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Assessment of the dynamic responses and allowable sea states for a novel offshore wind turbine installation concept based on the inverted pendulum principle

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Abstract

This paper presents a numerical study for preliminary assessment of the dynamic responses and allowable sea states for the installation of an offshore wind turbine (OWT) tower and rotor nacelle assembly (RNA) based on a novel method. This method is based on the inverted pendulum principle and consists of various sequential activities for which the allowable limits of sea states need to be established. For critical installation activities, numerical analyses methodologies have been applied to model the actual operations. For the parameters limiting the execution of the operations, response statistics are provided. It is found that at least 45 seeds are required to achieve convergence of snap force statistics during the OWT lift-off. The response statistics are used to calculate a characteristic value corresponding to a target probability of non-exceedance. For the lift-off and mating operations, these characteristic values are compared with the allowable limits of the response parameters to establish the allowable limits of sea states. In addition, sensitivity study on key modeling parameters are conducted. Spring coefficients of contact elements and hinged connections, winch speed, and hoist wire stiffness are shown to be important modeling parameters. The results provided in this paper are important for future finite element modeling (FEM) and cost-effective design of the structural components.

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Keywords: Offshore wind turbine installation; allowable sea states; time domain analyses; response statistics

1. Introduction

Installation is an important phase of the offshore wind turbine life cycle, where several activities are executed in sequence by following installation procedures. Each activity may have several critical events that may jeopardize or restrict the complete operation. These critical events have their own limiting (response) parameters, e.g., a sling breakage event has the tension as a limiting parameter. However, it is desired that the allowable limit of the tension is

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expressed in terms of allowable sea state parameters. The limits of allowable sea states can be derived for each installation activity, and by taking the lower envelope, the “operational limits” of the whole installation can be established. These operational limits need to be derived in a systematic manner.

In [3], a novel OWT tower and RNA installation concept was introduced and shown to be feasible. It allows the installation of a fully assembled superstructure using a medium size HLV, a cargo barge and an especially designed upending frame. The method is based on the inverted pendulum principle and takes advantage of the shielding effects of the HLV on the motions of the cargo barge. The foundations can be monopile, tripod and jacket structures. In addition, no major modifications of current designs are required for monopiles and tripods. In this paper, the tripod structure is selected arbitrarily. The installation procedure is summarized as follows: First, the stern of the cargo barge transporting the OWT in horizontal position is moored to the foundation, see Fig. 1 (a). Second, the HLV is positioned parallel to the cargo barge using mooring lines or a dynamic positioning (DP) system. The motions are monitored prior to the lifting operation. Third, the crane winch starts lifting the OWT tower until clearance of the saddle support on the bow of the cargo barge is achieved, see Fig. 1 (c). Fourth, mating between the upending frame bottom pin and the foundation support occurs, see Fig. 1, detail X. Fifth, the OWT is further upended to the vertical position, lowered to the foundation using hydraulic jacks, bolted to the foundation flanges, and the upending frame is removed, see Fig. 1 (d,e). During all installation activities except in the final OWT upending phase, it is required that the crane tip and the lifting point on the OWT tower are vertically aligned.

Based on the installation procedure, time domain (TD) simulations of the critical operations were conducted. It was identified by [3] that the critical events and corresponding limiting (response) parameters are: the wire rope or crane structure failure during the lift-off phase and the limiting parameter is the snap force in the hoist wire rope. For the mating operation between the upending frame bottom pins and the foundation support, the failed mating attempt is a critical event, and the limiting parameters is the horizontal motion of the pin. During the mating operation, another critical event is the structural damage of the foundation supports (docking cones) due to large impact forces or corresponding velocities. Finally, during the final upending stage of the OWT tower, the structural damage of the foundation supports and docking pins are critical events. The limiting parameters are the reaction forces in the structural connections.

To establish the allowable sea states of each installation activity, characteristic values S_c and allowable limits S_{allow} of limiting (response) parameters are needed. The allowable limits of sea states can be established in a straightforward manner for the condition satisfying the equality $S_{allow} = S_c$.

The allowable limits of sea states for the lift-off and initial phase of the mating activities can be assessed at this stage of the design because the allowable limits of the limiting (response) parameters can be reasonably estimated from manufacturer specifications and geometrical constrains. These limiting parameters were identified by [3], and they are the snap loads on the wire ropes and horizontal motions of the upending frame’s locking pin.

In this paper, the allowable limits of sea states for the lift-off and initial phase of the mating activity are established. In addition, the lower envelopes of these allowable limits of sea states are used to assess response statistics of impact velocities during the mating operation and reaction forces during the upending phase. Moreover, sensitivity study on key modeling parameters such as lifting winch speed, hoist wire stiffness and contact stiffness is conducted. The results provide “representative” values of dynamic responses for future cost-effective design of the structural components.

