Ocean Engineering 165 (2018) 293–306

Contents lists available at ScienceDirect

Ocean Engineering

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

Human exposure to motion during maintenance on floating offshore wind turbines

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ARTICLE INFO

Keywords:
Floating offshore wind energy
O&M
Workability
Maintainability
Human exposure to motion
Whole-body vibration

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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https://doi.org/10.1016/j.oceaneng.2018.07.016
Received 9 February 2018; Received in revised form 6 July 2018; Accepted 7 July 2018

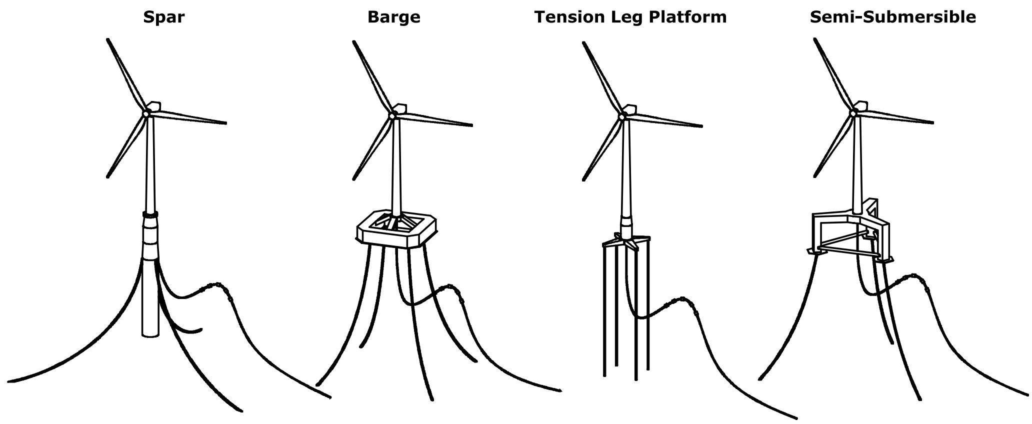

Fig. 1. Floating offshore wind turbine substructure design classes.

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

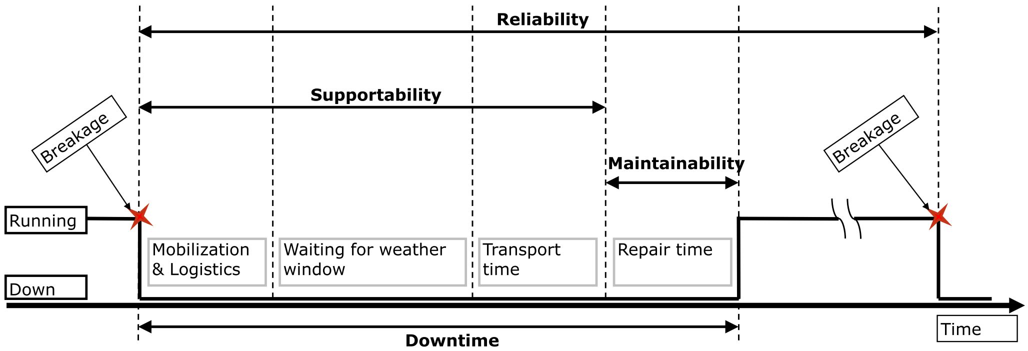

Fig. 2. Concept of reliability, supportability and maintainability.

wind energy (Fig. 2).

Taking a closer look into the supportability section, it can be seen that one main part of it is the waiting time for the availability of required spare parts and vessels (mobilization and logistics), as well as a weather window being long enough to conduct all required tasks; the following explanations are mostly related to restrictions related to a weather window. The weather window required predominantly depends on the limits set for the vessel or helicopter accessing the asset and the type of repair or replacement required (Scheu et al., 2012). There are three main means of transport used for accessing offshore WTs today:

- Crew transport vessel (CTV)
- Service operation vessel (SOV)
- Helicopter

For CTVs and SOVs, the main criterion limiting access is the sea state. CTVs operate up to significant wave heights of around 1.5 m; SOVs equipped with a motion compensated gangway enable personnel drop-offs up to 4.5 m (http://www.ampelmann.nl/systems), (https://www.siemens.com/stories/cc/en/smooth-service-on-the-rough-seas/) (in other studies the SOV type of vessel is referred to as a 'small accommodation vessel' (SAV) or 'mini daughter vessel' (Sperstad and et al., 2017)). As per the author's best knowledge, gained through extensive discussions with wind farm operators, the highest significant wave height under which transfers to offshore wind turbines have been conducted to-date is 3.5 m; which has also been chosen as the upper feasibility level for all studies.

Helicopters can operate independently from sea state conditions but are limited by wind speed, visibility (U.S. Department of Transportation, 2012) and the motion of the floating structure with respect to the helicopter deck (CAAP 92-4(0), 2013).

For the sake of simplification, it is further distinguished between a major and a minor intervention. Activities involving large lifting operations, such as a blade or transformer replacements, are considered as major interventions; small repairs not requiring large tools and cranes are considered as minor interventions.

Major offshore lifts require, regardless of acceptable sea state and visibility conditions, more or less zero wind speed conditions. As far as minor interventions are concerned, it is usually assumed that a successful access manoeuvre guarantees a successful maintenance activity (Scheu et al., 2012); even though it shall be noted that, based on industry experience of the author and co-authors, this simplified assumption may be questioned. In general, however, a failed activity would rather be related to an unsuccessful failure finding procedure, missing tools or spare parts than to the influence that motions have on personnel working on the asset. Due to this observation, the pure time of workable versus non-workable conditions is assessed in this study, independent of the respective task to be carried out. This mechanism is indicatively illustrated below (Fig. 3).

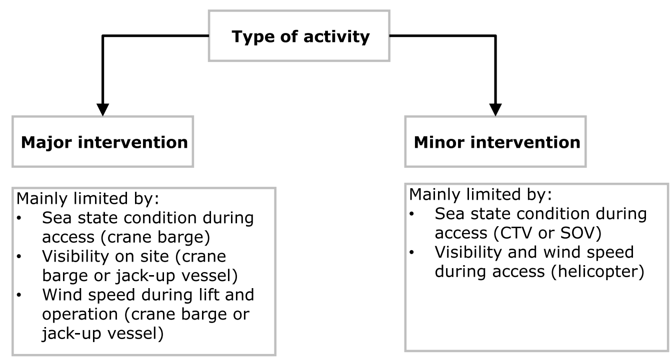

Fig. 3. Classification of offshore intervention types.

A factor that has not specifically been addressed in research studies or other materials available to the public today, is the way in which motion exposure may impact on personnel located on floating wind turbines whilst conducting maintenance works. This is in the focus of the present paper and further discussed in the following sections.

2.2. Human response to vibration

Several reports address the impact that motion has on comfort, but also on health and safety of personnel being exposed to such motion. These effects are well described by Griffin (1990) in his Handbook of Human Vibration. Results of studies investigating general implications of exposure to motion (Maritime and Coastguard Agency, 2009) classify effects into the following categories:

- Discomfort and adverse effects on performance
- General health and safety risk
- Aggravation of pre-existing injuries
- Motion sickness (low-frequency motions)

Mansfield (2005) suggests a classification of motions, depending on their characteristics with respect to frequency and acceleration magnitude. Such a classification is required to understand which kind of phenomena might be relevant for a given case. Fig. 4 presents an overall classification.

Global motions experienced on floating offshore WTs are typically located in the low frequency range, below 1 Hz. This is an area, in which nausea (or sea/motion sickness) is relevant. Under certain conditions, also when considering bottom-fixed offshore WTs, the area around 1 Hz may become important. The respective phenomenon is the so-called whole-body vibration (WBV). Higher frequency vibration may be experienced by personnel through hand-transmitted vibration when using, e.g., power tools during their works on the asset. This study is focused on WBV and sea sickness and hand-transmitted vibration is therefore not considered.

