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Stochastic modelling of wind and wave induced loads on jacket piles

Tragstrukturen von Offshore-Windenergieanlagen werden durch Wind und Wellen belastet. In größeren Wassertiefen werden fachwerkartige Strukturen, sog. „Jackets“, eingesetzt, die mit Rammpfählen im Meeresgrund verankert sind. Die Belastung dieser Pfähle wird bei Wassertiefen um die 40 m und Windenergieanlagen der 5MW-Klasse in etwa gleichermaßen durch Wind und Wellen beansprucht.

In diesem Beitrag werden Untersuchungen zur Überlagerung der beiden stochastischen Prozesse „Wind“ und „Welle“ vorgestellt. Es wird auf die Extremwertstatistik der dynamischen Systemantwort infolge der turbulenten Windeinwirkung detailliert eingegangen. Bzgl. des stochastischen Seegangs wird eine Methodik vorgestellt, mit der die nichtlinearen Eigenschaften großer Wellen für eine Überlagerung im Zeitbereich berücksichtigt werden können. Abschließend wird ein einfacher Ansatz präsentiert, der für die Ermittlung der Bemessungslasten infolge von Wind und Wellen verwendet werden kann.

Support structures for offshore wind turbines are loaded by wind and waves. In deeper water so-called “jacket” substructures are used, which use driven piles as foundations. In around 40 m water depth and for wind turbines of the 5MW class, these piles are approximately loaded equally by wind and waves.

This paper presents investigations into the superposition of the stochastic processes “wind” and “waves”. The response statistics due to turbulent wind loading are analysed in detail. For stochastic wave loading a method is given which allows for the consideration of the nonlinearity of large waves in the time domain. A simple approach to determine design loads for combined wind and wave loading is outlined at the end of this paper.

Keywords: Offshore, Jacket, Wind, Wave, Superposition, Extreme loads, Stochastic process

1 Introduction

Offshore wind turbines are supported by different types of structures. So far, predominantly monopiles have been used in relatively shallow waters and for smaller turbines. For deeper waters and larger turbines, jacket substructures [1] have emerged as a preferred solution, see Fig. 1.

Substructures for offshore wind turbines are loaded by wind and waves. In the case of jacket structures, the foundation piles often experience extreme loads from wind and waves which are of the same order of magnitude. The governing extreme load case is the 50-year storm event, for which the 50-year wind speed has to be considered together with the 50-year sea state. As the wind and waves create large loadings on the foundation piles, the superposition of both is of interest. In order to arrive at an economical design, the superposition should not be overly conservative, i.e. maximum loads from wind (or wave) should not be superimposed with maximum loads from wave (or wind) as these do not occur at the same point in time.

For reasons of secrecy only qualitative results of the response of the wind turbine and the jacket are shown.

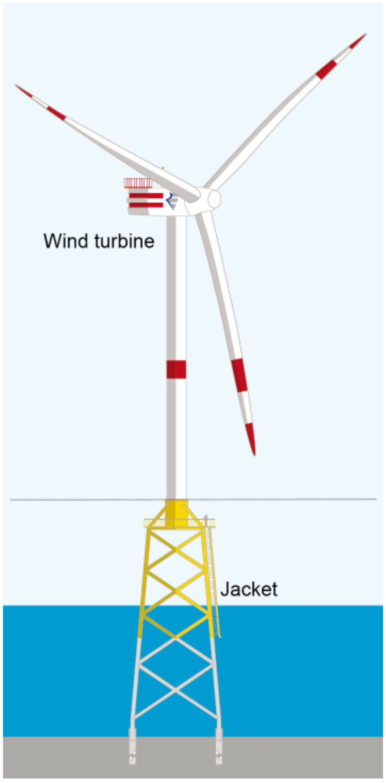


Fig. 1. Sketch of an offshore wind turbine with jacket substructure [2]

2 Wind turbine simulation and wind loading

2.1 General

Wind turbine load simulations are performed according to IEC 61400-1 in combination with IEC 61400-3 [3] for offshore wind turbines. Storm loading is covered by the design load cases (DLC) 6.1 and 6.2. For these load cases, the idling turbine is simulated during storm wind conditions with extreme wind speeds at hub height typically ranging between 40 m/s and 50 m/s for the 10-minutes mean wind speed.

