Loads and response from steep and breaking waves on monopiles

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Loads and response from steep and breaking waves on monopiles

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Henrik Bredmose
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Hydrodynamic loads

Simplest: Linear wave kinematics and Morison equation

\[ F = \frac{1}{2} \rho C_D D |U| U + \rho C_M A \frac{dU}{dt} \]

Better: Fully nonlinear wave kinematics and Morison equation

Advanced: CFD and coupled CFD

Zang and Taylor (2010)
Wave loads on offshore wind turbines
ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.

Task A:
Boundary conditions for phase resolving wave models

Task B:
CFD computation of monopile loads

Task C:
Aero-elastic response to fully nonlinear waves

Task D:
Physical validation test
Forces from a fully nonlinear potential flow solver

Allan Engsig-Karup, Harry Bingham and Ole Lindberg

\[ \partial_t \eta = -\nabla \eta \cdot \nabla \tilde{\phi} + \tilde{\omega}(1 + \nabla \eta \cdot \nabla \eta), \]

\[ \partial_t \tilde{\phi} = -g \eta - \frac{1}{2} (\nabla \tilde{\phi} \cdot \nabla \tilde{\phi} - \tilde{\omega}^2 (1 + \nabla \eta \cdot \nabla \eta)) \]

\[ \nabla^2 \phi + \partial_{zz} \phi = 0 \]

\[ \partial_z \phi + \nabla h \cdot \nabla \phi = 0 \]
Response in bottom of tower

Fully nonlinear waves versus linear waves

\[ H_s = 9.4 \text{ m}, \quad T_p = 14.2 \text{ s}, \quad W = 5 \text{ m/s} \]

Schløer et al (OMAE 2012)
Storm sea state. Turbine standstill.

Severe ringing/impulsive excitation.

Jacket and reference turbine modelled in Hawc2.

Fully nonlinear wave loads.

Torben Juul Larsen
Taesong Kim
Larsen et al Europ. Offsh. Wind 2011
Wave loads on offshore wind turbines
ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.

**Task D:**
Physical validation test

**Task A:**
Boundary conditions for phase resolving wave models

**Task C:**
Aero-elastic response to fully nonlinear waves

**Task B:**
CFD computation of monopile loads
The OpenFOAM® CFD solver

Open source CFD toolbox
Vast attention during last 3 years

This study: interFoam solver
  3D incompressible Navier-Stokes
  two phases (water and air)
  VOF treatment of free surface

Waves2foam wave generation toolbox has been developed and validated
(Niels Gjøl Jacobsen
Platform height of 8.96m

t=58.8s
Bredmose & Jacobsen OMAE 2011
Platform height of 8.96m

$t=58.9s$
Platform height of 8.96m

$t=59.1s$
Platform height of 8.96m

$t=59.2s$
Platform height of 8.96m

$t=59.3s$
Platform height of 8.96m

$t = 59.4\text{s}$
Platform height of 8.96m

$t=59.5s$

$z_p=8.96m$
Platform height of 8.96m

$t=59.6s$

$z_p = 8.96$ m
Platform height of 8.96m

$t=59.7s$

$F_t=59.7s$
Platform height of 8.96m

$t=59.8\text{s}$
Platform height of 8.96m

$t=59.9s$
Platform height of 8.96m

t=60.0s
Platform height of 8.96m

t=60.1s
Platform height of 8.96m

$t=60.2s$
Platform height of 8.96m

t=60.3s
Platform height of 8.96m

t=60.4s
Platform height of 8.96m

\[ t = 60.5 \text{s} \]
What is ringing?

Excitation of natural frequency by higher-harmonic forcing from nonlinear waves

Fig. 8. Resonant build-up of vibrations in model tests [3, Fig. 3.3]. Bending moment of the Draugen GBS (lower). \((k \eta_m, kR) = (0.22, 0.13)\). Wave elevation (upper). Reproduced with kind permission by Shell.
Detailed calculation of forces from steep regular waves

secondary load cycle

Bo Terp Paulsen
Third-harmonic force compared to FNV theory

- $kA=0.20$
- $kA=0.25$
- $kA=0.30$
- $kA=0.33$
- Huseby Grue - $kA=0.19$, $h/R=20$
- Huseby Grue - $kA=0.19$, $h/R=15$
- MM
- FNV

Terp Paulsen et al
IWWFB 2012
Coupling of OpenFOAM and OceanWave3D

Compute outer flow field with potential flow wave model
Compute inner field with wave-structure interaction with CFD-VOF model

