Offshore & Dredging Engineering

Technische Universiteit Delft

Offshore Wind Turbine Installation Using A Double Slip Joint

One of the challenges associated with offshore wind turbine installations is the mating phase. Aligning a transition piece onto its substructure under offshore conditions is a complicated and time-consuming procedure. Another issue found in a number of commissioned offshore wind turbines is related to the sustainability of the connection between the transition piece and the substructure.

With wind turbines increasing in size and wind farms being built further from shore in deeper waters, the current bolted- and grouted connections are seemingly not the most suitable future proof options. This is where the Double Slip Joint steps in. A simple plug- and go connection device provided by KCI The Engineers.
The Double Slip Joint's innovative solution takes away the time-consuming phases like manually fastening a number of bolts or the buffer period of waiting for grout material to fully solidify before commissioning a wind turbine. This study aims to gain more useful insights on the installation behavior of the Double Slip Joint during the mating phase under various offshore environmental conditions.
The chosen system for this study consists of a hoisted wind turbine tower which is lowered onto a monopile.

A numerical model for this tower-monopile system is developed in Excel where the user is able to manipulate input parameters such as mean wind velocity, tower lowering velocity, crane motions etc.

After a series of validation using ANSYS Finite Element models, simulations from the developed Excel model were carried out to study the Double Slip Joint's behavior during the mating phase from both a jack-up - and a floating vessel. A key finding from this study is the necessity to round off the sharp edges of the Double Slip Joints conical rings in order to avoid contact stresses that might lead to unwanted damage.

The simulation results indicate that installations carried out from a jack-up vessel can be optimised to perfectly tolerate a mean wind velocity of 15 m/s, whereas that of a floating vessel can be optimised up to 13 m/s.

The possibility of achieving higher mean wind velocities indicate that the weather window for offshore installations can have a greater range. The results obtained from this study confirm the potential of the Double Slip Joint for future offshore wind turbine
installations.

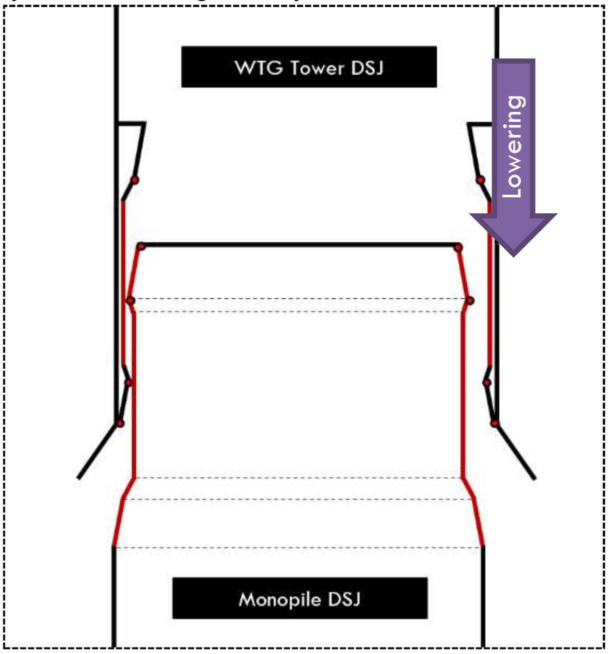

Figure 1 Tower-Monopile Lowering Phase (2D Front View)

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Offshore & Dredging Engineering

Optimized design of a seabed monopile gripper

To increase the benefit of wind energy, the next generation wind turbines are becoming larger and are moving into deeper waters. This significantly increases the size and weight of the corresponding monopile support structures. In current practice, the majority of monopiles are installed using jack-ups or floating vessels using so-called monopile gripper frames. Both vessels have their advantages and disadvantages. Jack-ups are limited by weather conditions and lifting capacity depending on the jack-up legs. For floating vessels, it is difficult to achieve stability and verticality of the monopile during installation, because the gripper frame moves with the vessel. This reduces the operating weather condition for installation of monopiles using a floating vessel.

To operate in larger weather windows and to be able to lift larger loads, Van Oord is investigating the use of a monopile gripper on the seabed, so that the gripper frame is no longer subject to the motions of the vessel. To install a monopile support structure using a seabed gripper, the monopile gripper frame is installed first. The monopile is then slewed into the gripper frame, which is able to hold the monopile in position and vertical while hammering it. After the installation of the monopile, the seabed gripper structure is removed and transported to the location where the next monopile is to be installed. This thesis covers the optimized design of such a re-usable seabed monopile gripper.

First, the different options for the gripper structure and its foundation currently available in practice are identified from a literature study. Suitable concepts for the gripper structure are generated based on the requirements, of which the two optimal concepts are selected based on a Multi Criteria Analysis (MCA). A four-legged Jacket and a Tripod are chosen as the best concepts for the gripper structure using either Helical piles or Suction buckets for its foundation.

A preliminary design of both the gripper structure and the foundation is done to identify the initial member sizing and reactions of the piles at the seabed. A FEM model of the gripper structure including a soil model is created in ANSYS and analysed for both members and joints in ULS conditions. Due to the required opening on one side of the gripper structure (to slew in the monopile), the stresses at the joints of the gripper frame are higher than anticipated and strengthened accordingly. Based on the soil-structure interaction, the four-legged jacket structure is selected as the best concept, because its piles are further apart than for the tripod structure, thereby leading to minimal interaction between the piles of the gripper structure and the installed monopile. Still, both helical piles or suction bucket can be used as the foundation for jacket. A fatigue analysis shows that the gripper frame is subjected to cyclic loads that lead to high bending stresses at the joints leading to possible failure. Based on this, certain modifications have been made to the gripper structure to properly distribute the stresses.
A case study has been performed comparing the monopile installation by a floating vessel with and without seabed gripper. This case study shows that the time taken and cost associated with monopile installation using the jacket gripper structure is most economical using suction buckets. However, modification of the installation using helical piles may lead to time- and cost-reduction compared to using suction buckets. Taking this into account, a more detailed analysis is required to determine whether helical piles or suction buckets should be used.
From this thesis, it is thus concluded that a four-legged jacket structure with either helical piles or suction buckets is an optimal seabed gripper structure. The optimized design is presented in the report.

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Offshore & Dredging Engineering

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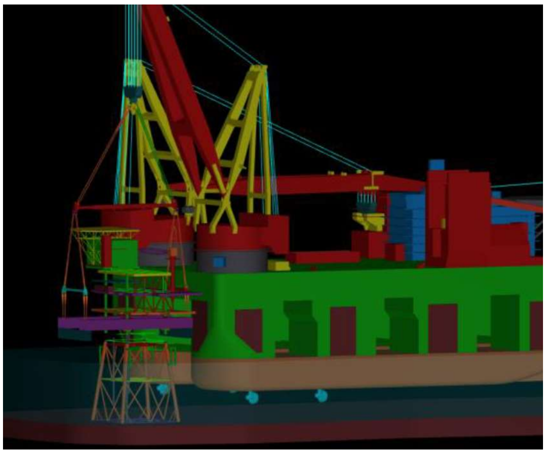
Development and optimisation of the lift beams topsides removal concept

A large number of light, modular topsides in the southern North Sea is planned to be removed in the near future. Heerema Marine Contractors (HMC) is currently not the most competitive in this market as smaller contractors can often provide cheaper removal solutions with the use of smaller heavy lift vessels. HMC therefore aims to find a more economically attractive solution for the removal of these topsides.

