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Design optimization of spar floating wind turbines considering different control strategies

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Larsen and Hanson (2007)

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**

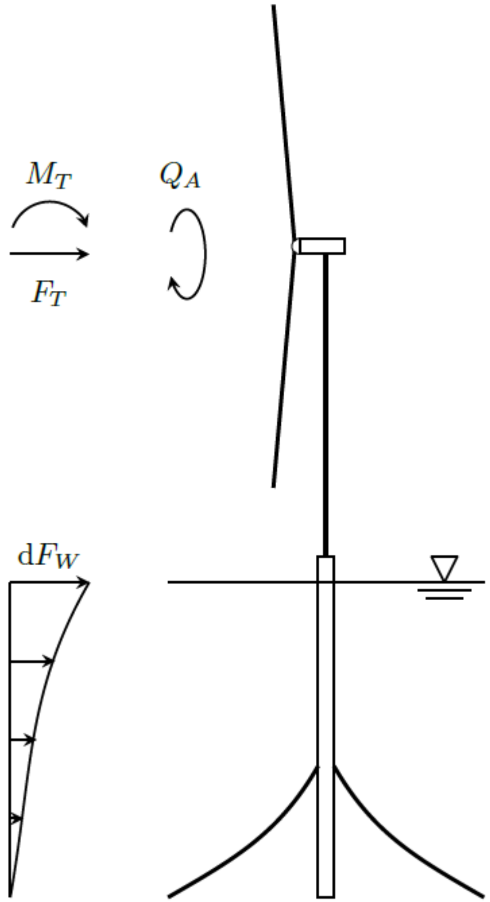
Linearized FWT model

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

$$\mathbf{x} = \mathbf{x_0} + \Delta\mathbf{x}, \quad \mathbf{u} = \mathbf{u_0} + \Delta\mathbf{u}$$

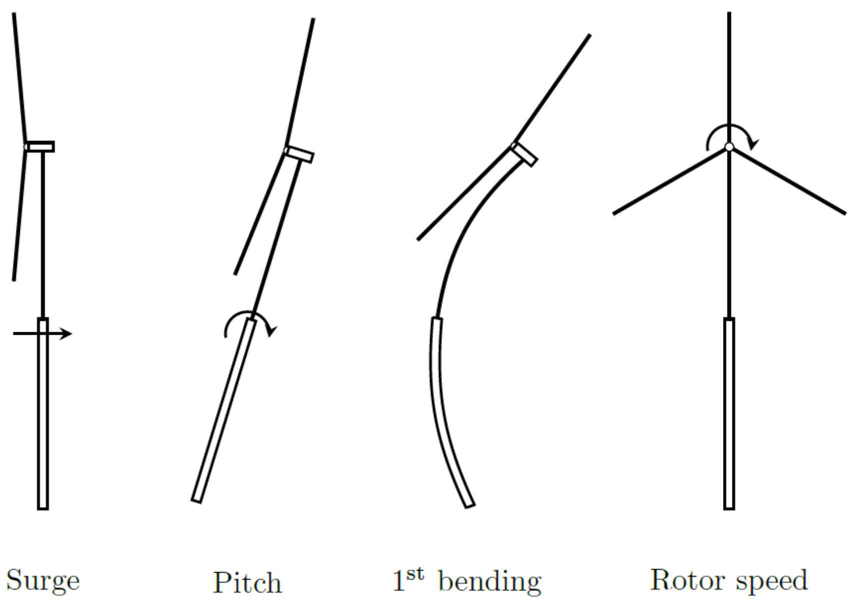
$$\Delta\dot{\mathbf{x}} = \mathbf{A}\Delta\mathbf{x} + \mathbf{B}\Delta\mathbf{u}$$

