What's "New" in Blade Aerodynamic Design

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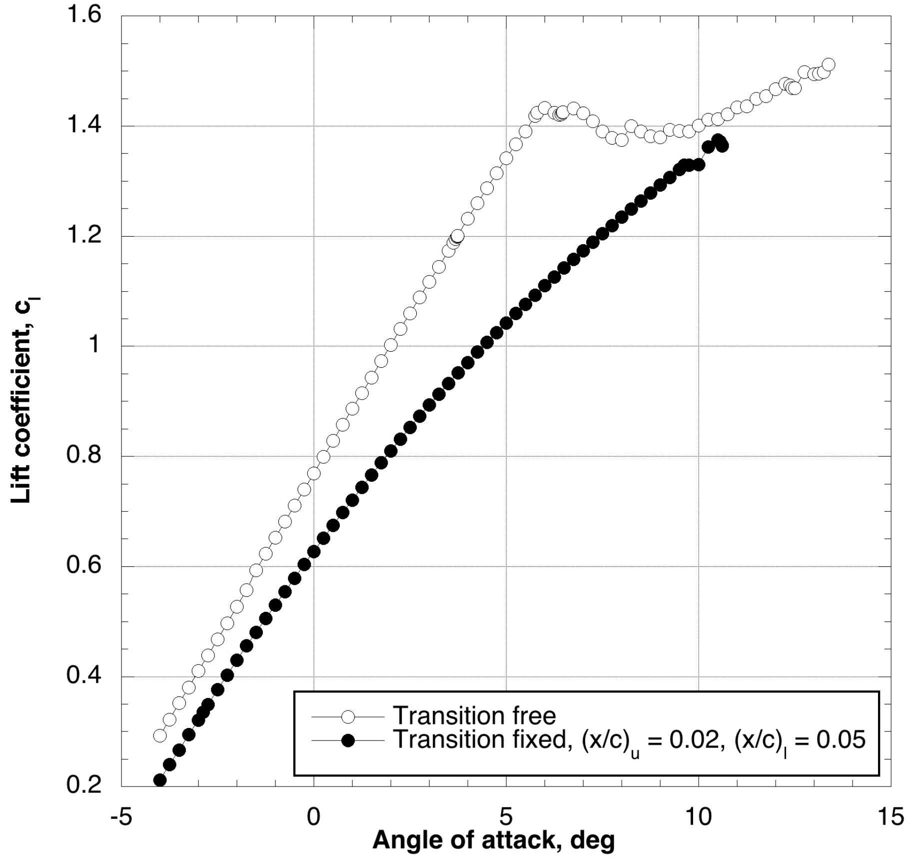
What's "New" in Blade Aerodynamic Design

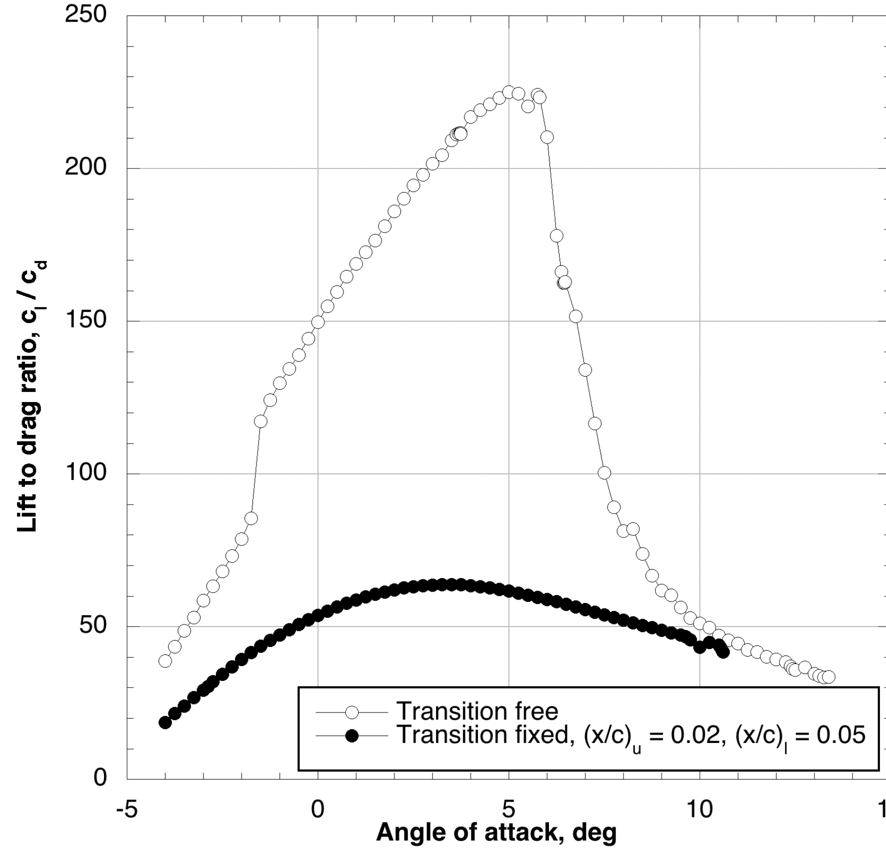
- Introduction
- Concepts:
  - High L/D outboard section shapes
  - Blunt trailing edge inboard section shapes
  - Swept blades
  - Vortex generators
  - Serrated trailing edges
  - Active load control
- Concluding remarks

Overview

- Wind turbine rotor aerodynamics has evolved considerably in past 30 years.
- Main developments:
  - Much improved computational tools for design and analysis
  - From NACA airfoil sections to custom designed section shapes
  - Iterative concurrent blade design: aerodynamics, structures, materials, manufacturing
  - Effect of surface soiling and erosion on performance a reoccurring problem
  - Aeroacoustic noise playing a critical role in blade design