Within HMC, a concept has been proposed to remove these modular topsides using so-called lift beams. The lift beams are large beams that are installed underneath the topsides, and are connected to the topsides' strong points. The ends of the lift beams provide lift points for the complete topsides, enabling removal in a single lift. Due to their high lifting capacity, and large available deck space, the modular topsides on the lift beams can easily be lifted by a single crane of one of the company's semi-submersible crane vessels (SSCV). Performing the lift by a single crane allows to put the topsides on deck of the SSCV for transportation. The concept is intended to be reused for a variety of modular topsides in the southern North Sea.

In this thesis, the lift beams are designed, and optimised, to withstand the governing load cases, while complying with the practical boundaries that each topsides imposes. Hereafter, it is investigated whether it is structurally feasible to lift the modular topsides using the lift beams. To determine this, structural integrity analyses are performed on a reference topsides using FEM software. The optimal lift beam setup is also determined at this stage. Furthermore, methods are designed for the connection between the lift beams and the topsides, and the installation of the lift beams. Finally, the efficiency of the final lift beams concept is assessed by comparing its performance to conventional removal methods for modular topsides.

The lift beams and the topsides are found to have sufficient capacity to withstand the loads during lifting. Ideally, the topsides is lifted using a setup which consists of two lift beams per jacket leg row, and cross-beams at each end-on side of the lift beams. The cross-beams add stiffness to the lift beams and thereby redistribute the lift loads in a favourable manner over the connection points. Using a pin-hole connection between the lift beams and the topsides legs is found to be most suitable. The lift beams are installed using water as the counterweight component. Compared to conventional removal methods, the lift beams concept appears to be profitable after a relatively small number of topsides removals.



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Offshore & Dredging Engineering

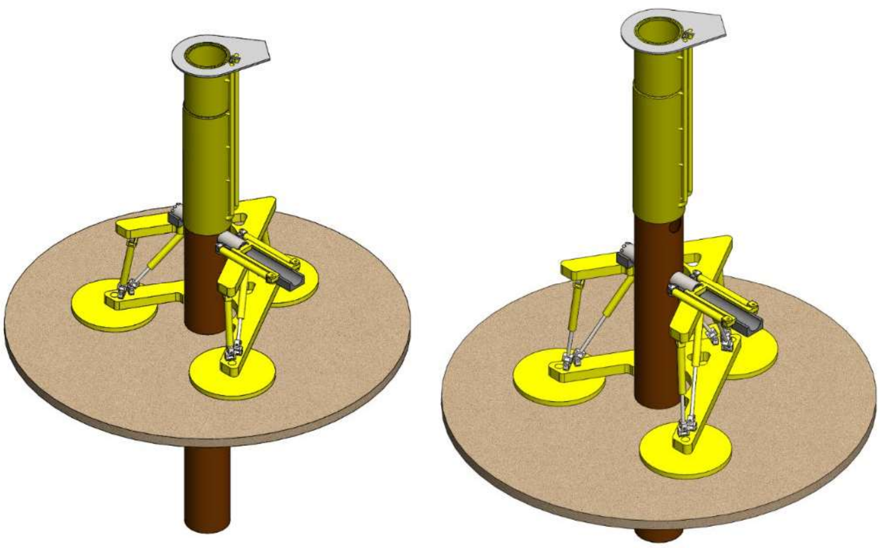
Entire monopile foundation removal

In the European seas 5202 turbines have been installed or are under construction. The vast majority, 4474, are built on monopile foundations. It is expected that all these foundations eventually need to be decommissioned. For the decommissioning of these monopiles there are two options: entire removal or partial removal. Most permits require partial removal during the decommissioning phase, but is this really the best method?

This study endeavours to find the most competitive, safe, and environmentally friendly method to remove entire monopile foundations. For defining the scope, the existing monopile foundations are analysed and categorized in an easy, normal, and difficult case scenario. After that, the extraction loads of the three scenarios are calculated for the situations with and without soil friction reduction. Using these load cases, potential extraction principles are assessed on their technical feasibility. The extraction principles are split in three categories: lift connection, lifting techniques and technical aids. Next, the most competitive, safe, and environmentally friendly combination of principles is selected with a Multi Criteria Analysis that is based on the perspective of marine contractor. The highest scoring solution is verified with calculations. The final step is to validate and verify the selected solution.

The result of this study is a bottom founded tool that uses axial cyclic loading and a beam-hole connection to extract monopile foundations. After the hole cutting and installation of the circular lifting beam, hydraulic jacks are used for cyclic loading and extracting the monopile foundation. For the easy case scenario, three to four lift-cycles are needed for the extraction process. A crane is used to position and retrieve the tool. In addition, the crane ensures a safe lifting operation. The removal tool is powered and controlled from the crane vessel.

In the end, the method proposed in this study is the most competitive, safe, and environmentally friendly for entire monopile foundation removal when considering the boundary conditions of this study. Even when it is compared with partial removal, it scores better. It is noted that the selection process has a high sensitivity to different criteria and scoring. Especially when all HSE-risks are considered mitigated, other concepts may score better than the one proposed. It is advised to do further research on the soil friction loads and beam-cutting techniques.



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Offshore & Dredging Engineering

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Earthquakes and Offshore wind turbine installation; A review and analysis of mitigation measures for cranes on jack-ups

Due to a high demand for offshore wind energy the industry is expanding to evermore challenging locations such as seismic prone areas. The corresponding seismic shocks and vibrations can be transmitted to jack-up vessels and their cranes used for the installation of these offshore wind turbines. Since a potential collapse due to seismic activity carries large human and financial risks, the main objective of this thesis is:

”To determine the best solution to mitigate the dynamic response of cranes for offshore wind turbine installation in seismic prone areas.”

Therefore, we study existing mitigation measures and find that the dynamic absorber and base isolation systems are promising solutions. However, we only find the dynamic absorber to be feasible for implementation.

Subsequently, we investigate the influence of the dynamic absorber on the dynamic response of the crane by performing seismic time history analyses. We find a mitigating influence for the vast majority of simulated cases. More specifically, the dynamic response in the out-of-plane direction is reduced by 10 percent on average. Furthermore, the dynamic absorber is highly effective in the mitigation of harmonic vibrations such as those that are induced by Rayleigh waves that occur near the end of earthquakes. This finding suggests that dynamic absorbers might also be suitable for mitigating wave and wind loads in the crane as these loads prescribe a rather harmonic signal.

The conclusions of this thesis give the offshore wind industry a clear indication that a dynamic absorber is an effective measure to mitigate the dynamic response of a crane that is based on a jack-up.

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Bayesian system identification for structures considering spatial and temporal dependencies

Bayesian system identification, including parameter estimation and model selection, is widely used to infer partially known, unobservable parameters of the models of physical systems when measurement data is available. A common assumption in the Bayesian system identification literature is that the discrepancy between model predictions and measurements can be described as independent, identically distributed realizations from a univariate Gaussian distribution. However, the decreasing cost of sensors and monitoring systems leads to more frequent structural measurements in close proximity to each other (e.g. fiber optics and strain gauges). In such cases, dependency in modeling uncertainty could be significant, both in space and time, and the assumption of uncorrelated Gaussian error may lead to inaccurate parameter estimation.

The aim of this thesis is to explore how Bayesian system identification can be feasibly performed using large datasets when spatial and/or temporal dependence might be present and to assess the impact of considering this dependence. A pool of models, each assuming a different correlation structure, is defined and Bayesian inference is performed. In particular, stress measurements obtained on a steel road bridge are used to update the parameters of the corresponding FE model and the parameters of the correlation structure. The results are compared to a reference model where only measurements of the response peaks are used under the assumption of independence. Nested sampling is utilized to compute the evidence under each model and Bayesian model selection is applied. The question of efficiently performing system identification for large datasets ($N > 10^2$ for temporal dependencies and $N > 10^3$ for combined spatial and temporal dependencies) is investigated, and a novel approach for efficiently calculating the exact log-likelihood is derived. An approximation based on the Fisher information matrix is used to efficiently calculate the information content of measurements.

