The DeRisk design database: extreme waves for Offshore Wind Turbines

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About me

• Mechanical Engineer Uni. Ancona (IT, 2007)

• PhD in wind turbine aerodynamics from NTNU (NO, 2014)

• Working with waves ever since
  – IFE (NO, 2014 – 2017)
  – DTU (DK, 2018 – )
Extreme loads from large waves: a possible design driver

- Turbines and monopiles size increases
- Waves and loads are "Extreme" in probabilistic terms
- Stochasticity needs to be handled together with nonlinearity of the waves

DeRisk
De-risked extreme wave loads for offshore wind energy

www.derisk.dk
Sea states: what does an Offshore Wind Turbine (OWT) experience?

At $h = 22 [m]$ depth

- Operational
  - $H_S = 1 [m]; T_P = 6 [s]$

- ULS
  - $H_S = 9.5 [m]; T_P = 12 [s]$

- $1.86 \times H_S$

LeMehaute (1976)
Standard IEC61400-3 annex D: extreme waves for design

- D.7.1: Explicit approach
  - Many realizations of fully nonlinear waves

- D.7.2 Wave non-linearity factor approach

- D.7.3 Regular wave approach

- D.7.4 Constrained wave approach
  - Embed a regular nonlinear wave in irregular, linear waves
    “Stream Function Embedment”

Our Approach

Common Industry Practice
Embedment of Stream Function waves: limitations

- Fully nonlinear
- Easily computed (e.g. Fenton 1988)
- Can be embedded into background state

- 2D Flat bed theory
- Periodic
- Wave transformation, transient group nature, current, 3D effects?
Nonlinearity + Stochasticity: the DeRisk database

- Fundamental idea:
  - Make a pre-computed database of fully-nonlinear extreme waves
  - Span the nondimensional space \((H,T,h)\)

- Make it publicly available

- Users pick suitable nonlinear kinematics

- Perform aeroelastic computations (e.g. HAWC2) by using the nonlinear input waves
The DeRisk database

NUMERICAL MODEL
Fully-nonlinear potential wave solver OceanWave3D
(Engsig-Karup et al. 2009)
The DeRisk database

NUMERICAL MODEL

Fully-nonlinear potential wave solver OceanWave3D

(Engsig-Karup et al. 2009)
How to use the database:
Distribution of $H_S$ and $T_P$

![Peak wave period $T_p$](image)

German Bight
$h=33$ m

Figure courtesy of Hans F. Hansen, DHI
How to use the database: Contour plots vs LeMehaute plot

German Bight, h=33 m
(from DHI)
How to use the database

Contour plots

- Pick a realization from the database

- Stochasticity
  - many 1-hr and 3-hr runs ("random seeds") for each combination of \((H_S, T_P)\)
  - Kinematics sampled at many depths \([h = 20m \div 60m]\)
How to use the database: Calculating the loads

- Use the kinematics to calculate loads on a foundation

- Choose a suitable slender body force model
  - Morison (1950)
  - Rainey (1995)
  - Kristiansen and Faltinsen (2017)
How to use the database: Load on a monopile

- We use a hypothetical monopile at German Bight
  - $D = 7 \text{ [m]}$
  - $C_M = 2 \; C_D = 0.7$ (DNV-RP-205, 2007)
  - Stiff monopile
  - Rainey force model (Rainey 1995)

- We got lucky!
  We have a simulation which has kinematics sampled at $h=30 \text{ [m]}$ and which corresponds to a 100-yr storm
    - $H_s = 8.84 \text{ [m]}$
    - $T_p=16.85 \text{ [s]}$
How to use the database: wave elevation and acceleration at free surface

**Surface Elevation**

- **t [s]**: Time in seconds ranging from 0 to 4000.
- **\( \eta [m] \)**: Wave elevation in meters.

**Kin. acceleration at free surface**

- **t [s]**: Time in seconds ranging from 0 to 4000.
- **\( \ddot{u} [m/s^2] \)**: Kinetic acceleration in meters per second squared.

**Distribution**

- **\( P [-] \)**: Probability density function.
- **\( \eta [m] \)**: Wave elevation in meters.
- **\( \ddot{u} [m/s^2] \)**: Kinetic acceleration in meters per second squared.

