Development of a hybrid RANS-LES methodology for incompressible flows.

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## Introduction

### RANS
- Full energy spectrum modelled.
- Devised for averaged quantities, but URANS possible.
- Mesh convergence possible.
- Mesh requirements not very strong.
- Variety of models with large deviation of results.
- Good for BL but not very accurate in separated flows.

### LES
- Small part of the spectrum modelled.
- Unsteady approach. Fluctuations available.
- Can produce more information than what is really needed.
- High CPU usage.
- Large mesh constrains due to the presence of walls.
- Highly dependant on the mesh construction.
Hybrid models.

- Combine the advantages of RANS (boundary layer) and LES (separated region)
- Use when RANS is not accurate and LES is prohibitive, or when fluctuations are needed
Hybrid methods

When flow is too complex for RANS (EVMs or SMCs) and the mesh requirements for LES are too large ($\Delta y^+ \sim 1$, $\Delta x^+ \sim 50$, $\Delta z^+ \sim 20$).
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- RANS: Statistically averaged.
- LES: Space filtered.

Two possibilities:
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- Prescribe an interface, one side RANS another LES.
  - Needs to add turbulent informations when going from RANS to LES.
  - Good for streamwise coupling using synthetic turbulence.
  - More difficult with wall normal coupling.
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- **Seamless methods.** Let the model change automatically.
  - Model needs a parameter to switch from RANS to LES, usually based on the cell size.
  - Fluctuations can easily die while in RANS
  - User needs to carefully design the mesh for the appropriate switch to occur.
Detached Eddy Simulation

In DES (Spalart, 2000) the turbulent lengthscale is changed from the RANS expression to the filter width ($\Delta$) in a similar manner to LES.

\[ l_{DES} = \min \left( \frac{k^{3/2}}{\varepsilon}, C_s \Delta \right) \]  

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This reduces the turbulent viscosity in the separated region.

(Strelets et al. 2008, DESIDER project)
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- Solves attached boundary layers with RANS, i.e. cheap.
- The separated region has more resolved scales and less modelled ones.
- Sensitive to the grid resolution. It can create *Grid Induced Separation*.
- Not very good where the separation point is not dictated by the geometry, large sensitivity to boundary layer turbulence.
- Several RANS models tested but mainly used with SST and SA.
Grid Induced Separation

If the mesh is refined inside the boundary layer, the model can switch to LES before actual separation.
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Solution:

- Use blending functions to *shield* from GIS.
- Take care on how to construct the mesh.
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a) Ideal DES
b) Ambiguous grid
c) LES grid.
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Refined needed in the trailing edge to capture separation.

(Menter et al. 2008, DESIDER project)
Grid Induced Separation

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Refined of structured grid on the top wall.

(Strelets et al. 2008, DESIDER project)
Two velocities hybrid model

The problem:

- RANS is statistically averaged velocity field. LES is instantaneous filtered. $\nu_a \neq \nu_r$, $k_a \neq k_r$ ....
- LES sub-grid model assumes inertial range $\rightarrow$ isotropic motions.
- As the wall is approached, mean shear introduces anisotropy $\rightarrow$ cell size must be reduced. Thus model must take into account sub-grid contributions to mean shear and isotropic dissipation effects.
- When $\Delta \rightarrow 0$, LES $=$ DNS but when $\Delta \rightarrow \infty$, LES $\neq$ RANS
Two velocities hybrid model

The velocity can be decomposed in averaged and fluctuating parts:

\[ \bar{U} = \langle \bar{U} \rangle + u' \]
Two velocities hybrid model

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In a similar way Schumann (1975) proposed that the subgrid stress tensor can be divided into two parts. One with the instantaneous contribution and one with the averaged.

\[ \tau_{ij}^r - \frac{2}{3} \tau_{kk} \delta_{ij} = -2\nu_r (\overline{S}_{ij} - \langle \overline{S}_{ij} \rangle) - 2\nu_a \langle \overline{S}_{ij} \rangle \]
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- locally isotropic
- inhomogeneous
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$\nu_r$ is the sub-grid viscosity, similar to standard LES.

$\nu_a$ is the RANS viscosity, computed from a mean velocity field obtained by a running averaged of the instantaneous field.