It is found that the choice of correlation function can significantly affect the posterior distribution of the model prediction uncertainty. Additionally, it is shown that using large datasets and considering dependence makes it possible to perform system identification for a larger number of parameters compared to the reference model. The results of the case study indicate that using measurements from multiple sensors under combined spatial and temporal dependence and additive model prediction error yields reduced uncertainty in the posterior and up to 29% reduction of the posterior predictive credible interval range compared to the reference case. Furthermore, the efficiency of the proposed likelihood evaluation method is assessed. Using this method, exact calculation of the log-likelihood can be performed for $>10^6$ points in under a second in the case of correlation in one dimension.
For combined spatial and temporal correlation it is shown to be approximately 900 times faster than naive evaluation for a 64 by 64 grid of observations. The results of the case study indicate that the described approach can be feasibly applied to real-world structures and can potentially improve parameter estimation and reduce prediction uncertainty. These findings suggest that further research into the approach could yield improvements over current methods.

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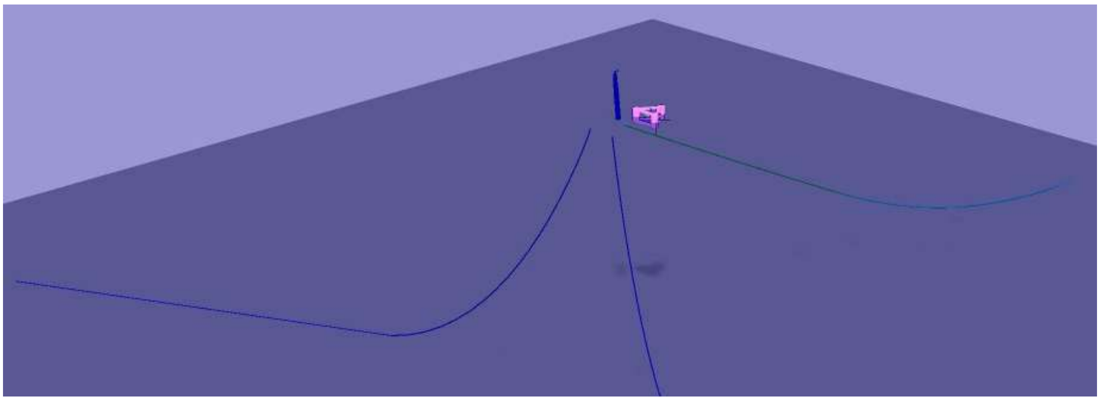
Feasibility of mooring system optimization for floating wind turbines in deep water based on static analysis

The goal of this thesis is to investigate the feasibility of optimizing the mooring line characteristics of a semi-taut (chain – polyester – chain) mooring system in combination with drag embedded anchors for a 12 MW wind turbine supported by a semi-submersible in deep water, based on static analysis of the Ultimate Limit State (ULS) condition. The optimization objective is mooring system material cost.
The hypothesis is that the ULS condition is design-driving. It is expected that static analysis optimization reduces optimization time and cost significantly in comparison to a full dynamic optimization. Additionally, a framework for a 6 wind turbine shared mooring farm concept is presented and challenges encountered are discussed. A gradient-based sequential quadratic programming optimization algorithm is implemented. Using static analysis results for optimization requires a relation between dynamic and mean mooring line tension. The initially implemented relation was found to be incorrect and showed that the relation is design- and condition-dependent. The optimizer reduces the mooring system costs by reducing the diameter of the mooring line segments, while the lengths of the polyester segment, bottom chain segment and anchor radius are increased to satisfy the constraints. The bottom chain segment is governing in material line material costs.
The Minimum Breaking Load (MBL), pretension and anchor uplift constraints are the most critical constraints. The top chain segment reaches the lower limit as it does not significantly affect the properties of the mooring system and other constraints. A total cost reduction of 48% with respect to the initial design and an estimated simulation time reduction of 40% with respect to a dynamic simulation were achieved. Fatigue Limit State (FLS) analysis of the optimized system showed that FLS is design driving, as failure in the chain segments would occur within 1 year.

To implement optimization based on static analysis a FLS constraint is required. A full dynamic FLS analysis is time consuming and a single degree of freedom model to estimate fatigue damage in the frequency domain based on surge motion and separation in frequency was implemented. The model was tested on two mooring system designs and compared to the simulated dynamic FLS simulation results. The model underestimates the accumulated damage consistently across the two designs and the segments. It significantly underestimates the damage accumulated in conditions with a long wave periods, which excite the natural frequency in heave, and showed that heave and pitch motion must be included for a more accurate damage accumulation estimate.
The shared mooring farm concept design is challenging due to the eccentric placement of the wind turbine. Additionally, the reduction in the number of anchor lines requires increased anchor line strength, causing a vertical force imbalance at the fairleads of the semi-submersible. This force imbalance requires a very robust finite element solution for use in optimization, which was not achieved. Adjustments of the positioning of each turbine, distribution of ballast or dynamic ballasting in the semi-submersible may be required to investigate the feasibility of the designed concept.



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Offshore & Dredging Engineering

Non-linear block load corrections for dry docking.

Damen is designing more and more slender hull forms, which leads to a small dock block contact area, and therefore a high load on the block bed. Dry docking is achieved by using multiple blocks located along the longitudinal length of the ship. Dock blocks are constituted by several layers, normally three or more. The configuration of the block bed (concrete in combination with hard- and softwood) creates the support of the vessel with non-linear behaviour. This study focuses on a prediction of the blockload in the dry dock, taking into account non-linear material behaviour of the timber layers.

Nowadays, the approach to predict the dock block load makes the assumption of linear elastic behaviour of the timber layers. The loads produced can cause a non-linear behaviour of each block, which might lead to an over-stress failure of one or more blocks. The assumption of linear elastic behaviour possibly results in wrong load distributions, which eventually leads to a redistribution of the loads on the other blocks. In turn this can force other block failures and ultimately this produces damages of the hull forms. The consequences of a poor dry docking analysis are potentially catastrophic. A docking failure can lead to extensive ship and dock damage, disruption of docking schedules, and loss of the ship to active duty until repairs can be made. Two set of models are conducted to predict the load on a dock block and evaluate the influence of the non-linear behaviour.

The Timoshenko beam theory with multiple springs is used to calculate the load on every single dock block location. The load on every particular location is used in the model for a single dock block formed by elastically connected beams. A double Winkler foundation system represents the interaction of the stacked block layers and dictates the non-linear behaviour. Non-linear material properties are captured by the secant modulus of the top layer.
A test campaign pointed out that for each layer of nominal identical specimens a large variability in material properties is noticed. Material properties found in the literature were different from those obtained during experiments. Moisture content has a significant influence on linear and non-linear affect, with the Young's modulus and yield point being shifted to lower values.
The variability in material behaviour and moisture content must be considered when predicting the block load. Moisture content variability lead to changing block bed load distributions. Underestimation of the moisture content can lead to large differences in the single dock block analysis. With the good matching in the validation work, this research confirms the reliability of a double Winkler system to prescribe non-linear material behaviour of a single dock block.
Although the analysis of a The model of a Timoshenko beam on spring supports gives reasonable results, but underestimates the load in case of local increased stiffness caused by a transverse bulkhead. Optimization on this particular section is needed to get more realistic results..

