Energy from wind and water extracted by Horizontal Axis Turbine

Wind turbines in complex terrain (NREL)

Instream MHK turbines in complex bathymetry (VP East channel New York)

Common features?
1) horizontal axis turbine producing power
2) complex incoming flow conditions (bridge pier, karman vortices, bluff body wakes and turbine wakes)
First goal of a power plant:
extract energy efficiently and for a long time
with minimal maintenance costs.

\[ P = \frac{1}{2} c_p \rho A U^3 \]

- mean power output given a mean incoming flow velocity
  representative of the actual flow distribution across the rotor
  of area A
- unsteady loads on the blades, low and high speed
  shaft, support tower (in general, on all device’s components)

Turbine lifetime
operation and
maintenance
costs

The source of such unsteadiness comes
from the turbulence of the incoming flow.
What else?
Second goal of a renewable energy power plant: work efficiently with a minimal environmental footprint

Wind Turbine: wake flow, alteration of the local heat flux, but most of it: noise, bats and birds

MHK instream turbines: No noise birds ↔ fishes erodible sediment layer → variable B.C. short and long term impacts on river morphodynamics and sediment transport

Let us consider that a renewable energy source does not automatically imply that the power plant is environmentally sustainable
Buck and Renne 1985: wake effect on full-scale 2.5 MW turbines

- Presented summary of turbine/turbine (power deficit) and turbine/met tower wake interactions (velocity deficit from freestream tower to wake tower)
- Examined wake changes due to thermal stability, wind speed, and turbulence

Source: Buck, Renne 1985
Chamorro and Porté-Agel 2010: Effects of thermal stability and incoming boundary-layer flow characteristics on wind-turbine wakes: a wind-tunnel study BLM 2010

![Diagram showing turbine wake development]

**Fig. 5** Normalized velocity deficit at hub height for the two stratification cases and its comparison with simple models
Raul Cal 2010, the problem of double averaging equation for modeling turbine wake

Entrainment of high momentum fluid into the wind power plant is due to turbulence at the “canopy” interface.

FIG. 4. Wind turbine array and PIV measurement plane locations (top view). The turbine diameter is $D=12$ cm.

the vertical flux of kinetic energy due to turbulence $\left( -\langle u'v' \rangle_{xz} \langle \bar{u} \rangle_{xz} \right)$ which enables kinetic energy to be entrained from aloft into the boundary layer towards the wind turbine) is of sufficient magnitude to account for the observed kinetic energy extraction from the flow.
- Chamorro and Porté-Agel 2010 – Effects of thermal stability and incoming boundary-layer flow characteristics on wind-turbine wakes: a wind-tunnel study
• Turbine wake research (miniature turbines)
  – Zhang, Markfort, Porté-Agel 2012 – Near-wake flow structure downwind of a wind turbine in a turbulent boundary layer
  • PIV and hot-wire anemometer
Main ingredients in the wake:
tip and hub vortices, vortex sheets
wake shear layers
wake expansion
wake deficit
Are these features observed at utility scale?

Tip vortex

Hub vortex

snow visualization and PIV: see Toloui 2014, Hong 2014
tip vortex system and wake shear layer
Wake meandering
We can define the meandering wavelength $\lambda$ and amplitude $A$, the expansion angle of the meandering domain $\gamma$ and the mean velocity $U_c$ in the domain.

Domain of low speed meander oscillation ...
Is it important? Does it depend on turbine operating conditions?
Two flow meander populations have a distinct Stouhdal number

\[ St = \frac{f_s D}{U_{hub}} \approx \frac{U_c}{\lambda D} \frac{D}{U_{hub}} = \frac{U_c}{\lambda D}. \]

Let us consider \( A_2 \) \( \lambda_2 \) \( U_{c2} \)

\[ St \sim 0.3 \]

Medici et al. 2008 reported values in the range of 0.15 \( \sim 0.25 \), Chamorro et al. 2013 observed a peak at 0.28 while Okulov and Sorensen 2014 estimated a peak at 0.23, both at \( x=D \approx 5 \).