High L/D Section Shapes





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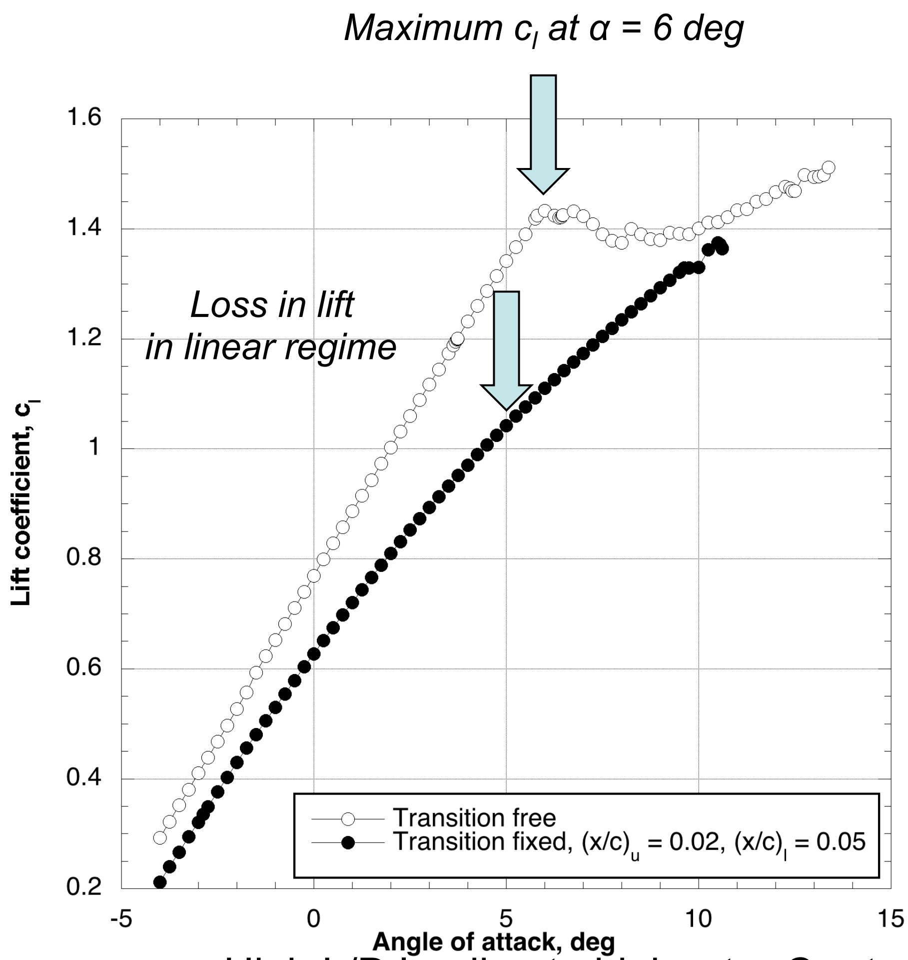
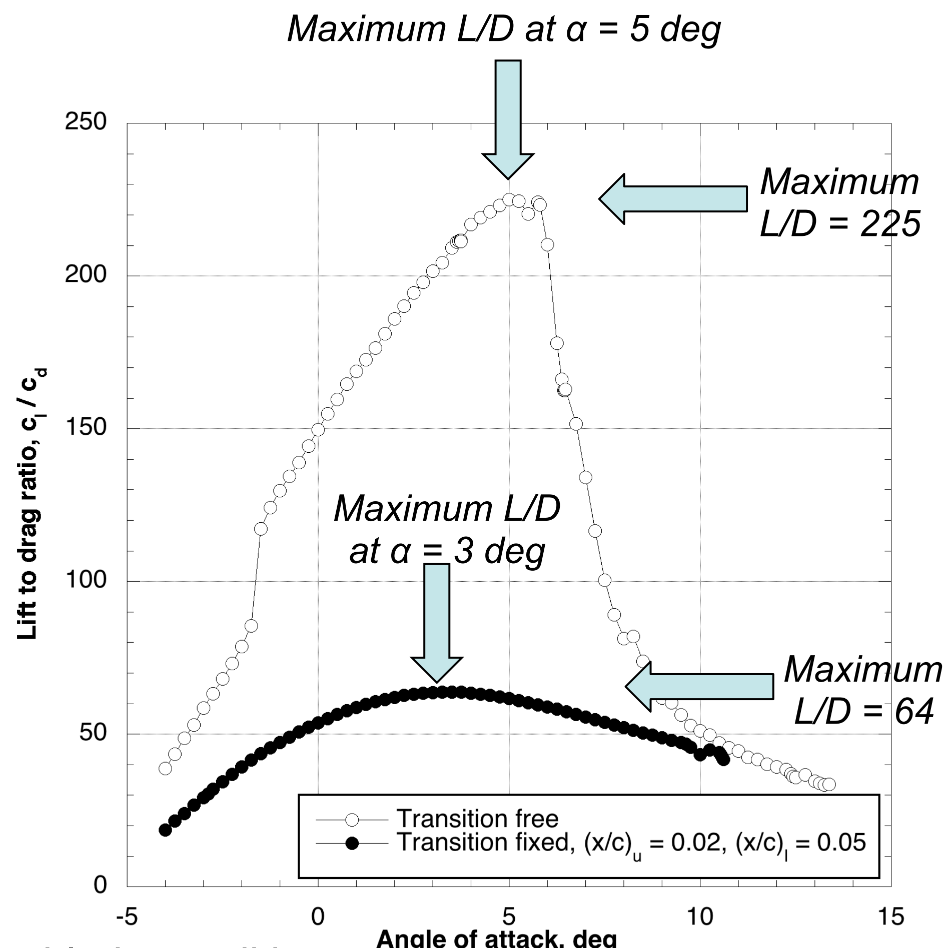
High L/D Section Shapes





- High L/D leading to high rotor C_p at clean blade conditions
- Concerns:
  - Large loss in L/D due to blade soiling and erosion
  - Modeling of soiling & erosion effects is not conservative
  - Small angle of attack margin between max L/D and blade stall

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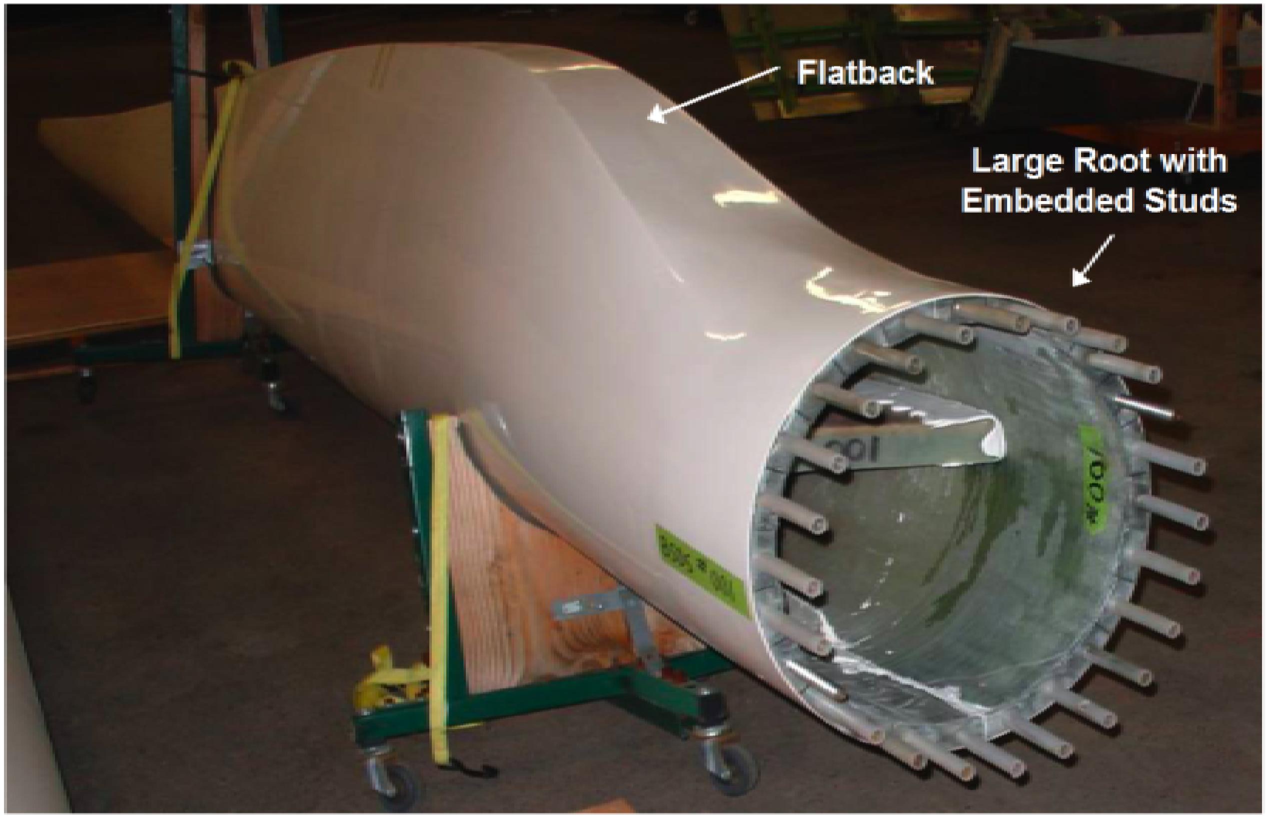
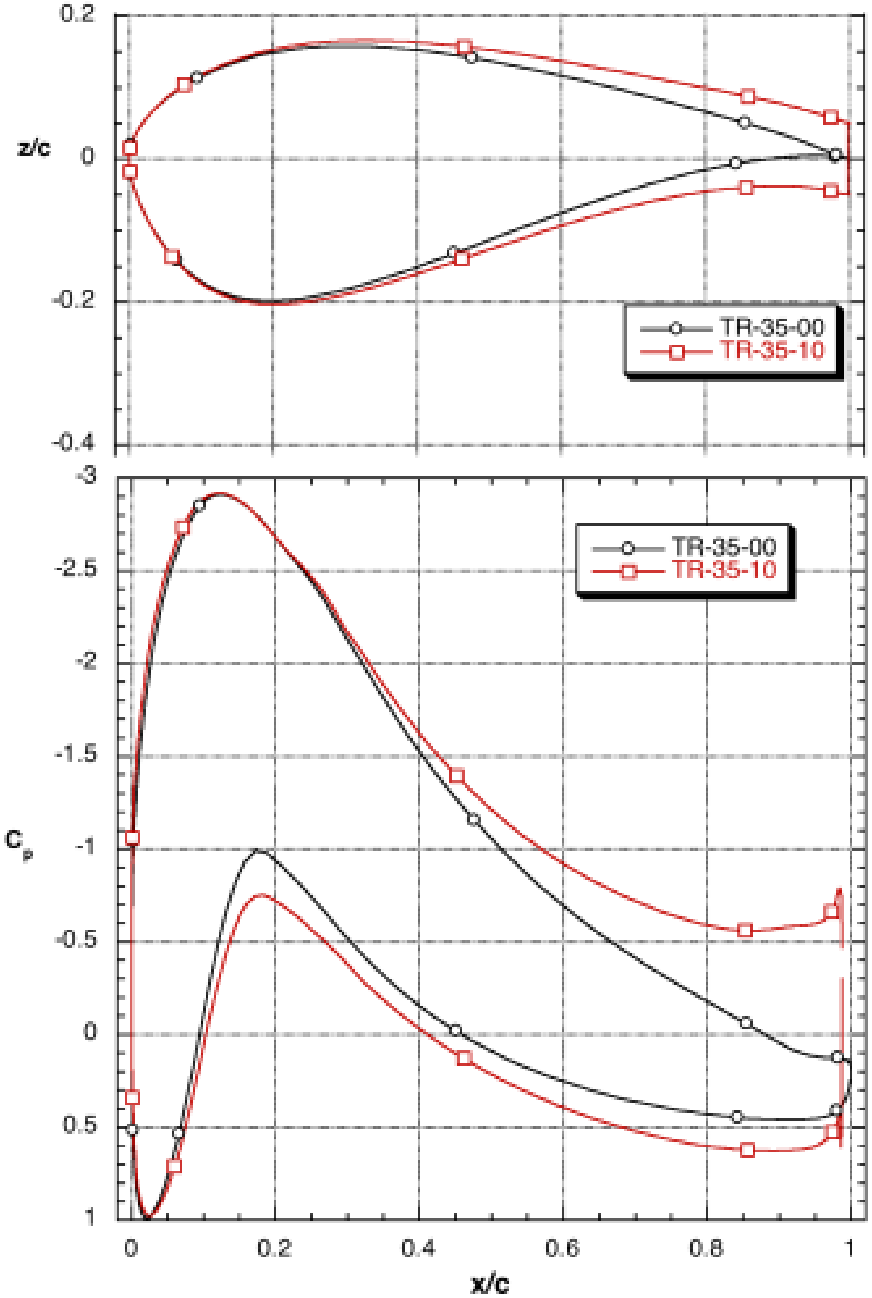
Blade System Design Study (BSDS)