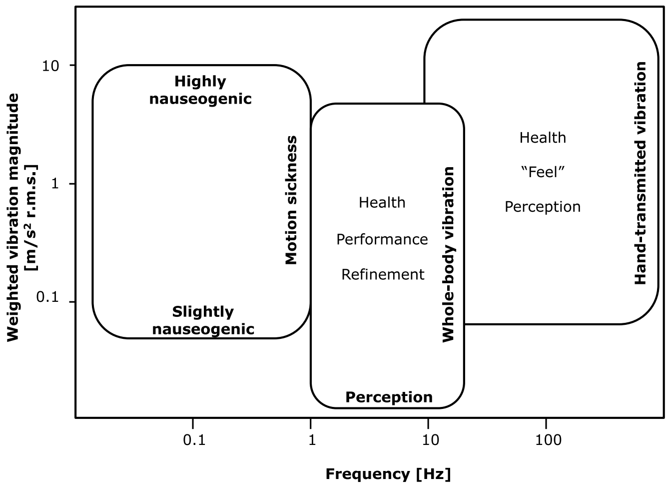

Fig. 4. Motion characteristics classification according to Mansfield (Mansfield, 2005).

2.3. Assessment of motions

There are several standards available today for assessing motions in different environments. Most relevant are the ISO 2631–1, referred to in (ISO 2631-1, 1997) and the ISO 6897, referred to in (ISO 6897, 1984). ISO 2631–1 provides general guidance on assessing motions but provides limiting exposure values only for a frequency range of greater than 1 Hz. ISO 6897 relies on the motion assessment in line with ISO 2631-1 but provides more guidance on treating low frequency motion in the range of 0.063 Hz–1 Hz. For measurement of motions, root-mean-square (r.m.s.) values are to be calculated with the following formula with x_i representing the acceleration magnitude over n time steps; it shall be noted that different standards require different frequency weighting and filtering techniques. Those have been applied during the post-processing of the presented simulation studies – however, since the main results consider unweighted r.m.s. values only, further theoretical background of the band-limiting low and high pass frequency filters, acceleration-velocity transition and upward step formulations are omitted in this paper for clarity (please refer to ISO 2631–1 for further details (ISO 2631-1, 1997)).

$$r.m.s. = \sqrt{\frac{1}{n}\sum_{i=1}^{n} x_i^2} \tag{1}$$

Weighted means that those frequencies which are not relevant for the assessment are filtered out. Accelerations occurring during other, more relevant, frequencies are amplified. ISO 2631-1 suggests two methods for doing this. Method I, the basic evaluation method, relies on amplification factors to be applied at certain frequencies (Clause 6 in (ISO 2631-1, 1997)). Method II, as described in Annex A of the same standard, relies on frequency weighting by parameterised transfer functions. Considering today's available computational capabilities, the latter, more advanced, method can usually be applied; it is chosen for all calculations presented in this paper. For the analysis of the vibration behaviour over time, a method from the railway industry described in BS EN 12,299 (BS EN 12299, 2009) suggests displaying the variation of the root-mean-square value over the time length of the signal. The simulation or measuring time is divided into multiple small-time windows; for each window one r.m.s. value is calculated. Caicedo et al. (2012) use this method in the evaluation of the dynamics of civil structures and give suggestions regarding the length of the time windows. The weighted r.m.s. value shall, subsequent to an on-site measurement or the evaluation of a simulation time series, be compared to exposure limit threshold levels. Those threshold limits suggest boundary conditions of personnel being exposed to certain, specified conditions – such as a maximum average acceleration over time. ISO 2631-1 suggests threshold values for frequencies above 1 Hz. As this is outside the expectable frequency range of the structures assessed in the present study, those limits are not taken into consideration. ISO 6897 suggests threshold levels at different frequency-acceleration combinations. In this standard it is explicitly stated that floating offshore structures are not within the scope of the assessable working areas (Clause 1.2/Note 3). Whilst the procedures for measuring accelerations are well described, it can be concluded that the guidance by standards for evaluating the impact of low frequency motions in terms of threshold values is very limited.

Apart from the standard literature, one publication from the Nordic research collaboration Nordforsk (1987) is used as a reference in several other studies. This publication is practically oriented and presents limiting motion exposure criteria for different kinds of works on vessels. It is, amongst others, referenced in Buchner et al. (2005) who present an assessment of the use of small tug boats for assisting liquefied natural gas carriers during berthing and departure operations. Smith and Thomas (1989) refer to Nordforsk in the course of a comparison study for motion criteria in naval missions. Dolinskaya et al. (2009) assess ship route optimization under the consideration of operational constraints as referred to in Nordforsk. Mathisen (2012) uses the Nordforsk motion exposure limits to evaluate workability on a floating fish farm far offshore; he further points out that currently used standards may be re-thought when moving further off the shore. Due to their wide application and the comparable motion characteristics of vessels and FOWTs, the motion criteria suggested by Nordforsk have also been applied in the studies performed in the course of the present research project. The values for un-weighted r.m.s. values are presented below (Table 1).

The choice of an adequate limit value for the case of maintenance conditions depends on different factors and was made between the limits of "Intellectual Work" and "Transit passenger". The "Intellectual work"-criterion from Nordforsk originates from the "Long-term tolerable" limit value formulated by Payne (1976) (Payne, 1976), for work of a more demanding nature. It is further described by the former ISO 2631/3 (1985) as reference value for "half an hour exposure period for people unused to ship motions" or for "scientific personnel on ocean research vessels" by Hutchison and Laible (1987) (Hutchison and Laible, 1987). This limit was taken into consideration because maintenance tasks (failure finding, inspections, component exchange, service) place a high demand on the concentration and accuracy of the executing personnel to complete more complicated works. However, a workday offshore counts 12 h of which approximately 10 h are spent on wind turbines and 2 h on the transfer vessel – depending on the distance to shore and the wind farm layout. The fact that the "Intellectual work"-criterion applies to an „half an hour exposure" does, from the author's perspective, not reflect the reality adequately and does not sufficiently account for the importance of exposure duration for motion sickness as described by Griffin (1990) and Mansfield (2005). For this reason, the "Transit passenger"-criterion was chosen, because it is the close to the "Intellectual Work" criterion and according to the old ISO 2631/3 (1985) it applies to a "two hours exposure period for people unused to ship motions". The two hours do not meet the exposure time of

Table 1
Limiting motion criteria according to (Nordforsk, 1987).

Root-mean-square criterion			Description
Vertical acceleration	Lateral acceleration	Roll	
0.2 g	0.1 g	6.0°	Light manual work
0.15 g	0.07 g	4.0°	Heavy manual work
0.10 g	0.05 g	3.0°	Intellectual work
0.05 g	0.04 g	2.5°	Transit passenger
0.02 g	0.03 g	2.0°	Cruise liner

maintenance personnel but are the longest period found within the Nordforsk criteria. This means that any situation in which the lateral acceleration is greater than 0.04 g, the vertical acceleration is greater than 0.05 g or the roll inclination is greater than 2.5° is classified as non-workable condition, i.e. it is assumed that no works may be carried out in those conditions.

Nordforsk draws the presented r.m.s. limit values in Table 1 from different sources. The "Light manual work" limit corresponds to the "Tolerable, less than one hour" criteria introduced by Payne (1976) in 1976 and the "Intellectual work" limit corresponds to the "Long-term Tolerable" criteria respectively. In his choice of motion criteria for naval vessels, Nordforsk does not emphasise the difference between frequency weighted and unweighted criteria. As the ISO 2631–1 (ISO 2631-1, 1997) recommends applying a broad band filter on the acceleration time signal of the structure in order to reflect the human perception of motion the threshold values used to assess this signal also need to be weighted r.m.s. acceleration values. Tracing back the thresholds of "Light manual work" and "Intellectual work" to Payne (1976) showed that at least these two limit values are of unweighted nature. No filter functions were thus applied on the resulting acceleration time signals in the main analysis of this paper.

