Software for integrated dynamic analysis of offshore wind turbines

Zhen Gao
CeSOS, NTNU

MARE-WINT Opening Seminar
Trondheim, Norway
Sept. 4, 2013
Contents

• Overview of offshore wind technology
• State-of-the-art software for integrated analysis of offshore wind turbines
  – Bottom-fixed wind turbines
  – Floating wind turbines
• Software validation

• Numerical simulation of marine operations – Offshore wind turbine installation
# Overview of offshore wind technology (1/3)

<table>
<thead>
<tr>
<th></th>
<th>Rated power</th>
<th>Support structure</th>
<th>Water depth (m)</th>
<th>Industry development</th>
<th>International standard</th>
<th>Software development</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2-3 MW</td>
<td>Monopile, gravity-based</td>
<td>0-30</td>
<td>Large commercial wind farms already exist (Denmark, UK, the Netherlands, Germany, Sweden, etc.)</td>
<td>IEC 61400-3, GL, DNV, BV and ABS; an extension of design code for onshore wind turbines</td>
<td>International Energy Agency (IEA), code-to-code comparison, OC3 (2005-2009) (monopile, tri-pod and spar, coordinated by NREL), OC4 (2010-2012) (jacket and semi-submersible, coordinated by Fraunhofer IWES and NREL)</td>
</tr>
<tr>
<td></td>
<td>2-3 MW</td>
<td>Tri-pod</td>
<td>10-40</td>
<td>Demonstration wind farms (Beatrice, Alpha Ventus), large farms planned</td>
<td>Refer to offshore design rules for support structures</td>
<td></td>
</tr>
<tr>
<td></td>
<td>3-5 MW</td>
<td>Jacket</td>
<td>30-80</td>
<td></td>
<td>DNV OS-J103</td>
<td></td>
</tr>
<tr>
<td></td>
<td>5 MW + (?)</td>
<td>Floating</td>
<td>&gt;100 (?)</td>
<td>Prototype (Hywind 2.3MW, WindFloat 2MW, BlueH, Sway, etc.)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Support structures:**
- Monopile, gravity-based
- Tri-pod
- Jacket
- Floating

**Rated power:**
- 2-3 MW
- 3-5 MW
- 5 MW + (?)
Overview of offshore wind technology (2/3) - Proposed concepts of floating wind turbines

Floater: spar, semi-submersible and TLP

Mooring system: catenary mooring and tendons

(a) Hywind spar, (b) WindFloat semi-sub, (c) MIT/NREL TLP, (d) ITI Energy barge, (e) Blue H TLP and (f) SWAY tension-leg spar

Floating wind turbines with different methods of achieving static stability (Butterfield et al., 2005)
Overview of offshore wind technology (3/3)

- Design of offshore wind turbine
  - Power production
  - Structural integrity, wrt ULS, FLS, ALS

- Integrated analysis of offshore wind turbine system
  - Environmental conditions
    - Turbulent wind field
    - Random waves
  - Load analysis:
    - Aerodynamics
    - Hydrodynamics
  - Response analysis:
    - Structural dynamics
    - Mooring analysis for floating WT
  - Control theory
    - To maximize power prod. (<U_{w\text{, rated}})
    - To keep constant power and reduce loads (>U_{w\text{, rated}})
    - Applied in time domain

- Design of components
  - Drivetrain, structural intersection (fatigue design)
  - Hierarchical analysis method (global / local)
State-of-the-art simulation tools and their capability

- **IEA OC3/OC4 benchmark study**
  - International Energy Agency, Offshore Code Comparison Collaboration
  - To assess the accuracy of aero-hydro-servo-elastic codes used in global response analysis for design of offshore wind turbines!
  - 2005-2009: OC3
    - Phase I, Monopile;
    - Phase II, Tripod;
    - Phase III, Spar-type floating (OC3-Hywind)
  - 2010-2013: OC4
    - Phase IV, Jacket;
    - Phase V, Semi-submersible
    - OC5? (code vs experiment)

*NB:* These are simulation tools for single horizontal-axis wind turbine!
Aerodynamics

• Wind field simulation
  – Deterministic: constant/uniform, wind shear, gust
  – Stochastic: turbulent wind field

• Numerical methods for wind turbine aerodynamics
  – BEM method, with corrections for tip loss, high value of axial induction factor, dynamic wake, dynamic stall and yaw
  – Lifting line/surface methods
  – Generalized actuator disc models
  – CFD

  • Applied in most of the simulation codes!
  • Using strip theory and accuracy strongly dependent on 2D airfoil data!
  • Aero-elasticity are modelled!

