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Craneless Upending of Large Offshore Monopiles Using a Specialised Floater

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ABSTRACT

The paper presents the concept of a Floater for Upending Piles (FlUP), which can be considered as an efficient approach for the installation of very large offshore monopiles in the offshore-wind industry. This principle is embedded in a concept that aims to decouple the monopile installation steps of upending and pile driving. The idea of the FlUP is to shift the pile from horizontal to vertical position with a self-ballasting floater and utilise a small crane-vessel docking on the floater for pile-driving operations afterwards. The key component of this concept is the FlUP, which is able to upend itself carrying the monopile by shifting ballast water using pumps. A feasibility study of this approach, including a preliminary design of a floater and corresponding design-relevant calculations is presented. The study includes examinations of hydrostatic stability as well as seakeeping behaviour computations to evaluate the limiting sea states for installation in an offshore environment. This is followed by a demonstration of the general feasibility of this concept regarding hydrostatic and seakeeping aspects.

1 INTRODUCTION

As the offshore wind industry is faced with increasing water-depths and wind turbine sizes, the monopiles, as the dominant foundation-type, are getting larger and heavier. This poses new requirements on the crane capacity of installation ships. To overcome these substantial restrictions in installation, different solutions for lifting a monopile have been investigated such as using the buoyancy of the monopile for reducing the crane load [2]. Moreover, a concept for a specialised installation vessel for whole wind turbines or foundations has been developed [3]. Thus, a new way of thinking of monopile installation is to decouple the upending of the heavy monopile from the operation of the lighter hydraulic hammer. This can be done with a specialised FlUP, a Floater for Upending Piles, prior to using a crane-equipped vessel, which only has to lift the hydraulic hammer for pile-driving. The main idea of the FlUP is the usage of a lightly equipped, unmanned structure that uses ballast water pumps and water tanks for self-upending. The concept of self-upending structures is generally known from self-erecting jackets in the offshore oil and gas industries [4, p. 1058] [5, p. 293] [6, p. 101], and from the floating instrument platform FLIP [7]. Pursuing the idea of a self upending structure, this paper presents a feasibility study on the deployment of an upending floater, called FlUP. Safe and efficient operation requires the calculations of relevant physical aspects and related forces. This applies primarily to the hydrostatic and seakeeping behaviour of the structure to ensure adequate upright stability at different floating states of the FlUP and to define the seastate limits for the installation process.

The short computation time of frequency-domain seakeeping calculation methods makes them a powerful tool to support the design process. The results allow for a deep understanding of the different components of motion response function. Therefore, a frequency-domain calculation method is applied to evaluate the motion behaviour of the structure during the transport and docking operations. The system of floater and monopile can be assumed to be a ”slender body” during the transport in such a way that the linear strip-theory program PDStrip can be utilised [8]. In the docking situation, the time-domain 3D-potential method *pan*MARE is used to generate response-amplitude-operators (RAOs). Potential flow methods use the superposition principal of mathematical potential functions to fulfil boundary conditions on the submerged body surface that is discretised with panels (boundary elements). Afterwards, the Bernoulli equation is applied to calculate the pressure on each panel based on the determined velocity potential. The integration of the pressure over the panel yields the forces and moments acting on the structure as a function of its floating condition and characteristics of the incoming waves.

Since the simulation methods used in the paper have been validated in numerous studies [9][10], these are not discussed further, and instead, the installation procedure is explained in more detail in order to define the requirements of the floater. In a further step, an approach for a preliminary design is presented; followed by explanations on the calculations required for the feasibility examinations. The design-relevant computations contain hydrostatic analyses of the different installation steps of the floater, a hydrostatic simulation of the upending process and seakeeping calculations to determine the behaviour of the floater in an offshore environment.

