Analysis of experimental data: The average shape of extreme wave forces on monopile foundations and the NewForce model

Experiments with a stiff pile subjected to extreme wave forces typical of offshore wind farm storm conditions are considered. The exceedance probability curves of the nondimensional force peaks and crest heights are analysed. The average force time history normalised with their peak values are compared across the sea states. It is found that the force shapes show a clear similarity when grouped after the values of the normalised peak force, $F/(\rho ghR^2)$, normalised depth $h/(gT_p^2)$ and presented in a normalised time scale $t/T_a$. For the largest force events, slamming can be seen as a distinct 'hat' on top of the smoother underlying force curve. The force shapes are numerically reproduced using a design force model, NewForce, which is introduced here for the first time to both first and second order in wave steepness. For force shapes which are not asymmetric, the NewForce model compares well to the average shapes. For more nonlinear wave shapes, higher order terms has to be considered in order for the NewForce model to be able to predict the expected shapes.

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Experimental and numerical statistics of storm wave forces on a monopile in uni- and multidirectional seas

Experiments with both uni- and multidirectional wave realizations with a stiff pile subjected to extreme wave forces are considered. Differences in crest heights and force peaks resulting from directional spread waves are analysed. The wave realizations are reproduced numerically in the fully nonlinear wave model OceanWave3D. The numerical reproductions compare well to the experiments. Only for the largest forces significant differences are seen, which is due to a very simple breaking filter applied in OceanWave3D. In the wave spectra, the higher harmonics occur for smaller frequencies than the straight multiples of the peak frequency. Further, the higher harmonics of the multidirectional wave spectra contain less energy. Both effects can be explained by the second order wave theory. Finally, the computed wave kinematics are used to investigate the dynamic response of an offshore wind turbine. The excitation of the first natural frequency is largest for the unidirectional wave realizations, as the higher harmonics are largest for these realizations.

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Extreme wave impacts on monopiles: Re-analysis of experimental data by a coupled CFD solver
Two different numerical models, OceanWave3D and a coupled solver, OceanWave3D-OpenFOAM (Waves2Foam), are used to reproduce extreme events in one sea state. The events are chosen as, the measured event that generates the largest peak moment (exceedance probability of 0.05%) and one event with a slightly smaller peak moment (exceedance probability of 0.3%). Time series of free surface elevation, depth integrated forces, bending moment at the sea bed and pressure time series at 5 different heights on the cylinder are compared for two events between the measurements and the numerical models. The numerical pressure field on the monopile at impact is analyzed and stagnation pressures at the back side of the cylinder, in addition to the main impact pressure at the front side are observed. There is a good agreement between the OceanWave3D results and the measurements in the reproduction of the first selected event. However, for the larger selected event, OceanWave3D results in the peaks of time series are smaller than the measurements. This illustrates the sensitivity of the strong impact loads to the state of wave breaking. For small values of the inline force, the OpenFOAM results provided good agreement with the measurements. The secondary load cycles are observed in the measured force and bending moment time series and the reproduced times series using OpenFOAM.

Prediction of the shape of inline wave force and free surface elevation using First Order Reliability Method (FORM)
In design of substructures for offshore wind turbines, the extreme wave loads which are of interest in Ultimate Limit States are often estimated by choosing extreme events from linear random sea states and replacing them by either stream function wave theory or the NewWave theory of a certain design wave height. As these wave theories super from limitations such as symmetry around the crest, other methods to estimate the wave loads are needed. In the present paper, the First Order Reliability Method, FORM, is used systematically to estimate the most likely extreme wave shapes. Two parameters of maximum crest height and maximum inline force are used to define the extreme events. FORM is applied to first and second-order irregular waves in both 2D and 3D. The application is validated against the NewWave model and also the NewForce model, which is introduced as the force equivalent of NewWave theory, that is, the most likely time history of inline force around a force peak of given value. The results of FORM and NewForce are linearly identical and show only minor deviations at second order. The FORM results are then compared to wave averaged measurements of the same criteria for crest height and peak force value. Relatively good agreement between the FORM results of free surface elevation including the second order effects, and the wave averaged measurements is observed. However, the inline force time series reproduced using the numerical method are not as consistent with the measurements as the free surface elevation time series. The discrepancies between the FORM results and the measurements is found to be a result of more nonlinearity in the selected events than second order and negligence of the drag forces above still water level in the present analysis. This paper is one step toward more precise prediction of extreme wave shape and loads. Ultimately such waves can be used in the design process of offshore structures. The approach can be generalized to fully nonlinear models.
A model for Quick Load Analysis for monopile-type offshore wind turbine substructures

A model for Quick Load Analysis, QuLA, of an offshore wind turbine substructure is presented. The aerodynamic rotor loads and damping are precomputed for a load-based configuration. The dynamic structural response is represented by the first global fore-aft mode only and is computed in the frequency domain using the equation of motion. The model is compared against the state of the art aeroelastic code, Flex5, and both life time fatigue and extreme loads are considered in the comparison. In general there is good similarity between the two models. Some derivation for the sectional forces are explained in terms of the model simplifications. The difference in the sectional moments are found to be within 14% for the fatigue load case and 10% for the extreme load condition.

