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Sandia Smart Rotor Project

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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

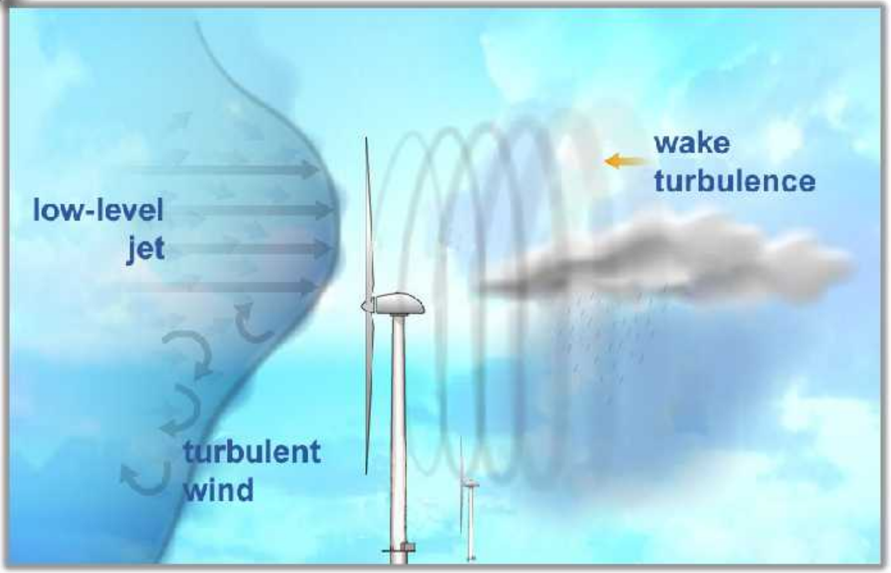
Impact:

- 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

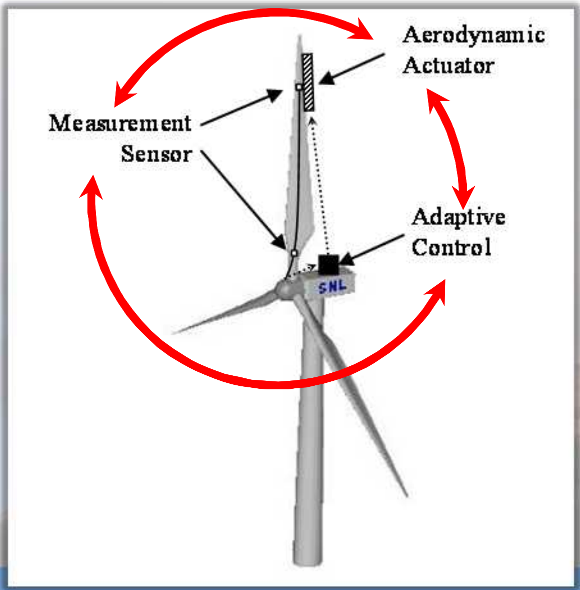
Challenges:

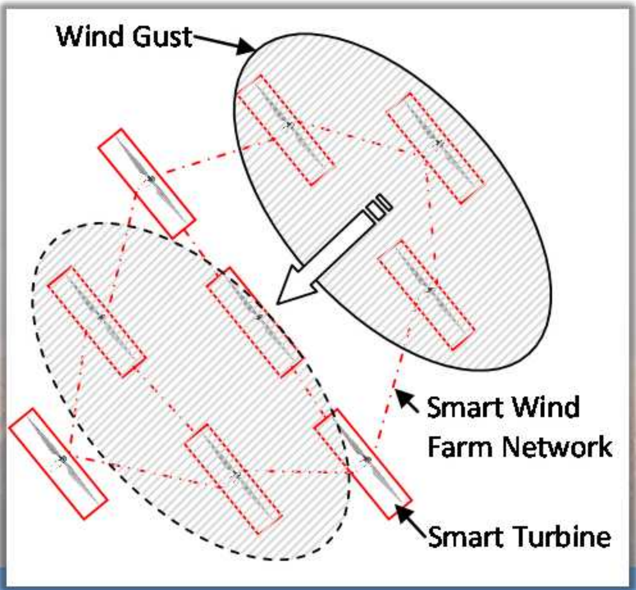
- Cost
- Reliability
- Industry acceptance

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.



