THE DESIGN CHALLENGES

NORCOWE summer school 2015
By Jørgen R. Krokstad
(with contributions from Loup Suja Thauvin and Lene Eliassen – and others)
Assumed knowledge basis for the student

- Dynamic analysis, transfer functions and DAF
- Modal shapes and dynamic analysis of cantilever beams (see later)
- Spectral and time domain representation
- Irregular stochastic waves and wind (see later)
- Basic fatigue theory

\[ F = C_m \rho \frac{\pi}{4} D^2 \ddot{u} + C_d \frac{1}{2} \rho D u |u|. \]
Content

- Design trends – turbines and support structures
- Hydrodynamic loads
- Standards and limit states
- Design loads and analysis
- Integrated analysis and design
- Soil stiffness and capacity
The bottom fixed offshore wind turbine
AN INTEGRATED structure

The “cut”

1. Foundation
2. Transition piece
3. Lower tower
4. Upper tower
5. Nacelle with two blades
6. Third blade

Modified container carrier ‘Ocean Hanne’
From A2SEA
<table>
<thead>
<tr>
<th>Foundation</th>
<th>Depth (m)</th>
<th>Cum 2012</th>
<th>Trend 2020</th>
<th>Comments</th>
</tr>
</thead>
</table>
| Gravity-based foundations   | < 20      | 21%      |            | • Environmental restrictions  
• Complicated logistics  
• Suitable only for lower water depth                                   |
| Monopiles (incl. XL)        | 10 - 40   | 75%      |            | • XL pipes will pot. replace Jackets < 40 m depth  
• Known technology                                                    |
| Tripod/Tripile              | 25-50     | 2%       |            | • High fabrication costs  
• Too heavy  
• Expensive logistics                                                    |
| Jacket                      | 35-60     | 2%       |            | • Stiffer structure/less steel  
• Higher installation efforts  
• Higher fabrication costs                                             |
| Floating                    | > 50      | < 1%     |            | • Commercial realisation long term only  
• Logistical challenges                                                  |

Monopiles remain the dominant foundation concept, but trend toward deeper water is shifting to jacket foundations.
Development of MP’s

<table>
<thead>
<tr>
<th></th>
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<tbody>
<tr>
<td>SIF</td>
<td>Horns Rev 1</td>
<td>2.0 MW</td>
<td>Water depth up to 14 m</td>
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<tr>
<td>MT Hojgaard</td>
<td>Lynn</td>
<td>3.6 MW</td>
<td>Water depth up to 18 m</td>
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<tr>
<td>EEW SPC/Bladt</td>
<td>London Array</td>
<td>3.6 MW</td>
<td>Water depth up to 25 m</td>
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<td>EEW SPC/Bladt</td>
<td>Baltic II</td>
<td>3.6 MW</td>
<td>Water depth up to 27 m</td>
<td></td>
<td></td>
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<tr>
<td>EEW SPC</td>
<td>Gode Wind II</td>
<td>6 MW</td>
<td>Water depth up to 35 m</td>
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<tr>
<td>Future MP’s</td>
<td></td>
<td></td>
<td>8+ MW</td>
<td>Water depth up to 40 m</td>
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</tr>
</tbody>
</table>

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**Source:** A2Sea News - Winter 2013 and EEW SPC
## Comparison MP’s vs. Jackets

### Fabrication Costs

<table>
<thead>
<tr>
<th></th>
<th>MP's/TP's</th>
<th>Jackets</th>
<th>XL MP's/TP's</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Turbine</strong></td>
<td>Siemens 3.6 MW</td>
<td>Siemens 3.6 MW</td>
<td>Siemens 6 MW</td>
</tr>
<tr>
<td><strong>Water depth</strong></td>
<td>23 - 27 m</td>
<td>27 - 44 m</td>
<td>25 - 40 m</td>
</tr>
<tr>
<td><strong>Diameter</strong></td>
<td>5,5 - 6,5 m</td>
<td>3 m</td>
<td>7,5 - 9 m</td>
</tr>
<tr>
<td><strong>Weight</strong></td>
<td>630 - 930 to</td>
<td>1160 to</td>
<td>900 - 1500 to</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td>100%</td>
<td>+34%</td>
<td>+8%</td>
</tr>
</tbody>
</table>

