

Wind Turbine Aerodynamics and Acoustics Research at SNL

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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 National Laboratories

Improvement of Inboard Blade Aerodynamics

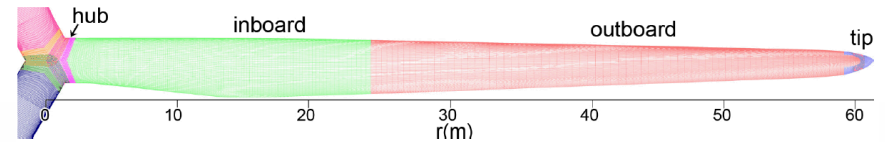
with Case van Dam and Ray Chow, University of California-Davis



- Inboard passive flow control devices are appearing on wind turbine blades.
- How, and how well, do they work?
- What is the optimal choice and configuration?

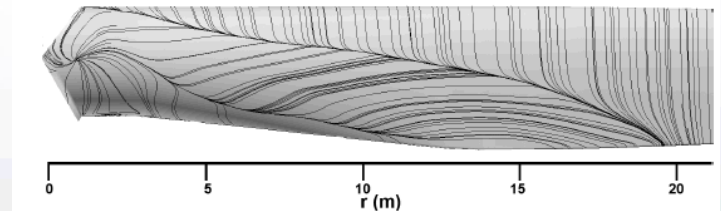
Simple single fence resulted in ~1% power increase at 11 m/s wind speed

Surface CFD Mesh for NREL 5 MW Reference Turbine

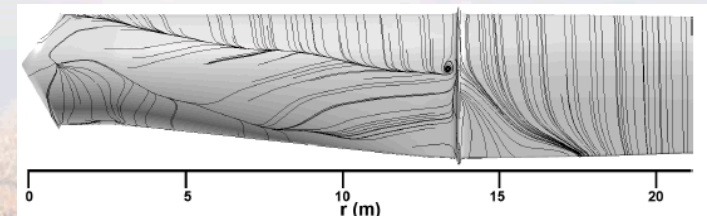


CFD Results: Suction surface streamlines

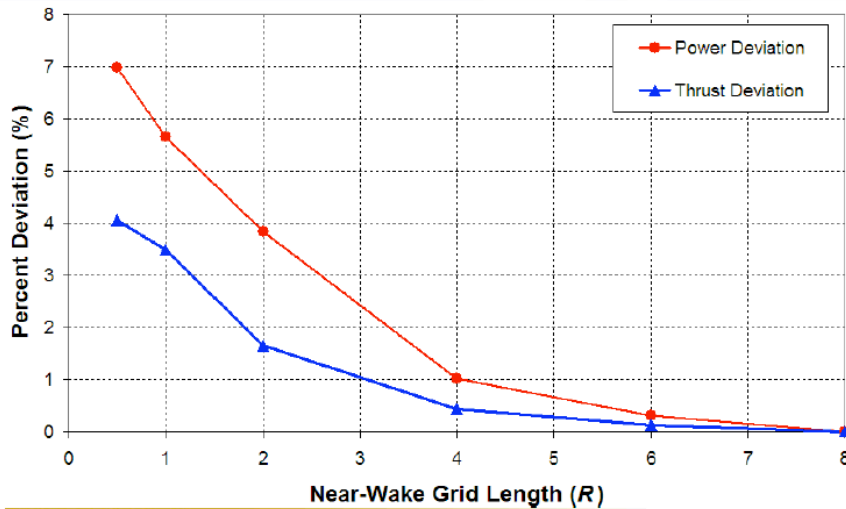
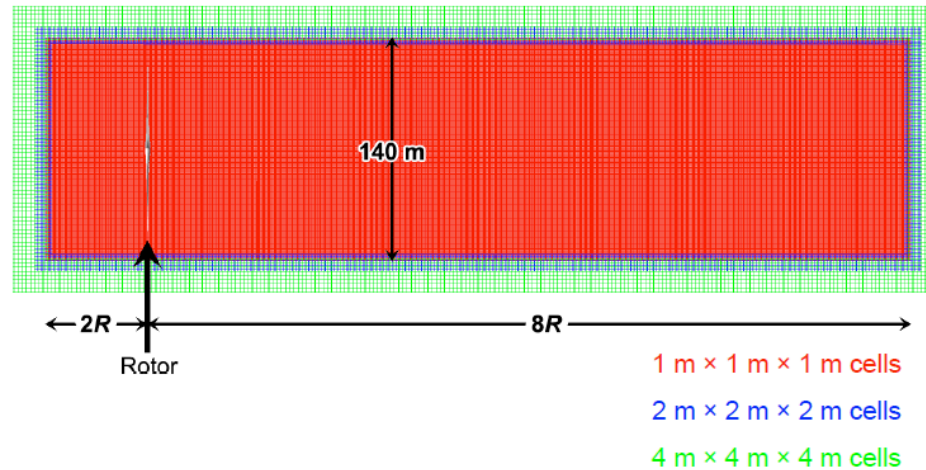
Clean blade



With inboard blade fence

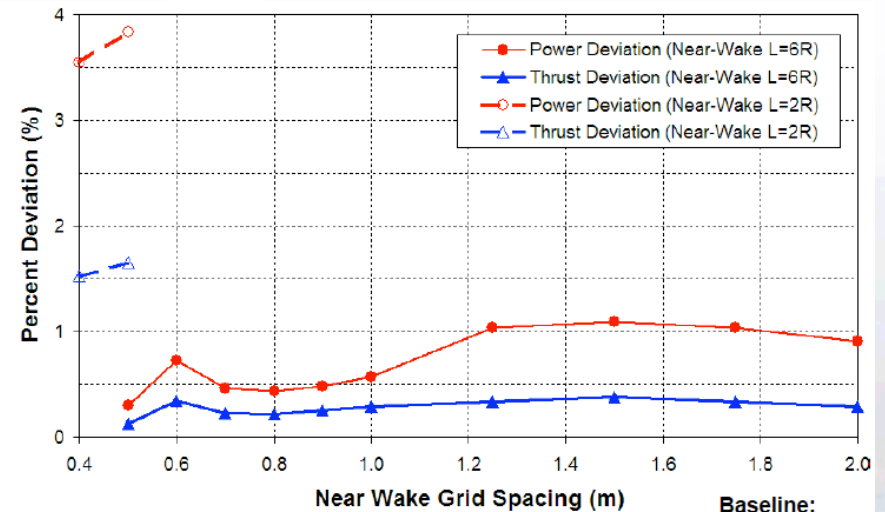


Wake Mesh Sensitivity Studies



UCDAVIS COLLEGE OF ENGINEERING

DS = 0.5 m



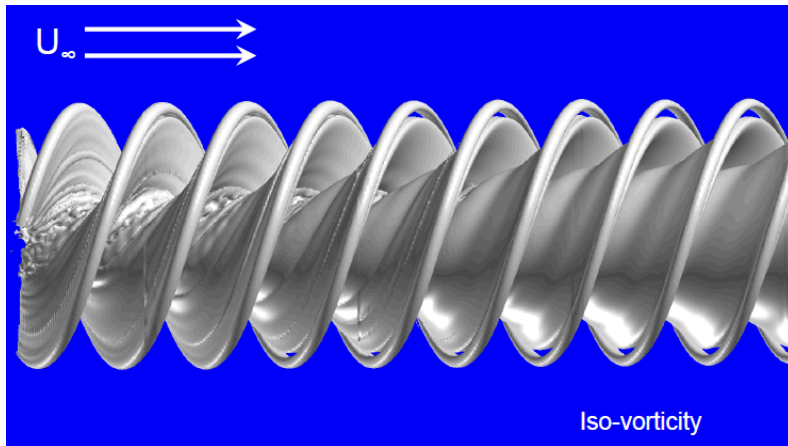
UCDAVIS COLLEGE OF ENGINEERING

Baseline: DS = 0.5 m, L = 8R

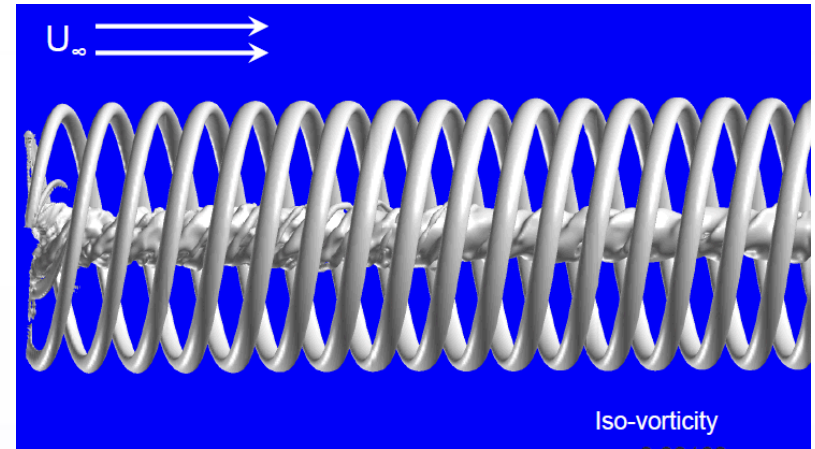


Wake Behavior vs. Wind Speed

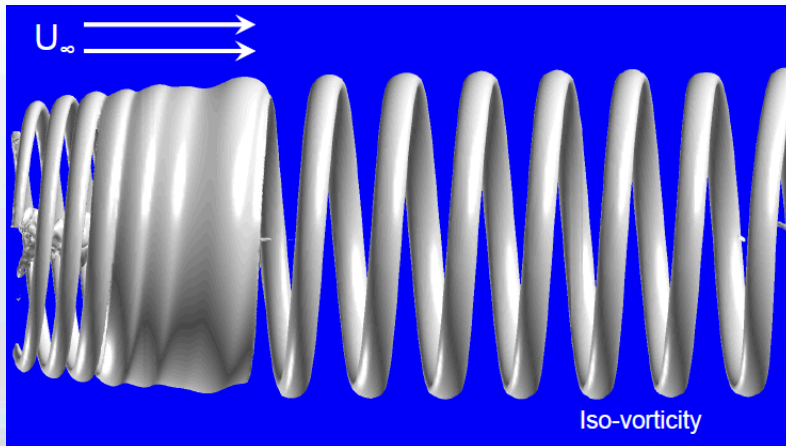
$U = 25 \text{ m/s}$



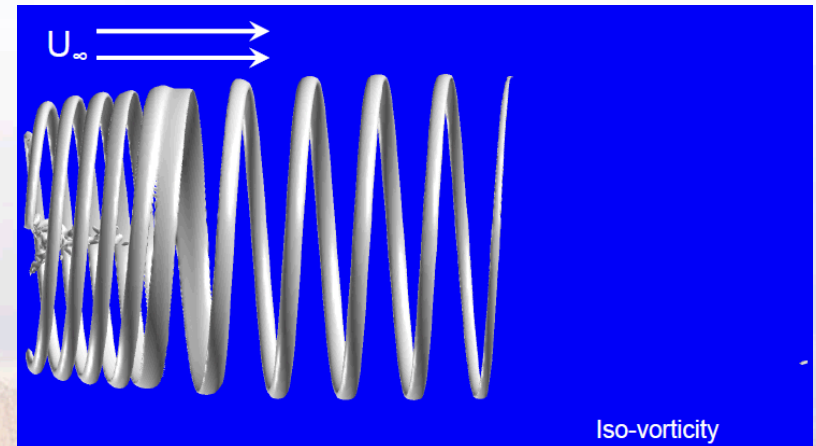
$U = 15 \text{ m/s}$



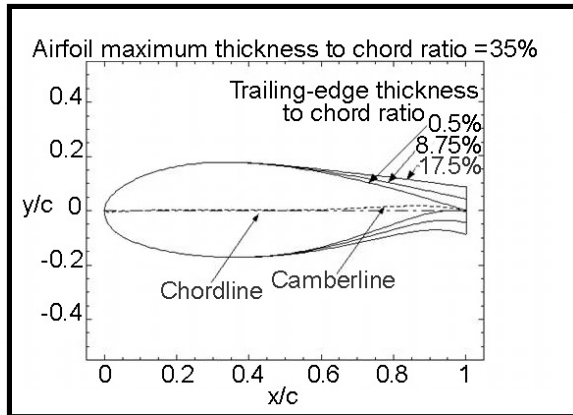
$U = 11 \text{ m/s}$



$U = 8 \text{ m/s}$



Flatback Airfoils

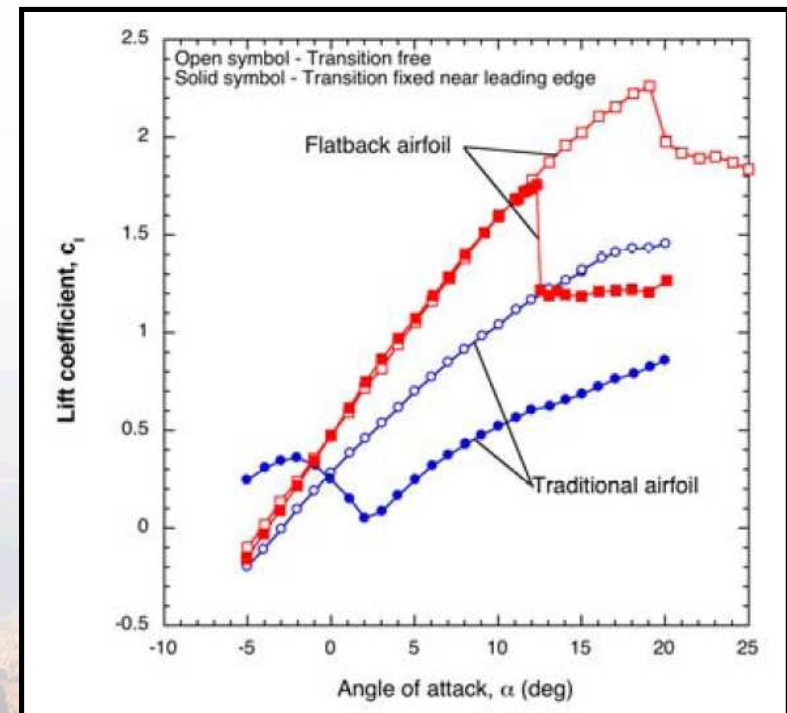


■ Structural Advantages

- Structural benefit of larger sectional stiffness for given chord and thickness.
- Results in higher blade strength, lower blade weight.

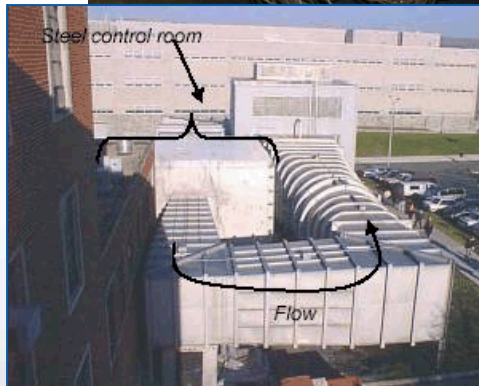
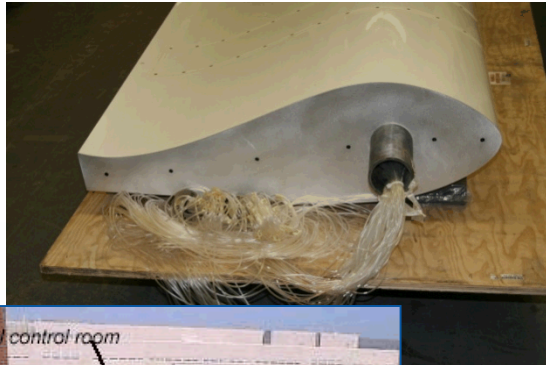
■ Aerodynamic Advantages/Disadvantages

- Sensitivity of lift to leading edge soiling is reduced.
- Drag is increased (although L/D may still increase).
- **Increased aerodynamic noise due to blunt trailing edge – potential industry barrier.**