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Low-Frequency Hydrodynamic Modeling of a 12 MW Semi-Submersible Wind Turbine

The natural frequencies of the INO WINDMOOR platform in surge and pitch are below the frequencies of typical wave energy, and thus large resonant motions are not excited by first order loads. A first and second order potential flow analysis is performed including a difference frequency quadratic transfer function. The resulting coefficients with a constant value of critical damping are used to predict the motions of the platform in wave only conditions. The predicted motions are compared to model test data for mono-chromatic, bi-chromatic, and irregular waves. The wave frequency motions are well predicted. The low frequency motion is under-predicted for short wave heights and is over-predicted in large wave heights. The discrepancies are attributed largely to a lack of accurate viscous effects.

With low-frequency resonance, viscous flow effects can become important. For the probable flows around the semi-submersible, it is predicted that the viscous flow effects are best described as a function of KC number. A computational fluid dynamics study was performed in OpenFOAM, including mono-chromatic and bi-chromatic forced oscillations over a range of KC numbers. A distributed model of the platform geometry was used with vertical divisions. From time series of forces on each division, three coefficients were extracted: added mass, linear radiation damping, and quadratic viscous damping. The potential flow contributions were subtracted, removing the frequency dependency and leaving only viscous corrections. The resulting functions of KC number were tested by predicting the forces of the combined oscillation cases.

The correction functions were implemented in the time domain motion prediction model. The functions were tested both with all three viscous correction coefficients included, and with only the quadratic damping coefficient included. The quadratic damping only model resulted in the most accurate motion predictions. It is concluded that the post-processing for forced oscillations is very sensitive, and it is difficult to remove the potential flow frequency dependence from the results. Because viscous changes to potential flow coefficients are so linked to frequency, it is more effective to neglect these for the KC number based functions, and only include the quadratic component. After analysis some changes would be made to the test procedure, but it appears that the method of adding KC number based viscous corrections from forced oscillation CFD simulations can offer improved low-frequency motion predictions.

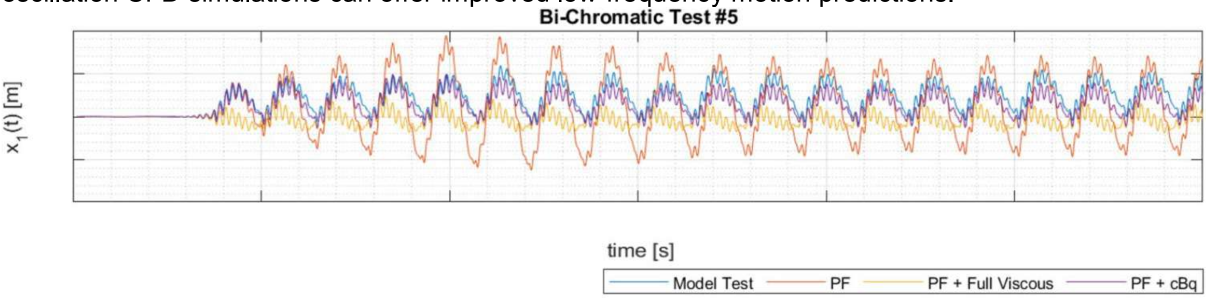

Figure 1: Reconstructed surge time series comparisons (model test data source: Sintef Ocean OMAE2021-62980)

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Offshore & Dredging Engineering

Workability optimisation of the Stella Synergy during monopile installation with a motion-compensated gripper and using its DP-system

It is essential to shift to a decarbonised energy supply by producing renewable energy on a large scale to stop climate change. Wind energy is one of the most promising renewable energy sources, and most wind turbines use a monopile as support structure. Using a floating vessel operating on its DP-system and using a motion-compensated pile gripper to install monopiles could be the installation method of the future. Therefore, this thesis focuses on this method. The main objective of this thesis project is to build a model that accurately describes the motions of the Stella Synergy, the monopile, and the motion-compensated gripper, depending on the environmental conditions.

This model is built in Anysim, which is a time-domain simulation software program of MARIN based on the RK2 numerical method. The model considers the early pile driving phase because this phase is governing in terms of risk. The monopile acts as an inverted pendulum in this phase, and the motion-compensated pile gripper must guarantee the stability of the monopile. The vessel uses its DP-system for station keeping. The DP-system contains a position reference system, a filter, a control system, and a thruster allocation algorithm.

The vessel describes the wind, current and wave forces on the monopile and vessel. The environmental conditions are assumed to be collinear, and wave spreading is added to the model for some simulations. The wave forces on the vessel are determined with diffraction calculations in Ansys AQWA. The diffraction calculation for the vessel is verified with a diffraction calculation of MARIN, and the diffraction calculation for the monopile considers the shielding effect and is verified with a calculation with the Morison equation.

A motion-compensated pile gripper with two PD-controllers is built in Python. One PD-controller is used to determine the force to compensate the vessel's motion, and the other controller is used to determine the force to keep the monopile vertical. The gripper considers static and dynamic friction forces and a maximum delta force per numeric timestep to model the pressure build-up time of the hydraulic cylinders. The gripper is capable of compensating the vessel's motion for 60% to 95%, depending on the sea condition it is operating in.

After verifying every single element of the model, multiple 3-hour simulations are run to generate results. These simulations, which considers each a different sea condition, are tested by the six limitations of the model. First, the preferable incoming angle of environmental conditions is determined. The workability of the Stella Synergy is calculated operating at the North Sea using this preferable incoming angle of attack. Then, two adaptations to the model are tested to increase the workability. Using fast-rotating thrusters or changing the DP-gains result in the workability of 96.4%. The governing limitation is the pitch motion of the vessel.

It is tested if using mooring lines in combination with the DP-system results in a footprint reduction. It is concluded that adding mooring lines could result in a footprint reduction, but it is crucial to gain insight into the optimal axial stiffness of the mooring lines. The monopile's influence on the vessel's motion is also tested. It is concluded that the vessel's surge, sway, roll and yaw motion increases significantly due to the environmental forces on the monopile, which are passed through the gripper to the vessel. Finally, the workability of the vessel during the worst-case single failure is determined. After improving the DP-gains for particular sea conditions, the workability for the worst-case single failure was 96.0%. The failure results thus in a minor difference in the workability.

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Development of clustering strategy to optimize the design of RNA and support structure in offshore wind farm under seismic conditions

Offshore wind energy is one of the emerging renewable technologies toward a zero-carbon emission society. Historically, offshore wind farms have been developed in the North Sea, but nowadays wind farms are expanded to other regions such as North America and Asia, which are seismic prone.

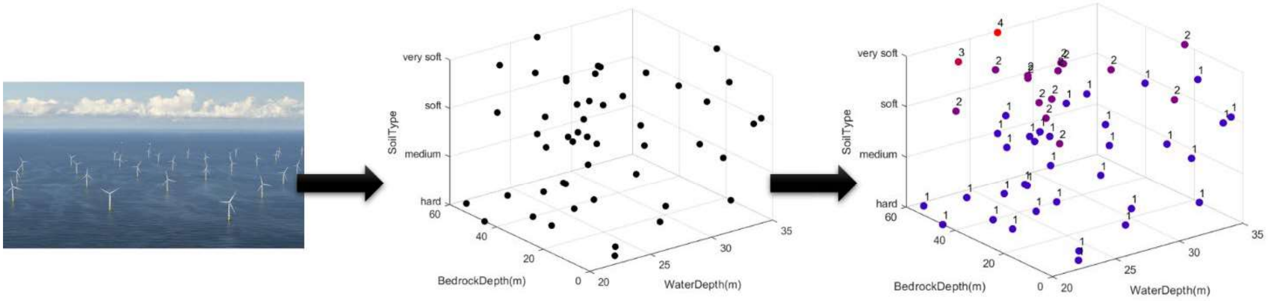
In the design of Rotor-Nacelle-Assembly (RNA) and support structure for offshore wind farms, the number of design positions is reduced by using representative design positions (i.e. clustering). The number of designs is directly related to the efficiency of the design work, so it is worthwhile to minimize it by wisely selecting the representative position. However, such a clustering methodology has not been systematically developed in seismic design due to the limited number of projects and researches in seismic regions.

