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Integrated structural optimisation of offshore wind turbine support structures based on finite element analysis and genetic algorithm

Theo Gentils, Lin Wang, Athanasios Kolios *

Centre for Offshore Renewable Energy Engineering, School of Water, Energy and Environment, Cranfield University, Cranfield MK43 0AL, UK

HIGHLIGHTS

- Combination of FEA and GA provides effective design optimisation of RES components.
- The proposed model achieves mass reduction of the support structure by 19.8%.
- The optimised geometry is more sophisticated than the initial one.
- Fatigue and natural frequency are the main design drivers.

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ABSTRACT

By accounting for almost 25% of the capital cost of an OWT (offshore wind turbine), optimisation of support structures provides an efficient way to reduce the currently high cost of offshore wind energy. In this paper, a structural optimisation model for OWT support structures has been developed based on a coupled parametric FEA (Finite Element Analysis) and GA (Genetic Algorithm), minimising the mass of the support structure under multi-criteria constraints. Contrary to existing optimisation models for OWT support structures, the proposed model is an integrated structural optimisation model, which optimises the components of the support structure (i.e. tower, transition piece, grout and monopile) simultaneously. The outer diameters and section thicknesses along the support structure are chosen as design variables. A set of constraints based on multi-criteria design assessment is applied according to standard requirements, which includes vibration, stress, deformation, buckling, fatigue and design variable constraints. The model has been applied to the NREL (National Renewable Energy Laboratory) 5 MW OWT on an OC3 (Offshore Code Comparison Collaboration) monopile. The results of the application of the integrated optimisation methodology show a 19.8% reduction in the global mass of the support structure while satisfying all the design constraints. It is demonstrated that the proposed structural optimisation model is capable of effectively and accurately determining the optimal design of OWT support structures, which significantly improves their design efficiency.

1. Introduction

Since its early development in the 1980s, wind energy has experienced an unprecedented development with more than 1500% increase in global wind power installation over the last 15 years, reaching a total installed capacity of 432 GW at the end of 2015 [1]. It is considered to be one of the key contributors to satisfying continuous, increasing energy demand and targets for reduced environmental emissions. Given the increasing trend of rotor sizes [2], and since OWTs (offshore wind turbines) benefit from the larger available space, higher wind shear and less variability on market price [3], considerable investments are being deployed in deeper sites located further from shore [4], sharing experience from onshore wind turbines and offshore technologies [5]. Studies have shown that offshore wind could contribute to around 5.5% of the world's electricity by 2050 [6].

Different types of support structures for OWTs exist, as illustrated in Fig. 1. The choice of types of support structure depends on multiple criteria, such as water depth, seabed conditions and financial constraints [7–11]. Monopiles (see Fig. 1b) are currently the most common foundation concept, representing 80.1% of total EU's installations in 2015 [12]. Preferred by industry for their simple and robust design, monopiles have been installed in water depths ranging from 5 m to 30 m. For deeper site locations, monopiles tend to become practically constrained and economically

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* Corresponding author.
E-mail address: a.kolios@cranfield.ac.uk (A. Kolios).

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Nomenclature

a	amplitude of the wave
c	cohesion value of soil
C_D	drag coefficient of the monopile
$C_{D,T}$	drag coefficient of the tower
C_f	frictional coefficient between the pile and the soil
C_M	inertia coefficient of the monopile
C_T	thrust coefficient of the rotor
d_{allow}	allowable deflection
d_{pile}	pile-head deflection
D	external diameter of the tower
f_{1P}	rotor induced frequency
f_{3P}	blade passing frequency
f_{1st}	first natural frequency of the support structure
$f_{sr,allow}$	allowable fatigue safety ratio
$f_{sr,\min}$	minimum fatigue safety ratio
F_{tower}	wind loads along the tower
F_h	hydrostatic force
F_{obj}	objective function
F_T	thrust force
h	local wave depth
H_{ave}	average significant wave height
H_{s50}	50-year extreme significant wave height
k	wave number
L_m	buckling load multiplier
$L_{m,allow}$	allowable buckling load multiplier
M_{global}	global mass of the support structure
n_{rated}	rated rotor speed
N_{Ini}	number of initial samples
N_{life}	design life number of cycles
$N_{MaxIter}$	maximum number of iterations
N_{PerIni}	number of samples per iteration
R	rotor radius
T_{ave}	average wave period
T_{s50}	50-year peak spectral period
u	horizontal velocity of water particles
$\dot{u}$	horizontal acceleration of water particles
u_c	current velocity
$u_{c,MSL}$	velocity of current at mean sea level
$V_{c,ex}$	extreme current speed
V_{ave}	annual average wind speed
V_{e50}	50-year extreme wind speed
V_{g50}	50-year extreme 3 s gust wind speed
V_{ref}	reference wind speed
$\bar{V}$	mean wind velocity
$\bar{V}_r$	reference wind speed measured at the nacelle altitude
$x_1, x_2, \cdots, x_{13}$	design variables

