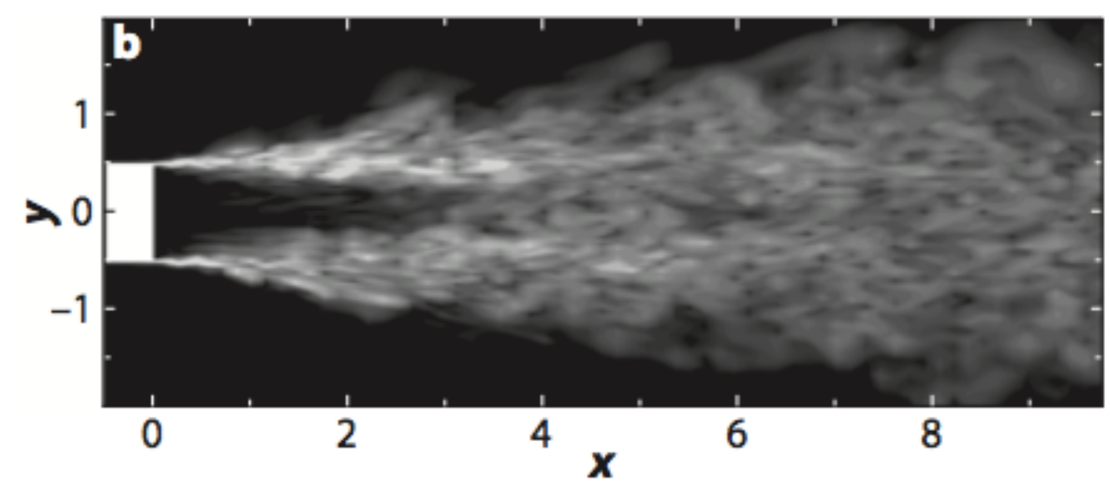
[1] Deck et al., High-fidelity simulations of unsteady civil aircraft aerodynamics: stakes and perspectives. Application of zonal detached eddy simulation, 2014

Motivation (2)

- Main issue in any Hybrid RANS/LES: The Grey Area.
  - Transition region between RANS and LES modes.
  - Detrimental impact on flows featuring shallow regions of boundary-layer separation and re-attachment, i.e., wings near the border of flight envelope and jet noise.
- Classification of Hybrid RANS/LES:
  - Non-zonal methods:
    - The model defines the regions in which RANS and LES are active, i.e., DDES.
    - More suitable to complex geometries and industrial problems.
  - Zonal methods:
    - The user defines the interface between RANS and LES by “injecting” turbulent content, i.e., RANS-WMLES.
    - The grey area tends to be reduced compared to non-zonal methods.



Original DDES



Implicit LES

Spalart, Detached Eddy Simulation, Annual Review in Fluid Mechanics, 2009.

Delayed DES

- Spalart-Allmaras Turbulence Model:

$$\frac{\partial \hat{\nu}}{\partial t} + \nabla \cdot \vec{F}^c - \nabla \cdot \vec{F}^v - Q = 0$$

$$Q = c_{b1} \hat{S} \hat{\nu} + \frac{c_{b2}}{\sigma} |\nabla \hat{\nu}|^2 - c_{w1} f_w \left(\frac{\hat{\nu}}{d} \right)^2$$

- Delayed DES:

$$\tilde{d} = d - f_d \max(0, d - C_{DES} \Delta)$$

  - Standard DDES[2]:

$$\Delta = \Delta_{max} = \max(\Delta_x, \Delta_y, \Delta_z)$$

Grey Area Mitigation

  - Vorticity Adapted SGS[3]:

$$\Delta = \Delta_\omega = \sqrt{n_x^2 \Delta_y \Delta_z + n_y^2 \Delta_x \Delta_z + n_z^2 \Delta_x \Delta_y}$$

  - Shear-layer adapted SGS[4]:

$$\Delta = \Delta_{SLA} = \tilde{\Delta}_\omega F_{KH}(< VTM >)$$

[2] Spalart et al. A New Version of Detached-eddy Simulation, Resistant to Ambiguous Grid Densities, 2006
[3] Deck, Recent improvements in the Zonal Detached Eddy Simulation (ZDES) formulation, 2012
[4] Shur et al., An Enhanced Version of DES with Rapid Transition from RANS to LES in Separated Flows, 2015

Grey Area Mitigation for Unstructured Codes

- Vorticity-based unstructured grid definition[3]:

$$\Delta_\omega = \sqrt{\bar{S}_\omega}$$

  - Average cross section of the cell normal to the vorticity vector.

- Shear-layer adapted:
  - Original multi-block structured grid definition[4]:

$$\tilde{\Delta}_\omega = \frac{1}{\sqrt{3}} \max_{n,m=1,8} \left|(I_n - I_m)\right|, I_n = n_\omega \times r_n$$

  - Proposed definition optimized for unstructured vertex-based codes :

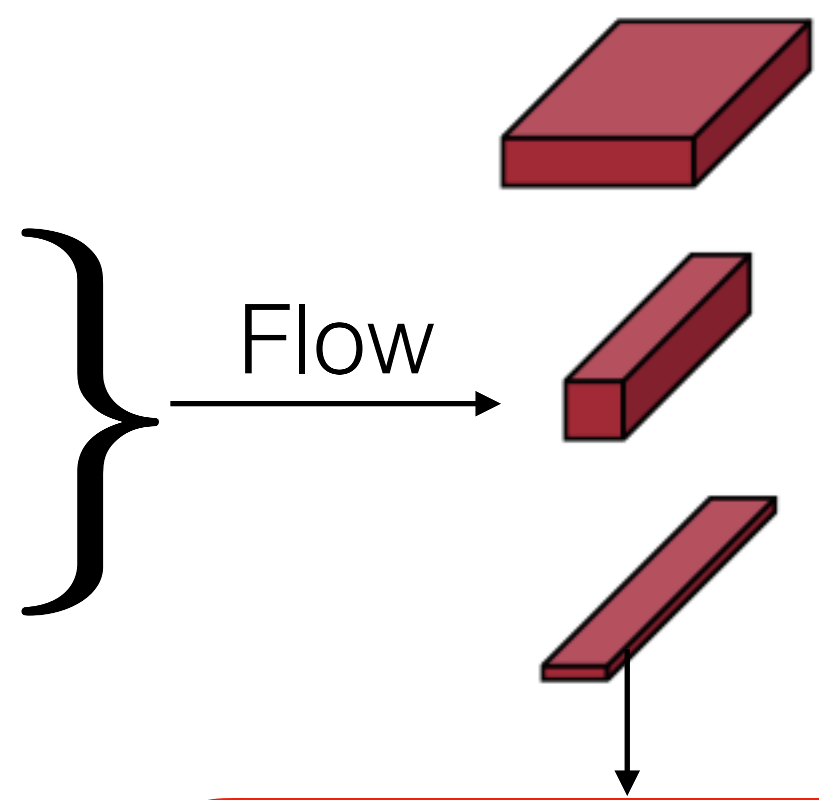
$$\tilde{\Delta}_\omega = \frac{1}{\sqrt{3}} \max_{j=1,n} \left|n_{\omega_i} \times r_{ij}\right|$$

  - Vortex Tilting Measurement (VTM):

$$VTM = \frac{\sqrt{6}|(\hat{S} \cdot \vec{\omega}) \times \vec{\omega}|}{\omega^2 \sqrt{3tr(\hat{S}^2) - [tr(\hat{S})]^2}} \max\{1, (\nu^*/\nu_t)\}, \quad \nu^* = 0.2\nu$$

  - Final form:

$$\Delta_{SLA} = \tilde{\Delta}_\omega F_{KH}(< VTM >)$$



$$\tilde{\Delta}_\omega \approx \frac{1}{\sqrt{3}} \sqrt{\left(\Delta_x^2 + \Delta_y^2\right)}$$

[3] Deck, Recent improvements in the Zonal Detached Eddy Simulation (ZDES) formulation, 2012
[4] Shur et al., An Enhanced Version of DES with Rapid Transition from RANS to LES in Separated Flows, 2015

Low Dissipation Schemes

- Introducing adaptive dissipation functions for High-Resolution convective schemes:
  - DDES f_d function[2]:

$$\sigma_{FD} = \max(0.05, 1 - f_d)$$

  - NTS sensor[6]:

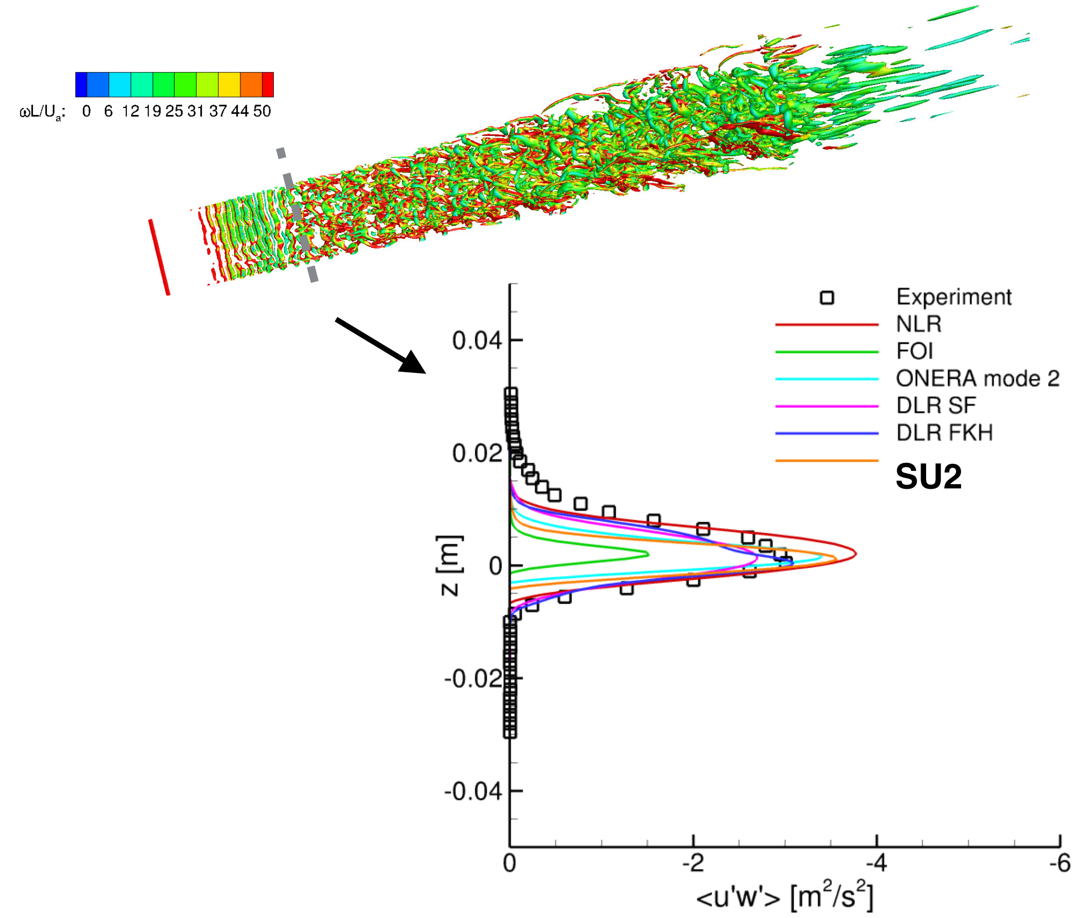
$$\sigma_{NTS} = \max(\phi_{max} \tanh(A^{ch1}), 0.05)$$

