An Overview of DDES in SU2

Implementation and Recent Results

Eduardo Molina and Roberto G.A. Silva

Aeronautics Institute of Technology (ITA), Brazil

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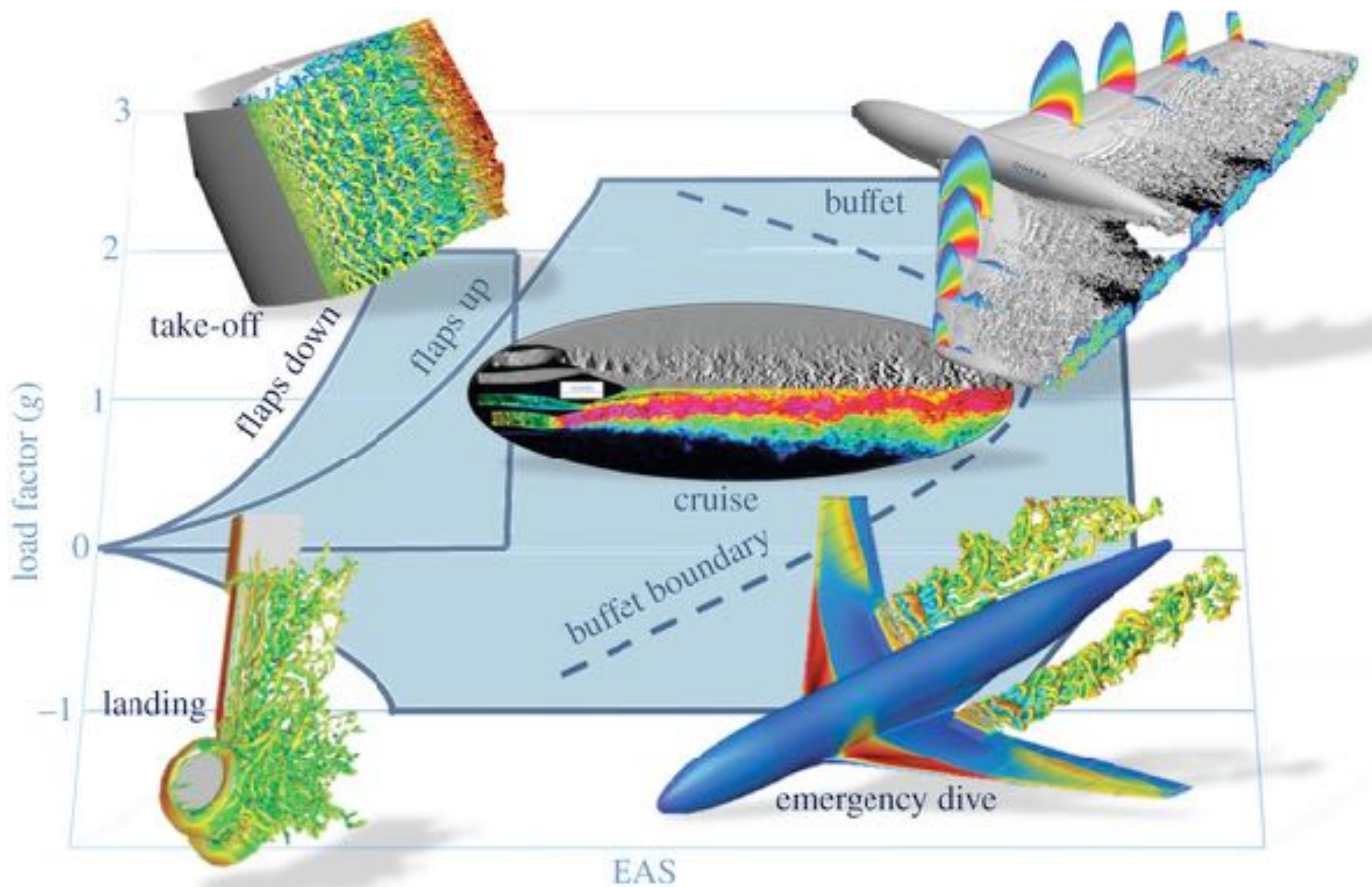
Motivation

- Extend SU2 to unsteady separated flows.
- Provide the community with an open-source framework for further improvement of hybrid RANS/LES models.
- Implementation of current state-of-the art Grey Area Mitigation (GAM) methods.



[1]

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

Motivation

- 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.

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]:

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

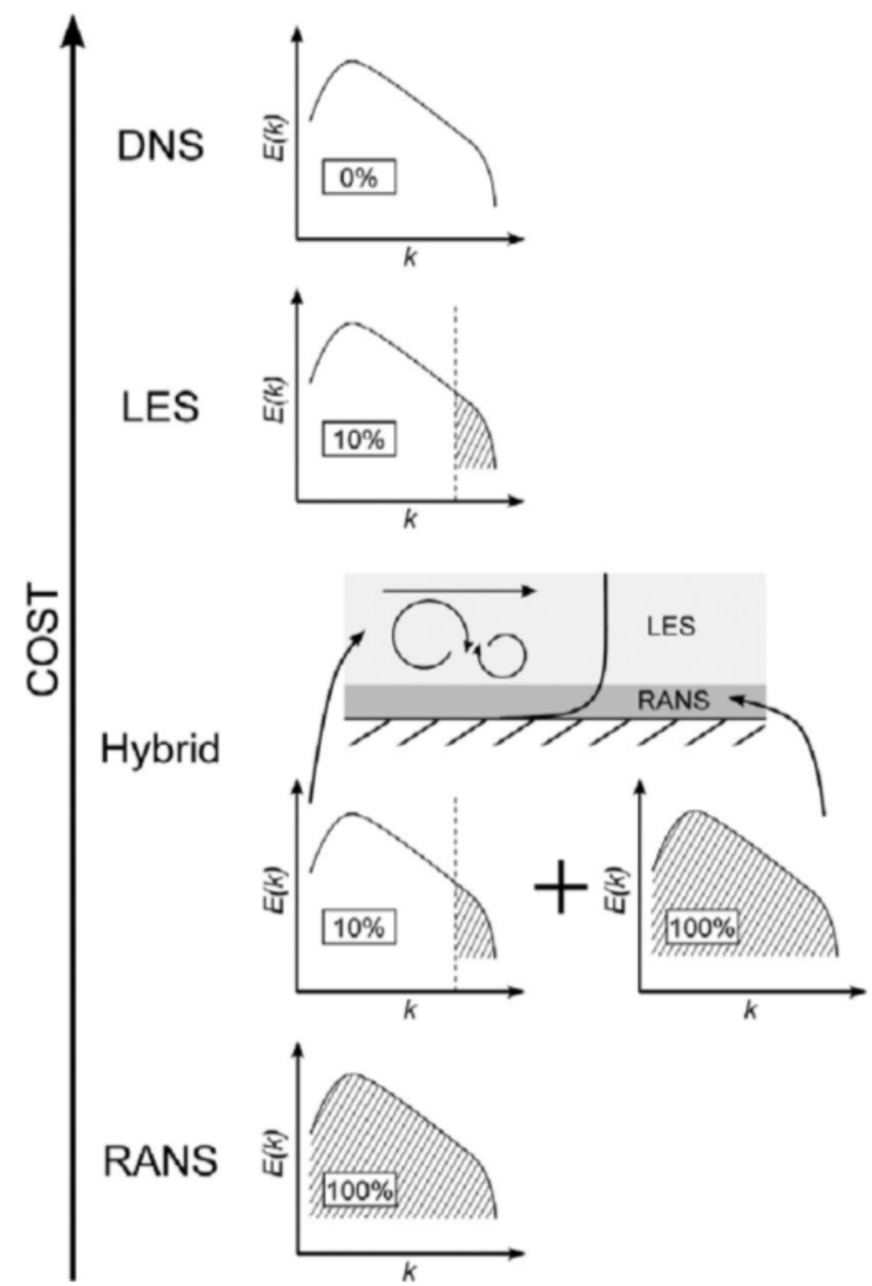
Grey Area Mitigation

  - 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]:

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



[5]

[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
[5] Tucker and Tyacke, Eddy resolving simulation in aerospace, 2016

Low Dissipation Schemes

- Introducing adaptive dissipation functions:
  - DDES f_d function[2]: $\sigma_{FD} = \max(0.05, 1 - f_d)$
  - Ducros' shock sensor[6]: $\sigma_{Ducros} = \dfrac{(\nabla u)^2}{(\nabla u)^2 + \omega^2}$
  - NTS sensor[7]: $\sigma_{NTS} = \max(\phi_{max} \tanh(A^{ch1}), 0.05)$
- Roe Scheme[8]:

$$\tilde{F}^c_{ij} = \left(\frac{\vec{F}^c_i + \vec{F}^c_j}{2} \right) \cdot \vec{n}_{ij} - \sigma \left\{ \frac{1}{2} P|\Lambda|P^{-1}(U_i - U_j) \right\}$$

