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Numerical Study of a Novel Procedure for Installing the Tower and Rotor Nacelle Assembly of Offshore Wind Turbines based on the Inverted Pendulum Principle

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Abstract: Current installation costs of offshore wind turbines (OWTs) are high and profit margins in the offshore wind energy sector are low, it is thus necessary to develop installation methods that are more efficient and practical. This paper presents a numerical study (based on a global response analysis of marine operations) of a novel procedure for installing the tower and rotor nacelle assemblies (RNAs) on bottom-fixed foundations of OWTs. The installation procedure is based on the inverted pendulum principle. A cargo barge is used to transport the OWT assembly in a horizontal position to the site, and a medium-size heavy lift vessel (HLV) is then employed to lift and up-end the OWT assembly using a special upending frame. The main advantage of this novel procedure is that the need for a huge HLV (in terms of lifting height and capacity) is eliminated. This novel method requires that the cargo barge is in the leeward side of the HLV (which can be positioned with the best heading) during the entire installation. This is to benefit from shielding effects of the HLV on the motions of the cargo barge, so the foundations need to be installed with a specific heading based on wave direction statistics of the site and a typical installation season. Following a systematic approach based on numerical simulations of actual operations, potential critical installation activities, corresponding critical events, and limiting (response) parameters are identified. In addition, operational limits for some of the limiting parameters are established in terms of allowable limits of sea states. Following a preliminary assessment of these operational limits, the duration of the entire operation, the equipment used, and weather- and water depth-sensitivity, this novel procedure is demonstrated to be viable.
Keywords: offshore wind turbine installation, crane vessel, shielding effects, critical events, limiting parameters, inverted pendulum, allowable sea states.

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1 Introduction

The process of installing an offshore wine farm is an important phase in its life-cycle. The most commonly used foundations are currently monopiles (MPs), tripods, and jackets. However, as the water-depth and size of the turbine and tower increase, large specialized floating and jack-up crane vessels (in terms of height and load capacity) are required for the installation. Since the cost of the installation phase is significant (corresponding to approximately 20% of the total capital expenditure (CAPEX) (Moné et al., 2013)), and the profit margins in the wind energy sector are low, it would thus be beneficial to reduce these costs by improving current installation procedures and developing more efficient methods.

Currently, the “split” installation procedure, as presented by Wang and Bai (2010), is mostly used to install the tower turbine components separately and in sequence. Operations are executed using jack-up crane vessels that have an allowable limit between 1.2 and 1.5 m of significant wave height (H_s) when moving into a location (Thomsen, 2014). These limits have been established based on industry experience and have not yet been derived systematically.

New vessels concepts and procedures for installation of a fully integrated offshore wind turbine (OWT) tower and rotor nacelle assembly (RNA) have also been proposed. A single-lift procedure using a huge heavy-lift vessel (HLV) was applied when installing a demonstration wind turbine tower assembly in the Beatrice offshore wind farm (Scaldis, 2016). However, this installation method was found to be challenging and unattractive (Sarkar, 2013). Huisman Equipment B.V. (2015) proposed a twin-hull installation vessel that requires an active heave compensation system to place the tower on the foundation, but this vessel concept has not yet been built. In addition, Seok (2013) proposed a modified jack-up vessel with an opening in the deck for the OWT foundation to be moved into. A frame on the deck allows for the vertical positioning of the OWT and for lowering it onto the foundation; however, this vessel has not yet been manufactured. Another novel installation procedure for a fully integrated OWT tower and monopile foundation was proposed by Sarkar and Gudmestad (2013a). However, this method requires OWT tower modifications, use of a telescopic tower, and a patented system

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to keep the blades out of the water during transportation. The authors claim that this installation procedure can be applied for significant wave heights up to 2.5 m. Wåsjø et al. (2013) proposed a concept of a self-installing fully integrated tower, RNA, and a gravity-based foundation (GBF), where the assembly is transported on two cargo barges and then installed using a controlled lowering process. In addition, Jin and Jo (2014) suggested using a stabilizing frame to constrain the pendulum motions of a tower assembly when it is lifted from a cargo barge and transported vertically. Furthermore, Graham (2010) developed a method for installing a tower assembly and foundation that uses a cargo barge to transport the OWT in a horizontal position to the site. The tower is then partially upended using hydraulic systems located on the deck of the cargo barge, and mating then occurs between the foundation and the supports located on the seabed. The barge is subsequently pulled backward from the stern (using winches and an anchor point on the seabed) until the OWT tower is in an upright position and secured with a clamping device. However, this procedure has not yet been demonstrated to be feasible.

To show that an installation procedure is feasible, model tests or numerical analyses of "actual" installation activities are required, and very little information has been published to date in this respect. Actual operations are mainly non-stationary and have non-linear features; they are therefore difficult to model. However, numerical analyses and model tests have been conducted to assess the feasibility of the GBF and OWT assembly installation mentioned above (Bense, 2014). A time domain (TD) simulation of the lift-off and lowering operations for a single lift of an OWT tower and RNA (using a floating HLV) was performed by Ku and Roh (2015), where several assumptions were implemented due to its complexity.

This short literature review presented here shows that few alternative concepts and procedures have been proposed for installing OWT assemblies. In addition, novel solutions require new vessels and procedures, for which very limited information regarding feasibility or numerical analyses of actual operations have been published. Moreover, the origin of operational limits in terms of allowable sea states is often not clear. Thus, it is necessary to develop alternative OWT installation methods that preferably use well-known offshore installation procedures, available installation vessels, and limited modifications of current foundation and tower designs. In addition, the operational limits need to be derived systematically for response parameters that limit operations, and these should be assessed using numerical simulations of the actual (non-stationary) activities of the entire operation.

In this paper, a novel installation procedure for an OWT tower and RNA is firstly developed. A general and systematic procedure for assessing operational limits is then introduced. Numerical methods and models are presented for analyzing real (non-stationary) operations, and an assessment of dynamic responses is subsequently conducted. Operational limits are then established for the various installation activities; these limits serve as the basis for a preliminary assessment of the feasibility of the developed installation procedure. Finally, conclusions and recommendations of this work are provided.

2 System Components and Installation Procedure

The system components, installation procedure, required modifications of the structures, and other practical issues are detailed in this section.

Table 1. Installation activities and necessary operations

Activity	Description	Operations	Estimated duration (hours)
1	Mooring the barge	Mooring the barge to the foundation and seabed, and adjusting the stern beams	4
2	Mooring the HLV	Mooring HLV to the seabed	8
3	Monitor motion responses	Monitor *Hs*, *Tp*, and upending frame bottom pin motions	0.5
4	Rigging connection	Connect slings to the pad-eyes	0.5
5	Lift-off	Lift tower from the barge, clearance of the bow support	0.1
6	Mating of upending frame	Align lifting point lift the tower, clearance of the barge stern support	0.2
7	Upending	Lift the tower, align lifting points, move HLV forward	0.5
8	Tower landing	Avoid crane tip interference, lock the upending frame, cut sea-fastenings, lower hydraulic jacks	1
9	Completion	Bolt flanges, remove upending frame	1

Figures 1 to 4 show the main system components; the main particulars of these components are provided in detail in Section 4. A medium-size HLV with a lifting capacity of approximately 1000 tons is required for installing the National Renewable Energy Laboratory (NREL) 5-MW OWT tower and RNA. This assembly is conveniently referred to as "tower" in the following text. A medium-size cargo barge is required to transport each tower with its removable upending frame that has two gripper devices located at its top and bottom; see Fig. 2. The main purpose of this upending frame is to transfer the moments and forces from the tower to supports on the foundation, and to provide support for the hydraulic jacks used to set the tower down in the final upending phase. The lifting point on the tower (including the upending frame), must be above its center of gravity (COG), and should be approximately 60 m (measured from the bottom of the upending frame), but it will vary in length depending on the final construction mass. Figure 4 (detail V) shows a typical pinned connection between the upending frame and the foundation. As shown in Fig. 1, the fender system provided for the cargo barge is similar to the one currently used in well-known float-over operations (Edelson et al., 2008 and Tahar et al., 2006). Finally, Fig. 1 (detail X) and Fig. 5 (detail W) show a locking guide required to secure the upending frame.

A summary of the sequential installation activities, necessary operations, and the estimated duration of their execution is given in Table 1, where it can be observed that the total installation time can be less than 16 hours. However, this time can be further reduced if a DP vessel is employed, because the mooring activity for the HLV is not required. The installation time using jack-up vessels is approximately 3 days (Herman, 2002), and such vessels can normally operate in water depths between 30 and 60 m (El-Reedy, 2012). Therefore, this novel installation procedure can offer an attractive installation time. In addition, the proposed method is not water-depth sensitive because it employs a floating HLV.

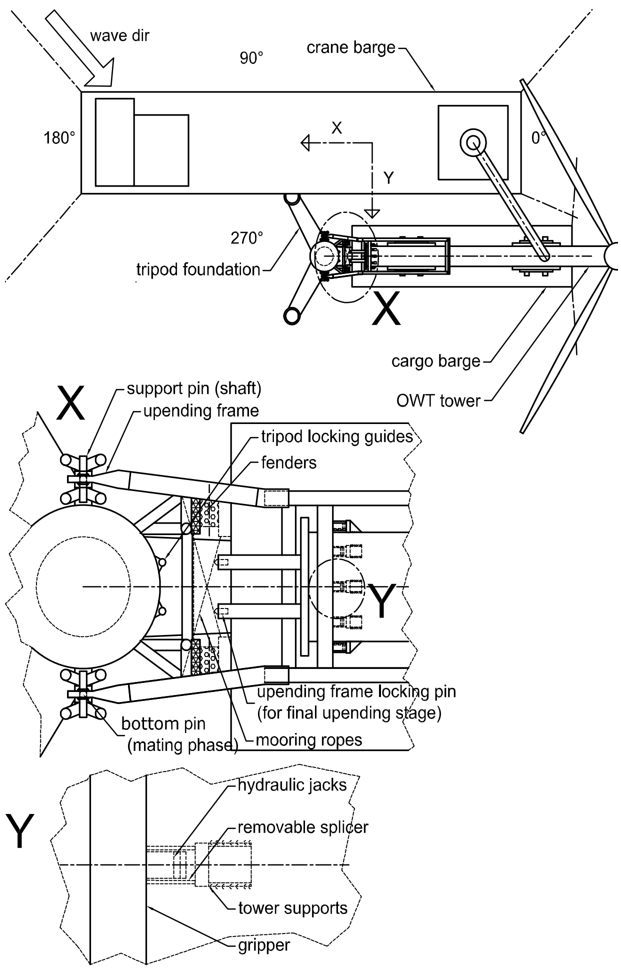

Fig. 1 Configuration of pre-lift system (top view)

2.1 Mooring Cargo Barge and Crane Vessel

The cargo barge loaded with the fully assembled tower arrives at the site. It is important that the blades do not experience wave impact during transit of the tower to the field.