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![Comparison MP’s vs. Jackets](image_url)
Dimensions MP’s/TP’s (note support structures including anodes)

Monopile

- Dimensions:
  - Diameter: 1.5 m to 7 m
  - Length: up to 120 m
  - Weight: up to 1000 t

XL Monopile

- Dimensions:
  - Diameter: up to 10 m
  - Length: up to 120 m
  - Weight: up to 1500 t

Transition Piece (incl. XL TP’s)

- Dimensions:
  - Diameter: up to 6.5 m
  - Length: up to 25 m
  - Weight: up to 300 t
Jacket development from pre-piled to suction bucket. Challenges?
Design trends on bottom fixed turbines

- Large turbines (6-10 MW, 150 - 200 meter diameter)
- Simple substructures – mono-columns, jackets
- Possible integrated installation (foundation, tower, nacell and rotor in one piece) but has not shown to be economical so far
- INTEGRATED design – optimize tower and foundation design
Reflections – Design trends on foundations

- What do we do with weight limitations on MP’s – about 1300 – 1500 tonn? Consequence for selection of dimensions?
- Reflect on MP’s versus Jackets
- Consequence of using suction foundations, mono columns, jackets.
Content

- Design trends – turbines and support structures
- Hydrodynamic loads
- Standards and limit states
- Design loads and analysis
- Integrated analysis and design
- Soil stiffness and capacity
Hydrodynamic loads through Morison equation

Two-dimensional loads on a single vertical strip

\[ F(t) = \frac{\pi}{4} \rho C_M D^2 \cdot \dot{u}(t) + \frac{1}{2} \rho C_D D \cdot u(t) \left| u(t) \right| \]

- \( F_D(t) \) = drag force per unit length of cylinder (N/m)
- \( C_D \) = dimensionless drag coefficient (-)
- \( D \) = cylinder diameter (m)
- \( u_e \) = water velocity amplitude (m/s)
- \( \omega \) = circular water oscillation frequency (rad/s)
- \( t \) = time (s)

- \( F_I(t) \) = inertia force per unit cylinder length (N/m)
- \( \rho \) = mass density of the fluid (kg/m³)
- \( C_M \) = dimensionless inertia coefficient (-)
- \( \dot{u}(t) \) = time dependent undisturbed flow acceleration (m/s²)

\( C_M \) has a theoretical value of 2 in a potential flow.

- Neglecting response acceleration and velocity
- Neglecting current (drag term only)
- Good or bad assumption ??
Inertia and drag force coefficients dependence

**Inertia or Drag dominance**

The KC-number can be utilized as an indication of the relative importance of Drag versus Inertia forces in a particular situation.

Comparing the force component Amplitudes of $F_d$ and $F_i$:

$$\frac{F_{\text{drag}}}{F_{\text{inertia}}} = \frac{1}{\pi^2} \frac{C_D}{C_M} \frac{u_a \cdot T}{D}$$

Dependent on roughness and diffraction – $\lambda/D < 5$.

Ref. Sarpkaya

- $KC < 3$ : Inertia Dominance, Drag neglected.
- $3 < KC < 15$ : Linearize the Drag.
- $15 < KC < 45$ : full Morison Equation (non linear Drag !).
- $KC > 45$ : Drag force is Dominant, Inertia neglected, near uniform flow.
- $KC \rightarrow$ infin. : constant current.
Hydrodynamic loads through Morison equation

\[ u(z, t) = \frac{\omega H}{2} \frac{\cosh \left[ k (z + h) \right]}{\sinh (k \cdot h)} \cos (\omega t) \]

\[ = u_a(z) \cdot \cos (\omega t) \]

\[ \dot{u}(z, t) = -\frac{\omega^2 H}{2} \frac{\cosh \left[ k (z + h) \right]}{\sinh (k \cdot h)} \sin (\omega t) \]

\[ = -\omega \cdot u_a(z) \cdot \sin (\omega t) \]

in which:

\[ \omega = \frac{2\pi}{T} \quad \text{wave frequency (rad/s)} \]
\[ k = \frac{2\pi}{\lambda} \quad \text{wave number (rad/m)} \]
\[ z \quad \text{elevation (+ is upward) from the still water level (m)} \]
\[ H \quad \text{wave height (m)} \]
\[ h \quad \text{water depth (m)} \]
\[ T \quad \text{wave period (s)} \]
\[ \lambda \quad \text{wave length (m)} \]
\[ u_a(z) \quad \text{amplitude of horizontal water velocity component (m/s)} \]
Deep water – intermediate- shallow water
Wave kinematics