- Multidisciplinary study to investigate and evaluate design and manufacturing issues for wind turbine blades in the one to ten megawatt size range
- DOE WindPACT award to TPI Composites
- Phase I resulted in preliminary design of 50 m blade
- Phase II focus was to validate gains identified in Phase I preliminary design by:
  - Building, testing, and flying scaled (9 m) prototype blades
  - Conducting more detailed aerodynamic evaluation

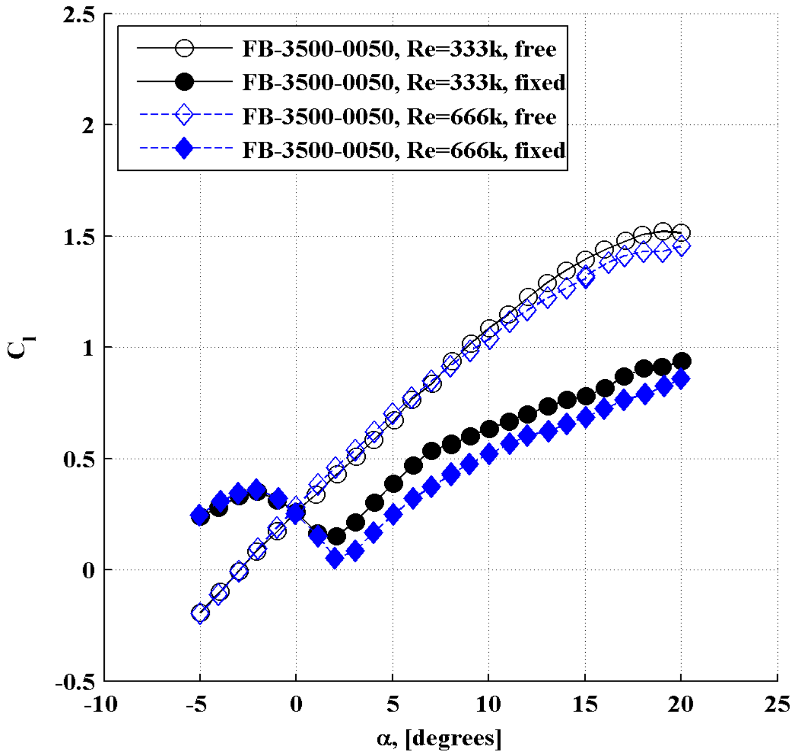


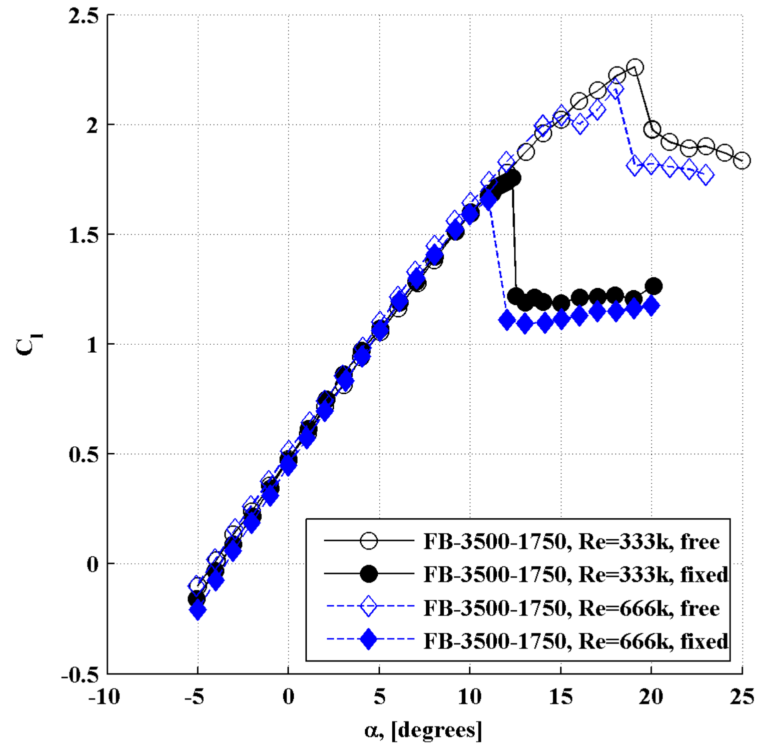
Blunt Trailing Edge or Flatback Airfoils