The positioning of the cargo barge and its alignment can be conducted using tug boats, after which, beams located at the stern of the cargo barge are adjusted to the tidal elevation (as explained below) and moored to the fender system of the foundation; see Figs. 1 and 2. Additionally, the bow of the barge has to be moored to the seabed.

Adjustable beams are used to align the upending frame bottom pins and to make corrections for changes in tidal variation. Figure 3 shows a possible geometric configuration occurring during this operation. Based on a maximum reference tidal elevation, the vertical distance between the hinged support on the deck of the barge and the support on the tripod is d_{z1}. The sagitta in this condition is,

$$h_1 = r_1\left[1-\cos(\Omega_1)\right] \tag{1}$$

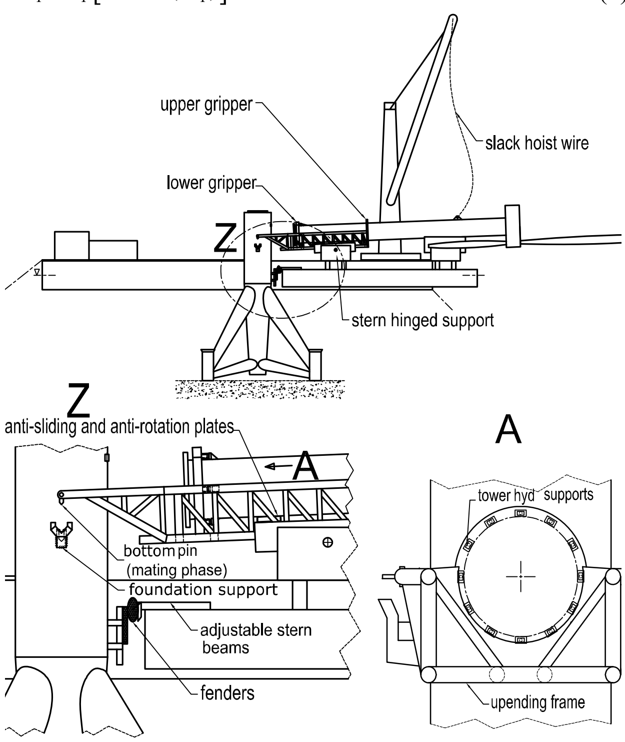

Fig. 2 Configuration of pre-lift system (side view)

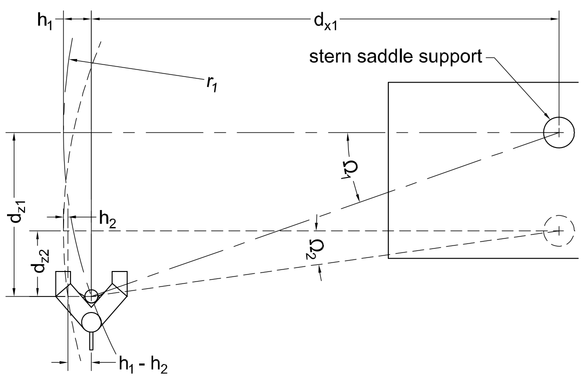

Fig. 3 Correction distance of stern beams due to tidal variation

For a new d_{z2}, by keeping the radius r_1 constant, Ω_2 and h_2 can be calculated. The difference $h_1 - h_2$ provides the distance that needs to be corrected to avoid geometrical interference during the subsequent mating operation. During this phase, enough clearance between the upending frame bottom pins and the supports on the foundations has to be guaranteed. This operation can be executed before the HLV arrives at the site.

The HLV is positioned parallel to the cargo barge (to shield the cargo barge from the incoming waves) and the lifting points in the crane and tower are aligned; see Figs. 1 and 2. If the HLV is moored to the seabed using the thruster assisted positioning mooring system (as used for example by pipelaying vessels), the anchor lines located at the stern of the port side of the HLV may interfere with the hull or the mooring lines of the cargo barge. Thus, a mechanism is required to lower the fair-lead position of this anchor point. Moreover, pre-installation of the mooring lines of this anchor point is recommended so that they can be picked up by the crane of the HLV and then be connected to the winch for adjustment to the required parameters. Alternatively, the HLV can be moored first prior to the cargo barge. If the HLV uses a dynamic positioning (DP) system, mooring line interference can be avoided and the procedure presented above will not be required.

2.2 Monitoring Motions of Upending Frame Bottom Pins

In this phase, the motions of the pins shown in Fig. 2 (detail Z) are monitored. The motion responses, together with the sea state parameters, such as significant wave height (H_s) and wave peak period (T_p), can be compared with operational limits given in the installation manual, and it can be decided whether or not to initiate the lifting operation.

2.3 Rigging Connection

If it is considered that operations should begin, then the lifting points are connected with the hoist wire in a slack condition; see Fig. 2. It is essential that enough slack is present in the wire, to avoid any snap load occurring during this activity. The lifting points should be aligned to minimize any horizontal load that may be transferred to the foundation and the station keeping system during the subsequent operation. An automatic release system is thus needed to disconnect the slings when the installation is finished.

2.4 Lifting-off the Tower

The tower is lifted from the cargo barge using a winch with a low and constant speed. The winch stops working when enough clearance (to avoid underneath strikes) is obtained between the underside of the tower and the saddle-support on the bow of the barge. Figure 4 (a) shows the loading condition reached after the lift-off process is finished. Note that the tower rotates around the hinged saddle-support located at the stern of the cargo barge. This hinged support has stopper plates that prevent the tower from rolling and sliding during this operation; see Fig. 2 (detail Z). No contact between the upending frame and the supports on the foundation has yet occurred. The tower is in an almost-horizontal condition, and therefore maximum mean tension in the hoist wires occurs in this phase. This operation requires the crane operator to provide periodic information pertaining to total tension readings.

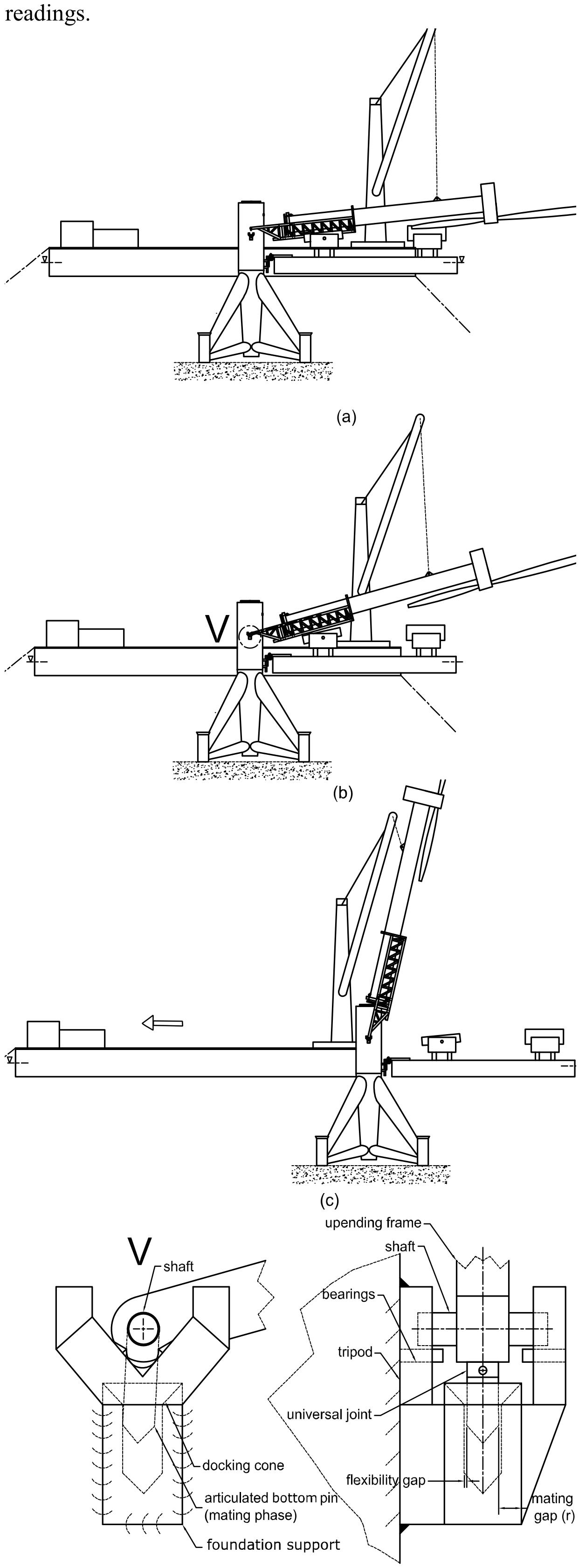

Fig. 4 Tower lifting and upending: (a) lift-off; (b) mating; (c) upending

2.5 Mating between the Upending Frame and the Supports on the Tripod

The HLV is moved forward until the crane tip is aligned with the lifting point on the tower. If the HLV has DP capabilities, it needs to be set to the line-tracking operational mode, also known as "dynamic tracking," when the ship follows a line or path. Alternatively, if a dynamic mooring system is employed, a combination of thrusters and mooring line winches are required to gradually move the vessel (this is a well-known technique used with pipe-laying vessels in shallow water). The tower is then further lifted so that the upending frame bottom pins mate with the foundation supports. Figure 4 (detail V) shows the typical construction when upending frame bottom pins are inside the docking cone of the foundation support. It shows that a bearing enables rotation of the upending frame, and a flexibility gap enables an amount of flexibility in the connection (this is discussed in the next subsection). The winch stops when enough clearance between the hinged saddle-support at the stern of the cargo barge and the underside of the tower has been reached; see Fig. 4 (b). The cargo barge is then moved to a safer location to avoid any interference.