\textbf{wake}

\textbf{meandering oscillation}

Let us consider \( A_1 \) \( \lambda_1 \) \( U_{c1} \)

\[ St \sim 0.7 \]

in the range 0.44 \( \sim 0.81 \)

explored by Viola, 2014, Iungo, 2014

recognized as the signature of the hub vortex

(Kang and Sotiropoulos 2014)

\[ St_{nacelle} = \frac{f_s d}{U_{hub}} \approx \frac{U_c}{U_{hub} d / D} \frac{d}{D} \frac{D}{U_{hub}} \approx 0.5 \times 0.08 \times \frac{0.7}{1} = 0.06 \]
Near and far wake distinction is based on the signature of turbine geometry on the flow statistics. Far wake instead has some intrinsic instability modes known as wake meandering.
The induction factor \( a \) is defined based on the velocity deficit “within” the rotor plane. Why? Because \( u \) is the average velocity at the low pressure side of the rotor. \( u \) must be \( >0 \) so the rotor becomes a porous disk.
The normalized thrust coefficient and power coefficient depend on $a \to a=1/3$ corresponds to a max $C_p$ identified by the Betz limit of 59.3%.

\[ C_T(a) = 4a(1-a) \]  
\[ C_p(a) := 4a(1-a)^2 \]

where the maximum power coefficient can be achieved with $a = \frac{1}{3}$, see Figure 3. Operating turbines at their maximum operating point may not be the optimal operating point of the whole wind farm. There is the potential to increase overall production out of a wind farm by operating the front turbines suboptimally [3].

Figure 3. $C_p$ vs. $C_t$ of an ideal turbine

$0 < a < 1$ implies that $u > 0$ and $u < U_\infty$

all flow passing through the turbine as if the turbine does not exist

no flow passing through the turbine
In fact, a depends on the turbine operating conditions, which are defined by the tip speed ratio $\lambda$ and by the pitch blade angle $\beta$.

where $\lambda = \frac{U_{\text{tip}}}{U_{\infty}} = \frac{\omega R}{U_{\infty}}$

while $\beta$ is used to change the blade angle of attach amplifying or reducing aerodynamic lift → torque.

2.2.3. Turbine Control and Dynamics

This section briefly reviews the control and dynamics of a single turbine. Additional details and references can be found in [25] [26]. If the turbine is modeled as an actuator disk, the power captured by a single turbine in steady state can be expressed by:

$$P = \frac{1}{2} \rho A U^3 C_P(a)$$

where $\rho$ [kg/m$^3$] is the air density, $A$ [m$^2$] is the area swept by the rotor, and $U$ [m/s] is the wind speed perpendicular to the rotor plane. $C_P$ is a function of the axial induction factor [4]. Equation [5] provides a static model using the induction factor as a controllable input to the power output.

A more realistic model for a utility-scale turbine involves blade pitch, $\beta$, [rad] and generator torque, $\tau_g$, [Nm] as controllable inputs. The aerodynamic forces depend on the nondimensional tip-speed ratio (TSR), $\lambda$, defined as $\lambda := \frac{\omega R}{U_{\infty}}$ where $\omega$ [rad/s] is the rotor speed. In this more realistic model, the power coefficient is $\tilde{C}_P(\beta, \lambda)$. Similar to Equation [5], the captured power can be expressed as $P = \frac{1}{2} \rho A U^3 \tilde{C}_P(\beta, \lambda)$. This leads to the following simplified, single degree-of-freedom rotor dynamics for the turbine:

$$\dot{\omega} = \frac{1}{J} (\tau_{\text{aero}} - \tau_g)$$

where $\dot{\omega}$ is the angular acceleration and $\tau_{\text{aero}}$ [Nm] is the aerodynamic torque. Equation [6] provides a dynamic relationship between the generator torque, $\tau_g$, and the rotor speed, $\omega$. The aerodynamic torque can be expressed in terms of the power and rotor speed by $\tau_{\text{aero}} = \frac{P}{\omega}$. Thus, the dynamic model in [6] can be rewritten as:

$$\dot{\omega} = \frac{1}{J} \left( \frac{p A U^3 \tilde{C}_P(\lambda, \beta)}{2\omega} - \tau_g \right)$$

