Insights into Rotor Performance and Loads through Three-Dimensional CFD

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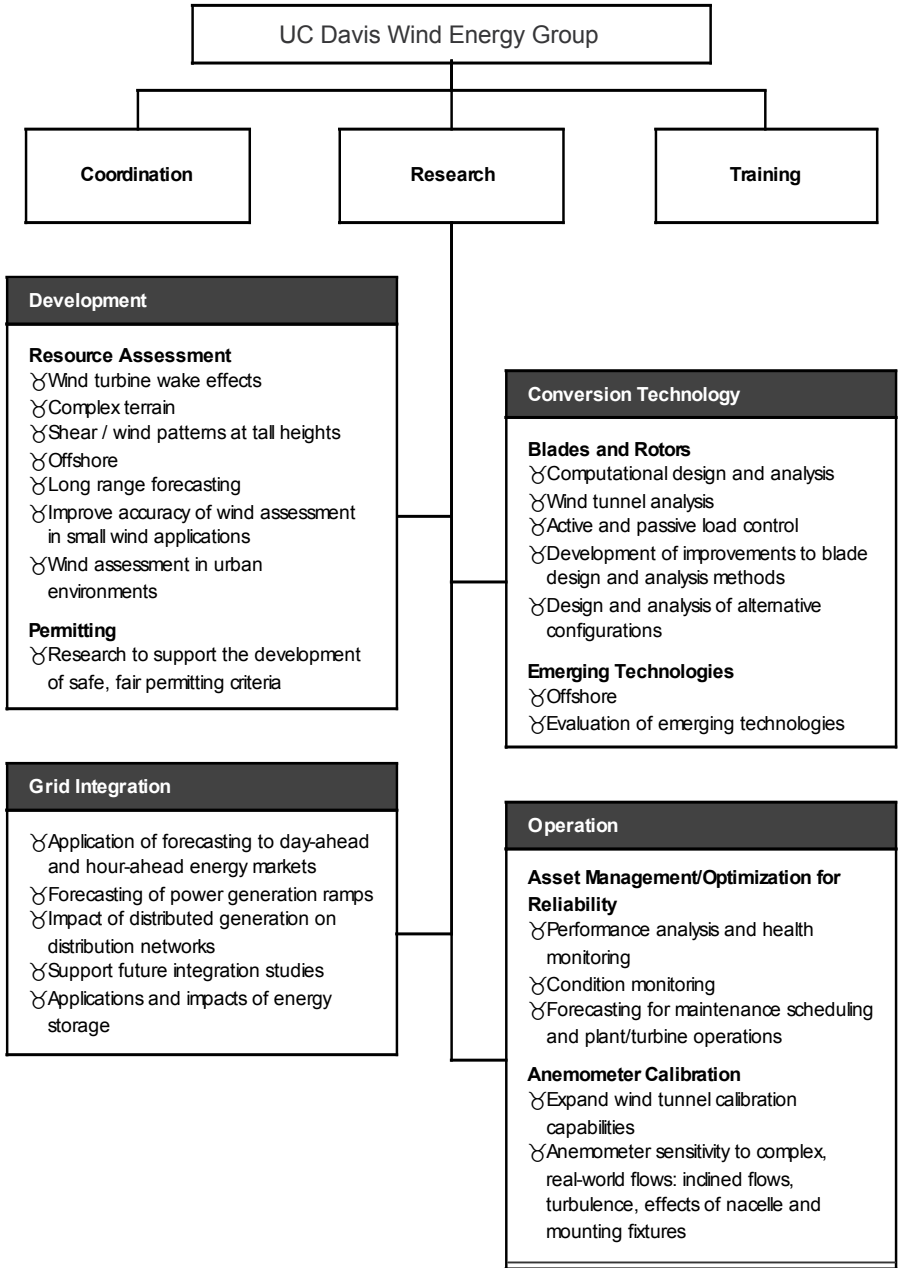
Research Focus



- Sample projects:
  - Conversion Technology
    - Airfoil design
    - Blunt trailing edge airfoils
    - Rotor analysis
    - Rotor active load control
    - Load limiting control algorithm
  - Development
    - Wake effects
    - Forecasting
    - Turbine setback
  - Grid Integration
    - IAP
    - Performance analysis of commericial windplants
    - Value of wind forecasting
  - Operation
    - Anemometer calibration

Presentation Outline

- Overview
- CFD analysis of wind turbine rotors
  - Early work:
    - STAR
  - NREL 5 MW / Upwind rotor
    - Twist
    - Fence
    - Flatback
- Concluding remarks

Pros and Cons of CFD Analysis

- Pros:
  - Provides insights into
    - flow development about and downstream of turbine
    - aerodynamic performance characteristics
    - aerodynamic loads
  - Can accurately analyze complex configurations
  - Predict scale effects
- Cons:
  - Time consuming pre- & post-processing
  - Time consuming computations (days to weeks)
  - Requires high end computer hardware
  - Requires expert users
  - Software can be expensive

CFD Methodology

- OVERFLOW-2
  - Reynolds-averaged Navier-Stokes solver (RANS)
    - Fully viscous, ⅓ y^+ near-wall spacing
    - 2-equation, k-ω SST turbulence model
    - 2-order spatial in viscous, near-body region
    - 2-order time-accurate
      - Dual-time stepping
    - Rotational source term applied to NS equations to model rotation
  - Chimera/overset grid topology
  - Wide variety of applications
  - Extensive experience
- Extensive validation using NREL Phase VI and NREL 5-MW rotor

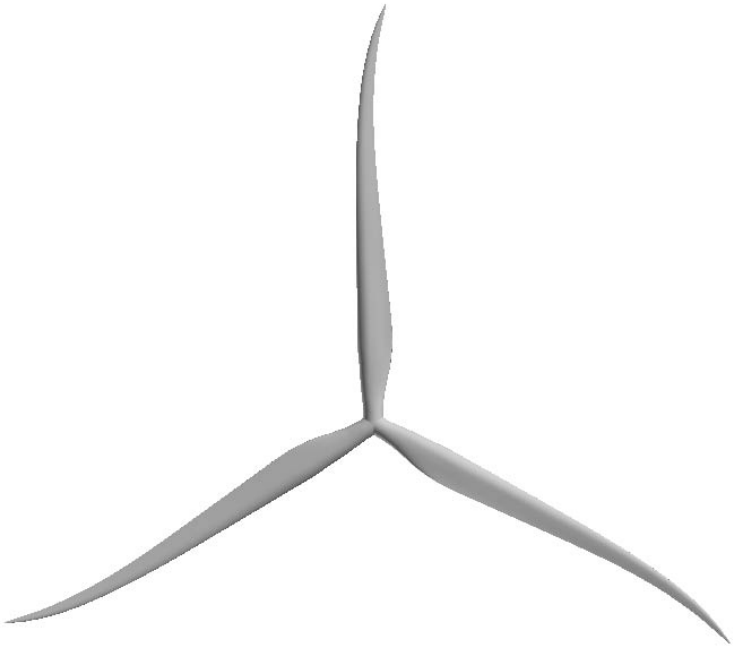
Sweep Twist Adaptive Rotor (STAR)

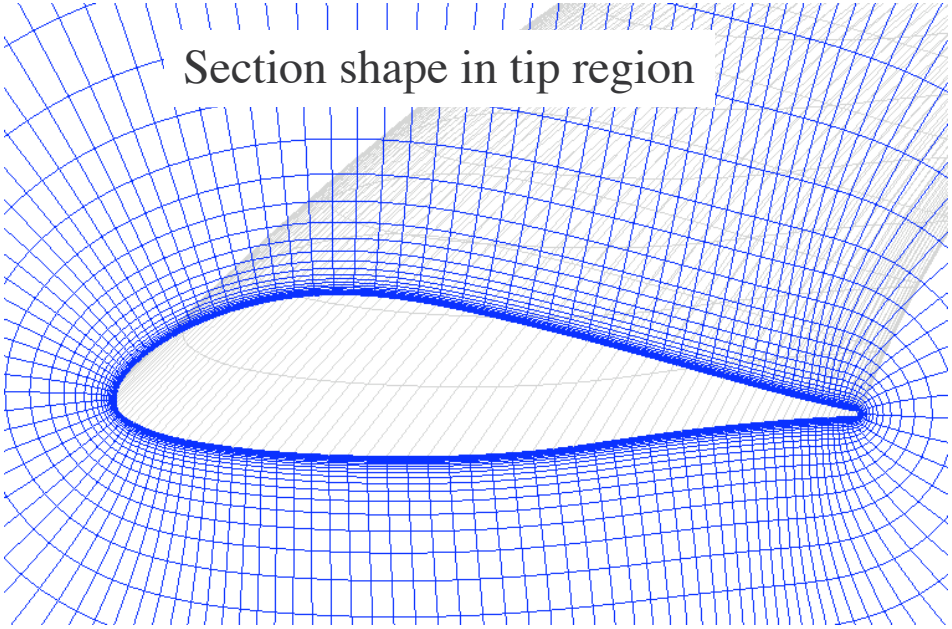
- 2004 DOE award to Blade Division of Knight & Carver to design, build, and demonstrate a rotor based on the sweep-twist concept
- Rotor designed for testing on a Zond Z48 turbine with 750 kW rating
- Goal to increase annual energy capture of baseline turbine by 5%-10% without exceeding baseline rotor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

