Cold Regions Science and Technology 123 (2016) 121–139

Contents lists available at ScienceDirect

Cold Regions Science and Technology

journal homepage: www.elsevier.com/locate/coldregions

Numerical study of ice-induced loads and responses of a monopile-type offshore wind turbine in parked and operating conditions

Wei Shi [a,b,*], Xiang Tan [a,b,d], Zhen Gao [a,b,c], Torgeir Moan [a,b,c]

[a] Department of Marine Technology, Norwegian University of Science and Technology (NTNU), Trondheim, Norway
[b] Centre for Ships and Ocean Structures (CeSOS), NTNU, Trondheim, Norway
[c] Centre for Autonomous Marine Operations and Systems (AMOS), NTNU, Trondheim, Norway
[d] Multiconsult AS, Tromsø, Norway

ARTICLE INFO

Article history:
Received 18 August 2015
Received in revised form 11 November 2015
Accepted 16 December 2015
Available online 22 December 2015

Keywords:
Offshore wind energy
Monopile
Numerical model
Ice–structure interaction
Coupled simulation

ABSTRACT

Offshore wind is an attractive source of renewable energy. In regions with cold climates, such as Canada, the Baltic Sea, and Bohai Bay, a good understanding of ice loads is essential to design a reliable and cost effective support structure for an offshore wind turbine. This paper presents a study of the dynamic ice–structure interaction of a commonly used monopile-type offshore wind turbine in drifting level ice in both parked and operating conditions. A semi-empirical numerical model for ice–structure interaction was coupled to the aero-hydro-servo-elastic simulation tool HAWC2. A convergence study was performed to determine the proper time step and simulation length to obtain reliable response prediction. The simulated ice load was compared with the formulations in international standards. The coupling between the ice loads and the structural response of the monopile-type wind turbine was investigated and found to be important. The effects of the ice characteristics (e.g., ice thickness and drifting speed) were examined with the turbine being in parked and operating conditions. Compared with current numerical model, standards from International Electrotechnical Commission (IEC) and International Organization for Standardization (ISO) predict lower ice loads. 3-D effect of ice–monopile interaction and failure of local ice sheet are considered. More stochastic dynamic phenomena are captured for ice–structure interaction in our numerical model. The effect of the ice thickness on the response was found to be significant. A negligible drifting speed effect is found on the bending moment response in the fore-aft direction. There is a large increase in the fore-aft response as the inclination angle of the cone increases. Further sensitivity studies and validation against model tests will be performed for the conical waterline of the wind turbine.

1. Introduction

Offshore wind energy is recognized as one of the world's fastest growing renewable energy resources. Deployment of wind turbine technology at offshore sites offers a promising but challenging solution due to the severe environmental conditions imposed by waves and currents. By the end of 2014, there was 8 GW of offshore wind energy installed in Europe, including 2488 turbines in 74 wind farms in 11 European countries (Corbetta et al., 2015). Another 12 on-going projects will contribute an additional 3 GW by 2016 according to the European Wind Energy Association (EWEA). Due to various challenges in developing offshore wind technology, numerical modeling and the automatic control of offshore wind turbines are currently being investigated intensively (Jiang et al., 2014; Karimirad and Moan, 2013; Perveen et al., 2014; Shi et al., 2013).

Offshore wind turbines (OWTs) have significant potential in northern regions with cold climates, such as Northern Asia, North America, and Northern Europe. Approximately 20% of the European OWTs, which produce 10 GW in total, is to be installed in the Baltic Sea by 2020 based on an EWEA forecast (Arapogianni and Genach, 2013). Bottom-fixed wind turbines are very suitable in these offshore areas. Besides the aerodynamic and hydrodynamic, ice loads would also be an important load for OWTs in cold areas. The design standards for bridge, lighthouses, and oil and gas platforms contain information about structural design against ice loads; however, those standards and guidelines are not always suitable for the design of OWT support structures due to the excessive dynamic effects that are typically present in the latter type of structure. Therefore, the challenges related to ice loads on OWTs are not well understood and have not been investigated in detail to date. Icing on OWT blades and drifting-level-ice-induced ice loads are two different ways that ice can affect wind turbines. Icing on OWT blades will increase the mass and thus change the aerodynamic performance of WTs, leading to increased dynamic loads and reduced power production (Etemaddar et al., 2014; Ronsten et al., 2012). Drifting ice could induce dynamic loads and may cause failure in the support structures of