Furthermore, allowable limits of structural components subjected to impact velocities during the upending frame mating operation and reaction forces during the OWT upending phase, require structural damage criteria based on FEM of the structural components. The detailed designs of these components are not available at this stage of the study, and thus, are not considered in this paper.

This installation method assumes that the horizontal transportation of the OWT tower and RNA is feasible. In practice, local permanent deformations and damage of the bearings and supports of the drive train can occur, and thus, affect their fatigue life. This is due to gravity and acceleration loads for which the allowable limits need to be established. These limits can be set based on structural damage criteria obtained from FEM of the complete nacelle structure. In addition, possible leakage of hydraulic fluids have to be considered. The issues discussed above need to be addressed for a complete assessment of the operational limits; however, these topics are out of the scope of this paper.

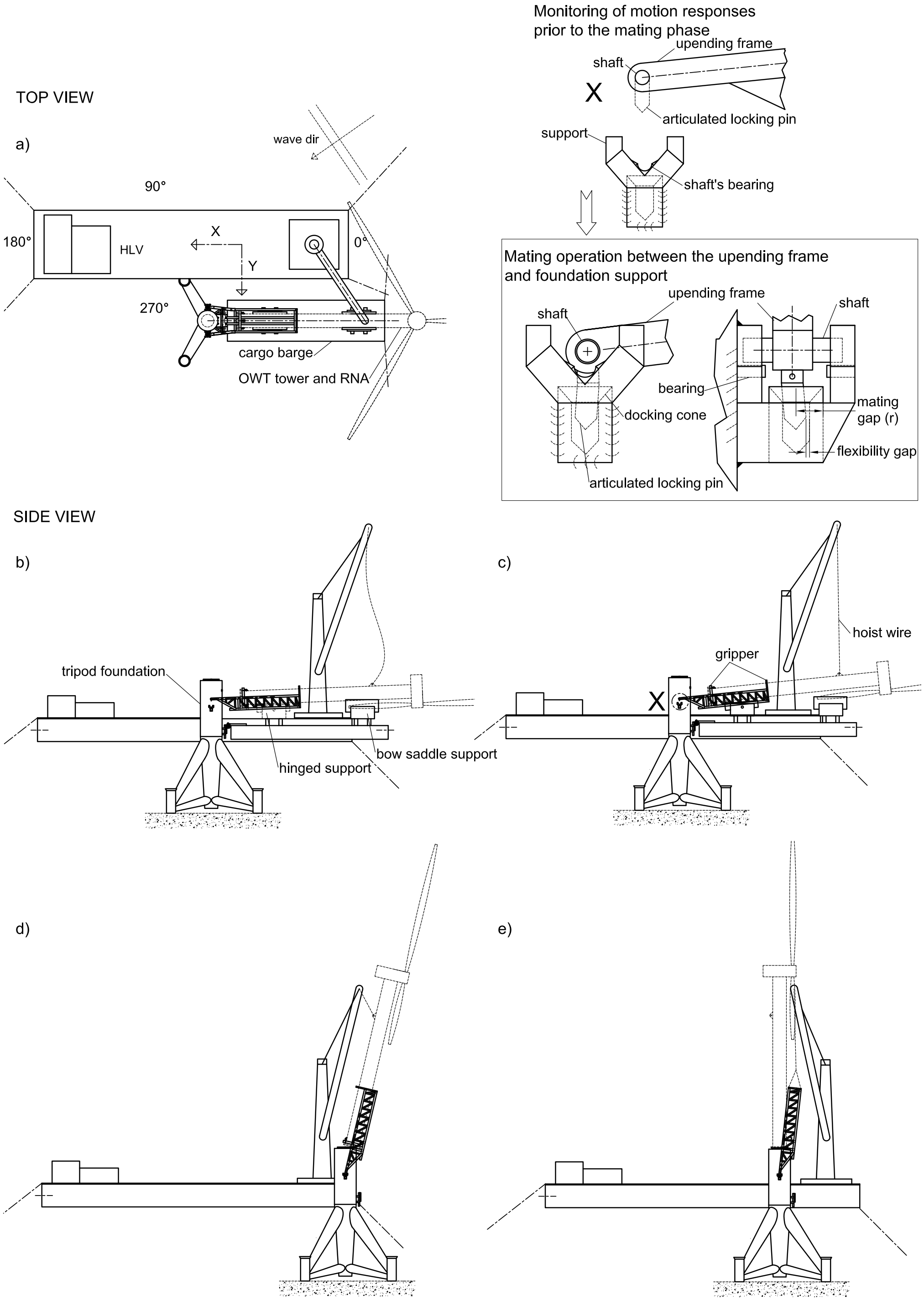


Fig. 1: OWT tower and RNA installation activities. (a,b) Pre-lift and mooring, upending frames bottom pin motion monitoring; (c) OWT tower lift-off and mating of upending frame and foundation docking cones; (d)OWT tower upending at final stage; (e) Upending frame removal

2. Modeling of the coupled dynamic system

Some aspects required for numerical modeling of coupled dynamic models used for critical installation activities are given in this section.

