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Sensitivity of the dynamic response of monopile-supported offshore wind turbines to structural and foundation damping

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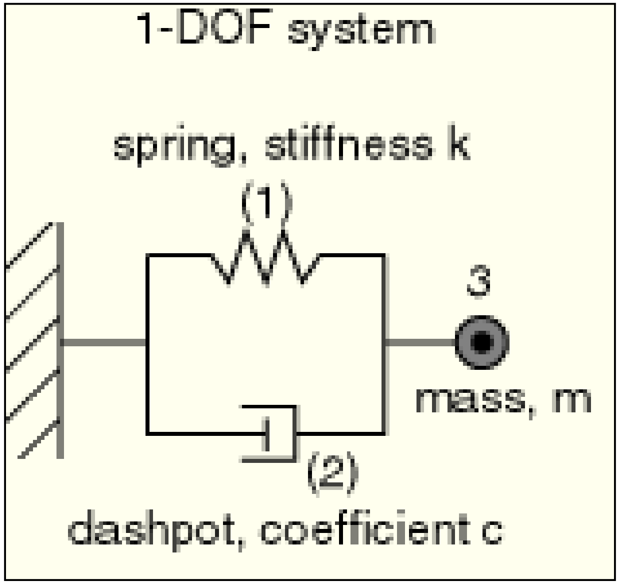
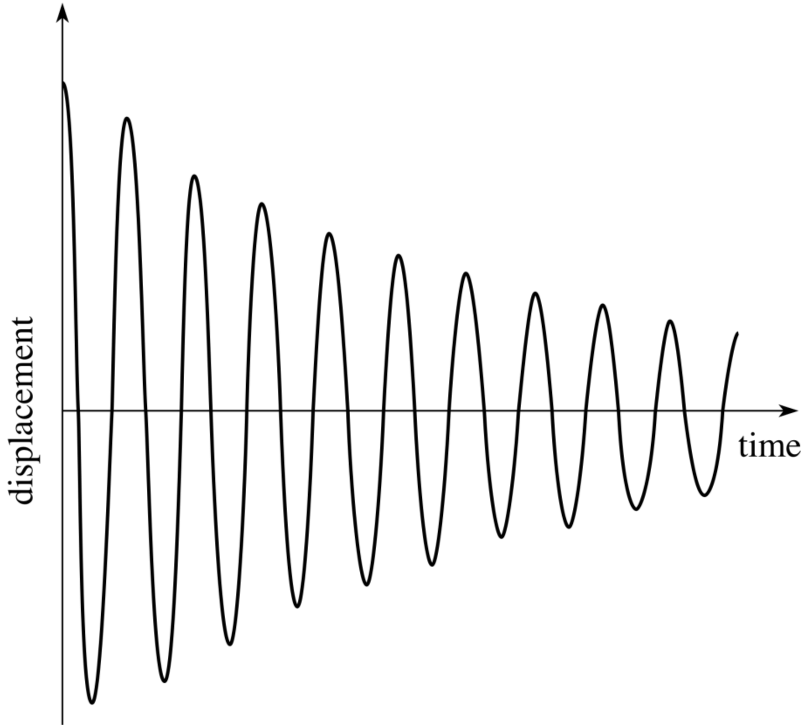
What is damping?

- Decrease in the amplitude of an oscillation as a result of energy being drained from the system to overcome resistive forces (i.e. frictional)

Dashpot proportional to damping





Free vibration after initial displacement

Overview

- Background
- Goal
- Tools, Software, and Models
- Conditions
- Parameter study methods
- Effects of increased foundation damping on peak loads
- Fatigue damage methods
- Effects of increased foundation damping on fatigue life
- Conclusions

Background and Motivation

Wind energy moving offshore to allow **larger turbines** access to higher, more consistent wind speeds

Offshore development requires **expensive** support structure: 20-30% total cost (Musial)

Costs kept low by using **minimum materials/weight**

Results in slender & flexible structure with **resonant frequency close to excitation frequencies**

Turbine falls subject to **load amplification** and **cyclic fatigue**

Foundation Damping

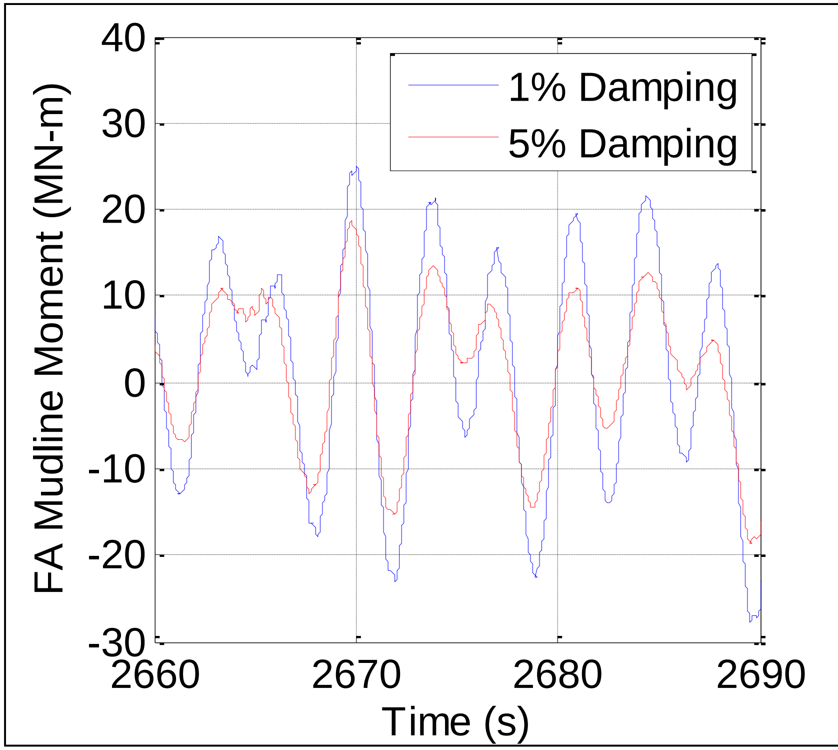
Damping counteracts load amplifications at or near resonant conditions

