Accuracy of calculation procedures for offshore wind turbine support structures

Pauline de Valk – 27th of August 2013
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- Approach
- Modeling
- Results
- Conclusions and recommendations
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Offshore wind energy shows potential to become one of the main energy suppliers

- Demand for energy continues to increase
- Offshore wind energy
  - More steady wind flow and average wind speed is higher than onshore
Offshore wind energy shows potential to become one of the main energy suppliers

- Demand for energy continues to increase
- Offshore wind energy
  - More steady wind flow and average wind speed is higher than onshore
- Cost of energy (€/kWh) should be decreased
  - Structural optimization design

![Energy demand chart](chart.png)
Optimize structural design of the support structure

- Support structure one of the main cost items
- In order to optimize one should have confidence in the outcome of calculation procedures

Introduction  Approach  Modeling  Results  Conclusions and recommendations
Thesis objective

"Investigate the validity and conservatism"
Thesis objective

“Investigate the validity and conservatism of the current calculation procedures"
Thesis objective

“Investigate the validity and conservatism of the current calculation procedures for offshore wind turbine support structures"
Thesis objective

“Investigate the validity and conservatism of the current calculation procedures for offshore wind turbine support structures and propose improved procedures"
Thesis objective

“Investigate the validity and conservatism of the current calculation procedures for offshore wind turbine support structures and propose improved procedures based on these findings.”
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Offshore wind turbine support structure is custom engineered for every wind farm

Foundation designer (FD)

Turbine designer (TD)
Offshore wind turbine support structure is custom engineered for every wind farm.
Offshore wind turbine support structure is custom engineered for every wind farm

- **Foundation designer (FD)**
  - (Adjust) design foundation

- **Turbine designer (TD)**
  - Integrate foundation model in aero-elastic model
Offshore wind turbine support structure is custom engineered for every wind farm.

Foundation designer (FD)

(Adjust) design foundation

Turbine designer (TD)

Integrate foundation model in aero-elastic model

Run aero-elastic simulation (and adjust tower design)
Offshore wind turbine support structure is custom engineered for every wind farm.

Foundation designer (FD)

1. Adjust design foundation

Turbine designer (TD)

2. Integrate foundation model in aero-elastic model

3. Run aero-elastic simulation (and adjust tower design)

4. Extract interface loads/displacements between tower and foundation
Offshore wind turbine support structure is custom engineered for every wind farm.

**Foundation designer (FD)**
- (Adjust) design foundation

**Turbine designer (TD)**
1. Integrate foundation model in aero-elastic model
2. Run aero-elastic simulation (and adjust tower design)
3. Extract interface loads/displacements between tower and foundation
4. Apply interface loads/displacements on detailed foundation model

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Offshore wind turbine support structure is custom engineered for every wind farm.

Foundation designer (FD):
1. (Adjust) design foundation
2. Run simulation
3. Apply interface loads/displacements on detailed foundation model

Turbine designer (TD):
4. Extract interface loads/displacements between tower and foundation
5. Run aero-elastic simulation (and adjust tower design)
6. Integrate foundation model in aero-elastic model

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Offshore wind turbine support structure is custom engineered for every wind farm

**Foundation designer (FD)**

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Calculation post-processing analyses

*Dynamic analysis*

- $f_{\text{wind}}$
- $f_{\text{wave}}$

*Force controlled*

- $f_{\text{wave}}$
- $g$

---

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Calculation post-processing analyses

Dynamic analysis

Force controlled

Dynamic or Quasi-static

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Calculation post-processing analyses

Dynamic analysis

Force controlled

Dynamic or Quasi-static

Displacement controlled
Calculation post-processing analyses

Dynamic analysis

- Force controlled
  - Dynamic or Quasi-static

- Displacement controlled
  - Dynamic or Quasi-static

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Calculation post-processing analyses

Dynamic analysis

- Force controlled
  Dynamic or Quasi-static

- Displacement controlled
  Dynamic or Quasi-static

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Dynamic versus quasi-static analysis