Figure 5-12 Surface Pressure and Cross-section Vorticity Isovalues at $\alpha = 18^\circ$

CFD for flow passing an airfoil (Bak, 2006)

An illustration of the BEM method (Hansen, 2008)
Hydrodynamics

- **Wave theory**
  - **Regular waves**: linear / nonlinear (Wheeler stretching, Stokes’ theory, stream function)
  - **Irregular waves**: linear, Wheeler stretching, second-order
  - Fully nonlinear wave theory and breaking waves not considered, but important in shallow waters

- **Hydrodynamic load analysis**
  - **Morison’s equation**:
    - Slender structures (like monopile, jacket, spar)
    - Empirical data of $C_m$ and $C_d$ (Re and KC number dependent)
    - Hydro-elasticity can be included
  - **Potential flow theory**:
    - Large-volume structures (like gavity-base, semi-sub, TLP)
    - Linear diffraction and radiation problems
    - Frequency-domain hydrodynamic code (e.g. WAMIT) needed
    - Second-order wave forces for moored structures
    - High-order wave loads (e.g. ringing)
  - **CFD**
    - Nonlinear wave loads: e.g. slamming force on monopile due to breaking waves (not yet included in the coupled tools)
Structural dynamics

- Methods for structural dynamic response analysis
  - Multi-body approach: geometrical nonlinearity
  - Modal representation: linear, limited DOFs
  - FEM: full model, computationally expensive

- Modelling technique
  - Rotor and tower
    - Flexible beam models, low natural frequency (aeroelasticity)
    - Large deformation considered for blades
  - Support structures
    - Flexible beam models for simple structures like monopile, tri-pod
    - Sub-model technique for complex structures like jackets
    - Large-volume floating structure usually considered as rigid-body due to high natural frequency

- Simulation outputs
  - Structural deformation, member force in beams, etc.
  - Need refined structural model e.g. to determine the SCF for fatigue analysis
# Aerodynamics

- Aerodynamic loads on floating wind turbines

<table>
<thead>
<tr>
<th>Analysis method</th>
<th>CFD</th>
<th>BEM or GDW with engineering corrections</th>
<th>Point force based on the thrust curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loads acting on blades (or rotor)</td>
<td>Distributed pressure and normal/shear stress due to viscosity</td>
<td>Distributed 2D lift and drag forces</td>
<td>Integrated thrust force</td>
</tr>
<tr>
<td>Blade (or rotor) structural model</td>
<td>Rigid, as body boundary</td>
<td>Flexible, beam element (Aeroelasticity incl.)</td>
<td>Rigid, point mass model (Just inertial effect incl.)</td>
</tr>
<tr>
<td>Wind field model</td>
<td>Constant wind speed only due to high CPU time?</td>
<td>Turbulent wind field</td>
<td>Time-varying wind speed at nacelle only</td>
</tr>
<tr>
<td>Applicability</td>
<td>To perform detailed blade and rotor design</td>
<td>To estimate global blade structural responses</td>
<td>To estimate rigid-body floater motions</td>
</tr>
</tbody>
</table>
# Hydrodynamics

- Hydrodynamic loads on floating wind turbines

<table>
<thead>
<tr>
<th>Analysis method</th>
<th>CFD</th>
<th>Potential theory + viscous effect (drag, empirical)</th>
<th>Morison’s formula (only applicable to slender members)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Loads acting on floater</strong></td>
<td>Distributed pressure and normal/shear stress due to viscosity</td>
<td>(Distributed pressure) Integrated force in 6DOFs + drag force</td>
<td>Distributed 2D mass and drag forces</td>
</tr>
<tr>
<td><strong>Floater structural model</strong></td>
<td>Rigid, as body boundary</td>
<td>Rigid-body (6DOFs)</td>
<td>Flexible, beam element (Hydroelasticity incl.)</td>
</tr>
<tr>
<td><strong>Wave theory</strong></td>
<td>Regular waves only due to high CPU time?</td>
<td>Regular/irregular waves with linear (and high-order) wave theory</td>
<td>Regular/irregular waves, linear/nonlinear wave theory</td>
</tr>
<tr>
<td><strong>Applicability</strong></td>
<td>To study strongly nonlinear problems</td>
<td>To estimate rigid-body floater motions (1\textsuperscript{st}+2\textsuperscript{nd} order problems)</td>
<td>To estimate structural responses in slender members</td>
</tr>
</tbody>
</table>
Mooring system (for floating wind turbines)