Global vibrations of offshore wind turbines on jackets are not affected significantly by the offshore conditions, i.e. wave and current loading. This is due to the fact that the jacket structure is very stiff and relatively transparent to wave loading. The global structural response (i.e. vibrations) is therefore governed by the turbulent wind loading, with the stochastic wave loading bearing minimal influence on this response. Because of this, it can be justified to treat the wind and wave induced responses as independent processes. This is an important condition for the following investigations. If this condition can not be justified, as would be the case e.g. for monopiles or other relatively soft structures, then other considerations regarding the interaction of wind and waves are necessary. For structures with intermediate stiffness, e.g. a Tripod, this method may be reasonable, but would probably need some adjustment to take account of the interaction between wind and wave induced responses.

The loading direction from wind and waves are both conservatively assumed to act over the diagonal of a four-legged jacket, which creates the largest pile loads, see also [4].

2.2 Response statistics

The structural response of a structure under turbulent wind loading is a stochastically induced process. According to Eurocode 1 [5] the design value is chosen as the mean value of the associated extreme value distribution, which is assumed to be a Gumbel distribution. The peak factor is therefore:

$$k_p = \sqrt{2 \cdot \ln(\nu \cdot T)} + \frac{0.5772}{\sqrt{2 \cdot \ln(\nu \cdot T)}} \qquad \text{Eq. 1}$$

where

ν	Zero-crossing frequency of the structural response
T	Length of time series

The design value, e.g. for the resulting shear force, is then determined as:

$$F_d = F_{mean} + k_p \cdot s_F \qquad \text{Eq. 2}$$

where

F_{mean}	Mean value of shear force
s_F	Standard deviation of shear force

Details can be found in [6] and in [7] (on stochastic processes in general). Detailed information on methods included in building codes is given in [8].

Simulations have been completed for 100 different stochastic wind fields, i.e. 100 individual realisations of the turbulent wind field have been generated and evaluated. As a result of the analysis, the following can be summarised:

- The instantaneous values of the time series can be well approximated by a Gaussian distribution. Fig. 2 shows the distribution instantaneous values for the resulting shear force at tower bottom to illustrate this. Similar results are found for the bending moment.
- Evaluating the extreme values of 100 seeds, a Gumbel distribution can be used to accurately approximate the extreme value distribution (see the black line in Fig. 3, again for the tower bottom shear force). A similar distribution (grey line) is found on basis of the distribution of the peak values (light-grey line), which are approximately normal-distributed (see also Fig. 3).
- Mean values and standard deviations of the tower bottom moments and forces do not vary significantly for different stochastic realizations.
- The design value according to IEC 61400-1 corresponds well to the mean value of the Gumbel distribution, with a tendency to the conservative side.
- The design value can be approximated using the formula Eq. 1 and Eq. 2, where ν is the first natural frequency of the system.

The results also show that the methods employed in the wind turbine industry correspond to those outlined in Eurocode 1 for buildings and chimneys.

