DEVELOPMENT OF A BENCHMARK PROBLEM FOR MODELING TRANSITIONAL UNSTEADY FLOWS

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Outline

• Measurement overview
• Near-wall measurements
• Motiving a benchmark problem
• Benchmark problem details
• Selected experimental and computational results
• Status and directions
Measurements for incompressible flow modeling applications

In order of difficulty (and relative uncertainty):

• Mean velocity
• Reynolds normal stresses
• Reynolds shear stresses
• Mean velocity gradients
• Instantaneous rate-of-strain/vorticity
• Any term above near a wall
• Instantaneous flowfield pressure
• Derived modeling terms (e.g., pressure diffusion, dissipation rate)

Which, if any, modeling terms hold the most value to the community if measured experimentally?
Measurements for incompressible flow modeling applications

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Which, if any, modeling terms hold the most value to the community if measured experimentally?
Specialty: Near-wall velocimetry

Profile velocimetry using beam through airfoil pressure tap (scanning DGV)

Fluorescent particle PIV

Position-resolving LDV

Symbols:
LDV
Line: beam

Fluorescent particle PIV
Motivation: Unsteady Wind Turbine Aerodynamics Modeling

- Blade-turbulence interaction modeling is the primary need for successful high fidelity wind farm modeling
- Past work ("PSU Cyber Wind Facility," Fig 1) exposed deficiencies
- Industry standard design tools even lower fidelity
- Combined computational/experimental approach to develop experiment that will optimally advance modeling
- Windplant modeling capabilities are a critical need:
  - Windplant layout for optimal performance, including addressing extreme cycling loads that may limit lifetime
  - Accurate acoustic impact prediction
  - Improved siting


Fig 1 CWF

(Vijayakumar 2015)
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Full-scale problem is too complicated and expensive for fundamental model development and VVUQ

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Fig 1 CWF
(Vijayakumar 2015)
Large-scale, intense turbulence interacting with downstream wall layers.

IR transition meas. @ $Re_c=1.5M$
Joseph et al. (2016)

Wind turbine airfoils have appreciable laminar flow.

Langtry et al. (2006)
Fundamental/Modeling Assessment

Model problem should capture:

1. *Low reduced frequency unsteadiness in approach flow*
2. **Transitional flow**
3. **Airfoil loading unsteadiness**

Wind turbine airfoils have appreciable laminar flow.

- IR transition meas. @ $Re_c=1.5M$
- Joseph et al. (2016)
- Langtry et al. (2006)
Concept and parameter space considerations

Approach: cambered airfoil in wake of cylinder, $D \sim c$

Considerations:
- Minimize potential flow interactions
- $Re_c$, reduced frequency, $D/c$

Practical aspects:
- Wind tunnel scale
- Instrumentation resolution
- Uncertainties

Wind Turbine operating in ABL:

<table>
<thead>
<tr>
<th>Time scale</th>
<th>Length scale</th>
<th>Blade Reynolds number</th>
<th>Reduced frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim O(10^{-3} - 10^1 s)$</td>
<td>$\sim O(10^{-6} - 10^2 m)$</td>
<td>$\sim O(10^7)$</td>
<td>$&lt; 10^{-2}$</td>
</tr>
</tbody>
</table>

Realistic in this benchmark problem:

<table>
<thead>
<tr>
<th>Time scale</th>
<th>Length scale</th>
<th>Blade Reynolds number</th>
<th>Reduced frequency</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\sim O(10^{-4} - 1 s)$</td>
<td>$\sim O(10^{-6} - 0.1 m)$</td>
<td>$\sim O(10^5)$</td>
<td>$&gt; 1$</td>
</tr>
</tbody>
</table>
## Benchmark Problem Parameters

<table>
<thead>
<tr>
<th>Design condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
</tr>
<tr>
<td>c</td>
</tr>
<tr>
<td>profile</td>
</tr>
<tr>
<td>L</td>
</tr>
<tr>
<td>h</td>
</tr>
<tr>
<td>$U_\infty$</td>
</tr>
<tr>
<td>AR</td>
</tr>
</tbody>
</table>

- $Re_D = 63,500$
- $Re_c = 170,000$
- $k = 1.53$
- Lateral vortex spacing: 58 mm
- Shedding wavelength: 200 mm
- Pressure influence: 6D

### NACA 63215b
- $t/c = 15\%$

From steady CFD model:
- $x/c_{\text{trans}} \sim 52\%$
- $x/c_{\text{sep}} \sim 70\%$
Benchmark Problem Parameters

<table>
<thead>
<tr>
<th>Diameter D</th>
<th>Chord c</th>
</tr>
</thead>
<tbody>
<tr>
<td>D</td>
<td>c</td>
</tr>
<tr>
<td>1.5 inches, set to achieve desired Re</td>
<td>4 inches, set to achieve desired k</td>
</tr>
<tr>
<td>NACA 63215B</td>
<td>NACA 63215b</td>
</tr>
<tr>
<td>L/D=10.67</td>
<td>t/c = 15%</td>
</tr>
<tr>
<td>AoA on centerline ±50deg</td>
<td>( x/c_{trans} \sim 52% )</td>
</tr>
<tr>
<td>26 m/s, upper limit of tunnel</td>
<td>( x/c_{sep} \sim 70% )</td>
</tr>
<tr>
<td>18, set by tunnel, ( \Lambda / D = 3 )</td>
<td>From steady CFD model:</td>
</tr>
</tbody>
</table>