DeRisk - Accurate prediction of ULS wave loads. Outlook and first results

Loads from extreme waves can be dimensioning for the substructures of offshore wind turbines. The DeRisk project (2015-2019) aims at an improved load evaluation procedure for extreme waves through application of advanced wave models, laboratory tests of load effects, development of hydrodynamic load models, aero-elastic response calculations and statistical analysis. This first paper from the project outlines the content and philosophy behind DeRisk. Next, the first results from laboratory tests with irregular waves are presented, including results for 2D and 3D focused wave groups. The results of focused wave group tests and a 6-hour (full scale duration) test are reproduced numerically by re-application of the wave paddle signal in a fully nonlinear potential flow wave model. A good match for the free surface elevation and associated exceedance probability curve is obtained. Finally, the utilization of DeRisk’s results in practical design is discussed. (C) 2016 Published by Elsevier Ltd.
Dynamic performance of a novel offshore power system integrated with a wind farm
Offshore wind technology is rapidly developing and a wind farm can be integrated with offshore power stations. This paper considers as case study a futuristic platform powered by a wind farm and three combined cycle units consisting of a gas turbine and an ORC (organic Rankine cycle) module. The first aim of this paper is to identify the maximum amount of wind power that can be integrated into the system, without compromising the electric grid balance. The stability of the grid is tested using a dynamic model of the power system based on first principles. Additionally, the dynamics of the system is compared with a simplified plant consisting of three gas turbines and a wind farm, in order to identify benefits of the installation of the ORC system. The maximum allowable wind power is 10 MW for a nominal platform load of 30 MW. The results show that the presence of the ORC system allows decreasing frequency oscillations and fuel consumptions of the platform, with respect to the simplified configuration. On the other hand, the dynamic response of the combined cycle units is slower due to the thermal inertia of the heat transfer equipment.
The influence of fully nonlinear wave forces on aero-hydro-elastic calculations of monopile wind turbines

The response of an offshore wind turbine tower and its monopile foundation has been investigated when exposed to linear and fully nonlinear irregular waves on four different water depths. The investigation focuses on the consequences of including full nonlinearity in the wave kinematics. The linear and nonlinear irregular wave realizations are calculated using the fully nonlinear potential flow wave model OceanWave3D [1]. The linear and nonlinear wave realizations are compared using both a static analysis on a fixed monopile and dynamic calculations with the aeroelastic code Flex5 [2]. The conclusion from this analysis is that linear wave theory is generally sufficient for estimating the fatigue loading, but wave nonlinearity is important in determining the ultimate design loads.

Application of CFD based wave loads in aeroelastic calculations

Two fully nonlinear irregular wave realizations with different significant wave heights are considered. The wave realizations are both calculated in the potential flow solver Ocean-Wave3D and in a coupled domain decomposed potential-flow CFD solver. The surface elevations of the calculated wave realizations compare well with corresponding surface elevations from laboratory experiments.

In aeroelastic calculations of an offshore wind turbine on a monopile foundation the hydrodynamic loads due to the potential flow solver and Morison's equation and the hydrodynamic loads calculated by the coupled domain decomposed potential-flow CFD solver result in different dynamic forces in the tower and monopile, despite that the static forces on a fixed monopile are similar. The changes are due to differences in the force profiles and wave steepness in the two solvers. The results indicate that an accurate description of the wave loads is very important in aeroelastic calculations especially in cases where the aerodynamic loads and damping are insignificant.
Concept Specifications/Prerequisites for DeepWind Deliverable D8.1

The work is a result of the contributions within the DeepWind project which is supported by the European Commission, Grant 256769 FP7 Energy 2010 - Future emerging technologies, and by the DeepWind beneficiaries: DTU(DK), AAU(DK), TUDELFT(NL), TUTRENTO(I), DHI(DK), SINTEF(N), MARINTEK(N), MARIN(NL), NREL(USA), STATOIL(N), VESTAS(DK) and NENUPHAR(F). The report discusses the design considerations for offshore wind turbines, both in general and specifically for Darrieus-type floating turbines, as is the focus of the DeepWind project. The project is considered in a North Sea environment, notably close to the Norwegian South West coast, at the site of the Hywind demonstration project. The report summarises standard characteristics for the North Sea and the Baltic, formulated by earlier EU projects, and compare these to the conditions met at the project site. Comparisons with existing measured met-ocean data are carried out. Similarly scaling considerations from the earlier projects are presented and seen in relation to and contrasted to the needs of the current project.
Effects from fully nonlinear irregular wave forcing on the fatigue life of an offshore wind turbine and its monopile foundation
The effect from fully nonlinear irregular wave forcing on the fatigue life of the foundation and tower of an offshore wind turbine is investigated through aeroelastic calculations. Five representative sea states with increasing significant wave height are considered in a water depth of 40 m. The waves are both linear and fully nonlinear irregular 2D waves. The wind turbine is the NREL 5-MW reference wind turbine. Fatigue analysis is performed in relation to analysis of the sectional forces in the tower and monopile.

