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

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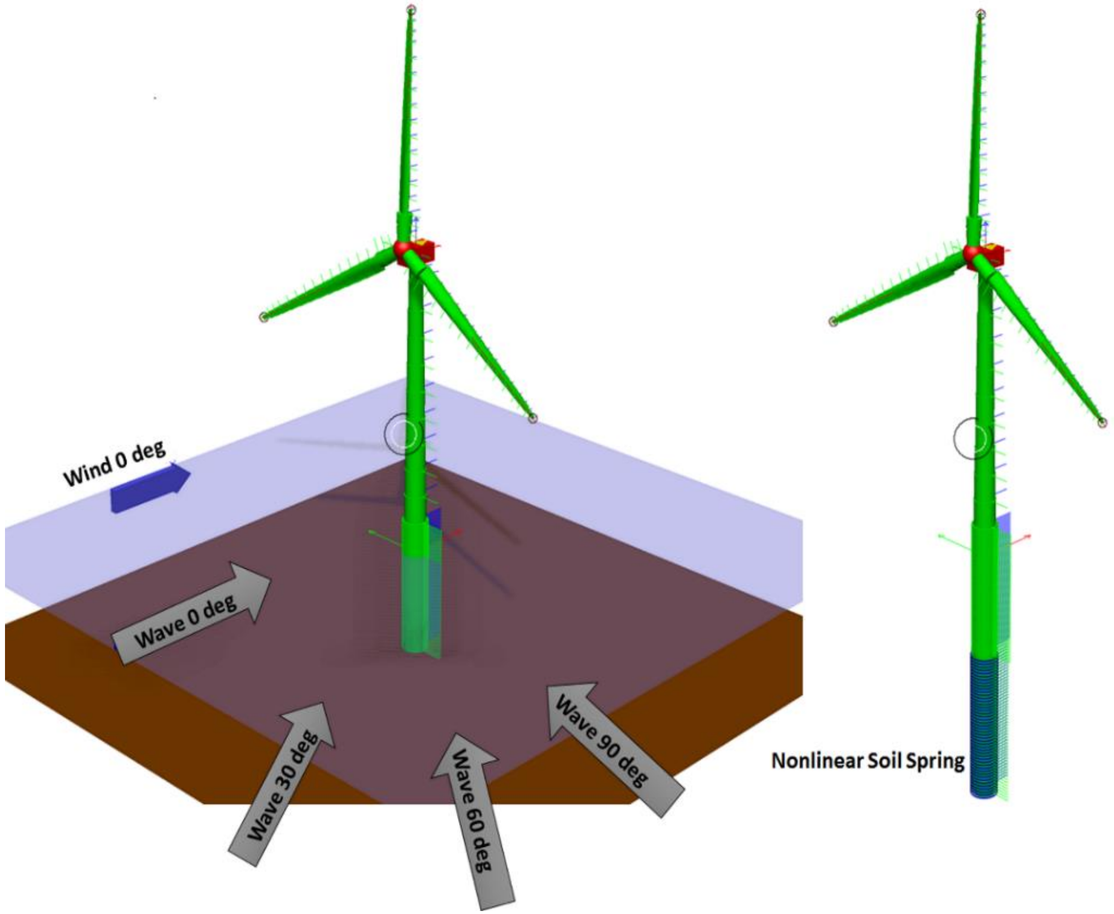

