Bergen Energy Lab Talk

Layout and Yaw Optimisation of an Offshore Wind Farm

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**Motivation**
Performance Optimisation of Offshore Wind Farms

- Planned expansion of offshore wind power by 61% by 2030 in Germany
- Power losses due to wake effects within wind farms
- Wake effects can be modelled analytically
- Wind farms can be optimised with respect to turbine wakes
  - Optimised turbine positioning
  - Innovative control concepts such as yaw angle control

How can wind farm performance be increased through optimised turbine positions and yaw angles?
Agenda
Performance Optimisation of Offshore Wind Farms

- Wake effects within wind farms
- Analytical modelling of wake effects

- Validation of proposed tool
- Insight into parameter study

- Optimised wind farm
  - Layout
  - Yaw angles
Wake Effects
Power Losses Within a Wind Farm

- Measured performance drop greatest from first to second row
- Subsequently asymptotic course
- Overlapping of several wakes hardly leads to further losses

First drop in performance must be reduced

Power loss within one turbine row [1, Barthelmie et al.]

Superimposing wake areas
Wake Effects
Proposals

Superimposing wake areas

1 Wake
2 Superimposed Wakes
3 Superimposed Wakes
Wake Effects
Analytical Modelling

Input
$C_T, u_0, T_{I_a}$

Wake model by Ishihara & Qian (2018)

Output
$\Delta u(x,y)/u_0, \Delta T_l(x,y)/T_{I_a}$

In- and output parameters of the wake model [3, Ishihara et al.]

ambient & turbine data

modelling

wind speed & turbulence in wake region
Wake Effects
Analytical Modelling

Input: $C_T, u_0, Tl_a$

Wake model by Ishihara & Qian (2018)

Output: $\Delta u(x,y)/u_0, \Delta Tl(x,y)/Tl_a$

In- and output parameters of the wake model [3, Ishihara et al.]

Computation points of the wake model

Superimposed wake areas
Wind farm with extensive performance data and comparative studies
Validation
First Main Wind Direction at $\alpha = 270^\circ$

- Power normalised to the yield of the first turbine row
- WAsP planning software as industrial standard
- Deviations in comparison to original data of Qian & Ishihara

Modelled and measured power of one turbine row

[2, Sukhman et al., submitted to: J. Phys.: Conf. Ser. (2023)]
Study on Wind Farm Performance Parameters

Axial Spacing $\Delta x$ & Turbulence Intensity $TI_a$

Impact of $\Delta x$ and $TI_a$ on the total power [2, Sukhman et al.]

Schematic illustration of the 3x3 wind farm

$u_{\text{Wind}} = 11.4 \text{ m/s}$

$\Delta x$  

$\Delta y$

$TI_a$
Avoid first shadowing

If unavoidable:
- Increase axial distance

Diagonal alignment of the turbines to wind direction

Reference and optimised layout proposal, [2, Sukhman et al.]
Study on Wind Farm Performance Parameters
Conclusion and Optimisation Outlook

- Avoid first shadowing
- If unavoidable:
  Increase axial distance

Diagonal alignment of the turbines to wind direction

Reference and optimised layout proposal, [2, Sukhman et al.]

Turbine in free inflow
Study on Wind Farm Performance Parameters
Conclusion and Optimisation Outlook

- Avoid first shadowing
- If unavoidable: Increase axial distance

Diagonal alignment of the turbines to wind direction

Reference and optimised layout proposal, [2, Sukhman et al.]

Axial turbine spacing
No positive effect on power by yawing the turbine
Study on Wind Farm Performance Parameters

Conclusion and Optimisation Outlook

\[ \alpha = 270^\circ \]

\[ \Delta \alpha \]
Wind Farm Optimisation

Overview

1. Layout Optimisation

2. Yaw Optimisation
Wind Farm Layout Optimisation

Overview

- Gradient-based extreme value search function \textit{fmincon}
- Reference Layout: Horns Rev 1
- Ambient Data
  - \(u_0 = 10 \frac{m}{s}\)
  - \(TI_\alpha = 6.4\%\)
- Optimisation carried out for all three main wind directions

\[
\alpha_1 = 222^\circ \\
\alpha_0 = 270^\circ \\
\alpha_2 = 312^\circ
\]
Wind Farm Layout Optimisation
Structure

- Gradient-based extreme value search function `fmincon`
- Reference Layout: Horns Rev 1
- Ambient Data
  - $u_0 = 10 \frac{m}{s}$
  - $TI_a = 6.4\%$
- Optimisation carried out for all three main wind directions
- Definition of position boundaries

Boundaries of turbine positions [2, Sukhman et al.]
Clearly visible, diagonal alignment of the turbines in relation to the inflow.

Optimal layout for main wind direction. Left schematic layout, right velocity distribution. [2, Sukhman et al.]
Section of the optimal layout. Left schematic layout, right velocity distribution.

Clearly visible, diagonal alignment of the turbines in relation to the inflow.
Wind Farm Layout Optimisation
Results Layout Optimisation First Main Wind Direction

- Clear increase in performance from an aerodynamic point of view
- Visible dependence on wind direction $\alpha$

![Bar chart showing increased performance due to optimised layout](image-url)

Optimised for $\alpha=270^\circ$

- +57.15%
- +18.53%
- +10.12%

Power wind farm in MW

$\alpha=270^\circ$  $\alpha=222^\circ$  $\alpha=312^\circ$

Increased performance due to optimised layout
Wind Farm Optimisation
Overview

1. Layout Optimisation

2. Yaw Optimisation
Wind Farm Yaw Angle Optimisation
Retrospect and Structure

- Wake steering potential off main wind directions
- Layout: Horns Rev 1
- Inclined inflow by $\Delta \alpha = 5^\circ$

Wake areas with inclined flow of the wind farm [2, Sukhman et al.]
Wind Farm Yaw Angle Optimisation
Results for Inclined Inflow $\alpha = 275^\circ$

- Power increase possible with yaw angle control for inclined inflow
- Consideration of the wind direction absolutely necessary
- Structural mechanics not considered

Predicted performance increase through yaw angle optimisation [2, Sukhman et al.]

<table>
<thead>
<tr>
<th>$P_{\text{reference}}$</th>
<th>$P_{\text{optimised}}$</th>
<th>$\Delta P_{\text{total}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>196,317 MW</td>
<td>209,500 MW</td>
<td>+6,29%</td>
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</table>
Conclusion & Ongoing Work

- Development of an analytical computation tool in MATLAB
  - Implementation of the Wake Model of Qian & Ishihara (2020)

- Validation using existing data on the Horns Rev 1 wind farm
  - Good agreement with measured data compared to the benchmark model
  - Potential for expansion of the model

Offshore wind turbines [6, EDF Renewables]

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Development of an analytical computation tool in MATLAB
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Momentum conserving superposition
[8, Zong, Porté-Agel]

Statistical wake meandering model
[9, Braunbehrens, Segalini]

Offshore wind turbines [6, EDF Renewables]
Conclusion & Ongoing Work

- Yield increase through layout optimisation shows high potential
- Yaw angle control interesting when operating off main wind directions
- Factors to include:
  - Wind direction
  - Turbine loads
  - Maintenance & costs

Offshore wind turbines [6, EDF Renewables]
Thank you!

Horns Rev 1 [Vattenfall]


