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A Comparison of Ultimate Loads from Fully and Sequentially Coupled Analyses

F. Wendt, R. Damiani

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. Although 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 poster summarizes the scope and preliminary results of a study conducted for the Bureau of Safety and Environmental Enforcement (BSEE) aimed at quantifying differences between these two modeling approaches through aero-hydro-servo-elastic simulations of two offshore wind turbines on a monopile and jacket substructure.

SUBSTRUCTURES

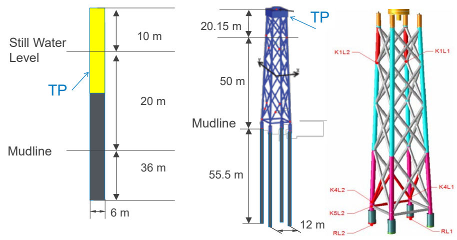


Figure 3. Select substructures for this study: monopile (left, from the Offshore Code Comparison Collaboration [1]) and jacket (right, from Offshore Code Comparison Collaboration Continuation [2])

TURBINE PARAMETERS

Parameter	Value
Rating [MW]	5
International Electrotechnical Commission 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]

MODELING APPROACHES

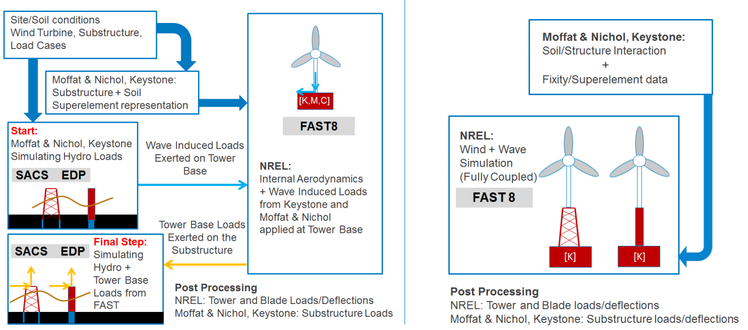
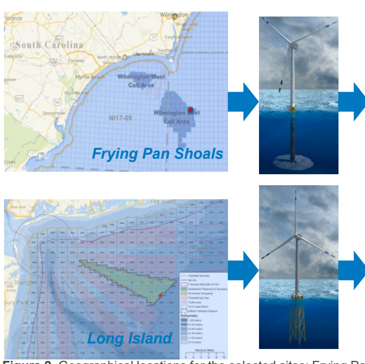


Figure 1. Sequentially coupled approach with NREL in the role of the turbine original equipment manufacturer (OEM) and Moffat & Nichol/Keystone in the role of the substructure OEM (left). For the fully coupled approach (right) the entire offshore wind system is modeled at NREL via FAST v8.

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

*National Oceanic and Atmospheric Administration (NOAA)

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, North Carolina (top, monopile location) and Long Island, New York (bottom, jacket location). *Illustrations by Josh 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

MODEL-TO-MODEL VERIFICATION

Parameter	Monopile FAST	Monopile EDP	Monopile Delta (%)	Jacket FAST	Jacket SACS	Jacket Delta (%)
Tower Mass [kg]	237,098	237,001	0.04	216,614	219,800	-1.47
Tower Z-CG abv. Still Water Line [m]	43.821	43.87	-0.11	50.55	49.83	1.43
Rotor Nacelle Assembly (RNA) Mass [kg]	350,000	350,000	0.00	350,000	350,000	0.0001
RNA Z-CG abv. Still Water Line [m]	89.571	89.57	0.00	89.57	89.57	0.0015
Substructure Mass (dry) [kg]	2.86E+05	285,432	0.03	6.74E+05	6.86E+05	-1.80
Substructure Z-CG (dry) abv. Still Water Line [m]	-5	-5	0.00	-21.90	-22.36	-2.08
Submerged Volume [m^3]	5.65E+02	565.49	0.00	497.36	497.31	0.01
Ballasted Volume [m^3]	0.00E+00	0	0.00	199.59	199.55	0.02
Buoyant Volume [m^3]				297.77	297.76	0.00

	Monopile (Only Substructure) FAST	Monopile (Only Substructure) EDP	Monopile (Only Substructure) Delta %	Jacket (Only Substructure) FAST	Jacket (Only Substructure) SACS	Jacket (Only Substructure) Delta %
Eigenfrequency [Hz]	2.75	2.76	-0.27	2.76	2.68	2.89
	2.75	2.76	-0.27	2.76	2.68	2.89
	5.93	5.93	0.02	5.00	5.25	-4.92
	16.3	16.78	-2.98	5.41	-	-
	16.3	16.78	-2.98	7.63	7.43	2.71

LOAD CASES

Parameters	Design Load Case (DLC)-1.1 (Operational) Monopile	Design Load Case (DLC)-1.1 (Operational) Jacket	DLC-6.1a (Parked, 50-yr Extreme Conditions) Monopile	DLC-6.1a (Parked, 50-yr Extreme Conditions) 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 [at -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	10 min		10 min	
Yaw Misalignments [degrees]	0		0,20	
Number of Simulations	4	8	4	8

COMPARISON OF EXTREME LOADS

Monopile – DLC 1.1 (Operational)