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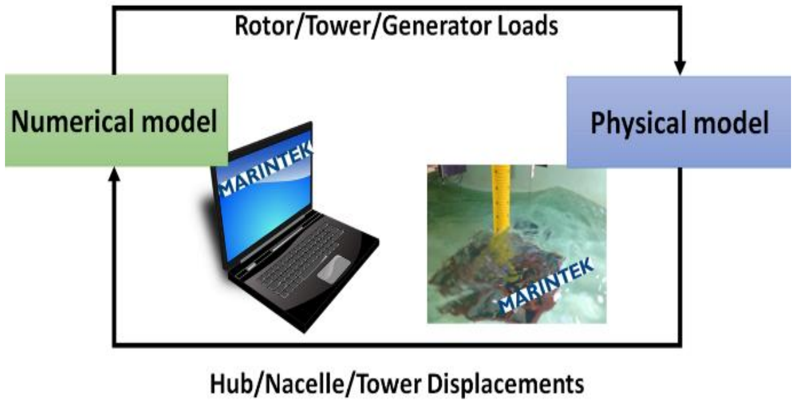
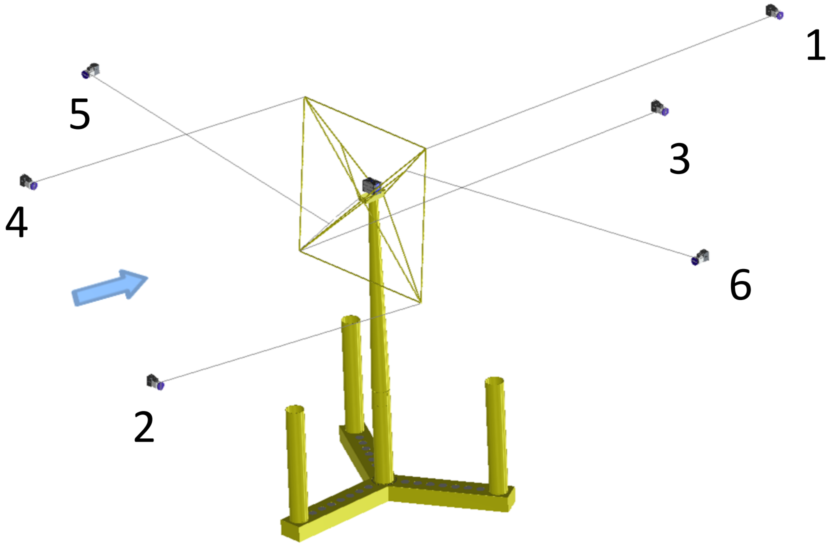
Context

- 