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Damage analysis of ship collisions with offshore wind turbine foundations

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ABSTRACT

Nowadays, a large number of wind turbines are being installed offshore due to more stable and steady flow of wind at sea and also less noise and visual impact compared to onshore wind farms. With the growing number of offshore wind installations, particular attention should be paid to the safe operation of assets. Offshore wind assets are subject to extreme environmental conditions and high dynamic stresses caused by wind, waves and currents. More importantly, they are largely exposed to hazards associated with collision with either commercial ships or infield support vessels passing closely at high speeds. To date, the damage analysis of collisions between infield support vessels and offshore wind turbine foundations has received very limited attention. In this study, a numerical nonlinear finite element analysis (NLFEA) approach is developed to evaluate the damage to wind turbine foundations when stricken by an offshore support vessel. The model is applied to a case study where 4000 tons class vessels collide with two common types of fixed-bottom foundations, namely monopile and jacket structure in shallow and deep waters respectively. Various accident scenarios are identified and the resulting damage to wind turbine foundations are analyzed. The number, location and the extent of damage to the members in each scenario are determined and the effects of reinforcement on the structure response are evaluated. The results of this research provide a good understanding of the factors that affect magnitude of damage caused by ship-wind turbine collision accidents and give an insight on how the next generation of wind turbine foundations can be designed in a more "collision-friendly" way.

1. Introduction

Cumulative wind power capacity has grown on average 22% per year worldwide in the past decade, reaching 432 GW at the end of 2015, with China, USA, Germany, India and Spain accounting for about 73% of the total installed capacity (Global Wind Energy Council (GWEC), 2016). There are in general two types of wind turbines in use: onshore and offshore. Onshore wind turbines are majorly located on land, whereas offshore wind turbines are located in bodies of water such as lakes and seas.

Nowadays, a large number of wind turbines are being installed offshore due to more stable and steady flow of wind at sea and also less noise and visual impacts compared to onshore wind farms. Presently, the United Kingdom (UK) with a total offshore wind power capacity of 5.1 GW ranks first in the world (Renewable UK, 2017), followed by Germany with 3.3 GW and Denmark with 1.3 GW of capacity. The share of offshore wind power in UK's electricity supply was 5% in 2016 and this is forecasted to grow to 10% by 2020 (The Crown Estate, 2017).

The components involved in both the onshore and offshore wind turbines are almost similar. One of the main differences between onshore and offshore wind turbine designs is on their foundation structures. Onshore wind turbines are fixed to the ground with a concrete foundation, whereas offshore wind turbines have their foundations on the sea bed (fixed-bottom) or in the water (floating). Several types of fixed-bottom foundations are currently used in the offshore wind sector, depending on the depth of water where the turbines to be installed, i.e., shallow water zone, intermediate water zone, and deep water zone. The common foundations used for current offshore wind projects are (see Fig. 1): *gravity based*, *suction bucket*, *monopile*, *tripod* and *jacket structures* (Byrne and Houlsby, 2003). Gravity based and monopile foundations are generally installed in shallow waters (with a maximum depth of 30 m), while tripod and jacket foundations are more appropriate for intermediate and deep waters at a depth of between 30 to 90 m.

With the growing number of offshore wind installations, particular attention must be paid to ensuring that safety and integrity of the assets are maintained throughout their service life (Shafiee and Finkelstein, 2015). In recent years, there has been an upward trend in the number of accidents occurring in the offshore wind energy sector. According to the accident reports complied by the (Caithness Windfarm Information Forum, 2017), an average number of 22 accidents per year took place

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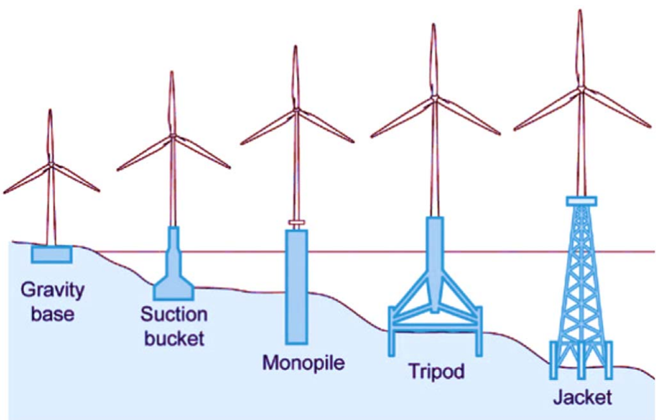

Fig. 1. The most common fixed-bottom foundations used in the offshore wind industry.

from 1997 to 2001 in the UK's wind farms, whereas this number increased to 70 accidents per year between 2002 and 2006, 135 accidents per year from 2007 to 2011, and 164 accidents per year between 2012 and 2016. A majority of these accidents occurred in offshore regions of the country and were caused by fire, structural failure, ice throw, environmental damage, ship collision, etc.