- A - deep water: \( l/h_A < 2 \): \( l \) – wave length
- B – intermediate water depth: \( 2 < l/h_B < 20 \)
- C – shallow water depth: \( l/h_C > 20 \)
  - Only horizontal particle motion
- Velocities are shown – maximum at crest and through
- Acceleration – maximum at up-crossing and down-crossing – 90 degrees out of phase from velocities
- Phasing important for the overturning moment sensitivity
Validity range wave theories – Ursell number

(Wave height H versus water depth d)
Short term (1 hour) waves or response statistics

- The assumption of Rayleigh distributions for wave heights is not valid having «shallow» water depth ($H_s/h=1/3$ or $H_{max}/h=\frac{1}{2}$)

$$H_m = H_s \sqrt{\frac{\ln N}{2}}$$

Rayleigh distribution predicts the most probable maximum wave height ($H_s$) in a storm as:

where:

- $H_m$ = most probable maximum wave height
- $N$ = Number of waves in storm time series

For $N=1,000$ waves, $H_m = 1.86 H_s$
Inconsistent wave theories due to shallow water – affect strongly statistical method

\( H_{\text{max}} \) given as deterministic input – destroy statistic
Morison in combination with different non-linear wave theories relevant for intermediate water depths

<table>
<thead>
<tr>
<th>Kimon Agyriadis</th>
<th>Po Wen Cheng</th>
<th>Jan v. d. Tempel</th>
<th>Tim Camp</th>
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</thead>
<tbody>
<tr>
<td>Germanisher Lloyd</td>
<td>General Electric</td>
<td>T.U. Delft</td>
<td>Garrad Hassan</td>
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<tr>
<td>Airy – wheeler stretching, embedded stream function regular wave</td>
<td></td>
<td>Irregular Airy with 'cut &amp; paste' extreme stream function wave</td>
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<tr>
<td>Stokes 2\textsuperscript{nd} order irregular waves, superposition</td>
<td>Second Order Wave (Stanford)</td>
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<td></td>
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<tr>
<td>Boussinesq irregular waves</td>
<td>Boussinesq irregular waves</td>
<td></td>
<td>Boussinesq irregular waves</td>
</tr>
</tbody>
</table>
Reflections – Hydrodynamic loads

- What is Morison based load models missing?.
Content

- Design trends – turbines and support structures
- Hydrodynamic loads
- Standards and limit states
- Design loads and analysis
- Integrated analysis and design
- Soil stiffness and capacity
Standards with high relevance, components

Managing Risk

Other exploration:
- Offshore wind farms
- Standards from other regions (Blue)
Target safety for Offshore Wind Turbines

*Fig. 1 Statistical Meaning of Safety*
Tools for targeting safety if not reliability analysis is used – ref DNV-OS-J101

- **Ultimate limit states (ULS)** correspond to the maximum load-carrying resistance
- **Fatigue limit states (FLS)** correspond to failure due to the effect of cyclic loading
- **Accidental limit states (ALS)** correspond to maximum load-carrying capacity for (rare) accidental loads or post-accidental integrity for damaged structures.
- **Serviceability limit states (SLS)** correspond to tolerance criteria applicable to normal use.

**Characteristic loads and load effects:**

According to the partial safety factor format, the design combined load effect $S_d$ resulting from the occurrence of $n$ independent loads $F_i$, $i = 1,...,n$, can be taken as

$$S_d = \sum_{i=1}^{n} S_{d,i}(\beta)$$

where $S_{d,i}(F_{ki})$ denotes the design load effect corresponding to the characteristic load $F_{ki}$.

- Partial safety factors
Content

- Design trends – turbines and support structures
- Hydrodynamic loads
- Standards and limit states
- Design loads and analysis
- Integrated analysis and design
- Soil stiffness and capacity
Some important considerations DNV-OS-J101

Combination of wind and wave loads a huge challenge for the offshore wind industry. Why? Consequence?