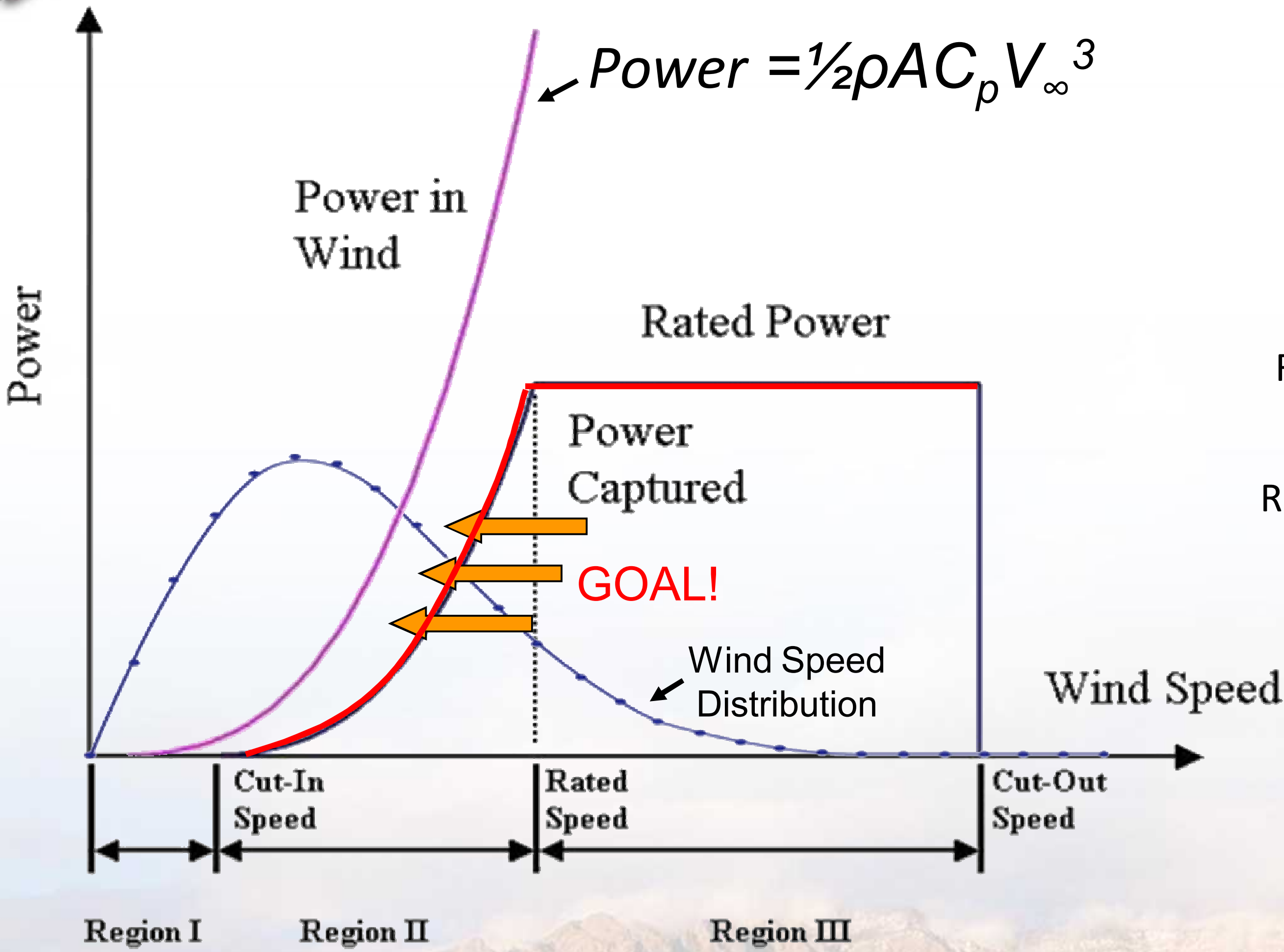


- A Smart Wind Farm uses collective and adaptive control of multiple smart wind turbines to improve wind plant performance.