2.6 Tower Upending

The lifting process continues until the tower is standing in an upright position on the foundation supports; see Figs. 4 (c) and 5 (a). During this operation, the HLV is moved forward in small increments, while maintaining alignment of the lifting points. At the final upending stage, a locking system is required at the contact points between the upending frame and the tripod to avoid any receding motion of the tower; see Fig. 5 (detail W). The hoist wire can then be set in a slack condition. The HLV stays in that position until the tower has been lowered and fastened to the foundation. It is necessary that the total tension in the hoist wires should be decreased to the minimum, while the forces on the foundation supports increase to their maximum values. To give an idea of the sizes, two shafts with diameters of 0.2 m are required for a typical mild steel with a shear strength of 115 MPa, a safety factor of 2, and the assumption of pure shear stresses; see Fig. 4 (detail V). A factor of 2 is assumed to account for dynamic effects occurring during the final upending phase. In addition, it is preferable to place the foundation supports and the upending frame bottom pins at an offset from the center-line of the foundation and the tower. This is to counteract the overturning moment exerted by the blades and hub when the tower is in an upright position.

The upending process requires that two simultaneous operations are conducted: lifting the tower while moving the HLV forward. This is a step-by-step procedure in which corrections of the crane-tip position are required as the lift progresses; coordination and communication between personnel in the winch room or on the DP console, the crane operator, and personnel on deck are thus required. The crane tip must be vertically aligned with the tower lifting point; this position is only not completely necessary during the final upending stage, when the total hoist wire tensions are small. This is because interference between the crane boom and tower needs to be avoided, and a horizontal tension to pull the tower to the final position is required; see Fig. 4 (c). Although the mean vertical-tension component in the hoist wire decreases to a theoretical value of zero, it may be necessary to maintain a pre-tension and avoid snap loads due to crane tip motions. The pinned connection on the foundation supports can experience large reaction forces due to a short-lifting wire and the motions of the crane tip. Additionally, the inclination of the tower in the final upending stage can be large, and thus it is necessary to control the flexibility gap (shown in Fig. 4 (detail V)). This can be assessed from a detailed structural analysis of the system under a characteristic force.

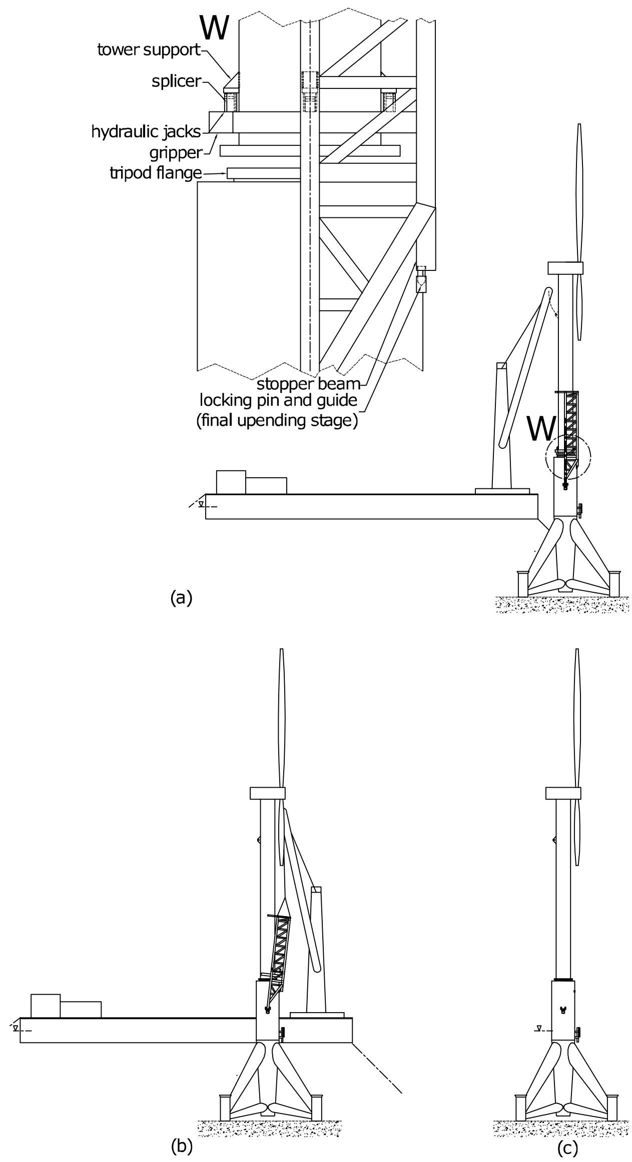

Fig. 5 Final upending and completion work: (a) locking upending frame; (b) removing frame; (c) installed tower

2.7 Tower Set-down or Landing

The hydraulic jacks shown in Fig. 1 (detail Y) and Fig. 5 (detail W) are first extended to carry the weight of the tower. The splicers are then removed and the anti-rotation and anti-sliding plates (sliding-guide type) are cut; see Figure 2, (detail Z). The jacks are slowly lowered until the bottom flange rests on the one of the transition piece (TP) or on the foundation. It is suggested that extra pins and guides are provided inside the tower and TP, respectively, during this operation, to guarantee that the bolted connections are perfectly matched and to correct any misalignment. It is of note that six hydraulic jacks are normally required for TP leveling onto a MP foundation with a total mass of 200 tons; it is thus suggested than between 20 and 25 jacks will probably be needed to lift the tower (depending on their capacity). This operation requires coordination between personnel controlling the jacking procedure and the hydraulic pressure supply.

2.8 Upending Frame-Removal and Completion Work

The OWT tower is bolted to the flange of the TP, the gripper devices are opened, and the upending frame is removed and placed on the cargo barge (this will be used to install the next tower structure); see Fig. 5 (b,c). The cargo barge then returns to the port and the HLV moves to the next location where another cargo barge is waiting.

2.9 Potential Critical Events Occurring during Installation Activities

Critical events are incidents that could cause structural system failure or personnel injury as a consequence of unacceptable structural responses. These events can occur during the execution of installation activities. Potential critical installation events are identified using a root cause analysis tree; see Fig. 6, and the corresponding activities are listed in Table 2.

A brief description of activities in which potential critical events may occur is given below:

• *Lift-off* activity can be considered critical because the tower is in an almost-horizontal position and the hoist wires take most of the weight of the tower. Therefore, snap loads in the hoist wires can occur during initial load transfer. The consequences of possible structural hoist wire breakage or crane boom failure are catastrophic; therefore, the probability of this event occurring needs to be minimal to ensure adequate safety margins.

• *Mating* between the upending frame bottom pins and the foundation supports can be another critical activity. Critical associated events would be any local structural damage occurring to the docking elements, or a failed mating attempt. In the initial mating phase, both, the mating pin motions and velocities need to remain within acceptable limits (otherwise the mating operation will not be successful). Although this installation activity may not lead to human injury or major structural issues (except local impact damages), excessive motions mean that the mating phase cannot be conducted. The upending of the tower can be a critical activity because it involves simultaneous operations, such as lifting and moving the HLV forward. It is thus a complex task for personnel offshore to conduct, especially when applying such procedures for the first time. Potential consequences of communication and coordination failure (human errors) may lead to events such as loss of crane vessel position. An observer is therefore required to continuously monitor the alignment between lifting points and to communicate this information to the crane, winch, and thruster operators.

• *The final stage of the upending phase* can be critical. The lifting wire shortens during this procedure, and if there is not adequate flexibility in the connections between the upending frame and the foundation supports, large reaction forces can occur and subsequent hoist wire breakage.

Table 2 shows a summary of potential critical operations and corresponding critical events, which are then analyzed numerically in Section 5 using numerical methods and models provided in Section 4.

The tower is in an almost-horizontal position during transportation and the initial installation phase. Associated potential critical events are thus leakage of hydraulic and lubricant fluids and structural damage of supports. However, these events are not covered by this paper, and thus, transportation of the tower in this position is assumed to be feasible.

Table 2. Potential critical installation activities and corresponding events

Activity	Description	Critical events
1	Tower lift-off	Hoist wire breakage
2	Upending frame mating	Structural damage of foundation supports and failed mating attempt
3	Tower upending	Structural failure of foundation supports, hoist wire breakage, and unacceptable tower inclination

3 Methodology for Assessing Operational Limits

In general, the execution of a marine operation (such as lift-off) depends on the allowable tension (including safety factors) of the rigging system. The parameter of tension is suitable for assesing mitigating actions that can be taken during execution of the operation when tension reaches its allowable limit. However, for on-board decision-making "prior" to execution of the operation, tension does not exist and can thus not be measured. Therefore, the decision whether to start the operation or not, relies on other parameters that can be monitored on-board vessels. Such parameters can be sea state parameters or vessel responses in a monitoring loading condition prior to execution. This section discusses the methodology employed to determine operational limits in terms of allowable limits of sea states. These operational limits are baseline for the viability or feasibility of the proposed (or of any) installation procedure.

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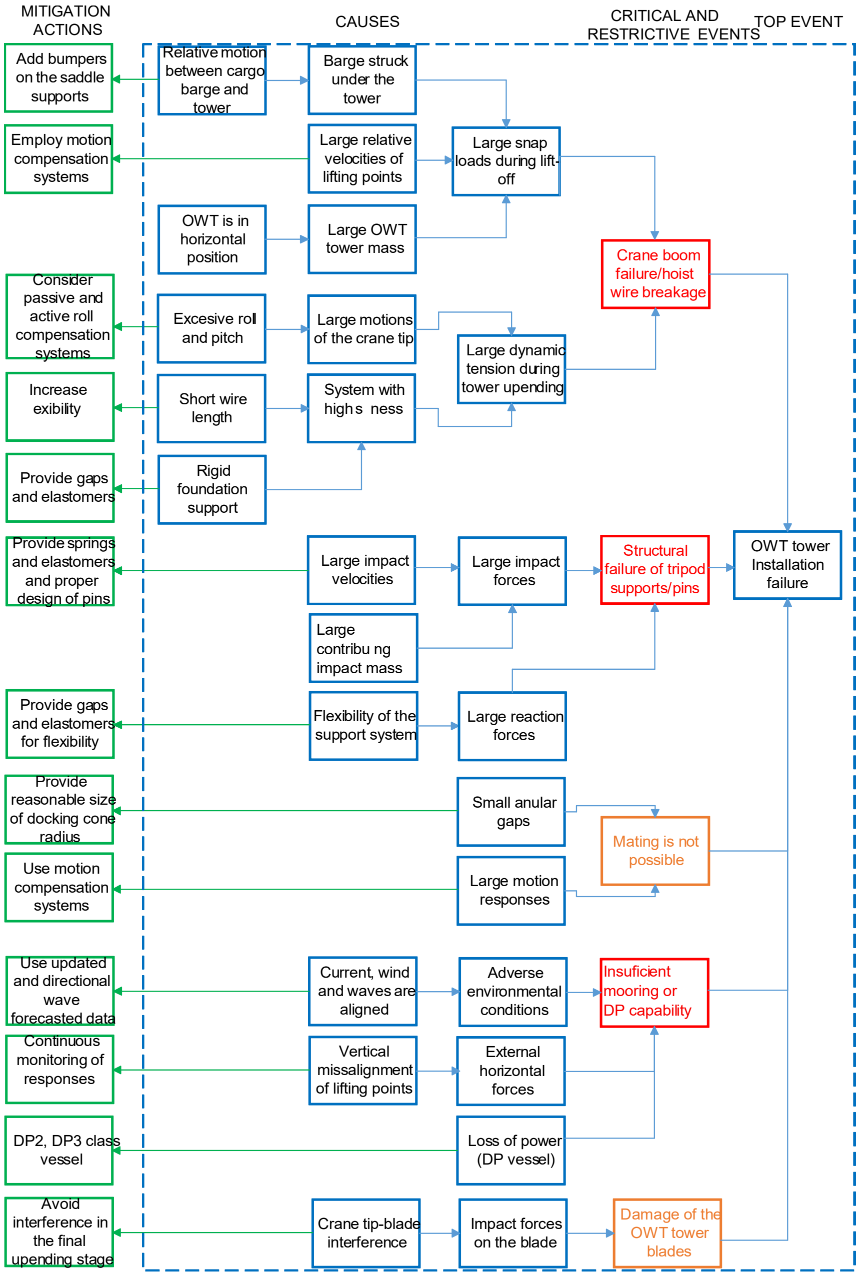

