How to reduce wake losses in wind farms: from CFD to simpler methods

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Outline

• Introduction to wind farm losses:
  – What are wind turbine wakes?
  – Why wind turbine wakes cause losses?

• Understanding wake impacts with CFD:
  – Wind farm layout;
  – Atmospheric stability.

• The Geometric Model (GM):
  – GM validation;
  – Optimizing wind farm layout with GM.
Horns Rev photos

From the South

12 February 2008
~10:10 UTC

From the Southeast

Photos by Christian Steiness
Lidars: wind speed deficit in wakes

lunghi et al. (JAOT 2013)
Simulated single- and multi-turbine wakes

In-house code WiTTS (Wind Turbine and Turbulence Simulator)
OpenFOAM-based SOWFA (Software for Offshore/onshore Wind Farm Applications)

Both are Large-Eddy Simulation (LES) codes
Wind speed deficit = reduced power

- Losses in generated power due to wakes of upstream turbines can be very large (>60%).
- Wake losses are affected significantly by farm layout, wind direction, and atmospheric stability.
LES of a wind farm

- Large-Eddy Simulations with **SOWFA** (Software for Offshore/onshore Wind Farm Applications);
- SOWFA was developed at NREL;
- Actuator lines;
- Finite-volume, C++, OpenFOAM;
- SGS model: Lagrangian scale-invariant;
- Incompressible, Boussinesq, all stabilities;
- Lillgrund offshore wind farm;
- 48 Siemens 2.3 MW wind turbines;
- Spacing 3.3D x 4.3D;
- ~80 million grid cells;
- Resolution 3.5-7 m;
- Complex initialization method to provide non-periodic boundary conditions (precursor run).
Layout effect: Original vs. staggered

Archer et al. (GRL, 2013)
Staggered layout better for wind from 225°

SOUTH-WEST (225°)

Original:
- Power: 695 kW
- Losses: 35.5%
- CF: 0.3

Staggered:
- Power: 787 kW
- Losses: 19.9%
- CF: 0.34
Trade-offs exist for other wind directions.

**ORIGINAL**

- **SOUTH-WEST (225°)**
  - Power: 695 kW
  - Losses: 35.5%
  - CF: 0.3

- **NORTH-WEST (315°)**
  - Power: 964 kW
  - Losses: 10.1%
  - CF: 0.42

**STAGGERED**

- **Power**: 695 kW
- **Losses**: 35.5%
- **CF**: 0.3

- **Power**: 787 kW
- **Losses**: 19.9%
- **CF**: 0.34

- **Power**: 939 kW
- **Losses**: 12.4%
- **CF**: 0.41

**STAGGERED (225°)**

**STAGGERED (315°)**
Atmospheric stability effects

Neutral
$P_{TOT} = 33.4\text{ MW}$

Unstable
$P_{TOT} = 35.1\text{ MW}$

Stable
$P_{TOT} = 30.3\text{ MW}$

- Initialized with same prescribed wind speed at 90 m (9 m/s);
- Neutral and stable case have reached equilibrium;
- Unstable case shows patterns of convergence and divergence;
- Wakes shorter in unstable, longer in stable, than neutral case.
How to optimize layout?

• Many attempts for fixed wind direction using LES:
  – Wu and Porté-Agel (2013);
  – Archer et al. (2013);
  – Stevens et al. (2014).

• Each LES takes ~45 days.

• Impossible to simulate all wind directions and all stabilities.

• **Aim:** Develop simpler models based on LES.

Observed wind direction vs. time at Lillgrund. Figure from Dahlberg (2009)
Suite of “Lillgrund” LES

- Data from LES:
  - Several “Lillgrund” layouts
  - Wind Directions \((225^0, 270^0, 315^0)\)
  - Stabilities: neutral, unstable, stable

- Final LES database:
  - 8 neutral,
  - 4 unstable,
  - 4 stable cases.