Flatback Airfoil Research at Sandia

Wind Tunnel Tests

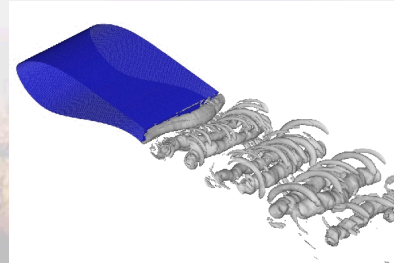


Field Tests



**Goal:
Predict and
Quantify Noise
and Drag of
Flatback Airfoils**

Computational Modeling

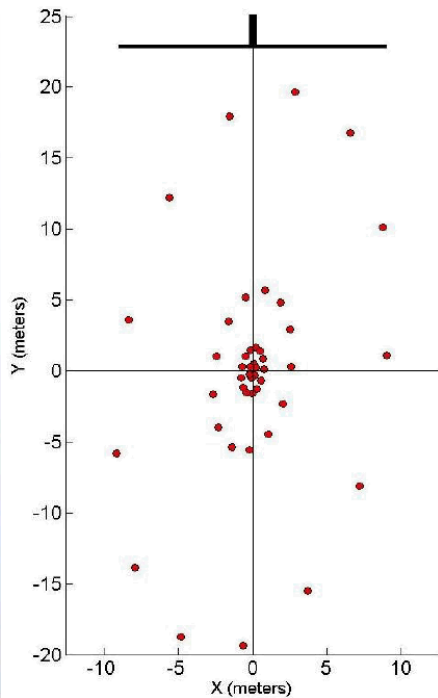


Acoustic Instrumentation for BSDS Field Test

With Pat Moriarty, NREL

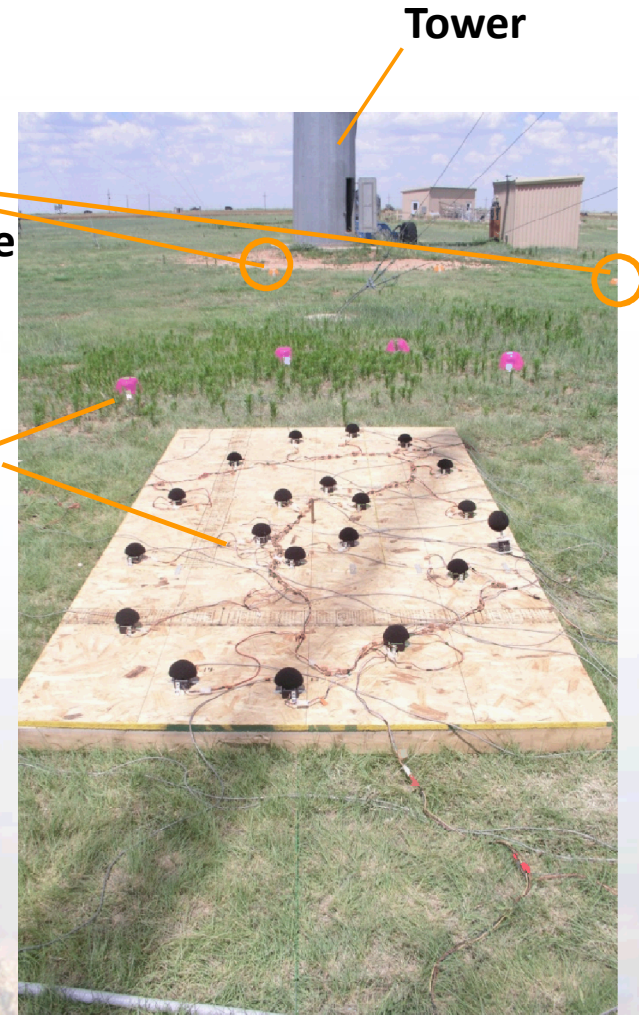
Microphone Phased Array Schematic

45 Total Sensor Locations, configurable to either a low-frequency or high-frequency array.



Low-frequency
Microphone Ellipse

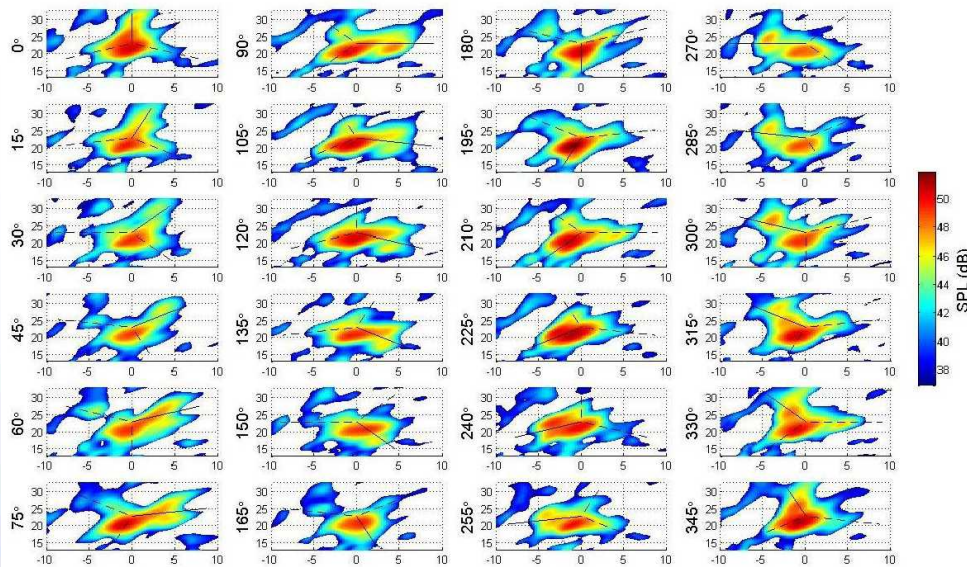
High-frequency
Microphone Ellipse



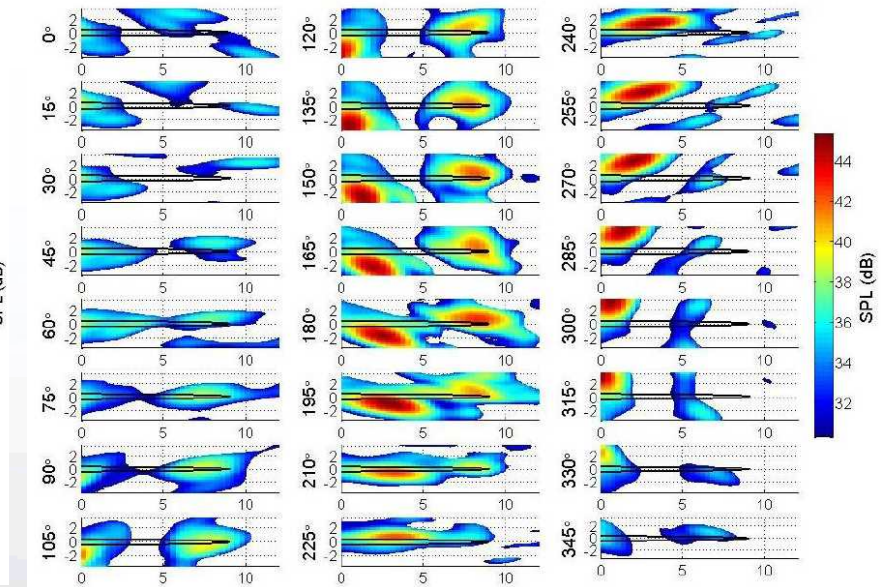
Acoustic Measurements

Averaged Noise Maps at Different Blade Azimuth Positions

250 Hz – Entire Rotor



1250 Hz – Single Blade



Drive train noise dominates low frequencies.

Blade aeroacoustic noise visible at higher frequencies.

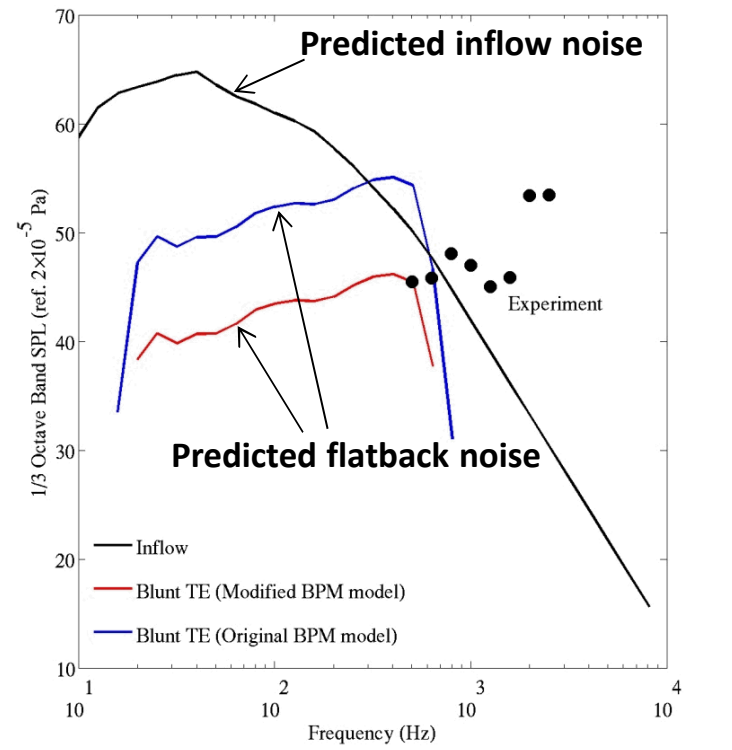


Modeling of Flatback Noise

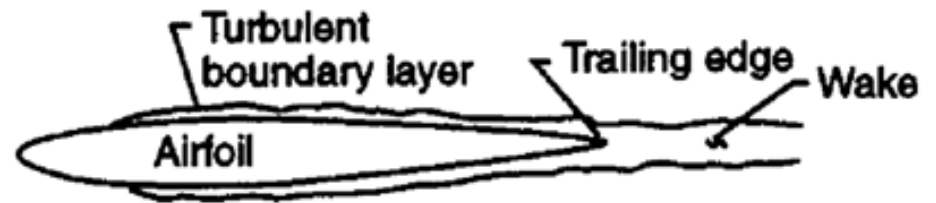
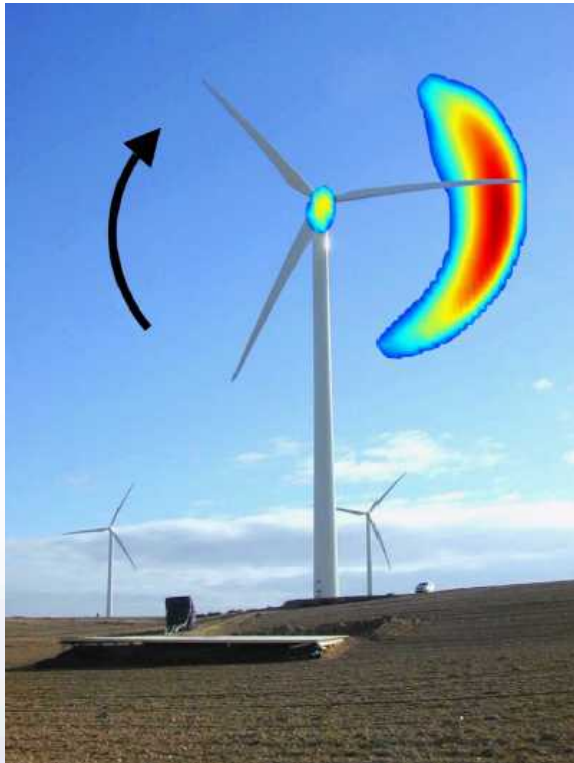
● Flatback Noise Source

Source characteristics determined from CFD and wind tunnel experiments

Rotor-averaged Noise spectra for a ground observer one hub height upwind
Wind Speed = 8 m/s



Wind Turbine Blade Trailing Edge Noise



Turbulent boundary layer - trailing edge (TBL-TE) noise

(from Brooks, Pope, Marcolini, NASA Ref. Pub. 1218)

Trailing edge noise is the dominant aeroacoustic noise source on modern utility-scale HAWTs.

(S. Oerlemans, Ph.D. Thesis, U. of Twente, 2009)



Acoustic Modeling Issues

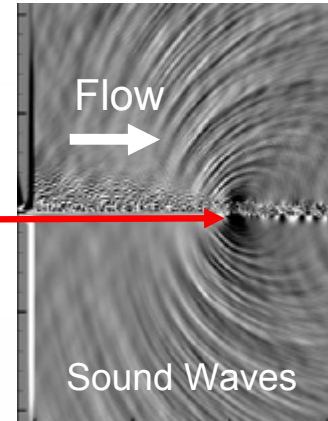
- **Trailing edge noise is difficult to predict using empirical models**
 - Sensitive to airfoil trailing edge shape
 - Sensitive to boundary layer properties
- **Direct computation of the trailing edge noise sources using high-fidelity CFD methods is possible – *if* we only focus on small flow regions of interest**
- **Large-Eddy Simulation (LES) of a complete wind turbine and all noise sources not feasible in the near future (especially for design purposes)**
 - Must divide the noise modeling problem into sub-parts which can each be solved in the most efficient way possible



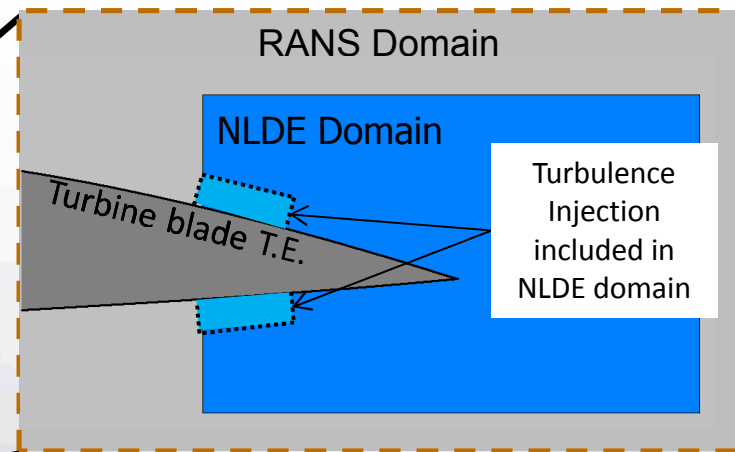
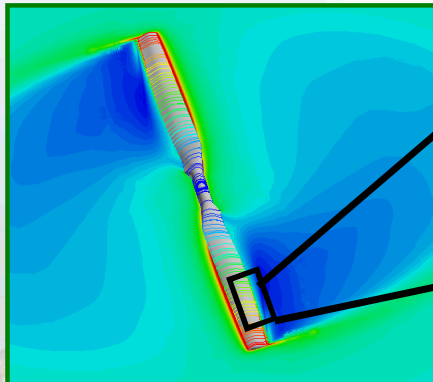
TANDEM (Turbulence And Noise using Disturbance Equation Method) Code

- In collaboration with Phil Morris, Ken Brentner, and Monica Christiansen at Penn State University
- Approach is based on the Nonlinear Disturbance Equations (NLDE), solved using Computational Fluid Dynamics (CFD).
- High-order numerical schemes accurately resolve aero-acoustic sources and sound waves.

Simulation of a turbulent boundary layer interacting with a sharp edge to produce sound
Sandberg & Sandham, J. Fluid Mech., 2008.



Step 1.
Full Rotor RANS Simulation



Step 2.
Isolate blade TE for detailed turbulent boundary layer simulation



CACTUS: **Code for Axial and Cross-flow Turbine Simulation**

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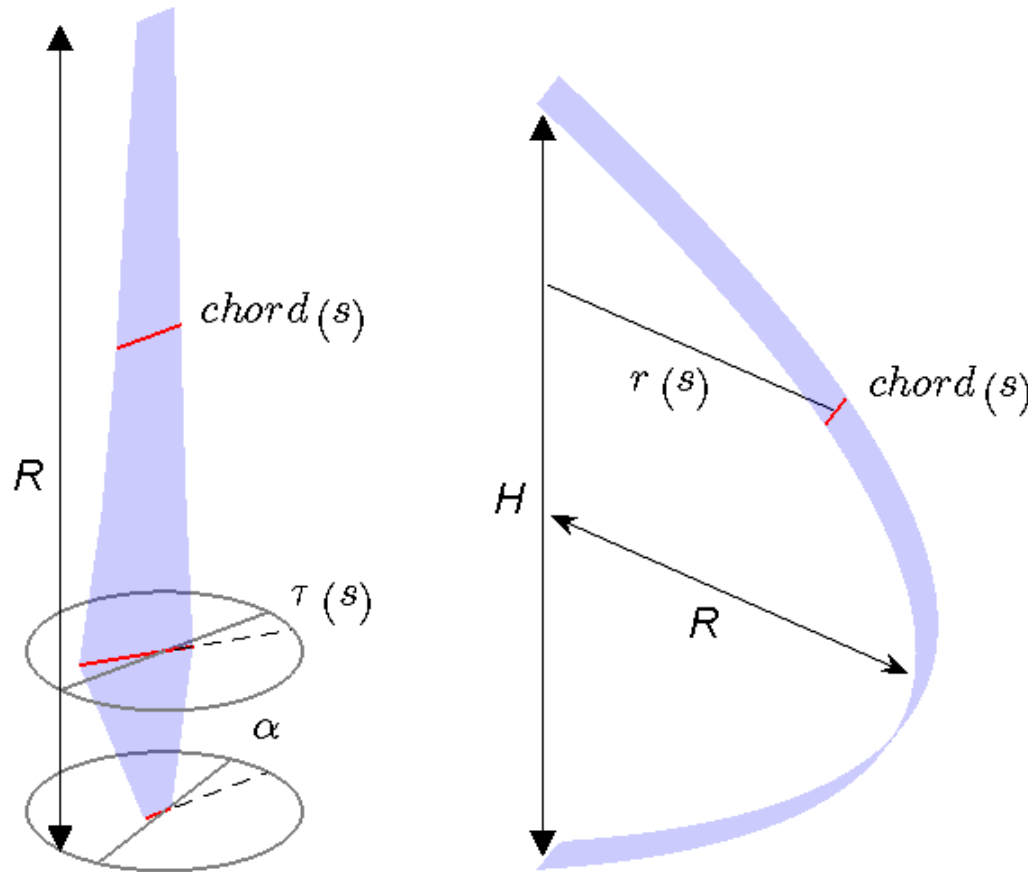
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CACTUS Overview

