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A dynamic simulation-based methodology for systematic assessment of workability on floating wind turbines

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Abstract. Floating offshore wind technology experiences significant motion responses when exposed to environmental wave and wind loads, possibly interfering with technicians conducting maintenance work. Industrial interest is rising in the assessment of workability, as impairments will decrease the availability of the asset and possibly affect the business case for the wind farm project. Quantification of impairments are formed from three workability indicators: Nordforsk Seakeeping Criteria, ISO 2631-1, and ISO 6897. The present work shows a likely workability decrease, quantified to 2.4 % for the Nordforsk Seakeeping Criteria, for the UMaine VolturnUS-S reference platform and the IEA 15 MW reference wind turbine. Peak wave period and wave heading direction are found to affect the results and indicate the importance of conducting the study in site-representative conditions. In addition, varying results for different indicators and methodological approaches indicate the need for common rules and standards in the floating wind industry to enable transparency during project development.

1. Introduction

Floating Offshore Wind Turbines (FOWT) are key technology in expanding the wind energy sector by unlocking access to deep-water sites, as the majority of offshore wind potential lie in regions where the water depth exceeds the technical-economical limit for bottom fixed turbines. The combination of complex technologies in harsher and more remote locations, leads to increased expenses during project commissioning and operation. Costs during operation typically make up to a third of the projects budget, which requires the project's business plan to rely heavily on assumptions regarding power production and availability [1].

As opposed to bottom-fixed wind turbines, the intrinsic and platform specific 6-Degree of Freedom (DoF) motion experienced by personnel working on FOWTs requires an assessment of workability [2], whereas workability is defined as the ability to perform safe and efficient maintenance work. The present work aims at introducing a methodology based on fully coupled simulations as a tool to reduce the uncertainty of workability assessment and to support commercial decision making. In this regard, the methodology herein presented can be adopted to refine input for availability analysis or by classifying the most workable design approach.

2. Workability in floating wind

2.1. State-of-the-Art

An extensive literature study concluded that the wind industry lacks an assessment method and threshold values to quantify the effects of FOWT motion on humans [3]. The authors discuss potential workability indicators, including the three applied in the present work (Nordforsk, ISO 2631-1 and ISO 6897), regarding their applicability for floating wind, as they originate from outside the floating wind industry.

In [4] a first simulation-based methodology is introduced, estimating up to 5 % decrease of the workable time window, for maintenance work on 10 MW FOWT. The analysis is based on time domain simulations and 10 minute bins, resulting in a stochastic score.

Workability on the UMaine VolturnUS-S Reference Platform, equipped with the IEA Wind 15-Megawatt Offshore Reference Wind Turbine is investigated in [5]. The calculations in the frequency domain, based on the platform's RAOs (Response Amplitude Operators), indicated no reduced workability for significant wave heights of up to $H_s = 3\,\mathrm{m}$, which surpasses typical CTV (Crew Transfer Vessel) operational limits. Both [4] and [5] utilize the workability indicator Nordforsk and do not investigate vibration exposure during transport and accommodation.

2.2. Motion affecting humans

Motion may interfere with human comfort, health and activities. The severity of disturbance is very individual and thus difficult to predict, due to a number of relevant parameters:

- vibration parameters: magnitude, frequency, direction, duration;
- intra-subjective parameters: body position, thermal-, visual-, olfactory effects;
- inter-subjective parameters: age, weight, habituation [6].

Low-frequent Whole Body Vibration (WBV) may cause motion sickness, predominantly in ranges below 1 Hz [7]. Accelerations received by one part of the human body (e.g. inner ear) mismatch other received signals (e.g. visual information), which causes symptoms like dizziness, nausea or vomiting [6]. Wind turbine technicians experiencing symptoms, even in weak form, are likely to decrease in work-efficiency and increase their risk of accidents and injury.

3. Methodology

Workability is calculated for the floating platform response in discrete sea states. Each sea state is defined by significant wave height (H_s), peak wave period (T_p) and wave heading (WH). Hindcast met-ocean data is used to classify discrete sea states, of which the respective occurrence probability is used as weight factor to calculate the site-representative workability result.

