Luft- und Raumfahrttechnik

Daniel Kaufer

Validation and Applicability of an Integrated Load Simulation Method for Offshore Wind Turbines with Jacket Structures

SHAKER VERLAG

Validation and Applicability of an Integrated Load Simulation Method for Offshore Wind Turbines with Jacket Structures

A thesis accepted by the Faculty of Aerospace Engineering and Geodesy of the University Stuttgart in partial fulfilment of the requirements for the degree of Doctor of Engineering Sciences (Dr.-Ing.)

by

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List of Abbreviations

1p	1p periodic excitation frequency of the rotor
3p	3p periodic excitation frequency of the rotor
AV1…AV12	Short name of the offshore wind turbines in Alpha Ventus
AV4	Research wind turbine Senvion 5M with jacket
BEM	Blade element momentum theory
COG	Center of gravity
DEL	Damage equivalent load(s)
DLL	Dynamic link library
DMS	Resistance strain gauge
DOF	Degree(s) of freedom
FE	Finite element(s)
FEED	Front-end engineering design
FEM	Finite element method(s)
FFT	Fast Fourier transformation
FINO 1	Research platform in the North Sea “Forschung in Nord und Ostsee 1”
FLS	Fatigue limit state analysis
GLGH	Germanischer Lloyd Garrad Hassan
HRD	High resolution data
IEC	International Electrical Commission
LJF	Local joint flexibility
Max	Maximum
MBS	Multi-body-system
Min	Minimum
MSL	Mean sea level
NFA	Natural frequency analysis
OC3	Offshore code comparison collaboration project under IEA Annex 23
OC4	Offshore code comparison collaboration continuation project
OWT	Offshore wind turbine

RNA	Rotor-nacelle-assembly
SCADA	Supervisory control and data acquisition
STD	Standard deviation
SWE	Stuttgart Wind Energy (SWE), University Stuttgart
TP	Transition piece
ULS	Ultimate limit state analysis
WT	Wind turbine

List of Symbols

Bold written symbols represent for matrices or vectors if not specified differently. A dot over a symbol is the abbreviation for the first derivative in time. Two dots mark the second derivative in time of a quantity.

Indices

aero	Aerodynamic
hydro	Hydrodynamic
i, j, l, n	Index number
m	Master
mean	Average
ref	Reference
res	Resulting
s	Slave
subst	Substitute

Greek Symbols

α	Wind shear exponent	[-]
β	Angle measured against horizontal plane	[deg]
λ	Eigenvalue	
$\boldsymbol{\varphi}$	Eigenvector	
ψ	Rotor azimuth angle (0 deg = blade pointing vertically down)	[deg]
ρ	Density	[kg/m³]
σ	Structural stress	[N/m²]

Latin Symbols

c_d	Coefficient of drag	[-]
c_m	Coefficient of mass	[-]
d	Damping	[kg/s]
D	Diameter	[m]
$\mathbf{D}$	Damping matrix	
f	Frequency	[Hz]
F	Force	[N]
$\mathbf{F}$	General force vector	

g	Acceleration of gravity	[m/s²]
H_s	significant wave height	[m]
$\mathbf{I}$	Identity matrix	[-]
m	Mass	[kg]
m	Woehler coefficient	[-]
$\mathbf{M}$	Mass matrix	
M	Bending moment	[Nm]
n	Number of stress cycles	[-]
N_{ref}	Number of reference cycles	[-]
p	Pressure	[N/m²]
P_{elect}	Electrical power	[W]
q	Modal DOF	
$\mathbf{q}$	Modal vector of DOF	
r	Distance, radius from jacket center	[m]
r_{cog}	Effective lever of the center of gravity	[m]
s	Stiffness	[kg/s²]
$\mathbf{S}$	Stiffness matrix	
S	Reference surface	[m²]
u	Horizontal flow velocity	[m/s]
$\mathbf{U}$	Modal matrix containing eigenvectors $\boldsymbol{\varphi}$	
$\mathbf{U}^*$	Reduced model matrix	
t	Time	[s]
T_0	Zero-up crossing period of waves	[s]
T_p	Peak period of waves	[s]
$\mathbf{T}$	Transformation matrix	
$\mathbf{v}$	Reduced vector of DOF	
v_w	Wind speed	[m/s]
v_{dir}	Wind direction	[deg]
v_{mean}	Average wind speed usually at hub height	[m/s]
x	Quantity of a DOF	
$\mathbf{x}, \mathbf{x}_m, \mathbf{x}_s$	Vector of DOF, indicating also master and slave sub vectors	