Structured Grid System

Total number of grid points = 3.5 million

Swept rotor



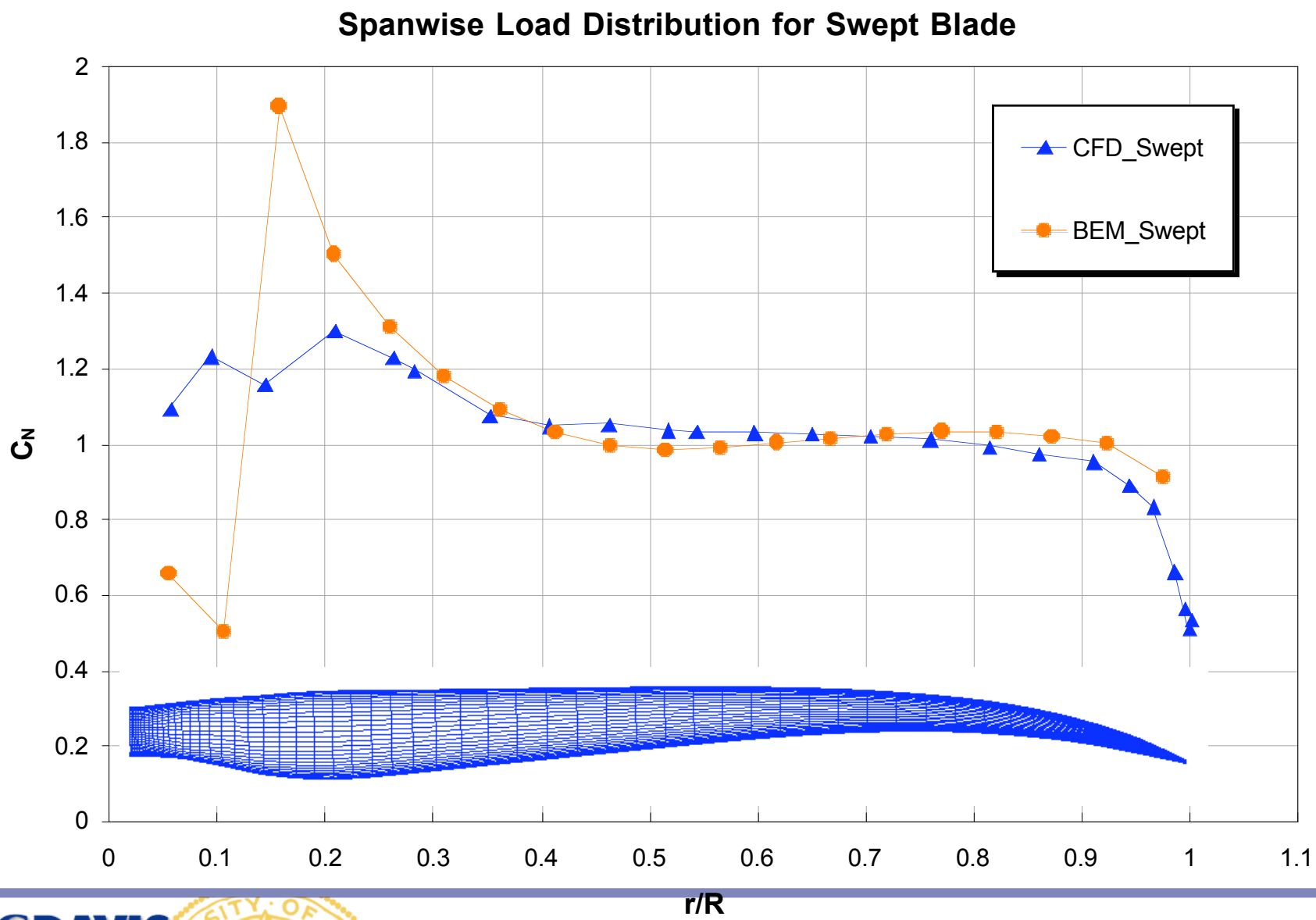


Unswept blade

Swept blade

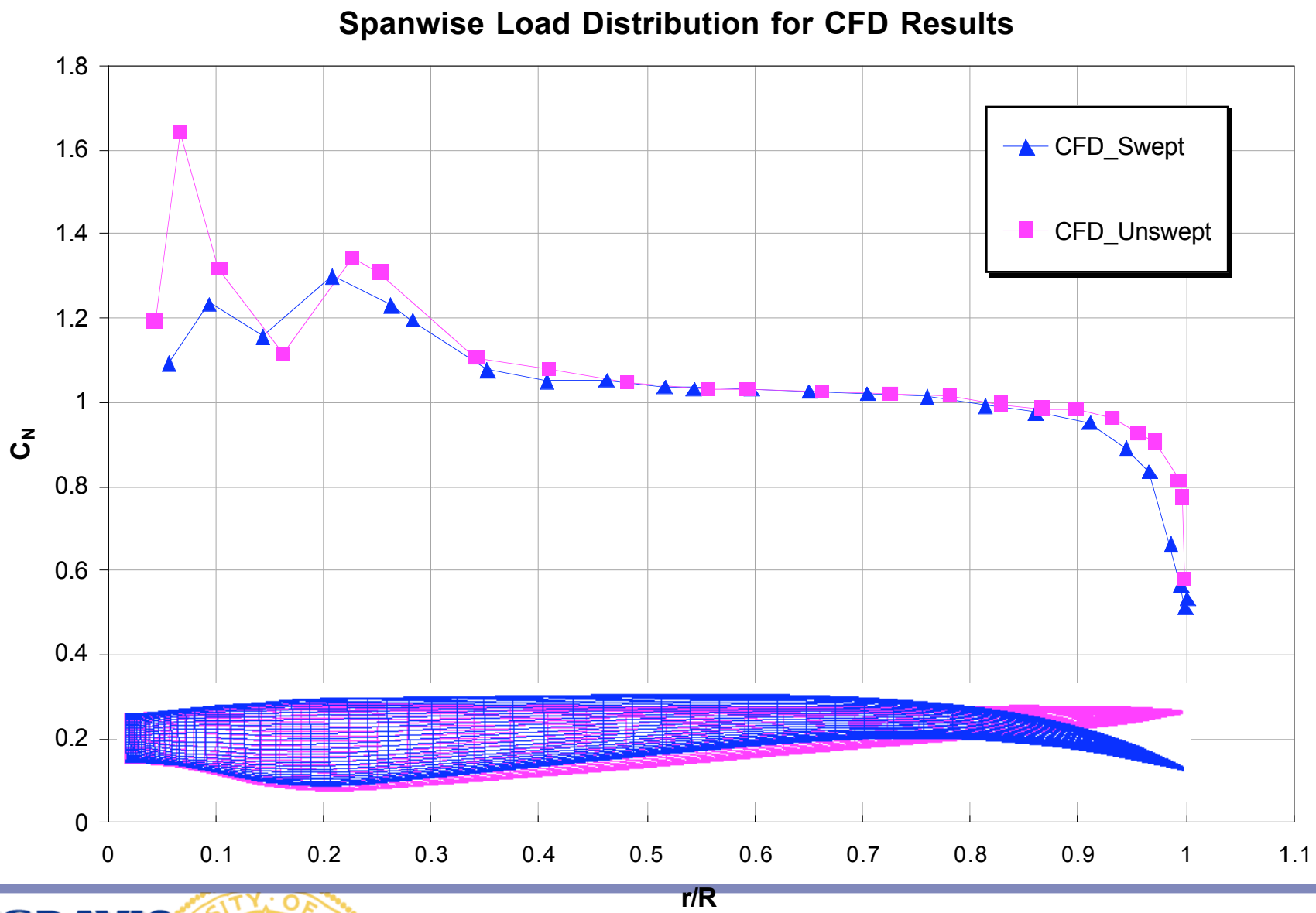
CFD vs. BEM Blade Spanwise Loads

Swept blade



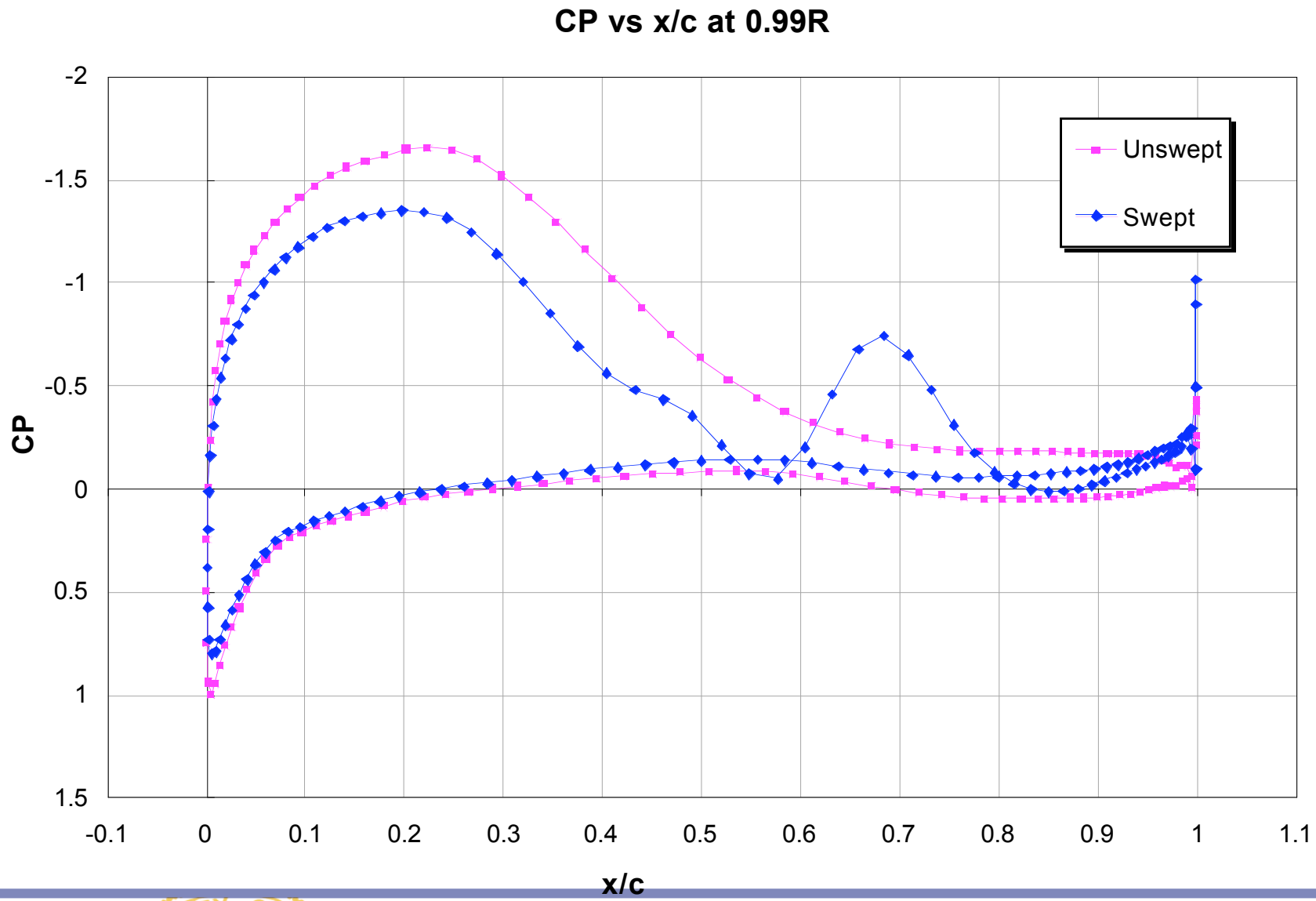
Effect of Blade Sweep on Spanwise Loads

CFD



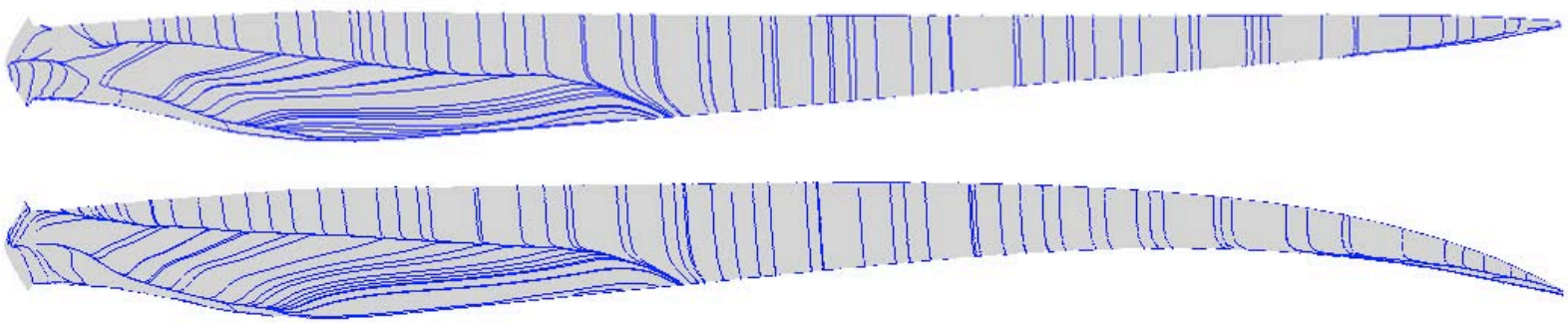
Effect of Blade Sweep on Blade Pressures

CFD, r/R = 0.99



Comparison of Oil Flow Simulations

Suction side, V_{wind} = 10 m/s, RPM = 26.6

