Load simulation and local dynamics of support structures for offshore wind turbines

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Executive Summary

The installation of the German offshore test field *alpha ventus* in the North Sea marks the beginning of a new era of offshore wind energy application. Fueled by European renewable energy targets and the increasing reliability of the technology, offshore wind energy has become a multi-billion euro market that attracts the interest of many stakeholders. Consequently, there is a potential of rapid growth of that market over the next decade.

The successful deployment of offshore wind turbines in a large scale will require innovative, lightweight, safe, and cost-effective support structures. For the severe North Sea conditions in water depths around 30m and more, braced or lattice support structures like tripod or jacket seem to be the preferred solution. Taking into account the dynamic interrelation of those support structures and their internal dynamics with the wind turbine in numerical models for dynamic simulations becomes crucial for a reliable and cost-effective design.

Therefore, in this thesis a new analysis approach is implemented and verified that takes the complete offshore wind turbine consisting of rotor nacelle assembly, tower, and substructure into account. This is achieved by coupling Poseidon, a finite element code specifically designed for the simulation of lattice offshore support structures by the author, to the quasi-industry standard wind turbine simulation code Flex5, which was available to the author in the version of the Endowed Chair of Wind Energy at the University of Stuttgart.

In lack of measurement data from real turbines with complex support structures the simulation results of the international benchmarking project OC3 have been used to verify the approach. Very good agreement with the results of other codes participating in that project could be achieved. The turbine model that is used within OC3, the NREL 5MW Baseline Turbine, is taken as reference turbine for the further investigations in the thesis, too.

The approach is applied to investigate the excitation of local vibrations of support structures for offshore wind turbines in combined aero-servo-hydro-elastic simulations. The parameters that influence the local dynamics are analyzed separately by means of coupled modal analysis at the example of a reference jacket. In subsequent coupled analyses in the time domain it can be shown how local vibrations of the braces of the jacket are excited by coupling effects between local brace modes with modes of the rotor nacelle assembly.

Based on the analyses it is concluded that particularly structures with internal modes at comparatively low eigenfrequencies are prone to excitation of local vibrations due to coupling effects. It is therefore recommended to identify potential sources of resonance by means of coupled modal analysis. Potential savings in the detailed structural design will pay off the additional computational effort required for fully coupled analyses in case significant contribution from local vibrations is to be expected.

Kurzzusammenfassung

Mit der Errichtung des Offshore Testfelds *alpha ventus* in der Deutschen Nordsee beginnt ein neues Zeitalter der Windenergienutzung. Angetrieben durch europäische Vereinbarungen zum Ausbau der Erneuerbaren Energien und durch die zunehmende Zuverlässigkeit dieser Technologie ist die Offshore Windenergie zu einem Multi-Milliarden Euro Markt herangewachsen der in den kommenden Jahren ein enormes Wachstumspotenzial aufweist.

Um Offshore Windenergieanlagen im großen Maßstab errichten zu können, werden innovative, leichte, sichere und wirtschaftliche Tragstrukturen für diese Anlagen benötigt. Für die Standorte in der Nordsee mit Wassertiefen von 30m und mehr sind so genannte aufgelöste Tragstrukturen wie der Tripod oder das Jacket die bevorzugten Varianten. Die Betrachtung der wechselseitigen Beeinflussung zwischen Windenergieanlage und Tragstruktur sowie deren interner Dynamik ist unabdingbar für eine zuverlässige und wirtschaftliche Bemessung.

In dieser Arbeit wird daher ein neuer Lösungsansatz implementiert und verifiziert, in dem die gesamte Offshore Windenergieanlage bestehend aus Rotor-Gondel-Einheit, Turm und Substruktur in Betracht gezogen wird. Dazu wird das vom Verfasser entwickelte Programm Poseidon, ein Finite-Elemente-Programm speziell für die Simulation von aufgelösten Offshore-Strukturen, mit dem weit verbreiteten Windenergieanlagensimulationsprogramm Flex5 gekoppelt, welches in der Version des Stiftungslehrstuhls Windenergie der Universität Stuttgart zur Verfügung stand.

Der Ansatz wird anhand von Ergebnissen des internationalen Benchmarking Projekts OC3 verifiziert. Es kann eine sehr gute Übereinstimmung mit den Ergebnissen anderer Simulationsprogramme, die in dem Projekt vertreten sind, erreicht werden. Das Modell der Windenergieanlage, das für die Berechnungen in OC3 verwendet wird, die NREL 5MW Baseline Turbine, wird auch für die weiteren Berechnungen als Referenzanlage herangezogen.

Der Ansatz wird verwendet, um die Anregung lokaler Schwingungen der Tragstrukturen unter kombinierter aero-servo-hydro-dynamischer Beanspruchung zu untersuchen. Die das lokale Schwingverhalten beeinflussenden Parameter werden separat mit Hilfe gekoppelter Modalanalysen am Beispiel eines Referenz-Jackets analysiert. In anschließenden Zeitbereichsanalysen wird gezeigt, wie lokale Schwingungen durch Koppelungseffekte zwischen den inneren Moden des Jackets und den Blättern der Windenergieanlage angeregt werden.

