Research on Thick Blunt Trailing Edge Wind Turbine Airfoils

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  - Benson Gilbert
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  - Kevin Standish
  - Tobias Winnemöller
  - Et al

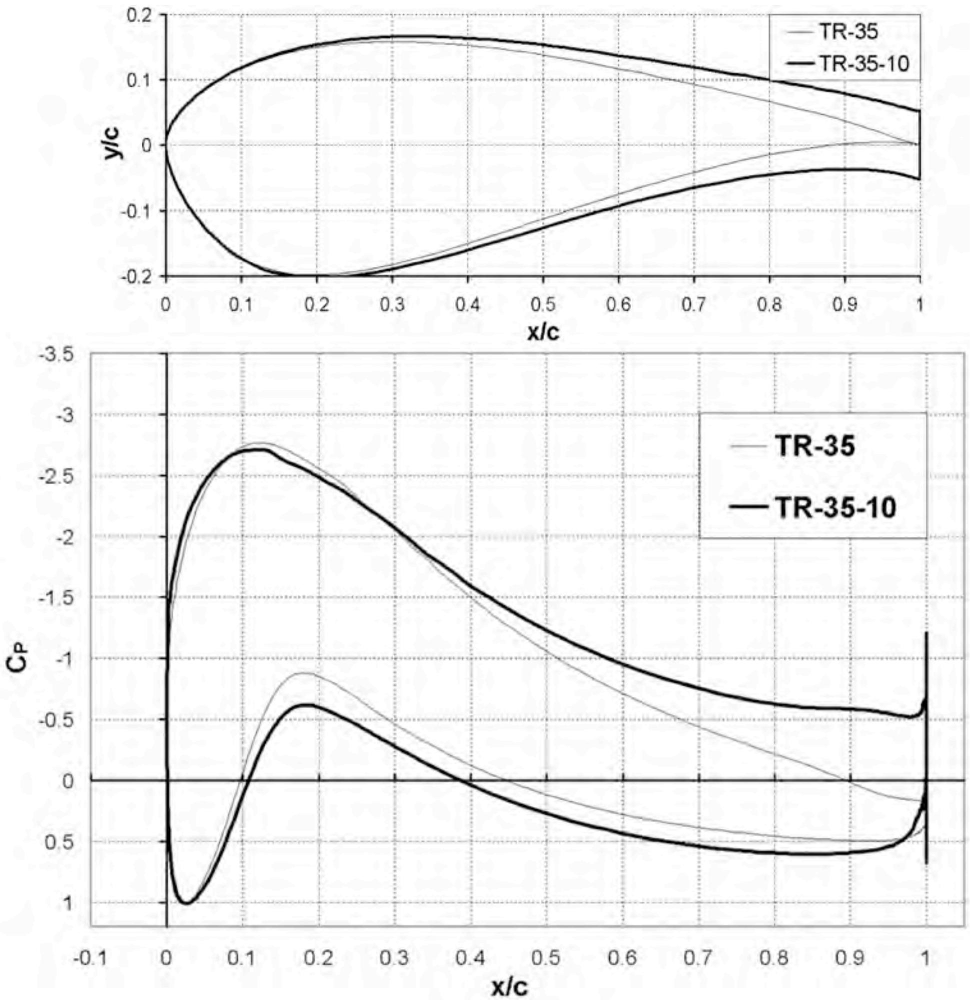
Blunt Trailing Edge Airfoils

- Background
- Experimental Results
  - BSDS airfoils
  - Wind tunnel results
- CFD
  - 2D airfoil design
  - 3D modified NREL Phase VI Rotor
- Future Work

Background

- The inboard region of large wind turbine blades requires large $(t/c)_{max}$ airfoils to meet structural requirements
- Use of blunt trailing edge airfoils proposed by the DOE supported Blade System Design Study (BSDS) conducted by TPI Composites, et al.
  - Benefits
    - Structural improvements by increasing sectional area and moment of inertia for a given $(t/c)_{max}$
    - Improves sectional maximum C_l and lift curve slope
    - Reduces sensitivity to leading edge surface soiling
  - Drawbacks
    - Increased base drag
    - Trailing edge vortex shedding (noise)
- Limited experimental research prompted study to validate concept

Blunt Trailing Edge Airfoil Concept



- Time-averaged pressure distributions of the TR-35 and TR-35-10 airfoils at α = 8 deg, 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

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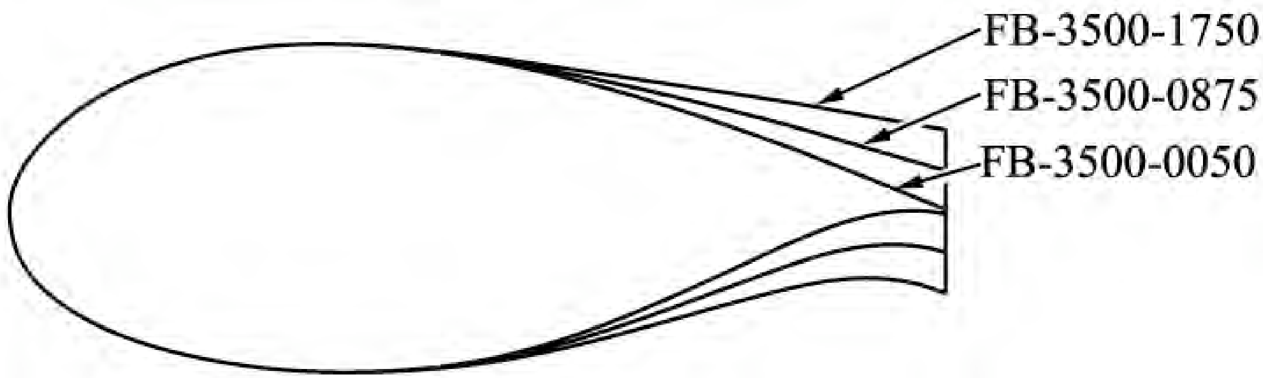
Wind Tunnel Testing of Thick Blunt Trailing Edge Airfoils

Airfoils

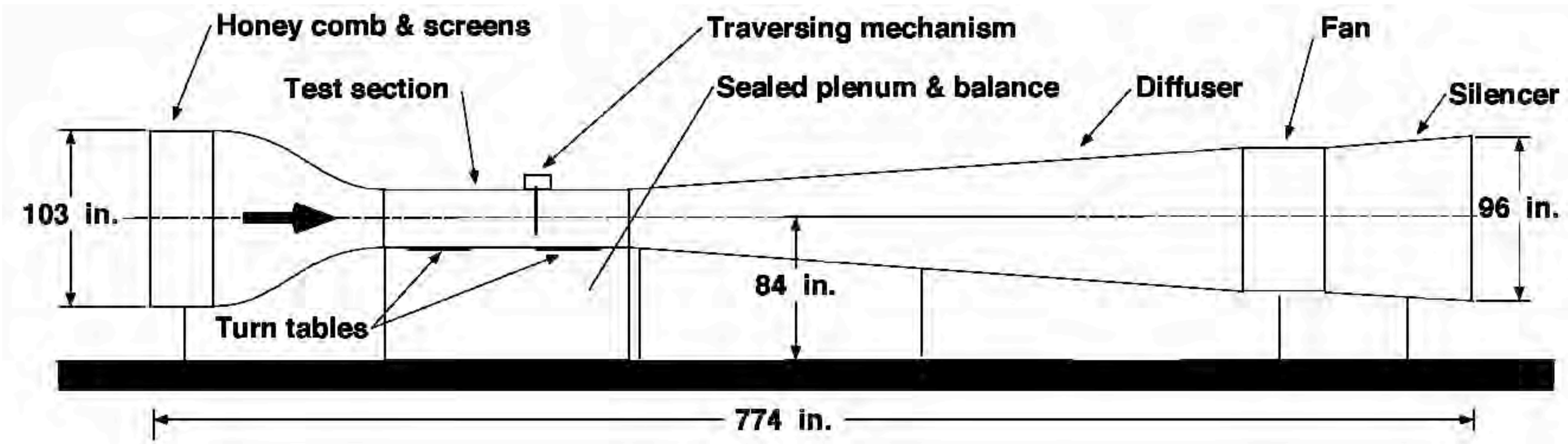


- FB Airfoil Series (FB-XXXX-YYYY)
  - Presented in BSDS Phase I final report
  - XXXX = % maximum thickness to chord ratio × 100, e.g. 3500 → 35% t/c
  - YYYY = % trailing edge thickness to chord ratio × 100, e.g. 0875 → 8.75% t_{te}/c
- Flatback generated by symmetrically adding thickness about the camber line
- Present study investigates FB-3500 airfoil series
  - FB-3500-0050 (nominally sharp trailing edge)
  - FB-3500-0875
  - FB-3500-1750