Terp Paulsen et al (2012)
Coupling of OpenFOAM and OceanWave3D

- Irregular waves: JONSWAP(\( T_p = 12\text{s} \), \( H_s = 8\text{m} \))
- Large domain \( \Rightarrow \) Impossible to resolve with CFD alone!
- Rather trivial test case as it serves as validation

Terp Paulsen et al (2012)
Coupling of OpenFOAM and OceanWave3D

- 3 hours times series of 2D irregular waves computed in hours with OceanWave3D
- Selected event analysed with OpenFOAM (~1 day)

Terp Paulsen et al (2012)
Coupling of OpenFOAM and OceanWave3D

- Small “warmup” period for the CFD-computations: No initialization of pressure and pseudo air velocities
- Morison forces and CFD-computations agrees for small wave heights
- Discrepancies after passage of main event is attributed to diffraction effects

Terp Paulsen et al (2012)
Wave loads on offshore wind turbines
ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.

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Physical validation test
Wave loads Task D
Physical validation test

New tests at DHI with a rigid and a flexible structure

DHI:
Flemming Schlütter
Anders Wedel Nielsen
Jacob Tornfeldt Sørensen

DTU:
Henrik Bredmose
Torben Larsen
Signe Schloer
Bo Terp Paulsen
Harry Bingham
Wave loads Task D
Physical validation test

PVC pipe
Scale 1:80
Two masses
→ right
natural frequencies (1,2)
Experimental setup

top-view of wave gauges

side-view
Results and brief analysis for flexible pile

Irregular JONSWAP waves, unidirectional
h=20m
Tp=14s
Hs=11m

Free surface elevation 0.15m from pile
Measured inline force on pile
Acceleration of top point
Displacement of top point
Results and brief analysis

The graph shows the following:

- **Bottom left**: Top displacement [m] with a scale from -0.1 to 0.1.
- **Bottom middle**: Top acceleration [m/s²] with a scale from -1 to 1.
- **Bottom right**: Top displacement [m] with a scale from -0.1 to 0.1.
- **Top left**: Force with a scale from $-2 \times 10^4$ to $2 \times 10^4$.
- **Top right**: Water level $\eta$ [m] with a scale from -5 to 15.

The graphs are plotted over a time range from 2100 to 2550 with a horizontal resolution of 100 units.
'continuous' forcing of 1st natural mode from wave-nonlinearity

Impulsive load from breaking/near breaking wave
Which waves give the largest accelerations?

Bredmose et al (OMAE 2013)

\[ \text{acceleration in top accelerometer [m/s}^2\text{]} \]
Which waves give the largest accelerations?

Bredmose et al (OMAE 2013)
Numerical reproduction of experiments

Linear wave detection

Nonlinear wave transformation

\[ \partial_t \eta = -\nabla \eta \cdot \nabla \tilde{\phi} + \tilde{\omega}(1 + \nabla \eta \cdot \nabla \eta), \]

\[ \partial_t \tilde{\phi} = -g \eta - \frac{1}{2} (\nabla \tilde{\phi} \cdot \nabla \tilde{\phi} - \tilde{\omega}^2 (1 + \nabla \eta \cdot \nabla \eta)) \]

\[ \nabla^2 \phi + \partial_{zz} \phi = 0 \]

\[ \partial_z \phi + \nabla h \cdot \nabla \phi = 0. \]

FEM model

Force model

\[ F_{\text{surface}} = -\frac{1}{2} \rho_w \mathcal{A} c_m \eta_x (u - \tilde{X})^2 \]

\[ f(t, z) = \rho_w \mathcal{A} c_m (\dot{u} - \tilde{X}) + \]

\[ + \rho_w A \dot{u} + \rho_w \mathcal{A} c_m w_z (u - \tilde{X}) \]

\[ + \frac{1}{2} \rho_w c_{DD} (u - \tilde{X}) |u - \tilde{X}| \]
Wave transformation
Response, $h=40.8$ m
Response, $h=20.8 \text{ m}$
Wave loads on offshore wind turbines
ForskEL. DTU Wind, DHI, DTU MEK. 2010-2013.

Task D:
Physical validation test
- Experiments with flexible monopile
- Impulsive response
- Numerical reproduction
- Structural excitation from nonlinear waves

Task A:
Boundary conditions for phase resolving wave models
- Higher-harmonic loads (ringing loads)
- Coupling of pot flow model and CFD

Task C:
Aero-elastic response to fully nonlinear waves

Task B:
CFD computation of monopole loads

Statkraft
Loads and response from steep and breaking waves on monopiles

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