2.4. Motion criteria and O&M

As described in the previous sections, humans are limited in their ability to work in certain conditions. If the conditions that a technician on a FOWT is exposed to would not allow him or her to carry out works, the downtime of the asset may increase.

It must be investigated whether or not the success criteria for offshore works assumed so far are still valid if technicians are exposed to significant motion. Limiting motion criteria are to be identified and assessed against expectable site conditions during maintenance works. Potentially identified motion criteria for work execution must be treated in the same way that weather windows are treated; i.e. there may be times in which access is possible but the exposure to motion in the working area is unacceptable leading to an increased waiting time. This mechanism is illustrated in Fig. 5 above. The quantification of the delta in downtime, highlighted with a grey background, is the focus of the study documented in this paper. A methodology for assessing this situation is suggested in the following sections. It is followed by a presentation of results from simulation studies and their interpretation.

3. Methodology

The following steps were undertaken through the application of the proposed methodology for workability assessment on (floating) offshore wind turbines; further details of each step are provided below (Fig. 6).

Step 1 encompasses the calculation of the geometric data of the wetted surface of the floating substructure under consideration, i.e. a meshed surface geometry of the hull. In the scope of this paper, the substructure designs are pre-defined and not specifically developed and designed for this study. For more information on the design process, reference is made to the design standard for FOWT structures (DNV-OS-J103, 2013) and its counterpart for bottom-fixed applications (DNVGL-ST-0126, 2016). It shall be noted that the design for workability is currently not described in the referred standards.

In ***Step 2***, hydrodynamic parameters are calculated for the respective geometry file with a frequency domain boundary element potential flow based solver. In this study the commercial WAMIT software is utilized to calculate first order wave force and motion transfer functions, second order wave drift forces, hydrostatic stiffness and radiation forces for the wetted area of the body. These parameters describe the wave interactions with the floating platform in the frequency domain.

Step 3 contains the simulation of the FOWT under consideration. This requires a definition of the environmental conditions in which the turbine will be operated and maintained. As identified earlier, the motion of the floater mainly depends on wave height and period under maintenance conditions, in which the rotor is in a parked or idling position. It is therefore appropriate to obtain the relevant information from Hs/Tp scatter tables as usually available in a Design Basis document (Hs = significant wave height/Tp = wave peak period).

The structure is then, in the aero-servo-hydro-elastic simulation software, exposed to the respective conditions for an interval of three hours plus ramp-up time per sea state in order to let transients decay.

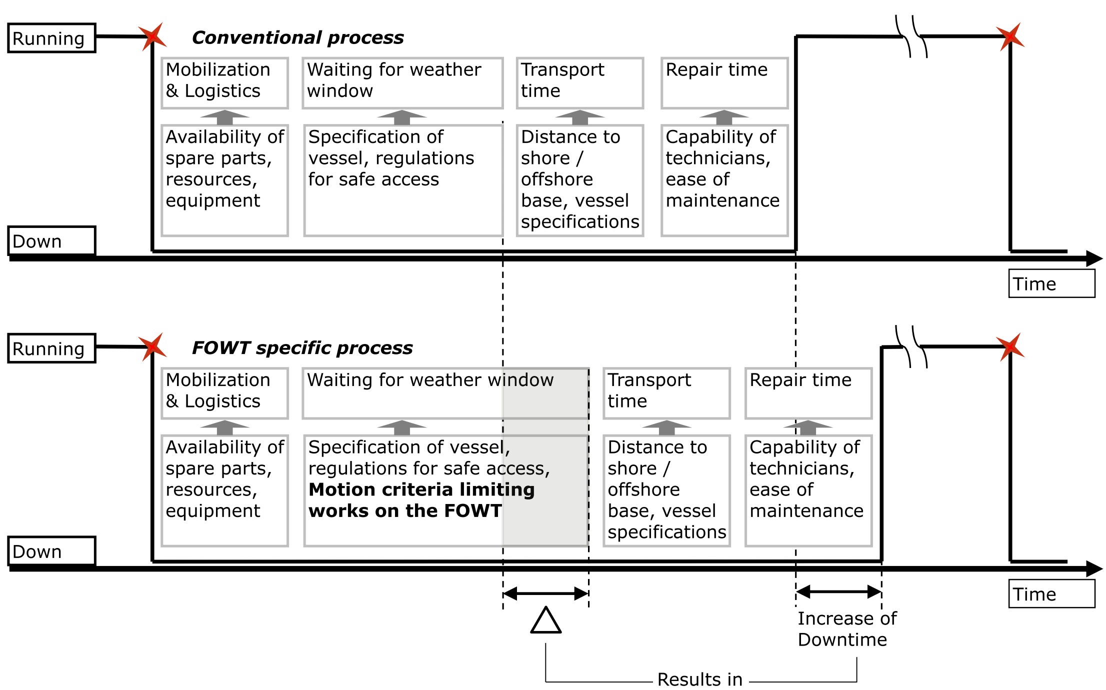

Fig. 5. Potential impact of motion criteria on downtime.

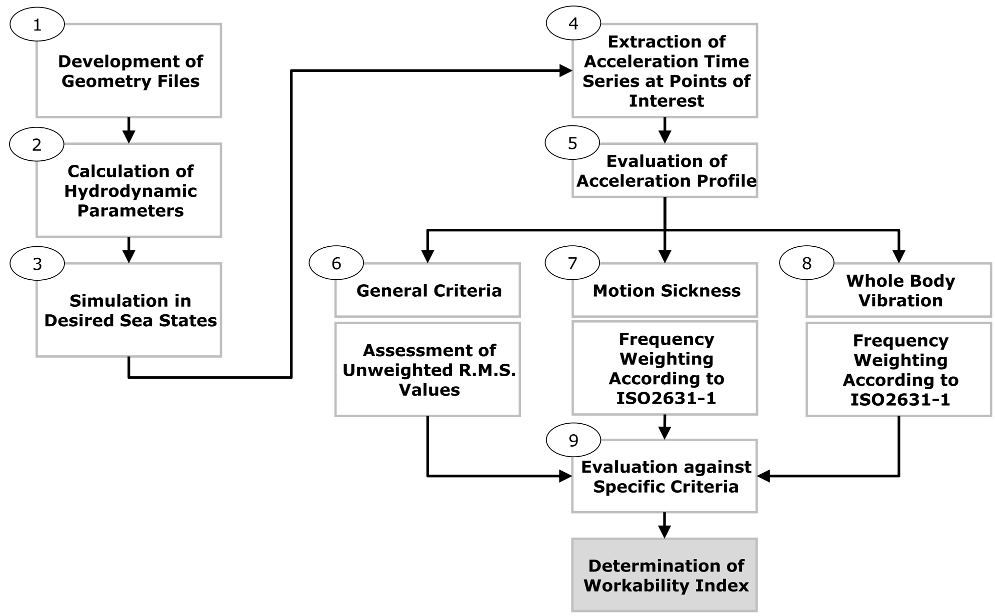

Fig. 6. Methodology for assessing motions on floating offshore wind turbines.

The simulation time of three hours is common practise in the offshore oil and gas industry and recommended by (DNV-RP-C205, 2007) and (DNV-RP-H103, 2011) for simulated, irregular sea states.