- **Marine and wind turbine performance simulation**
- **Potential flow representation of fluid dynamics**
 - Lifting-line element description of blade
 - Free vortex lattice description of wake
 - Panel elements used on boundaries (bottom and free surface)
- **VDART3 heritage**
 - SNL free vortex wake code for Darrieus wind turbines
- **Fortran 95 implementation**
 - Modular code structure



Rotor Geometry



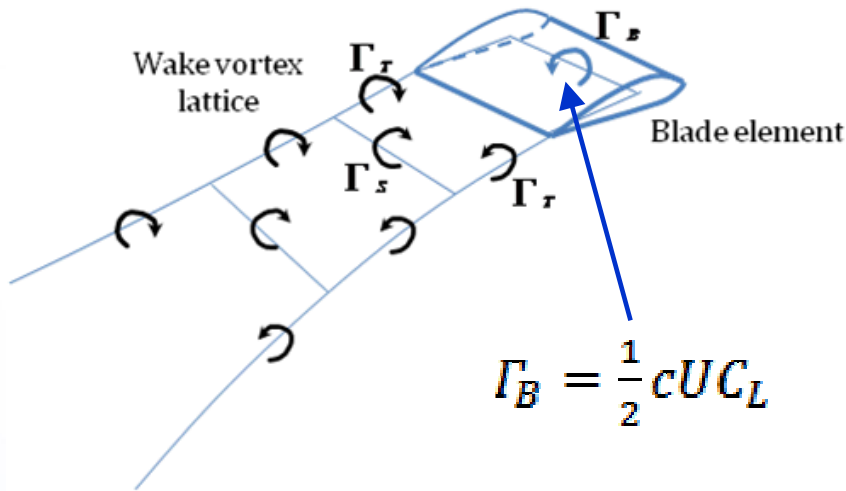
- Can model both axial and cross-flow rotors
- General user-specified geometry interface is planned

a) Axial turbine blade

b) Cross-flow turbine blade



Blade Element Method



■ Blade loads from empirical data

- Steady 2D airfoil data including non-linear effects
- Attached flow dynamic effects from pitching flat plate theory
- Additional models for dynamic stall effects

■ Blades represented as lifting lines

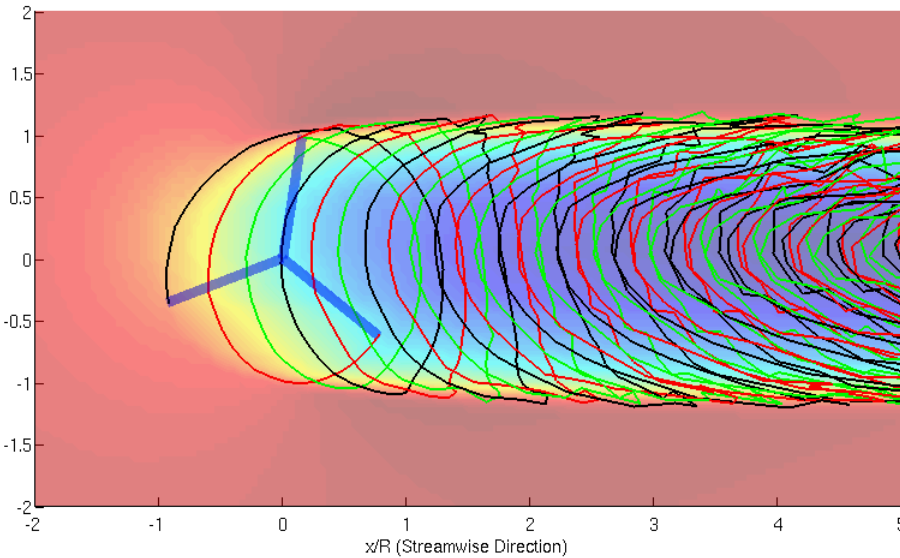
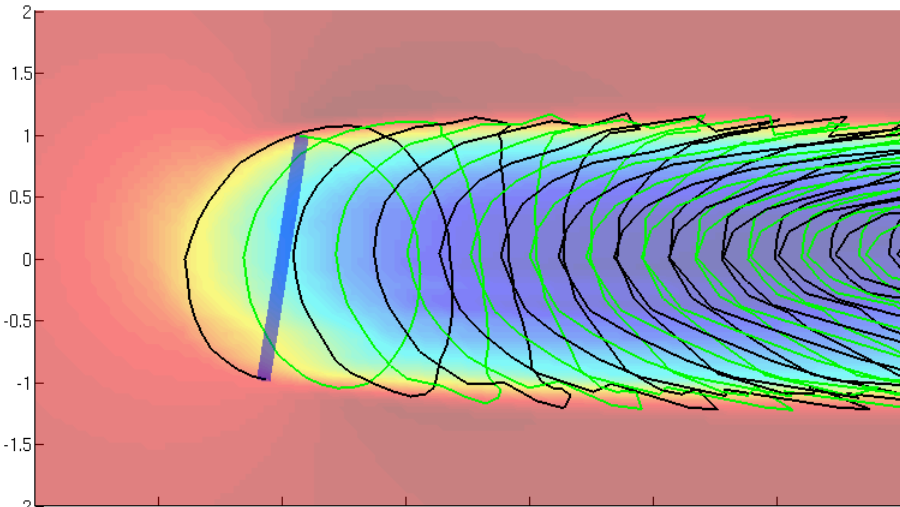
- Bound vorticity on each element given by Kutta-Joukowski theorem
- Spanwise variation in bound vorticity creates trailing wake vorticity
- Temporal variation in bound vorticity creates spanwise wake vorticity

■ Bound and wake vorticity model effects of rotor on fluid flow

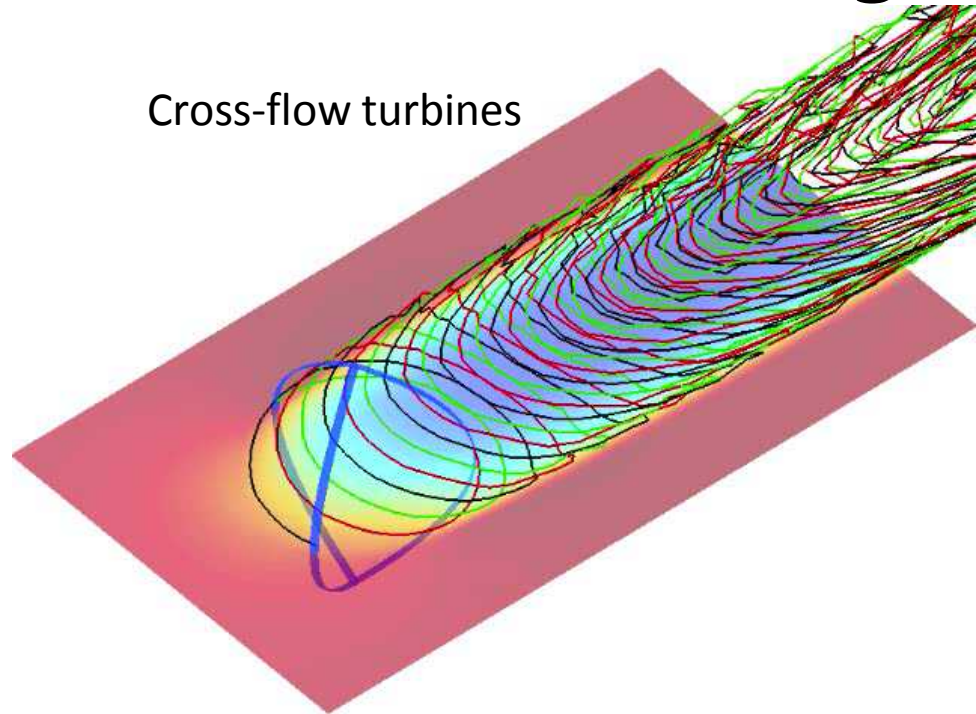


MATLAB Post Processing

Axial-flow turbines



Cross-flow turbines



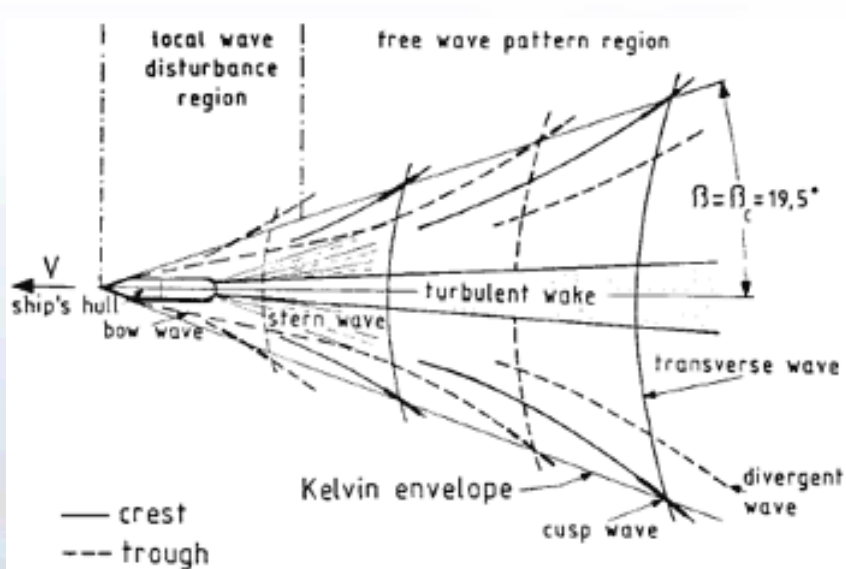
- Visualizations of velocity field and vortex filament traces.

Free Surface Verification

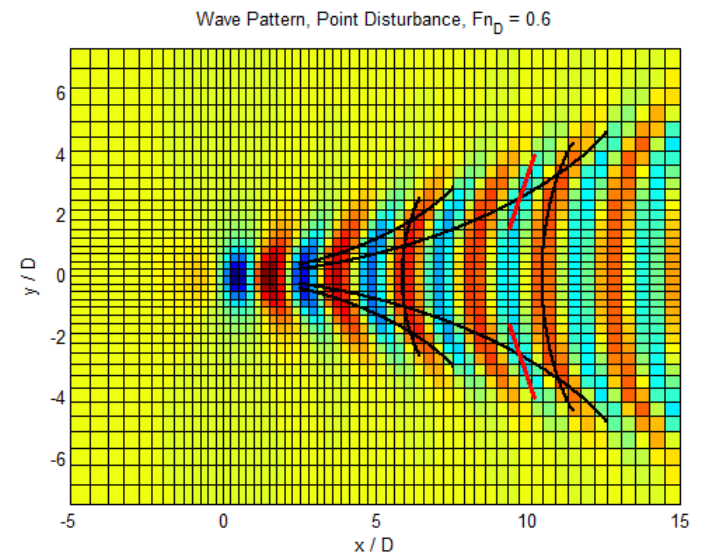
■ Point disturbance submerged below surface

- Water surface b.c. imposed by rectangular source panels
- Relevance to MHK problem: submerged rotor disturbance

Theoretical Wave Train



Calculated Wave Pattern



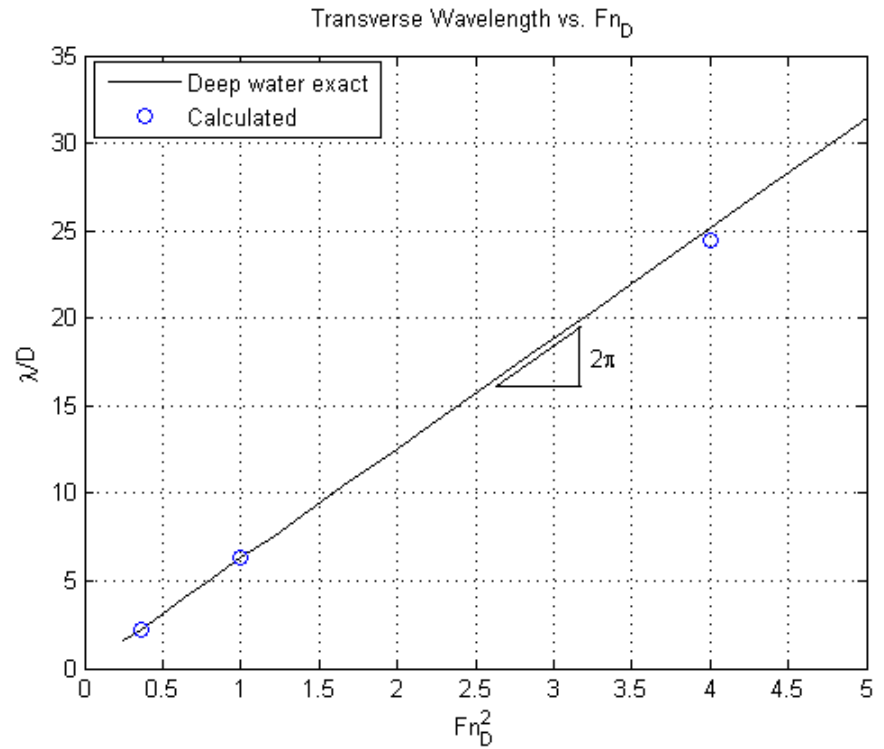
Free Surface Verification (cont.)

■ Free surface BC implemented as a quasi-static boundary

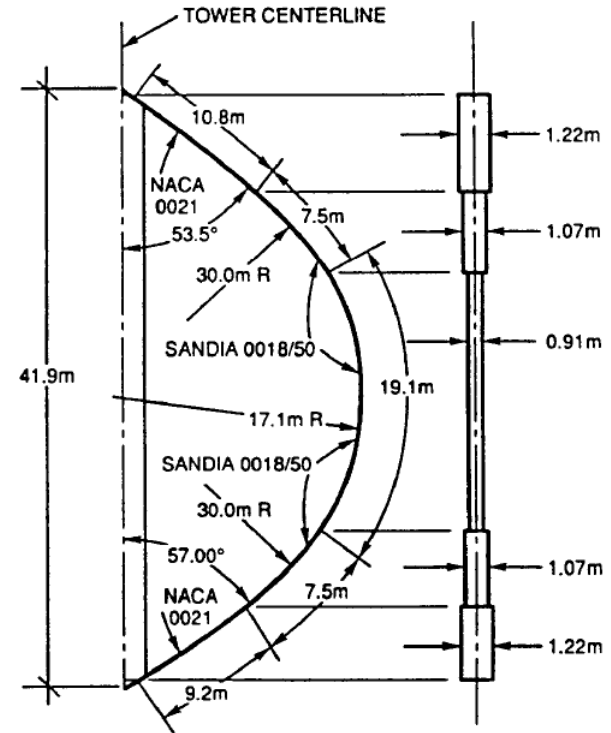
- Time scale of wake dynamics longer than turbine rotational period
- Better assumption at high tip speed ratio

■ Grid scale requirements

- Scale of Kelvin wave train decreases indefinitely with Fn
- In low- Fn limit, free surface BC becomes solid wall BC
- CACTUS replaces free surface with solid wall at low Fn



Validation: Sandia 34 Meter VAWT



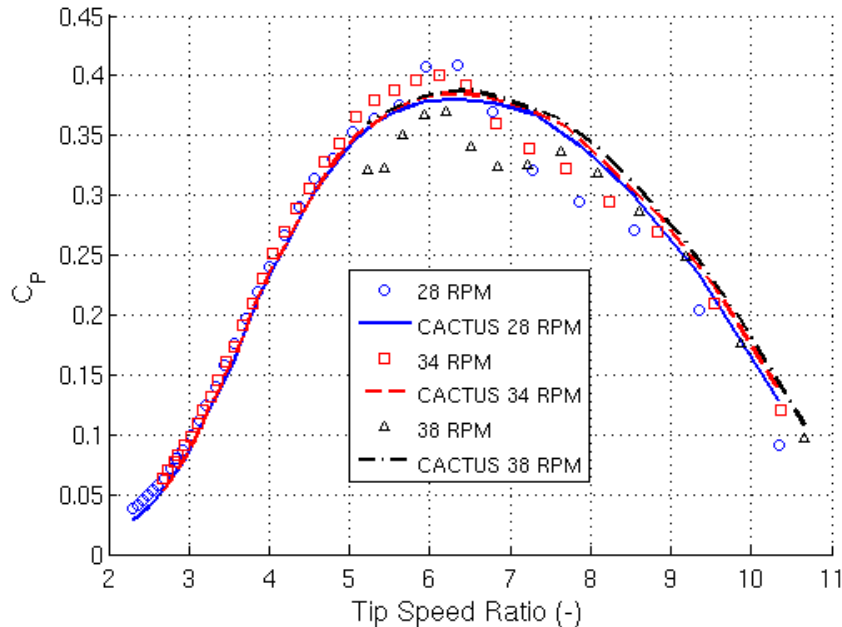
- 500 kW turbine built to study advanced VAWT concepts
 - 34 meter diameter, 1.23 height to diameter ratio, 13% solidity
- Variable chord along blades, NLF airfoil sections



