

Research paper

De-risking utilising a floating crane for floating offshore wind turbine maintenance

Alastair Ramsay^a, Vahid Vaziri^b, Sean Snee^c, Marcin Kapitaniak^{a,b},^{*}^a The National Decommissioning Centre, University of Aberdeen, Newburgh, United Kingdom^b Centre for Applied Dynamics Research, School of Engineering, University of Aberdeen, Aberdeen, United Kingdom^c Offshore Renewable Energy Catapult, Glasgow, United Kingdom

ARTICLE INFO

Keywords:

Floating offshore wind
In-situ maintenance
Dynamical modelling
Marine simulator
Floating structure dynamics
Major component exchange

ABSTRACT

The growing deployment of floating offshore wind turbines (FOWTs) presents new challenges in maintenance operations, particularly concerning in-situ component replacement. This study builds upon prior research into the feasibility of using a floating crane for generator exchange on a semi-submersible FOWT, specifically the UMaine VoltturnUS-S supporting a 15 MW reference turbine. Utilising a marine simulation environment at NDC, the dynamic responses of the generator, nacelle, and crane barge were evaluated under various sea states. The results highlight that while generator accelerations are a significant operational factor, the primary constraint is the risk of collision between the generator and turbine structure during lifting operations. Parametric studies revealed critical wave periods that exacerbate generator motions and collisions, and while modifications to the lifting methodology proved ineffective, reorienting the crane barge parallel to incoming waves showed a modest reduction in collisions. These findings underline the importance of vessel selection, wave direction, and sea state limitations in ensuring the viability of in-situ maintenance using floating cranes for FOWTs.

1. Introduction

Offshore wind deployment is projected to make up a significant portion of the renewable energy generation required to reduce the reliance on fossil fuels, which contribute greatly to climate change. The total installed capacity of offshore wind was 75.3GW in 2023 and is expected to increase to 380GW by 2030 to meet current climate goals [1]. To help meet these goals, the deployment of offshore wind in deeper waters will be required. Fixed offshore wind turbines are not suitable for deeper waters, which are generally considered to be greater than 60 m, meaning floating wind turbines will be required to meet these ambitious goals. However, at present the total installed capacity of floating wind is only 236 MW (including at Peterhead and Kincardine in Scotland by Hywind and WindFloat) and is expected to increase to 8.5 GW by 2030 meaning rapid development is required so these expectations can be met [1]. Several challenges exist which have thus far limited the progress of floating wind deployment. One of these is the cost of operations and maintenance, which can make up a half of the total investment cost of a FOWT along with installation and a third of the total cost of energy generated [2,3].

FOWT maintenance can be separated into two categories, tow-to-shore or in-situ maintenance. Tow-to-shore involves the disconnection of a floating platform from its mooring before it is towed to shallower water or to a port with appropriate infrastructure where major maintenance such as component exchange can be conducted [2]. Challenges around port infrastructure for tow-to-shore methods can also be closely related to requirements for FOWT assembly [5]. Weather windows of a sufficient length are also required

^{*} Corresponding author at: The National Decommissioning Centre, University of Aberdeen, Newburgh, United Kingdom.

E-mail address: marcin.kapitaniak@abdn.ac.uk (M. Kapitaniak).

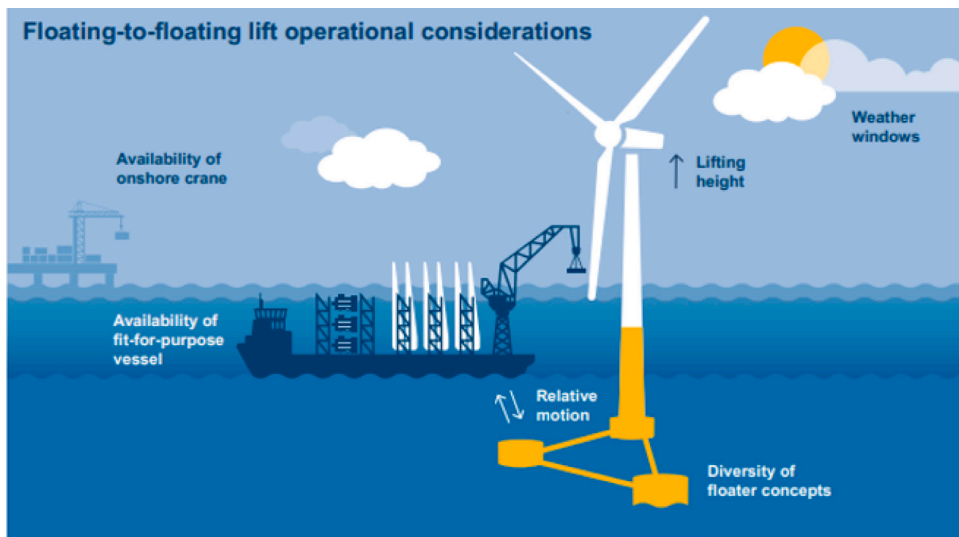


Fig. 1. Considerations required for a floating-to-floating lift using a floating crane.
Source: Image reproduced from [4].

for the operation which combined with the distances required to tow a FOWT can result in significant downtime for the asset which can contribute to higher costs [2,4,6]. Tow-to-shore has been used for the Hywind Spar platforms and for the FloatWind platforms off the coast of Scotland where they were towed to Norway and The Netherlands respectively [2,7]. In contrast, in-situ maintenance is carried out at the site of the FOWT while fully connected to its mooring, a recent example of this being with the FloatWind platforms at Kincardine off the coast of Scotland [2,4,8]. This also presents challenges with weather windows as well as challenges around the dynamics of floating-to-floating lifts and the ability for crew and vessels to access the FOWT under given sea states. Jack-up vessels lack the ability to be deployed in the deeper waters where FOWTs are to be deployed, so the use of a floating crane will need to be considered instead. This introduces several challenges including the aforementioned dynamics challenges of the relative motion present due to the floating-floating lift as well as having appropriate weather conditions to carry out the lifting operation. These considerations are summarised in Fig. 1.

To date, research regarding in-situ maintenance of FOWTs has been limited. Several studies consider the vibrations that crew on an FOWT would experience while on an FOWT platform. Scheu et al. [9] consider the accelerations of four different FOWT designs situated in different locations using frequency domain analysis. NORDFORSK standards [10] for acceptable accelerations on a cruise liner are applied as a limit which was assessed for different sea states based on the locations to determine the workability of the platform. Kaptan et al. [11] expand on this research by finding the platform accelerations for a spar and semi-submersible platforms using frequency domain analysis for two different locations and again the NORDFORSK standards [10] to determine the workability for the platforms. Jenkins et al. [12] use frequency domain analysis to obtain the platform accelerations for the UMaine VoltturnUS-S under different sea states for the nacelle using different wave spectra and a range of sea states. A correlation between the nacelle accelerations and the wave height and wave period as well as differences depending on the wave spectra used were found.

Studies regarding the use of walk-to-work gangways for FOWTs to determine limiting wave heights and the impacts of coupling effects have also been conducted. Guanche et al. [13] assess the feasibility of a walk-to-work gangway for crew transfer to an FOWT and finding limiting wave heights for two different vessels. Li et al. [14] furthers this research by considering the second order drift forces which are present during the use of a walk-to-work gangway using time domain analysis and found that by considering these drift forces reduced the significant wave height at which the walk to work gangway could be safely used. Yin et al. [15] employ a control system for a parallel active motion compensated gangway and use this to determine the limiting significant wave height for safe operation of the gangway. Moreno et al. [16] present a method considering the workability and accessibility of the UMaine Voltturn US-S 15MW reference turbine [17] with a Service Operation Vessel (SOV) using a walk-to-work gangway to determine the limiting wave height for different wave periods and show their findings in a heatmap format which is a useful means of visualising the workability for different operations.

Another area of in-situ maintenance which has been considered is blade installation using both floating cranes and jack-up vessels with a focus on performing such operations on fixed offshore wind turbines. Zhao et al. [18] determine the feasibility of using two different floating cranes for single blade installation on a 10MW fixed offshore wind turbine and comparing to the use of a jack-up vessel. This was done using SIMO-RIFLEX-Aero performing time domain analysis and it was found that the wave induced motions on the floating crane had a significant impact on the ability to install the blade safely. It was also found that a semi-submersible crane caused less motion in the blade being replaced when compared to a mono-hull crane and it was therefore concluded that a semi-submersible crane would be a more feasible option for single blade replacement. Wu et al. [19] expand on this by considering weather forecast uncertainties when evaluating the feasibility of floating cranes for single blade installations where they found that

by considering forecast uncertainty that the allowable sea states for the operation decreased. Yin et al. [20] study the hoisting of a wind turbine blade using a jack-up vessel where the aerodynamic loads imposed by wind are analysed and found that wind loads should be considered during the procedure and further to this that trajectories of the blade could be predicted so collisions could be prevented. Yin et al. [21] presents a study on a floating barge crane which is used to lift a wind turbine blade where they consider dynamic responses of both the vessel, lifting apparatus and the blade using a MATLAB program and verify the results they obtained against Adams and AeroDyn.

Several studies in the literature pertain to the dynamics of floating crane carrying payloads in a more general context. Schellin et al. [22] present a quantitative method for predicting the motions of floating cranes carrying payloads where they found that the system responses in beam seas were more favourable than head seas. Li et al. [23] considers the impact of uncertainties in wind and sea states on the operational limits for offshore lifting operations for both mono-hull and semi-submersible lifting vessels using a JONSWAP spectrum and find that the semi-submersible vessel has a lower response than the mono-hull vessel. Ellermann et al. [24] present an experimental study on the non-linear dynamics for floating crane carrying payload and compare time and frequency domain analysis methods. Haselsteiner et al. [25] review different solutions for lifting wind turbine components from a vessel at sea where they find that solutions are limited to single components. Maleki and Singhose [26] considers the swing dynamics of double-pendulum boom cranes where the oscillation frequencies for the first two frequency are determined by simulation before further studies in the dynamics are carried out by experiment and simulation. Lee and Roh [27] review the multibody dynamics of ships and offshore structures. One of the factors they consider are collisions that can occur during operations and discuss the two main methods for detecting a collision being the impulse method and force method. Ku and Roh [28] study the dynamics of a whole wind turbine assembly being carried by a floating crane using simulations as a part of installing a fixed offshore wind turbine. Ren et al. [29] review the operations and maintenance of offshore wind including lifting operations and the types of vessel which can be used for fixed offshore wind. Ren et al. [30] study anti-swing controls for a multi crane system where the lifting of a tower-nacelle-rotor assembly is used to verify the system. Chen et al. [31] study the dynamics of the lift off phase for a fixed wind turbine jacket under different sea states and determine the critical stages of the operation and determine the feasibility under different sea states. Ma et al. [32] consider the dynamics of lowering a tower-nacelle-rotor assembly which expands on studies where the system is considered to be a steady state. Shi et al. [33] consider the dynamics of a floating crane and FOWT while they are lashed together for the purposes of performing a maintenance operation where they found that the tethering reduced the relative motions between the FOWT and the crane vessel and reduces crane tip motions. Liu et al. [34] performs a complete analysis of the non-linear dynamics of a dynamic positioning crane vessel where simulation results are used to compare against mathematically obtained results.

This paper presents several key novelties advancing the feasibility of in-situ generator replacement on floating offshore wind turbines (FOWTs):

- Expanded analysis to higher sea states and a wider range of wave periods.
- Novel collision detection using generator accelerations and jolts.
- Integrated assessment of motion limits and collision risks to identify key operational constraints.
- Practical recommendations on crane barge orientation to reduce collisions.
- First combined study addressing floating-to-floating dynamics in offshore crane operations.

These contributions provide new insights to improve the safety and feasibility of offshore maintenance strategies. The paper is arranged as follows, in Section 2 the simulation background is set out and the model and lifting scenario used described. In Section 3 parametric studies on the obtained data are presented. In Section 4 presents a discussion on the findings and Section 5 gives the overall conclusions from this study.