The post-processing is initiated in ***Step 4***. First, the unfiltered acceleration time series of the full length of 11,100 s are extracted and prepared for subsequent analysis. Therefore the first 300 s are cut off and excluded from the post-processing in order to minimize the effects of the initial simulation transients on the resulting load statistics. Accelerations are recorded in all six degrees of freedom of the floater movements; illustrated generically for an arbitrary floating body in Fig. 7 below.

The accelerations in surge- and sway-directions are combined by taking the square root of the sum of the squares of both directions. The resulting values describe the lateral displacement in space. With the same procedure the roll and pitch rotational motions are combined into a resulting rotation. Yaw motions are not considered as their magnitudes are negligible under the investigated conditions. Heave motions are used as a direct single signal and they are not combined with other signals for processing. The following formulas describe the ways in which lateral and rotational acceleration signals were combined.

$$A_{lat}(t) = \sqrt{(A_{sway}(t))^2 + (A_{surge}(t))^2} \tag{2}$$

$$R_{rot}(t) = \sqrt{(R_{roll}(t))^2 + (R_{pitch}(t))^2} \tag{3}$$

In ***Step 5***, the evaluation of acceleration profiles is split into different aspects. Three aspects are considered here – namely general motion criteria, motion sickness and whole-body vibration (for further details, refer to Section 2.2). Each of the different phenomena is explained in Steps 6 to 8.

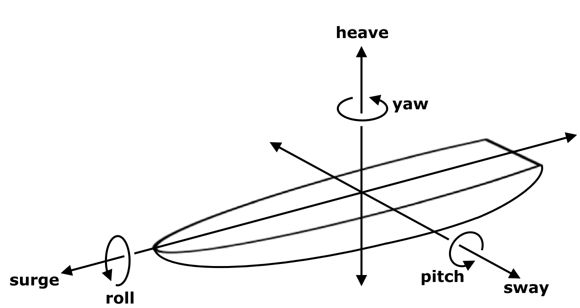

Fig. 7. Generalized 6 degree of freedom motion decomposition of floating body.

The assessment in ***Step 6*** is related to general motion criteria. The assessment is following the methods presented in (ISO 2631-1, 1997); i.e. calculating unweighted r.m.s. values of the different acceleration components.

The time series of the acceleration signals are divided into bins of a fixed duration and a r.m.s. acceleration value is calculated for each bin. This method is known from railway applications and it allows an evaluation of the r.m.s. accelerations along the route and to assign the values to their corresponding track section (BS EN 12299, 2009).

For the given problem, it is of interest to observe the changes in the accelerations during the simulation time. As a sensitivity study, the bin size has been varied between 1 min, 5 min, 10 min and 20 min to observe how the length of the interval changes the r.m.s. values of the peaks. In each bin, the recorded time step of the simulation should be at least four times the frequency of interest; for the given problem, frequencies are in a range up to around 0.5 Hz. Therefore, a minimum sampling frequency of 2 Hz or 0.5 s is chosen (Fig. 8).

The acceleration r.m.s. values are calculated for each exposure direction of interest within each bin. The bin size represents the acceptance criterion for exposure time of a technician being located in the working area. An exposure time of, for instance, one min means that one r.m.s. value is calculated for each minute of the simulation. The workability index changes with the bin size chosen; the parameter must therefore be treated with care. Based on the studies referred to in Section 2.3, a bin size of 10 min has been chosen (Caicedo et al., 2012); a sensitivity analysis of different bin sizes has also been carried out in order to illustrate the effects.

Within each bin, the r.m.s. value is calculated; depending on the assessment method, it is calculated either weighted or unweighted – similarly to steps 7 and 8 as described below. A histogram is produced based on the results. It encompasses the expectable range and frequency of acceleration magnitudes during specific Hs/Tp combinations. For every direction (lateral, vertical, and rotational) the r.m.s. values are compared to their specific r.m.s. acceleration limits. The percentage of occurrences outside the given limit values is denoted as a non-workable condition; the fraction of time in which the respective limiting motion exposure threshold is not exceeded is further denoted as the **Workability Index (WI)**.

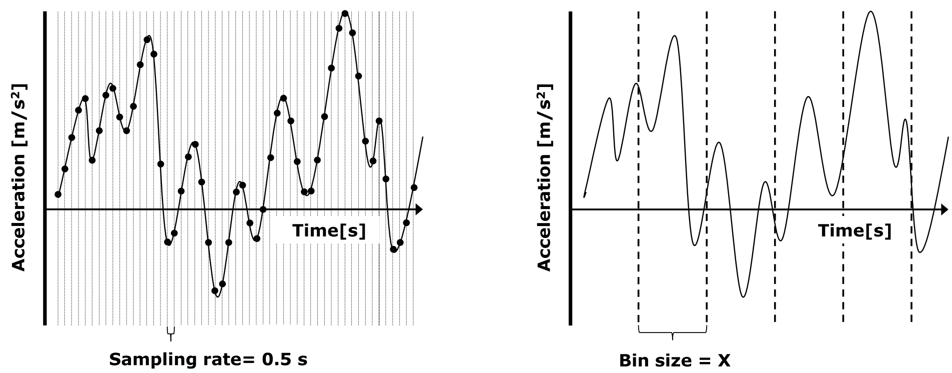

Fig. 8. Sampling rate and bin size for r.m.s. calculation from acceleration signals.

$$WI = \frac{Workable\quad Time}{Total\quad Duration} \tag{4}$$

The individual WIs from the different directions are multiplied and provide the WI of the specific Hs/Tp combination. The WI is calculated for each point in the Hs/Tp table of interest for a given site. This process is illustrated below (Fig. 9).

For the further assessment, the WIs are related to time series in order to account for the number of occurrences of certain Hs/Tp combinations. The average WI is calculated from all individual WIs. Time steps in which access is not given are excluded for this assessment (in the example below, the wave height boundary for access has been set to 2 m H) (Table 2).

Step 7 and ***Step 8*** are conducted similarly to Step 6 but with the main difference that the acceleration signal is filtered before assessing its properties. The filtering is done in accordance with ISO 2631–1 (digital method per Appendix A), as referred to in (ISO 2631-1, 1997).

4. Application and results

The methodology suggested above has been applied in several case studies, representing the technological state of the art. The meteorological data is derived from the applications described in the LIFES50 + project as referred to in (Iberdrola Ingeniería y Construcción, 2015). It encompasses the following sites, shown in Fig. 10:

The description of the 10 MW reference turbine used can be found in

Table 2
Calculation of the average workability index in the time domain.

Time	Hs [m]	Tp [s]	WI
1	1.8	8	0.91
2	2	9	0.89
…	…	…	…
t	2.2	9	(0.87)
Average			**0.90**

(Deliverable D3.2, 2016). The detailed specifications of the spar concept can be found in the public report (Xue, 2016). An in-house developed 3-legged tension-leg platform has been developed on the basis of Wehmeyer (Wehmeyer et al., 2015) and the publicly available definition by Bachynski (2014). A simplified semi-submersible concept from the developer Olav Olsen has been applied (University of Stuttgart, 2018) as well as an in-house conceptual design of a barge concept with the WT mounted on a centrally located transition piece.

