RECENT DEVELOPMENTS OF THE DESIGN AND ANALYSIS OF FLOATING WIND TURBINES

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Outline
• Background
  - the threat of climate change
  - renewable energy – from the oceans
• Wind energy offshore
• Wind technology development and research
  - concept development
  - design
  - analysis
• Demonstration projects (field testing)
• Concluding remarks

Background
Motivation: IEA/IPCC
“The threat of climate change calls for an energy revolution,
-especially to limit the GHG emissions”
- investment in renewable energy, led by wind and solar, is
  increasing substantially, and shows signs that this change is underway
(IEA Energy Technology Perspectives 2010; IPCC SRREN,2011)

Renewable energy is forecasted to increase its share from 12.9 % of the total global primary energy supply in 2008 to 21 % in 2050

Wind energy offshore - prognosis

In Europe 40 GW is planned by 2020, implying a 20-25 % annual growth in installed capacity

Installing 40 GW requires about 10-15 000 windmills. This will imply a multi-billion-euro/dollar-industry in the years to come.
Wind energy conversion into mechanical torque and finally to electrical power

- Kinetic energy in wind: \[ E = \frac{1}{2} m v^2 \] (J)
- Power in the wind: \[ P_{\text{wind}} = \frac{1}{2} \rho A v^3 \] (W (m/s^-1))
- Electrical power: \[ P = C_P P_{\text{max}} \]

Average annual produced power (kWh/h)
- Electrical to absorbed or aerodynamic power ("efficiency" = 95%)

Rated power (instantaneous peak power) for design of power take off or drive train system

Control system objectives:
- Ensure efficient and safe operation
  - control torque at below rated speed and the power above rated, and limit the structural loads.

Supervisory systems to control:
- Yaw control
- Rotor speed control (blade-pitch)
- Power control (generator torque)

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Control systems, continued

Development trends
- Deeper water from fixed to floating
- Increased rotor size (capacity):
  - California 1980: 55 kW to 3.6 MW and upwards
  - One of a kind OG install. versus mass produced WTs.
  - No hydro carbons and people on board wind turbines
  - The wind energy sector is a "marginal business"
  - Return are more sensitive to IMMR (O&M) costs (access)

To avoid negative damping implied by a conventional controller, the controller frequency should be less than the natural frequency of the floating wind turbine

Servo-induced negative damping

Combined wind speed and direction sensor.

Schematic illustration of power production by a 5 MW bottom fixed wind turbine

Control systems, continued

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Servo-induced negative damping
Operation & Maintenance costs

- Failure rates and down times
  - Need for robust design, (reliable and few components) & smart maintenance, but also improved accessibility
  - Larger turbine size? ( > 5 - 20 MW)
  - Predict, monitor and measure degradation

Costs of (bottom fixed) offshore wind turbines

- Contribution to total CapEx

<table>
<thead>
<tr>
<th>Component</th>
<th>Onshore</th>
<th>Offshore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Turbine</td>
<td>70-85%</td>
<td>40-50%</td>
</tr>
<tr>
<td>Support structure</td>
<td>1-10%</td>
<td>15-30%</td>
</tr>
<tr>
<td>Grid connection</td>
<td>2-10%</td>
<td>15-20%</td>
</tr>
<tr>
<td>Electrical install.</td>
<td>1-10%</td>
<td>5-10%</td>
</tr>
<tr>
<td>Engineering</td>
<td>2-10%</td>
<td>5-10%</td>
</tr>
<tr>
<td>Other</td>
<td>2-10%</td>
<td>1-10%</td>
</tr>
</tbody>
</table>

- Reduce costs as done for land based turbines:
  - Increase turbine size
  - Improve manufacturing
  - Improve infrastructure

Technology development

- Support structure and drive train
  - Minimize cost while complying with safety and durability requirements. Larger units and reduced failure rates

- Support structures

- Rotor to generator (drive train)

- Power system:
  - Innovation in transmission, grid connection and system integration while maximizing power availability, quality, and stability

- Marine operations:
  - Improve efficiency of installation (transportation, site surveying, cable laying; etc.) and personnel access to facilities while minimizing the risks and the cost of operation.