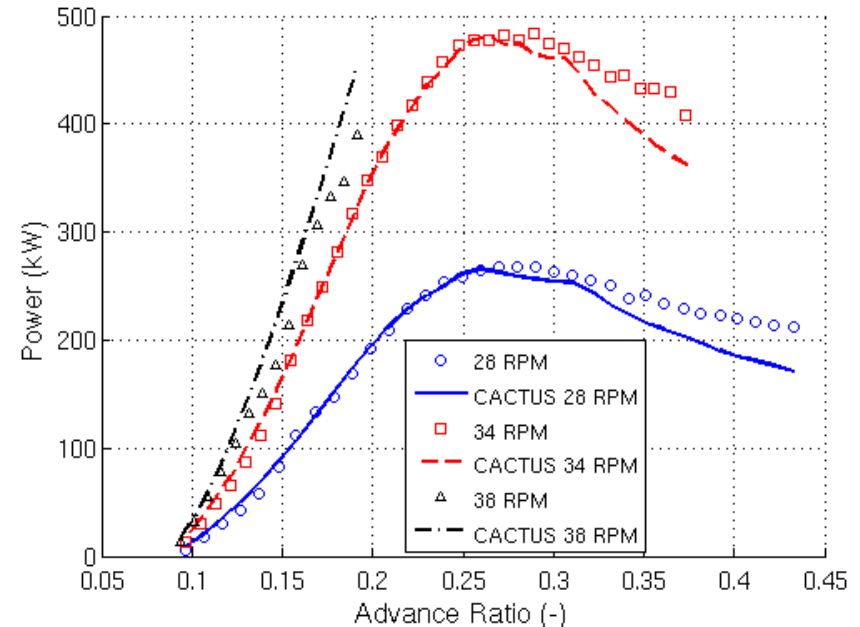
Sandia 34m Results

$$C_p = \frac{P}{\frac{1}{2} \rho U^3 A}$$

Power Coefficient, Measured and Predicted
Sandia 34m Turbine



Power, Measured and Predicted
Sandia 34m Turbine



■ Baseline simulations performed at each RPM

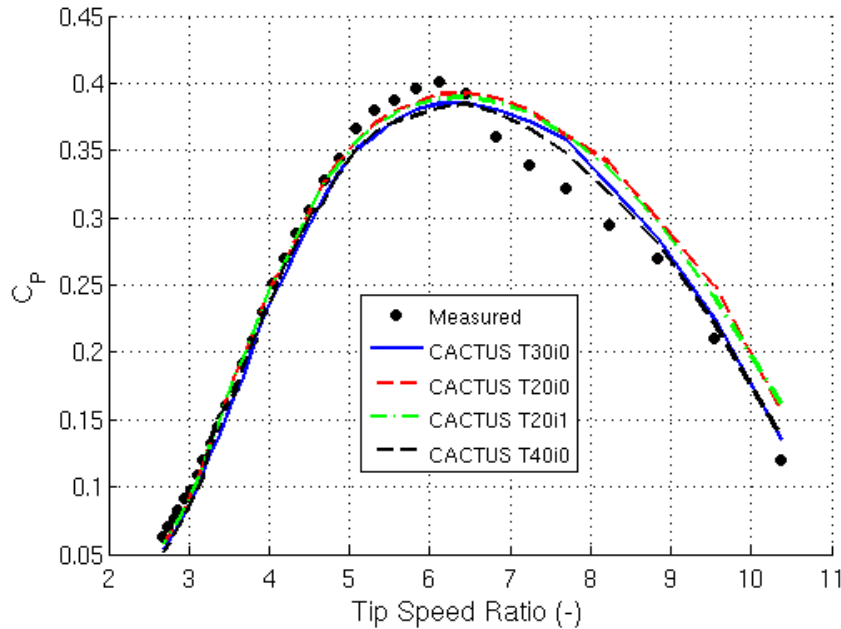
- 13 elements per blade, 30 time steps per revolution

■ Generally good agreement up to advance ratio of 0.3

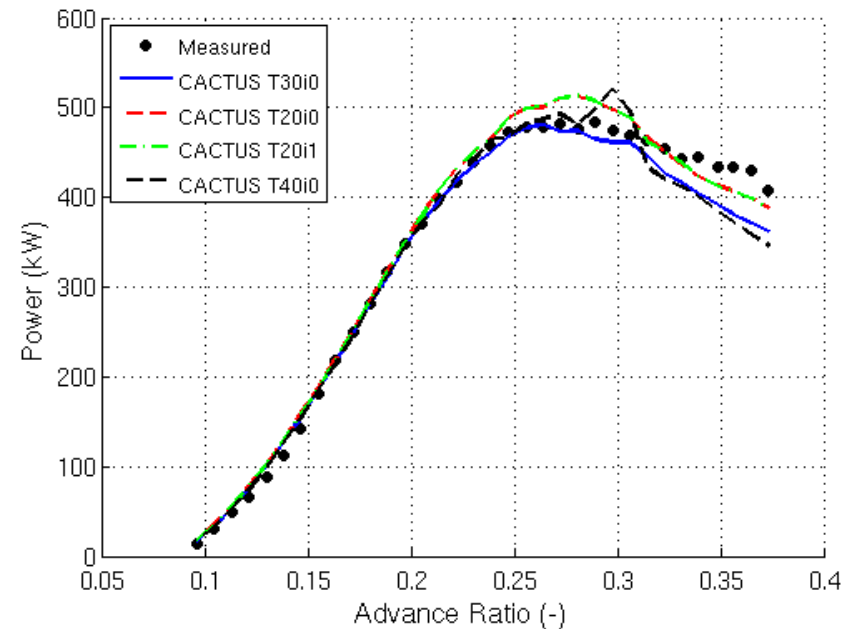


Sandia 34m Results-cont'd

Power Coefficient 34 RPM, Measured and Predicted
Sandia 34m Turbine



Power 34 RPM, Measured and Predicted
Sandia 34m Turbine



- **Convergence with temporal resolution investigated at 34 RPM**
 - 20-30 time steps per revolution required for 1% convergence
- **Wake velocity freezing has little effect on accuracy**



Future Enhancements

■ Cavitation onset prediction

- Significant damage is possible for blades^{mb4} operating in cavitating flow
- Onset when fluid pressure reaches vapor pressure

■ Panel element blades

- Full description of blade geometry and near field flow
- May be necessary for high solidity rotors

■ Acceleration of wake influence calculations

- Wake velocity influence calculation is very expensive
- Parallel implementation on GPU
- Calculation easily ported using CUDA programming language

■ Coupling with aero-elastic code



Slide 23

mb4

reworded

mbarone, 1/3/2011

High Performance Computing for Wind Energy: Research at SNL

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Sandia National Laboratories

Sandia High-Performance Computing Resources

- Sandia continues to extend a distinguished record in high performance computing.
- These resources are available for solving problems in wind and water power.



ASCI Red

World's First Teraflop Computer



1.3 Teraflops* (1997)

World Rank: #1



Thunderbird Cluster



53 Teraflops (2006)

World Rank: #6



500 Teraflops (2010)

World Rank: #10

Red Mesa Partition:

- Dedicated to EERE work
- NREL & Sandia users
- 180 Teraflops

*1 Teraflop = 1 Trillion floating point operations per second



Available HPC Resources at SNL

■ Red Sky / Red Mesa HPC Cluster

- Computing Capacity
 - ◆ Red Sky Unclassified: 22.5K cores, 264 Tflops
 - ◆ Red Mesa: 15.4K cores, 180 Tflops
 - ◆ Total: 37.9K cores, 444 Tflops
- Storage
 - ◆ 1100 TB disk space
- Accessibility
 - ◆ Unclassified SNL projects (including energy)
 - ◆ Red Mesa: NREL & SNL energy-related projects
 - ◆ External users under contract to SNL



■ Black Rose Visualization Cluster

- 512 cores for visualizing simulation results



HPC and Wind at SNL: Current Efforts

■ Wind Turbine Rotor Aerodynamic Simulations

- Collaboration with UC-Davis applying NASA Overflow code to full rotor Computational Fluid Dynamic simulations
- Enables innovative design of wind turbine rotors for improved energy capture

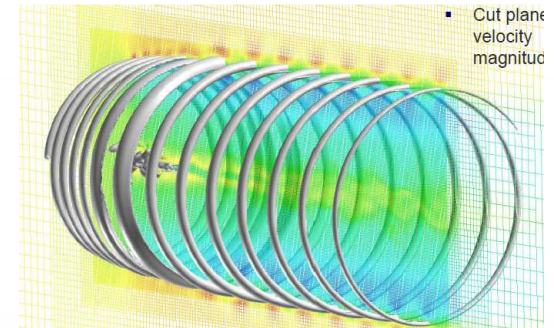
■ Wind Turbine Rotor Noise Prediction

- Investigations of aerodynamic noise of innovative blade shapes using Sandia and Penn State U. CFD tools
- Enables prediction and reduction of wind turbine noise through blade design innovations

■ Wind Turbine Probabilistic Design Methods

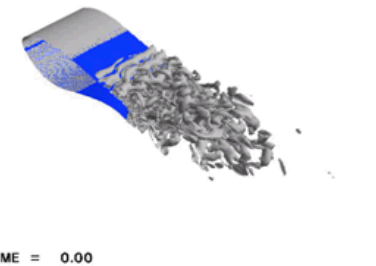
- Office of Science “Advancing Uncertainty Quantification (UQ) in Modeling, Simulation, and Analysis of Complex Systems” Project
- Collaboration between SNL’s Wind Energy, Optimization & UQ , and Computational Mechanics Depts.; Stanford U. and Purdue U.
- Combination of mathematical methods, high-fidelity fluid/structure modeling, and wind application expertise to advance the state-of-the-art in probabilistic design methods for wind turbines

Simulation of a 5 MW Wind Turbine Wake

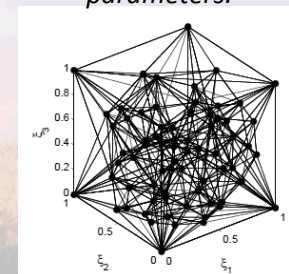


Flow and Noise Simulation of an Innovative Wind Turbine Blade Section

Flatback 10-degs (5h/65)



Sampling uncertain wind turbine design parameters.



Parallel WT Loads Simulations

- Address extreme load environments through large numbers of simulations



SNL Computational Science Expertise

■ **High Fidelity Multi-Physics Modeling**

- Aerosciences Department
- Advanced aerodynamic model development for CFD codes

■ **Massively Parallel Code Development for HPC**

- Computational Thermal and Fluid Mechanics Department
- Aria multi-physics code development (aero,thermal,structural)

■ **Optimization and Uncertainty Quantification**

- Optimization and Uncertainty Estimation Department
- Dakota Software Library

■ **Model Reduction, Optimization, and Inverse Problems using HPC**

- Numerical Analysis and Applications Department



Transformational Technology for Offshore Wind: *Vertical Axis Wind Turbines*

Wind & Water Power Technologies
Sandia National Laboratories



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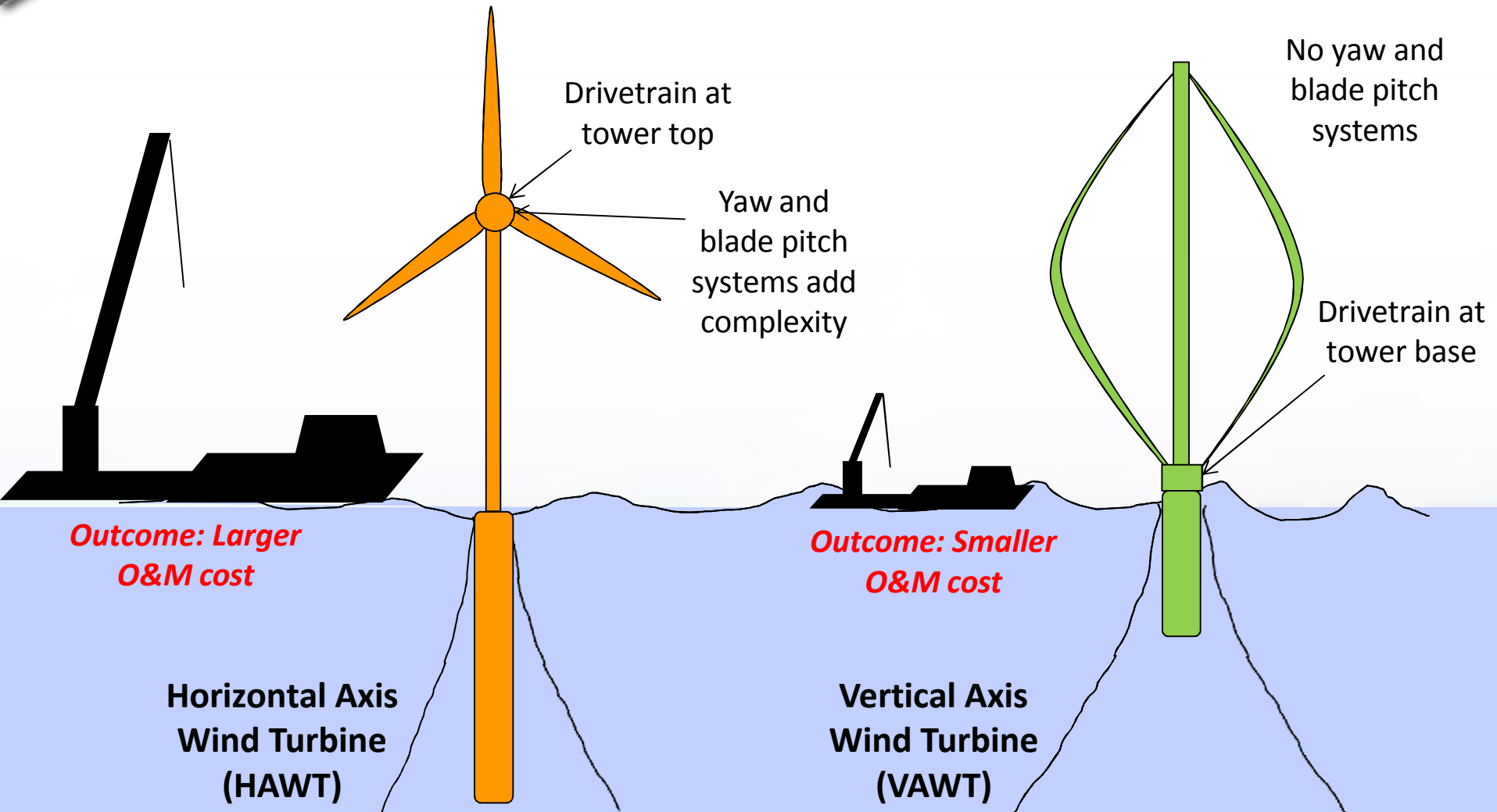


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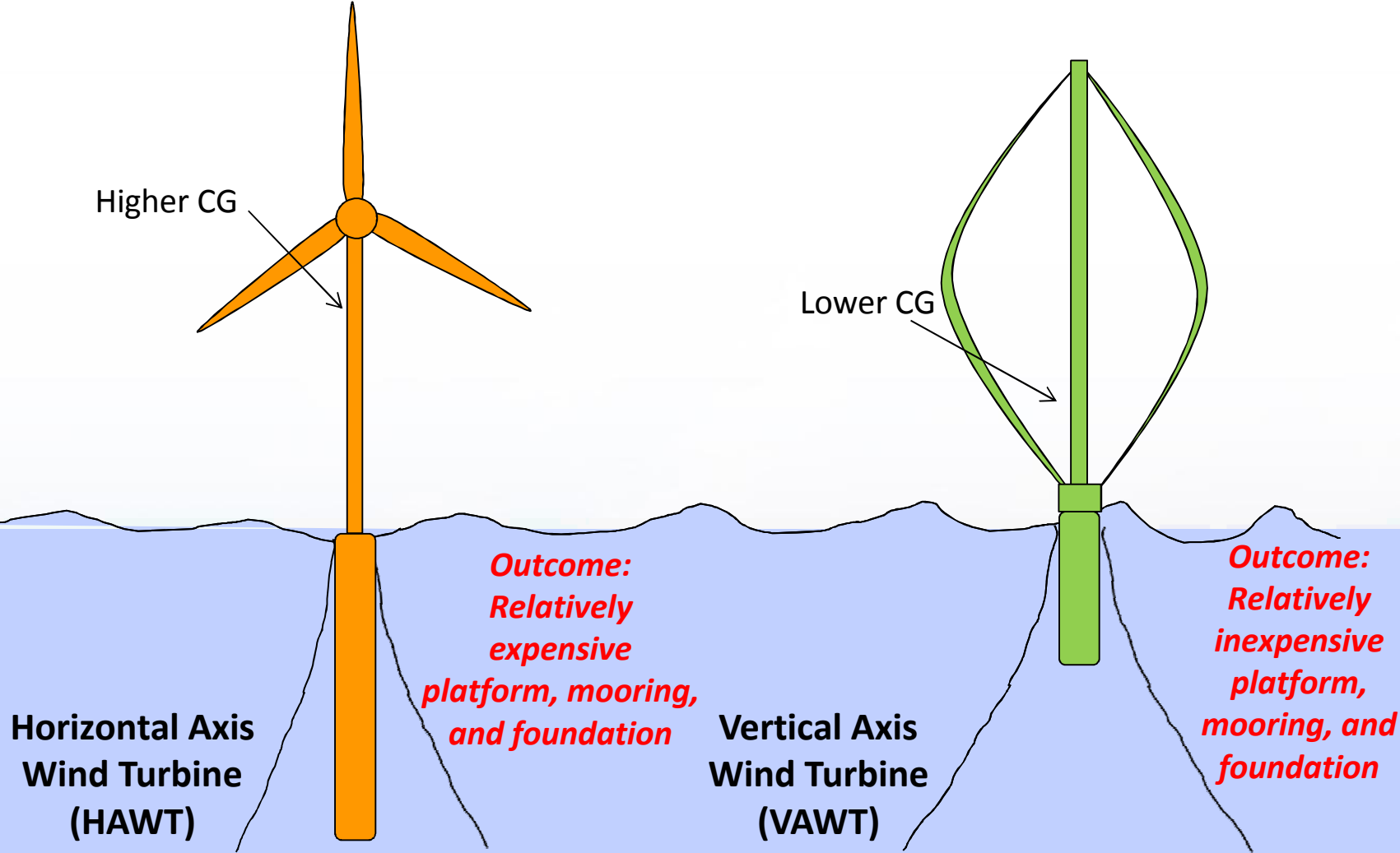
Opportunities