The simulations of the four concepts were performed with a coupled aero-servo-hydro-elastic simulation software SIMA, which has an integrated simulation workbench for advanced analyses of marine operations and floating systems. For the semi-submersible, the TLP and the spar concept, Riflex-Simo models are used, which are based on a nonlinear finite element formulation and comprise an elastic tower. The mooring systems in SIMA of the three concepts are represented by a dynamic mooring system model providing a sufficiently accurate behaviour of the mooring loads in the time domain. The floater of the TLP

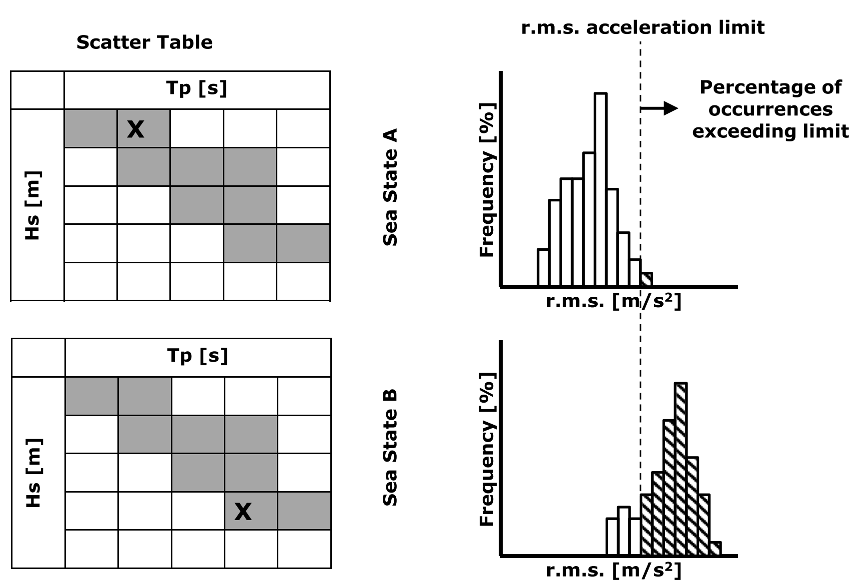

Fig. 9. Sea state dependent workability index.

Fig. 10. Sites from the LIFES50 + project. From left to right: West of Barra (Scotland), Gulf of Maine (U.S.A.), Golfe de Fos (South of France).

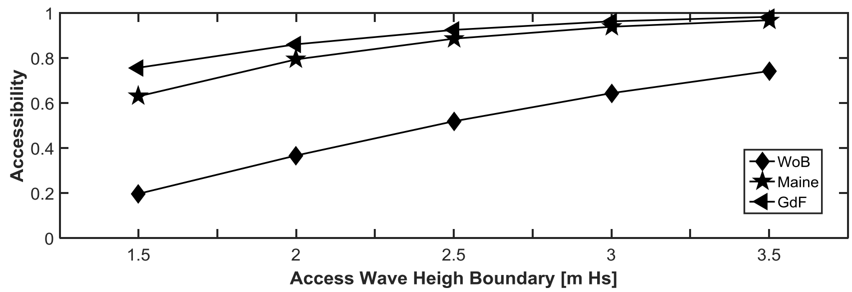

Fig. 11. Accessibility vs. wave height boundary at different sites.

and the semi-submersible are elastic models, the substructure of the spar is a rigid model from (Xue, 2016). The program evaluates the motion response of these concepts through hydrodynamic parameters which are created by a WAMIT simulation. All accelerations and rotations, which are the basis of the results presented in this report, have been calculated for the nacelle of the 10 MW WT mounted on the substructures. SIMA is a proven software, well tested in the oil and gas and offshore wind industry. The accuracy of its hydrodynamic module has been validated in numerous benchmark studies and wave tank campaigns. The aerodynamic forces on the blades, tower, nacelle and wind exposed parts of the substructure are neglected in this study, because they are considered minor compared to the wave induced loads. The blade pitch and generator torque controller is inactive in the simulations, as the turbine is in locked mode.

In contrast to the other three substructures where the hydrodynamic coefficients are directly computed with WAMIT using the hull geometry files, due to the lack of geometric data availability, the barge model is based on response amplitude operators (RAOs) which have been linearised for typical sea states. The mass of the tower and turbine are included in the RAOs. The mooring line behaviour is not included; their impact on the 1st order motions, however, is very low. The RAOs for the pitch and roll motion are very sensitive to the exciting wave amplitude, so that for predicted rotations above five degrees the sea state is out of range of applicability for the RAOs. Responses exceeding this limit have been excluded from the analysis. The four different structures used are, in the following, denoted as Design A, Design B, Design C and Design D. The focus of this paper is not to compare different substructure typologies, but to suggest a procedure applicable to any type of structure and to determine the ranges of results which are to be expected for FOWTs. It shall, in that respect, be noted that all results shown are based on models that have been provided by different developers, making the results representative of the whole range of floating wind substructure classes. All accelerations shown in this study are representing motion at the hub height of the turbine. For all structures investigated, this is the point at which the highest motion amplitude would be experienced – and most of the maintenance tasks on a wind turbine are executed in the nacelle which is in close vicinity of the wind turbine hub. Other points may be of interest, such as the tower base or a location within the floater; the principles shown in this paper may be applied likewise to such.

4.1. Accessibility

A number of different workability scenarios have been assessed in the course of this study. For those, it is required to determine accessibility at different sea states. It is assumed here that access solely depends on the sea state in terms of the significant wave height, i.e. a vessel approach is expected to be successful if the wave height during access lies below its upper threshold level. As indicated in Section 2.1, access of floating structures may also be restricted by other factors (particularly the combination of wave height and frequency as further assessed in (Martini et al., 2016)); however, the predominant restrictor is wave height and it is therefore considered an appropriate choice for assessing the given problem. Accessibility is further defined as the fraction of time in which an asset is accessible; the respective values for different wave height boundary levels are shown in Fig. 11 below for all three sites under consideration.

It can clearly be seen that accessibility increases significantly with an increasing wave height boundary restriction. Furthermore, it can be observed that accessibility varies considerably between the different sites. This factor has a great impact on the O&M strategy – an area which is subject to various research but not in the focus of this study. In the further assessment, workability is always treated under consideration of the single access restrictions as described above.

4.2. Characterization of motion

In the following, acceleration magnitude frequency spectra are shown in order to classify typical motion characteristics of different FOWT systems in accordance with Mansfield's (Mansfield, 2005) categories (Fig. 4). The graphs shown in Fig. 12 contain accelerations weighted with the motion sickness weighting curve according to ISO 2631–1 (ISO 2631-1, 1997). The represented frequency spectra show the superposed spectra of the individual sea states up to a wave height of 3.5 m H. The regarded sea states are the Hs/Tp combinations which show for at least one of the three sites under consideration an occurrence rate greater than zero.

