Lecture # 013: Wind Turbine Aeromechanics

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Wind Energy Production and Wind Turbine Installations in USA

- Targets of 20% of US electricity from wind energy by 2030 and 35% by 2050, have been set up by the Department of Energy (DOE) of United States.
- Iowa is the 3rd in the nation in installed wind energy capacity and it has the highest density of wind power generation capacity with 29.9 kW/km²
- According to DoE’s wind Technologies Mark Report, Iowa has reached the milestone of 27.4% of the state’s electricity in 2014, while the national average rate is about 4.9% in 2014.

Wind farm sites in USA

27.4% electricity of Iowa is from wind

Top Wind Energy Production States:
- Texas: 12,354 MW (8.3%)
- California: 5,829 MW (6.6%)
- Iowa: 5,177 MW (27.4%)
- Illinois: 3,568 MW (4.7%)
- Oregon: 3,153 MW (12.4%)
- Oklahoma: 3,134 MW (14.8%)
- Minnesota: 2,987 MW (15.7%)

(2014 DoE Wind Technologies Market Report)
Wind Resources Map in USA

Table 4-2. Land Area Relative to 2008 Technology

<table>
<thead>
<tr>
<th>Hub Height</th>
<th>2008 Turbine Technology (km²)</th>
<th>Current (2013) Turbine Technology (km²)</th>
<th>% Change from 2008 @ 80 m</th>
<th>Near-Future Turbine Technology (km²)</th>
<th>% Change from Current (2013) @ 80 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>80m</td>
<td>1,643,000</td>
<td>2,765,000</td>
<td>68%</td>
<td>3,518,000</td>
<td>27%</td>
</tr>
<tr>
<td>110m</td>
<td>3,420,000</td>
<td>5,235,000</td>
<td>108%</td>
<td>4,262,000</td>
<td>54%</td>
</tr>
<tr>
<td>140m</td>
<td>3,928,000</td>
<td>5,778,000</td>
<td>139%</td>
<td>4,629,000</td>
<td>67%</td>
</tr>
</tbody>
</table>

Sources: NREL Database, MAKE Consulting

Current wind farms with 80m turbine hub height

Wind resources with 140m hub height
Technical Challenges Related to Wind Energy

- Four focus areas identified in 2008
  DoE Wind Energy Workshop Report:
  - Turbine Dynamics
  - Micro-siting and Array Effects
  - Mesoscale Processes
  - Climate Effects

**Aerodynamics and Atmospheric Boundary Layer (AABL) Wind Tunnel @ Iowa State University**

- **AABL (Aero/ABL) Gust Tunnel**
  - Aero Test Section: 8 ft by 6 ft [110 mph]
  - ABL Test Section: 8 ft by 7.25 ft [85 mph]

### Table

<table>
<thead>
<tr>
<th>Parameter</th>
<th>R (mm)</th>
<th>H (mm)</th>
<th>(d_{pole}) (mm)</th>
<th>(d_{nacelle}) (mm)</th>
<th>(\alpha) (deg.)</th>
<th>(a) (mm)</th>
<th>(a1) (mm)</th>
<th>(A2) (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Dimension</strong></td>
<td>140</td>
<td>225</td>
<td>18</td>
<td>18</td>
<td>5°</td>
<td>78</td>
<td>15</td>
<td>50</td>
</tr>
</tbody>
</table>

**1:320 scaled model to simulate a 2MW wind turbine with 90m rotor blades**

ERS-100 turbine blade design by TPI
Experimental Setup to Study Wind Turbine Aeromechanics

Test flow conditions:
- $U_{hub} = 6 \text{ m/s}$,
- $Re_c = 10,000$
- Tip speed ratio: \( \lambda = 0 \sim 6.5 \).

Measured parameters:
- Characteristics of turbine wake flows
- Power output of wind turbine models
- Dynamic wind loads acting on wind turbines

Power law fit with exponent $\alpha \approx 0.12$
Near Wake Measurement Results at Tip-Speed Ratio, $\lambda = 3.0$

**Instantaneous PIV results**

**Time-averaged velocity distribution**

**Phase-Locked PIV measurement results**

**Turbulence intensity r.m.s. $u/U_0$**

**Turbulence intensity r.m.s. $v/U_0$**

**Normalized Turbulence kinetic energy**

$$\frac{(u'u' + v'v')}{2U_0^2}$$
Phase-Locked PIV Measurement Results at Tip-Speed Ratio, $\lambda=3.0$