2.1. Structures main particulars

The coupled dynamic models for the various installation activities are built in the AQWA suit of programs, see [1]. This is a state-of-the-art computer code suitable for modeling non-stationary processes such as lifting operations and controlled forward motion of the vessels. An HLV (L=140 m, B=30 m, T=6 m) a cargo barge (L=69 m, B=18 m, T=4 m) and the NREL 5 MW OWT (Ref. to [7]) are considered for the activities listed in Table 1, and are shown in Fig. 1. The models are composed of 4 structures: a heavy lift vessel, a cargo barge, a tripod, and an OWT & RNA and upending frame as single body. Hydrodynamic interaction between diffracting structures is included. During the OWT upending phase, the HLV is moved forward using a winch at a variable speed, which is limited by a maximum horizontal mooring line force of 2000 kN (in order to limit the lateral forces due to misalignment between the lifting points). The stern of the cargo barge is moored to the tripod foundation while the bow is moored to the seabed using catenary mooring. The crane tip and the OWT tower are connected using a wire rope with stiffness $k_{wire} = 5 \times 10^4$ kN/m. The winch lifting speed is selected to be $v_{winch} = 5$ m/min. For the upending phase, the winch speed is reduced to $v_{winch} = 3$ m/min.

The elastic contact elements for the cargo barge's stern saddle support and docking elements are modeled using linear springs and dampers. Based on numerical analyses of float-over operations carried out in [5,6], the stiffness $k_{con} = 1 \times 10^5$ kN/m and damping $b_{con} = 0.05 b_{cr}$ coefficients are selected. For the final stage of the upending operation a universal hinged connection between the end tip of the upending frame and the foundation with flexibility in the out of plane direction is used. Figure 1 detail X shows a possible solution for the locking system. The flexibility gap together with elastomers that can be placed on the annular surface of the locking device can provide the required system parameters. This device is modeled with a rotational spring and damper with coefficients of $k_r = 5 \times 10^6$ kNm/rad and $b_r = 0.1 b_{cr}$, which are taken arbitrarily. For more details on the modeling parameters given above Ref. to [3].

2.2. Modeling parameters for installation activities

The installation activities considered for the numerical analyses, starting and ending sub-operations and some numerical modeling parameters are summarized in Table 1.

Table 1: Aspects of the numerical modeling of installation activities

No.	*Activity*	*Starting*	*Ending*	*Modeling parameters*
1	OWT tower lift-off	hoist wire is slack	bow saddle support of cargo barge is cleared	hoist winch speed = 5 m/min, duration ≤ 1 min
2	Monitor upending frame bottom pin motions	lift-off is finished	pins are aligned with the docking cones and motions are acceptable	docking cone radius $r = 0.35$ m, crossing rate $\nu^+ = 0.0167$ Hz
3	Upending frame mating	Mating pins are aligned	stern saddle support of cargo barge is cleared	hoist winch speed = 5m/min, duration ≤ 1 min
4	OWT upending	Upending frame mating is completed	OWT is in vertical position	variable HLV forward speed ≤ 3 m/min, hoist winch speed = 3 m/min, duration ≤ 30 min

3. Numerical methods

For the coupled dynamic models of the installation phases shown in Fig. 1, the characteristic values of limiting parameters need to be assessed quantitatively by applying numerical methods. The numerical methods shown in Table 2 are applied.

For the OWT tower lift-off operation, the loading condition shown in Fig. 1 (b) is applied. In this phase, snap loads (caused by sudden wire rope loading from slack to taut condition in a short period of time) occur, they are of non-linear nature, and the operation is non-stationary. Then, TD simulations are used to assess response statistics, and thus, characteristic values of the snap forces can be established. By comparing characteristic values of snap forces with the allowable tension on the wire rope or crane capacity, the allowable limits of sea states can be established, see Sec. 4.