- Simple Low Dissipation AUSM (SLAU2)[9]:

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

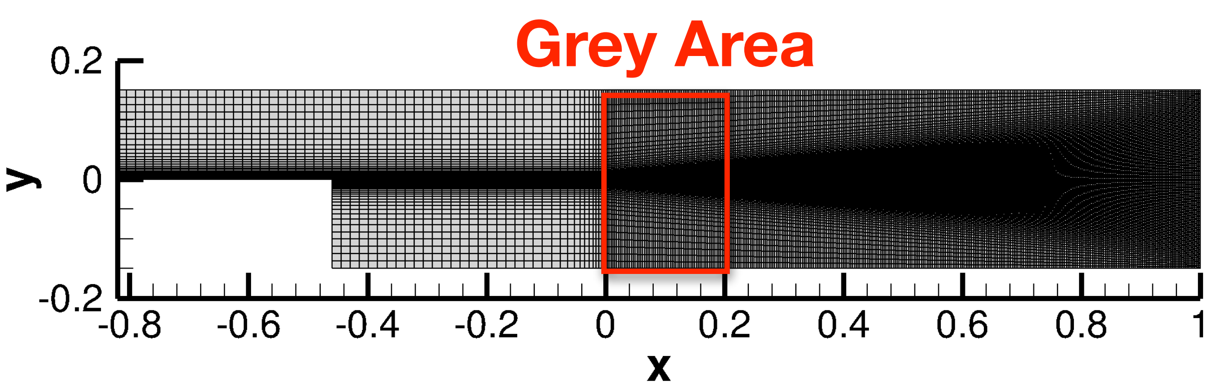
$$\mathbf{\Psi} = (1, u, v, w, H)^T, \quad \mathbf{N} = (0, n_x, n_y, n_z, 0)^T$$

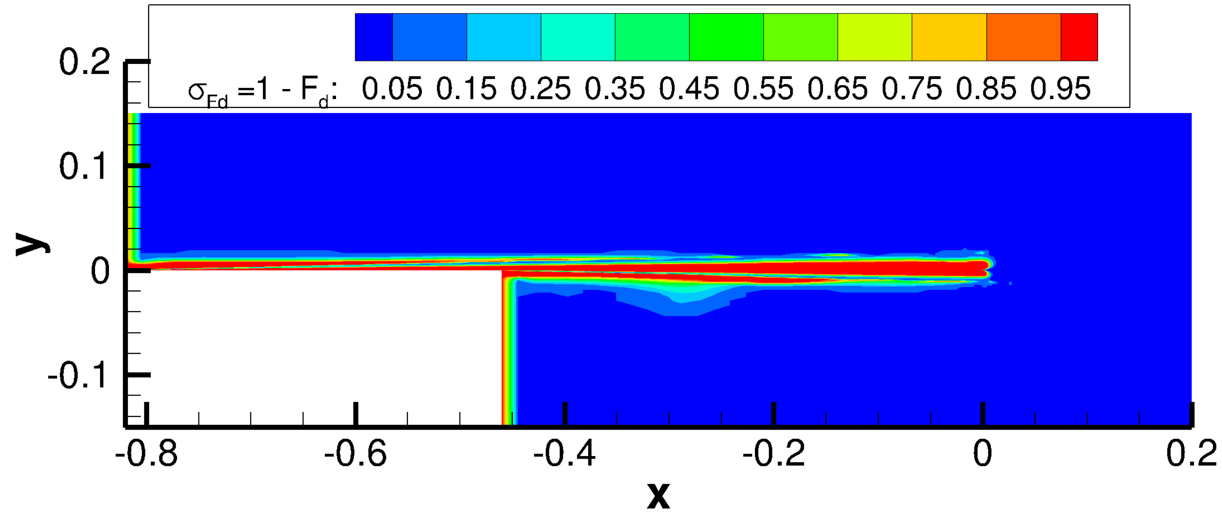
$$\tilde{p} = \frac{p_L + p_R}{2} + \frac{\beta^+ - \beta^-}{2}(p_L - p_R) + \sigma \sqrt{\frac{u_L^2 + u_R^2}{2}} \left(\beta^+ + \beta^- - 1\right) \bar{\rho}\bar{c}$$

[2] Spalart et al. A New Version of Detached-eddy Simulation, Resistant to Ambiguous Grid Densities, 2006
[6] Ducros et al. Large eddy simulation of the shock/turbulence interaction, 1999
[7]Travin et al., Physical and numerical upgrades in the detached-eddy simulation of complex turbulent flows, 2002
[8] Roe, Approximate Riemann solvers, parameter vectors, and difference schemes, 1981
[9] Kitamura and Hashimoto, Reduced dissipation AUSM-family fluxes, 2016

Free Shear Layer TC

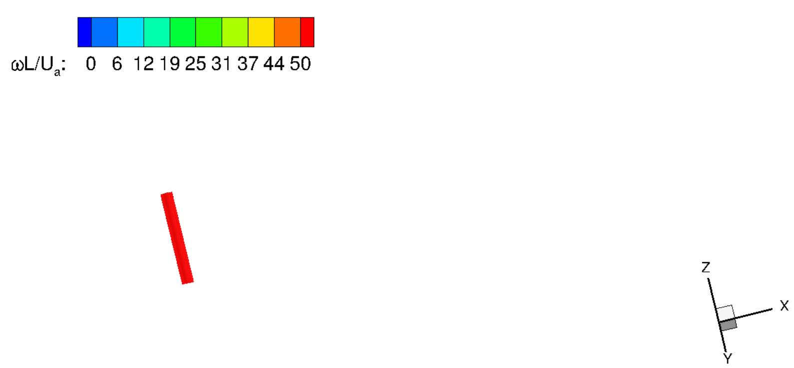
- Fundamental TC to mitigate the “grey area” for non-zonal methods.
- Domain of 2.0x0.3x0.15 m.
- U_high = 41.54 m/s and U_low = 22.4 m/s
- SLAU2 scheme with σ_{FD} dissipation function.
- Coarse grid: 3M cells. Step size = 0.003125m
- Fine grid: 10M cells. Step size = 0.0015625m.
- $\Delta t = 5 \cdot 10^{-6} s$ with 20 inner-iterations.



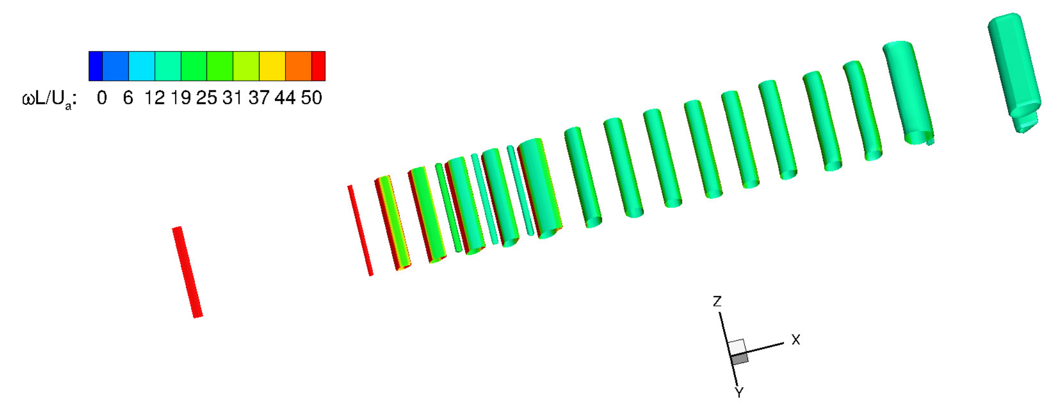


Free Shear Layer TC

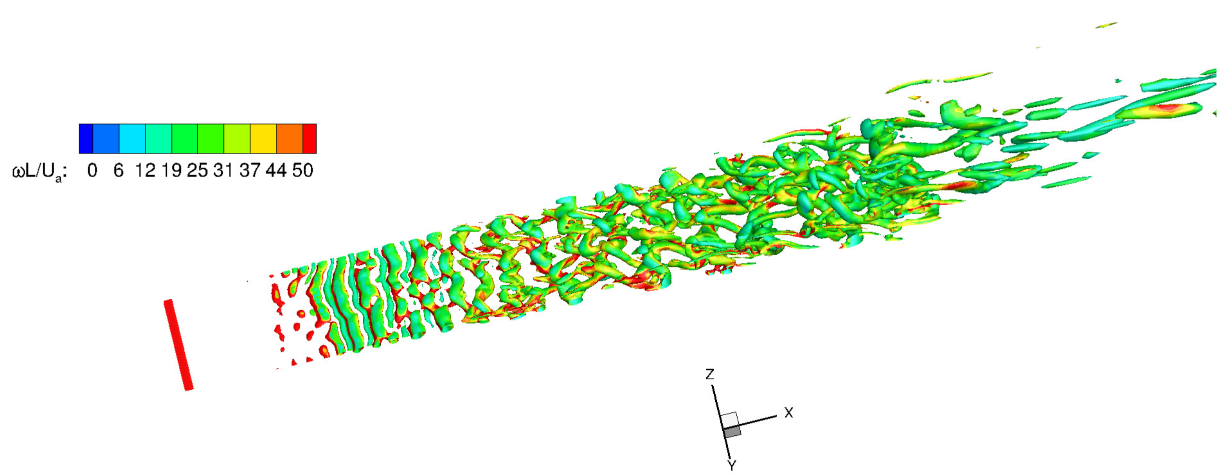
Iso Surface of Q colored by vorticity magnitude