Table 4-3 Statistical terms used for specification of characteristic loads and load effects

<table>
<thead>
<tr>
<th>Term</th>
<th>Return period (years)</th>
<th>Quantile in distribution of annual maximum</th>
<th>Probability of exceedance in distribution of annual maximum</th>
</tr>
</thead>
<tbody>
<tr>
<td>100-year value</td>
<td>100</td>
<td>99% quantile</td>
<td>0.01</td>
</tr>
<tr>
<td>50-year value</td>
<td>50</td>
<td>98% quantile</td>
<td>0.02</td>
</tr>
<tr>
<td>10-year value</td>
<td>10</td>
<td>90% quantile</td>
<td>0.10</td>
</tr>
<tr>
<td>5-year value</td>
<td>5</td>
<td>80% quantile</td>
<td>0.20</td>
</tr>
<tr>
<td>1-year value</td>
<td>-</td>
<td>Most probable highest value in one year</td>
<td></td>
</tr>
</tbody>
</table>

Table 4-9 Proposed load combinations for load calculations according to [4.6.5]

<table>
<thead>
<tr>
<th>Limit state</th>
<th>Load combination</th>
<th>Wind</th>
<th>Waves</th>
<th>Current</th>
<th>Ice</th>
<th>Water level</th>
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</thead>
<tbody>
<tr>
<td>ULS</td>
<td>1</td>
<td>50 years</td>
<td>5 years</td>
<td>5 years</td>
<td>50 years</td>
<td></td>
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<tr>
<td></td>
<td>2</td>
<td>5 years</td>
<td>50 years</td>
<td>5 years</td>
<td>50 years</td>
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<td></td>
<td>3</td>
<td>5 years</td>
<td>5 years</td>
<td>50 years</td>
<td>50 years</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>5 years</td>
<td>5 years</td>
<td>50 years</td>
<td>Mean water level</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>50 years</td>
<td>5 years</td>
<td>50 years</td>
<td>Mean water level</td>
<td></td>
</tr>
</tbody>
</table>
Important Load Cases for an Offshore Wind Turbine

**Ultimate loads**


**Blades:**
- Flapwise: Extreme turbulence (DLC1.3)
- Edgewise: Extreme wind (DLC6.1/6.2)

**Tower top:**
- Tilt: Safety system fault (DLC2.2)
- Yaw: Safety system fault (DLC2.2)

**Tower bottom:**
- Along wind: Gust & lost grid (DLC2.3)
- Across wind: Extreme wind (DLC6.1/6.2)

**Seabed:**
- Along wind: NTM & Extreme wave (DLC1.6)
- Across wind: Extr. wind & Wave (DLC6.X)
## Load cases

<table>
<thead>
<tr>
<th>Design situation</th>
<th>DLC</th>
<th>Wind condition</th>
<th>Waves</th>
<th>Wind and wave directionality</th>
<th>Sea currents</th>
<th>Water level</th>
<th>Other conditions</th>
<th>Type of analysis</th>
<th>Partial safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) Power production</td>
<td>1.1</td>
<td>NTM</td>
<td>$v_{in} &lt; V_{hub} &lt; v_{out}$</td>
<td>NSS</td>
<td>$H_s = E[P_{d1} \sqrt{V_{hub}}]$</td>
<td>COD, UNI</td>
<td>NCM</td>
<td>MSL</td>
<td>For extrapolation of extreme loads on the RNA</td>
</tr>
<tr>
<td></td>
<td>1.2</td>
<td>NTM</td>
<td>$v_{in} &lt; V_{hub} &lt; v_{out}$</td>
<td>NSS Joint prob. distribution of $H_p T_p / V_{hub}$</td>
<td>COD, MUL</td>
<td>No currents</td>
<td>NWLR or &gt; MSL</td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>1.3</td>
<td>ETM</td>
<td>$v_{in} &lt; V_{hub} &lt; v_{out}$</td>
<td>NSS</td>
<td>$H_s = E[P_{d1} \sqrt{V_{hub}}]$</td>
<td>COD, UNI</td>
<td>NCM</td>
<td>MSL</td>
<td>U</td>
</tr>
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<td></td>
<td>1.4</td>
<td>ECD</td>
<td>$V_{hub} = V_r - 2 \text{ m/s}, V_r$</td>
<td>NSS (or NWH)</td>
<td>$H_s = E[P_{d1} \sqrt{V_{hub}}]$</td>
<td>MIS, wind direction change</td>
<td>NCM</td>
<td>MSL</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>1.5</td>
<td>EWS</td>
<td>$v_{in} &lt; V_{hub} &lt; v_{out}$</td>
<td>NSS (or NWH)</td>
<td>$H_s = E[P_{d1} \sqrt{V_{hub}}]$</td>
<td>COD, UNI</td>
<td>NCM</td>
<td>MSL</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>1.6a</td>
<td>NTM</td>
<td>$v_{in} &lt; V_{hub} &lt; v_{out}$</td>
<td>SSS</td>
<td>$H_s = H_{s,SSS}$</td>
<td>COD, UNI</td>
<td>NCM</td>
<td>NWLR</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>1.6b</td>
<td>NTM</td>
<td>$v_{in} &lt; V_{hub} &lt; v_{out}$</td>
<td>SWH</td>
<td>$H = H_{SWH}$</td>
<td>COD, UNI</td>
<td>NCM</td>
<td>NWLR</td>
<td>U</td>
</tr>
</tbody>
</table>

