Sandia Wind Energy Program Overview – FY07

Presentations at TU Delft and Risø National Laboratory

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Sandia National Laboratories

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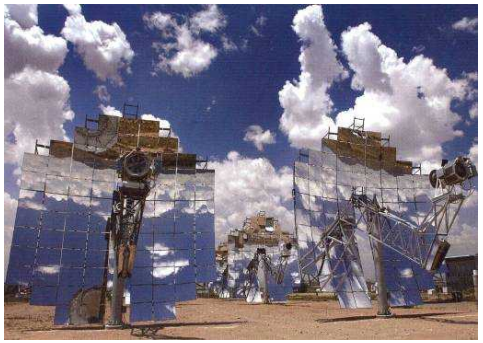
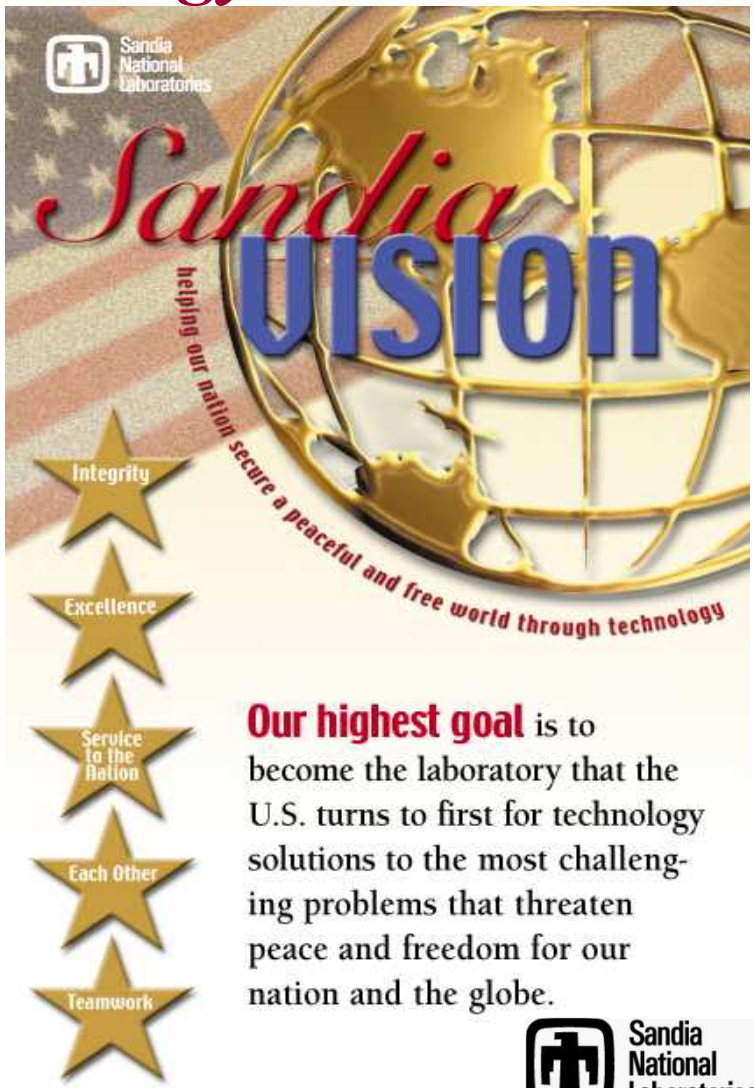
Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.

Sandia's Core Purpose

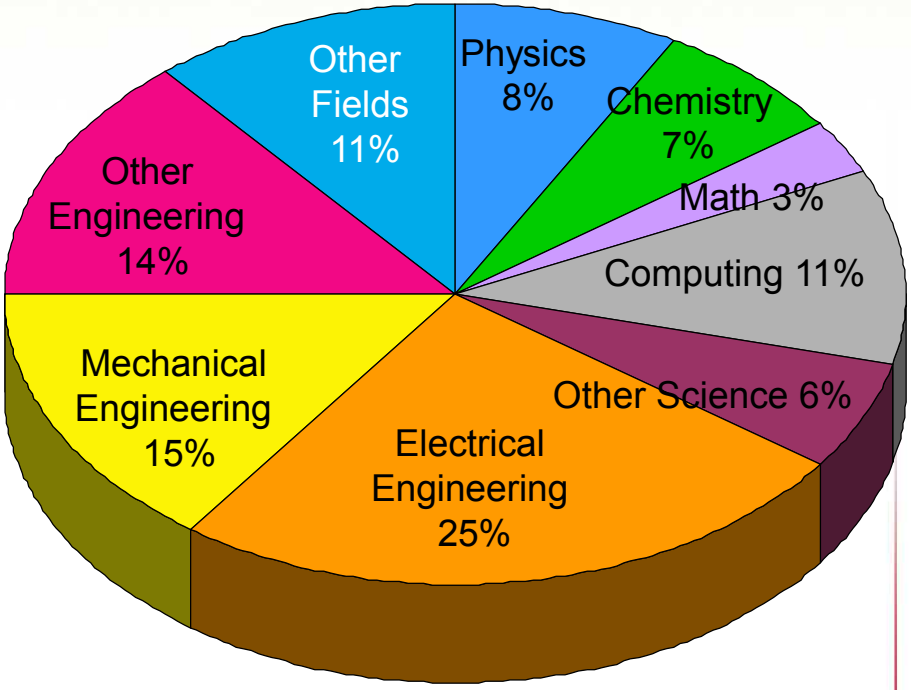
"Helping our Nation Secure a Peaceful and Free World through Technology"

- **National Security Laboratory**
- **Broad mission in developing science and technology applications to meet our rapidly changing, complex national security challenges**
- **Safety, security and reliability of our nation's nuclear weapon stockpile**





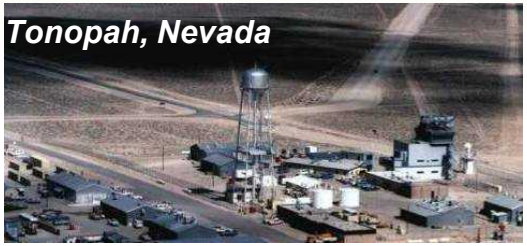
Sandia Employs More Than 8,000 Highly Skilled Workers

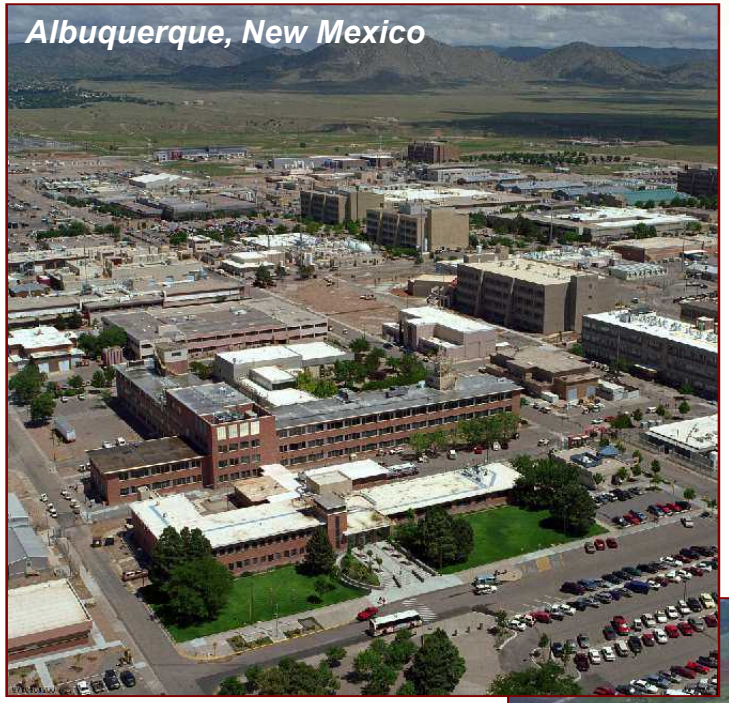


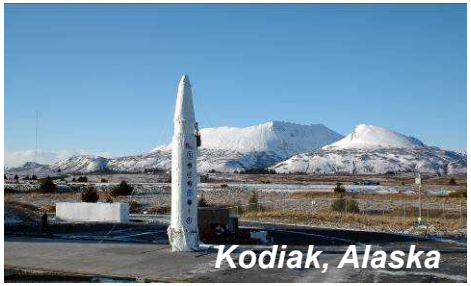
- **Over 8,500 employees**
- **Over 1,500 PhDs; over 2,500 MS/MA**
- **Over 700 on-site contractors**
- **$2.3 billion operating budget**

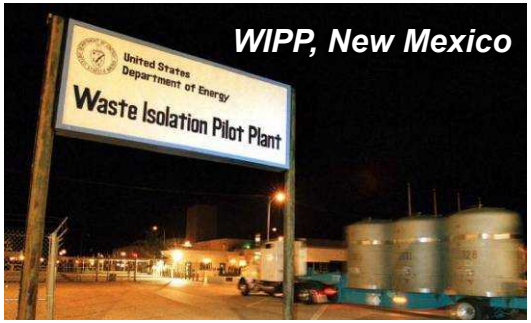
Sandia National Laboratories

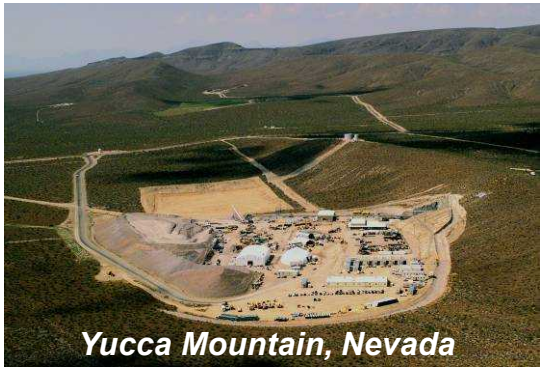
Sandia National Laboratories is Geographically Distributed







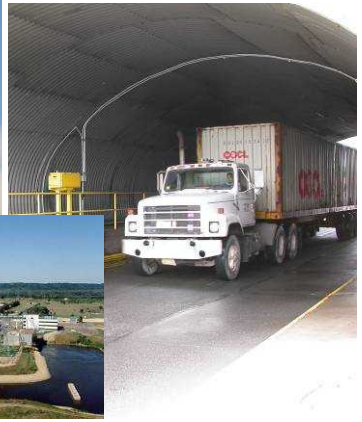


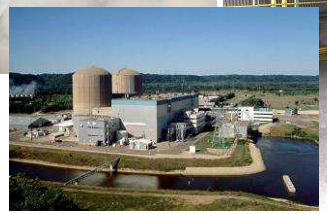


Sandia is Organized into Three Strategic Management Groups

Integrated Technologies and Systems
Three Management Units

- *Energy, Resources, and Nonproliferation*
- *Homeland Security*
- *Defense Systems & Assessments*



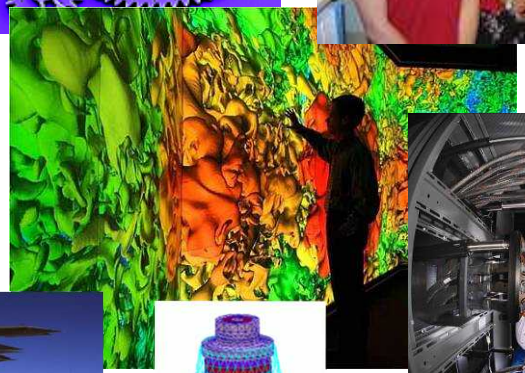


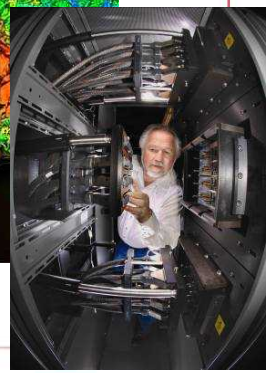
Nuclear Weapons
One Management Unit

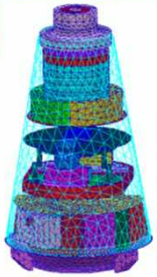
- *Nuclear Weapons*

Laboratory Transformation
Two Management Units

- *Integrated Enabling Services*
- *Science, Technology, and Engineering*







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Rush Robinett III, Senior Manager
Sandia National Laboratories

6330
Energy & Infrastructure Future
Rush Robinett

6337
Solar Technologies
Jeff Nelson

6335
Solar Systems Department
Charlie Hanley, Acting

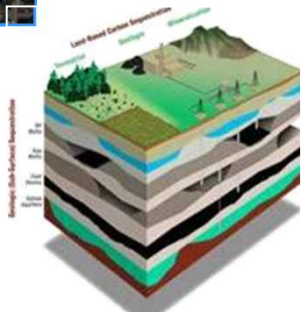
6333
Wind Energy Technology
Jose Zayas

6331
Geothermal Research
Douglas Blankenship

6336
Energy Infrastructure & DER
John Boyes

6332
Energy Systems Analysis
Juan Torres

6338
Fuels & Energy Transitions
Ellen Stechel



Sandia National Laboratories

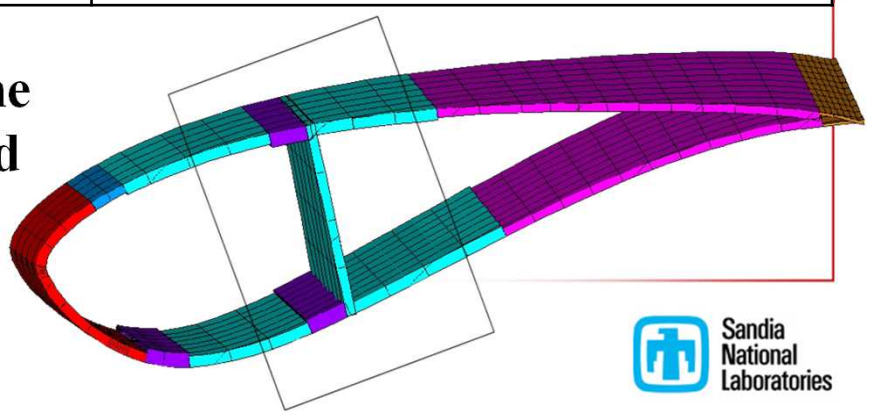
Department Background & Accomplishments

- Established in Mid 1970's
  - Primary focus VAWT's
  - Industry partnerships
- Transitioned to Blades in early 1990's
- 15 Full-Time Employees
- Several Contractors and Students

1975	SNL Wind Program Established
1977	17m VAWT Fabricated
1981	1st Wind-Turbine Specific Airfoils
1982	FloWind Technology Transfer
1984	34m VAWT Test Bed
1988	SNL/MSU Material Dbase Established
1994	SNL Blade Program Started
1998	Blade Manufacturing Initiative
2003	Incorporation of Carbon on Blades
2005	K&C Swept Blade Contract
2006	Reliability Program Started

Mission:

To provide a knowledge base expertise in the design and advancements of composite wind turbine blades and turbine reliability, in order to accelerate the penetration of Wind Energy.



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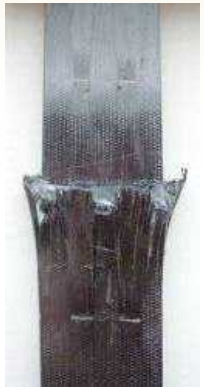
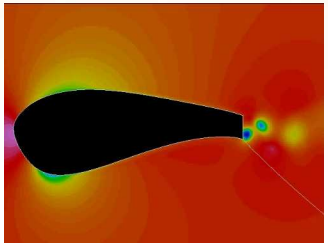
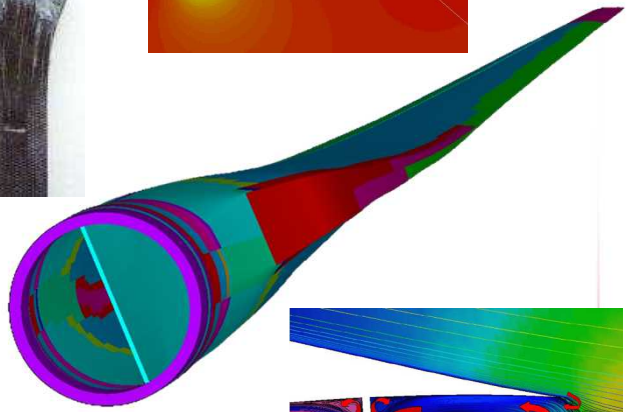
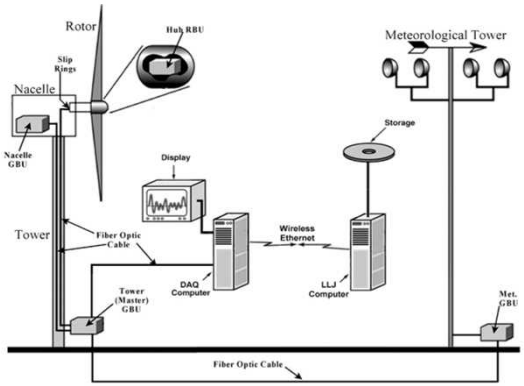
Wind Energy Technology Department

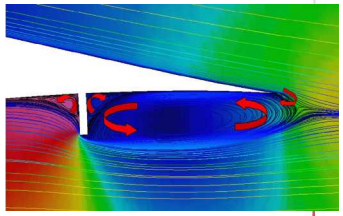
- **Blade Technology**
  - Materials and Manufacturing
  - Structural, Aerodynamic, and Full System Modeling
  - Lab - Field Testing and Data Acquisition
  - Sensors and Structural Health Monitoring
  - Advanced Blade Concepts
- **System Reliability**
  - Industry Data Collection
  - Improve reliability of the existing technology and future designs

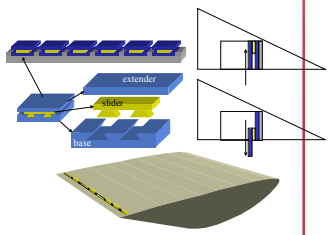












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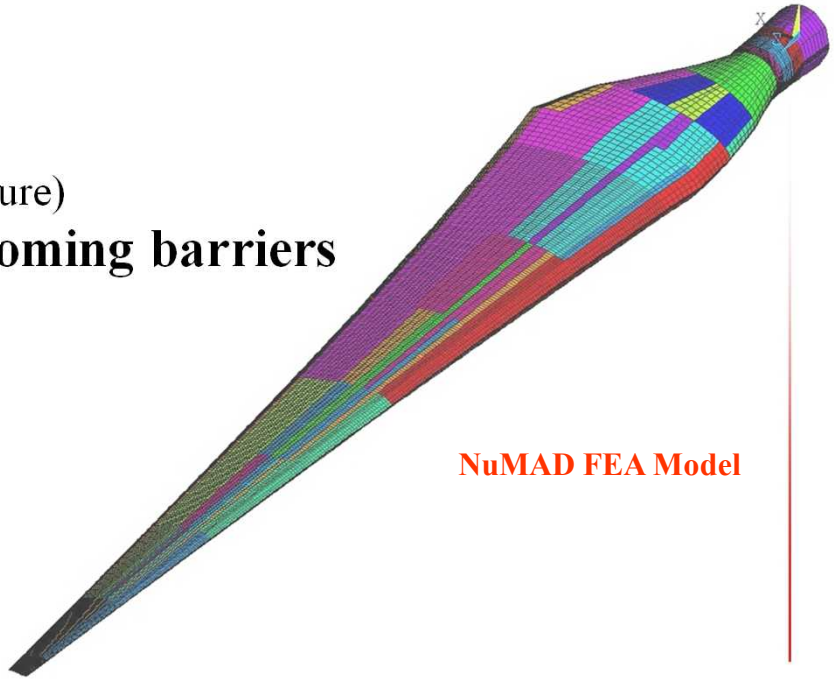
New Direction
FY07 & Future Research Focus

- **Program Focus On Industry Needs**
  - **Increase reliability**
  - **Improve turbine O&M**
    - Shift from scheduled maintenance to condition based maintenance
    - Redundant sensors
  - **Increase energy capture**
    - Active aerodynamic control
    - Advanced control research (adaptive architecture)
  - **Improve blade design to eliminate upcoming barriers**
    - Transportation (segmented blades)
    - Strategic use of advanced materials
    - Embedded sensors on blades
  - **Improve turbine availability**
    - Structural health monitoring
  - **Higher fidelity modeling**



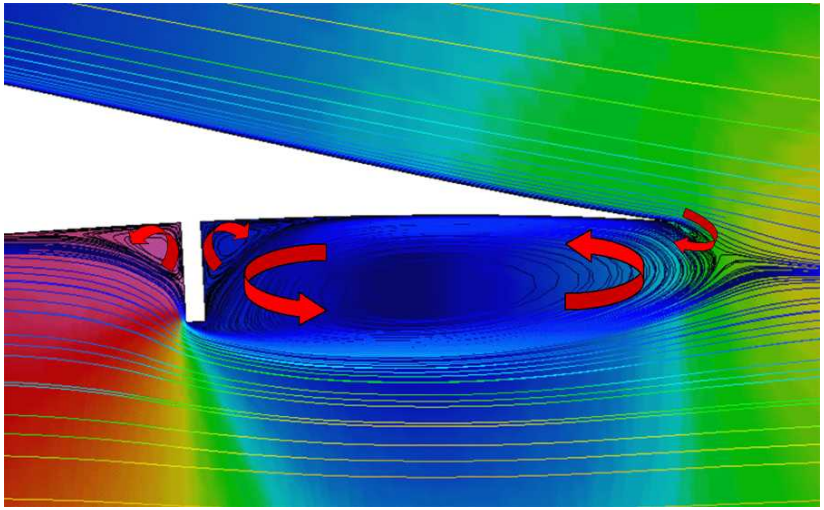
Smaller turbines → Larger turbines

$ → $$$

Build, Break, Redesign → Advanced Simulation

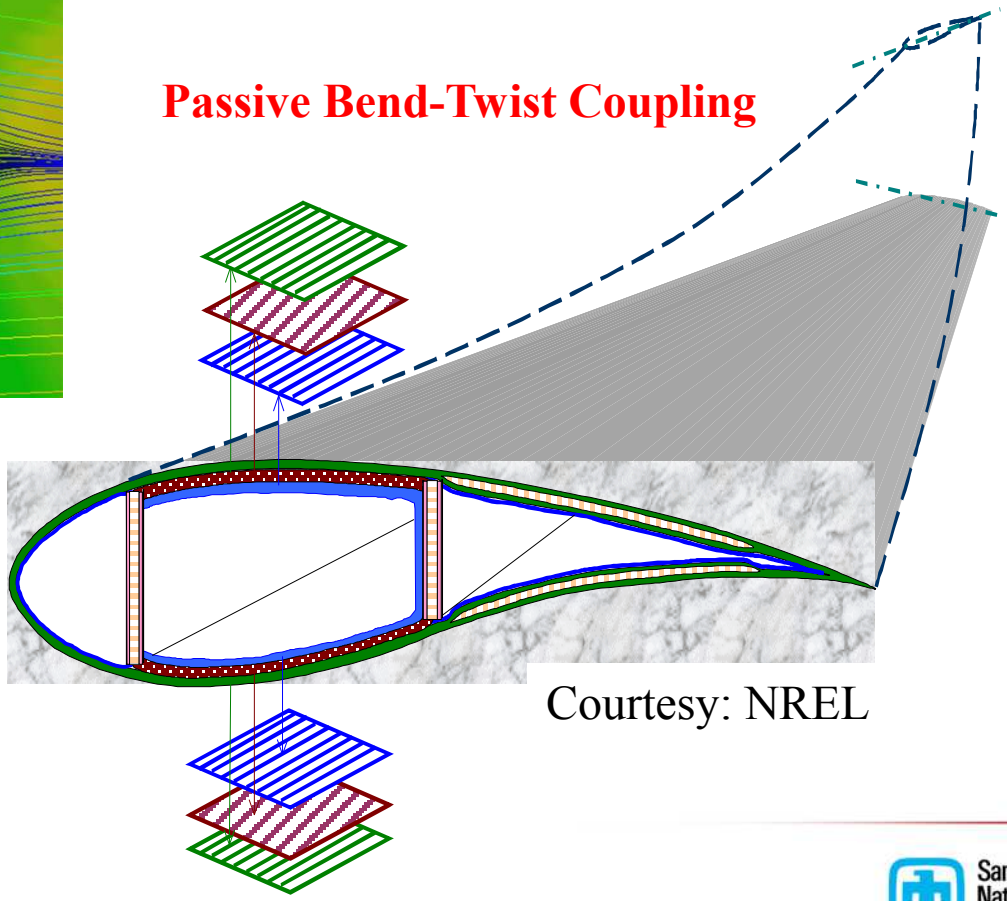
Passive and Active Blade Control

(PI: Dale Berg)



Active Devices

Passive Bend-Twist Coupling



Courtesy: NREL

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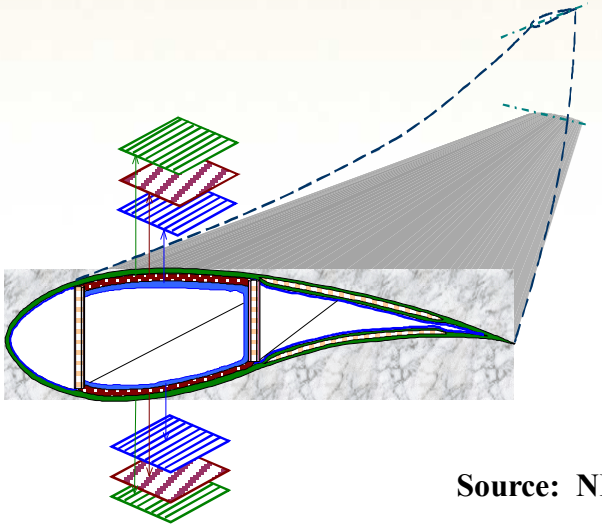
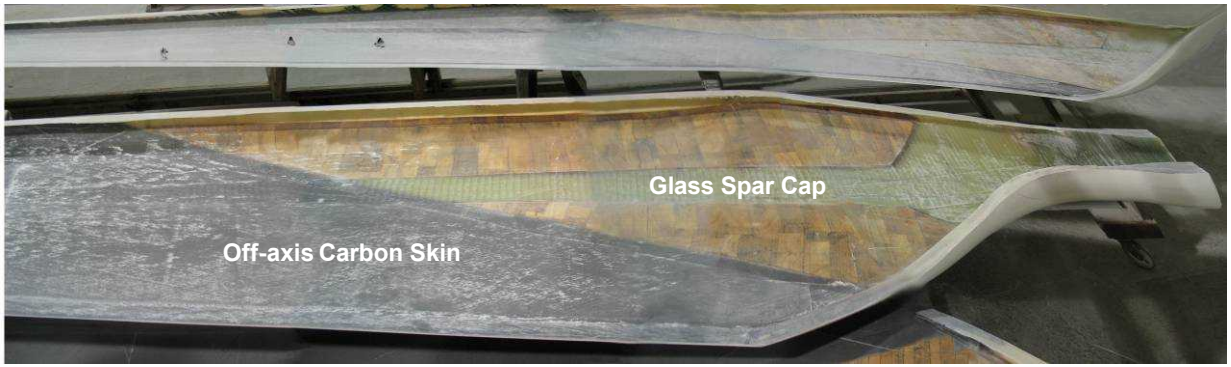
TX-100
Twist Experimental – 100kW

- Identical geometry to CX-100
- Partial length glass spar cap
- 20° off-axis carbon in outboard (~>3.5 m) skins to produce material-induced, passive aerodynamic load alleviation