x^L	lower bound of design variables
x^U	upper bound of design variables
z_r	nacelle altitude used as reference height
α	roughness coefficient
ϕ	friction angle of soil
γ_f	partial safety factor for consequence of failure
γ_m	partial safety factor for material
$\gamma_{m,f}$	material partial safety factor for fatigue
η_a	availability of wind turbine
θ_{allow}	allowable rotation
θ_{inc}	rotation due to installation incertitude
θ_{seabed}	rotation at the mudline
ρ_a	air density
ρ_w	water density
$\sigma_{f,allow}$	allowable fatigue stress range
$\sigma_{f,design}$	design fatigue stress range
$\sigma_{T,allow}$	allowable Tresca stress
$\sigma_{T,\max}$	maximum Tresca stress
$\sigma_{VM,allow}$	allowable von Mises stress
$\sigma_{VM,\max}$	maximum von Mises stress
$\sigma_{y,s}$	yield strength of the soil
ω	angular frequency of the wave

Acronyms

DEL	damage equivalent load
DLC	design load case
ECM	extreme current model
EWM	extreme wind model
FEA	finite element analysis
FLS	fatigue limit state
GA	genetic algorithm
IEA	international energy agency
MSL	mean sea level
NREL	national renewable energy Laboratory
NSS	normal sea state
NWM	normal wind model
OC3	offshore code comparison Collaboration
OWTs	offshore wind turbines
PSF	partial safety factor
RNA	rotor-nacelle assembly
RWH	reduced wave height
ULS	ultimate limit state
1D	one-dimensional
3D	three-dimensional

non-competitive [7]. Thus, different concepts such as jacket structures or, most recently, floating support structure are deemed more suitable. This study focuses on monopiles, as they still represent the vast majority of already installed or currently in design OWT support structures.

In addition to higher costs induced by offshore location, OWT support structures require site-specific design consideration in order to ensure the nominal 20–25 years of operational life. As a consequence, the levelised cost of energy (LCOE) of OWTs in 2013 was reported at 215 $/MWh, which was more than three times higher than onshore wind turbines [14]. Although the LCOE of OWT has been reduced recently, the contribution of support structures for OWTs still account for 20–25% of the capital cost [15]. Thus, reducing the support structure cost through structural optimisation is a key enabler to decrease offshore wind costs and make this solution less dependent on subsidy schemes [13].

A structural optimisation model of OWT support structures requires two main components, i.e. (1) a structural model which describes the structural behaviour of support structures; and (2) an optimisation algorithm which finds the optimal set of design variable(s), with regard to the objective function(s) and constraint(s).

Structural models used for OWT support structures can be roughly categorised into two groups, i.e. 1D (one-dimensional) beam models and 3D (three-dimensional) FEA (finite element analysis) models. A 1D beam model discretises the support structure into a series of elastic Euler or Timoshenko beam elements. Due to its computational efficiency and acceptable accuracy to model global structural dynamics behaviour, the beam model has been widely used in commercial codes (e.g. GH-Bladed [16]) to model OWT support structures. Although efficient, the beam model fails to represent accurately structural responses, such as stress concen-