2 INSTALLATION OF MONOPILES WITH A SPECIALISED FLOATER

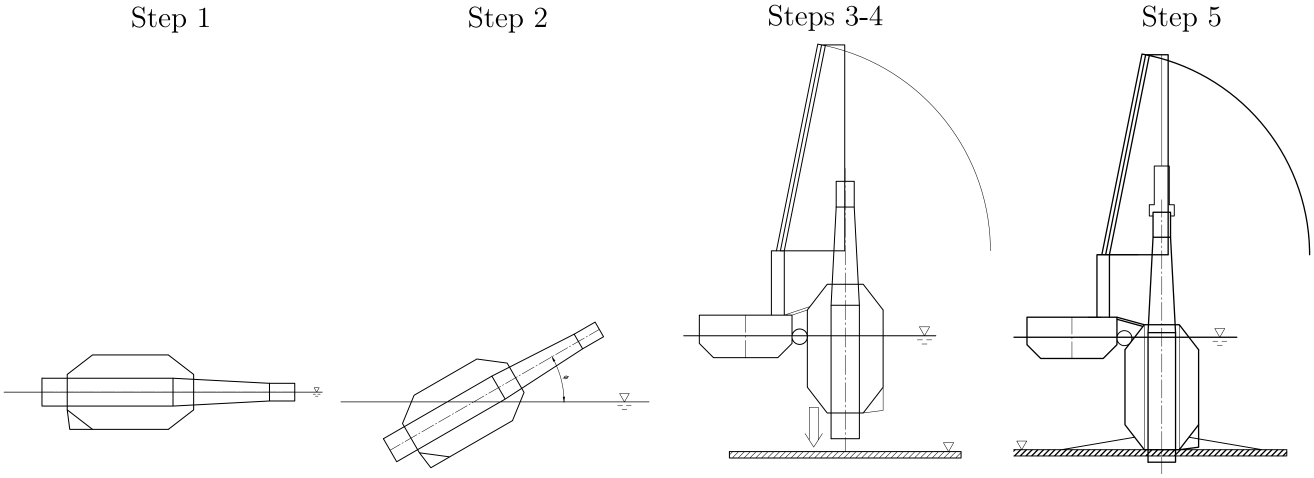
The key idea behind the proposed installation method is to decouple the installation-steps of upending and pile driving for monopile installation. To do so, a floater is intended to govern the upending part of the installation process by flipping itself with the monopile from a horizontal into a vertical position by shifting ballast water between different tanks. Based on this principle, the installation-process can be divided to the following steps (see also Figure 1):

1. Mounting the monopile to the floater in horizontal position and towing it to the installation location
2. Upending the floater with the monopile by shifting ballast water in the floater
3. Docking a crane-equipped vessel with the hydraulic hammer to the floater
4. Lowering the pile vertically to the touchdown on the seabed and further to self-weight penetration depth by further ballasting the floater
5. Driving the monopile with the hydraulic hammer operated from the crane vessel, using the floater as a guiding tool and for noise mitigation

These steps allow for a number of variations in the installation process using the upending floater. First, step 1 can be executed in the marshalling harbour and the floater with the pile can be towed to the location or the mounting can be done on site. Step 3 allows a selection from a large variety of crane-equipped vessels for operating the pile-driving hammer. This most probably includes Jack-Up vessels or heavy-lift vessels. In step 5, further important features of the floater are mentioned: As a steel-structure, which is surrounding the pile during the installation-process, it can be utilised as a gripper or guiding tool and for noise-mitigation purposes in the pile-driving phase. This requires additional measures and equipment on the floater.

3 DESIGN OF THE FLOATER

As the key part of the installation method is based on the capability for upending, a preliminary floater design is developed. This is intended to be a lightly-equipped and unmanned steel structure which


