A critical assessment of non-linear design wave loads on offshore wind turbines

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Objective and scope

The scope of this master thesis is to present and calculate wave loads according to industrial standard requirements for load cases of ultimate state limit (ULS). Different non-linear methods to improve the wave models applied to the wind mill structure shall be assessed, both in irregular and regular wave load calculations. Methods required in the wind mill industry shall be compared to methods known and developed for oil and gas offshore installations.

The objective is to implement different models in MATLAB to be able to compare the models on an equal basis. The validity of each model regarding the shallow water at the wind mill site will be assessed. The variation in ULS loads between methods, and also in the way of choosing environmental parameters, will be investigated and the significance to the design loads and security margins will be discussed.

Introduction

The background for this thesis is the development of bottom fixed wind mill structures at the shallow water site Dogger Bank outside England. There is good wind conditions, but the environmental loads is at the same time a challenge. The substructure foundation is a monopile which is connected to the tower 15m above the still water level. The monopile foundation has a rather low natural frequency compared to other substructure concepts and might be subject to dynamic excitation from higher order wave loads. ULS loads give design parameters to the structure, and this work try to perform a critical assessment of how these are determined in the view of applied models and industrial practice.

Standard

The DNV standard OS-J101 gives guidelines for offshore wind structures, and is followed by large contractors in the industry. The design period for wind mills is 50 years, and this will then be the return period of loads according to ULS. There are several load cases that involves ULS loads from waves, but the most important are:

- Load case 6.1a) 50 year maximal sea state
- Load case 6.2a) 50 year maximal wave

The load cases is determined from long term statistical analysis. **Case 6.1a** is found from the probability distribution of significant wave height, Hs, and is taken as the largest value occurring through the design period. The peak period, Tp, shall be varied appropriately from the conditional distribution of Tp given Hs from the long term analysis (figure 3). **Case 6.2a** is determined as the largest wave, taken all sea states into consideration. The wave period shall be varied with values given by the standard.

Simulations

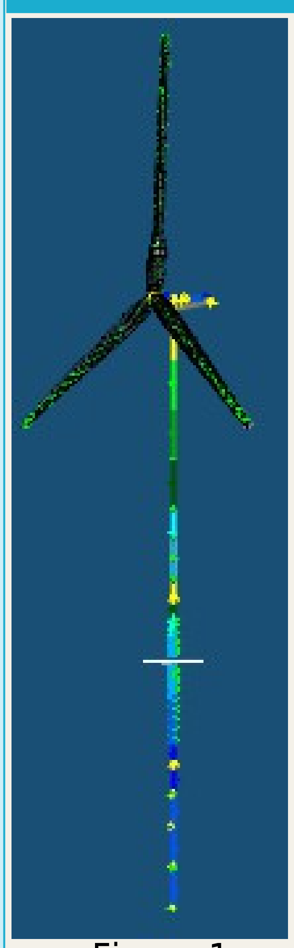

Figure 1

FEDEM

Dynamical analysis has been performed with FEDEM Windpower. An interface between calculated loads in MATLAB to the structural model in FEDEM has been developed.

The distributed wave loads along the substructure is transformed to nodal forces which is applied to the FEDEM model. This is done according to the trapezoidal rule and shown in figure 2.

Wind mill model: (figure 1)

Hub height.
- 85m

Platform level:
- 15m

Mean water level:
- 0m

Top mass:	226 000 kg	
Natural frequency:	0.249 Hz	
Depth:	25m	45m
Diameter:	6m	8m
Cm/Cd	1.79/1.00	1.87/0.81
Stiffness proportional damping ratios:		
Tower:	0.005	
Substructure	0.01	
Soil pile model:	0.05	

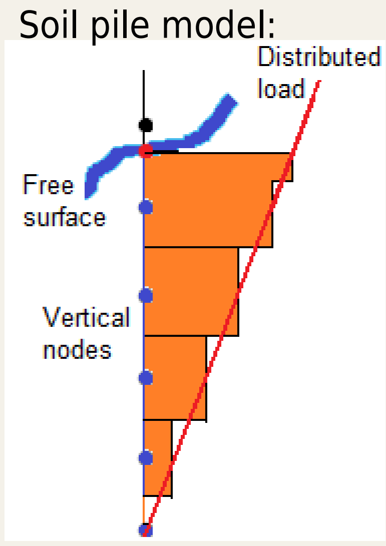

Figure 2:
The wave kinematics is evaluated at vertical points along the structure (blue points), and at the instantaneous wave elevation (red point). The integration is done at each time step to the free surface. The distributed load above the highest submerged node, will be applied to this node, as shown in the upper orange field.