Fig. 6 Root-cause analysis tree for critical (in red) and restrictive events and for preventive measures during OWT tower and RNA installation

Guachamin Acero et al. (2016b) have developed a general methodology for establishing operational limits in terms of allowable limits of sea states or vessel responses. Li et al. (2016c) have applied that methodology to derive operational limits for monopile installation. In this study, that methodology is customized and applied to assess the operational limits of the novel OWT tower and RNA installation procedure.

Figure 7 shows the approach used to establish operational limits. Potentially critical installation activities are identified based on the installation procedure previously described. This is achieved by applying qualitative risk assessment techniques, such as root-cause diagrams; see Step 2 in Fig. 7. These activities are then selected to build coupled numerical models (Step 3, see also Section 4) and also conduct global dynamic response analyses of the system under "typical" sea states. It is important to model the actual operations by applying numerical methods; see next section. A quantitative assessment of the dynamic responses (Step 4) is conducted, and parameters that can reach dangerous levels (limiting parameters) are identified by a comparison with their allowable limits (including safety factors) (Step 5).

For the TD simulations conducted in Step 4, it is not necessary to use a large number of seeds to assess the dynamic responses, because the responses are only used for the screening of limiting (response) parameters and are not used in the assessment of operational limits.

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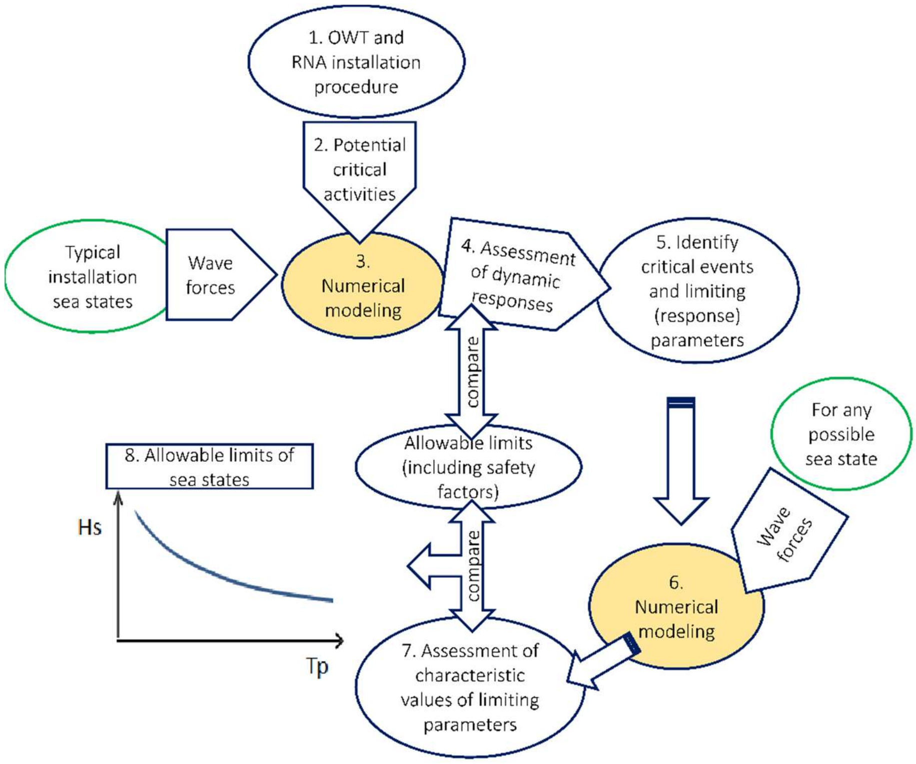

Fig. 7 General procedure used to establish operational limits

For the identified limiting parameters, corresponding dynamic coupled models (Step 6) are used to perform numerical simulations and build response statistics. These are conducted for "all" possible H_s and T_p combinations, although other environmental parameters may also be considered. The characteristic value of a limiting parameter, S_c, is selected (e.g., for a target probability of non-exceedance, P, based on extreme value distributions) (Step 7). This probability depends on the type of operation, duration, and the consequences of failure events.

For the TD simulations conducted in Step 7, a large number of seeds is usually required to achieve convergence of the response statistics, e.g., standard deviation and extremes. The characteristic values are then compared with the allowable limit (including safety factors), R_{allow}, of a limiting (response) parameter, and allowable limits of sea states are thus established (Step 8).

Equation (2) shows the condition that needs to be fulfilled for any sea state to be allowable.

$$S_c\left(H_s, T_p\right) \le R_{allow} \qquad (2)$$

For cases where equality holds, the sea state represents the operational limits of the activity. For contact-impact problems, the allowable limit of the limiting parameters should be derived based on an assessment of structural damage. This assessment is conducted via structural analysis or finite element modeling (FEM) of the structural components; see for example (Li et al., 2014a). However, for this novel OWT tower installation procedure, the structural damage criteria have not yet been considered because the structural design of components is not currently available.

4 Numerical Modeling of Installation Activities

As shown in Fig. 7 (Step 3), it is important to build numerical models to accurately analyze any potential critical OWT tower installation activities. This section discusses numerical methods, the main particulars of structures, and elastic contact models and couplings, which are necessary for the numerical modeling of installation activities and conducting a quantitative assessment of dynamic responses.

In the previous section, a preliminary screening of potential critical and restricting events was conducted. These events ocurred during tower lift-off, mating between the upending frame and the foundation supports, and upending of the OWT tower.

4.1 Main Particulars of Structures and Modeling Aspects

The main particulars of the structures are given in Tables 3-5. For the lifting operation, several hoist wire rope falls are needed. For a typical wire rope with a diameter of 60 mm, a metallic area of 2.18×10^{-3} m^2, and a minimum breaking load (MBL) of 3.5 MN (Lankhorst ropes, 2015), 8 lines will be sufficient for this installation. For a representative lifting wire length of 50 m that connects the crane tip and the lifting point on the tower, the stiffness is 7.3×10^4 kN/m. In this paper, a linear stiffness $k_{wire} = 5 \times 10^4$ kN/m that accounts for the flexibility of the wire and the crane's boom structure was applied. Hydrodynamic interaction between the diffracting structures was included to find the headings giving the best responses (in view of shielding effects).

Hamilton et al. (2008) reported some typical design values of the spring coefficients for mating receptacles used in a float-over operation (the coefficients were between 4 and 9 × 10^4 kN/m). The tripod and the upending frame were modeled as a single rigid tubular steel structure. The supports on the tripod and cargo barge were modeled using linear stiffness springs and dampers. The stiffness chosen for each contact element is k_{con} = 7 × 10^4 kN/m. In consideration of the fact that the suports include elastomers to absorb impact loads, the damping coefficient was set as $b_{con} = 0.1b_{cr}$, where b_{cr} stands for critical damping.

Table 3. Main particulars of the HLV

Parameter	Notation	Value	Units
Displacement	∇	2.55 × 10^4	Tons
Length	L	140	m
Breadth	B	30	m
Draught	T	6	m
Metacentric height	GM	7.5	m
Vertical position of COG above keel	VCG	8	m

Table 4. Main particulars of the cargo barge

Parameter	Notation	Value	Units
Displacement	∇	5.09 × 10^3	Tons
Length	L	69	m
Breadth	B	18	m
Draught	T	4	m
Metacentric height	GM	3.75	m
Vertical position of COG above keel	VCG	5.0	m

Table 5. Main particulars of the NREL 5-MW OWT
(Jonkman et al., 2009)

Parameter	Notation	Value	Units
Tower mass	M_{tower}	348	Tons
Nacelle mass	$M_{nacelle}$	240	Tons
Blades mass	M_{blades}	110	Tons

Elastic contact models (see Fig. 10) allow the upending frame to rotate in the vertical plane and provide flexibility in the out-of-plane direction. The stern of the cargo barge was connected to the tripod by means of fenders and mooring lines, which were modeled with spring coefficients of k_{fen} = 500 kN/m and k_{rope} = 200 kN/m. All springs only work under compression loads. The numerical modeling aspects of installation activities are provided in Table 6.

4.2 Multi-body Dynamic Analysis Software

Dynamic coupled models were built in the ANSYS-AQWA suite of computer codes developed by Century Dynamics-Ansys Inc. (2011), and an example of a dynamic coupled model is shown in Fig. 8. This state-of-the-art software is widely used in the offshore industry (Oosterlaak, 2011) and is capable of representing multi-body dynamic systems, hydrodynamic interaction between diffracting structures, joints with different types of constraints (such as articulations and ball connections), mooring lines, winches for lifting operations, and fenders. Non-stationary processes, such as HLV responses when imposing a vessel's forward speed, can be modeled using winches or an external force dynamic library, which is useful when modeling DP, steering, or towing systems. Based on these features, the code is suitable for modeling the operations involved in the procedure for installing the tower.