	YawBearingFz	YawBearingMx	YawBearingMy	YawBearingMz	TowerBaseFx	TowerBaseFy	TowerBaseFz	TowerBaseMx	TowerBaseMy	TowerBaseMz
Fully Coupled	3,566	5,274	5,653	5,974	981.4	282.6	5,900	23,530	72,470	5,974
Sequentially Coupled	4,328	5,014	5,842	6,036	1,012	271.8	7,245	22,120	72,900	6,036
Delta (%)	21.4	-4.9	3.3	1.0	3.1	-3.8	22.8	-6.0	0.6	1.0

	MSL_Mx	MSL_My	Mx_10m_depth	My_10m_depth	Fx_mudline	Fy_mudline	Fz_mudline	Mx_mudline	My_mudline	Mz_mudline
Fully Coupled	25.9	81.9	28.9	91.9	1.4	0.6	8.7	34	103	6.0
Sequentially Coupled	24.6	82.3	27.7	92.2	1.4	0.6	9.7	32	104	6.0
Delta (%)	-4.8	0.6	-4.2	0.3	-2.8	-0.9	12	-4.5	0.6	0.1

Monopile – DLC 6.1a (Extreme Conditions)

	YawBearingFz	YawBearingMx	YawBearingMy	YawBearingMz	TowerBaseFx	TowerBaseFy	TowerBaseFz	TowerBaseMx	TowerBaseMy	TowerBaseMz
Fully Coupled	3,429	2,697	3,941	6,086	1,057	860.9	5,764	65,050	62,680	6,086
Sequentially Coupled	3,526	2,842	3,943	5,661	1,008	893.8	5,981	69,260	58,550	5,661
Delta (%)	2.8	5.4	0.1	-7.0	-4.6	3.8	3.8	6.5	-6.6	-7.0

	MSL_Mx	MSL_My	Mx_10m_depth	My_10m_depth	Fx_mudline	Fy_mudline	Fz_mudline	Mx_mudline	My_mudline	Mz_mudline
Fully Coupled	72.9	73	83.9	89	3.5	3.6	8.6	114	112	6.1
Sequentially Coupled	78.0	67.6	88.4	80.4	3.5	3.2	8.5	102	97	5.7
Delta (%)	7.0	-7.0	5.4	-9.7	0.5	-12.7	-1.2	-10.3	-13.2	-7.5

Jacket – DLC 1.1 (Operational)

	YawBearingFz	YawBearingMx	YawBearingMy	YawBearingMz	TowerBaseFx	TowerBaseFy	TowerBaseFz	TowerBaseMx	TowerBaseMy	TowerBaseMz
Fully Coupled	3,562	7,287	5,993	5,259	894.6	656.3	5,692	47,220	60,680	5,259
Sequentially Coupled	3,560	7,234	6,019	5,141	910.2	637.1	5,691	47,410	60,700	5,141
Delta (%)	-0.1	-0.7	0.4	-2.2	1.7	-2.9	0.0	0.4	0.0	-2.2

	RL1_FZ	RL1_FY	RL1_FX	RL1_MZ	RL1_MY	RL1_MX	RL2_FZ	RL2_FY	RL2_FX	RL2_MZ
Fully Coupled	9,225	290	370	224	1,974	1,434	3,232	297	380	1,512
Sequentially Coupled	9,568	414	467	342	2,301	1,954	3,629	387	478	1,870
Delta (%)	3.7	43.0	26	52.7	16.6	36.3	12.3	30.5	25.7	23.7

Jacket – DLC 6.1a (Extreme Conditions)

	YawBearingFz	YawBearingMx	YawBearingMy	YawBearingMz	TowerBaseFx	TowerBaseFy	TowerBaseFz	TowerBaseMx	TowerBaseMy	TowerBaseMz
Fully Coupled	3,382	3,347	3,547	7,035	585.5	962.7	5,511	65,830	37,240	7,035
Sequentially Coupled	3,381	2,891	3,507	7,080	505.8	852.5	5,507	58,860	34,520	7,080
Delta (%)	0.0	-13.6	-1.1	0.6	-13.6	-11.4	-0.1	-10.6	-7.3	0.6

	RL1_FZ	RL1_FY	RL1_FX	RL1_MZ	RL1_MY	RL1_MX	RL2_FZ	RL2_FY	RL2_FX	RL2_MZ
Fully Coupled	10,440	913	916	295	4,482	4,321	12,350	922.7	924.8	4,351
Sequentially Coupled	11,705	1,089	990	278	4,784	5,256	7,660	1,207	960.7	5,752
Delta (%)	12.1	19.3	8.1	-5.8	6.8	21.6	-38.0	30.8	3.9	32.2

CONCLUSIONS

Monopile:

- Turbine ultimate limit state (ULS) loads agree within 20%
- Substructure ULS loads agree within 10%
- Sequentially coupled approach not always conservative

Jacket:

- Turbine ULS loads agree within 10%
- Substructure ULS loads agree within 30%
- Sequentially coupled approach not always conservative during extreme conditions

General Conclusions:

The sequentially coupled approach proved to be time consuming and required significant verification effort to minimize potential sources of errors related to data exchange and the specification of numerical model parameters. Additional research and targeted model verification is required to analyze and explain the observed differences.

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