Site parameters and Cd & Cm

Drag & mass coefficients for use in Morison equation are determined with all the guidelines available in the DNV standards (see references). Inertia loads dominate.

Site parameters:

State	Hs m	Tp s
1	9.56	12.76
2	10.29	13.52
3	10.97	14.28
4	11.52	15.04
5	12.00	15.80

Table 1

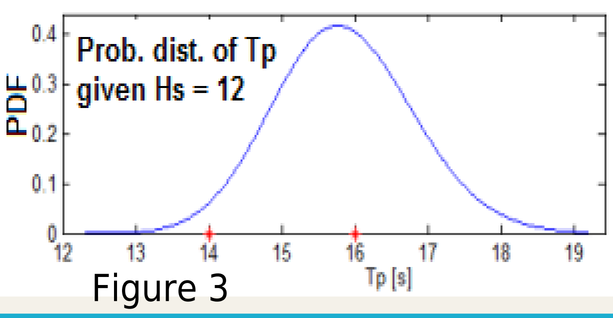

Figure 3

Methods - Irregular sea

Six different kinematic models have been considered. They are applied with Morison equation using drag and inertia loads, as required in the standards. Another model, FNV, is not mentioned in the standard, but is included as comparison because it builds on other assumptions and includes higher order load terms, that is neglected in Morison equation.

Model 1 – linear kinematics to z = 0
Model 2 – 2nd order kinematics z = 0
Model 3 – model 1, extrapolated to the free surface
Model 4 – model 1, stretched to the free surface
Model 5 – model 2, extrapolated to the free surface
Model 6 – model 4, but to the 2nd order free surface
FNV – 3rd order load model, includes only inertia load

Results

The models have been compared by performing a static load calculation in MATLAB for base shear force and overturning moment. Sea states of 50min duration and 20 seeds have been performed for each model at water depth 25 and 45 meter. The simulation was done with sea state 1 from table 1. A Gumbel plot was created for the extreme value in each model, and the 90% largest value is given in the table below:

	Depth 25m		Depth 45m	
Model	$F_{90\%}[MN]$	$M_{90\%}[MNm]$	$F_{90\%}[MN]$	$M_{90\%}[MNm]$
1	3.816	70.38	8.547	235.0
2	4.431	85.07	8.817	250.7
3	5.295	124.1	9.976	320.8
4	4.553	102.6	8.873	273.9
5	6.976	183.0	12.28	387.6
6	4.280	100.5	8.341	243.5
FNV	6.324	140.8	11.63	426.4

Table 2

Dynamic simulation of all the models have been performed around the point of largest crest and acceleration, determined from 20 seeds of 3 hours duration from linear time realizations. The results of shear (dynamic and static) in a 20min time realization around the point of largest acceleration are given below. Dynamic amplification and location (loc) of occurrence is given. Parameters: Sea state 1 from table 1 and water

Model	$F^{dyn}_{max}[MN]$	DAF	loc	$F^{stat}_{max}[MN]$	DAF	loc	DAF_{max}	loc
1	3.657	1.015	1966	3.60	1.015	1966	37.86	1215
2	3.553	1.038	1967	3.54	0.990	1966	44.4	662
3	4.703	0.962	1967	4.89	0.962	1967	581.3	2221
4	4.201	0.979	1967	4.29	0.979	1967	1260	553
5	5.23	0.988	1968	5.32	0.957	1967	183.7	2010
6	3.46	0.953	1966	3.64	0.953	1966	24.68	767
FNV	5.29	0.966	1967	5.48	0.966	1967	249	1203