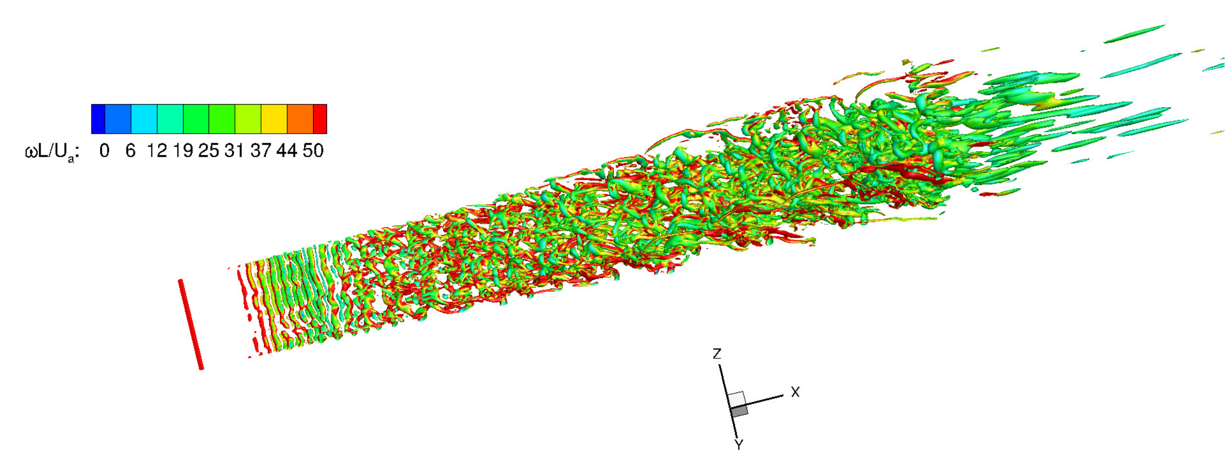
Coarse - $\Delta = \Delta_{max}$



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

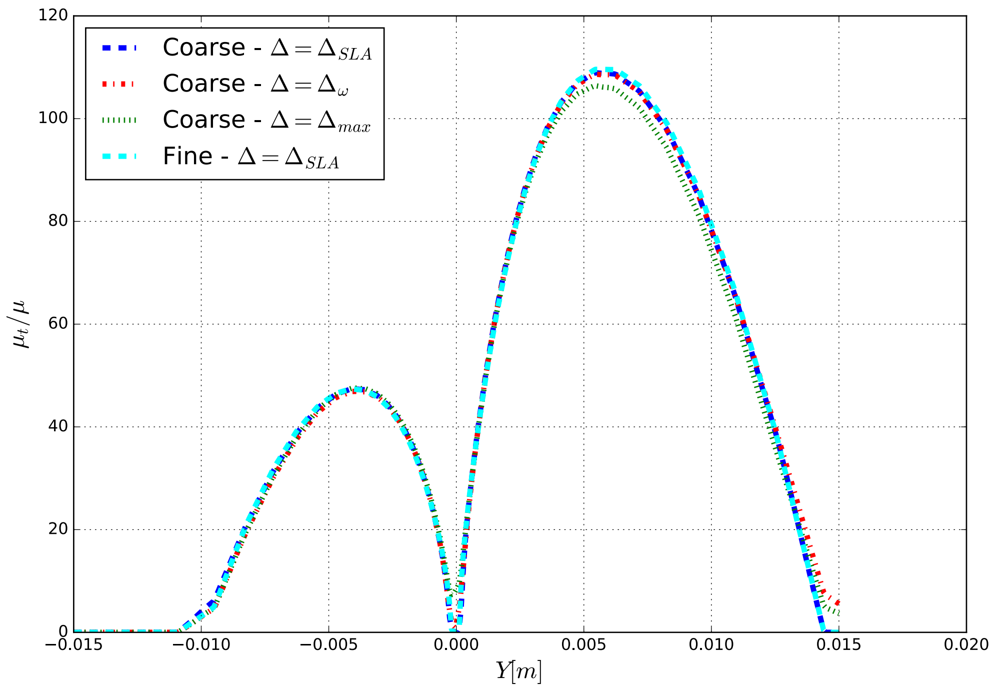


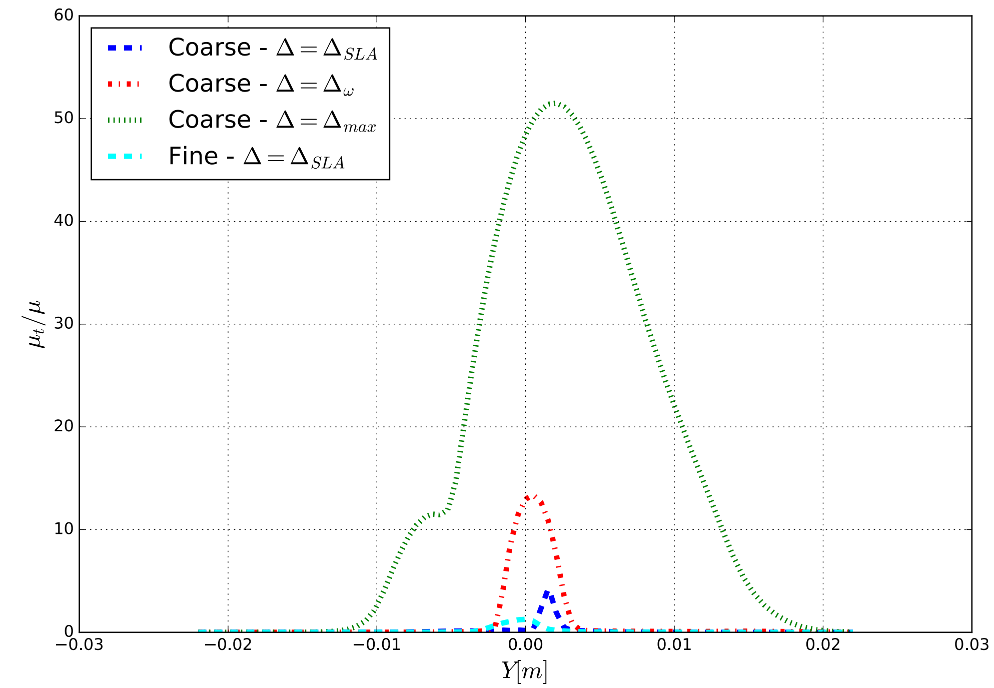
Coarse - $\Delta = \Delta_{SLA}$



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

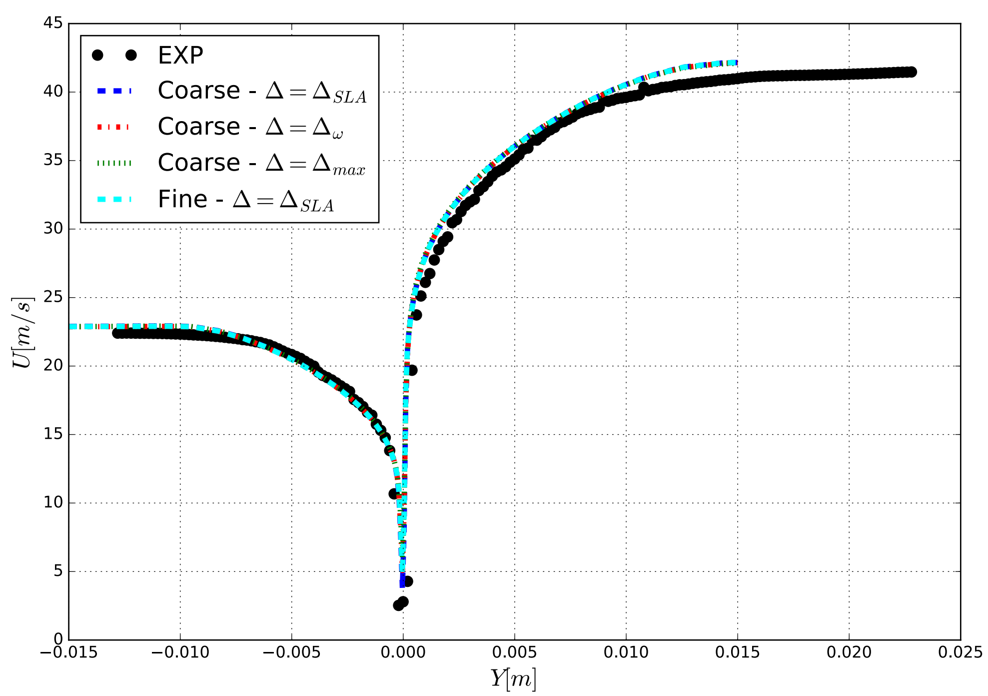
Free Shear Layer TC

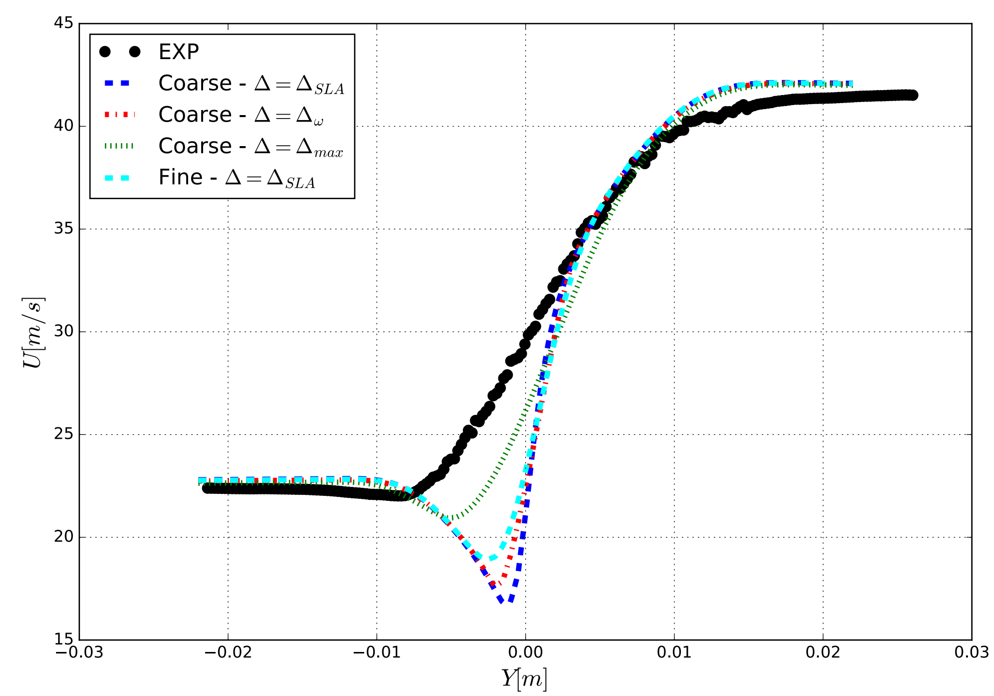




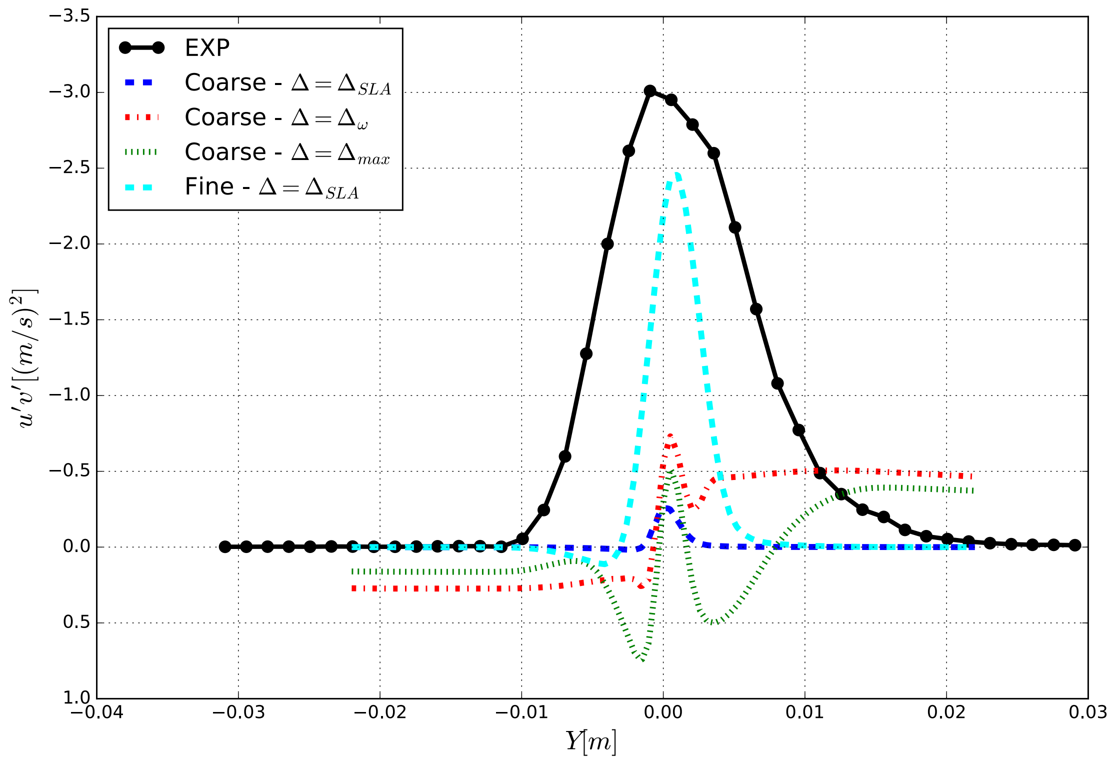
x=0.001m

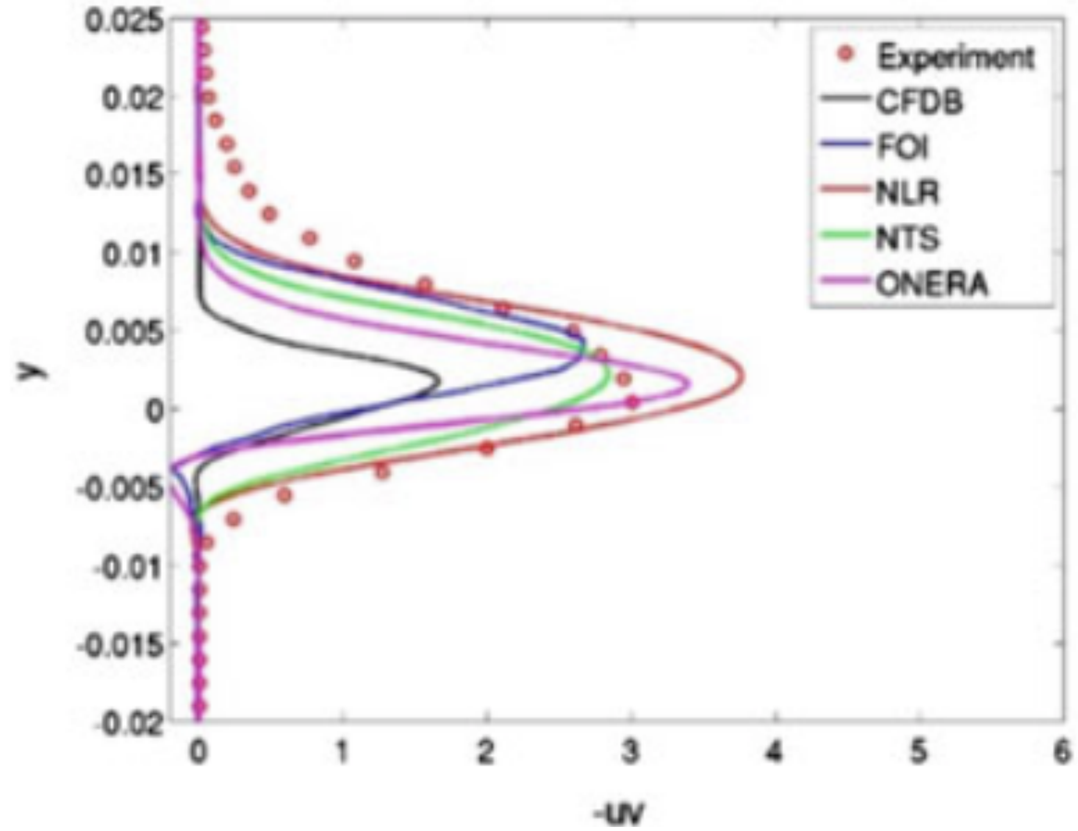
x=0.2m





Free Shear Layer TC