2. Methodology

2.1. Modelling background

The study was conducted using the Marine Simulator at the National Decommissioning Centre (NDC), a part of the University of Aberdeen. The simulation is developed by OSC, and uses the FATHOM HYDRO engine and Algoryx Dynamics to produce a fully interactive real-time physics environment which computes the hydrostatic and hydrodynamic forces experienced by objects within the simulation. This allows for the modelling of complex offshore systems and can serve as a useful tool for de-risking operations or prototyping new technologies as demonstrated by Martinez et al. who studied a variable buoyancy anchor and it is deployment and Terrero-Gonzalez et al. who study the dynamic response of a novel FOWT design under regular wave load with experimental validation [35–37]. Further to this the Marine Simulator has a 300 degree walk in dome with control stations which can be used to manipulate assets within the simulation such as cranes and vessels.

Individual models within the simulation have a triangular mesh, which allows then to compute the forces acting on the single mesh element and integrated over the surface of the whole object that itself is treated as rigid body. The hydrodynamic loads acting on the model, are found by applying the Cummins equation given in Eq. (1) to each section of the triangular mesh and then applying these forces to the centre of mass of the object using frequency domain analysis [35,36,38]:

$$(M + A(\infty)) \ddot{\mathbf{x}} + \int_0^t K(t - \tau) \dot{\mathbf{x}} d\tau + C\mathbf{x} = F, \quad (1)$$

where M gives the objects mass matrix, A gives the added mass matrix for an infinite frequency, $\mathbf{x}$ is the vector consisting of the six degrees-of-freedom of the object and can be given as $\mathbf{x} = [x, y, z, \phi_x, \phi_y, \phi_z]^T$ where x, y and z are translational degrees of freedom and ϕ_x, ϕ_y and ϕ_z are the rotational degrees of, K is the impulse response function, C gives the hydrostatic coefficient for the restoring force and F consists of all the exciting forces acting on the object [39].

The general equation of motion for objects in the simulation is given in Eq. (2):

$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F}, \quad (2)$$

where $\mathbf{M}$ is the inertia and added mass matrix, $\mathbf{C}$ is the linearised viscous damping matrix (not accounting for gyroscopic phenomena) and $\mathbf{K}$ is the stiffness matrix which accounts for mechanical, hydrostatic and mooring stiffness between the different rigid bodies within the system. $\mathbf{x}$ is the position vector for six degrees-of-freedom for each object and $\mathbf{F}$ are the external forces including the hydrostatic, hydrodynamic, mooring forces, crane tether forces and the weight of objects. In the case of a floating crane and floating platform, both unrestricted systems have six degrees-of-freedom each. Additionally, when the crane is lifting an object then the hook load will also have six degrees-of-freedom.

The zeroth and first order forces in $\mathbf{F}$ include the buoyancy, lift and drag forces which are given in Eqs. (3)–(5):

$$F_{\text{buoyancy}} = -\rho g \iint_S h \hat{\mathbf{n}} dS, \quad (3)$$

$$F_{\text{lift}} = - \iint_S p \hat{\mathbf{n}} \cdot \hat{\mathbf{k}} dS, \quad (4)$$

$$F_{\text{drag}} = - \iint_S p \hat{\mathbf{n}} \cdot \hat{\mathbf{i}} dS + \iint_S \tau \hat{\mathbf{n}} \cdot \hat{\mathbf{i}} dS, \quad (5)$$

where the unit vector $\hat{\mathbf{n}}$ is normal to the surface of the object submerged, S and the unit vectors $\hat{\mathbf{i}}$ and $\hat{\mathbf{k}}$ are parallel and vertical to the fluid velocity. ρ is the density of water, h height submerged, p the hydrostatic pressure, τ the shear force acting on the submerged surface, and g the gravitational acceleration [36,40]. The simulation also accounts for radiation forces, Froude–Krylov forces and diffraction forces. These are shown in Eqs. (6)–(8). Radiation forces can also account for an additional memory effect when irregular waves are used; however, in this particular study, regular waves are used to keep the system simple so the memory effect is not considered:

$$F_{\text{radiation}} = - \iint_S \rho \left(\frac{\partial \phi_{\text{radiation}}}{\partial t} \right) \hat{\mathbf{n}} dS, \quad (6)$$

$$F_{FK} = - \iint_S \rho \left(\frac{\partial \phi_{FK}}{\partial t} + gz \right) \hat{\mathbf{n}} dS, \quad (7)$$

$$F_{\text{diffraction}} = - \iint_S \rho \left(\frac{\partial \phi_{\text{diffraction}}}{\partial t} \right) \hat{\mathbf{n}} dS. \quad (8)$$

These are inertial forces and are dependent on the fluid velocity potential given by $\phi(t) = \phi_{\text{radiation}}(t) + \phi_{FK}(t) + \phi_{\text{diffraction}}(t)$ and is solved using bidirectional interpolation. z is the vertical position of the centre of gravity and $\phi_{\text{radiation}}$, ϕ_{FK} and $\phi_{\text{diffraction}}$ are the radiation, Froude–Krylov and diffraction fluid velocity potentials respectively [36,38].

Furthermore, the second order wave forces are also considered where they are solved for using the Quadratic Transfer Function (QTF) and in the case of a semi-submersible platform the first order mean drift force and second order slow varying drift forces are also a factor in platform response [36]. These are calculated using Eq. (9):

$$\mathbf{F}^2 = - \oint_{WL} \frac{1}{2} \rho \xi_r^{(1)} \cdot \xi_r^{(1)} \hat{\mathbf{n}} dL + \iint_{S_b} \frac{1}{2} \rho |\nabla \phi^{(1)}|^2 \hat{\mathbf{n}} dS + \iint_{S_b} \rho \left(\mathbf{x} \cdot \nabla \frac{\partial \phi^{(1)}}{\partial t} \right) \hat{\mathbf{n}} dS + M_s R \cdot \ddot{\mathbf{x}} + \iint_{S_b} \rho \frac{\partial \phi^{(2)}}{\partial t} \hat{\mathbf{n}} dS, \quad (9)$$

where $\xi_r^{(1)}$ is the first order wave elevation, $\phi^{(1)}$ and $\phi^{(2)}$ are the first and second order velocity potentials, $\mathbf{x}$ and $\ddot{\mathbf{x}}$ are the position and acceleration of the centre of gravity and M_s is the mass of the body. WL represents the water line and R is the rotational matrix [36].

The simulation can also calculate forces applied by wind and currents using a polynomial where the relative velocity between the object and the wind or current is used [36]; however, for the purposes of this study wind and currents are not considered to allow for a simpler case to be considered. Subsequent studies including the effect of wind and currents on the system can be completed.

As well as considering the hydrodynamic forces present in the system the forces due to the payload also need to be factored. The force acting on the payload at the crane hook can be given as:

$$\mathbf{F} = \begin{Bmatrix} -F_T \cos \alpha \\ -F_T \sin \alpha \cos \beta \\ m_{\text{payload}} g - F_T \sin \alpha \cos \beta \end{Bmatrix} \quad (10)$$

where F_T is the tension force due to the hoisting tethers and α and β are orthogonal angles in the x-z plane and y-z plane respectively [22]. The cables in the simulation are modelled using the lumped mass technique.

Table 1
Key properties of the UMaine VoltturnUS-S and 15MW turbine.

Component property	Value
Platform width	90.13 m
Platform length	102.13 m
Platform height	35 m
Steel platform mass	3914 t
Internal platform mass	15640 t
Tower/platform interface	100 t
Tower height	129.495 m
Tower mass	1263 t
Blade mass	65 t
Nacelle mass	991 t

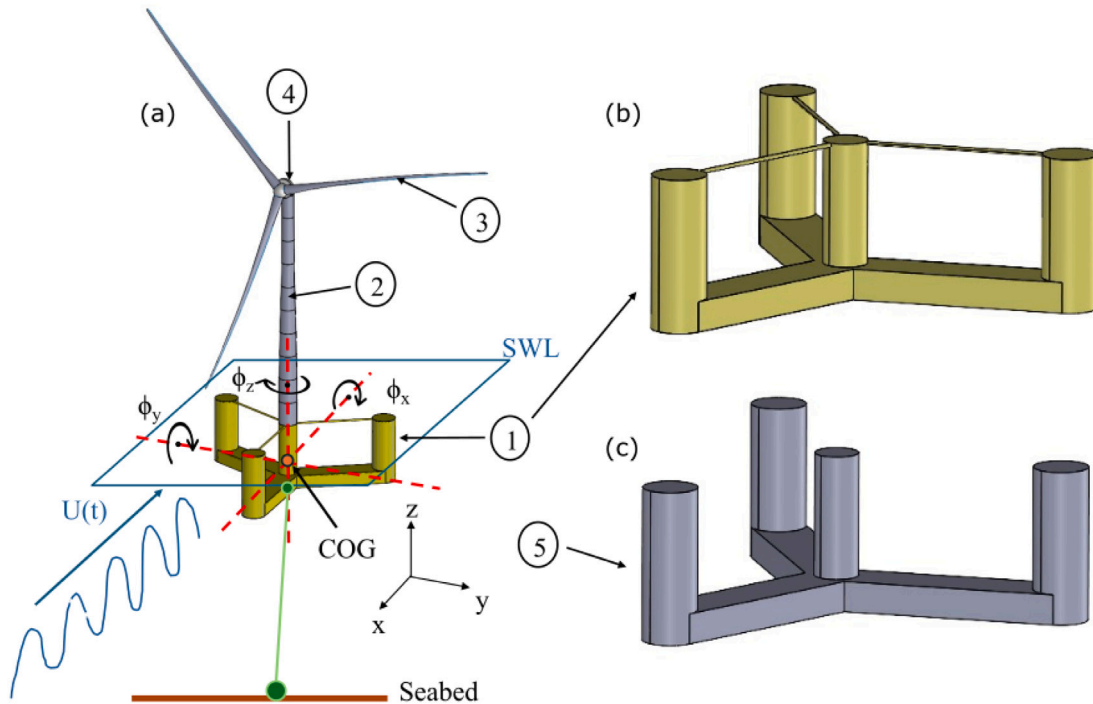


Fig. 2. UMaine VoltturnUS-S semi-submersible platform (1) and a 15MW reference turbine made up of a tower (2), blades (3), nacelle (4) and the platform inner volume which gives the buoyancy (5). An elastic connector to the seabed which serves as a simplified mooring system for the FOWT is shown in green.

2.2. Calibrated model

The UMaine VoltturnUS-S semi-submersible [17] and 15MW reference turbine [41] were used for this study due to its readily available hydrodynamical data and realistic 3D models which could be used to produce a calibrated model within the Manine Simulator. The platform consists of three buoyant columns containing iron ore ballast attached to a central column by a pontoon which is filled with seawater. Some of the key properties of the UMaine VoltturnUS-S are shown in Table 1 and Fig. 2 shows the full assembly. To represent the internal ballast of the platform, a solid block the same shape as the internal part of the platform was made with a mass corresponding to the mean density of ballast which allowed the platform to be buoyant and is shown in Fig. 2.