Source: NREL

Material Induced Twist-Bend Coupling



TX-100 Blade Skin

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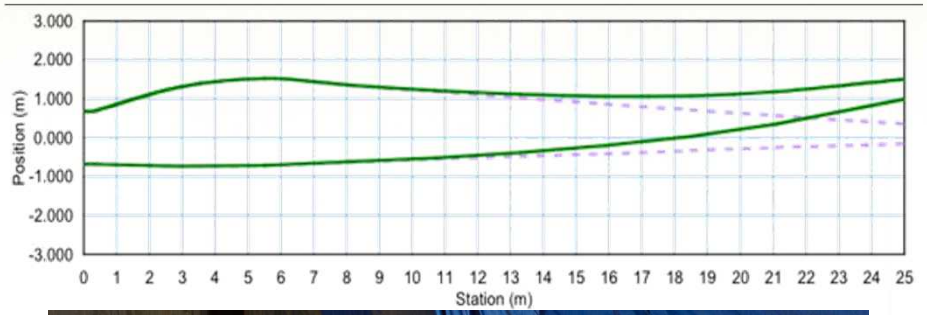
Low Wind Speed Technology Project – Swept Blade

- **Knight & Carver**
  - **27.1m swept blade**
  - **Replacement blades – Zond 750**
  - **5-10% increased energy capture**



Partnership with Knight & Carver in the Development of Passive-Bend Twist Coupled Swept Blade

Active Flow/Load Control

- **Active Load Control:**
  - **May remove fundamental design constraints for large benefits**
  - **May allow for lighter more slender blades designs**
  - **Could potentially be used in conjunction with VSVP control, to alleviate high frequency loads**

These Large Benefits are Feasible if Active Control Technology is Considered from the Beginning

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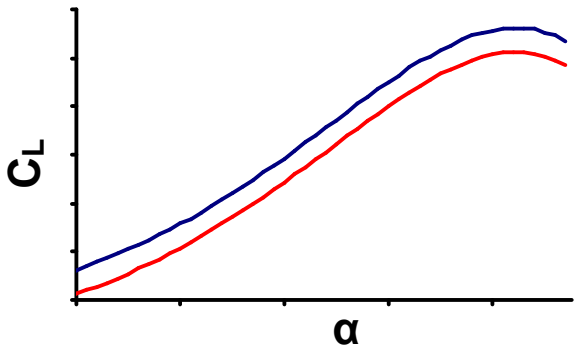
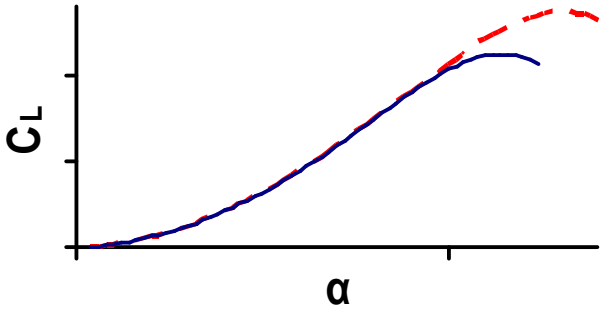
Active Flow/Load Control

- **Focus on Fast-Acting, Low Actuation Energy Devices**
  - **Will operate within the boundary layer of the blade**
  - **Must be rugged and easily implemented**
- **Active Load Control on Wind Turbine Blades can be Achieved by Modifying:**
  - **Blade incidence angle (pitch)**
  - **Flow velocity (modification in RPM)**
  - **Blade length**
  - **Blade aerodynamic characteristics through:**
    - Changes in section shape (aileron, smart materials, microtab)
    - Surface blowing/suction
    - Other flow control techniques (VG's, surface heating, plasma)



Current Technology - VSVP

Variable Speed Variable Pitch



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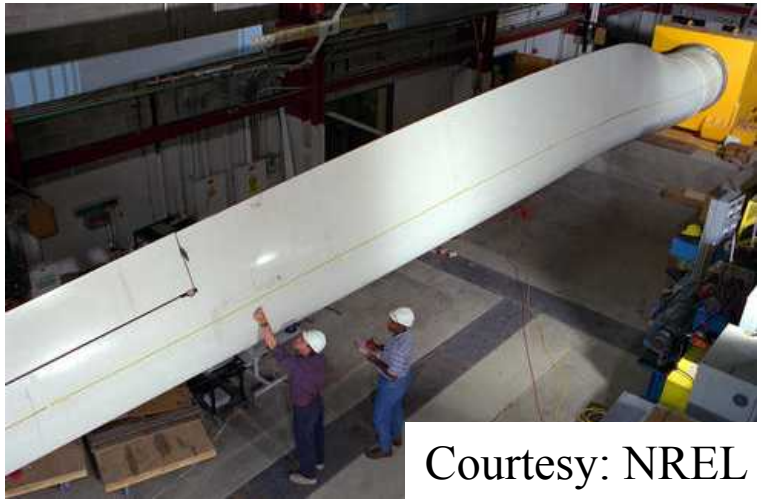
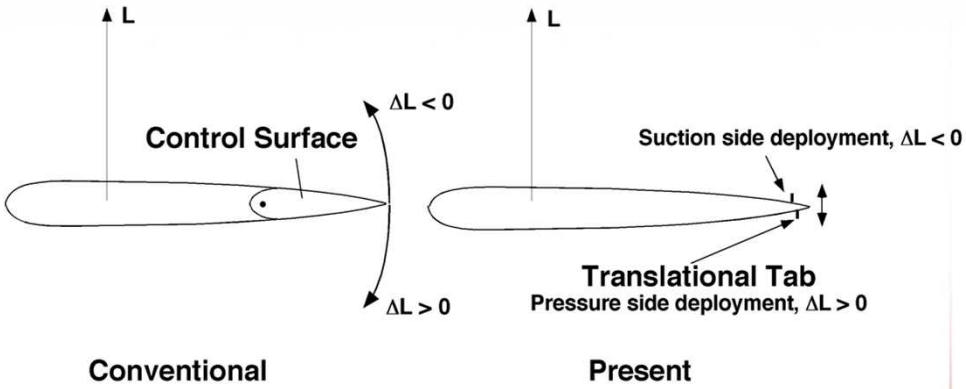
Examples of Active Flow/Load Control

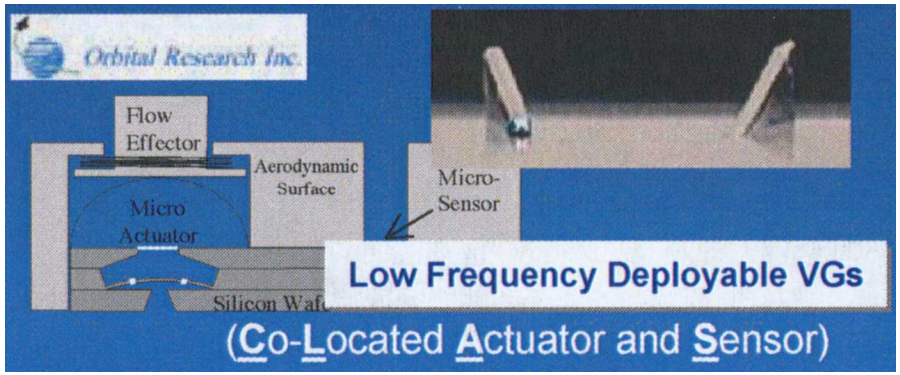


Courtesy: NREL

Active Aileron on a Zond 750 Blade



Microtab Concepts



Active Vortex Generators

Adaptive Airfoils

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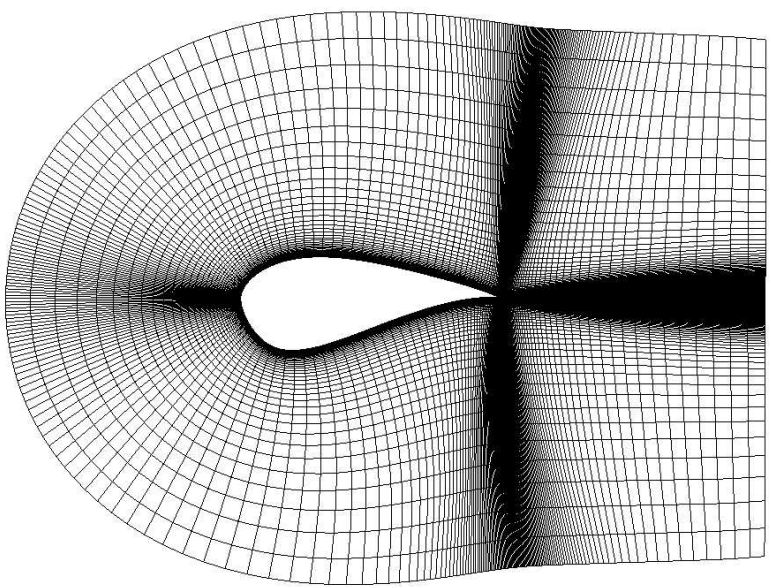
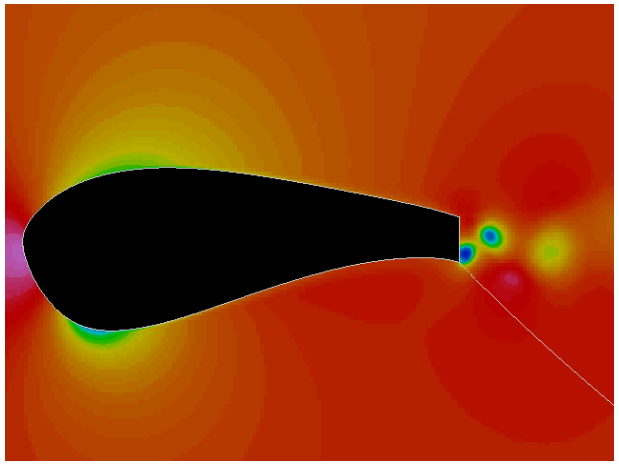
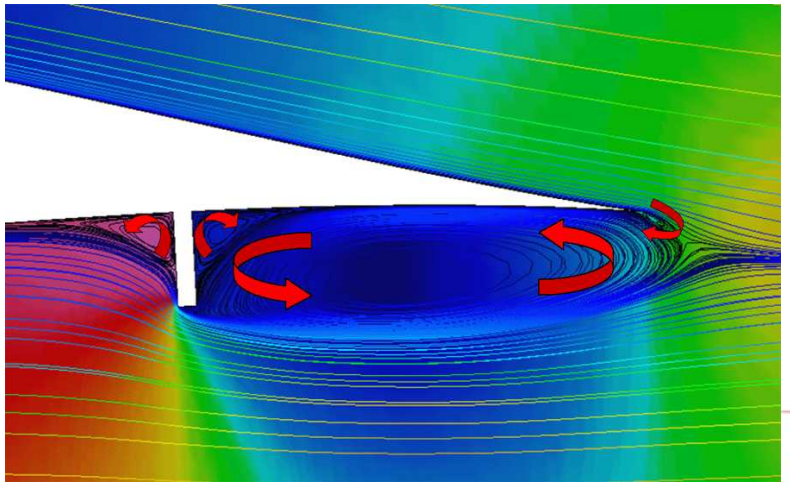
CFD Capabilities
(PI: Dale Berg)

- **Computational Fluid Dynamics Codes**
  - ARC2D
  - OVERFLOW 2.0y
- **Applications for CFD**
  - Airfoil performance predictions
  - Understanding of the effects of embedded devices







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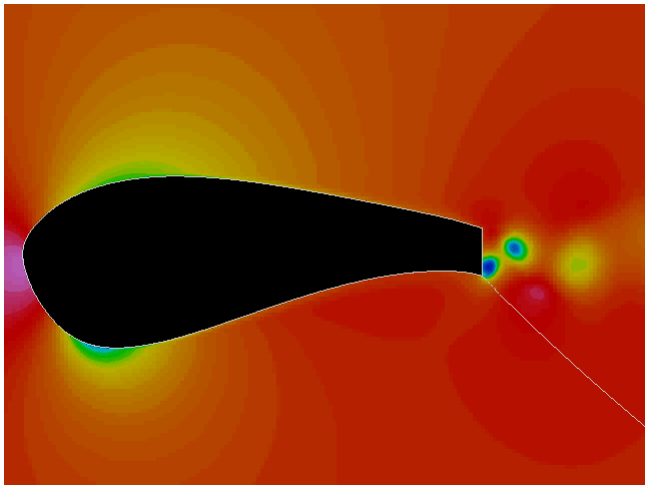
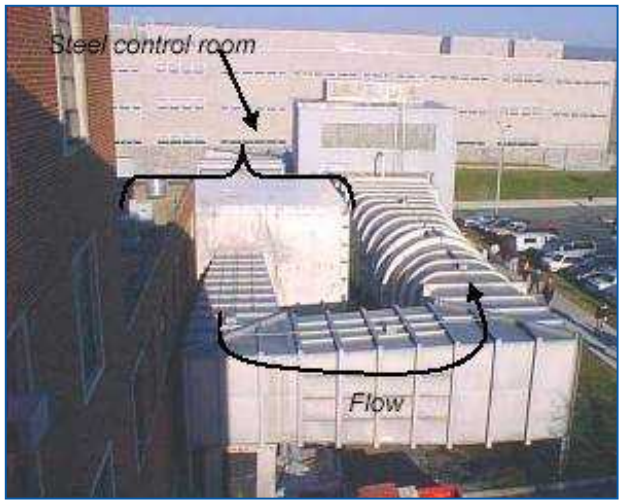
Aeroacoustics – New Effort

(PI: Dale Berg)

- Blade tip testing (NREL)
  - Possible FY ’07 and beyond
  - Storm turbine
  - 3-Bladed CART
- Wind tunnel testing
  - Virginia Tech – Summer ‘07
  - 3 LWST airfoils
  - High Reynolds number
  - Reduced test matrix due to budget constraints
- Code Development (SNL & NREL)
- Flatback Test – Fall ‘07



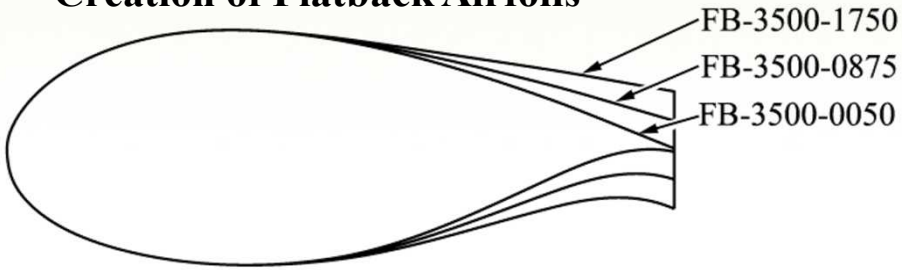


Virginia Tech – Aeroacoustic Tunnel

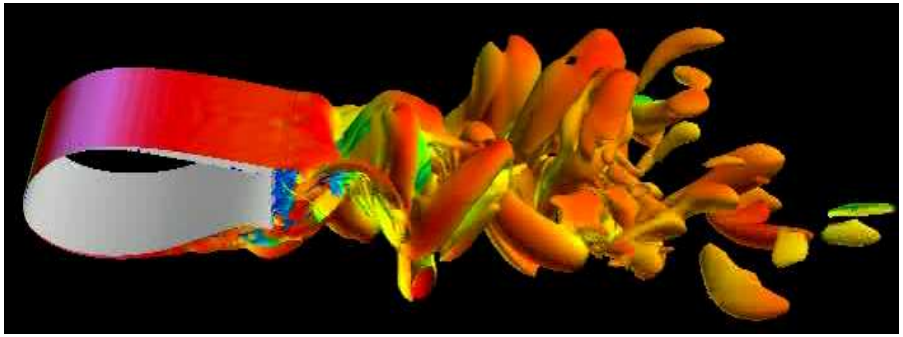
Flatback Airfoils

- **Flatback airfoils created by the symmetric addition of thickness about the camber line**
- **Different from truncated airfoils which "chop" the trailing edge off and thus lose camber**
- **Advantages**
  - **Structural:**
    - Increased sectional area
    - Increased sectional moment of inertia
  - **Aerodynamic:**
    - Increased maximum lift coefficient
    - Reduced sensitivity to surface soiling
- **Disadvantages**
  - **Increased drag**
  - **Unknown and complex 3D flow**
  - **Greater aero-acoustic emissions**
- **One solution for increasing thickness, others exist such as thick airfoil families**

Creation of Flatback Airfoils



Flatback Flow Field



Possible Trailing Edge Treatments to Reduce Drag

***Study of flatback airfoils performed in collaboration with UC Davis**

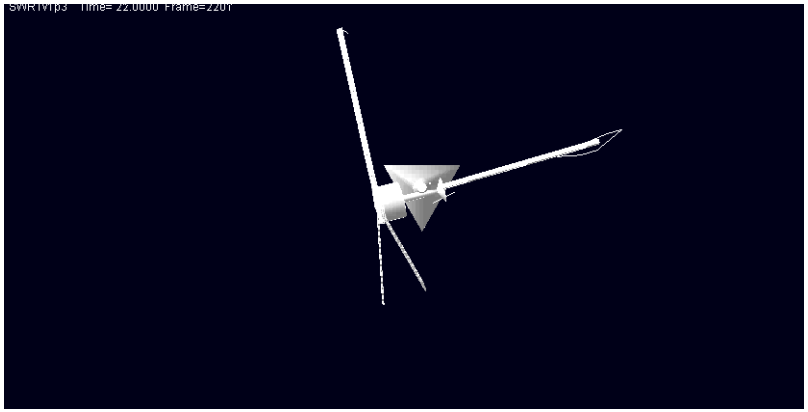
Source: Tanner (1973)

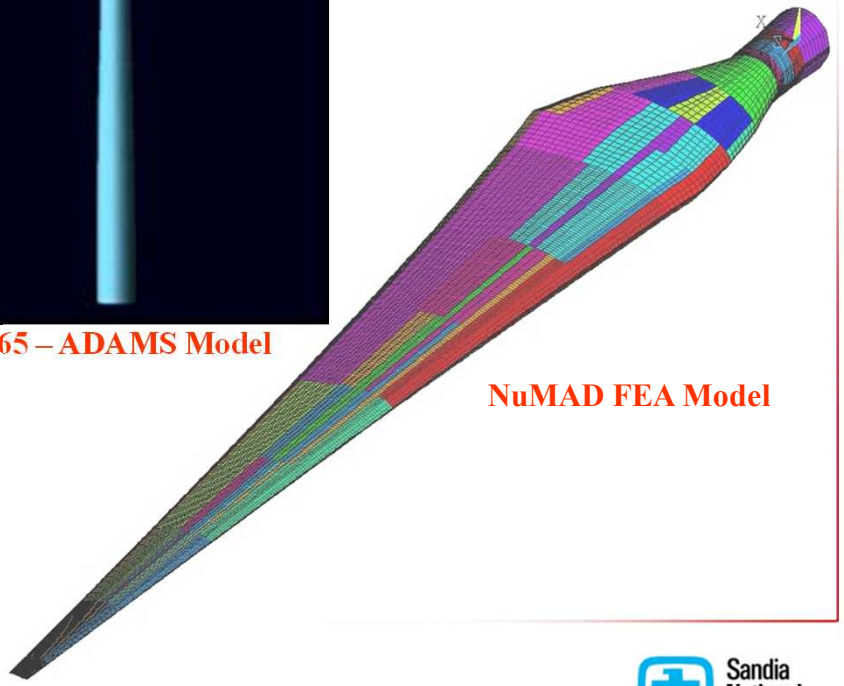
Numerical Analysis Tools

(PI: Daniel Laird)

- **NuMAD**
  - ANSYS FEA preprocessor
  - Linear and non-linear buckling
- **Dynamic Simulation Tools**
  - FAST (Fatigue, Aerodynamics, Structures, and Turbulence)
  - ADAMS (Automatic Dynamic Analysis of Mechanical Systems)
- **NASTRAN**
  - Flutter analysis and predictions

Micon 65 – ADAMS Model





NuMAD FEA Model

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NuMAD - Structural FE Analysis

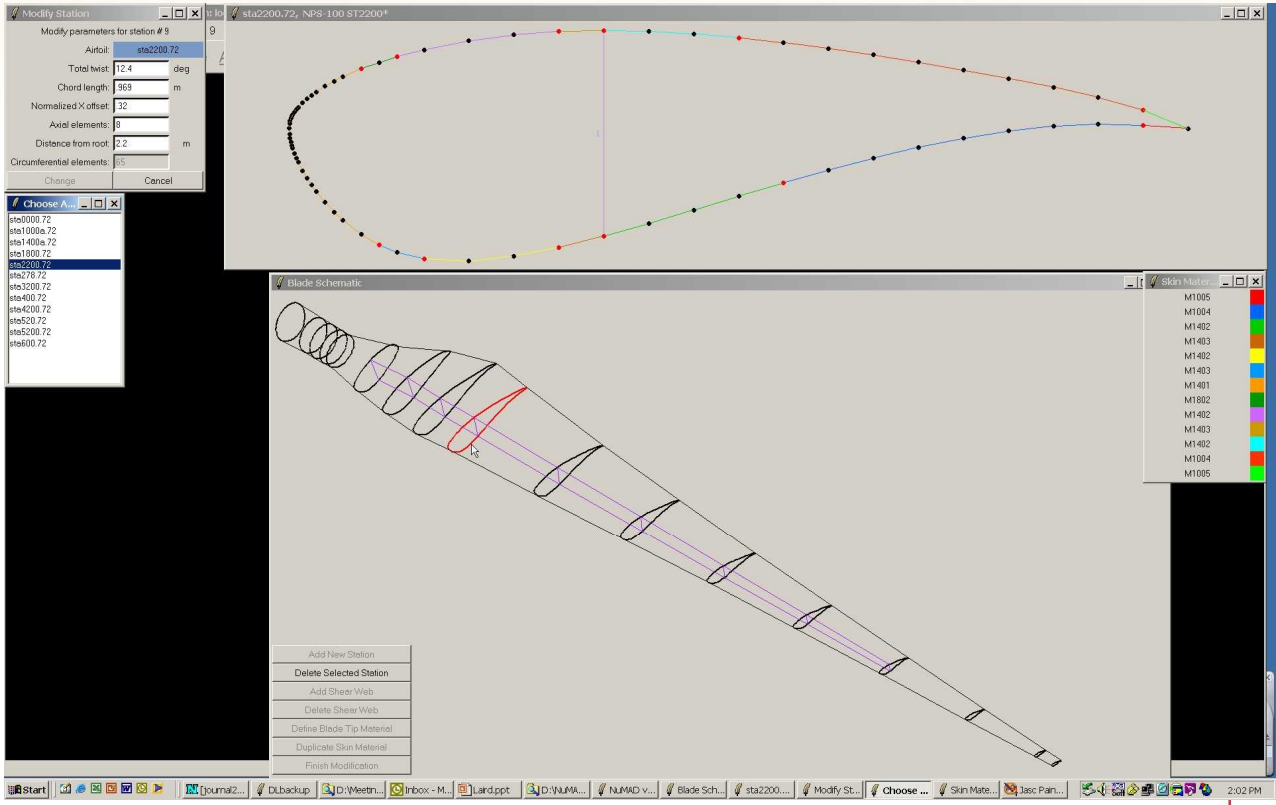
Will the blade break?

Pre-processor and post-processor for ANSYS® finite element analysis software

Standard MS Windows® application

Tailored to design and
Analyze wind turbine blade structures

Databases
materials
airfoils
loadings



- **Analysis used to find weak spots in blades**
- **Development guided by industry input**
- **Beam Property Extraction capability**

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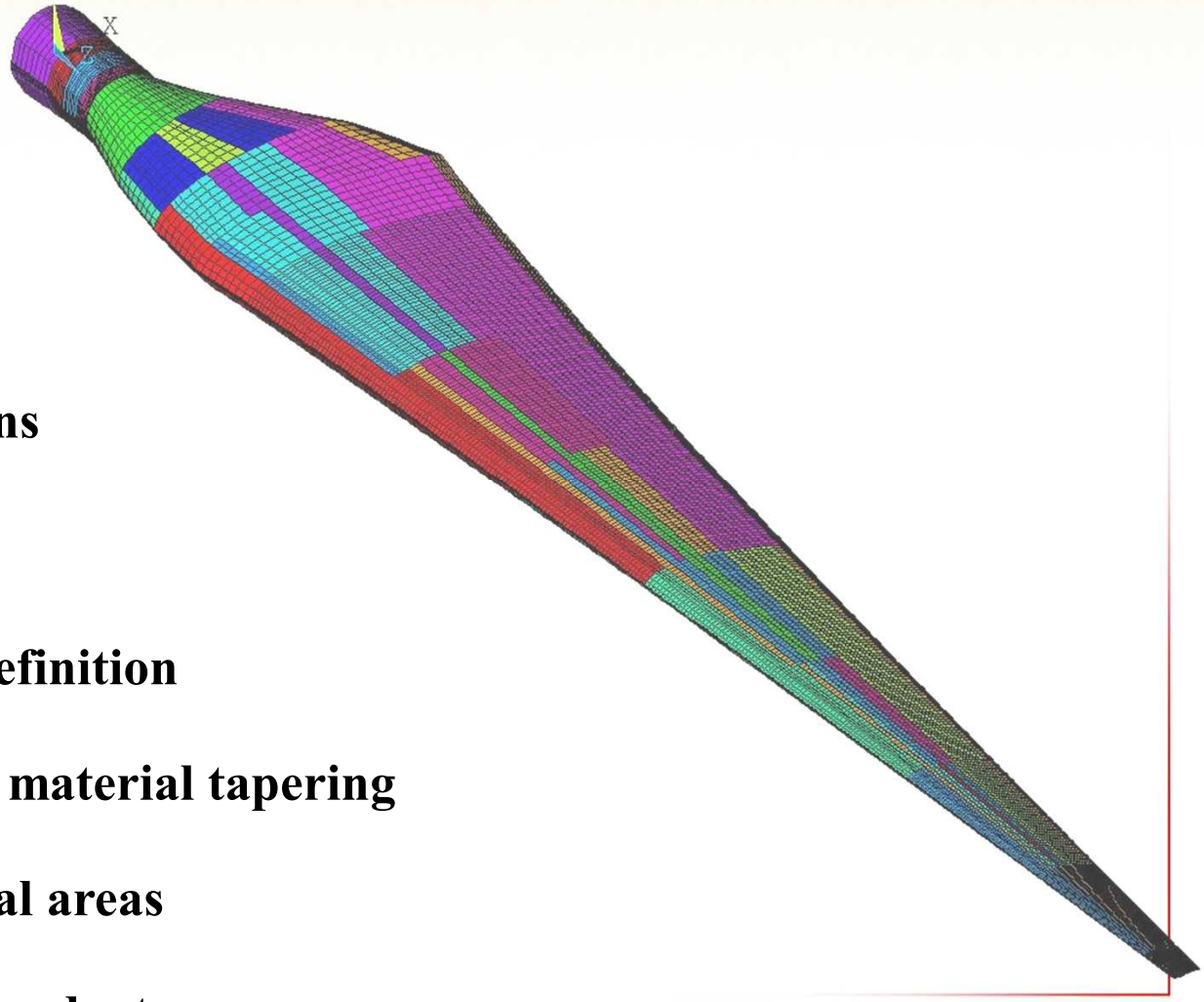
NuMAD - Structural FE Analysis

Current Improvements



- **Redesigned GUI**
- **Transitional meshing**
- **Multiple element options**
  Layered shells, and
  layered bricks
- **Precise skin material definition**
- **Inboard/outboard skin material tapering**
- **Triangular skin material areas**
- **Airfoil definition-independent**

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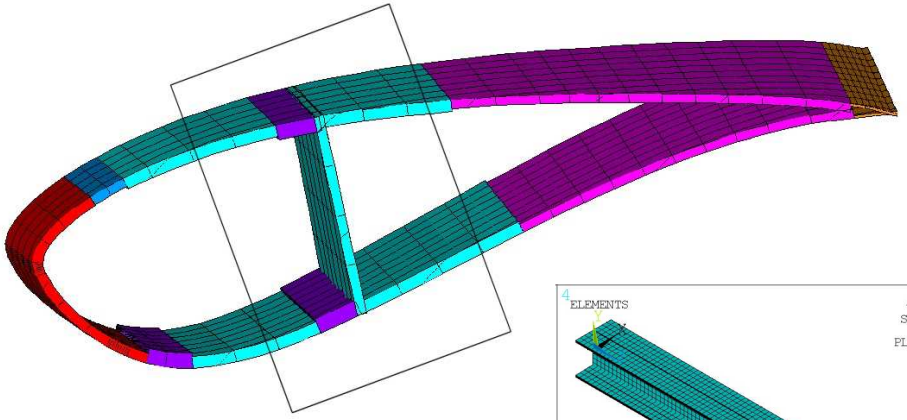
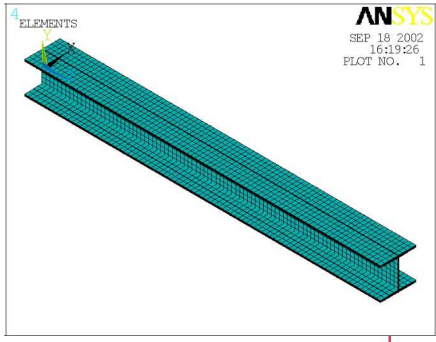
Computational Analysis Tools - Validated

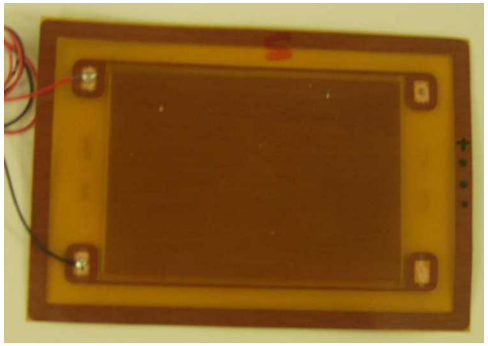




Sensors Research

(PI: Mark Rumsey)

- Focus on Cost Effective Sensors (for lab and field environments)
  - Strain sensors
  - Embedded composite pressure sensors for airflow measurements
  - Fiber optic sensors
  - Piezo-ceramic
  - Displacement and proximity (blade tip deflection)
- Sensor Networks
  - Control inputs
  - Damage detection and health monitoring
- Embedded Sensors
  - Composite structures
  - Exploring possibilities of collaborating with SNL MEMS facility
  - Working with NASA to explore the feasibility of PZT's for structural health monitoring



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Why Sensors?