- 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

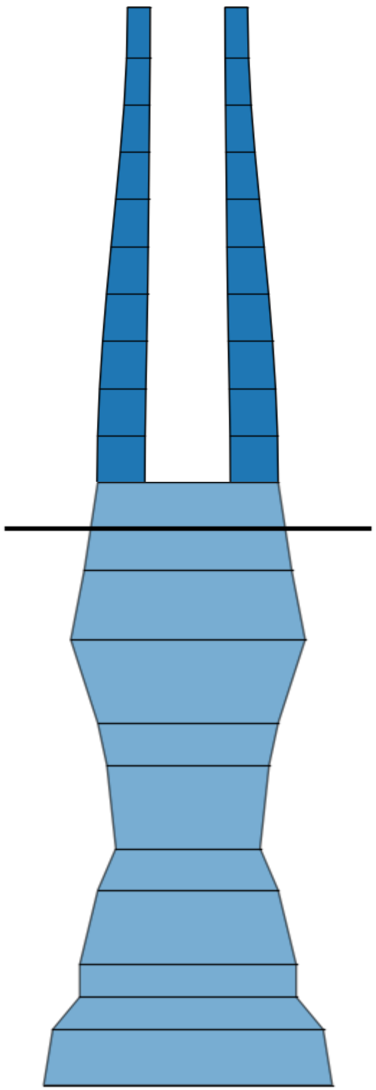
- Modified rotor speed reference in CS2-4:

$$\dot{\varphi}_0' = \dot{\varphi}_0(1 + k_f \dot{x}_f)$$

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
  - Minimize cost of platform + tower
  - Material and manufacturing

- Design variables, structure
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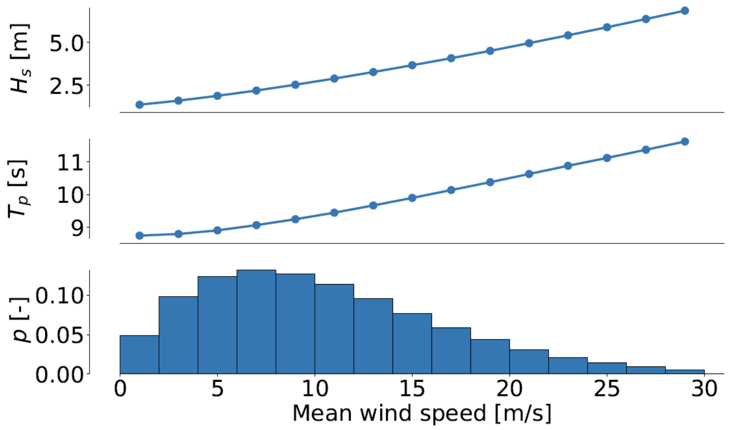
- Design variables, control
  - PI gains (k_p and k_i)
  - Velocity feedback gain (k_f)
  - Low-pass filter corner frequency (ω_f)

- 47 design variables in total

Design variable	k_p	k_i	k_f	ω_f
CS1	✓	✓		
CS2	✓	✓	✓	
CS3	✓	✓	✓	
CS4	✓	✓	✓	✓

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

Condition	1	2	3
Mean wind speed [m/s]	13.0	21.0	50.0
Significant wave height [m]	8.1	9.9	15.1
Spectral peak period [s]	14.0	15.0	16.0

