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Fully vs. Sequentially Coupled Loads Analysis of Offshore Wind Turbines

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INTRODUCTION

The design and analysis methods for offshore wind turbines must consider the aerodynamic and hydrodynamic loads and response of the entire system (turbine, tower, substructure, and foundation) coupled to the turbine control system dynamics. Whereas a **fully coupled** (turbine and support structure) modeling approach is more rigorous, intellectual property concerns can preclude this approach. In fact, turbine control system algorithms and turbine properties are strictly guarded and often not shared. In many cases, a partially coupled analysis using separate tools and an exchange of reduced sets of data via sequential coupling may be necessary.

In the **sequentially coupled** approach, the turbine and substructure designers will independently determine and exchange an abridged model of their respective subsystems to be used in their partners' dynamic simulations. Although the ability to achieve design optimization is sacrificed to some degree with a sequentially coupled analysis method, the central question here is whether this approach can deliver the required safety and how the differences in the results from the fully coupled method could affect the design. This work summarizes the scope and preliminary results of a study conducted for the Bureau of Safety and Environmental Enforcement aimed at quantifying differences between these approaches through aero-hydro-servo-elastic simulations of two offshore wind turbines on a monopile and jacket substructure.

SUBSTRUCTURES

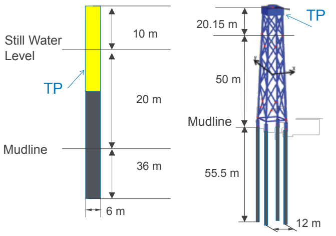


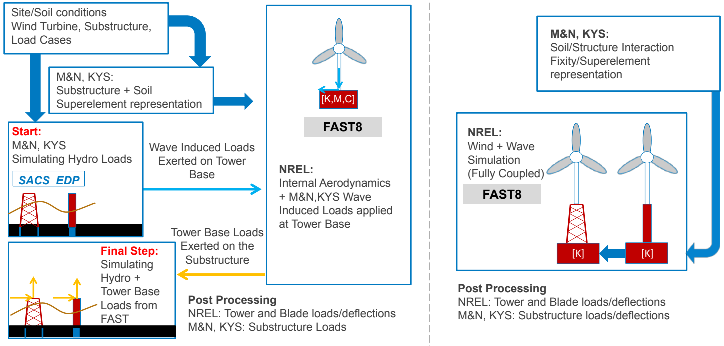
Figure 3. Select substructures for this study: monopile (left, from the Offshore Code Comparison Collaboration [1]) and jacket (right, from Offshore Code Comparison Collaboration Continuation [2]) .

TURBINE PARAMETERS

Parameter	Value
Rating [MW]	5
IEC Class	I-B
Rotor Configuration	Upwind, 3 blades
Control	Variable speed, collective pitch
Drivetrain	Multistage gearbox
Rotor/hub Diameter [m]	126 / 3
Hub Height [m]	90
Cut-in, Rated, Cut-out Wind Speeds [m/s]	3 , 11.4, 25 m/s
Cut-in, Rated, Cut-out Rotor Speeds [m/s]	6.9, 12.1 RPM
Rated Tip Speed [m/s]	80
Overhang, Shaft Tilt, Precone	5 m, 5° , 2.5°
Rotor Mass [tonnes]	110
Nacelle Mass [tonnes]	240
Acceptable System first Eigenfrequency Range [Hz]	(0.22 ; 0.3) Soft-stiff

NREL 5-MW Turbine [3].

ANALYSIS METHOD DIAGRAMS


Site/Soil conditions
Wind Turbine, Substructure,
Load Cases

M&N, KYS:
Substructure + Soil
Superelement representation

Start:
M&N, KYS
Simulating Hydro Loads
SACS EDP

Wave Induced Loads Exerted on Tower Base

[K,M,C]

FAST8

NREL:
Internal Aerodynamics + M&N,KYS Wave Induced Loads applied at Tower Base

Tower Base Loads Exerted on the Substructure

Final Step:
Simulating Hydro + Tower Base Loads from FAST

Post Processing
NREL: Tower and Blade loads/deflections
M&N, KYS: Substructure Loads

M&N, KYS:
Soil/Structure Interaction
Fixity/Superelement representation

NREL:
Wind + Wave Simulation (Fully Coupled)

FAST8

[K]
[K]

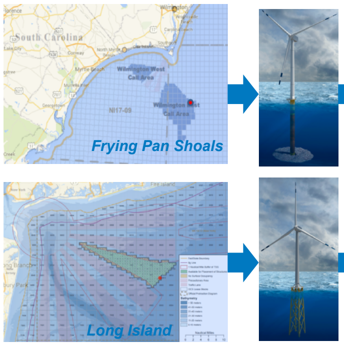
Post Processing
NREL: Tower and Blade loads/deflections
M&N, KYS: Substructure loads/deflections

Figure 1. Sequentially coupled approach (left) and fully coupled approach (right). Researchers at the National Renewable Energy Laboratory (NREL) performed the role of the turbine original equipment manufacturer; Moffat and Nichol (M&N) and Keystone Engineering (KYS) are substructure designers, for monopile and jacket, respectively.

