Scientific Computing

TECHNISCHE UNIVERSITÄT KAISERSLAUTERN

Scale-Resolving Simulations in SU2

Eduardo Molina[1], Juan Alonso[1]

Beckett Y. Zhou[2], Nicolas R. Gauger[2]

[1]Stanford University

[2]Chair for Scientific Computing, TU Kaiserslautern, Germany

SU2

The Open-Source CFD Code

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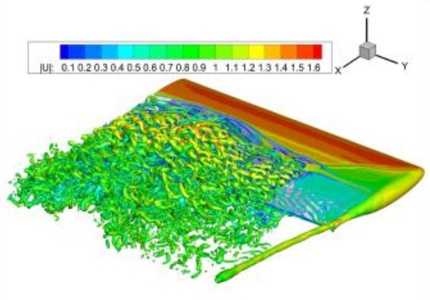
Scale-Resolving Simulations in SU2

Spalart-Allmaras Turbulence Model:

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

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

- Detached Eddy Simulation (DES):
  - $\tilde{d} = min(d, C_{DES} \Delta)$
  - $\Delta = \Delta_{max} = max(\Delta_x, \Delta_y, \Delta_z)$
  - HYBRID_RANSLES=SA_DES
- Delayed Detached Eddy Simulation (DDES):
  - $\tilde{d} = d - f_d max(0, d - C_{DES} \Delta)$
  - $\Delta = \Delta_{max} = max(\Delta_x, \Delta_y, \Delta_z)$
  - HYBRID_RANSLES=SA_DDES

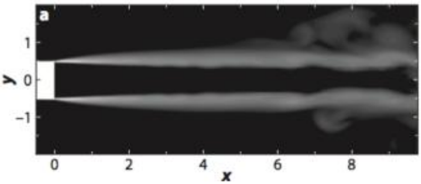


- DDES with Shear-Layer Adapted SGS (DDES-SLA): $\Delta_{SLA} = \tilde{\Delta}_\omega F_{KH}(< VTM >)$, HYBRID_RANSLES=SA_EDDES

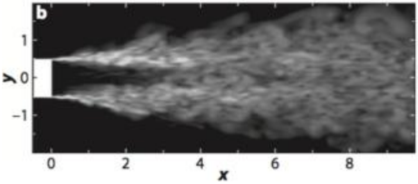
DDES with Shear-Layer Adapted SGS (DDES-SLA)

The 'Grey Area' Problem of DDES

- Location: Transition region between RANS and LES modes.
- Symptom: Unphysically slow development of the Kelvin-Helmholtz instability in free shear layer and delay of transition to 3D turbulence
- Reason 1: Excess modeled eddy viscosity convected from attached flow region treated by RANS into the separated LES region
- Reason 2: Excessive production of subgrid viscosity on strongly anisotropic grids
- Effect on turbulent flow prediction:
  - Under-prediction of resolved turbulent fluctuations in early shear layer
  - 'explosive' breakdown of large-scale structures when shear-layer finally disintegrates $\Longrightarrow$ over-prediction of turbulent fluctuations



Standard DDES



Implicit LES

Grey Area Mitigation (GAM) Method in SU2

Standard DDES length scale:

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

where f_d is a 'shielding function' which is 0 in RANS region and 1 elsewhere;

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

To remove the dominance of Δz in a strongly anisotropic grid and avoid solely using the smallest grid dimension Δy, adopt a vorticity-sensitive subgrid scale (SGS) proposed by Mockett et al. (2015):

$$\tilde{\Delta}_\omega = \frac{1}{\sqrt{3}} max|n_{\omega_i} \times r_{ij}|$$

where n_{ω_i} is the unit vector of vorticity and r_{ij} is the edge vector between vertices i and j

In initial shear-layer region ($\vec{\omega}$ aligned with $\hat{z}$):

$$\tilde{\Delta}_\omega = \frac{1}{\sqrt{3}}\sqrt{\Delta_x^2 + \Delta_y^2} = O(max(\Delta_x, \Delta_y))$$

In region of developed 3D turbulence: $\tilde{\Delta}_\omega = O(max(\Delta_x, \Delta_y, \Delta_z)) \rightarrow$ original DES SGS

Grey Area Mitigation (GAM) Method in SU2

In initial shear layer, outside boundary layer, cells can be nearly isotropic $\rightarrow \tilde{\Delta}_\omega \sim \Delta_{max} \rightarrow$ Need to further scale down SGS.