The turbine model is made up of nine separate parts, these being the semi-submersible platform, the inner volume, the tower, nacelle, rotor hub and three blades. These parts are rigidly connected to each other resulting effectively in one rigid body. The RAOs of the platform had to be calibrated for regular waves with different wave heights to ensure that the measured RAOs matched the RAOs given in [17] which were produced using OpenFAST, therefore meaning the model motion response was the same. During calibrations of the model, it was attached to the seabed using a simple elastic connector (representing equivalent mooring system) to limit some of the degrees-of-freedom. In this case the sway and yaw were restricted by setting the compliance of the connector to $1 \times 10^{-32} \text{ m N}^{-1}$ and the remaining degrees of freedom given a compliance of 100000 m N^{-1} so they could move freely. It was found

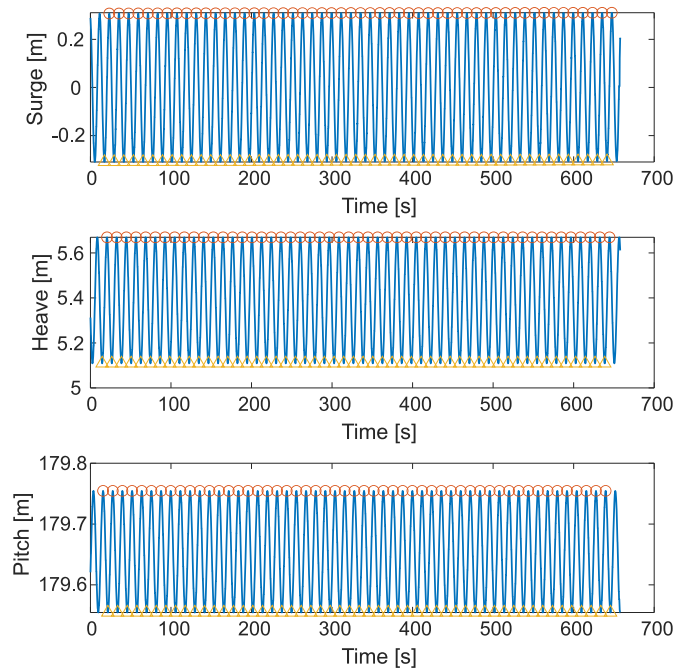


Fig. 3. Time histories used to calculate the platform RAOs with the peaks and troughs used marked for a wave height of 1 m and a wave period of 12 s.

that the heave and pitch motions required calibration, but the surge motions did not require calibration since the points either had a good fit or fell below the curve meaning that an increase in damping would not improve the fit. Eq. (11) was used to calculate the RAOs measured in the Marine Simulator from platform time history data, an example of which is shown in Fig. 3:

$$RAO = \frac{\text{Motion amplitude}}{\text{Wave amplitude}}. \quad (11)$$

Calibrations for a regular wave height of 1 m, 2 m, 4 m and 6 m were conducted where the calibration for the 1 m case was first presented in [40]. The data for a wave height of 1 m was used to calibrate the 1 m, 2 m and 4 m cases which were considered to be low sea states and the data for a wave height of 8 m used to calibrate for the 6 m case which was considered to be a high sea state [17].

The calibration was conducted by varying the damping values for a selection of wave periods where the initial measured RAOs fell above the curve. Using a Piecewise Cubic Hermite Interpolating Polynomial (PCHIP), a fit for the rest of the damping values could be obtained for the interval of 5 s to 30 s with a step size of 0.5 s. The RAOs of the platform were then measured again to check that the measured RAOs matched those in the data. Fig. 4(a) and (d) shows the calibrated RAOs for the low and high sea states in the surge, heave and pitch. Fig. 4(b) and (c) show the phase plane plots for the surge, heave and pitch for the different wave heights and for two different wave periods. It was found that in each case that the platform only presented period one motions and that a higher wave height resulted in a higher response. The calibration curves associated with the heave and pitch motions for the four different wave heights are shown in Fig. 4(e) where it can be noted that there is very little difference between the different calibrations meaning it could be possible to represent them as an average of all cases.

Once the calibration of the model had been completed so that the model RAOs displayed a good match as shown in Figs. 4(a) and (d), the model could be used to model a major component exchange and allow consideration of the platforms motions during such an operation which is covered in the remaining sections of this study.

2.3. Lifting scenario

The lifting scenario presented in [40] was used again for this study as seen in Fig. 5 (a) where a simple floating barge and a crane from the simulation library were combined so that the crane was at the front of the barge. A block of ballast was connected to the rear of the barge to act as a counterbalance to the crane. It means that the crane considered here is not representative of a particular floating crane vessel, but it is a representation created using available components from Marine Simulator library to focus the study on the feasibility of conducting such an operation itself. The crane from the library was also modified so it had a boom of length 166.4 m which allowed it to reach the height of the nacelle and therefore carry out the lifting operation. Table 2 gives the key properties of the floating crane used for the model. The crane was fully controllable by changing the lengths of different wires

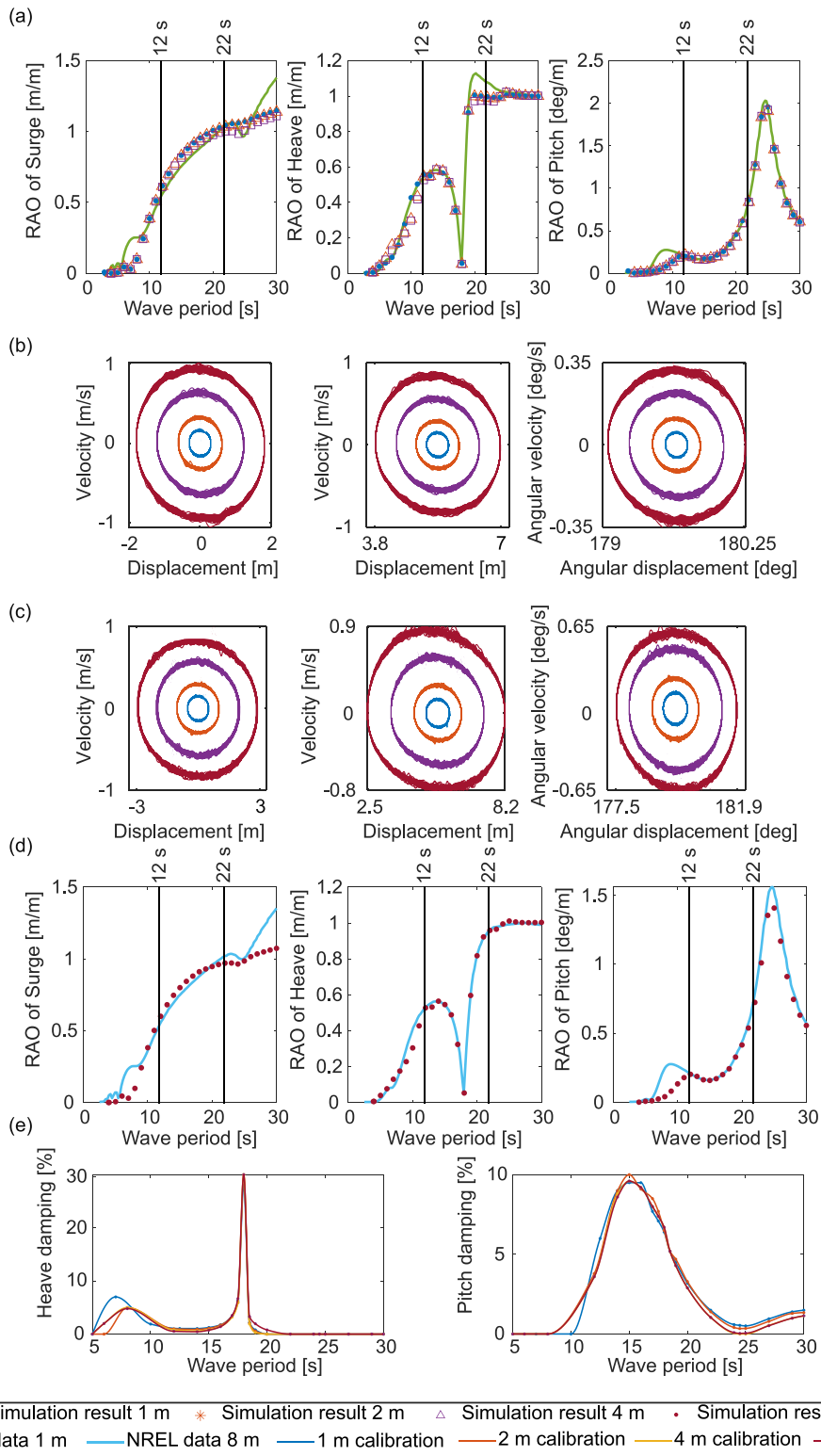


Fig. 4. RAO plots for low sea states (1,2 and 4 m) (a), phase planes for a wave period of 12 s (b), phase planes for a wave period of 22 s (c), RAO plots for high sea states (6 m) (d) and calibration curves for the platform RAOs (e).

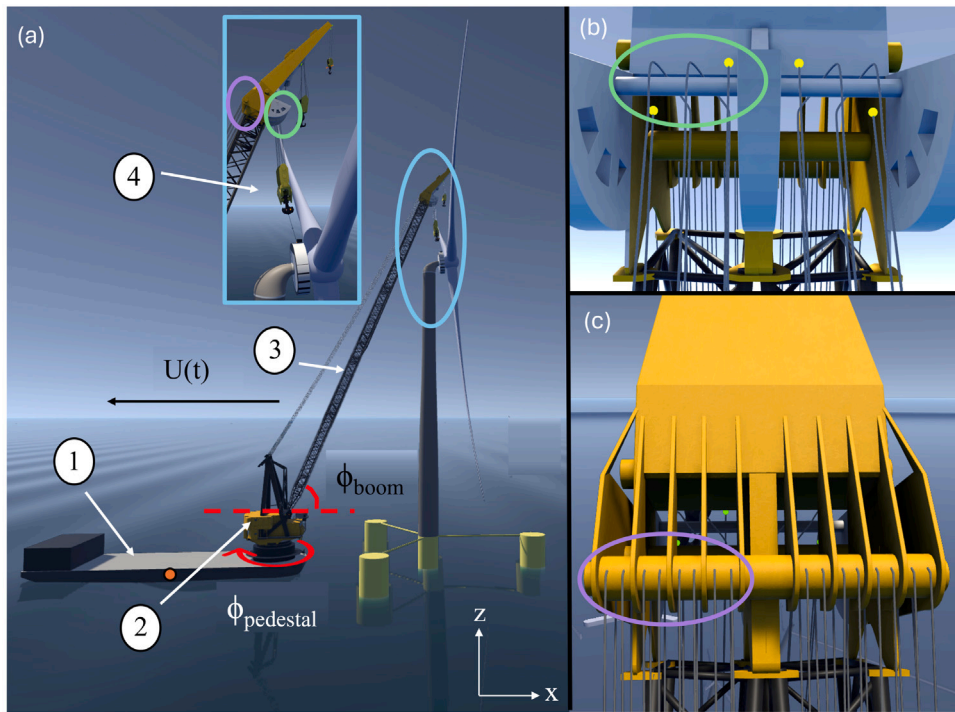


Fig. 5. (a) Arrangement for the lifting operation. (1) Crane barge, (2) crane pedestal, (3) crane boom, (4) crane hook. (b) Shows the tether set up that controls the crane hook. (c) Shows the tether set up that controls the crane boom.

Table 2

Key properties of the floating crane built utilising the Marine Simulator's offshore asset library.

Component property	Value
Barge length	166.4 m
Barge width	36.6 m
Total barge height	7.6 m
Barge freeboard	4 m
Barge draft	3.6 m
Crane boom length	166.4 m
Barge mass	10000 t
Crane mass	446.972 t
Ballast mass	1700 t

to move the boom and crane hooks and could be rotated on its pedestal through a full 360 degree range. The operation consists of the generator being removed from the wind turbine and recovered to the deck of the barge.

The lifting operation was split into six stages which are as follows [40]:

1. Taking the strain of the generator with the crane
2. Disconnecting the generator and lifting it clear of the nacelle
3. Increasing the boom angle from 67° to 73° so that the generator completely clears the FOWT
4. Rotating the crane on the pedestal 180°
5. Lowering the generator down to the barge with the crane winches
6. Disconnecting the generator so it rested on the barge without being attached to the crane.

During the operation the nacelle was considered to be switched off and not allowed to rotate which is consistent with a maintenance state for a wind turbine. This was achieved by locking the hinge actor which allows the turbine blades to rotate, hence effectively simulating the parked turbine condition for maintenance. The generator was modelled using a simple cylinder with dimensions and mass consistent with the information in [41] and is presented in Table 3 where the considered generator is connected to the nacelle rigidly in the location corresponding to the actual generator location. The generator is of a direct drive

Table 3
NREL 15MW generator properties.

Mass	371.57 t
Diameter	10.53 m
Width	2.28 m

Table 4
Real time for each stage to be conducted in the simulation.

