Sensitivity of Wave Fatigue Loads on Offshore Wind Turbines under varying Site Conditions

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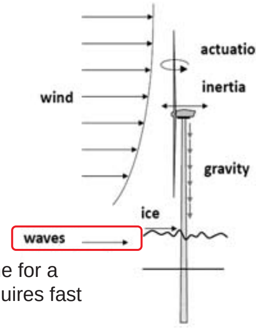
Site conditions vary in offshore wind farms

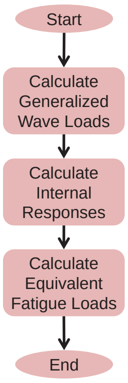
Three important trends in offshore wind energy:
- Larger wind farms (>100 turbines)
- Monopiles in deeper water (20-40m)
- Computational intensive time-domain tools for load calculation

Hence [1, 2]:
- Site conditions vary across wind farms
- Wave-induced fatigue loads dominate
- Loads calculated only for 2-3 design positions



Example: Gemini wind farm with 150 turbines on monopiles covers ≈100km^2 . Load calculation is done for a limited number of design positions. Optimization requires fast calculation tools and insight into load sensitivity.

Frequency-domain method calculates fatigue loads in seconds


Start

Calculate Generalized Wave Loads

Calculate Internal Responses

Calculate Equivalent Fatigue Loads

End

Frequency-domain methods (FDM) have been applied to wind turbines by several researchers [3,4,5].

Approach:
1. Obtain wave loads with linearized Morison equation using wave kinematic spectral densities from JONSWAP wave spectra
2. Derive structural transfer functions from FE model using modal synthesis to determine internal response spectra. Aerodynamic damping as function of wind speed and misalignment
3. Apply Dirlik's method to obtain equivalent load ranges and number of cycles from response spectra

Assumptions:
- Timoshenko beam elements for foundation and tower
- Consideration of first ten modes and eigenfrequencies
- RNA as lumped mass and Winkler model for soil
- Damping: structural, hydrodynamic, soil and aerodynamic
- Transfer functions for equivalent wave loads at mean sea level

Performance: 10s for one simulation case

Verification yields 90% accuracy

Verification of FDM with time-domain simulations using a non-linear aero-elastic tool (BHawC) in reference cases with:

- 4MW turbine
- 35m water depth
- Wind-waves (mis-)aligned
- Identical structural model

Qualitative: Good estimates of power spectral density (b) and probability density functions by Dirlik's method (d) compared to rainflow-count (c)

Quantitative: Max. difference of 8% in equivalent fatigue loads (EFL)

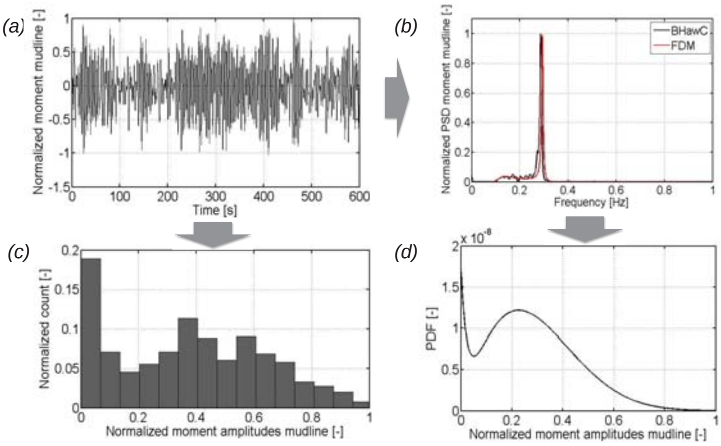


Fig. 1. (a) Bending moment time series. (b) Power spectral densities of bending moments. (c) Rainflow-count. (d) Probability density function by Dirlik's method.

Sea State	BHawC Mudline [-]	FDM Mudline [-]	BHawC Interface [-]	FDM Interface [-]
H_S=0.78m T_P=4.02s	1.0	0.97	1.0	0.99
H_S=2.40m T_P=7.23s	1.0	0.96	1.0	0.96
H_S=4.34m T_P=9.64s	1.0	1.08	1.0	0.94

Fatigue loads are especially sensitive to depth and wave period

Approach:
FDM is used to study effects of site variation of mean sea level (MSL), soil, wave height (H_S) and wave period (T_P) on fatigue loads. Soil variations are modeled by scaling soil stiffness with a factor over full depth.
- Local sensitivity: deterministic variation of parameters with deviation of 1% around nominal value
- Global sensitivity: parameter change over variability expected in wind farm
- Probabilistic assessment: 10000 Monte-Carlo simulations with independent, normal distributed input variables for realistic example wind farm

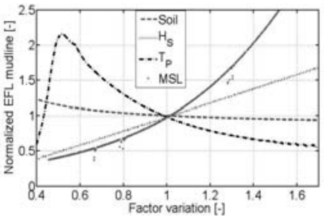
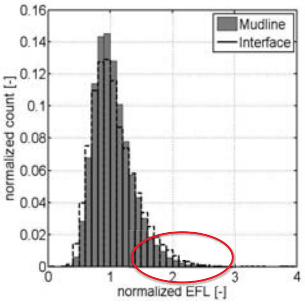


Fig. 2. Global sensitivity of normalized EFL as a function of parameter variation.

Variable	Nominal value	Global range	Sensitivity Mudline [-]	Sensitivity Interface [-]
Soil	1	0.1-1.9	-0.149	-0.203
MSL	35m	20-40m	1.807	1.533
H_S	2m	0-6m	0.991	0.991
T_P	7s	2-12s	-1.297	-1.707

Results:
- Most influence from MSL and T_P
- Linear relation with H_S
- Weak influence of soil in chosen example but higher uncertainty in soil data
- Normal distributed input parameter lead to positively skewed distribution of fatigue loads with stronger tail for higher loads
- Scatter plots show same trend for probabilistic assessment as in global sensitivity



Location	MSL [m]	Soil [-]	H_S [m]	T_P [s]	EFL mudline [-]	EFL interface [-]
Mean	31.5	1.0	2	7	1.05	1.07
STD	4.5	0.2	0.25	1	0.38	0.38
Skewness	0	0	0	0	6.20	1.65
Kurtosis	0	0	0	0	114.55	13.57

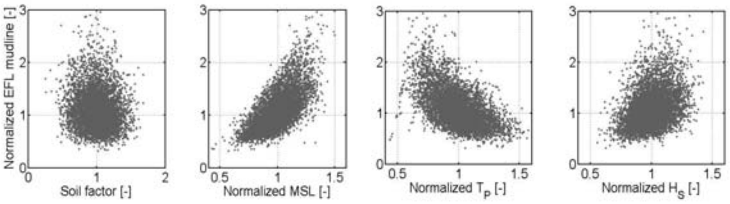


Fig. 3. Scatter plots of normalized EFL at mudline separated for each parameter.

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Ideal for preliminary design and optimization

The efficiency and accuracy of the developed tool make it ideal for application where fast simulations are needed while load estimates are sufficient, e.g.:
- ✓ Design position optimization
- ✓ Interpolation of wave fatigue loads
- ✓ Preliminary design

Sensitivity study shows strong influence of MSL and T_P on EFLs and a skewed fatigue load distribution. Further investigation is needed on:
- ✓ Reliability-based design compared to common deterministic approach
- ✓ Impact of uncertainty in wave scatter diagrams and effects of lumping