Scale-Resolving Simulations in Industrial CFD - Models and Best Practice

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Motivation for Scale-Resolving Simulation (SRS)

• **Accuracy Improvements over RANS**
  - Flows with large separation zones (stalled airfoils/wings, flow past buildings, flows with swirl instabilities, etc.)

• **Additional information required**
  - Acoustics - Information on acoustic spectrum not reliable from RANS
  - Vortex cavitation – low pressure inside vortex causes cavitation – resolution of vortex required
  - Fluid-Structure Interaction (FSI) – unsteady forces determine frequency response of solid.
LES - Wall Bounded Flows

• A single Turbine (Compressor) Blade (Re=10^5-10^6) with hub and shroud section
• Need to resolve turbulence in boundary layers
• Need to resolve laminar-turbulent transition

<table>
<thead>
<tr>
<th>Method</th>
<th>Number of Cells</th>
<th>Number of time steps</th>
<th>Inner loops per Δt.</th>
<th>CPU Ratio</th>
</tr>
</thead>
<tbody>
<tr>
<td>RANS</td>
<td>~10^6</td>
<td>~10^2</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>LES</td>
<td>~10^8-10^9</td>
<td>~10^4-10^5</td>
<td>10</td>
<td>10^6</td>
</tr>
</tbody>
</table>

Therefore Hybrid RANS-LES Methods
Q-criterion

Q-criterion ($\Omega^2 - S^2$): $Q=10^9$, colored by $z$-velocity:

- Due to high Re number and moderate $a$, it looks still ok near trailing edge even though span=0.05c
NACA 0012 Airfoil Noise

• NACA 0012: \( Re_{chord} = 1.1 \cdot 10^6 \)
WB Unstructured Hex Mesh

- Span: 0.05 chord; 80 nodes
- In total ~ 11.4 Mio nodes
- WALE LES model
- Periodicity in spanwise direction
5% chord, 11M cells, $\Delta t = 1.5 \mu s$

Pressure and skin friction coefficients

Even on this grid $c_f$ is too low -> WMLES (see later)
Detached Eddy Simulation (DES)

Hybrid Model:
- RANS equations in boundary layer.
- LES „ detached “ regions.

Switch of model:
- Based on ratio of turbulent length-scale to grid size.
- Different numerical treatment in RANS and LES regions.

- Overcomes threshold limit of LES
- Explicit grid sensitivity in RANS region
- Open question concerning transition region between RANS and LES

\[ L_t \leq c\Delta \] for RANS
\[ L_t \geq c\Delta \] for LES
DES for SST – Strelets (2000)

- **k-equation RANS**

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho U_j k)}{\partial x_j} = P_k - \rho \frac{k^{3/2}}{L_t} + \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \frac{\partial k}{\partial x_j} \right]
\]

\[
L_t = \frac{\sqrt{k}}{\beta^* \omega}
\]

- **k-equation LES**

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho U_j k)}{\partial x_j} = P_k - \rho \frac{k^{3/2}}{C_{DES} \Delta} + \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \frac{\partial k}{\partial x_j} \right]
\]

\[
\Delta = \max(\Delta x, \Delta y, \Delta z)
\]

- **k-equation DES**

\[
\frac{\partial (\rho k)}{\partial t} + \frac{\partial (\rho U_j k)}{\partial x_j} = P_k - \rho \frac{k^{3/2}}{\min \left( L_t; C_{DES} \Delta \right)} + \frac{\partial}{\partial x_j} \left[ (\mu + \mu_t) \frac{\partial k}{\partial x_j} \right]
\]
Grid Sensitivity with DES Model

Requirement:

\[ \Delta x > \delta \]

Alternative – Shielding functions – Delayed DES (DDES)
DES for SST – Delayed DES (DDES)

- DDES – provides shielding functions which keep DES in RANS mode in attached boundary layers even for fine grids:

\[ E = \rho \frac{k^{3/2}}{\min \left( L_i; C_{DES} \Delta \right)} = \rho \frac{k^{3/2}}{L_i \min \left( 1; C_{DES} \Delta / L_i \right)} = \rho \frac{k^{3/2}}{L_i \max \left( 1; \frac{L_i}{C_{DES} \Delta} \right)} \]