Step 1

Step 2

Steps 3-4

Step 5

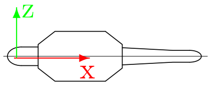
Figure 1: Installation steps 1 to 5

mainly contains ballast water tanks and pumps to manage the ballast water. Being part of this concept study, the presented design can only be seen as a first approach that has not been optimised. Guiding the design, some boundary-conditions are defined as follows: Length, diameter and mass of the considered monopile are 100 m length, 11 m diameter and 2000 t mass, respectively. The intended water depths for installation range from 30 to 45 m. The resulting floater is a large steel structure with a length of 50 m, a beam of 34 m and a height of 29 m. Although this geometry is used for the calculations, it could also be possible to develop a different setup with, for example, two floaters at the pile that are connected. For the first design, a cross-sectional shape of an asymmetric octagon, as illustrated in Figure 4, is selected. The idea behind the asymmetrical shape of the octagon is to get a different eigenperiod for the roll and pitch motion during upending and when the floater reaches the vertical position. The dimensions of the cross-section and the length of the floater are determined iteratively based on hydrostatic stability calculations under consideration of the constraints mentioned above. In addition to the secondary installation tools described in Section 2, it is advantageous to use a centre skeg at the aft of the floater for better course stability during transport. Reduction of the cross-section area of the bow and the aft of the floater as well as using conical caps for the pile during transport are intended to reduce the towing resistance of floater and pile. For the following hydrostatic calculations, the weights of the floater and the system with the monopile are estimated based on conservative approximation of the steel weight and COGs of the floater. The data of the monopile and assumptions of ballast water are also taken into account. These mass setups are listed for the different installation phases in Table 1. The selected coordinate system has its origin at the stern of the floater in horizontal position in the centre line at the height of the horizontal symmetry plane which coincides with the waterline level as depicted next to Table 1.

Table 1: Mass estimations

Item	Total dry Mass[1][t]	XCG [m]	YCG [m]	ZCG [m]
Monopile	2000	36.0	0.0	0.0
Floating Body	8000	22.0	0.0	0.0
Transport situation	17166	26.1	0.0	-4.2
Horizontal position	14071	24.8	0.0	-3.3
Vertical position	18200	18.2	0.0	0.0

[1] Without hydrodynamic masses



4 DESIGN-RELEVANT CALCULATIONS

Different simplifications and neglected effects are incorporated in the applied computational solutions for hydrostatics and seakeeping, which are discussed in this section. First, hydrostatic calculations are explained, as they play a central role in the overall design process of the floater. Next, the upending process as a core part of the installation method is examined using hydrostatic calculations. Finally, seakeeping simulations are executed to check the system's behaviour in waves. For this purpose, frequency-domain calculations are conducted for the design-relevant estimates of natural frequencies and operability, backed up by time-domain calculations in some detailed situations.

4.1 Hydrostatics

The applied hydrostatic calculations are intended to give an estimation on stability for the initial design of the floater. Therefore, static stability curves and the initial metacentric height GM are computed to obtain results on heel and trim stability [11, 12]. A major simplification is the negligence of the free surface effects in the tanks, as the detailed tank layout and tank filling is not known in the design phase. This has to be kept in mind during evaluation of the results because the stability will decrease with free surfaces. However, free surface size can be influenced by tank layout and filling procedures so that the effect can be kept within limits. Representing the most important result of the hydrostatic calculations, the static stability curve for the heel stability in the horizontal position is shown in Figure 2 and static stability in trim and heel for the vertical position are shown in Figure 3. The vertical situation is of special importance as it represents the final stage of the upending process and the situation in which the crane vessel must execute the docking operation. In this state, the large floater and monopile must behave in a stable manner to protect the ship from any damage.

The results show that the system is stable in the described positions: Both GMs are positive, and with 3.5 m for horizontal and 1.6 and 2.1 m for longitudinal and transverse initial stability, respectively, in the vertical state, are in a safe operational region. The stability at high angles is larger than the initial stability in both cases of the vertical position (additional stability). Due to the unsymmetrical cross-section of the floater (as described in Section 3), the trim stability is slightly lower than the heel stability. If it is necessary to reduce the natural roll and pitch frequencies, the stability in the vertical position could be lowered by moving ballast water upwards. In a similar way, the hydrostatics are computed for the transport operation condition and the results also show satisfying amounts of transverse and longitudinal stability. During the phase of lowering the floater in the final installation stage, the characteristics of stability remain the same as in the docking situation, but the magnitude of stability depends on the vertical position of the additional ballast water. It is possible to still increase the stability for this operational condition compared with the docking position.