Use a purely kinematic 'Vortex Tilting Measure' (VTM) to identify quasi-2D flow regions proposed by Shur et al. (2015):

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

Quasi-2D region: VTM ~ 0.0 | Region of developed 3D turublence: VTM ~ 1.0

Shear layer adapted SGS:

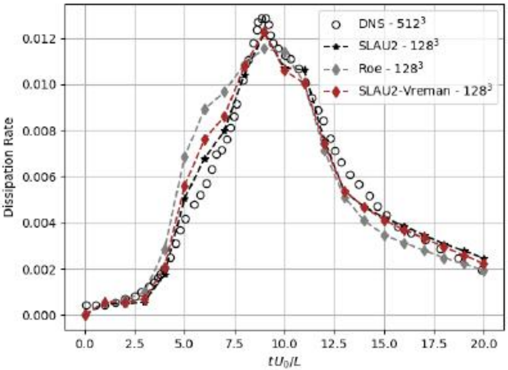
$$\Delta_{SLA} = \tilde{\Delta}_\omega F_{KH}(< VTM >)$$

where F_{KH} is a piecewise linear designed to remain at small values when VTM is below a certain prescribed threshold (in early shear layer) and then rapidly increases to 1.0 in high-VTM regions (3D turbulence).

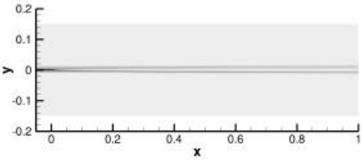
- Drastically reduces SGS viscosity exactly in early shear layers
- Unlocks the natural Kelvin-Helmholtz (KH) instability in initial shear layer
- Accelerates development of realistic resolved 3D turbulence
- Remains passive in other regions

Low Dissipation Convective Scheme

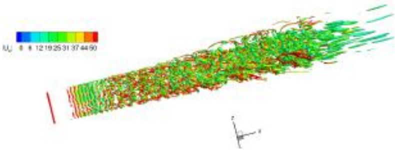
- Simple Low Dissipation AUSM (SLAU2):
  CONV_NUM_METHOD_FLOW=SLAU2
- Adaptive dissipation functions (σ):
  - DDES f_d function: ROE_LOW_DISSIPATION= FD
  - NTS Sensor: ROE_LOW_DISSIPATION= NTS

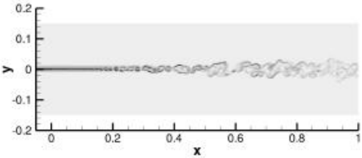


Mixing Layer



Standard DDES

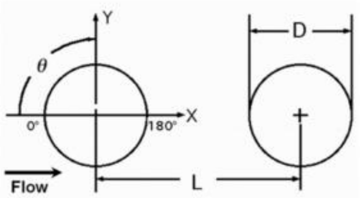




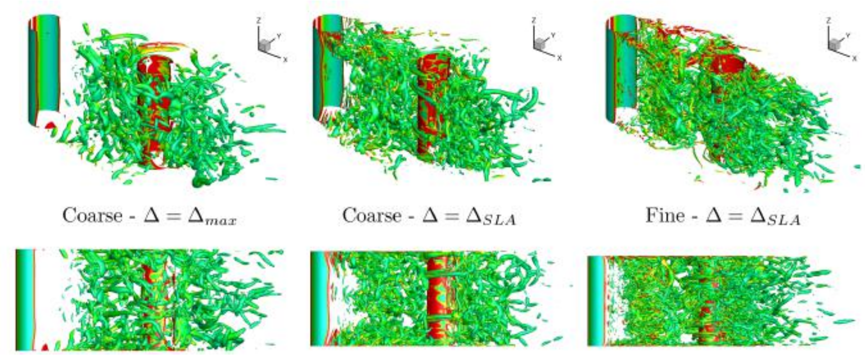
DDES-SLA

Tandem Cylinder

- 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.

