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Optimization and application of a crashworthy device for the monopile offshore wind turbine against ship impact

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ABSTRACT

The risk of offshore wind turbines collision with ships is on the rise during the service period with the increase of offshore wind farms and ship routings. In order to minimize the damage of offshore wind turbines caused by ship impact, a crashworthy device, which contains a rubber blanket and outer steel shell, is proposed. The rubber hardness and the rubber and steel shell thicknesses of the crashworthy device are optimized by comparing the collision-force and nacelle acceleration using LS-DYNA explicit code. The main reason for lessening the maximum collision-force and nacelle acceleration is that the rubber blanket could absorb a portion of ship energy by using its own structure deformation. Therefore, an optimal crashworthy device for the monopile offshore wind turbine, meeting the weight constraint, is suggested and implemented in various impact scenarios. The obvious effects of crashworthy devices are a decrease of the maximum collision-force and nacelle acceleration, especially for ships with smaller initial kinetic energy. The damage area of plastic strain for foundations is reduced to zero when crashworthy devices are used in the analysis scenarios. This paper may be useful in anti-impact design of offshore wind turbines.

1. Introduction

Offshore wind farms, whose wind power is much stronger than that of onshore wind farms, are the main source of renewable energy. Nowadays, offshore wind turbines (OWTs) have been built in many countries, especially in Europe, and the installed capacity is still increasing. By the end of 2012, the global installed capacity of existing OWTs has reached 5117 MW, and the top three countries, Britain, Denmark and China, own 2948 MW, 921 MW and 389.6 MW respectively [1]. Meanwhile, sea routes have become crowded gradually in recent years. As a result, the risk of OWTs stricken by ships is on the rise during the service period. Although several design codes regarding accidental collision loads, such as DNV-OS-J101, IEC 61400-3 and NORSOK standard N-004, have been found, collision between ships and OWTs is a highly nonlinear problem, including contact nonlinearity, material nonlinearity and geometric large deformation. The traditional method, which simplified dynamic load as quasi-static load, does not consider the dynamic effect of impact loads. Biehl and Lehmann [2] evaluated the anti-impact performance of different OWT foundation types (monopile, jacket, tripod, gravity based structure) from the perspective of structural buckling and stability using LS-DYNA code. The damage characteristic of jacket supported OWT was analyzed by Li et al. [3] and Ramberg [4] when ships collide with joints and columns of the jacket. Ding et al. [5] performed nonlinear finite element simulations of collision between ships and a large-scale prestressing bucket foundation of OWT.

In addition, in order to alleviate the OWT damage, various crashworthy devices, such as adaptive inflatable structure [6], steel sphere shell-circular ring aluminum foam pad [7] and different rubber fenders [8], were proposed to protect OWTs from being stricken by ships. Therefore, it is of practical significance to research a crashworthy system in the view point of accidental limit state (ALS) design. This paper compares the anti-impact ability of crashworthy devices with rubber and steel of different sizes and hardness, and gets the optimal crashworthy device for the monopile OWT using nonlinear finite element analysis. Moreover, this study investigates the effect of crashworthy devices in reducing the maximum collision-force, nacelle acceleration and the damage area of plastic strain through various impact scenarios.

2. Background of project

The offshore wind farm is located in the eastern coastal waters of Rudong county, Jiangsu province, China, where underwater terrain is relatively flat with precipitation facies of alluvial face, marine

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Nomenclature

σ_y	yield stress
σ_0	initial yield stress
σ_r	unloading stress
q	constant characterizing strain rate effect
F	constant characterizing strain rate effect
β	strain hardening parameter
E	elastic modulus or Young's modulus
E_t	tangent modulus
E_p	plastic hardening modulus
$\dot{\varepsilon}$	strain rate
ε_{eff}^p	effective plastic strain
$\dot{\varepsilon}_{ij}^p$	plastic strain rate
$\dot{\varepsilon}_{ij}$	total strain rate
$\dot{\varepsilon}_{ij}^e$	elastic strain rate
ε_f	failure strain
ν	Poisson's ratio
ρ	density
W	strain energy density function
I_1	first deviatoric strain invariants of right Cauchy–Green tensor
I_2	second deviatoric strain invariants of right Cauchy–Green tensor
I_3	third deviatoric strain invariants of right Cauchy–Green tensor
C_{10}	Mooney–Rivlin coefficient
C_{01}	Mooney–Rivlin coefficient
G	initial shear modulus
K	initial bulk modulus
d	incompressibility parameter
H_A	shore scleroscope hardness A (Shore A)
c_{soil}	spring damping
D_{pile}	pile diameter
V_s	soil shear wave velocity
F_d	dynamic force of spring
F_s	static force of spring
k_d	amplification factor
V	absolute value of the relative velocity between two nodes of spring
V_0	dynamic test velocity
φ	internal frictional angle
c_u	undrained shear strength
ε_{50}	strain occurred at one-half of the maximum stress in undrained compression test
C	damping matrix
M	mass matrix
ξ	damping ratio
ω	fundamental angular frequency
m	ship displacement
v	ship velocity
α	ship collision angle
A	damage area of plastic strain
ε	equivalent plastic strain
ε_0	yield strain
t_{start}	start time of collision
t_{end}	end time of collision