- Damping sources:
  - Aerodynamic
  - Hydrodynamic
  - Structural
  - Tuned mass
  - Soil (Foundation)

- Soil's complexity makes foundation damping difficult to define

  → IEC design standards do not account for it

  ∴Potentially overconservative (expensive)



Mudline moment time history

Effect of increased damping on load amplitude

Goal and Purpose

Determine how foundation damping affects structural demands over a variety of wind, wave, and operating conditions

↓

- Foundation damping advantageously incorporated into design guidelines
- More efficient OWT design
- Reduction in large cost of support structure

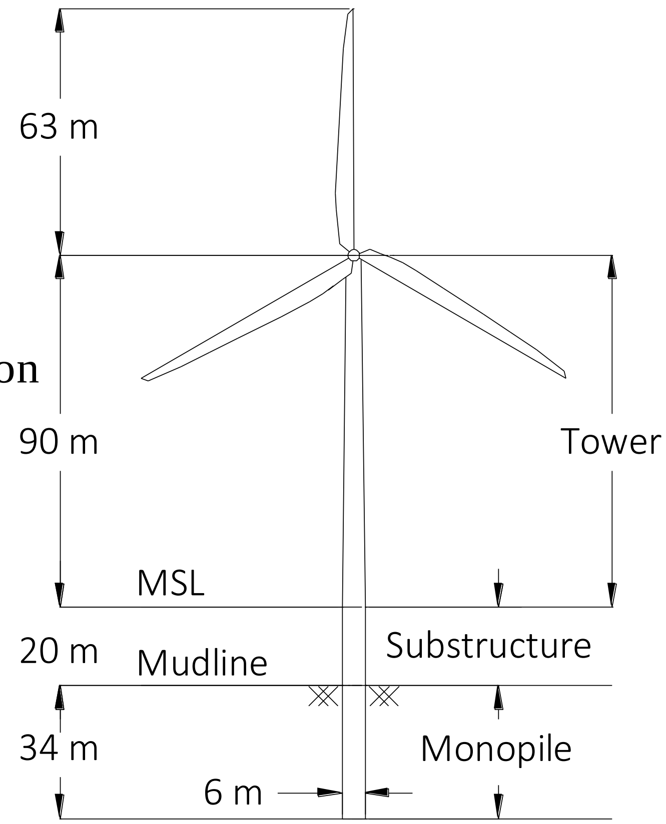
Tools, Software, and Models

- Theoretical OWT: **NREL 5MW Reference Turbine**
- Simulation Software: **FAST (NREL)**
  - Models both stochastic environmental loading and mechanical load effects
- Foundation Damping Model:
  - Total system damping for 1st bending mode

$$\zeta_1 = \zeta_{structural} + \zeta_{TMD} + \zeta_{aero} + \zeta_{hydro} + \zeta_{foundation}$$

  - No soil damping input, ζ_{soil}, in FAST → **Changes in soil damping modeled through changes in structural damping input,** $\zeta_{structural}$
  - Structural damping in FAST modeled with simplified Rayleigh damping

NREL 5MW Reference Turbine Schematic



Carswell

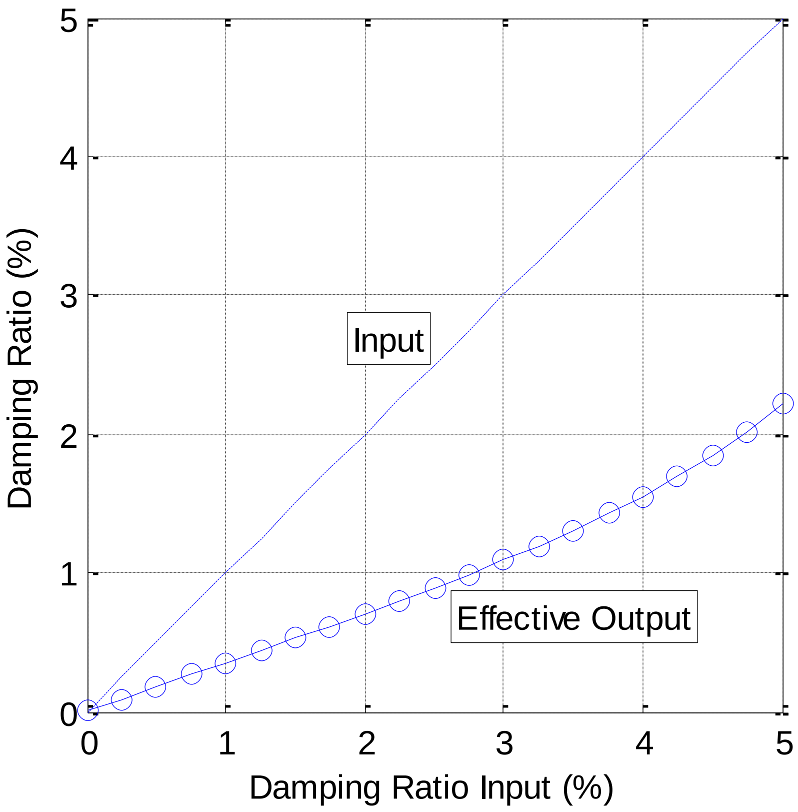
Input Conditions and Parameters

Conditions	
Water Depth	20 m
Platform Model	Fixed Bottom Monopile Offshore
Wind	Turbulent: TI = 11% IEC Kaimal Model
Waves	Irregular: JONSWAP/Pierson-Moskowitz spectrum

Parameters		
Damping Ratios	**1, 2, 3, 4, 5%**	
Significant Wave Heights	0, 2, 4, 6, 8 m	
Wind Speeds	3 m/s 11.4 m/s 25 m/s 30 m/s	$V_{cut\text{-}in}$ Rated $V_{cut\text{-}out}$ Parked and Feathered (P&F)

