DIMSELO KPN Project

Fabio Pierella
DIMSELO

- Knowledge Building Project
  - Awarded by NFR
- Challenge standard design practice for Offshore Wind Turbines
- Consequences of advanced engineering models

- IFE
  - Project responsible
- DTU, NTNU
  - Academic Partners
- Statoil, Statkraft
  - Industrial partners
Wave models

- Deep water
  - Low steepness \((A/\lambda)\) of the wave
  - Linear solution is satisfactory

- Shallower waters
  - \(h = 25m - 40m\)
  - High steepness
  - Nonlinear effects

- Bottom-fixed wind farms are positioned at this depth

Le Mehaute (1976)
Wave models

- Deep water
  - Low steepness ($A/\lambda$) of the wave
  - Linear solution is satisfactory

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  - High steepness
  - Nonlinear effects

- Bottom-fixed wind farms are positioned at this depth
Diffraction of waves

- Large structures scatter incoming waves
- Leads to reduction in loads
- Important for large monopiles
  - $T = 2.5 \text{ s}$
  - $h = 30 \text{ m}$
  \[ D = \lambda = 10 \text{ m} \]

Chakrabarti (1987)
Design calculations via integrated models
Current practice

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<tr>
<th>Kinematics model</th>
<th>Fatigue</th>
<th>Extreme loads</th>
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<td>Linear irregular waves</td>
<td>Embedded 50-yr nonlinear wave</td>
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<td>Directionality</td>
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Questions at the base of DIMSELO

Kinematic loads can drive the design

1. How conservative are standard kinematics and force models?

2. Are the better engineering models? Can they be used?

3. Can we quantify the consequences of applying them?

NREL (2016)
DIMSELO

Structure of the project:

WP1
Sea Load Modeling
- Slender body models
- Large cylinders (First order Diffraction)

WP2
Wave Modeling
- Irregular 2nd order waves
- Embedment of nonlinear waves

WP3
Aerodynamics VLR
- Coherence of turbulence spectra
- 6p and 2nd order bending moment interaction
WP1
Rainey slender body model

• Based on an energy balance methodology and not on pressure integration considerations

• Three contributions on a submerged structure
  • Distributed force $F_d$
  • Distributed moment $M_d$
  • Force on free end $F_{pfe}$
  • Force on piercing point $F_{pfs}$
WP1
McCamy-Fuchs load model

Scatter of waves by cylinder
WP1
McCamy-Fuchs load model

Ratio of force predicted by Morison force model over MacCamy-Fuchs force model
WP2
Embedment of streamfunction waves

- **Standard**: 50-yr wave «cut-and-paste» in irregular linear waves

- **DIMSELO**: «Find and replace» highest linear wave with nonlinear SF wave

- Use of the Hilbert transfer to calculate the embedment period
WP2
Second-order irregular short-crested

- Full second-order short-crested waves
  - Sharma and Dean (1981)

- **Standard**: not possible without simplifications

- **DIMSELO**: Full theory implemented
  - 2D FFT calculation in space
DIMSELO Reference wind turbines

- Site
  - Dogger Bank

- Water depth
  - $h = 25m$ ; $h = 35m$

- Metocean conditions: Statoil

- Foundations
  1. XL Monopile 25m
  2. XL Monopile 35m
  3. Jacket 35m
     - Designed by Kasper Sandal (DTU)
Monopile 25m 10MW

- **Turbine**
  - DTU 10MW reference wind turbine
  - $H_{hub} = 119. [m]$

- DTU controller

- **Tower**
  - Steel, onshore tower

- **Substructure**
  - Designed ad-hoc

- **Fatigue and Extreme loads**
10 MW Monopile 25m: design characteristics

• 1st bending natural frequency
  • \( f = 0.23 \ [Hz] \)
  • Between 1p and 3p

• Transition piece
  • Point mass \( z = 19 \ [m] \)

• Pile
  • Steel

\[ h = 25 \ [m] \]
\[ p = 35 \ [m] \]
\[ D = 9 \ [m] \]
\[ t = 0.09 \ [m] \]
Monopile 25m: Soil model

- P-y soil springs
- Logarithmic decrement of 1st tower bending oscillation
  - $\delta = \frac{1}{n} \ln \frac{x_n}{x_{n+1}}$
- 1.5 % damping as a fraction of critical
  - $\zeta = \frac{\delta}{2\pi} = 0.015$
- Achieved by installing dampers at the mudline
Monopile 25m
Jacket Model
Monopile 25m
Tower side-to-side bending

- $f = 0.23 \text{ Hz}$
Monopile 25m
Rotor edgewise bending

- $f = 0.48 \text{ Hz}$
Monopile 25m
Rotor flapwise with yaw

- $f = 0.57 \, Hz$
Monopile 25m
Rotor flapwise with tilt

- $f = 0.59 \, Hz$
Monopile 25
Collective flapwise

- $f = 0.62 \text{ Hz}$
MetOcean conditions for DIMSELO structures

- Northern sea location
  - Dogger Bank

- Wind speed
  - conditional on $H_S$
  - Aligned with waves

- Turbulence
  - IEC-61400-1

- $\sum P(H_S, T_P) = 100$

Wind Speed@100 [m] [m/s]