3.1. Calculation of Platform Response

The response of the holistic platform-turbine-mooring system is solved with RAFT v1.0.0 for each individual sea state [8]. RAFT solves the system's linearized equation of motion (Equation 1) for an all-rigid geometry in the frequency domain, thus assuming linearity of wave loads, with M, A, B, and C being respectively mass, added mass, damping and stiffness matrix of the holistic geometry for each discrete frequency ω. ξ is the displacement and $\vec{F}e^{-i\omega_e t}$ the real part of complex load vector $\vec{F}$.

$$[M + A(\omega)]\ddot{\vec{\xi}} + B(\omega)\dot{\vec{\xi}} + C\vec{\xi} = \vec{F}e^{-i\omega t} \tag{1}$$

3.2. Workability Indicators

The present work applies three different indicators to investigate workability. Each indicator defines discrete thresholds for specific levels of activity, of which three levels per indicator are introduced in the following section.

3.2.1. Nordforsk In 1987, the Nordic Research collaboration published limiting seakeeping criteria to enable safe transfer and work conditions on vessels for passengers and crew [9]. The Nordforsk indicator has been used to predict workability on floating wind turbines, floating fish farms, and in specific vessel operations (i.e., on tug boats) [3]. The workability levels, shown in Table 1, are defined based on acceleration in horizontal and vertical direction, as well as absolute roll angles. Sea conditions are considered as non-workable, if at least one of the directional limits is breached.

Table 1: Nordforsk workability level and respective root mean square limits. Vertical and horizontal accelerations are multiplied by the gravitational acceleration.

Level Unit	Vertical acceleration [m/s^2]	Horizontal acceleration [m/s^2]	Roll angle [°]
Cruise Liner	$0.02\,g$	$0.03\,g$	2.0
Transit Passenger	$0.05\,g$	$0.04\,g$	2.5
Intellectual Work	$0.10\,g$	$0.05\,g$	3.0

Since the worker's orientation during maintenance work is unknown and the platform moves omni-directionally, motion in different directions is combined, as reported in Equation 2, where a is the acceleration, r the rotational displacement.

$$a_{\text{horizontal}} = \sqrt{a_{\text{surge}}^2 + a_{\text{sway}}^2} \qquad ; \qquad r_{\text{rotational}} = \sqrt{r_{\text{roll}}^2 + r_{\text{pitch}}^2} \tag{2}$$

To account for the Rayleigh distribution of irregular waves a most probable maximum acceleration a_{mpm} is calculated based on the root mean square (rms) value a_{rms} in vertical and horizontal directions [10].

$$a_{\text{mpm}} = \sqrt{2a_{\text{rms}}^2 \ln\left(\frac{t}{T_p}\right)} \tag{3}$$

The duration t is set to 10 minutes for all sea states, in alignment to [4], who utilize 10-minute bins of time domain simulations. The short duration t as compared to typical maintenance work duration of 8-12 hours is due to the nature of motions sickness. The symptoms typically ease with omission of the cause. The short duration selection enables to investigate whether the motions sickness threshold is reached repeatably (i.e. every 10 minutes) and continuously causing symptoms, as opposed to breached once (i.e. during 8-12 hours) with subsequent decrease of symptoms.

3.2.2. ISO 2631-1 The international standard ISO 2631-1 [11] provides multiple approaches to estimate workability, of which the comfort estimation is determined to be the most critical for the motion of the VolturnUS-S platform in given sea states. This indicator was initially developed for public transport such as railways, yet general applicability during work activities is stated for vibrations between 0.5 and 80 Hz.

Acceleration a_i is weighted with principal frequency weights W_i, given for every one-third octave band i to account for human perception of WBV (Equation 4). Additionally, the acceleration rms values in x, y, and z-direction are combined as in Equation 5, with

