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# Human exposure to motion during maintenance on floating offshore wind turbines

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ABSTRACT

Working on floating offshore wind turbines is a complex operation. An important factor is the influence that the structural motion has on humans located on the asset in a harsh environment during maintenance activities and its implications towards personal safety, human comfort and the ability to work. For the research presented in this paper, extensive simulation studies were conducted to assess if and to what extend working on floating offshore wind turbines may be compromised due to extensive structural motion. Results show that weather windows for maintenance activities are reduced by up to 5% when adhering to guidelines suggesting limiting threshold values for acceleration exposure. The corresponding potential financial losses materializing due to longer turbine unavailability after a fault are significant. All the presented and discussed results underline the importance of considering motion criteria in the design phase of a new project - a factor which is not included in design procedures today.

## 1. Introduction

The use of offshore wind energy resources is playing an increasingly important role in the development of a sustainable, low emission future electricity supply (Corbetta et al., 2015). Conversion of the winds' kinetic energy into electricity is done through a sequence of aerodynamic, mechanical and electrical elements, altogether referred to as a wind turbine (WT) (Burton et al., 2011). The WT is mounted on a supporting structure comprised of a tower and a substructure, either fixed to the seabed or kept in position by a mooring or tendon system. WTs installed in an offshore environment today rely mostly on proven substructure concepts, predominantly comprised of monopiles, jackets, gravity-based foundations or tripods (the latter being applied in earlier wind farms) (Lesny, 2010). Certain restrictions are limiting the application of those bottom-fixed support structures; the most important being the water depth at the individual site under consideration. Values of around 50–70 m set the upper economic feasibility limit for structures under development today (Cruz and Atcheson, 2016), (Fischer, 2012), (Borisade and et al., 2016). For sites located in deeper waters, the application of floating substructure concepts is an alternative; an area being elaborated on today in demonstrator and pre-commercial projects. The portfolio of concepts proposed is comprised of four floating substructure design classes (Fig. 1).

The main difference between these four design classes is their stabilization mechanism in the water, i.e. how they achieve hydrostatic and hydrodynamic restoring. Generally, the motion behaviour of all concepts is dependent on the individual design and based on trade-offs between costs, motion characteristics and many other factors. In this section some general comments for each concept class and their typical motion characteristics are provided, however this may significantly differ for individual designs. The spar-type structure is ballast stabilized. This means that a relatively slender hollow structure is partly filled with a ballasting material in order to achieve a low centre of gravity (below the centre of buoyancy) and thus generate a counter-moment to the heeling moment by the turbine thrust loading in operation. Typically spar substructures are rather insensitive to wave excitation due to their small waterplane area (hydrodynamically transparent structure) and exhibit relatively small motions. The semi-submersible is partly ballast and partly water plane area stabilized. Its motion behaviour is mainly governed by the column diameters, their distances from each other, the draft, heave plates and its mass and inertia properties. Its motion characteristics can be adjusted by these parameters to match a desired behaviour - typically they are designed such that the natural periods for the substructure rigid body motions are well above the spectral peak period of the waves leading to limited motions. The barge concept is primarily water plane area stabilized; a

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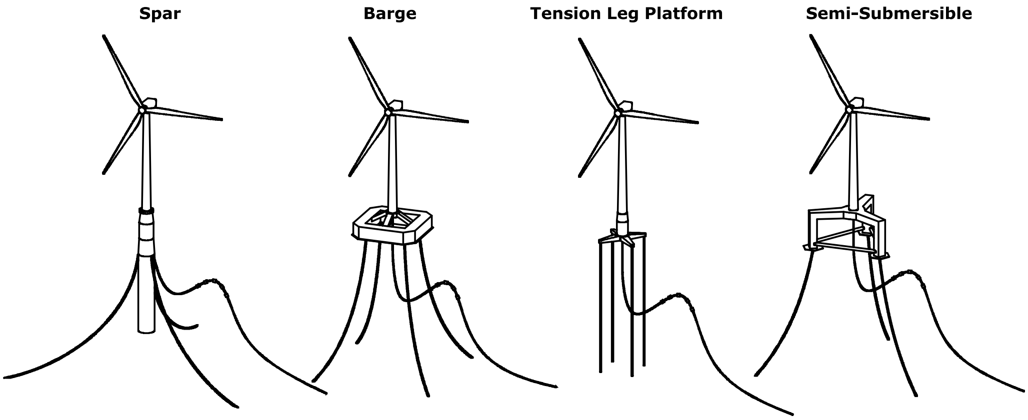