After the lift-off and before the mating phase, there is a "motion monitoring phase" corresponding to the loading condition shown in Fig. 1 (c), the horizontal displacements of the upending frame bottom pins need to be calculated. Since the process is stationary and the motions are small, the problem can be solved in the frequency domain using spectral analyses. To assess the allowable sea states, the "crossing rate method" recommended by [4] is applied. This method can be used to estimate the rate of crossing of the upending frame bottom pin, out of a circular boundary with radius r equivalent to the annular gap provided for mating purposes. Contributions from 1^{st} and 2^{nd} order motions were included. The available "mating gap" is shown in Fig. 1 (c) detail X. After comparing the crossing rates obtained for all possible Hs and Tp combinations with the allowable value (reasonable for the mating operation to take place), the allowable sea states can be established.

During the mating operation, the crane winch continues paying-in the wire that lifts the OWT tower, and mating between the upending frame bottom pin and the docking cone of the foundation support occurs, see Fig. 1 enclosed box. Since the problem is non-linear and the process in non-stationary, TD simulations are applied.

Finally, during the OWT tower upending, the winch continues paying-in the hoist wires, while the HLV moves forward by pulling-in a wire connected to the seabed. This operation corresponds to a non-stationary process, and thus response statistics of reaction forces on the hinged connection are assessed by applying non-stationary process TD simulations.

Table 2: Numerical methods for assessment of the dynamic responses and allowable sea states of installation activities

No.	*Installation activity*	*Dynamic response*	*Numerical method*
1	OWT tower Lift-off	Snap loads	TD analyses
2	Pin motion monitoring prior to mating	Horizontal motions	FD spectral analyses
3	Upending frame mating	Impact velocities	TD analyses
4	OWT tower upending	Articulation reaction forces & OWT inclination	TD analyses

4. Assessment of allowable sea states and dynamic responses

In this section, a preliminary assessment of the allowable sea states and response statistics is given.

4.1. Allowable sea states for the lift-off and mating operations

The allowable sea states were derived for some limiting parameters whose allowable limits can be reasonably estimated, i.e., the lift-off and pin motion monitoring phases, see activities 1 and 2 in Table 2.

For the lift-off operation, by considering that the mean tension just after finishing the operation is approximately T_{mean} = 5000 kN (Ref. to [3]), a crane with a capacity of at least 7000 kN at a lifting point of 60 m and a radius of approximately 32 m is needed. For all possible Hs and Tp combinations, a total of 60 seeds are used to calculate the maximum force of each simulation. All maxima are fitted into a Gumbel extreme value distribution, and a characteristic value of the snap force corresponding to a non-exceedance probability of 0.995 was considered; and example is shown in Fig. 2. The target probability will depend on the type of operation and failure consequences, and in this paper was assumed arbitrarily. Note that the actual lifting process and duration of the operations are modeled. This approach is suitable for assessment of extreme responses of non-stationary processes, Ref. to [8]. The allowable limit of the crane or the hoist wires including safety factors is assumed to be $F_{snap} = 5000$ kN. By comparing the characteristic values and the allowable limit of the crane, the allowable limits of sea states can be established, see Fig. 3.

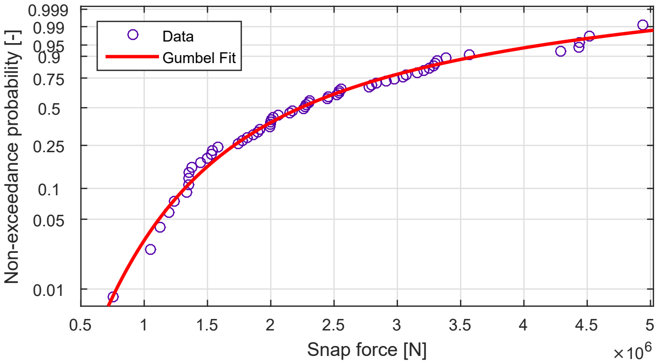


Fig. 2: Example of a cumulative distribution function for the maximum snap forces during OWT lift-off. Hs= 1.2 m, Tp= 8 s, wave dir= 160 deg, Number of seeds= 60, simulation duration ≤ 1 min

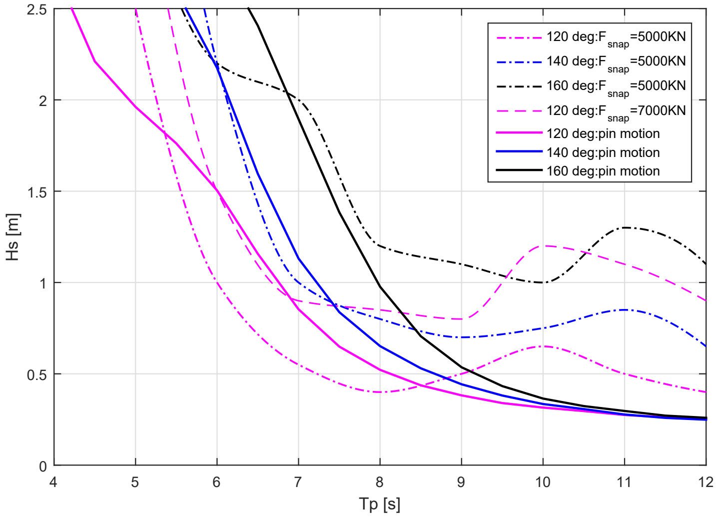


Fig. 3: Allowable limits of sea states for the lift-off and mating operations, allowable snap force: $F_{snap} = 5000\&7000$ kN (Number of seeds= 60, simulations duration ≤ 1 min), pin motion ($\nu^{+} = 0.0167$ Hz, $r = 0.35$ m)