- Very important load cases for substructure
- Very important load cases for wind turbine and tower
## Load cases

<table>
<thead>
<tr>
<th>Design situation</th>
<th>DLC</th>
<th>Wind condition</th>
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<th>Water level</th>
<th>Other conditions</th>
<th>Type of analysis</th>
<th>Partial safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>2) Power production plus occurrence of fault</td>
<td>2.1</td>
<td>NTM</td>
<td>$v_{in} &lt; v_{hub} &lt; v_{out}$</td>
<td>$H_{a} = E[v_{j} v_{hub}]$</td>
<td>COD, UNI</td>
<td>NCM</td>
<td>MSL</td>
<td>Control system fault or loss of electrical network</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>2.2</td>
<td>NTM</td>
<td>$v_{in} &lt; v_{hub} &lt; v_{out}$</td>
<td>$H_{a} = E[v_{j} v_{hub}]$</td>
<td>COD, UNI</td>
<td>NCM</td>
<td>MSL</td>
<td>Protection system or preceding internal electrical fault</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>2.3</td>
<td>EOG</td>
<td>$F_{w} = 6.0 \pm 2$ m/s and $F_{out}$</td>
<td>$H_{a} = E[v_{j} v_{hub}]$</td>
<td>COD, UNI</td>
<td>NCM</td>
<td>MSL</td>
<td>External or internal electrical fault including loss of electrical network</td>
<td>U</td>
</tr>
<tr>
<td></td>
<td>2.4</td>
<td>NTM</td>
<td>$v_{in} &lt; v_{hub} &lt; v_{out}$</td>
<td>$H_{a} = E[v_{j} v_{hub}]$</td>
<td>COD, UNI</td>
<td>No currents</td>
<td>NWP or ≥ MSL</td>
<td>Control, protection, or electrical system faults including loss of electrical network</td>
<td>F</td>
</tr>
<tr>
<td>3) Start up</td>
<td>3.1</td>
<td>NWP</td>
<td>$v_{in} &lt; v_{hub} &lt; v_{out}$</td>
<td>$H_{a} = E[v_{j} v_{hub}]$</td>
<td>COD, UNI</td>
<td>No currents</td>
<td>NWP or ≥ MSL</td>
<td>F</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>3.2</td>
<td>EOG</td>
<td>$F_{w} = 6.0 \pm 2$ m/s and $F_{out}$</td>
<td>$H_{a} = E[v_{j} v_{hub}]$</td>
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<td></td>
<td>U</td>
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<tr>
<td></td>
<td>3.3</td>
<td>EOG</td>
<td>$F_{w} = 6.0 \pm 2$ m/s and $F_{out}$</td>
<td>$H_{a} = E[v_{j} v_{hub}]$</td>
<td>MSL, wind direction change</td>
<td>NCM</td>
<td>MSL</td>
<td></td>
<td>U</td>
</tr>
</tbody>
</table>