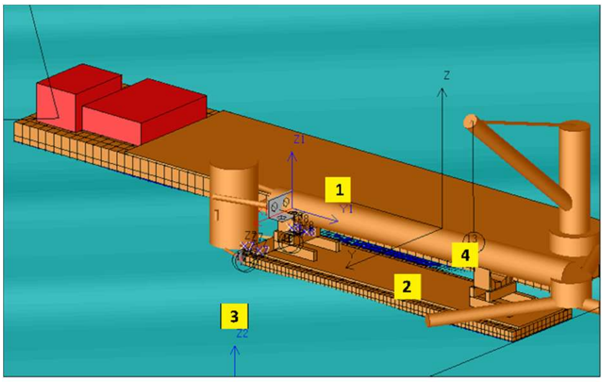

Fig. 8 Schematic outline of dynamic coupled model during tower lift-off in bow quartering seas. Structures: (1) HLV; (2) cargo barge; (3) tripod; (4) OWT tower and RNA

Table 6. Numerical modeling aspects of installation activities

Activity (Ref. to Table 2)	Start time	End Time	Modeling parameters
Tower lift-off	Hoist wire is slack	Bow saddle-support of cargo barge is cleared	Hoist winch speed = 5 m/min, duration ≤1 min
Upending frame mating	Tower lift-off is finished	Stern saddle-support of cargo barge is cleared	Hoist winch speed = 5 m/min, duration ≤1 min
Tower upending	Upending frame mating is completed	Tower in vertical position	Variable HLV forward speed ≤3 m/min, hoist winch speed = 3 m/min, duration ≤30 min

4.3 Numerical Methods

4.3.1 Frequency Domain Method

The frequency domain (FD) method is suitable for assessing the dynamic responses resulting from stationary processes and weakly non-linear systems. In the frequency domain, the equations of motion of a rigid body dynamic system can be written as follows,

$$-\omega^2\left[\boldsymbol{M}+\boldsymbol{A}(\omega)\right]\boldsymbol{X}(\omega)+i\omega\boldsymbol{B}(\omega)\boldsymbol{X}(\omega)+\boldsymbol{K}\boldsymbol{X}(\omega)=\boldsymbol{F}^{ext}(\omega) \quad ,(3)$$

where M is the multi-body structural mass matrix; A and B are the frequency dependent added mass and damping matrices (the coefficients of these matrices are normally calculated by diffraction analysis using the panel method); K is the stiffness matrix (which accounts for the hydrostatic, mooring, and coupling restoring terms); X is the vector of the motion of the system; and F^{ext} is the vector of external forces acting on the system. In this paper, only the first- and second-order wave actions are considered. The equations of motions can be solved for a response parameter under regular wave actions. The result is a transfer function or response amplitude operator (RAO), which can be used to conduct spectral analyses and assess the system dynamic responses in irregular seas.

4.3.2 Time Domain Method

The time domain (TD) method is suitable for analyzing responses resulting from non-stationary processes and non-linear systems. In the time domain, the equations of motion of a dynamic system can be written as follows,

$$\left[\boldsymbol{M}+\boldsymbol{A}^{\infty}\right]\ddot{\boldsymbol{x}}+\int_{0}^{t}\boldsymbol{h}(t-\tau)\dot{\boldsymbol{x}}(\tau)d\tau+\boldsymbol{Kx}=\boldsymbol{F}^{ext}\left(\boldsymbol{x},\dot{\boldsymbol{x}},t\right) \quad ,(4)$$

where $A\infty$ is the infinite frequency added mass matrix, x is the motion vector of the multi-body system, and the added mass and damping coefficients are incorporated in the equations of motion via the retardation function $\boldsymbol{h}$. The various coupling forces due to lifting wires and fender elements are included in the stiffness matrix, and non-linear terms are included in $\boldsymbol{F}^{ext}$. The equations of motion are solved in every time step increment by applying numerical techniques, e.g., Newmark-beta methods.

The OWT tower and RNA coupled dynamic models are basically composed of four rigid structures, as shown in Fig. 8. The tripod foundation has a fixed constraint, and therefore the system has 18 degrees of freedom (DOF). The equations of motion are solved numerically by applying the TD method, external actions are the first- and second-order wave forces, no wind and current forces are considered, and external actions (such as decisions made by operators) are not included. The TD method is applied to assess the dynamic responses occurring during OWT tower lift-off, upending frame mating, and OWT tower upending activities, which are described in the next section.

4.3.3 Method for Estimating Crossing Rate from a Circular Boundary

Guachamin Acero et al. (2015) proposed an efficient and practical method (the crossing rate method) for assessing the allowable limits of sea states during the initial mating operation. During this process, there is an installation phase where mating structures are aligned, and responses are monitored. In this phase the resulting processes are stationary and the system has time-invariant dynamic properties, so that the equations of motion of the dynamic system can be solved in the FD. The dynamic responses can then be used for assessing the crossing rates for given thresholds.

The crossing rate method is based on the number of crossings that a mating pin makes out of a circular boundary of radius r, (equivalent to the annular mating gap) in a particular time interval. For instance, an allowable limit of 1−2 crossings per minute out of an annular gap, can be used to identify corresponding responses and sea state parameters. The numerical solution for the crossing rate is obtained from spectral analyses of the mating pin stochastic responses, which can be computed by applying the FD method. This includes the first- and second-order motions of the mating pin, which are considered to be independent, and assumes that the second order motions follow a Gaussian distribution. The numerical solution is given by equation (5),

$$\nu_{SD}^{+}=\int_{x_2}E\left(\dot{x}_n\mid \boldsymbol{X}=x\right)f_{\boldsymbol{X}}\left(x_1=f\left(x_2,d\right),x_2\right)\mid J\mid dx_2 \quad , (5)$$

$$E\left(\dot{x}_n\mid \boldsymbol{X}=x\right)=\int_{0}^{\infty}\dot{x}_n f_{\dot{X}_n}\,d\dot{x}_n=\sigma_{\dot{x}_n}\exp\left[-\frac{1}{2}\left(\frac{m_{\dot{x}_n}}{\sigma_{\dot{x}_n}}\right)^2\right]+m_{\dot{x}_n}\Phi\left(\frac{m_{\dot{x}_n}}{\sigma_{\dot{x}_n}}\right) \quad , (6)$$

$$J=\frac{2r}{\left[d-\left(\frac{x_2}{r}\right)^2\right]^{0.5}} \quad . (7)$$

Equation (5) can be evaluated numerically, ν_{SD}^{+} is the outcrossing rate of a mating pin with surge (x_1) and sway (x_2) correlated stochastic responses; |J| is the Jacobian of the transformation of x_1 in the bivariate probability density function (PDF), which needs to be evaluated for d = 1 following the definition of the limit state function; r is the radius of the circle (docking cone); Φ is the Gaussian cumulative distribution function (CDF); and $\sigma_{\dot{x}n}$ & $m_{\dot{x}n}$ are the standard deviation and mean values of the normal velocities when solved for their conditional PDF. The numerical solution is applied for assessment of the allowable limits of sea states during the "initial phase of the upending frame mating activity",see Section 5.2.

4.4 Modeling of Couplings and External Forces

4.4.1 Shielding Effects from HLV on Motions of Cargo Barge

A main component of the proposed installation procedure is the wave shielding provided by the HLV on motions of the cargo barge. Figure 9 shows the wave elevation for bow quartering incoming waves with an amplitude of 1 m and a period of 7.4 s. The shielding effects are significant and make installation (using this novel procedure) possible for a wide range of headings. This is possible, because for a typical installation season and for a specific offshore field, waves will come from a mean main direction, which can be assessed using directional scatter diagrams.

The benefits of shielding effects during MP installation using floating HLVs have been studied by Li et al. (2014b).

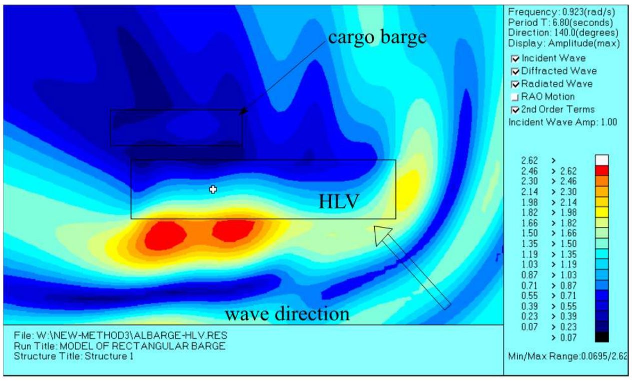

Fig. 9 Wave elevation contour plot including all wave components. Shielding of HLV on cargo barge for a heading = 141 deg

4.4.2 Tower and Cargo Barge Interaction

The cargo barge is transported to the installation site in a horizontal position. Prior to the lift-off operation, the total weight of the tower and upending frame is held by two saddle-supports on the cargo barge; see Fig. 2. These supports were modeled using springs and dampers that restrict vertical and lateral motions and rotations of the tower with respect to the cargo barge. The elastic model for the saddle supports is shown in Fig. 10 (a).

4.4.3 Upending Frame and Foundation Support Interaction

After the lift-off operation is completed, only the hinged saddle-support located at the stern is loaded. Two models were employed for the mating and upending activities. The elastic contact model shown in Fig. 10 (b) was used for the non-stationary lift-off and mating operations. This model is simply composed of a point (docking pin) that is allowed to dock into a support modeled with conically arranged fenders. A universal articulated joint was employed to connect the upending frame and the supports on the foundation, the elastic model is shown in Fig. 10 (c). A rotational spring was used to limit the roll motion of the tower and to provide some flexibility in the system. This is also necessary to reduce hoist wire tension and lateral reactions forces on the foundation supports. The spring coefficient was chosen as $k_r = 5 \times 10^9$ Nm/rad and the damping coefficient was set as $b_r = 0.1b_{cr}$. The spring coefficient was estimated by assuming that a typical 250 kN horizontal force (see Fig. 16 (e)) acts on the lifting point of the tower and causes a maximum tower deflection of 1 m, which is a reasonable value for avoiding interference between the foundation and the upending frame in the final upending stage. The damping coefficient was assumed in consideration of the foundation supports having annular elastomers or bumpers. The loading condition shown in Fig. 4 (c) was used for TD simulations of the upending operation. No rotational springs and dampers were added for pitch motions.