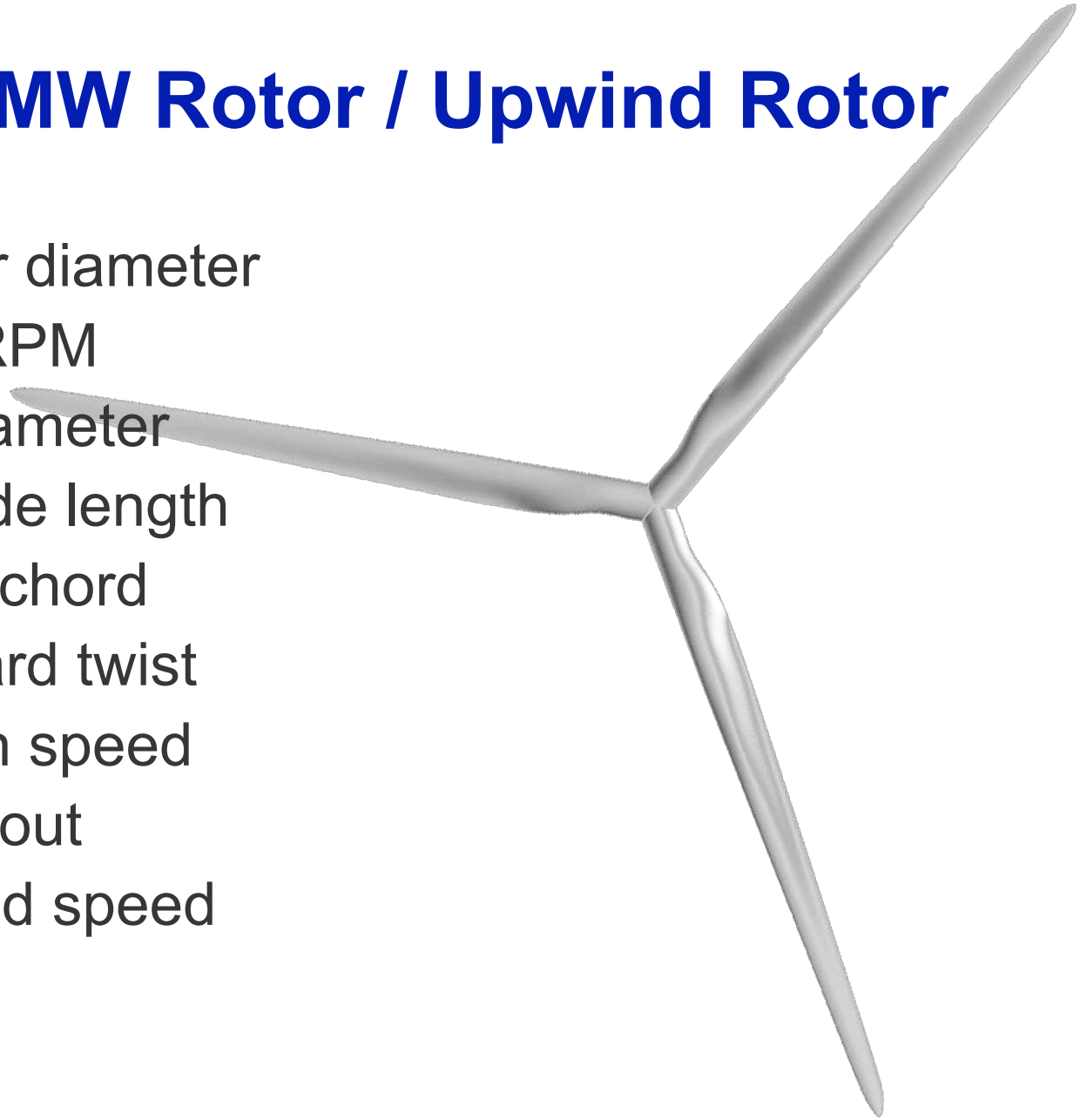


NREL 5-MW / Upwind Rotor

- Geometry based on 6MW DOWEC rotor
  - Conceptual off-shore turbine design
  - ECN (Energy Research Centre of the Netherlands)
- Rotor diameter truncated and hub diameter reduced

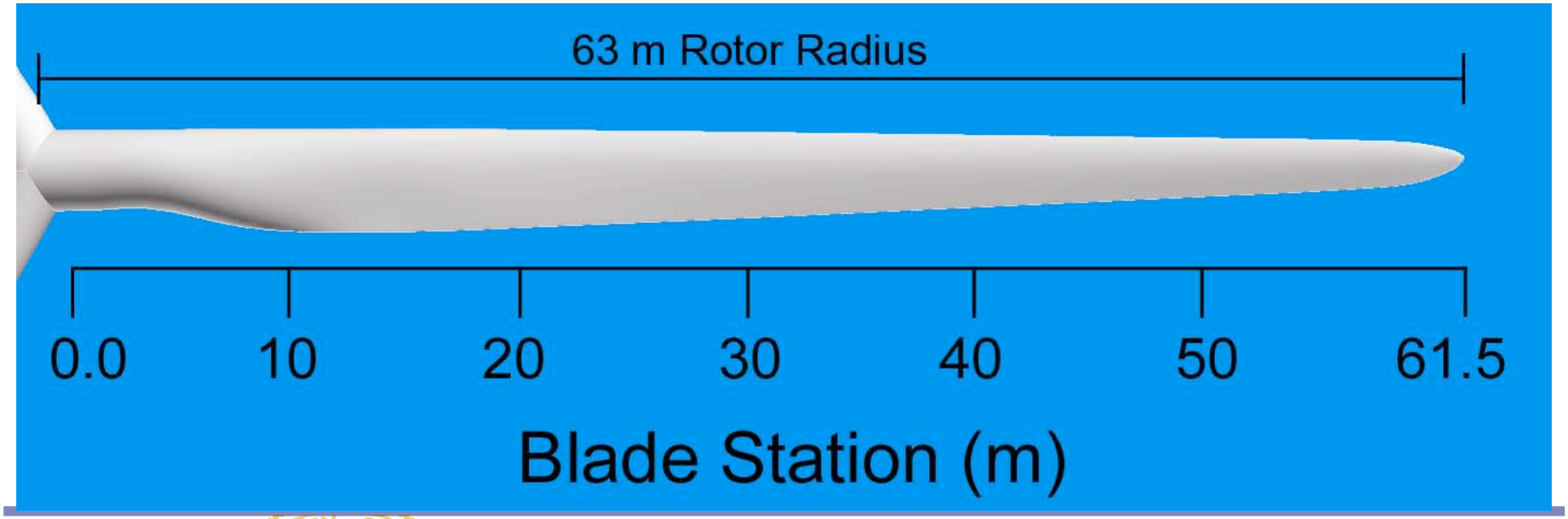
NREL 5-MW Rotor / Upwind Rotor

- 126 m rotor diameter
- 12.1 max RPM
- 3 m hub diameter
- 61.5 m blade length
- 4.7 m max chord
- 13.3° inboard twist
- 3 m/s cut-in speed
- 25 m/s cut-out
- 12 m/s rated speed