Optimization problem

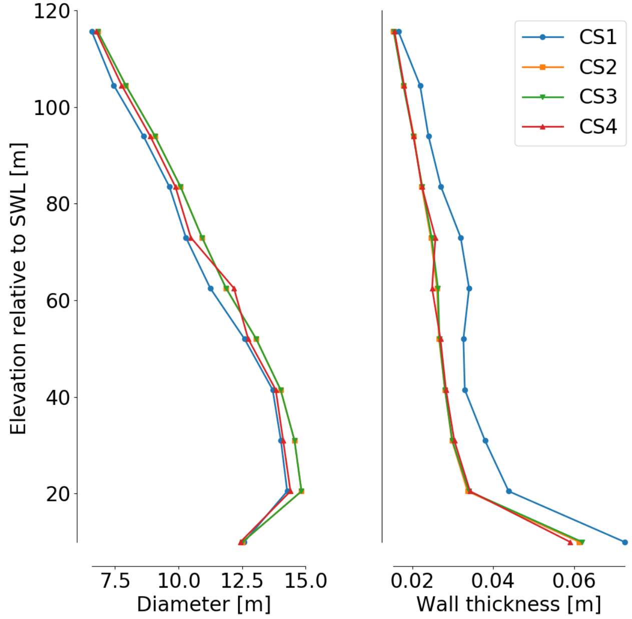
- Constraints, structure
  - Fatigue damage and buckling in tower
  - Maximum platform pitch angle, < 15°
  - Heave natural period, > 25 s
  - Most probable 1-h maximum value used as extreme response

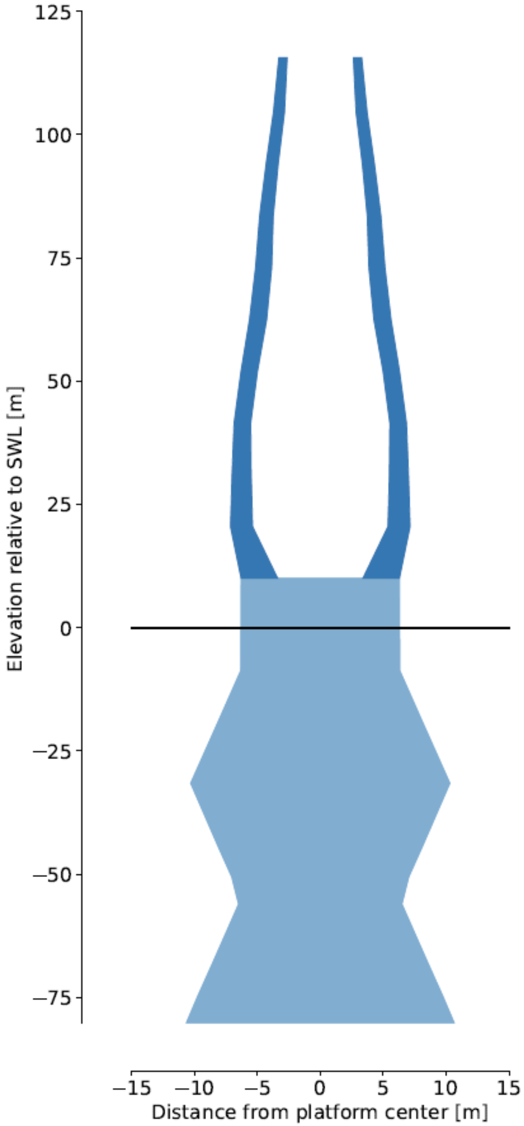
- Constraints, control
  - Rotor speed variation (std.dev.), blade pitch actuator use (ADC)
  - Constraint values based on land-based DTU 10 MW
  - Weighted average of short-term values

$$\mathrm{ADC}_i = \frac{1}{T}\int_0^T \frac{|\dot{\theta}_i(t)|}{\dot{\theta}_{\max}}\mathrm{d}t, \qquad \mathrm{ADC} = \sum_{i=1}^{N_{EC}} p_i \mathrm{ADC}_i$$