$f_b$ is a blending function (avoids double counting of the stresses).
Two velocities hybrid model

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![Graph showing instantaneous, time averaged, and running averaged velocities over time.](image-url)
Two velocities hybrid model

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- The averaged field is used to solve the RANS equations, in this case the elliptic relaxation model $\varphi - f$ (Laurence et al, 2004) is used.

\[
\nu_a = C_\mu \varphi kT
\]

\[
\nu = \frac{\overline{v^2}}{k}
\]

\[
T = \max \left( \frac{k}{\varepsilon}, C_t \frac{\sqrt{\nu}}{\varepsilon} \right)
\]
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- The subgrid turbulent viscosity is computed with the standard Smagorinsky (1963) model based on fluctuating velocities.

$$\nu_r = (C_s \Delta)^2 \sqrt{2s'_{ij}s'_{ij}}$$
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- The blending function is computed as a ratio of the turbulent length scale (from RANS equations) and the cell size

$$f_b = \tanh \left( C_l \frac{L_t}{\Delta} \right)^n$$

The turbulent length scale is $L_t = \varphi k^{3/2} / \varepsilon$. The filter width is $\Delta = 2Vol^{1/3}$. $C_l = 1.5$ and $n = 1$ are empirical constants.
The blending function

\( f_b \) with different mesh refinements.
The blending function

\[ f_b \] with different mesh refinements.

Shear stress

\[ y^+ \] with different mesh refinements.
The blending function

\( f_b \) with different mesh refinements.

Velocity Profiles

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Channel Flows

$Re_T = 395$. Mesh: 40x40x30. $\Delta x^+ = 59.25$, $\Delta z^+ = 39.5$
Channel Flows

$Re_\tau = 395$. Mesh: $40\times40\times30$. $\Delta x^+ = 59.25$, $\Delta z^+ = 39.5$
Velocity Profiles at higher Reynolds Numbers.

Channel Flows

<table>
<thead>
<tr>
<th>Re$_{\tau}$</th>
<th>Cells</th>
<th>$\Delta x^+$</th>
<th>$\Delta z^+$</th>
<th>Case</th>
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<tr>
<td>395</td>
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<td>59</td>
<td>39</td>
<td>C1</td>
</tr>
<tr>
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<td>40x40x30</td>
<td>88</td>
<td>59</td>
<td>C4</td>
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<tr>
<td>1100</td>
<td>50x50x40</td>
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<td>88</td>
<td>C6</td>
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<td>50x50x40</td>
<td>256</td>
<td>160</td>
<td>C8</td>
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<tr>
<td>4000</td>
<td>64x80x64</td>
<td>400</td>
<td>200</td>
<td>C10</td>
</tr>
</tbody>
</table>
Channel Flows

Velocity Profiles at higher Reynolds Numbers.

Normal stresses at $Re_\tau = 2000$
$Re_\tau = 4000$

$64 \times 80 \times 64$. 

$\Delta x^+ = 400$

$\Delta z^+ = 200$
$Re_\tau = 4000$

$64 \times 80 \times 64.$

$\Delta x^+ = 400$

$\Delta z^+ = 200$

$u'$ contours at $y^+ = 200$
\[ Re_\tau = 4000 \]
\[ 64 \times 80 \times 64. \]
\[ \Delta x^+ = 400 \]
\[ \Delta z^+ = 200 \]

\[ u' \] contours at \( y^+ = 5 \)
Trailing edge flow

- \( Re = 2.5 \times 10^6 \) based on chord, only rear-most 38% of domain computed.
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- Two simulations: DES + F1 shield function and Hybrid Model.
- DES predicts separation too early, even using F1 to prevent GIS.

- Hybrid model captures separation point correctly (From RANS near the wall)

- Hybrid predict good recirculation (From LES).

- $u_{\text{rms}}$ levels low near the wall on the incoming BL but better on the wake.

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- DES structures from inlet die fast as model is intended.
- Mesh too coarse to resolve finer structures but too fine to avoid GIS.
- Hybrid model does not kill fluctuations.
- Size of structures as small as the mesh allows.
Trailing edge flow

- RANS and LES zones.

Diagram showing the DES method with RANS and LES zones.
Trailing edge flow

- **RANS** and **LES** zones.
- Thick zone near the wall treated with RANS, necessary to reduce GIS.
Trailing edge flow

- RANS and LES zones.
- Thick zone near the wall treated with RANS, necessary to reduce GIS.
- Sharp transition interface.
Trailing edge flow

Hybrid

- **RANS** and **LES** zones.

Blending function

1.023e-24 1.429e-01 2.857e-01 4.285e-01 5.714e-01 7.143e-01 8.571e-01 1.000e+00
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Hybrid

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- Full LES part smaller than DES due to coarse mesh.
Trailing edge flow

Hybrid

- RANS and LES zones.
- Very thin zone near the wall treated with ONLY RANS.
- Full LES part smaller than DES due to coarse mesh.
- Smooth transition interface, the model allows for fluctuations to “survive”
Conclusions

- A new hybrid method has been presented based on splitting the contributions from the averaged and fluctuating velocity fields.
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• The introduction of wall effects via mean strain allows for the separation of dissipative effects.

• More tests are necessary to account for the mesh dependence effects on the model, especially on the blending function.