- Simple Low Dissipation AUSM (SLAU2)[7]:

$$\tilde{F}^c_{ij} = \frac{\dot{m} + |\dot{m}|}{2}\mathbf{\Psi}^+ + \frac{\dot{m} - |\dot{m}|}{2}\mathbf{\Psi}^- + \tilde{p}\mathbf{N}$$

$$\mathbf{\Psi} = (1, u, v, w, H)^T, \quad \mathbf{N} = (0, n_x, n_y, n_z, 0)^T$$

$$\tilde{p} = \frac{p_L + p_R}{2} + \frac{\beta^+ - \beta^-}{2}(p_L - p_R) + \sigma\sqrt{\frac{u_L^2 + u_R^2}{2}}\left(\beta^+ + \beta^- - 1\right)\bar{\rho}\bar{c}$$



[2] Spalart et al. A New Version of Detached-eddy Simulation, Resistant to Ambiguous Grid Densities, 2006
[6]Travin et al., Physical and numerical upgrades in the detached-eddy simulation of complex turbulent flows, 2002
[7] Kitamura and Hashimoto, Reduced dissipation AUSM-family fluxes, 2016

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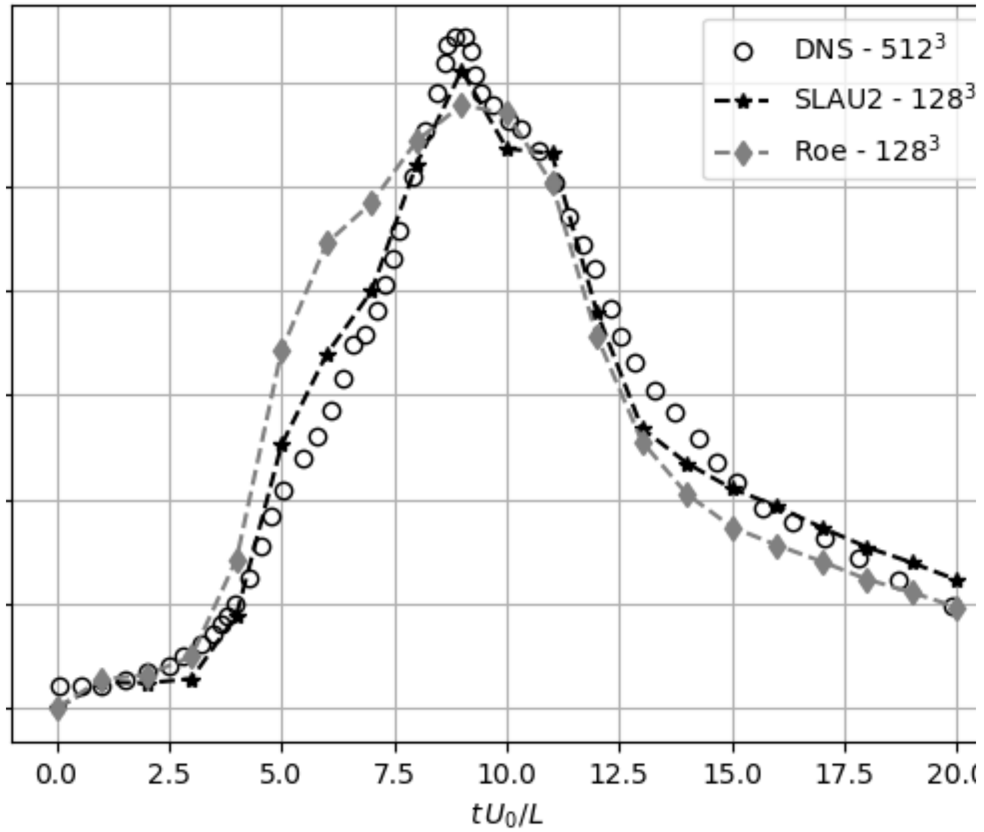

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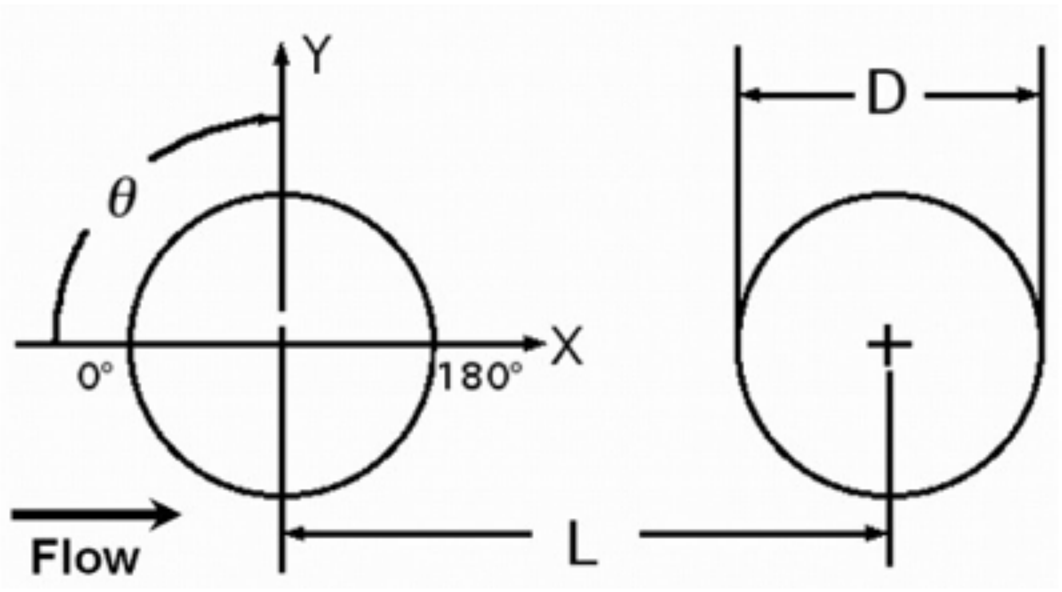
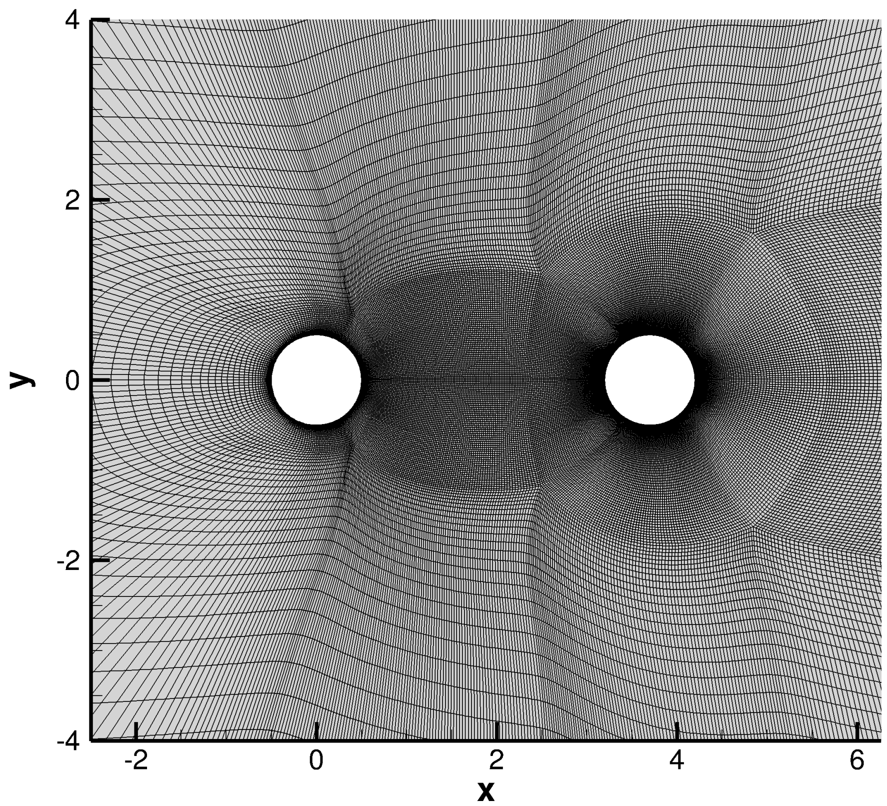
Tandem Cylinders

- The flow has been studied in a series of experiments performed at NASA Langley.
- It is a prototype for interaction problems commonly encountered in airframe noise, e.g., landing gear configuration.
- It shows some of the most important features of landing gear flow fields:
  - Separation of turbulent boundary layer.
  - Free shear layer roll-up.
  - Interaction of an unsteady wake of the upstream with the downstream cylinder.
- Selected as a test case for the Benchmark for Aircraft Noise Computation (BANC) and EU project ATTAC workshops.