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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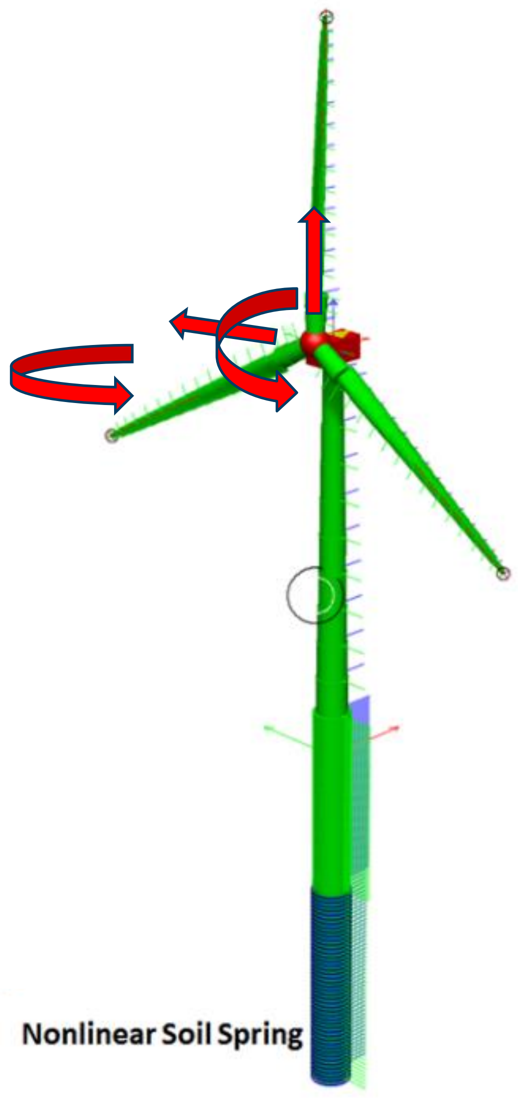
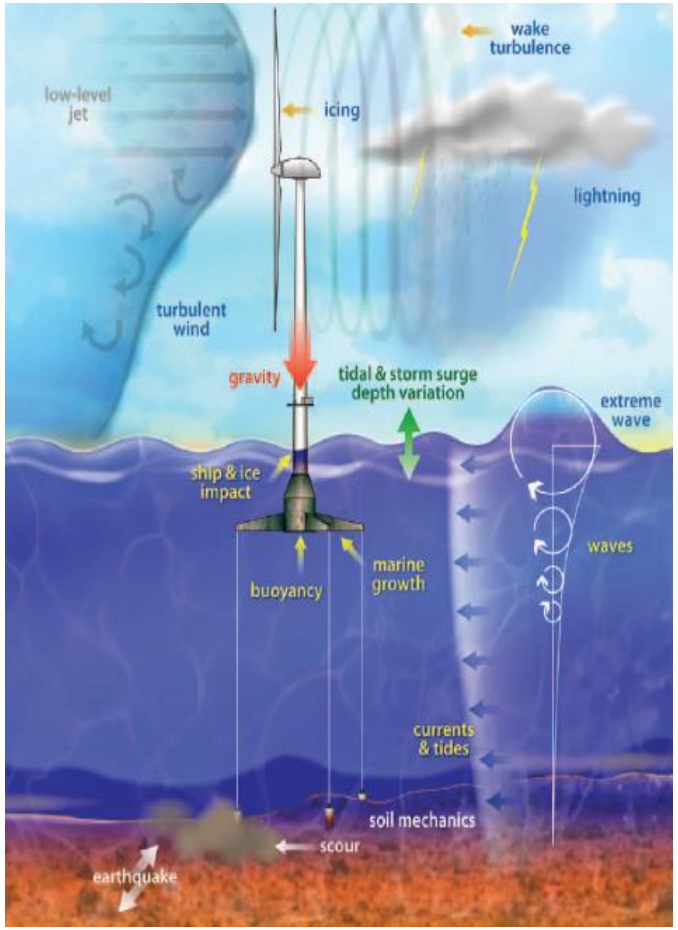
Outline