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



<u>Regions of the Power Curve</u>

Region I – not enough power to overcome friction

Region II – Operate at maximum efficiency at all times

Region III – Fixed power operation

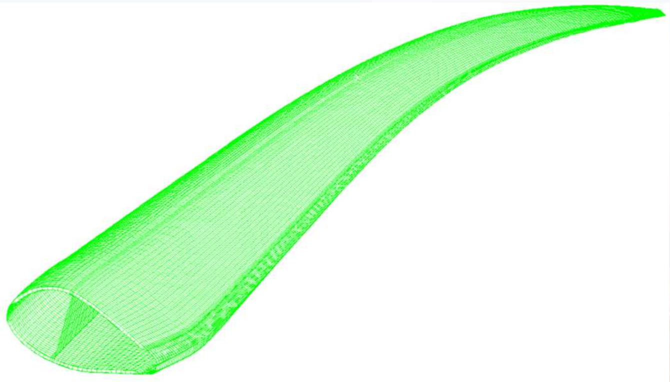
<u>Goal:</u>

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

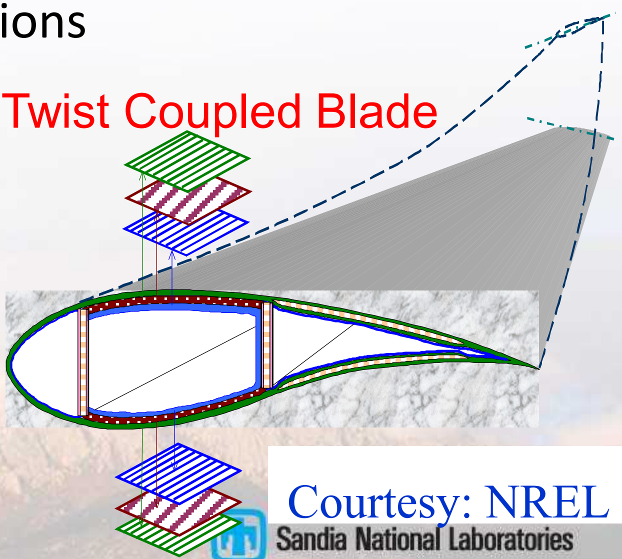
Past work has investigated blade load control

- 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



K&C STAR Sweep-Twist Coupled Blade

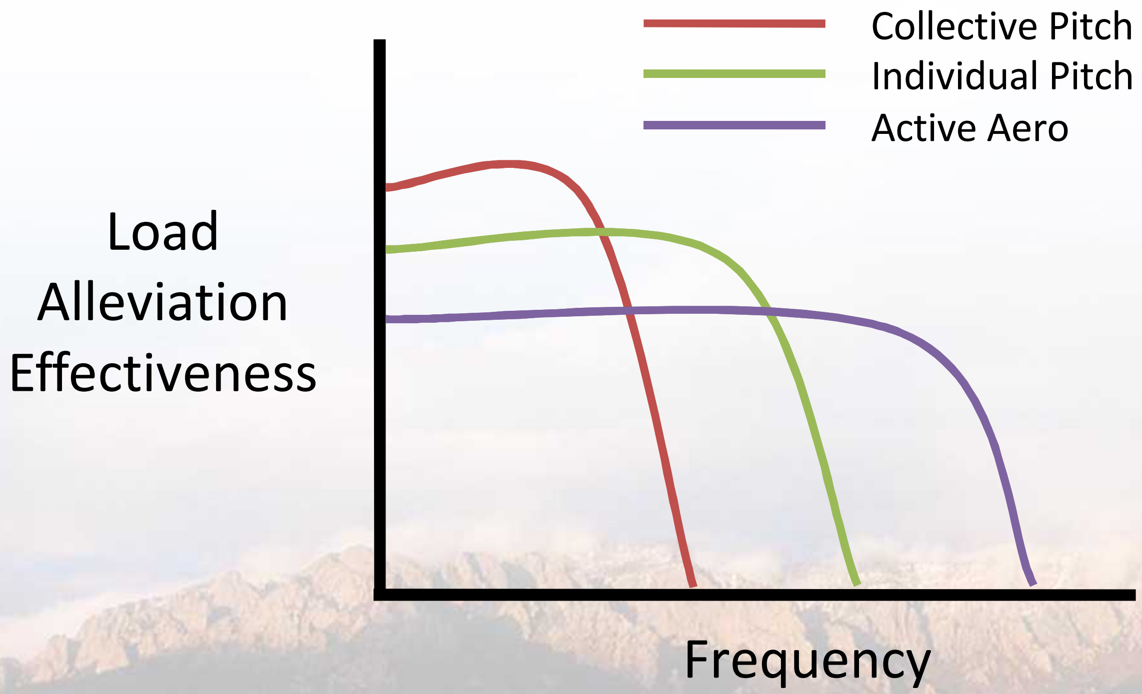
Passive Bend-Twist Coupled Blade



Courtesy: NREL

Effectiveness = function(Frequency)

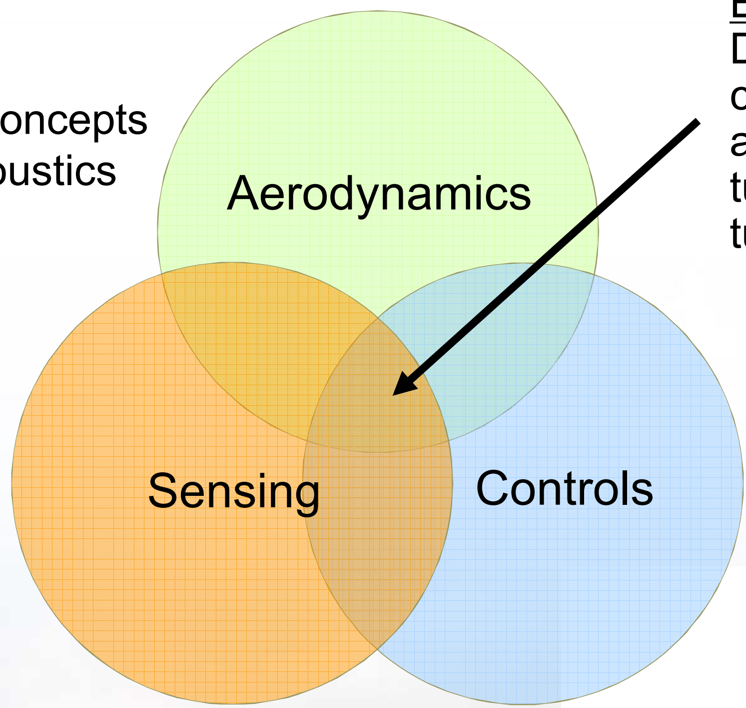
- **Active aerodynamic technologies operate at higher frequencies than current load control approaches (e.g. blade pitch)**
- **Current research aims to quantify overall effectiveness for various applications**