- Dynamic analysis

\[ M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = f(t) \]
Dynamic versus quasi-static analysis

- Dynamic analysis
  \[ M \ddot{u}(t) + C \dot{u}(t) + Ku(t) = f(t) \]

- Quasi-static analysis
  \[ Ku(t) = f(t) \]
Dynamic versus quasi-static analysis

- Dynamic analysis

\[ M\ddot{u}(t) + C\dot{u}(t) + Ku(t) = f(t) \]
\[ (-\omega^2M + j\omega C + K)u(\omega) = f(\omega) \]

- Quasi-static analysis

\[ Ku(t) = f(t) \]
\[ Ku(\omega) = f(\omega) \]
Dynamic versus quasi-static analysis

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- Quasi-static analysis
  \[ Ku(t) = f(t) \]
  \[ Ku(\omega) = f(\omega) \]

- Only accurate if structure is excited below first eigenfrequency

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Design cycle for offshore wind turbine support structure

1. Foundation designer (FD)
   - (Adjust) design foundation
   - Run simulation
   - Apply interface loads/displacements on detailed foundation model

2. Turbine designer (TD)
   - Integrate foundation model in aero-elastic model
   - Run aero-elastic simulation (and adjust tower design)
   - Extract interface loads/displacements between tower and foundation

Introduction   Approach   Modeling   Results   Conclusions and recommendations
Design cycle for offshore wind turbine support structure

Foundation designer (FD)

1. (Adjust) design foundation
2. Integrate foundation model in aero-elastic model
3. Run aero-elastic simulation (and adjust tower design)
4. Extract interface loads/displacements between tower and foundation
5. Apply interface loads/displacements on detailed foundation model
6. Run simulation

Turbine designer (TD)
Reduction of foundation to lower computation costs

\[
(-\omega^2 M + j\omega C + K)u = f
\]

\[u = R\tilde{u}\]

- Reduce large number of DoF into smaller set of generalized DoF
  - \text{Size}(\tilde{u}) \ll \text{size}(u)
  - Lower computation costs
  - Approximation of exact solution
Reduction of foundation to lower computation costs

\[-\omega^2 M + j\omega C + K)u = f\]

\[u = RU\]

- Reduce large number of DoF into smaller set of generalized DoF
  - Size(\(\tilde{u}\)) \(<\) size(\(u\))
  - Lower computation costs
  - Approximation of exact solution
- Reduction basis contains limited number of deformation shapes

Introduction  Approach  Modeling  Results  Conclusions and recommendations
Reduction of foundation to lower computation costs

\[ (-\omega^2 M + j\omega C + K)u = f \]

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  - Size(\(\tilde{u}\)) \(<\) size(u)
  - Lower computation costs
  - Approximation of exact solution

- Reduction basis contains limited number of deformation shapes

- Only accurate if
  - Spectral convergence
  - Spatial convergence
Reduction methods

Guyan reduction

\[ R = + \ldots + \]

Static constraint modes
Reduction methods

Craig-Bampton reduction

\[ R = \text{Static constraint modes} + \text{Fixed interface vibration modes} \]
Reduction methods

Augmented Craig-Bampton reduction

\[ R = \text{Static constraint modes} + \text{Fixed interface vibration modes} + \text{Modal Truncation vectors} \]
Impact on fatigue damage results

- Offshore wind turbine exposed to cyclic loading
- Fatigue is one of the main design drivers
- Impact of error in the response on the accuracy of the fatigue damage results
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### Monopile versus Jacket

<table>
<thead>
<tr>
<th>Eigenfrequency</th>
<th>OWT model $\omega_{\text{free}}$ [Hz]</th>
<th>Foundation $\omega_{\text{free}}$ [Hz]</th>
<th>Foundation $\omega_{\text{fixed}}$ [Hz]</th>
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<tr>
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<td>6.73</td>
<td>42.8</td>
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</tr>
</thead>
<tbody>
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<td>1.06</td>
<td>4.09</td>
</tr>
</tbody>
</table>
Wind, wave and operational loads