• **Types of mooring lines:**
  – Catenary mooring lines
  – Taut mooring lines
  – Tendons in TLP

• **Modelling of mooring system**
  – Linear or nonlinear springs: only stiffness contribution to the floater motions,
  – FEM: inertial and damping contributions in addition to stiffness

• **Dynamic response of mooring lines**
  – Uncoupled analysis: motion-induced line tension
  – Coupled analysis: vessel motions and mooring line tension are solved simultaneously
Wind turbine control

• Control strategy:
  (below/above rated wind speed)
  - Fixed-speed Fixed-pitch
  - Fixed-speed Variable-pitch
  - Variable-speed Fixed-pitch
  - Variable-speed Variable-pitch

• Pitch controller:
  - Collective pitch controller, PI controller with gain scheduling
  - Individual pitch controller
  - Controller tuned to avoid negative damping on platform motions for floating wind turbines.
**Structural Model**

- **Blades**: beam elements, cross sections with two symmetry planes
- **Tower**: beam elements, axisymmetric cross-sections
- **Hull**: rigid body, master-slave connection to tower base (fixed) and tendons (pinned)
- **Tendons**: beam elements, constant axisymmetric cross-section
- **Anchors**: fixed in translation, free in rotation

**External Load Model**

- **Blades**: turbulent wind, BEM or GDW sectional forces, including tower shadow effect
- **Hub and Nacelle**: no wind loads
- **Tower**: drag forces due to turbulent wind (in rotor region), or mean wind (below lowest blade passing point)
- **Hull**: hydrodynamic forces (1st/2nd order potential, Morison (drag), ringing)
- **Tendons**: hydrodynamic forces (Morison’s equation, wave kinematics at initial position)

**Simo/Riflex/Aerodyn**
(Ormberg & Bachynski, 2011)
## Selected simulation tools for bottom-fixed wind turbines and their capability

<table>
<thead>
<tr>
<th>Code</th>
<th>FAST</th>
<th>HAWC2</th>
<th>Flex5</th>
<th>Bladed</th>
<th>ADCoS-Offshore</th>
<th>USFOS/VPOne</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developer</td>
<td>NREL</td>
<td>Riso</td>
<td>DTU</td>
<td>Garrad Hassan</td>
<td>ADC + IWES</td>
<td>NTNU + VirtualPrototyping</td>
</tr>
<tr>
<td>Aero-</td>
<td>BEM (or GDW)</td>
<td>BEM DS</td>
<td>BEM DS</td>
<td>BEM DS</td>
<td>BEM DS</td>
<td>BEM DS</td>
</tr>
<tr>
<td>dynamics</td>
<td>DS</td>
<td>DS</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>dynamics</td>
<td>ME</td>
<td>ME</td>
<td>ME</td>
<td>ME</td>
<td>ME</td>
<td></td>
</tr>
<tr>
<td>Structural</td>
<td>Modal + MBS</td>
<td>FEM + MBS</td>
<td>Modal + MBS</td>
<td>Modal + MBS</td>
<td>FEM</td>
<td>FEM</td>
</tr>
<tr>
<td>dynamics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Control</td>
<td>DLL, UD, MS</td>
<td>DLL, UD, MS</td>
<td>DLL, UD</td>
<td>DLL</td>
<td>DLL, UD</td>
<td>DLL</td>
</tr>
<tr>
<td>interface</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

OC3 simulation tools (Jonkman et al., 2010)

* **BEM** (Blade Element Momentum theory); **GDW** (Generalized Dynamic Wake); **DS** (Dynamic Stall)
* **AW** (Airy theory with Wheeler stretching); **UD** (User-Defined); **Stream** (Stream function theory); **Stokes** (Stokes’ wave theory); **ME** (Morison’s Equation)
* **Modal** (Modal superposition); **MBS** (Multi-Body System); **FEM** (Finite Element Method)
* **DLL** (Dynamic Link Library); **UD** (User-Defined); **MS** (interface to Matlab/Simulink)
# Simulations tools for floating wind turbines and their capability