LOAD CASES

Parameters	DLC-1.1 (Operational)		DLC-6.1a (Parked + Grid Loss, 50-yr Extreme Conditions)	
	Monopile	Jacket	Monopile	Jacket
Wind Model	Normal Turbulence Model		Extreme Wind Turbulence Model	
Hub-Height Wind Speeds [m/s]	12 m/s		50 m/s at	
Wind Direction [degrees]	0	0, 45	0	0, 45
Wave Model	Normal Sea State		Extreme Sea State	
Significant Wave Height (H_s [m])/Peak Spectral Period (T_p [s])	1.38 / 6.97	1.34 / 6.48	10.8 / 13.3	9.5 / 12.5
Wave Directions [degrees]	0, 45, 90, 135		Co-directional and 90° Misaligned	
Current Model	Normal Current Model		Extreme Current Model	
Subsurface current speed at SWL [m/s]	0.6		1.2	
Near-Surface Current [@-20 m]	0.084		0.349	
Tidal Conditions	Normal Water Level Range		Extreme Water Level Range	
Surge/Tidal Offset [m]	0		1.25	2.5
Simulation Length	10min		10min	
Yaw Misalignments [degrees]	0		0,20	
Number of Simulations	4	8	4	8

ENVIRONMENTAL CONDITIONS



Frying Pan Shoals, NC	
NOAA BUOY #	41013
Depth [m]	20
50-yr H_s [m]	10.8
50-yr Tp_H_{max} [s]	13.3
50-yr H_{max} [m]	18.3

H_s =significant wave height
T_p =peak spectral period
H_{max}=maximum wave height

Long Island, NY	
NOAA BUOY #	44025
Depth [m]	50
50-yr H_s [m]	9.5
50-yr Tp_H_{max} [s]	12.5
50-yr H_{max} [m]	17.6

Figure 2. Geographical Locations for the selected sites: Frying Pan Shoals, NC (top, monopile location) and Long Island, NY (bottom, jacket location). Illustrations by J. Bauer (NREL).

SOIL CONDITIONS

Depth [m]	Specific weight [kN/m³]	Friction Angle [deg]
0-5	10	33
5-14	10	35
14-55.5	10	38.5

ULTIMATE LOADS COMPARISON

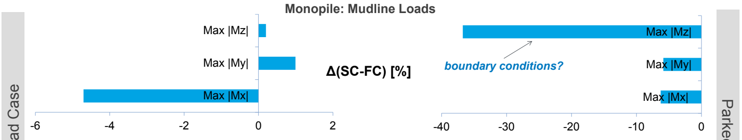


Figure 4. Monopile configuration: mudline moments. Left: operational case with 45° wind-wave misalignment. Right: parked case with 90° wind-wave misalignment and 20° yaw error. SC=sequentially coupled; FC=fully coupled.

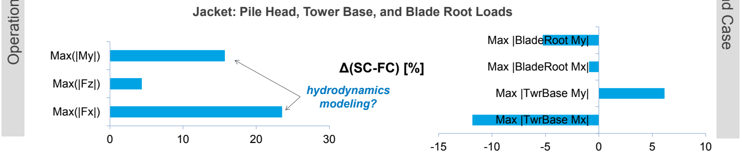


Figure 5. Jacket configuration. Left: upwind pile head key reactions for an operational case with aligned wind and waves. Right: blade root and tower base moments for a parked case with 90° wind-wave misalignment and 10° yaw error.

SHORT-TERM DEL COMPARISON

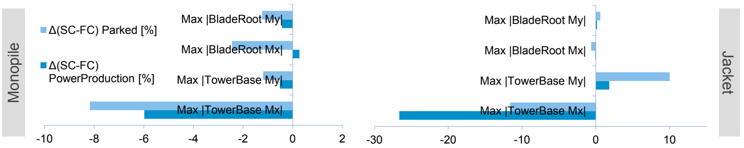


Figure 6. Short-term damage equivalent loads (DELs): blade root and tower base bending moments (for monopile left, and jacket right), for an operational load case with 45° wind-wave misalignment and a parked case with 90° wind-wave misalignment and a 10° yaw error. Left: with a monopile substructure. Right: with a jacket substructure.

CONCLUSIONS

This study revealed how a sequentially coupled approach to the loads analysis of offshore wind turbines with fixed-bottom substructures can perform reasonably well (especially for monopiles), if attention is paid to the details of the models and a robust communication protocol is established among all parties. For the monopile, calculated ultimate limit states loads are within 10% of those calculated via a fully coupled approach, except for a few load channels probably related to differences in assumed boundary conditions. For the jacket, some larger discrepancies are noted, which could be due to the differences in the modeling of the hydrodynamics between the parties.

Among the lessons learned, we emphasize the following characteristics of the sequentially coupled approach:

- It requires quality control throughout the entire process including the information exchange among all parties
- It is very time consuming and has a high risk of errors and oversights
- It is difficult to separate effects associated with different modeling implementation from actual differences in the results
- An extensive verification effort is required because different parties' models have different assumptions and physics that make it harder to verify and validate results
- Although results seem encouraging for ultimate limit states loads, fatigue limit states at the substructure level could reveal differences and a follow-on study is recommended.

ACKNOWLEDGMENTS

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