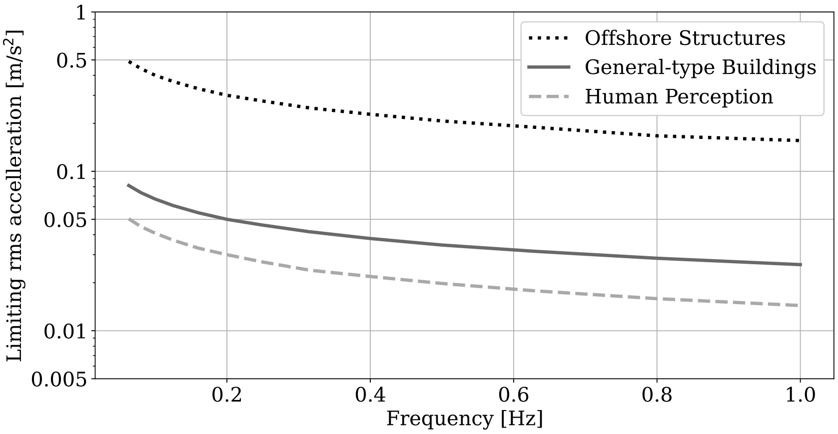


Figure 1: Limiting rms (root mean square) accelerations in buildings for different purposes, defined by ISO 6897.

multiplication factors $k_x = k_y = k_z = 1$ for standing persons. Table 2 shows the given ranges for comfort levels. The workability is evaluated based on the lower values.

$$a_{\mathrm{W}} = \sqrt{\sum_i (W_i a_i)^2} \tag{4}$$

$$a_{\mathrm{combined}} = \sqrt{k_x^2 a_{\mathrm{W}x}^2 + k_y^2 a_{\mathrm{W}y}^2 + k_z^2 a_{\mathrm{W}z}^2} \tag{5}$$

Table 2: Acceptable values of weighted and directional combined vibration magnitude for comfort as defined in ISO 2631-1. All values are in m/s^2.

Category	Lower value	Higher value
Perception	0.015	-
A little uncomfortable	0.315	0.63
Fairly uncomfortable	0.5	1.0

3.2.3. ISO 6897 The international standard ISO 6897 [12] introduces limits for the highest magnitude of acceleration at discrete frequencies for buildings and offshore structures. It explicitly excludes the applicability for floating platforms, most likely because the standard only investigates motions in horizontal direction and assumes neglectably small magnitudes in vertical or rotational direction. The standard provides satisfactory values at discrete frequencies which are depicted in Figure 1. The horizontal acceleration rms values are directionally combined as shown in Equation 2.

3.3. Workability Quantification

Two methodological approaches are introduced to quantify the workability based on **threshold exceedance** of one workability level, and based on **relative exceedance** between two workability levels.

However, the floating industry lacks a standardized workability indicator and level. Therefore, a *Most Applicable Workability Level* (MAWL) is defined for each of the three indicators:

- Nordforsk: Transit Passenger Limit
- ISO 2631-1: A little uncomfortable
- ISO 6897: General-type Buildings

Each MAWL has been chosen based on the description given in its guideline, that was found to match the expected work of an offshore technician. The three MAWLs have been determined to be of similar comfort level, as they are described to be in a medium-lower discomfort range. The limits are higher than vibration perception values, yet far below the maximum level of each indicator. This choice is made because of unknown effects of coupling of omni-directional motion, high exposure duration, additional vibration exposure during transport, and expected health and safety requirements of wind farm operators.

3.3.1. Threshold exceedance The simulated response of every simulation is individually assessed against the MAWL of each workability indicator. The occurrence probability of all sea states with motions above the MAWL-threshold are classified as non-workable and their probabilities are summed up to be site representative. The upper part of Figure 2 shows the classifying of simulated motions, each depicted with a light-grey cross. The 5 simulations with motions exceeding the orange limit will be non-workable and their occurrence probabilities will be summed to obtain the site-representative non-workable time.

3.3.2. Relative exceedance Investigating workability based on the absolute exceedance of a threshold implies workability to be a universal step function, resulting in 99 % of the limit being workable, 100 % is not. Even though recommended in standards and guidelines, it is highly questionable if this approach is valid to represent human comfort, especially under varying parameters like duration and changing sea states.

Therefore, softening the binary workability classification, a linear interpolation between two levels is proposed to estimate workability based on the relative exceedance. The relative exceedance factor $r_{workability}$ is then multiplied with the occurrence probability of the respective sea state and accumulated for all simulations.