- Time-averaged pressure distributions of the TR-35-00 and TR-35-10 airfoils at α = 8˚, Re = 4.5 million, free transition
- Blunt trailing edge reduces the adverse pressure gradient on the upper surface by utilizing the wake for off-surface pressure recovery
- The reduced pressure gradient mitigates flow separation thereby providing enhanced aerodynamic performance
- Note that airfoil is not truncated (this affects airfoil camber distributions) but thickness distribution is modified to provide blunt trailing edge

Experimental Results: FB-3500-0050 vs. FB3500-1750





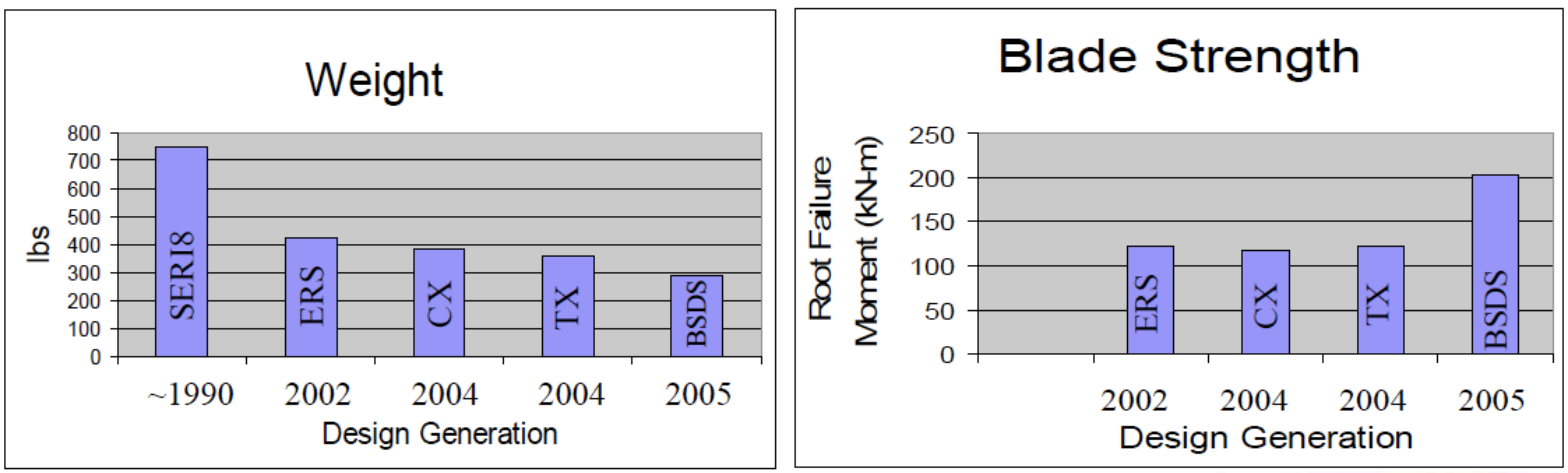
- Leading edge transition sensitivity for thick airfoils clearly shown
- Free transition stall occurs near 19° with maximum C_l near 1.5
- Fixed transition stall near 2°, lift continues to increase post stall but airfoil still stalled
- Minimal Reynolds number effects

Comparative Weight and Strength 9m BSDS blade

Comparison of CX-100 and BSDS Blade Properties and Testing Results

Property	CX-100	BSDS
Weight (lb)	383	289
% of Design Load at Failure	115%	310%
Root Failure Moment (kN-m)	128.6	203.9
Max. Carbon Tensile Strain at Failure (%)	0.31%	0.81%
Max. Carbon Compressive Strain at Failure (%)	0.30%	0.87%
Maximum Tip Displacement (m)	1.05	2.79

Historical Comparison of 9 m Blade Weights and Strengths



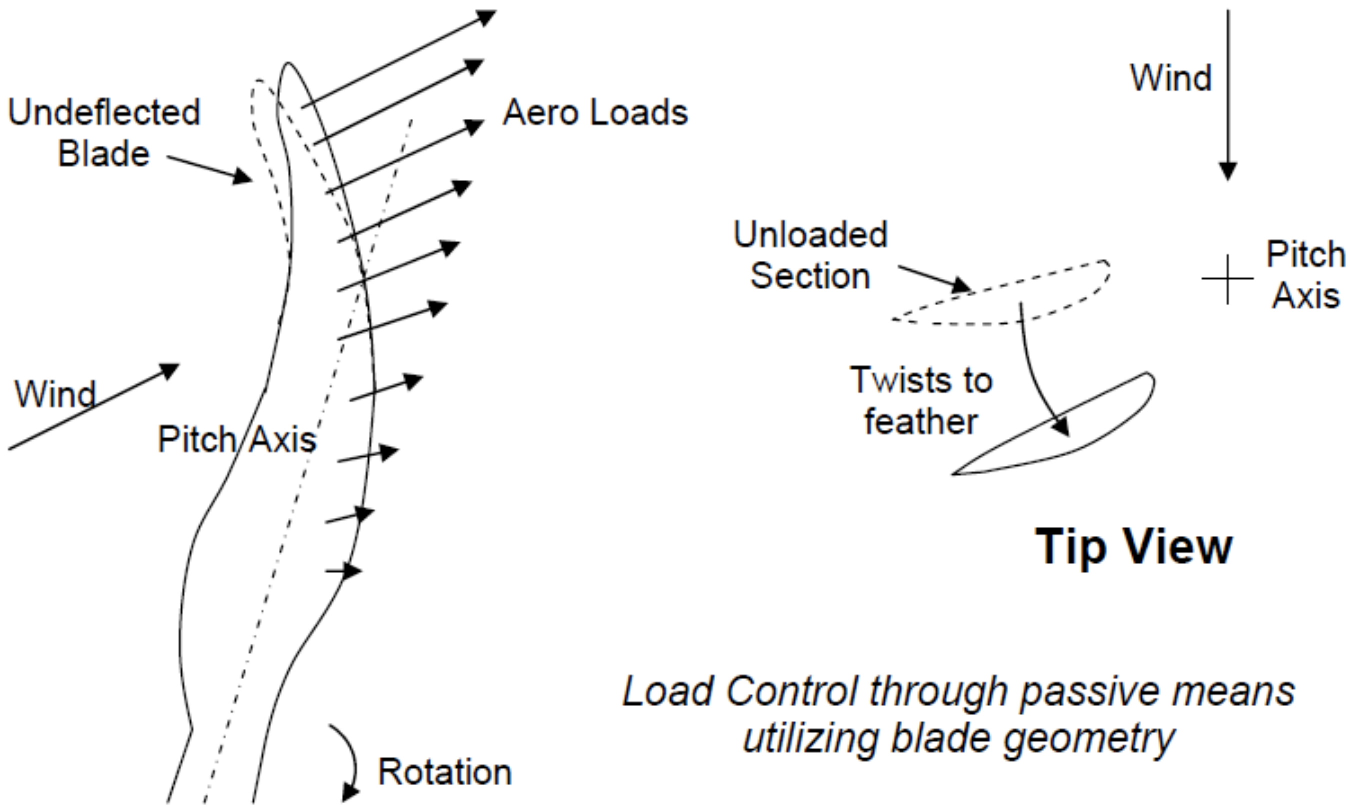
Source: Paquette & Veers, SNL

Flatback Airfoil Concept

- System approach to blade design is key to achieve combination of
  - high aerodynamic performance
  - high structural strength
  - low weight
  - simplified manufacturing
- Thick airfoils don't necessarily have poor aerodynamic performance characteristics. Blunt trailing edge design significantly improves lift performance at clean and soiled surface conditions
- Industry has been incorporating flatback airfoils in their blade designs.