This gives a dynamic model for the turbine with state $\omega$ and inputs ($\beta, \tau_g$). At low wind speeds, the objective of a turbine controller is to maximize power. This is done by maintaining an optimal blade pitch angle and TSR. Specifically, the blade pitch angle is fixed at the optimal blade pitch and the optimal TSR is maintained by controlling the generator torque, $\tau_g$ [26].
with increasing complexity and computational costs..

actuator lines models: blade rotation is implemented, no nacelle $\rightarrow$ no hub vortex (so far...) high resolution required

fully resolved turbine-blade geometry very high resolution is required
What are the modeling assumptions, so far?
1) uniform inflow
2) no turbulence

How can we make sure that the turbine is always operating at optimal conditions? Especially if:
the incoming flow is unsteady → angle of attack is varying ...
the mean incoming flow is not uniform (boundary layer, or flow within a farm, or complex terrain effects)

We have some options...
1) improve wake models
2) wind preview: measuring the incoming flow approaching the turbine
3) wind power plant optimization: do not operate each single turbine at optimal conditions but optimize the full power plant $C_p$

Remember Cal 2010: how do we bring more high momentum fluid in the turbine from flow layers above the top tips
increase mixing, increase power density (optimal streamwise-transverse turbine spacing,
1) Improve (static) wake models
Realistic wake with turbine in two operating conditions (optimal-rated) suboptimal (derated towards large $\omega$ low $\tau$)

An experimental investigation on the effect of individual turbine control on wind farm dynamics

J.R. Annoni et al.

Figure 6. Mean streamwise velocity behind Turbine 1

turbine is captured at the tips of the blades. Some studies have implemented modifications to the Park model by introducing different zones of the wake that provide a more accurate description of the wake [33]. An alternative approach may be to modify the Park model to incorporate a Gaussian velocity profile that evolves as a function of downstream distance [19].

note that we can modify the wake expansion angle $k$ (Park model), adding a dependency on $C_p$ e.g. derated $k=0.15$, rated $k=0.09$

or introduce a Gaussian profile instead of the Park “hat”
1) Improve (dynamic)wake models

1) test how turbine response (in freq.) propagates through the wind power plant

2) Build a dynamic model able to account for wake meandering (or any scale dependent incoming flow perturbation → amplitude modulation + phase shift). Question is: how can we optimize back wind turbines based on front turbines performance or state ...

![Diagram of wind turbine dynamics](image)

**Figure 12:** Input/output dynamics in the three turbine setup compared to the dynamic Park model
2) Upwind Preview

• Experimental setup:
  – Full-scale testing at Eolos, flow measurements with WindCube LiDAR
    • Inflow and wake data
    • Turbine SCADA data
  – Model-scale data for comparison
2) Upwind Preview

- Methods for velocity calculation with LiDAR
  - Standard WindCube N on north
  - 2D (Planar) Velocity Calculation with NS aligned with the mean wind

\[
\begin{align*}
  u &= \frac{RWS_N - RWS_S}{2 \sin \phi}; \\
  v &= \frac{RWS_E - RWS_W}{2 \sin \phi}; \\
  w &= \frac{RWS_N + RWS_S + RWS_E + RWS_W}{4 \cos \phi}; \\
\end{align*}
\]
2) Upwind Preview

Inflow and wake Analysis: Wind tunnel - EOLOS

- **LiDAR velocity profile**
  - 1 Hz measurement
    - 1 beam per second
  - Averaging volume
    - Calculates u,v,w from 3 previous measurements
    - Averaging region increases w/ height

- **PIV data**
  - To mimic LiDAR, average in x
    - Averaging distance defined from...
2) Upwind Preview