The interpolation is done between the two workability levels adjacent to the MAWL (referred to as MAWL-lower and MAWL-upper level). Full workability ($r_{workability} = 0$) is assumed for simulations below the MAWL-lower (left) level. On the other side, for movements breaching the upper level $r_{workability} = 1$ implies completely non-workable conditions. The lower part of Figure 2 depicts the relative exceedance approach, where the example motions between the green interpolation levels will contribute to the non-workable time quantification with $r_{workability} = 0.4$ and $r_{workability} = 0.6$.

The MAWL-adjacent level are reasonable for interpolation of the relative exceedance, since the MAWL-lower level indicates perception of vibration. It is fair to assume that workability will not be influenced below, if no motions are perceived. Workability indicator ISO 2631-1 and ISO 6897 specify a perception threshold in their respective definitions. The Nordforsk indicator defines the MAWL-lower limit as Cruise-Liner-category, yet this may be treated as perception threshold, as there is no lower category. The qualitative specification of the MAWL-higher level vary for the applied workability indicators. However, utilizing the MAWL-adjacent level for all three indicators allows to account for the individual scale within each indicator. This enables comparison of the results without changing the respective definition by introducing new workability levels.

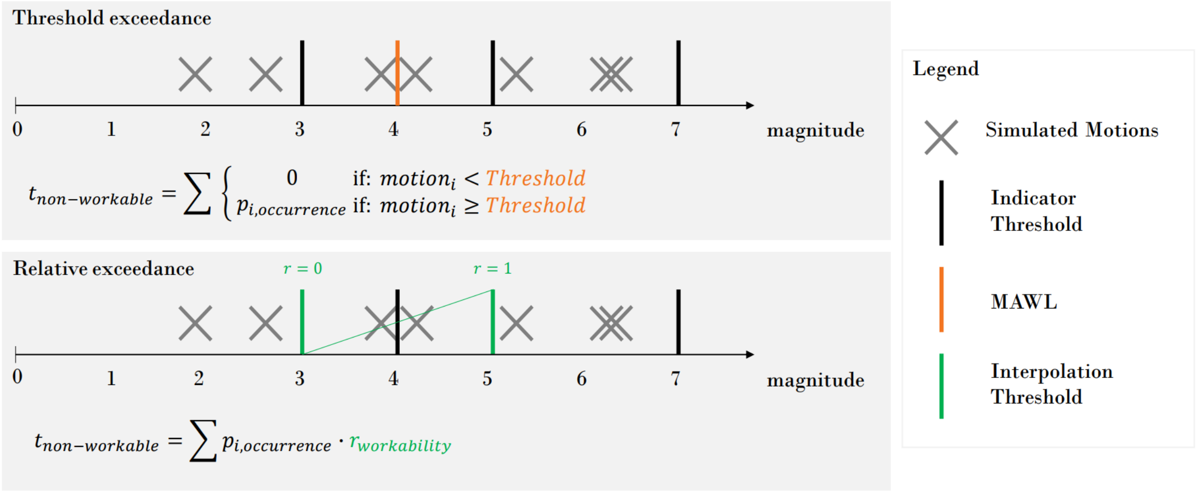


Figure 2: Schematic view of a fictional workability indicator and its workability levels on a scale. The different indicators define varying thresholds in terms of values (e.g., magnitude and frequency dependency) and scale (e.g., root mean square acceleration, roll displacement, weight factors), which is why a fictional example is shown and no direct comparison between indicators is possible.

4. Case study

The workability on the UMaine VolturnUS-S Reference Platform [13] and the IEA 15 MW Reference Turbine [14] is investigated for a Scottish wind farm, located approximately 5 km off the northern coast. The present work is analysing the 3000 most probable sea states, accounting for 97.2 % of the hindcast data. The sea states are clustered in 10 deg WH bins, between 0 and 180 deg, utilizing symmetry of platform and vessel, where the WH is referred to as relative to the platform installation angle, 0 deg being heading waves. A water depth of 200 m is assumed, enabling consistency with publicly available platform-turbine models without adapting the mooring line length. Wind forces are excluded from the investigation. Their effect is evaluated to be much smaller than the influence of wave loads, due to a parked rotor during maintenance work. The exciting waves are created based on a JONSWAP spectrum with peak wave factor $\Gamma = 1$ which follows the exclusion of wind effects.