Source: Windpower Monthly, 1 May 2014

Sweep Twist Passive Load Control

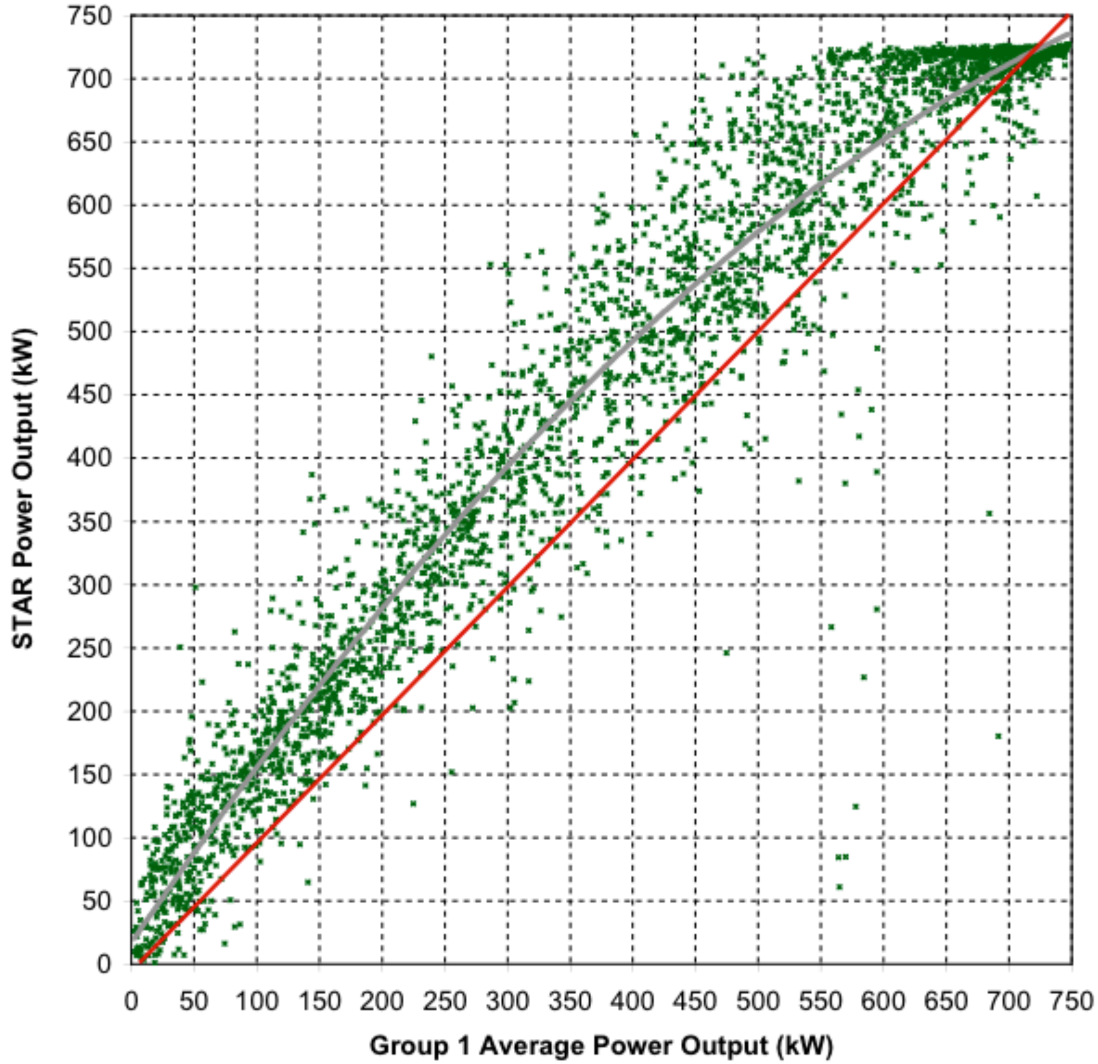


Load Control through passive means utilizing blade geometry

Sweep Twist Adaptive Rotor (STAR)

- 2004 DOE award to Blade Division of Knight & Carver to design, build, and demonstrate a rotor based on the sweep-twist concept
- Rotor designed for testing on a Zond Z48 turbine with 750 kW rating
- Goal to increase annual energy capture of baseline turbine by 5%-10% without exceeding baseline rotor loads
- To achieve this rotor radius was increased from 24 m to 27 m
- Rotor test commenced in April 2008
- Program results published in SAND2009-8037

Power Comparison



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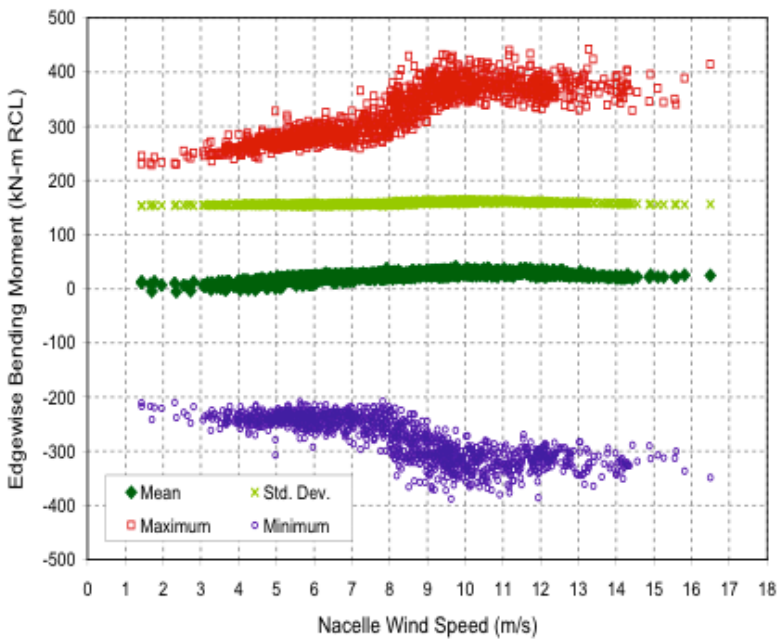
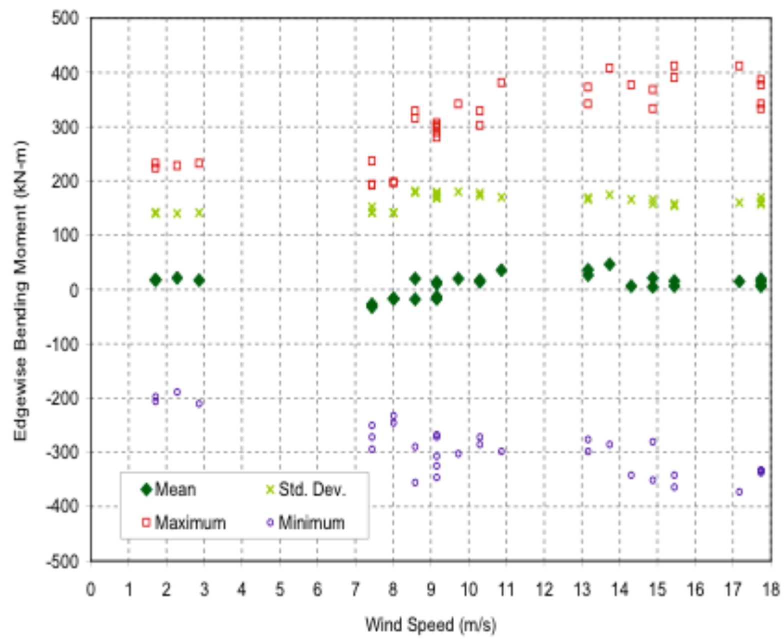
Edgewise Blade Root Moment Comparison

- STAR rotor loads compared to Z48 data collected at Lake Benton site.