- **Full Scale Velocity profile**
  - Profile curvature at x/D=-0.8
    - EOLOS convex curve over rotor
    - Blockage compared to clean flow

- **Scale Comparison**
  - Blockage at hub height
    - EOLOS – ΔU/U_{hub} ≈ 0.053
    - Model - ΔU/U_{hub} ≈ 0.049
  - Shear change – many influences
    - Re #, surface roughness, etc.
2) Upwind Preview

Wake Analysis: Full- to Model-Scale Profiles

Velocity profile comparison

 EOLOS - LiDAR

Wind Tunnel - Hotwire

Singh et al. subm.
2) Upwind Preview

- Tracking the response of the Eolos turbine to inflow
  - Power and strain appear to track velocity fluctuations
  - Gust event details strain response
  - Turbine response

- LiDAR $U_{hub}$
- LiDAR $U_{top-tip}$
- Eolos power

Black dots – Root blade strain
2) Upwind Preview

- Tracking the response of the Eolos turbine to inflow
  - LiDAR tracking up to 8 elevations within rotor swept area
  - Turbine power output, blade strain, etc.
  - Each time signal velocity time signal can be correlated to turbine data
2) Upwind Preview

- Cross-correlation – Power to inflow
  - Rotor averaged time signal
    - Full-scale data produces $\rho_{Pu} = 0.82$
    - Model-scale produces $\rho_{Pu} = 0.64$
  - Signal from each elevation
    - Full-scale peak at $z/z_{hub}=1.3$
    - Model-scale peak at $z/z_{hub}=1.2$
  - For turbine-turbine arrangement
    - First inspect turbine wake
    - Peak correlation occurs at hub height

At $z/z_{hub} \sim 1.3$ corresponding to $z=z_{hub}+L/4$ the wind velocity is mostly correlated with power output and blade strain. This signal can be thus used as a wind input for a predictive control strategy (front turbines). For back turbines $z/z_{hub} \sim 1$

Question: which control solution can we implement just due to the fact that the turbine is in boundary layer?
3) wind power plant optimization

• Experimental setup:
  – SAFL wind tunnel (same boundary layer conditions as previous)
    • Note that the ceiling was adjusted to account for blockage induced by the turbines
  – Voltage acquisition from each turbine
  – Wall parallel PIV (i) between rows and (ii) between columns (last row)
  – Four test conditions
    • Aligned
    • Staggered
    • Yaw Misalignment
    • TSR Adjustment
3) wind power plant optimization

- Aligned farm, spacing effect on total production
  - 4% reduction from $l_x = 6D$ to $5D$
  - 7% reduction from $l_x = 6D$ to $4D$
  - 13% reduction from $l_x = \infty D$ to $6D$

- Aligned vs Staggered total production
  - Staggered has 11.9% increase over aligned farm with the same spacing
3) wind power plant optimization

- Performance changes via control adjustments (5 rows 3 col)
  - Yaw Misalignment (4D by 3D spacing)
    - Front row only
    - Increase in downwind production at expense of front row
  - TSR Adjustment (5D by 3D spacing)
    - Center turbine only
    - Large increase in downwind production

\[ \gamma = +15^\circ \]

\[ \text{TSR} = 5 \]
3) wind power plant optimization

- Total Farm Production Change
  - Yaw Misalignment
    - Production from 5 rows and 3 columns

<table>
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<tr>
<th>$\gamma$ [°]</th>
<th>+30</th>
<th>+15</th>
<th>-15</th>
<th>-30</th>
<th>+/- 30</th>
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<tr>
<td>$\Delta V$ [%]</td>
<td>-1.1</td>
<td>-0.4</td>
<td>-0.3</td>
<td>-1.3</td>
<td>-1.6</td>
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- TSR Adjustment
  - Production from 4 rows and 3 columns