Offshore Design Challenge: O&M Costs > 25% of the Total Project Cost

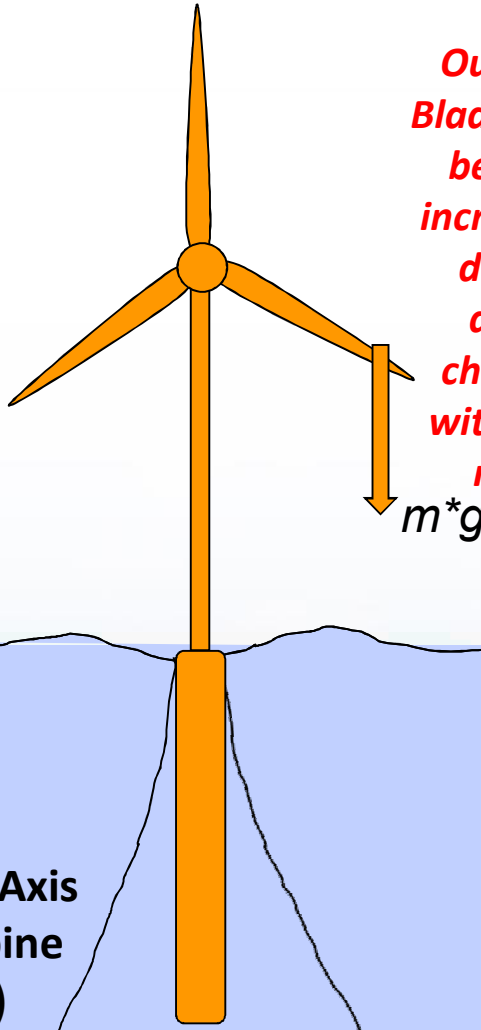


Offshore Design Challenge: Foundation Costs > 20% of Total Project Cost



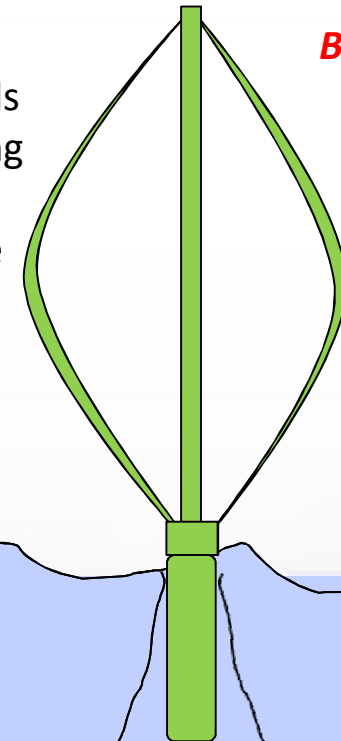
Offshore Design Challenge: Increased Supporting Infrastructure Cost Demand Larger Rotors

Operating cyclical gravity loads and resulting fatigue impact increase with rotor size



Outcome:
Blade weight becomes increasingly difficult design challenge with larger rotors

Operating cyclical gravity loads and resulting fatigue impact are minimal



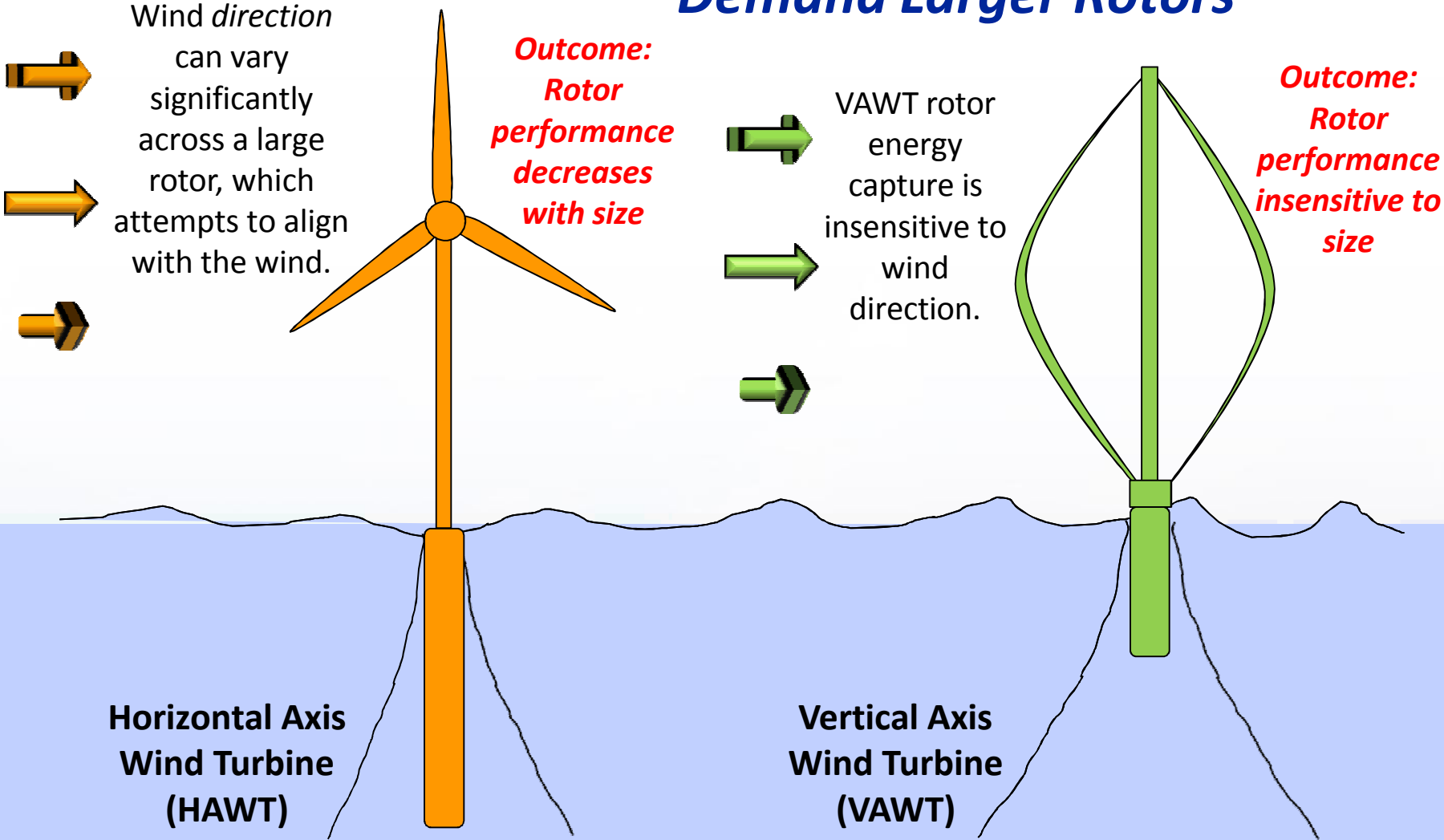
Outcome:
Blade weight does not limit rotor size

**Horizontal Axis
Wind Turbine
(HAWT)**

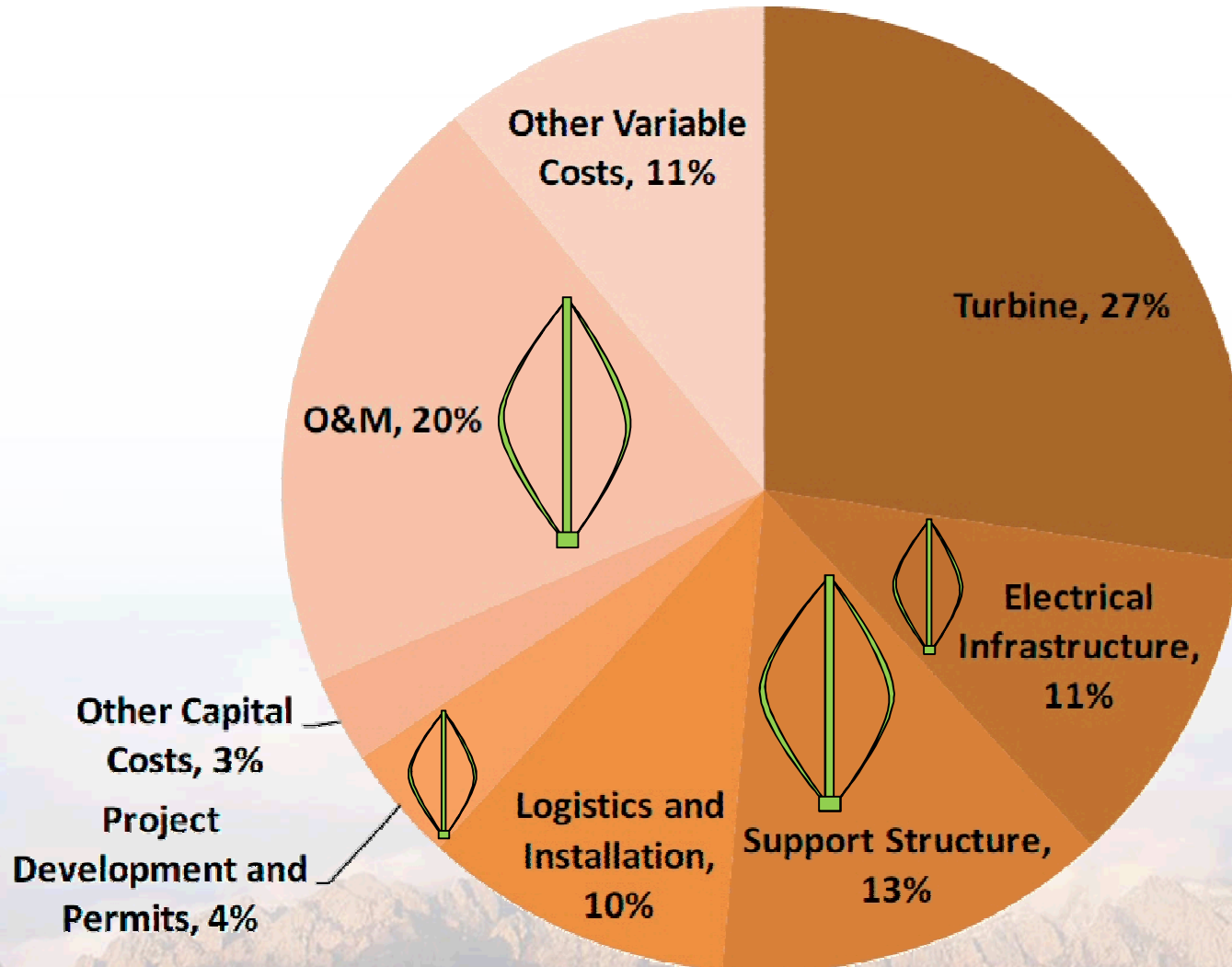
**Vertical Axis
Wind Turbine
(VAWT)**



Offshore Design Challenge: Increased Supporting Infrastructure Cost Demand Larger Rotors



Offshore Life-cycle Cost Breakdown

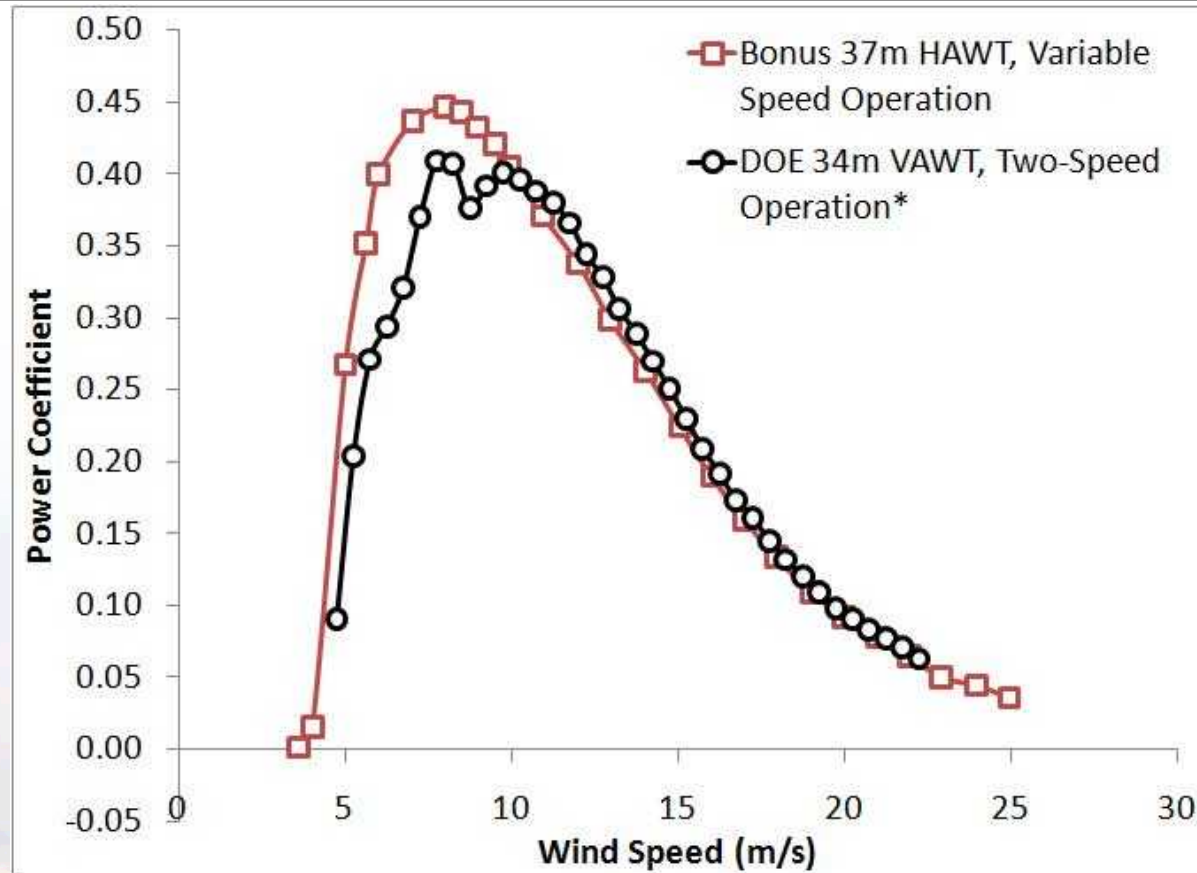


Challenges



VAWT Efficiency

Measured turbine efficiency for circa 1990 variable speed, stall regulated HAWT compared with the DOE 34 m research VAWT (1990).