4.1. Results: Threshold exceedance

The case study shows workability is only impacted in virtue of horizontal motion as perceived in the nacelle. Full workability is calculated for all work on platform level and in terms of heave and rotational displacement for the simulated VolturnUS-S platform. The quantified, site-representative workability results are displayed in Figure 3, for the three discussed workability indicators Nordforsk, ISO 2631-1 and ISO 6897, as well as both quantification approaches threshold exceedance (orange) and relative exceedance (green). The variation of results shows importance of finding a standardized approach across the floating industry.

The quantified workability decrease based on threshold exceedance for the Nordforsk indicator with MAWL *Transit Passenger* is $208/8760 = 2.4\,\%$. The result disagree with [5], where no workability decrease was concluded for the same platform-turbine combination. Discrepancies are due to the inclusion of a stochastic maximum accelerations for 10 minute periods (see Equation 3), as the pure rms value is likely to be temporarily exceeded in real life scenarios.

The non-workable hours reflect the conditions averaged over a full year, where night/day and

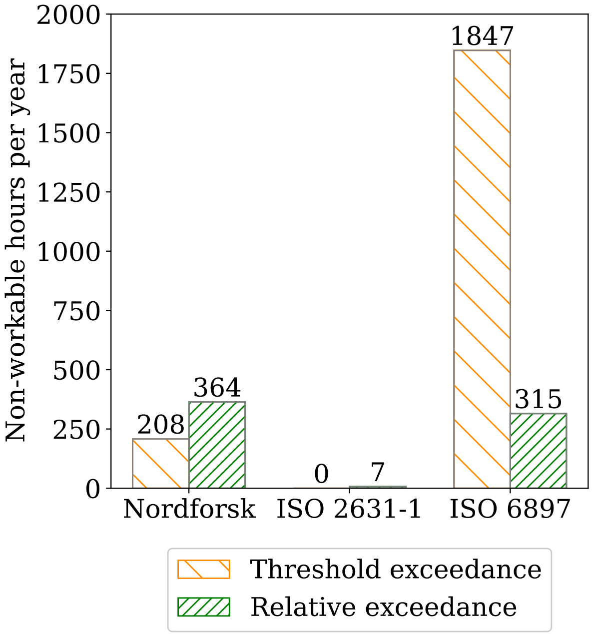


Figure 3: Site specific total of non-workable hours per year as perceived in the nacelle of the 15 MW reference turbine on the VolturnUS-S platform.

seasonal influences are not included. Maintenance is generally conducted during the day and campaigns are predominantly scheduled in summer, therefore the quantified non-workable hours may not necessarily occur at times where maintenance work is done.

Figure 4 shows the workability in the nacelle exceeding the Nordforsk MAWL for heading waves. 10 sea states (in red) are classified as non-workable, as they breach the workability limit ($a_{rms} > 0.04g = 100\,\%$). The lowest non-workable H_s is 2 m. Wave periods of 7 and 8 s excite the highest horizontal accelerations in the holistic model of WTG, platform and mooring lines. Sea states with $T_p \geq 11$ s show no workability breach for the simulated H_s, highlighting the T_p dependency of the workability limit, as opposed to traditional fixed-H_s limits.

4.1.1. Comparison of workability indicators The ISO 2631-1 MAWL (*A little uncomfortable*) has not been breached for any sea state, resulting in 0 non-workable hours per year, and is not depicted. The MAWL is found to be significantly less restraining than its counterparts of the other investigated indicators. Figure 5a shows the workability exceedance of the MAWL-lower level (*average perception*). A trend is observed, indicating higher comfort in higher wave periods. This is because long wave periods are weighted with the lowest weight factors, i.e. $W_i < 0.25$ for oscillation periods $T \geq 4$ s, where the biggest accelerations are found or the investigated platform model.

Figure 5b shows the workability for ISO 6897 MAWL *General buildings*. The 41 sea states, where a breach of workability was found, lay in a similar pattern as for ISO 2631-1, yet the frequency dependency of the limit is less extreme resulting in a lowest non-workable wave height of 1.25 m at wave periods of 8 and 9 s, as opposed to generally short wave periods. The ISO 6897 is the most conservative workability prediction indicator of the investigated MAWL, resulting in a total of 1847 hours per year (21 %).