Stage	Real time [s]
1	26
2	35
3	70
4	800
5	810
6	60

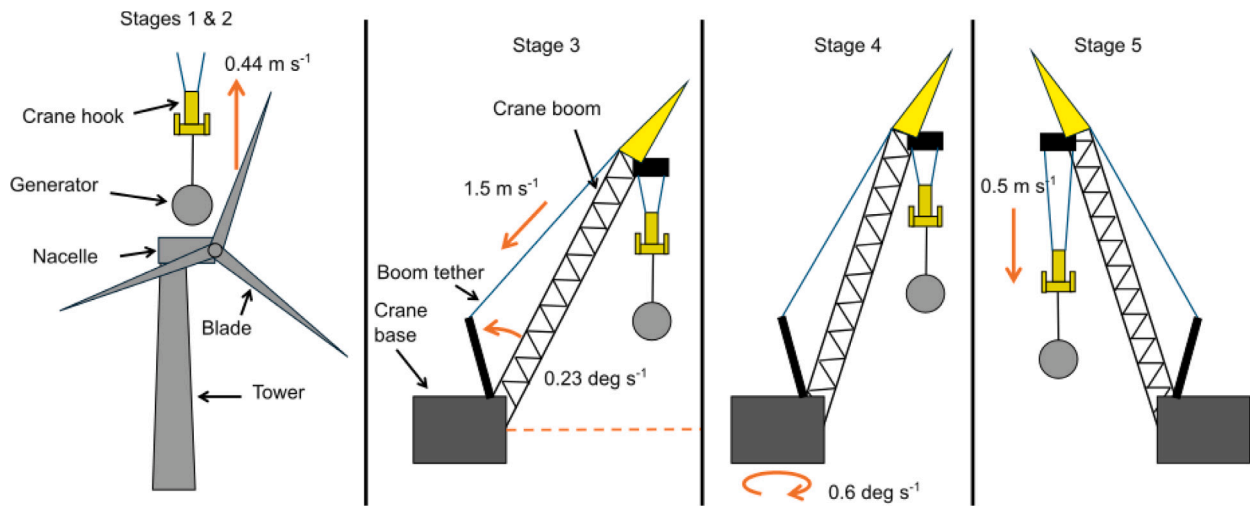


Fig. 6. Block diagram showing the lifting speeds used for the operation.

design type and as such direct removal would not likely be possible without disassembling the whole nacelle. As the study focuses on the dynamics of the in-situ maintenance, we keep the generator mass properties realistic to gain deeper overall understanding of the process and neglect particular constraints due to nacelle design as they will vary with every particular turbine design.

The barge was connected to the seabed with a simple, representing an equivalent station keeping system, which limited its motions in the surge, sway and yaw degrees-of-freedom while keeping heave, roll and pitch unrestricted. Such arrangement is representative of tug boats or mooring system keeping the barge in place for the duration of the lifting operation. No restrictions were directly applied to the motions of the crane or its hook, meaning their motion is unrestricted and affected by the crane dynamics and wave induced barge motions (heave, pitch, roll).

An automated script was developed to control the lifting process so that each operation was carried out in the same way by using fixed values to dictate the rate of change for raising and lowering the crane hook, raising the crane boom and rotating the crane pedestal for a set time. To change the hook height or the boom angle, winches controlling the lines connected to the crane hook or crane boom are used. Due to the way in which these tethers are set up the lifting speed of the winch does not correspond to the speed at which the hook is raised or the boom angles changes. Therefore, to obtain the actual speed of the hook or boom, displacement data for hook or boom angle were used for the given winch inputs so that the rate of change of the hook and position and boom angle could be obtained by finding the gradient of the line produced. This is due to the way the tethers that control the hook and the boom are set up, where the two crane hook tethers have six pulleys shown in Fig. 5(b) and the crane boom tethers run through eight pulleys. During Stage 1 and 2, crane hook was raised by reducing the length of the two crane tethers at a speed of 2.6 m s^{-1} which corresponds to the crane hook being raised with a speed of 0.44 m s^{-1} . During Stage 3, the tethers controlling the boom angle were reduced in length at a rate of 1.5 m s^{-1} to raise the crane boom which corresponds to the crane boom being raised with an angular speed of 0.23 deg s^{-1} . During Stage 4, the pedestal was rotated at a rate of 0.6 deg s^{-1} . During Stage 5, the tethers controlling the crane hook were increased in length at a rate of 3 m s^{-1} to lower the crane hook which corresponds to the crane hook being lowered with a speed of 0.5 m s^{-1} . Table 4 shows the length of time each stage took in the lift in real time and Fig. 6 shows a block diagram showing the lifting speeds for each stage.

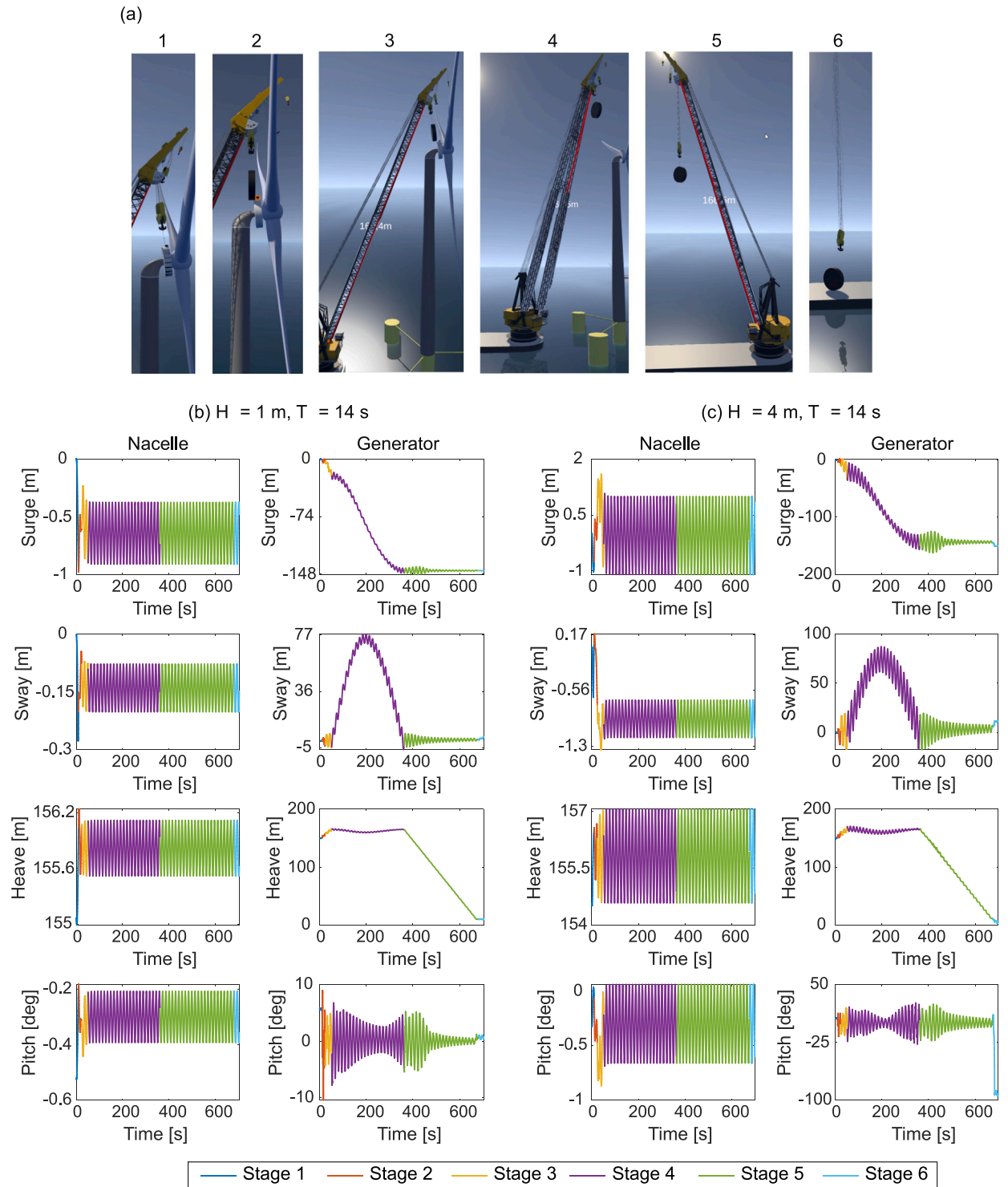


Fig. 7. (a) Screenshots of the six stages of the lifting operation simulated. Bottom: The time histories for the nacelle and generator for a wave height of 1 m and wave period of 14 s (b) and wave height of 4 m and wave period of 14 s (c) for the surge, sway, heave and pitch motions.

The six lifting stages are shown in Fig. 7 along with time histories for the nacelle and the generator during the whole lifting operation for a wave height of 1 m and 4 m with a wave period of 14 s.

3. Parametric studies

3.1. Peak to peak motions

The peak to peak motions of the generator and the nacelle during Stages 4 and 5 of the operation were considered in the surge, heave and pitch motions and are shown in Fig. 8(a) and (b). They were obtained by using time history data obtained by frequency domain simulation, examples of which can be seen in Fig. 7(b) and (c). This was done so that the motions of the generator and nacelle during the steady state motion of the nacelle could be compared. It is clear that the motions of the nacelle post disconnection follow a similar pattern to the RAOs presented in Fig. 4 and that a higher wave height gives a higher amplitude response. The peak to peak motions of the generator also follow a similar pattern where a higher wave height means a higher amplitude response. A peak in response can be seen at a wave period of 12 s for the generator motions. This possibly indicates that the barge experiences a resonance in motion at these wave periods, which highlights the challenges associated with the relative motions of the platform and lifting vessel. Fig. 14 shows the barge peak to peak motions which presents a similar pattern of response in the surge and pitch motions which confirms this.

The peak to peak motions of the generator during the initial stages of the lift can also be considered using the same method as previously outlined where the results are presented in Fig. 8(c). The pattern observed is similar to the generator during the early stages of the lift with higher responses measured overall. The same pattern of a peak in response at a wave period of 12 s continues to indicate that the barge experienced greater motions for these particular wave periods.

3.2. Generator accelerations

The accelerations that the generator experiences is another factor which can result in a failure of a major component exchange. Dueñas-Orsorio and Basu [42] indicated that if the generator is exposed to accelerations of 5 to 10 m s⁻² (0.5 to 1 g) that the wind turbine generator can be damaged. It should be noted that these values come from a previous study regarding the effects of earthquakes on buildings and the generators considered are diesel powered and is also a metric for considering the structural responses on the generator while at mounted in the nacelle. However, these values serve as a starting point for exploring how accelerations of the generator during a lift can limit a maintenance operation. An exploration of the accelerations of the generator during Stages 2, 3 and the first quarter of 4 are considered where only the lateral accelerations are considered, being the surge, sway and heave motions of the generator. Collisions could only be detected for the generator making contact with the blades since the nacelle collision had to be disabled to allow the generator to be mounted in the nacelle. This was due to the direct drive design of the generator which meant that it could not be fully removed without also removing the whole nacelle and that the model generator had to start in the same location as the generator in the nacelle assembly which presents a limitation of this study.

The simulation only produced displacement data so to obtain the accelerations the derivative of the displacement data with respect to time had to be taken twice to obtain acceleration values. The derivatives were taken by fitting line segments to sections of data with regard for the sampling frequency of the simulation and the wave period. Sample frequency was determined by finding the mean difference between time steps in the simulation which gave the sampling rate and then taking the inverse of this value to obtain sampling frequency which was found to be approximately 180 Hz. Eq. (12) shows the formula used to find the number of points contained in a subsample:

$$Subsample = \text{round} \left(\frac{T_s F_{\text{samp}}}{25} \right) \quad (12)$$

Fig. 9 shows the time histories of the acceleration of the generator for a wave period of 14 s and a significant wave height of 1 m and 4 m. Once the accelerations were obtained, the RMS accelerations were calculated using the RMS function in MATLAB and the absolute peak acceleration was obtained using the max function for both the positive and negative peaks and then selecting the maximum acceleration with the highest value. The results are shown as heat-maps in Fig. 10 where the green areas indicate a safe acceleration regions while the red areas indicate when the operation should not be carried out based on an unacceptable acceleration of 5 m s⁻² being exceeded [42].