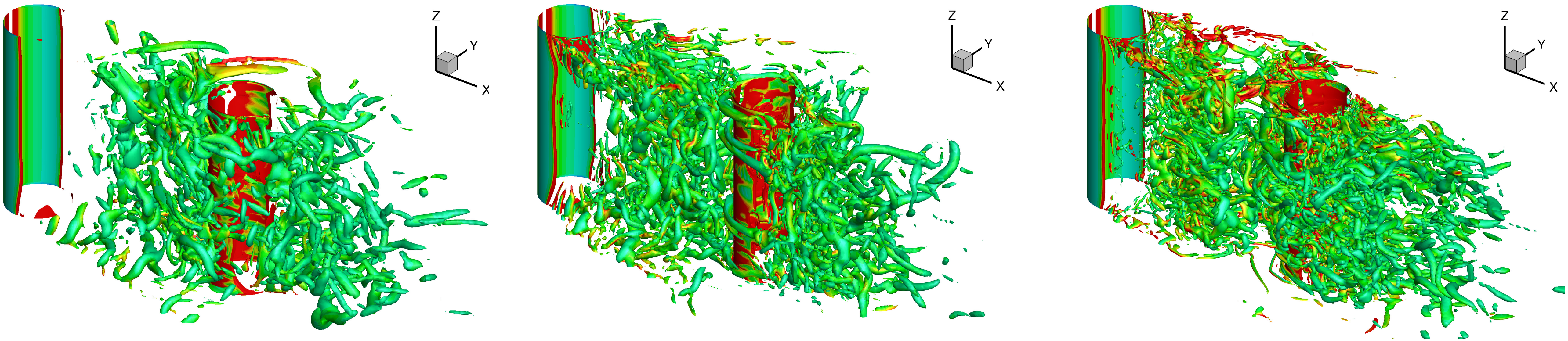
Tandem Cylinders

- Flow conditions:
  - Re=1.66 x 10^5, L=3.7D and M=0.115.
  - Tripping of BL on both cylinders to ensure turbulent separation.
- Grid and time step:
  - 2D grid of BANC workshop provided by NTS.
  - Spanwise is 3D.
  - Coarse grid: 5.5M grid points. $\Delta Z = 0.04D$
  - Fine grid: 11M grid points. $\Delta Z = 0.02D$
- Time step: $\Delta t = 0.02D/U_\infty$
- Time Sample:
  - Total simulation time is 350 CTUs, where statistical average is performed over the last 250 CTUs
- Wall clock time on Euler-CeMEAI (USP) machine with 400 cores:
  - 10 days for fine grid.
  - 5 days for coarse grid.

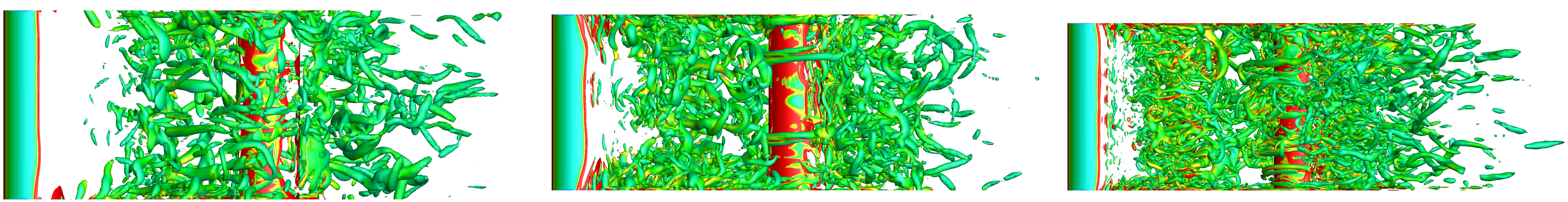




Tandem Cylinders

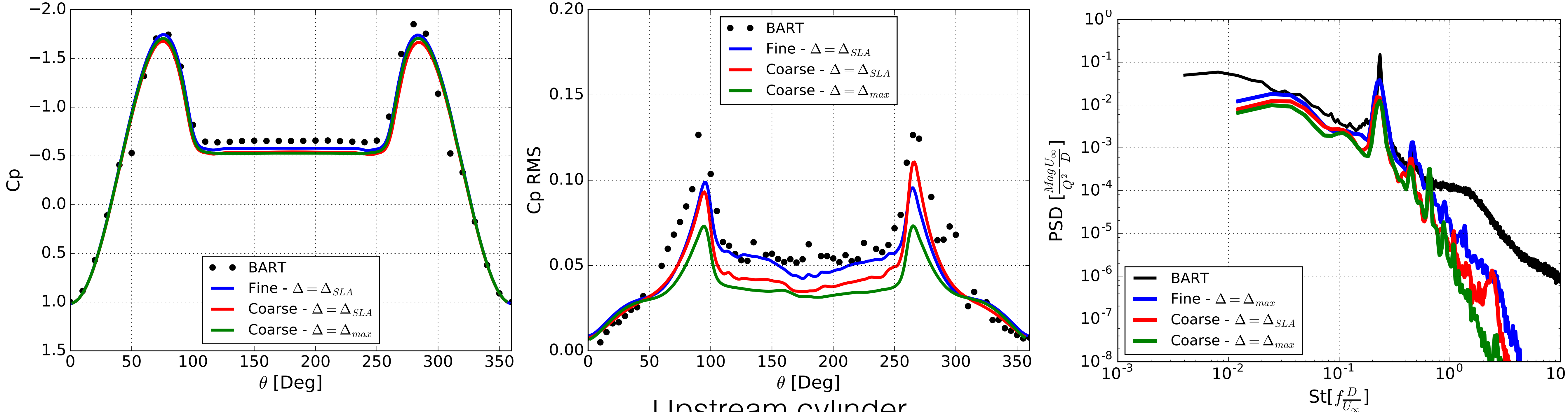


Coarse - $\Delta = \Delta_{max}$ | Coarse - $\Delta = \Delta_{SLA}$ | Fine - $\Delta = \Delta_{SLA}$

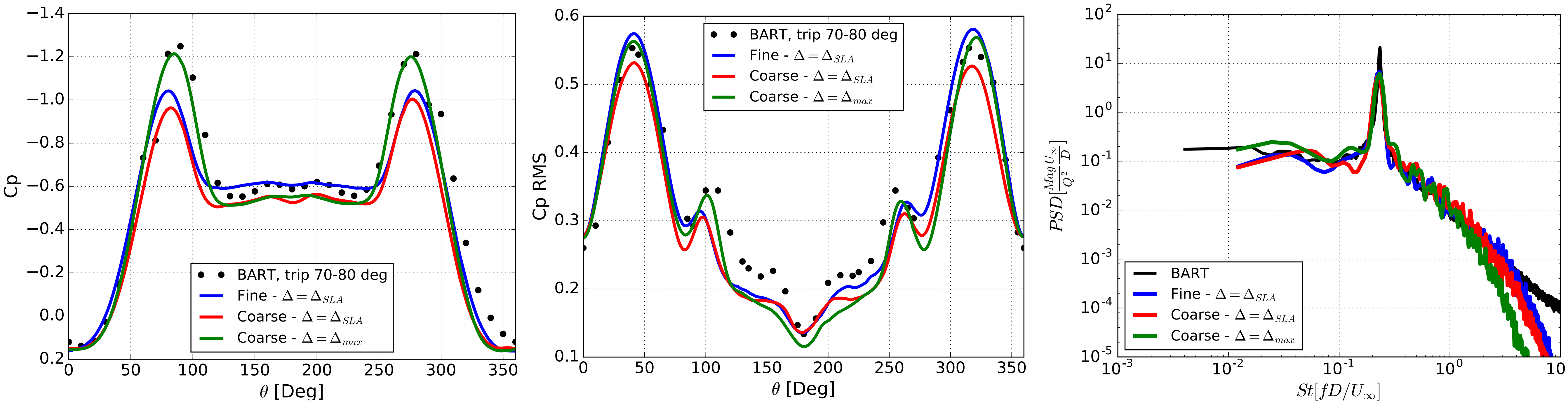


- Iso-surface of vorticity-coloured Q-criterion: It is clearly seen that results from the coarse grid using the standard SGS present a strong delay in the roll-up of the shed vortices and the consequent formation of the K-H instability. For the SLA SGS, the turbulent structures appeared closer to the upstream cylinder, accelerating the RANS to LES transition.