Damping Ratio Range

- FAST utilizes **simplified** Rayleigh damping model
  - Cuts simulation time
  - Reduces model accuracy



Damping ratio input/output inconsistencies verified by free vibration simulations

Wave Height Range

- Lower Limit → Still water → 0 m
- Upper Limit → Breaking Wave Criteria → 8 m

- Onset of breaking waves:

  $H_{max}/d = .78$

  $\mathbf{H_{max} = 15.6\ m}$

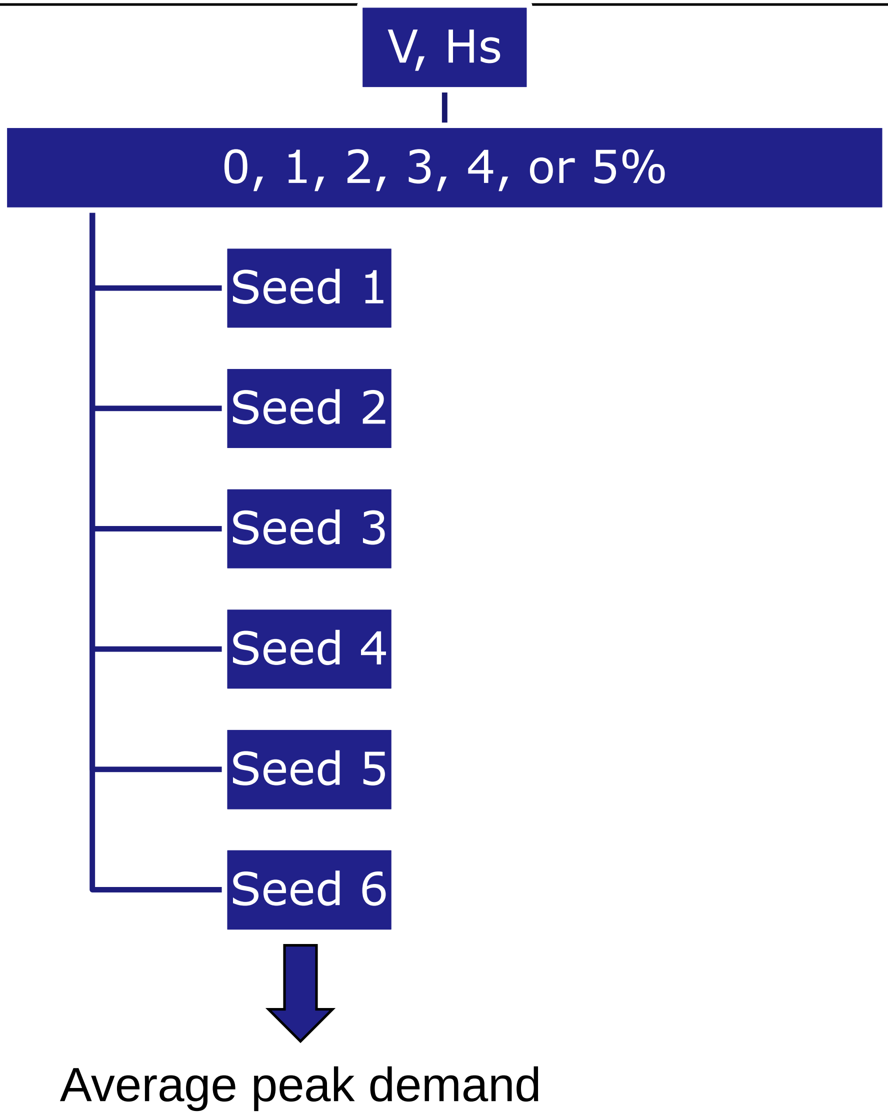
- Significant wave height:

  $H_{max} = 1.86H_s$

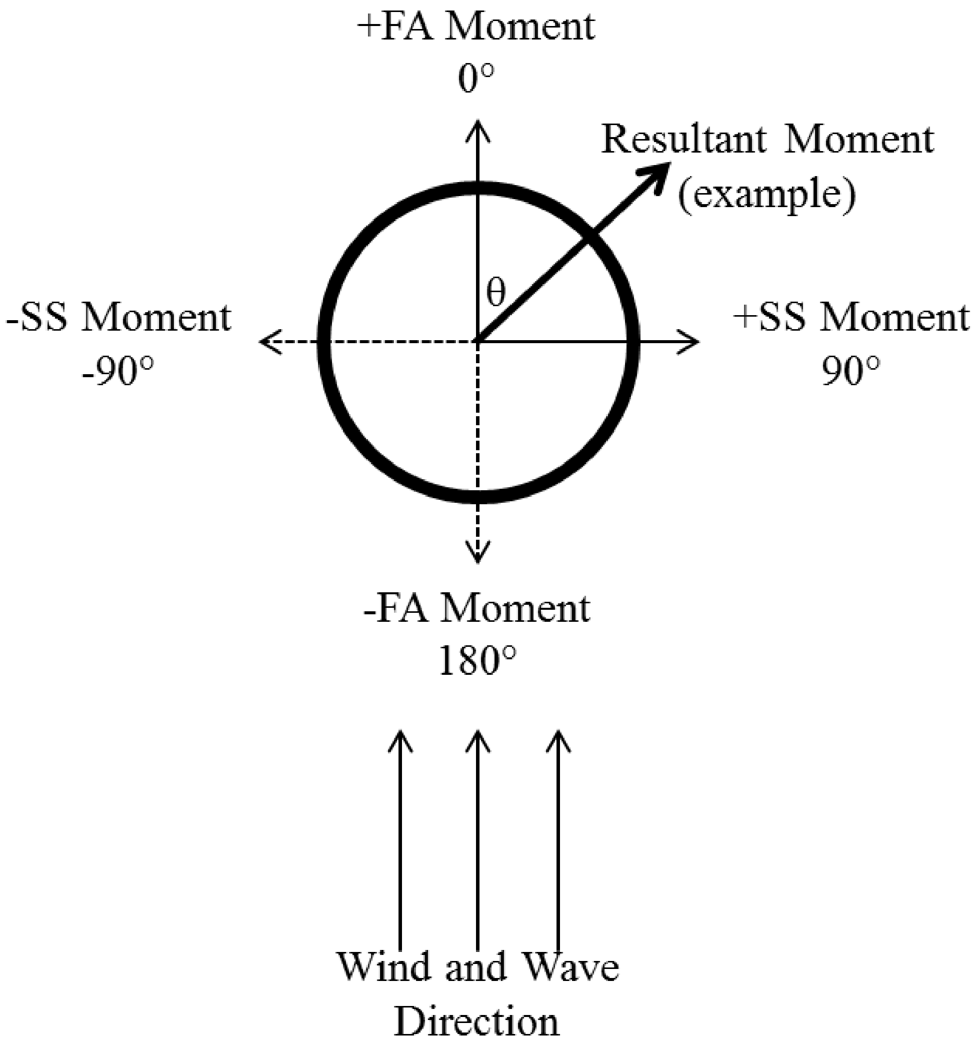
  $\mathbf{H_s = 8\ m}$

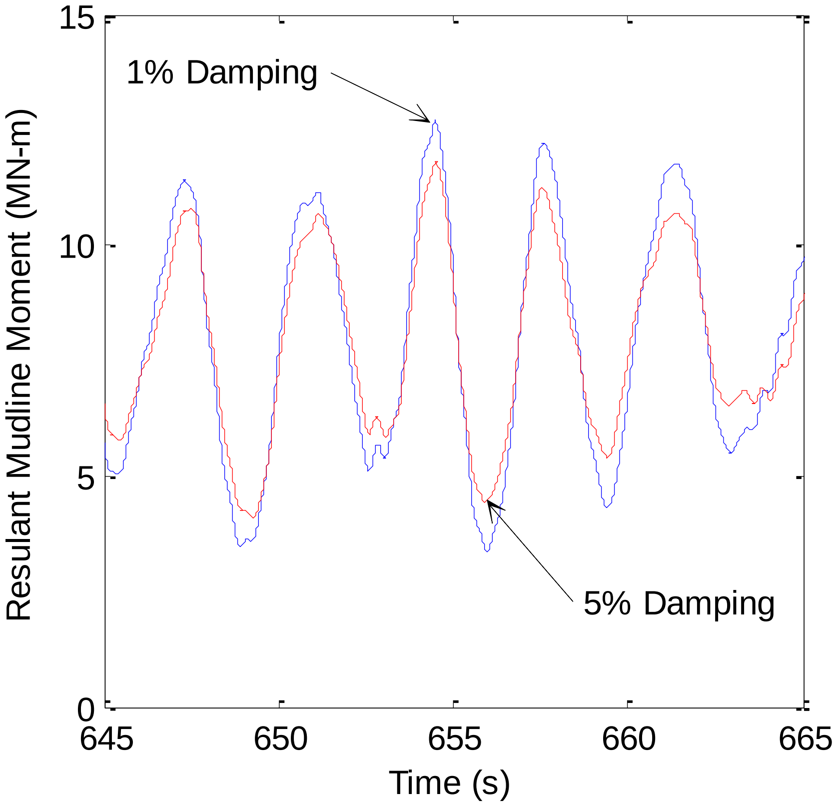
Methods of the Parameter Study

- For each distinct combination of wind speed and wave height:
  - 6 1-hr cases for each damping ratio 1-5%
  - Peak value from each differently seeded case averaged together



Effect of increased damping on resultant moment





Wind speed 3 m/s
Wave height 2 m

		Damping Ratio, %				
		1	2	3	4	5
		Resultant Moment, MN-m	Percent Reduction			
		Wind Speed 3 m/s (cut-in, operational)				
H_s, m	0	11.7	0.7%	1.3%	1.8%	2.2%
	2	26.3	**1.4%**	**2.5%**	**3.4%**	**4.2%**
	4	34.6	1.1%	1.8%	2.2%	2.5%
	6	49.9	0.8%	1.5%	2.1%	2.7%
	8	63.4	0.0%	0.0%	0.0%	0.0%
		Wind Speed 11.4 m/s (rated, operational)				
H_s, m	0	95.6	**0.5%**	**0.8%**	**1.1%**	**1.4%**
	2	102.1	0.4%	0.8%	1.1%	1.3%
	4	109.2	0.3%	0.6%	0.8%	1.0%
	6	116.2	0.2%	0.4%	0.6%	0.8%
	8	132.2	0.0%	0.0%	0.0%	0.0%
		Wind Speed 25 m/s (cut-out, operational)				
H_s, m	0	70.6	**1.3%**	**2.3%**	**3.0%**	**3.6%**
	2	74.0	0.9%	1.6%	2.2%	2.8%
	4	77.0	1.2%	2.1%	2.6%	3.1%
	6	80.9	0.5%	0.9%	1.2%	1.6%
	8	93.9	0.5%	0.9%	1.2%	1.4%
		Wind Speed 30 m/s (parked and feathered, non-operational)				
H_s, m	0	31.3	3.3%	6.1%	8.8%	10.5%
	2	35.3	**7.2%**	**11.3%**	**14.5%**	**17.3%**
	4	40.9	4.5%	9.7%	13.2%	15.6%
	6	53.0	5.1%	8.0%	9.8%	11.2%
	8	63.2	2.9%	3.7%	4.2%	4.5%

Effect of increased foundation damping on on resultant moment

- **Wind speed**
  - **Operating:** smallest effects on moment reduction
  - **P&F:** largest effects on load reduction

    →Lack of aerodynamic damping
- **Wave Height**
  - Maximum moment reductions in 0 or 2 m wave height cases (proximity to resonant conditions)