Wake vortex structures at different phase angles

Reconstructed 3-D wake vortex structures

Decay of tip vortex strength

$y = a^x; a=0.323, b=-0.197$

Measurement data

Effects of Tip-speed Ratio on the Wake Vortex Structures

**a). \( \lambda = 3.0 \)**

**b). \( \lambda = 3.5 \)**

**c). \( \lambda = 4.0 \)**

**d). \( \lambda = 4.5 \)**
Wake Profiles at X/D=0.5 Downstream of the Wind Turbine Model

Wind Energy $\propto \frac{1}{2} A \rho V^3$

Aerodynamic Force $\propto \frac{1}{2} A \rho V^2$

(Hu et al., Experiments in Fluids, Vol. 52, No. 5, pp1277-1294, 2012)
Wind Turbine Failures

Caithness Wind Farm, UK
http://www.caithnesswindfarms.co.uk/
(202 WT in operation + 198 in construction)

Total number of accidents: 1405

- Human fatalities & injuries: 136+145
- Blade failure: 265
- Fire: 202
- Structural failure: 138
- Ice throw: 34
- Transport: 113
- Environmental (bird death): 128
- Others: 282
Dynamic Wind Loads Acting on Wind Turbines

(a). Measured thrust coefficient data

(b). Measured bending moment data

(Hu et al., Experiments in Fluids, Vol. 52, No. 5, pp.1277-1294, 2012)
Wind Loads Acting on Various Components of Wind Turbine

Test conditions:

- **Oncoming ABL wind**
- **Velocity at hub height** \( U_{\text{Hub}} = 4.8 \text{ m/s} \)
- **Chord Reynolds number**, \( \text{Re} \approx 7,200 \)
- **Tip-speed-ratio**, \( \lambda = 4.6 \)

**Time-averaged loads:**

- **Dean thrust coefficients**
  - Rotating: 41.5%
  - Non-rotating: 13.3%
  - Tower+Nacelle: 9.6%

- **Mean bending moment**
  - Rotating: 39%
  - Non-rotating: 10%
  - Tower+Nacelle: 6%

**Fatigue loads:**

- **Dynamic thrust coefficients**
  - Rotating: 21.2%
  - Non-rotating: 9.3%
  - Tower+Nacelle: 8.3%

- **Dynamic bending moment**
  - Rotating: 21.6%
  - Non-rotating: 7%
  - Tower+Nacelle: 5.4%
Wind Farm Aerodynamics: Wake Interferences of Multiple Wind Turbines

- **Offshore wind farms:**
  - Wind turbine sitting on flat ocean surface.
  - High wind speed with relatively low ambient turbulence.
  - Near neutral atmospheric boundary layer winds.

- **Onshore wind farms:**
  - Atmospheric stability is rarely close to near-neutral, varying significantly between highly convective daytime conditions and highly stable nocturnal conditions.
  - Much higher turbulence level.
  - Wind turbine sitting over complex terrains.

Most of the existing wind farm design criterion and standards are derived based on the researches of offshore wind farms. They may not be applicable for onshore wind farms.
**Atmospheric Boundary Layer Winds: Offshore vs. Onshore Wind Farms**

**Terrain Category** | **Terrain description** | **Gradient height, \( Z_G \) (m)** | **Roughness length, \( Z_0 \) (m)** | **Wind Speed exponent, \( \alpha \)**
--- | --- | --- | --- | ---
1 | Open sea, ice, tundra desert | 250 | 0.001 | 0.11
2 | Open country with low scrub or scattered trees | 300 | 0.03 | 0.15
3 | Suburban area, small towns, wooded areas | 400 | 0.3 | 0.25
4 | Tall buildings, city centers, developed industrial areas | 500 | 3.0 | 0.36

\[
U(z) = U_{ZG} \left( \frac{Z}{Z_G} \right)^\alpha
\]

**Offshore wind farm**  
\( \alpha = 0.11 \)

**Onshore wind farm**  
\( \alpha = 0.15 \)

**Low turbulence intensity case**  
(10% at hub height)

**High turbulence intensity case**  
(18% at hub height)
The Effects of ABL Turbulence Level on the Wake Vortex Dissipation

### Low turbulence

The evolution of the tip vortex structures in the wake of wind turbine model

### High turbulence

Measured at $x/D=1.0$ downstream

The evolution of the tip vortex structures in the wake of wind turbine model
The Effects of ABL Turbulence Level on the Wake Characteristics
The Effects of ABL Turbulence Level on the Wake Characteristics