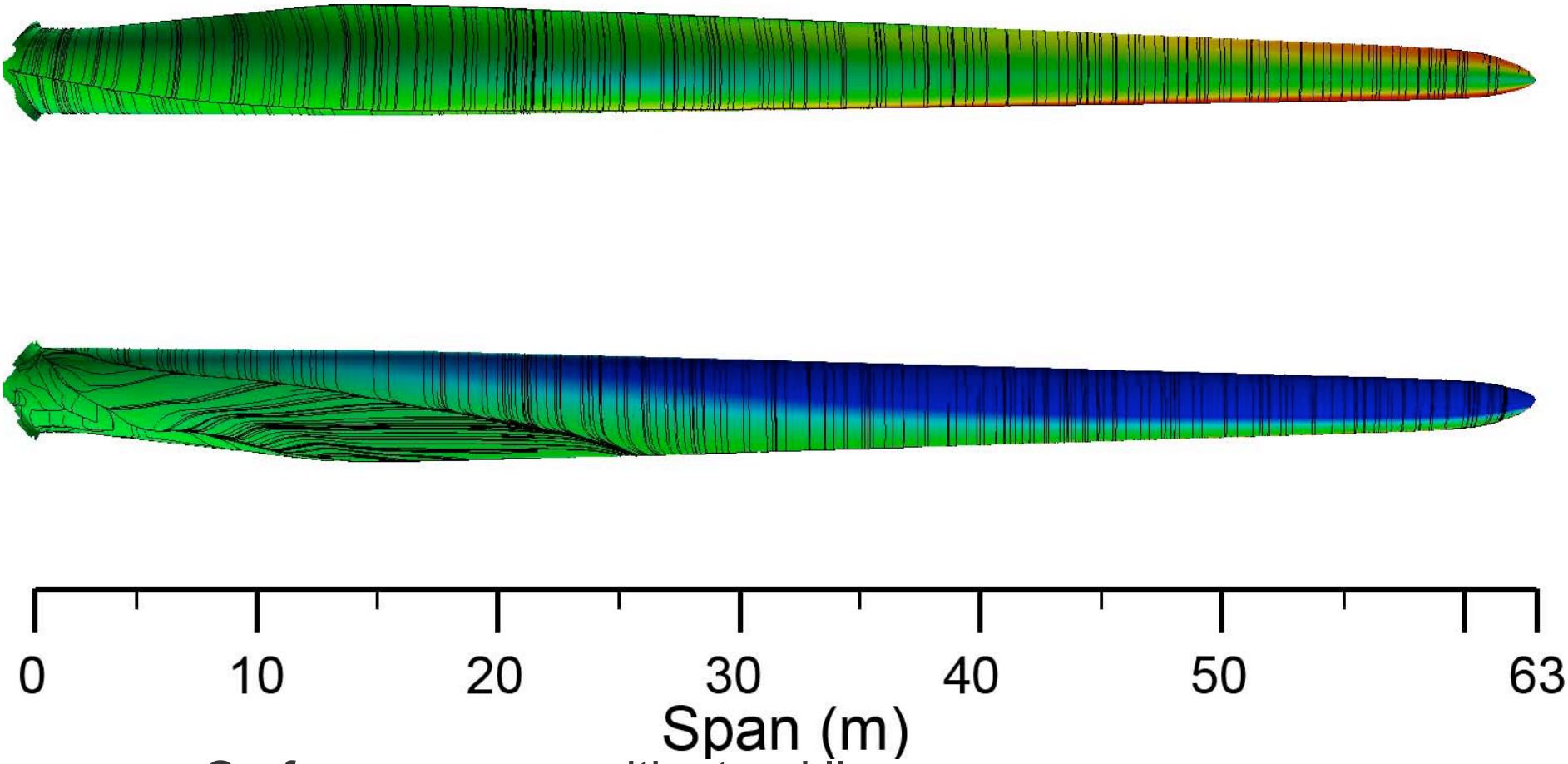


NREL 5-MW Blade

- Inner 58.5m as defined by Lindenburg (ECN) and Jonkman (NREL)
- Using a 3.0m tip region defined by Risø DTU



