A fast reduced order method for assessment of wind farm layouts

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Why is there a need for a fast and accurate method?

• There are many possible applications:
  – Assessment of layout
  – Long term energy yield estimation
  – Short term production forecasting

• But it is hard! The flow field in wind farms is complex due to interacting wakes
  – Wake losses depend on wind conditions and turbine positions

• Computational Fluid Dynamics (CFD) can be used, but is too slow for interactive assessment of different layouts

• Other computationally fast methods simplify the governing equations
  – Simplified models of turbine wakes (e.g. Jensen model)
  – FUGA: linearization of the flow equations
Model reduction

- Our proposed alternative fast technique
- Reduction of the solution space, while including the nonlinear RANS equations
- The solutions space is constructed from a set of steady state CFD simulations using the RANS equations
- The solution time is reduced from hours to seconds
Construction of the reduced space

- Run multiple CFD simulations for varying setups
  - Different turbine positions
  - Different wind conditions
- Use the simulations to produce a low dimensional space of basis modes

Example:
One CFD simulation  Three snapshots  Orthogonal basis modes
The solution in the reduced space

• The solution space is represented by a matrix of basis modes/vectors

\[ B = [\varphi_1, \varphi_2, \ldots, \varphi_M] \]

• Any solution for a tile is written as a coefficient vector

\[ a = [a_1, a_2, \ldots, a_M] \]

• This reduced space solution represents the reconstructed full-space solution

\[ u = B a \]
Tile coupling and fitting to RANS equations

- Minimize the sum of boundary discrepancies in the full space (least squares fitting)

- At the same time the reconstructed full space solution should satisfy the RANS equations as well as possible

- The weighting between tile coupling and fitting to RANS equations is controlled through a parameter $\alpha$
  - $\alpha = 0$: All weight to tile coupling
  - $\alpha = 1$: All weight to RANS

Find $[a_A^T, a_B^T, a_C^T]$ so that $L_1 + L_2 + L_3 + L_4 + L_5$ is minimized
Empty tiles and the background grid

- We have added “empty tiles” to propagate the flow field between non-overlapping turbine tiles
  - Empty tiles have a different basis than turbine tiles
  - Turbine tiles are placed on top of a grid of empty tiles

- The physical dimension of empty tiles is smaller than turbine tiles
  - Gives more flexibility when extracting snapshots for empty tiles
Results

- Movement of turbines in the cross-stream direction
- Multiple wake effect, turbines in line
- Varying wind speed
Cross stream movement of turbines

Solution of the x-component of the flow field at hub-height.


Production estimates for the wind farm for different positions of the three downstream turbines. The value 0 m refers to a center position of the cluster in a cross stream direction.
Multiple wakes

- Ten turbines in a row with a uniformly varying distance between the turbines
- A solution basis was created from CFD simulations with turbine distances of 5 and 9 rotor diameters
- An equal number of snapshots were used from the 5 and 9 diameter cases
Multiple wakes (cont.)

- The total deviation of the power production is less than 3.3% when using 4+4 or more modes.

Seven rotor diameters

Heggelund Y., Khalil M., Jarvis C., Interactive design of wind farm layouts using CFD and model reduction, EWEA 2014, Barcelona, Spain, 10-13 March 2014.
Varying wind speed

- Fixed turbine positions
- Wind speed between 7 m/s and 15 m/s at hub height

### Basis construction

<table>
<thead>
<tr>
<th>Basis name</th>
<th>CFD simulation</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>7 m/s</td>
</tr>
<tr>
<td>Basis 7-15</td>
<td>✓</td>
</tr>
<tr>
<td>Basis 7-11-15</td>
<td>✓</td>
</tr>
</tbody>
</table>
Varying wind speed (cont.)

Reproduction of the flow field for 9 m/s

<table>
<thead>
<tr>
<th>Basis name</th>
<th>Verification case</th>
</tr>
</thead>
<tbody>
<tr>
<td>Basis 7-15, $\alpha = 0.5$</td>
<td>Basis 7-11-15, $\alpha = 0.5$</td>
</tr>
<tr>
<td>9 m/s</td>
<td>11 m/s</td>
</tr>
<tr>
<td>2.3%</td>
<td>2.4%</td>
</tr>
<tr>
<td>0.9%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>
Varying wind speed (cont.)

- Sensitivity to the $\alpha$-parameter

![Graph showing production discrepancy for downstream turbine for wind speed 13 m/s.](image)
Technical status
Concluding remarks, and future perspectives

• The technique builds on CFD
  - The accuracy is controlled by the representativeness of the CFD simulations used to build the basis
  - Improvements to the CFD simulator can easily be transferred to the model reduction framework

• The model reduction technique saves significant computing time compared to CFD
  - All cases reported here takes less than one second to compute

• Verification against CFD
  - Plans for verification with larger setups
  - In the future we will validate against real production data

• Development plans
  - Include atmospheric stability