The DTU 10-MW Reference Wind Turbine

Bak, Christian; Zahle, Frederik; Bitsche, Robert; Kim, Taeseong; Yde, Anders; Henriksen, Lars Christian; Hansen, Morten Hartvig; Blasques, José Pedro Albergaria Amaral; Gaunaa, Mac; Natarajan, Anand

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The DTU 10-MW Reference Wind Turbine

Christian Bak
chba@dtu.dk

Frederik Zahle, Robert Bitsche, Taeseong Kim, Anders Yde, Lars Christian Henriksen, Morten H. Hansen, José Blasques, Mac Gaunaa, Anand Natarajan

Section for Aeroelastic Design and Section for Structures
Technical University of Denmark
DTU Wind Energy – Risø Campus
The DTU 10 MW Reference Wind Turbine
Background: Upscaling

Power ~ rotor diameter$^2$
Mass ~ rotor diameter$^3$

Source: International Energy Agency (IEA)
The DTU 10 MW Reference Wind Turbine
Background: Upscaling blades

\[ \text{Mass}_{\text{carbon}} = 9 \times 10^{-5} \times \text{Length}^{2.95} \]

\[ \text{Mass}_{\text{glass}} = 0.0023 \times \text{Length}^{2.17} \]

- Glasfiber
- Carbonfiber

Upscale from 40m blades with \( x^3 \)

Blade mass [tons] vs. Blade length [m]
The DTU 10 MW Reference Wind Turbine

Objective of 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.

- We need a reference wind turbine to compare our designs against
The DTU 10 MW Reference Wind Turbine

Objectives

• The purpose with the design is:
  - 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,
  - To provide a publicly available representative design basis for next generation of new optimized rotors.

• The purpose is not:
  - To design a rotor pushed to the limit with lowest weight possible,
  - To push the safety factors as much as 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.
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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 and use them in the design of the DTU 10MW RWT:
  – **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.
The DTU 10 MW Reference Wind Turbine Design Summary

<table>
<thead>
<tr>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rating</td>
<td>10MW</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>Medium speed, Multiple stage gearbox</td>
</tr>
<tr>
<td>Rotor, Hub diameter</td>
<td>178.3m, 5.6m</td>
</tr>
<tr>
<td>Hub height</td>
<td>119m</td>
</tr>
<tr>
<td>Cut-in, Rated, Cut-out wind speed</td>
<td>4m/s, 11.4m/s, 25m/s</td>
</tr>
<tr>
<td>Cut-in, Rated rotor speed</td>
<td>6RPM, 9.6RPM</td>
</tr>
<tr>
<td>Rated tip speed</td>
<td>90m/s</td>
</tr>
<tr>
<td>Overhang, Shaft tilt, Pre-cone</td>
<td>7.07m, 5°, 2.5°</td>
</tr>
<tr>
<td>Pre-bend</td>
<td>3m</td>
</tr>
<tr>
<td>Rotor mass</td>
<td>229tons (each blade ~41tons)</td>
</tr>
<tr>
<td>Nacelle mass</td>
<td>446tons</td>
</tr>
<tr>
<td>Tower mass</td>
<td>605tons</td>
</tr>
</tbody>
</table>
The DTU 10 MW Reference Wind Turbine

The method

- **Airfoil choice**
  - FFA-W3-xxx airfoils. 24.1% to 36.0% relative thickness, 48% and 60% airfoil scaled from FFA-W3-360 and cylinder.