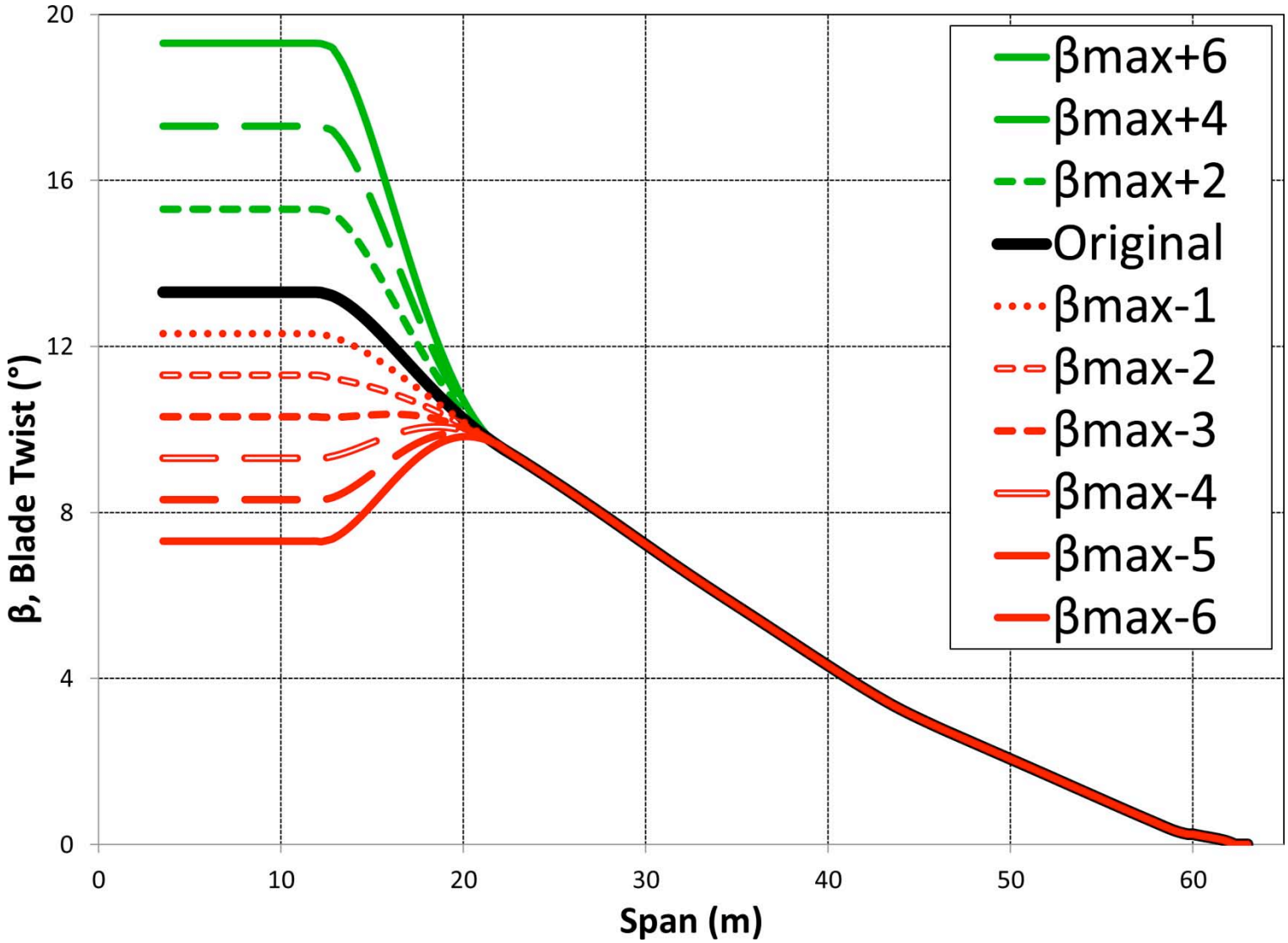
NREL 5-MW – U_∞ = 11m/s



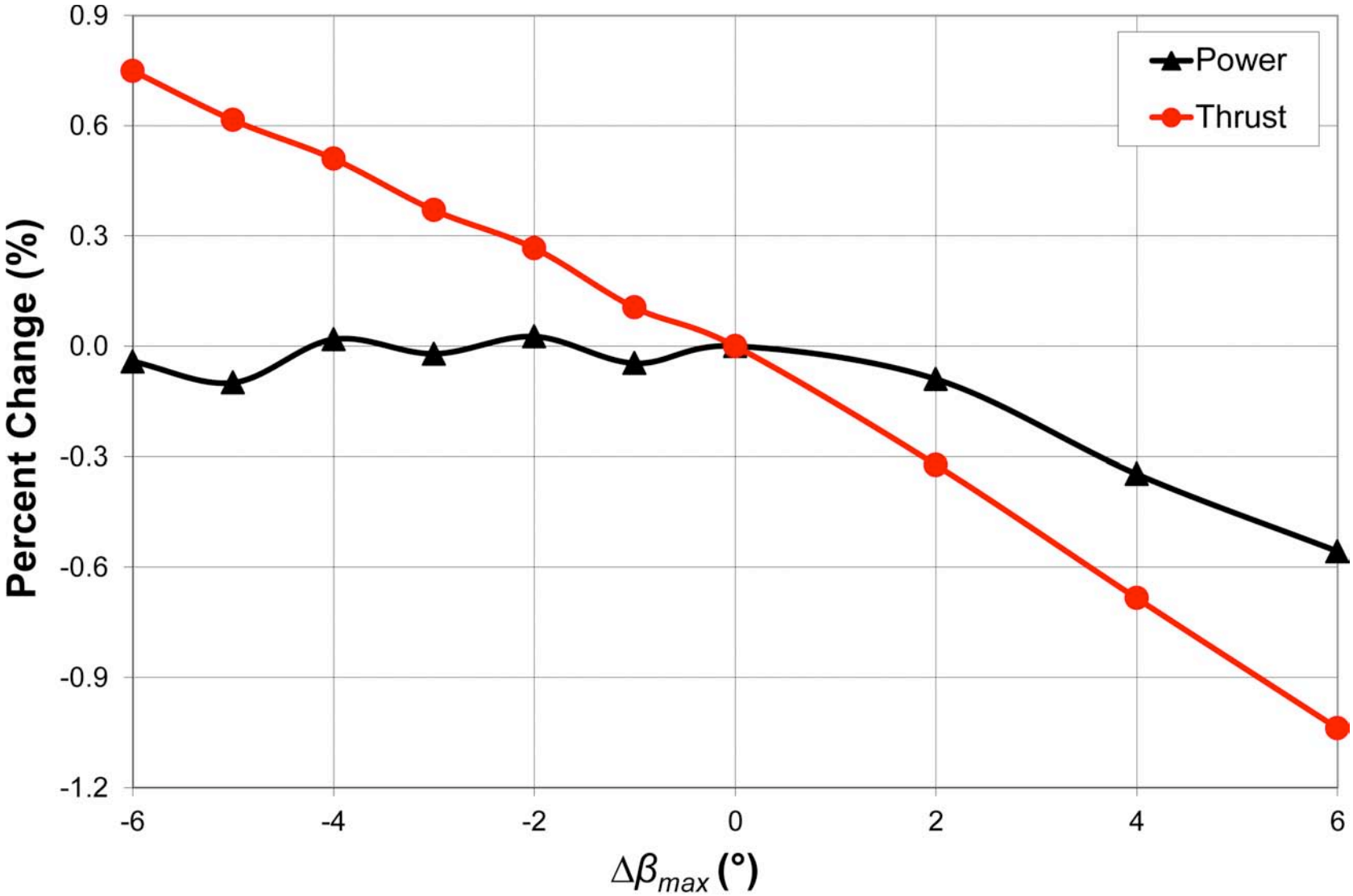
- Surface pressure with streaklines

Inboard Twist Modification

Twist Schedule



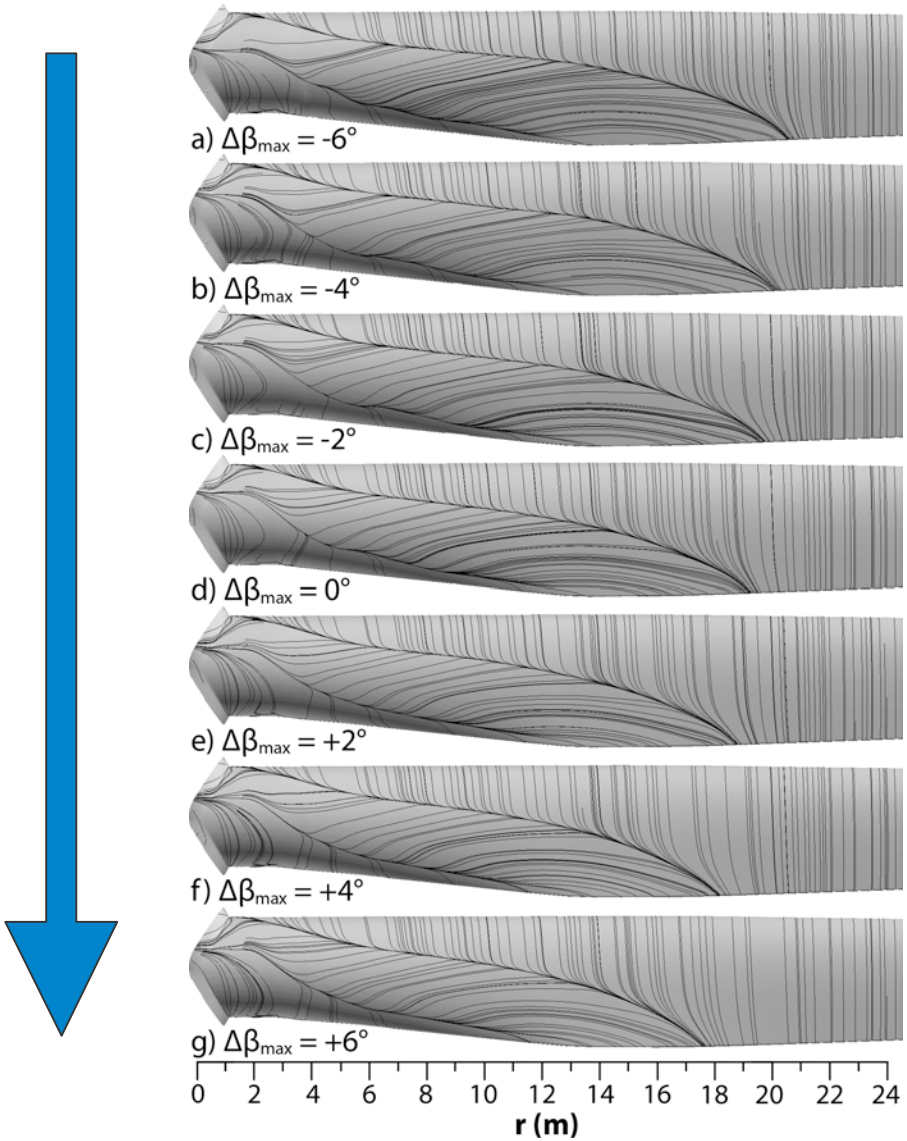
Inboard Twist Study



Inboard Twist Study

Increasing Twist

Reduced Separation

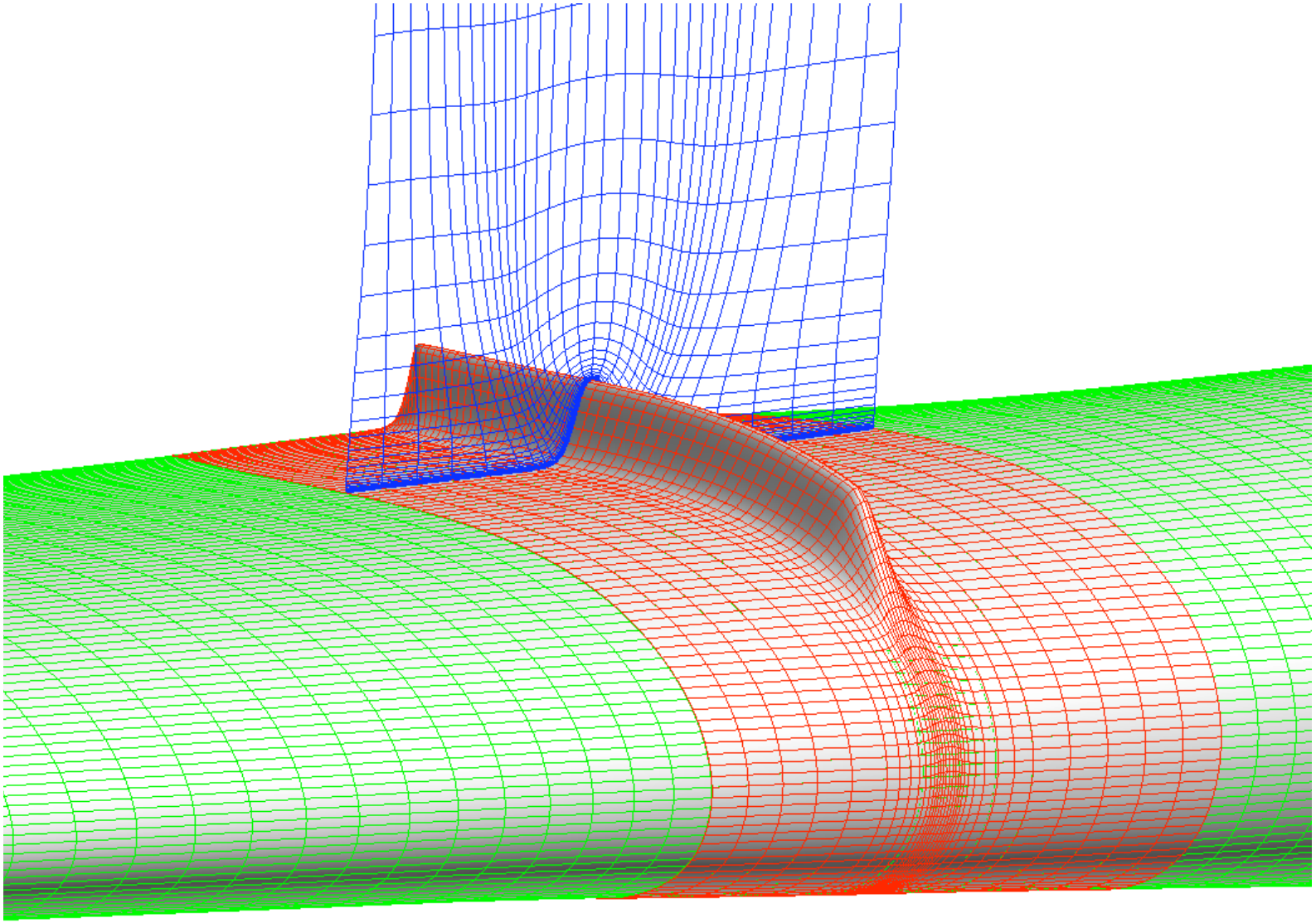