4.2 Upending process

The process of upending the floater with the monopile from the horizontal to vertical position, as described above, requires an appropriate tank compartmentation of the floater coordinated with a certain flooding order for the tanks to realise a continuous and safe upending process. In this sense, a ballast tank layout as presented in Figures 4 and 5 is designed. As for the hydrostatic calculation, free water surfaces are neglected for this case as well, assuming that the shown tanks build a set of design-relevant "macro-tanks". Following this approach, every macro-tank is either filled or empty so that only a small free water surface remains. Looking at Figures 4 and 5, tanks 1 and 2 are for ballasting in the transport and horizontal position and the water is shifted over to the aft-peak tank and tanks 3 and 4 during the upending process. To get an impression of the behaviour of the floater during the upending process, hydrostatic calculations for numerous intermediate steps of this process are evaluated.

The general ability of the floater to reach the final vertical position is demonstrated, as the mass distribution for the vertical position leads to an (up)turning moment in every other position and only vanishes in the vertical equilibrium state. For upending, the redistribution of ballast water is a continuous process of emptying and filling tanks. To simulate this process, the ballast water is shifted tank by tank and the

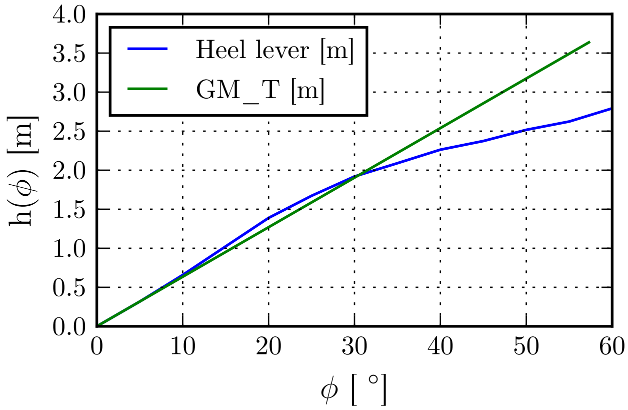


Figure 2: Static stability curve for heel in horizontal position

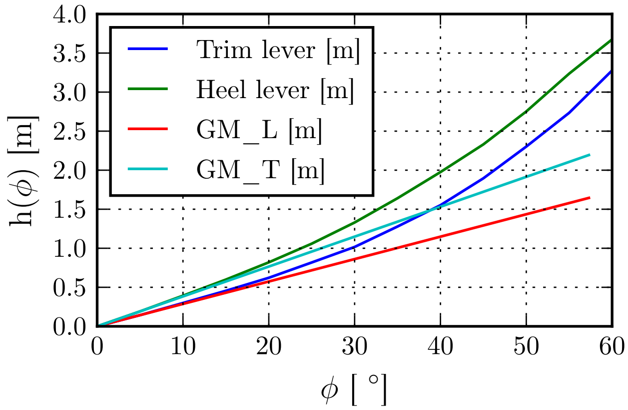


Figure 3: Static stability curves for heel & trim in vertical position

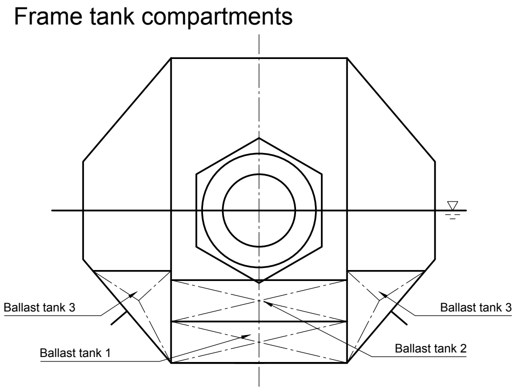


Figure 4: Tank compartments transverse view

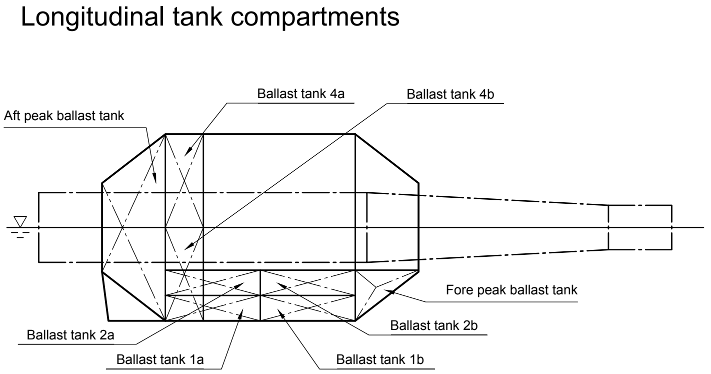


Figure 5: Tank compartments longitudinal view

resulting equilibrium position after every shift is recorded. In these intermediate stages of the upending process, the static stability is evaluated, which is shown by the initial stability over the upending angle in Figure 6. The diagram shows that the upending process is stable from a hydrostatic point of view and especially the transverse stability GM_T is large enough over the whole process to prevent the floater from capsizing. A check of the