Tandem Cylinders

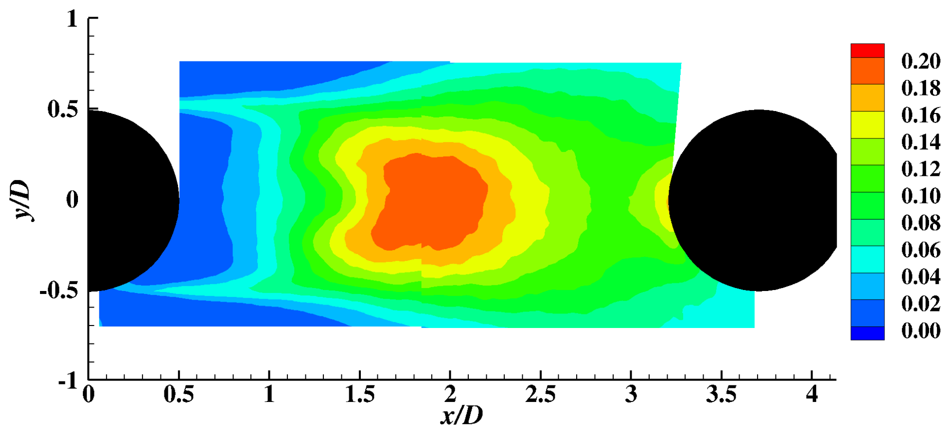


Upstream cylinder

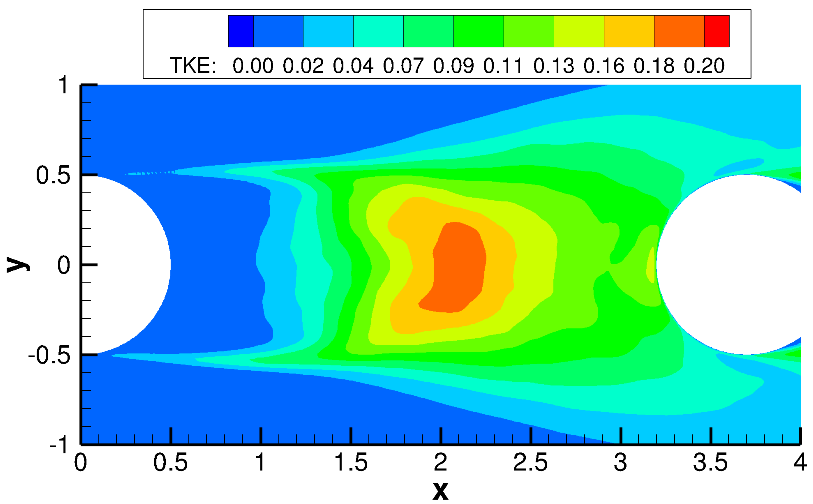


Downstream cylinder

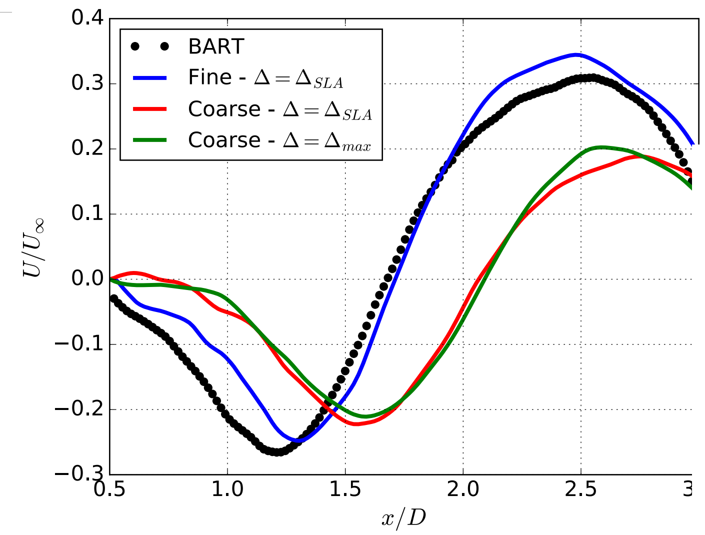
Tandem Cylinders

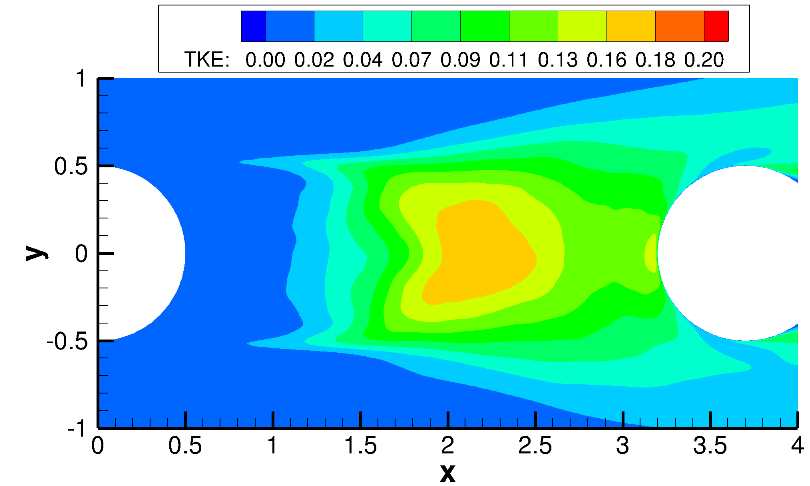


Experimental PIV

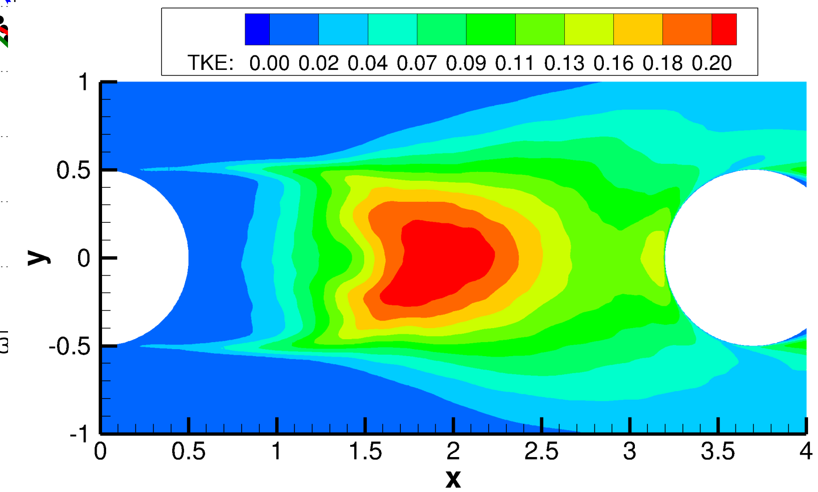


Coarse - $\Delta = \Delta_{SLA}$





Coarse - $\Delta = \Delta_{max}$

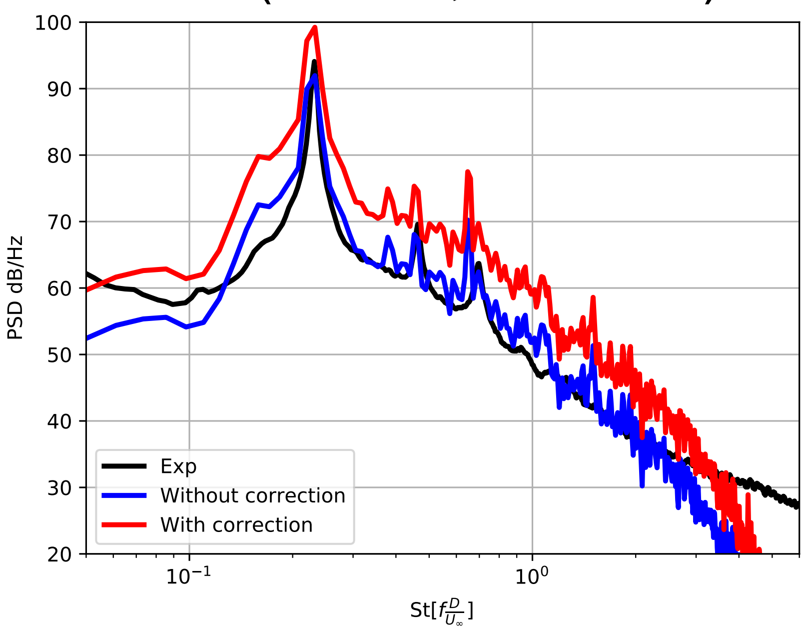


Fine - $\Delta = \Delta_{SLA}$

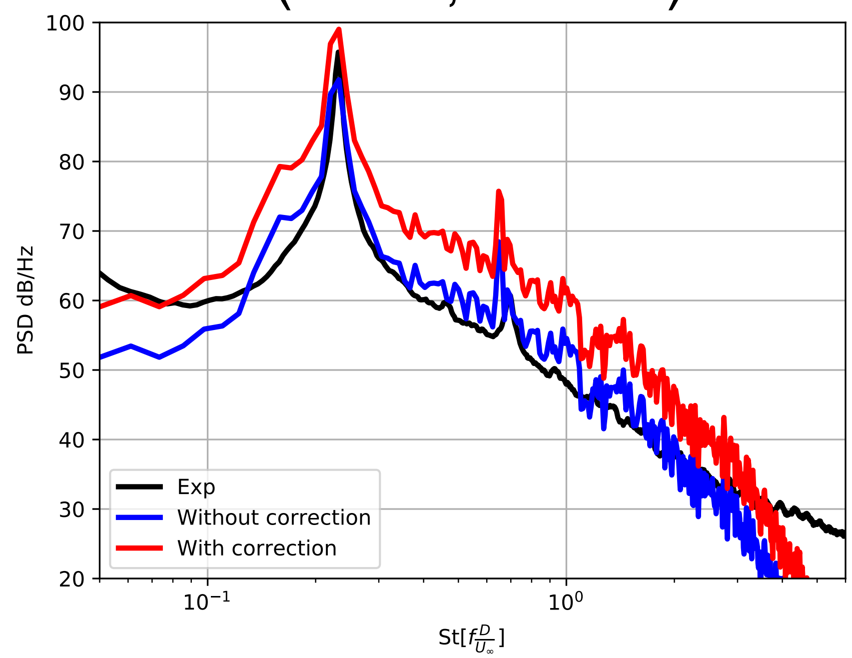
- Good level of similarity is observed between the experiment and the DDES, including the energetic spot

Tandem Cylinders

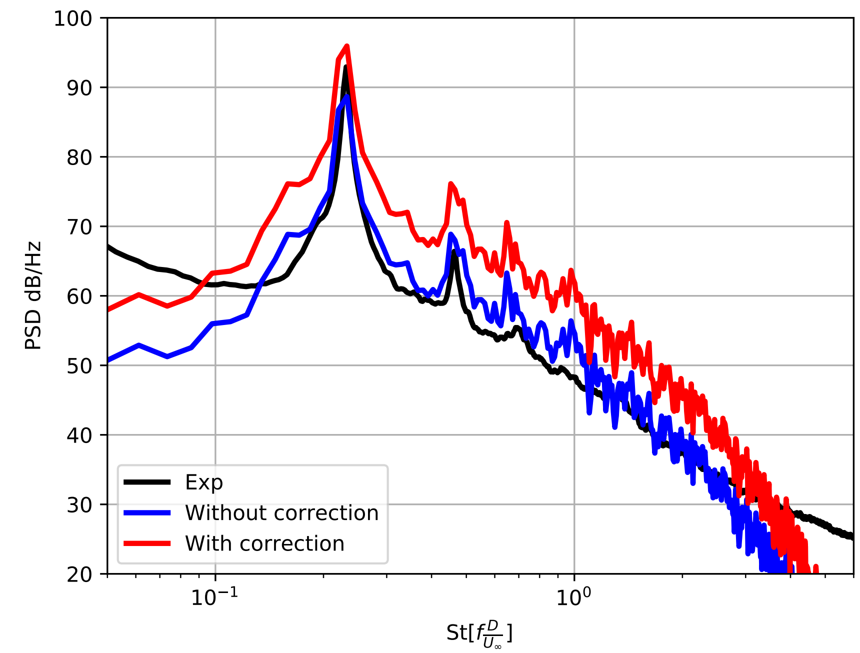
MicA: (-8.33D, 27.815D)



MicB: (9.11D, 32.49D)

