Towards an Integrated Design Complex for Wind Turbines

Design of a 10 MW Reference Turbine

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Outline

• Presentation of the recently developed DTU 10 MW Reference Wind Turbine.
  – The Light Rotor Project
  – What it is and what it isn’t!
  – Description of the design process

• A unified framework for design and analysis of wind energy systems.
  – The next steps towards a systematic integration of wind energy analysis tools into a single framework
The Light Rotor Project

- The Light Rotor project aims at creating the design basis for next-generation wind turbines of 10+ MW.
- Collaboration with Vestas Wind Systems
- The project seeks to create an integrated design process composed of:
  - Advanced airfoil design taking into account both aerodynamic and structural objectives/constraints,
  - Aero-servo-elastic blade optimization,
  - High fidelity 3D simulation tools such as CFD and FEM,
  - Structural topology optimization.
Upscaling of Wind Turbines

• One of the main challenges to the continuous up-scaling of wind turbines is to maintain low weight while achieving high power efficiency and the necessary stiffness of the blade.

• To meet the demands on structural stiffness, designs move towards higher relative thickness and increasingly flexible blades.

• This poses challenges to the aerodynamic design, since thick airfoils are generally less efficient than thin ones.

• The aeroelastic design likewise requires increasingly advanced tools to tailor the blade to the large deflections.

• New solutions, both aerodynamic, structural and aeroelastic are thus needed for the next generation of multi-MW turbines.
The DTU 10 MW Reference Wind Turbine

• The purpose with the design is:
  – To provide a publicly available representative design basis for next generation new optimized rotors.
  – To achieve a design made with traditional design methods in a sequential MDO process
  – Good aerodynamic performance and fairly low weight.
  – To provide a design with high enough detail for use for comprehensive comparison of both aero-elastic as well as high fidelity aerodynamic and structural tools.

• The purpose is not:
  – To design a rotor pushed to the limit with lowest weight possible,
  – Provide a design of a complete wind turbine – focus is on the rotor,
  – To provide a design ready to be manufactured; the manufacturing process is not considered.

  DISCLAIMER: DTU will not be held responsible for failures or financial loss should someone choose to manufacture this turbine!
The Design Process

• DTU Wind Energy is responsible for developing a number of wind turbine analysis codes that are all used by industry in their design of wind turbines:
  – HAWC2 (multibody time domain aeroelastic code)
  – HAWCstab2 (Aero-servo-elastic modal analysis tool)
  – BECAS (Cross-sectional structural analysis tool)
  – HAWTOPT (Wind turbine optimization code)
  – EllipSys2D / 3D (RANS / DES / LES Navier-Stokes solvers)
• Other solvers used: Xfoil, ABAQUS
• In our normal research context we do not normally use these tools in a synthesized manner in a design process.
• The exercise for us was to apply our tools and specialist knowledge in a comprehensive design process of a 10 MW wind turbine rotor, something we have not done to this level of detail before.
• Identify areas in the design process suited for more integrated MDO architectures.
Design Team

- The design of the 10 MW RWT was a team effort with several participants:
  - Christian Bak (PM, design lead and aerodynamic design),
  - Robert Bitche (structural design),
  - Taeseong Kim (aeroelastic analysis),
  - Anders Yde (aeroelastic analysis),
  - Morten Hartvig Hansen (stability analysis and control),
  - Frederik Zahle (aerodynamic analysis).

- And many others who contributed to development of the tools that we used in the design process.
Design Summary