heave eigenperiod over the upending process shows that it increases from 7 s in the horizontal to 11.5 s in the vertical position. This indicates an improving seakeeping behaviour of the system through the upending process, which is beneficial for the ship-floater operations in the vertical stage and will be examined more closely in the seakeeping analyses.

4.3 Seakeeping

For the general estimation of the motion characteristics of the FlUP in waves, a frequency-domain calculation is applied to calculate the response-amplitude-operators (RAOs). Furthermore, the motion in irregular sea state is computed to evaluate the operability of the floater based on long-term statistics. More complex time domain calculations are carried out to check the results obtained by the frequency domain computation.

Before conducting the seakeeping behaviour analysis of the floater, limiting criteria for the response in waves have to be established in order to be able to evaluate the calculation results. The applied set of

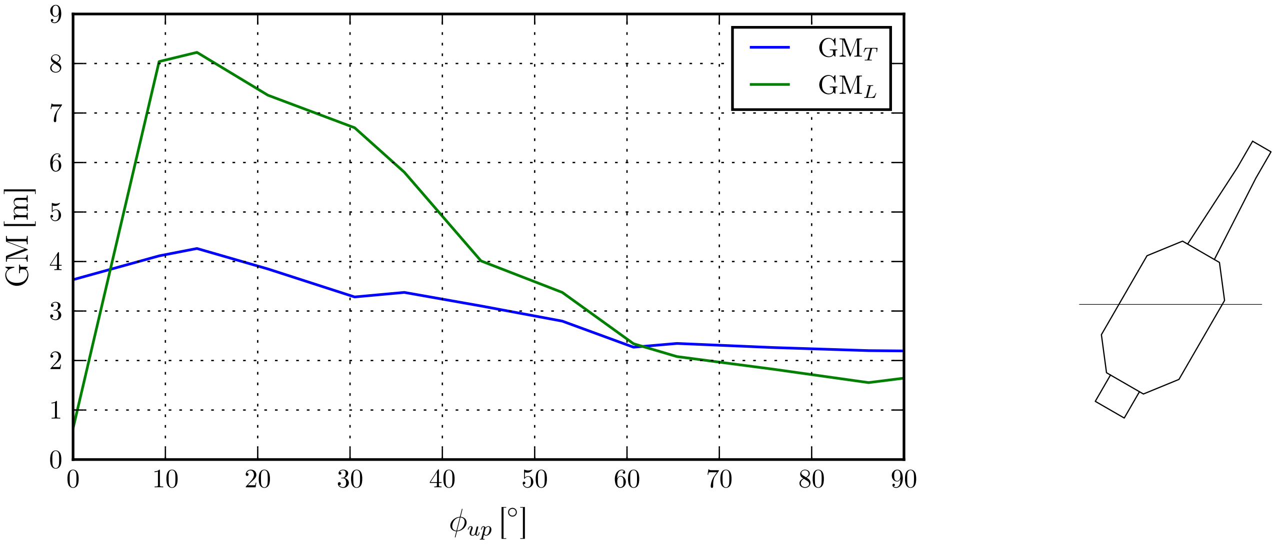


Figure 6: Transverse and longitudinal stability during the upending process

limits is given in Table 2 for the different installation steps with the floater from Section 2. Most of the criteria are based on assumptions for unmanned offshore barges [5]. The heave double amplitude is additionally established to restrict vertical motions, that are too large, especially for the sensitive situations of the docking position and the touchdown situation. In the latter case, the touchdown itself requires restrictions as the final push on the seabed will lead to an impulse through the whole structure. The roll and pitch angles are restricted sharply in the docking situation and even more for the touchdown case. During docking, the motions of the floater could lead to a collision between it and the crane vessel when approaching and therefore have to be kept in reasonable ranges. In the touchdown situation, the inclination of the pile is pre-determined by the requirements on verticality of the monopile after installation [13, p. 40]. It is assumed that the gripper system in the floater can correct the inclination by a small margin, but this still limits the allowable motions, as it is not possible to properly adjust its verticality during or after pile driving.

