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System reliability of floating offshore wind farms with multiline anchors

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ABSTRACT

This research assesses the reliability of floating offshore windfarms utilizing two different anchor configurations: a conventional single-line system in which each anchor is loaded by a single mooring line and a multiline system in which each anchor is loaded by three mooring lines. While there are advantages to adopting a multiline system for floating offshore wind farms, the interconnectedness of this concept introduces disadvantages, such as reduction of system reliability and the potential for cascading failures among multiple structures. The reduction in system reliability is investigated here by running Monte-Carlo simulations in which mooring line and anchor demands and capacities are sampled from probability distributions. Demand distributions are generated through dynamic simulations with environmental conditions corresponding to the 500-year storm. Failure of mooring lines or anchors are initiated when their capacity is exceeded by their demand. The results of this research show that the reliability of the multiline system degrades significantly when progressive failures are taken into consideration. This research also shows that design considerations, such as the sizing of mooring lines and anchors and designing for single-line or multiline loads, significantly influence the system reliability of a floating offshore wind farm.

1. Introduction

As the offshore wind industry continues the trend of installing turbines in deeper water to take advantage of better wind resources (Kumar et al., 2016; Rodrigues et al., 2015), floating offshore wind turbines (FOWTs) are still limited to demonstration projects (Statoil, 2009; Viselli et al., 2016). One of the largest barriers to the development of FOWTs is the increased cost relative to fixed based offshore wind turbines (Myhr et al., 2014). The increased cost of FOWTs can be attributed to additional material costs of larger support structures, increased number of geotechnical investigations needed for multiple anchor locations per turbine, expensive material costs of anchors and mooring lines installed in relatively deeper water than fixed base turbines, and more expensive transmission costs due to longer subsea cables (Myhr et al., 2014). According to the National Renewable Energy Lab (NREL), the substructure and foundation contribute upwards of 35% of the total capital expenditures of a floating offshore wind farm (Moné et al., 2015). To reduce the cost of the anchors of FOWTs, a configuration in which multiple FOWTs share a single anchor is proposed, creating multiline anchors (Diaz et al., 2016). The multiline anchor configuration not only reduces the number of geotechnical investigations and anchors to be fabricated and installed, but also leads to a reduction in the loads on the anchor (Fontana et al., 2016, 2017). One caveat of multiline anchors is that they must be designed for multi-directional loading, which, when combined with certain geotechnical conditions, limits the types of anchors capable of acting as a multiline anchor (Diaz et al., 2016; Fontana et al., 2017).

The introduction of multiline anchors within a FOWT farm means that the failure of an anchor leads to the loss of stationkeeping for multiple turbines. Turbines losing stationkeeping also lead to changes in forces on other interconnected multiline anchors, leading to the potential for cascading failure throughout the farm (Hallowell et al., 2017). For the multiline anchors, the interconnected behavior and potential for cascading effects causes a change in structural reliability for the entire system when compared to conventional single-line anchors (Hallowell et al., 2017). This research extends the authors' previous work by calculating system reliabilities for the floating platforms, rather than component reliabilities, and by comparing systems reliability that results from differing component design methodologies.> For the multiline

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Nomenclature

a_i	anchor number
i	single-line configuration
a_{ijk}	anchor *ijk*, multiline configuration
C_l	line capacity distribution
C_a	anchor capacity distribution
$F_{a,,i}$	anchor tension in anchor *i*
$F_{l,i}$:	mooring line tension in line *i*
FOWT	floating offshore wind turbine
l_i	line number *i*
MRP	mean return period
P_f	probability of failure
SLC	survivability load case
s	coordinate of position along mooring line
s_u	undrained shear strength
t_i	turbine number *i*
WWC	wind, wave, and current
α	soil adhesion factor
β	reliability index
θ	polar coordinate, counter clockwise from North
θ_{WWC}	wind, wave, and current direction

anchor concept to be implemented in a wind farm, the cascading failure mode must be well understood so that its effects may be incorporated into the overall design of the system. This research investigates the reliability of two components of the proposed multiline anchor system, the anchor and mooring lines, and compares them to their counterparts in a single-line anchor system.

According to Moan, structural damage is a relatively common event, with an occurrence of nearly 18 per 1000 platform-years for floating structures (Moan, 2009). There are several historical examples of failure of mooring lines or anchors of floating offshore structures (Sharples, 2006). For example, during Hurricane Ivan in 2004, the semi-submersible platform Noble Jim Thompson broke multiple mooring lines at the fairlead, leading to progressive failure of other mooring lines and loss of stationkeeping (Sharples, 2006). The loss of stationkeeping produced an out of plane loading on the connections between mooring lines and the padeye of the suction pile anchors, leading to the failure of several padeyes (Sharples, 2006). The Noble Lorris Bouzigard floating platform also experienced mooring failures due to Hurricane Ivan, most notably the failure of mooring lines at the fairleads, leading to anchors being dragged from their original location (Sharples, 2006). The 2005 hurricane season included Hurricanes Katrina and Rita, during which 6 and 13 platforms were set adrift from their moorings, respectively (Cruz and Krausmann, 2008). The most notable failure was that of the semi-submersible Deepwater Nautilus, which broke free from its moorings in Hurricane Ivan in 2004, and then again during Hurricane Katrina due to significant damage of its mooring system (Cruz and Krausmann, 2008; Sharples, 2006). In the above examples, it is assumed that the failure mechanism of the mooring lines and connections were due to ultimate tensile loads on the mooring lines under uni-directional forces.

