A Wind Tunnel Study on the Aeromechanics of a Novel Twin-Rotor Wind Turbine Model

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A target of 20% of US electricity from wind energy by 2030 has been set up by the U.S. Department of Energy (DOE).

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 2013 DoE wind Technologies Mark Report, Iowa has reached the milestone of 27.4% of the state’s electricity in 2013, while the national average rate is about 4.1% in 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.

Horns Rev offshore wind farm near Denmark

Entrainment of high-speed surrounding airflow to recharge the wake flow

 Hu et al. (2014)
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>
<thead>
<tr>
<th>Parameter</th>
<th>D (mm)</th>
<th>H (mm)</th>
<th>d_pole (mm)</th>
<th>d_nacelle (mm)</th>
<th>α (deg.)</th>
<th>a (mm)</th>
<th>a1 (mm)</th>
<th>A2 (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension</td>
<td>280</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:
- $U_{hub} = 6$ 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
Phase-locked PIV measurements
(TSR ≈ 5.0)
Ensemble-averaged PIV measurements

SRWT

TRWT

Normalized Velocity: $U/U_H$

Window #1

Window #2

SRWT

TRWT

Incoming ABL wind

$X/D=0.5$, SRWT

$X/D=1.0$, SRWT

$X/D=2.0$, SRWT

TRWT

$X/D=0.5$, TRWT

$X/D=1.0$, TRWT

$X/D=2.0$, TRWT
Ensemble-averaged PIV measurements

- **Turbulence kinetic energy (T.K.E.) distributions**

- **Reynolds stress distributions**
Stereo-PIV measurements

Experimental setup for Stereo-PIV measurements

Measuring locations

SRWT

TRWT
Stereo-PIV measurements

SRWT
X/D=1.0 cross plane

TRWT
X/D=1.0 cross plane
Stereo-PIV measurements

**SRWT**

**TRWT**

Normalized TKE: 0.004, 0.006, 0.008, 0.010, 0.012, 0.014, 0.016
Flow Characteristics in the far wake

![Diagram showing flow characteristics at different X/D values.](image)

- **X/D = 2.0**
- **X/D = 4.0**
- **X/D = 6.0**
- **X/D = 8.0**
Power outputs of SRWT and TWR models

- ~7% more power output for the downstream turbine at X/D=6.0

- ~4% more energy output for TRWT.

Entrainment of high-momentum surrounding airflow to recharge the turbine wake flow

\[ P_{ref} \text{ is the power output for an isolated SRWT} \]
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 Measurement Results

(a). Measured thrust coefficient data

(b). Measured bending moment data

(Tian, Ozbay, Hu, Physics of Fluids, Vol. 26, No.12, 125108, 2014)
Wind Loads Acting on Various Components of Wind Turbine

Test conditions:
- Oncoming ABL wind
- Velocity at hub height $U_{Hub} = 6.0$ m/s
- Chord Reynolds number, $Re \approx 10,000$
- Tip-speed-ratio, $\lambda = 5.0$

(Time-averaged loads: Dean thrust coefficients, Fatigue loads: Dynamic thrust coefficients)
(Time-averaged loads: Mean bending moment, Fatigue loads: Dynamic bending moment)

(Tian, Ozbay, Hu; Physics of Fluids, Vol. 26, No.12, 125108, 2014)
Wind Loads Acting on Wind Turbine at Different Phase Angles

- **Maximum difference**: ~10%
- **Time-averaged loads**: Mean thrust coefficients
- **Fatigue loads**: Dynamic thrust coefficients

- **Maximum difference**: 15%
- **Time-averaged loads**: Mean bending moment
- **Fatigue loads**: Dynamic bending moment
Dynamic wind loads of SRWT and TRWT models

\[ C_T = \frac{F_x}{0.5 \rho U_h^2 \pi R^2} \]

\[ C_M = \frac{M}{0.5 \rho U_h^2 \pi R^2 H} \]

\[ \sigma = \sqrt{\frac{1}{N} \sum_{j=1}^{N} (C_j - \bar{C}_j)^2} \]

Where:
- \( F_x \) ----- Force acting on streamwise direction
- \( R \) ----- Radius of main rotor
- \( C_j \) ----- Time-averaged coefficient

<table>
<thead>
<tr>
<th></th>
<th>SRWT</th>
<th>TRWT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean thrust coefficient, ( C_T )</td>
<td>0.346</td>
<td>0.401</td>
</tr>
<tr>
<td>The standard deviation of the thrust coefficient, ( \sigma_{C_T} )</td>
<td>0.123</td>
<td>0.215</td>
</tr>
<tr>
<td>Mean bending moment coefficient, ( C_M )</td>
<td>0.411</td>
<td>0.475</td>
</tr>
<tr>
<td>The standard deviation of the bending moment coefficient, ( \sigma_{C_M} )</td>
<td>0.133</td>
<td>0.324</td>
</tr>
</tbody>
</table>

- ~ 15% increase in time-averaged wind loads.
- up to 140% increase in the fluctuating amplitudes of the instantaneous wind loads.
Summary

- The aeromechanic performance and wake characteristics of a novel twin-rotor wind turbine (TRWT) design, which has an extra set of smaller, auxiliary rotor blades appended in front of the main rotor blades, was evaluated experimentally, in comparison with those of a conventional single-rotor wind turbine (SRWT).

- TRWT design was found to be capable of not only harvesting more energy from the same incoming wind by reducing the root losses of the main turbine rotor, but also improving wind farm efficiency by mitigating the wake losses for the downstream turbines through enhanced turbulent mixing of the turbine wake flows.

- The dynamic wind loadings acting on the TRWT model were found to be much greater (i.e., ~20% increase in time-averaged wind loads, up to 140% increase in the fluctuating amplitudes of the instantaneous wind loads) than those acting on the SRWT model.

- While the findings derived from the present study are helpful to gain further insight into underlying physics related to aeromechanic characteristics of TRWT, more comprehensive studies are still needed (e.g., Reynolds number effects, fatigue loading reduction, cost analysis,…) to explore/optimize design paradigms for higher power yield and better durability of wind turbines.
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