<table>
<thead>
<tr>
<th>Code</th>
<th>FAST</th>
<th>Simo/Riflex/Aerodyn</th>
<th>HAWC2</th>
<th>Bladed</th>
<th>3Dfloat</th>
</tr>
</thead>
<tbody>
<tr>
<td>Developer</td>
<td>NREL</td>
<td>NTNU+ Marintek (NREL)</td>
<td>Riso</td>
<td>Garrad Hassan</td>
<td>IFE, Norway</td>
</tr>
<tr>
<td>Aerodynamics</td>
<td>BEM (or GDW) DS</td>
<td>BEM (or GDW) DS</td>
<td>BEM DS</td>
<td>BEM DS</td>
<td>BEM DS</td>
</tr>
<tr>
<td>Hydrodynamics</td>
<td>A, UD ME, PT1</td>
<td>A, UD PT12</td>
<td>AW, UD ME</td>
<td>AW ME</td>
<td>A ME</td>
</tr>
<tr>
<td>Structural dynamics</td>
<td>Modal + MBS RSS</td>
<td>FEM + MBS RSS</td>
<td>FEM + MBS FSS</td>
<td>Modal + MBS FSS</td>
<td>FEM FSS</td>
</tr>
<tr>
<td>Control interface</td>
<td>DLL, UD, MS</td>
<td>DLL</td>
<td>DLL, UD, MS</td>
<td>DLL</td>
<td>DLL</td>
</tr>
<tr>
<td>Mooring system</td>
<td>NS</td>
<td>FEM</td>
<td>NS</td>
<td>NS</td>
<td>NS, FEM</td>
</tr>
</tbody>
</table>

* BEM (Blade Element Momentum theory); GDW (Generalized Dynamic Wake); DS (Dynamic Stall)
* AW (Airy theory with Wheeler stretching); A (Airy theory); UD (User-Defined); ME (Morison’s Equation); PT1 (Potential Theory using WAMIT, 1st-order wave force only); PT12 (Potential Theory using WAMIT, 1st- and 2nd-order wave forces);
* Modal (Modal superposition); MBS (Multi-Body System); FEM (Finite Element Method); RSS (Rigid Supporting Structure); FSS (Flexible Supporting Structure when using Morison’s equation)
* DLL (Dynamic Link Library); UD (User-Defined); MS (interface to Matlab/Simulink)
* NS (Nonlinear Spring); FEM (Finite Element Method)
Example: Dynamic response analysis of a jacket wind turbine

![Graph showing spectral density function of bending moment at the sea bed (Uv=15m/s, Hs=4m, Tp=8s)](image)

Jacket wind turbine and the first and third global eigenmodes (scale factor of 1000) with natural periods of 2.9 and 0.6 sec (Gao et al., 2010)

- The 5MW NREL reference wind turbine considered
- A jacket support structure in 70m water depth
- Analyses carried out using the HAWC2 and USFOS codes
- Analyses show:
  - Wind induces quasi-static and dynamic responses of the first and third global eigenmodes.
  - Wave-induced responses are mainly quasi-static.
  - Uncoupled analysis can give accurate results.

Spectral density function of bending moment at the sea bed (Uv=15m/s, Hs=4m, Tp=8s)
Example:
Comparative study of three floating wind turbines

- The 5MW NREL reference wind turbine considered
- Analyses carried out using the FAST code
- Analyses show significant platform motions of the barge concept due to wave loads, while those of the spar and TLP concepts increase slightly as compared to the land-based wind turbine.
Software validation

• Bottom-fixed wind turbines
  – Extensive validation carried out for onland wind turbines (aerodynamics and aeroelastic responses)
  – Validation against field measurement for offshore wind turbines:
    • Industry projects
    • Ongoing research projects like Alpha Ventus wind farm
  – Code-to-code comparison: OC3, OC4

• Floating wind turbines
  – Validation against field measurement:
    • Hywind
  – Validation against model test measurements:
    • Hywind: SIMO/RIFLEX+HAWC2 with Marintek test
    • WindFloat: FAST+TimeFloat with UC Berkeley test, rotor modelled by a disk
    • DeepCwind program: spar, semi-sub and TLP wind turbine tests at MARIN, comparison with FAST
  – Code-to-code comparison: OC3, OC4
Example: Code validation against Hywind-Demo measurements

- 2.3MW Hywind-Demo was deployed offshore, in Norway in September 2009.
- More than 200 channels of measurements with a sampling freq. of 25Hz.
- Comparison with the simulation tool HAWC2-SIMO-RIFLEX.

Comparison of bending moment at tower root (Hansen et al., 2011)

- The preliminary comparison show a good agreement between the full-scale measurement and the simulation.
- More comparison are needed to fully validate the simulation tool!
Example: Validation against model test measurements

- Model tests of the DeepCwind semi-sub wind turbine (1:50) carried out at MARIN, the Netherlands.
- Comparison with the simulation tool FAST.