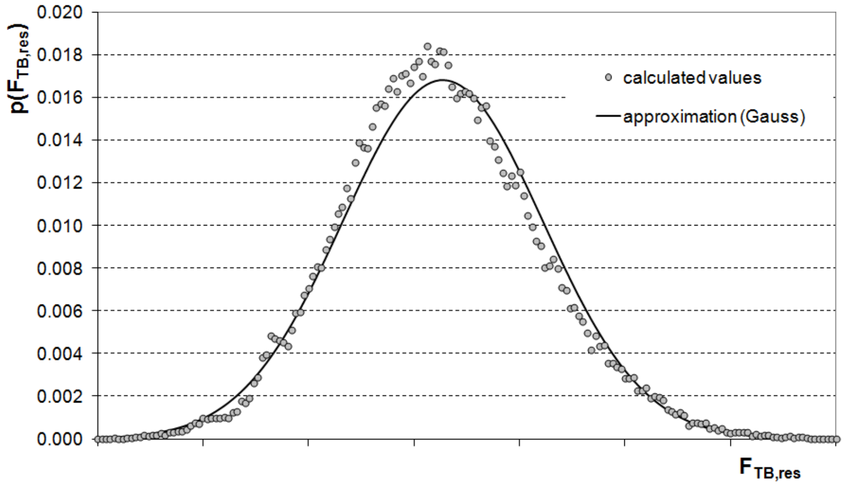


Fig. 2. Distribution of the shear forces at the tower base during a storm

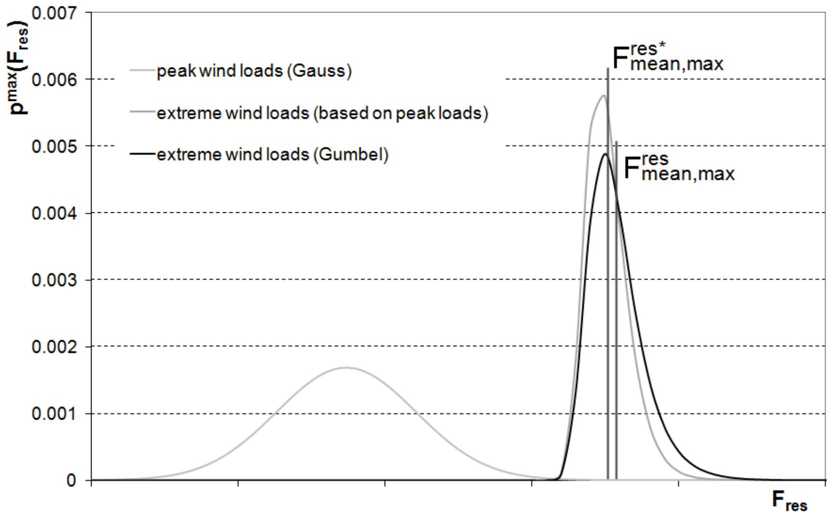


Fig. 3. Distribution of the extreme resulting shear force at the tower base

3 Wave loading

3.1 Stochastic wave loading

Wave loading is typically assumed to be statistically stable during periods of 3h. Such a 3h-seastate is simulated in the time domain by assuming that the wave loading can be modelled by superposition of individual wavelets according to the spectrum of the wave energy. A general overview can, for example, be found in Böker [9]. Detailed information about stochastic wave loading is provided by Goda [10].

Waves can be modelled using either linear or nonlinear methods. Linear models are sufficiently accurate for wave heights which are small compared to water depth. As wind turbines are located in relatively shallow water, this condition does not apply; therefore nonlinear methods must be implemented for design waves. Current state-of-the-art calculation methods unfortunately do not cover nonlinear random sea states so these can only be calculated using superposition of linear waves. Nonlinear waves can only be generated for deterministic individual waves, hence their effect on pile loads can normally not be considered when calculating random sea states. It is described later in this paper how this problem was solved.

Similarly as for wind loading, the wave surface elevation is assumed to be a Gaussian process. Individual wave heights are assumed to be Rayleigh distributed (see Fig. 4) with extreme waves assumed to fit to a Gumbel distribution.