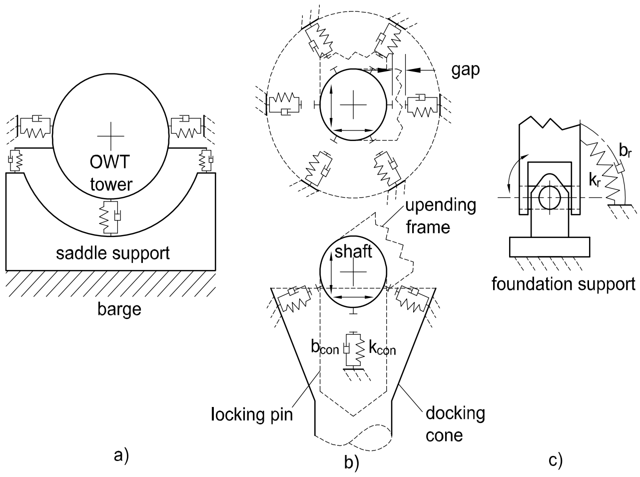

Fig. 10 Elastic contact models: (a) tower-cargo barge interaction; (b) lift-off and mating docking cone; (c) tower upending articulation

4.4.4 Connection between Upending Frame and Tower

For global dynamic analyses, the tower and the upending frame were modeled as a single rigid body because they are connected using two grippers; see Fig. 2. Note that the grippers provide a pair of supports to enable transfer of the bending moments and shear forces.

4.4.5 Forward Motion of Crane Vessel during Upending Operation

Figure 11 (a) illustrates a possible mooring arrangement for the HLV, while Fig. 11 (b) shows the model used in numerical analyses. In the numerical model, a winch located at the bow of the HLV was used to pull-in a stiff mooring line with a spring coefficient of 1×10^7 N/m. The winch speed was varied (maximum value of 3 m/min), and the HLV stopped when the mooring rope force exceeded a limit of 2000 kN (which occurred when the lifting points were not reasonably aligned). The heading and mean sway position were maintained using soft pre-tensioned lines.

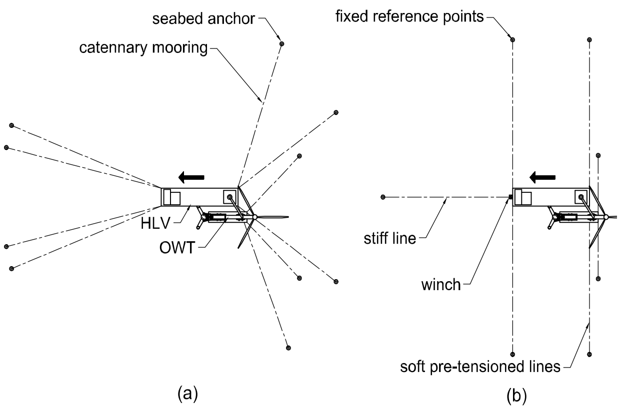

Fig. 11 Dynamic mooring configuration for HLV: (a) possible mooring pattern; (b) spring system used in numerical analyses of upending activity

5 Results

This section conducts a quantitative assessment of the dynamic responses of potential critical installation activities, with the aim of identifying limiting (response) parameters for which operational limits (in terms of allowable limits of sea states) are established. This assessment represents the basis for assessing feasibility of the proposed OWT tower installation procedure. The methodology provided above for assessing operational limits is applied.

5.1 Assessment of Dynamic Responses and Identification of Limiting Parameters

To identify limiting parameters and actual critical events, it is necessary to numerically model the potential critical activities given in Table 2. This is conducted by applying typical installation sea states and headings, as shown in Table 7. They are representative to account for shielding effects from the HLV on the cargo barge. Sea states were modeled using the unidirectional Pierson Moskowitz (PM) wave spectra, according to recommendations given by Det Norske Veritas (2010). The wave direction is measured counter-clockwise from the stern of the HLV. A total of 12 seeds were considered sufficient for this stage of analysis, because this is only a "screening" phase that is used to identify actual limiting parameters.

Table 7. Typical Installation Sea states for identification of limiting parameters

Environmental condition	Wave spectrum	Hs (m)	Tp (s)	Direction (deg)
1	PM	1	6	0, 45, 90, 135, 180
2	PM	1	7	0, 45, 90, 135, 180
3	PM	1	8	0, 45, 90, 135, 180

For the TD results shown below, the approximate start and end times of each activity are shown in Table 8.

Table 8. Start and end time used in analysis of installation activities (Ref. to Figs. 12–16)

No.	Activity	Simulation starting time [s]	Simulation ending time [s]
1	Tower lift-off	60	120
2	Upending frame mating	120	180
3	Tower upending	180	2000

5.1.1 Lift-off and Mating Activities

For lift-off and mating activities, TD numerical simulations were conducted for the load conditions shown in Fig. 4 (a, b). The lifting speed for heavy lift operations normally ranges between 3 and 15 m/min, depending on the magnitude of the payload. As shown in Table 6, a winch speed of 5 m/min was selected; this value is practical for a crane vessel with a capacity of approximately 1000 tons (Verkade, 2009). The elastic contact elements were modeled according to Fig. 10 (a, b). For each operation the simulation time was 3 min, and a time-step of 1×10^{-3} s was applied.

For the lift-off activity, Fig. 12 shows that snap loads on the hoist wire (at the beginning of the load transfer) can occur, and their magnitudes can be of the order of the mean tension after load transfer. As they can cause structural failure, tension is therefore a limiting parameter. It is also observed that the dynamic effects on the wire tension due to an underneath strike from the barge on the tower at the end of the load transfer are small. This impact load will not cause slack lines, and thus, is not a limiting parameter.

During the mating phase, Fig. 13 shows the impact forces on the foundation supports. They occur due to large initial impact velocities as a consequence of first-order motions of the cargo barge, crane tip motions, and hoist winch speed. It is observed that the impact forces can be larger than the static weight of the tower, and thus can cause local structural damage to the mating structural components (shown in Fig. 4, detail V). Consequences would cause delays in the project, and thus impact force is a limiting parameter.

Based on Figs. 12 and 13, there is a time-frame of approximately 120 s between the lift-off and mating phases, where no impact between the upending frame bottom pins and foundation supports has yet occurred. During this "initial mating phase", there is a "restrictive" event (not critical), which is a failed mating attempt if the motions of the pins (limiting parameter) were too large; see e.g., Fig. 15. However, the mating operation can be attempted again if the motions of the pin are acceptable.

Figure 14 shows that during the load transfer (after the snap events), the crane tip and the saddle-support on the cargo barge move in unison, and therefore their relative positions are small. The load transfer is a complex process involving many transient parameters, such as varying hoist wire tension, varying cargo barge draught, changing of the HLV heel angle, and stretching of the wire ropes. It is observed that the dynamic tensions in the hoist wires remain low and no slack lines are observed; therefore, no critical events are expected.

5.1.2 Tower Upending Operation

The dynamic responses of this installation phase were studied by applying TD simulations. Numerical analyses were conducted based on the modeling parameters given in Table 6 and the elastic model shown in Fig. 10 (c). The coefficients k_r and b_r are modeled according to the numerical modeling section; the duration of each simulation was 30 min and a time-step of 5×10^{-2} s was applied.

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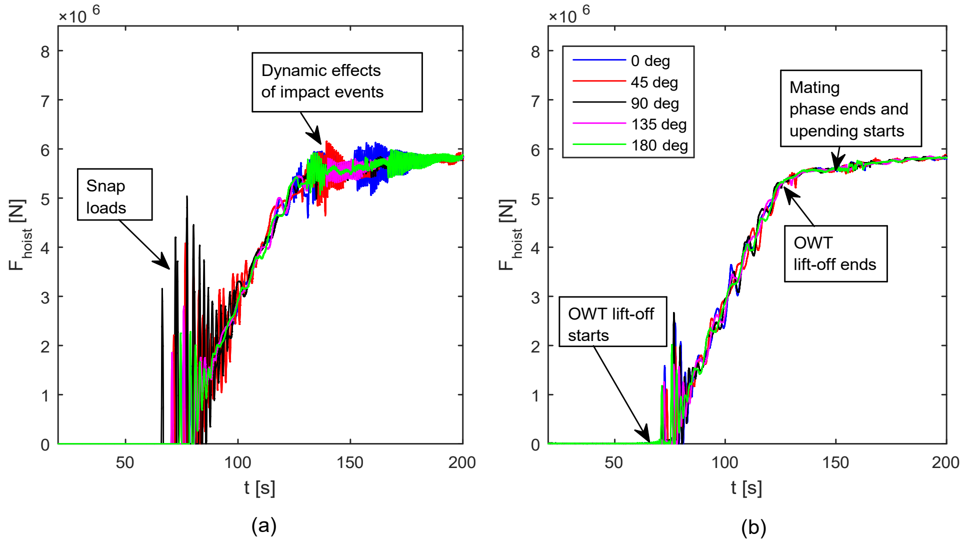

Fig. 12 Examples of hoist wire tension during tower lift-off. (a) H_s = 1 m, T_p = 8 s; (b) H_s = 1 m, T_p = 6 s

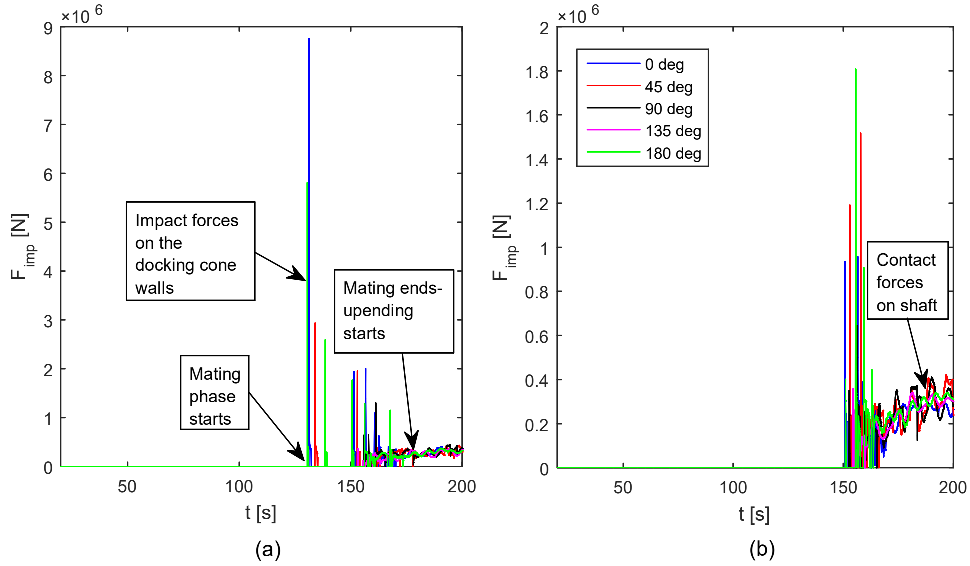

Fig. 13 Examples of impact force on foundation supports during mating phase. (a) H_s = 1 m, T_p = 8 s; (b) H_s = 1 m, T_p = 6 s