For lower limit wave heights, below 3.5 m, the shape of the

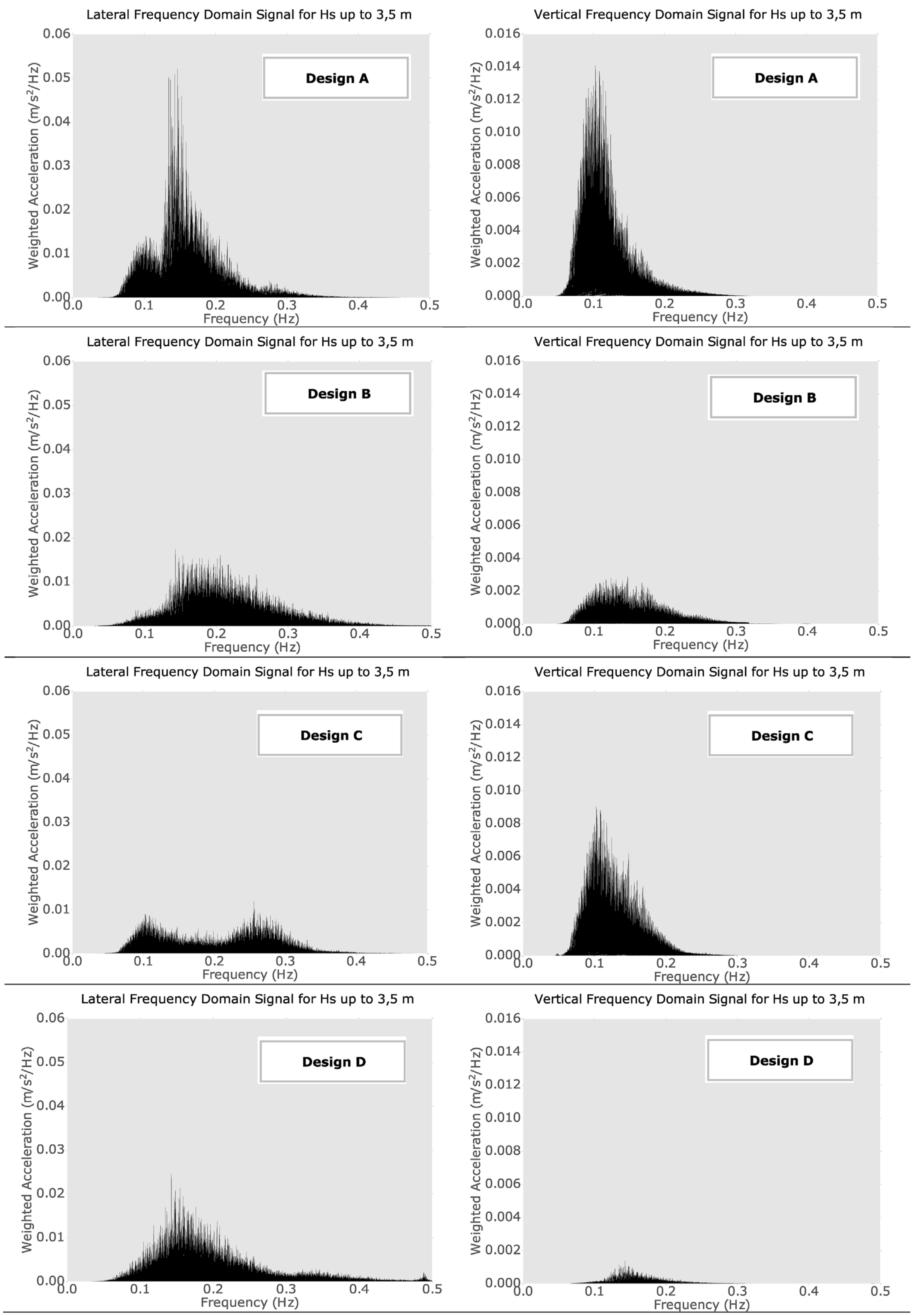

Fig. 12. Acceleration magnitude frequency spectra.

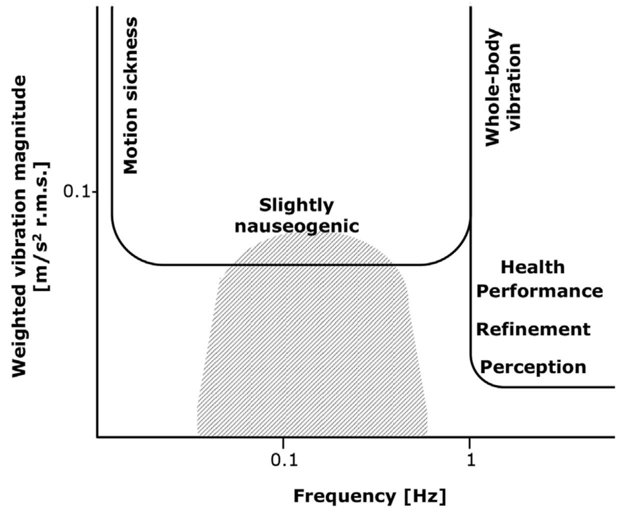

Fig. 13. Representation of the expectable motions during maintenance activities in Mansfield's categories (Mansfield, 2005).

frequency spectra is comparable to those shown here; the magnitude of acceleration is lower. The limit wave height can be chosen, such that it represents the limiting significant wave height for the boat access of the platform.

It is noticeable that all expectable motions in the low frequency area are dominated by the motion sickness condition, shown in Fig. 13. For this reason, the ISO 6897 is tested as the assessment standard, despite its limitation to fixed offshore structures (ISO 6897, 1984).

4.3. Assessment against ISO 6897

Fig. 14 shows the threshold values suggested by ISO 6897 (ISO 6897, 1984). All expected horizontal motions during maintenance conditions are highlighted in grey and summarized from the four lateral frequency spectra of Fig. 12. The marked area represents the frequency motion response of the four concepts in the relevant sea states of the three reference locations. It can be seen that all expectable motions are below the upper limit values for bottom-fixed offshore structures. The accelerations of the investigated concepts surpass, however, the average threshold and enter the area of perception of horizontal motion for humans. Even though this standard is excluding floating structures, it is deemed a valid exercise to investigate the motion profile against it as there is little guidance for floating structures.

4.4. Assessment against nordforsk

This case study covers the use of unweighted signals and the boundary conditions suggested by Nordforsk (1987); i.e. Step 6 of the variants presented in Fig. 6. The threshold level has, for the present case, been set to 'transit passenger' (see Table 1).

Workability is expressed by the average Workability Index (WI) per site and structure, and provided at different access wave height restrictions (Fig. 15).

Design C only shows very limited motion above the threshold suggested in (Nordforsk, 1987). Design A, B and D show, under some conditions, a WI below 1. The workability index varies to a large extent with an increasing access wave height boundary. Interestingly, for the site in Scotland, Design B shows an increasing WI at higher wave height access restriction.

This is due to the fact that the rarely occurring low sea states are causing unfavourable motions considering this design. Design D is performing better at lower sea states – workability on this structure is slightly reduced at higher sea states from 2 m H onwards; but as for Design B, workability is particularly bad during low sea states around 1.5 m; which is the today most common access limit for CTVs.

In contrast to asset accessibility, motion criteria play a role for O&M activities during low as well as during higher sea states. This finding is clearly counter-intuitive as one may assume that working conditions are worse during high compared to low wave conditions. The reason for this finding lies in the dynamic response of the floating structure, which is not solely relying on wave heights, but on a combination of all external influencing factors (such as wind speed and turbulence intensity, wave periods and direction, current velocity, profile and direction) and other factors such as the accumulation of marine growth or ice formations. Consideration of these parameters is required in order to perform a solid motion assessment.

It shall be noted that the vast majority of non-workable conditions is caused by translational accelerations. Rotational limits are exceeded in less than 5% of the cases.

4.5. Assessment of maxima against nordforsk

The assessment described in Section 4.4 has been repeated, using a more conservative assumption. For this, not all accelerations occurring during a certain condition have been treated equally. Here, more emphasis was given to local acceleration maxima.

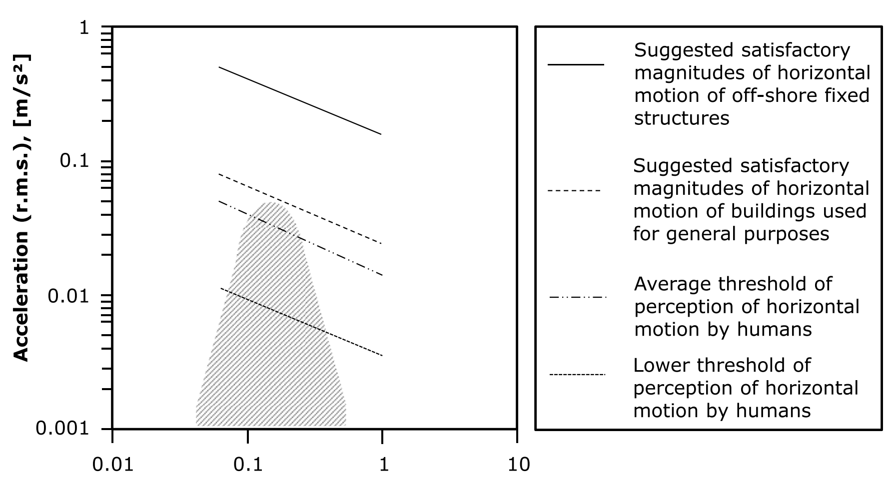

Fig. 14. Expectable motions during maintenance activities in relation to the acceleration/frequency threshold curves from ISO 6897.