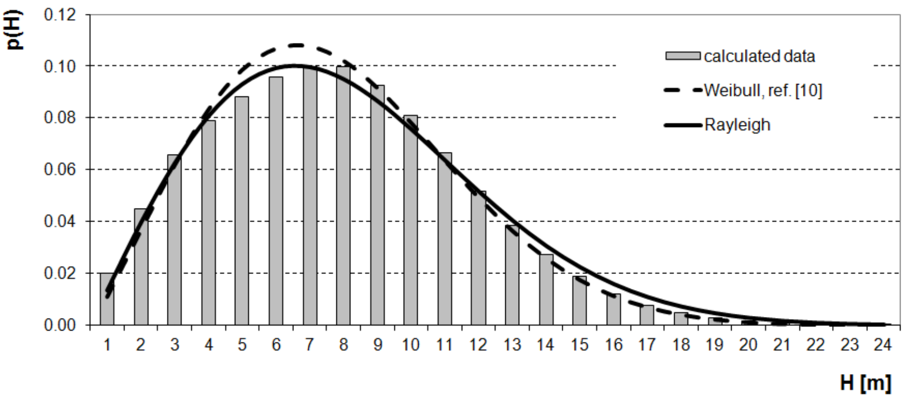


Fig. 4. Distribution of wave heights within the sea state

3.2 Consideration of nonlinear wave loading

As mentioned earlier, the nonlinearity of the wave loading must be considered for large wave heights. This is illustrated in Fig. 5 for three different waves in approximately 40m water depth. The wave profile can be found on the left hand side with the resulting pile loads given on the right hand side. This demonstrates that linear theory approximates the wave profile and wave loads well for a small wave of H=5 m height. For the 50-year wave height (H=20.77 m) significant differences in peak loading occur which should not be neglected.

A method has been developed to deal with this challenge especially for pile loads. Fig. 6 gives a flow chart outlining this method. The basic idea is to analyse wave heights in a stochastic sea state and to apply correction factors based on individual wave heights. Individual waves are identified between zero crossings of the wave elevation. The wave height assigned is the difference between wave peak and trough. Results for a short time interval are shown in Fig. 7. Also given are two different options for the application of the correction factor, which can be either constant or linearly varying. This is shown with the black lines (constant factor for each wave) and the grey lines (linearly varying factor) in Fig. 7. As the linearly varying factor results in a smooth curve, this method is preferred.

While this is certainly an approximation, it can be viewed as a practical and still reasonably realistic method to include the effect of nonlinearity in time domain simulations. What must be considered is that only few waves require correction factors significantly larger than unity as the majority of waves can still be reasonably approximated by linear theory. This is indicated in Fig. 4, where the distribution of individual wave heights within the 50-year sea state is shown. For the extreme wave, factors larger than 1.5 are applied to the maximum load.

