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Development and Verification of the Soil-Pile Interaction Extension for SubDyn

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INTRODUCTION

SubDyn is the substructure structural-dynamics module for the aero-hydro-servo-elastic tool FAST v8. SubDyn uses a finite-element model (FEM) to simulate complex multimember lattice structures connected to conventional turbines and towers, and it can make use of the Craig-Bampton model reduction. Here we describe the newly added capability to handle soil-pile stiffness and compare results for monopile and jacket-based offshore wind turbines as obtained with FAST v8, SACS, and EDP (the latter two are modeling software packages commonly used in the offshore oil and gas industry). The level of agreement in terms of modal properties and loads for the entire offshore wind turbine components is excellent, thus allowing SubDyn and FAST v8 to accurately simulate offshore wind turbines on fixed-bottom structures and accounting for the effect of soil dynamics, thus reducing risk to the project.

SUBDYN BASE THEORY AND FAST v8 FRAMEWORK

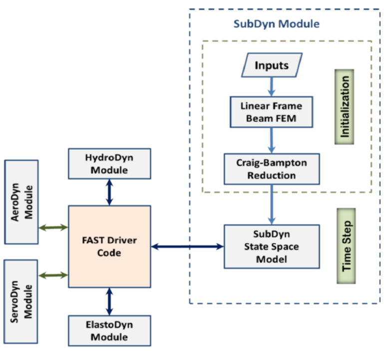

Figure 1. SubDyn layout within FAST's modularization framework

SubDyn Main Input File

BASE REACTION JOINTS: 1/0 for Locked/Free Degree of Freedom (DOF) at each Reaction Node
4 NReact - Number of Joints with reaction forces; be sure to remove all rigid motion DOFs of the structure

RJointID	RctTDXss	RctTDYss	RctTDZss	RctRDXss	RctRDYss	RctRDZss	SSIfile [Global C.S.]
(-)	(flag)	(flag)	(flag)	(flag)	(flag)	(flag)	(string)
61	0	0	1	0	0	1	"pile1_SSImat.txt"
62	0	0	0	0	0	0	"pile2_SSImat.txt"
63	0	0	1	0	0	1	"pile1_SSImat.txt"
64	0	0	0	0	0	0	"pile2_SSImat.txt"

Up to 21 unique elements per matrix per pile

K_{SSI} M_{SSI} Input Files

Modified FEM: Augment System K and M at Pile-Head Nodes' DOFs

$$\begin{bmatrix} M_{RR} & M_{RL} \\ M_{LR} & M_{LL} \end{bmatrix} \begin{Bmatrix} \ddot{U}_R \\ \ddot{U}_L \end{Bmatrix} + \begin{bmatrix} C_{RR} & C_{RL} \\ C_{LR} & C_{LL} \end{bmatrix} \begin{Bmatrix} \dot{U}_R \\ \dot{U}_L \end{Bmatrix} + \begin{bmatrix} K_{RR} & K_{RL} \\ K_{LR} & K_{LL} \end{bmatrix} \begin{Bmatrix} U_R \\ U_L \end{Bmatrix} = \begin{Bmatrix} F_R + F_{Rg} \\ F_L + F_{Lg} \end{Bmatrix}$$

U_R = Boundary nodes' DOFs including locked restraint nodes
U_L = Internal DOFs including "unlocked" boundary node DOFs
F_g = Applied Forces

Craig-Bampton Reduction + Interface DOFs Reduced at the TP Reference Point (see [1])

$$\begin{Bmatrix} U_R \\ U_L \end{Bmatrix} = \begin{bmatrix} I & 0 \\ \Phi_R & \Phi_m \end{bmatrix} \begin{Bmatrix} U_R \\ q_m \end{Bmatrix}$$

Φ_m = First m eigenmodes retained
Φ_R = physical displacements of the interior nodes for static, rigid body motions at the boundary

$$\begin{bmatrix} \tilde{M}_{BB} & \tilde{M}_{Bm} \\ \tilde{M}_{mB} & I \end{bmatrix} \begin{Bmatrix} \ddot{U}_{TP} \\ \ddot{q}_m \end{Bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & 2\zeta\Omega_m \end{bmatrix} \begin{Bmatrix} \dot{U}_{TP} \\ \dot{q}_m \end{Bmatrix} + \begin{bmatrix} \tilde{K}_{BB} & 0 \\ 0 & \Omega_m^2 \end{bmatrix} \begin{Bmatrix} U_{TP} \\ q_m \end{Bmatrix} = \begin{Bmatrix} \tilde{F}_{TP} \\ \tilde{F}_m \end{Bmatrix}$$