### Very important load cases for substructure

### Very important load cases for wind turbine and tower
## Load cases

<table>
<thead>
<tr>
<th>Design situation</th>
<th>DLC</th>
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<th>Other conditions</th>
<th>Type of analysis</th>
<th>Partial safety factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>4) Normal shut down</td>
<td>4.1</td>
<td>NWP ( V_{ref} &lt; V_{ref} \leq F_{ref} )</td>
<td>NSS (or NWA)</td>
<td>COD, UNI</td>
<td>No currents</td>
<td>NWLR or MSL</td>
<td>U</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>ECG</td>
<td>( V_{ref} &gt; 2 \text{m/s} ) and ( V_{ref} )</td>
<td>NSS (or NWA)</td>
<td>COD, UNI</td>
<td>No currents</td>
<td>MSL</td>
<td>U</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>5) Emergency shut down</td>
<td>NTM</td>
<td>( V_{ref} \geq 2 \text{m/s} ) and ( V_{ref} )</td>
<td>NSS</td>
<td>COD, UNI</td>
<td>No currents</td>
<td>MSL</td>
<td>U</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>6) Parked (standing still or idling)</td>
<td>6.1</td>
<td>EWM Turbulent wind model ( (\Delta_{wind}) \geq V_{ref} )</td>
<td>ESS</td>
<td>MIS, MUL</td>
<td>ECM</td>
<td>EWL</td>
<td>U</td>
<td>N</td>
<td></td>
</tr>
<tr>
<td>6.2</td>
<td>EWM Steady wind model ( (\Delta_{wind}) \geq V_{ref} )</td>
<td>EWW</td>
<td>MIS, MUL</td>
<td>ECM</td>
<td>EWL</td>
<td>U</td>
<td>N</td>
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<td>EWM Turbulent wind model ( (\Delta_{wind}) \geq V_{ref} )</td>
<td>ESS</td>
<td>MIS, MUL</td>
<td>ECM</td>
<td>EWL</td>
<td>U</td>
<td>A</td>
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<tr>
<td>6.3b</td>
<td>EWM Steady wind model ( (\Delta_{wind}) \geq V_{ref} )</td>
<td>EWW</td>
<td>MIS, MUL</td>
<td>ECM</td>
<td>EWL</td>
<td>U</td>
<td>A</td>
<td></td>
<td></td>
</tr>
<tr>
<td>6.4</td>
<td>NTM</td>
<td>( V_{ref} \geq 0 ) ( \text{or} \ V_{ref} )</td>
<td>NSS Joint prob. distribution of ( H_{x}, T_{x}, V_{ref} )</td>
<td>COD, MUL</td>
<td>No currents</td>
<td>NWLR or MSL</td>
<td>F</td>
<td>*</td>
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</tr>
</tbody>
</table>

**Very important load cases for substructure**

**Very important load cases for wind turbine and tower**

![Statkraft Logo]
# Example of use of load cases

### Load case table: M and RUL

<table>
<thead>
<tr>
<th>Design location</th>
<th>Design wind speed (m/s)</th>
<th>Wind speed (m/s)</th>
<th>Year average</th>
<th>Sea state</th>
<th>Wave period (s)</th>
<th>Direction (°)</th>
<th>Turbulence (m/s)</th>
<th>Wind speed (m/s)</th>
<th>Load case</th>
<th>Additional multiplex (x)</th>
<th>Description of load case (x)</th>
<th>Number of simulations (x)</th>
<th>Total runtime (min)</th>
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<td>10.3-12.4</td>
<td>10-12</td>
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<td>MWC</td>
<td>0.95</td>
<td>0</td>
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<td>10.3-14.4</td>
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<td>0</td>
<td>MWC</td>
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<td>0</td>
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<td>MWC</td>
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<td>3</td>
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<td>24</td>
<td>10</td>
<td>U</td>
</tr>
</tbody>
</table>

### Wind directions

- MTM: Normal Turbulence Model
- EOG: Extreme Operating Case
- NWA: Normal Wind Model
- EGM: Extreme Gust Model
- WML: Wavemeter Model

### Wave directions

- RUS: Randomized Wave
- SWH:瑞典Wave Height
- SWH:瑞典Wave Height
- NWA: Normalized Wave

### Timed-out

- 6U: Fatigue Level
- 8U: Ultimate Level

---

Note! A large number of simulations with only 10 min duration. Consequence on extreme values?
Reflections – Design loads and analysis

- Why do we have so many different ways of combining loads?
- How do we solve the problem with consistent time duration waves and wind?
Content