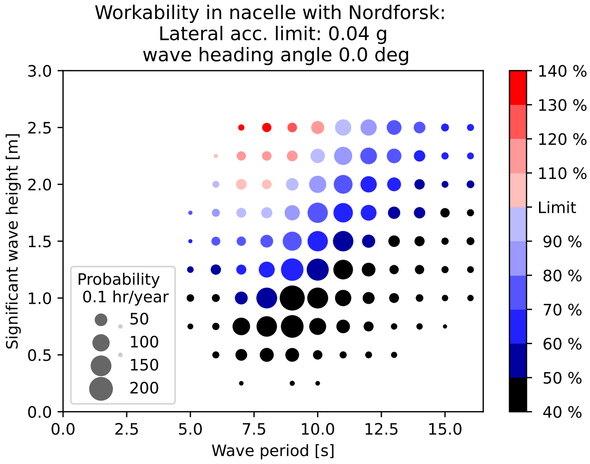
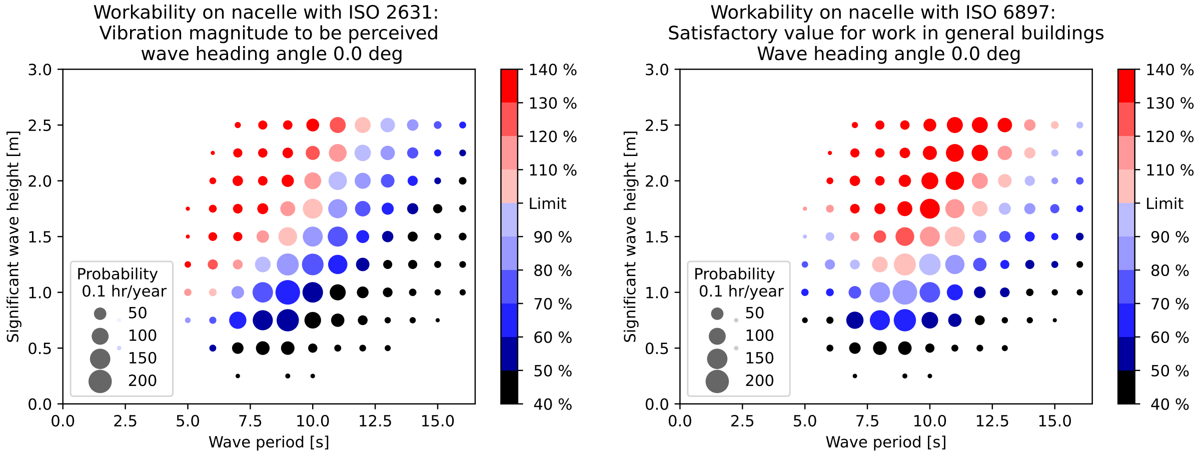


Figure 4: Nordforsk-based workability in the nacelle for various T_p and H_s combinations. The color indicates workability based on threshold exceedance, the size corresponds to the probability of occurrence.



(a) ISO 2631-1-based workability.

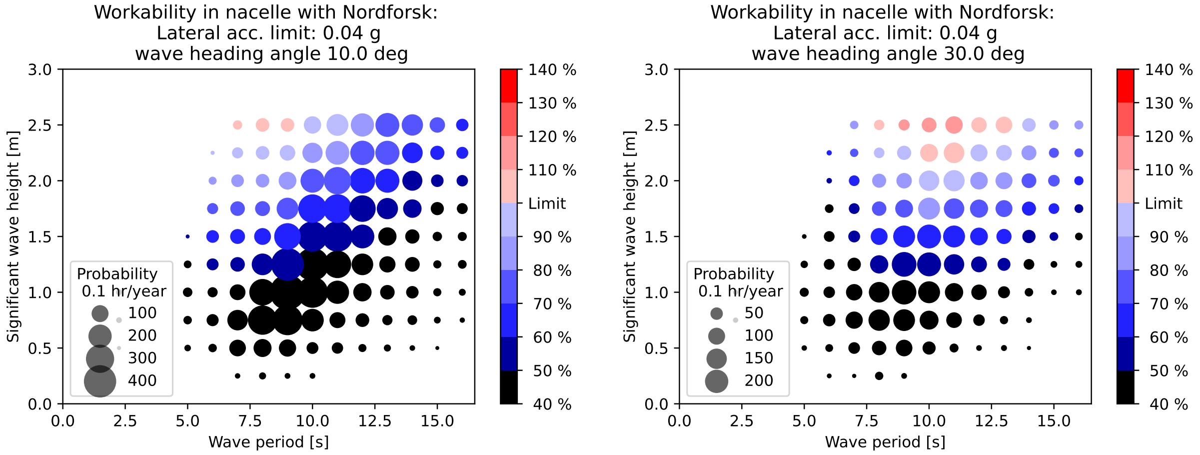
(b) ISO 6897-based workability.