- Wind loads
  - Random load, wide frequency spectrum
  - Excite frequencies up to 7 Hz
Wind, wave and operational loads

- **Wind loads**
  - Random load, wide frequency spectrum
  - Excite frequencies up to 7 Hz

- **Wave loads**
  - Wave frequencies are generally lower
  - Excite frequencies up to 0.5 Hz
Wind, wave and operational loads

- **Wind loads**
  - Random load, wide frequency spectrum
  - Excite frequencies up to 7 Hz

- **Wave loads**
  - Wave frequencies are generally lower
  - Excite frequencies up to 0.5 Hz

- **Operational loads**
  - Rotation frequency of the rotor (1P)
  - Blade passing frequency (3P)
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Quasi-static post-processing analyses

Dynamic analysis

\[ f_{\text{wind}} \]

\[ f_{\text{wave}} \]
Quasi-static post-processing analyses

Dynamic analysis

Quasi-static
Force controlled
Quasi-static post-processing analyses

Introduction   Approach   Modeling   Results   Conclusions and recommendations

Dynamic analysis

Quasi-static
Force controlled

Quasi-static
Displacement controlled
Accuracy of quasi-static post-processing

Elastic energy in the foundation structure

- Energy (J)
- Excitation frequency (Hz)
- $\omega_{\text{free}}$

Energy vs. Excitation frequency graph

Introduction   Approach   Modeling   Results   Conclusions and recommendations
Accuracy of quasi-static post-processing

Elastic energy in the foundation structure

- Energy [J]
- Excitation frequency [Hz]

- $\omega_{\text{free}}$
- $\omega_{\text{fixed}}$
Expansion of reduced response

- Response detailed foundation model obtained by expanding the reduced response of the foundation
- Only accurate if model converges spectrally and spatially

Dynamic analysis

\[ f_{\text{wind}} \rightarrow f_{\text{wave}} \rightarrow \tilde{f}_{\text{wave}} \rightarrow \tilde{f}_{\text{wave}} \rightarrow u = R\tilde{u} \]
Spectral convergence

Relative difference eigenfrequencies of reduced OWT model

- Red line: with Guyan reduced monopile
- Green line: with CB reduced monopile

Frequency [Hz]

Introduction   Approach   Modeling   Results   Conclusions and recommendations
Spectral convergence

Relative difference eigenfrequencies of reduced OWT model

- with Guyan reduced monopile
- with CB reduced monopile
- with Guyan reduced jacket
- with CB reduced jacket
- with ACB reduced jacket
Expansion of reduced response

\[ u = R\ddot{u} \]

**Relative energy difference of expanded response**

![Graph showing relative energy difference of expanded response](image)

- **Excitation frequency [Hz]**
- **Relative energy difference**
- **Legend:**
  - Red: Guyan
  - Green: CB
  - Orange: ACB
Expansion of reduced response

\[ u = R \tilde{u} \]

\[ (-\omega^2 M + j\omega C + K)R \tilde{u} = f + r \]

Relative energy difference of expanded response

Residual correction

\[ u = R \tilde{u} - K^{-1}r \]
Expansion of reduced response

\[ u = R \tilde{u} \]

Relative energy difference of expanded response

\[ (-\omega^2 M + j\omega C + K)R \tilde{u} = f + r \]

Residual correction

\[ u = R \tilde{u} - K^{-1} r \]
Post-processing analysis with reduced foundation in complete OWT model
Post-processing analysis with reduced foundation in complete OWT model

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Dynamic analysis

Force controlled
Dynamic and Quasi-static
Post-processing analysis with reduced foundation in complete OWT model

**Introduction**

**Approach**

**Modeling**

**Results**

**Conclusions and recommendations**

---

**Dynamic analysis**

- $f_{\text{wave}}$
- $\tilde{f}_{\text{wave}}$
- $\tilde{f}_{\text{wave}}$
- $f_{\text{wind}}$

