Blind Results for The Aerodynamic Wind Turbine Design Optimization Case Study for the IEA Task 37 on Wind Energy Systems Engineering

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Outline

• Acknowledgments
• Problem Description
• Survey of Tools
• Comparison of Preliminary Results
  • Performance of the initial design
  • Optimal design
  • Performance of the optimal design
• Closing Statements
Acknowledgments
Acknowledgments

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Problem Description
Research Objectives

• This IEA Task is meant to coordinate international research activities, towards the analysis of wind power plants as holistic systems

• Multi-disciplinary Design Analysis and Optimization (MDAO) is a valuable tool in systems engineering with all disciplines

• Starting with single discipline case studies because full turbine MDAO is complicated

• This will help us in the following ways:
  • Provides a baseline to help understand the differences in future studies
  • Allow more researchers to be involved by starting with simpler cases
  • Gives us experience in creating, managing and analyzing optimization case studies

• This is less about validation and more about developing design techniques
Initial Design

- Based on the DTU 10MW reference wind turbine with the following modification:
  - Reduced chord, less aggressive twist, thicker blades
  - No coning or tilt
Optimization Problem

- Load constraints based on initial design loads
- Structural considerations:
  - Minimum absolute thickness
  - Smaller center of thrust

Maximize Annual Energy Production
Varying Chord
Twist
Relative Thickness

subject to

\[ T \leq 1.14 \max T_0, \]
\[ M \leq 1.11 \max M_0, \]
Absolute thickness \( \geq \) limit
Aerodynamic Analysis

• Design evaluated with steady, uniform wind without turbulence
• Turbine operates between 4 and 25 m/s
• AEP based on Weibull distribution with scale and shape 8 and 2 respectively
• Must find optimal regulation based on:
  • Design Tip-Speed-Ratio: 7.8
  • Minimum RPM: 6
  • Maximum RPM: 9.6
  • Find optimal pitch to feather when in constant speed operation
Survey of Tools
Survey of Tools

• Typical set-up:
  - Steady-state BEM with angular moment and tip-loss functions
  - Spline parameterization with approximately 15 design variables
  - Sequential Quadratic Programming (SQP)
  - Finite-difference gradients

• Some exceptions:
  - Brigham Young University/NREL:
    - Analytic adjoint gradients mixed with automatic differentiation (Tapenade)
  - University of Massachusetts, Amherst
    - The NSGA genetic optimization algorithm
  - DTU Wind Energy
    - IPOPT optimization algorithm
  - University of Stuttgart
    - Sequential Least Squares Programming
  - SINTEF
    - Complex Step Gradients
Comparison of Blind Results
The Final Blind Results

- Researchers performed optimization without seeing other results
  - The results you get without best-practices
  - Most researchers required 2 attempts because of misunderstandings
  - Some researchers did see some of the preliminary results in June (not perfectly blind)
- The source of the results is anonymous
- Next round of optimization the results will be shared openly to understand the differences
Performance of the initial design
Initial Power

- Participant 1
- Participant 2
- Participant 3
- Participant 4
- Participant 5

Power [W] vs. Wind Speed [m/s]
Initial Thrust

![Graph showing the initial thrust vs. wind speed for five participants. The graph plots the rotor thrust (in Newtons) on the y-axis against wind speed (in meters per second) on the x-axis. The y-axis scale ranges from 0.0E0 to 1.4E6, and the x-axis scale ranges from 4 to 25. The graph includes lines for Participant 1, Participant 2, Participant 3, Participant 4, and Participant 5, each represented by a different color. The peak thrust occurs at around 12 m/s wind speed.]
Initial Blade Root Flap-wise Bending Moment

![Graph showing Initial Blade Root Flap-wise Bending Moment vs Wind Speed [m/s]. The graph includes curves for different participants: Participant 1 (blue), Participant 2 (orange), Participant 3 (yellow), Participant 4 (red), and Participant 5 (light blue). The y-axis represents Root Flap-wise Bending Moment [Nm] ranging from 0E0 to 3.0E7, and the x-axis represents Wind Speed [m/s] ranging from 4 to 25. The graph peaks at Wind Speed 12 with a bending moment of 2.5E7 Nm.]