For the initial phase of the mating operation, the crossing rate method is used. The allowable sea states are estimated for a mating gap (see docking cone radius in Fig. 1 detail X) $r = 0.35$ m and an allowable rate of crossing (of the locking pin out of the circular boundary) of one excursion per minute or $\nu^{+} = 0.0167$ Hz. The results are shown in Fig. 3 as well. It can be observed that for wind seas with peak periods lower than 7 s the snap forces in the wire ropes may limit the installation, while for longer waves the upending frame bottom pin horizontal motions will dominate. Moreover, it is observed that if the offshore crane capacity is increased to 7000 kN, the snap force will no longer be a limiting parameter. Then, mitigation actions and equipment upgrade are possible for increasing (in a cost-effective manner) the operability of an operation.

4.2. *Response statistics of snap forces during OWT lift-off*

The response statistics of the snap forces were used to estimate the characteristic values, and thus, the allowable sea states given in Fig. 3. A sensitivity study on the number of seeds was carried out; this was done to assess the convergence of the response statistics. Based on Fig. 4 (a), it can be concluded that approximately 45 seeds are required.

Figure 4 (b) shows the response statistics of the snap forces using 60 seeds for typical installation headings. Sensitivity study on the hoist wire stiffness k_{wire} was also carried out, and the maximum snap forces are shown in Fig. 5 (a). As expected, a crane with stiffer wires will lead to larger snap forces. In contrast, softer wire rope spring coefficients yield to smaller loads, but the heave natural period may get closer to first order resonant modes.

Furthermore, Fig. 5 (b) shows that by decreasing the winch speed, the maximum snap forces may get reduced. However, at lower winch speeds, the number of snap events will increase, and it is possible that larger snap forces than the case with a higher winch speed occur.

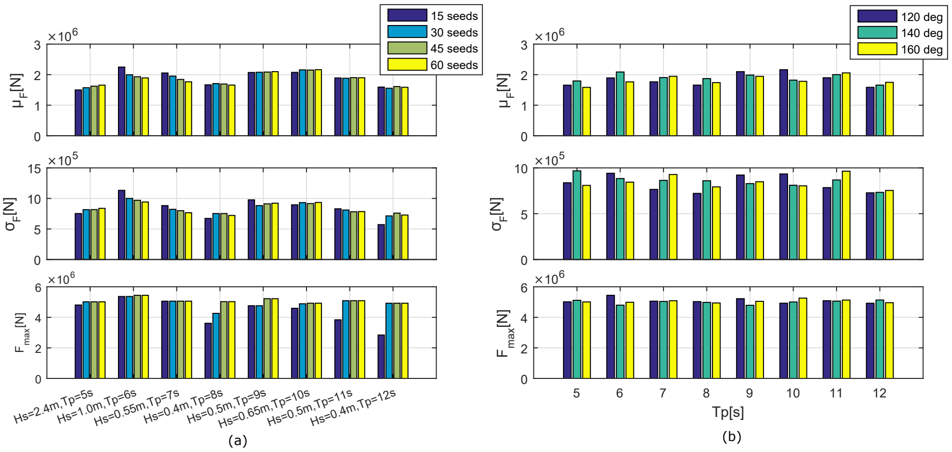


Fig. 4: Response statistics of the snap forces during OWT tower lift-off. (a) Sensitivity study on seed numbers, wave dir= 120 deg; (b) Snap force statistical parameters computed for the allowable limits of sea states given in Fig. 3 for various wave dir., No. seeds= 60. Duration of TD simulations for the snap load events ≤ 1 min