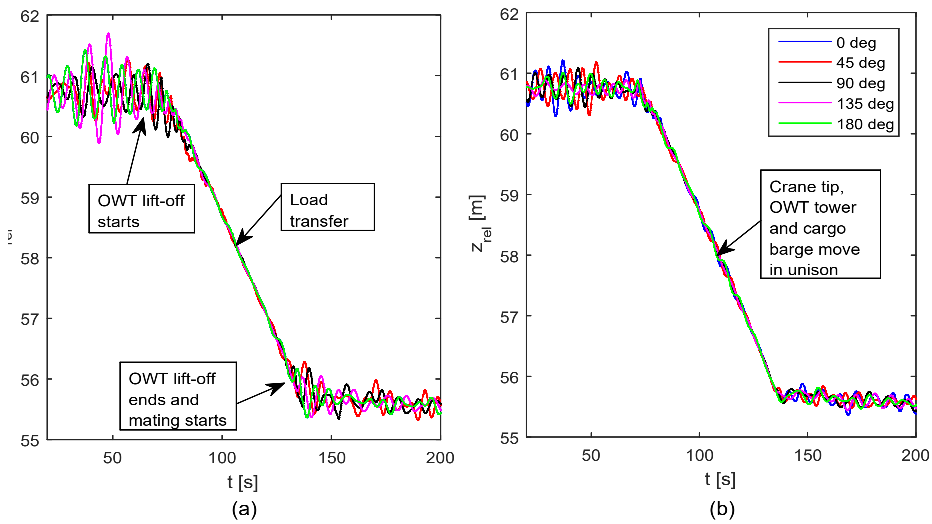

Fig. 14 Examples of relative position between crane tip and tower support on cargo barge. (a) H_s = 1 m, T_p = 8 s; (b) H_s = 1 m, T_p = 6 s

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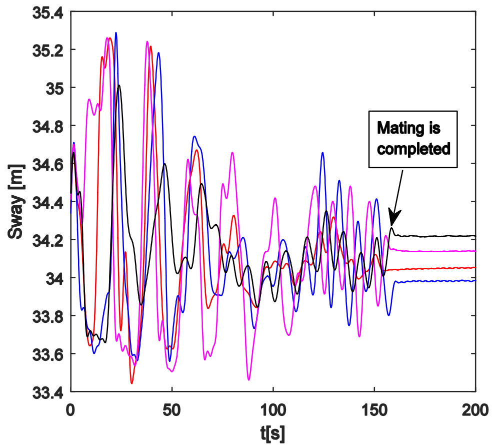

Fig. 15 Example of bottom pin motions for various seeds. H_s = 1 m, T_p = 7 s, wave dir = 135 deg.

Table 9. Limiting parameters, allowable limits, and numerical methods considered for assessing allowable sea states

No.	Activity	Limiting parameter	Allowable limit	Numerical method
1	Tower lift-off	Wire tension or snap force	5000 kN	TD, (see Subsection 4.3.2)
2	Initial mating phase	Upending frame bottom pin horizontal motions or crossing rate ν+	ν+ = 0.0167 Hz, for docking cone with r = 0.35 m	Crossing rate, (see Subsection 4.3.3)

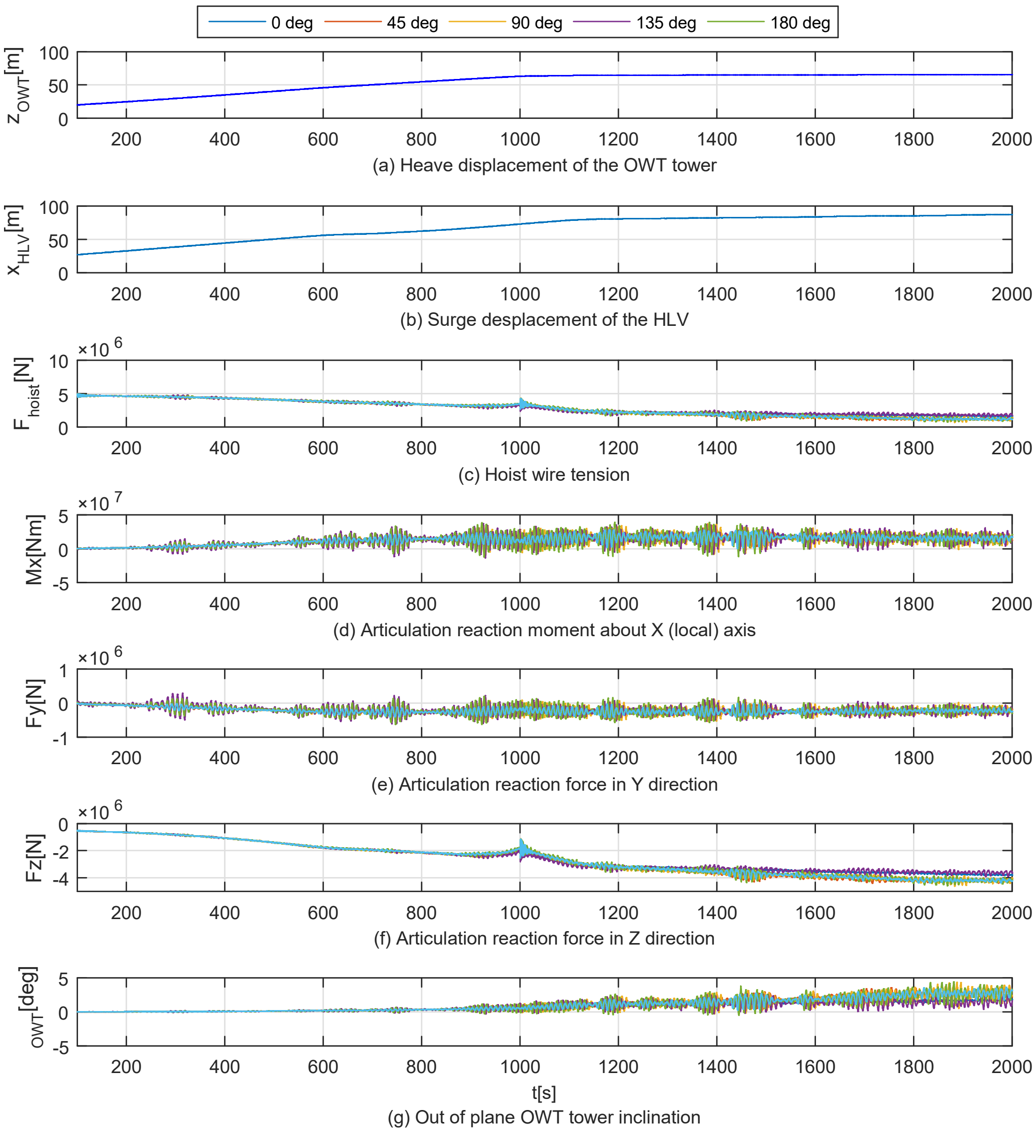

Fig. 16 Example of dynamic responses during tower upending operation (H_s = 1 m, T_p = 8 s). Local coordinate system of the articulation is parallel to the global one

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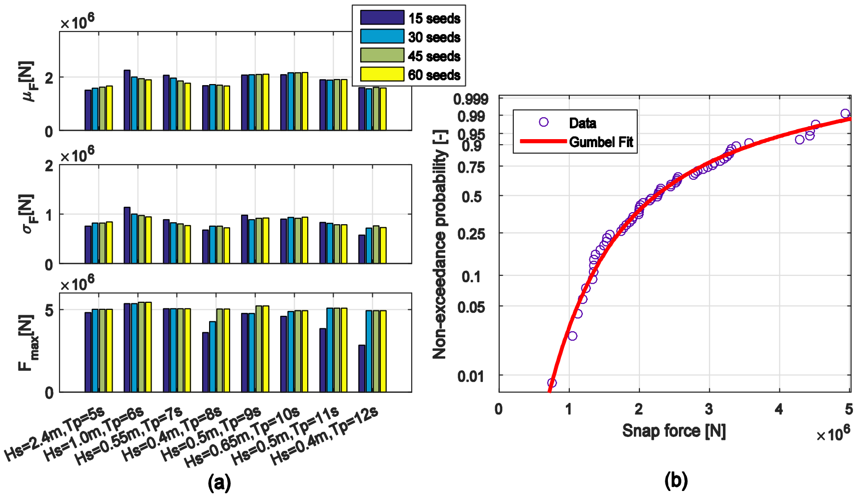

Fig. 17 Snap force during lift-off: (a) Statistical parameters, wave dir. = 120 deg; (b) typical Gumbel fitting for snap force maxima, H_s = 1 m, T_p = 6 s, No. seeds = 60

Figure 16 shows typical dynamic response time histories. It is observed that the hoist wire may not become slack, and the mean tension can continue to decrease as the tower is upended. In contrast, there is an increase in the articulation (foundation support) reaction forces and out-of-plane tower roll. Critical events could thus be structural failure of the docking cones of the foundation support and unacceptable out-of-plane tower inclination, which would cause interference between the upending frame and the foundation during the final upending stage. For the rotational spring coefficient selected in Subsection 4.4.3, Fig. 16 (g) shows that the maximum out-of-plane inclination of the tower would be unacceptable for some headings and sea states. Tower inclination is caused by misalignment of the lifting points and flexibility of the foundation support. It would thus be necessary to accurately select the amount of flexibility relating to the foundation supports to reduce their reaction forces while maintaining an acceptable tower inclination. This can be achieved using elastomers and by controlling the flexibility gap (as shown in Fig. 4, detail V).

5.2 Assessment of Allowable Sea States

To demonstrate the potential of this novel procedure, a preliminary assessment of allowable sea states is conducted.

As the structural damage criterion for the foundation hinged support is not available at this stage of the development of this installation procedure, it is thus not considered here. However, for limiting parameters, such as wire tension and bottom pin motion of the upending frame, allowable limits can be reasonably established. For this reason, only the tower lift-off and the initial mating phase are further analyzed below. The installation activities, corresponding limiting parameters, and numerical methods considered for numerical analyses and assessment of the operational limits are shown in Table 9.