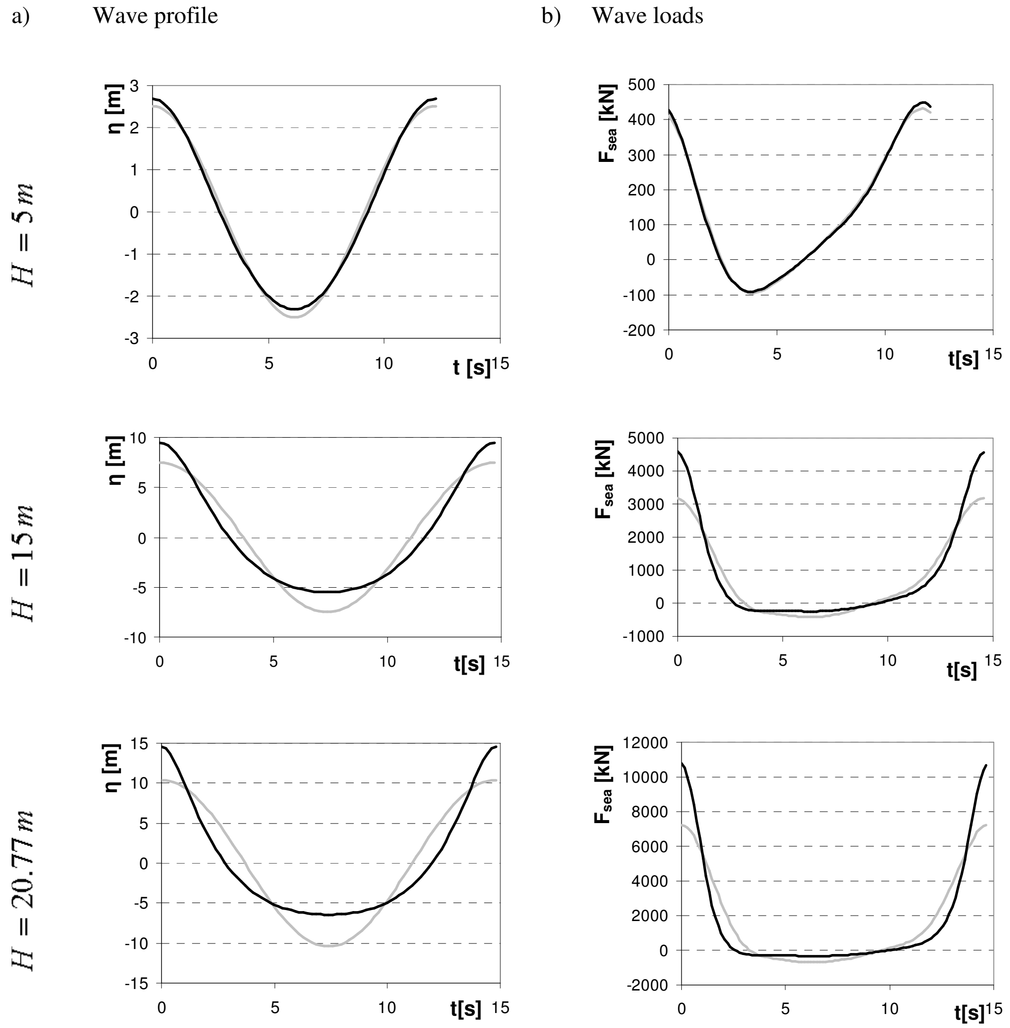


Fig. 5. Comparison of a) waves and b) wave loads, using the linear wave theory (grey line) or a non-linear wave model (black line) for different wave heights

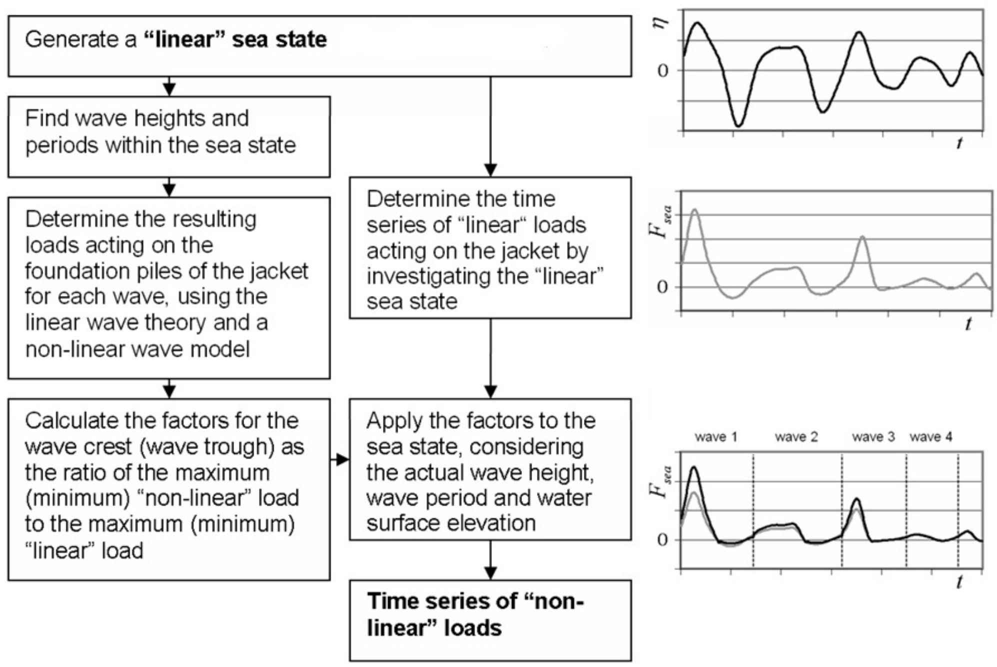
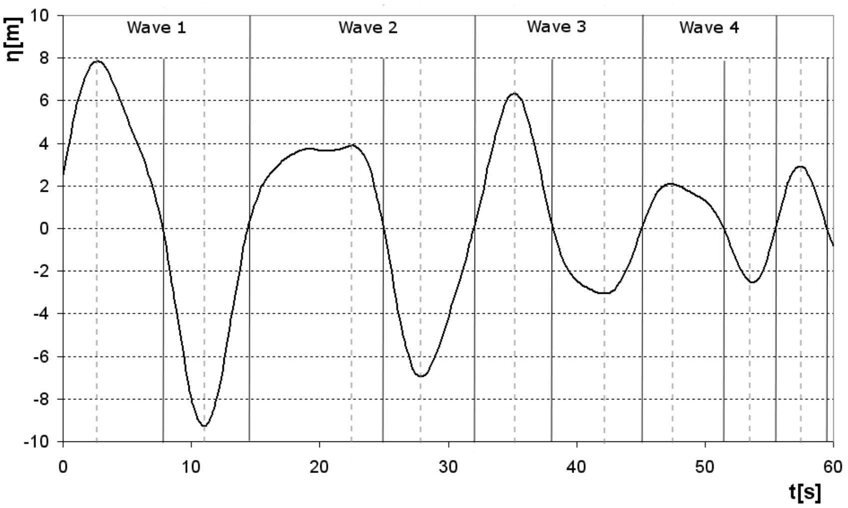
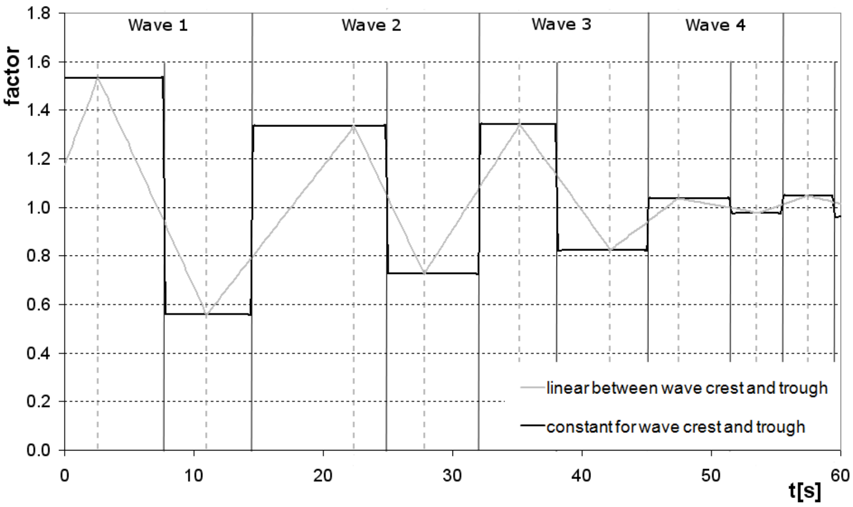