- Destruction term original DES-SST model:

\[ F_{DES-CFX} = \max \left( \frac{L_i}{C_{DES} \Delta} \cdot (1 - F_{DDES}), 1 \right) \]

\[ F_{SST} = 0, F_1 \text{ or } F_2, F_{DDES} \]

- DES function used for SST model to shield boundary layer from DES impact (Delayed DES – DDES)

\[ \Delta_{\text{max}} > 0.1 \cdot \delta_{BL} \]
DES/DDES of Separated Flow around a realistic Car model exposed to Crosswind

<table>
<thead>
<tr>
<th>Model</th>
<th>Exp.</th>
<th>DDES</th>
<th>DES</th>
<th>LES</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drag (SCx)</td>
<td>0.70</td>
<td>0.71</td>
<td>0.75</td>
<td>0.69</td>
</tr>
</tbody>
</table>

U=40 m/s Yaw angle 20° Re_H~10^6

Courteys PSA Peugeot Citroën
DES Problem “Grey Areas”

Model has not fully switched between RANS and LES mode
- Grid resolution too low
- Instability too weak

Balance of resolved and unresolved portions of the flow is not achieved – loss of turbulent kinetic energy

Undefined model
Further mesh refinement required

Courtesy: Herr Sohm – BMW AG
SAS and DES Model for triangular Cylinder

- SAS and DDES work well for strongly unstable flows
- Often produce very similar results
- Both, SAS and DES rely on flow instability to quickly produce unsteady turbulence – this works well for many flows
WMLES: Near Wall Scaling

- Turbulent length scale is independent of Re number.
- However, thickness of viscous sublayer decreases with increasing Re number.
- Turbulent structures inside sublayer are damped out.
- Smaller turbulence structures near the wall get “exposed” as Re increases.
- WMLES: models small near wall structures with RANS and only resolve larger structures – less dependent on Re number.
- Some Re number dependence for boundary layer remains as boundary layer thickness decreases with Re number.

\[ L_t = \kappa y \]
WMLES – Channel Flow at Different Re Numbers

- Solutions at very different Re numbers look essentially identical.
- Differences can only be seen near the wall.
- Visible is higher Eddy-Viscosity for higher Re number close to wall.
WMLES – Channel Flow Tests

<table>
<thead>
<tr>
<th>Reₜ</th>
<th>Cells Number</th>
<th>LES Cells Number</th>
<th>Nodes Number</th>
<th>ΔX⁺</th>
<th>ΔZ⁺</th>
</tr>
</thead>
<tbody>
<tr>
<td>395</td>
<td>384 000</td>
<td>384 000</td>
<td>81×81×61</td>
<td>40.0</td>
<td>20.0</td>
</tr>
<tr>
<td>760</td>
<td>480 000</td>
<td>1 500 000</td>
<td>81×101×61</td>
<td>76.9</td>
<td>38.5</td>
</tr>
<tr>
<td>1100</td>
<td>480 000</td>
<td>4 000 000</td>
<td>81×101×61</td>
<td>111.4</td>
<td>55.7</td>
</tr>
<tr>
<td>2400</td>
<td>528 000</td>
<td>19 000 000</td>
<td>81×111×61</td>
<td>243.0</td>
<td>121.5</td>
</tr>
<tr>
<td>18000</td>
<td>624 000</td>
<td>1 294 676 760</td>
<td>81×131×61</td>
<td>1822.7</td>
<td>911.4</td>
</tr>
</tbody>
</table>

- Very large savings between WMLES and wall-resolved LES
- Alternative is LES with wall functions – however Δx⁺ and Δz⁺ are a function of Δy⁺
Vortex Method

• In essence, vorticity-transport is modeled by distributing and tracking many point-vortices on a plane (Sergent, Bertoglio)

\[ \omega(x, t) = \sum_{k=1}^{N} \Gamma_k(t) \eta(|x - x_k|, t) \]

• Velocity field computed using the Biot-Savart’s law

\[ u(x, t) = -\frac{1}{2\pi} \int \int \frac{(x - x') \times \omega(x')e_z}{|x - x'|^2} \, dx' \]
Vortex Method