Abstract

Today the design of offshore wind turbines is an iterative process between different designers of special roles in order to ensure a cost-efficient solution. Responsibilities in offshore business are clearly split between the wind turbine designer and the support structure designer. A major collaborative task for both parties is the determination of the governing design loads due to the site-specific and stochastic met-ocean conditions over the lifetime including transport, installation, operation and decommissioning phases. The design calculations for the operation require an integrative model approach, which is able to consider all relevant subsystems and the governing loads. In general, these subsystems are the rotor, controller, nacelle, tower, substructure, foundation and soil. Common practise in industry application is that specialized structural models are applied for the wind turbine (i.e. rotor, tower, nacelle and controller) and the support structure (substructure, foundation and soil). Each of the specialized models considers an approximated and temporal constant model of the other subsystem during the design load iterations. For many applications this is a valid approach, but it can have disadvantages when dynamic interactions between the wind turbine and the support structure become excited or the natural frequency of the full system changes during subsystem optimization.

In this thesis an integrated model has been further developed and applied, which facilitates the combination of the wind turbine and the support structure in one direct solution by coupling the equations of motion during runtime. This ensures full dynamic interaction of the models without further simplification of the original models. Two applications have been realised: Flex5 coupled to Poseidon and Flex5 coupled to ANSYS. The coupled models are verified against other state-of-the art load simulation tools to proof the correct implementation.

In a next step the simulation method is validated against measurements from a commercial offshore wind turbine. The measurement campaign is carried out in the

wind farm Alpha Ventus, the first commercial wind farm in the German North Sea. The considered wind turbine is a Senvion 5M installed on a jacket in 28m water depth. The validation considers mainly the strain gauge measurements from the rotor blades, the tower and the jacket substructure at different operational states of the wind turbine. High resolution data and the derived statistical parameters are taken into account for the validation. The results consider natural frequencies, quasi-static loadings, time series, statistic parameters, damage equivalent loads and rainflow count distribution. Correlated wind and wave conditions from a nearby met-mast are used directly in the simulation model. In conclusion very good consistence between load measurements and the results from the integrated simulation approach is shown. Some differences remain because the turbulence of the wind field and the elevation of the random sea state do not correspond with the model in detail. The spatial and temporal resolution of the wind and wave data was not measured. This highlights the necessity of very accurate and correlated measurements of wind and waves for the design of offshore wind turbines and the relevance of models that can process more complex data.

The final part of the thesis addresses the distinctions between different simulation approaches compared to the newly developed fully-integrated approach for offshore wind turbines with jackets. The three alternative models differ mainly in the accuracy of the jacket subsystem or the limited dynamic interaction between wind turbine and support structure. For most components like the blades, the tower or the jacket legs good correspondences between the simplified models and the fully-integrated model are achieved. Larger differences occur in the local stresses of the jacket brace elements. This has a significant impact on the hot-spot stresses of tubular joints, which can be decisive for the entire jacket design. It is therefore recommended to use a fully-integrated model that is able to capture the dynamic interaction between wind turbine and local support structure components.

