Future trends of applications of CFD to industrial design

Fully-resolved LES (Large Eddy Simulation)

- Resolve such eddies that are responsible for production of turbulence in TBL
  - $\lambda_x^+=300$, $\lambda_y^+=30$, $\lambda_z^+=150$

- Only model eddies in dissipation scale, thus most reliable

- Provide as accurate solution as DNS as long as flow of interest is properly resolved, with approximately a 1/100 cost of DNS
How small are the active eddies in turbulent boundary layer?

Flat-plate turbulent boundary layer at $l = 1m$

<table>
<thead>
<tr>
<th>$Re_l$</th>
<th>$\delta$</th>
<th>$d$</th>
<th>$d/\delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1 \times 10^5$</td>
<td>37 mm</td>
<td>5.1 mm</td>
<td>0.140</td>
</tr>
<tr>
<td>$1 \times 10^6$</td>
<td>25 mm</td>
<td>600 μm</td>
<td>0.026</td>
</tr>
<tr>
<td>$1 \times 10^7$</td>
<td>15 mm</td>
<td>77 μm</td>
<td>0.005</td>
</tr>
</tbody>
</table>

$\delta$: Thickness of boundary layer

d: Scale of active eddies in TBL

Computer resources required for fully-resolved LES

Automobile aerodynamics

- Free-stream velocity: 30 m/s
- Length scale: $L=2$ m
- Reynolds number: $Re_x=4$ million
- Friction velocity: 1.2 m/s
- Viscous scale: 12.5 μm
- Diameter of active smallest vortices: 0.4 mm
- Minimum grid size: 0.1 mm (100 μm)
- Surface grids per 1 m²: 100 million
- Number of grids in total: 40 billion
- Computational resources: 40,000-200,000 cores
### Engineering Applications of Fully-resolved LES

**Applications of LES expected in 2015**

<table>
<thead>
<tr>
<th>products</th>
<th>specifications</th>
<th>$Re$</th>
<th># of TBLs</th>
<th>Total # of grids</th>
</tr>
</thead>
<tbody>
<tr>
<td>automobile</td>
<td>L=2m, U=28 m/s (100 km/h)</td>
<td>$4.0 \times 10^6$</td>
<td>20</td>
<td>40 billion</td>
</tr>
<tr>
<td>model ship</td>
<td>L= 5m (1/50 scale model), U=1.0 m/s</td>
<td>$4.6 \times 10^6$</td>
<td>1.2</td>
<td>20 billion</td>
</tr>
<tr>
<td>model pump</td>
<td>D$_p$=300 mm, 1500 rpm, L=0.15 m, U=24 m/s</td>
<td>$3.6 \times 10^6$</td>
<td>12</td>
<td>4000 billion</td>
</tr>
<tr>
<td>wind turbine</td>
<td>D$_p$=40 m, L=0.4 m, U=64 m/s</td>
<td>$2.5 \times 10^6$</td>
<td>3</td>
<td>40 billion</td>
</tr>
<tr>
<td>axial-flow fan</td>
<td>D$_p$=600 mm, 1800 rpm, L=0.2 m, U=56 m/s</td>
<td>$7.5 \times 10^5$</td>
<td>12</td>
<td>9 billion</td>
</tr>
<tr>
<td>propeller fan</td>
<td>D$_p$=500 mm, 600 rpm, L=0.2 m, U=16 m/s</td>
<td>$2.0 \times 10^5$</td>
<td>3</td>
<td>100 million</td>
</tr>
<tr>
<td>small cooling fan</td>
<td>D$_p$=80 mm, 3400 rpm, L=0.02 m, U=14 m/s</td>
<td>$1.9 \times 10^4$</td>
<td>7</td>
<td>1 million</td>
</tr>
</tbody>
</table>