Enabling Actively Controlled Rotors

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

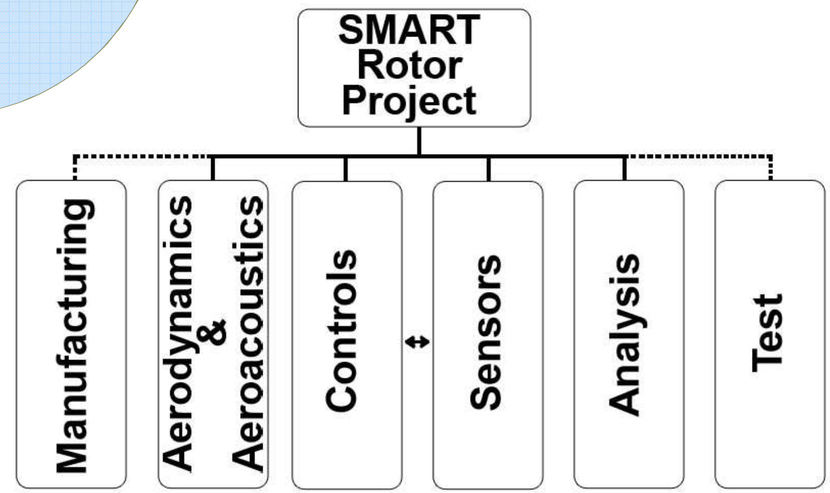
- Novel Concepts
- Aeroacoustics



- Advanced Control Strategies

- Advanced Embedded
- Sensors
- Structural Health
- Monitoring

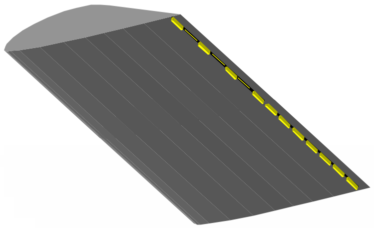
Also Need:
- Structural analysis
- Active aero device integration
- Manufacturing

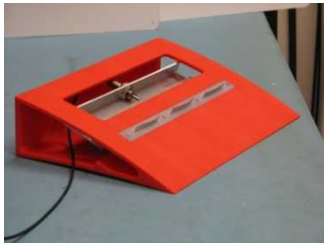


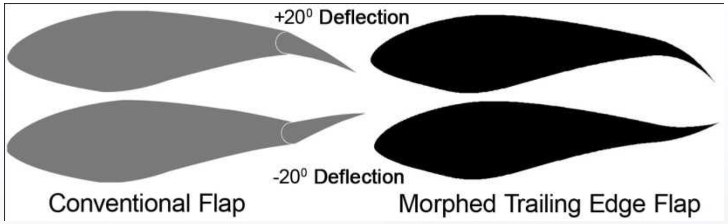
Active Aero Approach

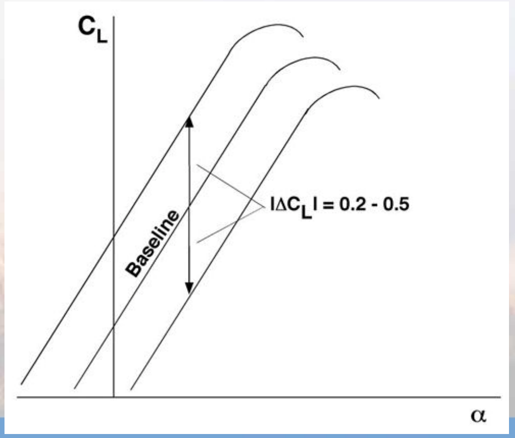
Investigate use of distributed active aerodynamic load control devices to address locally fluctuating blade loads