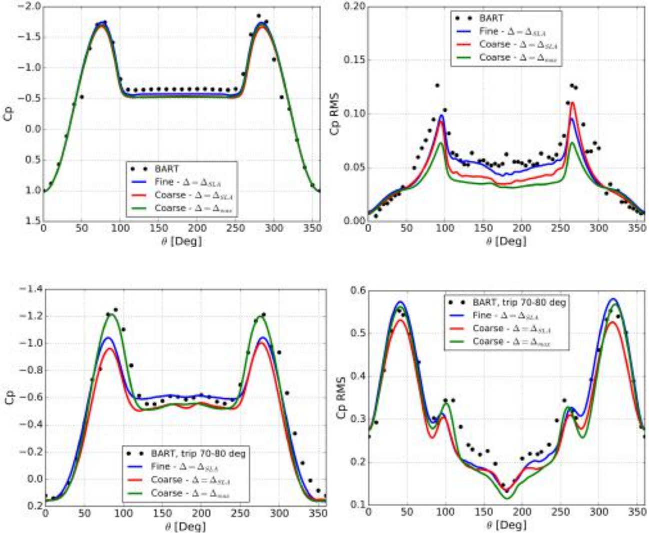


Tandem Cylinder

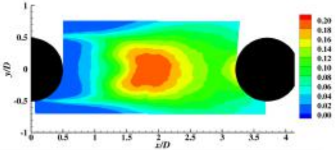


- Standard SGS present a strong delay in the roll-up of the shed vortices and the consequent formation of the K-H instability
- SLA SGS, the turbulent structures appeared closer to the upstream cylinder, accelerating the RANS to LES transition.

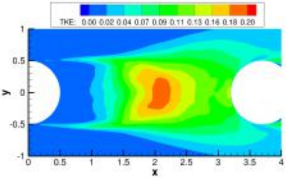
Tandem Cylinder



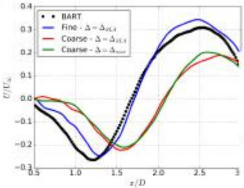
Tandem Cylinder

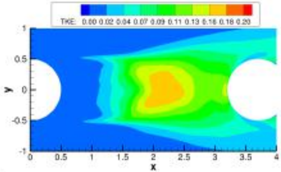


Experimental PIV

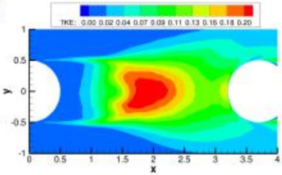


Coarse - $\Delta = \Delta_{SLA}$



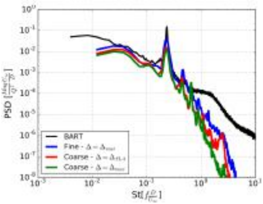


Coarse - $\Delta = \Delta_{max}$

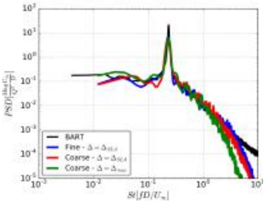


Fine - $\Delta = \Delta_{SLA}$

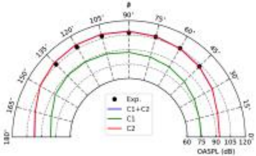
Tandem Cylinder



Wall Pressure PSD on Cylinder 1



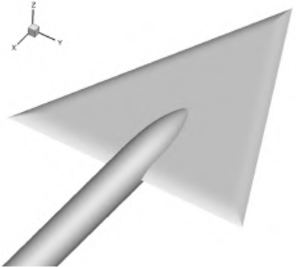
Wall Pressure PSD on Cylinder 2



Overall Sound Pressure Level

Vortex Breakdown Over a Delta Wing

- NASA delta wing
- 65° leading-edge sweep
- Sharp leading-edge
- $M_\infty = 0.07$, $Re_{mac} = 1 \times 10^6$, $\alpha = 23°$
- Vortex breakdown observed between $x/c_r = 0.60$ and $x/c_r = 0.80$



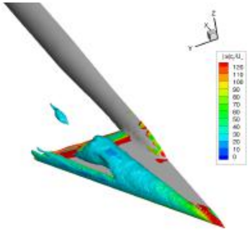
Experimental Studies

- Chu and Luckring, NASA Langley Research Center (1996)
- Furman and Breitsamter, TU Munich (2008, 2009)

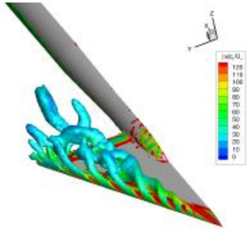
Recent Numerical Studies in EU

- ATAAC (2009 - 2012)
  - Used baseline DDES-type methods
  - Severe 'Grey Area' problem: delayed RANS-to-LES transition
- Go4Hybrid (2013 - 2015)
  - Grey Area Mitigation (GAM) methods for DDES
  - Significantly improved prediction with higher level of resolved turbulence