It can be seen that a similar trend to the peak to peak motions regarding high accelerations is present where wave periods of 10 to 16 s have higher generator accelerations in both RMS and maximum responses. As has previously been noted, the barge motions will contribute to this which can be seen in Fig. 14 showing the barge peak to peak motions. In these wave periods the barge motions are high which therefore contributes to the high accelerations of the generator, which is amplified by the height the generator is lifted from.

3.3. Generator collisions

It was difficult to determine from the displacement time histories alone if the generator had experienced a collision during the operation. A possible method for detecting collisions is to consider both the accelerations and the jolts (the third order derivative of displacement with respect to time with units [m s⁻³]) of the generator and finding peaks in these plots which would indicate high changes in acceleration and therefore collisions. Videos of different scenarios were compared against the time histories for the acceleration and jolt to identify if large changes corresponded to generator collisions with the tower, blades or blade hub and therefore determine if this method is capable of finding generator collisions from the acceleration and jolt time histories alone. Due

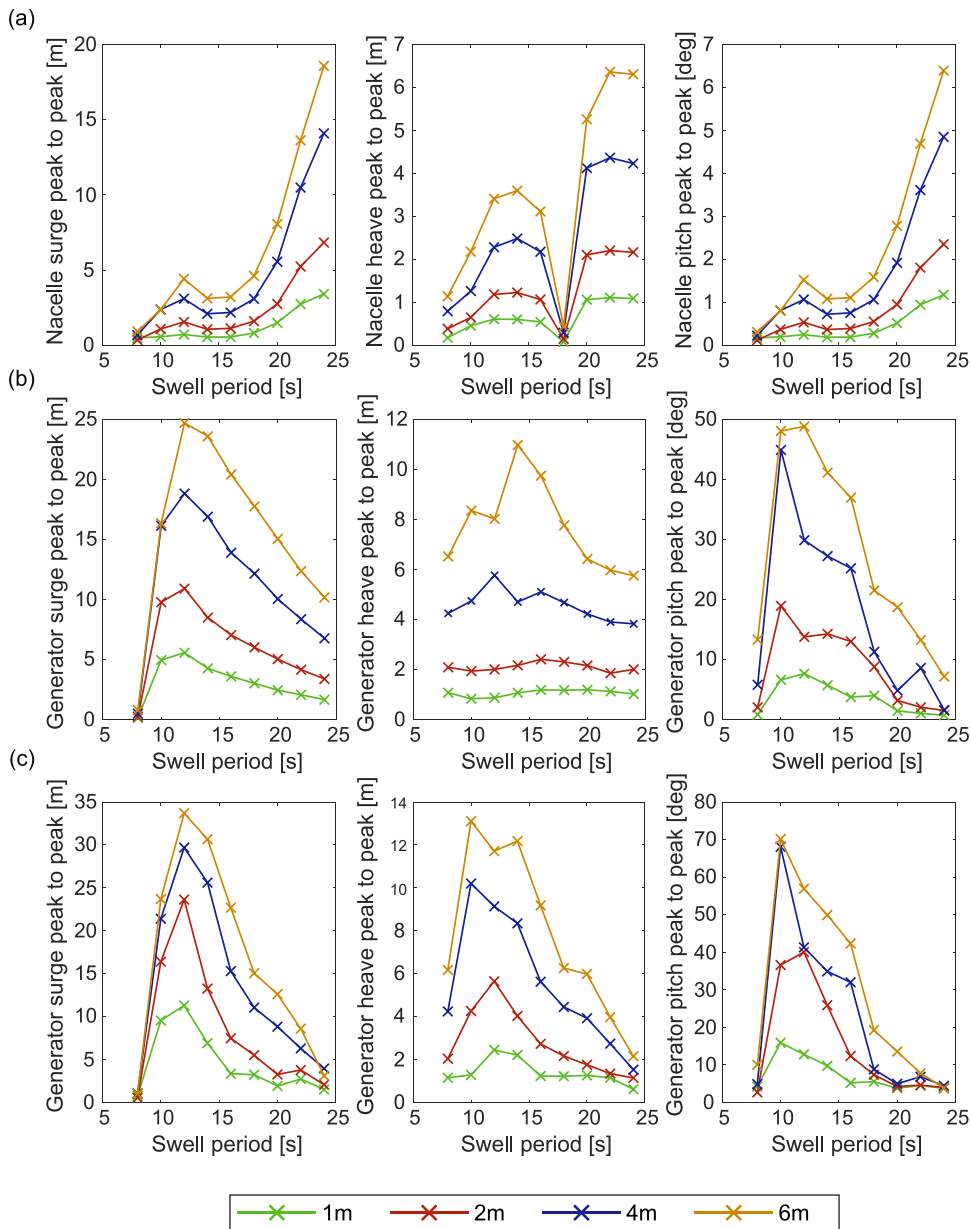


Fig. 8. Nacelle (a) and generator (b) peak to peak values for the four different wave heights in the surge, heave and pitch motions during Stages 5 and 6 of the operation. (c) shows the generator peak to peak motions during Stages 2, 3 and the first quarter of 4.

to the direct drive design of the wind turbine, collisions with the nacelle are not considered here, which represents limitation of the analysis and can be addressed in future when maintenance operation on an existing wind turbine is planned. Fig. 11 shows examples of acceleration and jolt plots for the generator during Stages 2 to 4 where collisions were most likely to occur. Significant jumps in the plots are shown which corresponded to the generator colliding as seen in video footage.

Upon inspection of all the cases with video footage, it was found that spikes in the acceleration and jolt generally corresponded to a generator collision. It was noted that some of the peaks in the acceleration and jolt did not correspond to collisions for the cases with available video. This could be due to calculation errors due to differentiation introducing noise into the higher derivatives which results in peaks in the acceleration and jolt in areas where no collision occurs. A filter was used to remove some of the noise generated by the differentiation. Formalising the determination of these notable events without the aid of video remains a challenge.

Fig. 12 shows the heat-maps presented in Fig. 10 but the cases in which a collision was detected are marked with a cross. It is clear from this that the generator accelerations are not the most important consideration since the generator collides in cases where the accelerations would be deemed to be acceptable according to the 5 m s^{-2} acceleration parameter set out [42]. Further consideration

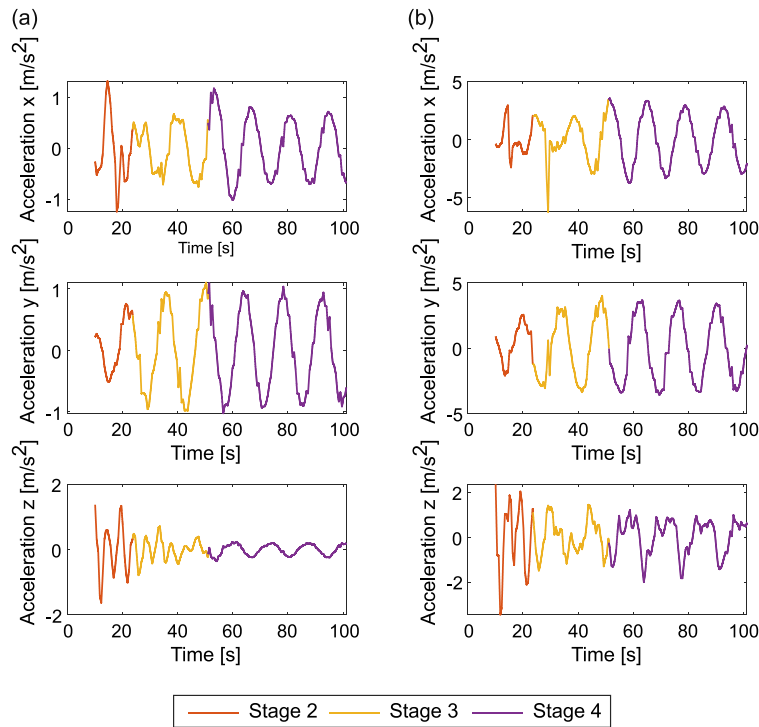


Fig. 9. Acceleration time histories for wave period of 14 s and a wave height of 1 m (a) and 4 m (b).

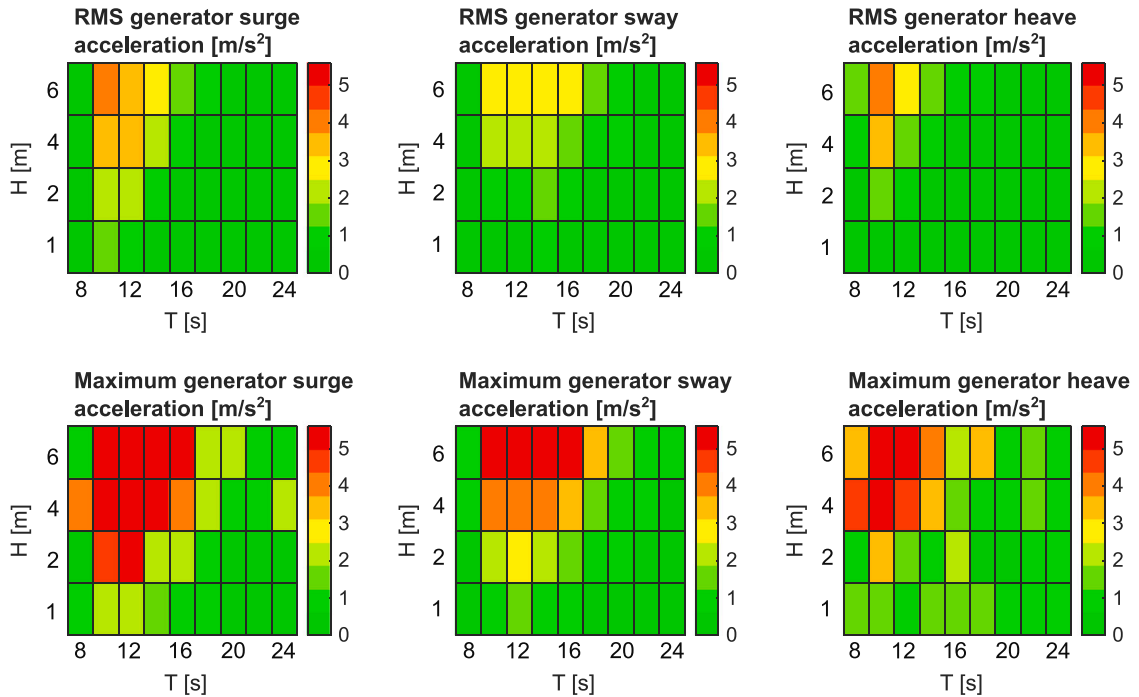


Fig. 10. Heat-maps of the generator acceleration for both RMS (a) and absolute maximum (b).

was given to determining a response-based criterion to help determine the incidence of collisions by considering the displacement, acceleration or jolt of the generator. However this presented several challenges. For instance, it is clear that acceleration alone is not a helpful measure since in some cases a low generator acceleration still resulted in a collision. This is in part because the rough