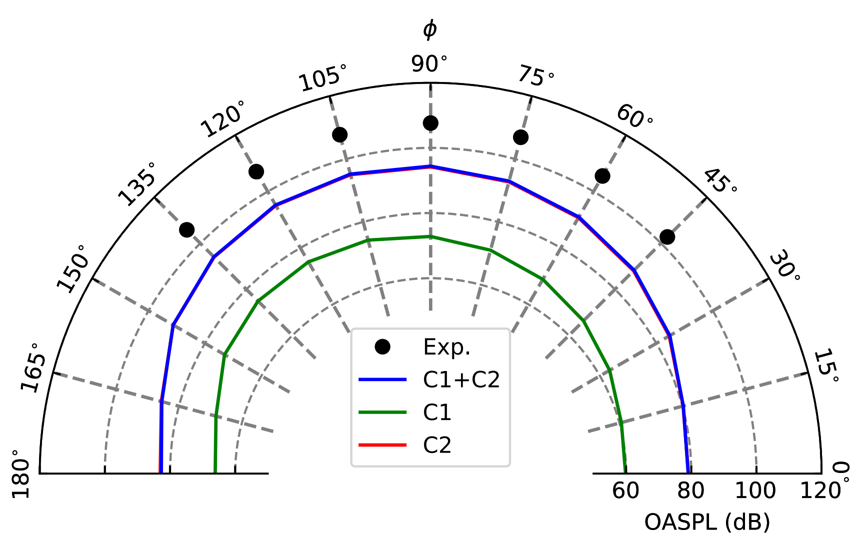


MicC: (26.55D, 27.815D)

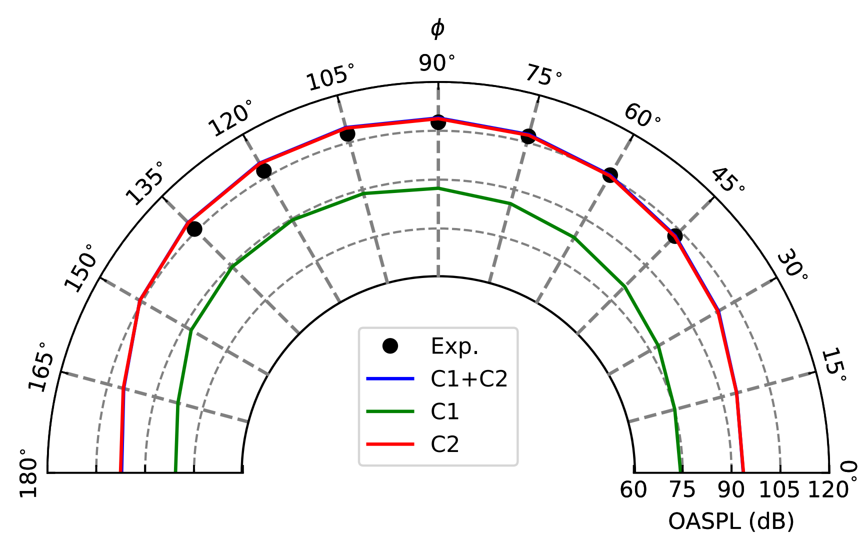


- Overall Sound Pressure Level (OASPL) at radii of 26.67D from point (9.11D, -2.4D):

Without correction:



With correction:



Delta Wing

- Mesh generation and adaptation for a delta wing undergoing vortex breakdown (B. Y. Zhou et al., to be presented at AVIATION 2019.)

- Led by TU Kaiserslautern, joint work with ODU, NASA and NIA.

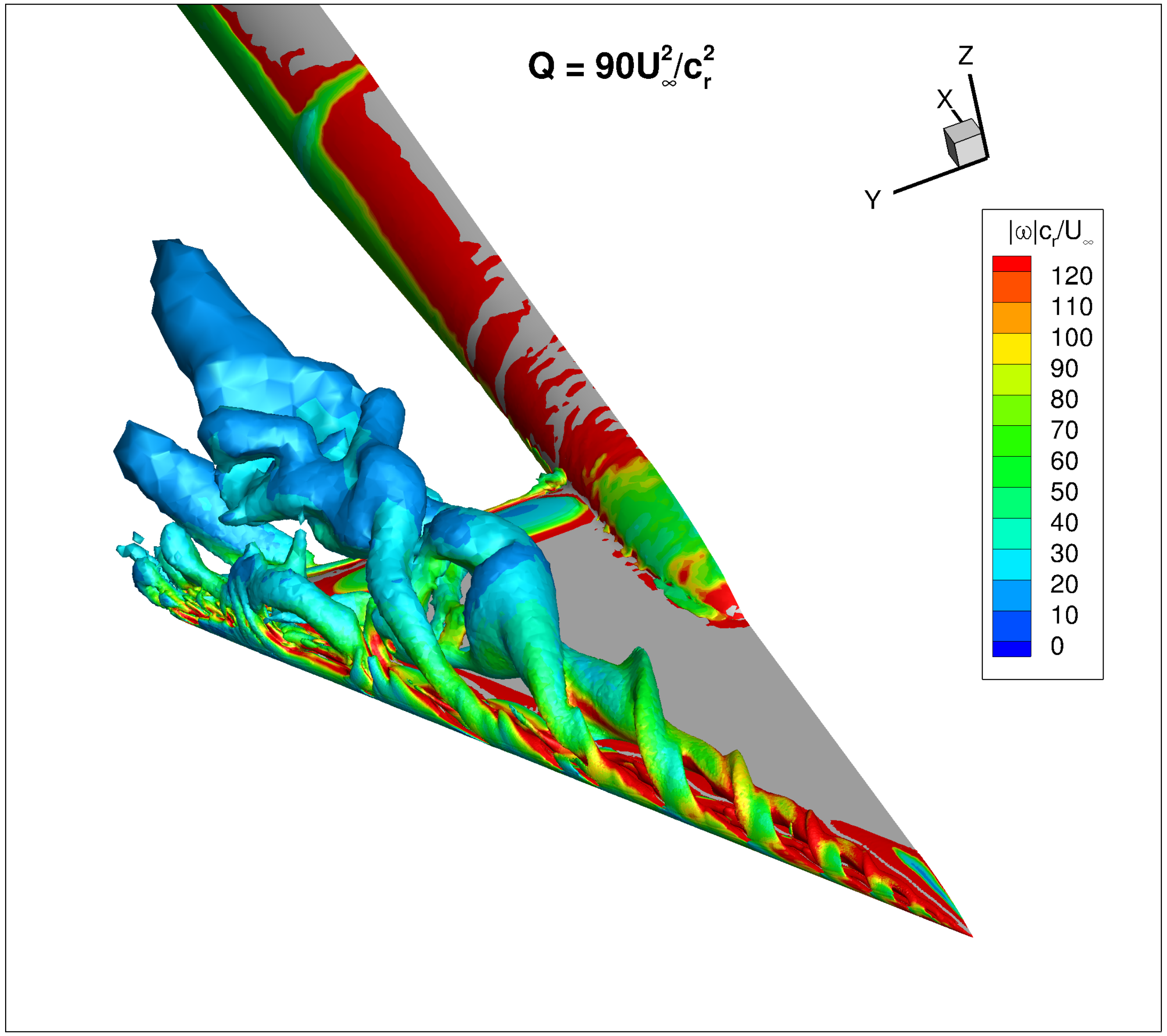
- 65 deg Delta Wing with sharp LE at high AoA

- Re = 1E6, M = 0.07

- Initial measurement done at NASA Langley; Recent simulation and measurement in EU Project Go4Hybrid.

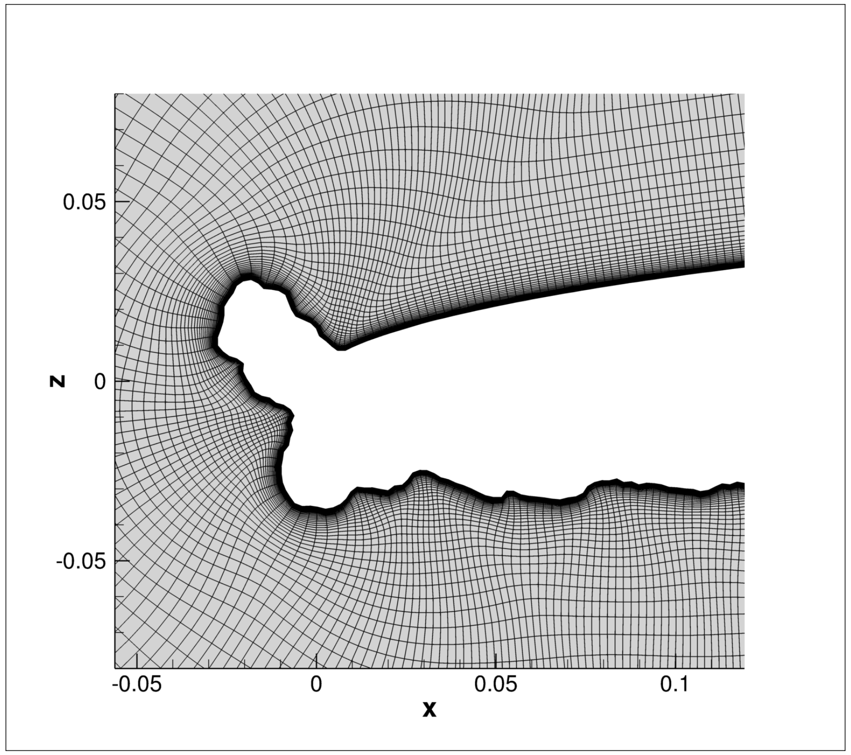
- Computed using SU2-DDES with SLA SGS

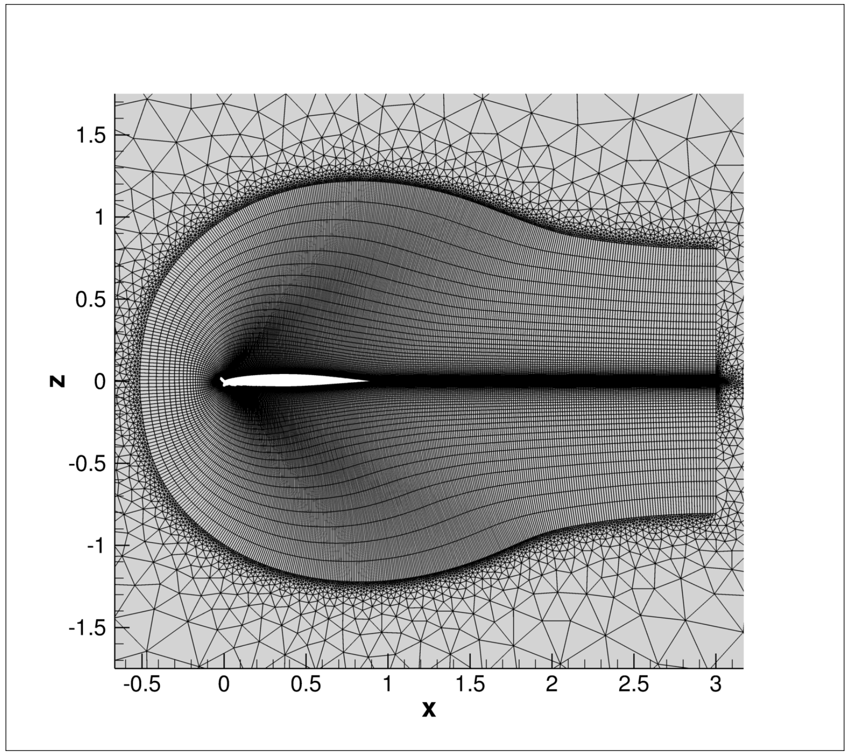
- Further mesh refinement being explored