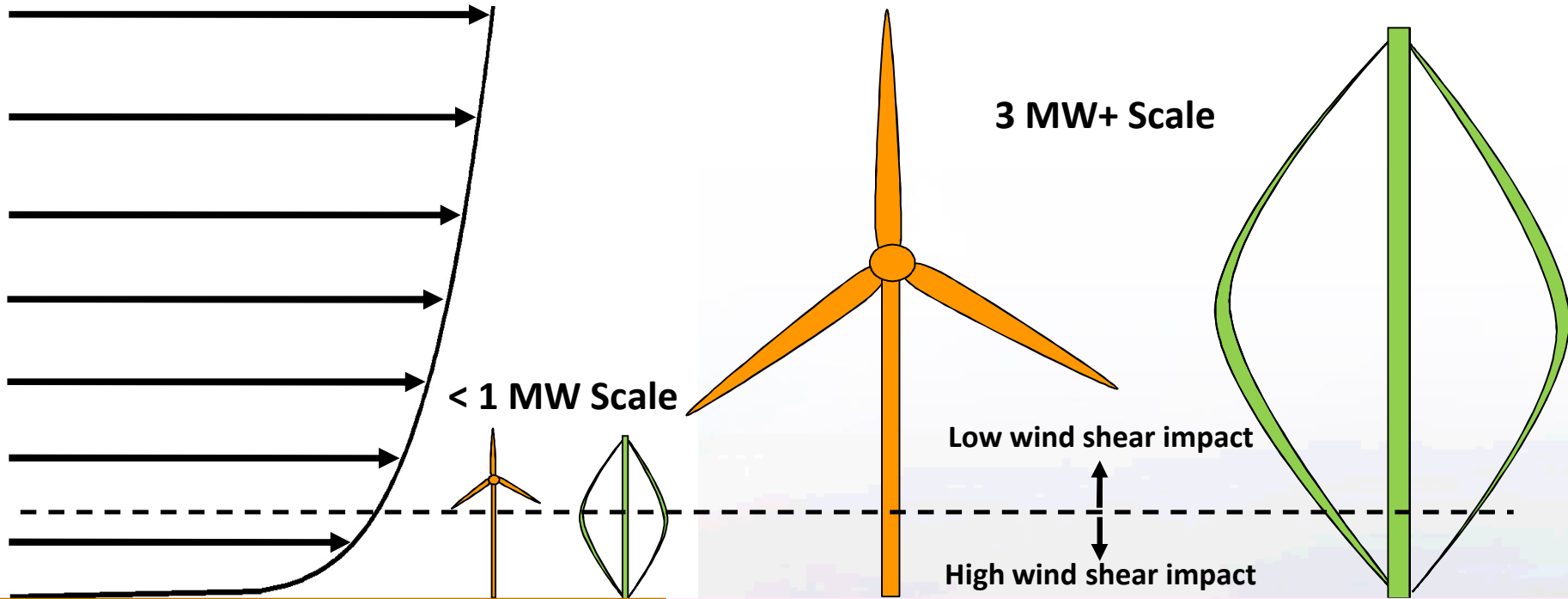


*True variable speed VAWT operation would improve performance at low wind speeds.



VAWTs and Wind Shear

Wind Velocity Profile



Impact of wind shear on VAWT performance decreases with turbine size.

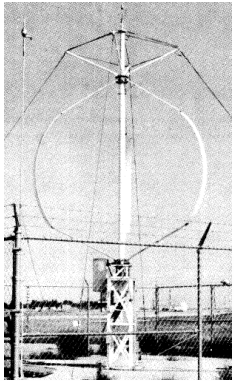




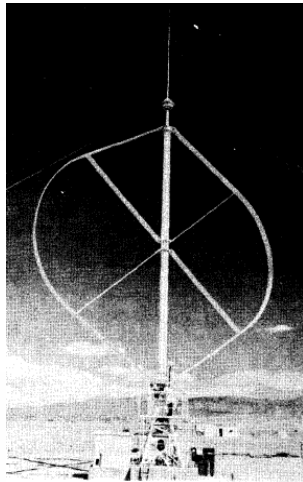
Sandia VAWT History



Sandia VAWT Research



5m VAWT



65kW 17m VAWT



500kW 34m VAWT Test Bed



3.5MW Eole (consultants)

**Original VAWT Research
Staff Available as Resource**

SNL Wind Staff

Tom Ashwill

Dale Berg

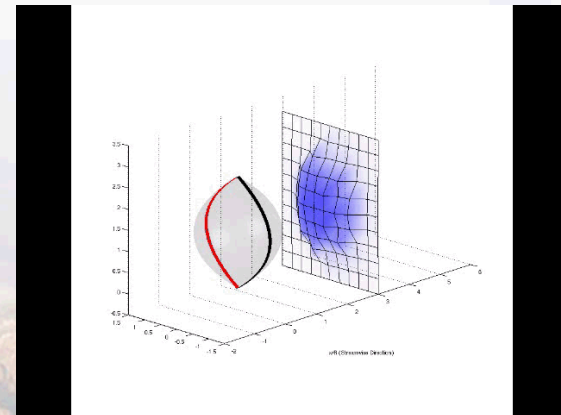
Mark Rumsey

Consultants

Herb Sutherland

Don Lobitz

**DOE Water Power Program – CACTUS code
Code for Axial and Cross-flow Turbine Simulation**



Sandia VAWT Accomplishments

1975	SNL Wind Program Established
1977	17m VAWT Fabricated
1979	VDART3 Vortex-based VAWT Aerodynamics Analysis Code Developed
1980	Dynamic Stall Model Incorporated in Aero Codes
1981	First Wind-Turbine Specific Airfoils Designed
1981	Impact of Stochastic Wind on Wind Turbine Fatigue First Investigated
1982	FloWind Technology Transfer Initiated
1984	VAWTPOWER Technology Transfer Initiated
1988	34m VAWT Test Bed Dedicated
1988	SNL/MSU Material Database Established



Sandia VAWT Publications

A representative listing of Sandia reports on VAWT Technology

"Measured Data for the Sandia 34 Meter Vertical Axis Wind Turbine"

T.D. Ashwill, SAND91-2228

"Numerical Simulation of VAWT Stochastic Aerodynamic Loads Produced by Atmospheric Turbulence: VAWT-SAL Code"

G.F. Homicz, SAND91-1124

"Selected Papers on Wind Energy Technology" (a compilation of 16 technical papers on VAWT Technology)

Sandia National Laboratories Staff, SAND90-1615

"Initial Structural Response Measurements and Model Validation for the Sandia 34-Meter VAWT Test Bed"

T.D. Ashwill, SAND88-0633

"Modal Testing the EOLE"

T.G. Carne, J.P. Lauffer, A.J. Gomez, SAND87-1506

"Aeroelastic Effects in the Structural Dynamic Analysis of Vertical Axis Wind Turbines"

D.W. Lobitz, T.D. Ashwill, SAND85-0957

"Structural Design of the Sandia 34-Meter Vertical Axis Wind Turbine"

D.E. Berg, SAND84-1287

Some 30 additional reports dealing with VAWT technology can be found on the Sandia Wind & Water Power Technology web site at <http://windpower.sandia.gov/topical.htm#VAWTARCHIVE>



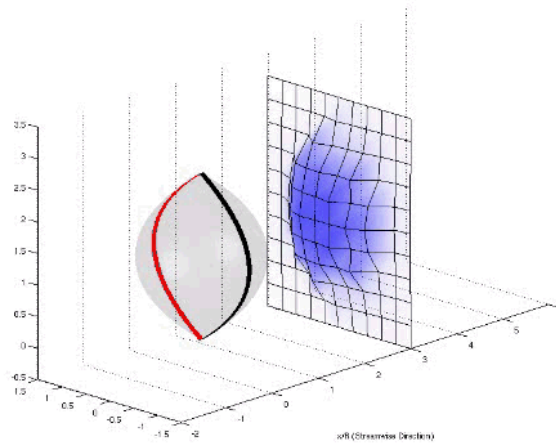
Current Activities



VAWT Performance Analysis: CACTUS Code

- Code for Axial and Crossflow Turbine Simulation
- Turbine Performance and Rigid-Body Hydrodynamic Loads Prediction
 - Blade aerodynamics described by a lifting line
 - Wake dynamics described by an array of vortex filaments
 - Empirical model for parasitic drag losses from strut and blade/strut attachments

Simulation of a Darrieus VAWT

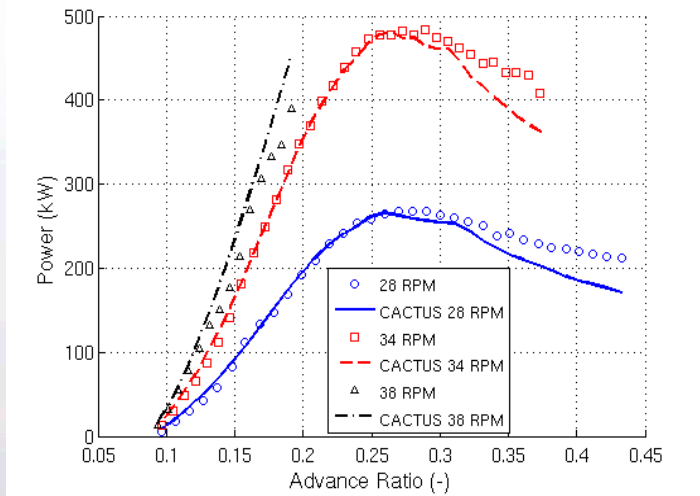


CACTUS Validation

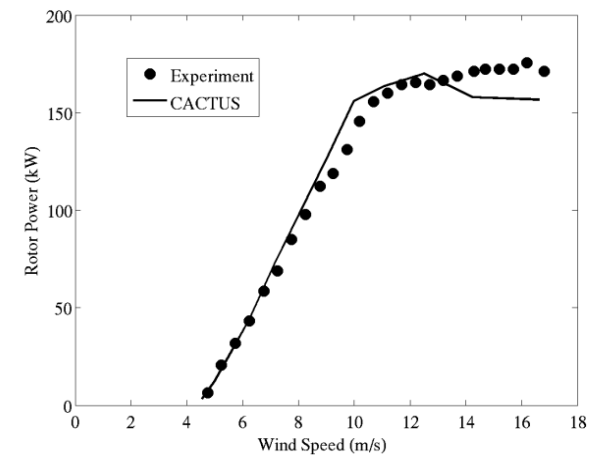
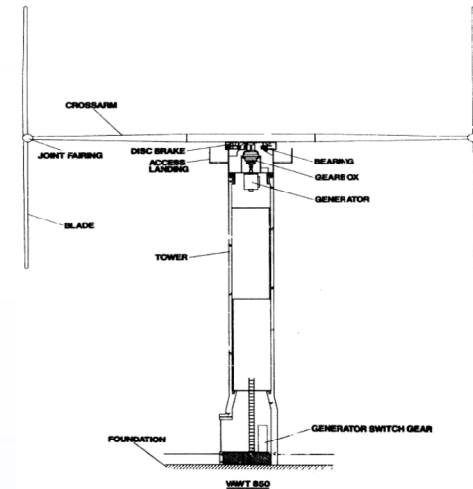
DOE 34 m Darrieus Testbed



Power, Measured and Predicted
Sandia 34m Turbine



UK VAWT 850 H-VAWT

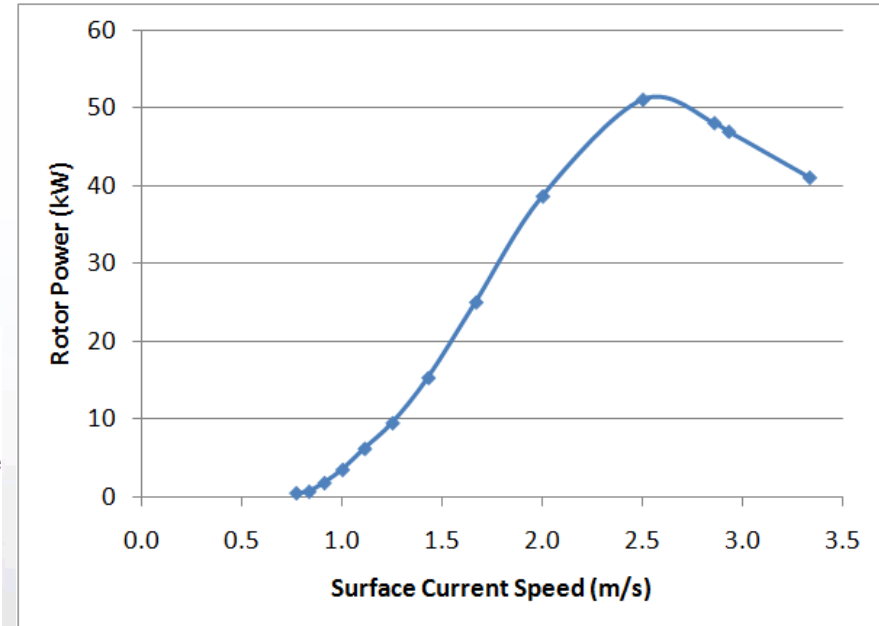
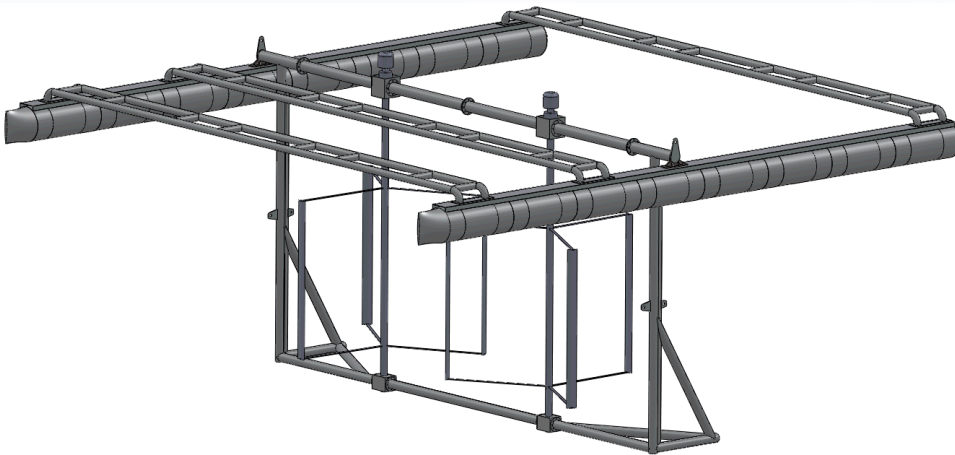


Murray, J. and Barone, M. "The development of CACTUS: a wind and marine turbine performance simulation code, ASME Wind Energy Symposium, Orlando, FL, January 2011.



MHK Reference Model for Riverine Device

Rotor Parameter	Value
Rotor Height (Blade Length)	4.84 m
Rotor Diameter	6.45 m
Rotor Swept Area	31.25 m ²
(Constant) Rotational Speed	14.8 RPM



European Offshore VAWT Research

- **“Future Deep Sea Wind Turbine Technologies”, or “DeepWind”, Project funded under the EU Seventh Framework Programme**
 - Consortium including Riso-DTU, TU-Delft, Aalborg U., industry partners
 - Investigating deep water offshore VAWTs
- **Dr. Carlos Simao Ferreira visited Sandia during the month of November**
 - Involved with aerodynamics of the DeepWind project from TU-Delft
 - SNL/Delft exchanged information on modeling techniques and design philosophies for VAWTs and MHK cross-flow turbines



Wind Turbine Aeroelastic Design Tools

Brian Resor
brresor@sandia.gov
Wind Energy Technologies
Sandia National Laboratories

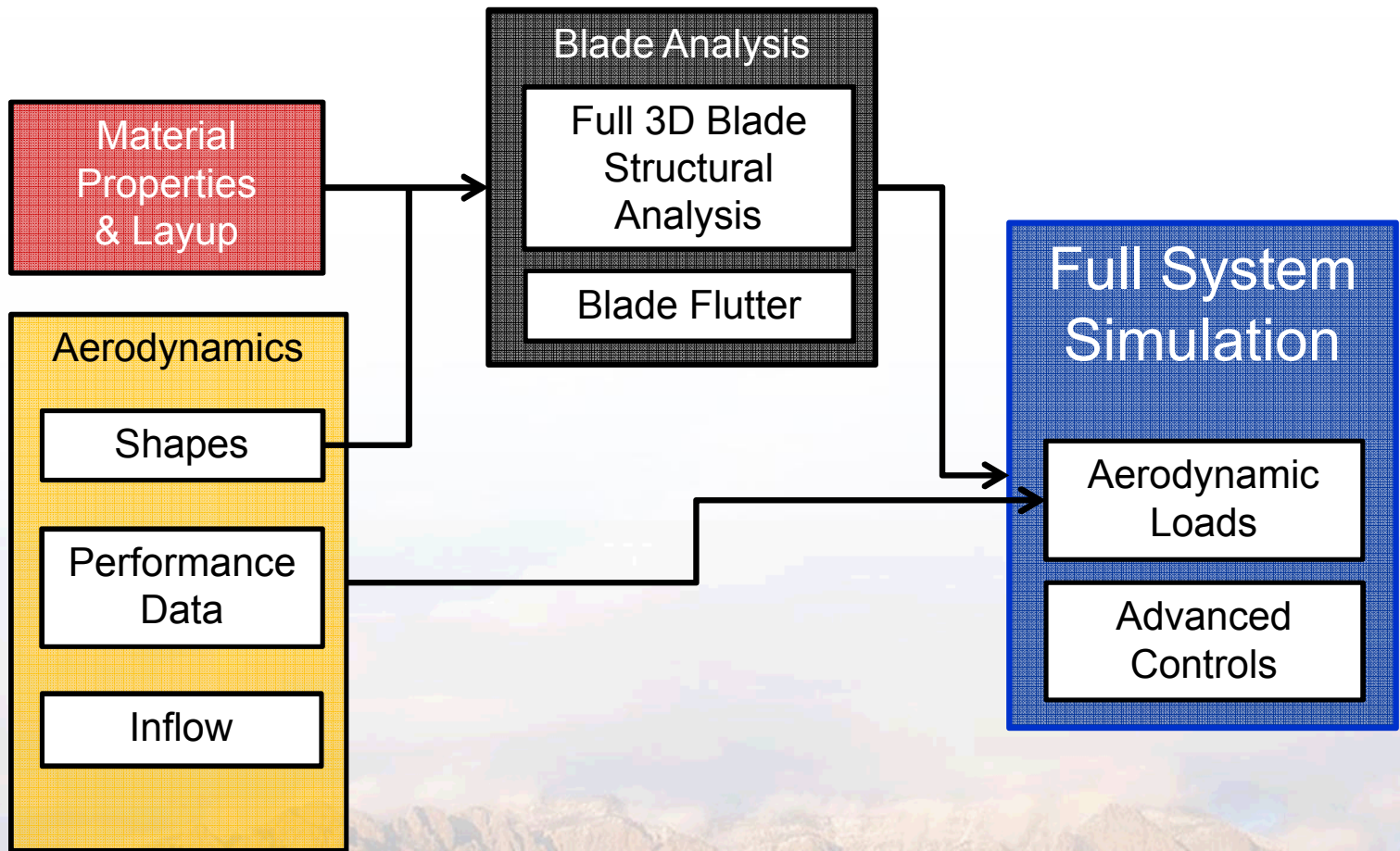


Sandia is a multiprogram laboratory operated by Sandia Corporation, a Lockheed Martin Company, for the United States Department of Energy's National Nuclear Security Administration under contract DE-AC04-94AL85000.