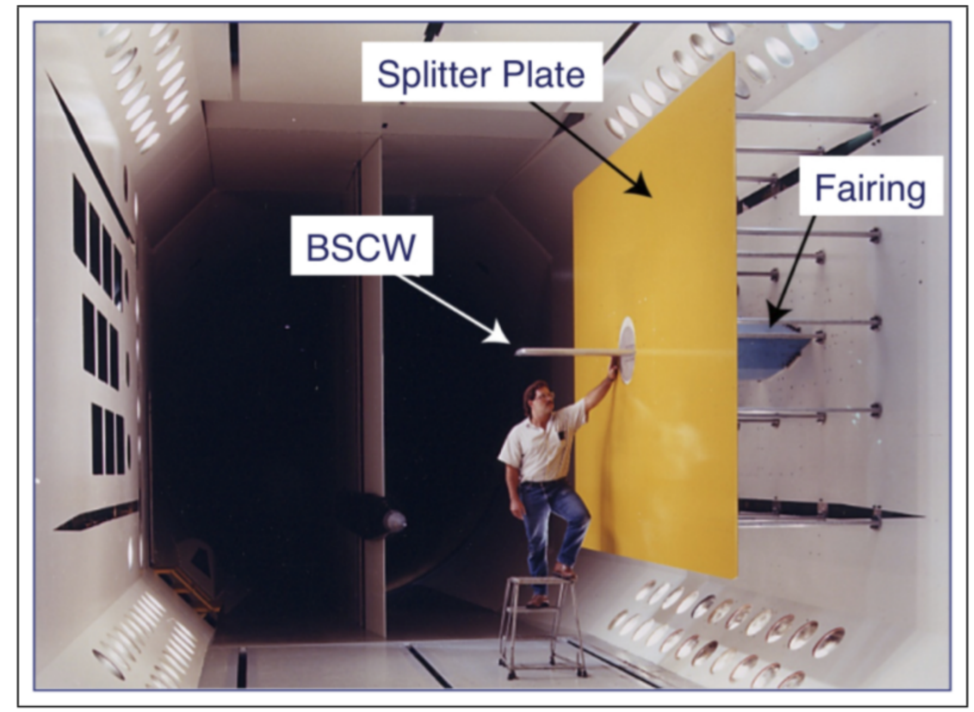
[10]

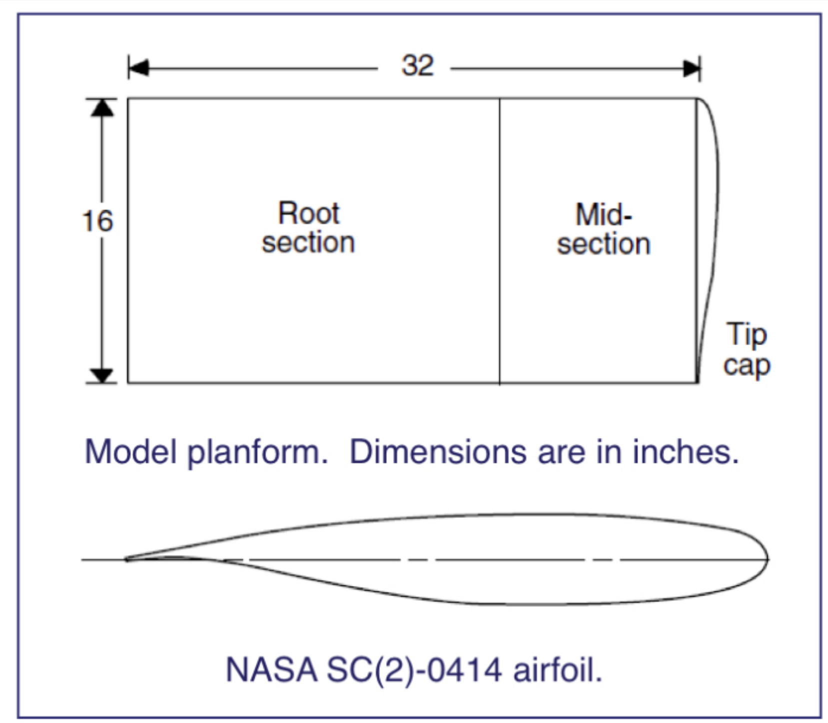
- Resolved turbulent stresses for the fine grid using the SLA SGS filter at 0.2m are comparable to state-of-the art Hybrid RANS-LES solvers [3]. The grey area is significantly reduced.

[10] Mockett et al., Free Shear Layer, Go4Hybrid: Grey Area Mitigation for Hybrid RANS-LES Methods, 2017

BSCW Test Case

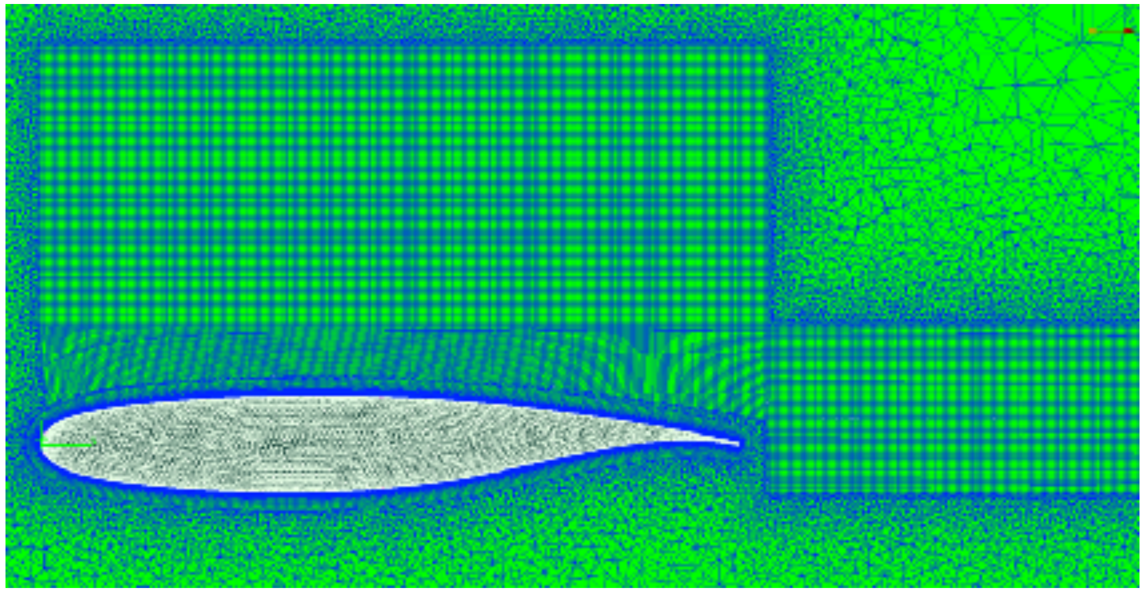
- Rectangular supercritical wing model tested at NASA-TDT
- Test Case 3a of AePW2