- Gradient-based optimization
  - OpenMDAO framework
  - Analytic derivatives

Design solutions



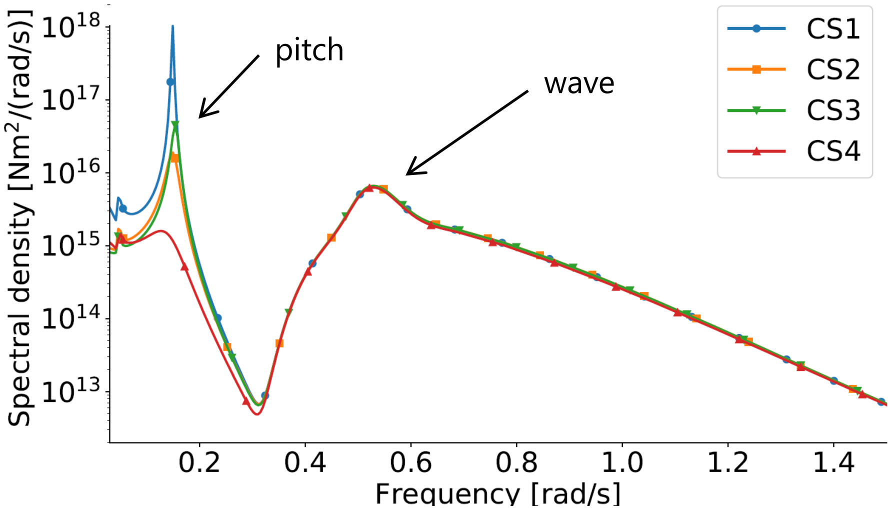


- Below wave zone
  - Heighten CoB, lower CoG
  - Increases pitch restoring stiffness

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

Structural response

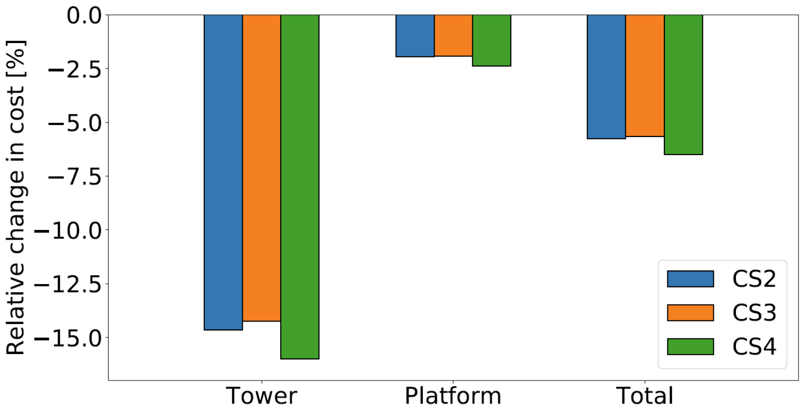
- Controller primarily affects resonant pitch response
  - More aerodynamic damping
  - Tower base bending moment spectrum, 15 m/s mean wind speed

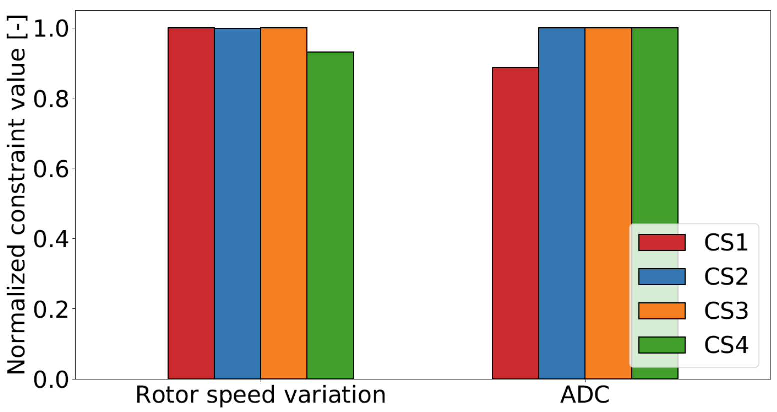


- Most critical extreme response found above cut-out
  - No impact from controller