Sandia National Laboratories

Wind Turbine Design/Analysis Elements

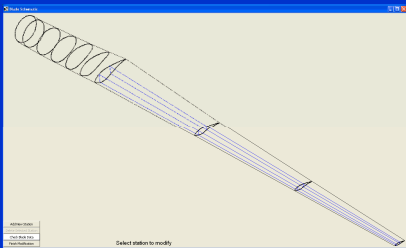


Blade Design with NuMAD

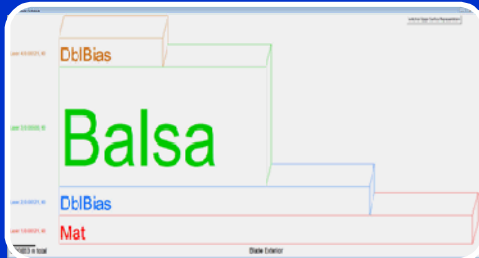
NuMAD

NuMAD:
Numerical Manufacturing
And Design Tool

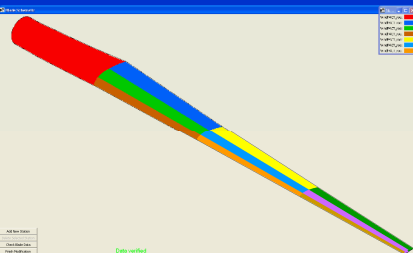
Blade Geometry



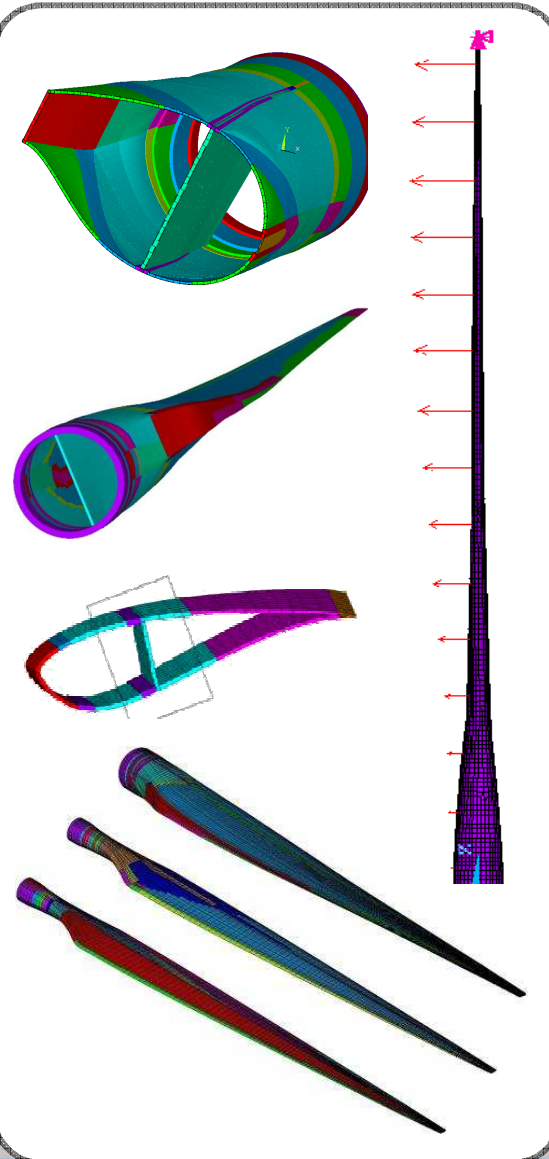
Materials & Layups



Stack Placement

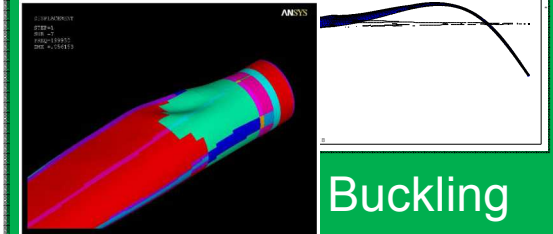


ANSYS FE Model



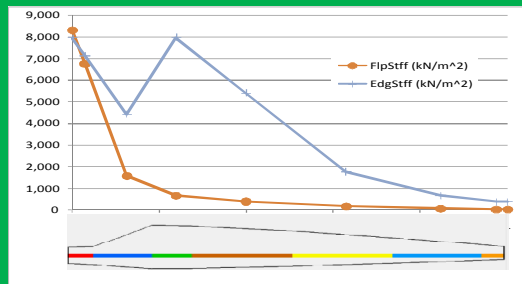
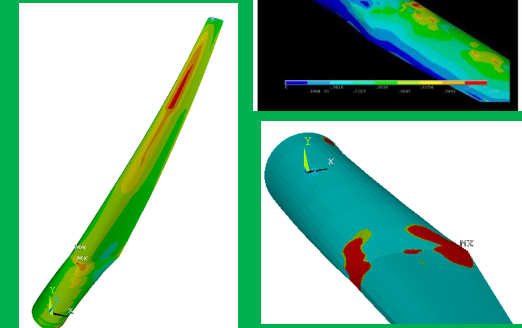
ANSYS Analysis

Modal



Buckling

Stress & Strain



Beam Properties

NuMAD Geometry and Materials

■ An example:

The screenshot shows the NuMAD software interface. The main window displays a 3D model of a blade section, segmented into different material layers. The control panel on the left includes the following sections:

Station Parameters:

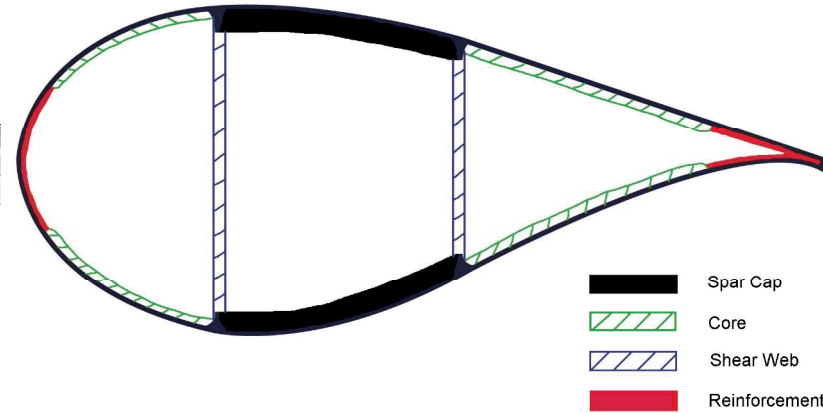
- Airfoil: WP15_root1
- TE: sharp
- Twist of station: 10.5 deg
- Chord length: 1.9846 m
- Normalized X offset: 0.48
- Aerodynamic Center: 0.25
- Distance from root: 1.96 m

Skin Material Division Points:

- number: 1
- type: single
- surface: Lower (HP)
- % chord: 50
- chordal distance: 0.9923
- surface distance: 1.4878

Shear Webs:

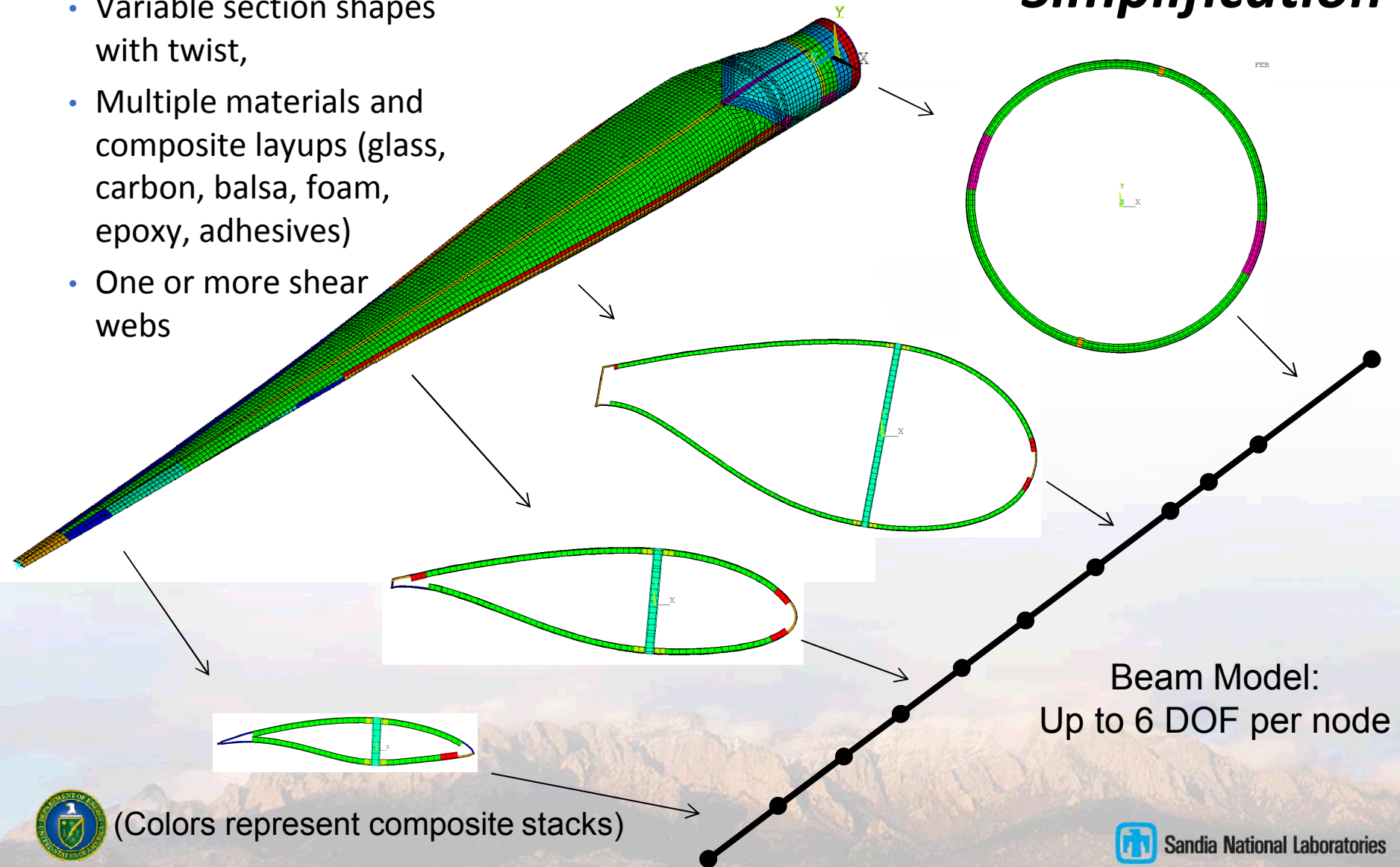
- number: [empty]
- material: **UNSPECIFIED**
- station: [empty]
- Upper DP: 4
- Lower DP: 1



Blade Structural Model Simplification

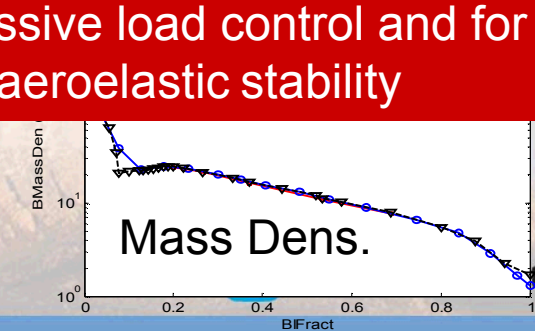
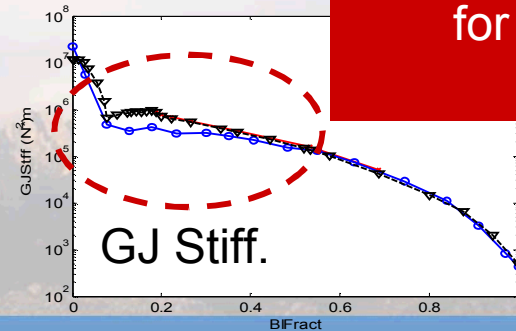
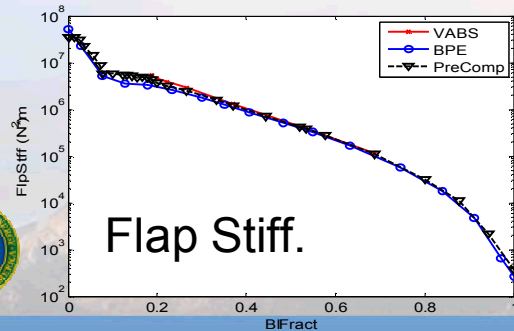
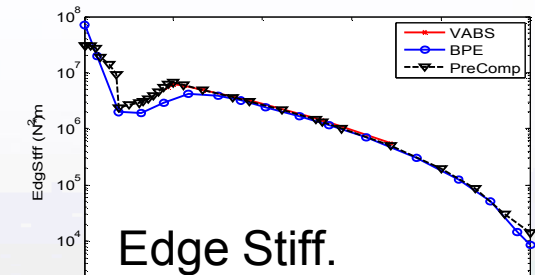
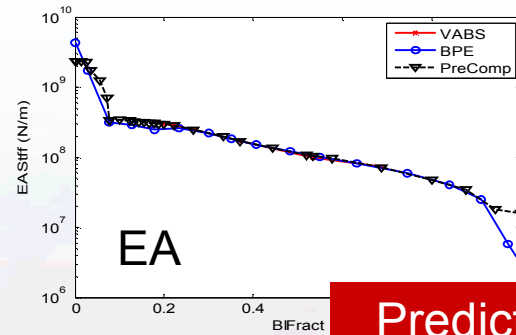
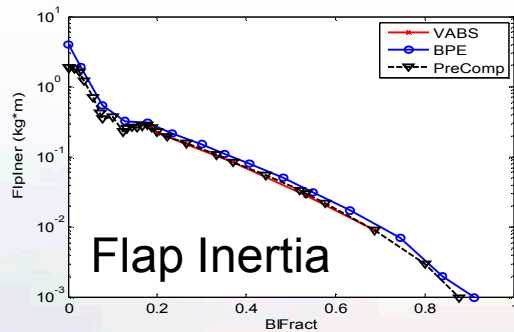
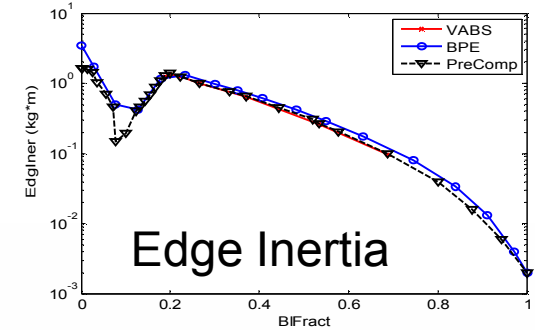
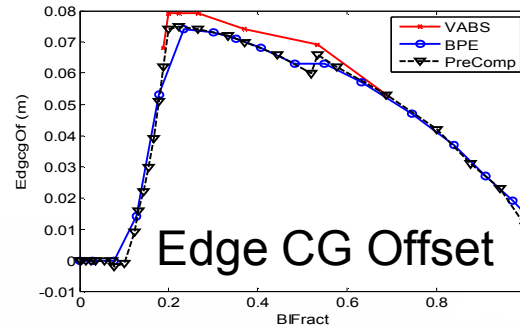
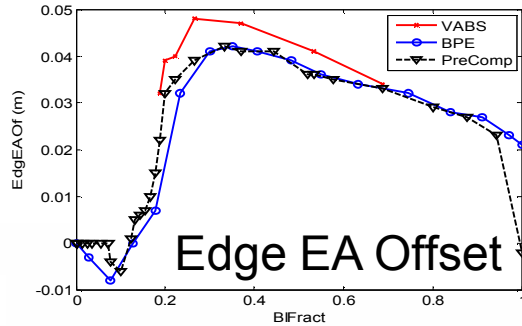
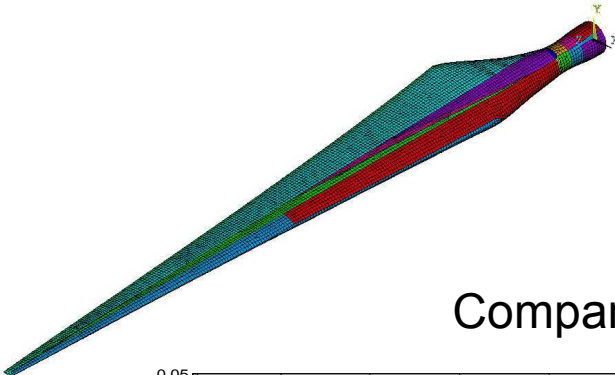
Wind turbine blades include

