Sandia Smart Rotor Project

Jon White
Representing Dale Berg
Lead, Advanced Rotor Technology
Wind & Water Power Technologies
Sandia National Laboratories
debeg@sandia.gov
(+1) 505-844-1030
June 22, 2010

SMART Team Members
David Wilson - controls
Brian Resor – dynamics/structures
Jon Berg – dynamics/controls/design
Matt Barone – aerodynamics
Josh Paquette – structures/test
Wesley Johnson - test
Mark Rumsey - sensors
Jon White – dynamics/sensors
Gary Fischer – actuator hardware
TPI Composites – blade hardware
Zuteck Consulting – design guidance

Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy’s National Nuclear Security Administration under contract DE-AC04-94AL85000.
Challenge from 20% Report

Increase wind turbine productivity by enabling larger rotors with limited increase in loads on the tower or drivetrain

Impact:
- Greater energy capture on a given tower/drivetrain
- Lighter tower/drivetrain for given rotor size
- Lower Cost of Energy (COE)
- Increased deployment of wind power

Challenges:
- Cost
- Reliability
- Industry acceptance
A Smart Adaptive Wind Turbine Farm

- A Smart Wind Turbine estimates and counteracts loads and deflections using embedded measurements, inference algorithms, adaptive control, and aerodynamic actuators to produce improved performance.

- A Smart Wind Farm uses collective and adaptive control of multiple smart wind turbines to improve wind plant performance.
Smart Wind Farm Benefits

Performance

- Estimate site-specific applied loading and resulting deflection.
- Track instantaneous maximum power coefficient (Cp) that is a function of individual blade pitch, blade actuators, etc. (increase in performance, increase in revenue)
- Minimize root bending loads, and therefore, grow the rotor to improve Region 2 performance.
- Coordinate wind farm control to increase energy capture and reliability (wind gust, wake effects).
- Track time-varying structural characteristics (temperature, surface finish)

Reliability

- Monitor and control response to oscillating, gust, and imbalance loads which cause fatigue and rapid life usage (decrease O&M cost)
- Archived operational loads (non-design, skewed, and oscillating fatigue)
- Predictive gearbox maintenance (un-balanced loading)
- Rotor damage detection and predictive gearbox maintenance
- Prognostic Operations (damage state and future load estimates)
Turbine Power Basics & Opportunity

Power = \( \frac{1}{2} \rho AC_p V_\infty^3 \)

Regions of the Power Curve

- Region I – not enough power to overcome friction
- Region II – Operate at maximum efficiency at all times
- Region III – Fixed power operation

Goal:

Develop advanced rotors which incorporate passive and/or active aerodynamics to address system loads, increase energy capture and decrease cost of energy.
Load Control Concepts

Past work has investigated blade load control

• Individual blade pitch (rather than collective)
  – Pitches entire blade (slow response)
  – Responds to some “average” blade load
  – Current “state-of-the-art” in commercially available hardware

• Passive bend/twist or sweep/twist blade load control (load causes blade to twist and reduce load)
  – Response fixed at time of design
  – Responds to some “average” blade load
  – Difficult to tailor to a variety of specific site conditions
Effectiveness = \text{function}(\text{Frequency})

- Active aerodynamic technologies operate at higher frequencies than current load control approaches (e.g. blade pitch)
- Current research aims to quantify overall effectiveness for various applications
Enabling Actively Controlled Rotors

Enabling New Technology
Develop small, light-weight control devices & systems to attenuate fatigue loads on turbine blades and increase turbine efficiency

- Novel Concepts
- Aeroacoustics
- Advanced Embedded
- Sensors
- Structural Health
- Monitoring

Also Need:
- Structural analysis
- Active aero device integration
- Manufacturing

SMART Rotor Project

Manufacturing
Aerodynamics & Aeroacoustics
Controls
Sensors
Analysis
Test
Active Aero Approach

Investigate use of distributed active aerodynamic load control devices to address locally fluctuating blade loads

- Improved load control capability
  - Respond to loads at locations along blade
  - Respond to site-specific conditions

- Utilize full system dynamic simulations
  - Develop control system
  - Analyze system response

- Develop prototype control devices
  - Microtabs, microflaps, morphing trailing edges
  - Fast response, low loads
  - Study impact on flow field (UC Davis)
    - Analytical (2-D and 3-D CFD)/experimental
AALC Decreases Blade Motion & Fatigue
Fatigue Damage Analysis

18.0 [m/s] MWS NTM IEC Type A Turbulence

Turbulent Wind Input

Turbine

FAST/Aerodyn/Simulink Simulation

Rain Flow Counting

Fatigue Damage Summary

<table>
<thead>
<tr>
<th></th>
<th>9m/s</th>
<th>11m/s</th>
<th>18m/s</th>
<th>Rayleigh Wind 5.5m/s</th>
<th>Rayleigh Wind 7m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Speed Shaft Torque</td>
<td>-1.7</td>
<td>-4.9</td>
<td>-33.5</td>
<td>-3.1</td>
<td>-7.3</td>
</tr>
<tr>
<td>Blade Root Edge Moment</td>
<td>1.7</td>
<td>1.9</td>
<td>-2.5</td>
<td>0.8</td>
<td>0.8</td>
</tr>
<tr>
<td>Blade Root Flap Moment</td>
<td>-31.2</td>
<td>-27.1</td>
<td>-30.4</td>
<td>-23.1</td>
<td>-26.3</td>
</tr>
<tr>
<td>Blade Root Pitch Moment</td>
<td>-11.4</td>
<td>-4.5</td>
<td>-14.1</td>
<td>-7.1</td>
<td>-7</td>
</tr>
<tr>
<td>Tower Base Side-Side Moment</td>
<td>-0.1</td>
<td>-8</td>
<td>-7.2</td>
<td>-0.9</td>
<td>-2.9</td>
</tr>
<tr>
<td>Tower Base Fore-Aft Moment</td>
<td>-18.6</td>
<td>-16.5</td>
<td>-13.8</td>
<td>-5</td>
<td>-8</td>
</tr>
<tr>
<td>Tower Top Yaw Moment</td>
<td>-53.2</td>
<td>-42.9</td>
<td>-43.4</td>
<td>-25.1</td>
<td>-32.2</td>
</tr>
</tbody>
</table>