Methods: Wind Tunnel Test Parameters

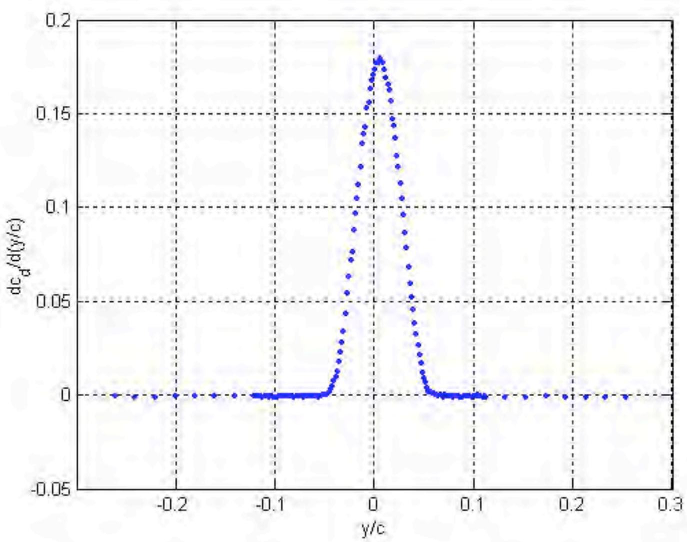
- Model chord length: 0.2032 m (8 in.)
- Re = 333,000 and 666,000
  - Reynolds number restricted by wake blockage and wind tunnel balance limits
  - CFD results for Re = 3×10^5 to 7×10^6 conditions show leading edge soiling sensitivity for sharp trailing edge airfoils and the improvements for flatback airfoils persist at high Reynolds numbers.
- Free and fixed transition
- Transition fixed using 0.25 mm (0.01 in.) zigzag trip tape
  - Suction surface at 2% chord
  - Pressure surface at 5% chord

Methods: Wind Tunnel



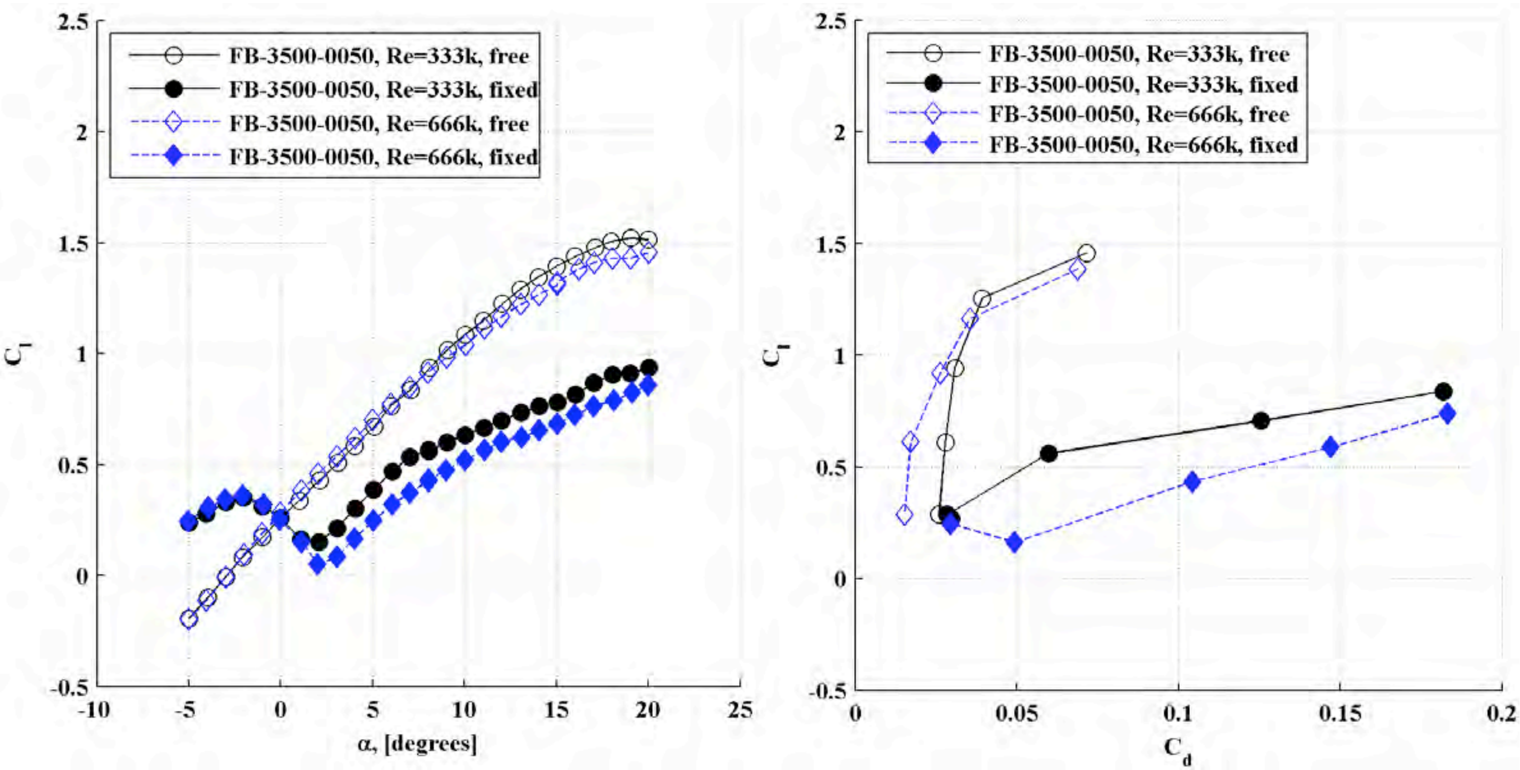
- Open circuit, low subsonic
- Test section dimensions
  - Cross section: 0.86 m x 1.22 m (2.8 ft x 4 ft)
  - Length: 3.66 m (12 ft)
- Low turbulence < 0.1% FS for 80% of test section

Methods: Wind Tunnel Measurements



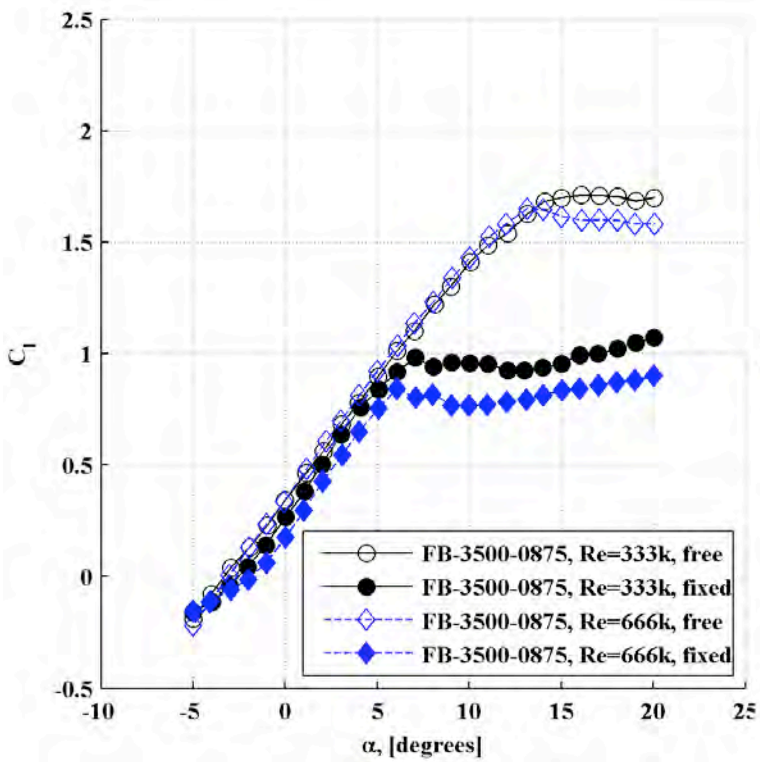
- Force measurement
  - Lift determined using 6-component pyramidal balance
  - Drag determined using wake measurements
    - Pitot-static probe measurements at fixed intervals in the wake (0.04 in.)
    - Based on Jones' Method
- Experimental measurements will be presented without corrections for wind tunnel wall effects

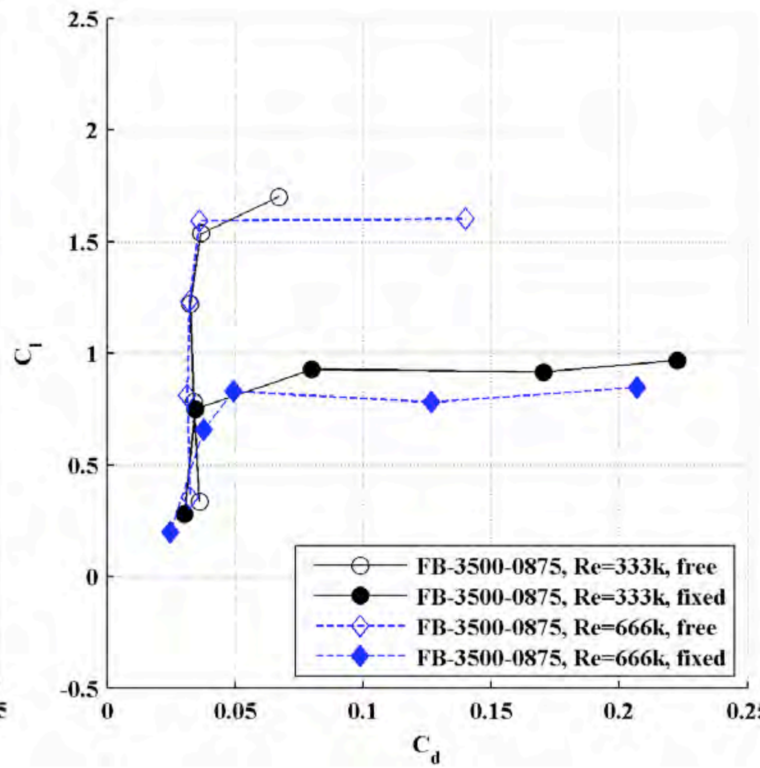
Experimental Results: FB-3500-0050



- Leading edge transition sensitivity 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 as shown by dramatic drag increase
- Minimal Reynolds number effects