Inboard Twist Conclusions

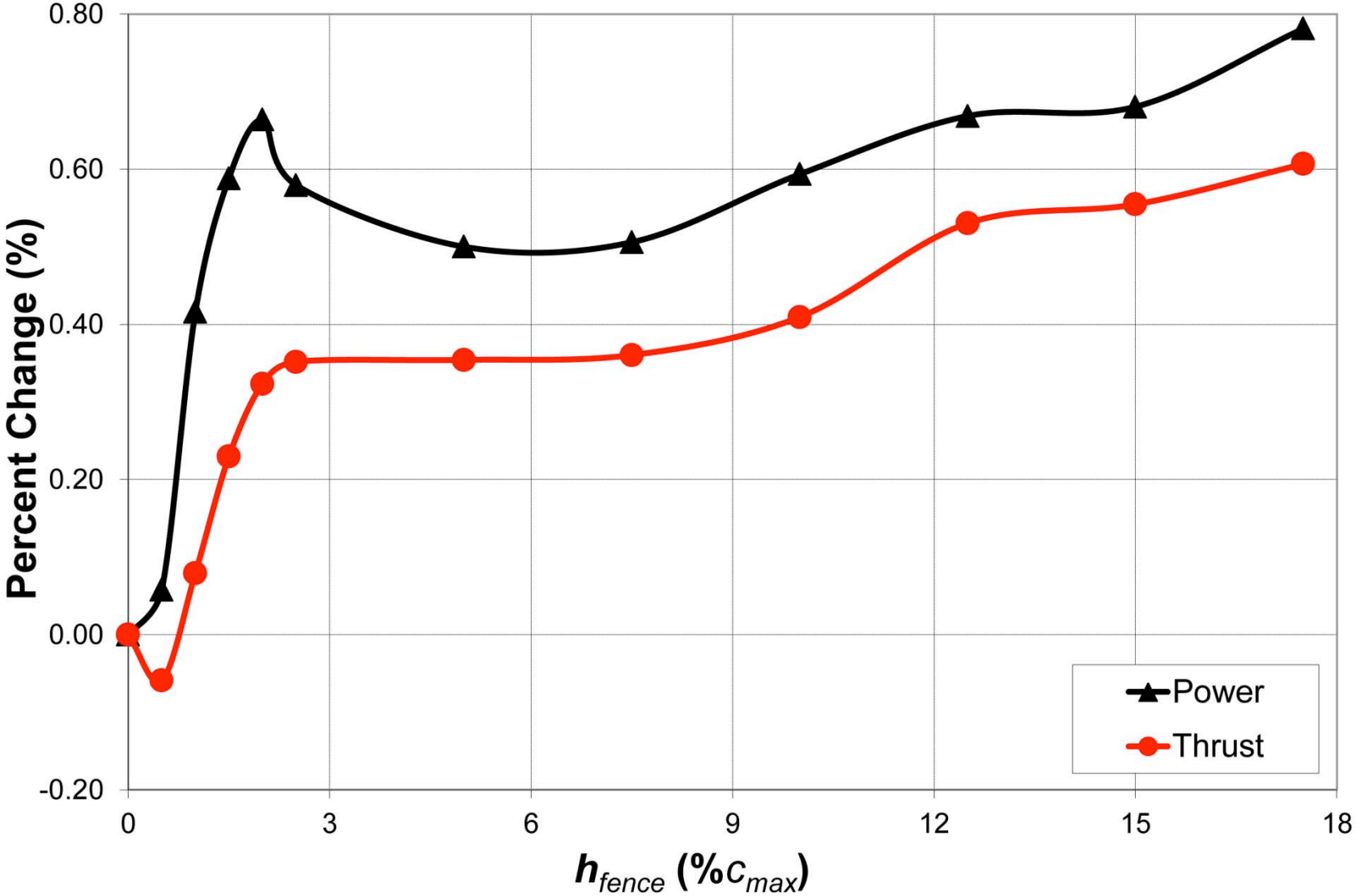
- Decreasing twist pushed the inboard section further into stall
  - Power remained constant
  - Thrust increased
- Increasing twist reduced thrust at a faster rate than power
  - Potential structural optimum may exist
- Twist changes appear to be insufficient to significantly reduce inboard separation