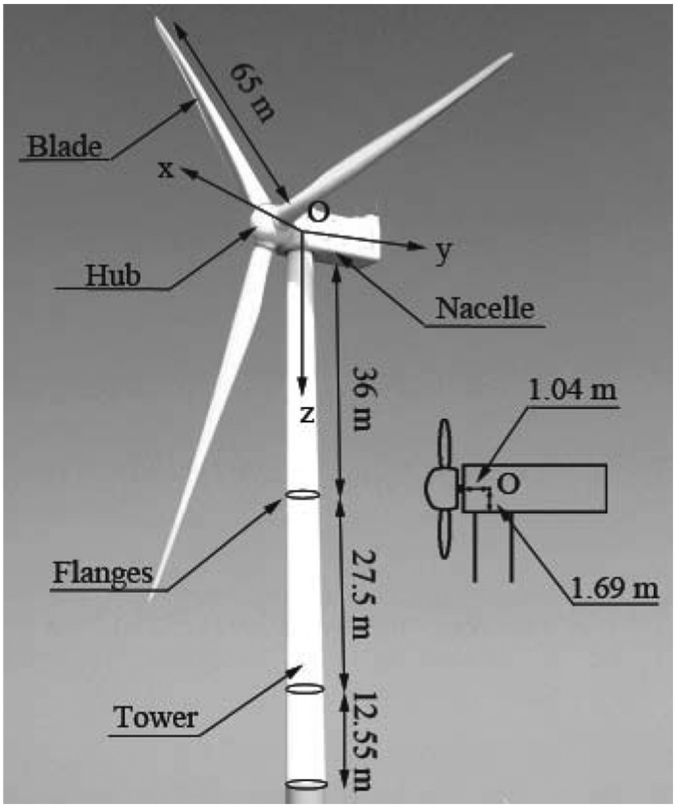

Fig. 1. The OWT components and the main dimensions.

deposition, estuarine and marine-continental sediments. Average seabed level and sea level at the location of offshore wind farm are −14.5 m and 0.01 m respectively on the base of 1985 National Elevation Datum. There is a busy shipping lane off the east of the offshore wind farm, and most of the ship displacement tonnage in this shipping route is less than 2000 tons. The ship traffic may become more crowded in the future. According to the exploration results from China General Nuclear Power Group, the subsoil of top-down can be divided into six layers or nine sublayers in the exploration depth and the exploration results are listed in Table 1.

The type of OWT foundations is a monopile sized 5.0–6.7 m in diameter, 55–70 mm in wall-thickness and 86.5 m in average length, whose top elevation is 14.0 m, and ⑥-1 soil layer acts as bearing stratum for the monopile. The OWT, SWT4.0-130 model (Fig. 1), is composed of a tower, a nacelle, a hub, blades, flanges and an electrical system, and the specific parameters are shown in Table 2. Each section of the tower is connected through the flanges. The center of gravity of the rotor–nacelle assembly is 0.00 m, 1.04 m and 1.69 m in transverse, fore-aft and vertical (above tower top) direction, shown in Fig. 1. The maximum allowable acceleration of nacelle is 6 m/s^2 according to SIMENS, what means that the risk of failure is considered to get strong beyond this value. The plastic strain is not allowed to appear in serviceability limit state for marine structures. Hence, it is of practical significance to find a crashworthy device guaranteeing the normal operation of OWTs with no maintenance or a light maintenance after a ship impact.

3. Numerical modeling

3.1. Material properties

3.1.1. Steel properties

Compared with static loads, plastic deformation of the steel subjected to impact loads will occur more rapidly, and the strain rate will increase significantly at the same time. Dynamic test of steel materials shows that a series of physical and chemical changes will happen with the increase of strain rate, leading to change in