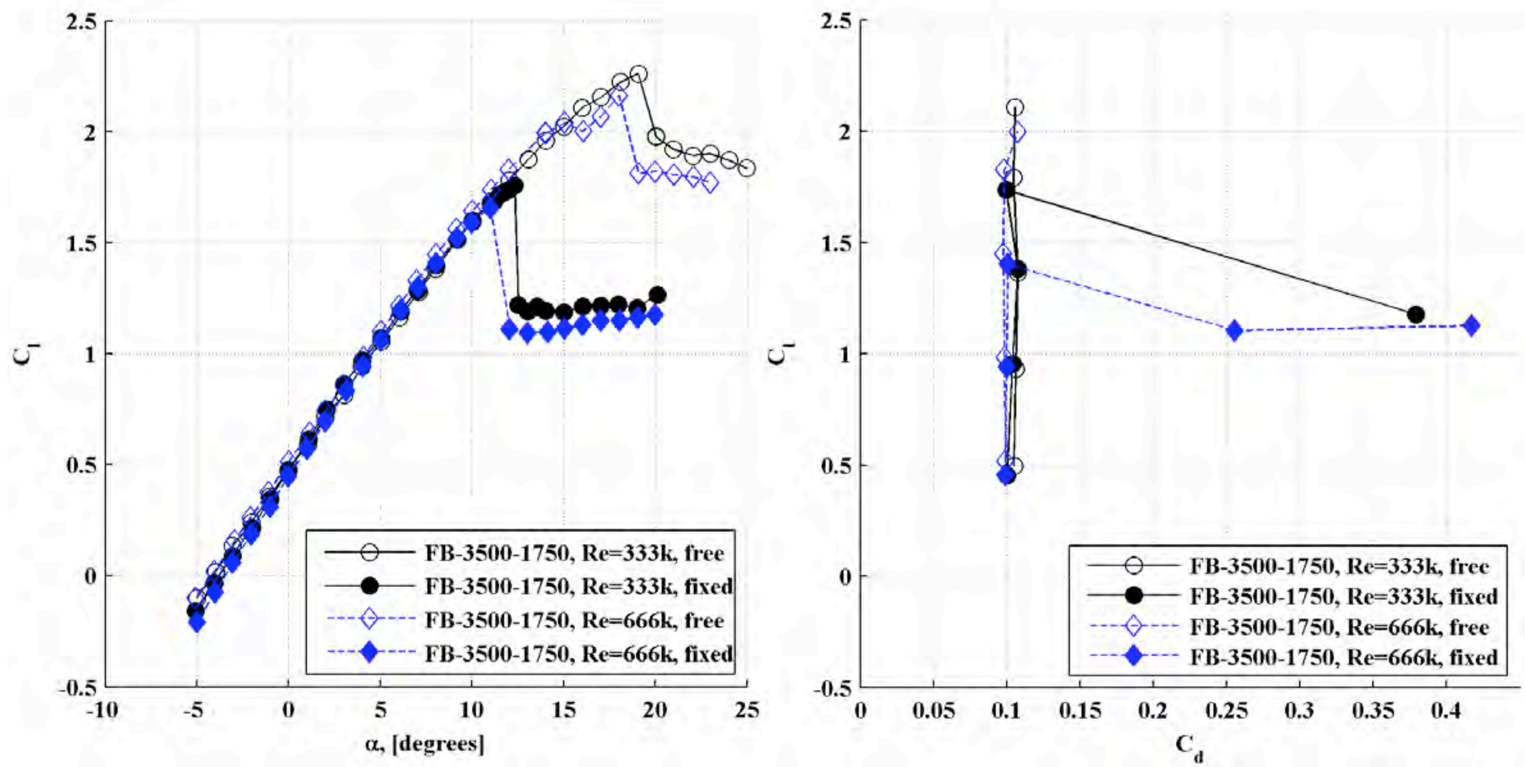
Experimental Results : FB-3500-0875





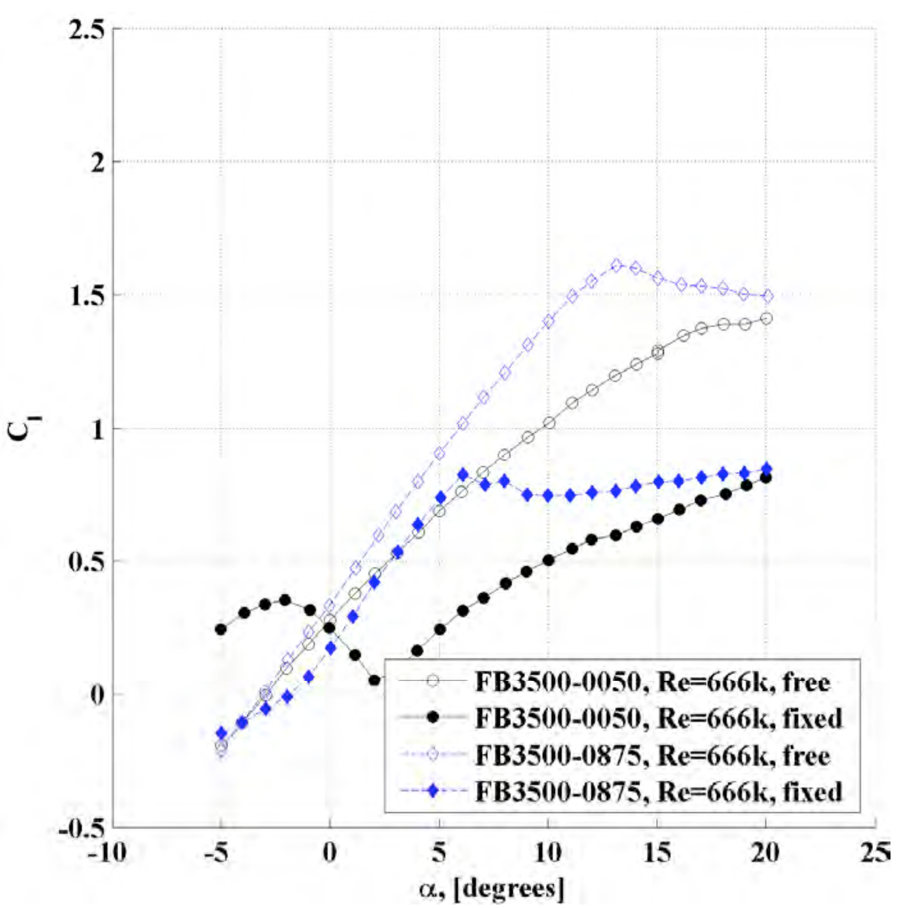
- Reduced in leading edge transition sensitivity
- Maximum C_l approx. 1.65 and 0.9 for free and fixed, respectively
- Lift curve slopes similar for fixed and free transition
- For free transition, increased minimum drag compared to sharp trailing edge airfoil