R & D of Offshore Wind turbines

- New or improved Concepts
  - (a system of rotor, machinery, generator, support structure)
    - Characteristic behaviour
    - Satisfy criteria
    - Costs

- Design criteria
    - Power production
    - Limit states
      - Ultimate failure (ULS)
      - Ultimate failure initiated by faults (ALS)
    - Degradation (fatigue, corrosion, wear)
    - Account of automatic control

- Methods of analysis/software
  - Land based wind industry: FAST, Hawc3, Bladed+
  - Offshore oil and gas: SIMO/Riflex, Orcaflex etc.
Development of Floating Wind Turbines

- no commercial wind farms based on floating turbines yet

Support structure concepts

Floating turbines especially for deep water areas in the North Sea, USA, Mediterranean sea, Japan, Korea

- Design for mass production and easy installation; i.e., cost reduction
- At which water depth would floating wind turbines be competitive?

Design of Semi-submersible or Spar Concepts

5 MW wind turbine

Criteria

“Stability” requirement

- The tilt angle should be limited (e.g., to 7 degrees) under design overturning moment (800KN*90m)
- implying pitch a minimum restoring stiffness (C55)

Hydrodynamic performance requirement

- Heave natural period (T33) should be above 20s
- Pitch natural period should (T55) be around 30s

Structure response

- ULS/ALS, FLS

Cost effectiveness

- Steel weight
- Displacement
- Fabrication complexity

Displacement of semi-submersible designs vary between 4500 – 14 000 t
Ref.: Spar: 7500 t

Spar for 320 m vs 150 m water depth

Spar WT can be used to capture additional power from wave-induced motions for the below-rated wind regime (“WEC”) by modifying the controller

Dynamics of spar type turbine of size 5 MW

If resonance can not be avoided damping becomes crucial

Displacement of semi-submersible designs vary between 4500 – 14 000 t

Ref.: Spar: 7500 t
Design of floating wind turbines
Spar designs for 5 MW turbines

Stability, hydrodynamic and structural aspects

Mooring system aspects

Initial development of HyWind: 320 m w.d.
320 m w.d. 150 m w.d.

Combined spar WT and Torus WEC

Power production
• Shared mooring system and cable
• Synergy in maintenance

Design of Tension Leg Platform Wind Turbine
-excessive buoyancy creates pretension and limited heave and pitch

Constraints
• Surge/Sway natural periods
  > 25 s
• Heave/Roll/Pitch natural periods < 3.5 s
• Mean surge offset
  < 5% water depth
• No tendon slack:
  Tendons may not yield for
  2 times initial tendon tension
• Minimum displacement
  2 000 tonnes

Challenge:
-non-converging design spiral

Rotor blades
(for a 5 MW turbine the blade is 63 m long)

Smart blades
• Can active devices
  - reduce loads?
  - improve energy capture in low wind conditions?
  - increase the area swept with the same blade?

Full-scale structural testing of blades

Larger blades

Wind turbine with rated power: 5 MW

Electrical Power Production (kW)
Vmean (m/s)
0 1000 2000 3000 4000 5000 6000 7 9 11 13 15 17 19

Mean Wind Power - Spar FWT alone
Mean Wind Power - STC
Mean Wave Power - STC
Drive train – from rotor to generator

- Machineries (Gear systems, yaw & pitch mechanism, bearings, shafts)
- Structure

\[ \approx 10 \text{ to } 1500 \text{ rpm} \]

Alternative drive trains?

- Fixed or variable speed w/gear box
- Direct drive variable speed

- With a weight penalty

A main question:
- Is the drive train, rotor,... used on bottom-fixed turbines feasible for floating ones?

Particular challenge for floating concepts:

Some alternative ways to reduce top weight

- Use of new materials and new designs

Analysis for design of offshore wind turbines

- Aerodynamic, hydrodynamics,....
- Integrated (aero-, hydro-, elastic-, servo-) analysis
- loads: irregular waves, turbulent wind, rotor rotation in a gravitational field and a nonuniform wind field,

- conditions: operating, parked – intact or with faults

- response extremes and histories - st.dev. (for fatigue, wear..) for different failure modes,

- time versus frequency domain simulation

- refined versus simplified methods

- Laboratory or field tests
Aerodynamic loads

BEM: blade element momentum theory based on lift, drag, moment coefficients (engineering methods)
- relies on airfoil data

CFD: Navier-Stokes (NS) equations for the global compressible flow in addition to the flow near the blades.