Fence Modification

Suction-Side Fence



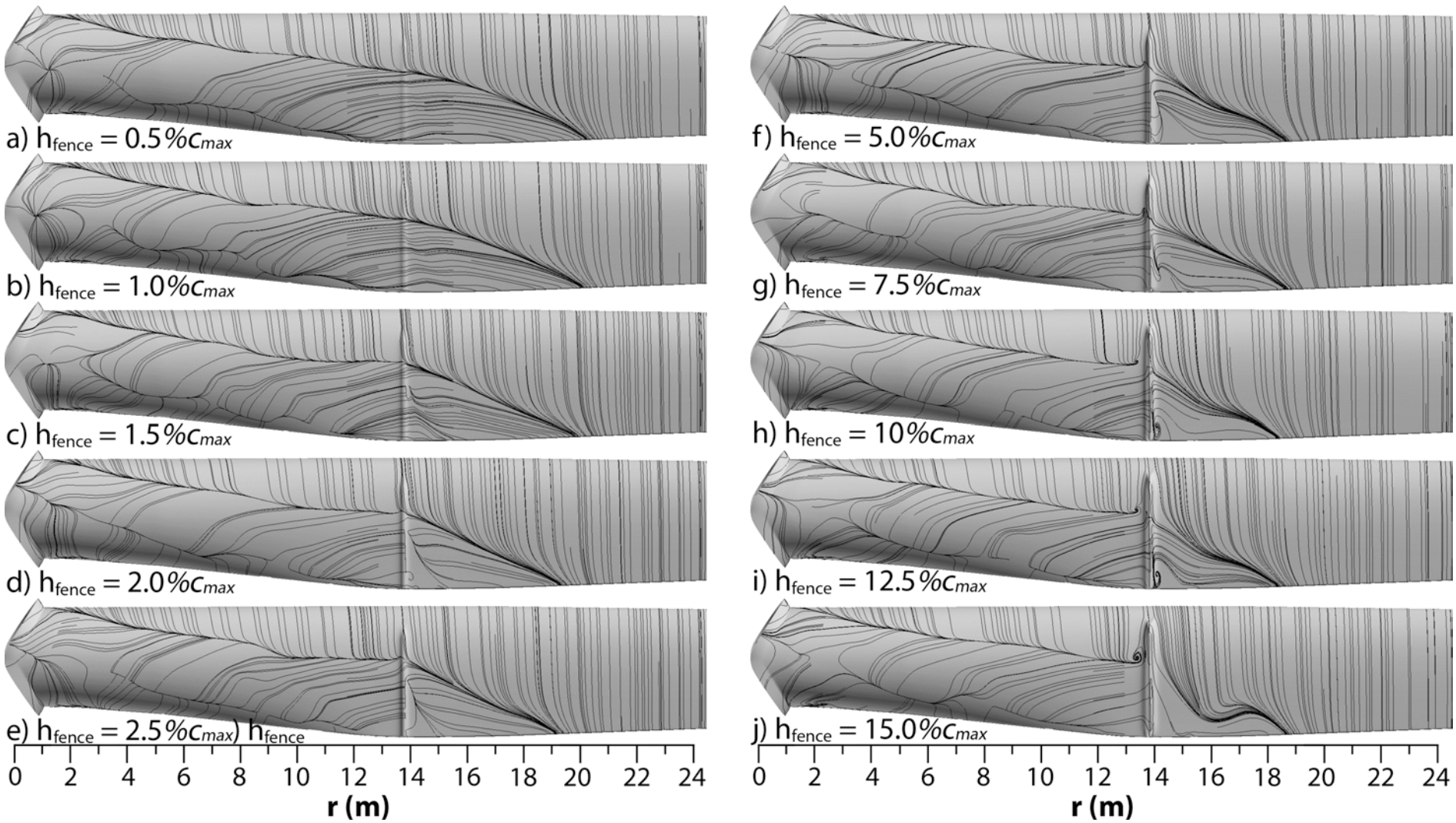
Fence Height Study



UCDAVIS

Constant spanwise location: $r_{fence} = r(c_{max}) = 13.7m$

Fence Height Study



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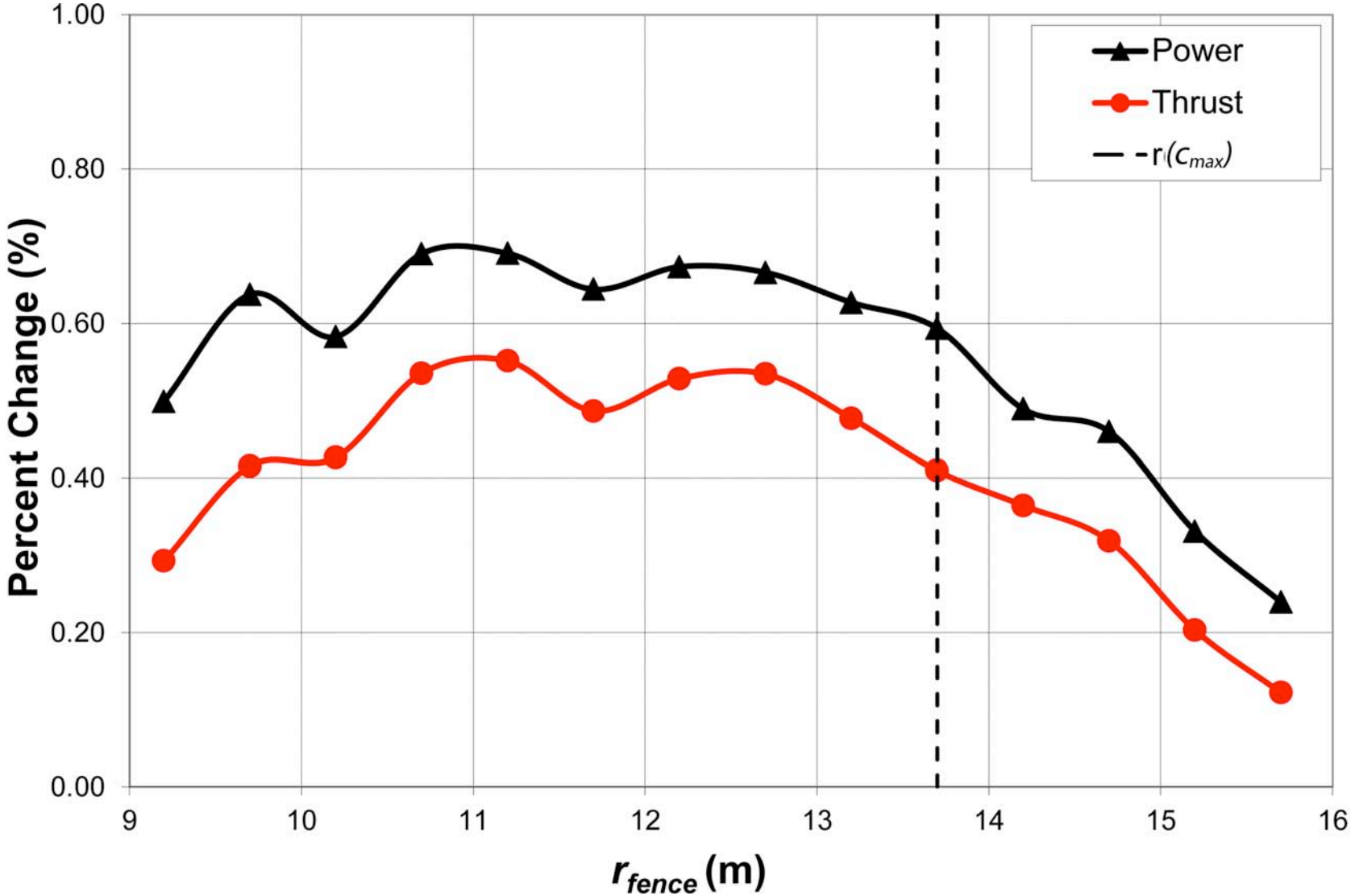
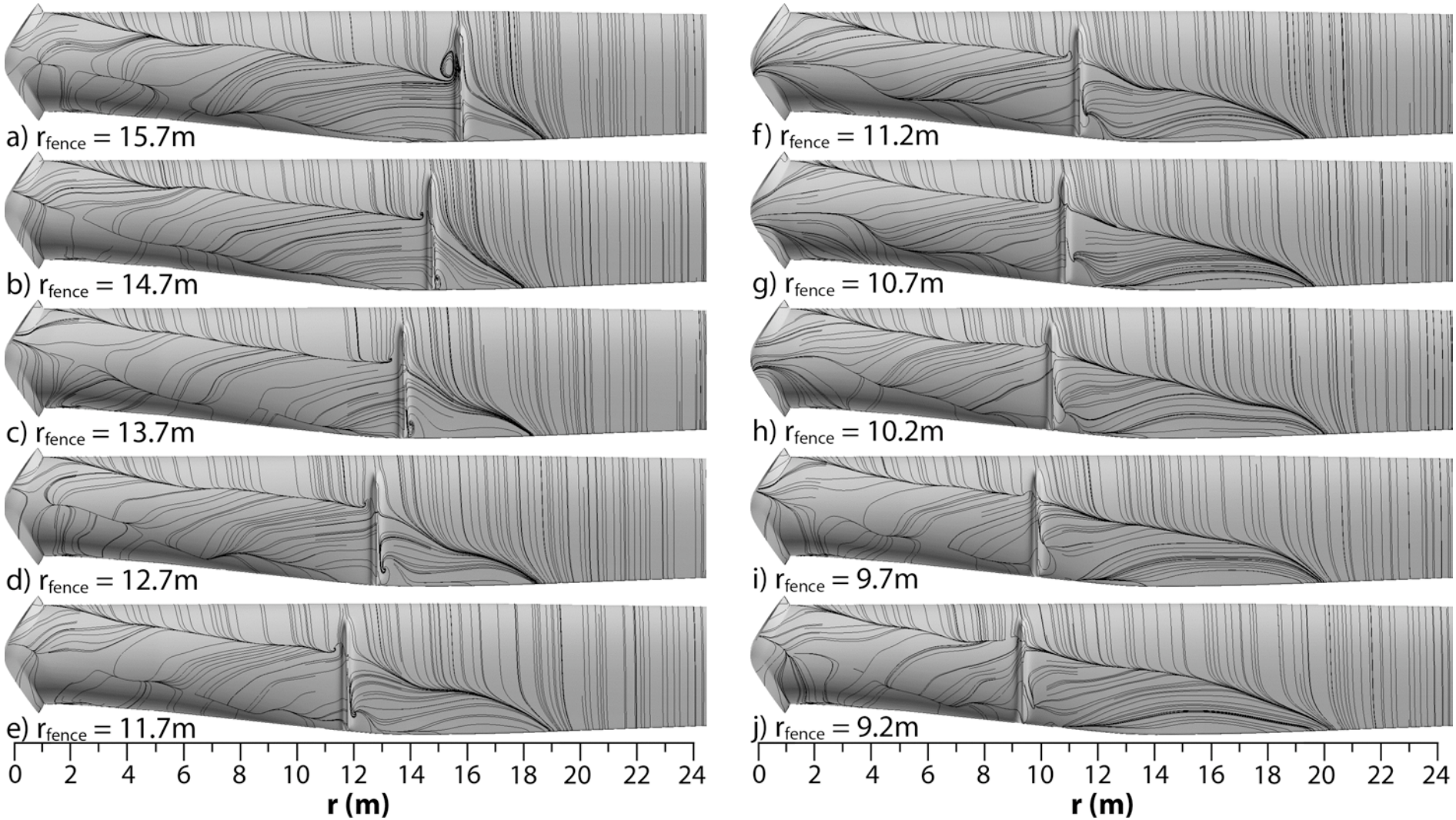
Fence Location Study



UCDAVIS

Constant fence height: $h_{fence} = 10\% c_{max} = 0.47m$

Fence Location Study

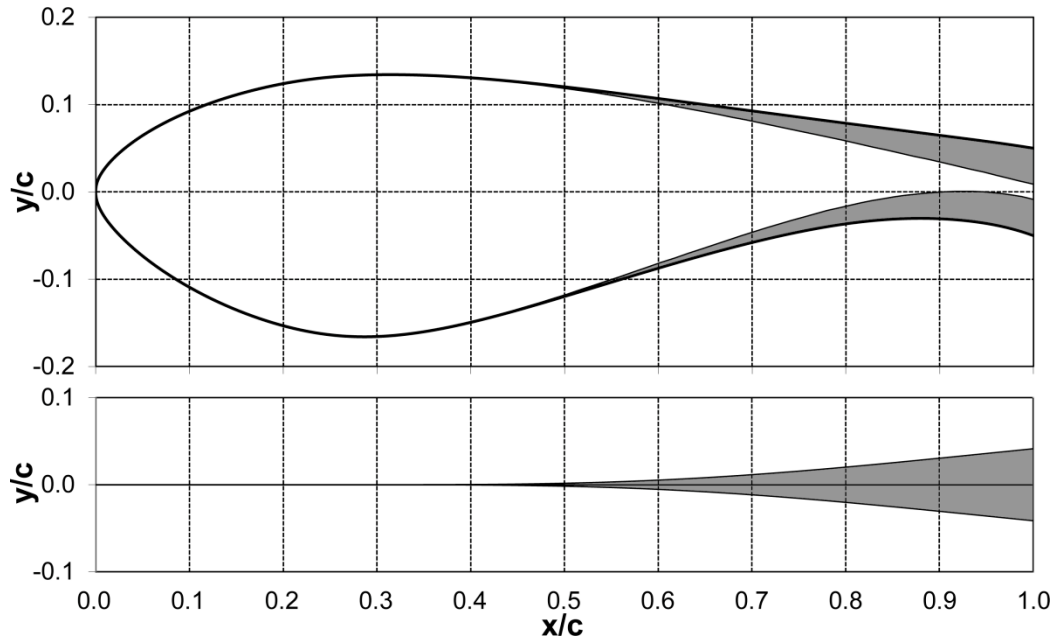


Constant fence height: h_{fence} = 10%c_{max} = 0.47m

Blunt Trailing Edge Modification

Blunt Trailing Edge Concept

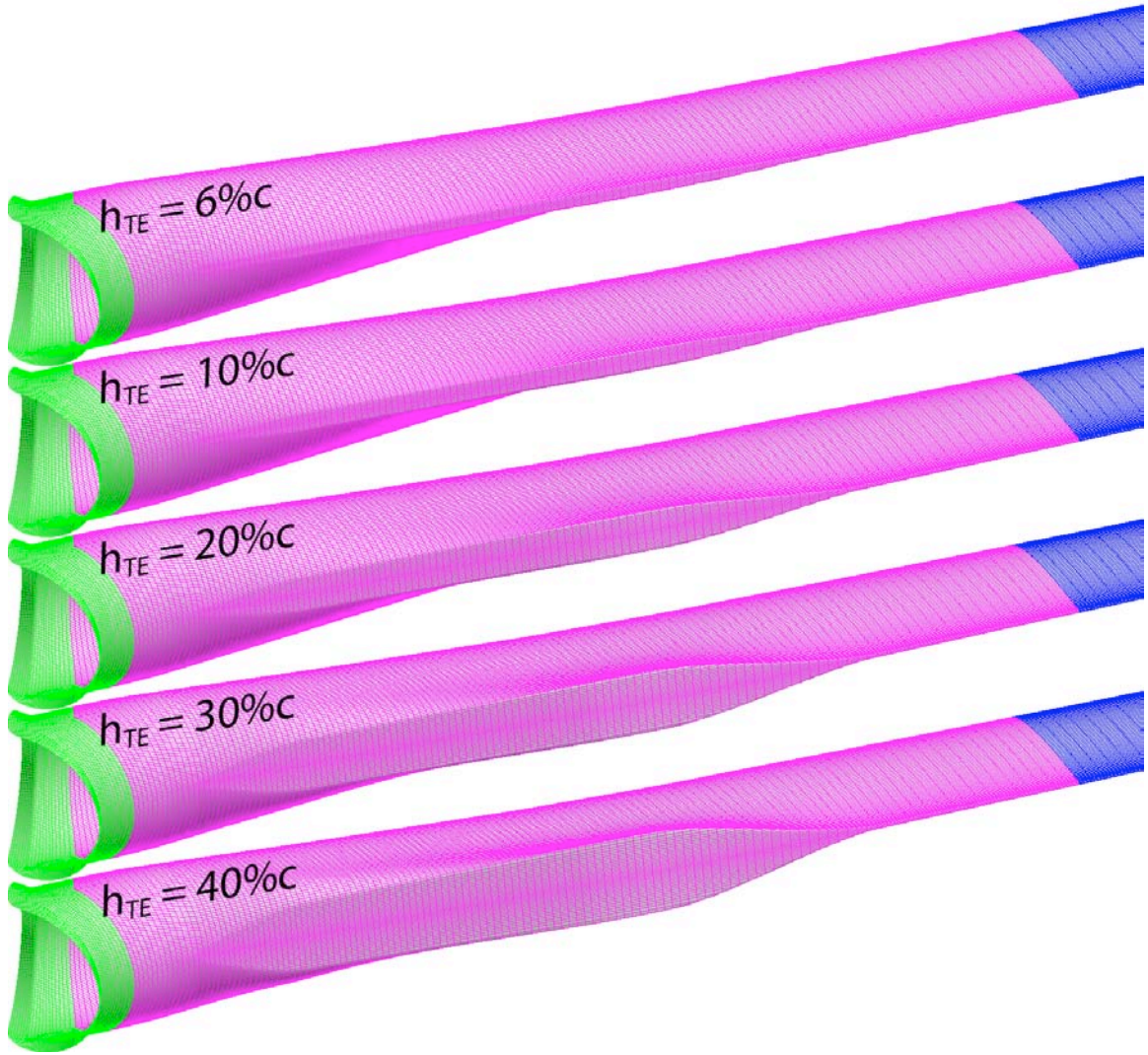
- Thickness is added symmetrically about the chord line
- 6th-order polynomial function
- Section is not truncated
- Extensive 2-D studies