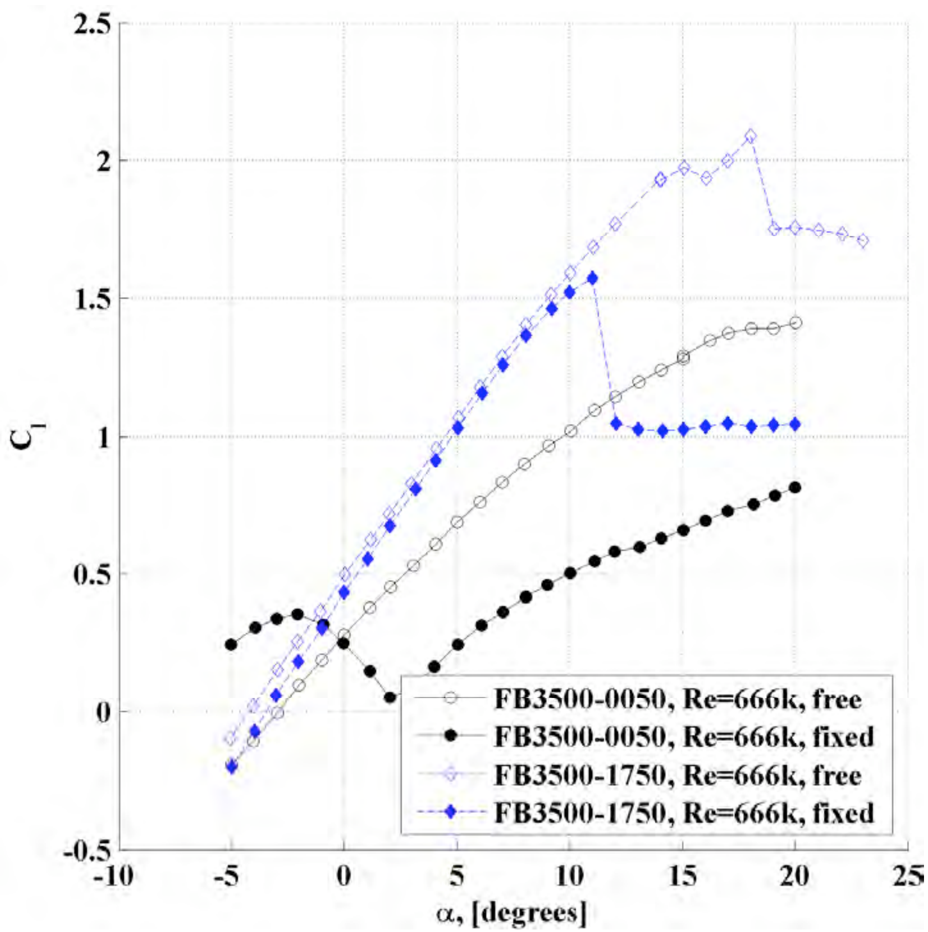
Experimental Results : FB-3500-1750



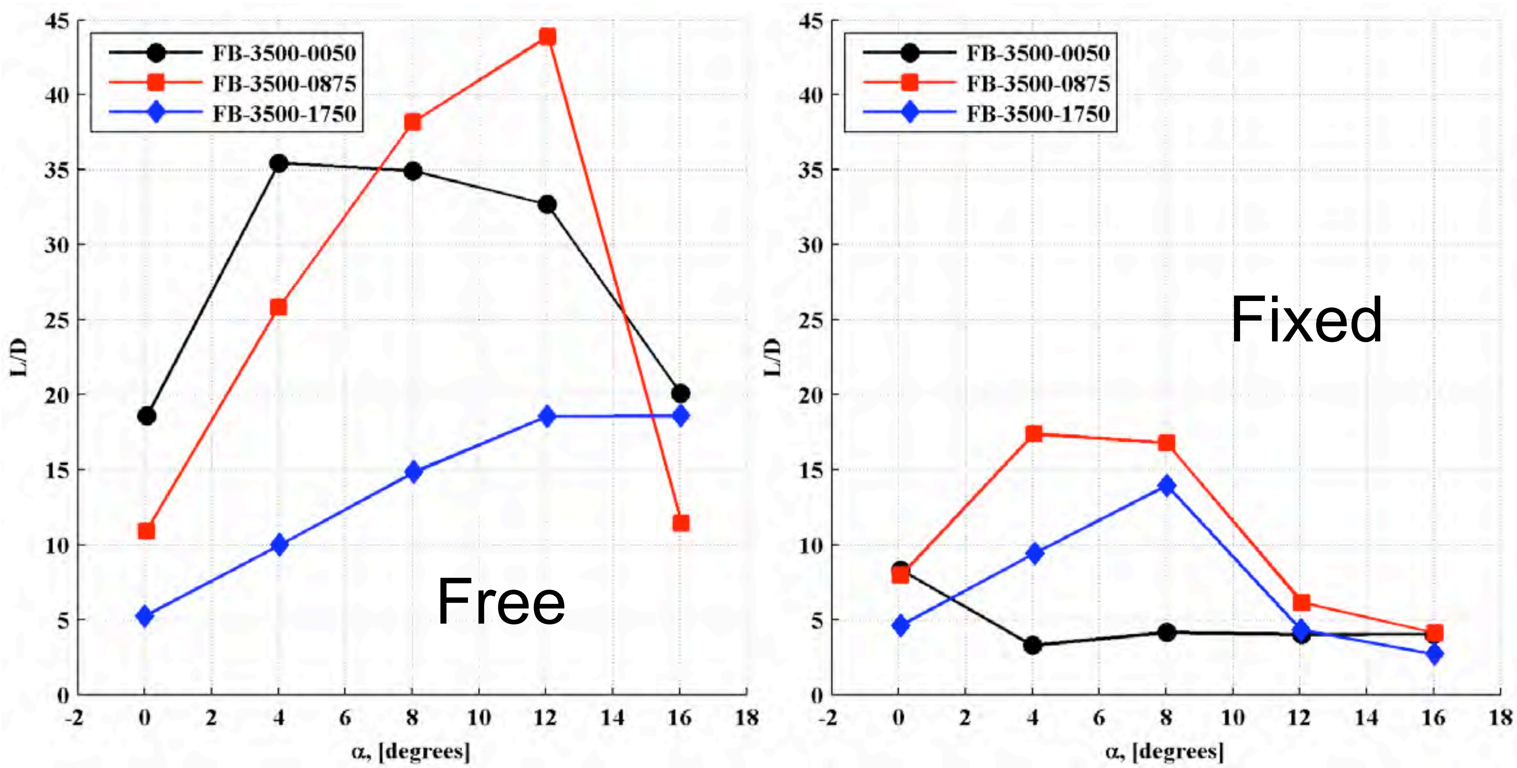
- Further reduction of leading edge sensitivity
- Maximum C_l near 2.2 (free) and 1.7 (fixed)
- Lift curve slope in excellent agreement
- Sharp stall behavior for fixed transition
- Nearly four-fold increase in minimum drag compared to free transition FB-3500-0050

Experimental Results: Lift Comparison





Experimental Results: L/D Comparison



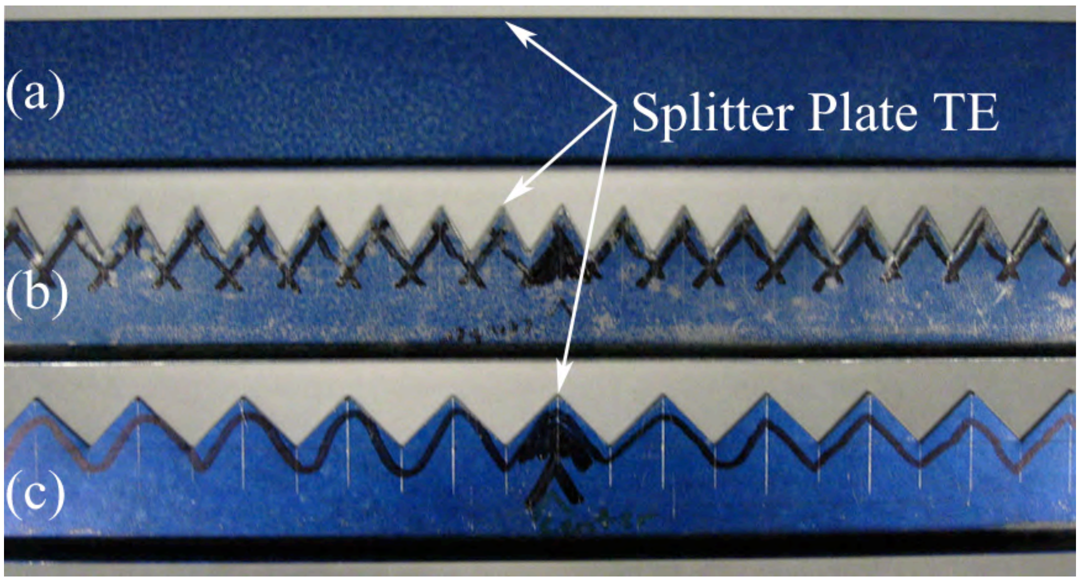
- Re = 666,000
- Free transition
  - FB-3500-0050 does well at low angles of attack, $(L/D)_{max}$ = 35.5
  - FB-3500-0875 produces $(L/D)_{max}$ = 44
- Fixed transition
  - Flatback airfoils outperform sharp trailing edge airfoil
  - FB-3500-0875 produces $(L/D)_{max}$ = 17.5
- Bluff-body drag reduction techniques could be used to further improve performance

2 Trailing-Edge Treatment

Design Question:

- The drag of blunt trailing edge airfoils is admittedly high but are there ways to reduce the drag?