Atmospheric boundary layer wind

Wake velocity deficit profiles for low turbulence inflow case

Wake velocity deficit profiles for high turbulence inflow case

Power output of the downstream wind turbine vs. X/D
The Effects of Oncoming Turbulence Level on the Wake Characteristics

Atmospheric boundary layer wind

X/D

D

Low Turbulence Inflow

High Turbulence Inflow

The mean thrust coefficient, $C_T$

Standard deviation of the thrust coefficient, $C_T$ vs. $X/D$

Turbulence shear stress in the wakes
Wake Interferences among Multiple Wind Turbines

Velocity profiles in the wake for low turbulence inflow case

Velocity profiles in the wake for high turbulence inflow case

Power outputs of the wind turbines in a line

Field measurement data (Barthelmie et al., 2007)

Power deficit in Horns Rev wind farm, 8 m/s, 2 degree sector

Deep array effect

Normalized Power

Turbine number

Relative Power Output, P/P_{nom}

Turbine number
Effects of Terrain Topology on the Performances of Wind Turbines

- **Quantifying the flow characteristics of surface winds** (both mean and turbulence characteristics) over a flat surface (baseline case) and complex terrains for the optimal site design of turbines.

- **Characterizing the turbulent wake flows and dynamic wind loads** (both forces and moments) as well as their relationships for single wind turbine sited over a flat surface (baseline case) and complex terrains for the optimal mechanical design of wind turbines.

- **Investigating the effects of array spacing and layout** on the wake interferences among multiple wind turbines sited over a flat surface (baseline case) and complex terrains for higher total power yield and better durability of wind turbines.
Effects of Complex Terrains on the Wind Turbine Performance

Low slope hill

\[ L = 2h \]

Gaussian curve:

\[ z = h \times \exp \left[ -0.5 \left( \frac{x}{\sigma} \right)^2 \right], \sigma = L/1.1774 \]

2-D ridge with Gaussian shape

Slope = 12°

High slope hill

\[ L = h \]

Slope = 22°

2-D ridge with Gaussian shape

Flat surface

pos1, pos2, pos3, pos4, pos5
Performances of Single Wind Turbine Sited over Complex Terrains

<table>
<thead>
<tr>
<th>Wind turbine position</th>
<th>pos1</th>
<th>pos2</th>
<th>pos3</th>
<th>pos4</th>
<th>pos5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power output low slope hill (normalized with power output of single wind turbine sited on flat surface)</td>
<td>0.91</td>
<td>0.93</td>
<td>1.82</td>
<td>1.28</td>
<td>0.94</td>
</tr>
<tr>
<td>Power output high slope hill (normalized with power output of single wind turbine sited on flat surface)</td>
<td>0.92</td>
<td>0.79</td>
<td>1.45</td>
<td>0.04</td>
<td>0.20</td>
</tr>
</tbody>
</table>
## Power Outputs of Wind Turbines over Flat Surface vs. Complex Terrains

<table>
<thead>
<tr>
<th>Wind turbine position</th>
<th>pos1</th>
<th>pos2</th>
<th>pos3</th>
<th>pos4</th>
<th>pos5</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Power output flat surface</strong> (normalized with power output of single wind turbine sited on flat surface)</td>
<td>1.00</td>
<td>0.85</td>
<td>0.79</td>
<td>0.73</td>
<td>0.72</td>
<td>4.09</td>
</tr>
<tr>
<td>Power output low slope hill (normalized with power output of single wind turbine sited on flat surface)</td>
<td>0.91</td>
<td>0.82</td>
<td>1.69</td>
<td>1.02</td>
<td>0.73</td>
<td>5.17 (~26% more)</td>
</tr>
<tr>
<td>Power output high slope hill (normalized with power output of single wind turbine sited on flat surface)</td>
<td>0.92</td>
<td>0.63</td>
<td>1.33</td>
<td>0.04</td>
<td>0.19</td>
<td>3.11 (~24% less)</td>
</tr>
</tbody>
</table>
Performances of Wind Turbines over Complex Terrains