4.3.1 Seakeeping calculations in frequency domain

The potential flow theory based methods "PDStrip" and "*pan*MARE " are applied. While PDStrip works in the frequency domain, *pan*MARE enables simulations in the time domain. According to potential flow theory, an inviscid, rotation-free fluid is assumed. The linear assumption for regular waves allows for the superposition and linear relation between response and wave-height [14]. The seakeeping behaviour of the FlUP during the transport condition is calculated with PDStrip, as the horizontal FlUP with the pile complies with the assumptions of the slender body theory. In the vertical conditions of the docking and lowering phases, the strip theory is no longer applicable and the calculations are carried out by using the *pan*MARE method. In this case, the diffraction forces are neglected. This simplification introduces

Table 2: Limiting criteria for the installation phases

Criterion	Transport	Upending	Docking	Touchdown
Heave double amplitude	2.5 m	2.5 m	1 m	1 m
Single roll amplitude	20 °	10 °	2.5 °	1.1 °
Single pitch amplitude	10 °	20 °	2.5 °	1.1 °
Heave acceleration	0.2 g	0.2 g	0.2 g	0.1 g

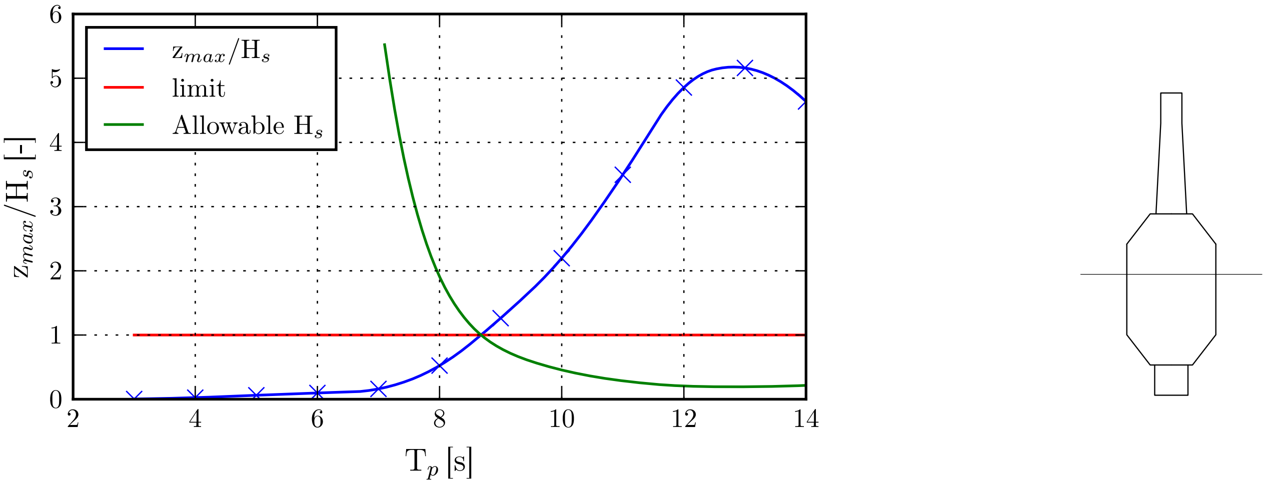


Figure 7: Maximum response over peak period for heave in the docking situation

certain uncertainty which is assumed to be acceptable for a feasibility study. The diffraction is considered to make an impact in the case of the diameter to wavelength ratio $\frac{\pi \cdot D}{\lambda} > 0.5$ [11, p. 6-20 f.] [15, p. 164]. With this criterion, diffraction can be neglected for waves longer than about 190 m, which corresponds with $T = 11\,\mathrm{s}$ in deep water. The relevant natural frequencies of the floater in the vertical state are in this range or above it so that the negligence can be applied for the most important motion characteristics. The frequency-dependent radiation is conservatively estimated for a cylinder in shallow water [16] and added to *pan*MARE ; this value is considered as a velocity-dependent term in the equation of motion. Thus, the damping might be smaller than in reality and the reaction at natural frequencies is not exactly precise. Making the step from response on regular waves to a more realistic sea state, a long-crested, single-peaked JONSWAP-spectrum with a peakedness factor of $\gamma = 3.3$ is applied to account for wind seas in a