3-D Wavy Channel (Re_H = 10,600)
Mathey and Cokljat (2005)

Flow
Computational Domain

LES predictions of the reattachment point

<table>
<thead>
<tr>
<th></th>
<th>X_r</th>
</tr>
</thead>
<tbody>
<tr>
<td>Exp.</td>
<td>4.7 h</td>
</tr>
<tr>
<td>Periodic</td>
<td>5. H</td>
</tr>
<tr>
<td>VM</td>
<td>5.2 h</td>
</tr>
<tr>
<td>Random</td>
<td>7.7 h</td>
</tr>
</tbody>
</table>
WMLES – Flat Plate Grid

- Geometry and Grid
  - \( L \times 0.4 \ L \times 0.1 \ L \)
    (Streamwise, Normal, Spanwise)
  - Approximately 3 \( \delta \) spanwise \((\delta_0=0.032)\)
  - Grid \( \sim 1\) Million cells (see table)
  - \( Y^+\sim0.05 \) (to allow for higher Re numbers)
  - Expansion factor 1.15
  - For each boundary layer thickness \( \delta \) one needs \( \sim10\times40\times20 \) cells

<table>
<thead>
<tr>
<th>( \text{Re}_\Theta )</th>
<th>Cells Number</th>
<th>Nodes Number</th>
<th>( \Delta X^+ )</th>
<th>( \Delta Y^+ )</th>
<th>( \Delta Z^+ )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>1 085 000</td>
<td>251\times71\times63</td>
<td>68</td>
<td>0.05 \div 300</td>
<td>34</td>
</tr>
<tr>
<td>10000</td>
<td>1 085 000</td>
<td>251\times71\times63</td>
<td>520</td>
<td>0.4 \div 2300</td>
<td>307</td>
</tr>
</tbody>
</table>
WMLES – Boundary Layer

- Boundary layer simulation:
  - WMLES
  - Inlet: synthetic turbulence
  - Vortex Method
  - 2 different Reynolds numbers

![Skin Friction Coefficient](image)

- $Re_\theta = 1000$
- $Re_\theta = 10000$

![Skin Friction Coefficient](image)

- $Re_\theta = 10000$
- $Re_\theta = 100000$
Embedded/Zonal Large Eddy Simulation (ELES, ZFLES)

- Suitable if zone with high accuracy demands is embedded into larger domain which can be covered properly by RANS models
- Limited zone can then be covered by LES or Wall-Modelled WMLES model
- LES zone needs to be coupled to RANS zone through interfaces
- LES zone requires suitable (WM)LES resolution in time and space
Embedded LES and Zonal Forced LES

• In many flows an area where (WM)LES is required is embedded in a larger RANS region
• In such cases, a zonal method is advantageous
• RANS and LES regions are separately defined and use different models
• Synthetic turbulence is generated at the interface to convert RANS to LES turbulence
Coupled Zonal Modelling

In ELES/ZFLES e.g. MODEL2 can be LES turbulence model embedded in a RANS or SAS model (MODEL1), or vice versa.

There is STRONG need for model interaction at this interface since models are different in Zone 2 → 3 and Zone 3 → 4.
Zonal LES: Test cases

DIT-x: resolved 3-D structures

- Q criterion
- Bounded CD advection scheme (BCD)
Zonal LES: Test cases

DIT-x: decay rate validation

- Modelled and resolved $k$

![Kinetic energy of turbulence](image)
Flow Types: Globally Unstable Flows

• Types of highly unstable flows:
  – Flows with strong swirl instabilities
  – Bluff body flows, jet in crossflow
  – Massively separated flows

• Physics
  – Resolved turbulence is generated quickly by flow instability
  – Resolved turbulence is not dependent on details of turbulence in upstream RANS region (the RANS model can determine the separation point but from there ‘new’ turbulence is generated)

• Models
  – SAS: Most easy to use as it converts quickly into LES mode, and automatically covers the boundary layers in RANS. Has RANS fallback solution in regions not resolved by LES standards ($\Delta t$, $\Delta x$)
  – DDES: Similar to SAS, but requires LES resolution for all free shear flows ($\Delta t$, $\Delta x$) (jets etc.)
  – ELES: Not really required as RANS model can cover boundary layers. Often difficult to place interfaces for synthetic turbulence.