Fig. 6. Flow chart of method to account for nonlinear wave loads

a) Water surface elevation



b) Factors depending on the water surface elevation



c) Resulting time series of "non-linear" loads

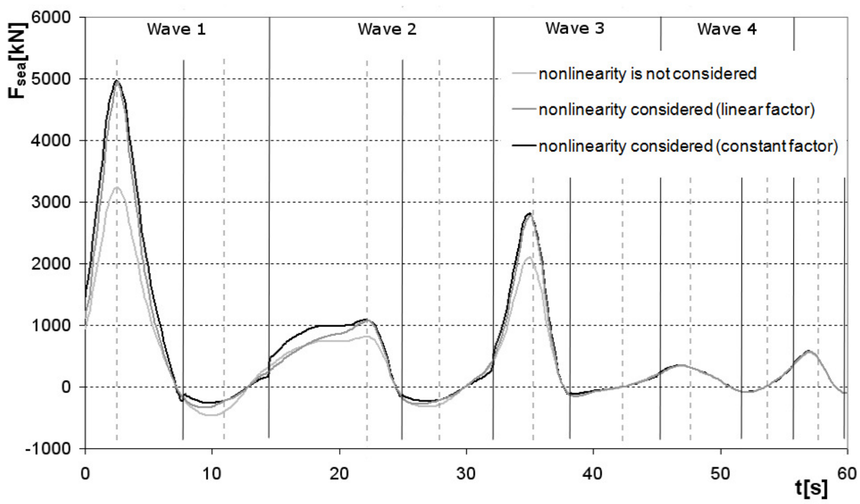


Fig. 7. Water surface elevation (a), nonlinearity correction factor (b) and resulting "non-linear" loads based on a "linear" wave (c)

3.3 Response statistics

Again, a large number of simulations were completed to determine the extreme value distribution of wave induced pile loads. The distribution is well approximated by a Gumbel distribution, see Fig. 8. As dynamic response is not relevant as mentioned in section 2.1, the wave load calculations were performed as quasi-static calculations.