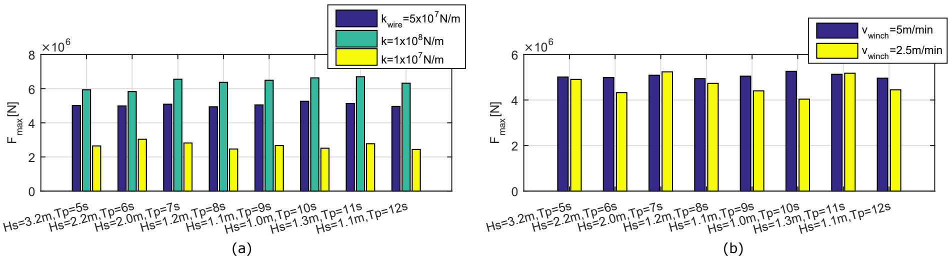
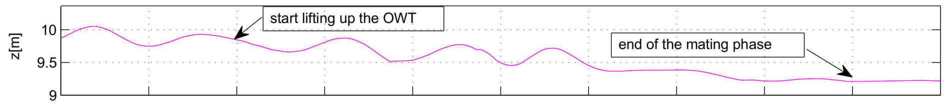


Fig. 5: Maximum snap forces during OWT tower lift-off, wave dir= 160 deg, No. seeds= 60. (a) Sensitivity on hoist wire stiffness; (b) Sensitivity on winch lifting speed. Duration of TD simulations for the snap load events ≤ 1 min

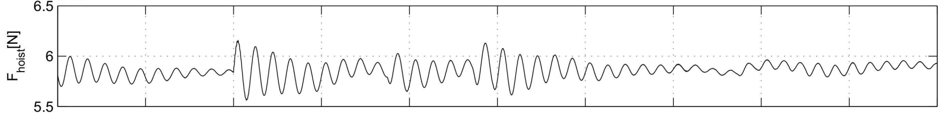
4.3. *Response statistics of impact velocities during the upending frame mating phase*

In order to establish the allowable sea states for the mating operation, information about the allowable impact forces on the docking cones is needed. These limits have to be derived from structural damage criteria obtained from FEM of the structural component under characteristic impact velocities and contributing masses. They are not available at this level of the design, and thus, they are not used in this paper for establishing the allowable sea states.

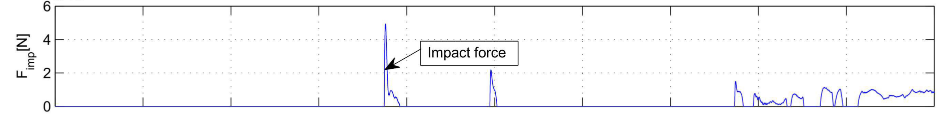
The impact velocities are studied for "typical" sea states, i.e. the allowable limits shown in Fig. 3. Figure 6 shows typical dynamic response time histories for various parameters during the mating phase. It is observed that the mating process may last approximately 1 min, during which several impact events occur.



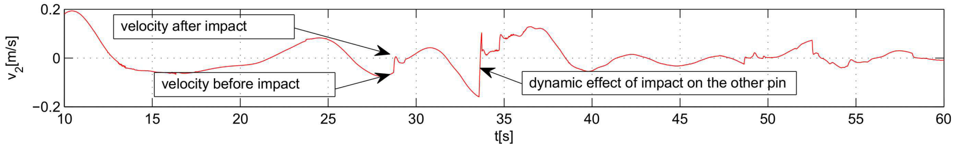
(a) Heave displacement of the docking pin



(b) Hoist wire tension during the mating operation



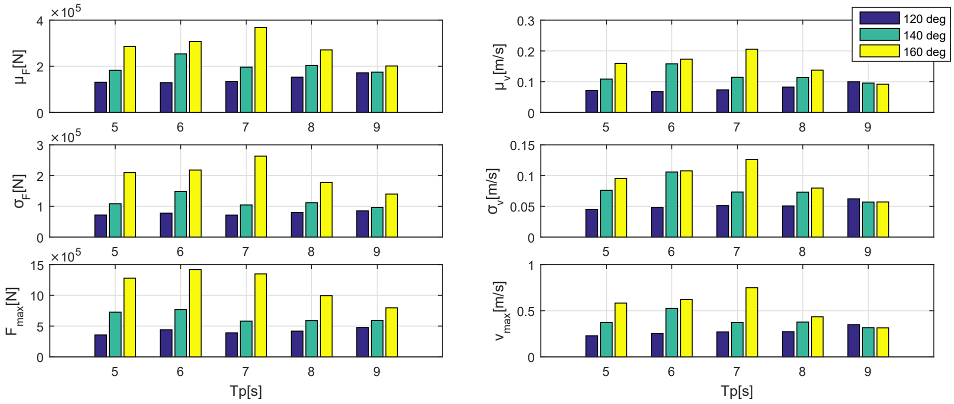
(c) Impact forces on a docking cone during the mating operation



(d) Sway velocities of a docking pin

Fig. 6: Typical TD histories for dynamic responses during the mating operation, Hs=2.86 m, Tp=5 s, wave dir=140 deg

The response statistics of the impact forces and corresponding impact velocities are shown in Fig. 7. It is observed that sea states with peak periods between 6 and 7 s give the largest dynamic responses and they occur for the wave direction of 160 deg. This is because the pitch resonant mode of the cargo barge gets excited.