**Force controlled**

*Dynamic and Quasi-static*

- $f_{\text{wind}}$
- $g$
- $f_{\text{wave}}$

**Displacement controlled**

*Dynamic and Quasi-static*

- $f_{\text{wind}}$
- $u_b$
- $f_{\text{wave}}$

Post-processing analysis with reduced foundation in complete OWT model

- Guyan reduction
- Craig-Bampton reduction
- Augmented Craig-Bampton reduction

Dynamic analysis

Force controlled
Dynamic and Quasi-static

Displacement controlled
Dynamic and Quasi-static

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Dynamic analysis

Force controlled
*Dynamic and Quasi-static*

Displacement controlled
*Dynamic and Quasi-static*
Post-processing analysis with Craig-Bampton reduced foundation in OWT model

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Relative energy difference with respect to exact solution

Excitation frequency [Hz]

Excitation frequency [Hz]

ω_free

ω_fixed

CB D FC

CB Qs FC

CB D DC

CB Qs DC
Post-processing analysis with Craig-Bampton reduced foundation in OWT model

- Quasi-static post-processing inaccurate
  - $\omega_{\text{free}}$ and $\omega_{\text{fixed}}$ within excitation spectrum
Post-processing analysis with Craig-Bampton reduced foundation in OWT model

- Introduction
- Approach
- Modeling
- Results
- Conclusions and recommendations

- Quasi-static post-processing inaccurate
  - $\omega_{\text{free}}$ and $\omega_{\text{fixed}}$ within excitation spectrum
- Dynamic post-processing accurate
  - CB reduced model converges spectrally
  - Internal dynamics included

Relative energy difference with respect to exact solution

![Graph showing relative energy difference with respect to exact solution. The graph illustrates the excitation frequency in Hertz (Hz) on the x-axis and the relative energy difference on the y-axis, with lines for different models and conditions, such as CB D FC, CB Qs FC, CB D DC, and CB Qs DC.](image-url)
Fatigue damage - Jacket

Relative damage difference with respect to exact damage

- Expansion
- Quasi-static Force controlled
- Dynamic Force controlled
- Quasi-static Displacement controlled
- Dynamic Displacement controlled
Fatigue damage - Jacket

Relative damage difference with respect to exact damage

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Conclusions

Following aspects tend to influence the accuracy of the calculation procedures:

- The characteristics of the structure
- First fixed and free interface eigenfrequency
- Qs FC significantly underestimates fatigue damage for jacket
- Use of a reduced foundation model in complete OWT model
- Spectral and spatial convergence
- Residual correction improves accuracy fatigue damage results
- Dynamic post-processing provides accurate fatigue damage results despite errors in interface loads/displacements
Conclusions

Following aspects tend to influence the accuracy of the calculation procedures:

- The characteristics of the structure
  - First fixed and free interface eigenfrequency
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Conclusions

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Following aspects tend to influence the accuracy of the calculation procedures:

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  - First fixed and free interface eigenfrequency
  - Qs FC significantly underestimates fatigue damage for jacket

- Use of a reduced foundation model in complete OWT model
  - Spectral and spatial convergence
  - Residual correction improves accuracy fatigue damage results

- Post-processing method
  - Dynamic post-processing provides accurate fatigue damage results despite use of reduced foundation
Recommendations

- Apply the different calculation procedures in BHawC with different load cases
Recommendations

- Apply the different calculation procedures in BHawC with different load cases
- Set up clear guidelines for spatial convergence
  - Error estimation methods
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- Apply the different calculation procedures in BHawC with different load cases
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- Determine an efficient and accurate calculation procedure for more complex models
Recommendations

- Apply the different calculation procedures in BHawC with different load cases
- Set up clear guidelines for spatial convergence
  - Error estimation methods
- Determine an efficient and accurate calculation procedure for more complex models
- Validate results with real OWTs and loads
Thank you for your attention
Levelized Cost of Electricity

€/kWh

Onshore LCoE
Offshore LCoE
Cost of electricity
EEX Leipzig
Fatigue damage computation