fetch-limited area as typical for the North Sea and the Baltic Sea [6, 17]. The impact of the response at natural frequency in irregular waves can be evaluated based on the governing criterion in the docking position: Figure 7 shows the ratio between the heave response amplitude and the significant wave height z_{max}/H_s over the wave period T_p, which is increasing significantly with the period rising towards the natural frequency. Furthermore, the limiting significant wave-height H_s (limit divided by z_{max}/H_s) is plotted as a guidance. This figure clearly shows that the system is prone to long waves as found in swell, but shows good results in sea states with a short peak period as usual for normal weather conditions. This behaviour is known for monopile installation processes with heavy-lift vessels as well [18]. An example for the resulting operability estimates using exemplary scatter diagrams from the North Sea and the Baltic Sea [19, Appendix E] for long-term statistics is shown in Figure 8. It shows the operability for the transport phase in the North Sea, which is generally estimated with at least 60 %, having the clear governing criterion of the heave motion. Results for the other installation phases in the North Sea with the limits defined in Table 2 are 63 % for the docking and 50 % in the touchdown situation. With the applied scatter diagram for the Baltic Sea, the operability reaches more than 88 % in every situation.

4.3.2 Seakeeping simulation in the time-domain

Time-domain calculations in irregular waves are carried out with *pan*MARE to support the frequency-domain results for the installation steps of docking to touchdown depth (the touchdown itself is not explicitly simulated). Thus, the lowering process after docking is evaluated in different sea states. As well as for the frequency-domain calculations, diffraction is neglected and radiation damping is only estimated for a cylinder in shallow water as an input [16]. An exemplary plot in Figure 9 shows the result for the vertical motion over time in a sea state with $T_p = 8\,\mathrm{s}$ and $H_s = 1.5\,\mathrm{m}$. It is visible that the lowering of the system by 5 m dominates the underlying oscillations due to waves. This plot confirms the rather

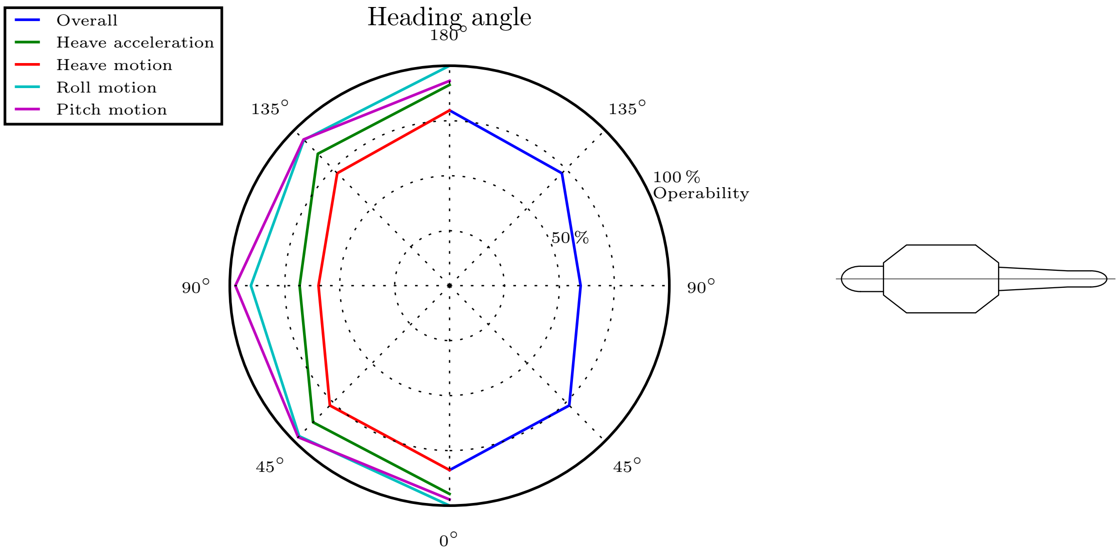


Figure 8: Operability percentage in the transport situation with 6 kn in the North Sea