Impulsive excitation of the sectional force at the bottom of the tower is seen when the waves are large and nonlinear and most notably for small wind speeds. In case of strong velocities and turbulent wind, the excitation is damped out. In the monopile no excitation of the force is seen, but even for turbulent strong wind the wave affects the forces in the pile significantly. The analysis indicates that the nonlinearity of the waves can change the fatigue damage level significantly in particular when the wave and wind direction is misaligned.

Fatigue and extreme wave loads on bottom fixed offshore wind turbines. Effects from fully nonlinear wave forcing on the structural dynamics.
Since the world's first offshore wind farm was built in the early 1990s in Denmark, the offshore wind industry has increased tremendously in Europe, and will increase even more the next years. Both the water depth and the size of the wind turbines have increased continually since the first offshore wind farms. As wind farms are being moved further offshore the wave loads become larger compared to the wind loads and therefore more important in the design of offshore wind turbines. Yet, the water depth is still only shallow or intermediate where the waves should be described by nonlinear irregular wave models. In today's design, however, often only linear or second-order irregular wave theory is used to describe the stochastic process of the waves. The extreme waves are often described by the fully nonlinear stream function theory, which only is valid for regular waves on a flat bed. For this reason it is important to investigate the significance of nonlinearity for irregular waves both in the determination of the extreme loads where the irregular nonlinear waves can become more steep than waves from nonlinear regular wave theory and in the determination of fatigue loads where nonlinear waves will transfer energy to higher frequencies which can be close to the wind turbines eigenfrequency. In the present thesis the response of an offshore wind turbine placed on a monopile foundation is investigated when exposed to linear and fully nonlinear irregular waves. The focus of the investigations is the consequence of incorporation of full nonlinearity in the wave kinematics. In the main part of the thesis six wind and sea states with increasing wind speed and significant wave height are considered. The wave realizations are considered at four different water depths to investigate the effect of water depth on the wave nonlinearity. A fully nonlinear potential-flow model, Engsig-Karup et al. (2009), is used to calculated both the linear and fully nonlinear wave kinematics. The wave forces are calculated by Morison's equation. The aeroelastic calculations are carried out in Flex5, Øye (1996), to study the dynamic effects of the wave nonlinearity. In first part of the thesis, the linear and nonlinear wave realizations are compared and the static wave forcing based on the two wave theories analysed. This analysis is followed by dynamic calculations where the effects of wave nonlinearity on the structural dynamics are investigated. Focus is on the sectional moments in the tower and monopile. The equivalent loads and accumulated equivalent load due to the six wind and sea states are further calculated and compared. The wind forcing and the aerodynamic damping are often dominating over the effects from the waves. The misalignment between the wind and wave directions is therefore also included in the analysis. In this way it is possible to investigate how the nonlinearity of the waves affects the structural dynamics and fatigue damage in situations where the effects of the wind are insignificant. Damping of the structural response is an important parameter, when the nonlinearity
of the waves is investigated. Besides aerodynamic damping other damping effects also exist which affect the structural dynamics. The magnitude of the hydrodynamic damping is therefore also investigated in the thesis. To investigate the effects of the soil in the dynamic analyses, a soil model, Hededal & Klinkvort (2010) and Klinkvort (2012), is implemented in Flex5. With this model it is possible both to investigate the structural response and damping due to the soil and compared it against classical p-y curves combined with a constant damping factor. The potential flow solver is further compared with a CFD-solver, where the detailed flow around the monopile when exposed to waves and the corresponding pressure acting on the cylinder are calculated. The structural response due to the forces from the CFD-solver is compared against the structural response due to the forces based on the potential-flow solver and Morison’s equation. Finally a small study of the effect of including wave directionality in the dynamic analysis is performed. All the analyses in this thesis contribute to the understanding of how important the wave nonlinearity is in the design of offshore wind turbines.