Green-recommended, Red=not recommended
Flow Types: Locally Unstable Flows

- **Types of moderately unstable flows:**
  - Jet flows, Mixing layers ...

- **Physics**
  - Flow instability is weak – RANS/SAS models stay steady state.
  - Can typically be covered with reasonable accuracy by RANS models.
  - DDES and LES models go unsteady due to the low eddy-viscosity provided by the models. Only works on fine LES quality grids and time steps. Otherwise undefined behavior.

- **Models**
  - **SAS:** Stays in RANS mode. Covers upstream boundary layers in RANS mode. Can be triggered into SRS mode by RANS-LES interface.
  - **DDES:** Can be triggered to go into LES mode by fine grid and small $\Delta t$. Careful grid generation required. Covers upstream boundary layers in RANS mode.
  - **ELES:** LES mode on fine grid and small $\Delta t$. Careful grid generation required. Upstream boundary layer (pipe flow) in expensive LES mode. Alternative – ELES with synthetic turbulence RANS-LES interface.
Flow Types: Locally Unstable Flows

- Resolving flow instability in moderately unstable flows is demanding in terms of:
  - Grid resolution – needs to be of LES quality
  - Numerics – more demanding than fully turbulent LES
  - Shielding – balance between shielding and capturing instability
  - Difficult in complex industrial flows
Flow Types: Stable Flows

• Types of marginally unstable flows:
  – Pipe flows, channel flows, boundary layers, ..

• Physics
  – Transition process is slow and takes several boundary layer thicknesses.
  – When switching from upstream RANS to SRS model, RANS-LES interface with synthetic turbulence generation required.
  – RANS-LES interface needs to be placed in non-critical (equilibrium) flow portion. Downstream of interface, full LES resolution required.

• Models
  – SAS: Stays in RANS mode. Typically good solution with RANS. Can be triggered into SRS mode by RANS-LES interface.
  – DDES: Can be triggered to go into LES mode by fine grid and small $\Delta t$. Careful grid generation required. Covers upstream boundary layers in RANS mode.
  – ELES: LES mode on fine grid and small $\Delta t$. Careful grid generation required. Upstream boundary layer (pipe flow) in RANS mode. Synthetic turbulence RANS-LES interface.

Green-recommended, Red=not recommended
Globally Unstable Flow – Jets in Crossflow

PhD project Benjamin Duda
- 18 month at Airbus Toulouse (Marie-Josephe Estève)
- 18 month ANSYS Germany (Thorsten Hansen, F. Menter)
- Scientific supervisors: Herve Bezard, Sebastien Deck

Problem:
- Hot air leaves engine nacelle and heats wall
- Heat shielding required
- Experiments too expensive
- RANS not accurate enough
- Simulations ANSYS-Fluent

Courtesy: Benjamin Duda, Airbus Toulouse
Generic Jet in Cross Flow Configuration

- Infrared Thermography
- Particle Image Velocimetry
- Laser Doppler Anemometry
- Hot and Cold Wire Measurements

Courtesy: Benjamin Duda, Airbus Toulouse
Hexahedral Mesh

12,900,000 Elements
Min angle = 28.1°
Max AR = 3,500
Max VC = 10

Courtesy: Benjamin Duda, Airbus Toulouse
Hybrid Tetrahedral Mesh

21,000,000 Elements
Min angle = 20.0°
Max AR = 7,600
Max VC = 8

20 inflation layers

Courtesy: Benjamin Duda, Airbus Toulouse
Hybrid Cartesian Mesh

13,100,000 Elements
Min angle = 6.0°
→ 30 Elements < 15°
Max AR = 6,000
Max VC = 16

20 inflation layers

Courtesy: Benjamin Duda, Airbus Toulouse
Mean Thermal Efficiency on Wing Surface

\[ \overline{\eta} \]

\begin{align*}
0.80 & \quad 0.75 & \quad 0.70 & \quad 0.65 & \quad 0.60 & \quad 0.55 & \quad 0.50 & \quad 0.45 & \quad 0.40 & \quad 0.35 & \quad 0.30 & \quad 0.25 & \quad 0.20 & \quad 0.15 & \quad 0.10 & \quad 0.05 & \quad 0.00
\end{align*}