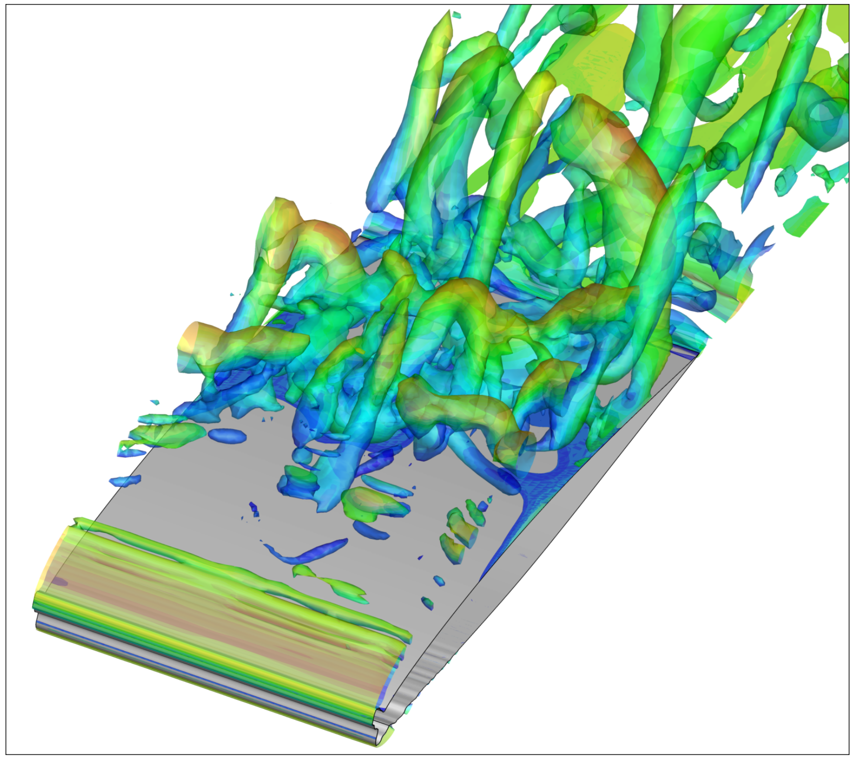
Iced-Airfoil (GLC 305)

- Study the influence of a glaze ice shape in the performance of an 3D airfoil in different conditions.
- Re = 3.5e6 and M = 0.12.
- AoA = 0.0, 4.0 and 6.0.
- Hybrid grid generated in Pointwise:
    - Baseline: 3e6 with 50 layers in span wise direction.
    - Fine: 10e6 with 100 layers in span wise direction.
- Collaborators:
    - Daniel Martins (Embraer)
    - Andy Broeren (NASA)
    - Marcello Righi (ZAWH)

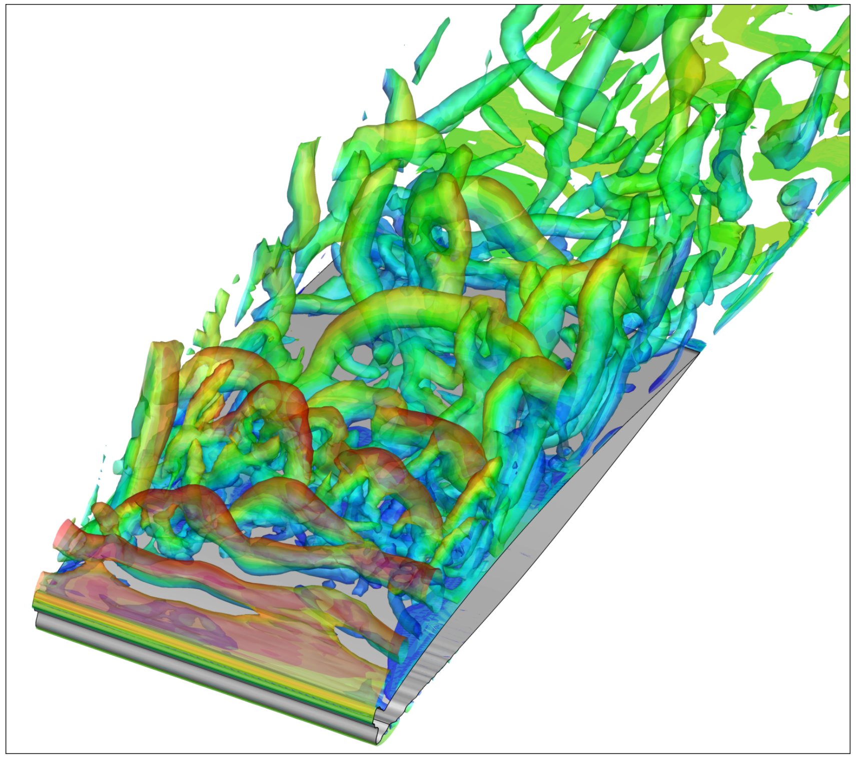




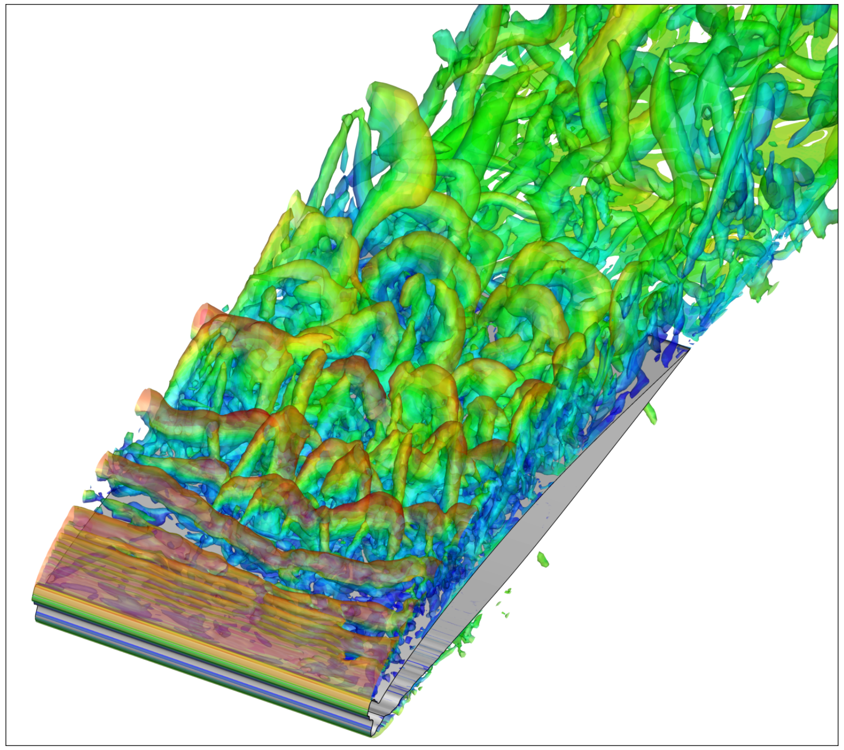
Iced-Airfoil (GLC 305)



