DESIGN OPTIMIZATION OF BEND–TWIST COUPLED WIND TURBINE BLADES

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2012 Wind Turbine Blade Workshop
May 30–June 1 2012, Albuquerque, NM, USA
Motivation: Up-Scaling and the Need for Load Mitigation

Trends in wind energy:
Increasing wind turbine size ►
Off-shore wind ▼

To decrease cost of energy:
• Reduce extreme loads
• Reduce fatigue damage
• Limit actuator duty cycle
• Ensure high reliability/availability
Presentation Outline

Load mitigation

- Active control
- Passive control
- Integrated active/passive control
- Passive blade design
- Blade design optimization
Integrated Active/Passive Load Control

**Active pitch control:**
- Limited temporal bandwidth (max pitch rate ≈ 7–9 deg/sec)
- Limited spatial bandwidth (pitching the whole blade is ineffective for spatially small wind fluctuations)

**Active distributed control (flaps, tabs, etc.):**
- Alleviate temporal and spatial bandwidth issues
- Complexity/availability/maintenance

**All sensor-enabled control solutions:**
- Complexity/availability/maintenance

**Off-shore:** need to prove reliability, availability, low maintenance in harsh hostile environments

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(Credits: Risoe DTU, Chow and van Dam 2007)
Passive Load Mitigation

**Passive control**: loaded structure deforms so as to reduce load

**Two main solutions:**
- **Bend–twist coupling** (BTC): exploit anisotropy of composite materials
  (Veers et al. ‘98, Lobitz et al. ‘01, Sandia ‘96–’11, Capellaro et al. ‘11 …)
- **Swept** (scimitar) **blades**
  (Liebst ’86, Zuteck ’02, …)

**Potential advantages**: no actuators, no moving parts, no sensors
(if you do not have them, you cannot break them!)

Other passive control technologies (not discussed here):
- Tuned masses (e.g. on off-shore wind turbines to damp nacelle–tower motions)
- Passive flaps/tabs
- …
Objectives

Present study:
- **Design** BTC blades (all satisfying **identical design requirements**: max tip deflection, flap freq., stress/strain, fatigue, buckling)
- Consider **trade-offs** (load reduction/weight increase/complexity)
- Identify optimal BTC blade **configuration**
- **Integrate** passive BTC and active IPC
- Exploit **synergies** between passive and active load control

Baseline uncoupled blade: **45m Class IIIA 2MW HAWT**

<table>
<thead>
<tr>
<th>Starting section (% span)</th>
<th>Ending section (% span)</th>
<th>Material type</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skin</td>
<td>0</td>
<td>100</td>
</tr>
<tr>
<td>Spar caps</td>
<td>3</td>
<td>97.8</td>
</tr>
<tr>
<td>Shear webs</td>
<td>10</td>
<td>97.8</td>
</tr>
<tr>
<td>Trailing and leading edge reinforcements</td>
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<td>80</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unidirectional fiberglass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stitched biaxial -45/+45 fiberglass</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Unidirectional fiberglass</td>
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</tbody>
</table>
Multi-level analysis: captures effects missed at the aeroelastic model level

“Coarse” aero-servo-elastic level:
1D spatial beam + 2D sectional models
Applications: loads, performance, aeroelasticity

“Fine” 3D structural level:
CAD + 3D FEM
Applications: buckling, fatigue, detailed analysis, ...

Aerodynamic verification (RANS & LES)
Applications: tip, 3D root effects, wind tunnel

Fully automated links

Multi-level analysis

Up–down fully automated links

Only weak up link (e.g. 3D root corrections)
Definition of sectional design parameters

- ANBA 2D FEM sectional analysis
- Computation of 6x6 stiffness matrices

Constraints:
- Maximum tip deflection
- 2D FEM ANBA analysis of maximum stresses/strains
- 2D FEM ANBA fatigue analysis
- Compute cost (mass)

SQP optimizer

min cost
subject to constraints

When SQP converged

Definition of complete HAWT
Cp–Lambda multibody model
- DLCs simulation
- Campbell diagram

