LARGE EDDY SIMULATION OF ANNULAR FLOWS, TUBE BUNDLES AND SLOT JETS WITH OPENFOAM

Joris Degroote
OUTLINE

- Introduction
- Slot jet
- Tube bundle
- Annular flow
- Domain decomposition
- Comparison CFD packages
- Conclusion
INTRODUCTION

Turbulence in flow
- Direct numerical simulation (DNS)
- Large eddy simulation (LES)
- Reynolds-averaged Navier-Stokes (RANS) simulation
- Hybrid methods such as (delayed) detached eddy simulation (D)DES

Source: https://www.evl.uic.edu/entry.php?id=2202
INTRODUCTION

Direct numerical simulation (DNS)
- 3D unsteady calculation of all scales
- Number operations is proportional to $Re^3$
- Extreme computational cost, only $Re \sim \mathcal{O}(10^3)$
INTRODUCTION

Large eddy simulation (LES)
- 3D unsteady calculation of scales above limit
- Model assuming isotropic turbulence below limit
- High computational cost, limited to $Re \sim \mathcal{O}(10^{4-5})$
INTRODUCTION

Reynolds-averaged Navier-Stokes (RANS) simulation
- 2D or 3D and steady or unsteady calculation
- Averaged flow equations
- Moderate computational cost, even for $Re > \mathcal{O}(10^6)$
INTRODUCTION

Large scale eddies

Energy flux

Dissipating eddies

$\ell$

$\eta = \ell/Re_L^{3/4}$

Resolved

Modeled

DNS

LES

DDES

DES

RANS
INTRODUCTION

DNS

LES

RANS

Resolved

Modeled

Energy spectrum $\log(E(k))$

Wave number $\log(k)$

Inertial range

Dissipation range
SLOT JET
SLOT JET

Cooling of gas turbine blades with impingement
→ Better cooling means higher gas temperatures and thus higher efficiency

Source: http://www.gepower.com
SLOT JET

Impingement cooling → Jet impinging on plate in turbine blade

Source: http://www.asme.org
SLOT JET

LES with dynamic Smagorinsky model in OpenFOAM [3]

– Central differencing with filtering of high-frequency ripples in space

– Second-order implicit in time

<table>
<thead>
<tr>
<th>Case</th>
<th>L/B</th>
<th>H/B</th>
<th>W/B</th>
<th>N_x</th>
<th>N_y</th>
<th>N_z</th>
<th>N_{tot} (M)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( H/B = 9.2, , \text{Re} = 20000 )</td>
<td>80</td>
<td>9.2</td>
<td>( \pi )</td>
<td>320</td>
<td>320</td>
<td>70</td>
<td>7.2</td>
</tr>
<tr>
<td>( H/B = 4, , \text{Re} = 18000 )</td>
<td>80</td>
<td>4</td>
<td>( \pi )</td>
<td>320</td>
<td>180</td>
<td>70</td>
<td>4.0</td>
</tr>
<tr>
<td>( H/B = 2, , \text{Re} = 10000 ) (fine)</td>
<td>80</td>
<td>2</td>
<td>( \pi )</td>
<td>540</td>
<td>200</td>
<td>140</td>
<td>15.1</td>
</tr>
</tbody>
</table>

→ Impossible without HPC (up to 1024 cores of gulpin)
SLOT JET

Time-averaged velocity magnitude, Q-criterion
SLOT JET

Scaling on nodes with 4x8=32 cores of gulpin

- Decomposition not optimal
- Not enough cells for 512 or 1024 cores

<table>
<thead>
<tr>
<th># nodes</th>
<th>cores</th>
<th>decomposition</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32</td>
<td>hierarchical zyx (8 4 1)</td>
</tr>
<tr>
<td>2</td>
<td>64</td>
<td>hierarchical zyx (8 4 2)</td>
</tr>
<tr>
<td>4</td>
<td>128</td>
<td>hierarchical zyx (16 4 2)</td>
</tr>
<tr>
<td>8</td>
<td>256</td>
<td>hierarchical zyx (16 8 2)</td>
</tr>
<tr>
<td>16</td>
<td>512</td>
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</tr>
<tr>
<td>32</td>
<td>1024</td>
<td>hierarchical zyx (32 8 4)</td>
</tr>
</tbody>
</table>

15.1M cells
TUBE BUNDLE

Fatigue and fretting wear in tube bundles
→ Tube rupture or leak
→ Cost and/or danger

Investigate contribution due to turbulence-induced vibration
TUBE BUNDLE

Vortices in gaps between cylinders in tube bundles
TUBE BUNDLE

LES with dynamic Smagorinsky model in OpenFOAM [2]

Infinite array $\rightarrow$ periodic boundary conditions
TUBE BUNDLE

LES with dynamic Smagorinsky model in OpenFOAM [2]

Geometry

- \( D = 0.2 \text{m} \)
- \( P/D = 1.02 - 1.4 \)
- \( D_h = 4 \left( P^2 - \frac{\pi}{4} D^2 \right) / (\pi D) \)
- \( \text{Re}_{Dh} = 10\,000 \)

\[ \text{~5M cells and 50k time steps} \]
TUBE BUNDLE

Velocity magnitude

Strouhal number for varying pitch/diameter

Simulation

Theory
ANNULAR FLOW
ANNULAR FLOW

LES with dynamic Smagorinsky model in OpenFOAM [1]

