Optimization of offshore wind turbine components in multi-body simulations for cost and load reduction
Agenda

• Motivation
• Reference turbine
• Modeling approaches
  ➢ Hydrodynamics
  ➢ Optimization method
• Results
• Conclusion
Motivation

• Offshore applications which exploit the high wind potential on the open sea gain more importance.

• Offshore foundations must be dynamically adapted with the wind turbines and designed cost-effectively.

➢ The aim of this work is to optimize offshore wind turbine components for load and cost reduction.
Reference Turbine

- Floating offshore wind turbine (FOWT) “OC3 spar-buoy” [1].
- Virtual wind turbine, developed within project IEA Annex XXIII - Offshore Code Comparison Collaboration (OC3).
- The spar-buoy floater consists of a shell made of steel filed with ballast material.
- Center of gravity is located far under the center of buoyancy.
- Wind turbine based on the 5 MW reference turbine (NREL)
- Tower and control system: adjusted to the floating system.
Optimization Setup

Interfacing

- Numerical optimization tool
- Simulation environment for Floating offshore wind turbines (FOWT)
Simulation environment - two levels of complexity

1. Reduced non-linear model
   - Developed by SWE, Uni Stuttgart
   - Implementation within MatLab
   - For the execution of multiple (design) load cases
   - Representation of the low frequent overall dynamics

2. Advanced SIMPACK model
   - Higher level of complexity for
     - Structural dynamics
     - Hydrodynamics
     - Aerodynamics
   - Insight into the dynamics on component level
### Reduced non-linear model

#### Structural model
- Unconstrained platform motion
- Tower bending (Translational nacelle displacement)
- Rotor speed

#### Aerodynamic model
\[
M_{aero} = \frac{1}{2} \rho \pi R^3 \frac{c_p(\lambda, \theta)}{\lambda} v_{rel}^2
\]
\[
F_{aero} = \frac{1}{2} \rho \pi R^2 c_T(\lambda, \theta) v_{rel}^2
\]

#### Hydrodynamic model
<table>
<thead>
<tr>
<th>Wave model</th>
<th>Linear (deepwater)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wave-Struct Interaction</td>
<td>Time-domain: Morison equation</td>
</tr>
<tr>
<td>Limitations</td>
<td>Only linear waves</td>
</tr>
<tr>
<td></td>
<td>No radiation</td>
</tr>
<tr>
<td></td>
<td>Slender bodies</td>
</tr>
</tbody>
</table>

Model contributed by SWE, Stuttgart University [2]
Advanced SIMPACK model [3]

- **External Wind Turbine Controller DLL CE 243**
- **Rotor aerodynamics AeroDyn (BEM) FE 241**
- **Hydrodynamics HydroDyn UR - SWE (FE 244)**
Hydrodynamics within SIMPACK

**INPUTS-2**
Frequency dependent hydrodynamic matrices

**INPUTS-1**
- Platform Properties and Wave Conditions
  - Platform Geometry
  - Wave-Excitation Force (Diffraction Problem)
  - Restoring (Hydrostatic Problem)
  - Damping Matrix
  - Added-Mass Matrix
  - Frequency-Domain Radiation / Diffraction
  - Hydrodynamics Preprocessor (SWIM or WAMIT)

**INPUTS-3**
- Platform Marker Kinematics
  - Frequency-Domain Hydrodynamics (HydroDyn)
    - Box-Muller Method
    - White Gaussian Noise
    - Inverse FFT
    - Morison’s Equation
    - Buoyancy Calculation
    - Time Convolution
    - Sum Forces

**OUTPUT**
Hydrodynamic Forces and Moments on Platform

**Hydrodynamic Calculations**
Available:
2. FE 224: HydroDyn

Fig.: NREL & Stuttgart University (SWE)
GESOP (ASTOS Solutions [4])

- Numerical optimization tool
- Problem definition: set of nonlinear differential equations, associated boundary conditions, path constraints and cost functions.
- GESOP offers several local and global nonlinear optimization methods.
- In the present study: only local methods are used.
- Based on the iterative Sequential quadratic programming (SQP) method.
Optimization step 1 - reduced model

Simulation Tool
- Reduced model (Matlab/Simulink)
- Loadcase DLC 1.1, IEC 61400-3, see [3]