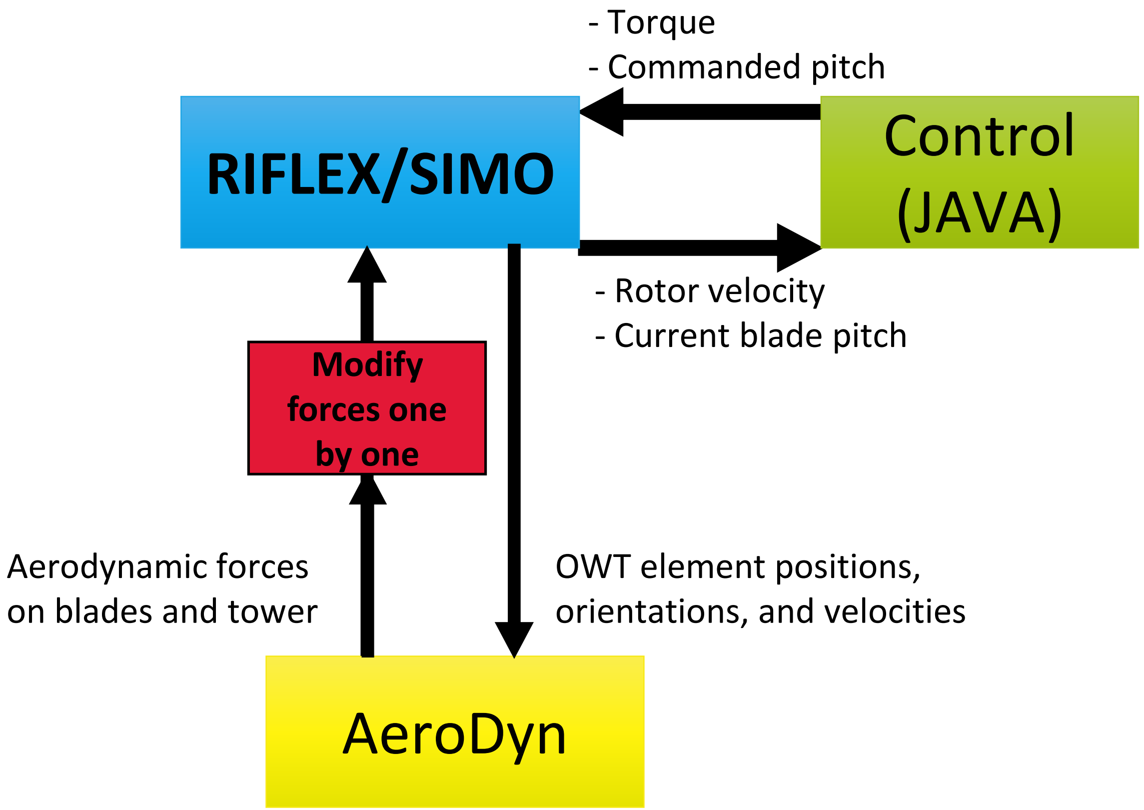
- Computational methodology
- Wind turbine models
- Load cases
- Sensitivity to
  - Aerodynamic loading in parked condition
  - Aerodynamic pitch moment
  - Aerodynamic sway force
  - Aerodynamic yaw moment
- Outlook



Computational methodology



Source: NREL/Wind power today, 2010.



