Progress in Tools for Turbulence Modelling & Simulation

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Overview

- The need for advanced (3D-capable) RANS models
  - 3D flows: academic & industrial
  - results with the more recent models in STAR CCM+

- Embedded Simulation, a way forwards for Hybrid RANS-LES
  - Embedded Simulation in STAR CCM+
  - Examples
  - Next Steps
2D vs 3D effects

- Over 90% of turbulence models are developed for 2D flows
  - 2D channel flow, 2D cylinder, 2D airfoil, 2D diffuser…

- There is good reason for this, … as this alone is a challenge!
  - turbulence anisotropy, flow separation, transition, curvature correction, wake recovery…
  - *each effect* can be controlled and tested, *one at a time*.

- but then one might wonder about highly complex 3D flows
  - fortunately 2-equation models do tend to do to quite well…

*complex geometry*
Direction of travel

- Long heritage of turbulence modelling work @University of Manchester
- Nuclear applications with EDF, Aerospace work with EU partners

Test cases combine a range of effects relevant to aerospace industry
- focus jointly on advanced RANS and novel Hybrid RANS-LES
- many cases, though the most detailed and reliable are 2D!

Best Reynolds Stress model is EBRSM (Manceau 2002)
- extensively tested this model and use insight to develop a family of other models

We also developed a cheaper version → Blended EVM
- based on BLV2K (Billard 2012)
Our approach:

In Manchester we test and develop these models in our own CFD codes, and then work with CD-adapco, to test them in STAR CCM+

We are looking for turbulence models which:

1. are capable of ‘responding correctly’ to complex 3D features
2. retain the best performance of existing 2D models (…this is a challenge)
3. have consistent and reliable near wall modelling
4. are computationally cheap and robust across a range of meshes

Academic cases:
- 3D NACA wingtip
- 3D Diffuser,
- 3D Swept wing,

Industrial cases:
- high-lift,
- LMP2 car
Case 1: NACA0012 Wing tip

Star-CCM+ 9.02 Coupled Solver
- 16.4 million cells with 25 prism layers
- Realizable K-e, SST, EB-RSM
- Ran until SD of drag coefficient < 1e-5

EBRSM does well, and convergence is good
Case 2: 3D diffuser

3D diffuser
- Incompressible fluid
- Re = 10,000 based on inlet channel height
- Fully developed flow at diffuser inlet

- Complex 3D flow
  - first separates in a corner
  - then on top surface

- Most RANS fail
  - predict separation on wrong wall

- EBRSM best by far
  - only model predicting correct separation
Case 3: Swept-wing

Swept wing
- $\text{Re} = 210,000$, $\text{AoA} = 9$
- 7.5 M cell mesh from Imperial College
- LES from Cranfield (Hahn 2009)

Experiment / Implicit LES

$k$-$\omega$ SST  
SSG  
EBRSM
Application Challenge 1

- Le Mans LMP2 car: TIGA racing
  - LMP2 car is being studied with RANS.

- Star-CCM+ 9.02 Coupled Solver
  - Low y+ polyhedral mesh, 20 prism layers
  - 128M cells (half-car model)
  - Realizable K-e, SST, B-EVM, EB-RSM
  - Ran until the SD of CD and CL < 1x10^{-5}

A student-led exercise;
exposure to ‘real-world CFD’

detail around rear wing

Good convergence with BEVM
Application Challenge 2

- High lift case: DLR F11 aircraft wing + fuselage + flaps + supports
  - 2nd AIAA high-lift workshop
  - detailed data available
  - highly complex geometry

- Star-CCM+ 9.02 Coupled Solver
  - Low y+ polyhedral mesh (up to 200 million cells) with 25 prism layers
  - Realizable K-e, SST, B-EVM, EB-RSM

- detailed analysis of results in progress

feedback so far: ... it runs and convergence is good!
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  - Examples
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Why Hybrid RANS-LES?

- Why resolve turbulent eddies?
  - and why on so many scales?

- Large scales generally dictate physics
  - Drag, mixing, heat transfer, chem. reactions …
  - Generated by/scale with obstacle

- But smaller scales are also often needed too…
  - especially for near wall flow, noise, combustion

- Problem is, it’s out of reach to simulate everything … e.g. Spalart 2000

<table>
<thead>
<tr>
<th>Method</th>
<th>Aim *)</th>
<th>Grid: Re-no. Dependence</th>
<th>Empiricism</th>
<th>Grid-Size</th>
<th>Number of time steps</th>
<th>Readiness</th>
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</thead>
<tbody>
<tr>
<td>2D URANS</td>
<td>Numerical</td>
<td>Weak</td>
<td>Strong</td>
<td>$10^5$</td>
<td>$10^{3.5}$</td>
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</tr>
<tr>
<td>3D-URANS</td>
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<td>Strong</td>
<td>$10^7$</td>
<td>$10^{3.5}$</td>
<td>1995</td>
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<tr>
<td>LES</td>
<td>Hybrid</td>
<td>Weak</td>
<td>Weak</td>
<td>$10^{11.5}$</td>
<td>$10^{6.7}$</td>
<td>2045</td>
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<tr>
<td>DNS</td>
<td>Numerical</td>
<td>Strong</td>
<td>None</td>
<td>$10^{16}$</td>
<td>$10^{7.7}$</td>
<td>2080</td>
</tr>
<tr>
<td>DES</td>
<td>Hybrid</td>
<td>Weak</td>
<td>Strong</td>
<td>$10^8$</td>
<td>$10^4$</td>
<td>2000</td>
</tr>
</tbody>
</table>
which Hybrid RANS-LES?