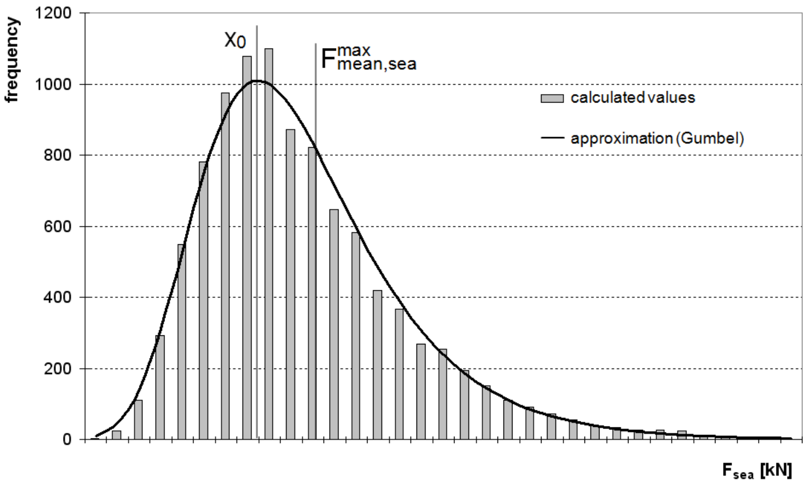


Fig. 8. Histogram of the greatest wave loads, evaluating 10,000 sea states

4 Combination of wind and wave loading

As a final step, wind and wave loading were combined in the time domain. 10,000 time series of combined wind and wave loads were generated and evaluated. The individual extreme value distributions for the pile loads induced by wind and waves are shown in Fig. 9. It can be observed that in this case the wave induced loads are higher than wind induced loads.

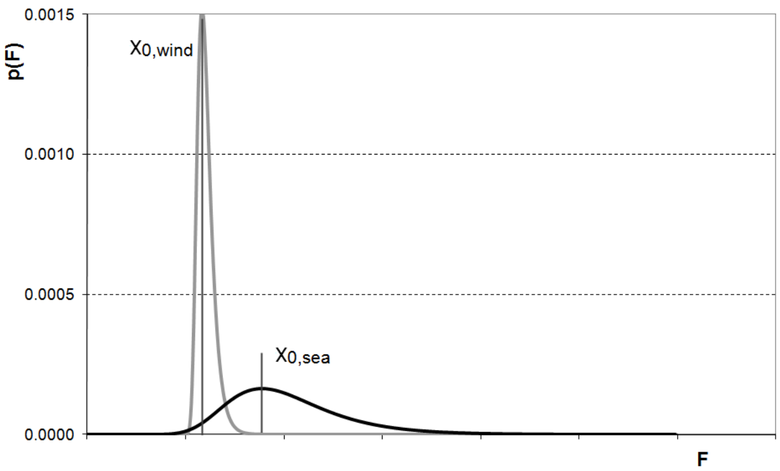


Fig. 9. Comparison of distributions of extreme wind loads (grey line) and extreme wave loads (black line)

The extreme value distribution for combined wind and wave loads is shown in Fig. 10. Again, this distribution can be approximated by a Gumbel distribution.

