On Innovative Concepts of Wind Turbine Blade Design

Find Mølholt Jensen, Per H. Nielsen, Agnieszka Roczek-Sieradzan, Tomasz Sieradzan, Kim Branner, Robert Bitsche,

Wind Energy Division – Risø DTU
Risø National Laboratory for Sustainable Energy,
Technical University of Denmark
Outline

• Motivation

• Overview of failure modes which are expected to be design driven for future blades

• New structural solutions preventing these failure modes

• An example on an ongoing research project where a blade is design and manufactured with some of these solutions

• Problems which must be addressed if a new light weight blade is installed in a WT
Motivation

**Present blade designs**

- In full-scale test 5000µS can be obtained before ultimate collapse
- In panel test of panels with same quality as the blade 15-30000µS is obtained before failure
- Conclusion: Compressive failure (static) of the material does not seem to be critical

**Future blade designs**

Goal: To find a better balance between structural strength collapse and material failure
Non-linear phenomena becomes more critical with flexible blades

- Collapse appears when the blade, at the same time, is exposed to flapwise load, which gives a large “crushing pressure”

- “Crushing pressure” rises in the second power with the longitudinal curvature and when it is expected that the blades will be significantly more flexible in the future, such problem will be of increasingly importance
Interlaminar failures in the load carrying laminate

Failure due to the interlaminar stresses

LVDT-Measuring center

Legs/fixture placed on top of stiff web

Measured cap deflections

Load [kN] vs. deflection [mm]
Interlaminar failures in the load carrying laminate

Failure due to the interlaminar stresses

3- /4-point bending tests of SSP cap specimens were performed at Imperial College – Department of Mechanical Engineering.

The bending tests lead to initial interlaminar failure after 8mm and 4mm deflections in the 3 and 4-point bending tests.
Max strain in unidirectional glass fiber laminate

Allowable tension strain in transverse direction

Allowable tension strain in longitudinal direction


Risø DTU, Technical University of Denmark
Material strength can be divided into two groups:
- Inplane strength (in the fiber direction)
- Interlaminar failure or tension failure transverse to the fibre direction
Interlaminar failure in caps can be solved by cap reinforcements

Cap stiffener decrease the ovalization increase the buckling capacity

Possible execution:
Dry fibre mat

Alternative execution:
Pultruded profile
Proof of concept of the cap reinforcement
Proof of concept for the cap reinforcer - Cap deformations reduce considerably

The deformation of the cap is reduced by approx. 30-40%!!
Combined flap- and edgewise loads distort the profile

Combined gravity and aerodynamic forces result in a load component different from the traditional flap- and edgewise loads applied in full-scale test.
Clamps which are used in full-scale test prevent shear distortion failure.

New load clamps are used in the new full-scale test facility at Risø DTU. The anchor plates allow the blade to distort.

An important task for Risø is to give input to future certification rules.
Transverse shear distortion of the cross section

Conclusion:
Shear distortion failure do not seem to be critical for a 34m blade but maybe for a larger blade.
The sections distort differently
Risø DTU patents reduce the risk for transverse shear collapse

The shear cross invention prevents the profile transverse shear distortion

Alternative to cross reinforcement
Cartoon illustrate the unused potential in nowadays blades

Full-scale test using traditionally clamps

Blade distort in an extreme wind condition

Still distort after the caps has been increased in thickness

Risø DTU Inventions prevent the blade to fail in transverse shear distortion

The thickness of the caps can be reduced together with extra reliability is obtained
Research project - Innovative Wind Turbine Blade

- The research project “Demonstration of new blade design using manufacturing process simulations” started in July 2009 supported by Danish Energy Agency through the Energy Technology Development and Demonstration Programme (EUDP 2009).

- The blade is designed at Risø DTU by use of the new design philosophy.

- The manufacturing is performed by SSP Technology A/S. The support is gratefully acknowledged.

- The blade is a 2.2MW wind turbine certificated to Class 1 where the extreme loads include loads such as a hurricane etc.

- The blade is in the range of 40-45m (actual length is confidential)
Use of internal structure to prevent non-linear failure behaviour

- Based on the new design philosophy which include nonlinear failure mechanisms a 40m load carrying box girder has been designed by Risø DTU

- The box girder include 3 innovative solutions patented by Risø DTU

Diagonal prevent transverse shear distortion

Cap stiffener with flat aerofoil

Cap stiffener with curved aerofoil

Failure due to the interlaminar stresses
Main results - weight saveness

The load carrying laminates have been reduced by approx. 40%, so the thickness is now in the range of 17-24mm.
Manufacturing

SSP-Technology has recently finished the manufacturing.
Manufacturing

The box girder will be tested in Risø’s full-scale test facility in Autumn 2010
Sub component test to verify strength of the adhesive joints

Reinforced Sample
max. Load: 68 kN
Future work

- The strength of box girder will be validated in Risø DTU’s research facility in Summer 2011.