*Active Aerodynamic Load Control (AALC) - 10% chord length in CFD test indicated 2% decline in displacement control stress levels
Grow the Rotor (GTR) Concept

Comparable Blade Flap Fatigue Damage – 1.5MW

% Increase in Yearly Energy Capture

<table>
<thead>
<tr>
<th>Annual Average Wind Speed, m/s</th>
<th>Original Rotor</th>
<th>16% Longer Blades</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>0</td>
<td>16</td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>14</td>
</tr>
<tr>
<td>6.5</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>7</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>7.5</td>
<td>7</td>
<td>10</td>
</tr>
<tr>
<td>8</td>
<td>9</td>
<td></td>
</tr>
</tbody>
</table>

% Decrease in Cost of Energy

<table>
<thead>
<tr>
<th>Annual Average Wind Speed, m/s</th>
<th>Cost of Energy</th>
<th>16% Longer Blade</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.5</td>
<td>10</td>
<td>7.6</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td>6.7</td>
</tr>
<tr>
<td>6.5</td>
<td>8</td>
<td>6.5</td>
</tr>
<tr>
<td>7</td>
<td>10</td>
<td>5.9</td>
</tr>
<tr>
<td>7.5</td>
<td>12</td>
<td>4.8</td>
</tr>
<tr>
<td>8</td>
<td>13</td>
<td>4.0</td>
</tr>
</tbody>
</table>
Industry and International Collaborations

- Validating and exercising enhanced fidelity dynamic simulation tool (DU_SWAMP) developed at TU-Delft (The Netherlands) under MOU signed in 2008
  - Improvements in simulation fidelity for active aero and advanced controls research
  - Podium presentation at 2010 Wind Energy Symposium (Orlando) and 2010 Making Torque from Wind Conference (Crete, Greece)

- Investigating impact of AALC on gearbox with Romax Ltd (member of NREL Gearbox Reliability Collaborative)
  - Reduces off-axis loading
  - Reduces bearing maximum loads
  - Reduces bearing misalignment

![Example results from Romax drivetrain analysis](image)
Fabrication of SMART Blade Set

Motivation: FY09 SMART rotor work identified a clear need for full system experimental data to meet the following objectives:

- Validate active aero simulations
- Demonstrate system integration of active aero on a real blade set
- Demonstrate operation of active aero, both by observing open-loop responses and by performing closed-loop

FY10 SMART Blade design process

- Design and analyses performed in-house at SNL
- Leverage existing CX-100 molds and previous design calculations where applicable
- Teaming with SNL Sensing Technologies for sensing design and installation (Rumsey and White)
SMART Blade Design

**Design keys**
- Maintain blade stiffness after removal of outboard trailing edge
- Support flow of loads with additional flange and rib
- Track sectional center of gravity

**Aeroelastic system structural loads**
- Normal operation
- Extreme events
- With and without flaps deflected
- Flap control authority simulations
- Flap hinge loads and module interface loads

**ProE Solid modeling –physical space planning**
- Supported by actual 3D surface map of manufactured blade
SMART Blade Construction

- Fabrication of skins and shear web completed by TPI
- Installation of internal sensors scheduled for early August
- Fabrication of aft flange and flap modules at SNL scheduled for late summer
- Integration of all components scheduled for late summer
- Initial blade flights at Bushland by end of FY10
  - Early actuations to focus on open-loop operations for system identification
  - Closed-loop control in FY11

First Active Load Control Rotor in the World
Future Work

- **Continue development of tools and advanced control concepts**
  - Improve system ID techniques
  - Continue to investigate SISO and MIMO (distributed) state space control
  - Integrated torque, collective pitch, IBP, passive twist and active aero control

- **Validate accuracy of simulation tools**
  - Requires experimental data, coming along with field test of SMART blade

- **Mitigate technology risk through prototype testing and demonstration**
  - Field test on 9-m Bushland turbine (FY10) *(i.e. Current SMART Blade)*
  - Field tests on small variable-speed/variable-pitch turbine
  - Scale up to commercial scale turbine
**Sensor Partners**

- Accelerometer
  - PCB Piezotronics
  - Purdue University
  - Silicon Designs

- Acoustic Emission
  - Physical Acoustics

- Active Piezoelectrics
  - Los Alamos Labs
  - NASA-KSC

- Digital Image Correlation
  - SNL
  - Univ. Mass. – Lowell

- Fiber Optic
  - Aither Engineering
  - Intelligent Fiber Optic
  - Luna Innovations
  - Micron Optics, Inc.

**Smart Rotor Interactions**

- Pitot Tube / Pressure Tap
  - Aeroprobe

- Stagnation Point
  - Tao Systems

- Strain Gage
  - Vishay

**Aerodynamic Actuators**

- Compliant Structures
  - FlexSys

- Micro Tabs
  - UC-Davis

- Fiber Optic
  - Aither Engineering
Smart Rotor Interactions

Testing Partners
- Fabrication
  - TPI Composites
  - SNL
- Testing
  - NREL NWTC
  - USDA-CPRL

Corporate Partnerships
- Frontier Wind

International Partnerships
- TU-Delft
- Risø
- Romax
Thank You