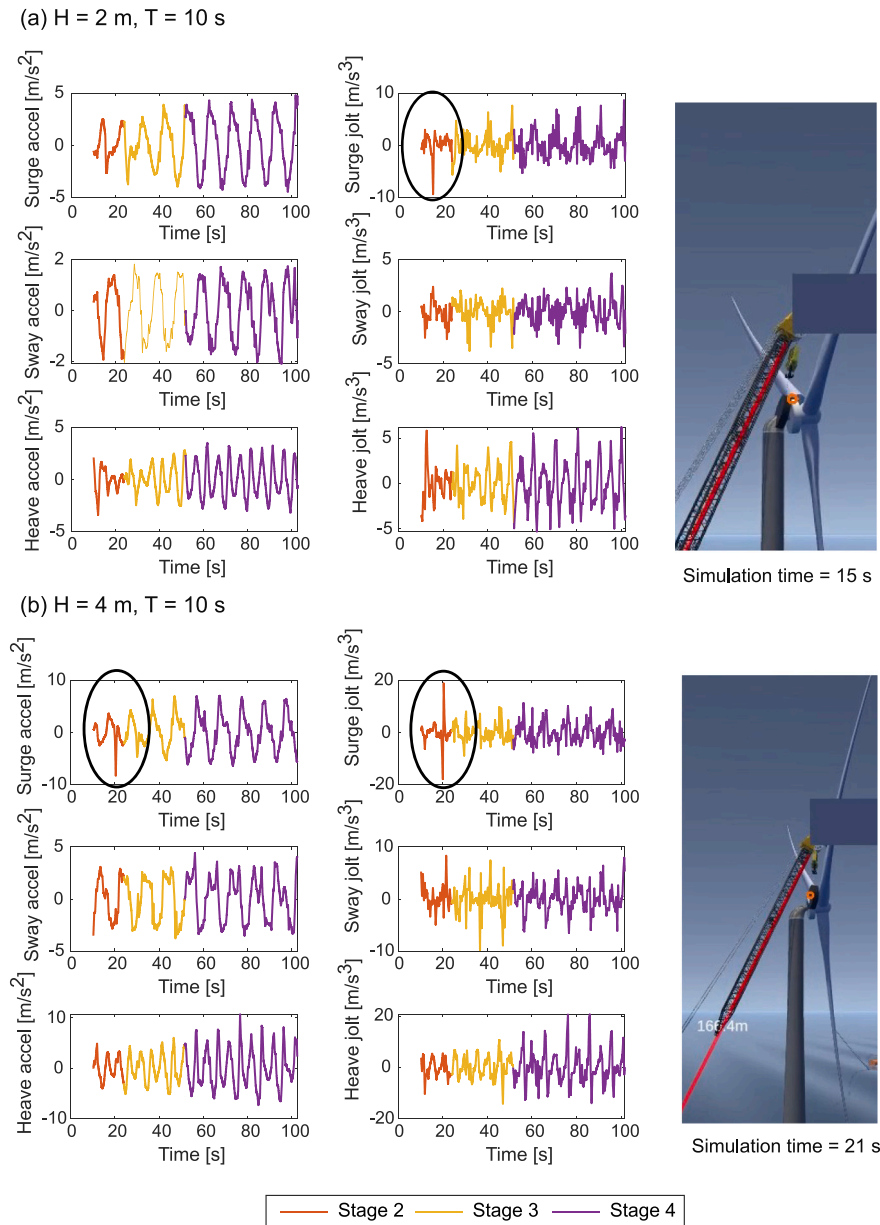


Fig. 11. Acceleration and jolt plots for two cases showing prominent peaks during Stages 2 to 4 and corresponding screen shots where a collision occurred. (a) wave height of 2 m and wave period of 10 s, (b) wave height of 4 m and wave period of 10 s.

method used detects any collision that happens irrespective of the forces involved in the collision. The further study of the detection of collisions within the simulation using time history data would merit its own detailed research.

3.4. Changing lifting method

Considering the high failure rate for the lift, further considerations to the method used for the lifting operation were taken to see if the incidence of collisions could be reduced. Alternative methods were considered focusing on the first three stages of the lift since it was possible that the generator motions were being induced by poorly operating the crane. Three different scenarios were considered and were as follows:

1. Raising the boom in Stage 3 over a different phases with a reduced rate to the rate used in Section 2.3:

(i) -5% for 60 s real time

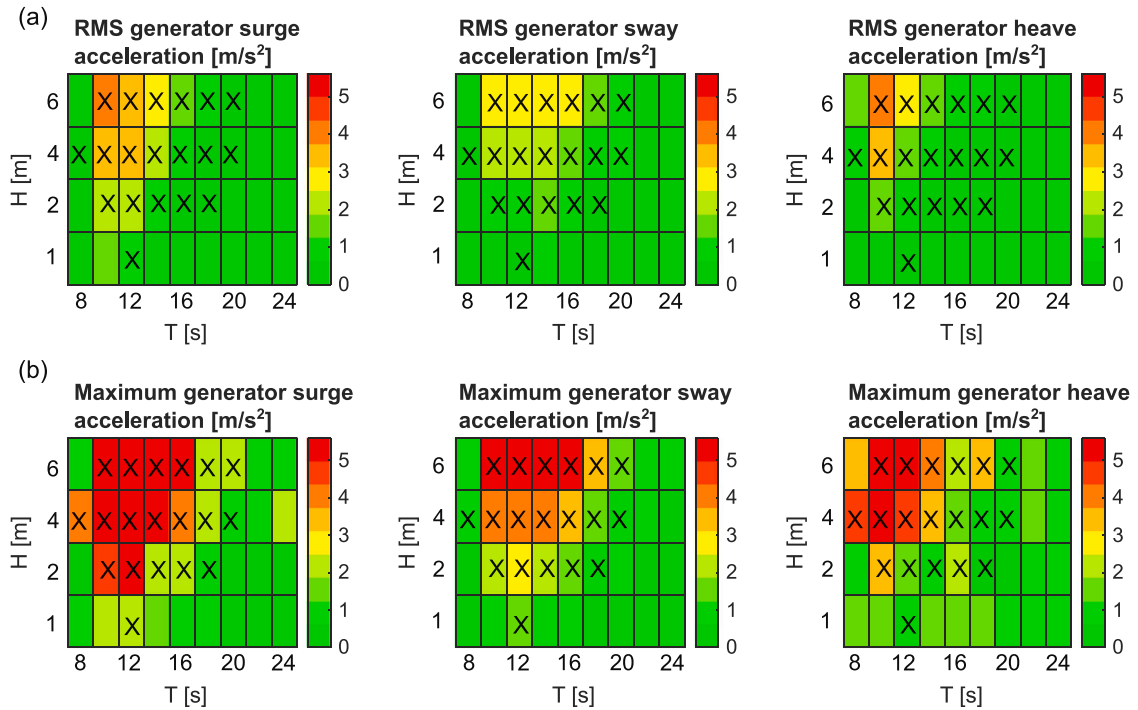


Fig. 12. Heat-maps where cases involving a collision are marked with a black cross for both the (a) RMS acceleration and the (b) absolute maximum acceleration.

- (ii) -10% for 90 s real time
- (iii) -15% for 90 s real time
- (iv) -10% for 60 s real time

2. Reducing the rate at which the crane hook was raised in Stages 1 and 2 to -10% and using the reduced boom lifting method in 1.
3. Raising both the crane boom and at the same time for the first 150 s where the rate of raising the crane boom done as in 1. and the crane hook was raised at a consistent rate of -10%. Stage 2 is considered to be the raising of the boom and crane hook together.

These scenarios were carried out for a significant wave height of 2 m and a wave period of 14 s and compared against the original method used to see if the collisions could be avoided. Fig. 13 shows the plots for the different methods compared against the original method.

In each of these alternative methods, it was found that a collision occurred as can be seen from the peaks in the acceleration and jolt plots. This indicates that the lifting method is not the primary cause of the generator collisions during the operation and that the barge motions significantly contribute to the viability of the operation.

3.5. Barge orientation

The simplest way to determine if the barge motions impact on the operation is to consider the peak to peak motions of the barge. Fig. 14 shows the barge peak to peak motions and it can be noted that particularly the surge and pitch motions closely follow the trend of the peak to peak motions of the generator. This indicates that the barge motions are significantly impacting on the motions of the generator.

It may be possible to mitigate the motions of the barge by changing its orientation so that the barge is parallel to the incoming waves. The wave length of the incoming waves, which is related to the wave period, relative to the length of the barge is a key factor in determining what wave periods cause the greatest motions in the barge. The barge is 122 m long and the wave length of the incoming waves can be calculated using linear wave theory for water waves shown in Eq. (13):

$$\lambda = \frac{g}{2\pi} T^2 \tanh\left(2\pi \frac{h}{\lambda}\right), \quad (13)$$

where λ is the wave length, T is the wave period, h is the water depth and g is the gravitational acceleration. In this simulation, the wave depth is 100 m and the gravitational acceleration is taken to be 9.81 m s^{-2} . Table 5 shows the wave length for each of the

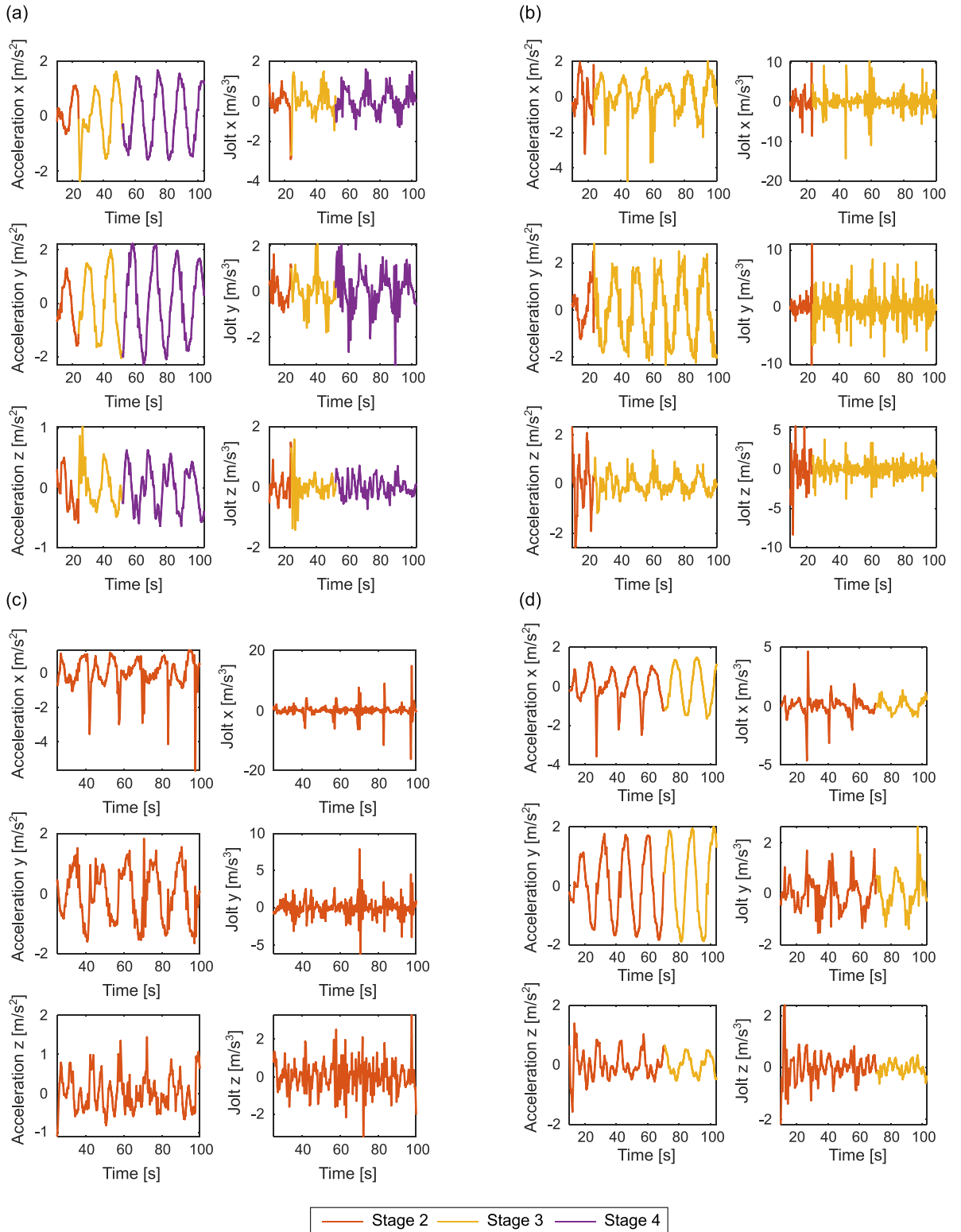


Fig. 13. Different lifting scenarios for wave height of 2 m and wave period of 14 s. (a) Method presented in Section 2.3, (b) Method 1 in Section 3.4, (c) Method 2 in Section 3.4, (d) Method 3 in Section 3.4.