17 DTU Wind Energy

Aero Optimization June 27, 2017
Optimal design
Notes on the optimization results

- Most researchers prescribed 0 pitch between 6-rated wind speed
- There is pitch setting optimization before 6 m/s
- Pitch control used to track power above rated
- Participant 3 contributed 2 results
  - The Fixed-Pitch results prescribed 0 pitch between 6-rated wind speed
  - The Free-Pitch results allowed pitch variations at near rated conditions for peak shaving
Performance of the optimal design
## Improvement in AEP

<table>
<thead>
<tr>
<th>Participant</th>
<th>Initial AEP</th>
<th>Optimal AEP</th>
<th>Increase</th>
<th>T-Const</th>
<th>M-Const</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>28.4 GWh</td>
<td>31.9 GWh</td>
<td>12.44%</td>
<td>13.98%</td>
<td>10.98%</td>
</tr>
<tr>
<td>2</td>
<td>29.0 GWh</td>
<td>31.1 GWh</td>
<td>10.26%</td>
<td>14.27%</td>
<td>13.25%</td>
</tr>
<tr>
<td>Fix</td>
<td>29.5 GWh</td>
<td>32.8 GWh</td>
<td>11.11%</td>
<td>12.65%</td>
<td>11.00%</td>
</tr>
<tr>
<td>3 Free</td>
<td>29.5 GWh</td>
<td>33.0 GWh</td>
<td>11.71%</td>
<td>9.95%</td>
<td>11.00%</td>
</tr>
<tr>
<td>4</td>
<td>29.2 GWh</td>
<td>32.3 GWh</td>
<td>10.49%</td>
<td>13.11%</td>
<td>10.95%</td>
</tr>
</tbody>
</table>

- Participant 1 demonstrated the greatest improvement
- Good convergence in power and relative improvement
- Only 1 participant had a feasible design with an active thrust constraint
- Participant 2 had an infeasible design
Optimal Power

![Optimal Power Graph](image)

- **Power [W]**
  - 1.2E7
  - 1.1E7
  - 1.0E7
  - 9.0E6
  - 8.0E6
  - 7.0E6
  - 6.0E6
  - 5.0E6
  - 4.0E6
  - 3.0E6
  - 2.0E6
  - 1.0E6
  - 0.0E0

- **Wind Speed [m/s]**
  - 4
  - 5
  - 6
  - 7
  - 8
  - 9
  - 10
  - 11
  - 12
  - 13
  - 14
  - 15
  - 16
  - 17
  - 18
  - 19
  - 20
  - 21
  - 22
  - 23
  - 24
  - 25

- **Legend**
  - Blue: Participant 1
  - Red: Participant 2
  - Orange: Participant 3 Fix
  - Green: Participant 3 Free
  - Brown: Participant 4
Optimal AEP Gain
Optimal Power Ratio

![Graph showing improvement ratio (P/P₀) vs wind speed in m/s for different participants. The graph includes lines for Participant 1, Participant 2, Participant 3 Fix, Participant 3 Free, and Participant 4, with various improvement ratios and wind speeds.]
Optimal Thrust

![Optimal Thrust Graph](image-url)

- **Participant 1**
- **Participant 2**
- **Participant 3 Fix**
- **Participant 3 Free**
- **Participant 4**

**Y-axis**: Rotor Thrust [N]

**X-axis**: Wind Speed [m/s]
Optimal Blade Root Flap-wise Bending Moment

Wind Speed [m/s] vs. Root Flap-wise Bending Moment [Nm]

- Participant 1
- Participant 2
- Participant 3 Fix
- Participant 3 Free
- Participant 4
Optimal Pitch

- Participant 2 does not optimization pitch at lower speeds
Closing Statements
Conclusions

• IEA Task 37 is meant to explore MDAO of wind turbines

• Simple aerodynamic case study is developed
  • Based on a modified DTU 10MW Reference Turbine
  • Maximize AEP by varying chord, twist and thickness
  • Subject to thrust, moment and some geometric constraints
  • Some artificial structural considerations
  • Must solve optimal regulation strategy
  • Analysis based on steady uniform wind

• Many researchers are applying their tools to this problem
  • Most set-ups based on splines for the design variables, BEM aerodynamics with SQP optimization and finite difference gradients
  • There are differences in the optimization algorithms and gradient algorithms

• First round of blind results obtained
  • Most participants have contributed results
  • Similar performance for the initial design
  • Large variation in the optimal design and performance
  • Some indication tool differences are driving the design
Thank-you for your interest

Comments or Questions?

Please approach me after if you want to participate