- Variable section shapes with twist,
- Multiple materials and composite layups (glass, carbon, balsa, foam, epoxy, adhesives)
- One or more shear webs



Calculate Beam Properties

Comparing three techniques: BPE, PreComp & VABS



Prediction of Stiffnesses are important for passive load control and for aeroelastic stability



Sandia Classical Flutter Capability

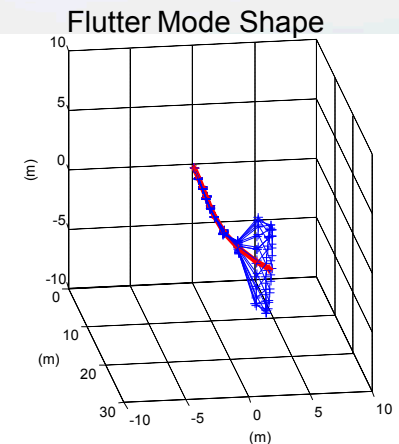
■ Current capability utilizes:

- MSC.Nastran: used for beam formulation and for complex eigensolver
- FAST2NAST.m (Matlab routine)
 - ♦ Required inputs: lift curve slope and pitch axis location along with information taken from ad.IPT and blade.DAT files utilized by AeroDyn and FAST
- Fortran executable
 - ♦ Determines necessary mass, stiffness, and damping matrix additions due to aerodynamic effects (Theodorsen)
 - ♦ Generates additional Nastran decks for the **complex eigenvalue solve**

■ Iterates on operating speed, following the complex modes, to find the flutter speed

$$[M + M_a(\Omega)]\{\ddot{u}\} + [C_C(\Omega) + C_a(\omega, \Omega)]\{\dot{u}\} + [K(u_0, \Omega) + K_{tc} + K_{cs}(\Omega) + K_a(\omega, \Omega)]\{u\} = 0$$

Matrix	Description
M, C, K	Conventional matrices (with centrifugal stiffening)
$M_a(\Omega)$, $C_a(\omega, \Omega)$, $K_a(\omega, \Omega)$	Aeroelastic matrices
$C_C(\Omega)$	Coriolis
$K_{cs}(\Omega)$	Centrifugal softening
K_{tc}	Bend-twist coupling



Challenges & Opportunities for Large Blade Development

Challenges:

Blade weight growth
Manufacturing &
reliability issues
Material volumes & cost
Transportation

Opportunities:

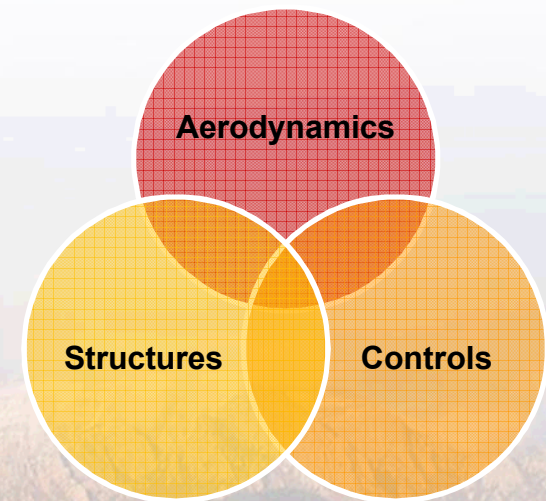
Very thick airfoils for structural efficiency
Material lay-up & choices
Multidisciplinary design optimization
Blade joints
Load alleviation concepts (active &
passive)
Other innovations



Importance of System Analysis

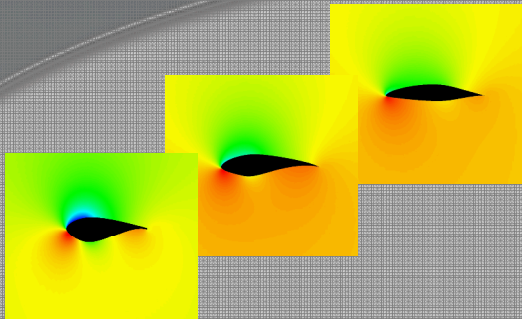
- Full system analysis is required in order to evaluate the capability of the design to withstand loads prescribed by certification standards
- It is just as important to understand and report the cost of an innovation as well as the benefit; Common system costs include
 - Increased forces and moments in the system
 - Increased complexity
 - Decreased energy capture

$$COE = \frac{FCR * ICC + (O \& M)}{AEP}$$

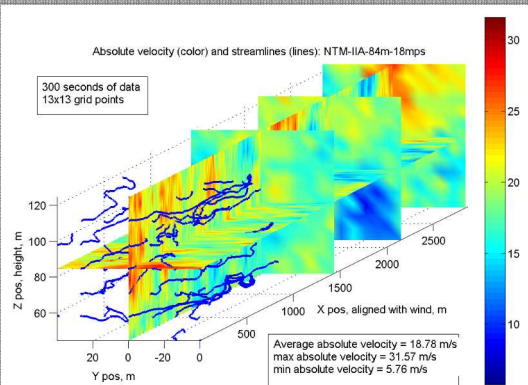


System Analysis with Wind Turbine Aeroelastic Simulation

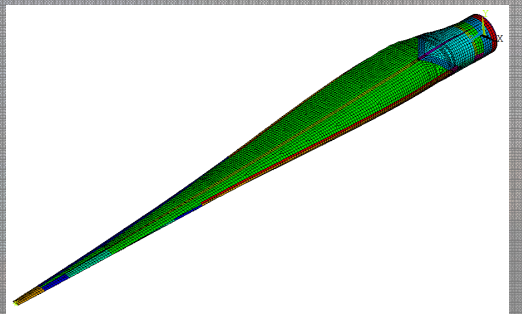
Aerodynamic Performance



Turbulent Wind Input



Structure and Materials

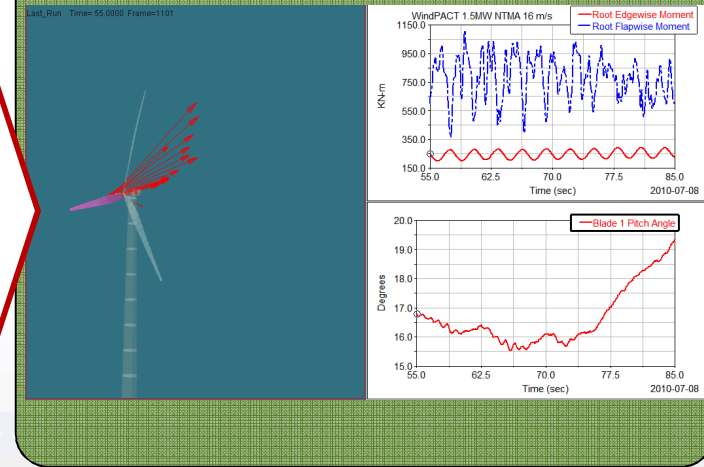


Aeroelastic System Dynamics Model



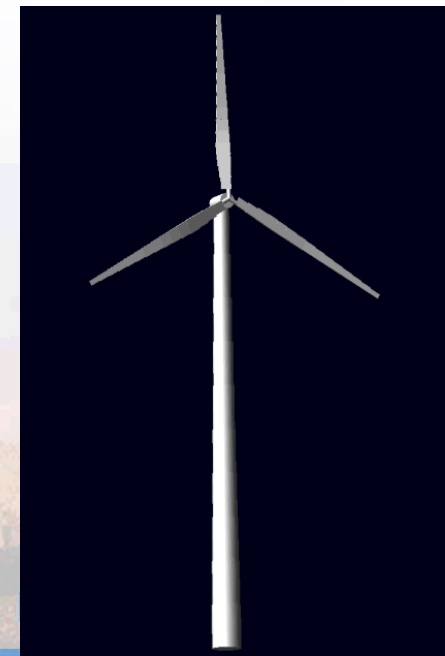
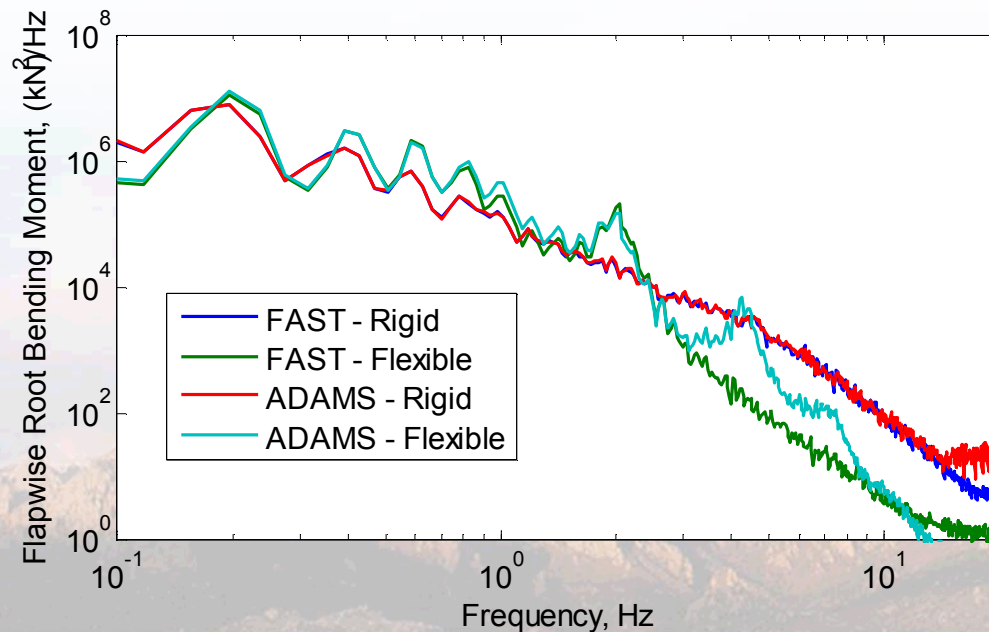
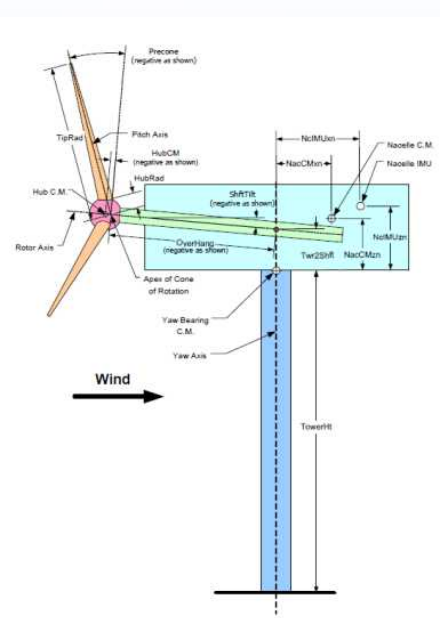
Includes Controls Implementation

System Response

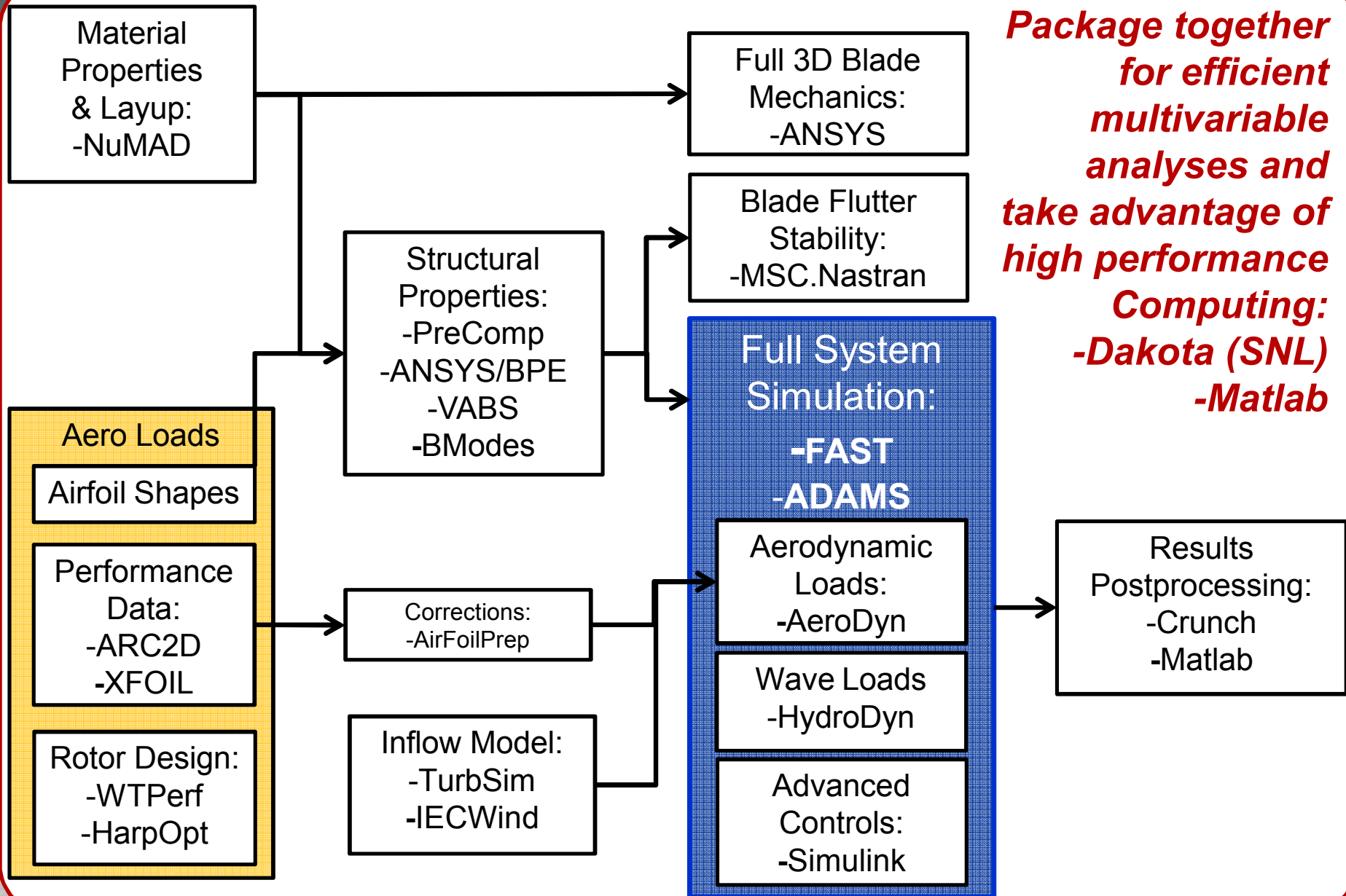


Tools: FAST and ADAMS

	FAST	ADAMS
Available from	NREL	MSC Corporation
Structural modes included	Up to 2 each of blade flap/edge and tower F-A/S-S	Unlimited; depends on discretization
Aerodynamic forces	AeroDyn	AeroDyn
Uses	Very fast computations; Adequate for most work, especially certification	Code verification; Simulations requiring several dynamic structural modes



Wind Turbine Design Tools in Use at Sandia



Areas of interest for the future

■ Full system simulation

- Simulation of passive and active fatigue and extreme load mitigation concepts
 - ◆ Development of effective aerodynamic models to support accurate full system simulation of these concepts
- High performance computing applied to large simulation problems

■ Blades

- Macro, meso and micro modeling of damage and defects
- Techniques for accurate prediction of equivalent beam properties for blades
 - ◆ And high quality experiments to validate these techniques
- Understand and mitigate the panel buckling barrier for large blades
- Blade weight optimization

■ Aeroelastic stability

- Blade design for aeroelastic stability; eg. flutter resistance
- Development/acquisition of a full system aeroelastic stability capability (includes floating turbines)



Thank You