In the aftermath of Hurricane Ivan, studies of failed mooring systems employing suction caissons for Mobile Offshore Drilling Units (MODUs) by Ward et al. (2008) report out-of-plane angles in excess of 90° in the case of the Deepwater Nautilus and angles approaching 45° in the case of the Noble Jim Thompson. In the latter case, the observed post-storm condition of the 9 anchors in the mooring spread showed the following: four anchors showed no evidence of geotechnical failure, three anchors experienced extreme rotation indicative of yield in pure torsion, and two anchors appeared to fail by an axial-lateral failure mechanism (Ward et al., 2008). None of the anchors actually failed in the sense of a complete pullout. However, one may reasonably conclude that 5 of 9 anchors experienced large deformations capable of degrading the soil to its residual state at the soil-caisson interface.

Less experience exists for the failures of anchors resisting multi-directional forces, as required by a multiline system. Experimental investigations have been conducted on suction caissons through centrifuge testing of specimens with multiline loading and have shown that simultaneous orthogonal loading can be treated as a net load on the caisson along the resultant direction (Burns et al., 2014).

There is little guidance in the literature in how to design mooring systems that are susceptible to cascading failure amongst multiple structures. ABS guidelines reference local accidents such as fires, drop loads, or blasts causing chains of cascading events within a solitary structure (American Bureau of Shipping, 2013). Bae et al. assessed the performance of FOWTs whose mooring lines have broken and found that broken lines may result in hundreds of meters of drift due to loss of stationkeeping and a large reduction in mooring line loads, leading to changes in structural reliability (Bae et al., 2017). The lack of guidance for modeling cascading failure amongst structures, and the effect of this failure mode on structural reliability is the motivation behind this research.

This research aims to quantify the reliability of the multiline anchor and mooring line system for a candidate wind farm, and is compared to the reliability of a single-line configuration. Reliability indices, β, are determined by counting the number of failures from Monte-Carlo analyses of a representative wind farm subjected to 500-year storm conditions. Here, β is defined as $\beta = -\Phi(P_f)$, where P_f is the hourly probability of failure given the 500-year storm, and Φ is the standard normal CDF. Failures are assumed to occur when a random sample from a demand distribution of a mooring line or anchor exceeds a random sample of a capacity distribution. Demand distributions are created from hour-long dynamic time history solutions of a full scale FOWT, including dynamic mooring line action. Capacities of mooring lines and anchors are estimated through four representative design philosophies: realistic single-line, exact single-line, realistic multiline, and exact multiline. Here, a "realistic" design is one which accounts for common design practices, such as accounting for misalignment of mooring lines and anchors during installation, as well as limiting the sizing and dimensions of both anchors and chains to reasonably constructible tolerances. An "exact" design is a theoretical representation of an anchor and mooring system in which the capacity is exactly equal to the demand times the safety factor. For the multiline case, failures are tracked and categorized into four different failure types according to how many mooring lines and anchors fail for a given numerical simulation. Conclusions about the results of the reliability analyses are made, and recommendations about further research are given.

2. Problem statement

The general configuration of the FOWT considered here is shown in Fig. 1, representing a plan view of DeepCwind semisubmersible platform used in this research (Robertson et al., 2014). The DeepCwind semisubmersible is a tri-floater platform that is moored to the seafloor with three mooring lines (l_1, l_2, l_3), each of which is attached to a fairlead at one of the columns and to a pad eye at one of the anchors (a_1, a_2, a_3). A coordinate system is established in which the x coordinate is parallel to l_1 and the x coordinate is perpendicular to l_1. A polar coordinate θ is defined with $\theta = 0°$ in the $+x$ direction and is positive for counterclockwise rotations. The mooring lines are equally spaced with $\theta_1 = 180°$, $\theta_2 = 300°$, $\theta_3 = 60°$.

The focus of this paper is on the reliability of two sets of components of the mooring system: the mooring lines and the anchors, neglecting the fairleads and pad eyes. This reliability depends on the capacity of and demand on the mooring lines and anchors, which are treated here as random processes or variables. Mooring lines and anchors are assumed to be identical so that the mooring line capacities can be represented by C_l and the anchor capacities by C_a.