**Next step is Stability Wind Tunnel experiments to** \( Re_c \sim 3M \)

**Lateral vortex spacing:** 58 mm

**Shedding wavelength:** 200 mm

**Pressure influence:** 6D
Computational overview

<table>
<thead>
<tr>
<th>Regions</th>
<th>Descriptions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Euler Region (ER)</td>
<td>Laminar flow, never entered by turbulence</td>
</tr>
<tr>
<td>Laminar (LR)/RANS Region (RR)</td>
<td>Primarily the boundary layer</td>
</tr>
<tr>
<td>Focus Region (FR)</td>
<td>Part of the turbulence is resolved</td>
</tr>
<tr>
<td>Departure Region (DR)</td>
<td>Smoothly blend into ER</td>
</tr>
</tbody>
</table>

Delayed Detached-Eddy Simulation (DDES) (Sparlart, 2006):
\[
\bar{d} \equiv l_{RANS} - f_d \max(0, l_{RANS} - c_{DES} \Delta)
\]

Boundary layer is preserved for RANS model \(k - \omega\) SST integrated with two-equation transition formulation (Langtry et al. 2006)
- Transition momentum thickness Reynolds number \(\bar{Re}_\theta\)
- Turbulence intermittency \(\gamma\)

- OpenFOAM implementation
- Grid includes wind tunnel side walls, but truncated out of plane
- Inflow conditions from experiment
Experimental overview

- Time-resolved, 2D particle image velocimetry
- Three focal regions for optimized spatial resolution
- Extra effort to obtain near surface measurements

More details in Cadel (2016)
Experimental overview

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Multiple planes of high resolution boundary layer development

More details in Cadel (2016)
Experimental overview

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Mean velocity: $\pm 0.006 U_\infty / \pm 0.1 u_\tau$

Reynolds stresses: $\pm 0.001 U_\infty^2 / \pm 0.5 u_\tau^2$

Local flow angle: $\pm 1^\circ$

Distance from wall: $\sim 50 \mu m / \sim 4 - 5^+$

More details in Cadel (2016)
**Objective:** assess basic unsteady circular cylinder wake flow ($Re_D = 6.4 \times 10^4$) and prediction performance

- Strouhal number
  
<table>
<thead>
<tr>
<th>Experiment</th>
<th>Simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$St = fD/U_0$</td>
<td>0.19</td>
</tr>
</tbody>
</table>

- Simulation shows slightly longer recirculation zone

- Local flow angle range is higher than full-scale blade in real conditions.

- Histogram of AOA at airfoil LE
  - Both peak at ±25° with extreme value up to ±50°
Reynolds stresses near cylinder

Qualitatively consistent, still needs detailed quantitative comparisons.
Cylinder/airfoil unsteady flow
Airfoil mean flow

Computation

\[ \frac{|V|}{U_0} \quad \text{No Cylinder} \]

\[ \frac{|V|}{U_0} \quad \text{Cylinder} \]

Experiment

\[ \frac{|V|}{U_0} \quad \text{No Cylinder} \]

\[ \frac{|V|}{U_0} \quad \text{Cylinder} \]
Value of detailed experimental data during implementation

- Basic checks during model development, such as Strouhal number consistency
- Correlation of major observations
  - Rapid distortion/pressure redistribution of wake turbulence around airfoil
  - Airfoil does not separate in wake, even instantaneously
- Physics-based insights
Value of detailed experimental data during implementation

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- Physics-based insights
Status and directions

- Benchmark case has simple geometry which creates complex unsteady flow with transitional features.
- Detailed experimental measurements for one configuration
  - Solid model, extensive database to be made available.
  - As Heng Xiao noted yesterday, more parametric variation would be useful data-driven methods
- Incorporated Langtry-Menter transition model into OpenFOAM DDES framework
  - Method qualitatively captures many key characteristics of problem.
  - Additional validation and comparison of modeling terms needed.
  - How do gray regions perform for this case/model? What do the experimental results tell us about discrepancies there?
- Even with advanced diagnostics, very difficult to measure many desired terms
  - e.g., We can measure intermittency, but is this the same as transported in the model? What does the intermittency mean in unsteady flow?


Extra slides
Example: advanced diagnostics

Approach: RANS simulations of wind tunnel and NACA 4412 airfoil model
Example: a priori parameter study

Cylinder/airfoil potential flow interaction

PotentialFoam result of pressure recovery along the centerline from cylinder rear stagnation point to airfoil leading edge

Airfoil reduced frequency/Re_{chord}

Cylinder diameter D=1.5 inches, NACA64215b airfoil chord c=4 inches, L=16 inches (10.67D), reduced frequency k=1.53. ReD=63,500, Rec=170,000
Unsteady airfoil results

Cylinder Strouhal frequency seen in boundary layer planes and in lift and drag.

Computational lift and drag:
Final experimental design

10.67D spacing from cylinder center to airfoil LE

- 1.5" chord cylinder
- 4" chord NACA 63215B

Chrome plated to mitigate laser flare

Uniform cross section entrance

sidewall

Flow exit
Unsteady inflow PDFs

- Large spread seen in the probability density function of instantaneous velocities

Variation suggests time-dependent nature of profile