Auf der Grundlage der Untersuchungen wird festgestellt, dass insbesondere Strukturen mit inneren Moden vergleichsweise niedriger Eigenfrequenzen zu durch Kopplungseffekte verursachten lokalen Schwingungen neigen. Es wird daher empfohlen, potentielle Resonanzquellen frühzeitig durch gekoppelte Modalanalysen zu identifizieren. Die so erzielten Materialeinsparungen werden den zusätzlichen rechnerischen Aufwand für eine voll gekoppelte Analyse aufwiegen.

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Nomenclature

Acronyms and Abbreviations

acc.	according
BEM	Blade-element-momentum theory
cf.	confer
COG	Centre of gravity
DEL	Damage equivalent load
DIBt	Deutsches Institut für Bautechnik
DOF	Degree of freedom
FE / FEM	Finite element method
FFT	Fast Fourier Transform
IEC	International Electrotechnical Commission
LAT	Lowest astronomical tide
MSL	Mean sea level
NREL	National Renewable Energy Laboratory, USA
NTM	Normal turbulence model
NWP	Normal wind profile
OC3	Offshore Code Comparison Collaborative
OWT	Offshore wind turbine
PSD	Power spectral density
RCM	Rainflow counting method
RNA	Rotor nacelle assembly
SWE	Endowed Chair of Wind Energy, University of Stuttgart
GL	Germanischer Lloyd
GH	Garrad Hassan and Partners Ltd.
IEA	International Energy Agency
eq. / eqs.	Equation / Equations
RISØ	National Laboratory for Sustainable Energy at the Technical University of Denmark
IWES	Fraunhofer Institute for Wind Energy and Energy System

	Technology
CWMT	Fraunhofer Center for Wind Energy and Marine Technology
LUH	Leibniz Universität Hannover
DTU	Technical University of Denmark
SCADA	Supervisory Control And Data Acquisition

Symbols

a	[-]	longitudinal flow induction factor
a'	[-]	tangential flow induction factor
a_s	[m/s^2]	structural acceleration normal to the member
a_w	[m/s^2]	water particle acceleration normal to the member
C_a	[-]	hydrodynamic added mass coefficient
C_D	[-]	aerodynamic drag coefficient
C_d	[-]	hydrodynamic drag coefficient
C_L	[-]	aerodynamic lift coefficient
C_m	[-]	hydrodynamic inertia coefficient
d	[m]	water depth
D	[m]	diameter of a tubular structural member
H_s	[m]	significant wave height
I	[-]	turbulence intensity
I_{ref}	[-]	reference turbulence intensity acc. to IEC 61400
m_n		n-th spectral moment of a stochastic process
t	[m]	wall thickness of a tubular structural member
T_p	[s]	peak period
T_z	[s]	zero-up-crossing period
$v(z)$	[m/s]	mean wind speed at height z
$v(z_{ref})$	[m/s]	mean wind speed at reference height z_{ref}
v_{hub}	[m/s]	10-minute mean wind speed at hub height
v_{ave}	[m/s]	annual mean wind speed at hub height
v_{in}, v_{out}	[m/s]	cut-in, cut-out wind speed
v_r	[m/s]	relative velocity of the flow normal to the member surface
u_{10}	[m/s]	hourly mean wind speed at 10m above sea surface
z	[m]	height coordinate
z_{ref}	[m]	reference height for definition of wind profile

γ	[-]	shape parameter for the JONSWAP spectrum
η	[m]	water surface elevation
σ_1	[m/s]	standard deviation of wind speed
α	[-]	wind shear exponent
V	[-]	dynamic amplification factor/function
η	[-]	frequency ratio
Ω	[rad/s]	excitation frequency
ω	[rad/s]	natural frequency
D	[-]	damping ratio

Parts of an Offshore Wind Turbine according to IEC 61400-3

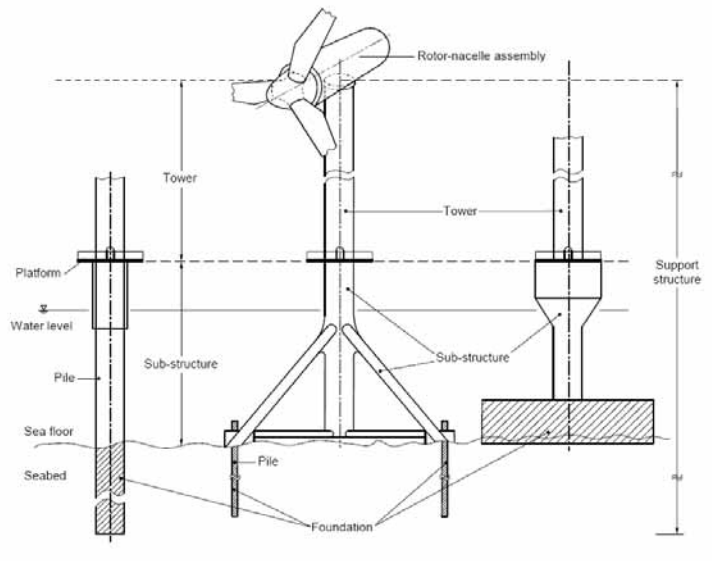

Figure 1: Parts of an offshore wind turbine, taken from IEC 61400-3