Offshore wind assets are subject to extreme environmental conditions and high dynamic stresses caused by wind, waves and currents (Shafiee, 2015). More importantly, they are largely exposed to hazards associated with collision with either commercial ships (such as tugboats, ferryboats, and private vessels) or in-field vessels (e.g. support vessels, maintenance vessels) passing closely at high speeds. Such collisions may damage or even destroy the wind turbine's and/or the ship's structure, cause pollution to the environment by oil and chemical spills, or lead to serious injuries or fatalities (Den Boon et al., 2004). The categories of impacts associated with ship-wind turbine collision hazards in terms of economic, environmental and health and safety are presented in Table 1.

In order to prevent collision between ships and wind turbines, it is crucial to analyze and evaluate the associated hazards and then reduce the risk of loss below a "tolerable" level through developing a range of cost-effective protection measures and techniques (see Presencia and Shafiee, 2017). To date, several models for hazard assessment of collisions between passing commercial ships and offshore wind turbines have been proposed. Some of the most widely used models include the following:

- COLLIDE is an analytical tool which was developed by Safetec Nordic AS (www.safetec.no/) for drill platforms, but it is currently used for evaluating the risk level of ship collision accidents with wind structures.

Table 1
The potential impacts associated with a ship-wind turbine collision.

Consequence	Damage to wind turbine	Damage to ship
Economic	• Damage to wind farm operator's reputation • Loss of asset • Repair costs • Costs for salvage • Loss of electricity production	• Damage to ship operator's reputation • Loss of asset • Repair costs • Costs for salvage • Loss of revenue to the ship owner
Environmental	Discharge of oil spills (e.g. wind turbine gearbox oil)	Discharge of chemical substances from the ship into the aquatic environment
Health and safety	Injuries or fatalities of maintenance crews present on-site	Injuries or fatalities of ship crews or passengers

- SAMSON (Safety Assessment Models for Shipping and Offshore in the North Sea) was developed by Maritime Research Institute Netherlands (MARIN) (www.marin.nl/) for hazard assessment of the collision between a ship and an offshore wind structure or between two ships at sea.
- CRASH (Computerized Risk Assessment of Shipping Hazards) and MARCS (Marine Accident Risk Calculation System) are two tools developed by Det Norske Veritas (DNV);
- COLWT is an analysis software developed by Germanischer Lloyd (GL);
- COLLRISK is an industry-leading software for collision risk assessment which was proposed by a British company called Anatec (www.anatec.com/);
- DYMITRI is a dynamic marine traffic simulation and risk assessment model which was developed by the British Maritime Technology (BMT) group (www.bmt.org/).

The above-reviewed hazard analysis tools for ship collision are often considered to be robust. They provide users with detailed and comprehensive probability calculations and estimates for different scenarios of ship collision with offshore wind turbines. Some of these models are also able to quantify the collision consequences to varying degrees of detail and accuracy. Despite all these benefits, the existing models have several shortcomings. One of the most important drawbacks is that the damage evaluation in these models are very simplistic—often relying on basic kinetic energy calculations and past accident statistics (Mehdi and Schröder-Hinrichs, 2016). This raises doubts as to whether or not the available models are sophisticated and detailed enough to accurately assess the consequences of ship-wind turbine collisions. The lack of adequately detailed damage assessment model may lead to under- or over-designed control measures for protection of wind foundations and ships against collision impacts, and thereby incurring extra cost to wind farm operators or ship owners. To overcome this shortcoming, a numerical nonlinear finite element analysis (NLFEA) approach is developed in this study to evaluate the damage to offshore wind foundations stricken by an infield vessel during the service period. The model is applied to a case study to simulate the collision of 4000 tons class vessels with a monopile foundation and a jacket support installed in shallow waters and deep waters respectively. The models are developed using nonlinear shell elements in ABAQUS software, taking into account the joint stiffness and local indentation. Multiple scenarios are simulated with various parameter combinations such as collision direction (head on bow or sideway), collision angle, and the ship's type, size, and speed. Various accident scenarios are identified and the resulting damage to wind turbine foundations are analyzed. The number, location and the extent of damage to the members in each scenario are determined and the effects of reinforcing the structure are evaluated. To the authors' knowledge, this is the first study investigating the damage impact of infield vessel collision with wind turbine foundations using shell elements.

The remainder of this article is organized as follows. Section 2 provides an overview of the hazard analysis process for ship collisions in the offshore wind energy industry. Later, in Section 3, a damage assessment model for offshore wind foundations stricken by infield vessels is proposed. The results of the implementation of the proposed model on two types of offshore wind foundations are presented in Section 4 and are subsequently discussed and evaluated in Section 5. Finally, the paper is concluded and possible future research directions are outlined in Section 6.

2. Research background

Collision of ships with wind turbines is one of the major risks that negatively affects the development and operation of offshore wind farms. Very few ship-structure collision accidents have been reported