As for seismic analysis, there are several challenges to develop an efficient clustering strategy. First, higher (and multiple) vibration modes are excited in the system consisting of the wind turbine itself in interaction with the soil. Second, blade vibration (and blade-structure tower effect) has a significant role in the output forces. Third, energy intake from the seismic ground motion is dependent on the position due to soil stiffness, soil amplification, etc. Considering the problem statement above, this research develops the clustering strategy for seismic analysis to optimize the design process on RNA and support structure for offshore wind farms.

To achieve this goal, as a first step, a simplified calculation model is created to efficiently carry out the sensitivity studies. A combination of point masses with Euler-Bernoulli beam is used for RNA model while lumped mass at the tower top is conventionally used in past researches, which allows to properly represent the blade-tower coupling effect. Considering modal participation mass, higher vibration modes are truncated, and principle vibration modes are detected, which improves the computational efficiency. Both the frequency domain method and the response spectrum method are developed and compared with proven software, BhawC, to verify their accuracy.

Then, a sensitivity study is carried out by using the developed model. Through the sensitivity study, the energy intake from the seismic excitation is quantified as a form of "scaling factor". Combining the scaling factor with acceleration response spectrum, the maximum bending moment for an arbitrary position (i.e. arbitrary water depth, soil condition and bedrock depth) can be quickly estimated. Subsequently, the positions in a wind farm are sorted into groups with similar load trends based on the estimated bending moment; this is the basis of the clustering strategy proposed in this thesis.

Finally, the strategy is applied to virtual wind farms and its applicability is verified. The accuracy is considered satisfactory to detect the worst positions and categorize the positions which have similar load trend. This is one of the main requirements for a reliable clustering methodology.



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Offshore & Dredging Engineering

Geotechnical design of offshore wind monopiles under cyclic loading

For supporting Offshore Wind Turbines (OWT), monopiles are currently the most common foundations. The role of a foundation is to transfer safely the loading to the ground. The wind and the wave loads are considered cyclic because they repetitively apply on the OWT. The North Sea is sand dominated in many areas. During cyclic loading, permanent strains develop in the surrounding soil while the soil stiffness and strength are irreversibly affected. Through time, the accumulation of strains can lead to the soil failure. Thus, assessing the behaviour and stability of monopiles under cyclic loading is essential.

To model the response of monopiles under lateral loading, the traditional design procedure is the use of p-y curves that express the lateral soil resistance in function of the pile deflection. The p-y curves are nowadays recommended to be calibrated on FE models.
The Stiffness Degradation Method (SDM) of Achmus et al. (2009) is a numerical strategy that assesses the behaviour of a monopile under cyclic loading. The method estimates the cyclically degraded stiffness based on the results of a static analysis. The soil stiffness is degraded based on a semi-empirical power law that accounts for the number of loading cycles, the stresses in the soil after the static analysis and two model parameters calibrated on cyclic triaxial tests.

The SDM was successfully implemented in PLAXIS 3D via a practical routine coded in Python and the use of soil clusters around the pile. The soil stiffness is degraded by updating the soil material within the clusters. The study model was verified by comparing results with the published reference system of Kuo (2008) for two piles with pile embedded length to pile diameter ratios of 2.7 and 5.3. The results indicate that the study model provides a stiffer pile-soil response than the reference model because the soil stiffness is overestimated. The degraded stiffness overestimation is attributed to the initial stiffness mismatch and the use of soil clusters. The impact on the short pile is greater than on the long pile because the short pile opposes less resistance to the loading and is thus more affected by the stiffness difference.

The study model was validated against three 1-g pile tests for homogeneous uniform and multi-layered dense sand. The numerical results are in agreement with the test data. In the absence of cyclic triaxial tests, the two model parameters were directly calibrated on the pile head displacement of the experiment. The two model parameters have a significant impact on the stiffness degradation. Thus, model parameters from literature were classified from the highest to the smallest estimation of pile lateral displacement.

The results of codified and published approaches (DNV-GL-0126; Duhrkop, 2009; Garnier, 2013) were compared with the results of the study model. The study model and the method of Garnier (2015) are in agreement. They both account for the loading amplitude, the number of cycles and the pile geometry. The codified procedure and the method of Duhrkop (2009) estimate higher lateral displacement compared to the study model. Finally, the 1D model was successfully calibrated with the highest displacement estimate of the study model. With this procedure, the 1D model accounts for the number of cycles, the pile geometry and the loading amplitude.

The study model provides a less conservative approach for determining the pile lateral displacement under cyclic loading. The calibration of the 1D model on the pile deflection curves of the study model is a promising procedure which will require further research.

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Offshore & Dredging Engineering

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Monopile Forever; Overcoming the Technical Boundaries of Monopile Foundations in Deep Waters

The demand for offshore renewable wind energy has experienced exponential growth and the power rating and corresponding dimensions of offshore wind turbines have increased significantly. Due to the ever-shrinking availability of easily accessible shallow water sites and the abundance of high-quality wind resources in deeper water, the industry is stimulated to come up with solutions to tap into these deep-water sites. Historically, the use of monopile foundations has been an important facilitator of cost reduction due to its relative ease of manufacturability, transportability and installability. Monopile foundations have, however, thus far only been used in relatively shallow water depths. With jacket-type and floating support structures remaining relatively costly, the question arises if the monopile could yet be scaled up further to be used in water depths beyond the current 40-60 m for future, 10+ MW wind turbines.

The goal of this research is to investigate the technical feasibility of monopile foundations in the water depth 'gap' of 60 to 120 meters, which is currently claimed by jackets, for large wind turbines and determine critical design parameters for up-scaling monopiles to these depths. With an eye on future developments a 15 MW reference turbine is adopted and to make the research widely applicable the Hywind Scotland site in the Northern North Sea is selected, a site with very severe wind and waves.
To define monopile designs, a parametric (static) monopile geometry optimization tool is developed in Excel, which transfers the environmental data to forcing components. The monopile geometry is optimized for first natural frequency and ULS resistance (yield and global buckling) by varying the outer diameter and wall thickness along the structure. It was found that the ULS check is governed by the inertial wave forcing during survival case. As the acting wave frequency is way lower than the system natural frequency, the monopile can be adequately assessed using a static approach. To assess the effect of critical variables, the tool is used to define monopile geometries for water depths ranging between 60 and 120 m, target first natural frequencies of 0.15, 0.17 and 0.20 Hz and a range of soil types, while complying with known manufacturing limits. The results show that all designs are within manufacturing limits and resistance against ULS decreases for lower target frequencies, making 0.15 Hz monopiles unfeasible.

