A Novel Rough Wall Boundary Condition for LES of high Reynolds Number Flows

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Outline

- Methodology
- Implementations
- Results
Methodology
Methodology—wall modeling

- For Large Eddy Simulation (LES) at high Reynolds number, wall shear stress should be modeled.

- The total wall shear stress is composed of the “smooth” part and the “rough” part:

\[ \tau_{total} = \tau_{smooth} + \tau_{rough} \]
Methodology—wall modeling

- Smooth wall modeling
  - Obtain flow velocity $U$ by interpolating from LES mesh.
  - Solve boundary layer equation in the wall-modeling mesh:
    \[
    \frac{d}{d\eta} \left( (\mu + \mu_{t,wm}) \frac{du_\parallel}{d\eta} \right) = 0,
    \]
    \[
    \mu_{t,wm} = \kappa \eta \sqrt{\rho \tau_w} \left[ 1 - \exp \left( -\frac{\eta^+}{A^+} \right) \right]^2 , \text{ with } A^+ = 17, \kappa = 0.41.
    \]
  - Obtain the shear stress $\tau_{smooth}$ from the velocity field in the wall-modeling mesh.
Methodology—wall modeling

- Rough wall modeling
  - Elevation of the elements expressed in $h$ on WM mesh.
  - Obtain flow pressure $P$ by interpolating from LES mesh.
  - Obtain the force induced by the pressure on each element.
Methodology—wall modeling

- Rough wall modeling

We have:

\[ \vec{n} = [-dh/dx, 1, -dh/dz]/dS \]

\[ d\vec{F} = -p \cdot \vec{n}dS \]

Finally,

\[ d\vec{F} = -p \cdot [dh/dx, -1, dh/dz] \]

\[ \tau_{\text{rough}} = -p/A \cdot [dh/dx, -1, dh/dz] \]

- Obtain the shear stress \( \tau_{\text{rough}} \) due to roughness.
Code Implementations

❖ OpenFOAM
❖ open-source
❖ C++ tool box

❖ OpenFOAM solver pisoFoam
❖ Incompressible solver
❖ PISO algorithm
Numerical tests

❖ Smooth wall modeling test
  ❖ High Reynolds number, channel flow.

❖ Rough wall modeling test
  ❖ High Reynolds number, channel flow. Roughness elements at bottom.
### Numerical tests

- **Case setup:** smooth wall modeling test.

<p>| | | | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td><strong>Reynolds number (Re)</strong></td>
<td>300,000</td>
<td><strong>domain size</strong></td>
<td>0.42 m × 0.04 m × 0.18 m</td>
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<tr>
<td><strong>average flow velocity</strong></td>
<td>17.15 m/s</td>
<td><strong>CFD cells</strong></td>
<td>240 × 31 × 100</td>
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<tr>
<td><strong>y+</strong></td>
<td>100</td>
<td><strong>computational cost</strong></td>
<td>3,200 CPU hours</td>
</tr>
<tr>
<td><strong>computational cost</strong></td>
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</tbody>
</table>

CPU hours
Numerical tests

- Smooth wall modeling test ($Re_{bulk} = 300,000$)

Mean velocity profile
Numerical tests

- Smooth wall modeling test ($Re_{bulk} = 300,000$)

- Reynolds stresses: $R_{xy}$
Numerical tests

❖ Rough wall modeling test
  ❖ Validation test: simulations of turbulent flow over rough surface.
  ❖ Half-sphere elements.
  ❖ High Reynolds number flow.
Numerical tests

- Case setup: rough wall modeling test.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds number (Re)</td>
<td>100,000</td>
</tr>
<tr>
<td>Domain size</td>
<td>0.22 m × 0.06 m × 0.11 m</td>
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<tr>
<td>Average flow velocity</td>
<td>27 m/s</td>
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<tr>
<td>CFD cells</td>
<td>80 × 30 × 40</td>
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<tr>
<td>y+</td>
<td>80</td>
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<tr>
<td>Computational cost</td>
<td>400 CPU hours</td>
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<tr>
<td>Roughness element diameter</td>
<td>2 mm</td>
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<tr>
<td>Distance between elements</td>
<td>11 mm</td>
</tr>
</tbody>
</table>
Numerical tests
Numerical tests

- Rough wall modeling test:

- Mean velocity profile
Numerical tests

- Rough wall modeling test:

- Reynolds stresses: $R_{xy}$
Numerical tests

- Rough wall modeling test:

- Power spectral density
Questions?