Cp-Max: an MDO framework for the design of wind turbines

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RESEARCH FRAMEWORK
Research framework

- Wind turbines are steadily upscaling

- Some design challenges:
  - High flexibility of elements
  - Unsteady, non-uniform inflow
  - Increased aero-elastic couplings
  - Increased dynamic complexity
Research framework

- Multi-disciplinary design algorithms (MDO):
  - Improve physical description (*modelling fidelity*)
  - Implement a system-level design based on COE
  - Manage a wide number of different variables
  - Significant research in the last years
CP-MAX: A MULTI-DISCIPLINARY DESIGN PHILOSOPHY

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Cp-Max Timeline

2011: Roll-out of the 2MW-45m blade

2012: Roll-out of the 700kW-23m blade

2012 - 2015: Studies about aero-structural design

2016: Cp-Max in its new multi-level architecture

2017: Prebend design module

2017-2019: Extensive testing and design studies

2007: First implementation, parametric design only

2011: External 3D FEM module

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Macro Design Loop
Variables: WT global parameters
Objective: Minimize COE

Aerodynamic Design Submodule
Variables: Chord, Twist, Thickness
Objective: Maximize AEP

Control Synthesis Toolbox
Objective: Create control laws for the wind turbine

Prebend Design Submodule
Variables: Blade prebend
Objective: Maximize Swept area

Structural Design Submodule
Variables: Rotor & tower structure
Objective: Minimize ICC

Acoustic Analysis External Tool

Stability Analysis External Tool

3D FEM External Tool
Multi-body modelling of wind turbines

Simulation tool: Cp-Lambda

- Multibody solver
- Lifting line + BEM Inflow
- Spatial grid + wind time history
- Nonlinear beam formulation (Bauchau et al. 2001)
- Fully-populated mass/stiffness matrix
MACRO DESIGN LOOP

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Macro Design Loop (MDL)

- Optimizes *global features* of the turbine to minimize COE

- Macro design variables:

  \[ p_g = [R, H, \varphi, \gamma, \sigma_c^g, \tau_c^g, \sigma_t^g, \tau_t^g] \]

  - Rotor radius
  - Hub height
  - Rotor tilt angle
  - Blade coning
  - Shape parameters

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Macro Design Loop (MDL)

- The shape parameters are computed from chord and thickness distributions:

**Rotor solidity**

\[ \sigma_c^g = \frac{3 \int_0^R c(r)dr}{\pi R^2} \]

**Rotor tapering**

\[ \tau_c^g = \frac{\int_0^R r c(r)dr}{\int_0^R c(r)dr} \]

**Thickness solid area**

\[ \sigma_t^g = \frac{1}{100} \int_0^1 t(\eta) d\eta \]

**Thickness weighted area**

\[ \tau_t^g = \frac{\int_0^1 \eta t(\eta) d\eta}{\int_0^1 t(\eta) d\eta} \]

- They link the MDL with the submodules
Macro Design Loop (MDL)

• Simplified workflow of the MDL:

\[
\text{MDL} \quad (\text{COE}^*, p_g^*) = \text{MinCOE}(p_a, p_b, p_s, p_g, D)
\]

\[
\text{ADS} \quad (p_a^*, AEP^*) = \text{MaxAEP}(p_a, p_b, p_s, p_g, D)
\]

\[
\text{CST} \quad (r^*_\epsilon) = \text{CreateControlLaws}(p_a^*, p_b, p_s, p_g, D)
\]

\[
\text{PDS} \quad (p_b^*, A_\delta^*) = \text{OptimizePrebend}(p_a^*, p_b, p_s, p_g, D, r^*_\epsilon)
\]

\[
\text{SDS} \quad (p_s^*, ICC^*) = \text{MinICC}(p_a^*, p_b^*, p_s, p_g, D, r^*_\epsilon)
\]

\[
\text{COE} = \text{CostModel}(AEP^*, ICC^*, p_a^*, p_b^*, p_s^*, p_g, D, r^*_\epsilon)
\]

• Available cost models:
  Scaling (NREL, 2006), Industrial (SANDIA), Refined scaling (INNWIND)
DESIGN SUBMODULES
Aerodynamic Design Submodule (ADS)

- Optimizes the aerodynamic design variables $p_a$ of the rotor to maximize AEP

\[
(p_a^*, AEP^*) = \max_{p_a} (AEP(p_a, p_b, p_s, p_g))
\]

subject to:

- $v_{tip} \leq v_{tip}^{max}$
- $g_a(p_a, p_g) \leq 0$

Design variables:
- Chord
- Twist
- Thickness (position of airfoils)
Aerodynamic Design Submodule (ADS)