STAR 54



Z48

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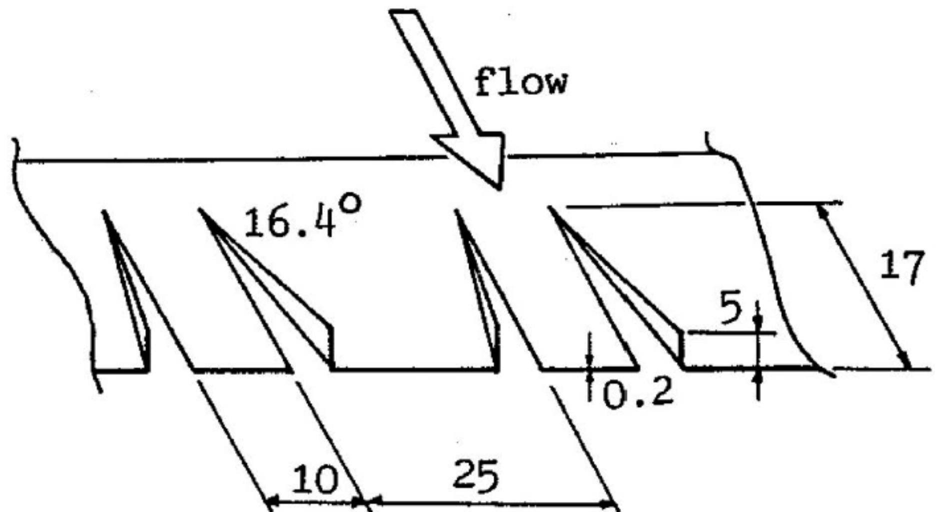
Sweep Twist Adaptive Rotor

- Increased rotor energy capture through aeroelastically tailored blade design is feasible
- STAR-54 captured 12% more energy over baseline Z48 turbines without increasing blade loads.
  - Reports at http://www.sandia.gov/wind/TopicSelection.htm
- Prototype STAR-54 is continuing to operate without any issues more than 3 years after installation and it remains the highest grossing “Z48” in Tehachapi
- Problem remains that many of industry’s design codes do not properly model sweep twist feature.

Vortex Generator (VG)

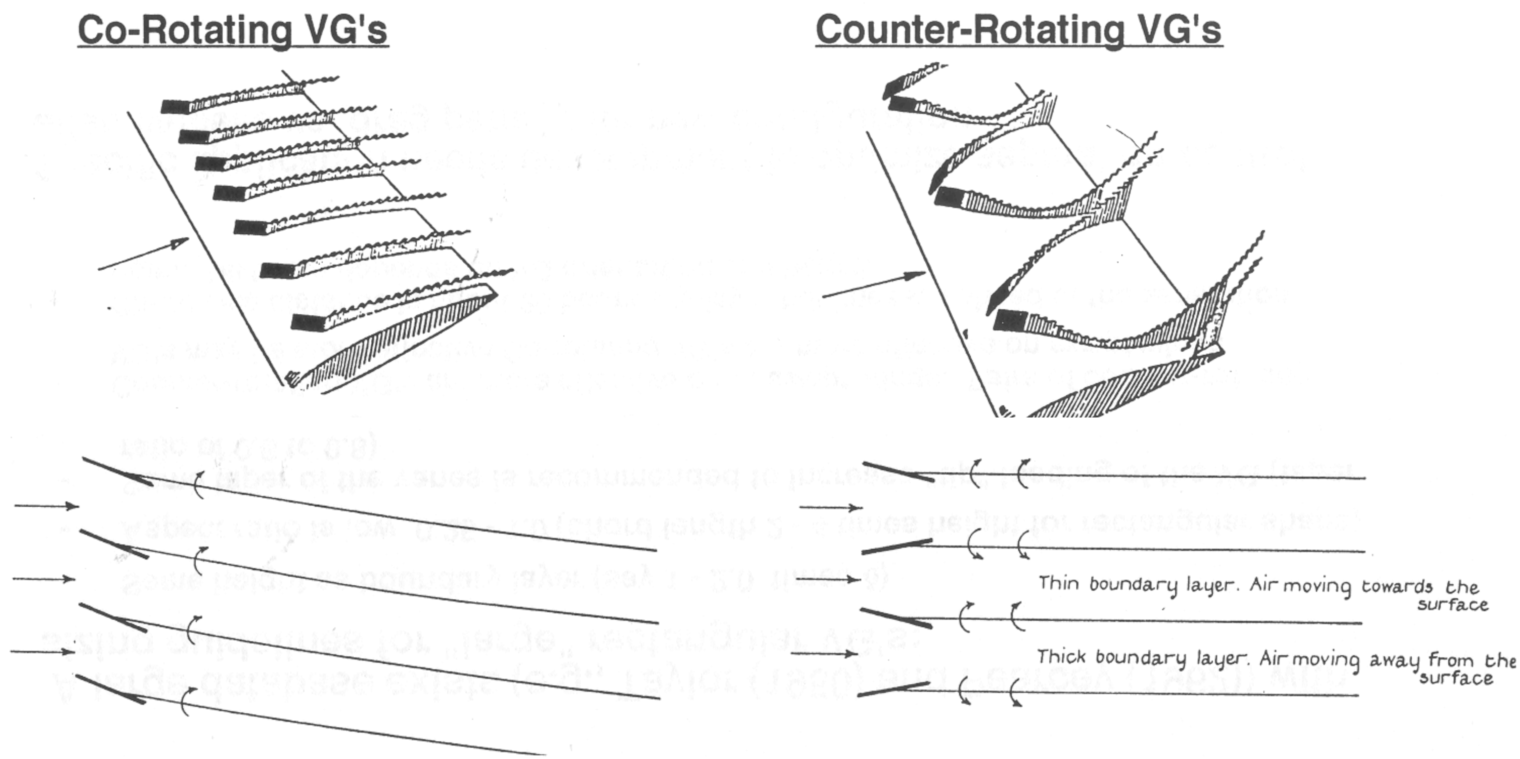
- Passive aerodynamic control device
- First developed in 1940s to mitigate flow separation on swept wings
- VGs come in varies sizes and shapes
- Significant increases in maximum lift
- Device used to tune rotor performance



Source: Timmer & van Rooij (2003)