\textbf{Courtesy: Benjamin Duda, Airbus Toulouse}
Mean Thermal Efficiency on Wing Surface

**Courtesy: Benjamin Duda, Airbus Toulouse**
Hot Jet in Crossflow: Conclusions

- RANS models are not able to reliably predict such flows and are therefore not useful as design tools.
- A systematic study was carried out to evaluate SRS models for such applications.
- In this study (for several test case configurations) it was found that all SRS methods worked equally well in predicting the main flow characteristics.
- On suitable grids (~$10^6$ cells) good agreement even in the secondary quantities (stresses) could be achieved.
- More complex geometries studied.

Courtesy: Benjamin Duda, Airbus Toulouse
Flow schematic

Main Pipe:
T=19°
Q=9 [l/s]
Ø=0.14 [m]
Developed Flow

Branch Pipe:
T=36°
Q=6 [l/s]
Ø=0.1 [m]
δ_{BL}=0.01 [m]

The target values are mean and RMS wall temperatures in the fatigue zone.

Water of different temperature is mixing in the T-junction at Re=1.4\times10^5 (based on the main pipe bulk velocity and on its diameter)
Isosurfaces of Q-criterion Colored with Temperature for Different SRS Models

- Sensitivity to numerics depends on the SRS model
- SAS with BCD is virtually steady
- The reason is that the flow is not enough unstable
- Unsteady solution with resolved turbulent structures is obtained for the CD scheme
- For other models the effect of numerics is not seen from instantaneous fields
Comparison of Different SRS Models

- CD scheme is used for comparison between different SRS models
- All models are able to predict mean and RMS profiles with sufficient accuracy
Influence of Zonal LES, weak BCD

Wall temperature in the fatigue zone

- Noticeable differences appear when looking at the wall temperature.
- All global models failed to provide the correct temperature distribution right past the intersection.
- Only zonal (embedded) formulation is able to provide the correct mixing already from the start of the mixing zone.

\[ \bar{\theta} = \frac{\bar{T} - T_{\text{cold}}}{T_{\text{hot}} - T_{\text{cold}}} \]

Graph showing experimental data and simulations with and without zonal LES.
Influence of Zonal LES, weak BCD

With DDES, $Q=1000$

With zonal LES, $Q=8000$

View from the top

Different mixing pattern
Flow over a wall mounted hump

Flow configuration:

Simulation: baseline (no flow control)
Testcase of EU Project ATAAC

http://cfd.mace.manchester.ac.uk/twiki/bin/view/ATAAC/WebHome
Flow over a wall mounted hump, Geometry and Grid

Geometry:
- Spanwise extent:
  - 3.16 H (bump height)
  - 5.6 $\delta_{\text{interface}}$ ($\delta$ – boundary layer thickness).

Grid:
- RANS grid with only 5 cells in spanwise direction
- LES grid: 200x100x100 (2 million)
- Grid resolution per inlet boundary layer ($\Delta x/\delta=10$, $\Delta z/\delta\sim20$, NY~40).
Flow over a wall mounted hump

Q criterion:

Contours of Z Velocity (m/s) (Time=2.0003e-01)
ANSYS FLUENT 13.0 (3d, dp, pbns, sstk, transient)
Flow over a wall mounted hump Wall Shear Stress and Wall Pressure

- The Re number at the RANS-LES interface is $Re_{\theta}=7000$
- If the simulation in the LES region is carried out with a standard LES model (WALE) the solution is lost immediately after the interface
- The WMLES formulation is able to carry the solution smoothly across and provide a good agreement with the data for two different time steps (CFL~0.5 and CFL~0.12)
Overall Summary

- RANS modelling key to industrial CFD
  - Grid quality is key issue
- Transition modelling important for many applications
  - Turbomachinery
  - Wind turbines
  - ...
- SRS is making its way into industrial CFD
- Different types of model recommended for different types of applications
- Currently favored methods within ANSYS software:
  - SAS – globally unstable flows
  - DDES – globally and locally unstable flows
  - ELES/WMLES marginally unstable flows
Best Practice: Scale-Resolving Simulations in ANSYS CFD

Version 1.03

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