Wave Height, (m)	Wave Loading Frequency, f_{wave} (Hz)	*Frequency Ratios*		
		f_{wave}/f_n	f_{wave}/f_{1P}	f_{wave}/f_{3P}
0	∞	∞	∞	∞
2	0.20	0.74	1.00	0.59
4	0.14	0.52	0.71	0.41
6	0.12	0.43	0.58	0.34
8	0.10	0.37	0.50	0.29

Fatigue Damage Accumulation

Recommended Practice DNV-RP-C203
(Fatigue Design of Offshore Steel Structures)

- Palmgren-Miner linear cumulative damage

$$D = \sum_{i=1}^{k} \frac{n_i}{N_i} \leq \eta$$

D = accumulated fatigue damage

k = # of stress blocks (minimum 20)

n_i = # of stress cycles in stress block i

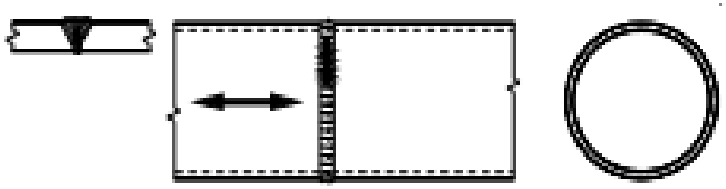
N_i = # of cycles to failure at stress range $\Delta\sigma$

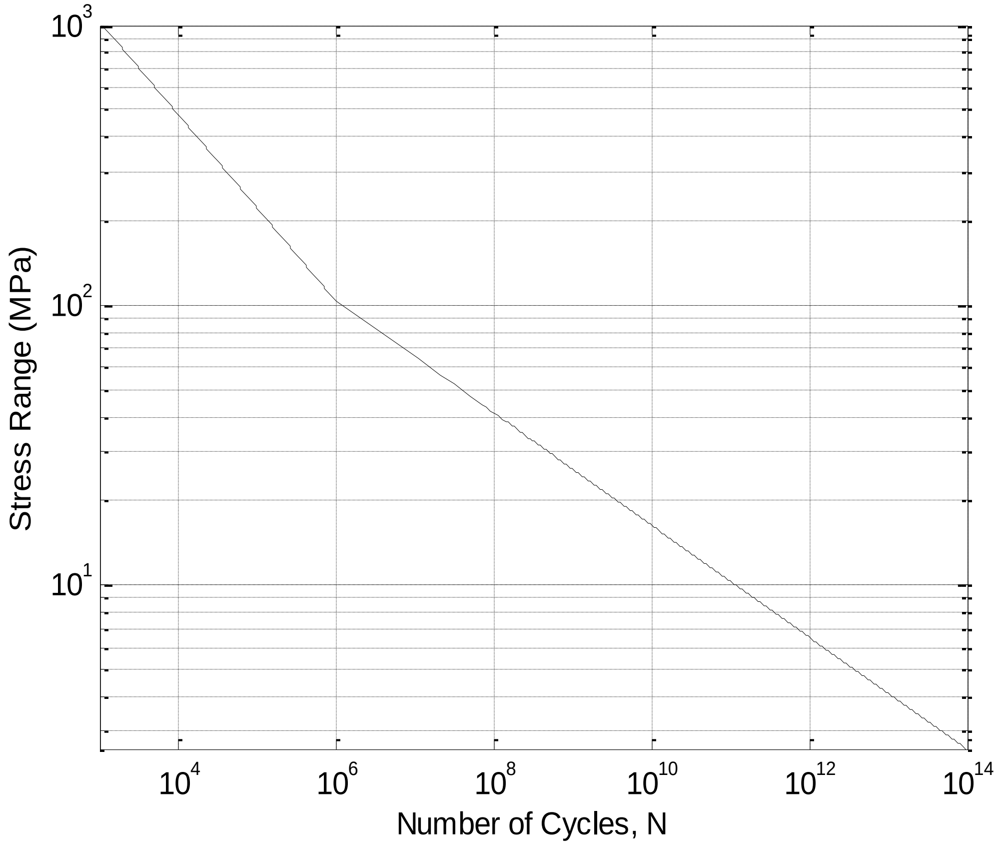
η = usage factor (1/Design Fatigue Factor)

Step 1: Select S-N curve

Stress life curve to determine cycles to failure

- Curve C1 best modeled tubular steel pipe connecting the turbine to the foundation at the mudline





C1 S-N curve for steel in seawater with cathodic protection (DNV 2005)

Step 2: Stress time histories

Use resultant moment to calculate bending stress

$$\sigma_{total}(t,\theta) = \sigma_b(t,\theta) + \sigma_n$$

Use weight to calculate normal stress

$$\sigma_n = \frac{P}{A}$$

NREL 5MW Turbine

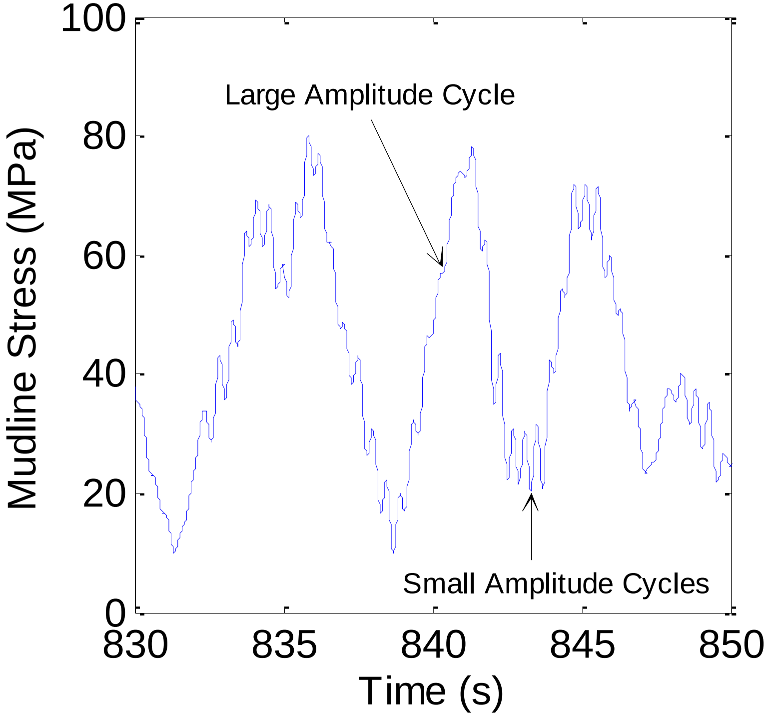
- FAST simulations → Resultant mudline moment, M
- Base diameter = 6 m → y = 3 m (maximum)
- Mass = 778,524 kg → P = 7,637 kN
- Base thickness = 0.027 m → I = 2.26 m^4