Dimensions in mm

VG Orientation and Effectiveness

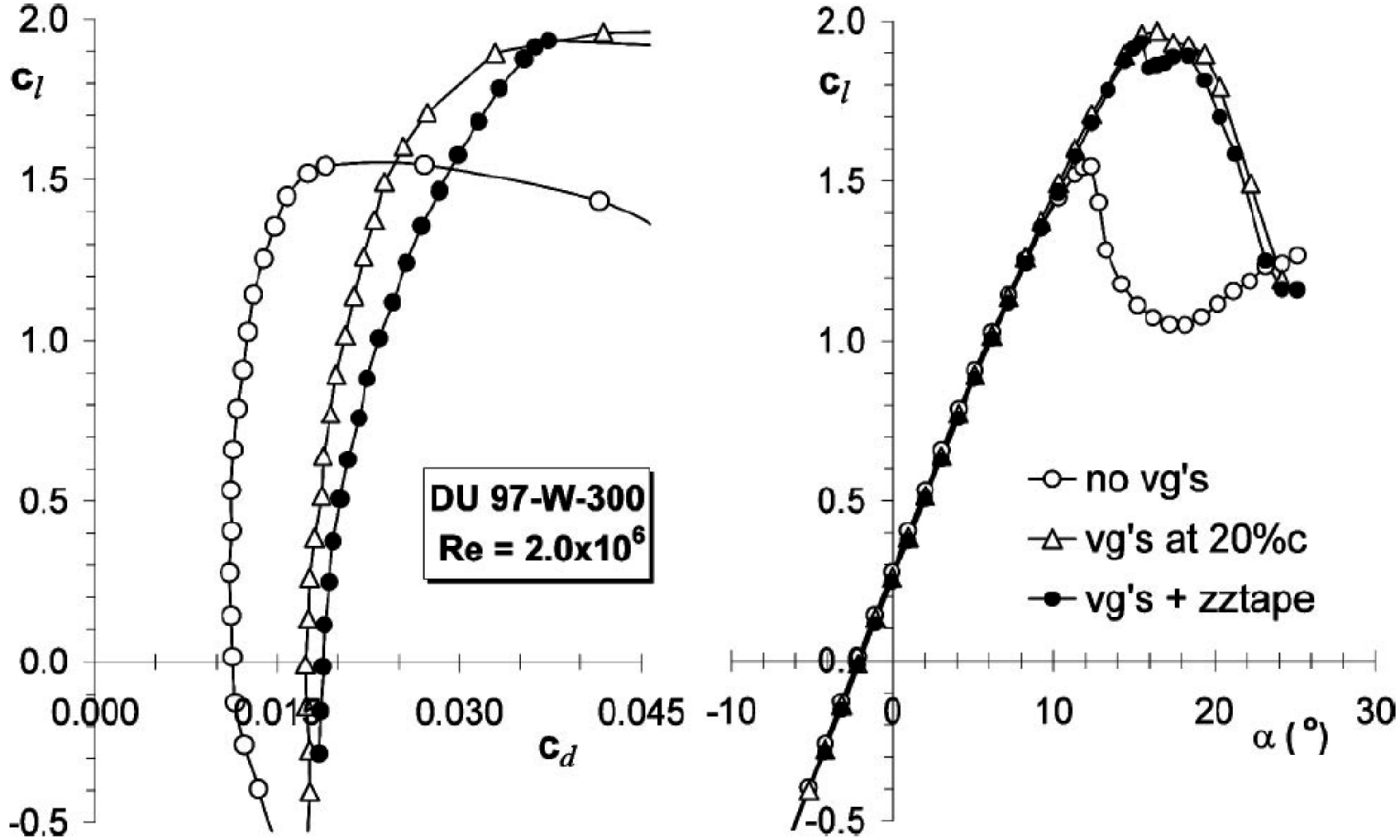


- Counter-rotating vortex pairs more effective in controlling given specific separation problem. Vortex-pair dynamics induces vortex lift-off from wall and limits chordwise range of effectiveness
- Co-rotating pairs remain stable near surface over much longer chord distance

Vortex Generators

VG Effect on Lift and Drag

Timmer & van Rooij (2003)



- Counter-rotating vanes at x/c = 0.20
- Zig-zap tape used to simulate soiled airfoil surface effect

Serrated Trailing Edges

Blade Aerodynamic Load Control

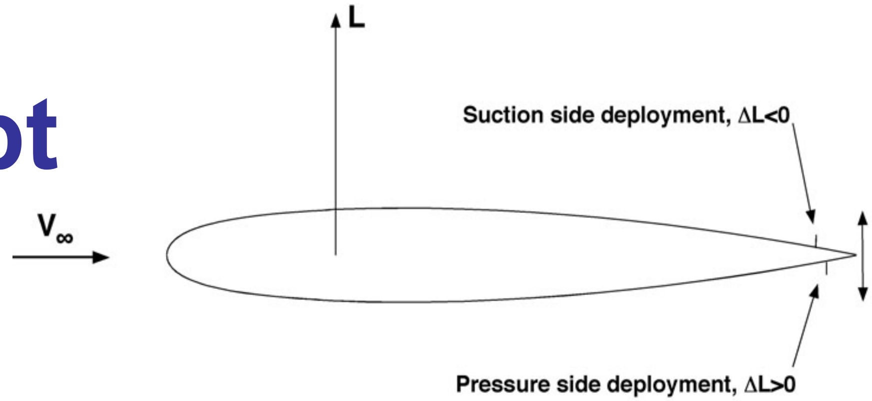
- Techniques to control blade loads and rotor performance:
  - Blade size (variable blade length)
  - Incidence angle (variable pitch, variable twist)
  - Airspeed (variable speed)
  - Section aerodynamic characteristics

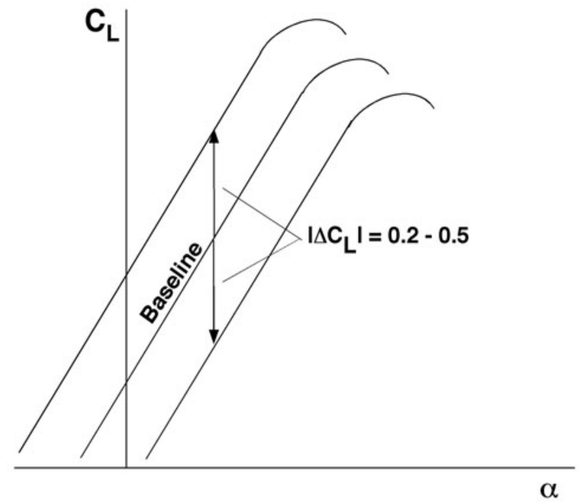
$$L = \int_{r=0}^{R} \left[C_L \, {}^{1}\!/_{2} \rho \left\{ V_{wind}^2 + (2\pi n r)^2 \right\} c \right] dr$$

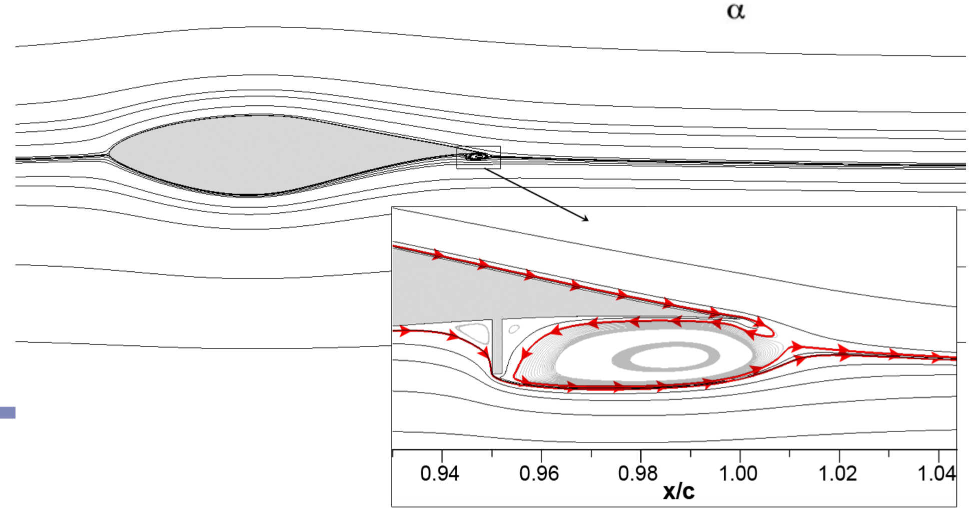
$$C_{L_{min}} \le C_L = C_{L_\alpha} \left(\alpha + \beta - \alpha_o \right) \le C_{L_{max}}$$

Microtab Concept

- Conceptualized in 1998
- Tabs that deploy (near-) normal to flow direction
- Forward of the trailing edge
  - Upper or lower surface
- Hingeless device
  - Small actuation forces
- h_{tab} ~ boundary layer thickness
- Trailing-edge flow condition is altered