Integration via state-space formulation (see [1])

$$\begin{cases} \dot{x} = X = Ax + Bu + F_X \\ -Y_1 = C_1x + D_1\bar{u} + F_{Y1} \\ Y_2 = C_2x + D_2u + F_{Y2} \end{cases}$$

x = states $[q_m, \dot{q}_m]^T$
u = inputs $[U_{TP}, \dot{U}_{TP}, \ddot{U}_{TP}, F_L, F_{HDR}]^T$ displacements, velocities, and accelerations of the TP and external forces applied to the structure Y_1,
Y_2 = outputs $[-F_{TP}; \bar{U}_R, U_L, \dot{\bar{U}}_R, \dot{U}_L, \ddot{\bar{U}}_R, \ddot{U}_L]^T$, i.e., the reaction at the TP; deflections, velocities, and accelerations of the substructure
$A, B, C_1, C_2, D_1, D_2, F_X, F_{Y1}, F_{Y2}$ = matrices and arrays functions of $\tilde{M}_{BB}$, $\tilde{M}_{Bm}$, $\tilde{M}_{mB}$, $\tilde{K}_{BB}$, Φ_R, Φ_m, ζ, Ω_m, $\tilde{F}_{TP}$, $\tilde{F}_m$

MODEL VERIFICATION WITH ANSYS

An initial comparison against ANSYS was performed in terms of modal and transient (decay) analysis

OFFSHORE WIND TURBINE

Credit : J. Bauer, NREL

PILE STIFFNESS MATRIX (Monopile)

Monopile K-matrix	X [1/m]	Y [1/m]	Z [1/m]	XX [1/rad]	YY [1/rad]	ZZ [1/rad]
X [N]	1.23E+05	-1.85E+01	0.00E+00	-8.65E+01	-7.66E+05	0.00E+00
Y [N]		1.23E+05	0.00E+00	7.66E+05	8.65E+01	0.00E+00
Z [N]			4.29E+06	0.00E+00	0.00E+00	0.00E+00
XX [Nm]				7.40E+06	5.12E+02	0.00E+00
YY [Nm]		sym.			7.40E+06	0.00E+00
ZZ [Nm]						5.80E+06

CALCULATED EIGENFREQUENCIES (Monopile)

Eigenfrequencies [Hz]	Ansys no SSI	SubDyn no SSI	Ansys SSI	SubDyn SSI	Deviation with SSI [%]
1st	6.108*	6.073*	1.33/1.34	1.33*	0.0/0.0
2nd	25.987	25.726	6.5/6.76	6.45/6.71	0.7/0.7
3rd	33.175*	28.320	17.935	17.929	0.0
4th	41.895	41.473	25.975	25.975	-
5th	82.515*	58.591*	38.61/38.66	33.76/33.81	14.3/14.3
6th	84.992	77.962	84.978	61.82/61.83	
7th	137.019	83.405*	88.66*	84.948	
8th	154.187	101.875*	91.66	91.657	0
9th	167.180*	114.525*	154.15	154.154	-

*Double eigenvalues (FA/SS bending) are printed only once

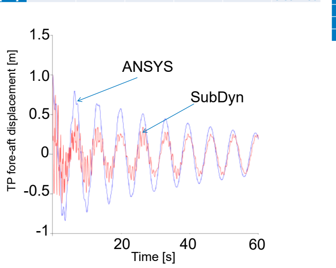

Figure 2. Decay response. Time series of the transition piece displacement in the fore-aft direction after a 1-m initial deflection

Differences attributable to more eigenmodes in ANSYS than SubDyn, especially for the tower, and inertia effects of the transition piece (TP) and rotor nacelle assembly (RNA) not fully captured in ANSYS

OFFSHORE WIND TURBINE

Credit : J. Bauer, NREL

PILE STIFFNESS MATRIX (Jacket)

Jacket K-matrix (each pile)	X [1/m]	Y [1/m]	Z [1/m]	XX [1/rad]	YY [1/rad]	ZZ [1/rad]
X	1.87E+08	1.23E+08	4.97E+08	-1.02E+06	-7.73E+08	1.91E+08
Y		3.30E+08	8.62E+08	7.76E+08	8.74E+05	-1.11E+05
Z			3.60E+09	-1.92E+08	1.10E+08	1.48E+05
XX				1.10E+12	1.89E+12	7.65E+12
YY		sym.			3.29E+12	1.33E+13
ZZ						5.36E+13