- The manufactured parts must be optimized so it is fast to insert internal structure in the blade when the blade is in the mold.
Summary - Why do we first observe these failure types now?

Non-linear geometric simulations are needed to get a full picture of representative failure modes.

Combined load cases with realistic boundary supports result in other failure modes than required by design and testing procedures today.

New design and testing rules must be included if the full potential of the material should be used.

Full-scale tests with more (and advanced) measuring equipment supported by FE-results give the optimal value.

Risø DTU believes that the repair costs can be reduced and that the weight of nowadays wind turbine blades can be reduced significantly!
Thank you for your attention

Any Questions?

Any questions please email or call
Find Mølholm Jensen – fimj@risoe.dtu.dk
+45 61464018
Wind Turbine Structural Path Stress & Fatigue Reductions Resulting from Active Aerodynamics

Dale Berg
Lead, Advanced Rotor Technology
Wind & Water Power Technologies
Sandia National Laboratories
debra@sandia.gov
(+1) 505-844-1030

WINDPOWER 2011
May 23-25, 2011
Anaheim, CA
Acknowledgements

- Brian Resor
  - Sandia National Laboratories, Albuquerque, NM.

- Zachary Wright, Ashley Crowther and Chris Halse
  - Romax Technology Ltd., Boulder, CO

- SMART Team Members
  - David Wilson, Jonathon Berg, Matt Barone, Joshua Paquette, Wesley Johnson, Mark Rumsey, Jonathon White
Romax Technology

- Rotating machinery experts with 200 employees worldwide
- Boulder office dedicated to serving US customers for wind engineering

Gearbox Design
Drivetrain dynamics
Pitch and Yaw System Design and Analysis

Instrumentation
Drivetrain inspections
Gear and bearing durability and vibration

Contact: Ashley Crowther, VP Engineering – Wind
ashley.crowther@romaxtech.com, +1 303 562 6064
Presentation Outline

- Review of GRC & Active Aerodynamic blade Load Control
- Drive train model
- Turbine model
- Analysis
- Impact of AALC
  - hub
  - gearbox
  - extreme bedplate loads
- Summary
- Conclusions & future work
Industry has been plagued with numerous gearbox failures

NREL established the Gearbox Reliability Collaborative to address this issue

- heavily instrumented gearbox
- extremely detailed gearbox model (Romax)
- model validated against experimental data

Simulations reveal bearing loads quite sensitive to non-torque loading

- main shaft bending
- out of rotor plane moments
- non-uniform wind loading
Impact of Active Load Control on COE

- “20% by 2030” report: Decrease in blade fatigue loading will yield COE decrease

- Active Aerodynamic Load Control (AALC)
  - sense local loads along blade
  - attenuate local loads with fast-acting distributed aero control surfaces

- Simulation results
  - controller designed to minimize blade-tip deflection
  - reduce blade fatigue loads
  - reduce turbine COE

![Graph showing % Decrease in Cost of Energy vs. Annual Average Wind Speed](image-url)
Preliminary work in 2010

- AALC also reduces non-torque loading on drive train (Resor)

- Romax performed limited analysis of impact on gearbox
  - small change in gear stresses due to off-axis loading
  - larger changes in carrier bearing off-axis moments
  - reduction in magnitude of stress cycles on bearings
  - conclusion:
    - may decrease fatigue damage
    - may increase fatigue life

- Conclusions:
  - AALC may mitigate gearbox damage
  - more complete analysis is needed
**Gearbox Model**

- Finite element representation of shafts
- Solid finite element representation
  - gearbox housing
  - gear blanks
  - planet carrier and torque arms
  - 6DOF spring connections for (elastomeric) trunnion mounts
- Semi-analytical formulations for gears and bearings
  - misalignment
  - area of contact under load
  - gear and bearing microgeometry
  - radial and axial clearances
  - preload and material properties

Gearbox model
Current Drive Train Analysis

- GRC 750 Turbine
- Gearbox model validated against experimental loads data
- Extended to simulate drive train
  - bedplate
  - hub
  - blade pitch system
- Active pitch control system
- Detailed finite element modelling of all components
- AALC simulations on GRC 750 turbine model
  - reduce blade root flap fatigue loads
- Apply extreme and operating time-series loads to drive train
- Perform strength & fatigue analyses of components
GRC Gearbox Details