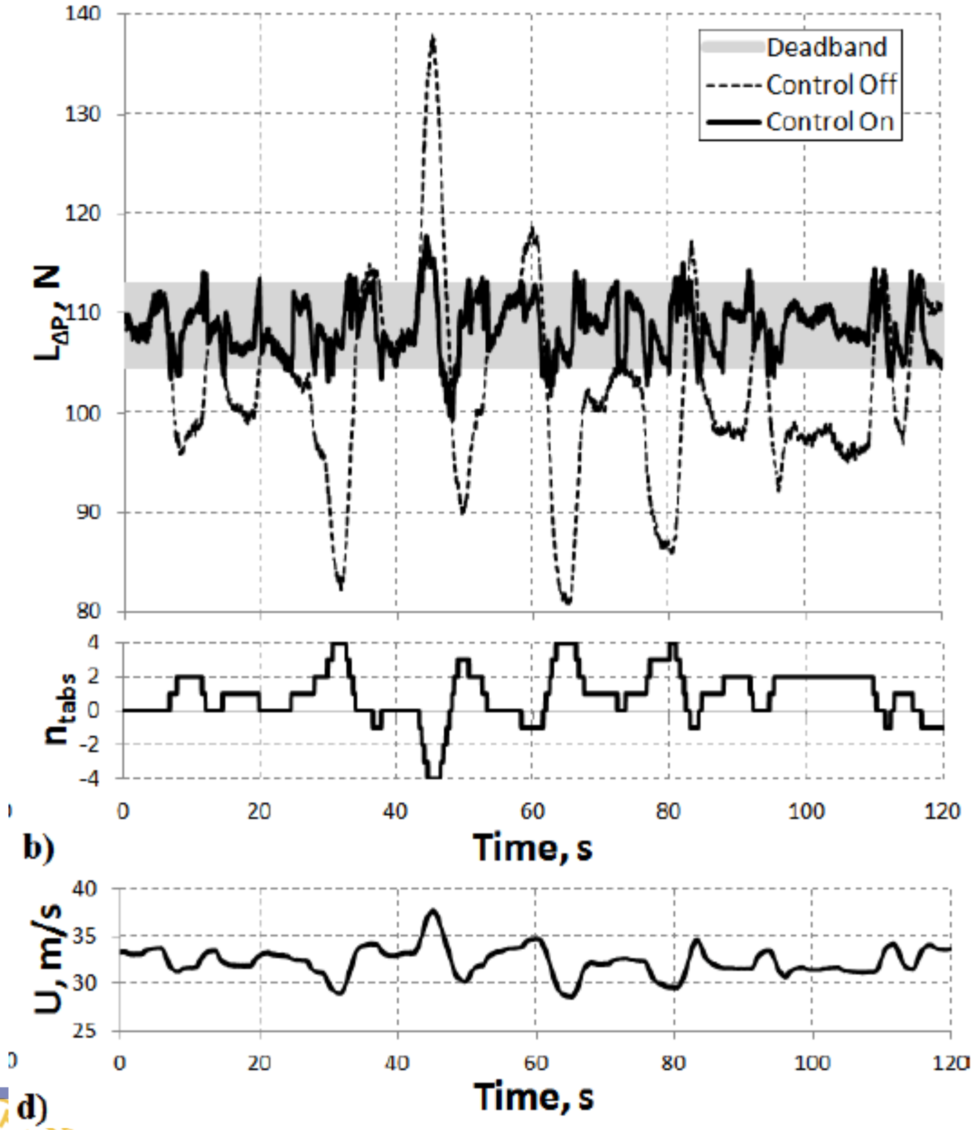




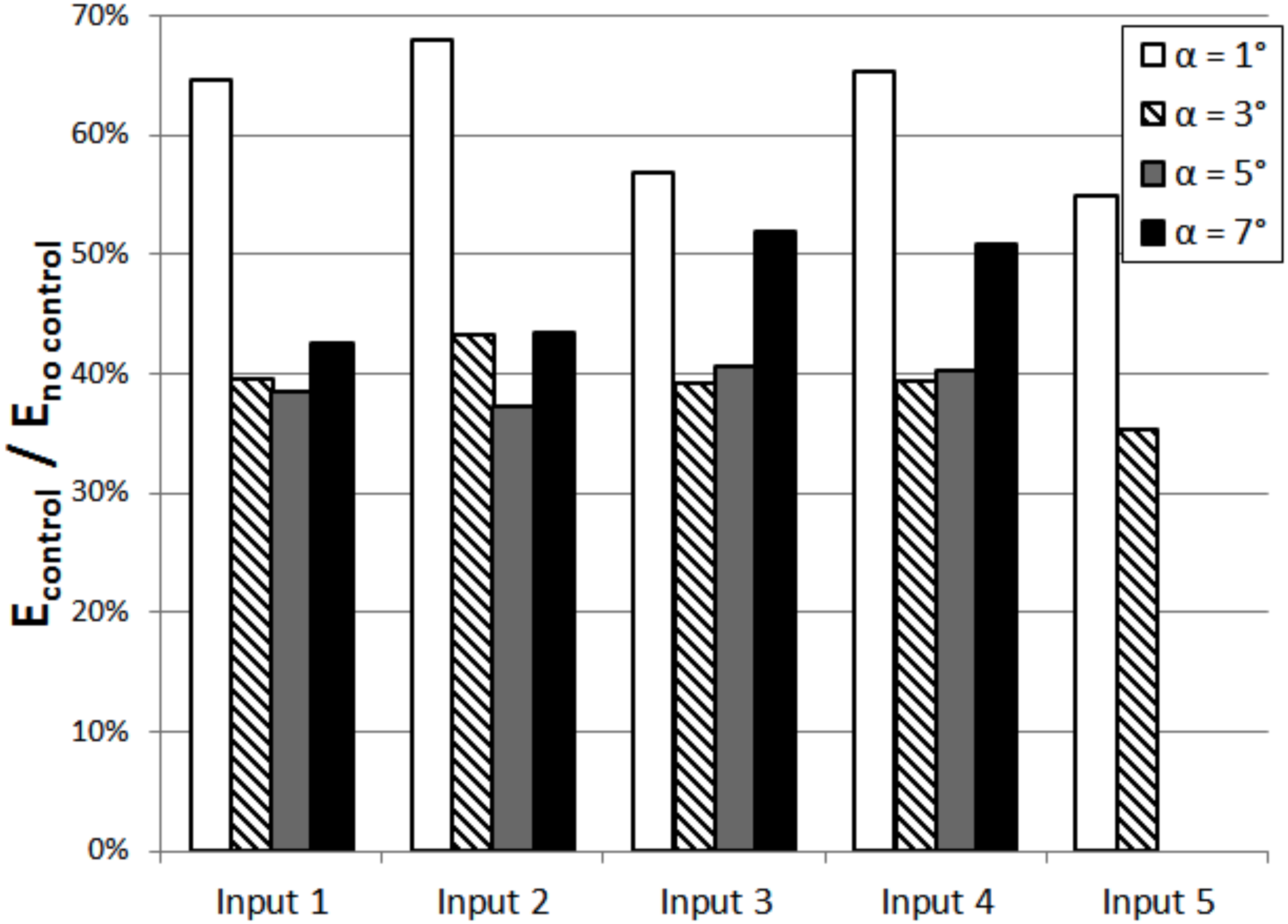


Effect of Controls on Lift Error

Control input-pressure, Lower & upper surface tabs, α = 3 deg, Input 1, Δ_L = ±4.4 N



Lift Error Reduction Summary



Departing Thoughts

- Wind turbine rotor aerodynamics has evolved considerably in past 30 years.
- Main developments:
  - Much improved computational tools for design and analysis
  - Custom design airfoils norm
  - Iterative concurrent blade design: aerodynamics, structures, materials, manufacturing
  - Effect of surface soiling and erosion on performance a reoccurring problem (hence, VGs)
  - Aeroacoustic noise playing a critical role in blade design (hence, serrated trailing edges)
  - Active aerodynamic load control receives significant attention

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