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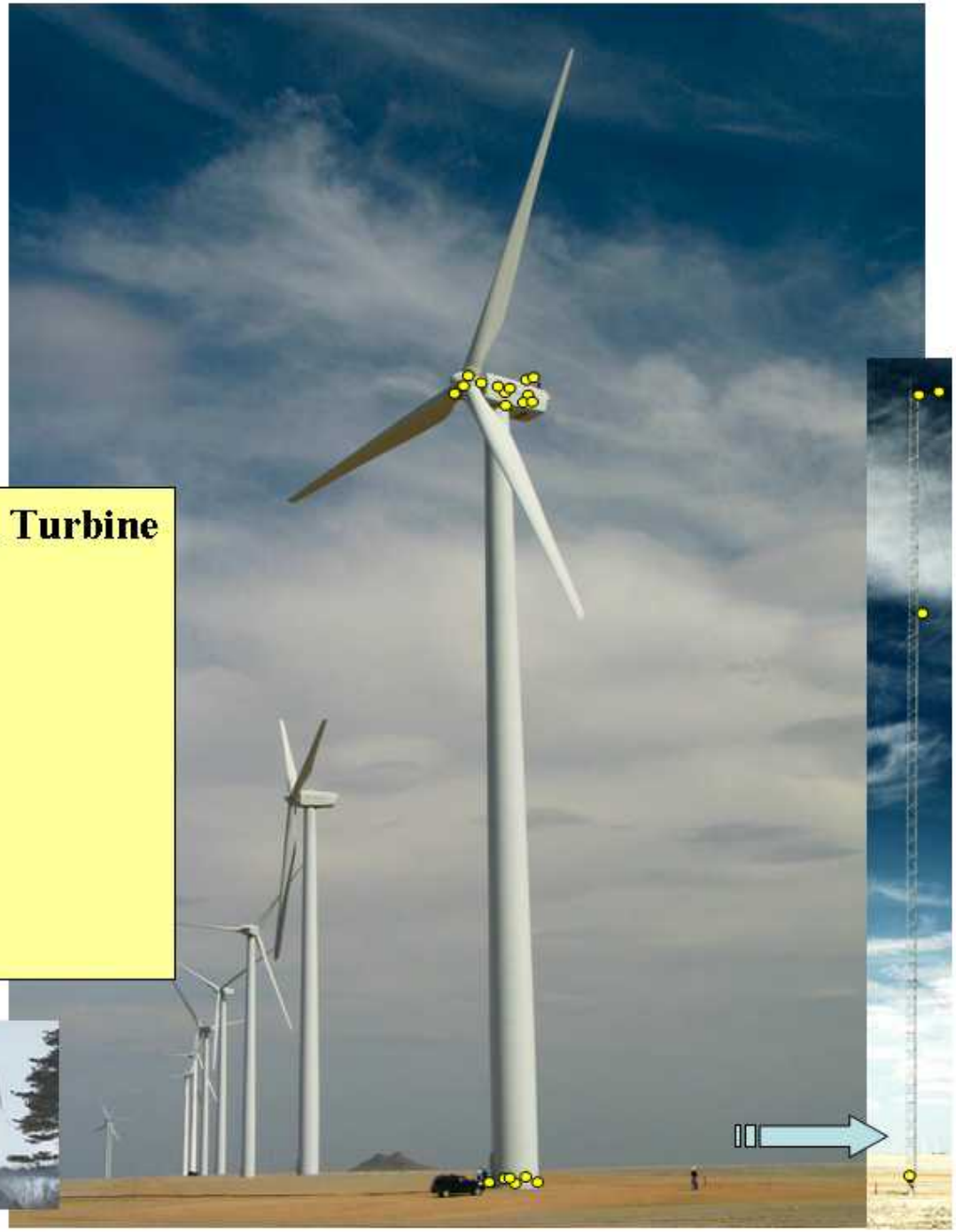
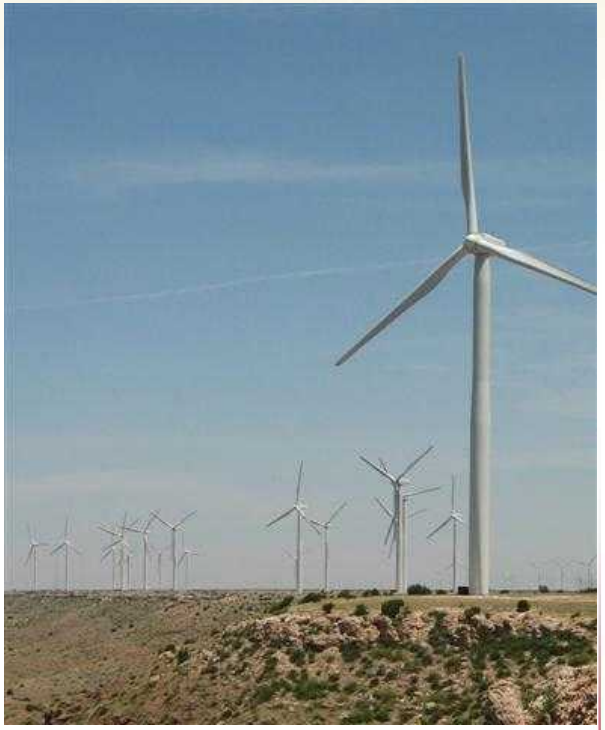


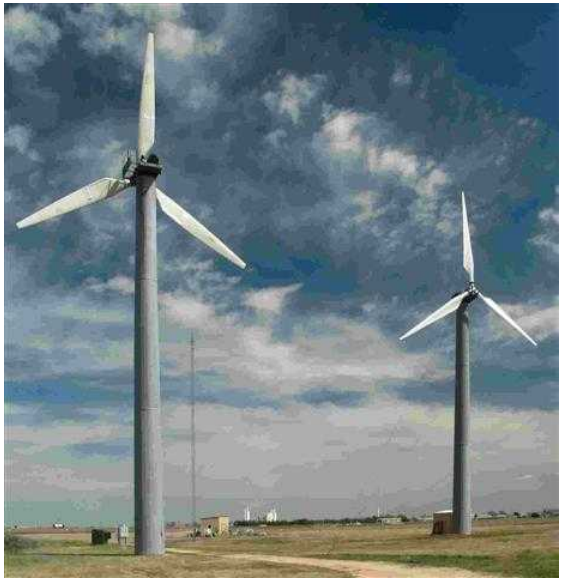
Current Location of Sensors on a Wind Turbine

- **Nacelle**
  - Wind inflow
  - Structural, Mechanical and Electrical
  - Basic control and status
- **Inflow meteorological tower**
- **Tower Base**
  - Structural, Mechanical and Electrical
  - Main turbine control and status
  - SCADA I/O
- **Blades** - **No sensors!**

Drivers for Blade Sensors

- Diagnostic tools in lab and field testing (R&D)
- Provide “missing” sensors on wind turbines
- Increase energy capture
- Decrease O&M costs
- Smarter structures
- Increase reliability
- Advanced Controls





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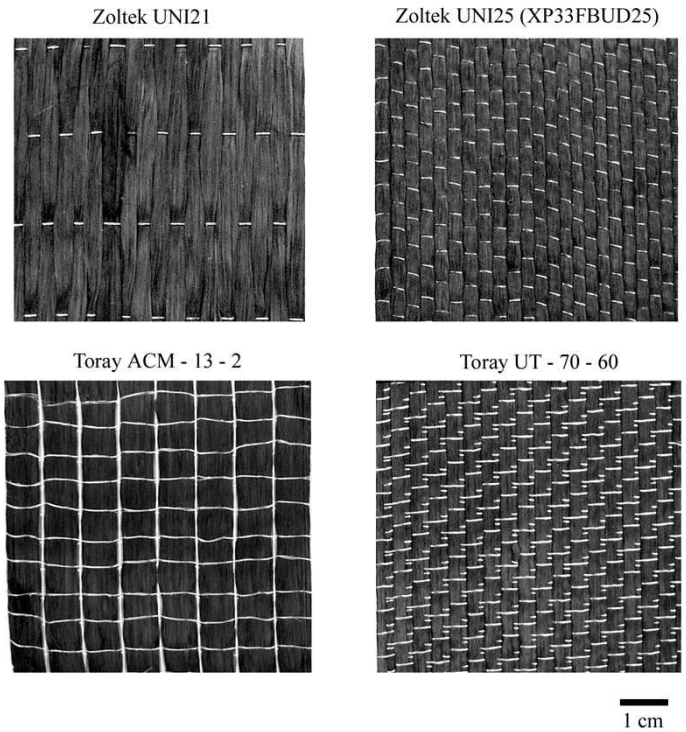
Materials & Manufacturing Research
(PI: Tom Ashwill)

Carbon Coupon Tests

New Forms – Large & Medium Carbon Tows

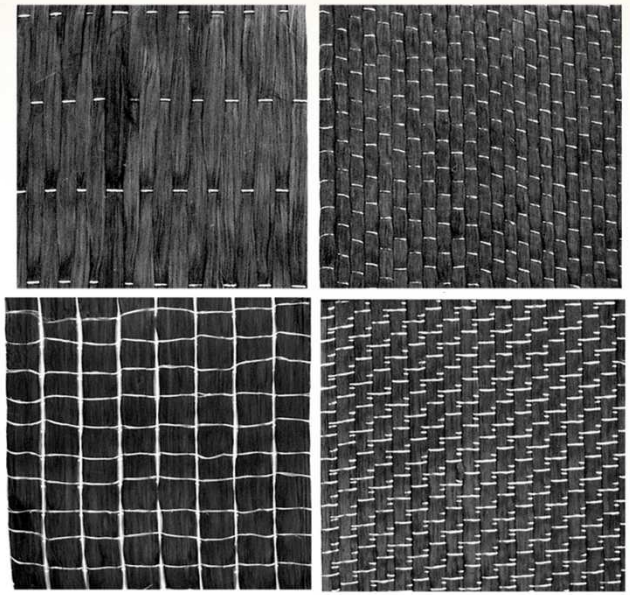


Large Database in Collaboration with Montana State University

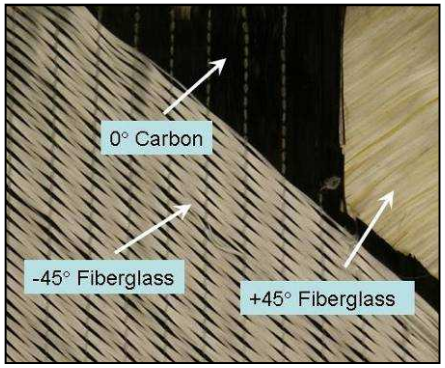
Carbon in Blades

- **Advantages:**
  - **High stiffness/weight ratio**
  - **Excellent properties with straight fibers**
- **Disadvantages:**
  - **Higher cost**
  - **Limited availability**
  - **Difficult to infuse**
  - **Poor properties with wavy fibers**
- **Potential solution: SAERTEX glass/carbon triax fabric**
  - **Relatively inexpensive**
  - **Permeable**
  - **Dry fabric for conventional infusion techniques**
  - **Maintains excellent fiber straightness**

Common Dry Carbon Fabrics



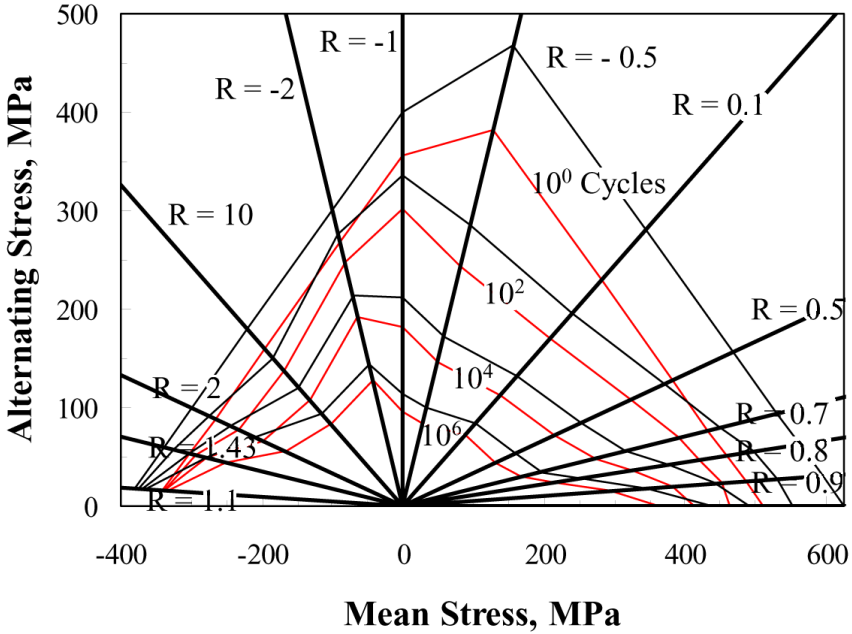
SAERTEX Glass/Carbon Triax used in SNL 9 m Blades



***Study of carbon materials performed in collaboration with GEC and MSU**

Materials and Fatigue

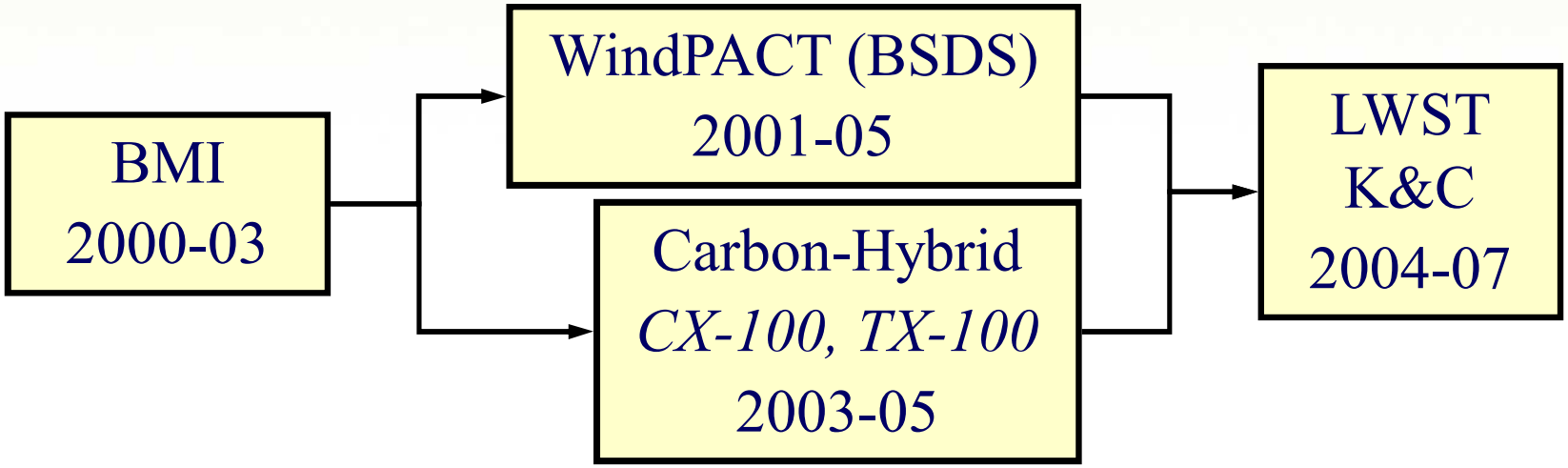
- **SNL & MSU**
  - Composite Material Testing (1989-present)
  - PI: Prof. John Mandell
  - Material Properties (10000+ tests for 175 Materials)
  - Database updated once per year – Last update 04/2007



http://www.sandia.gov/wind/

Manufacturing

Building Block for Integrated Process



- **Manufacturability**
  - **Hard-tooling**
  - **Remote build**
- **Material selection**
  - **Infusability**
  - **Epoxy versus PE/VE**
- **Better processes**

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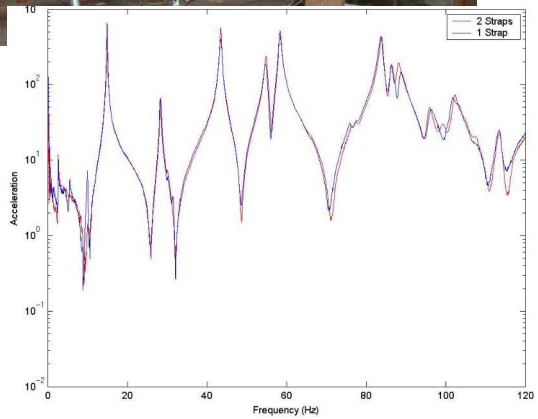
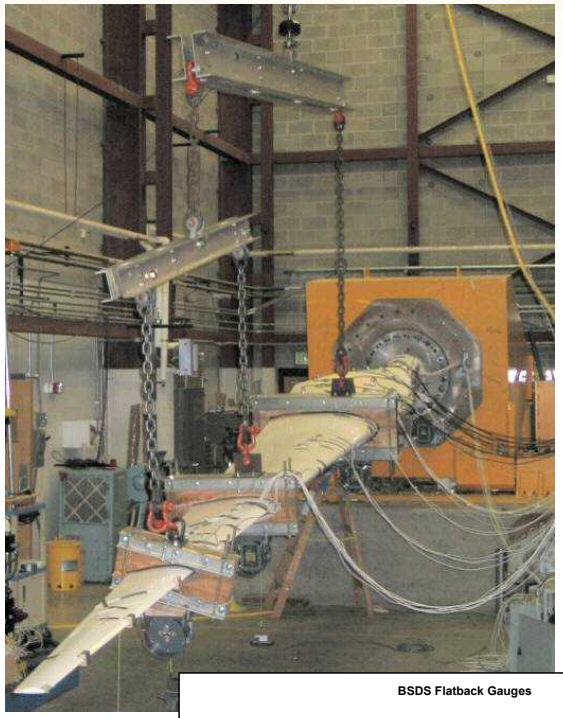
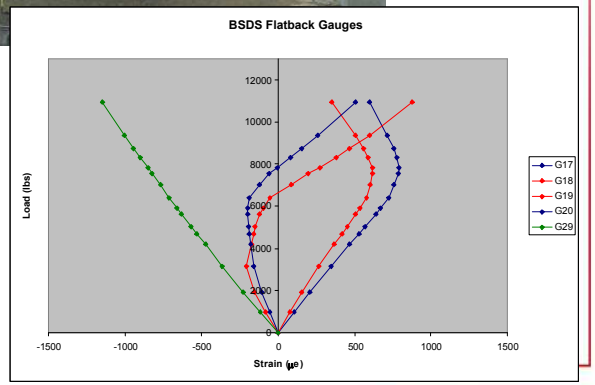
Laboratory Testing

(PI: Josh Paquette)





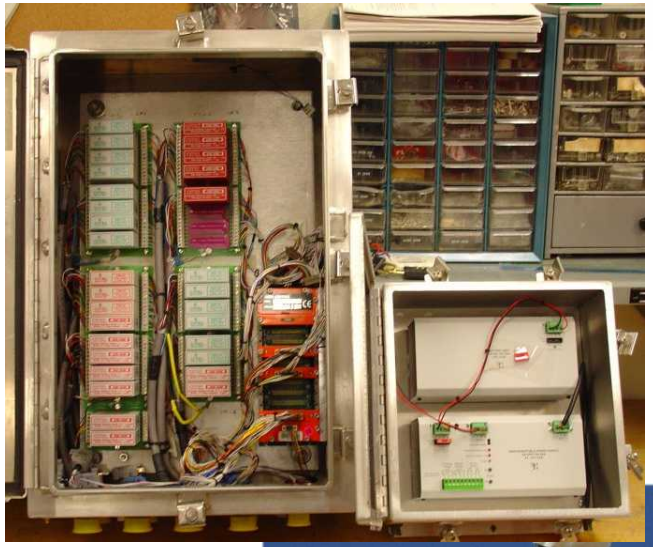


- Modal Testing
- Static and Fatigue Testing
- Sensor Evaluation
- Acoustic Emissions

ATLAS II DAS System

(Accurate Time-Linked data Acquisition System)

- Based Built for Wind Turbine Applications
- Small Size
- Continuous Operation (24/7)
- High Reliability
- Automated Acquisition and Archiving
- Lightning Protection on all Channels
- Field Tested
- Easy Installation



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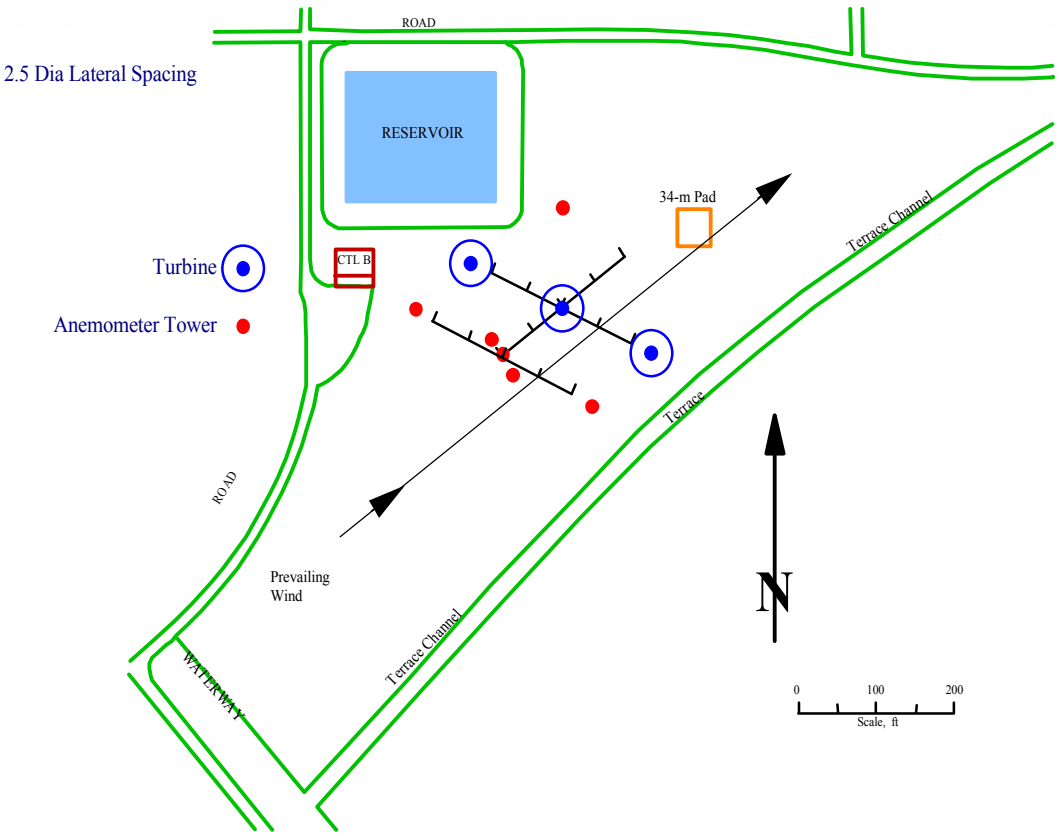
Blade Test Site (near Amarillo, TX)

(PI: Perry Jones)



- **3 Micon 65/13 (modified)**
  - **115 kW generator**
  - **Stall regulated**
  - **55 RPM**
  - **Heavily Instrumented**
    - 15 rotor strain gauges
    - Rotor speed and position
    - Nacelle acceleration
    - Tower instrumentation
- **Inflow Array**

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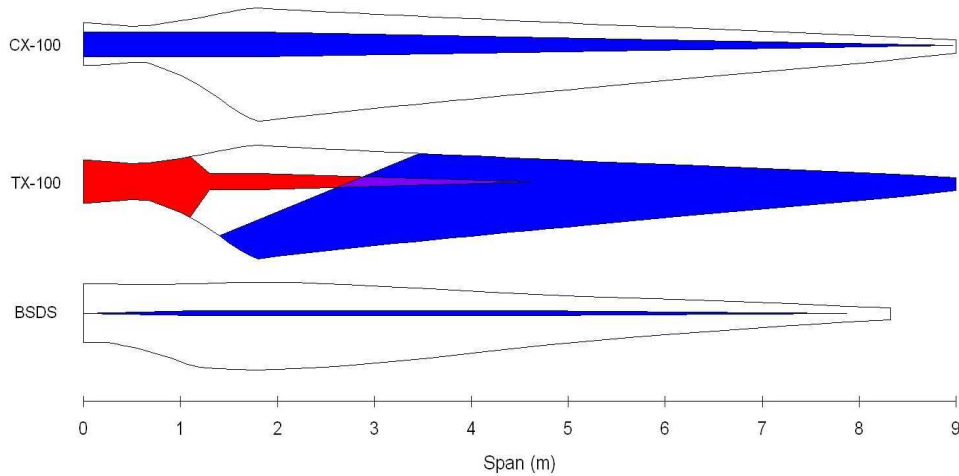
Applications of Blade Innovations

