A two equation VLES turbulence model with near-wall delayed behaviour

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Introduction

- RANS simulations are still the dominant approach to turbulence modelling for high Reynolds number flows.
- DES approaches are used to offset the cost of the LES by retaining RANS characteristics in boundary layers while using LES away from the walls.
  - DES approach requires LES-like resolution away from the walls.
- Coarse meshes → DES away becomes unresolved LES.
- Introduces a delayed two equation VLES model.
  - Model constants selected to give Smagorinsky subgrid-scale model for grids approaching the resolution required for LES.
  - Near wall RANS behaviour is obtained using blending functions.
VLES Model

• Start with VLES model from Speziale (1998)

Sub-grid scale stress: \( \tau_{ij}^{\text{sub}} = F_r \tau_{ij}^{\text{RAS}} \); Resolution function:

\[
F_r = \left[ 1 - e^{-\frac{\beta L_c}{L_k}} \right]^n
\]

Kolmogorov dissipation length scale – \( L_k = \frac{V^{0.75}}{\varepsilon^{0.25}} \)

• Use result from Han and Kranjnovic (2013)

Redefine resolution function:

\[
F_r^* = \frac{F_r(L_c, L_k)}{F_r(L_i, L_k)}
\]

\[
F_r(L_c, L_k) = \left[ 1 - e^{-\frac{\beta L_c}{L_k}} \right]^n
\]

\[
F_r(L_i, L_k) = \left[ 1 - e^{-\frac{\beta L_i}{L_k}} \right]^n
\]

turbulent cut-off: \( L_c = C_x \left( \Delta_x \Delta_x \Delta_x \right)^{1/3} \)  integral length-scale: \( L_i = \frac{k^{3/2}}{\varepsilon} \)

enforce realisability limits: \( F_r^* = \min(1, F_r^*) \)
VLES Model cont’d

- Resolution function contains constants $\beta$, $n$ and $C_x$
  - Values from Speziale (1998) $\beta=0.002$ and $n=2$
  - $C_x$ chosen to be consistent with Smagorinsky const.:

$$C_x = \frac{\sqrt{0.3C_s}}{C_\mu}$$

- $F^*_r$ scales the stress tensor everywhere.

- Delayed behaviour close to wall is required to maintain the correct turbulence energy production.

$F_1$ from k-\(\omega\) SST model used to detect boundary layer

$$F_r(L_c, L_k) = \left[1 - (1 - F_1)e^{\frac{-\beta L_c}{L_k}}\right]^n$$

$$F_r(L_i, L_k) = \left[1 - (1 - F_1)e^{\frac{-\beta L_i}{L_k}}\right]^n$$
Square Cylinder

- Transient, turbulent, 3D flow over a square cylinder, $Re_D = 21,400$; Grid: $\sim 700,000$ hex cells;
- Solver: SLIM; Software: Caelus
Square Cylinder

- Comparison with experimental data of Lyn et al. (1995) and numerical results from Voke (1997).
<table>
<thead>
<tr>
<th>Set</th>
<th>$I_r$</th>
<th>St</th>
<th>$C_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lyn et al. (1995)</td>
<td>1.38</td>
<td>0.132</td>
<td>2.1</td>
</tr>
<tr>
<td>SLIM-VLES</td>
<td>1.33</td>
<td>0.124</td>
<td>2.36</td>
</tr>
<tr>
<td>Other CFD (max)</td>
<td>1.44</td>
<td>0.15</td>
<td>2.79</td>
</tr>
<tr>
<td>Other CFD (min)</td>
<td>1.2</td>
<td>0.13</td>
<td>2.03</td>
</tr>
</tbody>
</table>
Rudimentary Landing Gear (RLG)

- RLG is a benchmark test case from the Airframe Noise Comparisons (BANC) workshops.
- Exp. results reported in Venkatakrishnan et al. (2011)
- CFD results reported in Spalart and Mejia (2011).
Rudimentary Landing Gear cont’d

- \( \text{Re}_D = 1 \text{ million}; \) Grid: \( \sim 20 \text{ million hex cells}; \)
- Solver: SLIM; Software: Caelus
Rudimentary Landing Gear cont’d

- Exp. pressure data mapped onto a surface grid of the landing gear.
- High-pressure zone on the inboard side of front wheel was captured well by VLES.
- Low-pressure region on top of the rear wheel was not captured as well.
- Pressure coefficient on outboard side of front wheel is in excellent agreement with exp. results.
Rudimentary Landing Gear cont’d

<table>
<thead>
<tr>
<th>Set</th>
<th>$C_D$</th>
<th>$C_L$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Venkatakrishnan et al. (2011)</td>
<td>1.54</td>
<td>-0.62</td>
</tr>
<tr>
<td>SLIM-VLES</td>
<td>1.50</td>
<td>-0.18</td>
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<tr>
<td>Other CFD (max)</td>
<td>1.81</td>
<td>-0.18</td>
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<tr>
<td>Other CFD (min)</td>
<td>1.70</td>
<td>-0.28</td>
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</table>
Computational Cost

- Simulations for square cylinder conducted using URANS, DDES, and LES. Each simulation used 60 Intel Xeon E5-2620v3 cores.

<table>
<thead>
<tr>
<th>Model</th>
<th>CPU time (s) per 1s flow time</th>
</tr>
</thead>
<tbody>
<tr>
<td>URANS</td>
<td>1.69</td>
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<tr>
<td>DDES</td>
<td>1.73</td>
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<tr>
<td>VLES</td>
<td>1.57</td>
</tr>
<tr>
<td>LES</td>
<td>1.32</td>
</tr>
</tbody>
</table>

- VLES model is very efficient. Additional testing required to establish general cost of the algorithm.
Conclusions

• Introduced a delayed two equation VLES model.
  – Performance evaluated for Square Cylinder and RLG
    • Square Cylinder - efficiently captures the flow structures on relatively coarse meshes. Gave very good agreement with experimental data and comparable to previous LES and DES simulations.
    • RLG - favourable agreement with experimental surface pressure results for the majority of azimuthal positions.
      – Drag showed excellent agreement with experimental data.
      – Lift prediction, poor agreement with the experimental data, but comparable to other CFD predictions.
  
• Case studies showed the VLES model is an efficient approach for resolving large flow structures with predictive performance comparable to previous studies.