Sensitivity Analysis of Limited Actuation for Real-time Hybrid Model Testing of 5MW and 10MW Monopile Offshore Wind Turbines

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Erin Bachynski (NTNU)
Context

- Design of ReaTHM® tests of large monopile wind turbines
  - Physical hydrodynamic loads
  - Virtual aerodynamic/turbine loads, applied in an integrated manner
- How important are each of the turbine load components?
- How important are aerodynamic effects in parked, extreme conditions?

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Outline

• Computational methodology
• Wind turbine models
• Load cases
• Sensitivity to
  • Aerodynamic loading in parked condition
  • Aerodynamic pitch moment
  • Aerodynamic sway force
  • Aerodynamic yaw moment
• Outlook
Computational methodology

RIFLEX/SIMO

Control (JAVA)

Modify forces one by one

Aerodynamic forces on blades and tower

OWT element positions, orientations, and velocities

- Torque
- Commanded pitch
- Rotor velocity
- Current blade pitch

AeroDyn

Present limitation: rigid blades (elastic blades in near future)

Source: NREL/Wind power today, 2010.
Computational methodology: aerodynamic force modification

Rigid body dynamics: Jacobian matrices used for transformation of forces and velocities between frames

\[ \tau_a^R = J_{BR}^F \tau_a^B \]

\[ \tau_a^B = J_{BR}^F \tau_a^R \]

\[ \hat{\tau}_a^R = \tau_a^R + \text{modifications} \]

\[ \hat{\tau}_a^B = J_{BR}^F \left( \sum_{i=1}^{N_b} \sum_{j=1}^{N_e} \hat{\tau}_{a_{ij}}^R \right) \frac{1}{N_e N_b} \]
5MW and 10MW monopile wind turbine models

- 30 m water depth
- 5MW: based on OC3, but extended due to deeper water
- 10MW: new design, soil-pile characteristics assumed same as OC3 despite larger diameter
- Sensitivity study is carried out with torsional spring (as in lab) rather than soil springs

<table>
<thead>
<tr>
<th></th>
<th>5MW</th>
<th>10MW</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>NREL 5MW</td>
<td>DTU 10MW</td>
</tr>
<tr>
<td>Monopile</td>
<td>OC3</td>
<td>Representative</td>
</tr>
<tr>
<td>Soil stiffness</td>
<td>OC3*</td>
<td>OC3*</td>
</tr>
<tr>
<td>Rated thrust (kN)</td>
<td>710</td>
<td>1500</td>
</tr>
<tr>
<td>Hub height (m)</td>
<td>90</td>
<td>119</td>
</tr>
<tr>
<td>Monopile diameter (m)</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>Thickness (cm)</td>
<td>6</td>
<td>8</td>
</tr>
<tr>
<td>Embedded length (m)</td>
<td>46</td>
<td>56</td>
</tr>
</tbody>
</table>
## Eigenfrequencies and eigenmodes

<table>
<thead>
<tr>
<th></th>
<th>Mode</th>
<th>Linear distributed springs (below the seabed)</th>
<th>Single torsional spring (at seabed)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5 MW</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; bending (Hz)</td>
<td>0.261</td>
<td>0.261</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; bending (Hz)</td>
<td>1.239</td>
<td>1.423</td>
</tr>
<tr>
<td>10 MW</td>
<td>1&lt;sup&gt;st&lt;/sup&gt; bending (Hz)</td>
<td>0.262</td>
<td>0.261</td>
</tr>
<tr>
<td></td>
<td>2&lt;sup&gt;nd&lt;/sup&gt; bending (Hz)</td>
<td>1.219</td>
<td>1.365</td>
</tr>
</tbody>
</table>

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Load cases

• Based on hindcast data for 29m water depth, North Sea site (Li et al., 2013)

• 3 operational cases, one storm (parked)

• EC 2 cases repeated with fault
  • Grid loss (with shutdown)
  • Blade seize (without shutdown)
  • Blade seize (with shutdown)