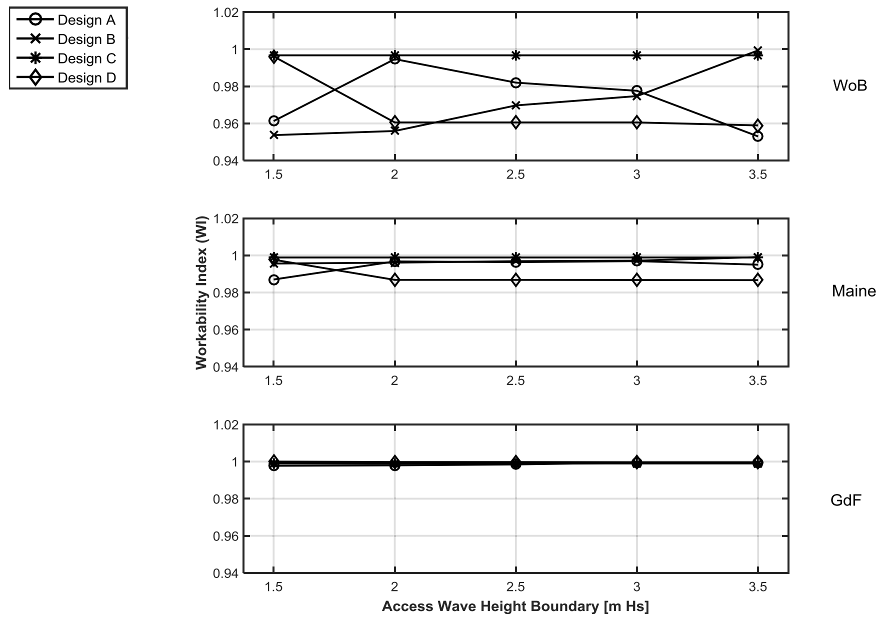

Fig. 15. Workability vs. access wave height boundary for WoB (top), Maine (mid) GdF (low).

A comparable approach has been presented by Boggs (1997). The approach relies on assessing motions based on peak-to-peak maxima observed during a certain time interval. Applying this method would lead to very large accelerations which are, from the author's perspective based on own experience and conversations with offshore technicians, deemed to not adequately represent the circumstances during works on offshore wind turbines. Boggs (1997) supports the theory that a person is affected most by the largest individual peak cycles and tends to "forget" about lesser cycles. Further it is stated by Cheung (Cheung and Nakashima, 2006), that vertical motions in a frequency range between 0.167 and 0.5 Hz with higher magnitude provoke vomiting earlier than motions with a low magnitude. Here he refers to McCauley et al. (McCauley, 1976). Cheung further states that little is known about the effects of lateral oscillations except that severe translational oscillations for short vibration cycles can easily provoke vomiting to a person who has already succumbed to motion sickness.

Considering the above, the authors suggest to calculate the r.m.s. values of maxima during specific time intervals. The resulting values are not as high as peak-to-peak values but emphasise actually occurring peak accelerations more than the traditional r.m.s. method. This method is novel and should be supported by lab and/or field testing campaigns in order to evaluate applicability further.

This is done for several time intervals, in accordance with the assessment presented in Section 4.6. Absolute values are assessed in order to account for negative peaks. The procedure is illustrated below in order to ease understanding (Fig. 16).

The impact of motions has been investigated similarly to the procedure applied in Section 4.4. The corresponding workability indices for the different designs at the different sites are shown in Fig. 17.

It can clearly be seen that the workability is affected on all structures and at all sites considering the amended r.m.s. method. Just as before, it is shown that workability and accessibility need to be treated with care; i.e. it is not a given fact that workability is becoming worse during harsher conditions. The response of the floater may show larger accelerations during lower sea states if the excitation happens at a frequency closer to the floaters' natural frequency.

As described above, this means that working conditions must be evaluated by considering all factors that potentially affect the dynamic response of the floater.

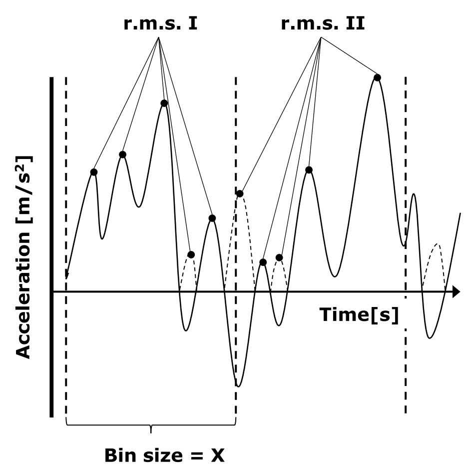

Fig. 16. Calculation of r.m.s. of local acceleration maxima.

4.6. Influence of bin sizes

As described in Section 3, it is of high importance to set the acceptance criteria for the exposure time to the desired level. This is expressed by the exposure duration resolution. It represents the lower time limit, from which the exposure to certain conditions is deemed relevant. Literature suggests using acceleration r.m.s. values in bins of 10 min (Caicedo et al., 2012). Higher bin sizes can underestimate the peak values though the averaging effects of the r.m.s.

The sensitivity of the WI value (and its spread) is illustrated in Fig. 18. The figure shows all calculated WIs (all sites and floater concepts) at different exposure time bin sizes using the traditional r.m.s. calculation method. The vertical axis represents the workability index and four different exposure duration resolutions are plotted on the horizontal axis (1 min, 5 min, 10 min, 20 min). The boxes frame the edges of the 25th and 75th percentiles and the central line in each box represents the median of the values obtained. The whiskers are reaching out to the extreme values (lowest and highest in each series) and outliers are marked with a '+'. As per Matlab standard, data points are considered outliers if they are greater than $q_3 + w*(q_3 - q_1)$ or less than $q_1 - w*(q_3 - q_1)$; with w representing the maximum whisker length, q_1 the 25th percentile and q_3 the 75th percentile (MATLAB,

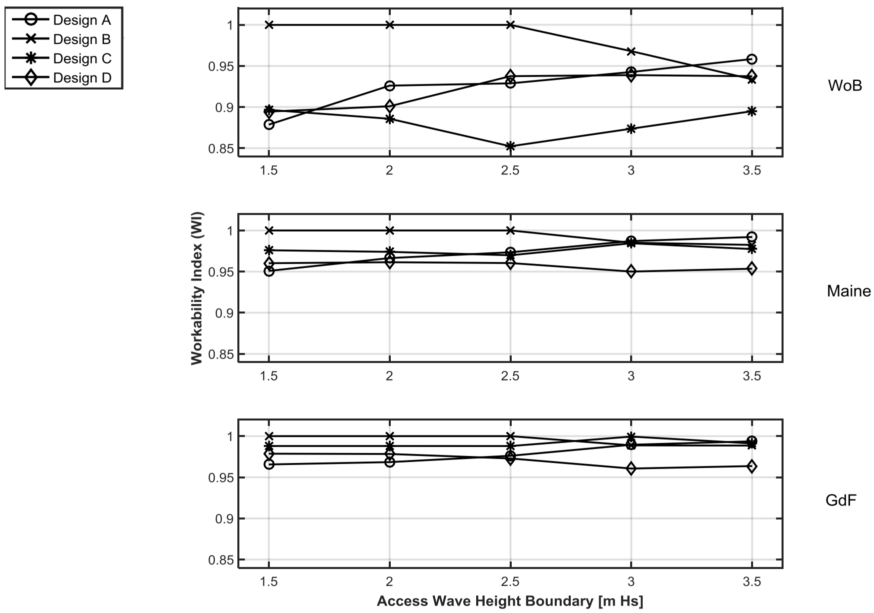

Fig. 17. Workability vs. access wave height boundary for WoB (top), Maine (mid) and GdF (low).