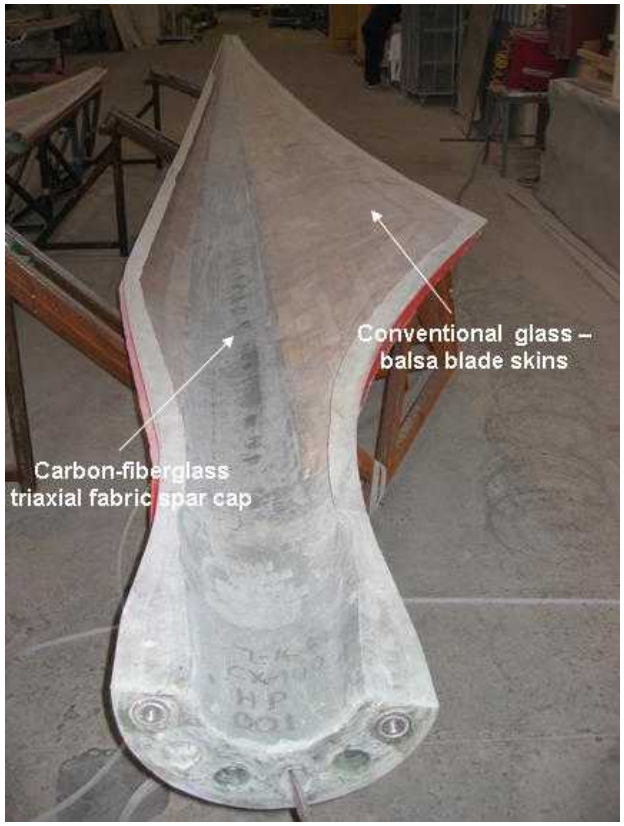
- **Prototype Sub-scale Blades Manufactured (9 meters)**
  - **CX-100**
    - Carbon spar cap
    - Glass skin and shear web
  - **TX-100**
    - Carbon triax in skin for bend-twist
    - Constant spar cap thickness
  - **BSDS (Blade System Design Study)**
    - Flatback airfoils
    - Carbon spar cap
    - Slenderized planform
    - Large scale architecture
    - Highly efficient structural design



CX-100
Carbon Experimental 100kW

- Manufactured using existing 9 m molds
- Based on ERS-100 blade with NW-100 root
- Glass-Epoxy blade with full length carbon spar cap
- Conventional design methodology

Aerodynamic
↓
Structural
↓
Manufacturing



CX-100 Blade Skin

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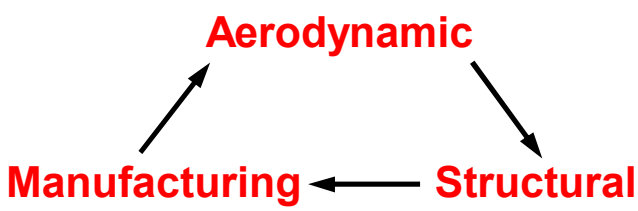
BSDS
Blade System Design Study

- Advanced design
  - Flatback airfoils
  - Full-length constant thickness
  - Carbon spar cap
  - Embedded root studs
  - High performance airfoils
  - Large, thin root
- 8.325 m in length
- Arrived at through system design approach



BSDS Blade

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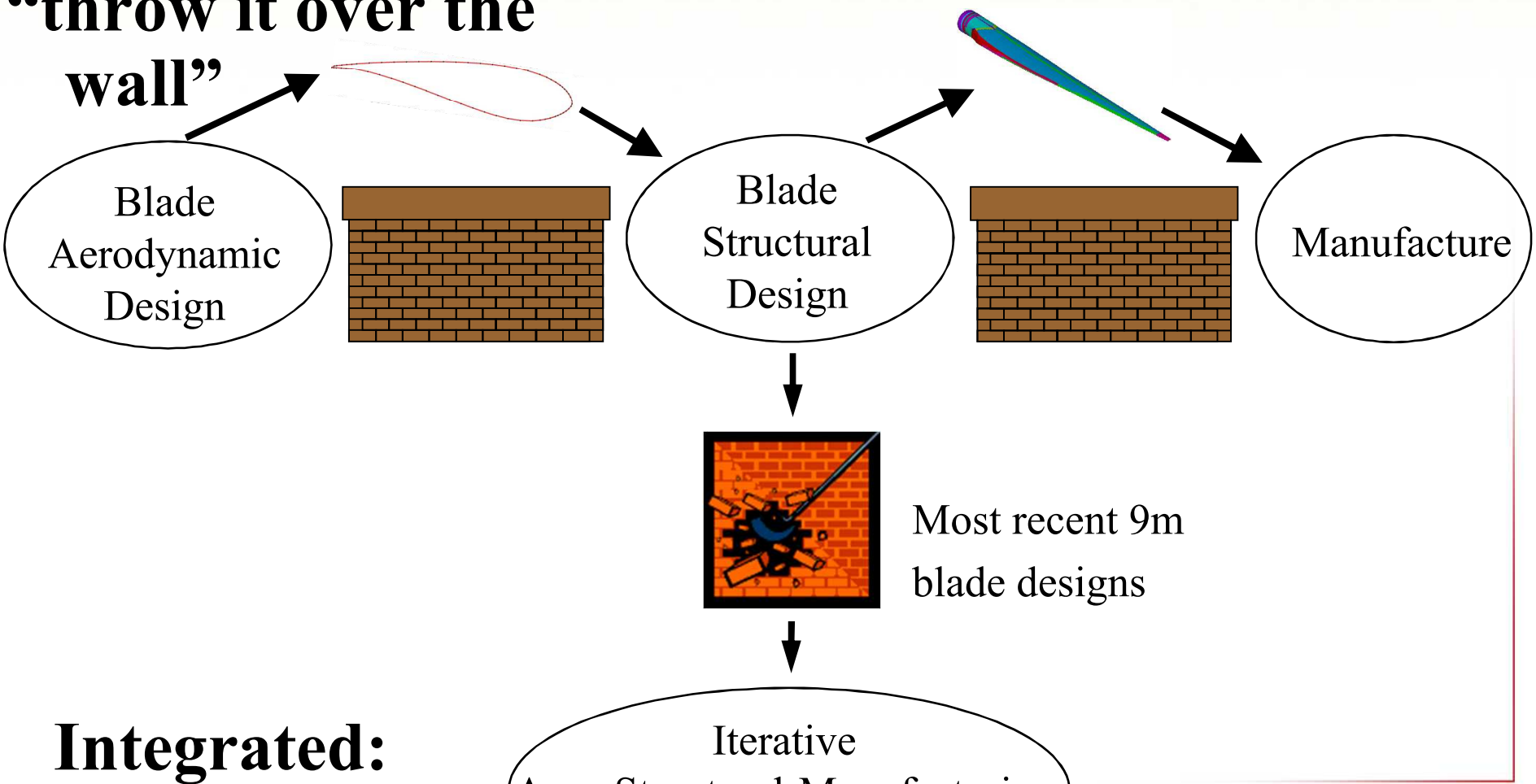
New Design Approach

Traditional:
"throw it over the wall"



Integrated:

Iterative Aero-Structural-Manufacturing Process

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Blade Comparison

Property	ERS-100	CX-100	TX-100	BSDS
Weight (lb)	426	383	361	289
% of Design Load at Failure	110%	105%	197%	310%
Root Failure Moment (kN-m)	122.8	117.0	121.4	203.9
Max. Carbon Tensile Strain at Failure(%)	NA	0.31%	0.59%	0.73%
Max. Carbon Compressive Strain at Failure(%)	NA	0.30%	0.73%	0.87%
Maximum Tip Displacement (m)	1.43	1.05	1.80	2.79

Integrated aero/structural design process resulted in lighter, less expensive, stronger blade

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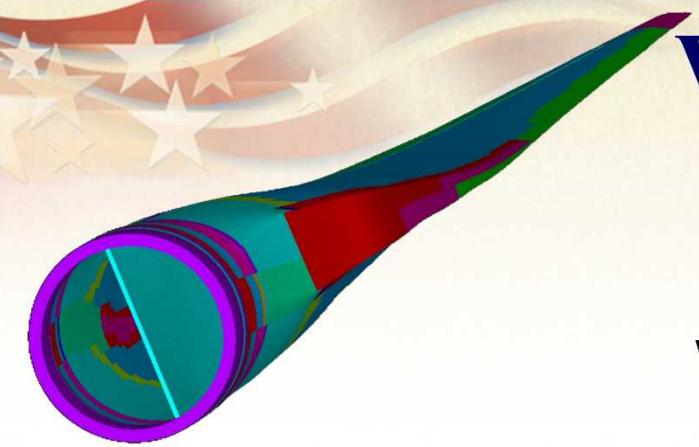
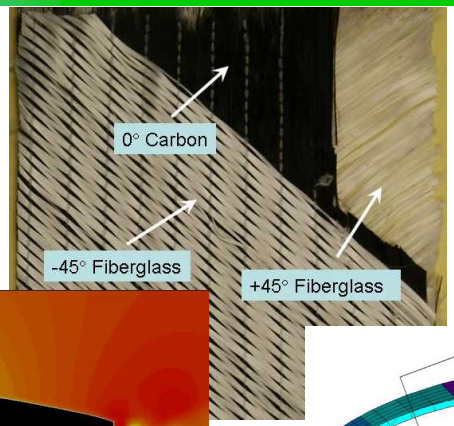
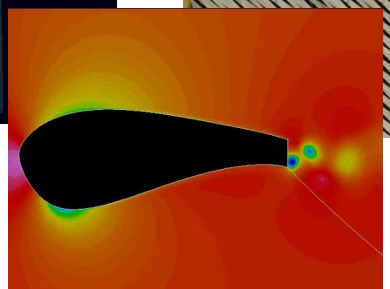


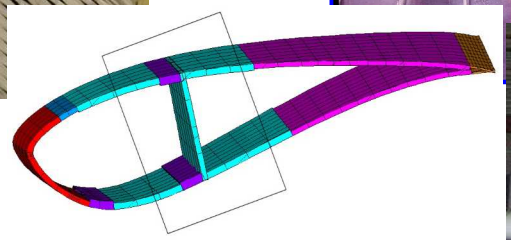
Wind Turbine Blade Evolution

System analysis identifies research initiatives with increasing industry involvement as it gets closer to the commercial product

Concepts → **Preliminary Design** → **Detailed Design** → **Prototype Fabrication** → **Test and Evaluation** → **Commercial Product**







Load Extrapolation
(PI: Paul Veers)

Goals:

- **Today**
  - Present finding that might resolve some outstanding issues in extrapolation
  - Gather action items for what needs to be done to establish a viable procedure
- **Future (near-term)**
  - Draft a procedure that will resolve troubling issues in extrapolation loads for design purposes

Things that need to be addressed:

- **Current philosophy**
- **Automation**
- **Distribution Type**
- **Number of Simulations**
- **Effects of ontrol actions on the ability to extrapolate**

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Prediction of Long Term Extreme Loads using Statistical Extrapolation

Three distinct approaches researched:

- **Method of Global Maxima**
  - Use one maximum value from each 10-minute file
- **Peak-over-threshold Method**
  - Use a variable number of peaks from each 10-minute file
- **Process Models**
  - Use first four statistical moments and mean crossing rate of the entire process

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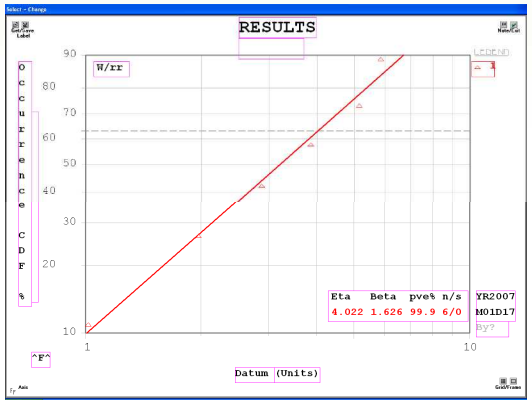
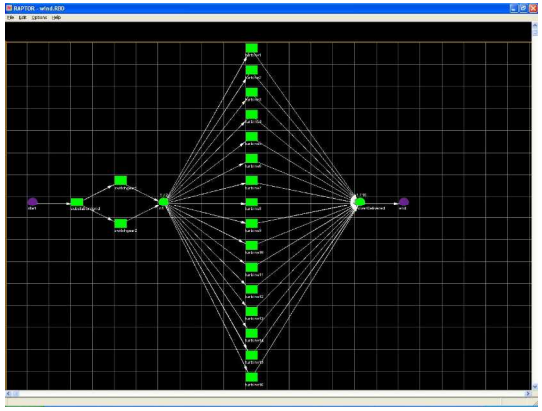
Reliability Analysis

(PI) Roger Hill

Rationale and Approach:

- Wind Turbine Reliability is a recognized problem
- While recognized, there are no public statistics, even rough lifetimes are not known
- Failures affect operations and cost of energy
- Partnerships with Industry and AWEA
- Document key problems areas as foundation to determine approaches for resolution
- Identify Technology Improvement Opportunities
- Goals: Reduce failures, Improve operations, Reduce costs
- Technical Approach: Analysis, Target areas for engineering, Operations best practices





Initial Partners from AWEA O&M Working Group Meeting:
Acciona, Shell Wind Energy, American Electric Power, Noble Power, Excel, Nebraska Public Power, ENEL, BP Alternatives

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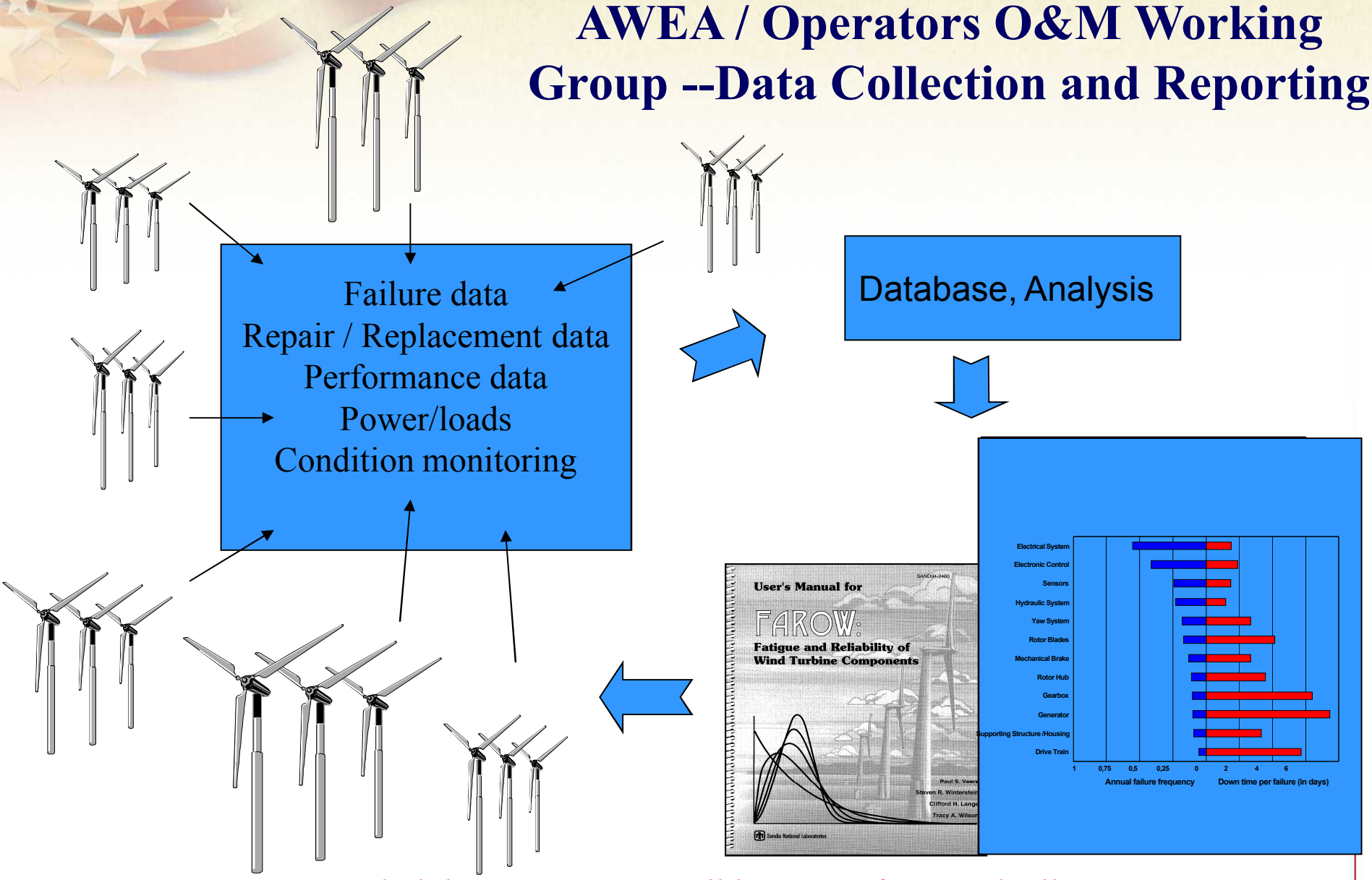
AWEA / Operators O&M Working Group --Data Collection and Reporting



Reliability assessments will have interfaces with all aspects of design, as well as O&M requirements and limitations, and life cycle costs

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Reliability Analysis Direction

- Initially, the system will be broken down into components, failures and understanding of failure modes and effects
- System reliability results are calculated using failures populated with real data, to do this….
  - Recruit partners
  - Obtain data
    - Support AWEA O&M Users Group
    - Other groups/individual operators
    - SCADA
    - Input forms / Work orders
    - Interviews with Industry stakeholders

  } In Progress
- Results of model analysis will initially be basic lifetime information, system mean time between failures (MTBF), system mean time to repair (MTTR), availability
- Create models and estimate costs, identify key areas for attention

2nd Reliability Workshop in September 2007

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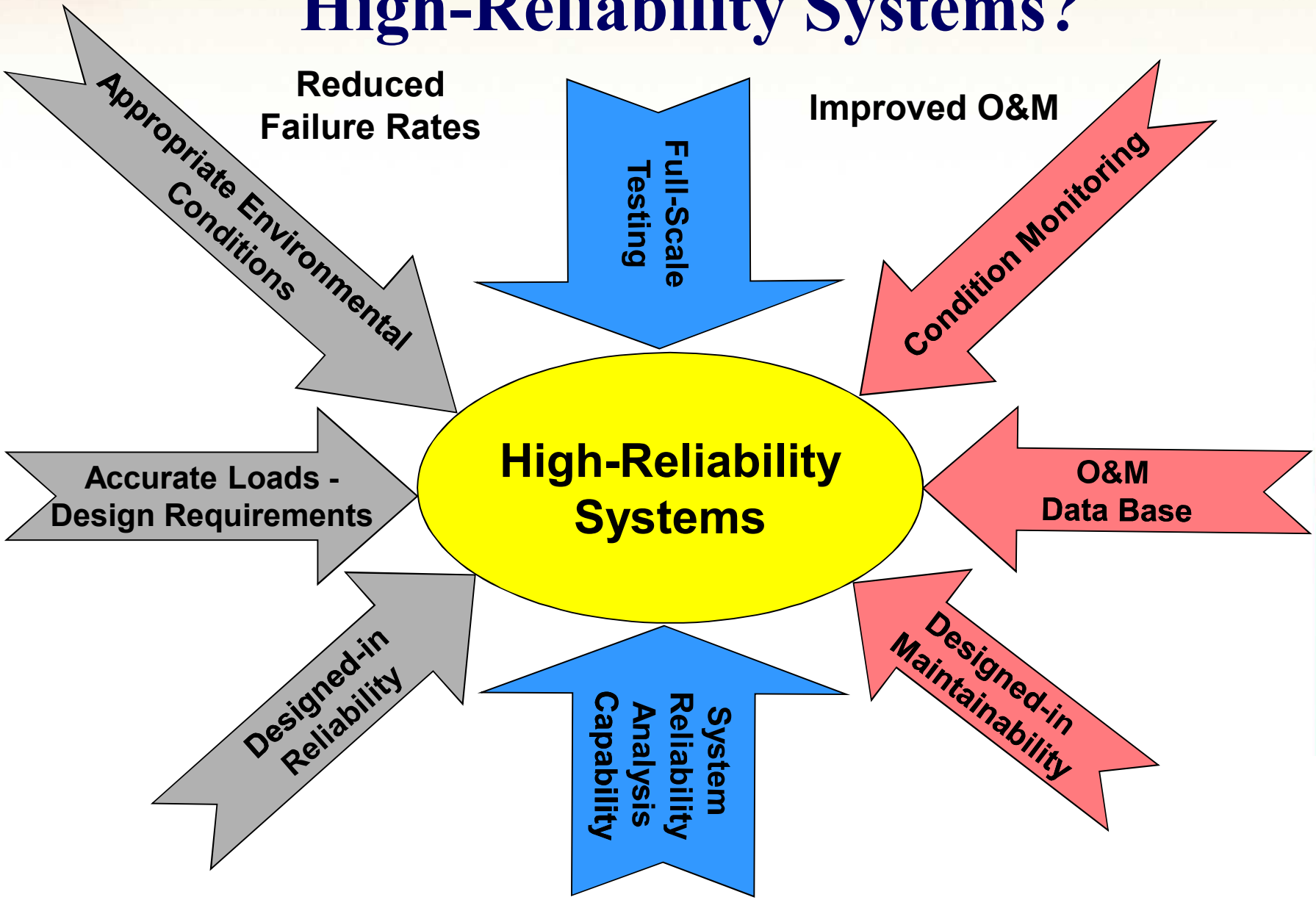
What is Required to Develop High-Reliability Systems?



Department's Recent Transformation & Future Direction

- **Incorporating Short and Long Term Strategy**
  - Essential to increase collaboration with manufacturers and developers
  - Near-term technology transfer
  - Developing strategic partnerships with industry
- **Increasing Collaboration with Other SNL Groups – Increase Dept. Strengths and Core Competencies**
- **Industry Outreach**
  - CRADA collaborations
  - WFO agreements
- **Remove Industry Barriers (RADAR, Transportation)**

National Laboratories are Well Positioned to Reduce Industry Risks

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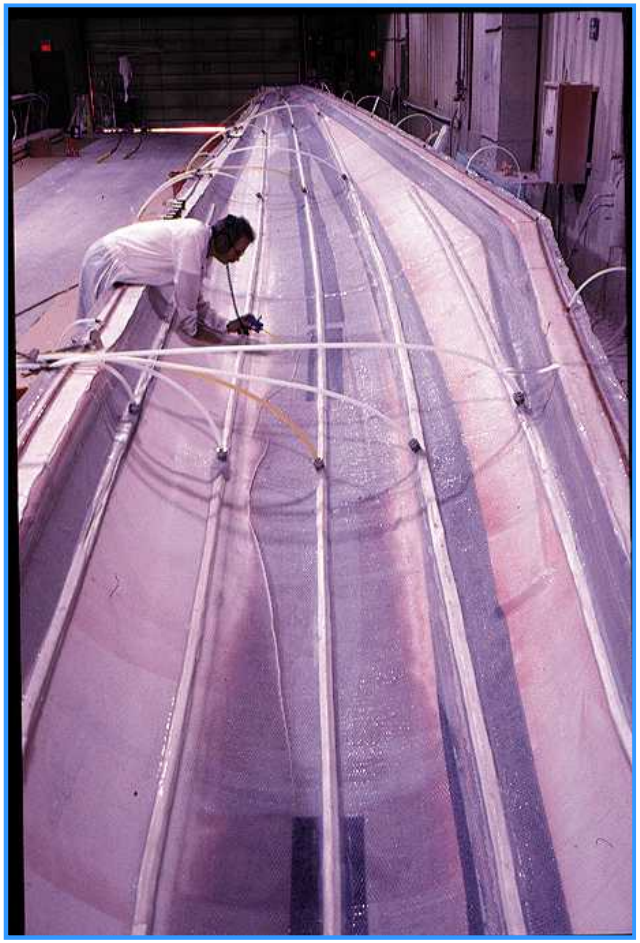
Sandia Customers & Partnerships

- **Current Customers**
  - Texas Tech (DAS & Field Testing)
  - 3TEX (Materials & Field testing)
  - Aither (Sensors)
  - NASA (Sensors)
  - Acellent (Sensors)
  - Owens Corning (Materials)
  - Clipper Wind (Manufacturer)
- **Past Partnership Success**
  - TPI Composites
    - TPI and Mitsubishi have a joint venture – Vienteck in Juarez, Mexico
    - Manufacturing blades for 1-2 MW Mitsubishi machines
    - 40m long blade now being tested
    - TPI patented SCRIMP® technology



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Summary

- **SNL Primary Research Focus is on Blades & System Reliability**
  - **Efforts Underway to Reduce Blade Weight Growth for Larger Blades**
    - **Hybrid composite subscale blades have been manufactured**
    - **Development of structurally efficient airfoils**
    - **Advanced research has enabled weight reductions of 66% - 750lb -> 250lb**
- **Engaged in Increased Reliability Efforts**
  - **Developing strategic partnerships with industry**
  - **Improvements in O&M**
- **Establishing Relationships with other Outside Groups to Increase Capability and Improve Response Time**
- **SNL is supporting the effort of the 20% Action Plan**

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"…we could generate up to 20% of our electricity needs through wind…"

President George W. Bush - February 21, 2006

Thank You!!!

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Active Aerodynamics Controls & Aerodynamic Tools

Dale Berg

Wind Energy Technology Dept.

Sandia National Laboratories

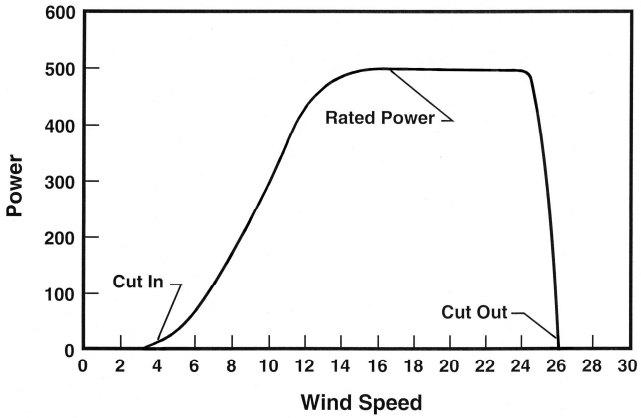
www.sandia.gov/wind

deberg@sandia.gov

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.