Table 3

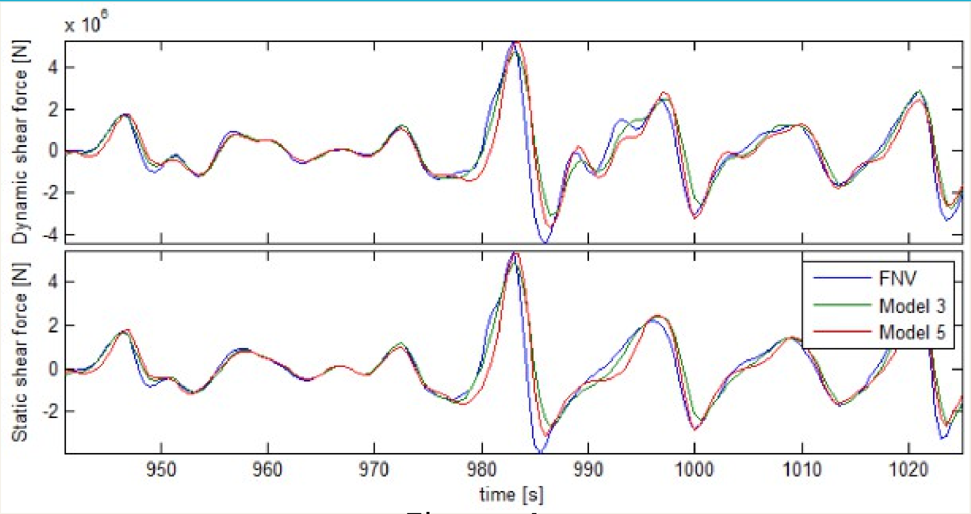

Figure 4

Ongoing **dynamic calculations** are performed with model 4 to investigate the effect of using sea states along the 50 year contour line according to table 1, contra using Tp variation at the largest Hs (load case 6.2a).

Methods - Largest wave

Four different kinematic models have been used with Morison equation. Stream function wave theory has been implemented in MATLAB with the use of an available FORTRAN script on the internet (see references: Dalrymple).

Model 1 – linear regular wave stretched to the free surface
Model 2 – regular stream function wave
Model 3 – embedded stream function
Model 4 – embedded stream function, smoothing functions

Embedding is a widely used method in the verification process of the wind mill industry. The method is to put a stream function wave in to a irregular time realization. The method makes the ability to include the wave of 50 year return period in to a realization, with the non-linearity of such a large wave correctly represented. The wave is put into an arbitrary zero-up crossing in the realization, shown in figure 5. The red dots were previously connected. Smoothing functions at the transition can be used, model 4.

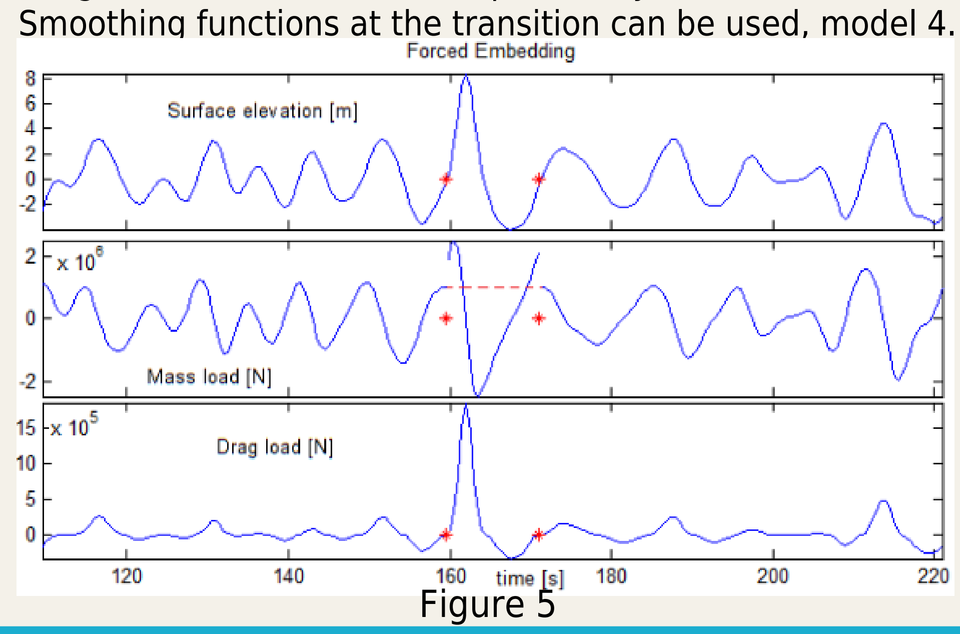

Figure 5

Conclusion

The irregular load models are compared in the frequency plane, both for static and dynamic load calculation. There is found significant variation in the level of energy at the natural frequency of the structure, which is around 3x 1/Tp in sea state 1 (table 1). This is the reason for including a sea state of significantly lower Hs in the search for design loads, due to the reason of dynamic amplification in the structure. The dynamic shear loads in table 3 are found to be lower then the static loads, but the situation are turned around in the case of overturning moment. Tables 2 and 3 were included to illustrate the difference between the load models. FNV and model 5 gives clearly the largest loads, but we must remember that 2nd order irregular sea has restricted validity at 25m water depth, and that FNV only is valid at deep water. The load models are also found to be less different at 45m due to the reduced effect of non-linearity from free surface integration.

Largest wave calculation with embedding creates a discontinuity of mass load as shown in figure 5, because the acceleration does not follow the wave profile. The method is widely used on smaller structures, but the goodness should be questioned when the inertia load is dominating.

Important References in the work process

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