In contrast to the ultimate limit failures, the fatigue damage is largely incurred from normal rather than ultimate wave states, which embrace the first natural frequency of the system, thus warranting a full dynamic analysis. To assess the fatigue resistance of 0.17 and 0.20 Hz monopiles, which pass the ULS check, an analytical full dynamic model is developed in Maple based on the fundamental equations of motion, including (added) mass, aerodynamic damping and soil/structural stiffness. The model is verified and validated against numerical modelling using ANSYS FEA software and found to be in very good agreement. I was shown that the fatigue damage accumulated over the 25-year design lifetime is governed by the bending stress cycles induced by inertial wave forces. The model is used to generate a transfer function between this wave forcing and the resulting bending stress over the entire range of present wave frequencies. The transfer functions are used to transfer the wave scatter diagram to accumulated fatigue damage against a B2, C1 and D graded S-N curve. The analysis results show increasing fatigue damage for decreasing first natural frequency due to the increasing slenderness and more prominent interference with present wave frequencies, which causes the 0.15 and 0.17 Hz monopiles to fail on fatigue damage. Given the very demanding site conditions assumed in this research, slenderer monopiles may be feasible in deep waters with a milder wave climate.
Overall, the results show no fundamental technical limitations for a monopile supported 15 MW wind turbine in water depths of up to 120 meters, provided that the stiffness of the structure is sufficiently high. Since steel usage increases for increasing stiffness, technically feasible monopiles will need to be relatively heavy, thus costly. Therefore, a range of strategies to reduce steel weight have been quantitatively assessed. It is found that the amount of steel can be reduced up to 35% by adopting higher-grade steel types and improved weld quality. Based on the fundamental limiting factors for monopiles found, also a novel hybrid floating-fixed bottom concept is proposed aiming at steel weight reduction. Although the concept can be considered promising, it does add complexity to the system and unfortunately does not (yet) result in steel reduction.

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Offshore & Dredging Engineering

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Structural response impact on floating offshore wind turbine performance under operating conditions

A rapid increase in global energy demand and the international objective of increasing the contribution of renewable energy to satisfy this demand have spiked the interest in offshore wind energy. Depletion of suitable locations for bottom founded turbines has led to a new chapter in offshore wind development: floating wind farms. This relatively new business brings many uncertainties and no large-scale projects have been deployed yet. The performance impact of an increase in structural motions, in comparison with bottom founded offshore wind turbines, is not yet fully investigated with respect to power production of the system. This thesis seeks to quantify this impact on performance by performing an integrated system analysis of a 15-MW semi-submersible based offshore wind turbine for operational conditions at a site north of Scotland.

All considered elements in the fully integrated simulation model are broken down individually and assembled in a finite element analysis framework via OrcaWave and OrcaFlex. OrcaWave develops system RAOs and QTFs using linearised potential-flow hydrodynamic radiation and diffraction theory in the frequency domain, whereas OrcaFlex is a finite element analysis software tool with full non-linear capability in the time domain. The non-linear flow separation induced quadratic drag in a real system, which is not included in potential flow theory, is introduced via a damping matrix by addition of Morison elements to the structure. The overall system including tower, RNA, controller and mooring is analysed by OrcaFlex in time domain. This overall integrated model was first validated and verified against a well-documented open-source reference model, provided by NREL and the University of Maine, and then adapted to the semi-submersible substructure selected for this study. A case matrix is developed representing the site environmental loading scenarios under operating conditions to simulate the dynamic interactions between substructure, RNA and controller.

The impact of wind-induced yaw misalignment mean offset angles on the mean power production is examined. For wind speeds below rated, an increase in yaw misalignment angle corresponds to a decrease in mean power production. For a functioning active yaw control system, misalignment angles of the rotor will be small and consequently the mean power reductions will be as well. For above-rated wind speeds, sufficient lift can be generated to compensate for the reduced rotor swept area caused by the yaw misalignment and therefore no reduction in mean power production occurs.
Load case results show that with increasing sea state severity, the motions of the system increase. The impact of this increase in motions can be observed in the generator power and rotor thrust response through their fluctuations. Performing an FFT on these parameters shows that most energy in the fluctuations is situated at the incident-wave frequencies and correspondingly, the wind and wave unidirectional load cases present the largest spectral density values for generator power and rotor thrust fluctuations.

Furthermore, the results present a connection between the severity of power output fluctuations and the mean power production for above-rated wind speeds. For increasing power production fluctuations, the mean power production experiences a reduction up to 0.39\%. A hypothesis is formed that links the mean power production reduction due to its fluctuations to the response time of the controller. In further research this hypothesis is to be tested and it should be further investigated whether a more detailed integrated analysis model produces similar results.
The fluctuations in power production impose challenges on the ability to connect to the grid. Connection of a single floating wind turbine to the power grid is not recommended, but when considering a group of multiple turbines it is assumed that the peaks in power production are flattened out over the total power production of the group. Capacitor banks can then be implemented to create a stable power output to the grid. Quantification of this farm effect is recommended for further research.

Finally, an indication of the rotor thrust impact on bending stresses at the tower-substructure interface is presented. A more detailed analysis is to be performed to find local stress concentrations and to address potential structural adjustments to fatigue-prone members.

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Technische Universiteit Delft

Offshore & Dredging Engineering

Motion analysis of EkoH suspended jacket transport with the Heerema SSCV Sleipnir
Comparison of model jacket motions vs actual jacket motions based on motion measurements and exploration of crane fatigue

This research explores the development of an accurate yet fast methodology to use measured vessel motions for a fatigue damage calculation in the cranes during suspended transport. First, the kinematics, definitions and particulars of the system of interest – the vessel including crane and suspended jacket - are provided. Then, literature research is done on the main two problems with any transport at sea: the inconvenient draft problem, and the forward speed problem. To remove the inaccuracies introduced by both problems, the novel TF A2B Method is introduced. The method can be used to find the required force transmissibility functions at location of the cranes that are most prone to fatigue: the welds at the crane boom pivots. It is mathematically proven that the TF A2B Method can be used and with validation tests set up for unrestrained suspended transport it is shown that the required RAO's can be obtained from in-house modeling software Liftdyn. Overall, its concluded that the TF A2B Method works in principle, removing the need to consider inconvenient draft and forward speed.

The hypotheses proposed in this research are further validated by the proposed validation tests in combination with a synthetic data model created in software tool Liftdyn. The Synthetic Data Model (SDM) uses a Jonswap Spectrum to obtain the motions at the Motion Reference Unit (MRU, 'A') and the Control Point ('B') at the modelled SSCV Sleipnir, which is assumed as a rigid body. After successful validation, the SDM model is then used to calculate the motions at the Jacket Sensor ('B'). Further validation of the found responses is done and it is confirmed that the location 'B' can in fact be located on another rigid body as the MRU, which in this research was the location of the jacket sensor. It is also shown that the transmissibility functions (TFs) between A and B are independent of draft, resulting in that the TFs between A and B are independent of the hydrodynamic properties of the modelled system. Therefore, it is concluded that the TF A2B Method can correctly find motions at location B by using the motions of location A in combination with the corresponding TFs between A and B.

The TF A2B Method is then applied to calculate the jacket motions using measured vessel motions. Data obtained from the EkoH suspended transport were processed and applied using the Measured Data Model. The calculated jacket motions are compared to the measured jacket motions during the EkoH suspended transport to the accuracy of the TF A2B Method with real data. An approximate 70% accuracy match with the measured suspended jacket motions, Roll and Pitch during the EkoH Suspended Jacket transport was found. It is noted that not all data was found to be suitable for use. Suggestions for improving this have been made and are expected to further improve accuracy of the match. The validated Liftdyn model of the EkoH transport is then used to model the suspended transport of EkoH. From the Liftdyn model Force RAO's can be obtained at the selected fatigue location of the cranes. A Fatigue Data Model using the TF A2B Method is proposed to find the stress cycles and thereby the fatigue damage during suspended transport.