**Fig. 1.** Floating offshore wind turbine substructure design classes.

mechanism comparable to a ship. The shallow draft generally leads to lower natural periods compared to a spar and semi-submersible, but still above the peak spectral wave period. Additionally, barges may be equipped with features increasing the damping and reducing motions, such as a moon pool or heave plates. Tension leg platforms (TLPs) are tendon system-stabilized, with tensioned vertical synthetic, steel wire or tubular steel tendons connected to anchors fixed to the seabed. The tendons are under sufficiently high pre-tension, generated by the surplus buoyancy of the TLP hull (Cruz and Atcheson, 2016), to typically avoid slacking of the tendons under all conditions. The natural periods of a TLP in pitch and roll are typically below the peak spectral wave period making them much stiffer systems with a dynamic behaviour similar to bottom-fixed systems.

Floating offshore wind turbine (FOWT) systems show, generally, larger amplitude motions than bottom-fixed structures. Understanding these motions is essential in order to be able to assess their potential implications towards safety, human comfort and the general ability of technicians to perform works on the asset. During maintenance works conducted by humans on the platform, the WT rotor is in the parked position with blades pitched to reduce wind loading. In this state, the dynamic response of the FOWT is predominantly excited by hydrodynamic loads; whereas the dynamic response of FOWTs can generally be described as the interaction between the floating structure and its surrounding elements (such as mooring lines or anchors) on the one hand and the form and magnitude of hydrodynamic and aero-servo-elastic excitations on the other hand (Matha, 2009).

Ongoing research activities in the field show a strong focus on enhancing the understanding of the structural response and dynamic behaviour of FOWTs in their various operating conditions. The knowledge gained is subsequently used for the development of best practise design standards, considering, amongst others, limiting motion criteria to be respected for operability of turbine components or loads acting on the substructure and its foundation.

As of today, the research and development focus is only to a limited extent considering operations and maintenance (O&M) of these structures. Some published works, describing general floating wind-specific O&M implications, are available (Santos et al., 2016), (Brons-Illing, 2015). Other reports, such as (Guanche et al., 2016) and (Martini et al., 2016) have investigated in detail the accessibility of the structures – one major factor restricting O&M activities in a marine environment. However, to the authors' knowledge, there is currently no study available addressing the potential implications that dynamic motion may have on personnel working on such structures. This is assessed in the presented work.

## 2. Background

### 2.1. O&M context

The performance of operating assets may be evaluated based on several factors; such as safety, cost or availability. The latter is a predominant measure of indicating the level of performance of offshore wind farms; availability being defined as the 'ability to be in a state to perform as and when required, under given conditions, assuming that the necessary external resources are provided' (EN 13306, 2010). A high availability level is usually a primary objective in order to maximize revenues and yield a positive financial result. Availability depends on multiple factors that can be grouped into the three categories of Reliability, Supportability and Maintainability as briefly discussed below.

**Reliability** – defined as the 'ability of an item to perform a required function under given conditions for a given time interval' (EN 13306, 2010). In other words, if an item were never to break, reliability would be at 100%. There is still significant uncertainty in offshore wind asset reliability, as addressed in multiple publications (Faulstich et al., 2011), (Tavner et al., 2007), (Wilkinson et al., 2010), (Carroll et al., 2015), (Gintautas et al., 2016). For context, new offshore wind farms built today typically assume 95% availability in their service level agreements but actually achieve often 97% or more from the author's industry experience.

**Supportability** – defined as the 'ability of a maintenance organization to have the correct maintenance support at the necessary place to perform the required maintenance activity when required' (EN 13306, 2010). Considering corrective operations, this covers all activities which take place from occurrence of a fault until the actual repair or replacement activity is started. With respect to the offshore wind industry, supportability is, to a large extent, restricted by access limitations due to weather conditions, but also the availability of suitable vessels and spare parts to carry out the maintenance activity (Nielsen and Sørensen, 2011), (Scheu et al., 2012), (Irawan et al., 2017).

**Maintainability** – defined as the 'ability of an item under given conditions of use, to be retained in, or restored to, a state in which it can perform a required function, when maintenance is performed under given conditions and using stated procedures and resources' (EN 13306, 2010). In the offshore wind energy industry, a good maintainability figure may be achieved by a modular design which allows for easy component replacements.

The basic mechanisms of reliability, supportability and maintainability are illustrated below, based on a simplified model valid for corrective maintenance activities in the field of bottom-fixed offshore