conservative results of the frequency-domain analyses as the visible response in the time-domain analysis is low at a T_p of 8 s compared to Figure 7.

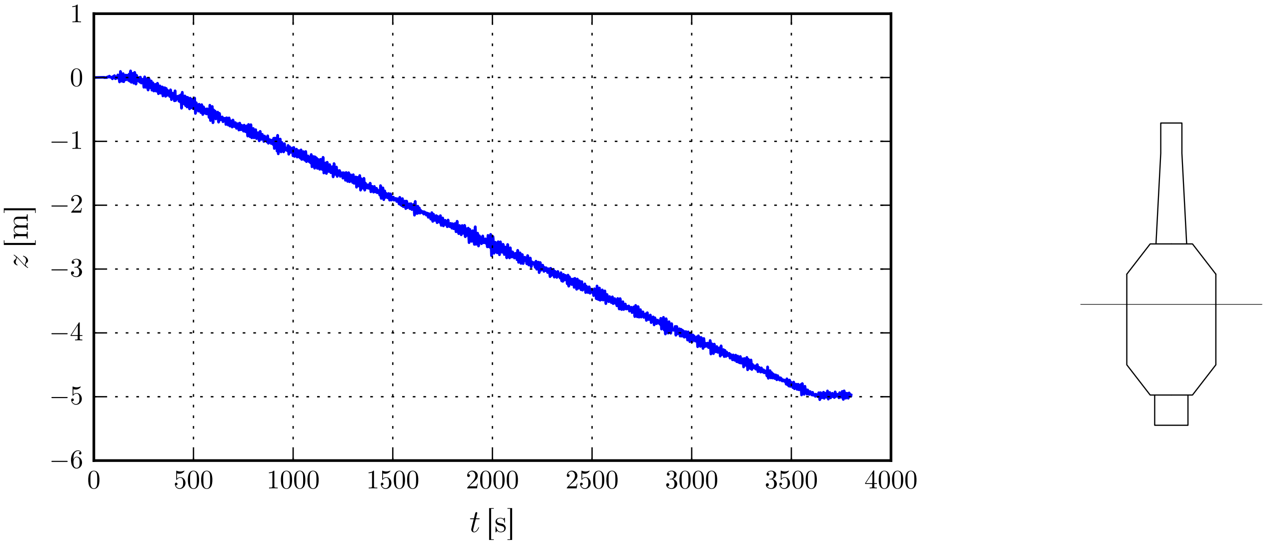


Figure 9: Vertical motion lowering in irregular waves, $T_p = 8\,\mathrm{s}$ $H_s = 1.5\,\mathrm{m}$

5 CONCLUSION

A preliminary design for a specialised floater for upending large monopiles as a new installation method which requires less crane capacity is presented. The calculation results confirm that the concept is generally feasible from a hydrostatic and seakeeping point of view. The hydrostatic stability is examined for all installation steps. These are the transport condition, upending and docking phases as well as the lowering-to-touchdown step. The general feasibility in an offshore environment could be shown by frequency-domain calculations, which reveal a reasonable behaviour in the transport and docking phases. These results of generally satisfactory seakeeping behaviour are supported by the time-domain seakeeping calculations for the lowering process.

On the way towards a possible implementation of this (or similar) new installation methods, more elaborated designs are possible and required. Furthermore, more precise and advanced calculations on the presented topics as well as on not yet considered aspects like structural strength and ballast water treatment are necessary. Finally, the presented solution in the paper confirms the feasibility of a new approach for installation of large monopiles which may be needed for the upcoming challenges in the offshore industry.

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