**Frequency Spectrum**

- **f [Hz]**: Frequency in Hertz.
- **\( \eta [m] \)**: Wave elevation in meters.
- **\( \ddot{u} [m/s^2] \)**: Kinetic acceleration in meters per second squared.
How to use the database:
Example of extreme value computation
How to use the database:
Example of extreme value computation

Fit an extreme distribution (Gumbel, GEV...) to the non-exceedance probability and estimate confidence level for extreme value

\( H_s = 8.84 \, [m]; \ T_p = 16.85 \, [s] \)

Repeat for many (\( H_s, T_p \)) in the probability plane
How to extend the database: Froude scaling

- Waves are kinematically similar if they have the same Froude Number

\[ Fr = \frac{L}{g T^2} \]

- "Real life" wind farm
  - \((H_S, T_P, h) = (6[m], 10[s], 25[m])\)
  - Point 3 in database
    - \((H_S^{DB}, T_P^{DB}, h^{DB}) = (9.37[m], 12.5[s], 39.1[m])\)

\[ Fr = \frac{L}{g T^2} = Fr^{DB} \Rightarrow \lambda = \frac{h}{h^{DB}} = 0.64 \Rightarrow \frac{u}{u^{DB}} = \sqrt{0.64}, \frac{a}{a^{DB}} \]
Proof of concept: Froude scaling
Perfectly scaled computational domains

- Domain Scale = 1
- Wave Scale = 1
- \((N_x, N_y, N_z) = (8193, 1, 17)\)

- Domain Scale = 0.64
- Wave Scale = 0.64
- \((N_x, N_y, N_z) = (8193, 1, 17)\)
Proof of concept: Froude scaling
Input spectra

Wave Scale = 1  ->  \(H_s = 8.84\) [m]; \(T_p = 16.85\) [s]
Wave Scale = 0.64 -> \(H_s = 5.66\) [m]; \(T_p = 13.48\) [s]
Proof of concept: Froude scaling surface elevation (upscaled)
Proof of concept: Froude scaling surface elevation $h=40m$ (upscaled, statistics)
Generation of the database: parameter space

- Physically:
  - Problem has three parameters
  - \((H_S, T_P, h)\)

- Two are removed by using:
  - Froude scaling
  - Sampling at different depths

- One parameter left
  - A family of runs at different \(H_S / g T_P^2\)
Generation of the database: parameter space

• In reality, there are two other "hidden" parameters
  1. Breaking waves
  2. Wave generation depth

• Ideal conditions
  1. Handle the viscous breaking process via accurate models
  2. Start runs in deep water (all wave components $kh \geq 3$)
Generation of the database: parameter space

- In reality, there are two other "hidden" parameters
  1. Breaking waves
  2. Wave generation depth

- Current study
  1. Simplified breaking model: energy subtracted when the surface particle acceleration overcomes threshold value (Engsig-Karup et al. 2009)
  2. Choose the starting points carefully

The DeRisk design database

26  DTU Wind Energy, Technical University of Denmark

The DeRisk design database 1/25/2019
Wave generation depth: “law of the short blanket”

- Generation depth: 100 [m]
  - $kh = 3 \rightarrow k = 0.03$
  - $\lambda = 210 \text{ [m]} \rightarrow T = 11 \text{ [s]} \rightarrow 0.091 \text{ [Hz]}

- Part of the spectrum is not in deepwater

- To generate all waves in deep water:
  - Very short waves -> high grid resolution
  - Very long waves -> make the domain deeper (longer slope)

- What consequences does it have?
  - Statistically speaking

\[ H_s = 8.84 \text{ [m]}; \ T_p = 16.85 \text{ [s]} \]
Generation of the database:
wave generation depth

- Domain Scale = 1
- Wave Scale = 1

\[ H_s = 8.84 \, [m] \]
\[ T_p = 16.85 \, [s] \]

- Domain Scale = 1
- Wave Scale = 0.64

\[ H_s = 5.66 \, [m] \]
\[ T_p = 13.48 \, [s] \]

NOTE: sampling depths were updated to match the wave scale
Generation of the database: wave generation depth

Wave Scale = 1 \rightarrow H_s = 8.84 \text{ [m]}; T_p = 16.85 \text{ [s]}

Wave Scale = 0.64 \rightarrow H_s = 5.66 \text{ [m]}; T_p = 13.48 \text{ [s]}
Froude Scaling of database: unscaled results

\[ H_s = 8.84 \text{ [m]} \]
\[ T_p = 16.85 \text{ [s]} \]
\[ h = 30 \text{ [m]} \]
Froude Scaling of database: scaled results

Hs = 8.84 [m]
Tp=16.85 [s]
h=30[m]
Froude Scaling of database: scaled results

\[ H_s = 8.84 \text{ [m]} \]
\[ T_p = 16.85 \text{ [s]} \]
\[ h = 30 \text{ [m]} \]
\[
\begin{align*}
H_s &= 8.79 \text{ [m]} \\
T_p &= 13.72 \text{ [s]} \\
h &= 30 \text{ [m]}
\end{align*}
\]

\[
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Froude Scaling of database: scaled results

Hs = 8.79 [m]
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Froude Scaling of database: scaled results

$H_s = 8.79 \text{ [m]}$
$T_p = 13.72 \text{ [s]}$
$h = 30 \text{ [m]}$
Conclusions

- The DeRisk database gives a practical way of calculating extreme loads on offshore wind turbines
  - Handles stochasticity and nonlinearity

- The validity of the database can be extended via Froude scaling
  - We verified Froude scaling is respected

- Identified limitations relative to the simplified parameter space
  - Offshore boundary condition must respect sufficiently high $kh$