Blade Load Control Decreases Cost of Energy

- **Blade Loads Vary Dramatically Due to Wind Gusts, Direction Changes, and Large Scale Turbulence**
- **Blade Pitch Controls Power Level, Maximum Average Loads**
  - **Collective (traditional)/Individual (contemporary)**
  - **Low frequency response**
- **Load Control Reduces Cost of Energy (relative to "Danish" design)**
  - **Same energy capture/lower loads**
  - **Same loads/increased energy capture**



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Two Basic Options for Blade Load Control

- **Passive Blade Load Control**
  - **Responds to integrated blade loading**
  - **Response dictated by design (fixed)**
  - **Knight & Carver (LWST Contract) building 27m blade**
- **Active Blade Load Control**
  - **Response dictated by control system/sensors**
    - Integrated blade loading (blade pitch)
    - Point loading (small, fast-acting devices)

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Active Blade Load Control

- **Active Control can be Achieved by Modifying:**
  - **Blade incidence angle (blade pitch)**
  - **Flow velocity (modification in RPM)**
  - **Blade length**
  - **Blade aerodynamic characteristics (active aerodynamics load control) through:**
    - Changes in section shape (aileron, smart materials, microtab)
    - Surface blowing/suction
    - Other flow control techniques (VG's, surface heating, plasma)

Current Technology - VSVP
Variable Speed Variable Pitch
(controls low frequency loads)

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Active Load Control Benefits

- **Active Load Control:**
  - **May yield large benefits from removing fundamental design constraints**
  - **May enable the development of lighter, more slender blade designs**
  - **May potentially be used to alleviate both low and high frequency loads**

These Large Benefits are Feasible if Active Control Technology is Considered from the Beginning of Turbine Design

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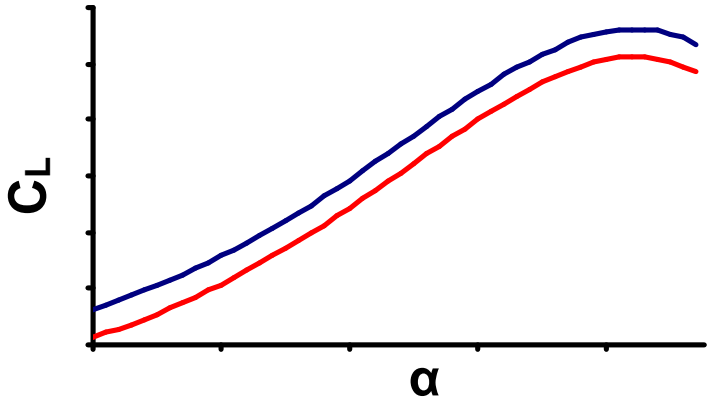
Effects of Active Aerodynamic Load Control Devices

Active devices cause two types of effects:



Increase Maximum Lift

- Plasma
- Active VG's
- Surface Blowing/Suction
- Surface Heating
- Synthetic Jets

Increase/decrease lift

- Ailerons
- Spoilers
- Microtabs
- Flaps
- Airfoil Morphing

Load control requires ability to decrease lift

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Active Aerodynamics Load Control can Reduce Cost of Energy

- **Active Load Control can Reduce Turbine Capital Cost**
  - **Reduce demands on pitch motors**
  - **Reduce fatigue loads**

  } **lower capital costs**
    - **reduce structural requirements for entire turbine**
- **Active Load Control Can Reduce Turbine Cost of Energy**
  - **Reduced fatigue loads throughout turbine**
  - **Lower COE**
- **Current Research Effort**

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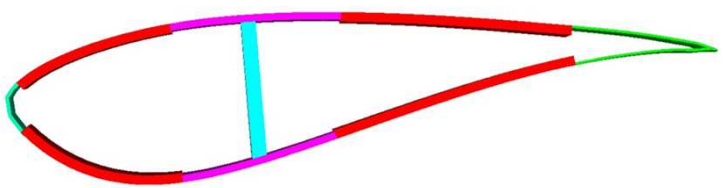
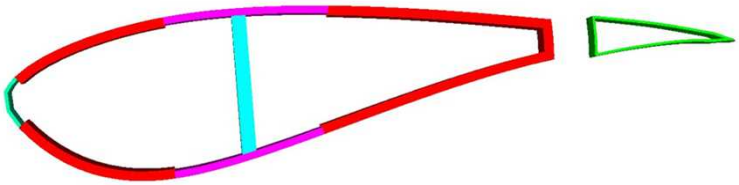
Active Aerodynamics Load Control can Reduce Cost of Energy

- **Active Aero Load Control Does Add to Blade Cost**
  - **Keep basic blade structure**
  - **Add control unit as separate replaceable section**
  - **Turbine can operate even if active aero unit fails**
    - Requires adaptive control system



Traditional design



Potential active aero design

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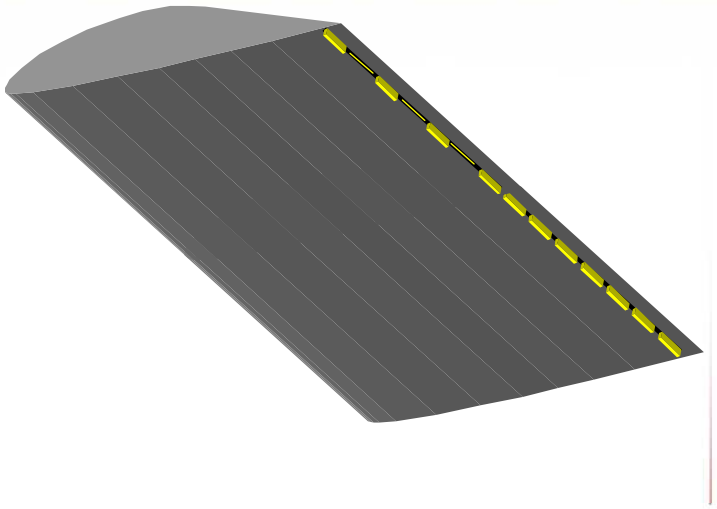
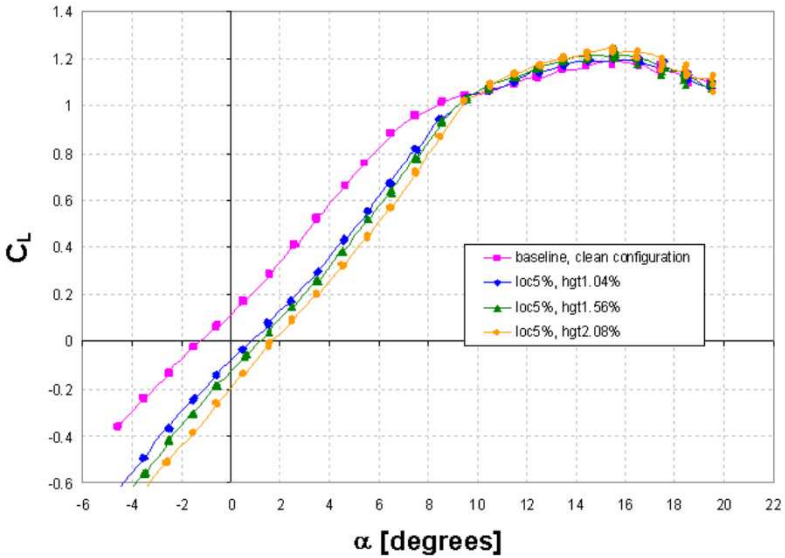
SNL/UC Davis Effort is Focusing on "Microtab"

- Small, Simple, Fast Response
- Retractable and Controllable
- Lightweight, Inexpensive
- Two-Position "ON-OFF" Actuation
- Low Power Consumption
- No Hinge Moments
- Expansion Possibilities (scalability)
- Do Not Require Significant Changes to Conventional Lifting Surface Design (i.e., manufacturing or materials)

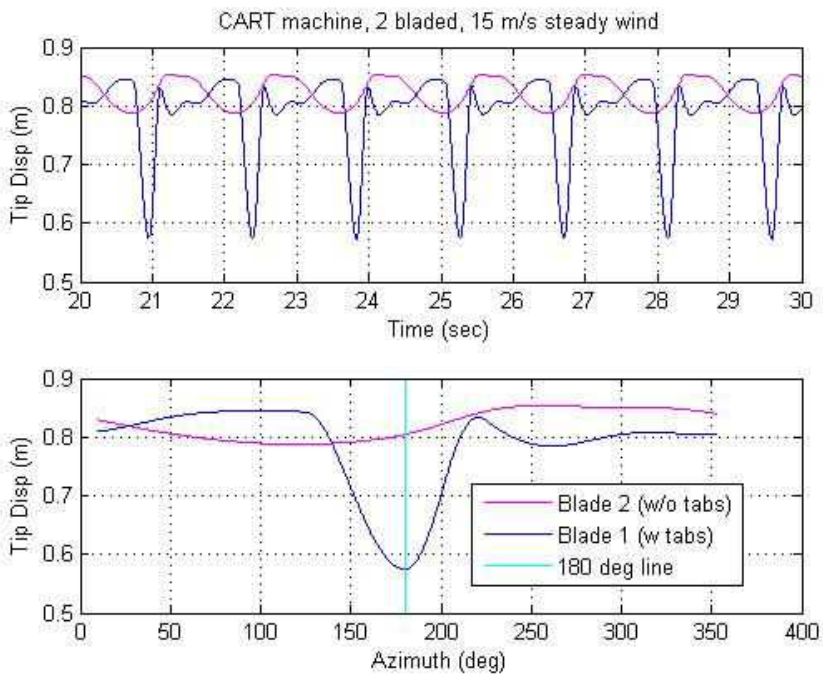




Tabs Deployed on the Suction Surface for Load Mitigation

Example of Microtab Control Capability
(simplistic control)

Impact on Upwind Rotor Blade Tip Deflection



Microtabs Fully Deployed at 130°, Fully Retracted at 220°

Current Active Aero Controls Efforts

- **Modify NREL FAST Dynamics Code**
  - **Add controls simulation (similar to GEC effort in 2005)**
  - **Evaluate potential impact on maximum loads, fatigue loads**
  - **Develop controls system**
- **Build and Test Laboratory Model**
  - **Integrate functional microtabs/flaps**
  - **Evaluate prototype control system**
- **Deploy on Small Test Turbine**
  - **Quantify actual reduction of loads**
  - **Monitor power produced**
  - **Optimize control system**

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Future Direction/Plans

- Document Aerodynamic Load Control Techniques
- Develop Actuators for Microtabs
- Integrate Realistic Control into Dynamic Model
  - Evaluate Potential Impact on Maximum Loads, Fatigue Loads
- Place AeroAcoustic Contract with Penn State
  - Predict noise generated by CX-100/BSDS
  - Predict noise generated by active aero devices
- Continue Active Aero Contract with UC/Davis
  - Continue computation/experimental work on microtabs

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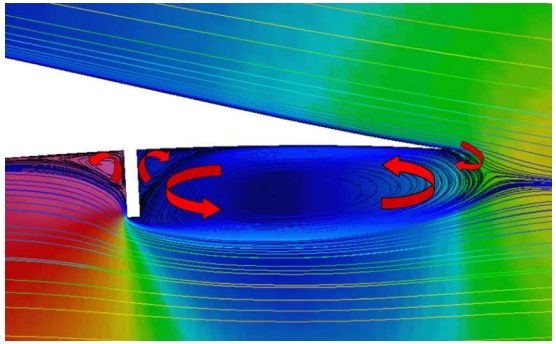
Aero Computational Tools

- **Experimental Parametric Studies are Slow and Expensive**
- **Computational Studies are "Fast" and Less(?) Expensive**
  - **Model development**
  - **Computing hardware**
- **Accurate Aero Computational Tools are Needed to:**
  - **Predict:**
    - turbine performance
    - active aero device performance
    - noise generation /propagation
  - **Understand:**
    - How devices affect flow/basic flow phenomena



- **Traditional Blade Element Momentum Tools are not Satisfactory**
  - **3-D Effects may be important**
  - **Separated flow may be important**

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Utilizing CFD Tools

- **Overflow is CFD Code of Choice for Sandia**
  - **Revisit NREL NASA/Ames Experiment**
  - **Recent turbulence model enhancements**
- **3-Dimensional CFD is Expensive**
  - **Long execution times on large parallel machines**
    - SNL has hardware available and accessible (as do lots of other places)
  - **Experienced people needed to run codes**
    - Sharp learning curve
    - Use it or lose it
- **Overflow is State of the Art for Helicopter Application**
  - **Well funded (Quiet Helicopter Development)**
  - **Well suited for wind turbine application**
    - Rotational effects
    - Separated flow

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Objective of Helicopter Quieting Program

- Develop a physics-based tool enabling the design of quiet rotors without performance penalties.
- Key features of our program:
  - Adaptive turbulence simulation of multi-scale physics of high Reynolds number rotor flows:
  - Dynamically evolving subgrid closure for LES
  - Numerical scheme which maintains high-order in space and time in the entire domain
  - Adaptive grid to resolve tip vortices and shock waves
  - Efficient coupling of CFD and CSD
- Final Product – integrated set of tools based on:
  - OVERFLOW (enhanced rotor aerodynamics)
  - DYMORE (rotor trim and structural dynamics)
  - PSU-WOPWOP (acoustics)

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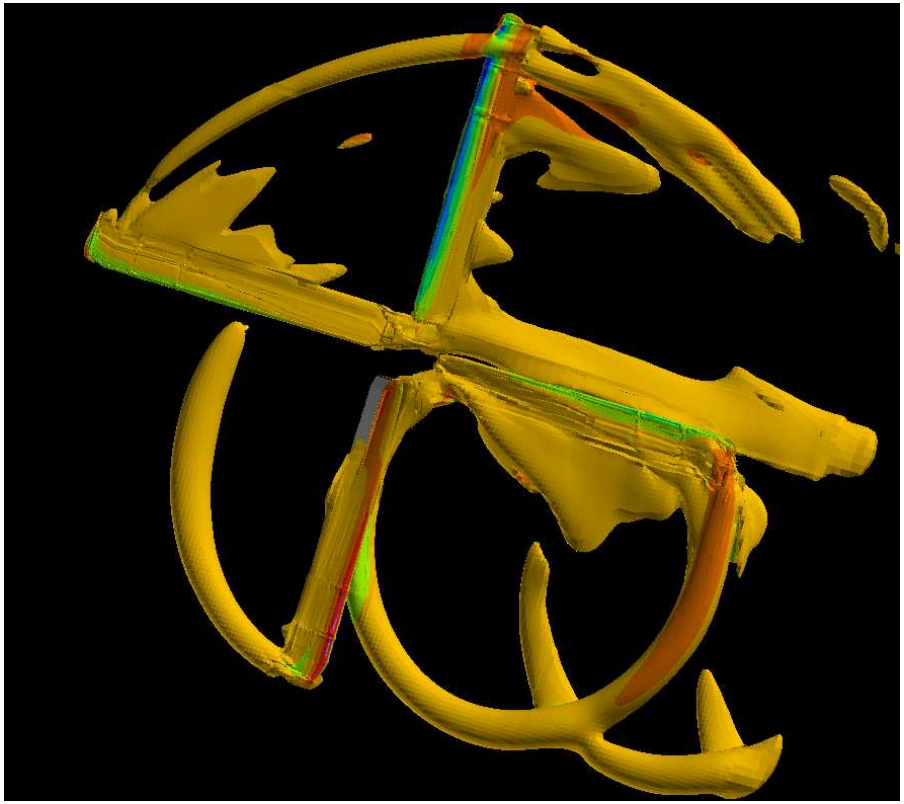
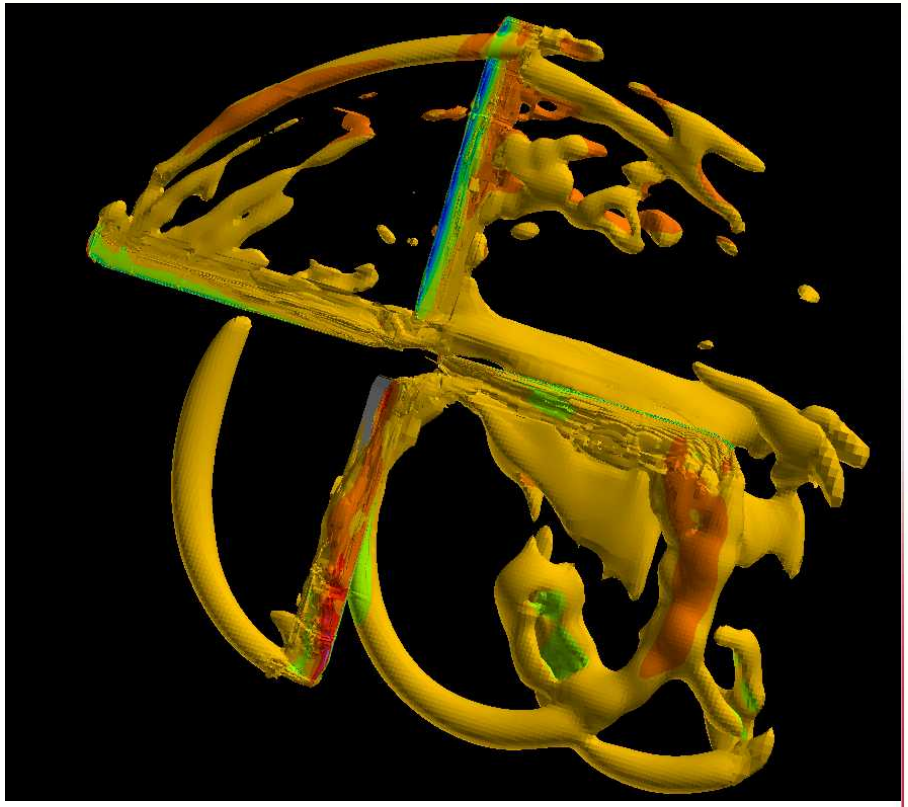
Demonstration of High-Order Algorithms Rotor Wake Visualization



HRLES 4



HRLES 6

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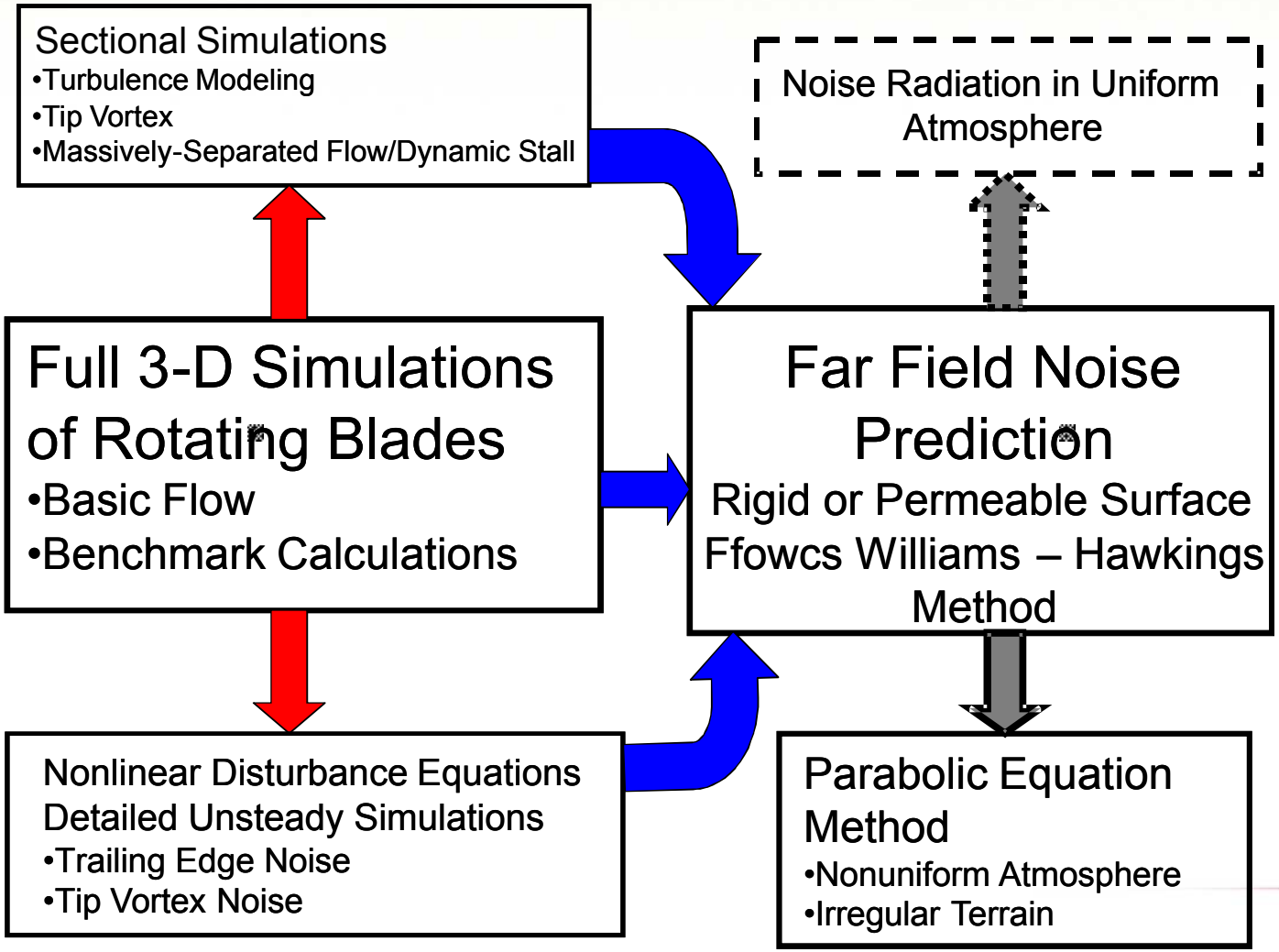
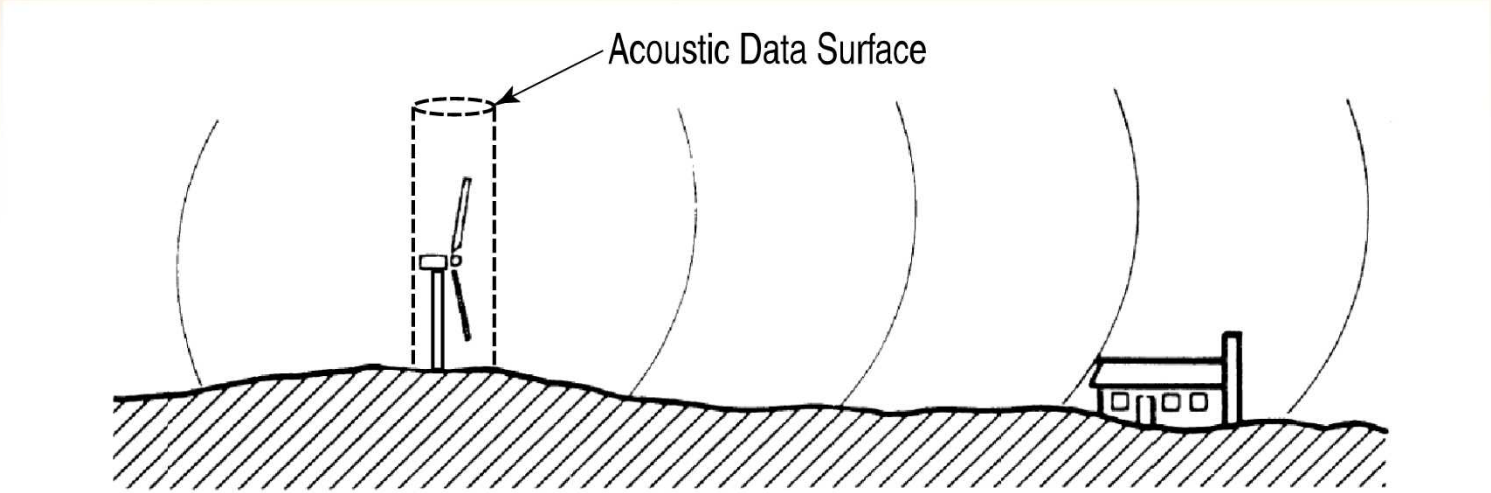
Overview of PSU's Prediction Strategy



How it works



- Flow data is computed on the blade surface or on an acoustic data surface
  - OVERFLOW is used to compute the rotational loading (or with KES the complete loading)
  - CHOPA is used to compute the unsteady loading due to flow separation (Strip computation with DES (KES) – short span) or leading or trailing edge noise (NLDE)
- PSU-WOPWOP uses the surface loading to find the sound on a cylindrical surface surrounding the wind turbine
  - Full unsteady CFD could predict information on acoustic data surface (but this would add more computational expense)
- Parabolic equation used to propagate sound to distance observer

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Flow and Noise of 3-D Airfoils

- **Full DNS or LES impractical for high Reynolds number turbulent flows**
- **Hybrid RANS/LES/DES is more appropriate.**
  - **turbulence model automatically transitions to different form for separated flow**
- **Good average flow is obtained from the OVERFLOW code – including rotational effects**
- **Solve the Nonlinear Disturbance Equations (NLDE) for disturbances about the mean flow**

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Computational Aeroacoustic Analysis of Wind Turbines at Penn State

- **Purpose: to develop a Computational Aeroacoustics Analysis System to predict wind turbine noise more accurately than empirically based methods.**
- **Previous Work Done under NREL Contract through 2006**
- **NREL funding cut due to DOE Budget Cuts**
- **3D Parabolic equation for long range propagation was the only component carried to completion.**
- **Work is being continued under Sandia Funding**

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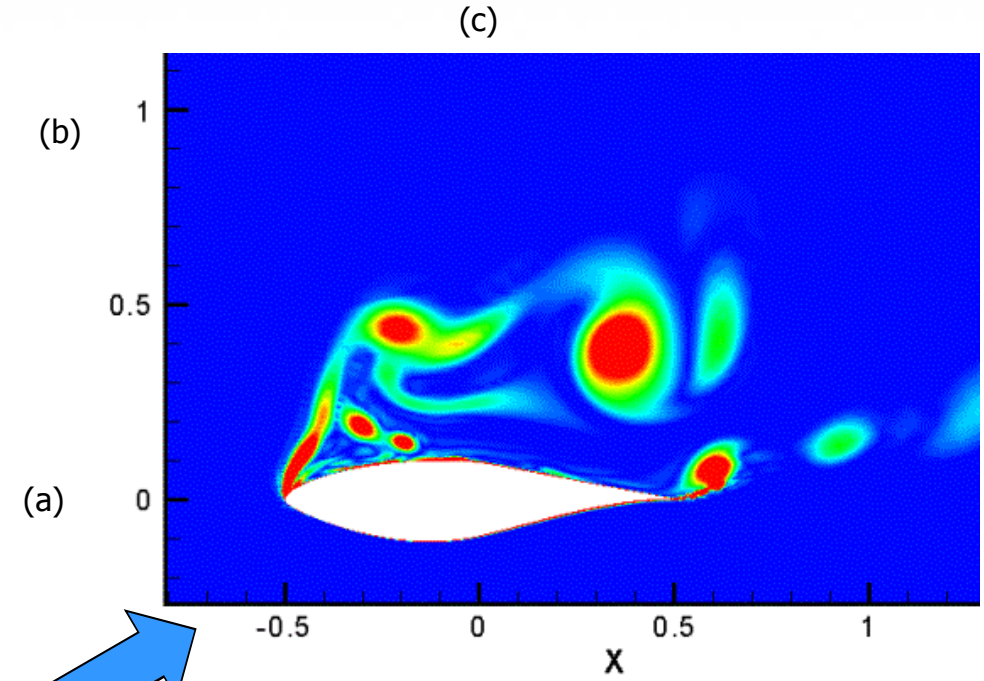
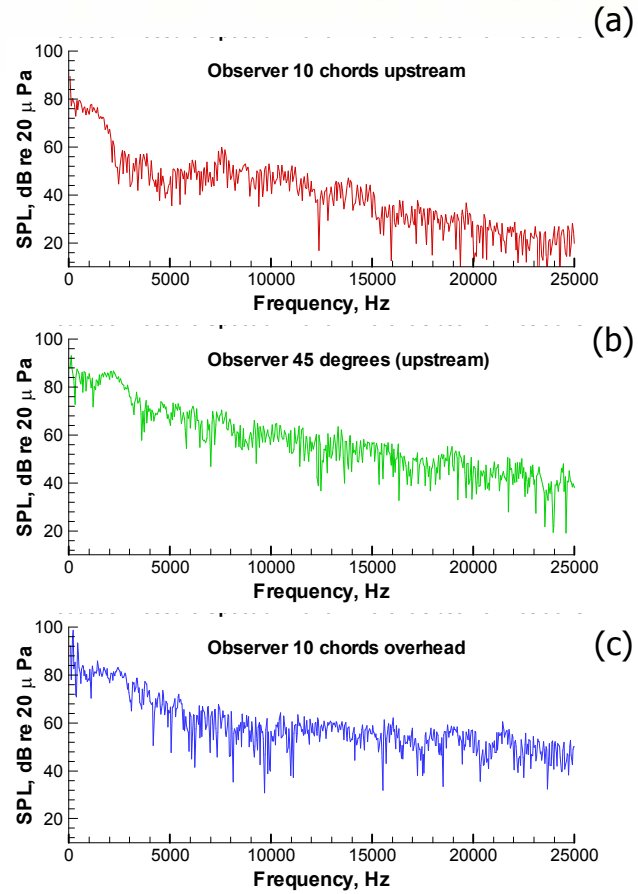
Computation of Broadband Acoustic Spectrum

S809 Airfoil at 30° Incidence



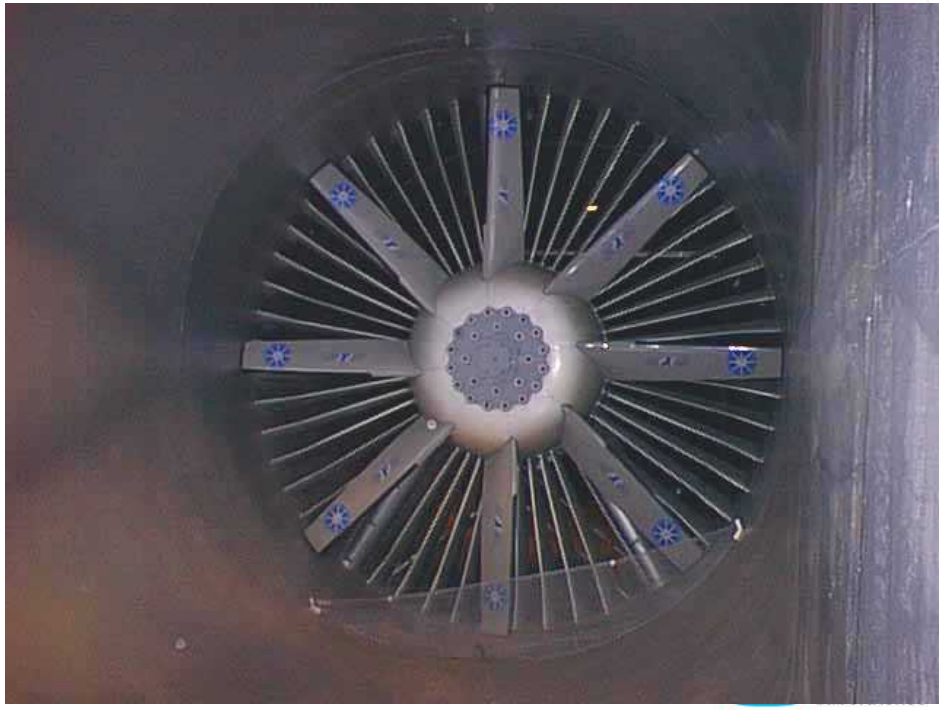
Preliminary



Acoustic spectrum at 3 observer locations (0 deg.-upstream; 45 deg; and 90 deg – overhead) 10 chords from an S809 airfoil at 30 deg. incidence, chord = 12 inches; span = 24 inches.