Example of CFD analysis: Effect of atmospheric icing on the blades
- Ice accumulation on the leading edge and - rime influencing the surface roughness (sand grain roughness height of 0.5 mm)

Atmospheric icing on a blade after 24 hours in a relevant offshore site

Numerical (RANS/K-ε) and experimental results for profile ICE-2 after 24 hours

Effect of icing on the lift coefficient
Effect of icing on the power

Aerodynamics for ice blade using the Fluent CFD code
Validation – especially the turbulence model; mesh sensitivity

Effect of wakes

Two or three turbines on a single floater

Benchmarking exercise from Offshore Wind Accelerator
- Turbines are arranged in a regular grid
- Measurements from Horns rev in Denmark

Challenging hydrodynamics phenomena for floating structures (wind turbines):

Load formulation for catenary moored spar based on Morison formula and pressure on the bottom,
- load calculation at the instantaneous position

Springing and ringing response in TLP tendons
- Wave - and high frequency
  - Springing occurs when steady state load components with frequencies 2ω, 3ω, 2ω or 3ω coincide with a natural frequency

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Particular challenges for floating concepts: System modelling, including automatic control

- Nacelle
- Rotor
- Blades
- Column
- Floater hull
- Mooring lines
- Water depth > 50 m
- Electrical cable (insulated conductor and armour)

Different concepts
- Modeling of excitation mechanisms (wind, waves and current)
- Rotor aerodynamics
- Hydrodynamics
- Structural dynamics
- Automatic control theory
- Power generation

- Tightly coupled system
- Nonlinear

Integrated dynamic analysis
Example: Spar type wind turbines

Example: Structural dynamic response of Catenary Moored Spar

Example: Ameliorating the negative damping in the dynamic responses of a TLS with downwind turbine

Figure 13: Bending moment at spar/tower interface induced by wind and wave for constant and turbulent wind cases (Operational and survival conditions), the statistical characteristics are based on 1 hour samples.
**Simplified aerodynamic response analysis**

The resulting wind forces on the rotor consist of 3 force and 3 moment components. A simplified model is achieved by only considering the thrust force.

\[ T = \frac{1}{2} \rho A R^2 C_T U_{rel} \]

Further simplification is achieved by simulating the effect of control in the over rated response up to cut-out wind speed by a filter.

**Comparison of drivetrain responses in FWT and WT**

- Decoupled analysis to determine Tooth contact forces, Bearing forces, Gear deflections.
- Global aero-hydro-servo-elastic simulation
- Drivetrain multi-body simulation based on main shaft loading and nacelle motions

**Tower bending moment**

The simulation time for 1 hour real time:
- 15 min for SRT
- 24 hours for the “full” method

**Example: response analysis under faults during power production of a spar wind turbine**

- IEC code requires checking of nearly 40 cases with environmental loads for a system which is intact or fault. One case is:

**Marine operations**

Installation of wind turbines
- Requires a weather window
- Consideration of human factors
- Analysis of operations

**Perspective on marine operations**

- Alternative installation: Windflip
- HyWind installation

(Jiang et al, to appear)
Field tests or demonstration projects

- Laboratory tests
  - Rotor blades
  - Drive train
  - Support structure
  - Model basins/wind tunnels.
- Field tests to demonstrate
  - functionality
  - validate analysis tools

Beatrice, UK, 2 5-MW
Alpha Ventus, Germany, 12 5-MW (during construction)
Blue H (Dutch), in Italy
HyWind, Norway, 1 2.3-MW turbine

Other projects for floating wind turbines:
- Noweri (NOWITECH-NORCOWE); Norway
- Principle Power (American) at a site in Portugal
- Japan, Spain, USA

Concluding remarks

- A huge untapped potential for offshore wave and wind power exists. Only wind power is currently "commercial"
- Technology is still at an early stage, especially for floating wind turbines
  - Various concepts need to be pursued
  - possible influence on rotor and drive train design
- Rules and standards for design of floating wind turbine is urgently needed.
- Significant efforts are required to
  - increase robustness/reliability,
  - reduce costs (utilise mass production potential)
- Concerted efforts in R & D are required by the industry, research institutes and universities
- integrated dynamic analysis
- consideration of faults

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