→ A = .507 m^2

Step 3: Rainflow counting

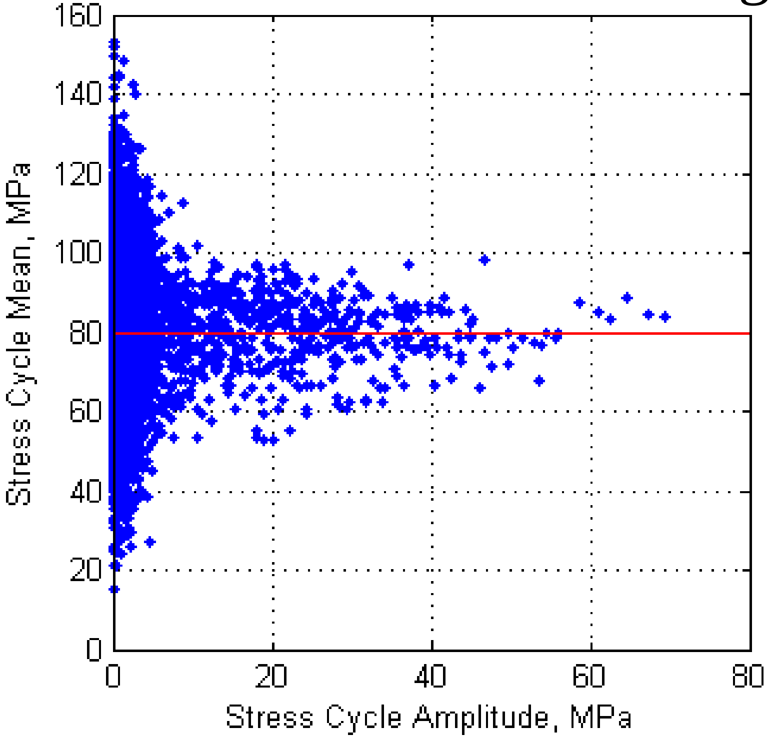
FA Upwind Location

Needs rainflow counting



Wind speed 25 m/s
Wave height 8 m
Damping ratio of 1%

Results of rainflow counting



Wind speed 11.4 m/s
Wave height 8 m
Damping ratio %1

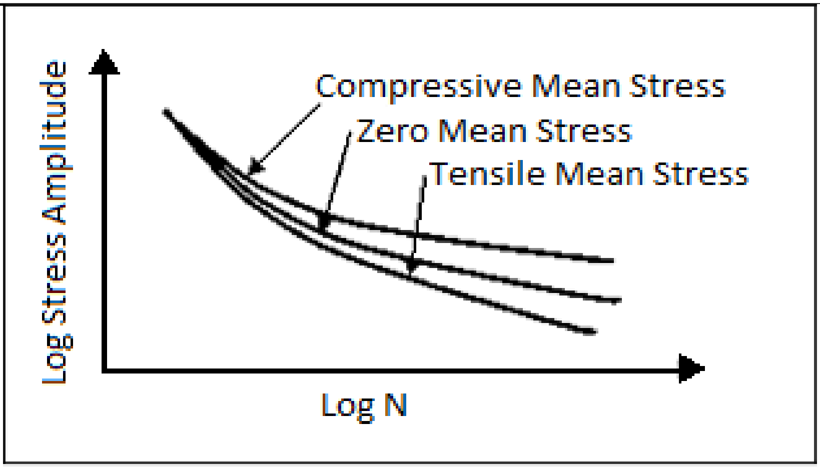
Step 4: Mean stress effects and 2D binnding

Mean stress effects

- Goodman correction

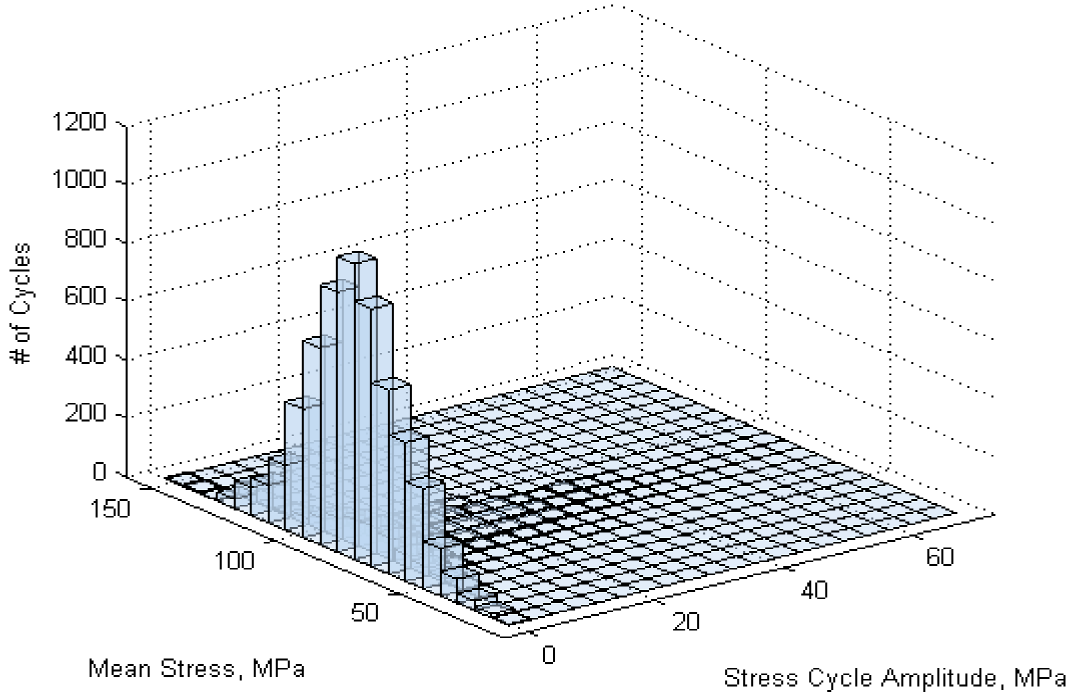
$$\frac{\sigma_a}{\sigma_e'} + \frac{\sigma_m}{\sigma_u} = 1$$