Virginia Tech Stability Wind Tunnel

- Built 1940 at Langley
- Donated to VT in 1958
- Closed circuit design with 6'x6'x24' test section
- 14' dia., 600 h.p. fan produces flow speeds to 80m/s



Stability Wind Tunnel Flow Quality

- **Closely Uniform, Very Low Turbulence Level (0.01-0.03%) Flow in a Large Test Section**
- **Flow Speeds to 75m/s, Re= 5,000,000/m**

Freestream Velocity	RMS Streamwise Fluctuations
V [m/s]	u'/V
12	**0.016%**
21	**0.021%**
30	**0.024%**
48	**0.029%**
57	**0.031%**

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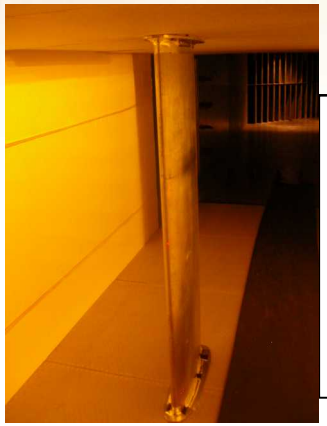
Unique Capabilities of Stability Wind Tunnel

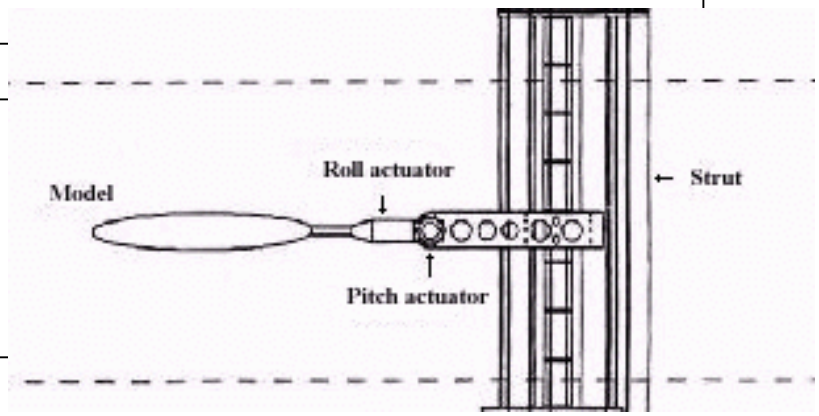


Removeable Anechoic System.

- Largest university-owned anechoic wind tunnel in the US
- Allows acoustic farfield noise measurements
- Unique Kevlar acoustic window system
- Unique modular anechoic chamber system surrounding test section
- Details in following slides

The DyPPiR (Installs in test section)

- Rapid pitch, plunge, roll of models up to 2m in length, with unique force and moment technologies.
- Unique system for the study of unsteady maneuvers and aerodynamics



Deterministic Disturbance Generator

- Programmable repeatable cyclic (two wavenumber) and impulsive disturbances.
- Provides deterministic onset flows for aero/hydro-acoustic and aerodynamic linear and non-linear response measurement.
- Allows low uncertainty response measurement in the time domain.
- Configurable as an active turbulence generator

Stability Wind Tunnel Instrumentation

- 6 Component Strut and Sting Balances, Turntable, In-test-section Traverse.
- LaVision Stereoscopic PIV System with 12" x 12" Interrogation Area.
- Multi-channel 16-bit Data Acquisition
- Also Available Through Associated Research Groups:
  - Miniature 3-Component LDA (Simpson)
  - Miniature two-point 3-component hot-wire anemometry (Devenport)
  - 32 and 64 microphone phased arrays (Burdisso)

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Future Plans for Aerodynamic Tools

- **Develop Simplified Tools to Model Aero Device Performance**
  - **Inexperienced user (Sandia)**
- **Contract for Overflow Support**
  - **Long term/low level**
  - **Short term/high level**
- **Develop Computational AeroAcoustics under Contract**
- **Exercise Newest Overflow Turbulence Modeling Capabilities**
  - **NREL NASA/Ames experimental data**
- **Perform Aeroacoustic Tests in Virginia Tech Wind Tunnel**

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Active Aerodynamic Load Control of Wind Turbine Blades

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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.

Presentation Outline

- Wind Energy Background
- Motivation for Active Controls Effort
- Active Control Background
- European Adaptive Flap Effort
- Sandia Microtab Effort
  - CFD work
  - Wind tunnel results
  - Simulation results
- Other Considerations
- Summary

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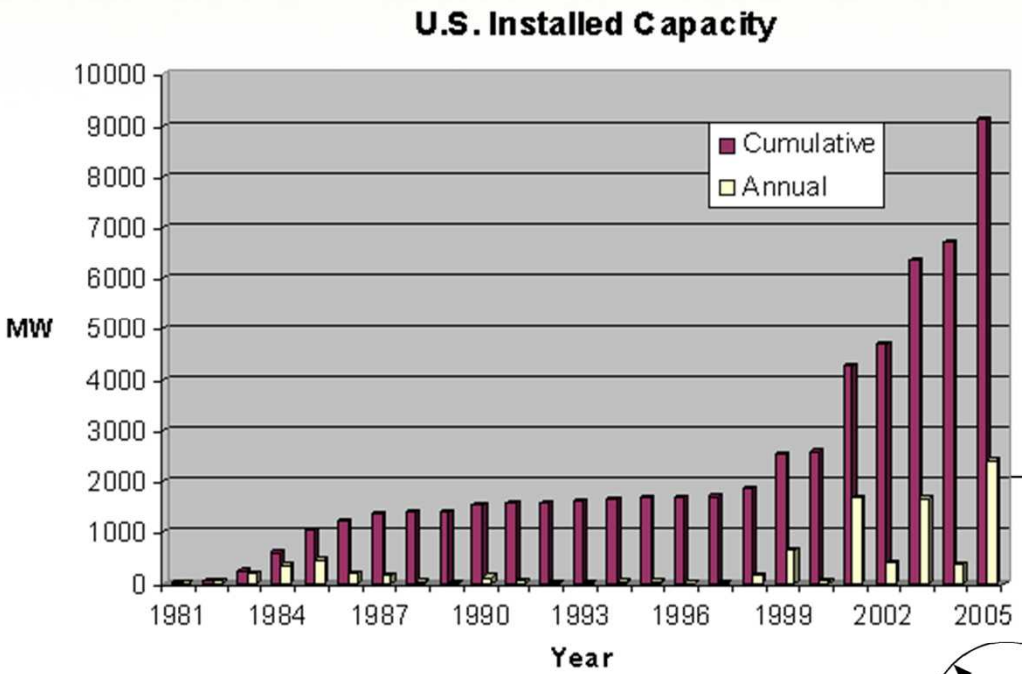
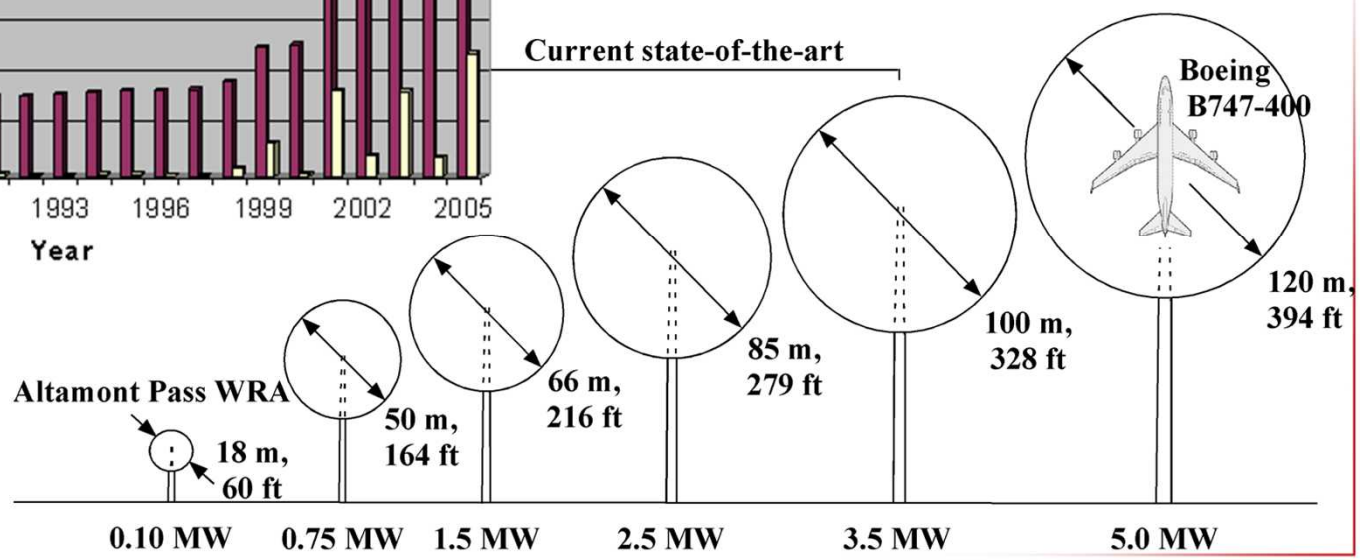
U.S. Installation and Wind Turbine Size Trends



10,000 MW Wind Installed Capacity Exceeded in 2006



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5 MW RePower Wind Turbine

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Motivation for Considering Active Controls

Problem Statement:

•Continued Increase in Size of Wind Turbine Blades Makes Weight Reduction Increasingly Important.

- Can Active Aerodynamic Load Control be Used to Reduce Fatigue Loads?
- Can Energy Capture in Low Wind Conditions be Improved with Active Devices?

Research Goals:

Evaluate the Potential Impact of Active Aerodynamic Load Control on:

- Reduction of Wind Turbine Fatigue Loads
- Increase in Wind Turbine Energy Capture
- Resultant Decrease in Wind-Generated Cost of Energy

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Active Aerodynamics Blade Load Control

- **Blade Loads Vary with Time Due to Wind Gusts, Wind Direction Changes, and Large Scale Turbulence**
- **Active Load Control can Attenuate Load Variation**
- **Active Load Control on Blade/Turbine can be Achieved by Modifying:**
  - **Blade incidence angle (pitch)**
  - **Flow velocity (modification in RPM)**

    Current technology – VSVP (Variable Speed, Variable Pitch)
  - **Blade aerodynamic characteristics through:**
  - **Blade length**
    - Changes in section shape (aileron, smart materials, microtab)
    - Surface blowing/suction
    - Other flow control techniques (VG's, surface heating, plasma)

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Active Aerodynamics Blade Load Control

- **Active Load Control:**
  - **May remove fundamental design constraints for large benefits**
  - **These large benefits are feasible if active control technology is considered from the onset**
  - **May allow for lighter, more slender blades designs**
- **Active Load Control is Already Implemented in Wind Turbine Design. e.g.:**
  - **Yaw control**
  - **Blade pitch control**
  - **Blade aileron (Zond 750)**

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Why Consider Distributed Load Control?

- **Individual Pitch Control is State-of-the-Art**
  - **Currently experimental**
  - **Reductions in fatigue loads of up to 28% predicted**
  - **Involves pitching of entire blade**
    - Slow response
  - **Cannot alleviate load variations along blade span**
    - Respond only to "average" load
- **Distributed Sensors/Distributed Load Control Needed**
- **Focus on Small, Fast-Acting, Distributed System to Alleviate Fatigue Loads and to Reduce Tip Deflections during High Load Conditions**

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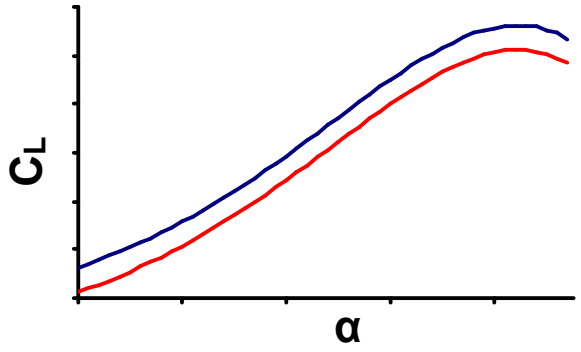
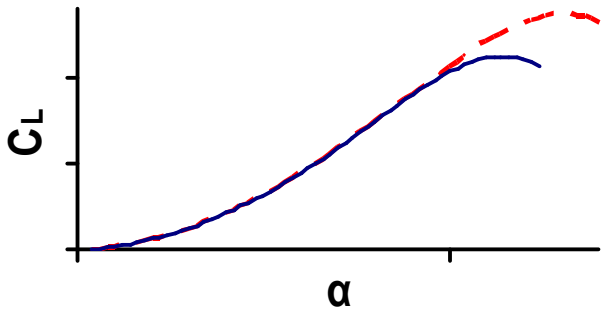
Airfoil Flow/Load Control Devices

- Active Aerodynamic Devices Fall into Two Categories
  - Shift entire lift curve (change camber)
  - Enhance maximum lift
- Load Control Requires Lift Attenuation
  - Limited to camber changing devices





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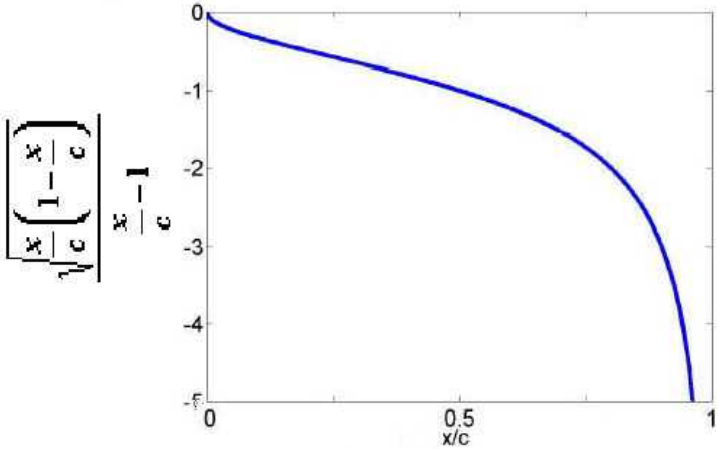
Why Consider Trailing Edge Camber Modification?

- **From Thin Airfoil Theory**

$C_l = C_{l\alpha} + C_{lc}$

Where
$C_{l\alpha} = 2\pi\alpha$ *is lift due to airfoil angle of attack*

$$C_{lc} = 4\int_{x/c=0}^{1} \frac{d(y_c/c)}{d(x/c)} \frac{\sqrt{\frac{x}{c}\left(1-\frac{x}{c}\right)}}{\frac{x}{c}-1} d(x/c)$$ *is lift due to airfoil camber*

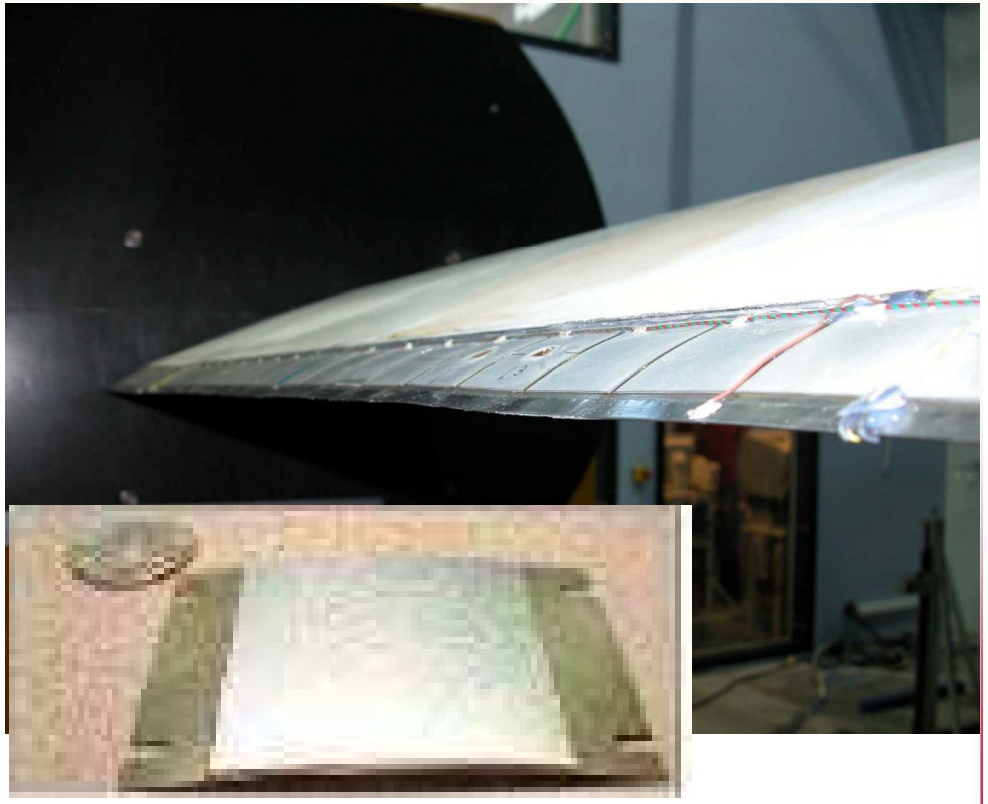


- **Effect of Camber is Greatest at Trailing Edge**
- **Aerodynamic Loads are Low at Trailing Edge**

European Efforts are Concentrating on "Conventional" Flaps

Active Aileron Control on Zond 750 Turbine

- Flap chord ≈ 40% of airfoil chord
- Flap inset in airfoil



Distributed Flaps on Risø Experiment

- Flap chord ≈ 10% of airfoil chord
- Flaps integral with airfoil

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European Efforts are Demonstrating Feasibility

- **Both Risø and TU Delft have Analyzed Concept Analytically**
- **Both Risø and TU Delft have Run Wind Tunnel Experiments**
- **Deterministic Loading of Blade (Sinusoidal)**
  - **Similar motion, varied phase lag for flap**
- **With Good Control, Observe 80 - 90% Reduction in Oscillating Loads**
- **Poor Control can Lead to 60-70% Increase in Loads**

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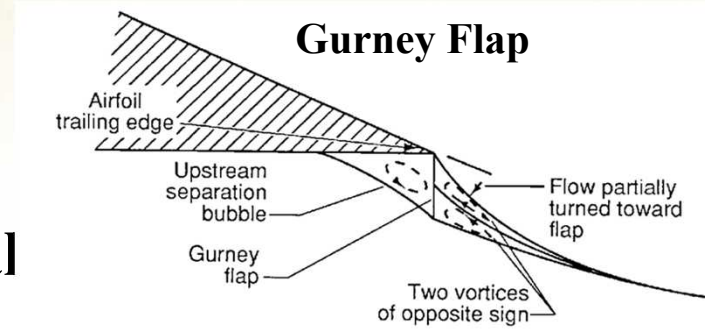
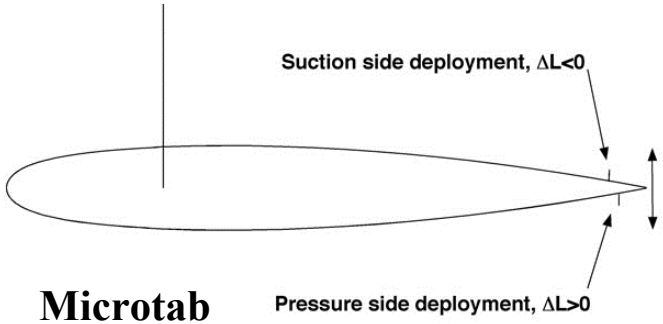
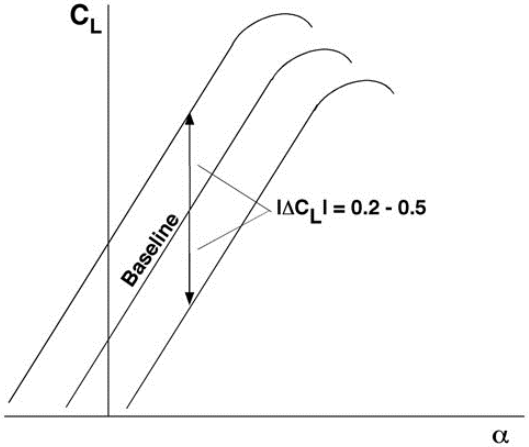
Sandia Effort Focuses on Microtab Concept

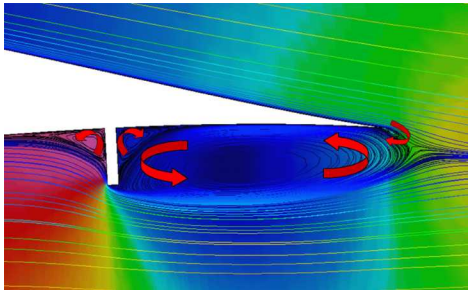
- **Microtab is Evolutionary Development of Passive Gurney flap (Liebeck, 1978)**
- **Tab Near Trailing Edge Deploys Normal to Surface**
- **Deployment Height on the Order of the Boundary Layer Thickness**
- **Modifies Trailing Edge Flow Development (so-called Kutta condition) and Effectively Changes Sectional Camber**





Microtab





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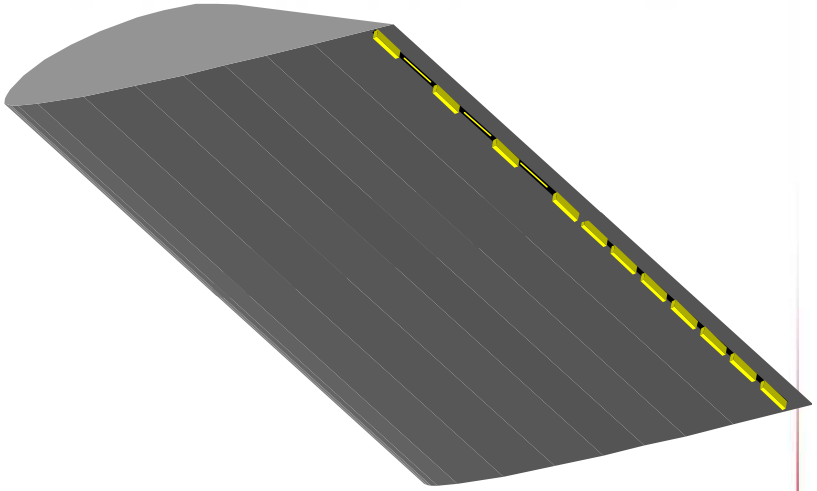
Microtab Advantages

- Operates within the Boundary Layer of the Blade
- Small, Simple, Fast Response
- Retractable and Controllable
- Lightweight, Rugged, Inexpensive
- Two-Position "ON-OFF" Actuation
- Low Power Consumption
- No Hinge Moments
- Expansion Possibilities (scalability)
- Do Not Require Significant Changes to Conventional Blade Design (i.e., manufacturing or materials)