* Corresponding author at: Department of Marine Technology, Norwegian University of Science and Technology (NTNU), Trondheim, Norway. Tel.: +47 73595602.
E-mail address: shi.wei862@gmail.com (W. Shi).

http://dx.doi.org/10.1016/j.coldregions.2015.12.007
0165-232X/

OWTs. For a 5 MW OWT on a monopile with diameter of 6 m interacting with drifting ice that has a thickness 0.5 m, the ice–structure interaction could generate dynamic forces as high as maximum of 15 MN under conservative simplifications (Nguyen et al., 2014); this is far higher than the wind thrust force of 0.8 MN for 5 MW wind turbine at 11.4 m/s turbulent wind. Ice loads on the support structures for OWT in cold regions could add risks and increases cost of construction and maintenance (Salo and Syri, 2014). These ice loads can thus be of critical concern in the design of WTs; this calls for a detailed study of ice-induced vibrations in OWTs.

For offshore structures used in oil and gas industry in cold regions, ice loads may be dominant over wind and wave loads (Hou and Shao, 2014; McGovern and Bai, 2014). Many studies have been conducted to predict the ice loads on cylindrical or sloped offshore structures. Bekker et al. (2009) carried out simulations of the ice–structure interaction between the ice cover and the offshore structures. Gürtner et al. (2009) simulated ice actions on Norströmsgrund lighthouse by means of a finite element model of the ice with the computational cohesive elements model. Zvyagin and Sazonov(2014) used a probabilistic model to simulate the stochastic ice loads. Bekker et al. (2013) estimated contact interaction of ice hummock and ice floe to predict the ice load on a cylinder using commercial CFD-software. Spencer et al. (2014) used the quantile regression method to analyze global ice pressure data for a wide range of structures. Taylor and Richard (2014) developed a probabilistic ice load model based on empirical method. Conical structures have been suggested for most offshore structures where ice is present because they can induce bending failure in level ice by introducing a vertical force component into the total interaction force using upward or downward cones (Xu et al., 2014). The cone reduces the ice load magnitude and ice-induced structural response compared to a cylindrical structure with the same waterline diameter (Barker et al., 2014). A conical structure is also less likely to lead to severe dynamic ice load because the period of bending failure in level ice, which depends on the ice thickness and the drifting speed, is typically longer than that of crushing failure in level ice against a vertical structure. Ralston's formula was adopted in IEC 61400-3 (2009) and DNV-OS-J101 (2014) to calculate static ice loads on conical structures based on plastic limit analysis. Several Design Load Cases are provided in IEC standard to consider both parked and power production modes. Modern standards for ice load prediction of offshore structures were reviewed by Frederking (2012). Popko et al. (2012a) studied the sea ice loads on offshore support structures by comparing different ice models from different guidelines and standards. They indicated that the interaction of sea ice, other metocean loads and OWT should be considered.

Serious ice induced vibrations of offshore structures have been seen to occur in situ. A limited number of campaigns measured ice loads and response in model tests and field observations involving the ice-induced vibrations (Jefferies et al., 2011). Määttänen et al. (2011) conducted near full-scale ice crushing tests in Aker Arctic test basin. Frequency lock-in crushing may cause severe vibration at certain ice velocities for cylindrical structures (Bjerkås et al., 2013, 2014; Xu et al., 2014). It is also important to determine the force and frequency of loads cycles for fatigue assessment (Hendrikse et al., 2014). This phenomenon is specially addressed in ISO (2010) and IEC standards (2009). Murray et al. (2009) did model tests in a scale of 1:30 and 1:50 to predict ice loads of an ice resistant spar design. Nord et al. (2015) identified the force induced by level ice on a generic bottom-fixed offshore structure using a joint input-state algorithm to describe experimental ice-induced vibrations. Zhou et al. (2013) compared numerical simulations of ice breaking loads with the model tests in an ice tank, where the ice loads were measured during the different ice drift speeds, ice properties and ice drift angles. Full-scale testing was conducted by Yue et al. (2009) on a cylindrical monopile in Bohai Bay to investigate the dynamic ice forces and structural vibrations; three speed-dependent ice force modes were observed. Following their previous work, Xu and Yue (2014) experimentally investigated the dynamic ice force on a jacket structure with an upward ice-breaking cone in the Bohai Sea.