Chord, twist and thickness are parameterized by multiplicative/additive *bumping* functions

\[
c(\eta) = s_c(\eta)c_{bl}(\eta) \\
\theta(\eta) = s_\theta(\eta)\theta_{bl}(\eta) \\
t(\eta) = s_t(\eta)t_{bl}(\eta)
\]

\[
s_c(\eta) = n_c(\eta)c \\
s_\theta(\eta) = n_\theta(\eta)\theta \\
s_t(\eta) = n_t(\eta)t
\]

\(n\) are spline shape functions

\(\theta, c\) and \(t\) are the associated nodal parameters

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Aerodynamic Design Submodule (ADS)

• Theoretical AEP from flexible $C_p$-$TSR$ curves

• The structure is frozen

• Blade shape and thickness constrained by the MDL:
  \[
  \sigma_{c}^{Aero}(c(\eta), R) = \sigma_{c}^{g} \\
  \tau_{c}^{Aero}(c(\eta), \eta, R) = \tau_{c}^{g} \\
  \sigma_{t}^{Aero}(t(\eta), R) = \sigma_{t}^{g} \\
  \tau_{t}^{Aero}(t(\eta), \eta, R) = \tau_{t}^{g}
  \]

• Other constraints on max chord, tip speed, shape regularity

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Control Synthesis Tool (CST)

- Determines the control laws $r^*_e$ of the turbine
- Required to perform DLC simulations
- Available options:
  - PID on pitch + LUT on torque
  - PID on pitch + PID on torque (DTU)
  - MIMO-LQR model based
  - Individual Pitch Control

\[ T = \frac{1}{2} \rho AR V^2 C_P^*/\lambda^* \]
\[ \Omega = \frac{V \lambda^*/R}{\Omega^*} \]
Prebend Design Submodule (PDS)

- Optimizes prebend to maximize the deformed swept area

\[
(p_b^*, A_{\delta}^*) = \min_{p_b} (A_{\delta}^*(p_a^*, p_b, p_s, p_g, r_e^*))
\]

s.t.:

\[
g_a(p_a, p_g) \leq 0
\]

Design variables:

- Prebend shape

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Prebend Design Submodule (PDS)

• Prebend is parameterized by a Bézier curve

• Static analysis at rated conditions

• Possible constraints on:
  o Max tip prebend
  o Max steepness
  o Shape regularity

• No associated variables in the MDL

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Structural Design Submodule (SDS)

- Optimizes *internal structure* of blade, tower to minimize the ICC

\[
(p_s^*, \text{ICC}^*) = \min_{p_s} \text{ICC}(p_a^*, p_b^*, p_s, p_g, r_\varepsilon^*)
\]

s.t.

\[
g_s(p_a^*, p_b^*, p_s, p_g, r_\varepsilon^*) \leq 0
\]

Design variables:
- Thickness of blade structural components
- Wall thickness of tower segments
- Diameter of tower segments
Structural Design Submodule (SDS)

- Thickness of elements is defined at selected stations
- Sectors defined along tower height
- Mass, stiffness, stress/strain and buckling computed analytically
- Loads and deformations from $Cp$-$Lambda$ sensors

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Structural Design Submodule (SDS)

Computation of DLC

Aero-elastic optimization

3D FEM verification

Loads Displacements

Refined solution

Coarse solution

Constraints:
- Blade tip deflection
- Frequencies
- Manufacturing limits
- Ultimate stress, strain
- Fatigue damage
- Buckling

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AN EXAMPLE: DESIGN OF THE POLIMI 20MW BASELINE WT
## Definition of the initial 20 MW model