  - M = 0.85, Re = 4.491M and AoA= 5.0.
  - Unforced oscillation.

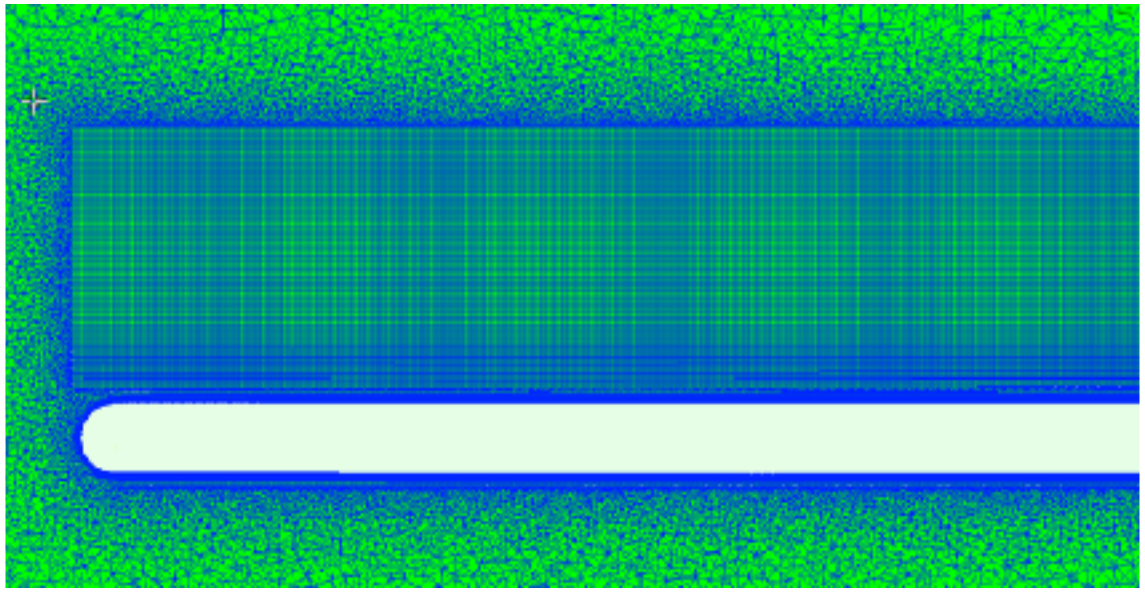




BSCW Test Case

- In external aerodynamics, the separated flow is only a small portion of the domain.
- Features of the grid:
    - Hybrid grid (tetrahedra, prisms and hexahedra) on the volume mesh.
    - Block of structured cells in the wake region.
    - Shock and wake resolution of 0.005c.
    - Surface grid:
        - Quadrilaterals on the wing and triangles on the wing tip.
- The final grid has ~50M cells.