- **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



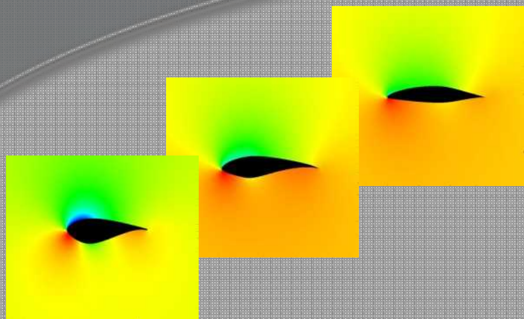




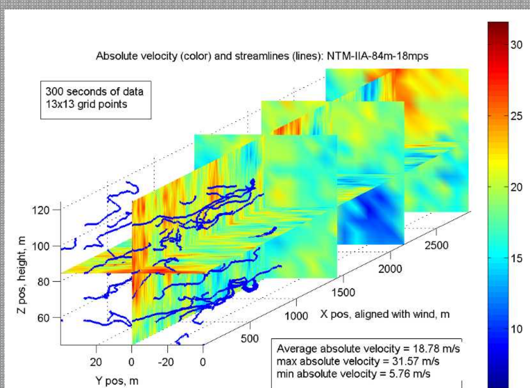


System Analysis with Wind Turbine Aeroelastic Simulation

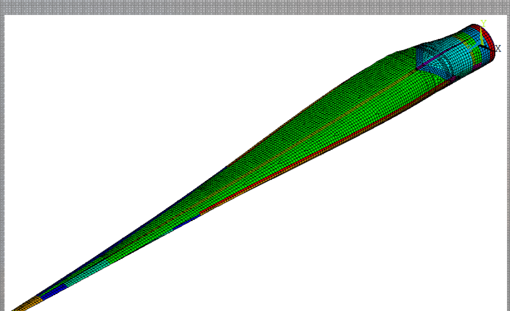
Aerodynamic Performance



Turbulent Wind Input

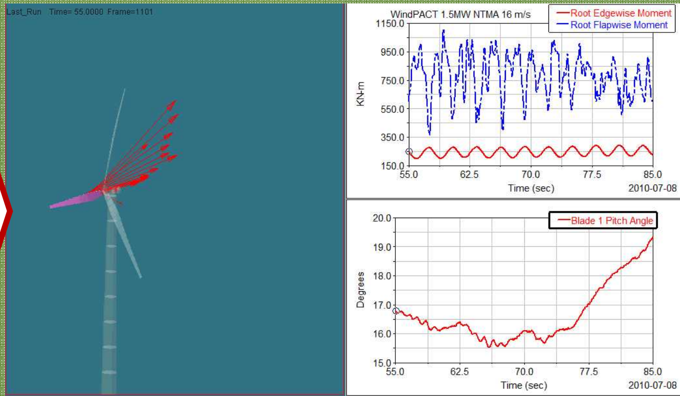


Structure and Materials



Wind Turbine System Dynamics Model

Dynamic Response



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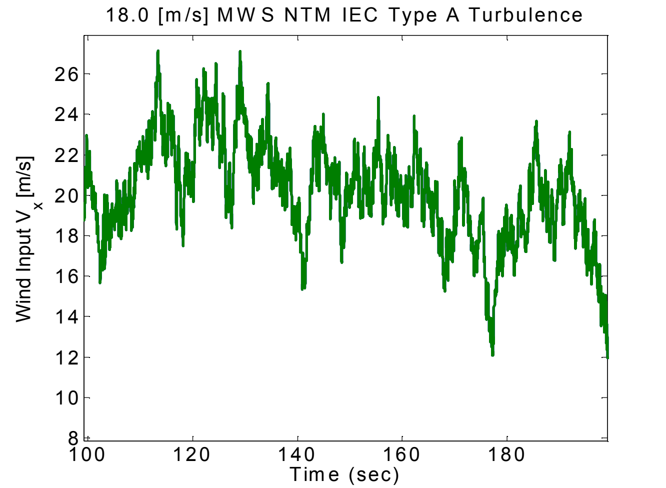
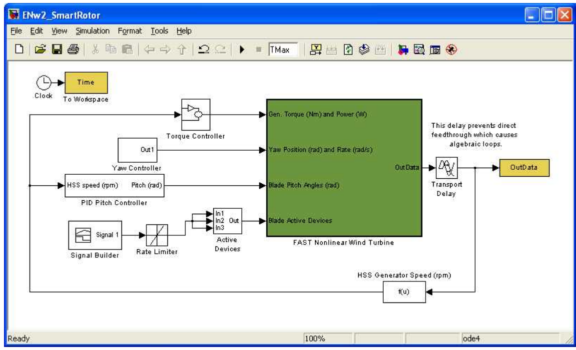
AALC Decreases Blade Motion & Fatigue

