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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Statkraft
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

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

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

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

\[ \partial_z \phi + \nabla h \cdot \nabla \phi = 0 \]
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)
The OC4 jacket

Jacket and reference turbine modelled in Hawc2.

Non-linear wave loads.

Storm sea state. Turbine standstill.

Severe ringing/impulsive excitation.

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

$t = 58.9s$

$z_p = 8.96 \text{ m}$
Platform height of 8.96m

$t=59.0s$
Platform height of 8.96m

$t=59.1\text{s}$

$z_p=8.96\text{ m}$
Platform height of 8.96m

$t=59.2s$
Platform height of 8.96m

t=59.3s
Platform height of 8.96m

t=59.4s
Platform height of 8.96m

t=59.5s
Platform height of 8.96m

$t=59.6s$

$z_p = 8.96 \text{ m}$
Platform height of 8.96m

$t=59.7s$

$z_p = 8.96 m$
Platform height of 8.96m

t=59.8s
Platform height of 8.96m

t=59.9s
Platform height of 8.96m

t=60.0s
Platform height of 8.96m

$t=60.1s$

$z_p = 8.96$ m
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=60.5s
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
Third-harmonic force compared to FNV theory

Terp Paulsen et al
IWWFFB 2012
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\( \left( T_p = 12\text{s}, H_s = 8\text{m} \right) \)
- Large domain \(\Rightarrow\) Impossible to resolve with CFD alone!
- Rather trivial test case as it serves as validation
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.

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
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 Schløer
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

Wave maker

Rock berm

0.36

1.00  6.75  2.25  5.25  1.75  2.00

side-view

top-view of wave gauges
Results and brief analysis for flexible pile

Irregular JONSWAP waves, unidirectional

- $h=20\text{m}$
- $T_p=14\text{s}$
- $H_s=11\text{m}$

Free surface elevation 0.15m from pile

Measured inline force on pile

Acceleration of top point

Displacement of top point
Results and brief analysis

[Graphs showing various data trends over time]
'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)
Which waves give the largest accelerations?

$h = 40.8$ m

$h = 30.8$ m

$h = 20.8$ m

$H_s = 11$ m

$H_s = 8.3$ m

Bredmose et al. (OMAE 2013)
Numerical reproduction of experiments

Linear wave detection

Nonlinear wave transformation

\[ \partial_t \eta = -\nabla \eta \cdot \nabla \phi + \ddot{\eta} (1 + \nabla \eta \cdot \nabla \eta), \]
\[ \partial_t \phi = -g \eta - \frac{1}{2} (\nabla \phi \cdot \nabla \phi - \ddot{\phi} (1 + \nabla \eta \cdot \nabla \eta)) \]

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

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

FEM model

Force model

\[ F_{\text{surface}} = -\frac{1}{2} \rho_w c_m \eta_x (u - \dot{X})^2 \]
\[ f(t, z) = \rho_w c_m (\dot{u} - \dot{X}) + \rho_w \ddot{u} + \rho_w c_m w_z (u - \dot{X}) \]
\[ + \frac{1}{2} \rho_w c_D D (u - \dot{X}) |u - \dot{X}| \]
Wave transformation
Response, $h=40.8\, m$
Response, $h=20.8$ 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
  - Higher-harmonic loads (ringing loads)
  - Coupling of pot flow model and CFD
  - Structural excitation from nonlinear waves

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

**Task B:**
- CFD computation of monopile loads

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

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Loads and response from steep and breaking waves on monopiles

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