- **Good News:** *a bit of ‘Eddy Simulation’ can go a long way*
  - non-local effect

- **Bad News:** *many Hybrid Schemes to chose from!*
  - Non-zonal, e.g. Detached Eddy Simulation (DES)
  - Zonal, e.g. wall-modelled LES (WMLES)

One thing in common... a RANS model!

- recent Best practice guidelines state:
  - “different methods are suited to a particular application…”
  - we made an attempt to group flows into different categories
Embedded Simulation

- **Embedded Simulation** is a practical compromise
  - cheaper than full LES
  - allows you to choose where you want more detail

- **RANS**: use in regions where you can trust it
  - e.g. attached boundary layers
  - or where you don’t need high accuracy

- **LES**: use sparingly, where you really need it
  - (e.g. noise, fatigue, complex flow)
  - in this way you can afford to do it well!

- The problem is then one of **boundary conditions**
  - i.e. moving from RANS to LES we need fluctuations

Example from EDF
1. Use **RANS data** to provide mean quantities at boundary
   - mean velocity
   - turbulence magnitude and length scale

2. **Synthetic Eddies** are generated in a box at random locations
   - they move through the box with RANS velocity
   - fluctuating velocities are constructed from superimposition of the eddies

3. A **plane is extracted** from the box and used as the LES inlet
   - time and space coherence is preserved
   - fluctuations are recalculated at each time step
Instantaneous turbulence

- But how do you generate the fluctuating velocities?
  - Random noise doesn’t work!
    - white noise added to mean flow: quickly re-laminarises
  - Coherent structures are needed
    - information on turbulence structure is required! (space and time correlations)

Random Fluctuations

<table>
<thead>
<tr>
<th>Synthetic Turbulence</th>
<th>Full Large Eddy Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>(~0.2 CPU seconds)</td>
<td>(~1000 CPU hours)</td>
</tr>
</tbody>
</table>
An example in STAR CCM+

- A double pipe bend set up in STAR CCM+ v8,
  - Expt by Yuki 2011, Re=50,000

Complex 3D separation  |  RANS alone fails ...
|  ... so use embedded simulation

- We compared results from an LES with 8D upstream to 2D upstream
  - results show *time averaged* velocity
  - only minor differences

LES: with 8D upstream  |  Embedded LES: 2D upstream

this was with the existing SEM, and we have been working on an improvement
Improvement of SEM

Skin friction coefficient development

Shear stress development

- Periodic LES
- Improved SEM
- Original SEM
- Vortex Method

Vortex Method (common alternative)

Original SEM

Improved SEM
Improves with Reynolds

- Embedded LES of channel flow with improved SEM
  - Development length decreases with increasing Reynolds.

Increasing Reynolds

Development length

Re$_\tau$ = 180

Re$_\tau$ = 395

Re$_\tau$ = 590
Embedded DDES example

- Embedded Simulation can also be used with other Hybrid RANS-LES
  - e.g. Delayed Detached Eddy Simulation (DDES)

- Ahmed car body (Re=768,000)
  - Low $y+$ 16 million cell structured mesh
  - Time Step: 0.001s

**mean velocity profiles along rear slant**

- RANS: full domain
  - SST used here

- DDES: full domain
  - more resolved turbulence
  - prediction still poor

- Embedded DDES
  - with SEM at interface
  - best results obtained
Embedded LES: next steps

- Multiple embedded regions in a domain
  - need to handle different boundary conditions

- Semi-automated ELES
  - minimize user input
  - LES domains are suggested
  - grid is automatically refined from RANS
  - flow is initialised

Flowchart:
1. Automatically define LES regions
2. Automatically refine LES mesh
3. Initialise LES flowfield using synthetic turbulence
4. Apply synthetic turbulence at type 1 boundaries
Run ELES

Run steady RANS
grid convergence reached?
Yes
No
refine grid
optional user input
Conclusions

- There is a need to test RANS for 3D flows
  - EBRSM does very well
  - B-EVM will inherit some of these advantages
  - Hybrid RANS-LES always has RANS!

- Embedded Simulation is a promising and efficient tool
  - Synthetic turbulence is now even better
  - enables affordable use of eddy simulation

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