Fatigue Damage Analysis

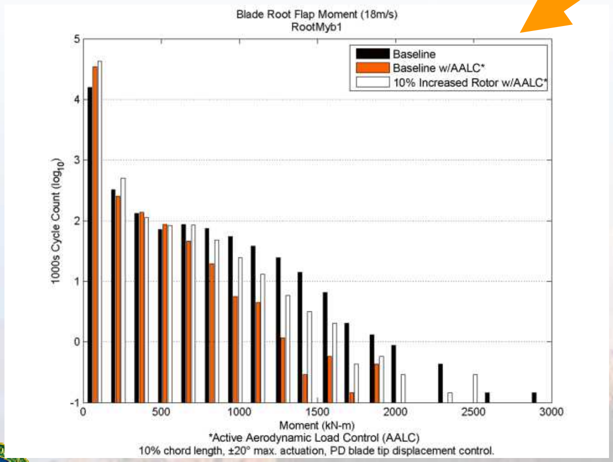


Turbulent Wind Input

Turbine



FAST/Aerodyn/Simulink Simulation



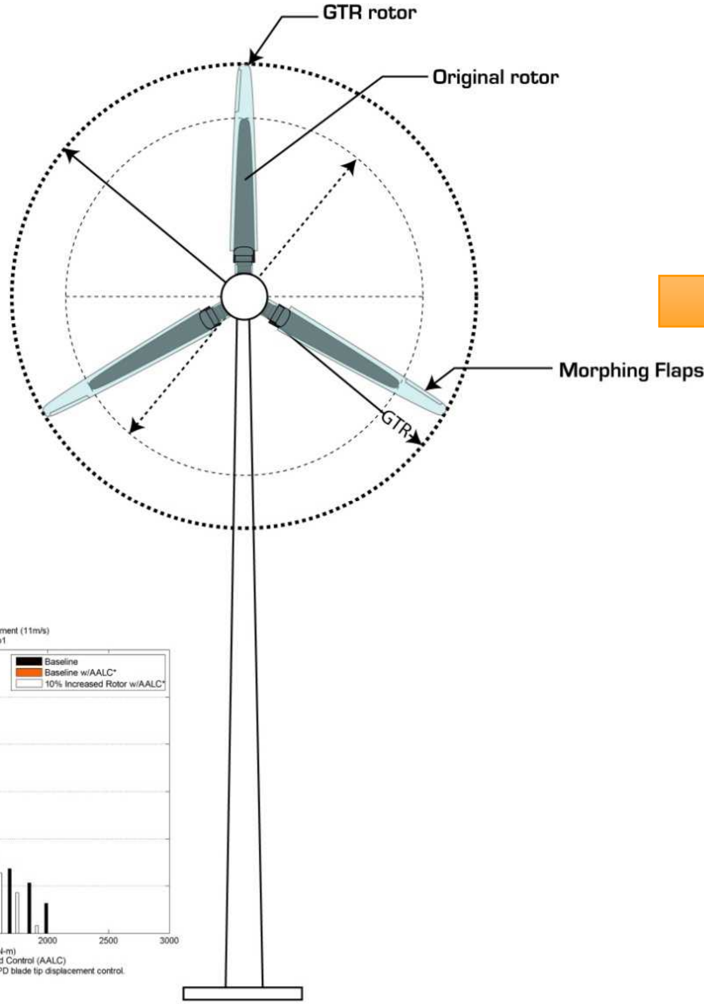
Rain Flow Counting

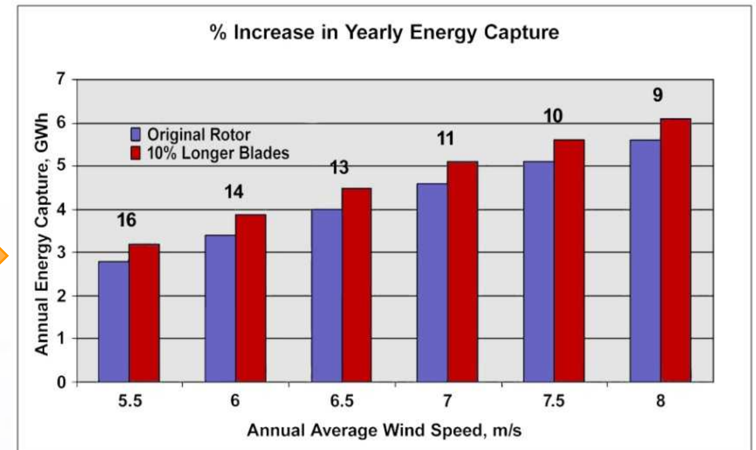
	9m/s	11m/s	18m/s	Rayleigh Wind 5.5m/s	Rayleigh Wind 7m/s
Low Speed Shaft Torque	-1.7	-4.9	-33.5	-3.1	-7.3
Blade Root Edge Moment	1.7	1.9	-2.5	0.8	0.8
Blade Root Flap Moment	-31.2	-27.1	-30.4	-23.1	-26.3
Blade Root Pitch Moment	-11.4	-4.5	-14.1	-7.1	-7
Tower Base Side-Side Moment	-0.1	-8	-7.2	-0.9	-2.9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