Trailing-Edge Treatments

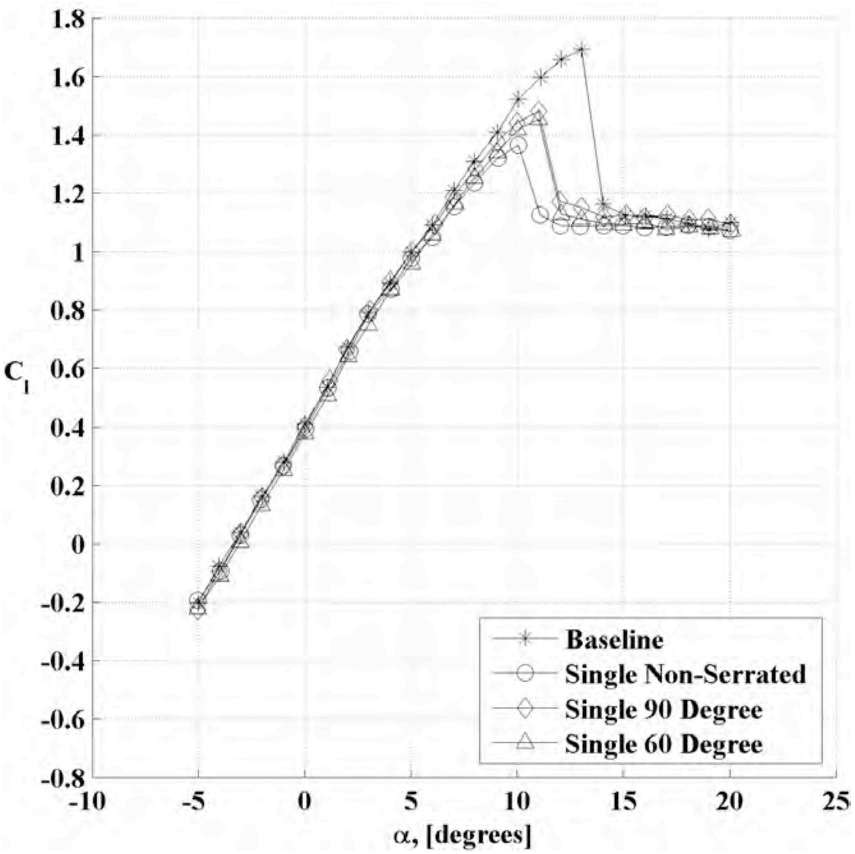


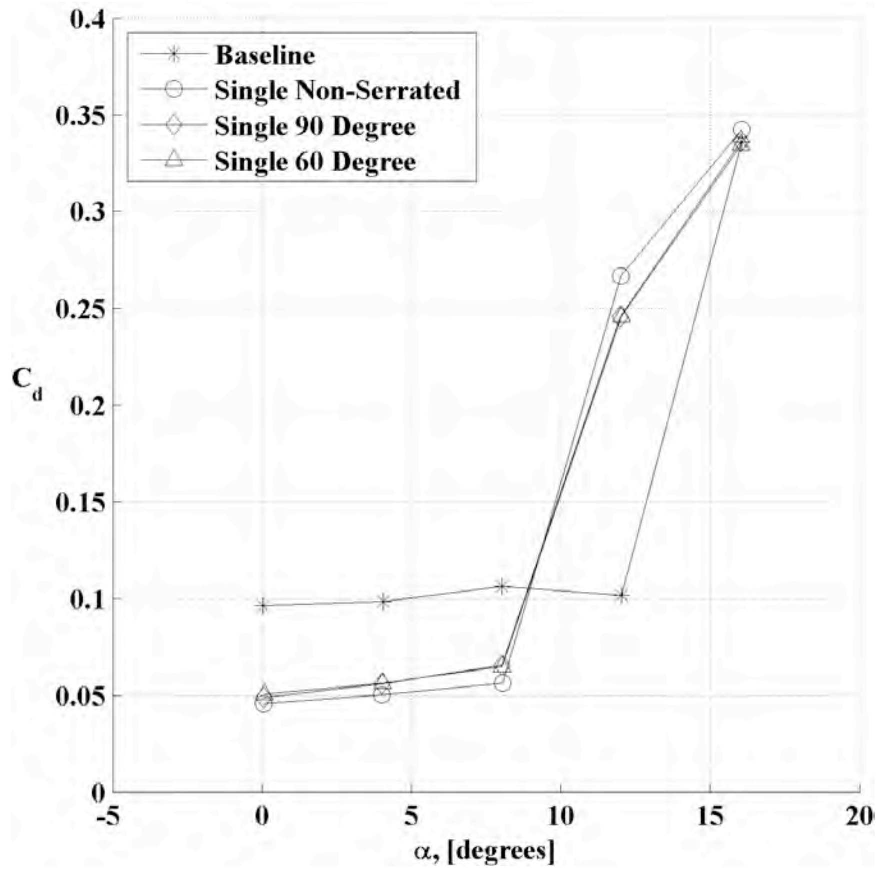
(a) Non-serrated
(b) 60-deg serrated
(c) 90-deg serrated

FB3500-1750 with 90-deg serrated splitter plate

Experimental Results : FB-3500-1750

Re = 0.67 million,Transition fixed at leading edge





Design Answer:

- Yes, techniques are available to reduce the base drag and hence the overall drag by 50% or more through simple trailing edge treatments. These techniques also tend to mitigate bluff body vortex shedding.

3 Thick Airfoil Design

Design Question:

- If we design a thick airfoil (maximum thickness to chord ratio > 35%) from scratch, will it end up with a blunt trailing edge?

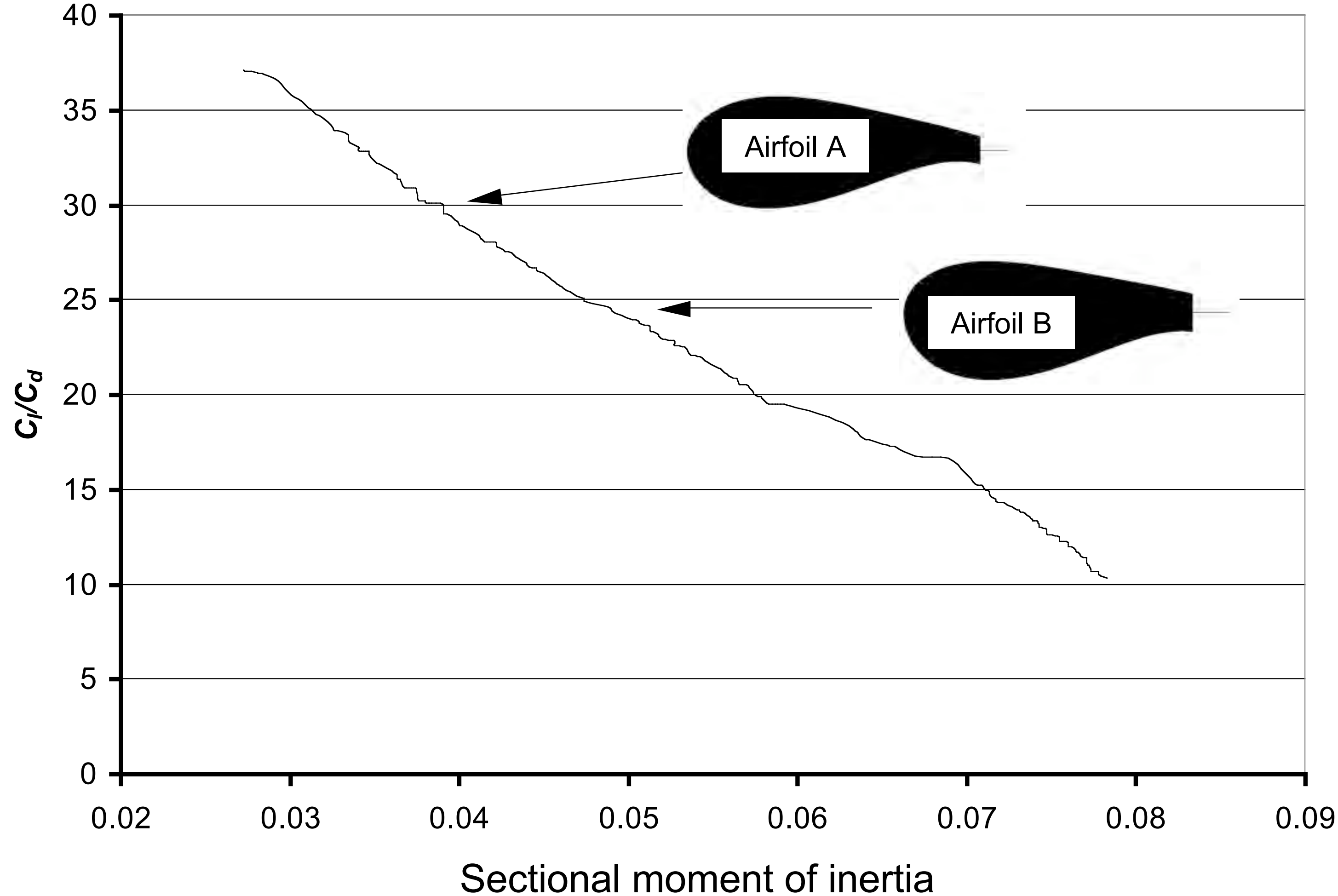
Numerical Methods

- Surface Generation
  - Based on Sobieczky‘s PARSEC surface definition
  - Design parameters:
    - Upper/ lower leading edge radius ($r_{le,u}$, $r_{le,l}$)
    - Point of upper/ lower crest ($x_{u,max}$, $x_{l,max}$)
    - Ordinate at upper/ lower crest ($z_{u,max}$, $z_{l,max}$)
    - Thickness of trailing edge (t_{te})
    - Trailing edge direction (*teg*)
    - Trailing edge wedge angle (*tew*)
- Numerical Optimizer
  - Combination of zero-order and first-order method
    - First-order method to optimize airfoils with fixed thickness for maximum lift-to-drag ratio
    - Results from the first-order method are used as a basis for the multi-objective optimization with the zero-order method
- Aerodynamic Analysis Method
  - Reynolds-averaged Navier-Stokes solver ARC2D