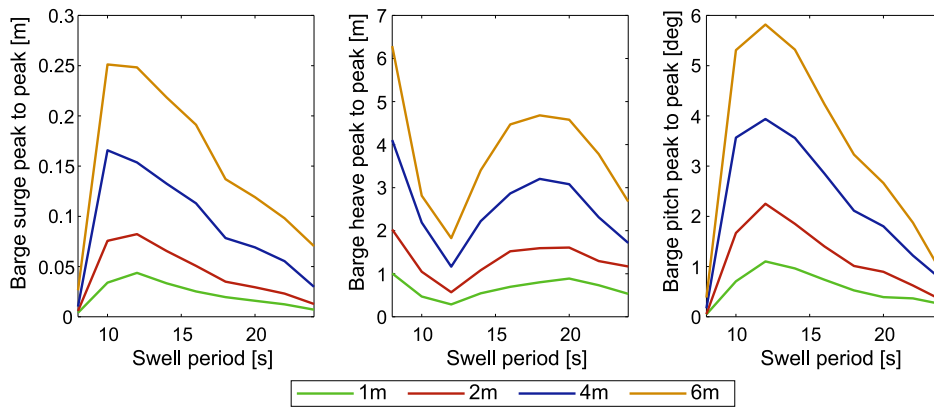


Fig. 14. Barge peak to peak motions during Stages 2 to 4 for surge, heave and pitch.

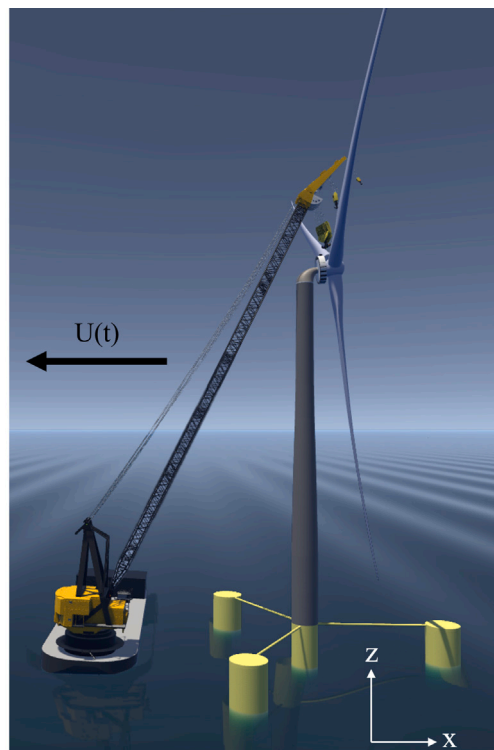


Fig. 15. Lift set up with the barge parallel to the incoming waves.

wave periods considered [43]. The wave length at a period of 12 s is around twice that of the length of the barge which is where the peak in the motions occur. Fig. 15 shows this new lifting setup which consists of the floating crane and platform, however the barge is now positioned so it is parallel to the incoming waves.

The operation was carried out up to the end of Stage 4 using the same operation parameters as presented in Section 2.3, except the real time taken for Stage 4 was reduced to 200 s. The data obtained was then used to calculate the acceleration and jolt of the generator during Stages 2 to 4 to see if any collisions occurred which are shown in Fig. 16.

Fig. 16(b) indicates that major collisions do not appear to occur during the operation which indicates that for this particular case that the change in barge orientation reduces the likelihood of a collision of the generator occurring. The generator accelerations for the two cases can be compared and are shown in Table 6.

The generator accelerations are notably lower for the surge and sway for the parallel arrangement, however the heave is higher than in the perpendicular case which is notable. It can be seen from the plots that the heave acceleration is initially higher post disconnection in the parallel case which may be an indication of increased generator heave motions just after the disconnection has occurred.

Table 5
Wave length of incoming waves for different wave periods.

Wave period [s]	Wave length [m]
8	99.8
10	155.9
12	223.0
14	267.0
16	372.8
18	447.8
20	521.2
22	593.0
24	663.4

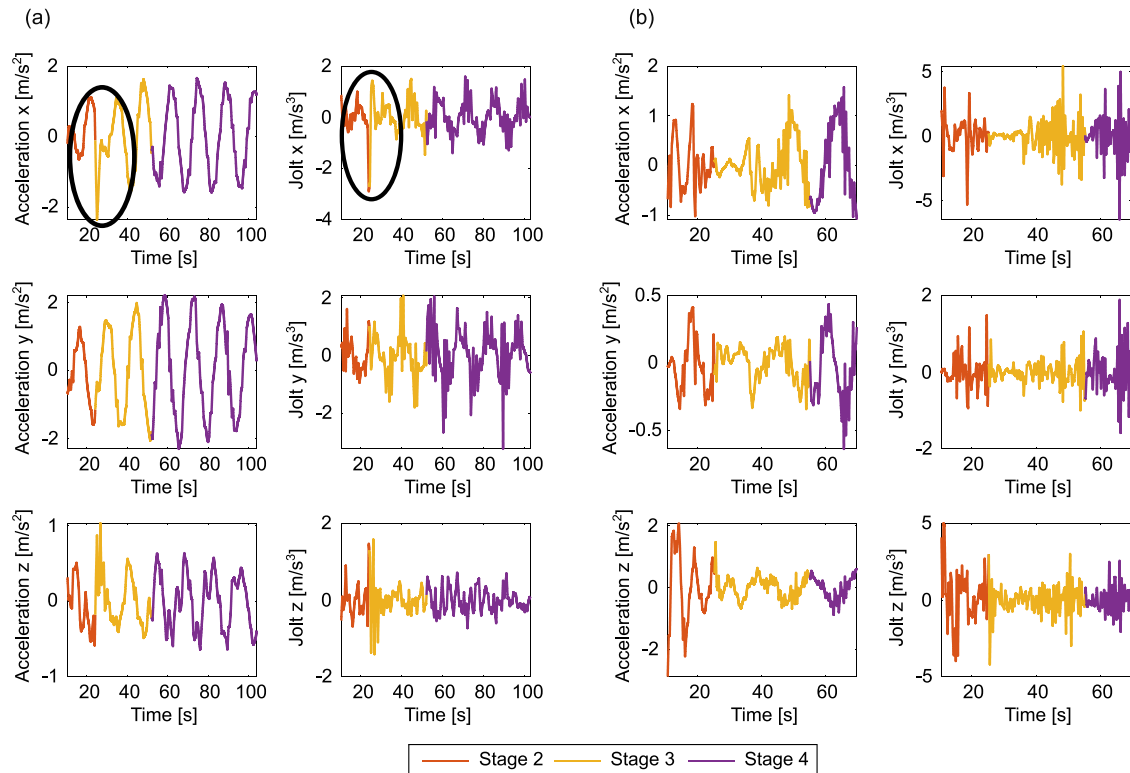


Fig. 16. Generator accelerations during stages 2 to 4 for wave height of 2 m and wave period of 12 s with the barge set up (a) perpendicular to the incoming waves and (b) parallel to the incoming waves.

Table 6

Generator accelerations for $H_s = 2$ m and $T_s = 14$ s with the floating crane perpendicular and parallel to incoming waves.

Generator acceleration [m s^{-2}]	Perpendicular			Parallel		
	Surge	Sway	Heave	Surge	Sway	Heave
RMS acceleration	0.9647	1.254	0.3357	0.5411	0.174	0.6046
Maximum acceleration	2.356	2.297	1.029	1.577	0.6351	2.871

Further tests were run for this new setup exploring a subset of wave periods for a wave height of 2 m between 10 and 18 s and a small heat-map of the generator accelerations using the same limiting parameters as in Fig. 10 that is shown in Fig. 17.

It is clear that the surge accelerations are lower than in the perpendicular case in both RMS and maximum, however the maximum heave accelerations are overall higher. There are also fewer cases where a collision is recorded when compared to the perpendicular set up which presents a benefit to this method. However, further testing would be required to determine if there were other challenges associated with this lifting method such as the rolling motions of the floating crane.

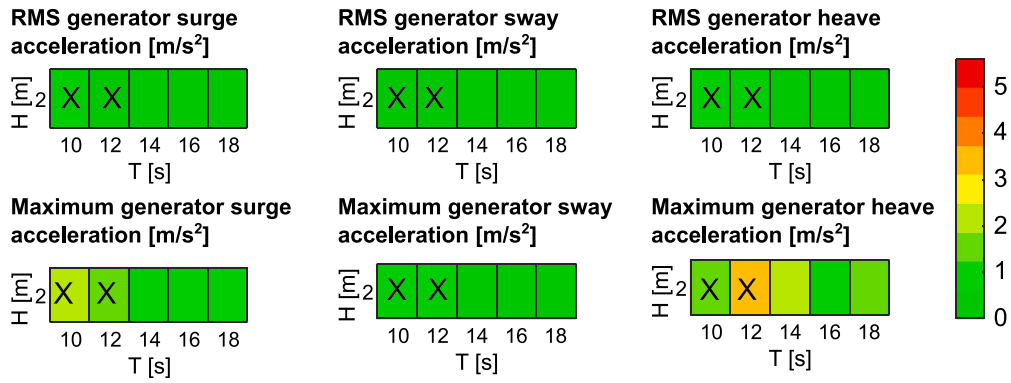


Fig. 17. Heat-maps of the generator accelerations for 2 m wave height and a subset of wave periods with the barge set up parallel to the incoming wave where (a) is the RMS and (b) is the maximum.

3.6. Operation under irregular waves

The lifting system under irregular waves is presented in this section as a means of comparison against the regular wave cases and to present some initial steps towards further study. The use of irregular waves is a better representation of the types of waves which would be present in the sea and is therefore a logical progression for the study and presents the chance to determine if there are major differences between the regular and irregular waves for the operation. The JONSWAP spectrum for irregular wave is used which is given in Eq. (14):

$$S_{JONSWAP}(f) = \alpha g^2 (2\pi)^{-4} f^{-5} \exp \left[\frac{5}{4} \left(\frac{f}{f_p} \right)^{-4} \right] \gamma^b,$$

where,

$$b = \exp \left[-\frac{1}{2} \left(\frac{\frac{f}{f_p} - 1}{\sigma} \right)^2 \right],$$

$$\sigma = \begin{cases} \sigma_a & \text{if } f \leq f_p, \\ \sigma_b & \text{if } f \geq f_p. \end{cases} \quad (14)$$

In the equation α is the Phillips constant, f_p is the peak frequency at the maximum of the spectrum, γ is the peak enhancement factor and σ_a and σ_b give the width for the left and right side of the spectral peak.

The operation and set up presented in Section 2.3 and Fig. 5 was used where six different irregular wave cases were considered, these being significant wave heights of 1 and 2 m and spectral wave periods of 12, 16 and 20 s for each wave height. Fig. 18 shows time history data obtained for the nacelle and generator with a significant wave height of 2 m and a spectral period of 12 s. It can immediately be seen that the generator and nacelle motions are not periodic due to the use of the JONSWAP spectrum. This data was then used to obtain the acceleration and jolt data for the generator where examples are shown in Fig. 19.

When considering Fig. 19 it is notable that there are no indications of collisions occurring from the jolt plots (a) and only a false sign of a collision in (b) due to the methodology for calculating the derivative of the data. This may indicate that under more realistic sea states that the operation might be easier to carry out without a generator collision occurring. However, it should be noted that a limitation in this study is that the time it takes to complete the lifting operation is significantly shorter than the time it takes for one full cycle of the JONSWAP spectrum.