(a) (b)

Fig. 7: Response statistics of dynamic responses during the mating phase. (a) Impact forces; (b) Impact velocities of the upending frame bottom pin. Number of seeds= 60, duration of TD simulation for impact events ≤ 1 min

Response statistics for various stiffness coefficients k_{con} of the contact elements in the foundation support (docking cone) are shown in Fig. 8. As expected, the contact stiffness has a large influence on the impact forces. It is also observed that the initial impact velocities are similar. In other words, the system global dynamic responses are not affected by impact events.

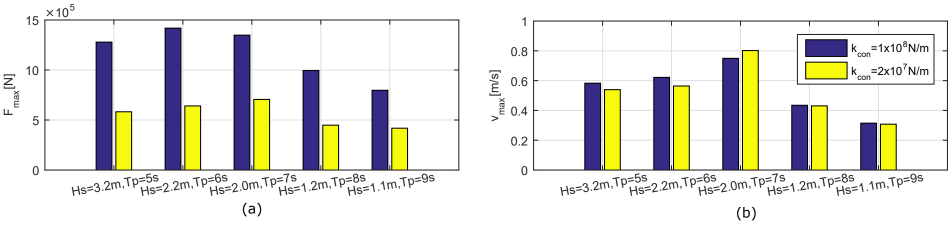
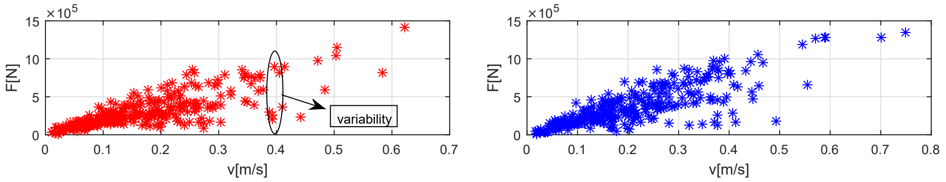


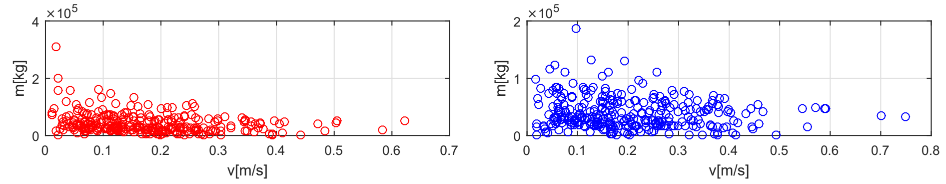
Fig. 8: Sensitivity study on contact stiffness during the mating operation. (a) Maximum impact forces; (b) Maximum impact velocities. Number of seeds= 60, wave dir= 160 deg, duration of TD simulation for impact events ≤ 1 min

Figure 9 (a,b) shows the relation between the impact forces and the change on the impact velocities for each impact event applying relevant sea states. It is observed that in general impact forces increase with increasing impact velocities. However, variability on the impact forces for the same impact velocities is observed. This happens because the contributing impact masses are different. The maximum force should be selected for FEM.



a) Hs=2.2m, Tp= 6s, wave dir= 160deg

b) Hs=1.9m, Tp= 7s, wave dir= 160deg



c) Hs=2.2m, Tp= 6s, wave dir= 160deg

d) Hs=1.9m, Tp= 7s, wave dir= 160deg

Fig. 9: Impact forces, velocities and contributing masses for representative impact events and sea states. (a,b) Impact force vs impact velocity; (c,d) Contributing impact mass vs impact velocity

By balancing the kinetic energy of the docking pins and the potential energy of the elastic contact elements, the contributing mass for each impact event can be calculated from equation (1), Ref. to [2,6]. In this equation, F is the impact force on the docking cone, v is the upending frame pin impact velocity, k_{con} is the elastic stiffness of the contact pair and m is the contributing impact mass. The results are plotted in Fig. 9 (c,d). This information is relevant for design of the docking structural elements.

$$F = v\sqrt{k_{con}m} \tag{1}$$

4.4. Response statistics of reaction moments and OWT tower inclination during the final upending stage

Based on non-stationary process TD simulations, it was identified that the maximum reaction forces and OWT tower inclination occur during the final upending stage [3]. For the loading condition shown in Fig. 1 (d), a total number of 20 seeds for a simulation time of 15 min were considered.