Optimization Process

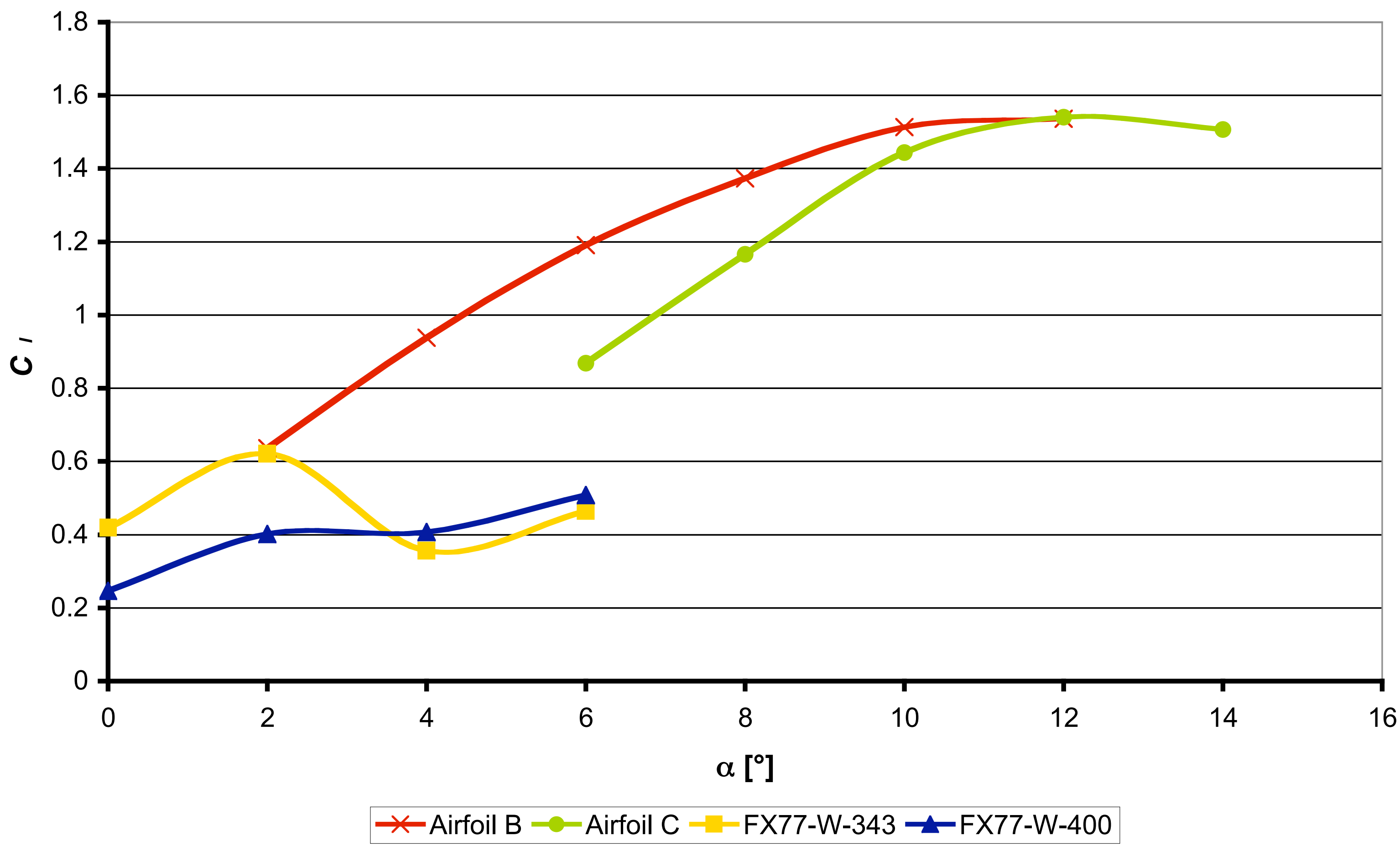
- Optimization objectives are lift-to-drag ratio and moment of inertia of the thin shell airfoil
- The following constraints and design conditions were used
  - Re = 1.0 million, Ma = 0.3, fully turbulent flow, $C_l = 1.0$
  - The main constraints of the design space are:
    - Projected thickness to chord ratio: $0.35 \le t/c \le 0.42$
    - Thickness of trailing edge: $0.005 \le t_{te}/c \le 0.20$
  - A lift-to-drag ratio lower boundary of $C_l/C_d = 10$ was set for Pareto front airfoil selection

Resulting Pareto Front



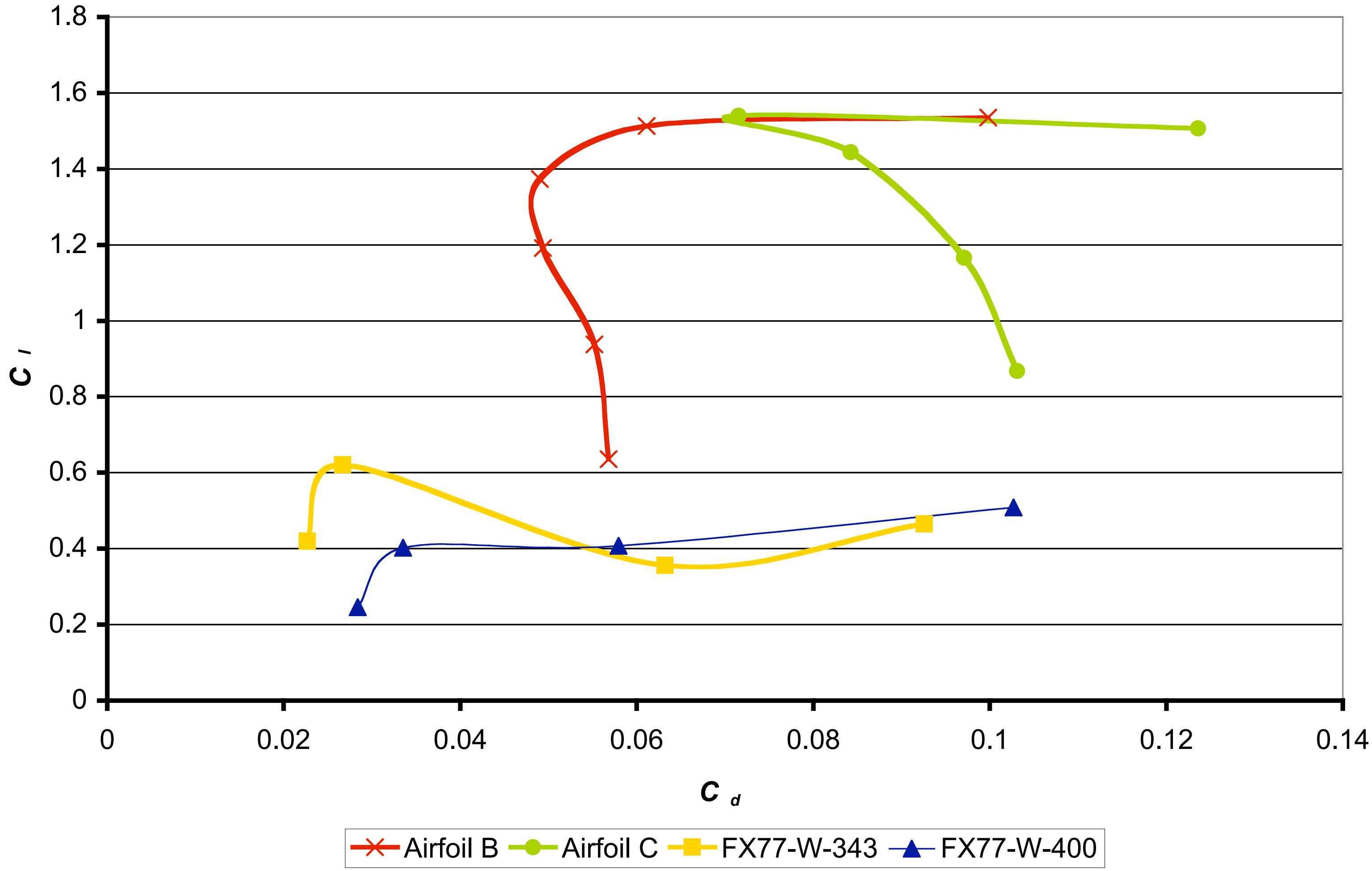
Lift Curve Comparison

Re = 1.0 million, Transition fixed near leading edge



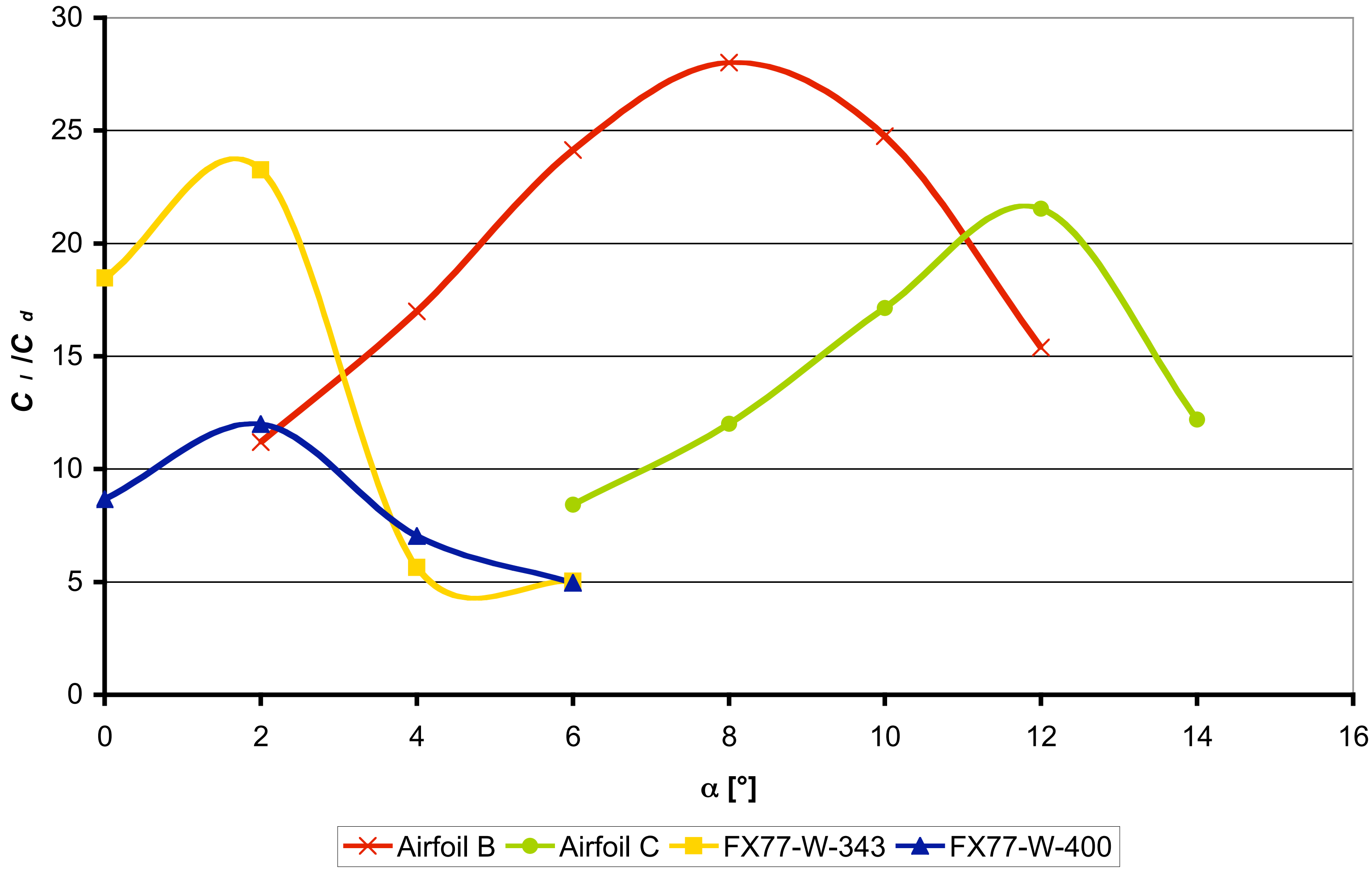
Drag Polar Comparison

Re = 1.0 million, Transition fixed near leading edge



L/D Comparison

Re = 1.0 million, Transition fixed near leading edge



Design Answer:

- Yes, a blunt trailing edge does appear if we aerodynamically design and optimize thick airfoils (maximum thickness to chord ratio > 35%)

4 Rotor with Blunt Trailing Edge Section Shapes

Design Question:

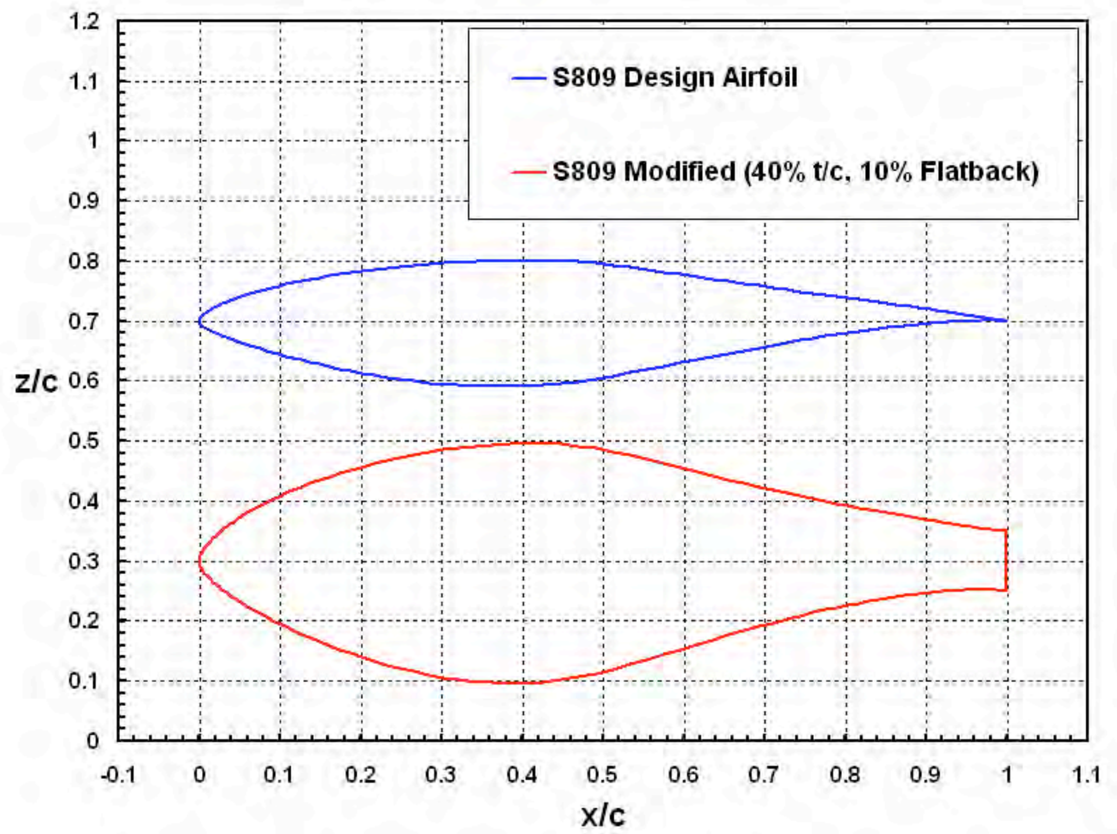
- If we incorporate thick, high-drag, blunt trailing-edge airfoils in the root region of the rotor, will there be a penalty in rotor torque?

Computational Study

- Study the effects of modifying the inboard region of the NREL Phase VI rotor using a thickened, blunt trailing edge section shapes on the performance and load characteristics of the rotor
- Study the effect of different numerical solution techniques of the compressible, three-dimensional, Reynolds-averaged Navier-Stokes equations on the accuracy of the numerical predictions

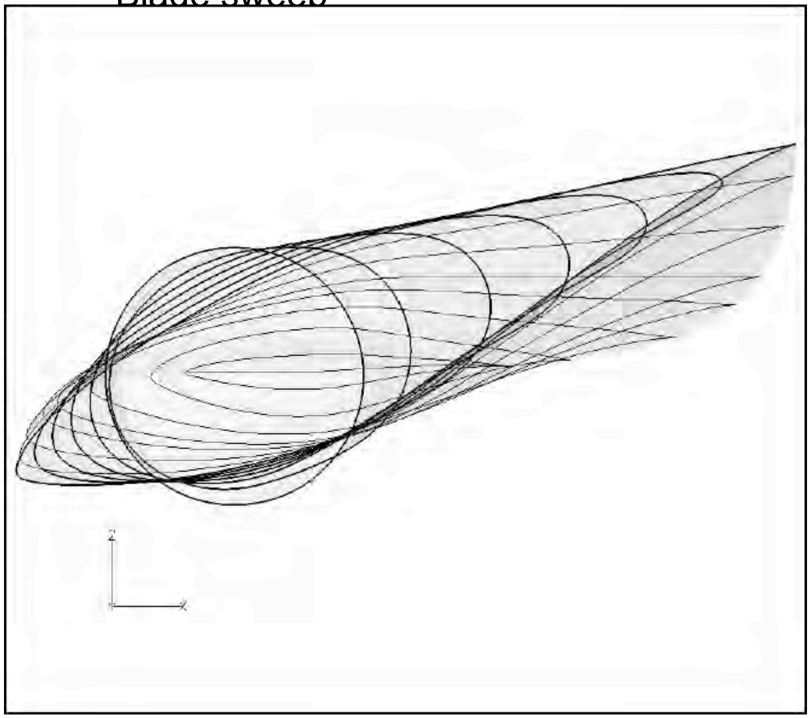
Blade Section Shapes

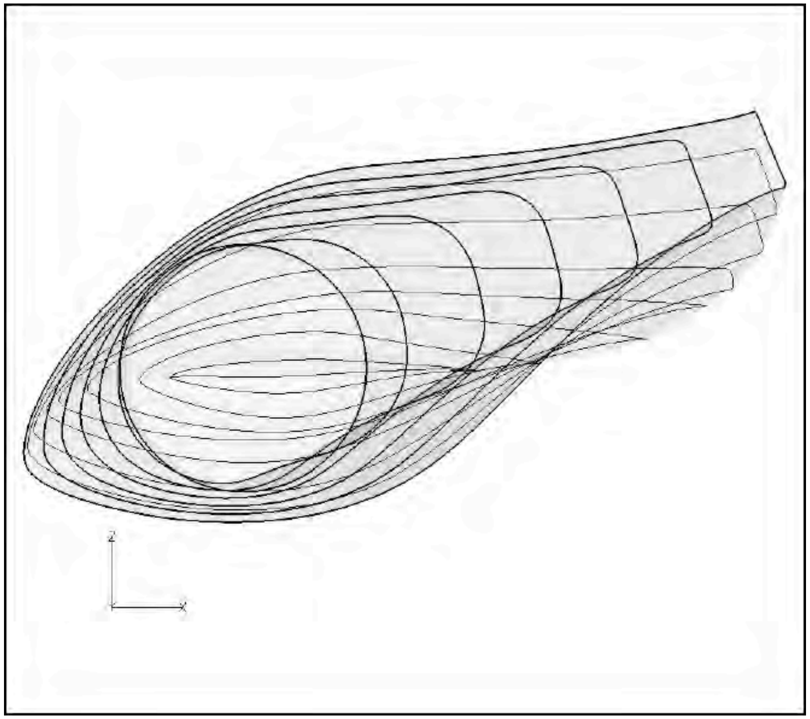
- Baseline rotor
  - S809 airfoil
- Modified rotor
  - r/R ≥ 0.45 S809 airfoil
  - 0.25 ≤ r/R < 0.45 thickened blunt trailing edge airfoil (S809 camber distribution retained)
  - Max. chord (r/R = 0.25) t/c = 0.40, t_{te}/c = 0.10



Blade Configurations (Tunnel View)