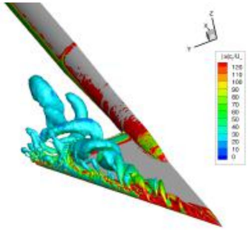
Vortex Breakdown Over a Delta Wing



Coarse Mesh



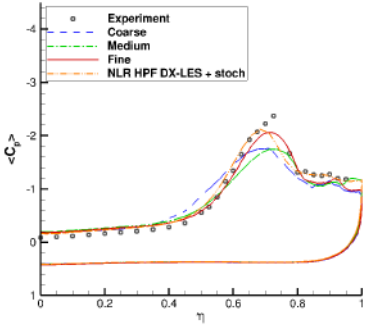
Medium Mesh



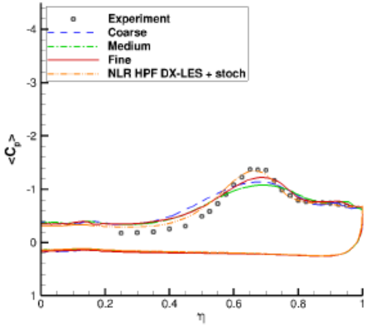
Fine Mesh

- Effort led by TU Kaiserslautern, joint work with ODU, NASA and NIA.
- Reference: B. Y. Zhou, N. R. Gauger, B. Diskin, J. K. Pardue, A. Chernikov, C. Tsolakis, F. Drakopoulos, N. N. Chrisochoides, "*Hybrid RANS/LES Simulation of Vortex Breakdown Over a Delta Wing*", In AIAA Aviation 2019 Forum, No. 2019-3524, Dallas, TX, 2019.

Time-Averaged Pressure Coefficient (Around Vortex Breakdown)



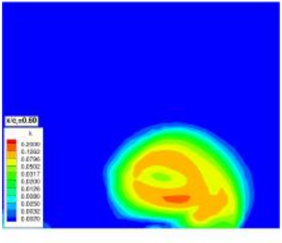
$x/c_r = 0.60$



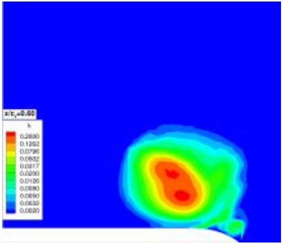
$x/c_r = 0.80$

- Additional numerical result using XLES with Stochastic Backscattering shared by J. Kok, NLR
- Vortex breakdown observed in experiment between $x/c_r = 0.60$ and $x/c_r = 0.80$
- Before and after vortex breakdown, fine mesh result is in good agreement with experiment and NLR result

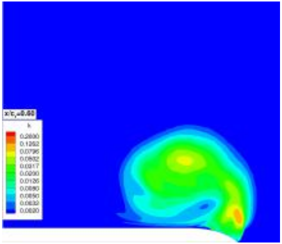
Measured vs. Resolved Turbulence Kinetic Energy ($x/c_r = 0.60$)



Experiment (HWA)



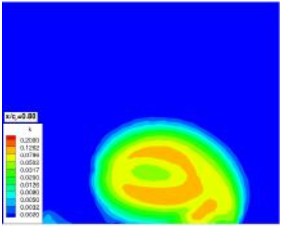
Medium Mesh



Fine Mesh

- Shortly before 'known' vortex breakdown location ($x/c_r = 0.60$), medium mesh significantly over-predicts TKE level $\rightarrow$ likely due to existing, premature vortex breakdown at that location
- Post vortex breakdown ($x/c_r = 0.80$): fine mesh TKE in good agreement with measurement both in terms of peak level and topology

Measured vs. Resolved Turbulence Kinetic Energy ($x/c_r = 0.80$)



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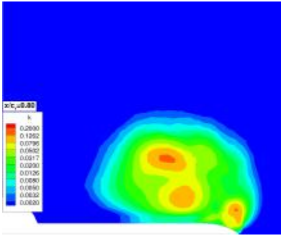
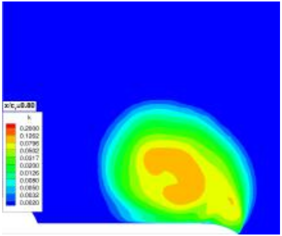


Medium Mesh



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Scale-Resolving Simulations in SU2

Reference Publications

- E. Molina, “Detached Eddy Simulation in SU2”, PhD Thesis, 2018
- E. Molina, B. Y. Zhou, J. J. Alonso, M. Righi, R. G. Silva, “*Flow and Noise Predictions Around Tandem Cylinders using DDES approach with SU2*”, In AIAA Scitech 2019 Forum, No. 2019-0326, San Diego, CA, 2019.

On-going Efforts

- Further validations: jet noise, NASA Hump, 30P30N, etc
- IDDES
- Wall-modelled LES