Design of floating wind turbine system with DeepLines Wind

GDR-EMR : Journée Eolien Offshore
Principia – Main activities

**Offshore engineering activity**

Global engineering offer
In offshore Oil & Gas

R&D to basic and detailed design

**Expertise & rules justification**

Engineering services
In Naval & Harbor

Expertise & simulation studies
In Nuclear

**Expertise & analysis**
Summary

- DeepLines Wind (in partnership with ifp Energies nouvelles)
- Validation
- Design Considerations
DeepLines

Floater side:
- Wind, current drag loads
- Wave loadings 1st and 2nd order
- Mooring & risers restoring forces

Mooring lines & risers side:
- Current drag loads + wave loadings (Morison)
- Soil Contact

Radiation/Diffraction of the incident wave on the FU hull (large body)
Wind turbine modeling software based on DeepLines solver

DeepLines GUI

Aerodynamic library (DLL)
- Blade Element Momentum
- HAWT
- VAWT

CONTROL External (DLL)

Hydrodynamics
- non linear hydrostatics
- 1st–2nd order, Full QTF
- Finite Element Method

Hydrodynamic database

Diffraction - radiation
Blades: beam elements

Flexible nacelle / tower connection: flexjoint

Tower: beam elements

Floater: rigid floater or beam elements

Mooring lines

Hub and Nacelle: rigid bodies

Low speed shaft: beam elements

Generator: node control

Pitch/yaw actuators: node control

New elements
- Blades, struts and tower: beam elements
- Control
- Specific aerodynamic models
FEM: Lagrangian Formulation

- Defines the local reference at this node: \( \bar{d}_{xi} = R_x(\bar{\theta}_x)\bar{e}_i \)

- Let the rotation vector be \( \bar{\theta}_x = \begin{pmatrix} \theta_1 \\ \theta_2 \\ \theta_3 \end{pmatrix} \) and, the Rodrigues' formula is written as:

\[
R_x(\bar{\theta}_x) = I_d + \frac{\sin \theta}{\theta} \begin{pmatrix}
  0 & -\theta_3 & \theta_2 \\
  \theta_3 & 0 & -\theta_1 \\
 -\theta_2 & \theta_1 & 0 \\
\end{pmatrix} + \frac{1 - \cos \theta}{\theta^2} \begin{pmatrix}
  \theta_2^2 + \theta_3^2 & \theta_1 \theta_2 & \theta_1 \theta_3 \\
  \theta_2 \theta_1 & \theta_1^2 + \theta_3^2 & \theta_2 \theta_3 \\
  \theta_3 \theta_1 & \theta_3 \theta_2 & \theta_1^2 + \theta_2^2 \\
\end{pmatrix}
\]
Infinite rotation handling: 2 options

**Option 1**

- **Updated Lagrangian Formulation**
  - The reference is the previous step (static or time)
  - The unknowns are the variation from the reference position
- **Problem: adaptation of the code**

**Option 2**

- **Apply a transformation when necessary at the entrance of the step**
- **Proposed by Cardona, A., Gerardin, M., 1988**
- **Criteria on the norm of the pseudo-rotation vector to stay below** $2\pi$
- **Introduce an updated pseudo-rotation vector:**
  \[ \vec{\theta}^*_x = \left(1 - \frac{2\pi}{\|\vec{\theta}_x\|}\right)\vec{\theta}_x \]
Pseudo-rotation vector becomes discontinuous with time at a given node.

The quantities rotational velocity and acceleration are continuous.

Numerical time marching scheme does not damp the results (constant rotational speed with constant moment).
Motion measurement
Hydrodynamic/Mechanical coupling

- Validation with respect to model test: anchored buoy coupled motion (2007)
 Validation on OC3 cases
Comparisons with FAST

**OC3 wind turbine with rigid foundation**

- Blades: 3 * 34 beam elements - damping 0.5%
- Shaft: 1 beam element – damping 1%
- Tower: 20 beam elements – damping 0.3%
- Nacelle: rigid body (RB) with inertia matrix
- Hub: RB with inertia matrix
- Flexible tower / nacelle coupling

**Load cases**

- HH1: constant wind speed: 2-25 m/s – Vertical gradient 0.14
- HH2: Linear ramp 5-50 m/s - yawed conditions @ 20°
- HH3: Extreme operating gust 25m/s
- NTM1: 3D turbulent wind - 11.2 m/s

<table>
<thead>
<tr>
<th>Variable ID</th>
<th>Description</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTDspFA</td>
<td>fore aft nacelle displacement</td>
<td>meter</td>
</tr>
<tr>
<td>TTDspSS</td>
<td>side to side nacelle displacement</td>
<td>meter</td>
</tr>
<tr>
<td>RootMxc1</td>
<td>blade root moment due to the rotor in plane forces</td>
<td>kN.m</td>
</tr>
<tr>
<td>RootMyc1</td>
<td>blade root moment due to the rotor out of plane forces</td>
<td>kN.m</td>
</tr>
<tr>
<td>TwrBsMxt</td>
<td>tower Base Moment due to the side to side rotor force</td>
<td>kN.m</td>
</tr>
<tr>
<td>TwrBsMyt</td>
<td>tower Base Moment due to the rotor fore- aft force</td>
<td>kN.m</td>
</tr>
<tr>
<td>TwrBsMzt</td>
<td>tower Base Moment in yaw</td>
<td>kN.m</td>
</tr>
<tr>
<td>RotSpeed</td>
<td>rotor rotational speed</td>
<td>rpm</td>
</tr>
<tr>
<td>RotThrust</td>
<td>rotor thrust</td>
<td>kN</td>
</tr>
<tr>
<td>BldPitch1</td>
<td>blade pitch angle</td>
<td>°</td>
</tr>
<tr>
<td>GenPwr</td>
<td>generated power</td>
<td>kW</td>
</tr>
</tbody>
</table>
NTM1 3D turbulent wind@11.2 m/s – time series