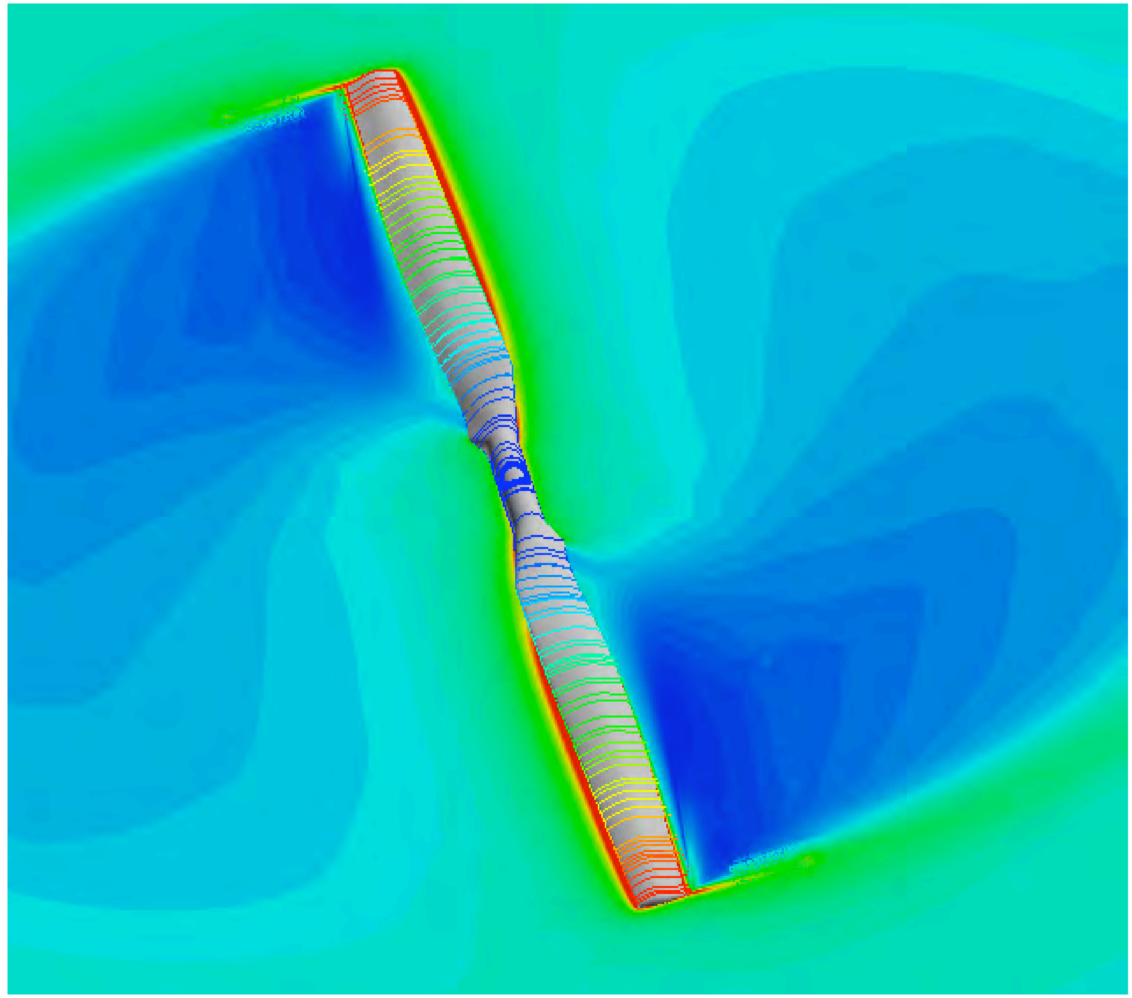
- Constant:
  - Section shape r/R ≥ 0.45
  - Span (5.03 m)
  - Pitch angle (3.0 deg)
  - Twist distribution
  - Chord distribution
  - Blade sweep


Baseline


Modified

Flow Solver

- OVERFLOW 2
- 3-D compressible Reynolds-averaged Navier-Stokes (RaNS) flow solver
- Developed by Buning et al. at NASA
- Steady and time-accurate solutions on structured block or Chimera overset grids
- Wide range of turbulence models available: Spalart-Allmaras model used in present study
- Capability to model moving geometries



NREL Phase VI rotor

Torque Comparisons

	Baseline		Modified
		Source term formulation with low Mach preconditioning	
Wind Speed (m/s)	Experiment (N-m)	CFD (N-m)	CFD (N-m)
5	220-370	160	158
7	700-870	815	815
10	1210-1380	1750	1385

Conclusions

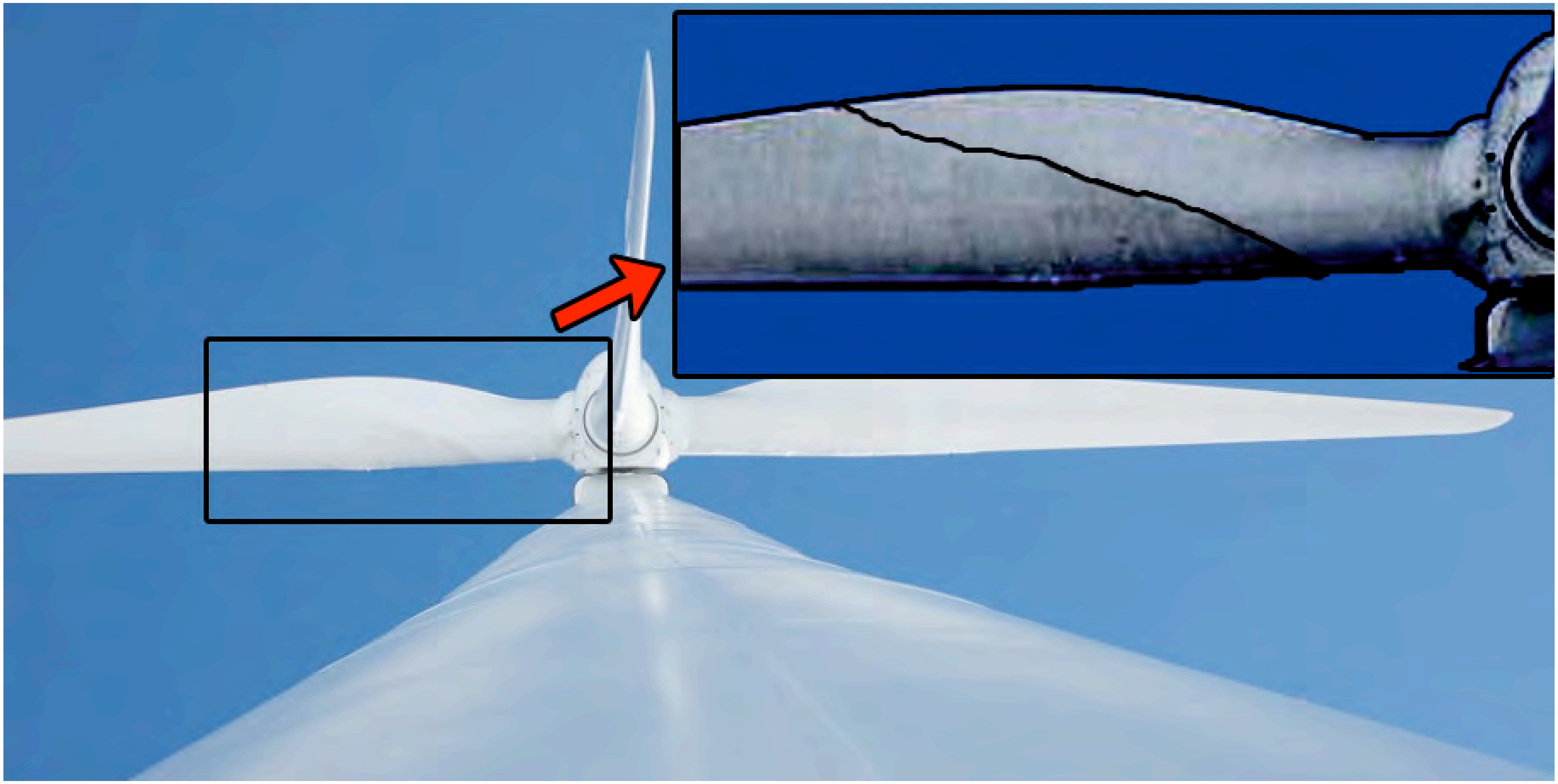
- Numerical study on effect of modifying inboard region of NREL Phase VI rotor with a thickened, blunt trailing edge version of the S809 design airfoil
- Flow solver validated by comparing predictions for baseline rotor with benchmark wind tunnel results
- At attached flow conditions (5, 7 m/s) inboard blade modification does not affect rotor performance
- At stall onset (10 m/s) modified rotor generates less torque. Drop in torque caused by outboard flow separation triggered by changes in inboard loading
- Results of study demonstrate:
  - CFD is viable tool to evaluate effects of blade geometry changes on loading and performance
  - Thick, flatback blade profile can serve as a viable bridge to connect structural requirements with aerodynamic performance in designing future wind turbine rotors

Design Answer:

- For the NREL Phase VI rotor no significant losses in rotor torque where observed as a result of thickening the section shape and incorporating a blunt trailing edge in the root region.
- More analysis is required

5 What Next?

Power Loss: Inboard Flow Separation



Unnecessary power loss on modern multi-megawatt turbines

Industry Ad Hoc Solutions

Stall Fences

Spoilers

Source: REpower Systems AG

Current Work

- Thick section shapes and limited blade twist are resulting in flow problems in inboard region of rotating blades
- BEM does not properly model inboard flow development of rotors
- Study inboard flow behavior using unsteady, 3-D, viscous RANS
- Evaluate aerodynamic design techniques to mitigate flow separation
- Improve current turbine design methodologies

More Info

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