For the envelope of the allowable sea states given in Fig. 3, the statistical parameters of the articulation reaction moments and OWT out of plane inclinations are shown in Fig. 10. For the allowable sea states with $Tp = 7$ s

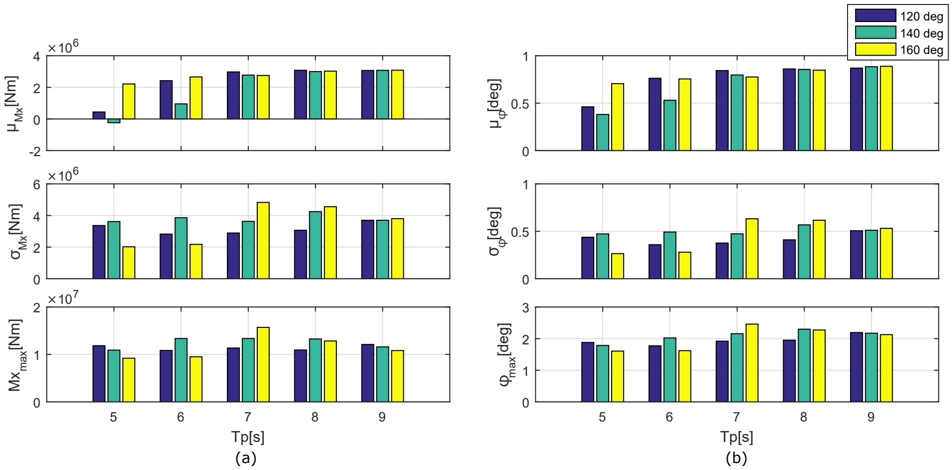


Fig. 10: Response statistics during the final OWT upending stage. (a) Articulation reaction moment M_x (about the local axis); (b) OWT tower out of plane inclination ϕ_{OWT}. Number of seeds= 20, duration of simulation= 15 min

(a representative case giving the largest dynamic responses), the reaction moments and OWT tower inclination for various rotational spring coefficients k_r are provided in Fig. 11. For sake of clearness, the mean values have been subtracted form the maxima.

Figure 11 shows that by increasing k_r, the reaction moments increase as well. In contrast, the out of plane OWT inclination is reduced. Proper selection of these coefficients will depend on the final design of the docking cone and locking pin (see e.g., Fig. 1 detail X), and should be set for acceptable OWT inclination angles during the final upending stage.

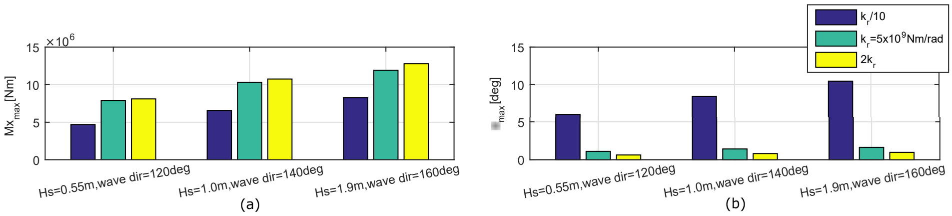


Fig. 11: Sensitivity study on k_r during the final stage of the OWT upending operation, Tp= 7 s. (a) Maximum articulation reaction moments; (b) Maximum out of plane OWT inclination

5. Conclusions and recommendations

A preliminary assessment of the dynamic responses and allowable sea states for a novel installation concept of an OWT tower and RNA based on global dynamic analyses has been presented.

The response statistics of limiting parameters were assessed by simulating non-stationary processes of the actual lifting operations, where non-linearities of the dynamic systems were included. The approach followed in this paper is adequate, and was applied to the lift-off, mating and upending operations. For the lift-off and mating operations, the allowable limits of sea states were established.

At least 45 seeds were needed to achieve convergence on the response statistics of the snap force. Larger snap forces were observed when the hoist wire stiffness was increased. Reducing the winch lifting speed not necessarily reduces the magnitude of the snap loads, because more snap events can occur.

Snap forces are not longer limiting parameters for HLVs with crane capacities larger than 7000 kN. For waves with peak periods longer than 7 s, the horizontal motions of the upending frame pins limit the operation.

The response statistics of limiting parameters during the mating and upending operations as well as impact forces and contributing impact masses were provided. They are required for future FEM and cost-effective design of structural components. It was observed that the stiffness of contact elements greatly influences the impact loads but has little influence on other system dynamic responses.

Hinged connections with rotational spring coefficients larger than $k_r = 5 \times 10^6$ kNm/rad will be required to keep the OWT within acceptable limits in the final upending stage. The flexibility could be achieved by controlling the flexibility gap, see Fig. 1 detail X.

Assessment of the limiting parameters and operational limits for horizontal transportation of the OWT tower and RNA need to be carried out as part of the future work.

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