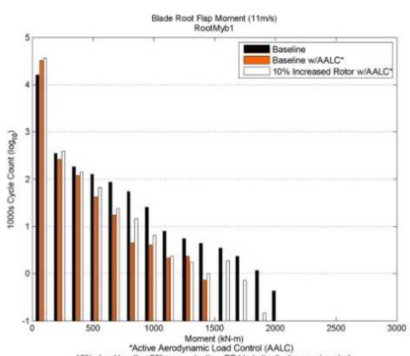
Fatigue Damage Summary

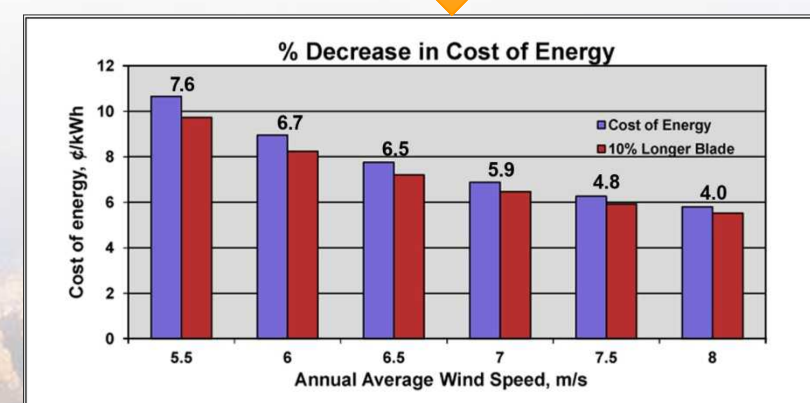
Grow the Rotor (GTR) Concept

Comparable Blade Flap Fatigue Damage – 1.5MW



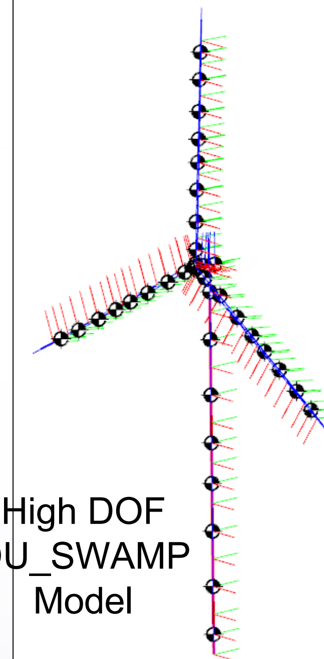




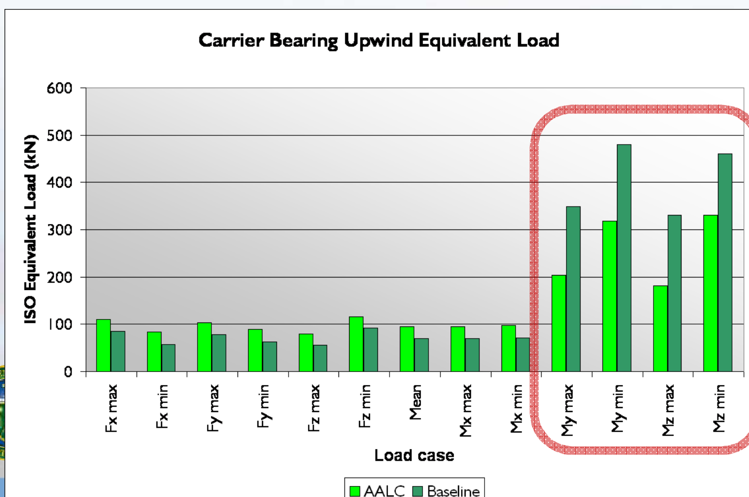


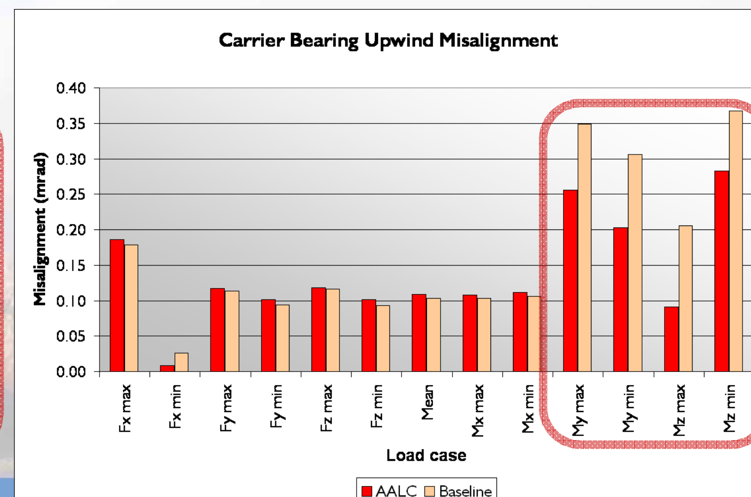
Industry and International Collaborations