Archer et al. (GRL, 2013)
Geometric quantities – Blockage Ratio

• Consider a 3-turbine wind farm;
• For each turbine $i$, define Blockage Ratio ($BR_i$):
  – Fraction of rotor area blocked by upstream turbines.

\[
BR_1 = 0, \quad BR_2 = \frac{A_2}{\pi R^2}, \quad BR_3 = \frac{A_3}{\pi R^2}
\]

Ghaisas and Archer (JAOT, 2015)
Geometric quantities – Blockage Distance

Blockage Distance (BD<sub>i</sub>):

- Distance to upstream blocking turbine weighted by fraction of area blocked;
- Limit to 20D wherever no blockage.

\[
\begin{align*}
BD_1 &= 20D, \\
BD_2 &= L_{12} \left( \frac{A_2}{\pi R^2} \right) + 20D \left( 1 - \frac{A_2}{\pi R^2} \right), \\
BD_3 &= L_{13} \left( \frac{A_3}{\pi R^2} \right) + 20D \left( 1 - \frac{A_3}{\pi R^2} \right),
\end{align*}
\]

Ghaisas and Archer (JAOT, 2015)
Hypothesis

- Turbines with $BR_i = 0$ (unblocked) generate rated power ($P_{\text{max}}$);
- Relative power of other turbines is a function of $BR_i, BD_i$.

\[ \frac{P}{P_{\text{max}}} = \begin{cases} 
1, & BR_i = 0 \\
 f(BR_i, BD_i), & BR_i \neq 0 
\end{cases} \]

Ghaisas and Archer (JAOT, 2015)
Correlations: Neutral

- Individual correlations of $BR_i$ and $BD_i$ are high;

Ghaisas and Archer (JAOT, 2015)
Correlations: Neutral

- Individual correlations of BR\textsubscript{i} and BD\textsubscript{i} are high;
- Multiple Linear Regression (MLR) gives even higher correlation;
- Geometric Model (GM): use MLR with coefficients calibrated from the LES.

\[ P_i / P_{\text{max}} = f_N(BR_i, BD_i) \]

Ghaisas and Archer (JAOT, 2015)
\[ \frac{P_i}{P_{\text{max}}} = \frac{f_U(BR_i, BD_i)}{f_{U_{\text{max}}}} \]

\[ \frac{P_i}{P_{\text{max}}} = \frac{f_S(BR_i, BD_i)}{f_{\text{S_{max}}}} \]

\[ \frac{P_i}{P_{\text{max}}} = \frac{f_N(BR_i, BD_i)}{f_{N_{\text{max}}}} \]

- Similarly high correlations for unstable and stable cases.
GM validation – LES of Horns Rev

- Comparisons to neutral LES of Horns Rev (Porté-Agel et al., 2013);
- Geometric Model (GM) trained on Lillgrund translates very well to other farms, like Horns Rev.
Application of Geometry-based Model

• Geometry-based Model is very inexpensive (~1 minute for a 100-turbine layout for each wind direction);

• Multiple wind directions can be evaluated efficiently;

• Used in a search-based optimization procedure.
Wind Rose

- Use the Wind Rose (WR) to compute weighted-average power in a year:

\[
\frac{P_{WR}}{N_T P_{\text{max}}} = \sum_{k} F_k \frac{P_k}{N_T P_{\text{max}}}
\]

= 0.723

- Total power generated is a function of Wind Rose.
Layout optimization

- Layout design variables:
  - $\alpha_1$, $\alpha_2$: [0: 10°: 180°]
  - $S_1$, $S_2$: [4D: 1D: 12D]
  - $N_T$ varies; max: 2 x 48.
  - Total n. of layouts: 9477

- Compute $P_{WR}/N_T P_{\text{max}}$ for each layout, with neutral stability and real WR.
Evaluation of layouts

- Efficiency decreases as $N_T$ increases;
- Total power increases as $N_T$ increases, but with diminishing returns.
Evaluation of layouts – Zoom in

- Close-up view around $N_T = 48$.
- Several layouts more efficient than Lillgrund.
- Some layouts with 47 turbines produce more power than existing Lillgrund.
Conclusions

• Wind farm power can be modeled in terms of geometric parameters.
• Linear regression model has been calibrated based on data from LES.
• Neutral, unstable, stable conditions treated separately.
• Effect of multiple wind directions can be considered efficiently.
• Search-based optimization methodology applied to Lillgrund identifies several better layouts.