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Loads and response from steep and breaking waves on monopiles

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RANS-based simulation of turbulent wave boundary layer and sheet-flow sediment transport processes

A numerical model coupling the horizontal component of the incompressible Reynolds-averaged Navier–Stokes (RANS) equations with two-equation k–ω turbulence closure is presented and used to simulate a variety of turbulent wave boundary layer processes. The hydrodynamic model is additionally coupled with bed and suspended load descriptions, the latter based on an unsteady turbulent-diffusion equation, for simulation of sheet-flow sediment transport processes. In addition to standard features common within such RANS-based approaches, the present model includes: (1) hindered settling velocities at high suspended sediment concentrations, (2) turbulence suppression due to density gradients in the water–sand mixture, (3) boundary layer streaming due to convective terms, and (4) converging–diverging effects due to a sloping bed. The present model therefore provides a framework for simultaneous inclusion of a number of local factors important within cross-shore wave boundary layer and sediment transport dynamics. The hydrodynamic model is validated for both hydraulically smooth and rough conditions, based on wave friction factor diagrams and boundary layer streaming profiles, with the results in excellent agreement with experimental and/or previous numerical work. The sediment transport model is likewise validated against oscillatory tunnel experiments involving both velocity-skewed and acceleration-skewed flows, as well as against measurements beneath real progressive waves. Model capabilities are exploited to investigate the importance of boundary layer streaming effects on sediment transport in selected velocity-skewed conditions. For the medium sand grain conditions considered, the model results suggest that streaming effects can enhance onshore sediment transport rates by as much as a factor of two. Moreover, for fine sand conditions streaming (and related convective) effects are demonstrated to potentially reverse the direction of net transport (i.e. from offshore to onshore) relative that predicted in oscillatory tunnel conditions.
The developed model is implemented within the popular Matlab environment, and hence may be attractive for both research and educational purposes.

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**Ringing and impulsive excitation of offshore wind turbines. Results from the Wave Loads project**

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**Steep wave loads from irregular waves on an offshore wind turbine foundation: Computation and experiment**

Two-dimensional irregular waves on a sloping bed and their impact on a bottom mounted circular cylinder is modeled by three different numerical methods and the results are validated against laboratory experiments. We here consider the performance of a linear-, a fully nonlinear potential flow solver and a fully nonlinear Navier-Stokes/VOF solver. The validation is carried out in terms of both the free surface elevation and the inline force. Special attention is paid to the ultimate load in case of a single wave event and the general ability of the numerical models to capture the higher harmonic forcing. The test case is representative for monopile foundations at intermediate water depths. The potential flow computations are carried out in a two-dimensional vertical plane and the inline force on the cylinder is evaluated by the Morison equation. The Navier-Stokes/VOF computations are carried out in three-dimensions and the force is obtained by spatial pressure integration over the wetted area of the cylinder. In terms of both the free surface elevation and inline force, the linear potential flow model is shown to be of limited accuracy and large deviations are generally seen when compared to the experimental measurements. The fully nonlinear Navier-Stokes/VOF computations are accurately predicting both the free surface elevation and the inline force. However, the computational cost is high relative to the potential flow solvers. Despite the fact that the nonlinear potential flow model is carried out in two-dimensions it is shown to perform just as good as the three-dimensional Navier-Stokes/VOF solver. This is observed for both the free surface elevation and the inline force, where both the ultimate load and the higher harmonic forces are accurately predicted. This shows that for moderately steep irregular waves a Morison equation combined with a fully nonlinear two-dimensional potential flow solver can be a good approximation.
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The effect on wave nonlinearity on monopile and tower. Fatigue loads in misaligned wind/sea conditions

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The Wave Loads project

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Comparisons of wave kinematics models for an offshore wind turbine mounted on a jacket substructure

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Examples of Important Ongoing Research Topics for Offshore Wind Energy

The aim of the paper is to address some challenges related to offshore wind energy. A first example shows some results from an ongoing project on accurate computation of wave loads on monopole foundations. The effects of wave nonlinearity and bottom slope are examined and detailed CFD computations for an overturning wave impact are presented. Next the existing servo aero- hydrodynamic code VpOne used for estimating loads on offshore wind turbines is briefly described and an example of a fatigue analysis for a jacket foundation supporting the 5 MW NREL virtual wind turbine is shown.

Irregular Wave Forces on Monopile Foundations. Effect of Full Nonlinearity and Bed Slope

Forces on a monopile from a nonlinear irregular unidirectional wave model are investigated. Two seabed profiles of different slopes are considered. Morison's equation is used to investigate the forcing from fully nonlinear irregular waves and to compare the results with those obtained from linear wave theory and with stream function wave theory. The latter of these theories is only valid on a flat bed. The three predictions of wave forces are compared and the influence of the bed slope is investigated. Force-profiles of two selected waves from the irregular wave train are further compared with the corresponding force-profiles from stream function theory. The results suggest that the nonlinear irregular waves give rise to larger extreme wave forces than those predicted by linear theory and that a steeper bed slope increases the wave forces both for linear and nonlinear waves. It is further found that stream function theory in some cases underestimate the wave forces acting on the monopile.