Several studies have been performed on relevant feature for OWT. When calculating ice loads, the coupling effect due to WT aerodynamic loads is typically not considered in most standards. The excitation of a complete OWT structure and the vibration of its blades were reported by Heinonen et al. (2011) and Hetmanczyk et al. (2011) in a numerical study of the dynamic ice loads on an OWT. Gravesen and Kärnä (2009) focused on the static ice crushing occurring on a vertical structure of an OWT in the South Baltic Sea based on the ISO standard (2010) with necessary corrections to the ice reference strength. Barker et al. (2005) and Gravesen et al. (2003, 2005) performed an extensive model testing to investigate the ice-induced vibrations in OWTs in Danish waters. Mitigation of ice-induced vibrations in an OWT was studied using a semi-active model (Mróz et al., 2008) and semi-active tuned mass damper (STMD) system (Karna and Kolari, 2004). Yu et al. (2013, 2014) considered the floating ice cover as a rigid-plastic structure supported by an elastic foundation. The quasi-static ice loads were generated using relationship between ice force and displacement field of the ice using the mode approximation method. They used both limit strain and limit strain rate as ice breaking criteria. In their model, the contact between the ice and the structure is simply assumed as a single point contact for three-dimensional application. Interaction between the level ice and OWT considering structure motion and velocity were not included. No detailed contact information between ice and OWT were included.

Wind turbine design and analysis rely on the use of aero-hydro-servo-elastic simulation tools to predict the coupled dynamic loads and responses of an OWT; however, limited amounts of research have considered fully coupled analyses, which simultaneously investigate the effects of both aerodynamic and ice loads on the behavior of offshore wind turbines.

As an extension of a previous study by Shi et al. (2014), this paper aims to develop and implement a numerical semi-empirical ice load analysis method in the aero-hydro-servo-elastic tool HAWC2 (Larsen and Hansen, 2014) to investigate the intricate dynamic ice-structure interaction process for a monopile WT. The level ice load model used in this study has been well validated for level ice and a circular platform (Su et al., 2010; Tan et al., 2013, 2014; Zhou et al., 2013). An inverted ice-breaking cone is added to the monopile at the mean sea level (MSL) to mitigate the ice loads on the structure. Different from other ice models (Yu et al., 2013, 2014), the proposed model uses the dynamic ice bending model to take into account the relative motion and velocities between structures and ice such that the monopile response influenced the interaction force between the cone and the ice. A series of icebreaking events could be simulated and detailed contact information could be observed based on the updated ice geometry. A dynamic link library (DLL) is used to feed the ice forces at each time step into the HAWC2 based on the input position and velocity of the monopile using an iterative procedure. Meanwhile, the instantaneous ice-breaking pattern can be checked for the contact status between the cone and the ice. Especially, the proposed ice load model, based on 3D contact model, makes it possible to estimate the ice load in the Side-to-Side (S-S) direction, which may be of similar magnitude as that in the Fore-After (F-A) direction. Particular efforts are made to study convergence w.r.t. time step and simulation length. Coupled dynamic analyses are carried out to study the effects of the ice parameters, such as ice drifting speed and ice thickness. The simulated ice load from this study is then compared with the characteristic loads given in design standards of IEC and DNV. The responses of the wind turbine under parked and operating conditions are finally compared under different ice conditions.

In this model, the downward ice-breaking cone is attached to the monopile at the MSL. The cone will reduce the ice loads by changing failure mode from crushing to bending. However, due to increased waterline diameter, D_{wl}, the hydrodynamic loads from wave and current may increase. For a wave condition at Gulf of Bothnia with 50-year ice-time-