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

Computational methodology: aerodynamic force modification

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

rotor frame

local frame

$$\tau_a^R = J_{BR}^F \tau_a^B$$

Aero forces/moments

Jacobian

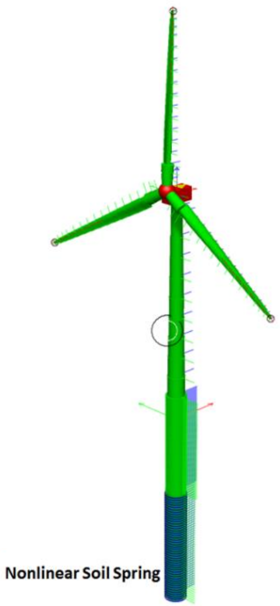
$$\hat{\tau}_a^R = \tau_a^R + modifications$$

$$\hat{\tau}_a^B = {J_{BR}^F}^{-1} \hat{\tau}_a^R$$

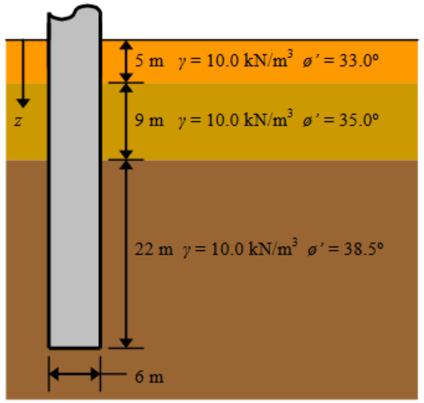
$$\hat{\tau}_a^B = {J_{BR}^F}^{-1} \frac{\sum_{i=1}^{N_b} \sum_{j=1}^{N_e} \hat{\tau}_{a\,ij}^R}{N_e N_b}$$

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



	5MW	10MW
Turbine	NREL 5MW	DTU 10MW
Monopile	OC3	Representative
Soil stiffness	OC3*	OC3*
Rated thrust (kN)	710	1500
Hub height (m)	90	119
Monopile diameter (m)	7	10
Thickness (cm)	6	8
Embedded length (m)	46	56



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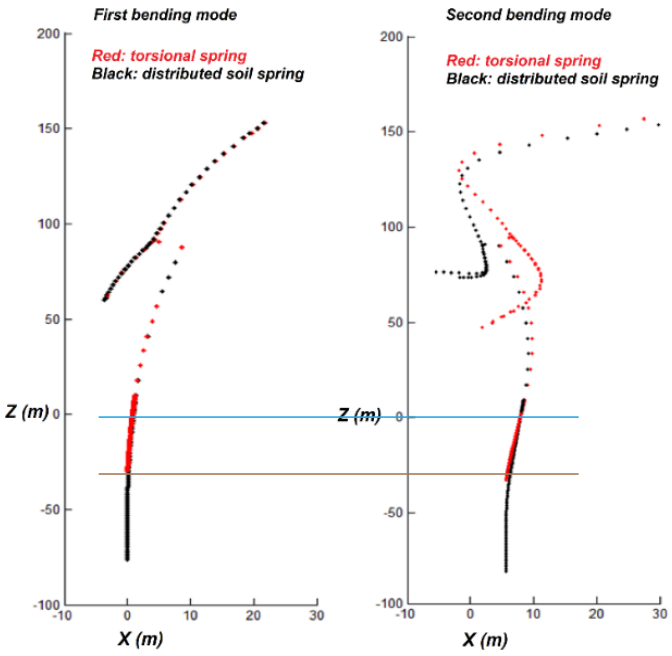
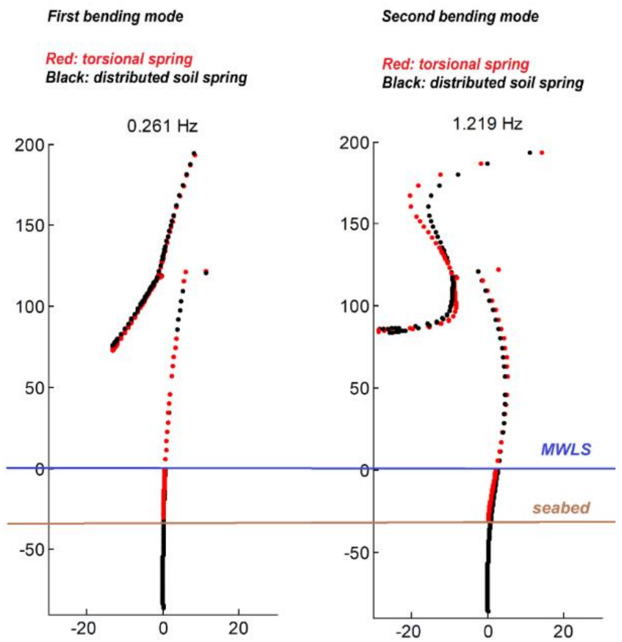
Eigenfrequencies and eigenmodes