solve for

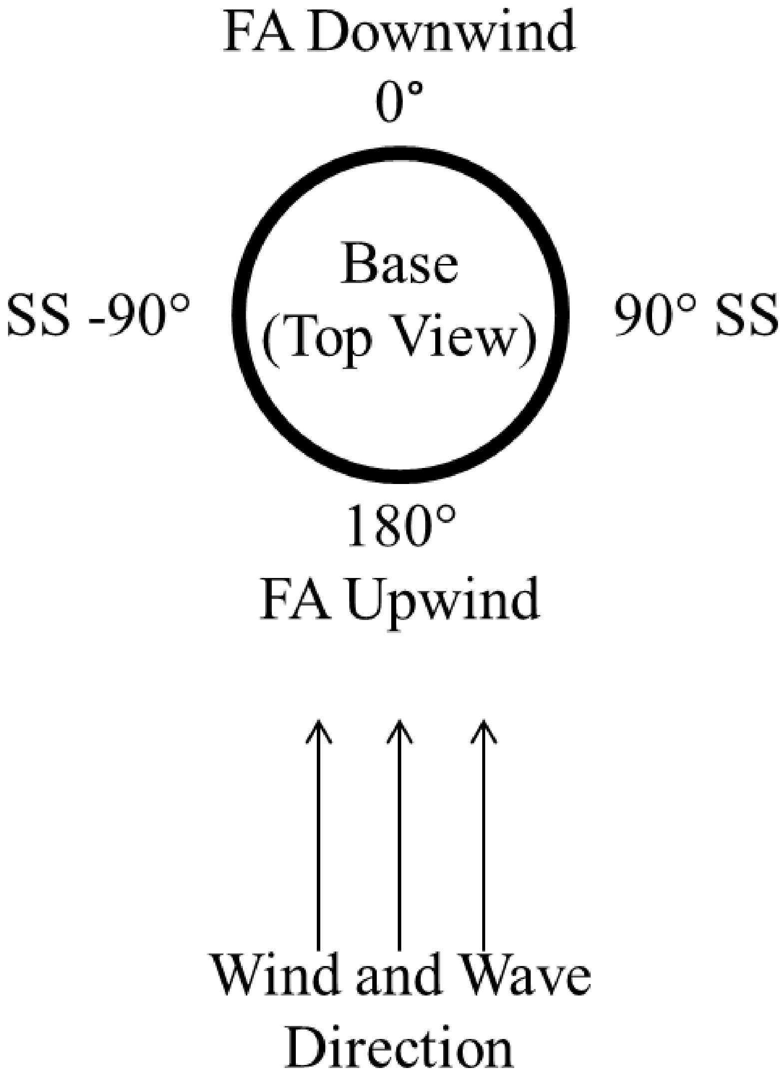


2D Binning

- 400 bins with nonzero mean and amplitude → 20 bins with zero mean and amplitude