2018a, 2017).

The WI is increasing by increasing the exposure duration; the spread of WIs decreases at greater magnitude. This phenomenon has been observed throughout all sites and floater concepts similarly, so that results can be shown in one figure. The reason for an increasing WI with higher exposure duration resolutions can be explained by reflecting the way the index is calculated: it represents the fracture of time during which the conditions on the assets allow for works to be conducted; i.e. if the WI is zero, no works are possible to be carried out, considering the respective threshold level applied. This is illustrated in Fig. 19 below. The same threshold level is applied to the same acceleration time signal. A shorter bin size is chosen for the figure on the left and a longer duration on the right side. In the left figure, the workability threshold level is exceeded during two time intervals; leading to a WI of 0.75 when considering that the complete time series consists of eight segments. On the right hand side, a sufficient contribution of low accelerations are counteracting to the ones above the threshold so that the overall WI is one. The impact of single short-term phenomena is balanced out.

This also explains why the spread of results is decreasing for increasing WIs: the workability on all floaters is increasing with increasing bin size (it converges to one – if, for instance, a whole year of measurement data would be used as one single bin, the WI would be one for all sites under consideration). For a 20 min exposure duration resolution, almost all structures would exceed the threshold only in a very limited amount of cases. The respective outliers can be explained by the time shift that prevails when applying different bin sizes; i.e. Fig. 18 reflects the overall trend with some exceptions due to the slightly different intervals assessed against the threshold criteria.

5. Conclusions

The studies presented in this paper address an area which is of increasing importance to (floating) offshore wind developers, operators, financers, insurers, service providers and other stakeholders. It addresses the safety and well-being of the technicians working in the harsh offshore environment every day. Considering floating offshore wind technology, one can easily imagine which motions technicians may be exposed to during rough sea states. Modern access technology, such as motion compensated gangways, allow for higher and higher waves during the personnel transfer to the structure.

As the first of its kind, this paper presents a methodology to assess the influence of those motions on humans being located on the asset during maintenance activities. The methodology suggested includes procedures described in international standards as well as practical books. It is shown that the low frequency motion, which is the predominant motion characteristic of floating wind assets, is not covered in the required detail. The vast majority of available literature addresses motions in frequency ranges above 1 Hz; the assets considered here are operating in a range up to 0.5 Hz. The lack of guidance by standards has led to the application of practical recommendations which have been applied in the ship, fish farming, military and other naval industries. Additionally, it shall be noted that the proneness to sea sickness and other motion-related responses by the human body are highly subjective. Whilst some technicians are able to work under highly severe conditions, others may get sick already during low sea states. Only a large-scale lab test or site investigation is considered appropriate in order to diminish this subjectivity. Aside of medical implications, such a study could also investigate effects of motion exposure with respect to

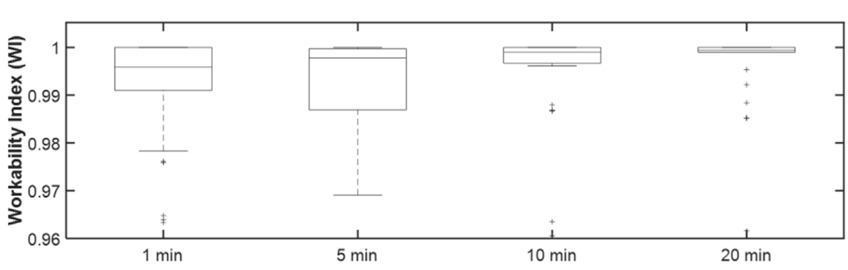

Fig. 18. Workability Index vs. exposure duration resolution.

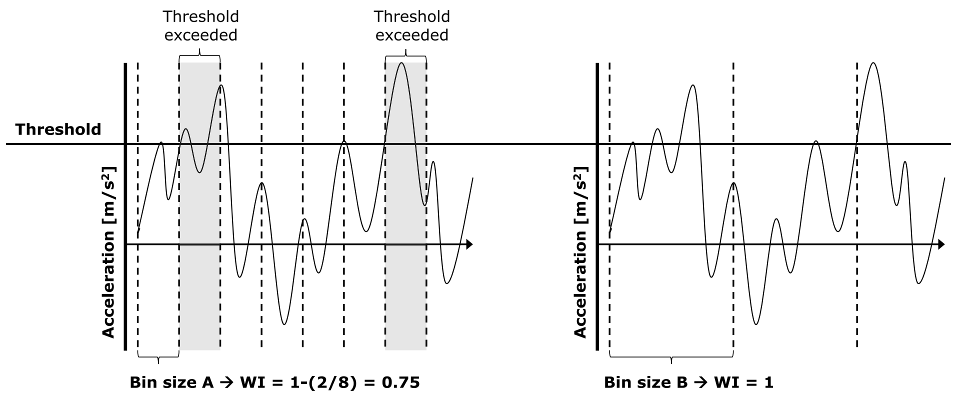

Fig. 19. Influence of bin size on WI.

the duration and quality of maintenance tasks carried out under different conditions as well as the impact of duration and sequence of threshold exceeding situations on the respective results.

Results show that the motion exposure limiting values applied for the assessment of the working environment during maintenance activities has an impact on the time in which those activities may be carried out. The waiting time for a weather window may increase under certain sea states due to critical conditions for human comfort. By that, this paper suggests that the pure assumption of a successful completion of a maintenance task once access is enabled is not applicable for modern large scale (floating) offshore wind turbines.

In numbers, up to 5% of the time in which an asset is accessible (it should be noted that depending on the design, this applies for wave heights between 1.5 m H and 3.5 m H), accelerations are in a range which are unacceptable for technicians to carry out their work. The potential production losses due to this situation are significant, considering large offshore wind farms. If more conservative assessment methodologies are applied, those numbers increase accordingly. For future work, it is suggested that potential losses associated to the factor of workability are quantified more accurately, considering different wind turbine sizes and park layouts.

A fundamental finding of this study is that workability is not necessarily becoming worse at higher sea states. The response of the floater, leading to high accelerations, may even be more significant in low wave height and low frequency wave states. During all sea states, the exceedance of translational acceleration threshold values is predominant; rotational accelerations are causing non-workable conditions in less than 5% of all cases under the conditions studied.

All described phenomena lead to the recommendation that already in the design stage of a new project the influence of human comfort criteria must be taken into consideration. The factors influencing workability are aside from the environmental conditions, the structural design and more specifically the eigenfrequencies of the floating offshore wind turbine system. The methodology suggested in this paper helps to assess how significant the influence of motion may be on O&M activities.

Acknowledgements

This project has received funding from the European Union's Horizon 2020 research and innovation program under grant agreement No 640741 (LIFES50+). The studies have also been greatly supported by SINTEF Ocean who provided the SIMA Software which was used for simulation. SINTEF Ocean's experts provided great support throughout the whole study which was a key enabler to its success. Special thanks are also expressed to Olav Olsen for providing representative information enabling a realistic representation of the semi-submersible floating structure. A main part of this work was supported by grant EP/L016303/1 for Cranfield University and the University of Oxford, Centre for Doctoral Training in Renewable Energy Marine Structures - REMS (http://www.rems-cdt.ac.uk/) from the UK Engineering and Physical Sciences Research Council (EPSRC)" and Ramboll Energy (http://www.ramboll.com/energy).

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