Figure 1 Unrestrained suspended transport

Concluding, the TF A2B Method developed in this research shows positive results overall. The method can in principle be used to translate vessel measurements during suspended transport into fatigue life consumption of the crane. Further research is needed to improve the Measured Data Model, for which the use of a Surge and Sway motion sensor at the MRU is recommended. Furthermore, smaller vessel motions and more data samples should be used to further validate the accuracy of the method which is required to validate the Liftdyn model of the transport. Finally, to verify the results of the Fatigue Data Model, it is suggested to install strain gauges at the welds of the crane boom pivots for validation.

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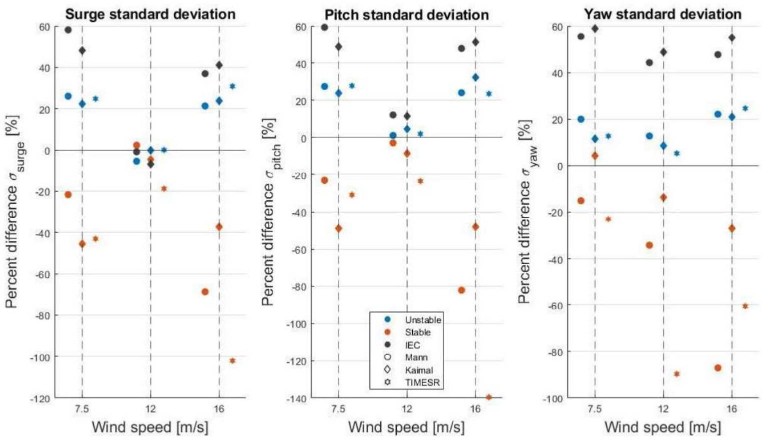
Atmospheric Stability Effects on a Spar-Type Floating Wind Turbine

Simulations of a spar-type floating wind turbine supporting the DTU 10 MW reference turbine under fitted atmospheric conditions are performed. Atmospheric conditions are modelled using the turbulent models recommended by the IEC: the Mann model and the IEC Kaimal and exponential coherence model. Model parameters are fitted to measurements at the FINO-1 platform to generate turbulent boxes that are as close as possible to measurements. The simulations are carried out using OpenFAST for three mean wind speeds: 7.5, 12 and 16 m/s and the power law wind profile is used with fitted shear exponent. The motions, wind, loads spectra are quantified using the WAFO toolbox and the loads are assessed with short-term damage-equivalent loads using MLife. Depending on the wind model, global motions differ by up to 52%. Generally, Kaimal resulted in higher surge and pitch motions, and the opposite was found for the yaw motions. The influence of atmospheric stability on global motions was found to be important as well, unstable conditions giving the largest motions and stable conditions the lowest. It was observed that the wind model influenced the fairlead tension and tower top loads. Mann resulted in up to 35% higher loads on the tower top yaw moment and Kaimal resulted in up to 30% higher fairlead tension loads. Tower base fore-aft bending moment and blade root out-of-plane moment were not very sensitive to the choice of wind model. Atmospheric stability had an influence on all loads by up to 30%. Unstable conditions led to the most damage while stable conditions generally led to the least. Whether the choice of the wind model or the change in atmospheric stability has more influence on the global motions of the platform and the loads depended on the wind speed, the degree of freedom or the load considered. It was found that wind models should always consider atmospheric conditions, not only neutral. Finally, impact of Mann turbulence model parameter variations on the wind, global motions and loads was investigated. It was found that turbulence intensity is influenced by the three parameters and has a bigger impact than the differences in coherence.



Technische Universiteit Delft

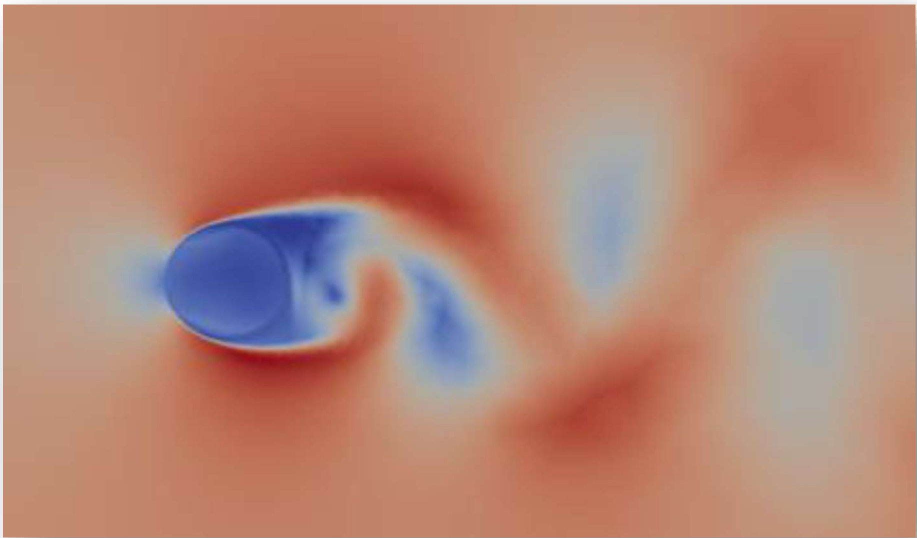
Offshore & Dredging Engineering

Exploratory research on application Multi-Level Multi-Fidelity Monte Carlo in fluid dynamics topics: study on flow past a porous cylinder

In offshore engineering complex simulation models are constructed for design optimization using Monte Carlo methods. These models incur large computational costs. Multi-Level Multi-Fidelity Monte Carlo is proposed as a method to reduce the computational cost of these simulations. In addition, research is conducted on the use of porous media as passive damping systems. Hence, an analysis on the effect of porosity on the vortex shedding frequency is conducted.
This thesis is an exploratory investigation on the application of Multi-Level Multi-Fidelity Monte Carlo in fluid dynamics topics and its particular use for analysis of the effect of porosity on the vortex shedding frequency on a porous circular cylinder.

Three case studies are conducted. Firstly, applying Multi-Level Multi-Fidelity Monte Carlo on a solid circular cylinder case, which is deemed as a successful application, based on the estimated quantity of interest, variance reduction and computational cost reduction. Furthermore, two parametric studies are conducted: 1) to discover empirical relationships (low-fidelity models) and 2) forward uncertainty propagation with Multi-Level Multi-Fidelity Monte Carlo using a uniform input distribution. Both parametric studies consist of a number of equally distributed points of porosity on a case setup of flow past a porous circular cylinder. The parametric studies use a frequency detection algorithm, which approximates the vortex shedding frequency using the frequency of lift force oscillation. The results of the first parametric study indicate there is a drop in vortex shedding frequency as experienced by the cylinder for increasing porosity. The hypothesis is that for increasing porosity the formation length of vortex shedding increases.

Two empirical relationships are derived from the results by curve fitting the Strouhal number (dimensionless form of the vortex shedding frequency) versus porosity. These empirical relationships are incorporated in the Multi-Level Multi-Fidelity Monte Carlo method and applied to a similar parametric study on the effect of porosity on the vortex shedding frequency. The results indicate the presence of systemic errors in the high-fidelity model. The conjecture is that the major influence on these errors is due to the resolution of the frequency detection algorithm being too low. For this reason, no clear conclusion on the validity of the empirical relationships is obtained and further research is required.