- Initial aeroelastic definition obtained from upscaling the INNWIND.EU 10 MW

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Rated power</strong></td>
<td>20 MW</td>
</tr>
<tr>
<td><strong>IEC Class</strong></td>
<td>IC</td>
</tr>
<tr>
<td><strong>Rotor orientation</strong></td>
<td>Clockwise, upwind</td>
</tr>
<tr>
<td><strong>Control</strong></td>
<td>Variable speed</td>
</tr>
<tr>
<td><strong>Cut-In speed</strong></td>
<td>4 m/s</td>
</tr>
<tr>
<td><strong>Cut-Out speed</strong></td>
<td>25 m/s</td>
</tr>
<tr>
<td><strong>Rated wind speed</strong></td>
<td>11.4 m/s</td>
</tr>
<tr>
<td><strong>Max tip speed</strong></td>
<td>90 m/s</td>
</tr>
<tr>
<td><strong>Cone angle</strong></td>
<td>2.5°</td>
</tr>
<tr>
<td><strong>Tilt angle</strong></td>
<td>5°</td>
</tr>
<tr>
<td><strong>Rotor radius</strong></td>
<td>126 m</td>
</tr>
<tr>
<td><strong>Hub radius</strong></td>
<td>3.95 m</td>
</tr>
<tr>
<td><strong>Hub height</strong></td>
<td>168 m</td>
</tr>
<tr>
<td><strong>Tower height</strong></td>
<td>163 m</td>
</tr>
<tr>
<td><strong>Blade mass</strong></td>
<td>118 ton</td>
</tr>
<tr>
<td><strong>Hub mass</strong></td>
<td>278 ton</td>
</tr>
<tr>
<td><strong>Nacelle mass</strong></td>
<td>1098 ton</td>
</tr>
<tr>
<td><strong>Tower mass</strong></td>
<td>1779 ton</td>
</tr>
<tr>
<td><strong>Generator Inertia</strong></td>
<td>8488 kg/m²</td>
</tr>
<tr>
<td><strong>Generator efficiency</strong></td>
<td>94%</td>
</tr>
</tbody>
</table>

Reference: INNWIND Deliverable 1.25: PI-based assessment (application) on the results of WP2-WP4 for 20 MW wind turbines, June 2017

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Design assumptions

- Classic *spar-box* layout
- No initial prebend
- Fixed-radius optimization
Baseline vs. Redesign comparison

Chord

Prebend

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Baseline vs. Redesign comparison

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Structural solution of the redesigned rotor

Shell Panels

LE Panels

Spar Panels

Shear Webs

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### Baseline vs. Redesign comparison

<table>
<thead>
<tr>
<th></th>
<th>Units</th>
<th>Baseline 20 MW</th>
<th>Redesign 20 MW</th>
<th>Var. %</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Regulation</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rotor speed</td>
<td>[RPM]</td>
<td>6.77</td>
<td>6.82</td>
<td>+ 0.74</td>
</tr>
<tr>
<td>Max tip speed</td>
<td>[m/s]</td>
<td>89.4</td>
<td>89.93</td>
<td>+ 0.59</td>
</tr>
<tr>
<td>Optimal TSR</td>
<td>[-]</td>
<td>7.73</td>
<td>7.86</td>
<td>+ 1.68</td>
</tr>
<tr>
<td>Rated wind speed</td>
<td>[m/s]</td>
<td>11.56</td>
<td>11.45</td>
<td>- 0.95</td>
</tr>
<tr>
<td><strong>Design parameters</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max chord</td>
<td>[m]</td>
<td>8.77</td>
<td>8.27</td>
<td>- 5.70</td>
</tr>
<tr>
<td>Prebend at tip</td>
<td>[m]</td>
<td>0</td>
<td>4</td>
<td>-</td>
</tr>
<tr>
<td>Spar caps fiber angle</td>
<td>[deg]</td>
<td>0</td>
<td>6</td>
<td>-</td>
</tr>
<tr>
<td><strong>KPIs</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total blade mass</td>
<td>[ton]</td>
<td>113.5</td>
<td>107.8</td>
<td>- 5.05</td>
</tr>
<tr>
<td>AEP</td>
<td>[GWh/yr]</td>
<td>91.63</td>
<td>91.74</td>
<td>+ 0.12</td>
</tr>
<tr>
<td>COE</td>
<td>[€/MWh]</td>
<td>84.92</td>
<td>84.56</td>
<td>- 0.42</td>
</tr>
</tbody>
</table>

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Baseline vs. Redesign comparison

Ultimate loads

Fatigue loads

BR  Blade Root
HC  Hub Center
TT  Tower Top
TB  Tower Base

Baseline 20 MW
Redesign 20 MW

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STATE OF THE ART AND OUTLOOK
Completed research projects

- Definition of 10~20 MW reference wind turbines
- Definition of a 3.4 MW reference WT for the IEA-Task 37 project
- Integration of active/passive load mitigation in the design
- Development of upwind/downwind two-bladed rotors
- Study of the impact of WF control on a single WT design
- Global WT design with noise emissions constraints

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Completed industrial projects

1m (for wind tunnel)

100kW – 10m

300kW – 16m

2MW – 45m

700kW – 24m
Ongoing activities

- Integration of airfoil design
- Development of numerical tools for aero-acoustic modelling and design
- Application of the design to down-scaled WTs for wind tunnel
- Integration of WF-level simulation and design modules
- Integration of additional sub-component design modules (DT & generator, support structure)


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