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<tr>
<th>TSR</th>
<th>5.0</th>
<th>4.6</th>
<th>3.8</th>
<th>3.4</th>
<th>3.2</th>
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<tr>
<td>$\Delta V$ [%]</td>
<td>0.98</td>
<td>0.70</td>
<td>0.44</td>
<td>0.59</td>
<td>REF</td>
<td>0.17</td>
</tr>
</tbody>
</table>

- Needs further refinement to measure production change of derated turbine
3) wind power plant optimization

• Summary of Findings
  – Aligned farm spacing
    • Intuitive, larger spacing is better – 7% reduction for 6D to 4D
    • optimal spacing is an economic problem, not a fluid mechanic problem
  – Staggered vs aligned
    • Staggered 12% more production for 5 rows, 3 cols spaced at lx = 5D and ly = 3D
  – Farm performance modification
    • Yaw misalignment
      – Smallest reduction at 0.3% for farm production
    • TSR adjustment
      – Most effective change, from TSR 3.2 to 5 with nearly 1% increase
      – Provides promising results, needs further investigation
If we change the point of view and we investigate:

1) what flow structures the turbine feels? *(unsteady loads cascading down from blades to foundation)*

2) in the TKE scale by scale budget, what survives in the wake?

3) What do we have to take into account in the turbine control?
what are the relevant scales \( \rightarrow \) of the order \((1/2, 1/3)\) of the rotor diameter depending on the tip speed ratio (on non erodible-concrete channel, Chamorro et al. 2013) similar evidence is provided for the EOLOS wind turbine

Moving on with this talk...
What are the large scales of the flow in the atmospheric boundary layer?
Very large scale motion

Kim & Adrian 99
Balakumar 07
Guala et al. 06, 10, 11

Super-structures

Hutchins et al 2007, 2013
Monty et al 2009
Mathis et al. 2009
Marusic, et al. 2011
Upwind flow perturbations

1) Turbine in baseflow
2) Two turbines in series
3) Sinusoidal hill upwind of turbine

DC motor $\rightarrow$ voltage

Simultaneous PIV measurement windows
Turbine and Turbine interactions

\[ \rho_{xy}(\tau) = \frac{\langle v_x(t)v_y(t+\tau) \rangle}{\sqrt{\langle v_x^2 \rangle \langle v_y^2 \rangle}} \]

\[ \lambda = \tau u_{convection} \]

<table>
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<th>Neutral</th>
<th>ST</th>
<th>TT</th>
<th>HT</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>0.164</td>
<td>0.124</td>
<td>0.143</td>
</tr>
<tr>
<td>Turbine Voltage</td>
<td>( \frac{V_{xT} - V_{ST}}{V_{ST}} ) [%]</td>
<td>-24.3</td>
<td>-13.0</td>
</tr>
<tr>
<td>Turbine Voltage RMS</td>
<td>( \frac{V_{RMS_{xT}} - V_{RMS_{ST}}}{V_{RMS_{ST}}} ) [%]</td>
<td>-44.1</td>
<td>5.9</td>
</tr>
</tbody>
</table>

\(~6\-10 \delta\) consistent with VLSM (rotational inertia ?)
What is the effect of a turbine on the incoming flow?

**Premultiplied spectral difference (f, z)**
- **x/D**
- **near wake**
- **far wake**

2<x/D<6
- enhanced turbulence

8<x/D<12
- dampened turbulence

Chamorro, Guala, Arndt & Sotiropoulos, JOT 2012
Figure 6. Dominant length scale in the wake at various locations.
Adding complexity: Varying thermal stability regimes

(Howard K.B., Chamorro L.P., Guala M. AIAA 2012, to be submitted to BLM)
RESULTS: thermal stability regimes coupled with topographic effects

see also Singh, Howard, Guala PoF 2014
The curious case of hill-turbine in the stratified (stable) regime


The very large scales motions are deflected by the hill for all thermal regimes.

However, thermal stratification inhibits momentum flux in the vertical direction expanding the wake in the cross-flow direction.

Thus, in the stratified regime the hill exerts a sheltering effect on the turbine.