<table>
<thead>
<tr>
<th></th>
<th>EC 1</th>
<th>EC 2</th>
<th>EC 3</th>
<th>EC 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$U_w$ (m/s)</td>
<td>8</td>
<td>11.4</td>
<td>20</td>
<td>31.5</td>
</tr>
<tr>
<td>$H_s$ (m)</td>
<td>1.2</td>
<td>1.8</td>
<td>3.6</td>
<td>9.5</td>
</tr>
<tr>
<td>$T_p$ (s)</td>
<td>5.8</td>
<td>6.5</td>
<td>8.2</td>
<td>12.3</td>
</tr>
<tr>
<td>$I%$ (NTM)</td>
<td>17.1</td>
<td>14.0</td>
<td>11.5</td>
<td>11.0</td>
</tr>
</tbody>
</table>
Fault cases

![Graph showing PileBMY (kNm) vs time (sec) for different fault cases: No fault, Grid loss, Blade seize, Blade seize shutdown.]

- Turbulent wind at 11.4 m/s, waves, wave direction 0 deg.

![Graph showing spectrum of PileBMY (kNm²/rad/sec) vs frequency (rad/sec) for different fault cases: No fault, Grid loss, Blade seize, Blade seize shutdown.]

- First elastic bending mode.
- Rotor harmonic 1P.

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Aerodynamic loading in parked condition

- Aerodynamic **damping** is important even in parked conditions for the dynamic bending moment response
  - 100% difference
- Dynamic shear force is less affected
- Similar results for 5 MW and 10 MW
## Sensitivity study results: summary

<table>
<thead>
<tr>
<th></th>
<th>5MW, normal</th>
<th>5MW, fault</th>
<th>10MW, normal</th>
<th>10MW, fault</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aerodynamic damping, parked</td>
<td>100%</td>
<td>N/A</td>
<td>100%</td>
<td>N/A</td>
</tr>
<tr>
<td>Aerodynamic pitch</td>
<td>&lt;5%</td>
<td>20-30%</td>
<td>10-30%</td>
<td>25-40%</td>
</tr>
<tr>
<td>Aerodynamic sway</td>
<td>&lt;7%</td>
<td>&lt;5%</td>
<td>&lt;5%</td>
<td>&lt;10%</td>
</tr>
<tr>
<td>Aerodynamic yaw</td>
<td>60% *</td>
<td>100% *</td>
<td>90% *</td>
<td>100% *</td>
</tr>
<tr>
<td>Dynamic torque</td>
<td>&lt;5%</td>
<td>&lt;5%</td>
<td>&lt;20%</td>
<td>&lt;10%</td>
</tr>
</tbody>
</table>

*only for torsion/yaw

- Key observations:
  - Only effects on “responses of interest” are shown
  - 10 MW is generally more sensitive to limited actuation
  - Aerodynamic yaw is important for torsion/yaw responses, but largely decoupled from other responses
  - Aerodynamic pitch moment is less important for bottom-fixed concept compared to NOWITECH FWT
Aerodynamic pitch moment

- Different effects for 5 MW vs 10 MW.
- Less important for 5 MW monopile than for 5 MW floating.
Aerodynamic yaw moment: fixed vs. floating

- Natural periods in yaw/torsion:
  - Bottom-fixed: <2s
  - CSC 5MW: 62s

- Aerodynamic yaw is primarily a low-frequency excitation, so it can excite yaw resonant response in the floating concept, but only quasi-static response for the bottom-fixed turbines

5 MW CSC results for yaw, above-rated wind speed
Conclusions/outlook

• Monopile wind turbine designs for basin tests, including torsional stiffness
• Preliminary response analysis for physical test design
• Application of a methodology developed for FWT to bottom-fixed concepts, and to a new turbine
• Aerodynamic damping should be included in tests with extreme waves (in some way)
• Aerodynamic pitch moment is important in fault cases and for the 10 MW concept
• Aerodynamic yaw moment is only important for torsional responses
• Aerodynamic sway and dynamic torque have minor effects

• Future work:
  • Extension to flexible blades
  • Sensitivity to other limitations (frequency, delays)
  • NOWITECH tests in 2017
Teknologi for et bedre samfunn