BSCW Test Case

- Roe scheme with an adaptive dissipation function.

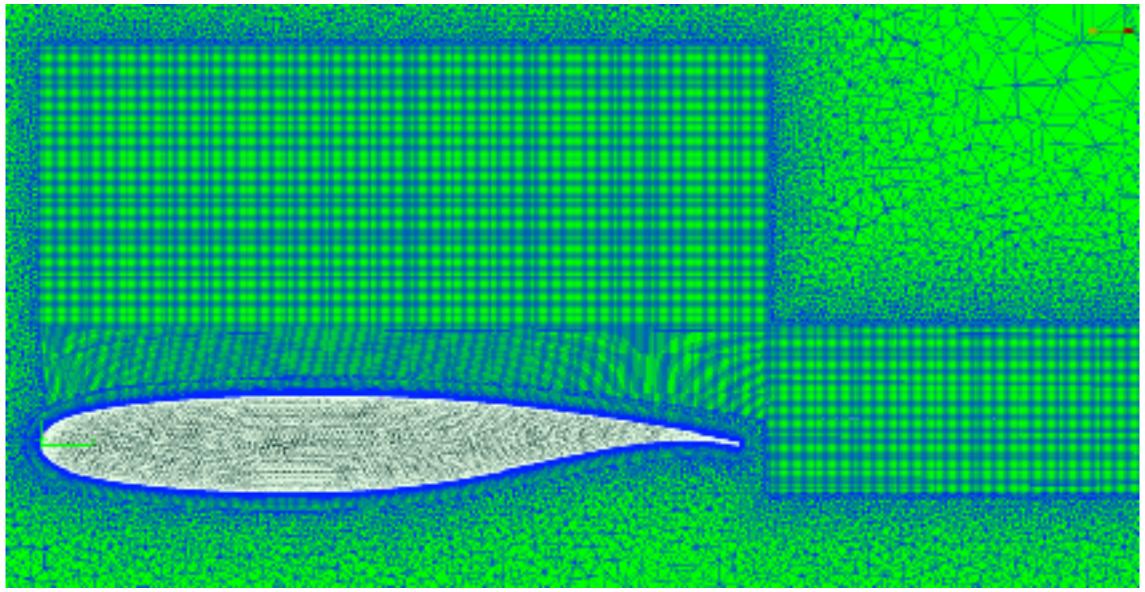
$$\sigma = \sigma_{Ducros} + \sigma_{NTS} - \sigma_{Ducros} \cdot \sigma_{NTS}$$

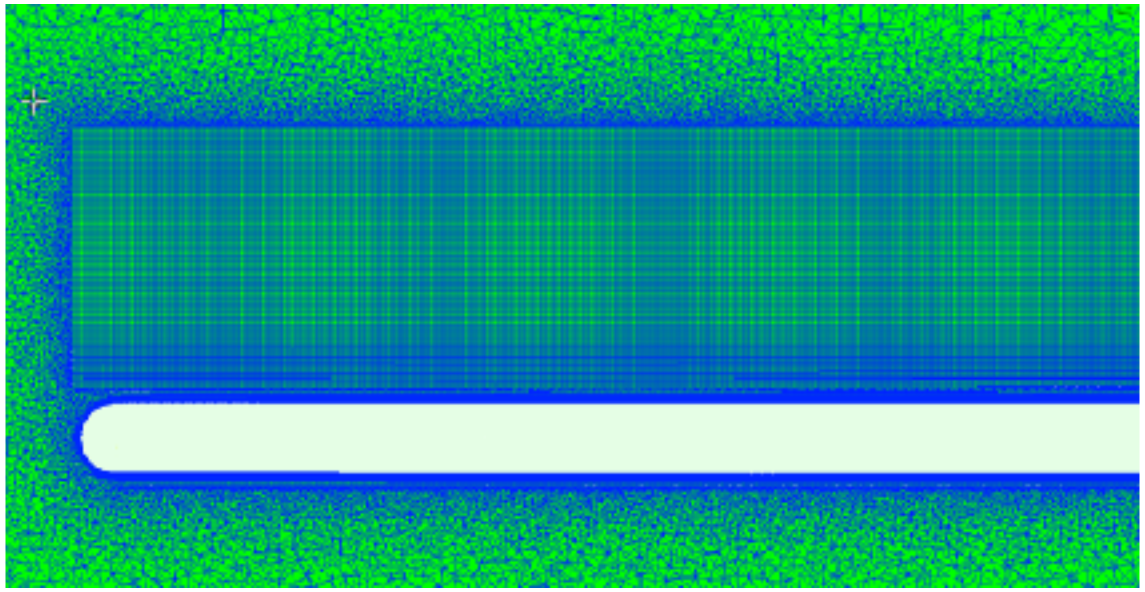
- DDES with different SGS

- Each simulation was run on Euler-CeMEAI-USP on 600 cores: 600 convective time scale and 18 days of wall-clock time.

- The chosen time-step was:

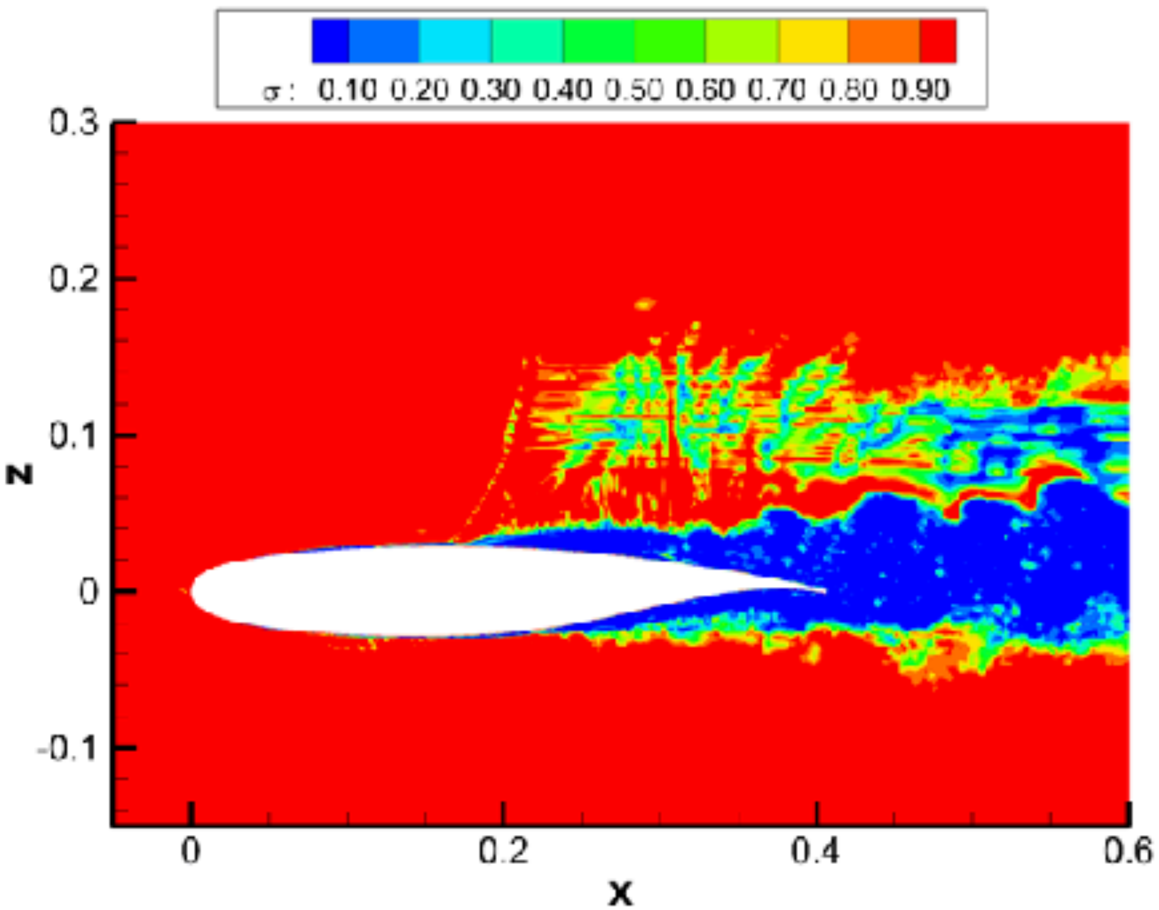
$$\Delta t^* = 0.01 c / U_\infty$$



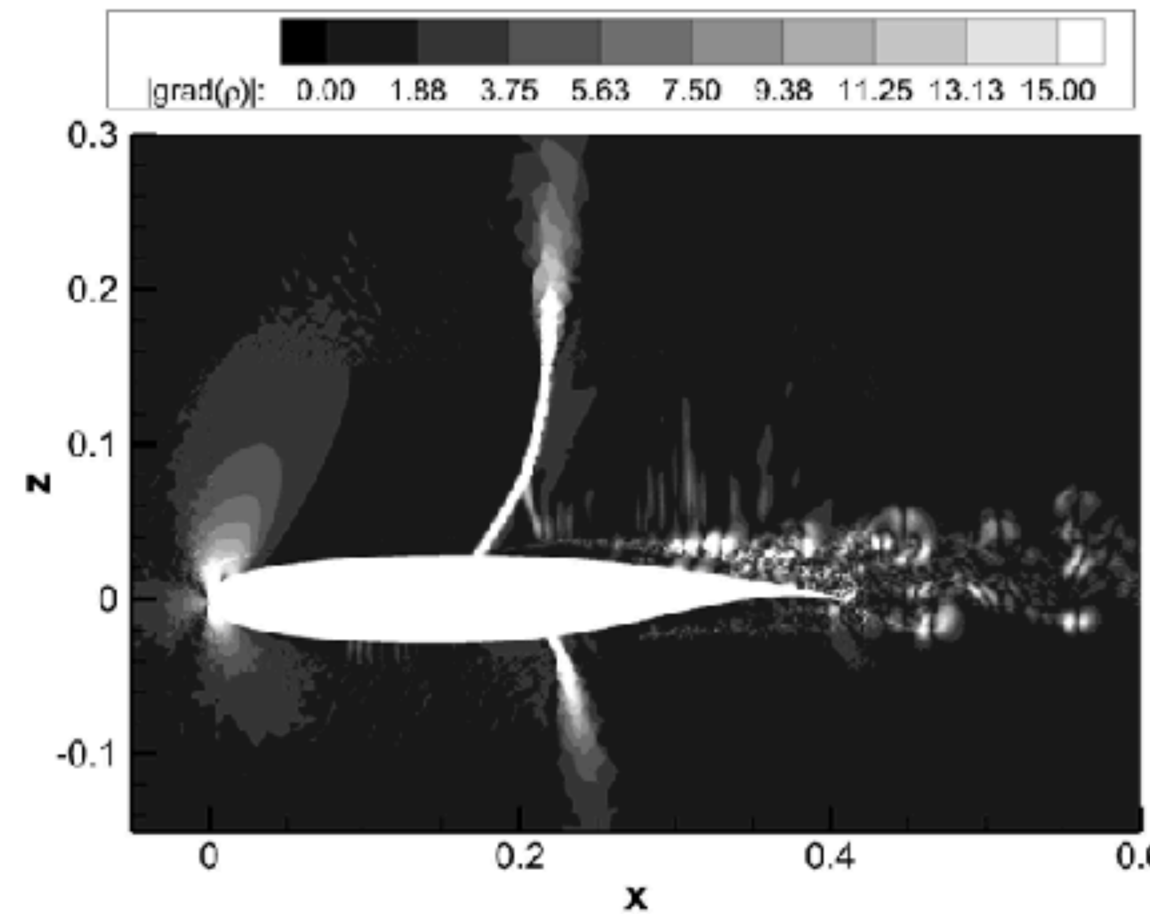


BSCW Test Case

Adaptive dissipation function



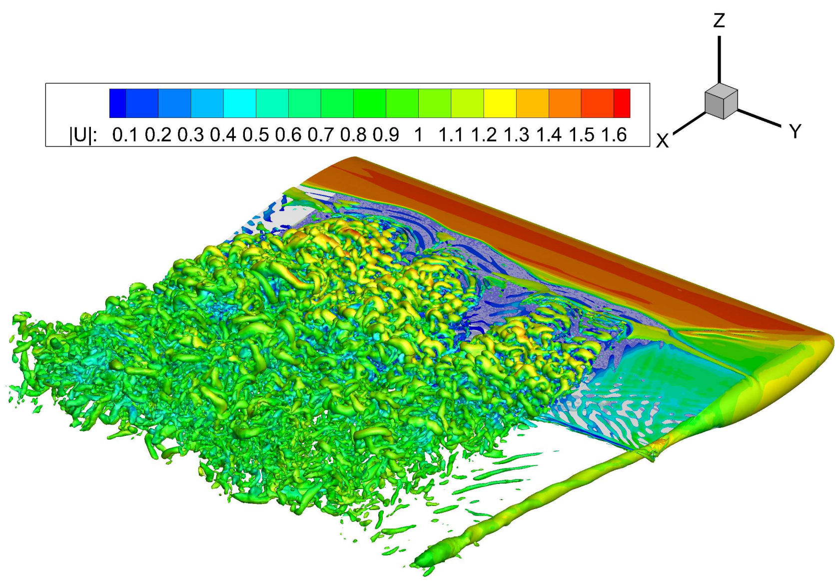
Density Gradient Magnitude



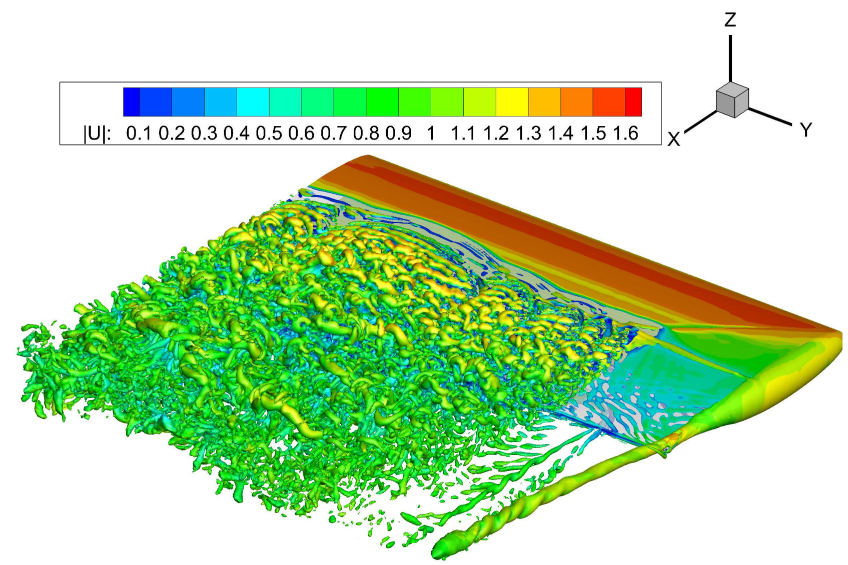
- The adaptive function is designed to have a value of 1.0 away from the wall (including the shock-wave region, whereas it is designed to effectively reduce the dissipation ($\sigma \approx 0$) in the shear layer/wake region.

- Pronounced lambda shock is observed as well as interactions between the shocked flow, large-scale turbulent structures, and the trailing-edge.