- **Airfoil characteristics**
  - 2D CFD computations at $Re \, 9 \times 10^6$ to $13 \times 10^6$
  - 3D corrected

- **Aerodynamic design**
  - HAWTOPT numerical optimizations. Max tip speed $= 90 \text{m/s}$, $\lambda = 7.5$, min relative airfoil thickness $= 24.1\%$

- **Structural design**
  - ABAQUS (6.11) FEM computations. Uniaxial, biaxial and triaxial laminates were used together with Balsa as sandwich core material

- **Aeroelastic stability and control tuning**
  - HAWCSTAB2 (aero-servo-elastic stability tool) computations including controller tuning.
  - HAWC2 (aeroelastic code) computations. Class IA according to IEC-61400-1 standard for offshore application

- **Aeroelastic time simulations: Loads**

- **Final design**
The DTU 10 MW Reference Wind Turbine
Aerodynamic Design: Geometry
The DTU 10 MW Reference Wind Turbine
Aerodynamic Design: Performance

- Graphs showing performance metrics for different wind speeds and radii.
- CP (Power Coefficient) and CT (Torque Coefficient) plotted against radius.
- Mechanical power and thrust plotted against wind speed.
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 of 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).
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Structural Design: Basic design choice

- A “box-girder” design approach is used.
- For layup definition the blade is partitioned into 100 regions radially and 10 regions circumferentially.
- A complete description of the blade’s geometry and layup is generated in the form of a finite element shell model.
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Structural Design: Design loop

- ABAQUS: layered shell model
- Automatic generation of ABAQUS input files
- Geometry, material and composite layup definition
- Automatic generation of BECAS input files
- Local stress and failure
- BECAS: cross section analysis
- Cross section stiffness properties
- HAWC2: aeroelastic analysis
- Ultimate loads
- Buckling

<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>
</tr>
</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>
<td>-52.9810</td>
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<tr>
<td>min</td>
<td>1.35</td>
<td>-0.0541</td>
<td>1.1863</td>
<td>1.3783</td>
<td>1.1872</td>
<td>-41.9922</td>
</tr>
</tbody>
</table>
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How the blade compares to existing ones

\[ \text{Blade mass [tons]} \]

\[ \text{Blade length [m]} \]

- 73.5m blade upscaled with \( x^3 \)
- 73.5m blade upscaled with \( x^{2.16} \)
- Glasper
- Carbonsfber
- Upscale from 40m blades with \( x^3 \)

\[ \text{Mass}_{\text{carbon}} = 9 \times 10^{-5} \times \text{Length}^{2.95} \]

\[ \text{Mass}_{\text{glass}} = 0.0023 \times \text{Length}^{2.17} \]
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Aero-servo-elastic analysis

- 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 = 6.
- Report and source code on controller available.
The DTU 10 MW Reference Wind Turbine
Load calculations: HAWC2

- DTU 10MW RWT: IA according to IEC-61400-1 (3rd edition)

- The suggested load cases by IEC standard must be verified in order for withstanding all loading situations during its life time.

- Most of design load cases are considered except DLC8, which is for transport, assemble, maintenance, and repair cases, and DLC 1.4, DLC 2.2, DLC 3.1, DLC 3.2, and DLC 3.3 which are very depending on controller.
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Load calculations: HAWC2
The DTU 10 MW Reference Wind Turbine
Summary of design challenges

• Transition from laminar to turbulent flow in the boundary layer of the airfoils:
  – The result is uncertainty of the aerodynamic performance and thereby on loads and especially the power

• The efficiency of thick airfoils, i.e. airfoils with relative thickness greater than 30%, is significantly better when using Gurney flaps,
  – The result is an increase of the power of several percent

• To reduce the blade weight, the blade design needs to be “stress/strain” driven rather than “tip deflection” driven.
  – The result is 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,
  – The result is determination of the minimum rotational speed

• Blade vibrations in stand still
  – Vibrations at 90 degrees inflow direction can probably be avoided by pitching each blade differently
  – Vibrations at 30 degrees inflow direction can be reduced by ensuring “smooth” airfoil characteristics
The DTU 10 MW Reference Wind Turbine 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.
• Within days it will 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.

• Go to: dtu-10mw-rwt.vindenergi.dtu.dk
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Acknowledgements

• Thanks to:
  – EUDP for partly financing the EUDP 2010 I Light Rotor
  – The EU project InnWind for reviewing the wind turbine
  – A lot of people that has been a part of the discussions.
Thank you for the attention!