DTU Wind Energy
Department of Wind Energy

Fully Nonlinear Wave Forcing on an Offshore Wind Turbine. Structural Response and Fatigue.

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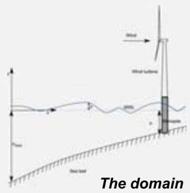
Model setup

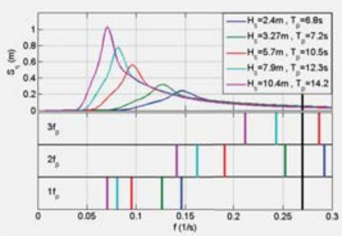
The effect from fully nonlinear irregular wave forcing on the fatigue life of the monopile foundation and offshore wind turbine tower is investigated through aeroelastic calculations. Five representative sea states with increasing significant wave height are considered in a water depth of 40 m. The response is analysed for both linear and nonlinear wave forcing and the results are compared. The wind turbine is the NREL 5MW reference wind turbine.

The fully nonlinear potential flow wave model of Engsig-Karup et al. (2009) is used to compute unidirectional irregular waves. The dynamic behavior of the wind turbine and foundation is calculated in the aeroelastic code Flex5, Øye (1996).



The domain

Fatigue analysis is performed together with analysis of the sectional force in the bottom of the tower.



The spectra of the five sea states at the wave inlet (h=135m). Below the specta the three first harmonics of the sea states are indicated. The black line indicates the first eigenfrequency of the structure. The incident wave spectra are truncated at f=0.3 hz.

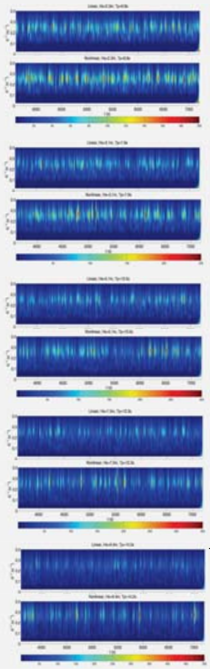
The wind speed in the aeroelastic computations are small, constant and equal for all five sea states. The effects of larger wind speeds and turbulence is discussed in column three.

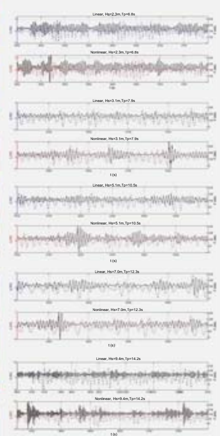
H_s	T_p	W
m	(s)	(m/s)
2.3	6.8	5.0
3.1	7.9	5.0
5.1	10.5	5.0
7.0	12.3	5.0
9.4	14.2	5.0

Wave and wind data

Response in bottom of tower

The sectional force in the bottom of the tower is very dependent on whether the waves are linear or nonlinear, cf. the figure in the next column. Excitation of the structural eigenmode in a ringing-type behavior is seen when steep waves hit the structure and almost only for nonlinear waves. The excitation is also seen for the smallest sea states.





The linear and nonlinear surface elevation and the corresponding sectional force in the bottom of the tower.

Left: Wavelet transformation of one hour time sequence of the sectional force in the bottom of the tower.

Equivalent load range

The equivalent load range, L_{eq}, represent one load value that for a certain number of cycles, N_{eq}, results in the same damage level as the history of fatigue loads which are investigated, here N_{eq} =7200

H_s	T_p	W	$\frac{L_{eq,NL}}{L_{eq,L}}$	$\frac{L_{eq,NL}}{L_{eq,L}}$
(m)	(s)	(m/s)	m=3	m=5
2.3	6.8	5.0	1.24	1.28
3.1	7.9	5.0	1.33	1.52
5.1	10.5	5.0	1.32	1.53
7.0	12.3	5.0	1.53	2.34
9.4	14.2	5.0	1.93	2.65

Ratio between the nonlinear and linear equivalent load range in the bottom of the tower for damage exponents m = 3 and m = 5.

It is clear that L_{eq} is largest in case of nonlinear waves and also that the ratio increases with increasing significant wave height.

Relative fatigue analysis

The fatigue analysis is based on the relative probability of occurrence

$$P_{i,rel} = \frac{P_i(H_s, T_p)}{\sum P_i(H_s, T_p)}, \quad i = 1, 2, ..., 5$$

The fatigue analysis states that for the linear waves the contribution from each sea state is close to the probability of occurrence. For the nonlinear waves the largest sea states contribute significantly to the relative fatigue damage, despite their low probability of occurrence.

H_s	T_p	W	$P_{i,rel}$	Linear		Nonlinear	
(m)	(s)	(m/s)	(%)	m=3	m=5	m=3	m=5
2.3	6.8	5.0	53	46.5	41.5	40.3	15.0
3.1	7.9	5.0	35	36.6	36.5	39.9	31.2
5.1	10.5	5.0	10	14.2	17.5	14.9	15.2
7.0	12.3	5.0	1.4	2.3	3.6	3.8	26.4
9.4	14.2	5.0	0.15	0.4	0.9	1.2	12.3

The relative contribution to the fatigue damage per sea state in the bottom of the tower for damage exponents m = 3 and m = 5.

Discussion

The analysis shown here indicate that the nonlinearity of the waves can change the response significantly. One example is the impulsive excitation of the force in the bottom of the tower for nonlinear waves. Also the equivalent loads are significant larger in case of nonlinear waves than in case of linear waves. Further, the largest sea states contribute significant to the fatigue damage level in case of nonlinear waves.

More realistic conditions may be obtained by incorporation of turbulent wind climates with speeds that better correspond to the sea states. Preliminary results of such computations show that the effect from nonlinear waves still exist. For this case, however, the aerodynamic damping is stronger and the ringing response is thus damped out faster. Further, interpretation is less clear, as the signal is overlaid with the response from the turbulent wind fluctuations.

The situation analysed here with a small wind velocity provides a clear base for analysis. For the case of a zero wind speed, the aerodynamic damping will be absent and the effects from wave nonlinearity are expected to be larger. This corresponds to the situation where the wind and wave direction are misaligned or a storm condition where the wind turbine is idled. As both situations are part of the design basis, the present results are highly relevant for practical design.

References

Engsig-Karup, A., Bingham, H. and Lindberg, O. (2009). An efficient flexible-order model for 3D non-linear water waves. *Journal of Computational Physics* 228(6), 2100–2118..

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