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Offshore & Dredging Engineering

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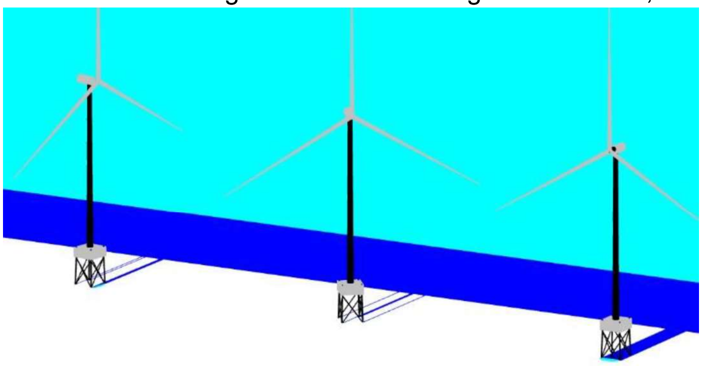
Influence of ice jams on ice-induced vibrations of multi-legged sub-structures

The world is transforming its energy production towards more sustainable sources of energy. In Europe, there is currently 25 GW of installed offshore wind power capacity. This is expected to grow with 29 GW over the next five years. Offshore wind farms can be expensive and challenging to build, design and maintain. Understanding the offshore environment will ensure that the to be produced offshore wind turbines are of sufficient quality while reducing costs. Monopiles are currently the most common sub-structure, but jacket sub-structures are becoming more relevant due to increasing water depth or changing soil conditions. Structures in icy waters, such as the Baltic Sea, may be subjected to ice induced vibrations while they encounter sea ice. These vibrations have to be considered in vertically-sided offshore structures' design and are the most critical load case when ice is concerned.
Multi-legged sub-structures, such as jackets, can have a problem that does not exist for monopiles, namely ice jamming, where ice fills the space between the legs of a multi-legged sub-structure. The legs and the jammed ice may then act as a single structural unit. Which leads to the main research question: how does an ice jam influence ice-induced vibrations of a multi-legged sub-structure?
First, a literature study of ice jams and multi-legged sub-structures was performed. This study concluded that different ice jamming situations are possible and have occurred with multi-legged structures, which not all have survived. The ratio between leg spacing and diameter plays a vital role in the ice action on multi-legged structures. Furthermore, the combination of ice-induced vibrations and ice jamming had not been studied yet.
Secondly, a model is made based on a phenomenological ice crushing model using COMSOL Multiphysics and MATLAB to simulate the structural response. The sub-structure is based on the jacket design for the NREL 5-MW reference turbine. Different situations from the literature study are used to make several design scenarios for which the structural response is calculated. In total, there are five situations: a base case, an angled base case, an internal jam, a frontal jam and an angled frontal ice jam. The base case does not have an ice jam, and the angled frontal jam has an increased thickness of the jam to twice the incoming ice. For the other jams, the thickness is equal to the incoming ice.
The different scenarios are simulated for a range of ice drift velocities to capture the different ice-induced vibration regimes and see how the structural response changes due to the presence of an ice jam. First, a baseline was established of the jacket's structural response for the base case. Afterwards, the three different ice jams were simulated. Results show that the base case is excited in all three ice-induced vibration regimes. At lower ice drift speeds, intermittent crushing is observed. Then at around 0.05 ms^{-1}, it transitions into the frequency lock-in regime. Here the structure is excited at its second natural frequency. For higher ice drift velocities (>0.2 ms^{-1}), continuous brittle crushing is seen. For the angled base case, the transition between intermittent crushing and frequency lock-in happens at around 0.1 ms^{-1}, and it stays longer in the frequency lock-in regime. The internal stresses around the contact area between ice and leg for the internal and frontal jam did significantly exceed the ice strength. Thus these jams would have failed on crushing at the contact area. The stresses inside the angled frontal jam exceed the ice strength but by a small margin. With all the assumptions made taken into account, the jam might hold. The structural response shows an increase in period for intermittent crushing and a lower amplitude in structural displacement than the base case.



The main conclusion is that an ice jam that would significantly impact the ice-induced vibrations cannot be sustained. The internal stresses exceed the ice strength which would cause the jam to fail. The ice jam that can be sustained acts as additional stiffness for the system and decreases the structure's displacement amplitude for the intermittent crushing regime. The properties of the frequency lock-in regime are similar in all scenarios because the maximum velocity of the structure will roughly be the same as the incoming ice floe because that is what excites the structure.

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Offshore & Dredging Engineering

Dynamic ice-structure interaction for jacket substructures

With a growing global demand of clean renewable energy, offshore wind activities will extend to more harsh environments, including sub-arctic areas like the Baltic Sea. Sea ice can occur here which needs to be taken into consideration in the design of substructures, i.e. jacket substructures, of offshore wind turbines. Several ice mitigating measures exist for jacket substructures, of which one is disregarding braces crossing the waterline. In this way, ice cannot induce loads to the relatively slender braces in the jacket. However, disregarding these braces has disadvantages in terms of structural integrity in comparison to a jacket including these braces.

Figure 1 – Jacket types without (Type 1, Left) and with (Type 2, Right) waterline crossing braces

In Part I of this thesis, two types of jackets, one without (Type 1, Fig. 1) and one with (Type 2, Fig. 1) waterline crossing braces, are implemented in a numerical model and subjected to ice loading in order to conclude whether the use of a Type 1 jacket design can be justified or whether a Type 2 jacket design is also suitable in sub-arctic areas.

Since over the past years the modelling techniques regarding ice-structure interaction have been updated and improved significantly, assessing the loads at the jacket braces can be done more accurately, allowing to give a more thorough conclusion on whether to use braces crossing the waterline on jackets in sub-arctic areas. As a result, a design including these braces could become feasible, whereas in the past it would be disregarded.

Two types of ice failure are considered in this research, being ice bending failure and ice crushing failure. First, a model is developed to quantify the ice actions occurring at a jacket substructure as function of the approach angle of the ice direction relative to the structure and as function of an introduced 'threshold angle'. It was found that ice failing in bending is equally significantly present as ice failing in crushing. Subsequently, numerical models are introduced that describe the failure behaviour of bending and crushing ice and the force that both ice failure types will induce to the structure. The structure is represented by a 5 [MW] offshore reference turbine supported by a jacket substructure. Using these models, dynamic simulations are performed in order to investigate the local susceptibility to ice induced vibrations (IIV), as well as assessing the Ultimate Limit State (ULS) load at the braces. As a result, local brace IIV regimes could be recognised, however frequency lock-in could not be observed. Furthermore, it was found that a Type 2 jacket could be suitable to use in sub-arctic areas considering the ULS load effects due to ice loading, but care should be taken for the ULS brace load, as that is of great importance for the design.

In Part II of this thesis, it is assessed whether coupled dynamic ice-structure interaction can be modelled using a dynamic substructuring modelling technique, also known as Craig-Bampton method, since it is industry practice to use such a method when jackets are involved. This method is based on a model order reduction of the full finite element model representing the structure, resulting in improved computational time and allowing assembly of multiple (reduced) substructures. The method is successfully implemented allowing to solve coupled ice-structure interaction problems and a framework to do so is provided. It is shown that excluding the loaded degrees of freedom (DoFs) in the jacket from the reduction leads to more accurate results and is considered convenient since few DoFs are loaded by ice, maintaining the effectiveness of the reduction method. As a result, IIV can be investigated using this reduction method, however challenges related to the accumulation of numerical accuracy errors arise with truncation of more higher frequency modes and require further development to be resolved.

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