Blade Boundary Layer Resolved Computations of the NREL 5MW Rotor in a Realistic Atmospheric Boundary Layer using Hybrid URANS-LES

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**Cyber Wind Facility**
- highly resolved 4-D cyber data
- coupled atmospheric turbulence-blade loadings-shaft torque data
- coupled wave structure – platform motion – turbine loadings data
- experiment design, test-bed, turbine design, controls concepts and testing

**Wake Turbulence**
- Blade-Wake-Atmosphere

**Atmospheric Boundary Layer Turbulent Winds**

**Platform-Wave Hydrodynamics and 6-DOF Motions**

**Wake-Turbine Interactions**
- (wind plant)

**Mesoscale, Weather**

**Elastic Deformation**
- Blade and Tower

**Sensor, Controllers, Diagnostics**
Motivation and objective

Wind turbines fail sooner than expected

- **Gearboxes, blades, shafts, ...**  
- Atmospheric Boundary Layer (ABL)
- **Size of most energetic turbulence structures ~ wind turbine disk**

Study the response of blade boundary layer to forcing by Atmospheric Turbulence
The Current Cyber Wind Facility

NREL 5 MW Wind Turbine Model based on RePower 5 MW wind turbine with LM Glasfiber 61.5 m blade

complex multi-scale ABL-CFD OpenFOAM Domain

CAD blade design and refined surface grid for NREL 5MW wind turbine

ABL turbulence inflow at the “microscale” driven at the “mesoscale” by weather events

hybrid URANS/LES over turbine blades (openFOAM)

Daytime ABL precursor large-eddy simulation

AMI driven at the “mesoscale” by weather events
Study the response of blade boundary layer to forcing by Atmospheric Turbulence

1. Quantify length and time scales in the atmosphere relevant to non-steady wind turbine loads.
   - PHYSICS OF ABL

2. Propagation of ABL turbulence into wind turbine OpenFOAM ABL-CFD domain
   - NUMERICAL METHODS

3. Interface ABL with blade boundary layer dynamics
   - NUMERICAL METHODS

4. Results
Turbulence structure in the Atmospheric Surface Layer

Moderately Convective Boundary Layer
Atmospheric Boundary Layer - LES

ABL – Code
- Pseudo-spectral low dissipation
- Domain – 5km x 5km x 2km
- Grid – 512 x 512 x 256
- 14 m/s - Mean velocity @ Hub Height – Region III

Mesoscale – weather
- \( \sim 10 – 100 \, km \)

ABL - Eddies \( \sim 100 \, m \)

Blade boundary layer \( \sim 1 \, mm \)

Blade viscous sublayer \( \sim 50 \, \mu m \)
Study the response of blade boundary layer to forcing by Atmospheric Turbulence.

1. Quantify length and time scales in the atmosphere relevant to non-steady wind turbine loads.

2. Propagation of ABL turbulence into wind turbine OpenFOAM ABL-CFD domain.

3. Interface ABL with blade boundary layer dynamics.

4. Results.
Design of Wind Turbine Geometry and Grid

Diameter – 126m, Rated power - 5MW @ 11.4 m/s and 12.1 rpm

Blade $Re \sim 10^7$

- Designed to capture blade boundary layer separation dynamics
- 58 Million cells
- 9 Million cells ~ 50 million near blade
- 9 Million cells
- ~ 5.5 million near blade
- 250m
- Complex rotor fitted grid – rotating mesh
- OpenFOAM
Designed to capture blade boundary layer separation dynamics

Blade $Re \sim 10^7$

9 Million cells 58 Million cells
~ 5.5 million near blade ~ 50 million near blade

Million cells
Coupling LES of ABL to CFD around wind turbine

2010-2011
Collaboration with Dr. Churchfield and Dr. Moriarty

\begin{align*}
\text{Momentum:} & \\
\frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_j} & = - \frac{1}{\rho_0} \frac{\partial P}{\partial x_i} - \frac{1}{\rho_0} \frac{\partial P^*}{\partial x_i} - 2\Omega_i U_j \epsilon_{ijk} \\
& - g \frac{(\theta - \langle \theta \rangle)}{\theta_0} - \frac{\partial \tau_{ij}}{\partial x_j}
\end{align*}

\text{Coriolis}

\text{Buoyancy - Boussinesq}

\text{Blade } Re \sim 10^7

\text{OpenFOAM (ABL)}

Extend spectral LES of ABL algorithm to finite volume method

Designed to capture blade boundary layer separation dynamics

Complex rotor fitted grid – rotating mesh

Vijayakumar et. al. AIAA 2012-0817
Study the response of blade boundary layer to forcing by Atmospheric Turbulence

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Mesoscale – weather \(\sim 10 \sim 100 \text{km}\)

**Rotor - ABL Turbulence** \(\sim 100 \text{m}\)

- **Blade chord** \(\sim 1 \text{m}\)
- **Blade boundary layer** \(\sim 1 \text{mm}\)
- **Blade viscous sublayer** \(\sim 50 \mu\text{m}\)

1eq – LES of ABL

\(\sim 100 \text{m} \) (eddy)

\(\sim 100 \text{m} \) (rotor)

~ 3m (chord)
New method to blend LES of ABL with Hybrid URANS/LES near blade
New method to blend LES of ABL with Hybrid URANS/LES near blade

Momentum: \[ \frac{\partial U_i}{\partial t} + \frac{\partial U_i U_j}{\partial x_j} = -\frac{1}{\rho_0} \left( \frac{\partial P}{\partial x_i} \right) - \frac{1}{\rho_0} \frac{\partial P^*}{\partial x_i} - 2\Omega_i U_j \varepsilon_{ijk} - g \left( \frac{\Theta - \langle \Theta \rangle}{\Theta_0} \right) - \frac{\partial \tau_{ij}}{\partial x_j} \]

\[ \tau_{ij} = 2 \nu S_{ij} \]
\[ \nu = c \ l^* u^* \]

\[ l^* \sim \frac{\sqrt{k^{tot}}}{\omega} \]
\[ u^* \sim \sqrt{k^{tot}} \]

\[ l^* \sim \Delta_f \]
\[ u^* \sim \sqrt{k^{sfs}} \]

Distance from the blade

OpenFOAM turbulence model class

Advection  Diffusion  Production  Dissipation term
Study the response of blade boundary layer to forcing by Atmospheric Turbulence

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OpenFOAM tools for data analysis

Sampling on cut planes rotating with the inner domain

Blade surface data without interpolation

Interpolation to a coarse mesh for volumetric analysis
The largest fluctuations on the wind turbine loads are due to ABL structures ~ 0(rotor disk).

Disk 10m in front of blade
Atmospheric turbulence causes fluctuations in the integrated loads primarily through changes in the angle of attack.
Particular problems with OpenFOAM implementation

- ✔ Scaling to large number of cores with AMI – Adam Lively

- ☺ File I/O at large # cores – Too many files – Working on a HDF5 based solution with Dr. Anirban Jana and Si Liu @ XSEDE

- ❌ Interpolation near the blade surface – grid sizes - ~ 1 μm
The turbulence structures \( \sim O(\text{rotor disk}) \) cause the largest fluctuations in the integrated loads primarily through changes in the angle of attack.
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