→ Target function
  \[ f(x) = \frac{m_{\text{steel}}}{AEP} \]

→ Constraint variables

Constraints
- Min. Overall Restoring Torque
- Min. Periodic duration
- Max. Damage Equivalent Load
- Max. Equivalent Stress
- Max. mean and maximum Rotor Speed
- Min. AEP

Parameters
\[ 10 \leq h_{\text{Cyl}} \quad [m] \leq 200 \]
\[ 3,25 \leq R_{\text{Cyl}} \quad [m] \leq 20 \]
\[ 0,04 \leq e_{\text{Cyl}} \quad [m] \leq 0,08 \]
\[ 15 \leq h_{\text{trans}} \quad [m] \leq 50 \]
\[ 2,0 \leq R_{\text{trans}} \quad [m] \leq 10 \]
\[ 1000 \leq \rho_{\text{ballast}} \quad [kg/m^3] \leq 2500 \]
\[ 2,0 \leq R_{\text{tower}} \quad [m] \leq 10 \]
\[ 0,027 \leq e_{\text{tower}} \quad [m] \leq 0,04 \]
\[ 1 \times 10^{-3} \leq K_p \quad [\cdot] \leq 2 \times 10^{-2} \]
\[ 1 \times 10^{-4} \leq K_i \quad [\cdot] \leq 2 \times 10^{-3} \]
\[-0,5 \leq a_1, ..., a_5 \quad [\cdot] \leq 0,5 \]

Control System:
- \( K_i, K_p \)
- Gain Correction

Optimization Tool: SQP-method

Scaled target function \( f(p) \)
Scaled constraints \( g(p) \)
Scaled parameters \( p \)

Tower:
- \( R_{\text{Tower}} \)
- \( e_{\text{Tower}} \)

Floating Structure:
- \( R_{\text{Transition}} \)
- \( h_{\text{Transition}} \)
- \( R_{\text{Cylinder}} \)
- \( h_{\text{Cylinder}} \)
- \( e_{\text{Cylinder}} \)
- \( \rho_{\text{ballast}} \)
Optimization step 2 - advanced SIMPACK model

Simulation Tools
- Detailed model (SIMPACK)
- \( v = 12 \text{ m/s}, \) Loadcase DLC 1.1, IEC 61400-3
- Target function \( f(x) = \frac{m_{\text{Steel}}}{AEP} \)
- Constraint variables

Constraints
- Max. Damage Equivalent Load
- Max. Equivalent Stress
- Max. mean and maximum Rotor Speed
- Min. AEP

Parameters
\[
\begin{align*}
2.0 & \leq R_{\text{Tower}}[m] \leq 10 \\
0.027 & \leq e_{\text{Tower}}[m] \leq 0.04 \\
1e^{-3} & \leq K_p \quad [\text{ ] } \leq 2e^{-2} \\
1e^{-4} & \leq K_f \quad [\text{ ] } \leq 2e^{-3}
\end{align*}
\]

Scaled target function \( f(p) \)

Scaled constraints \( g(p) \)

Scaled parameters \( p \)

Optimization Tool: SQP-method
Optimization Results

Values regarding "OC3 spar-buoy"-%
- "OC3 spar-buoy"
- Optimized solution reduced model
- Optimized solution detailed model

Parameters
- \( P \), Tower
- \( e \), Tower
- \( k_r \)
- \( k_i \)

Gain-Correction Factor
- "OC3 spar-buoy"
- Optimized solution

Rotor-Collectiv Blade-Pitch Angle [°]
Conclusion

- Numerical optimization is worthwhile for the dynamical adaption of a wind turbine and the offshore support structure.

- An interface of GESOP and SIMPACK has been developed.

- To reduce the computational effort, a two-stage approach featuring models with increasing levels of complexity is beneficial.

- The hydrodynamic module HydroDyn within SIMPACK could be successfully used for the project.
Thank you for your attention...

References


[5] GESOP© by Astos Solutions

Acknowledgements

Università di Stoccarda

Germany

SWE

MesH Engineering

Ulrichstraße 23
73230 Kirchheim/Teck
Telefon: 07021/7366340

Stuttgarter Engineering Park
Curiestraße 2
70563 Stuttgart
Telefon: 0711/65226484

www.mesh-engineering.de