Moderate slope 2D-Ridges

<table>
<thead>
<tr>
<th>Wind turbine position</th>
<th>pos1</th>
<th>pos2</th>
<th>pos3</th>
<th>pos4</th>
<th>pos5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power output wind turbines (normalized with power output of single wind turbine sited on flat surface)</td>
<td>0.90</td>
<td>1.91</td>
<td>0.67</td>
<td>2.13</td>
<td>0.91</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Wind turbine position</th>
<th>pos1</th>
<th>pos2</th>
<th>pos3</th>
<th>pos4</th>
<th>pos5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two hills</td>
<td>Thrust Coefficient $C_T$</td>
<td>0.117</td>
<td>0.282</td>
<td>0.093</td>
<td>0.298</td>
</tr>
<tr>
<td></td>
<td>Bending moment Coefficient $C_{MZ}$</td>
<td>0.124</td>
<td>0.258</td>
<td>0.096</td>
<td>0.284</td>
</tr>
</tbody>
</table>

(Tian et al, Renewable Energy, 2013)
Root Loss and Wake Loss of Wind Turbines

- **Root Loss (~5%)**: 
  - Inner 25% of rotor blades are designed to provide structural integrity.
  - The aerodynamically poor design at the root region would result in a “dead” wind zone where virtually no energy is extracted from the incoming wind.

- **Wake Loss (up to 40%)**: 
  - Aerodynamic interaction between wind turbines will result in significant energy loss (up to 40%).
  - Wake loss is due to the ingestion of low-momentum air in wakes from upstream turbines by the downstream turbines.

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**DRWT concept**
- Main rotor - root designed for loads
- Aero-tailored secondary rotor

**SRWT**

**DRWT**

**Horns Rev offshore wind farm near Denmark**

**Hu et al. (2014)**

**ABL wind**

Entrainment of high-speed airflow from above to recharge the wake flow
Dual-Rotor Wind Turbine Models and Counter-Rotating Rotor Concept

Soviet Ka-2 helicopter with counter-rotating rotors

Contra-rotating propeller

SRWT

Co-rotating DRWT

Counter-rotating DRWT

0.25D

0.25D
SRWT vs. Co-Rotating DRWT vs. Counter-rotating DRWT

Phase-locked PIV measurement results
Ensemble-averaged PIV measurements

**Velocity distributions**

**SRWT**

**CO-DRWT**

**CN-DRWT**
Streamwise flow quantities in the wake
Stereo-PIV measurement Results: SRWT and DRWTs

Phase Angle = 0 deg

SRWT

Phase Angle = 0 deg

CO-DRWT

Phase Angle = 0 deg

CN-DRWT
Stereo-PIV measurement Results: SRWT and DRWTs
SRWT vs. Co-rotating DRWT vs. Counter-rotating DRWT

**ABL wind**

- Entrainment of high-speed airflow from above to recharge the turbine wake flow

- Power measurement for the same downstream wind turbine

- Varying R

- A small generator inside the nacelle

- X/D

---

**Graph**

- ~ 8% more energy output for CN-DRWT.
- ~ 10% more energy output form the same turbine at X/D=4.0 when it is installed in the wake of CN-DWRT.
Dynamic wind loads for SRWT and DRWTs

SRWT

CO-DRWT

CN-DRWT

IOWA STATE UNIVERSITY
Comparison of SRWT and DRWT: Thrust Force and Bending Moment

- **Time-averaged wind loads acting on the wind turbines:**

<table>
<thead>
<tr>
<th>Configurations</th>
<th>Thrust loading ($C_{Fx}$)</th>
<th>Bending Moment ($C_{My}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRWT</td>
<td>0.35</td>
<td>0.42</td>
</tr>
<tr>
<td>Co-rotating DRWT</td>
<td>0.39</td>
<td>0.44</td>
</tr>
<tr>
<td>Counter-rotating DRWT</td>
<td>0.36</td>
<td>0.43</td>
</tr>
</tbody>
</table>

- **~10% more mean wind loads for DRWTs**

- **Fluctuations of the dynamic wind loads acting on the wind turbines:**

<table>
<thead>
<tr>
<th>Configurations</th>
<th>$\sigma C_{Fx}$</th>
<th>$\sigma C_{My}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>SRWT</td>
<td>0.123</td>
<td>0.133</td>
</tr>
<tr>
<td>Co-rotating DRWT</td>
<td>0.161</td>
<td>0.178</td>
</tr>
<tr>
<td>Counter-rotating DRWT</td>
<td>0.132</td>
<td>0.151</td>
</tr>
</tbody>
</table>

- **10%~30% higher wind load fluctuations for DRWTs**
Thank you Very Much for Your Time!

Questions?

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