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Effects of soil–structure interaction on real time dynamic response of offshore wind turbines on monopiles

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ABSTRACT

Offshore wind turbines are highly dynamically loaded structures, their response being dominated by the interrelation effects between the turbine and the support structure. Since the dynamic response of wind turbine structures occurs in a frequency range close to the excitation frequencies related to environmental and parametric harmonic loads, the effects of the support structure and the subsoil on the natural vibration characteristics of the turbine have to be taken into account during the dynamic simulation of the structural response in order to ensure reliable and cost-effective designs. In this paper, a computationally efficient modelling approach of including the dynamic soil–structure interaction into aeroelastic codes is presented with focus on monopile foundations. Semi-analytical frequency-domain solutions are applied to evaluate the dynamic impedance functions of the soil–pile system at a number of discrete frequencies. Based on a general and very stable fitting algorithm, a consistent lumped-parameter model of optimal order is calibrated to the impedance functions and implemented into the aeroelastic nonlinear multi-body code HAWC2 to facilitate the time domain analysis of a wind turbine under normal operating mode. The aeroelastic response is evaluated for three different foundation conditions, *i.e.* apparent fixity length, the consistent lumped-parameter model and fixed support at the seabed. The effect of soil–structure interaction is shown to be critical for the design, estimated in terms of the fatigue damage 1 Hz equivalent moment at the seabed. In addition, simplified foundation modelling approaches are only able to capture the dynamic response reasonably well after tuning of the first natural frequency and damping within the first mode to those of the integrated model. Nevertheless, significant loss of accuracy of the modal parameters related to the second tower modes is observed.

1. Introduction

As a consequence of the increasing reliability of offshore wind technology, wind energy has become a competitive source of renewable energy. Currently, turbines with rotor diameters and tower heights of more than 100 m are in production. Optimisation of the turbine blades and the towers leads to slender and therefore extremely flexible structures. Consequently, the first modes of resonance of the total structure, including the foundation, tower, hub, nacelle and blades, are close to the excitation frequencies related to environmental loads from wind and waves. Thus, a modern wind turbine may undergo large deformations, not only during extreme weather conditions but also during power production. In general, offshore wind turbines are exposed to: (a) steady quasi-static loads from the self-weight of the rotor, nacelle, tower and mean wind, (b) stochastic loads from the wind turbulence and the irregular sea states, (c) transient loads from the start, stop and emergency breakdown procedures, and finally (d) cyclic loads from the rotor frequency 1P generated by mass imbalance in the blades and the 3P frequency due to shadowing effects from the wind each time a blade passes the tower. The operational speed of the rotor of state-of-the-art wind turbines is typically about 7–12 rounds per minute (RPM), corresponding to a 1P frequency of 0.12–0.20 Hz. In addition, waves related to sea states with high rate of concurrency typically have wave frequencies of 0.10–0.20 Hz [1]. Therefore, in order to avoid large–amplitude stress variations in the wind turbine structure, three design philosophies are defined and illustrated in Fig. 1a [2]:

- Soft–soft design, where the resonance frequency of the turbine is lower than the rotor frequency 1P and the frequencies related to the dominant wave actions.

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Nomenclature

Scalars:

A_n	residues corresponding to the real poles s_n
α_{0n}	real-valued coefficient in a partial fraction-form
α_{1n}	real-valued coefficient in a partial fraction-form
β_{0n}	real-valued coefficient in a partial fraction-form
β_{1n}	real-valued coefficient in a partial fraction-form
c^{∞}	real-valued constant selected so that the singular part of the impedance function provides the entire stiffness in the high-frequency range
δ_1	modal damping in terms of the logarithmic decrement related to the lowest eigenmode
Δ_j	moment width of the jth load cycle n_{fj}
ε	real-valued parameter for weighted least-squares fitting
E_p	Young's modulus of monopile
f	physical frequency
f_c	frequency constant
f_1	undamped eigenfrequency related to the lowest eigenmode
F	object function
G	constraint for weighted least-squares fitting
γ	real-valued coefficient for a discrete-element model
H	depth of soil layer
κ	real-valued coefficient for a discrete-element model
k^{∞}	real-valued constant selected so that the singular part of the impedance function provides the entire stiffness in the high-frequency range
L_p	length of monopile
L_0	height of cylinder
$M_{eq,1}$	fore–aft fatigue damage 1 Hz equivalent moment
$M_{eq,2}$	side–side fatigue damage 1 Hz equivalent moment
M_1	fore–aft moment as a function of time t
M_2	side–side moment as a function of time t
m	Wöhler exponent
M	order of the rational filter $\hat{Z}_r(i\omega)$
n_{fj}	jth identified load cycle
ν_p	Poisson's ratio of monopile
ν_s	Poisson's ratio of soil
1P	harmonic frequency equal to the rotor frequency
$P(i\omega)$	polynomial and numerator of the rational filter $\hat{Z}_r(i\omega)$
$p(t)$	pulse load
p_n	polynomial coefficients of $P(i\omega)$
$Q(i\omega)$	polynomial and denominator of the rational filter $\hat{Z}_r(i\omega)$
ρ_p	density of monopile
ρ_s	density of soil
ρ_0	density of cylinder
r_0	radius of cylinder
r_p	radius of monopile
ϱ	real-valued coefficient for a discrete-element model
ς	heuristic parameter
s_n	N complex roots of $Q(i\omega)$
s_n^*	N complex conjugated pairs of $2N$ roots of $Q(i\omega)$
$S_{ij}(\omega)$	dynamic impedance function
$S_{ij}^0(\omega)$	static stiffness component of the dynamic impedance function $S_{ij}(\omega)$
3P	harmonic frequency equal to three times the rotor frequency
t_p	thickness of monopile
t	time
T	simulation time
ϑ	real-valued parameter for weighted least-squares fitting
υ_0	wave velocity of the ground
υ_s	shear wave velocity of soil
v_{mean}	normal turbulent longitudinal mean wind speed
ω	circular frequency
w	weight function
$Z_{ij}(\omega)$	normalised dynamic impedance component
$Z_s(\omega)$	singular part of the normalised dynamic impedance component $Z(\omega)$
$Z_r(\omega)$	regular part of the normalised dynamic impedance component $Z(\omega)$
$\hat{Z}_r(i\omega)$	rational filter
ζ_s	hysteretic soil damping

Vectors and matrices:

$\mathbf{r}$	complex amplitude vector of forces Q_i and moments M_i
$\mathbf{S}$	impedance matrix
$\mathbf{u}$	complex amplitude vector of translational degrees of freedom V_i and rotational degrees of freedom Θ_i

- Soft–stiff design, where the resonance frequency is in the range between the rotor frequency 1P and the blade passing frequency 3P.
- Stiff–stiff design, where the resonance frequency is higher than the blade passing frequency 3P.

The soft–stiff design is often chosen, since the high wave loading may induce wave fatigue for the soft–soft design and a stiff foundation is required for a stiff–stiff design leading to a costly design. In order to identify potential sources of resonance and the safe region for the soft–stiff design, a Campbell diagram is

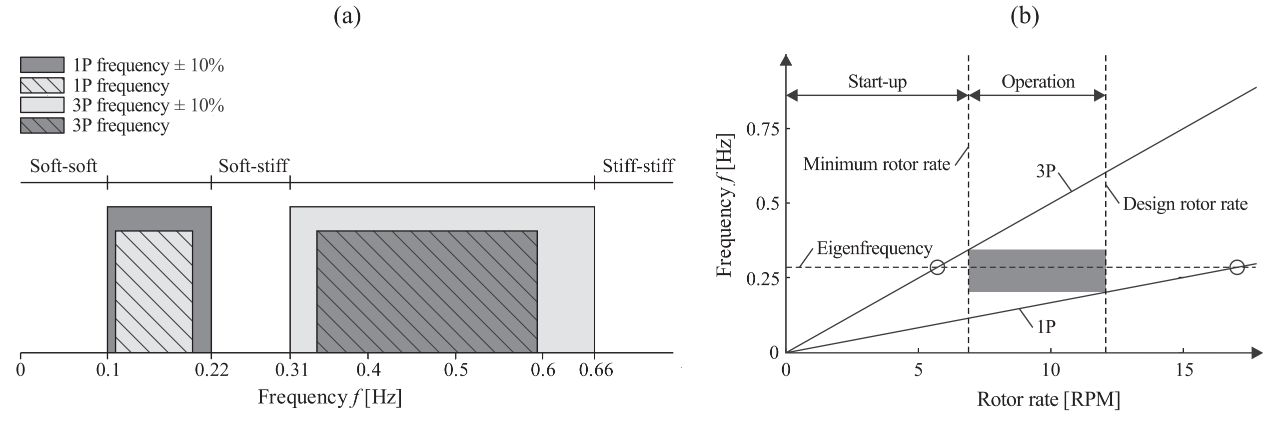

Fig. 1. Design approaches for an offshore wind turbine: (a) 1P and 3P harmonic excitation (after [2]), (b) sparse Campbell diagram for a soft–stiff design (after [3]).