Table 6.1.: Gross Properties for the DTU 10MW RWT

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating</td>
<td>10 MW</td>
</tr>
<tr>
<td>Rotor Orientation, Configuration</td>
<td>Upwind, 3 Blades</td>
</tr>
<tr>
<td>Control</td>
<td>Variable Speed, Collective Pitch</td>
</tr>
<tr>
<td>Drivetrain</td>
<td>High Speed, Multiple-Stage Gearbox</td>
</tr>
<tr>
<td>Rotor, Hub Diameter</td>
<td>178.2 m, 5.6 m</td>
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<tr>
<td>Hub Height</td>
<td>127.37 m</td>
</tr>
<tr>
<td>Cut-In, Rated, Cut-Out Wind Speed</td>
<td>4 m/s, 11.4 m/s, 25 m/s</td>
</tr>
<tr>
<td>Cut-In, Rated Rotor Speed</td>
<td>7 rpm, 9.6 rpm</td>
</tr>
<tr>
<td>Rated Tip Speed</td>
<td>90 m/s</td>
</tr>
<tr>
<td>Overhang, Shaft Tilt, Precone</td>
<td>7.07 m, 5, 2.5</td>
</tr>
<tr>
<td>prebend</td>
<td>5m</td>
</tr>
<tr>
<td>Rotor Mass</td>
<td>224,000 kg</td>
</tr>
<tr>
<td>Nacelle Mass</td>
<td>393,800 kg</td>
</tr>
<tr>
<td>Tower Mass</td>
<td>494,572 kg</td>
</tr>
</tbody>
</table>
Workflow

Preliminary Design

- Upscaling: roughly based on NREL 5MW RWT
- Airfoil choice & airfoil data (based on 2D CFD)
- Preliminary aerodynamic layout
- Estimate of structural properties
- Establish DVs, constraints, and objectives

Design cycle

- Quasi-steady BEM aerodynamic optimization of $C_p$ based on parameterized blade geometry
- 3D Geometry generation
- FEM structural design
- 3D CFD evaluation
- Stability analysis and controller tuning
- Aeroelastic IEC load basis evaluation
- Structural failure analysis
Aerodynamic Optimization

- Airfoil choice limited to open source airfoils.
- No public WT airfoils exist that are designed or tested for high Re (>10e6).
- Airfoil choice: FFA-W3 series.
- Optimization carried out using HAWTOPT
  - in-house quasi-steady BEM based rotor optimization code,
  - Gradient-based optimizer (SLP),
- Objective: power coefficient
- Three TSRs – 7, 7.5, 8.06.
- Design variables:
  - Chord (14 cps), twist (13 cps), relative thickness (13 cps) – all Bezier
- Constraints:
  - rotor radius fixed at 89.166 m - direct upscale of the NREL-5MW-RWT,
  - minimum relative thickness = 24.1% - challenge aerodynamics
  - max thrust at rated – constrain loads in normal operation
  - Mean thrust at standstill – implicit constraint on maximum chord
  - Additional geometric constraints on design variables
Aerodynamic Design
3D CFD Analysis

- Automated workflow from 2D blade definition/airfoil family -> 3D shape -> 3D volume mesh,
- 3D CFD validation of performance predicted using BEM,
- Blade performance in the root area was not satisfactory due to use thick airfoils \((t/c > 0.36\) for \(r/R < 0.30\)).
- Gurney flap were used to remedy this, increase in CP of 1.2% at design TSR.
- Resulted in adjustment of airfoil data and new design iteration adopting the modified root layout.
- (Automated derivation of 3D airfoil data).
Structural Design

Geometry, material and composite layup definition

- Automatic generation of ABAQUS input files
- ABAQUS: layered shell model
- Local stress and failure
- ultimate loads
- HAWC2: aeroelastic analysis
- Cross section stiffness properties
- BECAS: cross section analysis
- Automatic generation of BECAS input files

<table>
<thead>
<tr>
<th>Load case</th>
<th>$\gamma_F$</th>
<th>$F_x$ [MN]</th>
<th>$F_y$ [MN]</th>
<th>$F_z$ [MN]</th>
<th>$F_{res}$ [MN]</th>
<th>$M_z$ [MNm]</th>
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</thead>
<tbody>
<tr>
<td>$F_x$ max</td>
<td>1.35</td>
<td>0.9531</td>
<td>-0.2915</td>
<td>1.0163</td>
<td>0.9967</td>
<td>25.2834</td>
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<tr>
<td>min</td>
<td>1.35</td>
<td>-0.8724</td>
<td>0.3672</td>
<td>2.2653</td>
<td>0.9465</td>
<td>-8.9863</td>
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<tr>
<td>$F_y$ max</td>
<td>1.35</td>
<td>0.4949</td>
<td>1.6055</td>
<td>2.4138</td>
<td>1.6801</td>
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<tr>
<td>min</td>
<td>1.35</td>
<td>-0.0504</td>
<td>-1.1862</td>
<td>0.2782</td>
<td>1.1879</td>
<td>44.0092</td>
</tr>
</tbody>
</table>
Aero-Servo-Elastic Analysis