Cost and performance comparison

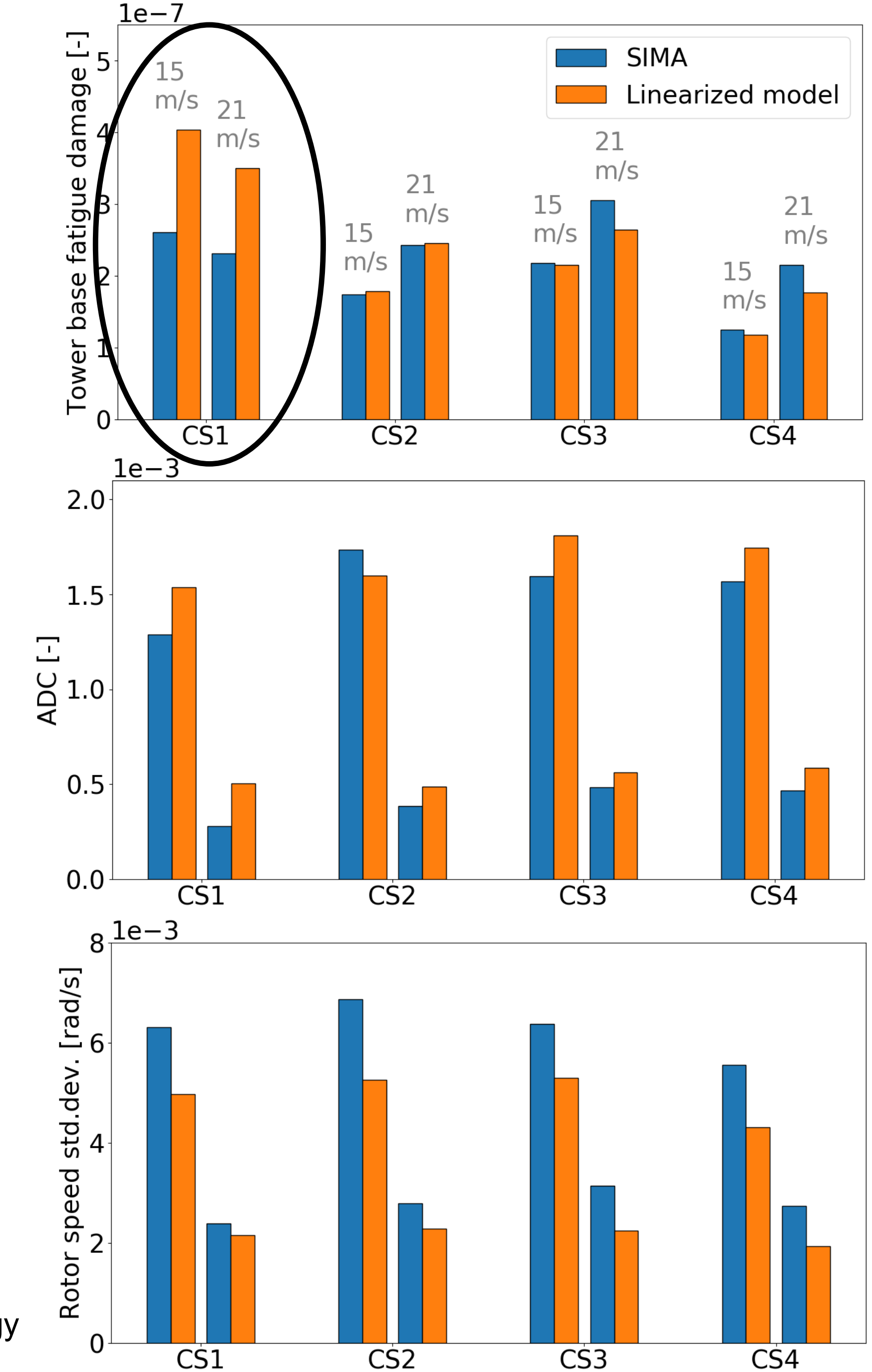
- Cost reduction mainly in tower due to lower fatigue loads
  - Some reduction in platform costs, coupling with tower
- CS1 unable to fully utilize available actuator capacity
- CS4 does not offer much additional reduction in cost, but
  - Less rotor speed variation
  - Larger improvements likely for 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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