Design optimization of spar floating wind turbines considering different control strategies

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Motivation

• Controller design is challenging for FWTs

• Several control strategies suggested
  – Trade-offs between structural loads, rotor speed tracking, and blade-pitch actuator use
  – Non-trivial to find optimal control parameters

• Interactions between controller and structure
  – Should be designed together for fair comparison between solutions

• Simultaneous design optimization with realistic design limits
Linearized FWT model

• Linearized model
  – aero-hydro-servo-elastic
  – frequency-domain
  – stochastic wind/wave input

\[ x = x_0 + \Delta x, \quad u = u_0 + \Delta u \]

\[ \Delta x = A\Delta x + B\Delta u \]

• External loads
  – wave excitation
  – thrust
  – tilting moment
  – torque

• Control inputs
  – generator torque
  – collective blade pitch angle
Linearized FWT model

- Four structural DOFs
- Rigid blades
- Internal forces from dynamic equilibrium
- Valid for spar platforms (circular cross section) with catenary mooring

\[ \mathbf{x}_s = \begin{bmatrix} \xi_1 \\ \xi_5 \\ \xi_7 \\ \dot{\xi}_1 \\ \dot{\xi}_5 \\ \dot{\xi}_7 \\ \dot{\varphi} \end{bmatrix} \]
Blade-pitch control strategies

- CS1: PI
- CS2: PI + platform pitch velocity feedback
- CS3: PI + nacelle velocity feedback
- CS4: PI + nacelle velocity feedback + WF low-pass filter

- Modified rotor speed reference in CS2-4:

\[
\dot{\varphi}_0' = \dot{\varphi}_0(1 + k_f\dot{x}_f)
\]
Optimization problem

• Objective
  – Minimize cost of platform + tower
  – Material and manufacturing

• Design variables, structure
  – Tower/hull dimensions
  – Hull scantling design not considered
Optimization problem

- Objective
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- Design variables, control
  - PI gains \((k_p\text{ and } k_i)\)
  - Velocity feedback gain \((k_f)\)
  - Low-pass filter corner frequency \((\omega_f)\)

<table>
<thead>
<tr>
<th>Design variable</th>
<th>(k_p)</th>
<th>(k_i)</th>
<th>(k_f)</th>
<th>(\omega_f)</th>
</tr>
</thead>
<tbody>
<tr>
<td>CS1</td>
<td>✔</td>
<td>✔</td>
<td></td>
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<tr>
<td>CS2</td>
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<td>CS4</td>
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</tbody>
</table>

- 47 design variables in total
Environmental conditions

• Long-term fatigue
  – 15 ECs
  – 1-30 m/s with 2 m/s step
  – Most probable $H_s$ and $T_p$

• Short-term extreme response
  – 3 ECs
  – 50-year contour

<table>
<thead>
<tr>
<th>Condition</th>
<th>1</th>
<th>2</th>
<th>3</th>
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</thead>
<tbody>
<tr>
<td>Mean wind speed [m/s]</td>
<td>13.0</td>
<td>21.0</td>
<td>50.0</td>
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<tr>
<td>Significant wave height [m]</td>
<td>8.1</td>
<td>9.9</td>
<td>15.1</td>
</tr>
<tr>
<td>Spectral peak period [s]</td>
<td>14.0</td>
<td>15.0</td>
<td>16.0</td>
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</tbody>
</table>
Optimization problem

• Constraints, structure
  – Fatigue damage and buckling in tower
  – Maximum platform pitch angle, < 15°
  – Heave natural period, > 25 s
  – Most probable 1-h maximum value used as extreme response

• Constraints, control
  – Rotor speed variation (std.dev.), blade pitch actuator use (ADC)
  – Constraint values based on land-based DTU 10 MW
  – Weighted average of short-term values

\[
ADC_i = \frac{1}{T} \int_0^T \frac{|\dot{\theta}_i(t)|}{\dot{\theta}_{max}} \, dt,
\]

\[
ADC = \sum_{i=1}^{N_{EC}} p_i ADC_i
\]

• Gradient-based optimization
  – OpenMDAO framework
  – Analytic derivatives
Design solutions

- **Below wave zone**
  - Heighten CoB, lower CoG
  - Increases pitch restoring stiffness

- **Intersection platform/tower**
  - Balance between wave loads and fatigue resistance
Structural response

- Controller primarily affects resonant pitch response
  - More aerodynamic damping
  - Tower base bending moment spectrum, 15 m/s mean wind speed

- Most critical extreme response found above cut-out
  - No impact from controller
Cost and performance comparison

- Cost reduction mainly in tower due to lower fatigue loads
  - Some reduction in platform costs, coupling with tower

- CS1 unable to fully utilize available actuator capacity

- CS4 does not offer much additional reduction in cost, but
  - Less rotor speed variation
  - Larger improvements likely for designs with more WF response

- Cost comparison strongly dependent on chosen constraint values
Verification

• Comparison with nonlinear time domain simulations

• Mostly, trends are captured with reasonable accuracy

• Fatigue damage for CS1 significantly overpredicted
  – Optimal design has small aerodynamic damping in pitch
  – Does not occur with velocity feedback control

• Rotor speed variation quite consistently underestimated
  – Can be considered by lowering constraint value
Conclusions

• Integrated optimization of a spar FWT
  – Evaluation of trade-off effects in a lifetime perspective

• Linearized model captures trends, but
  – Overestimates pitch response if aerodynamic damping is low

• Controller mainly affects resonant pitch response
  – Cost reductions in tower due to lower fatigue loads
  – Actual values depend on rotor speed variation and ADC constraints
  – Alternative to use multi-objective approach

• No effect from controller on extreme response
  – Limited coupling effects
  – Small variations for the platform design
Limitations/future work

• Transient and nonlinear events
  – Extreme rotor speed excursions

• Consider impact of controller on
  – Blades
  – Drivetrain
  – Mooring system

• Additional modifications
  – Torque controller
  – IPC
Thank you for your attention!

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