Model of GRC Gearbox
GRC Gearbox Details

- Gearbox Housing
- High Speed Pinion
- Ring Gear
- Planetary Carrier
- Mainshaft
- Planetary Carrier Bearing PLC-A (Upwind)
- Planet Bearings PL-A & PL-B
- Planetary Carrier Bearing PLC-B (Downwind)
- High Speed Bearings
- High Speed Shaft
- Intermediate Gear
- Low Speed Bearings
- Low Speed Shaft
- Spline
GRC Drivetrain Axis Definition

- Main Bearing
- Gearbox
- Bedplate
AALC Impact on Hub Loading

Hub Forces

Hub Moments
AALC Impact on Bearing Moments

Main Bearing

Upwind Carrier Bearing

Downwind Carrier Bearing

Sandia National Laboratories
## AALC Impact on Bearing Fatigue Damage

<table>
<thead>
<tr>
<th>Bearing</th>
<th>Relative Change in Fatigue Damage due to AALC (ISO 281)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Main</td>
<td>-7%</td>
</tr>
<tr>
<td>Upwind Carrier</td>
<td>-32%</td>
</tr>
<tr>
<td>Downwind Carrier</td>
<td>-16%</td>
</tr>
</tbody>
</table>
AALC Impact on Extreme Bedplate Loads - $M_{xMax}$
AALC Impact on Extreme Bedplate Loads - $M_{y\text{Max}}$
Summary

- Detailed computational model of drive train utilized to examine impact of AALC on drive train components
- AALC significantly reduces the extreme loads on drive train components
  - bearing static stresses for limiting cases reduced by as much as 50%
  - fatigue damage reduced between 7 and 32% for the load carrying bearings
  - extreme load bedplate non-torque stresses reduced
- Greatest advantage for the turbine appears to be the reduction of the off-axis moments, which are often the design limiting loads for strength
Conclusions & Future Work

Conclusions:

• AALC reduces off-axis drive train moments, which are often the design limiting loads for strength
• AALC has great potential to reduce ultimate and fatigue loads throughout the drive train of a turbine

Future Work:

• investigate impact on fatigue damage on other drivetrain components
• investigate impact of drive train damage reduction on turbine cost of energy
• investigate sensitivity of results to drive train details (different main shaft, gearbox and bedplate configurations) and turbine size
Thank You

Questions?
Nonlinear Model Predictive Control of Wind Turbines Using LiDAR

David Schlipf¹, Dominik Schlipf², Martin Kühn³

¹Endowed Chair of Wind Energy, Universität Stuttgart
²Institute of Combustion and Power Plant Technology, Universität Stuttgart
³AG Wind Energy Systems, Universität Oldenburg
Motivation NMPC

- NMPC advanced process control tool in chemical engineering
- Optimizes control inputs online
- Nonlinear and multivariable control
- Considers actuator and system constrains
- Information about important disturbance needed

![Diagram](image)

- Optimization criteria
- NMPC
- Optimization
- Turbine model
- Wind model
- Outputs
- Inputs
- Prediction
- Wind turbine
Motivation LiDAR

Measurements from a 5MW turbine in 2009

First results show that LiDAR can...

- provide preview wind information
- improve yaw control
- provide input for feed forward pitch control

NMPC and LiDAR promising combination for load reduction
Content

1. Modeling of the Wind Turbine
2. Controller Design
3. Simulated LiDAR Measurements
4. Results
5. Conclusion and Outlook
Modeling of the Wind Turbine

The Aeroelastic Model (FAST/Simulink)
- NREL 5MW onshore baseline turbine (16 DOFs)
- Collective pitch actuator added: 2nd-order (+1DOF)
- 3D stochastic wind input (TurbSim)

The Reduced Nonlinear Model
- 3 DOFs: 1st tower fore-aft bending, rotor motion, collective pitch actuator
- Control inputs: collective pitch, generator torque rate
- Rotor effective wind input
Modeling of the Wind Turbine - Comparison

Closed loop comparison (baseline controller)
- Aeroelastic model + Turbsim
- Reduced nonlinear model + rotor effective wind speed from Turbsim
- Good correlation for rotor speed
- Coherence shows also good correlation for tower movement up to ~0.2 Hz

Reduced model suitable for collective pitch control
Solves optimal control problem: Optimizes control inputs over a finite horizon

Closed loop by iteration:
- application of short control sequence
- update of initial conditions

Can handle multivariable control tasks naturally
Considers actuator and system constrains
Can use nonlinear models, trade-off between performance and computational effort
Controller Design – Optimal Control Problem

„less loads and more power“

Optimal control problem

\[
\min \int_{t_0}^{t_0+T_f} F(x) d\tau
\]