- Design trends – turbines and support structures
- Hydrodynamic loads
- Standards and limit states
- Design loads and analysis
- Integrated analysis and design
- Soil stiffness and capacity
Challenges – Dynamic Analysis

- Offshore wind turbines – highly dynamic – integrated
- How to cut a dynamic structure in two parts – contractual issues
- How to optimize foundation (different designs for a selection of park locations) with tower (wants to keep one design)
- The troublesome top mass (nacelle and rotor)
- Waves and wave loads are non-linear in extreme weather and at shallow water

Design consequences (dimension selection)
1. Ensure no or limited frequency interaction between turbine and structural frequencies
2. Document sufficient design life (FLS)
3. Ensure sufficient structural capacity or integrity in storm conditions (ULS)
Eigenmodes and eigenfrequencies

\[ [K - \omega^2(M + m_a)]\Phi = 0 \]

- where \( K \) is stiffness matrix, \( M \) is structural mass and \( m_a \) is the added mass (zero in air – significant in water).
Qualification of Design Assumed 5 MW NREL turbine
(External and Internal use of Fedem Windpower Software package)
Status integrated analysis – real ongoing projects

- Operator is defining load cases together with turbine supplier
- Research institute is producing wave load data
- Turbine contractor is running integrated aerodynamic loads (including controller) and calculates global load responses for tower and foundation
- Foundation engineer do independent calculations for their foundation contract based on input from turbine contractor – sequential approach

The design situation is truly not INTEGRATED – plausible cause LACK OF ACCESS TO CONTROLLER – and INDUSTRY ESTABLISHED PRACTICE
Aerodynamics loads (nP – frequencies) illustrated on a blade. Changing distance

By Lene Eliassen
NTNU
Design challenge of support structure with increasing rotor diameter

Lower rotational speed of large turbines give lower 1P and 3P regions

By Loup/Lene
Statkraft/NTNU
Reflection on integrated design

- Future designs – in what frequency range do we want to design our support structure to reduce cost? Consequence?
Park effects on aerodynamic loading – Interaction between turbines

Standard IEC 61400-1 says:
“The increase in loading generally assumed to result from wake effects may be accounted for by the use of an effective turbulence intensity, which shall include adequate representation of the effect on loading of ambient turbulence and discrete and turbulent wake effects.

For fatigue calculations, the effective turbulence intensity, $I_{eff}$, may be derived according to Annex D.

For ultimate loads, $I_{eff}$, may be assumed to be the maximum of the wake turbulence intensity from neighbouring wind turbines as defined in Annex D.”

• This refers to the model of Frandsen (2005)
Park effects on aerodynamic loading – Interaction between turbines

- **Standard IEC 61400-1 says:**

  Is dist. > 5*D sufficient?
  
  Is turb class C sufficient?

---

[Graphs showing effective combined ambient & wake turbulence intensity for fatigue loads and ultimate loads, with annotations indicating increasing Wöhler constant from 1 to 12 and ambient turb. intensity = 0.1.]
Content

- Design trends – turbines and support structures
- Hydrodynamic loads
- Standards and limit states
- Design loads and analysis
- Integrated analysis and design
- Soil stiffness and capacity
Support structure types
Offshore Oil&Gas versus Offshore Wind Support structure challenges

**Oil & Gas Platforms**
- relatively stiff
- structural dynamics not critical
- wave loads dominant
- straight forward relation force-response
- ‘prototype’

**Offshore Wind Turbines**
- relatively flexible
- structural dynamics very critical
- wind and wave loads both important
- complex, uncorrelated loading
- generally large numbers
The soil stiffness models

Simplified: p-y curves and springs

More complicated: FEA models.
Design considerations

Typical North Sea wind farm design conditions:

- Relatively shallow water (10 – 30 m)
- Generally sandy soil conditions
- "Walking" sandbanks (Sand waves)
- Scour (influence of current and waves)
- Large cyclic loads on monopile
Foundation Design & Soil Conditions

• Foundation design and selection influenced by chalk, or the «absence» of it (within foundation depth), i.e. when chalk is:
  • Shallow -> MPs
  • Deep -> Jacket piles (in Swarte Bank)

• Uncertainty relates to Swarte Bank dominated infill (blue and green areas)