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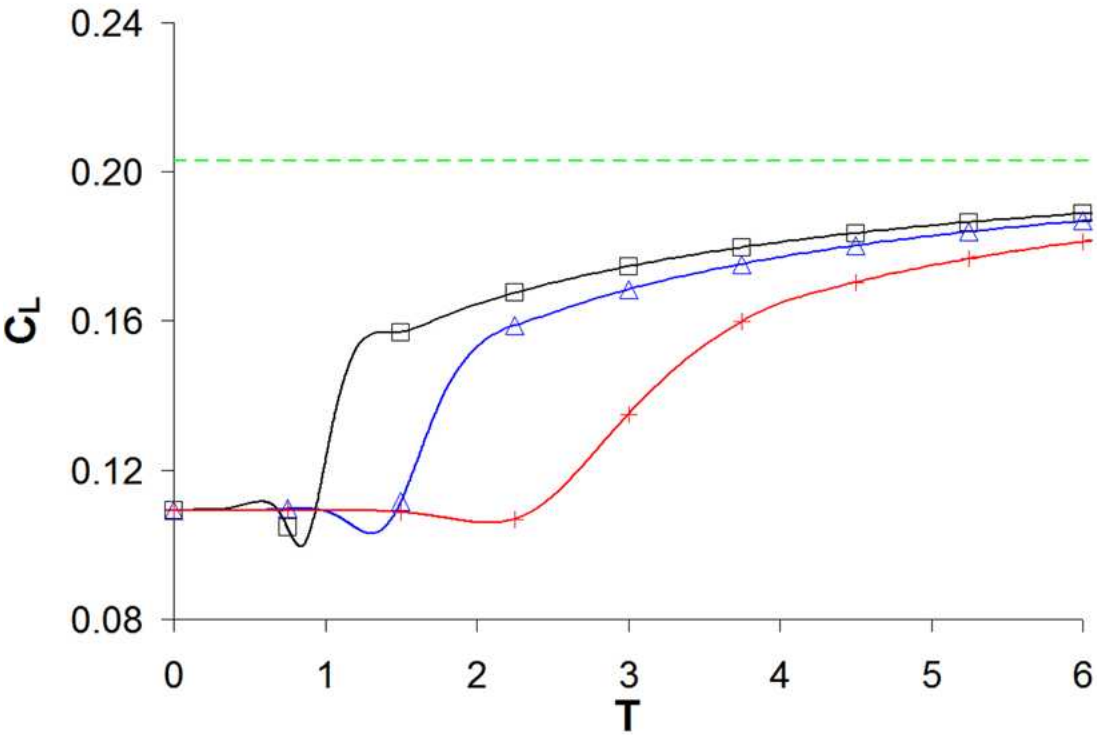
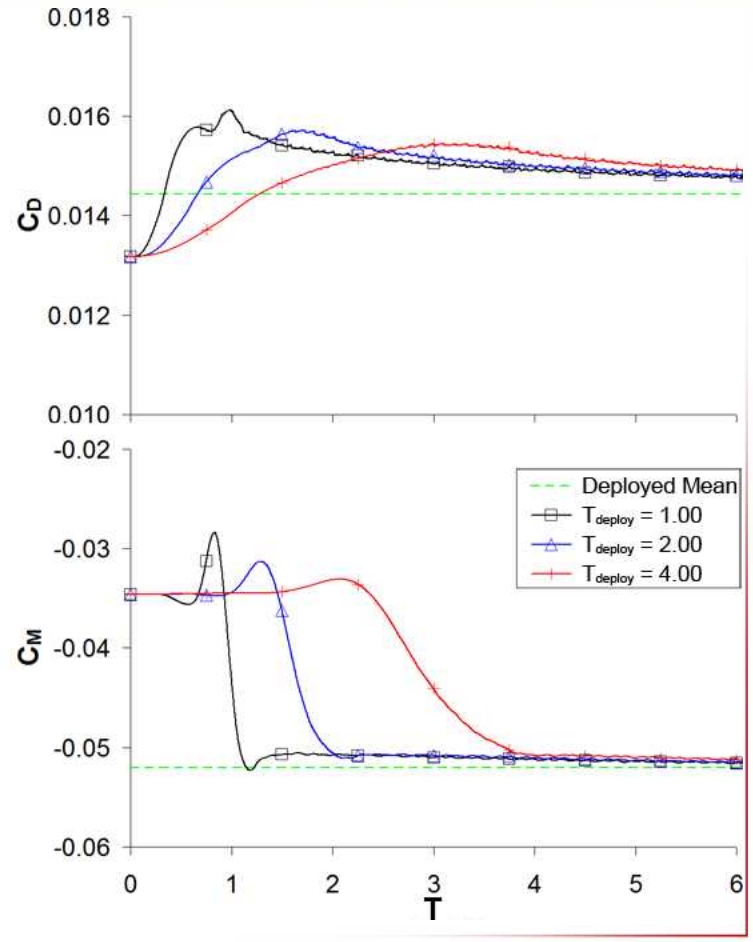
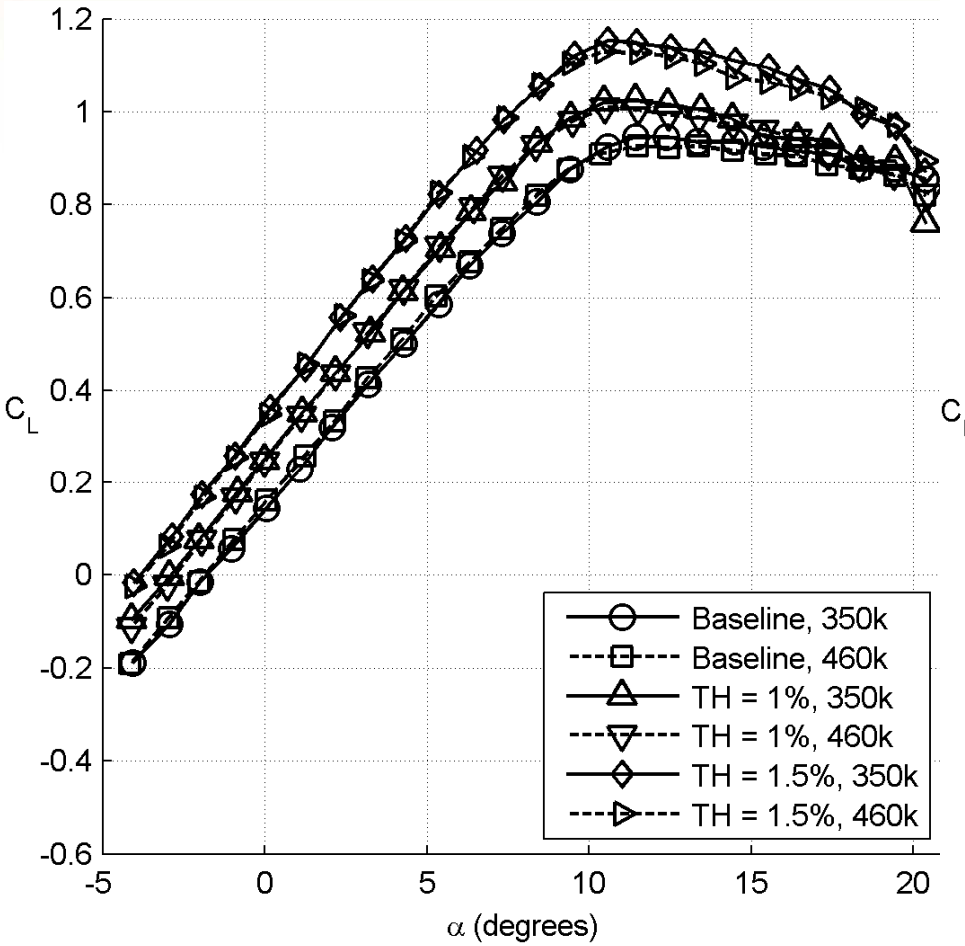
Deployment Time Impact on Microtab Effects

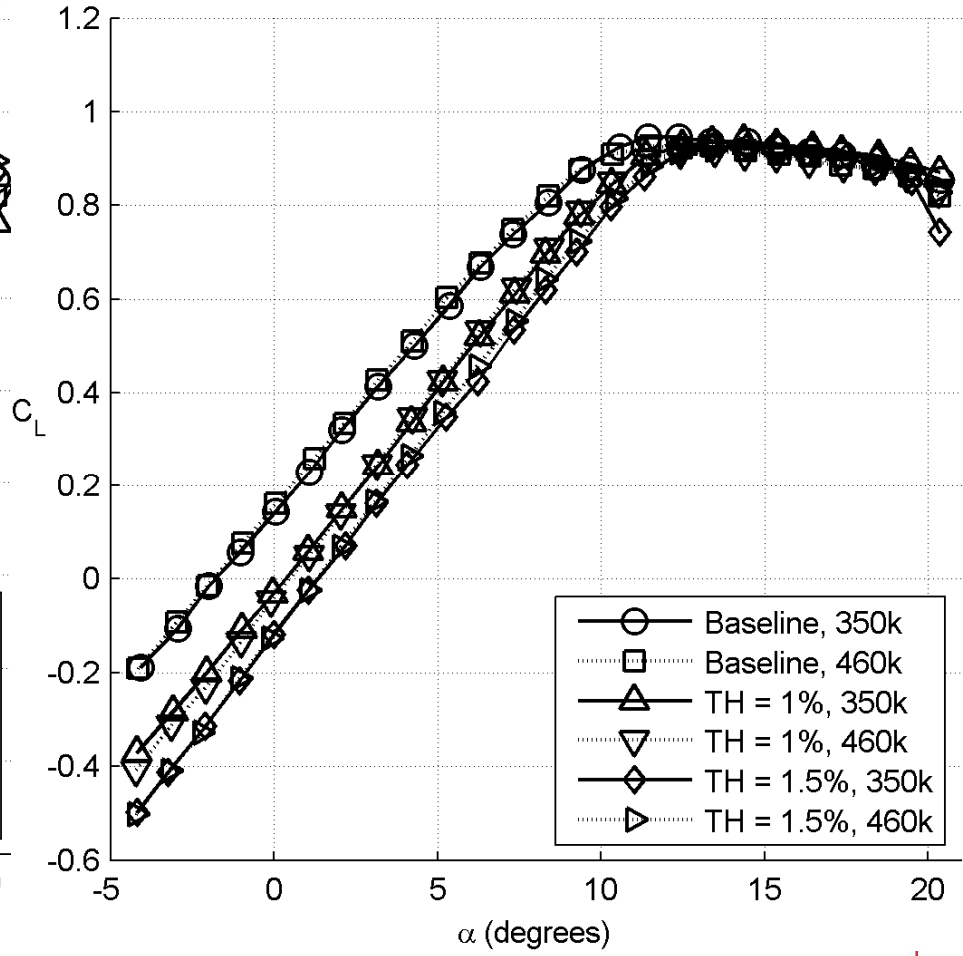




Experimental Measurement of Tab Effectiveness on Blade Tip Model



Pressure Surface Tabs @ 95%c



Suction Surface Tabs @ 95%c

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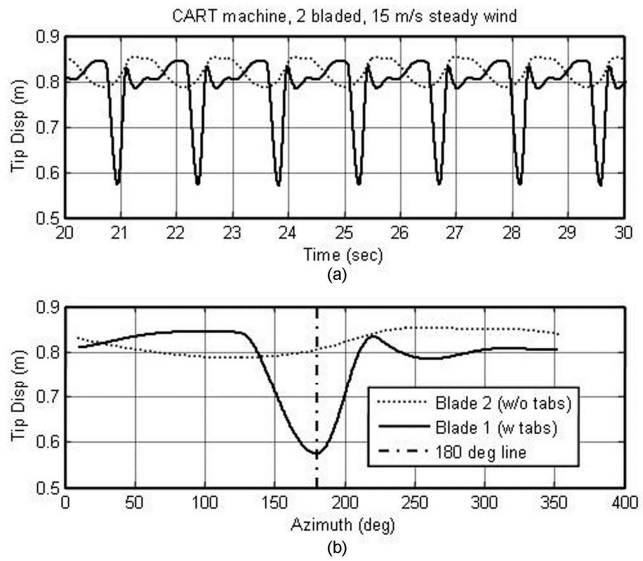
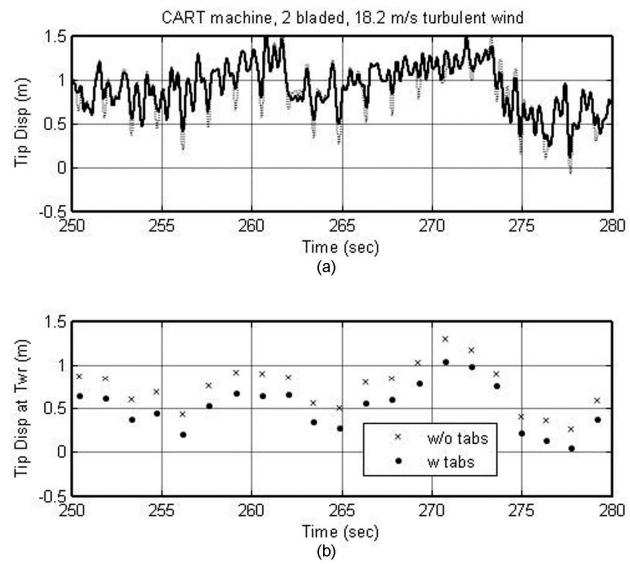
Microtabs Exert Significant Control Authority

- **Simulated with FAST (Structual Dynamics) & Simulink (Control) Codes**
- **Microtabs deploy from suction side of one blade, outer 25% of span**
- **Deployment timed for maximum impact at tower passing**



Steady Wind



Turbulent Wind

- **Tip displacement reduced by about 25%**
- **Minimal effect on power production**

System Requires Sensors, Actuators, Controls

- **Need Sensors Distributed Along Blade**
  - **Cheap, durable and accurate**
  - **Fiber-optic FBG under consideration**
  - **Pressure sensors, other technologies?**
- **Need Actuators/Tabs Distributed Along Blade**
  - **Durable, cheap, low power consumption**
- **Controls Development will be Challenge**
  - **Integrate pitch control with active distributed devices**
  - **Many questions to be answered**
    - Response times?
    - When to respond?
    - Appropriate control targets?

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Active Aero Wind Turbine Blade Project Control Technology

David G. Wilson and Rush D. Robinett, III

Energy, Resources & Systems Analysis Center 6300

August 2007

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.

Research Objectives

- Define the active aero control problem (critical path /drivers, analysis/simulation scenario, performance index: minimize tip speed, root moment, other)
- Proof-of-concept (i.e., microtab control to reduce fatigue loads/cycling)
- Preliminary Technical Approach:
  - Initial optimization (FMINCON, DP) for tab on/off sequencing
  - Initial feedback control for reducing load/fatigue in turbulent case
  - Simple flutter problem analysis w/ exergy limit cycle control proof-of-concept

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Generate Work Plan for Active Aero Control Technology R&D

To Incorporate:

- Tab devices (microtabs, trailing edge flaps, etc.)
- Morphing wing concept
- Bench testing
- Field testing (proof-of-concept)
- Transition to industry

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Performance Analysis with Trailing Edge Systems - Optimization

- **Power regulation above rated wind speed while shedding load**

$$\min W_1 \left| Power_{rated} - Power(PITCH, FLAP) \right| + W_2 \left| M_{flap_{nominal}} - M_{flap} \right|$$

$$subject:$$

$$lowerbound_{pitch} \le PITCH \le upperbound_{pitch}$$

$$lowerbound_{flap} \le FLAP \le upperbound_{flap}$$

- **Power output below rated wind speed to increase energy capture**

$$\max\left[Power_{rated} - \left| Power_{rated} - Power(RPM) \right| \right]$$

$$subject:$$

$$lowerbound_{RPM} \le RPM \le upperbound_{RPM}$$

$$lowerbound_{pitch} \le PITCH \le upperbound_{pitch}$$

$$lowerbound_{flap} \le FLAP \le upperbound_{flap}$$

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Initial Feedback Control to Reduce Load/Fatigue - Conventional

- Conventional control good starting point for closed-loop controller design for fixed- and variable-speed turbines and initial flap/tab assessment
- Conventional control for variable trailing edge geometry (Buhl,Gaunna,Bak at Riso National Labs, Denmark)

$$\beta = K_P(y - y_i) + K_D\dot{y} + K_A\ddot{y} + K_\alpha \frac{2\pi}{H_{dydx,defl}}(\alpha_{meas} - \alpha_i)$$

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Modern Control to Reduce Load/Fatigue/Improve Energy Capture

- Modern control design by Griffin and McCoy (GEC) for initial LQR approach with
  - Investigate model from FAST/Simulink code and assess linearized model for potential control design
  - Initiate SNL control design model with verification using FAST/Simulink
- LQG/estimator/observer and sensor assessment and evaluation
- Load reduction and power optimization (Boukhezzar, Siguerdidjane, Hand)
- Further review (work-in-progress)

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Nonlinear Control to Reduce Load/Fatigue/Improve Energy Capture

- Lightweight adaptive blade design with embedded sensors and actuators with variable pitch
- Combined blade pitch/flap control system (reduced loading above rated speed, increased energy capture below rated speed)
- Nonlinear flutter control system identifies stability boundary, improved performance by promoting lightweight/high strength blade design
- Individual pitch control system (reduces fatigue loading) as compared to collective pitch control

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Sandia 15+ YRS of R&D in Flexible Robot Dynamics and Control

- **The results of SNL's research experience will be applied to the active aero blade control project**
- **The fundamental breakdown is categorized as:**

Wind Turbine is a Flexible Robot

Open-loop
Input Shaping

Closed-loop
Classical Control
-PID type

Modern State-space Control
•LQR/LQG (Kalman filter)

Nonlinear Control
•VS – Sliding Mode Control
•Adaptive SMC

Nonlinear Systems
Limit Cycle Control

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Flexible Robot Dynamics, Controls, and Optimization Documentation

- R.D. Robinett, III, C. Dohrmann, G.R. Eisler, J.T. Feddema, G.G. Parker, D.G. Wilson, D. Stokes, **Flexible Robot Dynamics and Controls**, Kluwer Academic/Plenum Publishers, N.Y., Jan. 2002, ISBN 0-306-46724-0
- Robinett, R.D., III, Wilson, D.G., Eisler, G.R., and Hurtado, J.E., **Applied Dynamic Programming for Optimization of Dynamical Systems**, SIAM, Advances in Design and Control Series, July 2005, ISBN 0-89871-586-5
- D.G. Wilson, **Nonlinear/Adaptive Control Architectures with Active Structures for Flexible Manipulators**, PhD Dissertation, Mechanical Engineering, University of New Mexico, May 2000

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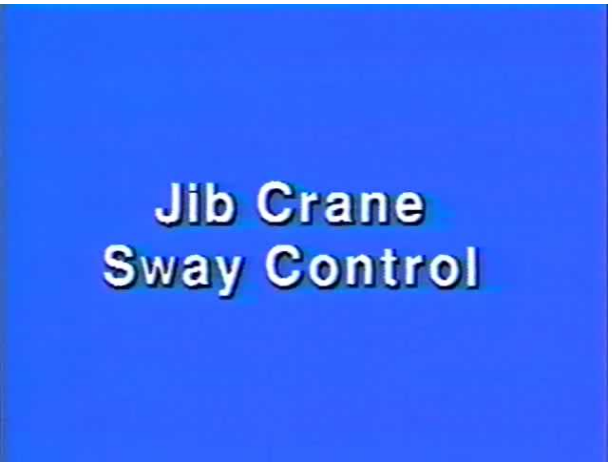
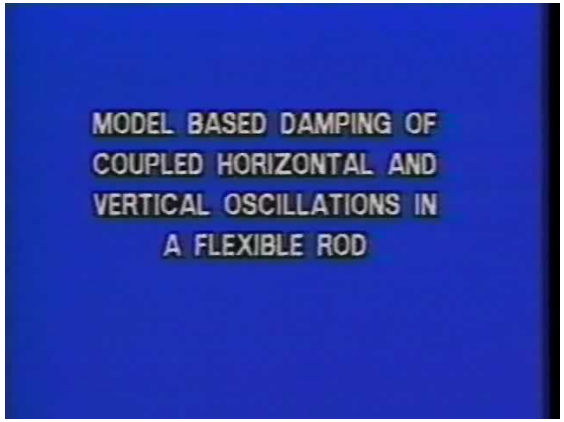
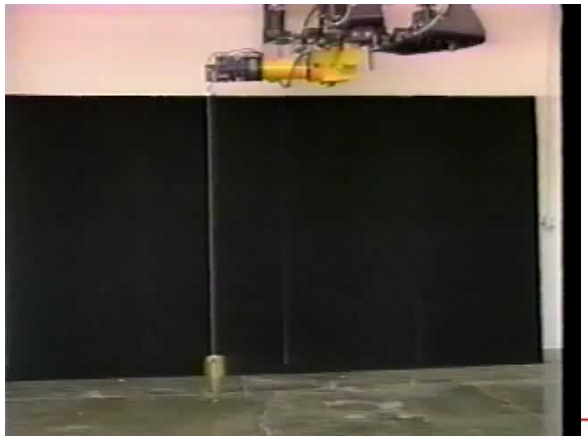
Previous Work
Open-Loop Input Shaping

From laboratory proof-of-concept to actual hardware demonstrations







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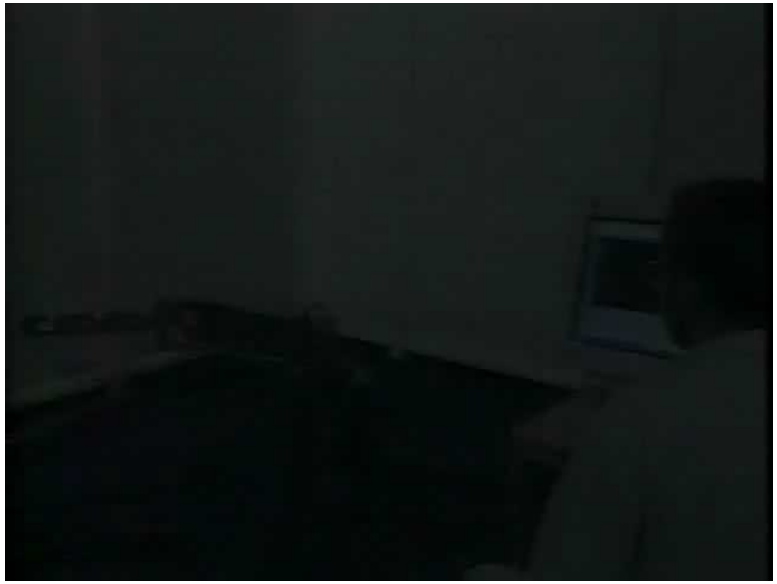
Previous Work Closed-Loop Control (Classical and Modern)

2-DOF Planar flexible-link direct-drive robot



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Previous Work
Nonlinear Sliding Mode Control

- **Photo and Figures**

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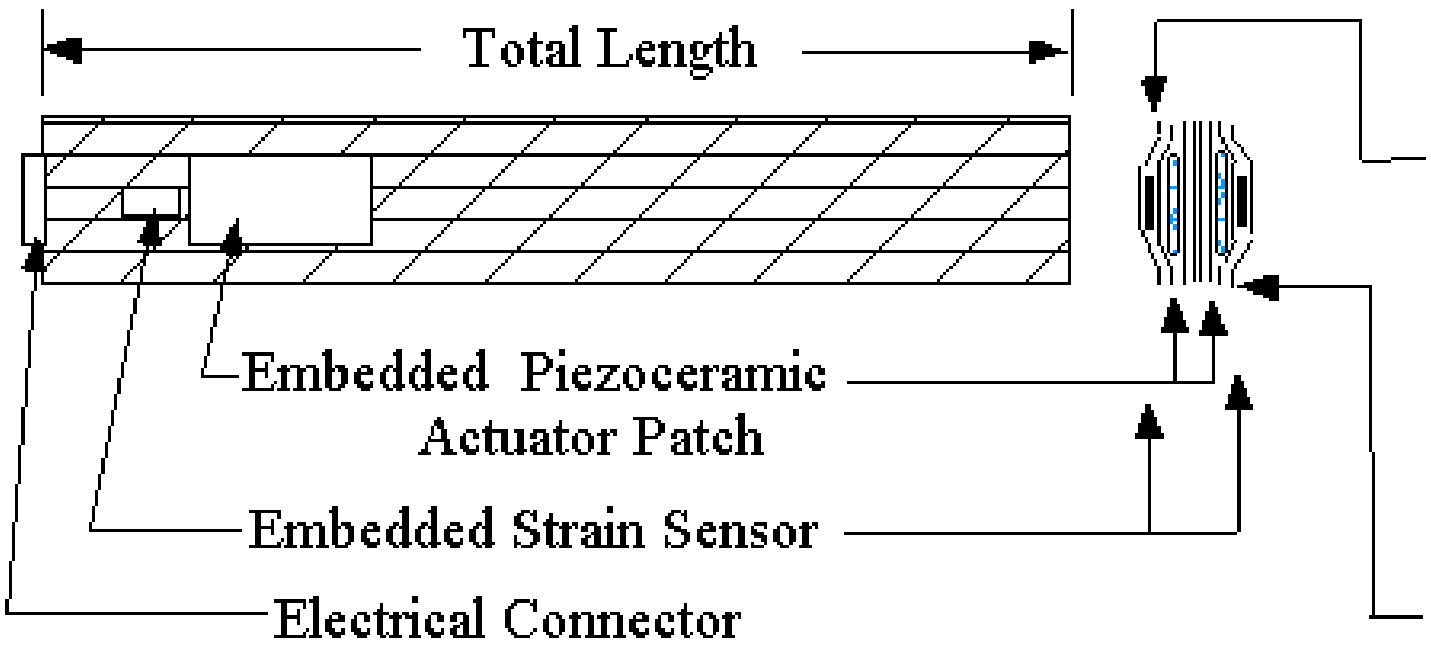
Composite Smart Link Design



Ply #	Angle
1	45
2	0
3	0
4	-45
5	45
6	0
7	0
8	-45

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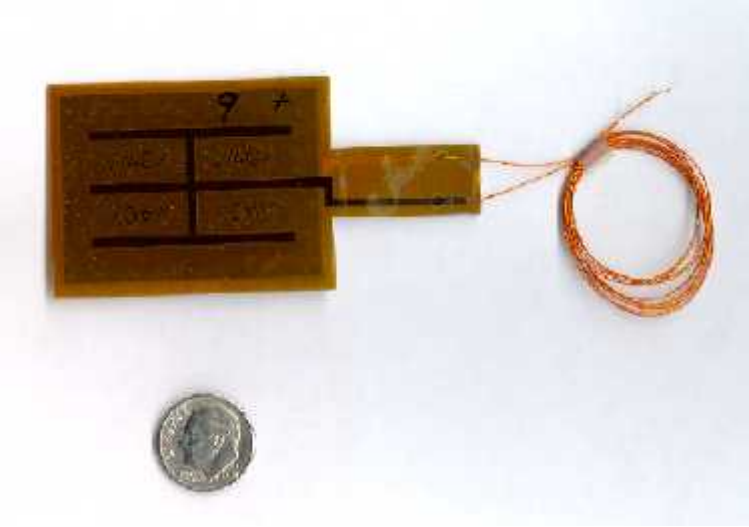
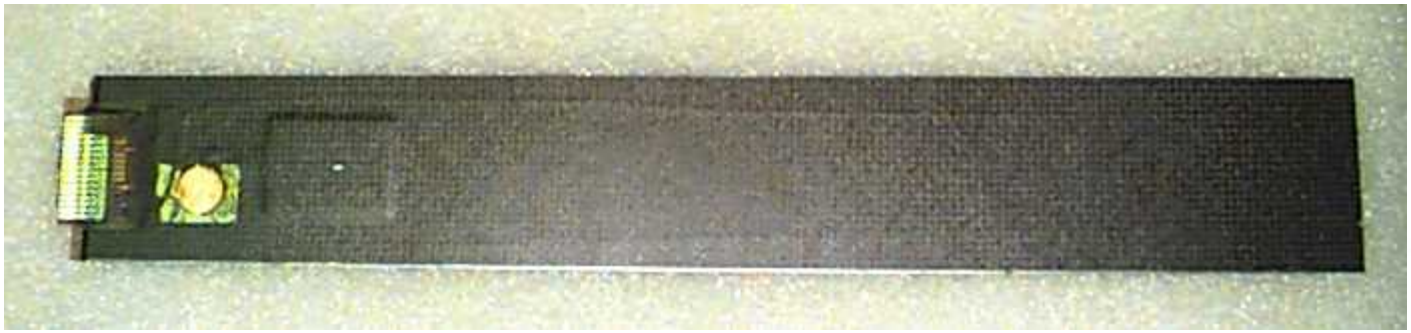
Composite Smart Link Experimental Hardware



