A Wall Model for Large Eddy Simulation with an Immersed Boundary Method

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Academy Colloquium Immersed Boundary Methods: Current Status and Future Research Directions 15-17 June 2009, Academy Building, Amsterdam, the Netherlands
Summary

• Motivation
• State of art
• The IBM
• The wall-layer model
• Results
• Concluding Remarks
Motivation

• Real life fluid-mechanics problems are often characterized by:
  
  - Geometric complexity;
  
  - Inertia dominated regimes (high Re, Ra, etc.)
• State of Art: IBM

- Immersed boundary methodology in conjunction with structured grids is nowadays a robust alternative to unstructured grid solvers

- Standard IBM has been implemented with Cartesian staggered-grid solvers (see Mittal & Iaccarino, 2005)

- Recently IBM has been coupled to structured curvilinear solvers (Milici et al., 2006; Ge and Sotiropoulos, 2007; Roman et al., 2009)
• State of Art: IBM for High Re numbers flows

Wall-modeling mainly used within the RANS framework (Craft et al., 2002, Kalitzin et al., 2005)

Few attempts directed toward wall-layer modeling in conjunction with LES for IBM.

Solution of a boundary layer equation over a nested very fine grid in the wall region (Tessicini et al., 2002; Cristallo & Verzicco, 2006)
THE IBM

We have implemented a direct forcing curvilinear coordinate immersed boundary technique.

This technique merges the advantages of the curvilinear coordinates with those of the IBM (Roman et al., 2009)
INTERFACE DETERMINATION

Ray-tracing method:

even intersections = fluid
odd intersections = solid

INTERFACE

IB points: fluid points closest to the solid nodes
Working nodes:

- **IP** projection on the wall of IB
- **PP** mirror of IP with respect to IB
- **V** closest fluid point to PP

**INTERPOLATION AT IB NODES** carried out using a Taylor expansion as described in Marchioli et al., C&F 2007)

Distance IB-IP usually taken equal to PP-IB

(we are checking another possibility, based on the choice of PP as a point closer the fluid node used for the Taylor expansion)

**PP nodes in case of edges**
Wall-layer modeling:

- Direct imposition of the wall stress usually accomplished when the boundaries of the computational domain coincide with a solid surface.

- This operation is not possible (or at least cumbersome) with IBM

Operations required with wall-layer modeling:

1. To set a velocity profile
2. To set the proper tangential stress at the wall (this ensures integral balance between the driving force and the total drag)
Our wall-layer model [Roman et al., 2009, submitted]:

1. velocity interpolation

1a) Tangential velocity at IB NODES obtained through the use of log-profile extrapolation

\[ U_{IB}^+ = \frac{1}{\kappa} \log (y_{IB}^+) + B \]
\[ U_{PP}^+ = \frac{1}{\kappa} \log (2y_{IB}^+) + B \]

1b) Wall normal component obtained as parabolic interpolation:

\[ u_n = ay^2 + by + c \]

with coefficients calculated in such a way to have zero normal velocity at the immersed surface

\[ u_{n,IB} = u_{n,PP} \frac{y_{2IB}}{y_{2PP}} \]
Our wall-layer model [Roman et al., 2009, submitted]:

2. setting the wall shear stress

We modify the viscosity at the IB node using a RANS-like value obtained through analytical considerations

\[ \frac{\tau}{\rho} = \nu_t \frac{du}{dy} \quad \Rightarrow \quad \nu_t \approx \frac{u^2_\tau}{du} \Rightarrow \nu_t = C_w \nu_{T,an} = C_w k \nu_\tau y_{IB} \]

\( k=0.41 \) is the von Karman constant

\( y_{IB} \) is the distance between the IB node and the solid immersed surface

\( u_\tau \) is the friction velocity obtained by iterative solution of

\[ \frac{U_{IB}}{u_\tau} = \frac{1}{k} \log \left( \frac{y_{IB} u_\tau}{\nu} \right) + B \]

\( C_w \) is a constant to be determined
Our wall-layer model:

3. determination of the constant

The constant is needed to take into account that:

1) The Reynolds shear stress at the IB node is different from the wall shear stress

2) The eddy viscosity has to be imposed at the cell face rather that at the cell center

\[ C_W = \frac{V_t}{V_{T,an}} = \frac{\tau_{IB}l}{\tau_w y_{IB}} \approx 1.35 \div 1.9 \]
Results: plane channel flow with IB

<table>
<thead>
<tr>
<th>Domain</th>
<th>x</th>
<th>y</th>
<th>z</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grid</td>
<td>64</td>
<td>20/40</td>
<td>32</td>
</tr>
<tr>
<td>$\Delta x^+\Delta y^+\Delta z^+$</td>
<td>128</td>
<td>&gt;30</td>
<td>51</td>
</tr>
</tbody>
</table>

- Standard Smagorinsky SGS model with constant equal to 0.065
- Wall normal discretization: 20 and 40 cells
Results: plane channel flow with IB

1) Absence of intensification of eddy viscosity at IB nodes

- Setting the velocity at IB node through log-extrapolation is not enough to predict a correct slope of the velocity profile
- The intercepts change with the distance of the IB node from the immersed surface
Results: plane channel flow with IB

2) Effect of the a-priori variation of the coefficient $C_w$

- The correction of the eddy viscosity at the IBM node gives a correct slope of the velocity profile.

- The intercept $B$ depends on the value of eddy viscosity.

The optimal value is obtained with

$$C_W = \frac{\tau_{IB}}{\tau_w y_{IB}}$$

<table>
<thead>
<tr>
<th>$C_W$</th>
<th>$\tau_{\tau}$</th>
</tr>
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<tbody>
<tr>
<td>1.3</td>
<td>1.08</td>
</tr>
<tr>
<td>1.47</td>
<td>1.03</td>
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<tr>
<td>1.57</td>
<td>0.991</td>
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<tr>
<td>1.8</td>
<td>0.929</td>
</tr>
</tbody>
</table>
Results: plane channel flow with IB

3) Coefficient $C_w$ calculated as in equation reported before
Results: plane channel flow with IB

4) Eddy viscosities with and without wall modification

• The effect is confined at the first grid point. The eddy viscosity supplied by the SGS model is not enough to reproduce a correct wall stress.
Results: plane channel flow with IB

4) Second order statistics

- Very good prediction of turbulent intensities but at the first grid point off the IB node.
Concluding remarks:

• A simple wall-layer model has been developed in conjunction with IBM for LES of complex geometry, high Re flows.

• The model is based on:
  
  - Log-extrapolation of the tangential velocity at the first point off the IB surface (IB node);
  
  - Setting of a RANS-like eddy viscosity at the IB node calculated by analytical argumentations.
  
  - The eddy viscosity depends on a coefficient $C_w$ whose optimal value is determined a-priori.

• Very good results for plane channel flow

• In progress:  
  - Validation in separated-flow cases
  - Extension of the model to the scalar fields