The Role of Structural/Foundation Damping in Offshore Wind Turbine Dynamics

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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

Overview

- Motivation
- Tools, software, and models
- Conditions
- Parameter study methods
- Effects of damping on peak loads
- Fatigue damage methods
- Effects of damping on fatigue life
- Conclusions

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**

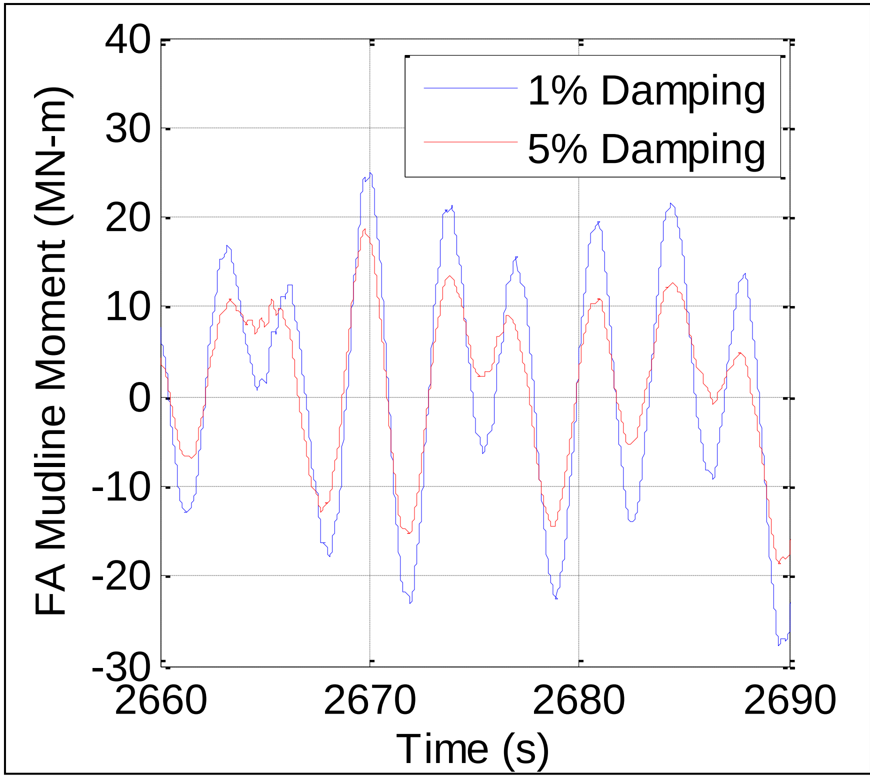
Turbine falls subject to **load amplification** and **cyclic fatigue**

Foundation Damping

Damping is crucial in counteracting load amplifications at or near resonant conditions

- Damping sources:
  - Aerodynamic
  - Hydrodynamic
  - Structural
  - Tuned mass
  - Soil (Foundation)
- Most damping sources determined accurately, but soil's complexity makes damping difficult to define

  → IEC standards do not account for soil damping, which can be 1.5% (Versteijlen, 2011)