4. Discussion

It was found that the accelerations the generator experienced during the lift depended on the wave period and the wave height and that, particularly when considering the maximum accelerations of the generator with a wave periods between 10 and 16 s causing the greatest challenge. However, the results presented in Fig. 11 highlight the importance of unwanted collisions during the lifting operation and shows that when this is considered the conditions in which the operation can be conducted are limited. This suggests that the generator colliding is the greatest risk during the operation. Further to this it was determined that ensuring that the lifting method was slow enough to reduce induced motions on the generator had no impact on the incidence of collisions which suggested that there was a challenge relating the motions of the barge and the floating–floating dynamics of the lift. By considering the barge peak to peak motions it was found that they followed a similar trend to the generator peak to peak motions

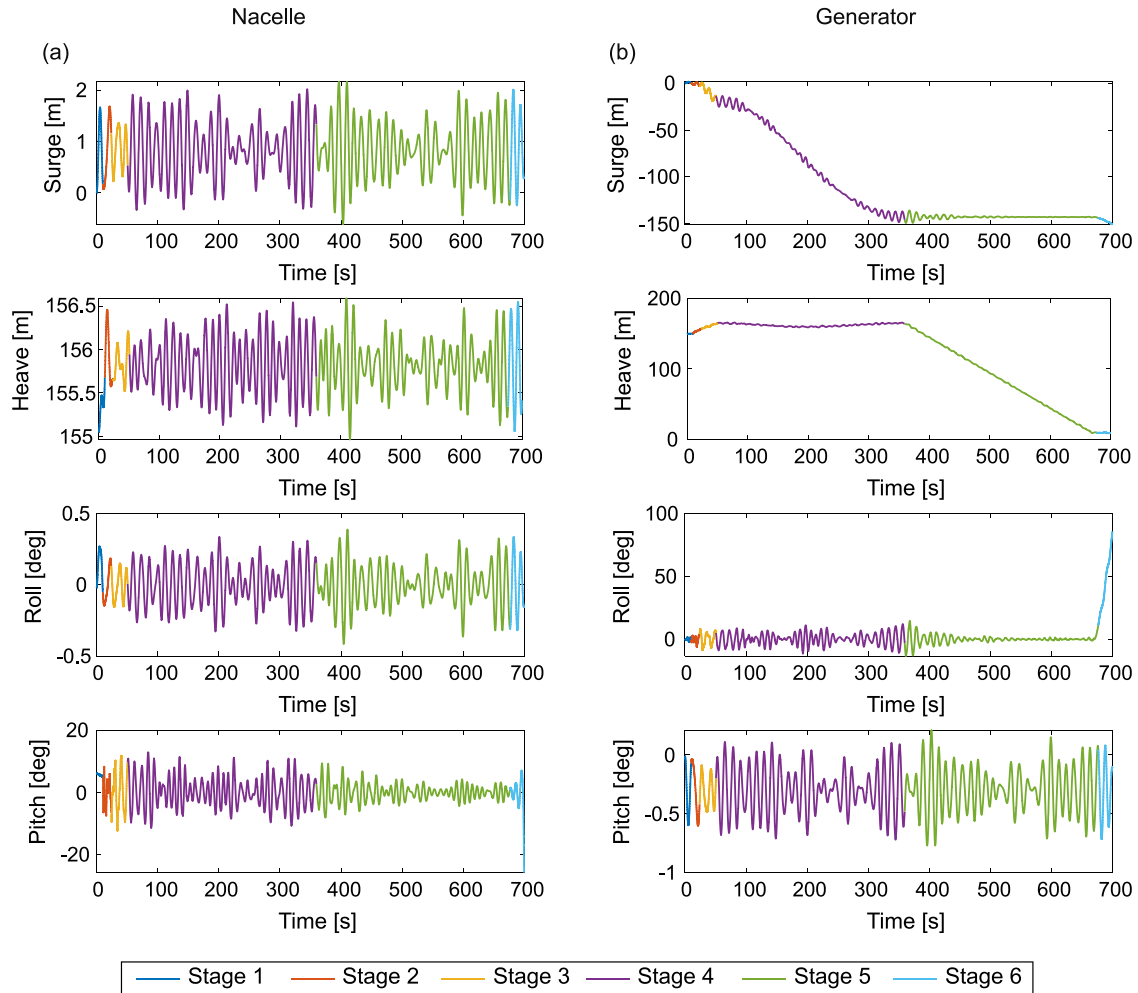


Fig. 18. Time history data for a significant wave height of 2 m and a spectral period of 12 s for (a) the nacelle and (b) the generator during the operation.

which indicates a correlation between the two. This backs up claims that the relative motions between the lifting vessel and the FOWT can present challenges to the successful completion of the operation and that this can limit the sea states in which an operation can be safely conducted. As well as considering regular waves, a selection of cases where the operation was carried out with a JONSWAP spectrum were also considered. It was found with these cases that the incidence of collision was different to the regular wave case for the significant wave heights and spectral periods selected which indicated that by using a more realistic wave spectra will likely change the incidence of generator collisions.

The orientation of the barge was also considered by running a smaller set of wave periods for a wave height of 2 m with the barge parallel to the incoming waves to see if this reduced the incidence of unwanted collisions by the generator. It was found for this subset of scenarios that the generator accelerations appeared to be lower for the surge and sway motions but were higher for the heave motions than when the crane was set up perpendicular to the incoming waves. It was also found that fewer collisions occurred with this method but did not eliminate them entirely. This could be due to collisions being induced by the rolling motions of the floating crane while parallel to the incoming waves and would therefore mean that considerations to the direction of incoming waves would be required for a successful operation to be conducted. It also suggests that performing in-situ maintenance in sea states with a wave height above 1 m can present significant challenges for accessibility and would need to be factored into such a strategy. The choice of vessel will have an impact on the success rate of the operation, since a vessel which has more favourable motions for a wider range of sea states could in principle be more capable of performing the operation without collisions or the generator experiencing high accelerations.

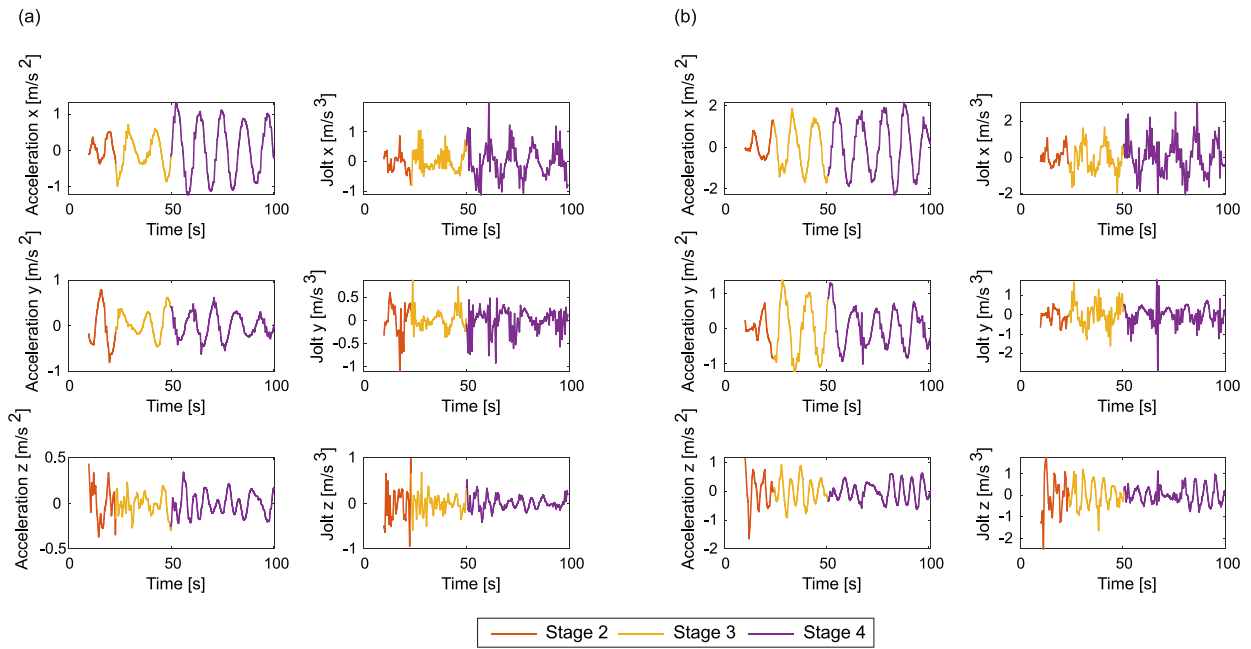


Fig. 19. Acceleration and jolt plots for the generator during operations with a spectral period of 12 s and a significant wave height of (a) 1 m and (b) 2 m.

5. Conclusions

In this study the feasibility of using a floating crane to replace the generator of a floating wind turbine was considered where the dynamics of the generator, nacelle and barge were analysed during the different stages of the operation for a range of different sea states. The peak to peak motions of the generator, nacelle and barge as well as the generator accelerations were the core metrics used to help determine this. Further to this by considering the generator accelerations and jolts the incidence of collisions between the generator and the blades, hub and tower of the FOWT could be detected. The following conclusions can be drawn from this study:

1. The incidence of generator collisions was the greatest risk factor for the failure of the lifting operation occurring. With the crane barge orientated so it was perpendicular to the incoming waves, it was found that generator collisions occurred for several different sea states for all the wave heights explored particularly for wave periods between 10 and 18 s. This indicates that the operation is severely limited by the sea state. Changing the lifting methodology was found to have no impact on the incidence of collisions during the lift which shows the motions of the generator during the operation were most important for the for one case with a recorded impact, and changing the barge orientation was found to slightly reduce the incidence of impacts for a wave height of 2 m.
2. Although the accelerations of the generator during the operation were not the main limiting factor, it was found that the maximum accelerations experienced by the generator exceeded the proposed limit of 5 m s^{-2} . This indicates a further limit on the operation even if the generator did not experience collisions.
3. Overall, the removal of the generator by the floating crane was possible for some sea states, particularly for a wave height of 1 m, however it was found that the motions of the barge were an important factor for the motions of the generator during the operation. The sea states for which collisions and high accelerations occurred corresponded to the barge having high surge and pitch responses which would impart this motion onto the generator. This indicates the choice of vessel and appropriate measures to mitigate these motions would be required to reduce the motions which could contribute the lower accelerations and a lower incidence of generator collisions.

Further study

The work presented here can further be expanded by considering the lifting operation with the floating crane set up parallel to the incoming waves and performing an in depth analysis on these cases. Modelling a fully calibrated mooring system for the FOWT could also be conducted which would increase the realism of the system. More work on the collision detection system could also be completed to allow for easier detection of generator collisions from the acceleration and jolt time histories and an automated system. In this study the use of irregular waves, specifically a JONSWAP spectrum was not covered in full depth and this would

constitute a major study to determine feasibility under more realistic conditions along with an improved collision detection system that will also consider specific nacelle design constraints. The effects of wind on the operation could also be considered. Different in-situ lifting techniques could be considered such as using add-on cranes which attach directly to the FOWT which removes the floating–floating dynamics involved with a floating crane. Finally, further controls on the lift and means of restricting the barge motions could be considered during the lifting operation to try to mitigate motions imparted onto the generator. A more realistic nacelle design could also be implemented to the model which would allow for collision detection on the main body of the nacelle where the generator is housed. Passive heave compensation techniques could also be considered to help reduce the motions of the floating crane.

CRedit authorship contribution statement

Alastair Ramsay: Writing – original draft, Visualization, Validation, Methodology, Investigation, Formal analysis. **Vahid Vaziri:** Writing – review & editing, Visualization, Supervision, Methodology, Investigation, Conceptualization. **Sean Snee:** Writing – review & editing, Supervision, Resources, Conceptualization. **Marcin Kapitaniak:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work has been funded by the National Decommissioning Centre, School of Engineering and Offshore Renewable Energy Catapult [Grant number: A18646]. This work has also benefited from the support and funding received from Net Zero Technology Centre and the University of Aberdeen, United Kingdom through their partnership in the National Decommissioning Centre (NDC) and the Scottish Government's Decommissioning Challenge Fund in part-funding the establishment of the marine simulator research facility at the NDC.

Data availability

Data will be made available on request.

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