	Mode	Linear distributed springs (below the seabed)	Single torsional spring (at seabed)
5 MW	1st bending (Hz)	0.261	0.261
	2nd bending (Hz)	1.239	1.423
10 MW	1st bending (Hz)	0.262	0.261
	2nd bending (Hz)	1.219	1.365





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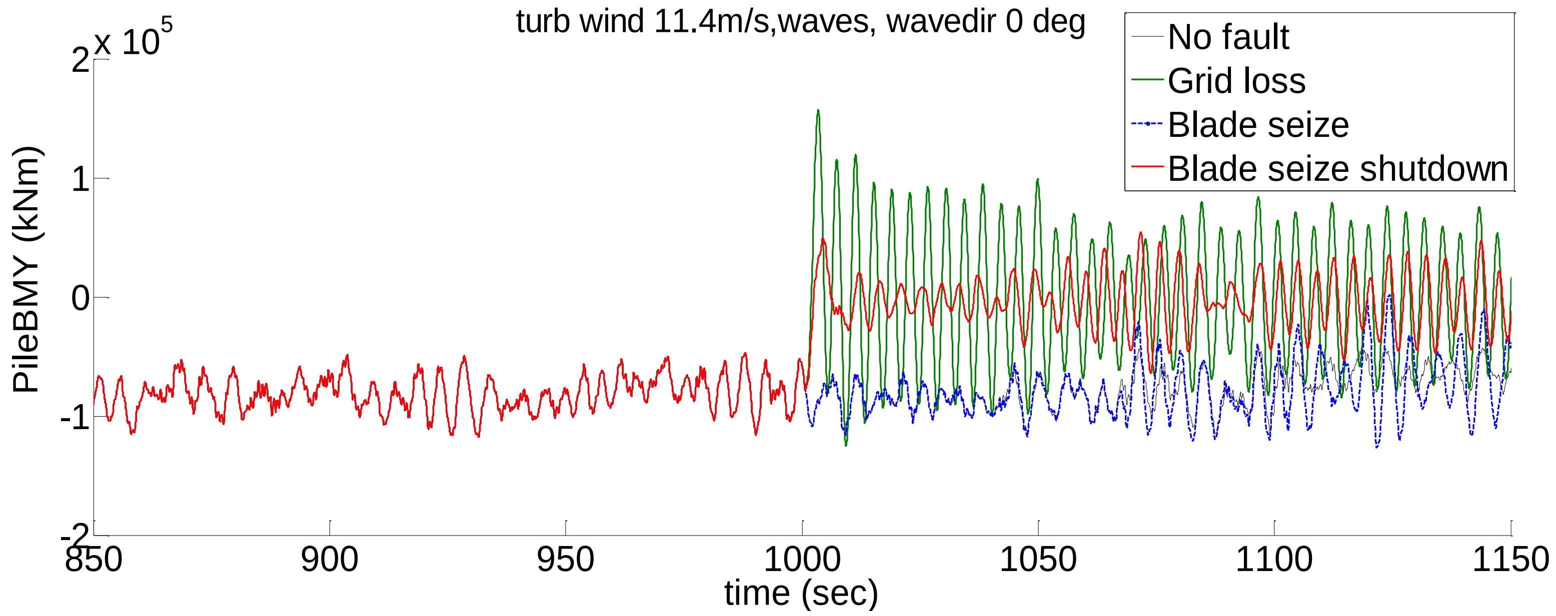
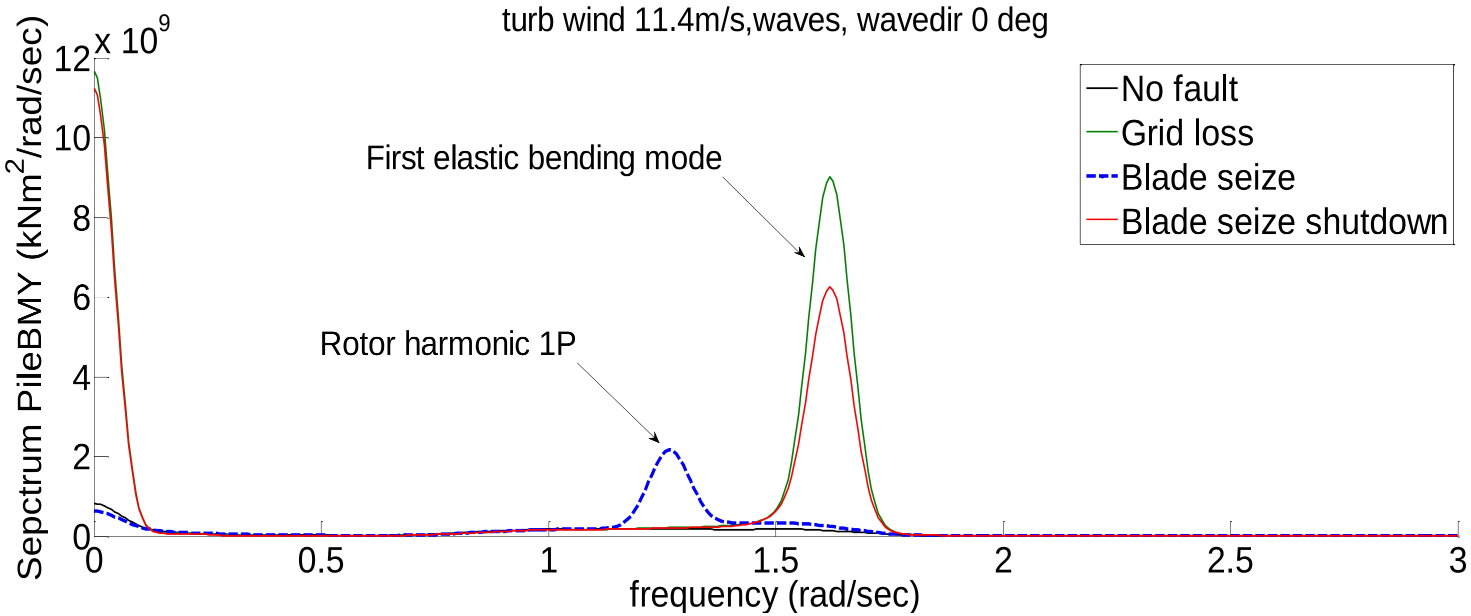
Load cases