Mudline moment time history

Effect of increased damping on load amplitude

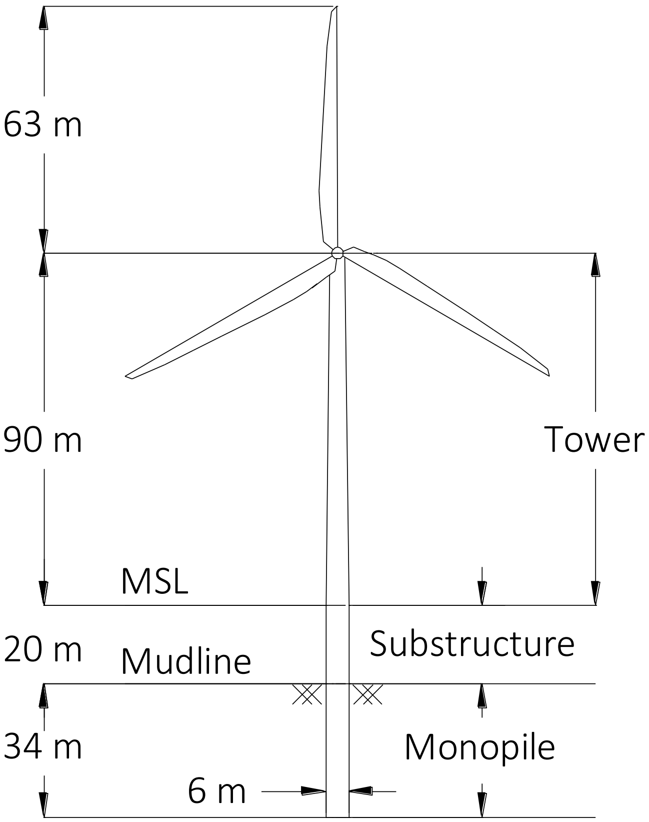
Tools, Software, and Models

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

$$\zeta_1 = \zeta_{\text{monopile}} + \zeta_{\text{tower}} + \zeta_{\text{aero}} + \zeta_{\text{hydro}} + \zeta_{\text{soil}}$$

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

NREL 5MW Reference Turbine Schematic



Carswell

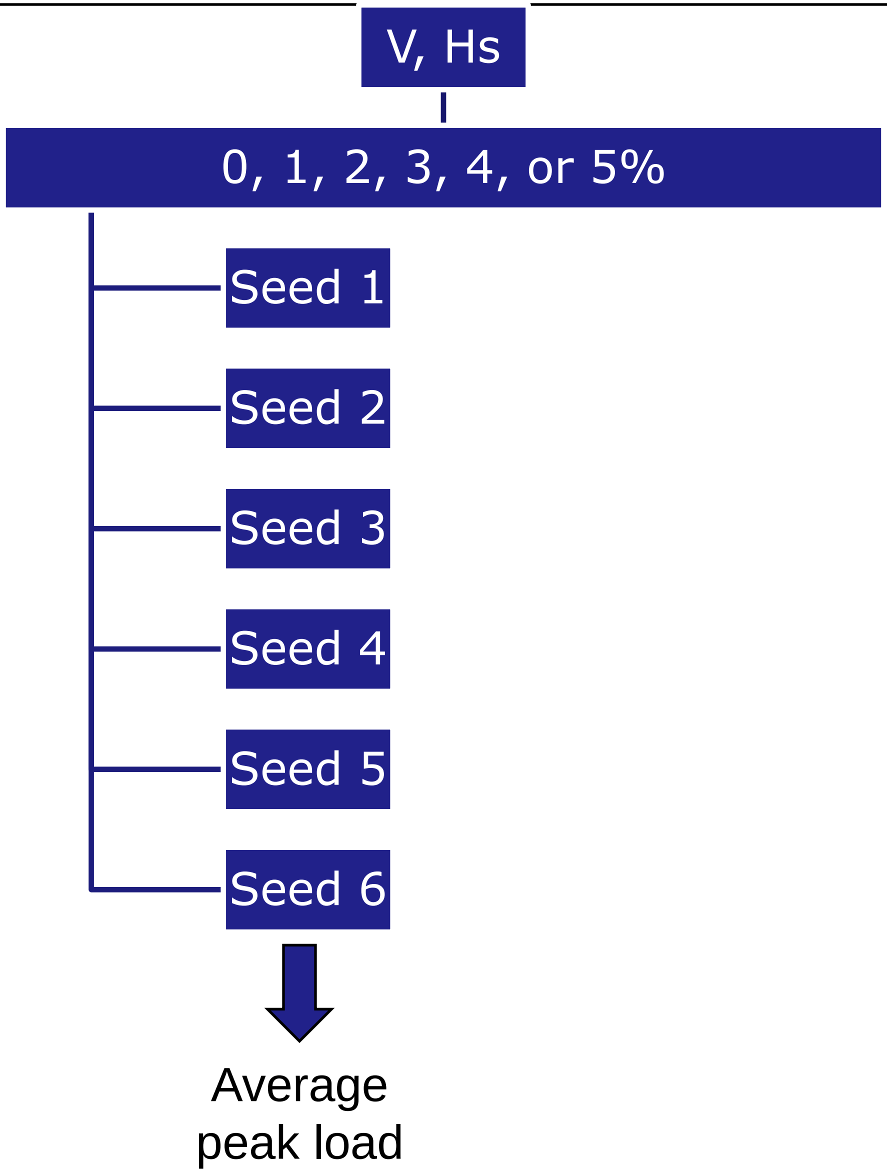
Conditions and Parameters

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

Methods

- For each distinct combination of wind speed and wave height:
  - 6 1-hr cases for each damping ratio 0-5%
  - Peak value from each differently seeded case averaged together