CALCULATED EIGENFREQUENCIES (Jacket)

Eigenfrequencies [Hz]	Ansys no SSI	SubDyn no SSI	Ansys SSI	SubDyn SSI	Deviation with SSI [%]
1st	2.756*	2.756*	1.357	1.344	1
2nd	5.027	5.004	1.443	1.432	0.7
3rd	5.418	5.413	2.705	2.642	2.4
4th	7.685*	7.634*	3.475	3.377	2.9
5th	8.508	8.462	4.056	3.986	1.8
6th	9.088	8.937	4.538	4.381	3.5
7th	9.583	9.404	5.661	5.456	3.7
8th	10.140*	9.781*	8.843	8.595	2.9
9th	10.817	10.633	9.987	9.322	7.1

*Double eigenvalues (FA/SS bending) are printed only once

ACKNOWLEDGMENTS

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MODEL VERIFICATION WITH EDP AND SACS

In the course of a study conducted for the Bureau of Safety and Environmental Enforcement (BSEE), SubDyn's new capabilities were tested against commercial FEM packages, such as SACS and EDP [2-3]. The substructures investigated were the OC3 monopile and the OC4 jacket, both supporting the NREL 5-MW turbine.

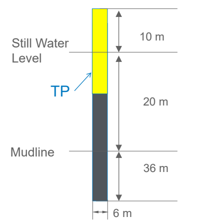


Figure 3. Monopile substructure used in [2]

MODELED SUBSTRUCTURES and 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

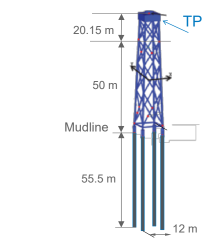


Figure 4. Jacket substructure used in [2]

CALCULATED STIFFNESS MATRICES (SUBSTRUCTURE + PILES)

SubDyn	X [1/m]	Y [1/m]	Z [1/m]	XX [1/rad]	YY [1/rad]	ZZ [1/rad]
X [N]	1.16E+08	0.00E+00	0.00E+00	0.00E+00	-2.65E+09	0.00E+00
Y [N]		1.16E+08	0.00E+00	2.65E+09	0.00E+00	0.00E+00
Z [N]			3.84E+08	0.00E+00	0.00E+00	0.00E+00
XX [Nm]				8.33E+10	0.00E+00	0.00E+00
YY [Nm]		sym.			8.33E+10	0.00E+00
ZZ [Nm]						1.21E+10
Deviations from EDP: (EDP-SubDyn) / EDP [%]						
X	-0.03				-0.03	
Y		-0.03		-0.03		
Z			0.00			
XX		sym.		-0.01		
YY						
ZZ						0.00

Relative Error <0.03%

SubDyn	X [1/m]	Y [1/m]	Z [1/m]	XX [1/rad]	YY [1/rad]	ZZ [1/rad]
X [N]	5.18E+07	7.05E+01	-1.51E+03	1.24E+03	-1.53E+09	-5.32E+02
Y [N]		5.19E+07	-1.76E+02	1.53E+09	-9.29E+02	5.41E+03
Z [N]			1.66E+09	-8.89E+03	1.30E+04	1.96E+02
XX [Nm]				8.60E+10	4.39E+04	1.78E+05
YY [Nm]		sym.			8.59E+10	2.34E+04
ZZ [Nm]						5.76E+09
Deviations from SACS: (SACS-SubDyn) / SACS [%]						
X	-1.64				5.51	
Y		-1.76		5.45		
Z			-1.00			
XX		sym.		6.47		
YY					6.50	
ZZ						-0.83

Relative Error <7%

CALCULATED EIGENFREQUENCIES

Eigenfrequencies [Hz] Monopile + Tower + RNA (Operational Conditions)

FAST	EDP	Delta %
0.23	0.25	-7.05
0.24	0.25	-2.59
1.42	1.47	-3.50
1.33	1.47	-10.51

Eigenfrequencies [Hz] Jacket + Tower + RNA (Operational Conditions)

FAST	SACS	Delta %
0.30	0.30	-1.04
0.30	0.30	-1.54
0.94	0.90	4.21
0.93	0.91	1.80
2.06	1.73	15.97

