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Dynamic analyses of operating offshore wind turbines including soil-structure interaction

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ABSTRACT

In the dynamic analyses of offshore wind turbines subjected to the external vibration sources, the wind turbines are normally assumed in the parked condition and the blades are considered by a lumped mass located at the top of the tower. In reality, the geometrical characteristics and rotational velocity of the blades can directly influence the wind loads acting on the blades. Moreover, the centrifugal stiffness generated by the rotating blades can increase the stiffness and natural frequencies of the blades, which in turn can further affect the structural responses. The lumped mass model, therefore, may lead to inaccurate structural response estimations. On the other hand, monopile, a long hollow steel member inserting into the water and sea bed, is generally designed as the foundation of an offshore wind turbine. The soil-monopile interaction can further alter the vibration characteristics and dynamic responses of offshore wind turbines. In the present study, the dynamic responses of the modern NREL 5 MW wind turbine subjected to the combined wind and sea wave loadings are numerically investigated by using the finite element code ABAQUS. The blades are explicitly modelled and soil-structure interaction (SSI) is considered. The influences of operational condition and rotor velocity on the dynamic behaviours are systematically investigated. It is found that the responses of the wind turbine in the operating condition are much larger than those in the parked condition; SSI can affect the tower vibrations substantially, while it has a negligible effect on the in-plane vibrations of the blades.

1. Introduction

Offshore wind turbines play an important role in producing electrical energy. Multi-megawatt offshore wind turbines with slender tower and large rotor are widely adopted in the state-of-the-art designs to more efficiently extract the vast wind energy resources. For example, the tower height and rotor radius of the modern NREL 5 MW horizontal axis wind turbine reach 87.6 m and 63 m respectively [1]. These flexible wind turbines are vulnerable to the external vibration sources. For example, wind and sea wave loadings, which are experienced constantly during the whole lifetime of an offshore wind turbine, can result in excessive vibrations to the structures. These adverse vibrations may compromise the wind energy output, cause the fatigue damage to the structural components, and even direct structural damage under extreme conditions. To ensure the safe and effective operations of these offshore wind turbines, it is important to accurately understand the dynamic behaviours when they are subjected to the external vibration loadings.

Extensive research works have been conducted by different researchers to investigate the dynamic behaviours of wind turbines under wind, sea wave and/or seismic loadings. To simplify the analysis, the wind turbines were normally assumed in the parked condition, and the blades were modelled as a lumped mass located at the top of the tower [2–8] by neglecting the geometrical configurations of the blades and the interaction between the tower and blades. In reality, the geometrical characteristics and rotational velocity of the blades can directly influence the wind loads acting on the blades [9]. Moreover, the geometry of the rotor can influence the vibration characteristics of the wind turbine especially when it is in the operating condition since the locations of the blades are changing periodically and the centrifugal stiffness generated by the rotating blades can increase the stiffness and the natural frequencies of the blades [10], which in turn can indirectly affect the dynamic responses of wind turbines. The simplified lumped mass model therefore may lead to the inaccurate structural response estimations.

To investigate the influence of blades on the dynamic behaviours of wind turbines, Prowell et al. [11], Kjørlaug and Kaynia [12] and Santangelo et al. [13] considered the geometrical characteristics of the