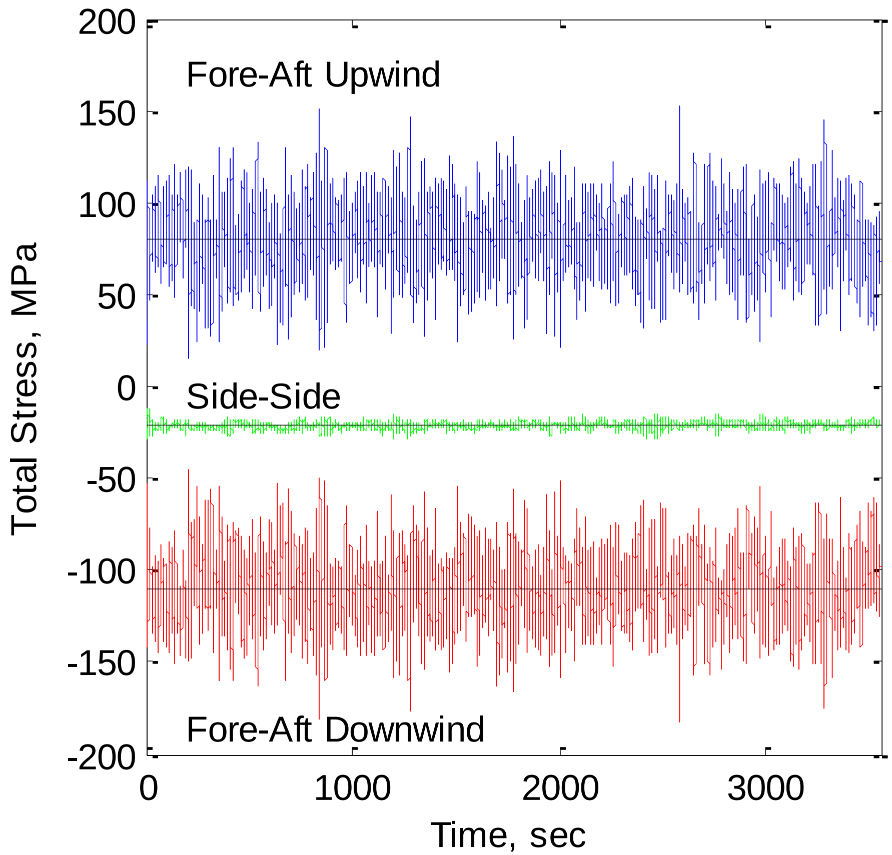


Locations of Maximum Damage Accumulation

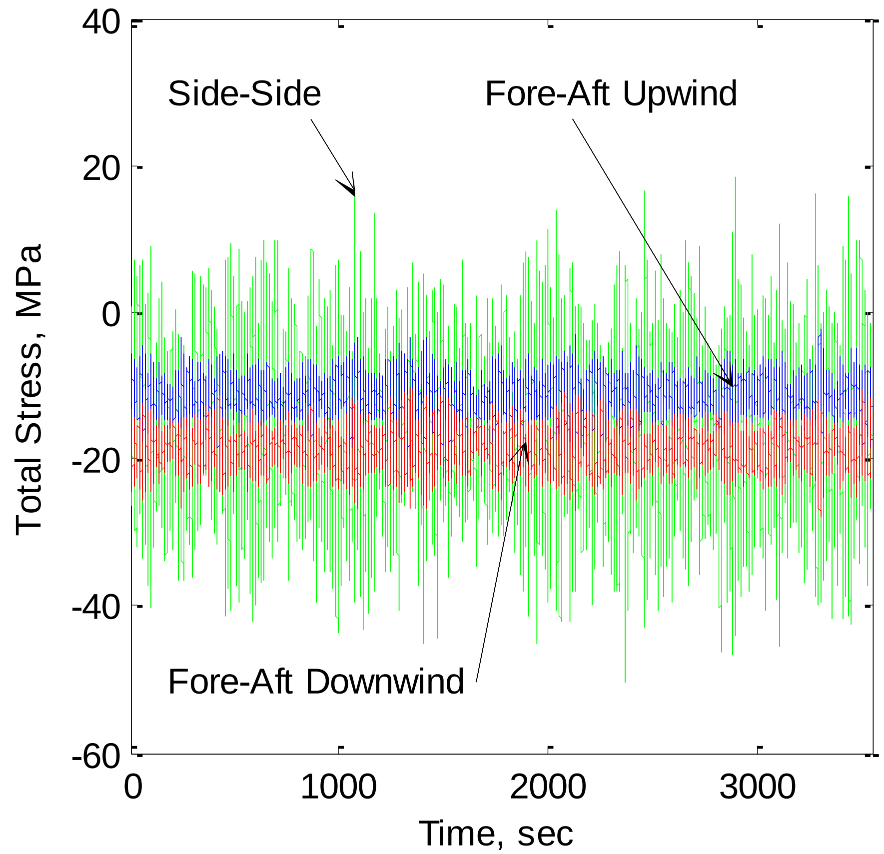


		Wind Speed, m/s			
		3	**11.4**	**25**	**30**
Wave Height, m	**0**	180°	180°	-170°	90°
	2	180°	180°	-175°	90°
	4	180°	180°	-175°	165°
	6	180°	180°	-175°	180°
	8	180°	180°	-175°	180°

Total Stress Time Histories and Means



Wind speed 11.4 m/s (operating)
Wave height 8 m
Damping ratio 5%



Wind speed 30 m/s (P&F)
Wave height 0 m
Damping ratio 5%

		Damping Ratio, % 1	2	3	4	5
		Damage	Percent Reduction			
		Wind Speed 3 m/s (cut-in)				
Hs, m	0	2.0e-11	**24%**	15%	**30%**	**47%**
	2	5.2e-07	11%	**18%**	24%	29%
	4	3.4e-06	8%	14%	18%	21%
	6	1.3e-05	4%	8%	12%	14%
	8	3.6e-05	3%	7%	10%	12%
		Wind Speed 11.4 m/s (rated)				
Hs, m	0	9.4e-06	**6%**	**10%**	**14%**	**17%**
	2	2.2e-05	5%	9%	12%	16%
	4	4.5e-05	4%	8%	10%	13%
	6	8.0e-05	3%	6%	8%	10%
	8	1.4e-04	2%	5%	6%	7%
		Wind Speed 25 m/s (cut-out)				
Hs, m	0	2.0e-05	**11%**	**20%**	**26%**	**31%**
	2	3.1e-05	10%	17%	23%	28%
	4	5.1e-05	7%	11%	16%	20%
	6	8.1e-05	6%	11%	15%	19%
	8	1.3e-04	5%	10%	13%	15%
		Wind Speed 30 m/s (parked and feathered)				
Hs, m	0	5.5e-06	18%	31%	40%	49%
	2	5.6e-06	18%	31%	41%	50%
	4	1.4e-05	**38%**	**55%**	**64%**	**69%**
	6	3.7e-05	33%	46%	54%	59%
	8	7.7e-05	28%	40%	46%	50%

Percent Reduction in Damage due to increased damping

- **Wind speed**
  - **Operating:** smallest effects on damage reduction
  - **P&F:** largest effects on load reduction

    →Lack of aerodynamic damping
- **Wave Height**
  - Maximum moment reductions in 3m wave height case
    - Smallest wave height (frequency ratio)
    - in which wave loading dominates

Damage contribution from stress amplitude percentiles

Increased foundation damping creates greater percent reductions in fatigue damage values than for resultant moment

Stress Amplitudes	Percent Contribution to Total Damage	Stress amplitude percentile to damage contribution ratio
Top 10%	18%	1.8
Top 20%	30%	1.5
Top 30%	48%	1.6
Top 40%	66%	1.6
Top 50%	82%	1.6

→ Small decrease in stress amplitude can translate to a large decrease in damage and large increase in fatigue life

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