Zusammenfassung

Der Entwurf von Offshore-Windkraftanlagen ist ein iterativer Prozess mit dem Ziel, ein kostengünstiges Gesamtkonzept zu entwickeln. Dabei gibt es klar aufgeteilte Verantwortlichkeiten zwischen Anlagenhersteller und Entwickler von Tragstrukturen. Ein wichtiges gemeinsames Ziel ist die Bestimmung der Entwurfslasten aufgrund standortspezifischer Randbedingungen von Wind und Welleneinflüssen über die gesamte Lebensdauer hinweg. Es werden sowohl Transport, Installation, Betrieb und Rückbau betrachtet. Die Berechnungen für den Betrieb erfordern einen integrierten Gesamtansatz, welcher alle relevanten Teilsysteme inklusive der äußeren Lasten abbildet. Gängige industrielle Praxis ist die Verwendung verschiedener spezialisierter Strukturmodelle für die Windkraftanlage einerseits (Rotor, Gondel, Turm und Regler) und für die Tragstruktur andererseits (Unterstruktur, Fundament und Boden). Diese Modelle benutzen stets vereinfachte Teilmodelle des jeweils anderen Modells und nehmen diese innerhalb der Lastiteration als konstant an. Dieser Ansatz ist für viele Anwendungen geeignet. Die Nachteile zeigen sich sobald die dynamische Interaktion zwischen Windkraftanlage und Tragstruktur relevant wird oder sobald sich die Eigenfrequenzen des Gesamtsystems bei Optimierung der Teilmodelle verändern. Dadurch steigen die Anzahl der Lastiterationen und der notwendige Datenaustausch.

Im Rahmen dieser Arbeit wird ein Verfahren weiterentwickelt und angewendet, welches diese dynamischen Interaktionen in einer Gesamtsimulation ermöglicht. Die Bewegungsgleichungen (Modelle) der Teilsysteme werden während der Lösung im Zeitbereich kombiniert. Dadurch ist die Kopplung aller Freiheitsgrade der Modelle gewährleistet, ohne dass zusätzliche Vereinfachungen der ursprünglichen Teilmodelle von Windkraftanlage und Tragstruktur nötig werden. Zwei konkrete Anwendungen werden umgesetzt: Flex5 gekoppelt mit Poseidon und Flex5 gekoppelt mit ANSYS. Beide Lösungen sind mit anderen gängigen Simulationsprogrammen verifiziert, um die korrekte Implementierung der Kopplungen zu prüfen.

Im Weiteren wird das gekoppelte Verfahren zur Lastberechnung mit Messdaten validiert. Die Messdaten entstammen Alpha Ventus, dem ersten deutschen Offshore-Windpark in der Nordsee. Eine Windkraftanlage vom Typ Senvion 5M ist auf einer Jacket Tragstruktur in rund 28m Wassertiefe installiert und messtechnisch ausgestattet. Die Validierung basiert hauptsächlich auf Dehnungsmessungen an den Komponenten Rotorblatt, Turm und Jacket, wobei verschiedene Betriebszustände berücksichtigt werden. Hochaufgelöste Signale sowie deren statistische Größen werden genutzt, um Eigenfrequenzen, quasi-statische Lasten, Lastzeitreihen, statistische Parameter, schädigungsäquivalente Lasten und Schwingweiten-Klassifizierung zwischen Simulation und Messung zu vergleichen. Korrelierende Wind- und Welleninformationen vom nahegelegenen Messmast werden direkt im Simulationsmodell verwendet. Die Ergebnisse von Simulation und Messung stimmen sehr gut überein. Unterschiede entstehen im Wesentlichen aufgrund der gemittelt bestimmten Umgebungsbedingungen. Der turbulente Wind sowie Seegang sind messtechnisch nicht räumlich erfasst und können ohnehin nur bedingt im Modell approximiert werden, so dass eine exakte Nachbildung unrealistisch bleibt. Dies verdeutlicht aber auch die Notwendigkeit, sowohl möglichst genaue standortspezifische und zeitgleiche Messungen von Wind und Wellen für den Entwurf von Offshore Windkraftanlagen durchzuführen, als auch die notwenigen Modelle für deren Umsetzung zu entwickeln.

Alternative Simulationsverfahren und deren Vergleich mit dem entwickelten integrierten Ansatz werden am Schluss untersucht. Drei Verfahren sind berücksichtigt, die sich jeweils in der Abbildung des Jacket Modells und ihrer dynamischen Interaktion mit der Windkraftanlage unterscheiden. Für viele Hauptkomponenten (d.h. Rotor und Turm, sowie Jacket-Beine) liefern die bisherigen Ansätze plausible Ergebnisse, jedoch werden größere Unterschiede bei lokalen Stäben deutlich, was Einfluss auf die Bemessung der Knoten hat, die oft Design entscheidend sind. Daher werden Berechnungen mit Modellen empfohlen, die eine Kopplung zwischen Windkraftanlage und Jacket möglichst exakt abbilden.