### Development and Validations of Flow and Acoustical Solvers
Benchmark tests for airfoil flow

NACA0012 at angle of attack, 9 degrees, Reynolds number of 200,000

Surface pressure distribution

Drag coefficient
Code tunings-1/3

- Data reordering for minimizing occurrence of L1, and L2 cache miss

Code tunings-2/3

- Sustained performance of the hot kernel

<table>
<thead>
<tr>
<th></th>
<th>Hexahedral element</th>
<th>Tetrahedral element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original (1core)</td>
<td>5.9%</td>
<td>2.4%</td>
</tr>
<tr>
<td>Full unroll (1core)</td>
<td>10.8%</td>
<td>4.2%</td>
</tr>
<tr>
<td>Full unroll (8core)</td>
<td>5.4%</td>
<td>3.0%</td>
</tr>
<tr>
<td>Full unroll + Reordering (1core)</td>
<td>10.2%</td>
<td>10.2%</td>
</tr>
<tr>
<td>Full unroll + Reordering (8core)</td>
<td>8.1%</td>
<td>7.7%</td>
</tr>
</tbody>
</table>
Code tunings-3/3

- Overall Performance and speed-ups

![Graph showing performance and speed-ups](image)

Ratio of sustained to peak performance

Parallel computing performance

Sensitivity Studies on Grid Resolutions

- Comparisons of Instantaneous Streamwise Velocity

![Comparisons of grid resolutions](image)

22 million grid

55 million grid
Validation Studies-1/2

Comparisons of Time-averaged Wake Profile

Instantaneous flow Near wake at x=1.5D

Validation Studies-2/2

Comparisons of PSD of Streamwise Velocity

Fully developed wake (x=3D)
Experimental Setup

- Measured: drag & lift, surface pressure, velocity profile, sound

Instantaneous Flow
Validation Studies

Instantaneous flow structures

Time-average pressure distribution near tip (z/c = -0.1)

Validation Studies (continued)

- PSD of static pressure fluctuations at tip

- x/C = 0.1

- x/C = 0.6
**Predicted far-field sound**

- Acoustical field computed by Lighthill equation:
  \[ \frac{\partial^2 \rho}{\partial t^2} - a^2 \frac{\partial^2 \rho}{\partial x_i^2} = \frac{\partial^2}{\partial x_j \partial x_j} T_{ij} \]

![Graph showing comparison of sound pressure level](image1)

Comparison of sound pressure level

Sound field at St=5.7 (760 Hz)

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**Benchmark test for HVAC sound**

- Sound field at 760 Hz

![ benchmark test image ]

Comparison of sound pressure level
Application Examples

Drag Reduction of Passenger Car by Controlling Vortical Structure behind Car

(Reynolds number=1.0 × 10^6, # of grids = 2 billion)

Collaborator: Toyota Motor Corporation
How automatic grid refiner works?

Overall flow structures

Vortices in viscous sub-layer

Comparison with Wind-tunnel Data

Accuracy Validations

Static Pressure Distribution around Car Body

Reynolds Number Dependency of Drag

EXP.
LES
Predicted drag coefficients

<table>
<thead>
<tr>
<th></th>
<th>Time average</th>
<th>RMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original shape</td>
<td>0.181</td>
<td>0.0041</td>
</tr>
<tr>
<td>Controlled shape</td>
<td>0.168 (-7%)</td>
<td>0.0031</td>
</tr>
</tbody>
</table>

Drag prediction for model ship

(Reynolds number=5 million, # of grids = 8 billion)

Collaborator: SREC
Grid-convergence Studies

100 million grids

1 billion grids

8 billion grids

Vortex Behaviors

16 million grid

Refined 8 billion grid
Comparisons of Velocity Contours on Propeller Plane

- Experiment
- 16 million-grid LES
- 100 million-grid LES
- 1 billion-grid LES

Reference:
T. Nishikawa et al. “Application of Fully-resolved Large Eddy Simulation to KVLCC2 – Bare Hull Double Model Ship Reynolds Number –”, 日本造船海洋工学会論文集, Vol. 16 (2013)