Spectral comparison of surge motion for wave only condition.

Shows the importance of the second-order wave loads for resonant surge motions.

Spectral comparison of tower base moment for wave only condition.

Overall good agreement obtained, but there exists a discrepancy in resonant responses (pitch motion and tower bending), indicating a different damping estimation.
Example:
**Code-to-code comparison**

- OC3: spar wind turbine
- Big discrepancy observed in the first-round comparison. Comparison becomes better after several rounds due to improvements in individual codes.

*Comparison of various response parameters in irregular waves (Jonkman et al., 2010)*
Offshore wind turbine installation

- **Foundation installation**
  - Jack-up vessel
  - Floating installation vessel

- **Turbine and tower installation**
  - Jack-up vessel

Installation of wind turbine components involves crane operations!
Numerical simulation of marine operations

An example of monopile installation using floating vessel (Li et al., 2013):
- The purpose is to investigate the operational limit in terms of wave conditions (max. Hs) for such operation by numerical simulations.

Installation Procedure:
- Upending the monopile from a horizontal position on the vessel to a vertical position;
- Lowering the monopile through the wave zone down to the sea bed;
- Hammering the monopile into the sea bed;
- Lifting the transition piece from the vessel and lowering it on top of the monopile.

Simulation tool – SIMO from Marintek

- Flexible modeling of multi-body systems and couplings
- Wind, waves and current loads
- Non-linear time domain simulation
- Passive and active control forces

<table>
<thead>
<tr>
<th>Vessel</th>
<th>Monopile</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length overall [m]</td>
<td>183.0</td>
</tr>
<tr>
<td>Breadth [m]</td>
<td>47.0</td>
</tr>
<tr>
<td>Operational draught</td>
<td>13.5</td>
</tr>
<tr>
<td>Displacement [tons]</td>
<td>52000</td>
</tr>
<tr>
<td>Total mass [tons]</td>
<td>500</td>
</tr>
<tr>
<td>Length [m]</td>
<td>60</td>
</tr>
<tr>
<td>Outer diameter [m]</td>
<td>5.7</td>
</tr>
<tr>
<td>Thickness [m]</td>
<td>0.06</td>
</tr>
</tbody>
</table>
Transient system behaviour

Time-varying property:
- Hydrodynamic property of the monopile (modified Morison’s equation)
- Stiffness of the lift wire
- Coupling between the installation vessel and the monopile

Natural periods of the monopile rigid-body motions during the lowering process

<table>
<thead>
<tr>
<th>Motion mode</th>
<th>Initial position</th>
<th>Transition position</th>
<th>Final position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge [s]</td>
<td>1.19</td>
<td>2.0</td>
<td>1.56</td>
</tr>
<tr>
<td>Sway [s]</td>
<td>1.19</td>
<td>2.0</td>
<td>1.56</td>
</tr>
<tr>
<td>Heave [s]</td>
<td>1.33</td>
<td>1.86</td>
<td>2.01</td>
</tr>
<tr>
<td>Roll [s]</td>
<td>0.73</td>
<td>5.16</td>
<td>1.51</td>
</tr>
<tr>
<td>Pitch [s]</td>
<td>0.73</td>
<td>5.16</td>
<td>1.51</td>
</tr>
<tr>
<td>Yaw [s]</td>
<td>40.04</td>
<td>40.04</td>
<td>40.04</td>
</tr>
</tbody>
</table>

Position of the monopile during the lowering process
Response time series

Phase 1: lowering phase.
- Increasing wire length
- Changing stiffness
- Coupling at gripper device

Phase 2: landing phase.
- Increasing wire length
- Changing stiffness
- Coupling at gripper and landing devices

Phase 3: steady state phase.
- Steady stiffness
- Coupling at gripper and landing devices

Hs = 2.5 m
Tp = 6.0 s
Dir = 45 deg
Summary

• Numerical tools for integrated global response analysis have been developed in recent years.
• Code-to-code comparison through the OC3 and OC4 projects has been very helpful for the development of various tools.
• These tools should be further validated against model test and field measurements, for different types of bottom-fixed and floating wind turbines.
• Additional features (e.g. nonlinear wave loads) is also important to be implemented in these tools.

• Numerical analysis of marine operations is challenging due to the transient nature of such operations. Further software development and validation are needed.
Thank you!