ACX Piezoceramic Actuator Patch

Graphite/Epoxy Composite Link with embedded strain sensor and ACX piezoceramic actuator patch



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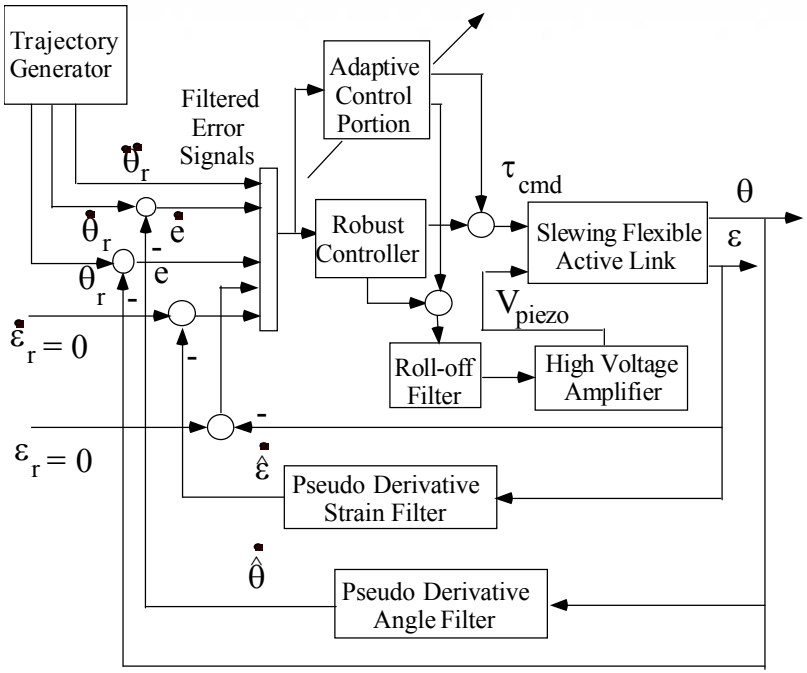
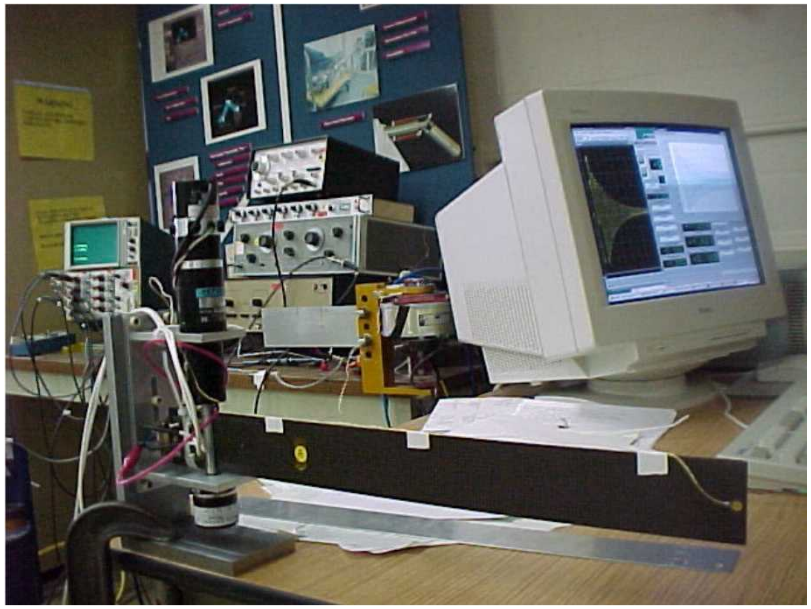
Nonlinear Adaptive Control Architecture
Slewing Smart Link Set-Up



Controller Architecture



Hardware setup

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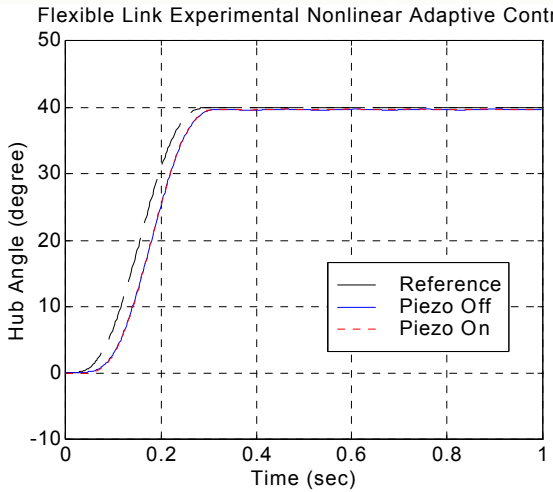
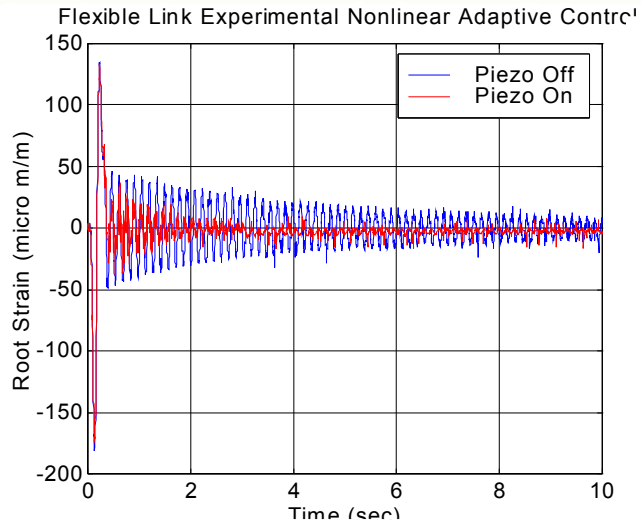
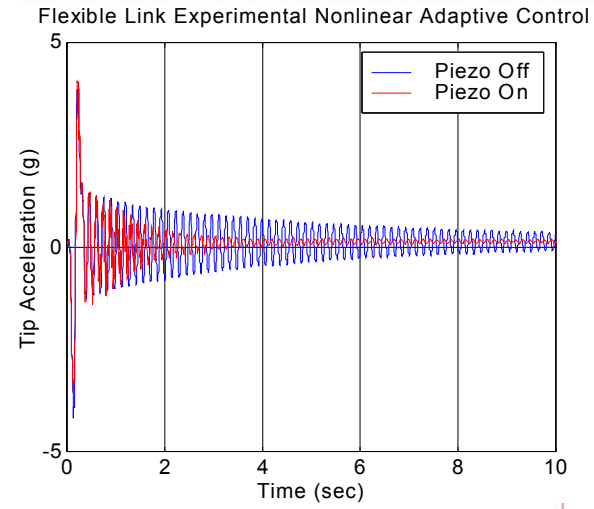
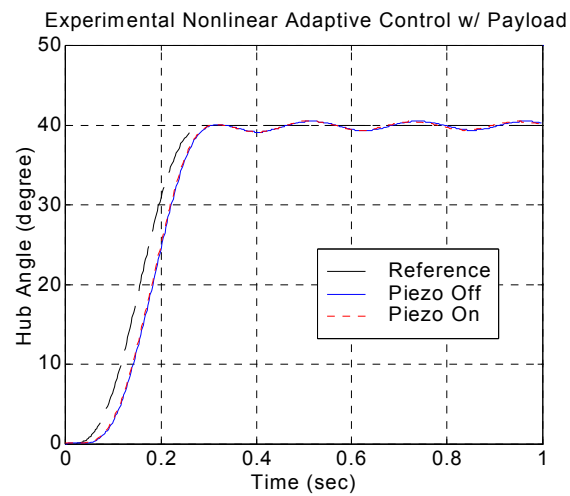
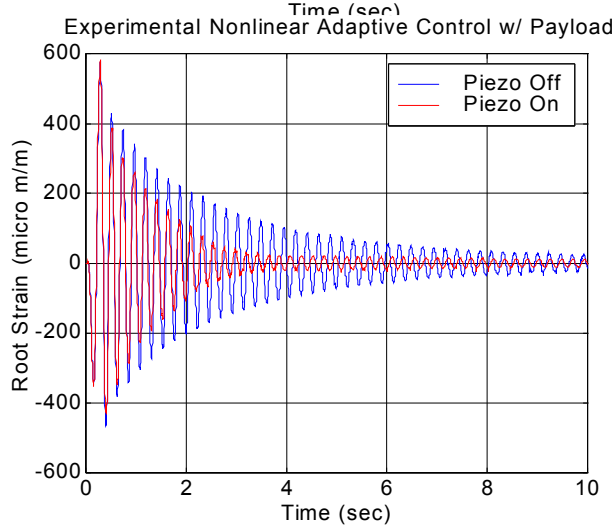
Slewing Smart Link Experimental Results

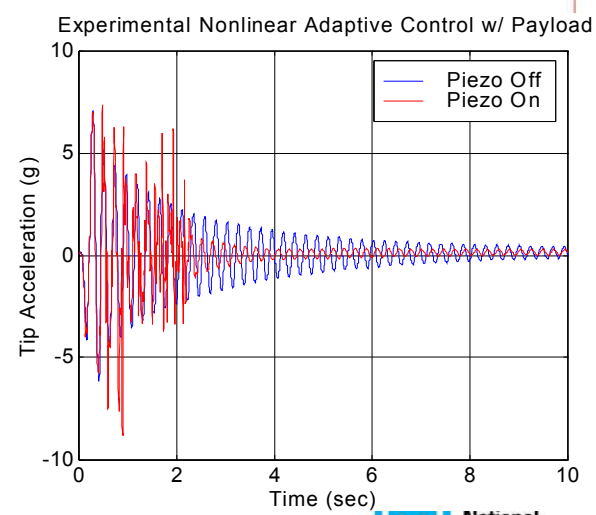












Hub Root Strain Tip Accel

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Dynamic Programming for Optimization of Dynamical Systems

- **Photo and Figures**

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Summary

- **15+ yrs of research development in flexible robot dynamics, controls, and optimization to be applied to the wind turbine active aero blade control project**

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Navy Advanced Technology Demonstrator

Backup photo

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Summary

- Active Aerodynamic Load Control has Potential to Reduce Fatigue Loads
- Distributed Control Devices are Required
  - Respond to local loads
- Preferred Device Location is Near Trailing Edge
  - Modify blade camber
- European Efforts Target Conventional Flaps
  - Significant load improvement over current technology (80-90% reduction)
- Sandia Effort Targets Microtab Concept
  - Simple shape
  - Low loads
  - Potentially quick response
- Simulations Show Significant Control Authority
- Many Challenges Remain to be Solved

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Thank You!!!

Questions?

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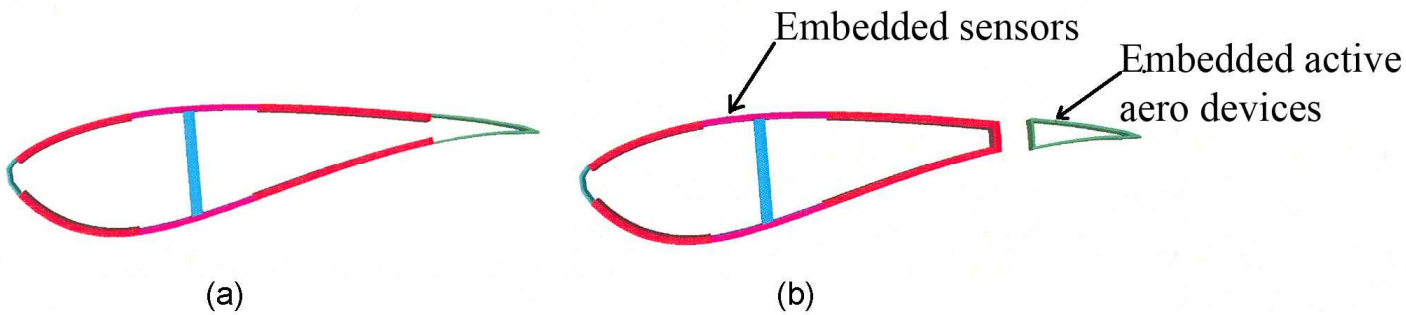
Mounting Considerations are Important

- **Maintain Current Blade Manufacturing Techniques**
- **Incorporate Ability to Repair Malfunctioning Units**



Current Blade Fabrication **Conceptual Blade Fabrication**

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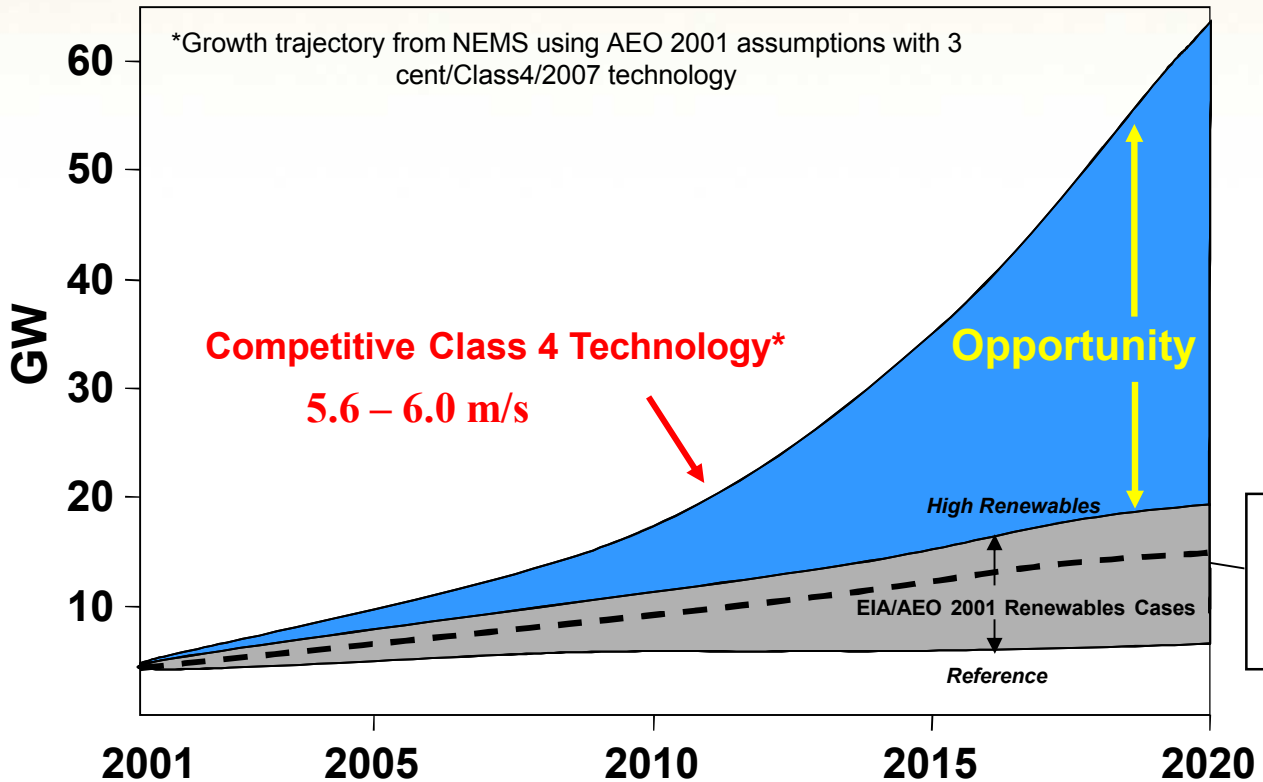
Impact of Cost Goals



Current Class 4 cost:
4.3 cents/kWh

Class 4 goal (2014):
3.6 cents/kWh

Baseline (15 GW in 2020)
- No technology breakthrough
- *Class 6 Plateau*
- 6.4 – 7.0 m/s

Program Goal:
3.6 cents/kWh
Class 4 COE
in 2014

- Expands resource base **20-fold**
- Reduces average distance to load **5-fold**
- **35 GW** additional opportunity by 2020

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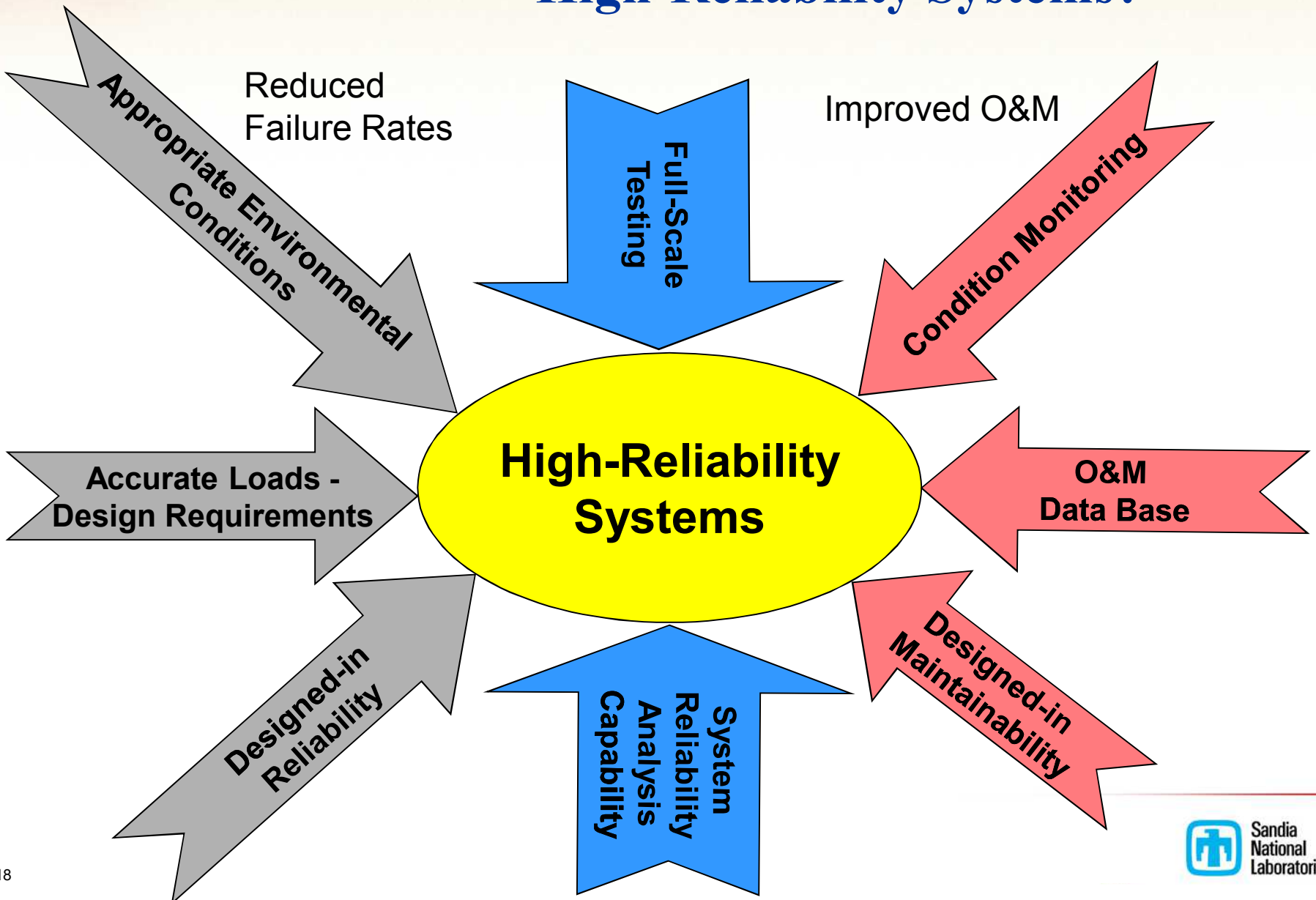
Wind Industry Trends

- Costs
  - System < $3/lb
  - Blades < $5/lb
  - ~ $0.75/Watt *
  - $0.03-0.05/kWh *

* Recent cost of steel increases have increased cost by 30 -50% - New Challenges

- Size
  - 1.5-5.0 MW
  - Towers: 65-100 meters
  - Blades: 34-50 meters
  - Weight: 150-500 tons

What is Required to Develop High-Reliability Systems?



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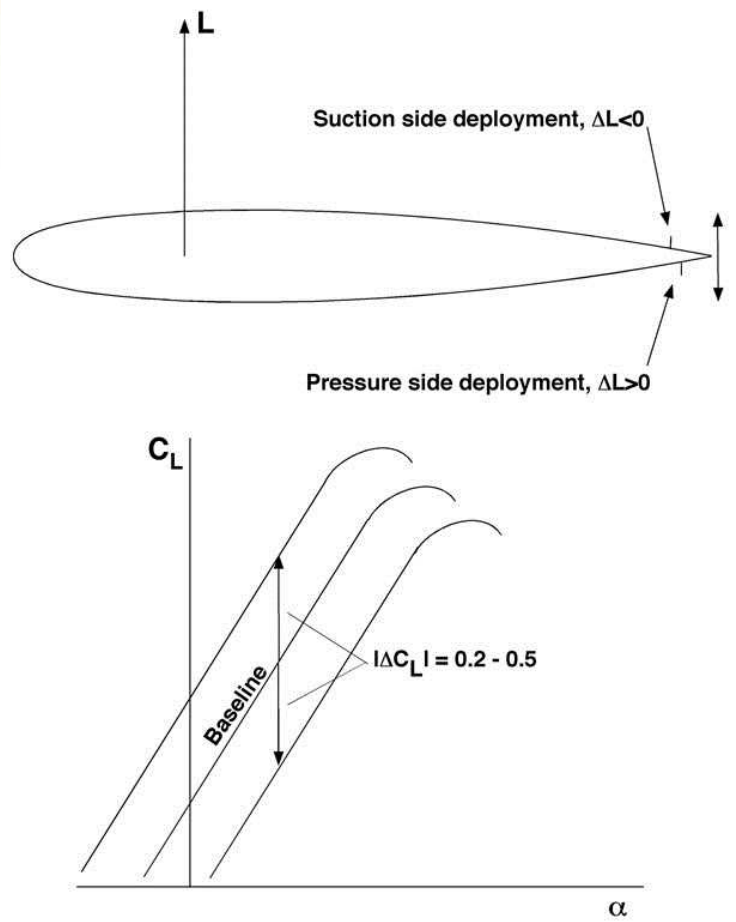
Microtabs are Alternative to Flaps

Active Aileron Control on Zond 750 Turbine



Microtab Concept

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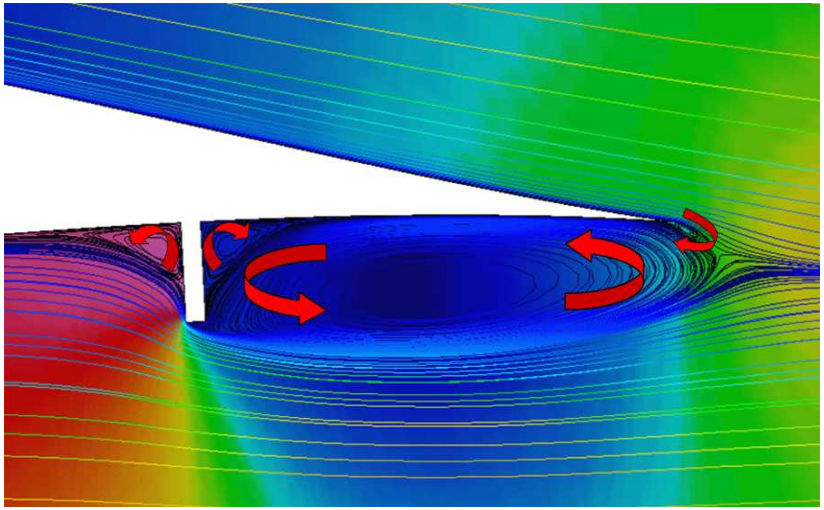
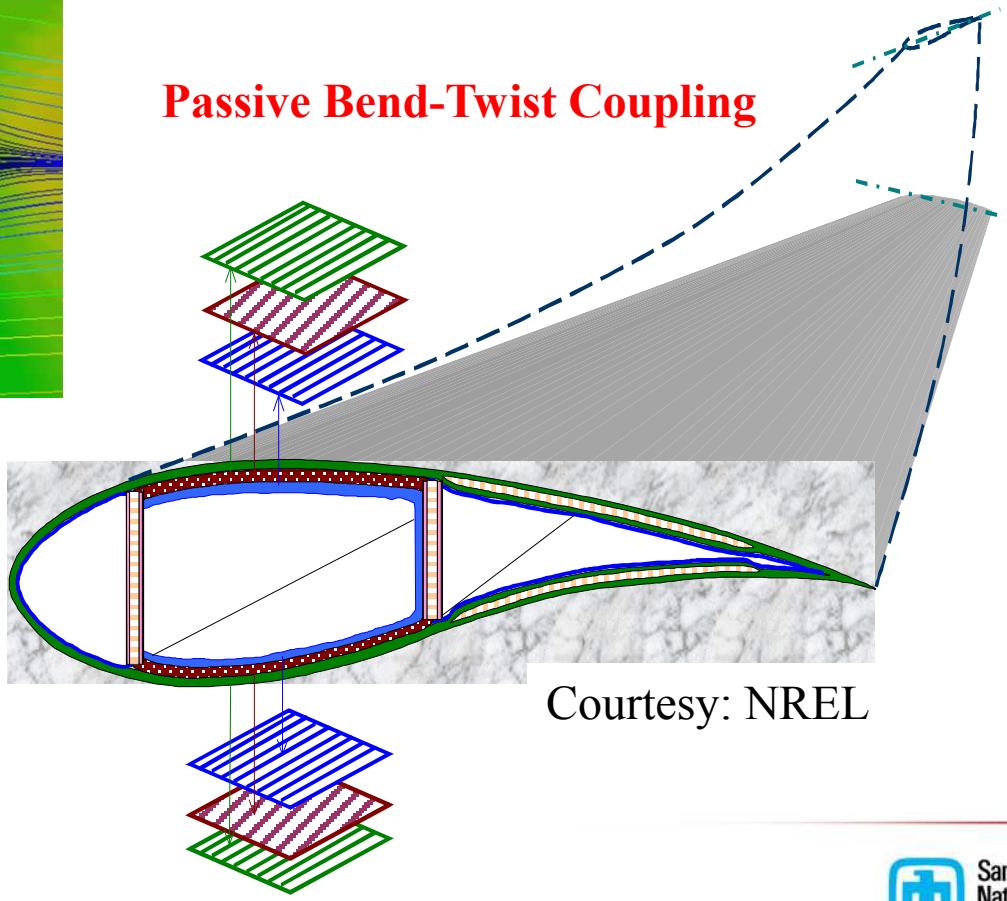
Passive and Active Blade Control



Active Devices

Passive Bend-Twist Coupling



Courtesy: NREL