Tuning in terms of changing quantities: trade-off between
- rotor speed variation
- tower movements
- power variation above rated wind speed
- pitch variation
- generator torque variation
- pitch angle below rated wind speed

\[
F(x) = Q_1 (\Omega - \Omega_{ref})^2 \\
+ Q_2 \dot{x}_T^2 \\
+ Q_3 (P - P_{rated})^2 \ \forall \ (v > v_{rated}) \\
+ R_1 \dot{\theta}^2 \\
+ R_2 \dot{M}_{gen}^2 \\
+ R_3 \theta^2 \ \forall \ (v < v_{rated})
\]
Controller Design – Optimal Control Problem

Constrains
- pitch variation
- generator torque variation
- rotor speed variation
- tip speed ratio below rated wind speed

\[
\min \int_{t_0}^{t_0+T_f} F(x) \, d\tau
\]

such that:
\[
\begin{align*}
|\dot{\theta}| &\leq \dot{\theta}_{max} \\
|\dot{M}_{gen}| &\leq \dot{M}_{gen,max} \\
\Omega &\leq 1.2 \Omega_{rated} \\
\lambda_{min} &\leq \lambda \leq \lambda_{max} \quad \forall \ (v < v_{rated})
\end{align*}
\]
Controller Design – Direct Multivariable Shooting

Usage of open source HQP
a solver for sparse nonlinear optimization
LiDAR Measurements - Simulation

Simulation of a real system
- Pulsed system with scanner
- 12 points in 5 cycles every 2s
- Line-of-sight wind speed
- Volumetric measurement
- Taylor’s Hypothesis is used

Realistic scanning of the stochastic wind field used in the aeroelastic simulation
LiDAR Measurements - Processing

- Direction corrected assuming perfect alignment
- Moving average over each circle
- Combined to one rotor averaged wind speed
- Filter depending on mean wind speed to use only those frequencies which have been detected by real measurements

\[
f_{cutoff} = \frac{\hat{k}\hat{u}}{2\pi} \approx 0.03 - 0.24 \text{Hz}
\]

Correlation LIDAR \cdot Turbine

\[\gamma^2 [-] \]

\[k \text{ [rad/m]}\]
Results – Extreme Loads

- Reference: baseline controller [NREL]
- Extreme operating gust (IEC) at 12.5 m/s
- Gust smoothed through spatial and temporal filter effects
- $\text{NMPC}_{\Omega}$: tower base bending moment still high, when only penalizing rotor speed
- NMPC: tower base bending moment reduced by 58% on maximum value, when penalizing tower velocity
- Controller uses generator torque to slow down rotor speed (MIMO)
Results – Extreme Loads

- Reference: baseline controller [NREL]
- Extreme operating gust (IEC) at 12.5 m/s
- Gust smoothed through spatial and temporal filter effects
- $\text{NMPC}_\Omega$: tower base bending moment still high, when only penalizing rotor speed
- $\text{NMPC}_\Omega$: tower base bending moment reduced by 58% on maximum value, when penalizing tower velocity
- Controller uses generator torque to slow down rotor speed (MIMO)
Results – Fatigue Loads

- Significant reduction in frequency domain, where wind can be predicted

Detailed fatigue load analysis
- IEC Design load case 1.2
- Turbulence class A
- Rayleigh distribution $A = 12$ m/s
Results – Fatigue Loads

Tuning for load and pitch action reduction:

- Overall high load reduction on tower ($M_{YT}$), blades ($M_{YB}$) and shaft ($M_{LSS}$)
- Standard deviation of pitch speed $\sigma(\dot{\theta})$ and rotor speed $\sigma(\Omega)$ reduced
- Small increase in AEP (+0.30%)
- Increase of power fluctuation $\sigma(P_{el})$

Relative Reduction of DEL (20 years lifetime N=2E06)
Conclusions

- NMPC with realistic simulation of a LiDAR system over full operation introduced
- Controller coordinates both generator torque and collective pitch
- Low frequencies detection of wind disturbance sufficient
- High fatigue and extreme load reduction on tower, blades and shaft
- Reduction of rotor speed variation and pitch activity
- not yet real-time (factor ~6 on PC)
Outlook

- Coupling with GH Bladed and comparison to feed forward controller and advanced controller of the European UpWind project
- Comparison with linear and multilinear model predictive control
- Implementation for floating wind turbines using LiDAR and buoys
- Learning from new offshore measurements: two scanning LiDAR system actually installed on alpha ventus
Thanks for you attention!

Acknowledgement
This research is funded by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) in the framework of the German joint research project “LIDAR II - Development of nacelle-based LIDAR technology for performance measurement and control of wind turbines”.

WindForS
The Southern German Wind Energy Research Alliance
Questions and Answers