DLC post-processing:
load envelope, DELs, Markov, max tip deflection

“Coarse” level: 2D FEM sectional & beam models

“Fine” level: 3D FEM

Automatic 3D CAD model generation by lofting of sectional geometry

Automatic 3D FEM meshing (shells and/or solid elements)

Update of blade mass (cost)

Analyses:
- Max tip deflection
- Max stress/strain
- Fatigue
- Buckling

Verification of design constraints

Constraint/model update heuristic (to repair constraint violations)
The Importance of Multi-Level Blade Design

**Stress/strain/fatigue:**
- Fatigue constraint not satisfied at first iteration on 3D FEM model
- Modify constraint based on 3D FEM analysis
- Converged at 2\(^{nd}\) iteration

**Buckling:**
- Buckling constraint not satisfied at first iteration
- Update skin core thickness
- Update trailing edge reinforcement strip
- Converged at 2\(^{nd}\) iteration
Fully Coupled Blades

1. **Identify optimal section-wise fiber rotation**

Consider 6 candidate configurations

<table>
<thead>
<tr>
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<th>Skin [deg]</th>
<th>Spar caps [deg]</th>
</tr>
</thead>
<tbody>
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<td>10</td>
<td>0</td>
</tr>
<tr>
<td>Sk+20</td>
<td>20</td>
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</tr>
<tr>
<td>Sk+30</td>
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<td>0</td>
</tr>
<tr>
<td>SC+05</td>
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<td>5</td>
</tr>
<tr>
<td>SC+10</td>
<td>0</td>
<td>10</td>
</tr>
<tr>
<td>Sk+20&amp;SC+05</td>
<td>20</td>
<td>5</td>
</tr>
</tbody>
</table>

BTC coupling parameter:

\[
\alpha = \frac{K_{BT}}{\sqrt{K_B K_T}}
\]
Fully Coupled Blades: Effects on Weight

**Stiffness driven design** (flap freq. and max tip deflection constraints): Need to restore stiffness by **increasing spar/skin thickness**
2. Identify optimal span-wise fiber rotation: 5 candidate configurations

- **F0**: Reduce fatigue in max chord region
- **F30**: Avoid thickness increase to satisfy stiffness-driven constraints
Effects on Duty Cycle

Less pitching from active control because blade passively self-unloads

Twist due to flap (1st modal shape)

Much reduced life–time ADC ▼
Effects on Blade Mass

Fully coupled blade

Too little coupling
Effects on Loads

F30: load reduction close to fully coupled case
**Integrated Passive and Active Load Alleviation**

**Individual blade pitch** controller (Bossaniy 2003):
- Coleman transform blade root loads
- PID control for transformed d–q loads
- Back–Coleman–transform to get pitch inputs
Integrated Passive/Active Control: Effects on Loads

Two IPC gain settings:
1. **Mild**: some load reduction, limited ADC increase
2. **Aggressive**: more load reduction and ADC increase

Five blade/controller combinations:
- **BTC**: best coupled blade + collective LQR
- **IPC1**: uncoupled blade + mild IPC
- **BTC+IPC1**: best coupled blade + mild IPC
- **IPC2**: uncoupled blade + aggressive IPC
- **BTC+IPC2**: best coupled blade + aggressive IPC

▲ Synergistic effects of combined passive and active control ▲
Integrated Passive/Active Control: Effects on Duty Cycle

Same ADC as baseline (but great load reduction!)
Conclusions

- **Optimization-based blade design tools**: enable automated design of blades and satisfaction of all desired design requirements.

- **BTC passive load control**:
  - Skin fiber rotation helps limiting spar-cap fiber angle
  - Partial span-wise coupling limits fatigue and stiffness effects

Reduction for all quality metrics: loads, ADC, weight

- **Combined BTC/IPC passive/active control**:
  - Synergistic effects on load reduction
  - BTC helps limiting ADC increase due to IPC (e.g., could have same ADC as baseline blade with collective pitch control)

**Outlook**:
- Manufacturing implications of BTC and partially coupled blades
- Passive distributed control and integration with blade design and active IPC control