- 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)

	EC 1	EC 2	EC 3	EC 4
Uw (m/s)	8	11.4	20	31.5
Hs (m)	1.2	1.8	3.6	9.5
Tp (s)	5.8	6.5	8.2	12.3
I% (NTM)	17.1	14.0	11.5	11.0

Fault cases





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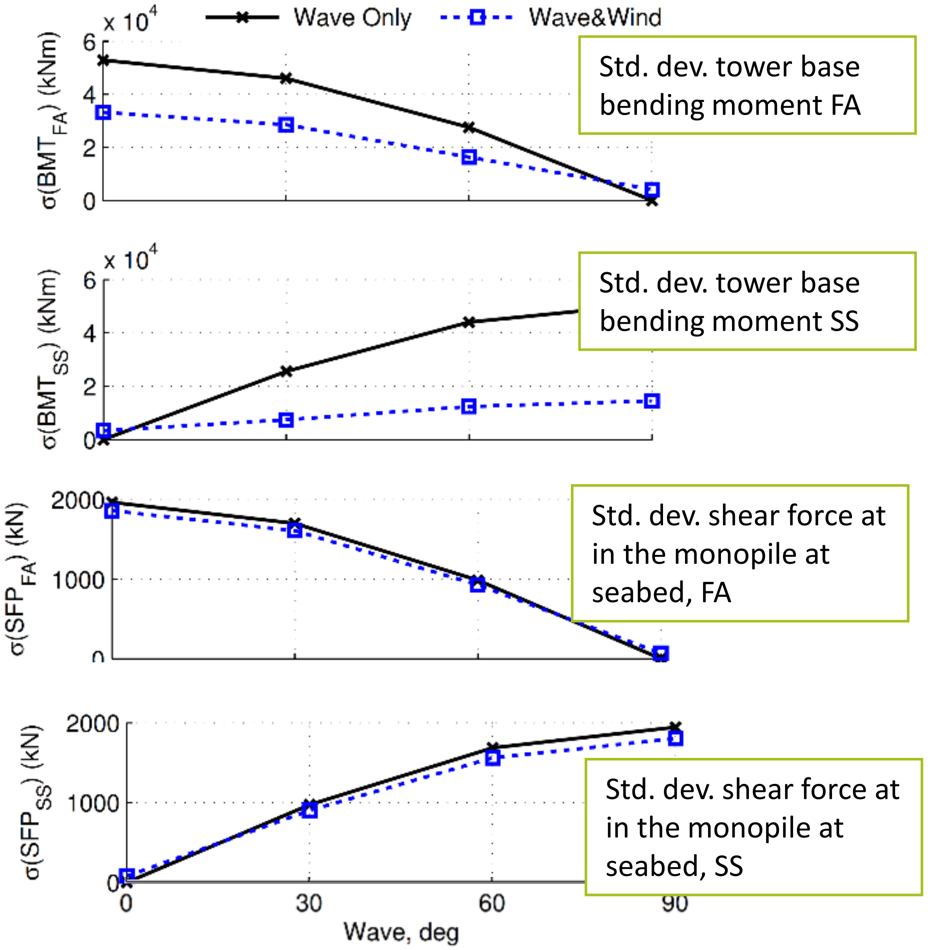
Aerodynamic loading in parked condition

- 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



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Sensitivity study results: summary

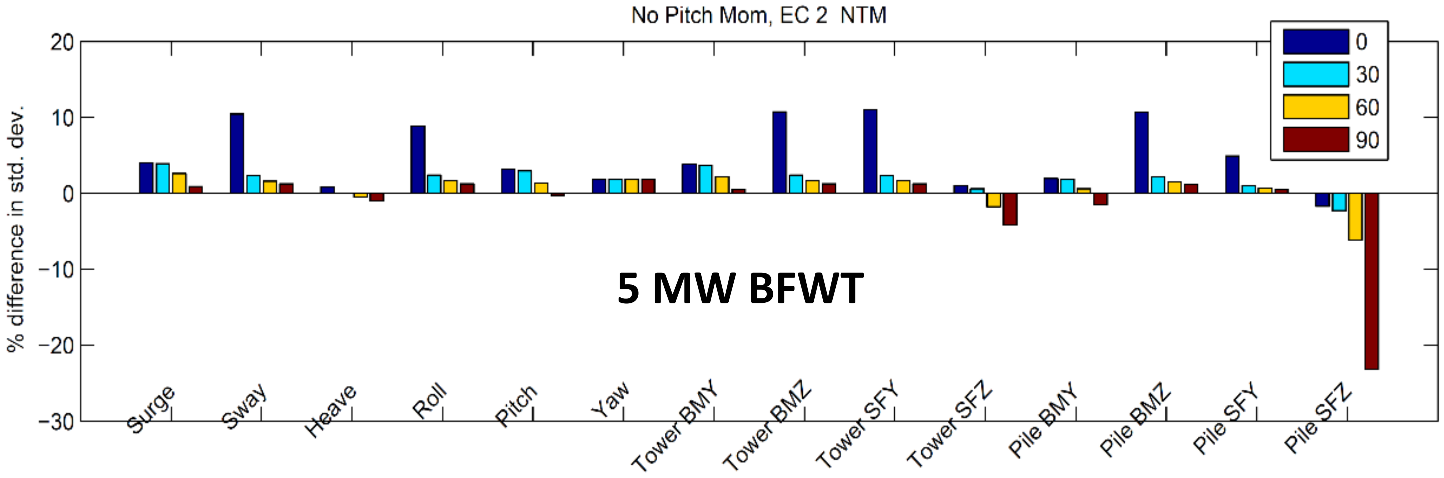
	5MW, normal	5MW, fault	10MW, normal	10MW, fault
Aerodynamic damping, parked	100%	N/A	100%	N/A
Aerodynamic pitch	<5%	20-30%	10-30%	25-40%
Aerodynamic sway	<7%	<5%	<5%	<10%
Aerodynamic yaw	60% *	100% *	90% *	100% *
Dynamic torque	<5%	<5%	<20%	<10%