- HAWC2 used to evaluate the comprehensive IEC design load basis in parallel on an HPC cluster.
- HawcStab2 used to analyze the modal properties of the wind turbine:
  - frequencies, damping ratios, and mode shapes.
- The DTU Wind Energy controller was revised and tuned specifically for the DTU 10 MW RWT.
- To avoid tower mode excitation from 3P frequency, minimum RPM = 7.
- Report and source code on controller available.
Summary of design challenges

• Transition from laminar to turbulent flow in the boundary layer of the airfoils showed surprising differences between the Xfoil  model and the $\gamma - \theta$ correlation based model,

• The efficiency of thick airfoils, i.e. airfoils with relative thickness greater than 30%, is significantly better when using Gurney flaps,

• To the reduce the blade weight, the blade design needs to be “stress/strain” driven rather than “tip deflection” driven. This lead to a pre-bend design,

• The control of the rotor must take several instability issues into account, e.g. coinciding frequencies from the tower eigen frequency and 3P at low wind speeds,

• Blade vibrations in stand still
Availability

- The DTU 10 MW RWT has been released to the European InnWind project for review and will be used as the reference turbine in this project.
- Will within weeks be available as a comprehensive release consisting of:
  - Fully described 3D rotor geometry,
  - Basic tower and drive train,
  - 3D corrected airfoil data (based on engineering models),
  - 3D CFD surface/volume meshes,
  - Comprehensive description of structural design,
  - Controller,
  - Load basis calculations using HAWC2,
  - Report documenting the design.
Towards a unified framework for design and analysis of wind energy systems

- Next steps in the Light Rotor project to synthesize the design process enabling employment of more advanced MDO architectures.

(from openmdao.org)
Towards a unified framework for design and analysis of wind energy systems
New Framework

• The idea is to think beyond optimization,
• A common platform for executing all codes, regardless of level of fidelity,
• Once a plugin is developed for a code, the code can enter into any type of analysis, parameter study or optimization and can be coupled to other codes,
• Built-in parallelization for comprehensive design space exploration,
• It’s a collaborative platform, open-source at the core level,
• Possibility to have closed-source modules for commercial tools and open-source modules for research tools,
• Base class structure common to all applications,
• Base classes define basic inputs/outputs, geometry and connectivity,
• Plans to collaborate with NREL,
• Based on Python and OpenMDAO.
Geometry tools

CAA

Panel methods

2D airfoil CFD

3D rotor CFD

Vortex methods

Empirical noise models

CAA

Modal analysis codes

Aerelastic time domain codes

Lo-fi structural models

Cost models

Cross-section structural tools

Geometry tools

3D FEM tools
Airfoil Shape Optimization

Airfoil acoustic characteristics

Blade acoustic optimization

Controller tuning

Stability analysis

Blade structural optimization

Rotor aerodynamic characteristics

Rotor acoustic characteristics

Rotor aerodynamic optimization

Wind Turbine geometry generation

Rotor aeroelastic tailoring

Aerodynamic load basis calculations

Cross-sectional structural characteristics

Rotor structural characteristics
Open source WE framework

- Airfoil Shape Optimization
- Airfoil acoustic characteristics
- Blade acoustic optimization
- Airfoil aerodynamic characteristics
- Controller tuning
- Stability analysis
- Blade structural optimization
- Rotor structural characteristics
- Rotor aerodynamic characteristics
- Rotor acoustic characteristics
- Rotor aeroelastic tailoring
- Rotor aerodynamic characteristics
- Wind Turbine geometry generation
- Cross-sectional structural characteristics
- Aeroelastic load basis calculations
- Open source WE framework
Conclusions

• The DTU 10 MW RWT design has been finalized – release imminent.
• Design carried out by a team of expert researchers using a sequential approach employing state-of-the-art wind turbine analysis codes
• Highly detailed – useful for researchers for inter-code comparison
• Basis for future designs of optimized large MW turbines

• The activities in the Light Rotor project (as well as other projects) has led to an initiative to synthesize the workflows involving our design codes into a unified framework for design and optimization of wind energy systems.
• Open-source core, mix of open/closed analysis modules
• Facilitate deployment of research codes into research / industry design processes.