- **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



High DOF DU_SWAMP Model





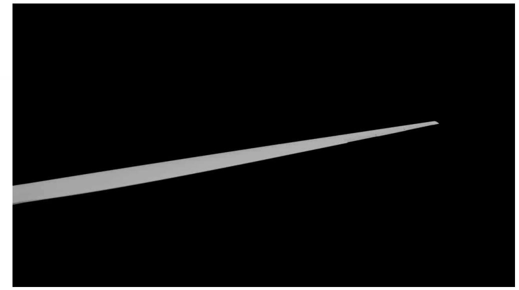
Example results from Romax drivetrain analysis

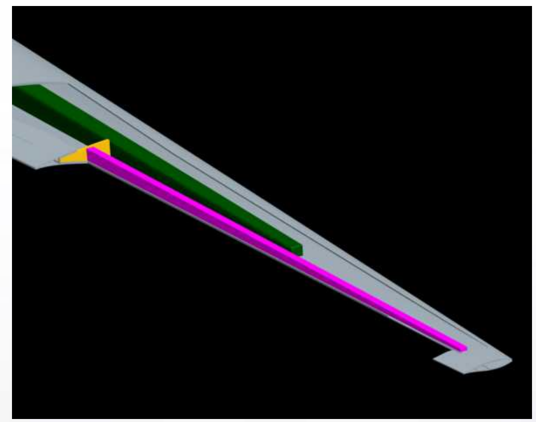
Fabrication of SMART Blade Set

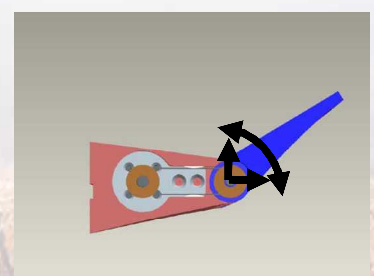
- **Motivation: FY09 SMART rotor work identified a clear need for full system experimental data to meet the following objectives:**
  - Validate active aero simulations
  - Demonstrate system integration of active aero on a real blade set
  - Demonstrate operation of active aero, both by observing open-loop 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)

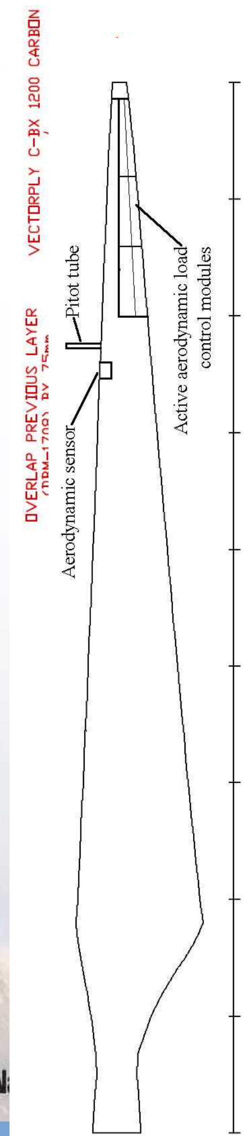
SMART Blade Design

- **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









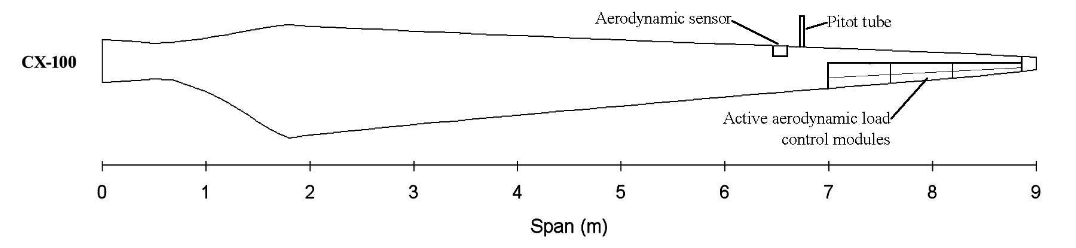
SMART Blade Construction

- **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



9-m AALC Blade Concept

Smart Rotor Interactions

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.
- Pitot Tube / Pressure Tap
  - Aeroprobe
- Stagnation Point
  - Tao Systems
- Strain Gage
  - Vishay

Aerodynamic Actuators

- Compliant Structures
  - FlexSys
- Micro Tabs
  - UC-Davis

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

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