V, Hs

0, 1, 2, 3, 4, or 5%

Seed 1

Seed 2

Seed 3

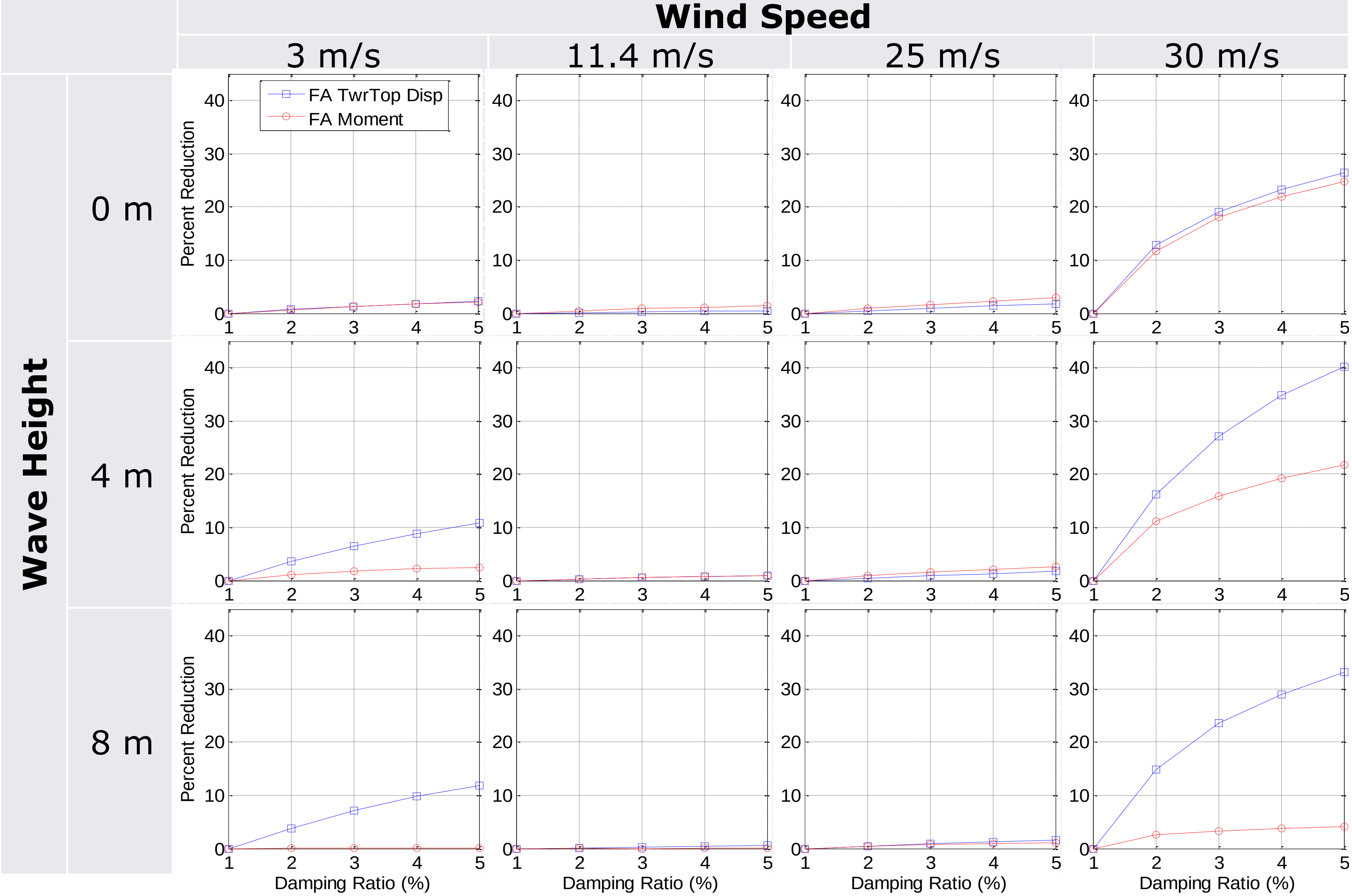
Seed 4

Seed 5

Seed 6

Average
peak load

Percent Reduction of **FA Tower Top Displacement** & **FA Mudline Moment** from Value at 1% Damping Ratio