FAST
DeepLines
OC4 phase 1 - LC 5.6

**PRINCIPIA/ Deeplines WT**

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Enabled DOF</th>
<th>Wind Conditions</th>
<th>Wave Conditions</th>
<th>Analysis Type</th>
<th>Initial Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.6</td>
<td>All, Rotor speed and blade pitch via controller</td>
<td>Steady, uniform, no shear: $V_{hub} = 8 \text{ m/s}$</td>
<td>Regular stream function (Dean, 9th): $H = 8\text{ m}$, $T = 10\text{ s}$</td>
<td>Periodic time-series solution</td>
<td>$\Omega = 9\text{ rpm}$\n$\Phi = 0\text{ deg}$\n$\Theta = 0\text{ deg}$\nwave simulation starts from crest at $x = 0$, $y = 0$ (global system)</td>
</tr>
</tbody>
</table>
Structure Deflection

Transition Piece Fore-Aft Deflection

35 OC4 - Phase 1 - LC 5.6 Rev4 - 10.02.2012 - 08:29

TPX [m]

Time [s]
Aero loads on Tower

Tower Top Fore-Aft Shear Force

29 OC4 - Phase 1 - LC 5.6 Rev4 - 10.02.2012 - 08:29

Time [s]

YawBrFx [kN]
## OC4 phase 2

**Table 4: Load-Case Set 2, Inverted Pendulum**

<table>
<thead>
<tr>
<th>Load Case</th>
<th>Description</th>
<th>Enabled DOFs</th>
<th>Sim. Length</th>
<th>Wind Condition</th>
<th>Wave/Current Condition</th>
<th>Time series</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1</td>
<td>Deterministic waves</td>
<td>Support structure</td>
<td>60 s</td>
<td>No air</td>
<td>Regular Airy: $H = 6$ m, $T = 10$ s</td>
<td>Time-series-generated PDFs and PSDs</td>
</tr>
<tr>
<td>2.2</td>
<td>Stochastic waves</td>
<td>Support structure</td>
<td>60 min</td>
<td>No air</td>
<td>Irregular Airy: $H_s = 6$ m, $T_o = 10$ s, $\gamma = 2.87$, JONSWAP spectrum</td>
<td>Quasi-steady equilibrium position and loads</td>
</tr>
<tr>
<td>2.3</td>
<td>Current only</td>
<td>Support structure</td>
<td>N/A</td>
<td>No air</td>
<td>Surface = 0.5 m/s, $1/7$th power law decrease with depth</td>
<td>Time series</td>
</tr>
<tr>
<td>2.4</td>
<td>Current and deterministic waves</td>
<td>Support structure</td>
<td>60 s</td>
<td>No air</td>
<td>Regular Airy: $H = 6$ m, $T = 10$ s waves; Current at surface = 0.5 m/s, $1/7$th power law decrease with depth</td>
<td>Time-series-generated PDFs and PSDs</td>
</tr>
<tr>
<td>2.5</td>
<td>50-year extreme wave</td>
<td>Support structure</td>
<td>60 min</td>
<td>No air</td>
<td>Irregular Airy: $H_s = 15.0$ m, $T_o = 19.2$, $\gamma = 1.05$, JONSWAP spectrum</td>
<td>Time-series-generated “effective RAOs”</td>
</tr>
<tr>
<td>2.6</td>
<td>RAO estimation, no wind</td>
<td>Support structure</td>
<td>60 min</td>
<td>No air</td>
<td>White noise, $H_s = 6$m</td>
<td>Time-series-generated PDFs and PSDs</td>
</tr>
</tbody>
</table>
LC 2.2 – Irregular Wave – Mooring Response

- Larger response for dynamic mooring models – excitation of mooring natural frequencies?
- Below wave frequency, Morison-based models show more response at platform frequencies
- At pitch frequency, see separation into three groups: QS+QD, Dyn+QD, Dyn+Mor
OC5 phase 1 and 2

Model test:

- Wave Forces
- Floating windturbine
Statoil Hywind

- Beam model: mooring lines, floater, tower, blades, shaft,…
- Floater beam modeling calibrated with a potential model
- Time domain simulation of the whole coupled system (hydro/aerodynamic loadings and turbine controller)
- Large number of ULS, FLS & ALS analyses
- Verification of design criteria (acceleration, pitch, offset, angles, etc…)
- Mooring design (extreme and fatigue)
- Floater, Tower design (extreme and fatigue)
- Comparison and verification of the simulations with Company and turbine manufacturers’ software.

Hydrodynamic

Low impact on blade loads

Low impact on Mooring lines
Hydrodynamic

Low impact on platform motions (for usual wave loadings)

Considerable impact on Nacelle acceleration Tower loads platform loads
Control

- Bladed Interface
- Specificity of floating turbine
- IT issues
Cross Validation

- Aerodynamic / Controller
  - Onshore cases
  - Offshore cases
- Hydrodynamic
  - Model Tests
  - Prototypes
- Hydrodynamic simplified model
Simplified aerodynamic model

- Turbine / Cd / Constant load
- Extreme / Fatigue analysis
Load Cases

- Turbine vs Mooring / Structure design
- 10 min / 3 hours

![Bar chart showing fatigue life (years) for different time durations: 3h, 1h, 30 min, and 10 min.]

![Graph showing damage (1/year) over time (seconds).]
Conclusion

- Floating wind turbine
  - Interaction of two disciplines
  - Two designs in one with their own focus
  - Communication / Feedback

- Model
  - Keep in mind the objective of your model
  - Choose the proper simplifications