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

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Spalart-Allmaras Turbulence Model:

\[
\frac{\partial \hat{v}}{\partial t} + \nabla \cdot \tilde{F}^c - \nabla \cdot \tilde{F}^v - Q = 0
\]

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

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

- 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):
  - \( \Delta_{SLA} = \tilde{\Delta}_w F_{KH}(\prec VTM \succ) \), 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 $\implies$ over-prediction of turbulent fluctuations.

![Standard DDES](image1.png) ![Implicit LES](image2.png)

**Scale-Resolving Simulations in SU2**
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 $\Delta z$ in a strongly anisotropic grid and avoid solely using the smallest grid dimension $\Delta y$, 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 $n_{\omega_i}$ 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: $\tilde{\Delta}_\omega = O(\max(\Delta_x, \Delta_y, \Delta_z)) \rightarrow \text{original DES SGS}$
Grey Area Mitigation (GAM) Method in SU2

In initial shear layer, outside boundary layer, cells can be nearly isotropic → $\tilde{\Delta}_w \sim \Delta_{max}$ → 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):

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

Quasi-2D region: VTM $\sim 0.0$ | Region of developed 3D turbulence: VTM $\sim 1.0$

Shear layer adapted SGS:

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

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

Scale-Resolving Simulations in SU2
Low Dissipation Convective Scheme

- Simple Low Dissipation AUSM (SLAU2):
  
  \[
  \text{CONV\_NUM\_METHOD\_FLOW=} \text{SLAU2}
  \]

- Adaptive dissipation functions (\(\sigma\)):
  - DDES \(f_d\) function: \(\text{ROE\_LOW\_DISSIPATION=} \text{FD}\)
  - NTS Sensor: \(\text{ROE\_LOW\_DISSIPATION=} \text{NTS}\)
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

- Graphs showing pressure coefficients ($C_p$) and root mean square ($C_p$ RMS) for BART and coarse simulations with different resolutions.

Scale-Resolving Simulations in SU2
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

- Effort led by TU Kaiserslautern, joint work with ODU, NASA and NIA.
Time-Averaged Pressure Coefficient (Around Vortex Breakdown)

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 ($x/c_r = 0.60$)

- Shortly before ‘known’ vortex breakdown location ($x/c_r = 0.60$), medium mesh significantly over-predicts TKE level → 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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Reference Publications


On-going Efforts

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