Observations

- **Operating cases**
  - Increased damping has negligible effects on load reduction
- **Parked & Feathered cases**
  - Increased damping has significant effects on load reduction

→Lack of aerodynamic damping from spinning rotor

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)

= ⅓ for turbine base connection

Fatigue Damage Accumulation: Step 1

Use moment to calculate bending stress

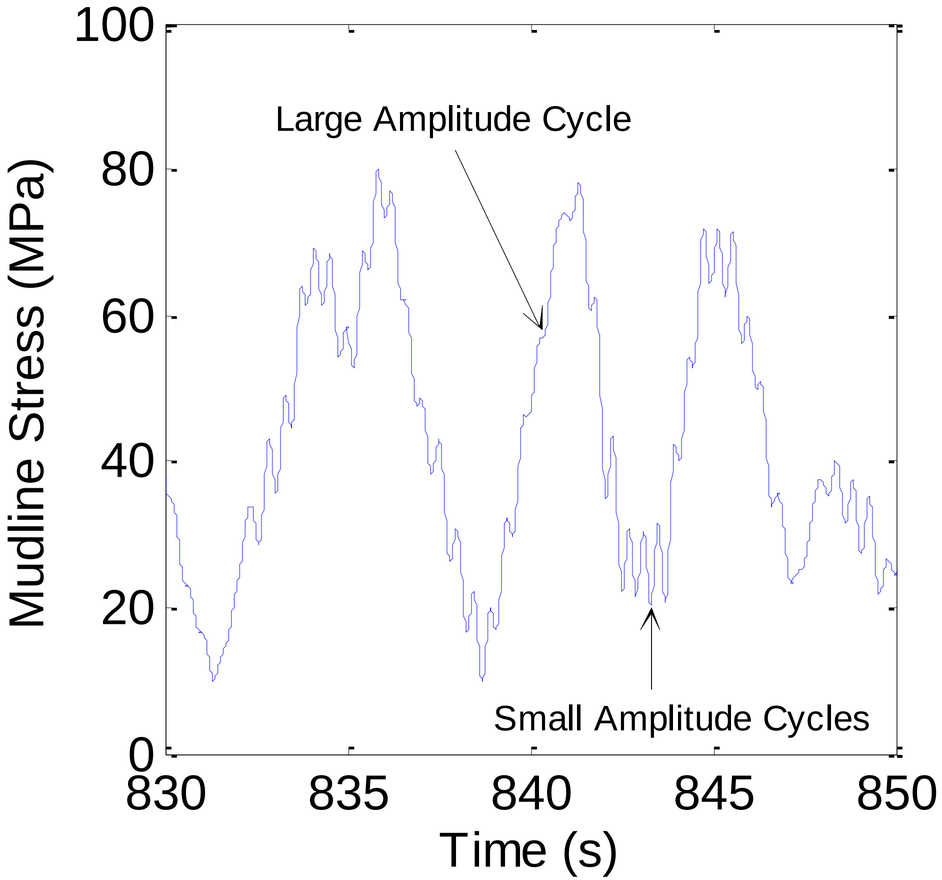
$$\sigma = \frac{My}{I}$$

- NREL 5MW Turbine
    - FAST simulations → FA mudline moment, M
    - Base diameter = 6 m → y = 3 m (maximum)
    - Base thickness = 0.027 m → I = 2.26 m^4

Fatigue Damage Accumulation: Step 2

Rainflow counting to interpret stress time history

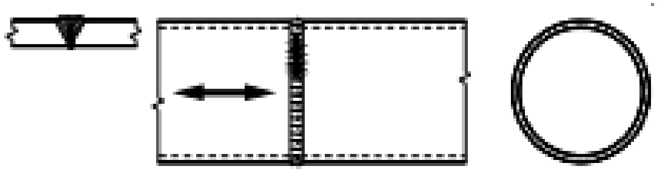
- Stochastic environmental loading → large variations in stress cycle amplitudes
- Rainflow counting digests stress time history to produce # of cycles, n_i, at different stress ranges, $\Delta\sigma$