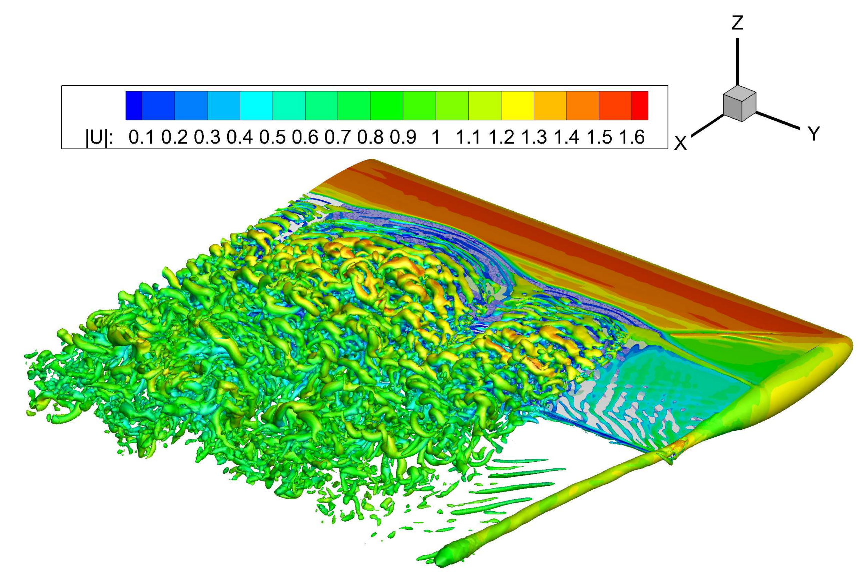
BSCW Test Case



Standard DDES SGS



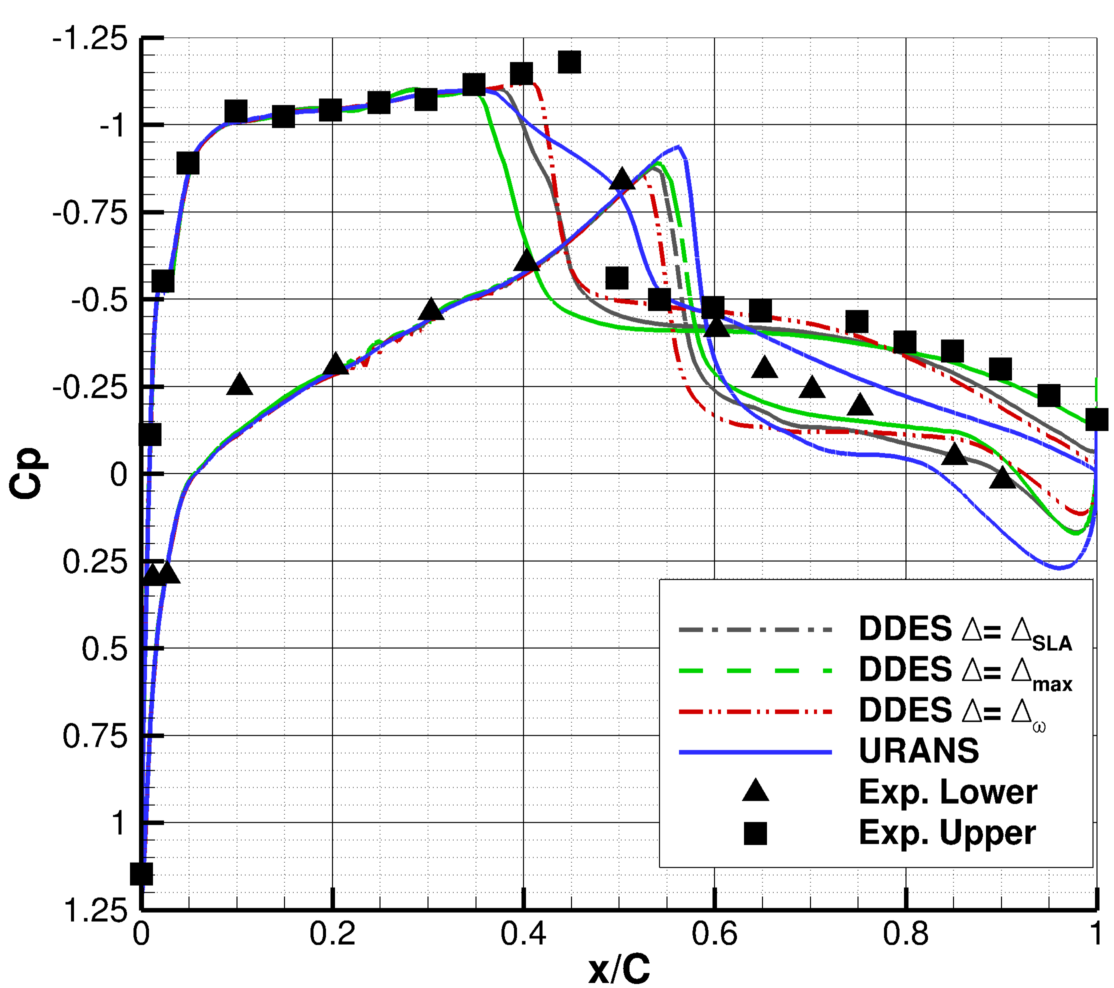
Vorticity-based SGS

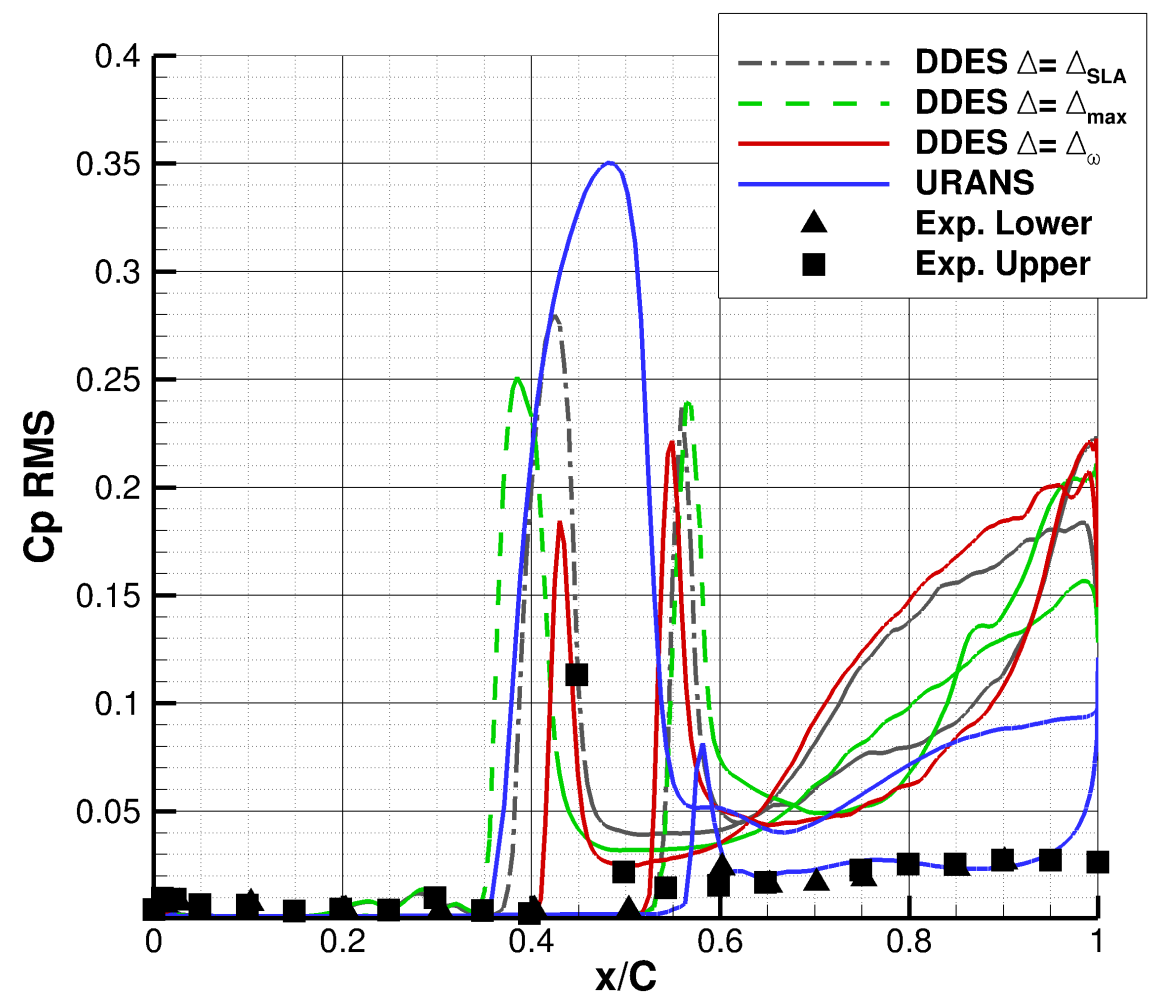


Shear Layer Adapted SGS

- Iso-surface of Q colored by velocity magnitude shows the improvement in RANS to LES transition behind the shock of the grey area mitigation methods compared to the standard DDES SGS.

BSCW Test Case





- Although the shock moves slightly upstream, the prediction of the separated zone downstream of the shock is significantly improved using DDES compared to URANS and experimental data.

- The amplitude of the pressure fluctuation caused by the shock is reasonably captured, whereas the pressure fluctuations downstream of the shock are over-predicted.

Conclusions and Future Work

- Conclusions:
  - The aim of the present study was to implement/extend the DDES capabilities of SU2 to unsteady flows on industry-relevant geometries and the results obtained so far are very encouraging, demonstrating that the hybrid models have been implemented correctly.
  - The implementation of gray area mitigation methods shows that SU2 is comparable to state-of-the art Hybrid RANS/LES solvers for subsonic flows.
  - The effect of GAM methods needs to be better understood in transonic Hybrid RANS/LES methods. Zonal methods or high-order solvers?
- Future/on going work:
  - Implement novel stochastic backscatter for non-zonal Hybrid RANS/LES (with M. Righi).
  - Implement Synthetic Turbulence Generators (STG) for zonal RANS-WMLES.

https://github.com/su2code/SU2/tree/feature_DDESv5.0

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