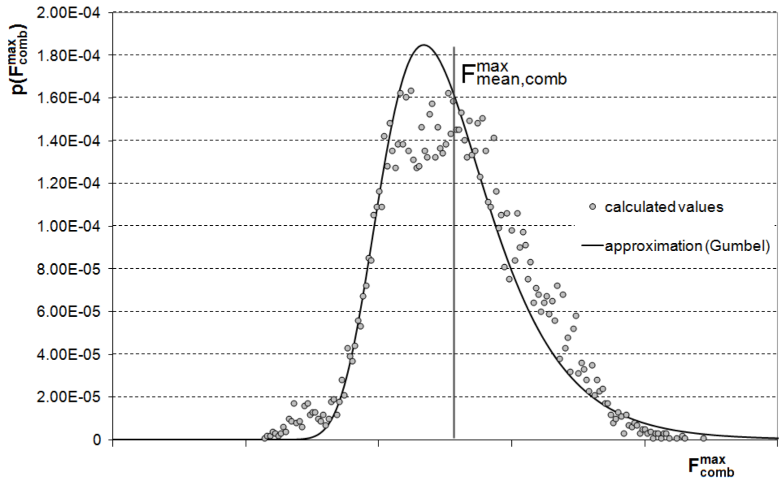


Fig. 10. Extreme value distribution for combined wind and wave loads

5 Turkstra's rule – a simple design method

Turkstra's rule states that the greatest occurring load of several combined load time series, which are independent from each other, can be determined by the addition of the maximum load occurring during one load time series and the mean values of the other time series.

$$F_{j,\max} = \max\{F_j(t)\} + \sum_{\substack{i=1 \\ i \neq j}}^{N} \overline{F}_i, \quad j = 1, \ldots N \qquad \text{Eq. 3}$$

The greatest load occurring during a period by applying Turkstra's rule is then given by

$$F_{\max} = \max_{j=1,\ldots N} \{F_{j,\max}\} \qquad \text{Eq. 4}$$

In this study, solely two load time series independent of each other were evaluated, leading to

$$F_{\max} = \max\{\max\{F_{wind}\} + \overline{F}_{sea}, \max\{F_{sea}\} + \overline{F}_{wind}\}. \qquad \text{Eq. 5}$$

Practically, the extreme value distributions are shifted by the mean value of the second process (see Fig. 11). The mean value of the wave loads is typically small, as the wave load is an oscillating load with a mean value close to Zero. The mean value of the wind loading is comparably larger, although significantly smaller than the maximum design value as given in section 2.2.

It has been found that the design value determined using Turkstra's rule corresponds almost exactly (within 1%) to the mean value of the Gumbel distribution derived from 10,000 simulations (Fig. 10). This empirical proof of the method provides good confidence at least for the presented case, where wave loading dominates over wind loading. In cases where wind loading dominates over wave loading (e.g. in more shallow water or less severe extreme wave conditions) additional verification should be performed.

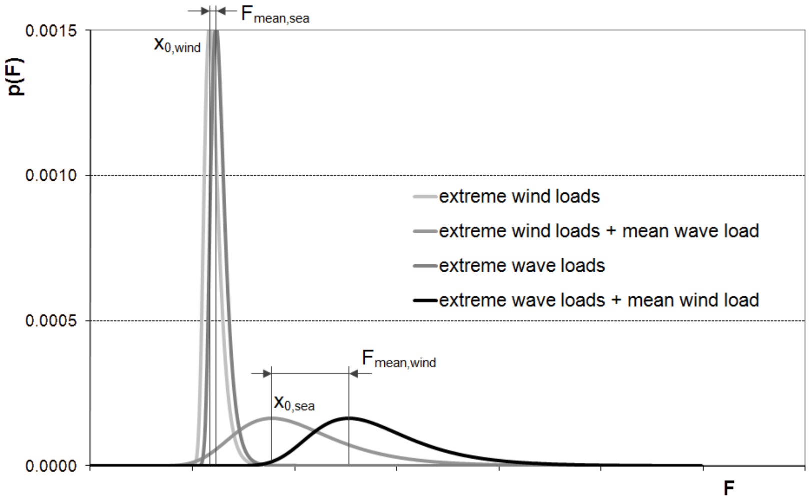


Fig. 11. Distribution of the extreme combined loads

6 Summary

In this paper, stochastic modelling of loads on foundation piles for jackets supporting offshore wind turbines has been investigated. The following outcomes from the study can be summarised:

1. Extreme value distributions for loads induced by stochastic wind and stochastic wave as well as combined extreme loads can be well approximated by Gumbel distributions.
2. Nonlinearity of large waves needs to be considered appropriately. A method has been proposed using correction factors (based on ratios of linear to nonlinear wave loads) which are applied in the time domain.
3. Design loads, which are taken as the mean value of the extreme value distribution, can be reliably derived by Turkstra's rule. This is an extremely easy and fast method to arrive at design values.
4. The method can also be used to generate time series for assessment of pile performance subject to cyclic loading, see [11].

7 Acknowledgements

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