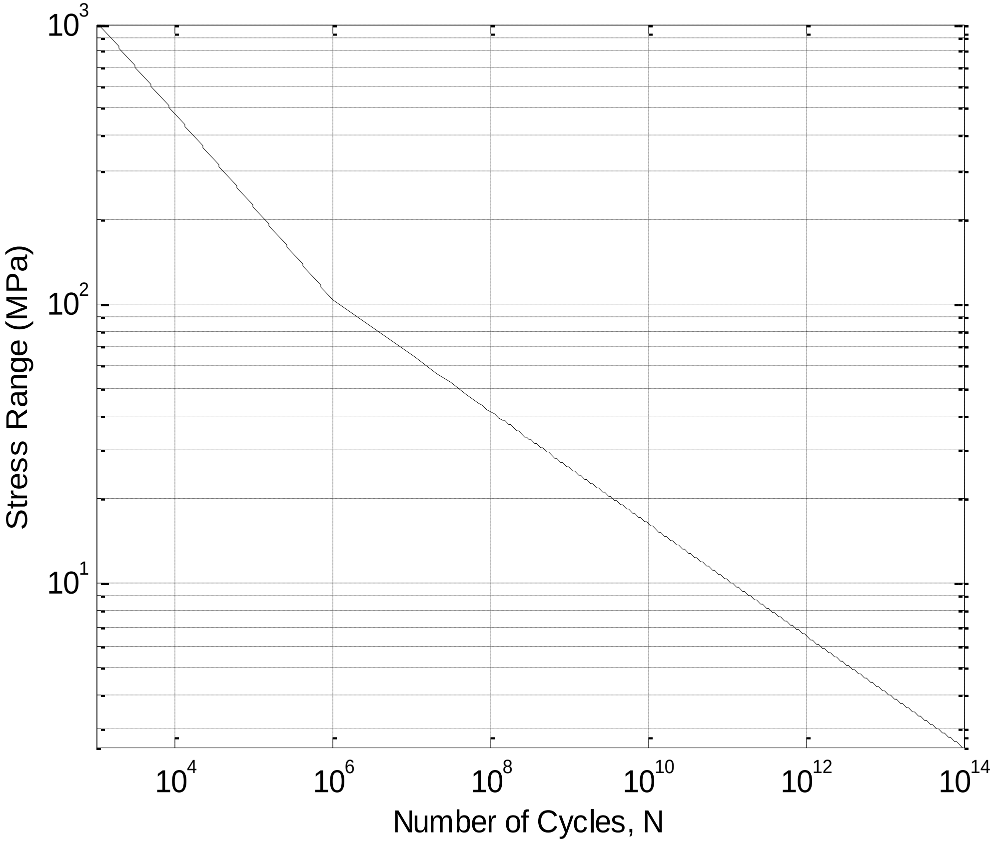
Fatigue Damage Accumulation: Step 3

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 in section A.9 (Hollow Sections): circumferential butt weld made from both sides dressed flush



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

Fatigue Damage Accumulation Results

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

Accumulated Fatigue Damage, D, for 1 hour (scaled)

		Wind Speed											
		3 m/s			**11.4 m/s**			**25 m/s**			**30 m/s**		
		0%	**3%**	**5%**	**0%**	**3%**	**5%**	**0%**	**3%**	**5%**	**0%**	**3%**	**5%**
Wave Height	**0 m**	1e-4	4e-5	3e-5	1.7	1.4	1.3	7.2	5.0	4.3	0.17	4e-3	2e-3
	2 m	0.28	0.20	0.17	4.1	3.4	3.1	11.5	8.3	7.2	11.0	0.61	0.36
	4 m	1.7	1.3	1.2	8.7	7.5	7.0	19.4	14.8	13.2	31.6	2.9	2.0
	6 m	6.6	5.5	5.1	18.0	15.7	14.9	32.3	25.6	23.3	57.0	9.6	7.3
	8 m	18.8	16.1	15.3	36.3	32.5	31.4	56.6	46.2	42.6	115.8	24.9	19.9

Least damage ▭ Most damage

*Values for **comparison purposes only**

Conclusions

Increased damping in Operational Conditions

- **Small effect** on peak load reduction (<5% most cases) and fatigue damage reduction

Increased damping in Parked & Feathered Conditions

- **Significant peak load reduction and fatigue damage reduction** due to lack of aerodynamic damping
  - Up to 40% reduction in peak FA tower top displacement
  - Up to 27% reduction in peak FA mudline moment

Future Work	Use NREL Mlife software to: 1.) Calculate fatigue life and compare to Palmgren-Miner 2.) Evaluate effect of damping on both short-term and lifetime damage equivalent loads (DELs)

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