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Nomenclature

m_e	effective mass of monopile
m_p	physical mass of monopile
m_a	added mass of monopile
C_a	added mass coefficient
A_p	cross section area of monopile
ρ_w	sea water density
f_y	yield strength
ε_1, ε_2	elastic and total strains
Z_R	transition depth
Z	depth below sea bed
s_u	undrained shear strength of soil
d_P	outer diameter of monopile
γ'	effective unit weight of soil
J	empirical constant
p, p_u	lateral force and ultimate lateral soil resistance per unit length of monopile
y	lateral displacement of monopile
y_c	deformation corresponding to one-half of the ultimate soil resistance
ε_c	strain corresponding to one-half of the maximum stress
z	axial deflection of monopile
z_{peak}	displacement corresponding to the maximum soil-monopile adhesion
t, t_{max}	mobilized and maximum soil-monopile adhesion
Q, Q_p	mobilized and end bearing capacities
S_{vv}	fluctuating wind velocity spectrum
h	height
f	frequency in Hz
$\bar{v}$	mean wind velocity
v_*	friction velocity
c	Monin coordinate
K	Von-Karman's constant
z_0	roughness length
$S_{f,j}$	modal fluctuating drag force spectrum
C_{dt}	drag coefficient of tower
A	area of tower exposed to wind
ρ	air density
ϕ_j	jth mode shape of tower
$\hat{v}$	average mean wind velocity
D	decay constant
coh	spatial coherency loss function
ω	angular frequency in rad/s
v_{app}	apparent wave velocity
f_{mean}	mean wind drag force
v_{rel}, v_f	relative and fluctuating wind velocities
Ω	rotor velocity
a, a'	axial and tangential induction factors
r	radial distance from hub centre
t_s	time in sec
H_{hub}	height of hub
θ	phase difference between blades
p_l, p_d	local lift and drag forces on blade
l	chord length
C_{lb}	lift coefficient of blade
C_{db}	drag coefficient of blade
α, β	attack and pitch angles
κ, φ	pre-twist and flow angles
p_t, p_n	local wind loads in the directions parallel and perpendicular to rotor plane
F_t, F_n	in-plane and out-of-plane wind loads on blade
R	rotor radius
$\phi_{e,1}$	first edgewise mode shape of blade
$\phi_{f,1}$	first flapwise mode shape of blade
η	sea surface elevation
g	gravitational acceleration
γ	peak enhancement factor
α_P, σ	constants in JONSWAP spectrum
f_m	peak wave frequency in Hz
v_{10}	mean wind velocity at 10 m above sea surface
F	fetch length
Φ	random phase angle
x_w, z_w	horizontal and vertical coordinates
v_x, a_x	velocity and acceleration of water particles
d_w	water depth
H	wave height
k_w	sea wave number
T, λ	wave period and length
F_w	sea wave load per unit length of monopile
C_{dp}	drag coefficient of monopile
C_m	inertia coefficient of monopile

blades and explicitly developed the finite element (FE) models of the blades in the seismic analyses of wind turbines. However, only the parked condition was considered in these studies, rotating induced blades location changes and stiffness increment therefore were not considered. To investigate the dynamic behaviours of operating wind turbines, Prowell et al. [14] performed shaking table tests to investigate its seismic responses, additional damping in the fore-aft direction was observed compared to the parked condition. Some researchers simplified each blade as a single [15,16] or two [17] degrees-of-freedom (DOF) system, and the structural responses were estimated by using the home-made programs (e.g. in MATLAB). A lot of mathematics are involved in the calculations, these methods are therefore not convenient for other researchers/engineers to use. Moreover, wind loads acting along the height of the tower and the length of the blades are inevitably different, hence the structural responses may not be realistically captured by these simplified models. Some other researchers modelled the wind turbines by using the commercially available software such as FAST (e.g. [18]) or validated their models against FAST [19]. The structural components can be explicitly developed and the blades rotation can be considered by using FAST. However, as indicated in the user's guide [20], FAST employs a combination of modal and multibody dynamics formulations and models the blades and tower as flexible elements using a linear modal representation that assumes small deflections. In other words, FAST can only simulate the elastic response of wind turbines. Under the extreme loading conditions, the wind turbine may experience nonlinear deformations, which may not be realistically considered by FAST.

On the other hand, the monopile is widely designed as the foundation of offshore wind turbines due to its simplicity [21,22]. A typical monopile is a long hollow steel member with 3–6 m outer diameter and 22–40 m length [6], inserting into the sea water and sea bed. It can be regarded as an extension of the wind turbine tower. For such a slender flexible foundation, the interaction between the monopile and the surrounding soil is inevitable and can reduce the vibration frequencies or even vibration modes of the structure, which in turn may further influence the dynamic behaviours of offshore structures [23]. Many numerical [24,25] and experimental [26,27] studies have been carried out to investigate the influence of SSI on the vibration characteristics of wind turbines. Andersen et al. [24] and Arany et al. [25] investigated the effect of soil uncertainty on the first natural frequency of offshore wind turbine; Lombardi et al. [26] and Bhattacharya and Adhikari [27] conducted laboratory tests on a scaled wind turbine model and found that the natural frequencies of wind turbine were strongly related to the foundation flexibility. Some researchers also investigated the influence