CALCULATED RESPONSE

Operational Conditions Simulated

Parameter	Monopile	Jacket
Mean Wind Speed [m/s] (NTM)	12	12
Water Depth [m]	50	
Significant Wave Height H_s [m]	1.38	1.34
Peak Spectral Period Tp_H_{max} [s]	6.97	6.48
Subsurface Current Speed at SWL [m/s]	0.6	0.6
Near-Surface Current [at -20 m]	0.084	0.084

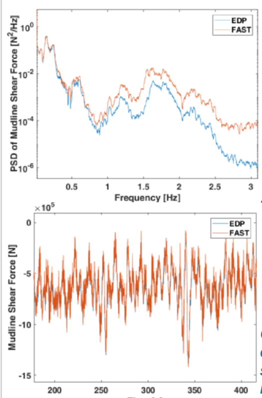


Figure 5. Power spectral density (PSD) (top) and time series (bottom) of the shear force at mudline for the monopile-based configuration used in [2], as calculated by FAST with SubDyn and EDP

Overall response captured well; some discrepancies exist in the response spectra, especially at high frequencies, likely due to other modeling parameters not perfectly matched among the different software codes

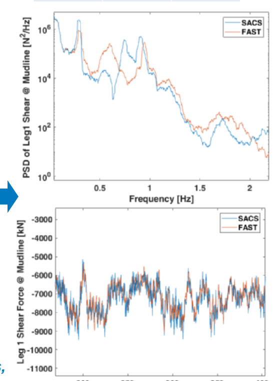
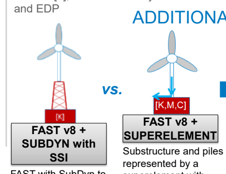


Figure 6. PSD (top) and time series (bottom) of the shear force at the base of the upwind leg for the jacket-based configuration used in [2], as calculated by FAST with SubDyn and SACS

ADDITIONAL VERIFICATION: SubDyn vs. SUPERELEMENT APPROACH



FAST with SubDyn to model both jacket and piles

Substructure and piles represented by a superelement with equivalent stiffness (K) and mass (M) matrices from SubDyn with SSI

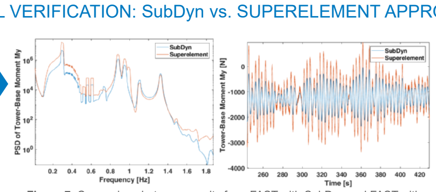


Figure 7. Comparison between results from FAST with SubDyn and FAST with a superelement model. PSD (left) and time series (right) of the tower base fore-aft bending moment (My) for the jacket-based configuration used in [2]

Differences attributable to the absence of a damping matrix in the superelement model; frequency content captured

CONCLUSIONS

Modal and decay analyses of offshore wind substructures, with equivalent pile stiffness and mass matrices, proved that SubDyn with SSI extension produces results that match those from commercial-grade finite-element analysis packages such as ANSYS.

The main elements of the stiffness matrix and the first four eigenfrequencies calculated by FAST with SubDyn for monopile- and jacket-based offshore wind turbines closely matched those calculated by SACS and EDP (7% maximum relative error).

Verification efforts thus far have been conducted in support of recent studies for BSEE [2-3].
Although loads and structural response have proven to be comparable between FAST v8 with SubDyn and commercial software, further targeted verification and validation is recommended.

REFERENCES

[1] Damiani, R., J. Jonkman, G. Hayman. 2015. *SubDyn User's Guide and Theory Manual* (Technical Report). NREL/TP-5000-63062. National Renewable Energy Laboratory (NREL), Golden, CO (US). http://www.nrel.gov/docs/fy15osti/63062.pdf.

[2] Damiani, R., F. Wendt, W. Musial, Z. Finucane, L. Hulliger, S. Chilka, D.Dolan, J. Cushing, D. O'Connell, S. Falk. 2017. *Fully vs. Sequentially Coupled Loads Analysis of Offshore Wind Turbines*. NREL/PO-5000-68368. National Renewable Energy Laboratory (NREL), Golden, CO (US). http://www.nrel.gov/docs/fy17osti/68368.pdf.

[3] Wendt, F., R. Damiani. 2017. *A Comparison of Ultimate Loads from Fully and Sequentially Coupled Analyses*. NREL/PO-5000-70160. National Renewable Energy Laboratory (NREL), Golden, CO (US). Poster at AWEA Offshore WindPower 2017, New York, NY

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