Response → Stresses → SN-curve → Fatigue damage

\[ S_a = \sigma_a \] (MPa)

\[ D = \sum \frac{n_i}{N_i} \]

\( N_f \), cycles to failure
Force versus displacement controlled

\[
\begin{pmatrix}
-\omega^2 \begin{bmatrix}
M_{ii} & M_{ib} \\
M_{bi} & M_{bb}
\end{bmatrix} + j\omega \begin{bmatrix}
C_{ii} & C_{ib} \\
C_{bi} & C_{bb}
\end{bmatrix} + \begin{bmatrix}
K_{ii} & K_{ib} \\
K_{bi} & K_{bb}
\end{bmatrix}
\end{pmatrix}
\begin{bmatrix}
u_i \\
u_b
\end{bmatrix}
= \begin{bmatrix}
f_i \\
f_b
\end{bmatrix} + \begin{bmatrix}
g_i \\
g_b
\end{bmatrix}
\]

- **Force controlled approach**

\[
(-\omega^2 M + j\omega C + K)u = f + g
\]

\[
Ku = f + g
\]

- **Displacement controlled approach**

\[
(-\omega^2 M_{ii} + j\omega C_{ii} + K_{ii})u_i = f_i - (-\omega^2 M_{ib} + j\omega C_{ib} + K_{ib})u_b
\]

\[
K_{ii}u_i = f_i - (-\omega^2 M_{ib} + j\omega C_{ib} + K_{ib})u_b
\]
Relative energy difference quasi-static analysis
Interface loads - Monopile
Interface loads - Jacket
Guyan reduced jacket in complete OWT model
Augmented Craig-Bampton reduction

1. External load represented by a spatial and temporal part
\[ \sum_{p=1}^{g} f_p \alpha_p(t) = F\alpha(t) \]

2. Quasi-static response and orthogonalize w.r.t. fixed interface vibration modes
\[ \tilde{\Phi}_{MTA} = PK^{-1}_ii F \]

3. Orthonormalize w.r.t. each other
\[ (\tilde{\Phi}_{MTA}^T K_{ii} \tilde{\Phi}_{MTA})y = \sigma^2 (\tilde{\Phi}_{MTA}^T M_{ii} \tilde{\Phi}_{MTA})y \]
\[ \Phi_{MTA} = \tilde{\Phi}_{MTA} y \]

4. Construct reduction basis
\[ \begin{bmatrix} u_b \\ u_i \end{bmatrix} = \begin{bmatrix} I & 0 & 0 \\ \Psi_C & \Phi_i & \Phi_{MTA} \end{bmatrix} \begin{bmatrix} u_b \\ \eta_i \\ \zeta \end{bmatrix} = R_{ACB} \begin{bmatrix} u_b \\ \eta_i \\ \zeta \end{bmatrix} \]
Augmented Craig-Bampton reduced jacket in complete OWT model
Facts wind energy

Wind turbine
- Power capacity
  - 3 MW
- Energy production
  - 6 – 7.5 GWh per year
  - Serves ± 2000 households

Household
- Average household
  - 2.2 persons
- Energy usage
  - 3500 kWh per year
### Requirement for calculation procedures

<table>
<thead>
<tr>
<th></th>
<th>Detailed foundation in OWT model</th>
<th>Reduced foundation in OWT model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expansion</td>
<td></td>
<td>✓ If spectrally and spatially converged</td>
</tr>
<tr>
<td>Force controlled</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dynamic</td>
<td>✓</td>
<td>✓ If spectrally and spatially converged</td>
</tr>
<tr>
<td>Quasi-static</td>
<td>✓ If $\omega_{\text{free}} &gt;&gt; \max(\omega_{\text{ext}})$</td>
<td>✓ If spectrally and spatially converged If $\omega_{\text{free}} &gt;&gt; \max(\omega_{\text{ext}})$</td>
</tr>
<tr>
<td>Displacement controlled</td>
<td></td>
<td></td>
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