Coarse - $\Delta = \Delta_{max}$

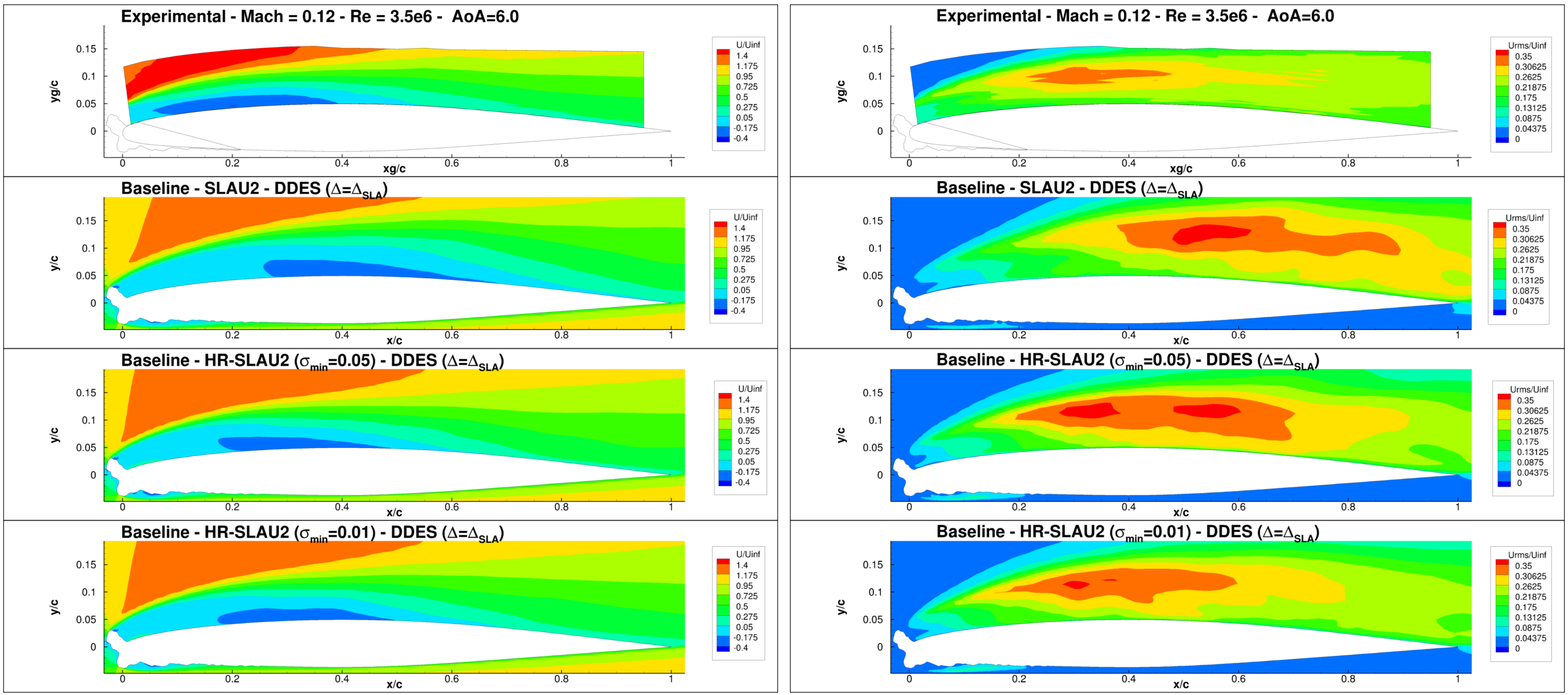


Coarse - $\Delta = \Delta_{SLA}$

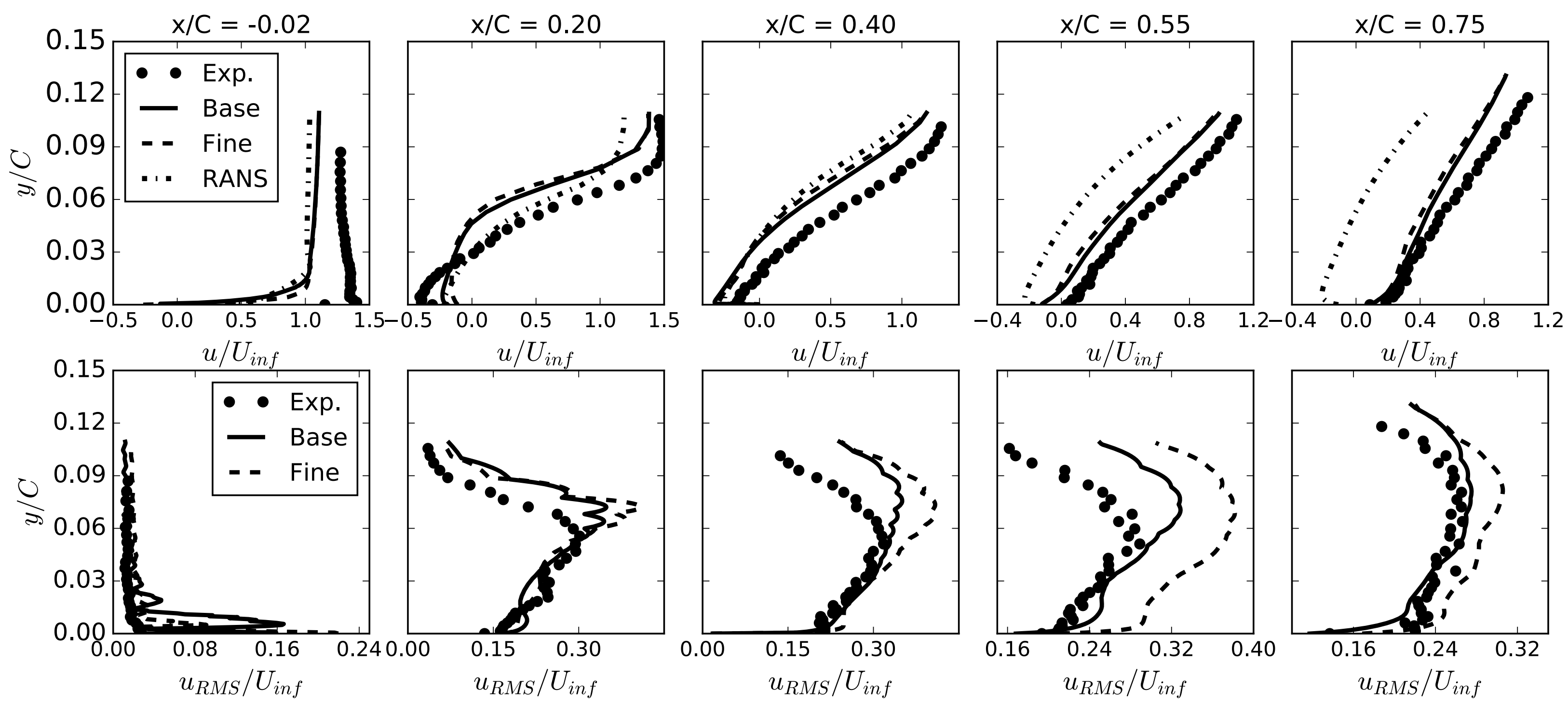


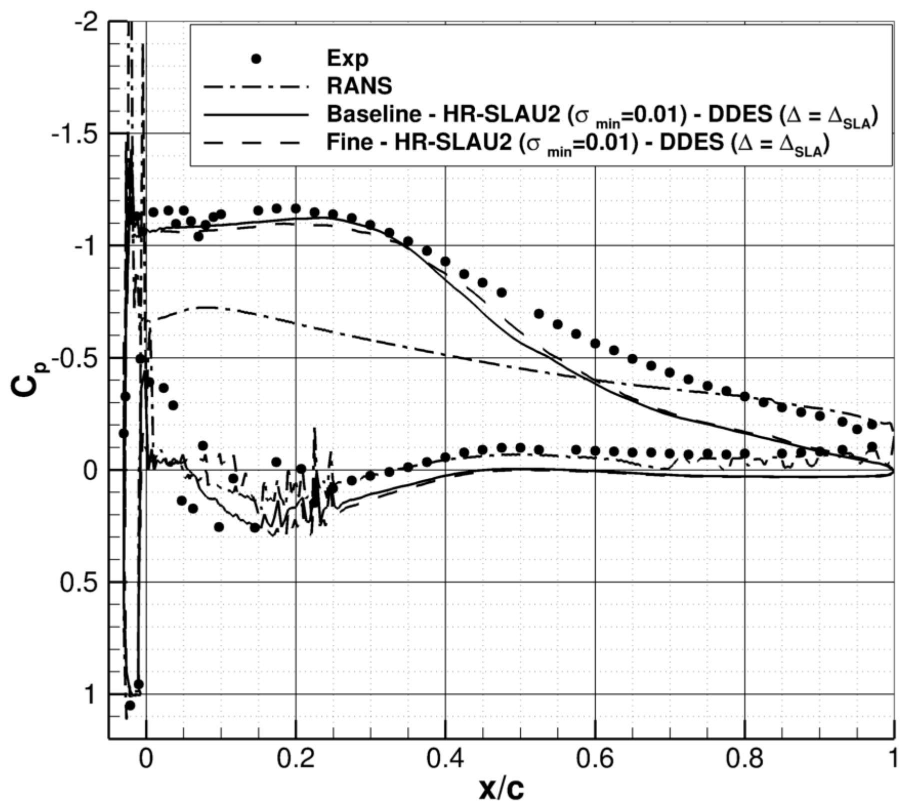
Fine - $\Delta = \Delta_{SLA}$

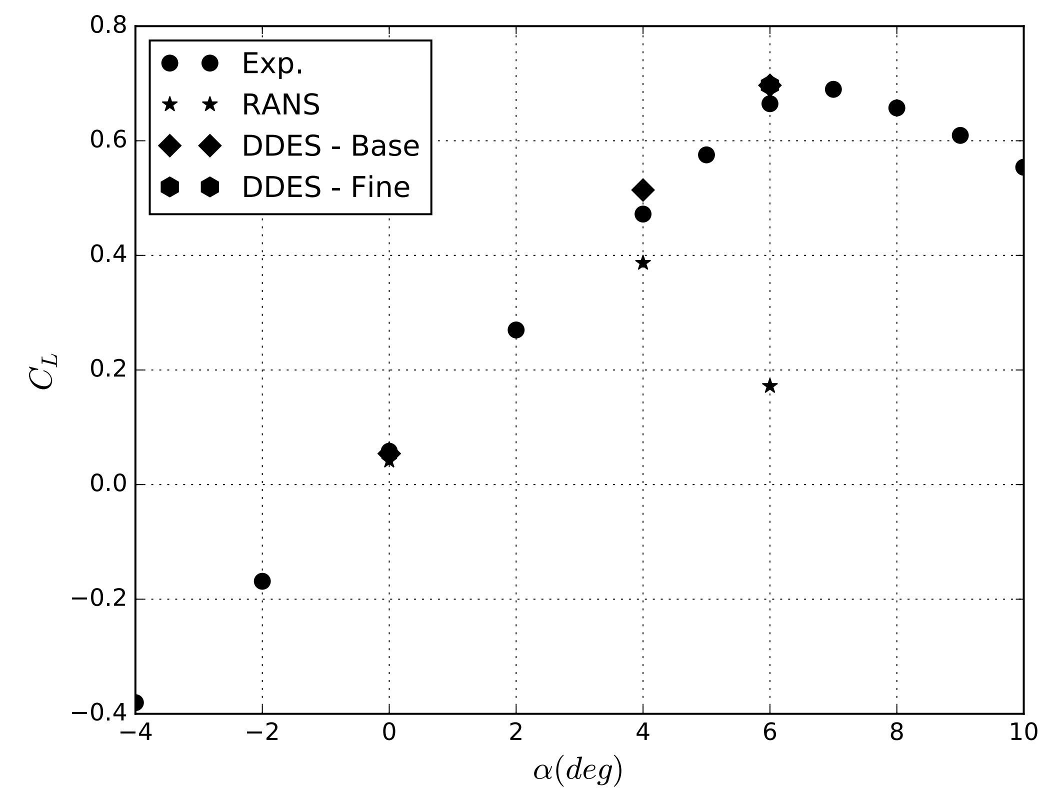
Iced-Airfoil (GLC 305)



Iced-Airfoil (GLC 305)