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24.01.2018
Combination of models

- Force models
  - Rainey force model
  - McCamy-Fuchs force model
  - Morison force model

- Wave kinematics
  - First-order irregular waves
  - Second-order irregular waves

- Directional Spread
  - Short crested
  - Long crested

10 simulations per \((H_S, T_P)\)
Jonswap spectrum
Example: effect of kinematics
1st vs 2nd order

- Time series 30 min
- Sea state
  - $H_s = 3.5 \, [m]$, $T_p = 7.5\, [m]$
- Mudline x-wise force

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1 2

Example: effect of kinematics
1st vs 2nd order

- Time series 30 min
- Sea state
  - $H_s = 3.5 \, [m]$, $T_p = 7.5\, [m]$
- Mudline x-wise force
Example: effect of kinematics 1st vs 2nd order

- Histogram
- Sea state
  - $H_S = 3.5 \, [m], T_P = 7.5 \, [m]$
- Mudline $x$-wise force

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Example: effect of kinematics
1st vs 2nd order

- Exceedance probability
- Sea state
  - $H_S = 3.5 \, [m], T_P = 7.5 \, [m]$ 
- Mudline x-wise force

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A more compact view

- Fatigue IEC-61400-1
  - LC 1.6 → operation with NTM
- Simulate N series of 30 minutes
- Extract timeseries of important parameters
  - Mudline Fx [kN]
  - Mudline My [kNm]
  - Blade root Flapwise Mf [kNm]
- DAMAGE EQUIVALENT LOAD (DEL)
  - Regular load that would do the same damage as the irregular one if applied in a 1-min sinusoid

\[ D \propto DEL^m \]

- D : damage (inverse of lifetime)
- DEL : damage equivalent load
- m : Wöhler exponent (m=3 for steel)
Morison – 1st order – Long Crested (Base case)

Fatigue due to Mudline Fx

\((H_s, T_p)\) joint probability
MacCamy-Fuchs – 1st order – Long crested

Fatigue due to Mudline Fx

Force Model: maccamy_fuchs, Order: 1, Spread: Swell
Total damage 0.85

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Example: effect of force model

- Time series
- Sea state
  - $H_S = 3.5\ [m], \ T_P = 7.5\ [m]$
- Mudline Fx

|                 | Morison   | Maccamy
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- Histogram
- Sea state
  - $H_S = 3.5 \ [m], T_P = 7.5 \ [m]$

- Mudline Fx

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Example: effect of force model

- Power spectral density
- Sea state
  - $H_S = 3.5 \, [m], T_P = 7.5 \, [m]$
- Mudline Fx

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Rainey – 2nd order – Swell

Fatigue due to Mudline Fx
MacCamy-Fuchs – 1st order – Swell

Fatigue due to Blade Root Flapwise moment

Force Model: maccamy_fuchs, Order: 1, Spread: Swell

Total damage 1.00

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Example: effect of force model

- Power spectral density
- Sea state
  - \( H_S = 3.5 \, [m], \, T_P = 7.5 \, [m] \)
- Blade root Flapwise moment

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Rainey – 2nd order – Long crested waves

Fatigue due to Blade Root Flapwise moment
Morison – 1st order – Short vs Long crested

Fatigue due to Mudline moment around y-axis

Force Model: morison, Order: 1, Spread: MultiD
Total damage 0.98

Force Model: morison, Order: 1, Spread: Swell
Total damage 1.00
Effect of wave spreading

- Time series
- Sea state
  - \( H_S = 3.5 \, [m] \), \( T_P = 7.5 [m] \)
- Mudline x-wise force

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- Histogram
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Conclusions

• DIMSELO has shed light into effect of improved models on OWT dimensioning loads

• It helped understand when it is useful to adopt a more complex wave force or kinematics model

• For example, on a 25m Monopile fatigue load case:
  • 1st order diffraction made a difference on tower base fatigue
  • the blade loads were insensitive to wave load models
  • 2nd order waves do not significantly influence fatigue loads

• Timeline: Complete the calculations and deliver final report
MacCamy-Fuchs – 1st order – MultiD

Mudline moment $M_y$

Force Model: maccamy_fuchs, Order: 1, Spread: MultiD
Total damage 0.84

24.01.2018
Design calculations: today’s practice

- Fatigue calculations
- Linear irregular waves
- Morison equation

- Some critical points
  - Non-linearity in irregular waves
  - Non-linearity in the force model
  - What about wave diffraction of large monopiles?

- Extreme loads
- Embedment of a 50-yr nonlinear wave in long-crested waves
- Morison equation

- Some critical points
  - Directionality in the extreme loads?
  - Non-linearity of the force?
  - Statistical significance of extreme load?