For the lift-off activity, the capacity of the HLV crane is assumed to be at least 7000 kN; an allowable limit for the snap force F_{snap} = 5000 kN is considered to include a safety factor for the crane capacity. This factor is added because of the uncertainties and large variation observed in the snap force; see Fig. 12. Non-stationary process TD simulations were conducted. “All possible” combinations of H_s and T_p were applied, with a total of 60 seeds for each sea state. Figure 17 (a) shows that by using more than 45 seeds, the maximum force remains almost constant. The minimum number of seeds used can be determined by assessing the standard error of the averaged maxima to a target value, e.g., 10% as it was assumed in this paper (Guachamin Acero et al., 2016a). A maximum of every 1 min (duration of lift-off operation; see Fig. 12) of the TD simulation was fitted to a Gumbel extreme value distribution, and the characteristic value was selected for a non-exceedance probability of 0.995; see Fig. 17 (b). The target probability was assumed by considering that the consequences of wire rope failure can be catastrophic.

The operational limits are then established by comparing the characteristic value with the allowable limit of the snap force.

For the initial mating phase, a docking cone radius r = 0.35 m is assumed for the foundation support. The allowable limit can be expressed in terms of the rate that the pin crosses out the docking cone radius; see structural components in Fig. 4, (detail V). A reasonable assumption is that the mating operation is possible if the crossing rate of the pin is less than once per minute, i.e., v^+ = 0.0167 Hz. Based on this criterion, allowable sea states can be established by applying the numerical solution proposed by Guachamin Acero et al. (2015), and the results are shown in Fig. 18.

Figure 18 shows that allowable limits of sea states are low for wave periods longer than 7 s because most of the first-order resonant modes of the floating structures become excited. The natural period for heave and pitch of the cargo barge are 8 s and 7 s, respectively, and the roll natural period of the HLV prior to lift-off of the OWT tower is 8.7 s. It is therefore not practical to install the towers for wave periods of around 8 s, due to resonance. In addition, bow quartering waves (with respect to the HLV) are preferred.

Current offshore practice for tower installation employs jack-up vessels, which (as previously mentioned) may have a limitation of H_s = 1.5 m. From Fig. 18, it is evident that this novel installation method can allow higher sea states when the wave periods are shorter than 7 s, and that limits can be further increased if roll compensation systems are applied (because it is the dominant mode for longer wave periods).

In general, allowable sea states can be increased if the equipment is upgraded in a cost-effective manner, and if mitigation actions are taken for critical events that could occur by modifying installation procedures.

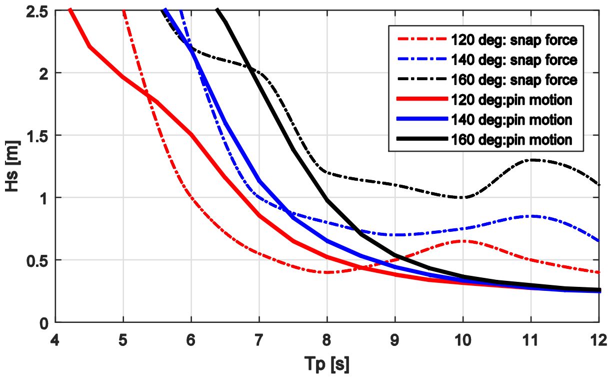

Fig. 18 Overview of allowable limits of sea state for relevant headings for the tower lift-off and initial mating phases; allowable snap force F_{snap} = 5000 kN (lift-off) and allowable horizontal pin motions (initial mating) for a docking cone r= 0.35 m and allowable crossing rate v^+= 0.0167 Hz

5.3 Discussion

For safety reasons, Det Norske Veritas (2011, 2014) recommends that snap loads should be avoided as much as possible; however, in practice, they can occur. Figure 12 shows that snap loads cannot be avoided and that they can lead to a critical event, such as structural failure of the rigging system. To avoid such an event, it is essential that activities are not executed when the allowable limits of sea states provided in Fig. 18 are exceeded; however, these limits are system dependent, and thus will vary for each HLV.

For the vessel and equipment specifications used in this paper, Fig. 18 shows that operational limits are often larger than H_s = 1.5 m, which appears to be the operational limit for current jack-up installation vessels.

Figure 13 shows that during the upending frame mating operation, impact forces on the docking cones occur. However, at this point in developing the novel installation procedure, a detailed structural design of the mating structures is not available; therefore, the associated structural damage criteria was not considered. Allowable limits should be expressed in terms of impact velocities and contributing masses. As previously stated, there is a phase prior to mating where the mating components are aligned (initial mating phase) and for which allowable limits of sea states were reasonably estimated; see Fig. 18. Provided that the mating structural components are designed to cope with characteristic impact loads or sea state parameters (such as the allowable limits of sea states for the initial mating phase), execution of subsequent mating activities is possible.

For the lower envelope of allowable limits of sea states given in Fig. 18, Guachamin Acero et al. (2016a) provided response statistics and conducted a sensitivity study on key modeling parameters involved during the mating and upending operations. For the mating operation, the maximum impact velocity on the docking cones was found to be 0.74 m/s; where the corresponding contributing mass was 33 tons. The maximum contact force on the docking cone shown in Fig. 10 (b) is 1350 kN, which is smaller than the static weight that each pin has to carry in the final stage (approximately 3500 kN). By considering that mating structures for float-over operations of the oil and gas industry are designed for much larger forces, the future design of structural components for this novel procedure is thus viable. For the final upending stage of the tower, it was found that the maximum out of plane moment Mx is 15.7 × 10^4 kNm (about the local axis of the articulation) and the maximum tower inclination is 2.4 deg. Based on a sensitivity study on the rotational spring coefficient, k_r, it was also found that the inclination can be decreased by reducing the flexibility of the foundation support.

Based on Fig. 18, the preferred headings are bow quartering seas (with respect to the HLV), so the foundations should be installed for these headings. For a given offshore site, a typical installation season will be summer, and there will always be a predominant wave direction, which can be determined from wave statistics and, preferably from the use of hindcast directional wave spectra. It should also be possible to optimize the heading of the HLV (in view of better responses obtained when using weather forecasts) while providing shielding effects on the cargo barge; however, the HLV will need to be moved in a direction parallel to the cargo barge. The proposed installation procedure can therefore allow a wide range of headings, provided that the cargo barge can be positioned on the leeward side of the HLV.

6 Conclusions and Recommendations

6.1 Conclusions

A detailed novel procedure was introduced for installing an offshore wind turbine (OWT) tower and rotor nacelle assembly (RNA) on various types of bottom-fixed support structures (monopiles, tripods, and jackets). This procedure is based on the inverted pendulum principle and requires a cargo barge, a medium-size heavy lift vessel (HLV), and an upending frame. The novel installation method requires minor modifications of the foundations and certain equipment. The main advantage of this procedure is that it does not require a huge HLV (in terms of lifting height and capacity). To account for the shielding effects of the HLV on the motions of the cargo barge, the foundations need to be installed with a specific heading that is based on directional wave spectra statistics. For the NREL 5-MW tower, an HLV with a crane capacity of at least 700 tons at a 32-m radius and a minimum lifting height of 70 m would be required.

For a preliminary assessment of the viability of the novel OWT installation procedure, the operational limits (in terms of allowable limits of sea states) of potential critical installation activities were determined. A generic and pragmatic approach to identify these activities and corresponding critical events and limiting (response) parameters was applied. The approach is based on numerical modeling of real and sequential operations in stochastic seas (wind and current actions were not included).

Potential critical activities determined are OWT tower lift-off, upending frame mating, and OWT tower upending. Critical events are hoist wire breakage, structural failure of the foundation hinged supports, a failed mating attempt for the upending frame, and unacceptable OWT tower inclination during the final upending stage. The limiting parameters were identified as tension in the lifting wire, impact force and reaction forces on the docking cones of the foundation supports, horizontal motions of the upending frame bottom pins, and OWT tower inclination. These parameters were identified by quantitatively assessing the dynamic responses, which are obtained by numerically simulating "actual" operations. The time domain method was applied.

Wire tension during lift-off and horizontal motion of the upending frame bottom pins during the initial mating phase were selected for assessment of the operational limits. To assess wire tension during lift-off, the time domain method was applied. The characteristic value of the wire tension was selected for a target non-exceedance probability, based on a Gumbel extreme value distribution; this value was compared with the allowable tension (including a safety factor) and operational limits were established. For the initial phase of the mating operation, operational limits were assessed by applying the crossing rate (from a circular boundary) method; the method relies on the number of times that a mating pin is allowed to cross a circular boundary (docking cone radius) in a given time interval. Operational limits were established for various vessel headings; it is shown that the novel procedure is not very sensitive to wave direction, and thus, variability on this parameter for a typical installation season would not be an issue.

This novel installation procedure is demonstrated to be viable following a preliminary assessment of the operational limits, the duration of the operation, equipment used, and weather- and water depth-sensitivity.

Numerical modeling of the actual OWT installation activities is complex, but it is necessary for proper identification and quantitative assessment of dynamic responses. The approach used in this paper is systematic and can be applied for any marine operation.

6.2 Recommendations for Future Work

To document the usefulness of the new installation procedure, it is important to conduct a systematic workability analysis including all installation activities, associated duration, operational limits, and seasonal hindcast directional wave spectra, preferably obtained from potential offshore fields.

In addition, it is necessary to establish allowable limits for transporting the OWT tower and RNA in a horizontal position using structural damage criteria based on FEM of the RNA under characteristic acceleration forces. Furthermore, mitigating actions for the possible leakage of hydraulic and lubrication systems needs to be proposed.

Issues regarding structural connections between the upending frame and the tower also need to be addressed. A proper design of the mating elements should be conducted so that they absorb and dissipate impact loads, allow flexibility, and allow adequate space for pin horizontal motions. The allowable limits of these structural components should be established in terms of allowable motions and impact velocities that can be used in a global dynamic analysis.

The largest snap loads during lift-off will occur in beam seas; therefore, anti-roll devices or motion compensation systems on the HLV should be considered to increase operational limits. Strategies that minimize operational times for mooring line deployment and transportation of the towers should also be investigated.

The origin of operational limits for current installation methods employing a jack-up and a floating HLV is unclear, or they are simply unavailable. Therefore, these limits need to be systematically derived. A comparative study between this novel procedure and current practice can then be conducted to further assess the competitiveness of the proposed OWT installation method.

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