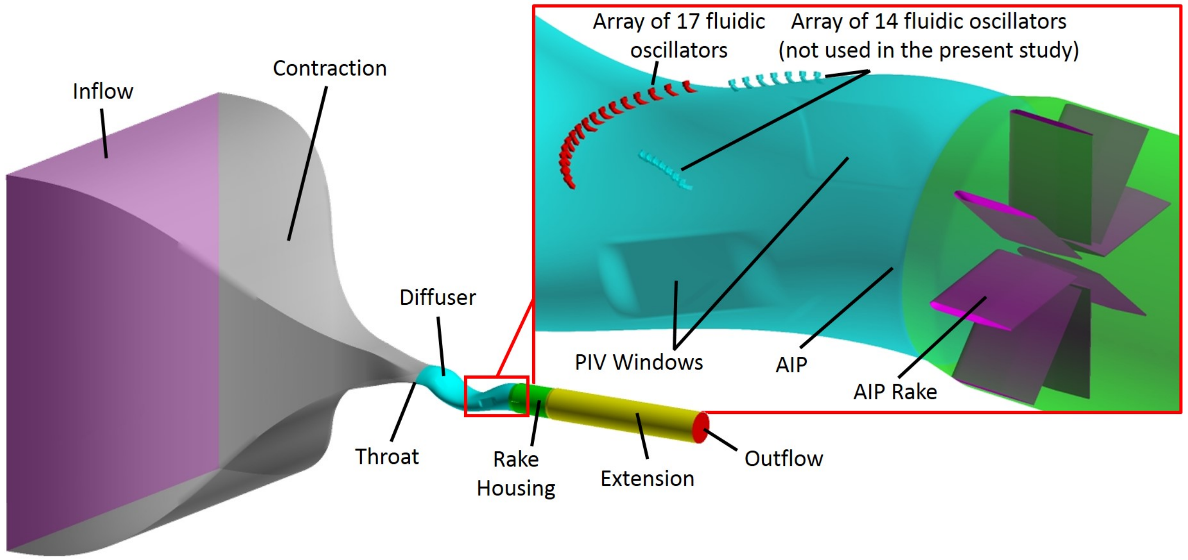


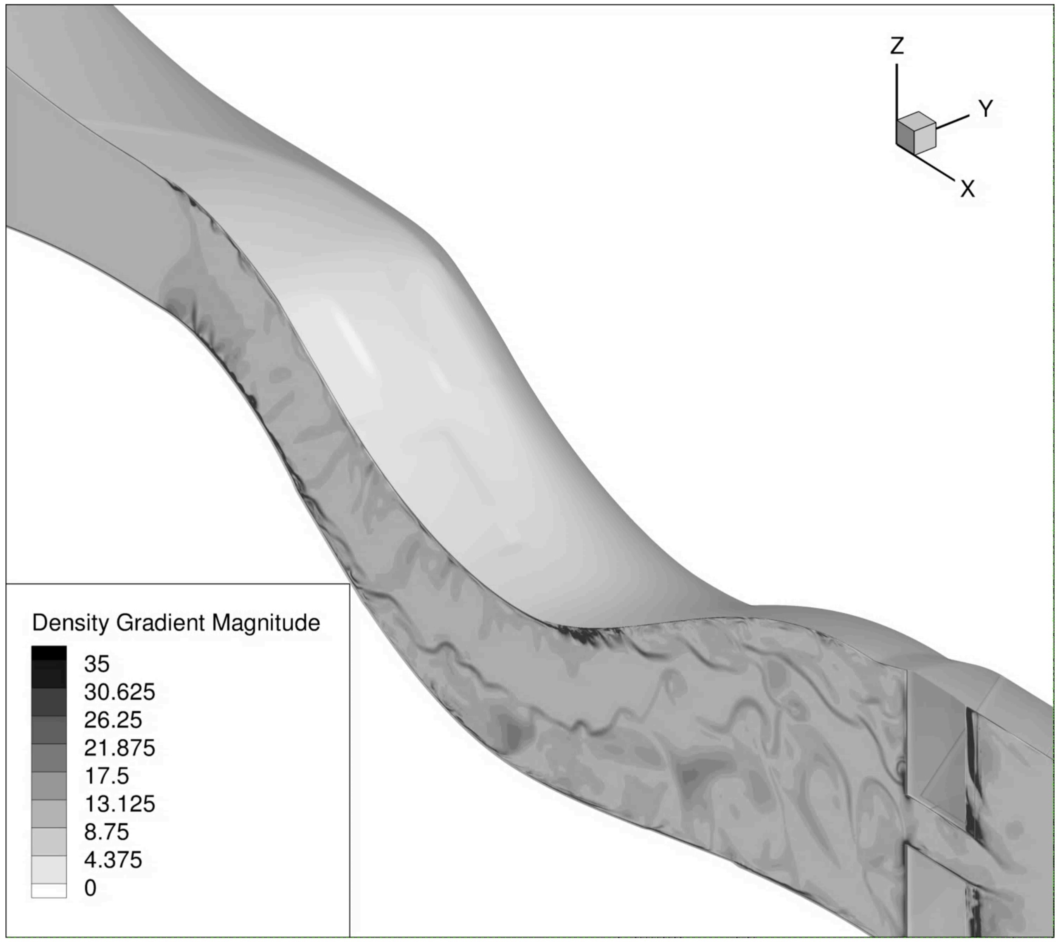




Serpentine Diffuser (SD2) (ongoing)

- SD2 Case 1:
  - Inlet total pressure and temperature: 14.34 psi and 525.9 R. Outflow pressure: 12.0 psi
  - Aerodynamic Interface Plane (AIP) flow rate: ~5.3 lb/s. Area-averaged throat Mach number: ~0.77
  - Grid provided with ~93M elements.
- Numerical Setup:
  - DDES with SLA SGS and SLAU2 convective scheme..
  - Dual-time stepping with a time-step of 1.25e-6 sec and 5 internal iterations.
  - GMRES + ILU(0) preconditioner for the linear solver.
- Collaborators:
  - Paul Urbanczyk (Stanford University)
  - Boeing and IAI





[2] M.Lakebring and M.Moni, Numerical Investigation of Dynamic Distortion and Flow Control in a Serpentine Diffuser, AIAA Paper-1283, 2018

Development of Wall-Models (Ongoing)

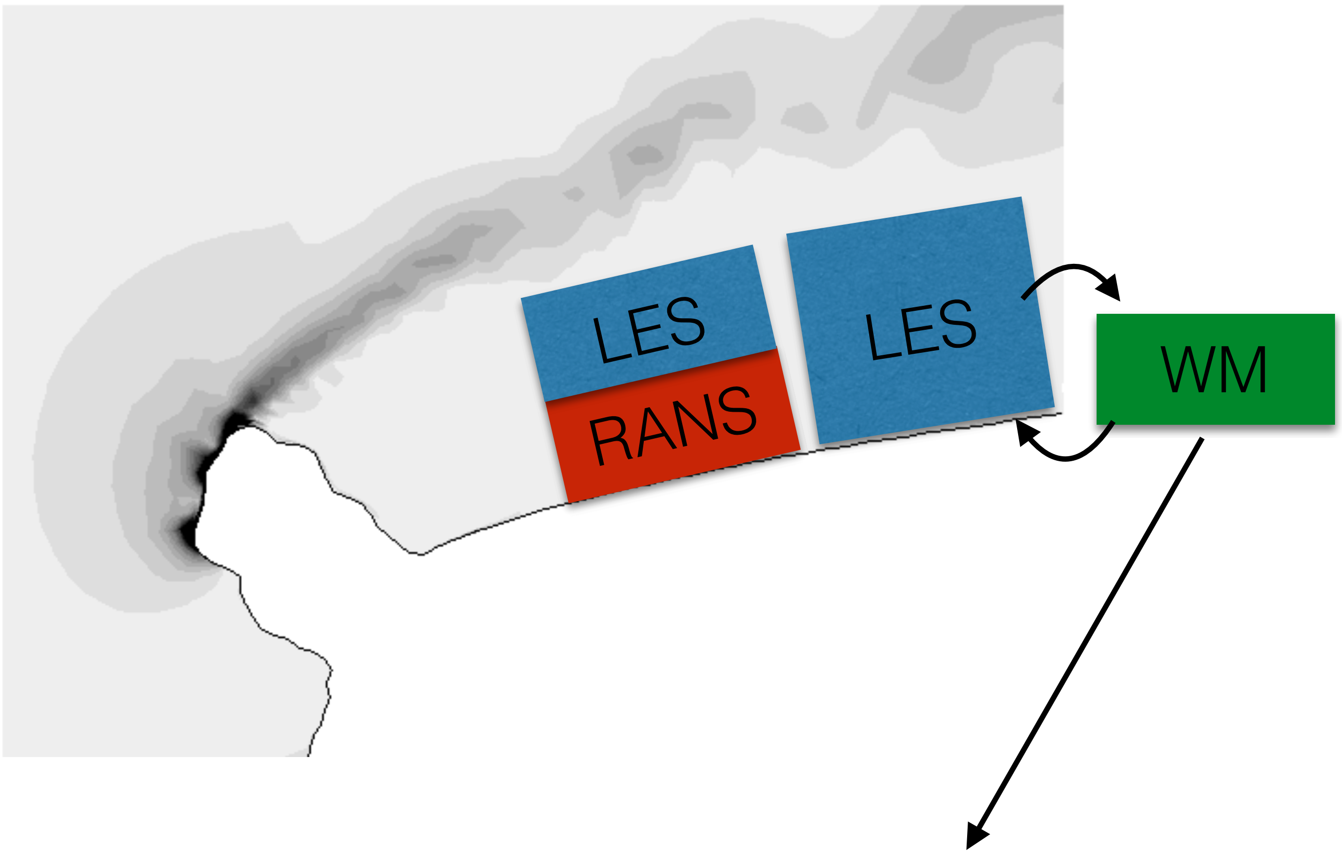
- Wall-Modelled LES:
    - Inner BL is modeled and outer BL is resolved.

        A. Hybrid RANS/LES:

        1. IDDES
            - DES is the wall model and needs STG. Exchange location is set by the grid and/or solution.

        B. Wall-stress models (Physics based):

        2. Algebraic (Log of the wall)
        3. 1D Equilibrium Wall Model
            - LES extends all the way to the wall with another decoupled wall parallel grid for the WM.
- Collaborators:
    - Tom Economon, Paul Urbanckzy and Edwin van der Weide



$$\frac{d}{dy}\left[(\mu - \mu_t)\frac{d\tilde{u}_{\parallel}}{dy}\right] = 0$$

$$\frac{d}{dy}\left(\bar{p}\right) = 0$$

$$\frac{d}{dy}\left[\tilde{u}_{\parallel}\left(\mu + \mu_t\right)\frac{d\tilde{u}_{\parallel}}{dy} + \left(\frac{\mu c_p}{Pr} + \frac{\mu_t c_p}{Pr_t}\right)\frac{d\tilde{T}}{dy}\right] = 0$$

SU2

The Open-Source CFD Code

Thank You!