Figure 5: Workability in the nacelle for various T_p and H_s combinations. The color indicates workability based on threshold exceedance, the size corresponds to the probability of occurrence.

4.1.2. Influence of wave heading Two exemplary plots are depicted in Figure 6 for 10 and 30 deg WH. The relative positioning and number of breached sea states indicates an additional workability sensitivity to WH, together with previously shown H_s and T_p. It signals the importance to include site representative data to estimate workability to obtain results that will be accurate enough to support availability prediction during project development.

4.2. Results: Relative exceedance

Figure 3 includes the non-workable hours of the relative exceedance approach, based on interpolation between two MAWL-adjacent limits. It results in a similar workability decrease for Nordforsk and ISO 6897 (364 and 315 hr, respectively). This enables good comparison between the two workability indicators, contrary to the threshold exceedance approach, for the investigated site and FOWT.



(a) Nordforsk-based workability for 10 deg WH. (b) Nordforsk-based workability for 30 deg WH.

Figure 6: Workability in the nacelle for various T_p and H_s combinations. The color indicates workability based on threshold exceedance, the size corresponds to the probability of occurrence.

The increased non-workable hours for the Nordforsk MAWL indicates that more sea states excite accelerations with magnitudes between *Cruise Liner* and *Transit Passenger* than above the *Transit Passenger* limit. These motions are assumed to be perceived, emphasising the importance of having good workability standards and possibly taking exposure duration into account, as some studies show even small accelerations to aid the occurrence of motions sickness.

The estimation of non-workable hours with ISO 2631-1 leads to neglectably small non-workable hours which are unlikely to impact the maintenance work. The relative exceedance approach for ISO 6897 gives an extremely undersized result compared to the threshold exceedance. Relatively many sea states are found to breach the MAWL limit, but are still far from the MAWL-upper limit, accentuated by the logarithmic spacing between levels (Figure 1). These sea states result in small interpolation factors $r_{workability}$ due to linear interpolation to be consistent with the other indicators.

5. Conclusion

The present work investigates three indicators and 2 methodological approaches to quantify workability on a FOWT:

i Workability may be affected for maintenance work on the VolturnUS-S platform with 15 MW reference turbine. It is therefore recommended to include workability assessments into any floating development process, e.g. during the Integrated Load Analysis (ILA) phase, to evaluate any negative OPEX or business case impairments at an early project development stage.

ii The workability results are shown to vary with H_s, T_p, WH. It shows that simplified limiting assumptions, e.g. based on a constant H_s, are invalid for floating offshore wind. Only the results of a site specific analysis can be utilised as an indicator for availability modelling, and other commercial decisions during O&M preparations.

iii Varying results, with only partial agreement to previous publications show the need for a standardized approach to predict workability in the floating industry. Additional research is necessary to assess which methodological approach represents real life data most efficiently.

iv Many types of maintenance work are necessary on a FOWT, e.g. visual inspection, troubleshooting, craning or major component replacement. Each type requires different work activities which are expected to vary in terms of workability limits. Therefore, any quantified results need to be transparent in terms of applied limits and should provide a sensitivity for more conservative or opportunistic workability assumptions.

Future site specific workability studies shall investigate detailed effects of wind and current loads, as well as effects of a non-rigid tower. The relationship between yearly non-workable hours and the occurrence probability of maintenance work can be refined by accounting for day and night, as well as monthly or seasonal weather data trends. Additional studies are necessary to investigate workability indicators for equipment transfer, i.e. craning. Coupling of human workability and O&M strategy related turbine accessibility may lead to new insights and increased accuracy in availability predictions.

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