Annular geometry

Flow field from LES
→ Pressure on wall
→ Vibration
ANNULAR FLOW

LES simulation corresponding to experiments by Chen
- Average velocity = 10 m/s
- Water density = 1000 kg/m$^3$
- Water viscosity = $10^{-3}$ kg/ms
- Hydraulic diameter = 0.0127 m
- Length = 10 hydraulic diameters
- Reynolds number = 127000
# ANNULAR FLOW

## Discretization parameters

<table>
<thead>
<tr>
<th>Case</th>
<th>Nr</th>
<th>Δr+</th>
<th>Nθ</th>
<th>Nz</th>
<th>Cells</th>
<th>L/Dh</th>
<th>Integration time</th>
<th>Equivalent computing time for 0.1s on single core</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>80</td>
<td>3</td>
<td>200</td>
<td>500</td>
<td>8M</td>
<td>20</td>
<td>0.5 s</td>
<td>63 days</td>
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<tr>
<td>B</td>
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<td>1</td>
<td>300</td>
<td>1000</td>
<td>42M</td>
<td>20</td>
<td>0.3 s</td>
<td>600 days (2 years)</td>
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<tr>
<td>C</td>
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<td>2</td>
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<td>800</td>
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<td>10</td>
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<tr>
<td>D</td>
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<td>2</td>
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<td>1100</td>
<td>176M</td>
<td>10</td>
<td>0.25 s</td>
<td>10000 days (28 years)</td>
</tr>
</tbody>
</table>

→ Impossible without HPC (up to 2048 cores of muk)
ANNULAR FLOW

Instantaneous velocity

Averaged velocity profiles
ANNULAR FLOW

Power spectral density of force/meter
DOMAIN DECOMPOSITION

Cavity case with icoFoam in OpenFOAM/4.1-intel-2016a on BrENIAC

$U_x = 1 \text{ m/s}$

d = 0.1 m

Pressure, p (Pa)

Velocity, $U$ (m/s)
DOMAIN DECOMPOSITION

Scaling tests

– Strong scaling: problem size stays fixed
– Weak scaling: problem size assigned to each processing element stays fixed

→ Here strong scaling on 51M and 206M cells because goal is to solve given problem as fast as possible
DOMAIN DECOMPOSITION

Procedure

- Generate coarse mesh (blockMesh)
- Domain decomposition (decomposePar)
- Repeat
  - Select all cells (topoSet)
  - Refine selected cells (refineMesh)
- Solve on refined mesh (icoFoam)
Two Xeon E5-2680v4 processors per node of BrENIAC

→ 28 cores split in 4 groups of 7 cores per node
DOMAIN DECOMPOSITION

numberOfSubdomains 3584;
method multiLevel;
multiLevelCoeffs
{
  level0
  {
    numberOfSubdomains 128;
    method simple;
    simpleCoeffs
    {
      n (16 8 1);
      delta 0.000001;
    }
  }
  level1
  {
    numberOfSubdomains 28;
    method simple;
    simpleCoeffs
    {
      n (4 7 1);
      delta 0.000001;
    }
  }
}

numberOfSubdomains 7168;
method multiLevel;
multiLevelCoeffs
{
  level0
  {
    numberOfSubdomains 256;
    method simple;
    simpleCoeffs
    {
      n (16 16 1);
      delta 0.000001;
    }
  }
  level1
  {
    numberOfSubdomains 28;
    method simple;
    simpleCoeffs
    {
      n (4 7 1);
      delta 0.000001;
    }
  }
}
Strong scaling on 206M cells (448x448 refined 5 times), with 448=28x16 (reference 2 nodes, too large for 1 node)

<table>
<thead>
<tr>
<th># nodes</th>
<th># cores</th>
<th># x-dom</th>
<th># y-dom</th>
<th># x-cells</th>
<th># y-cells</th>
<th>Actual Speedup</th>
<th>Efficiency %</th>
<th># cells/core</th>
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</table>
Strong scaling on 206M cells (448x448 refined 5 times), with 448=28x16
Strong scaling on 51M cells (448x448 refined 4 times), with 448=28x16 and insufficient #cells/core

<table>
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</tr>
</tbody>
</table>
Strong scaling on 51M cells (448x448 refined 4 times), with 448=28x16 and insufficient #cells/core
COMPARISON CFD PACKAGES
COMPARISON CFD PACKAGES

OpenFOAM compared with Fluent (personal opinion/feeling, not facts!)
+ Access to source code (but not always needed…)
+ No licenses, so good for HPC (but cost small compared to salary…)
+ Facilitates local and international collaboration
+ Accepted in scientific community
+ Fun!
- Less systematic validation (but always good to test it yourself…)
- Less documentation (but you can look in code…)
- Fewer features (but catching up and possibility to add your own…)
- Different branches (.com/.org/-extend) and incompatible versions
- Longer learning curve (developing requires C++ skills, no GUI…)}
CONCLUSIONS

LES simulation in OpenFOAM
- Results in agreement with other data
- Think about domain decomposition

CFD course
- Exercises in OpenFOAM next year
- Project can already be done in OpenFOAM this year
REFERENCES


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