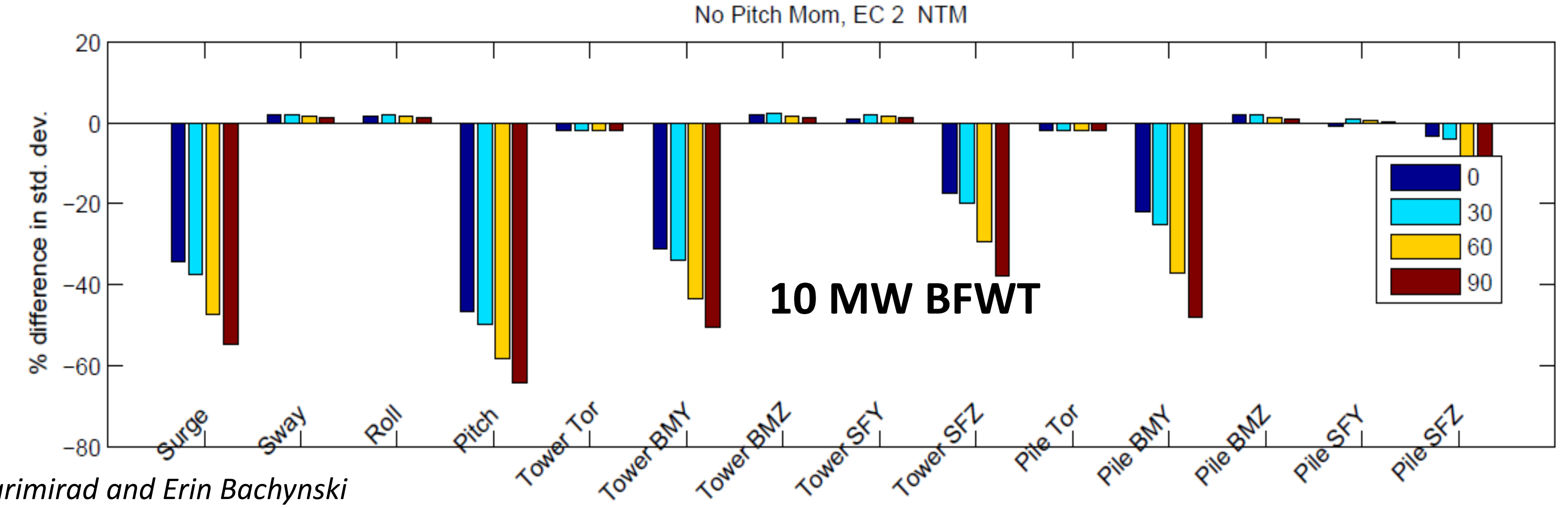
*only for torsion/yaw

- 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.





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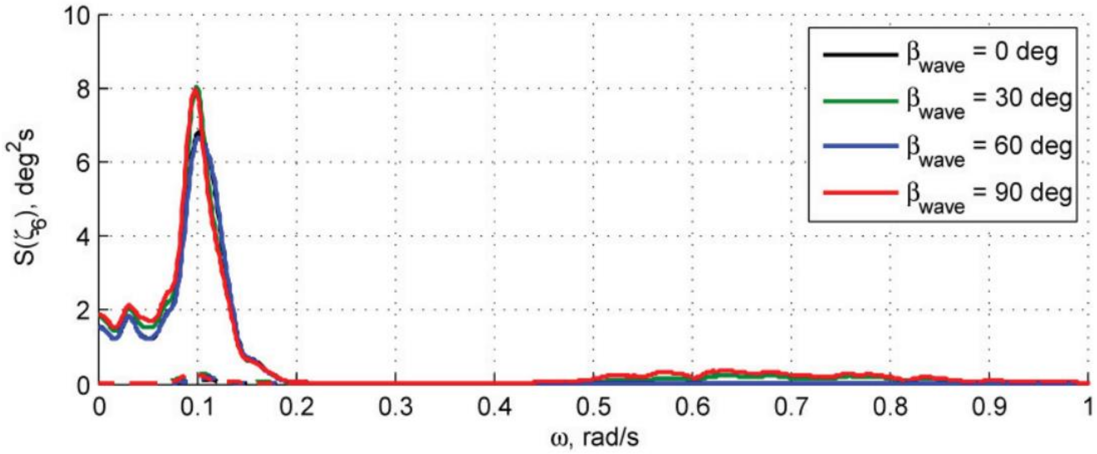
Aerodynamic yaw moment: fixed vs. floating

- 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

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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

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