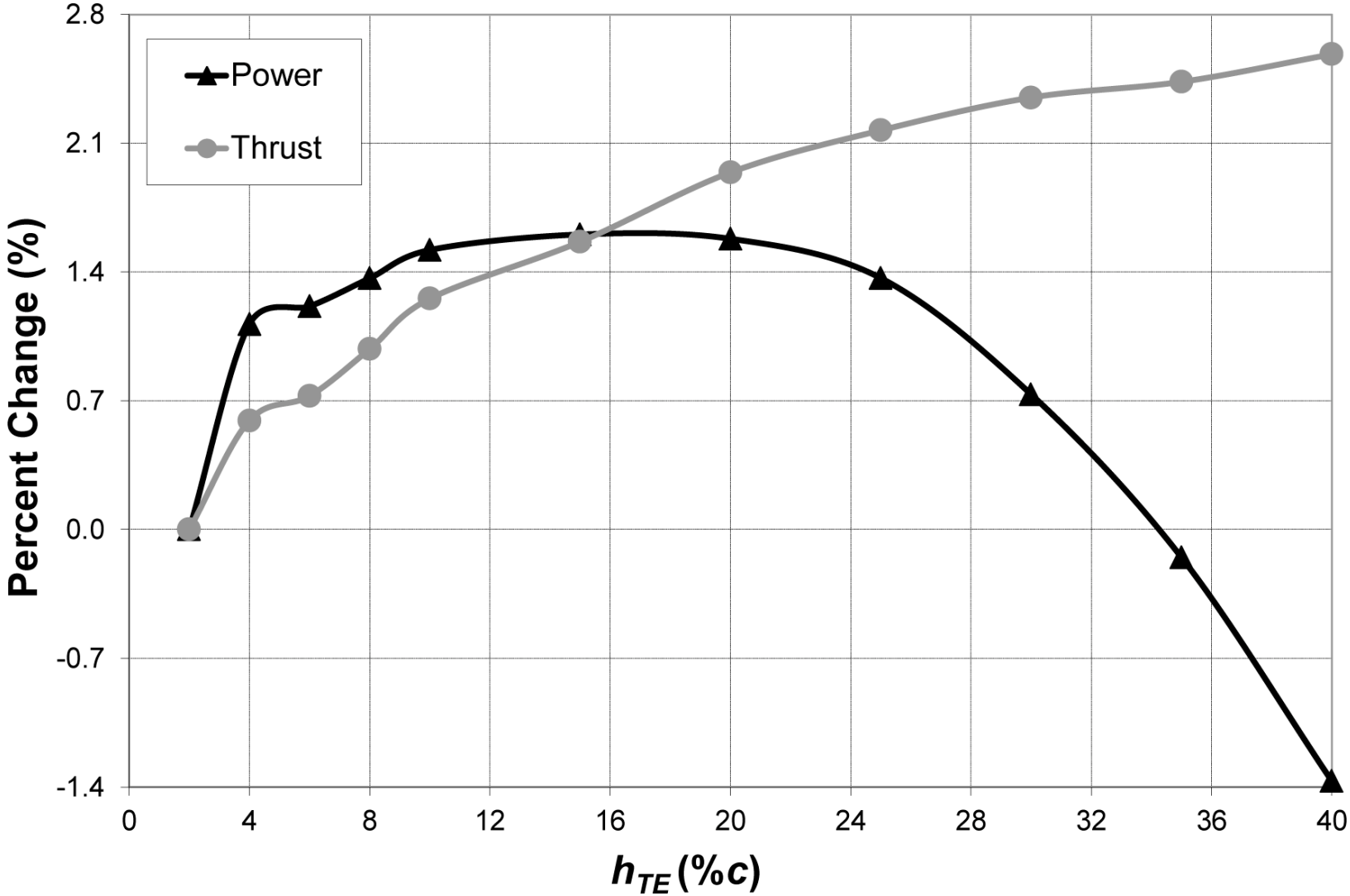
- Pressure recovery occurs aft of the airfoil
- Delays stall, increasing $C_{L,max}$
- Drag increases due to the decrease in base pressure
- Reduces sensitivity to soiling

Flatback / Blunt Trailing Edge Modification

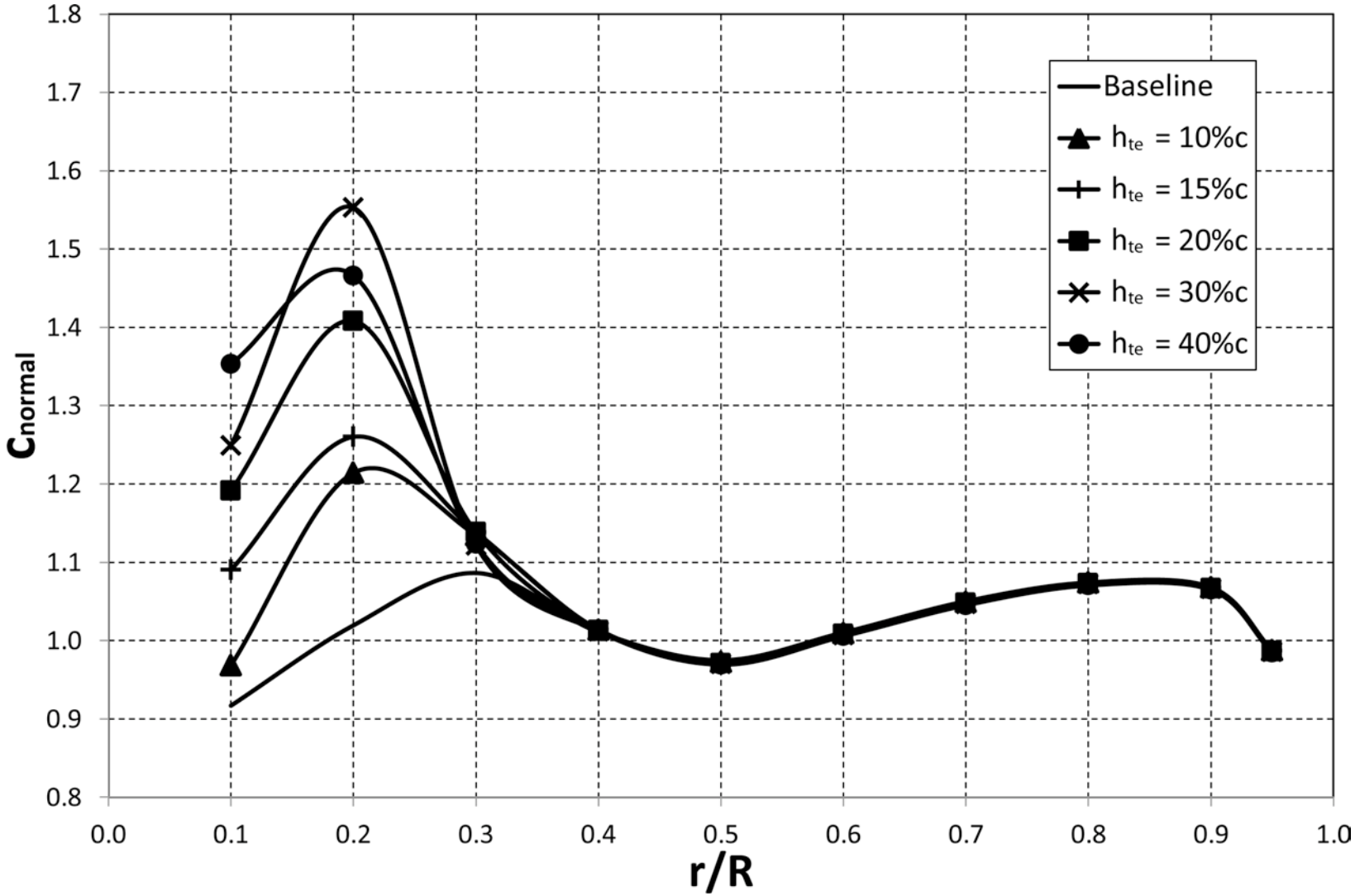
- Changes isolated to inboard grid
- r_{in} = 3.4 m
  = 5.4%R
- r_{out} = 20 m
  = 31.7%R
- h_{TE} = 4, 6, 8, 10, 15, 20, 25, 30, 35, and 40%c
- Based on local chord



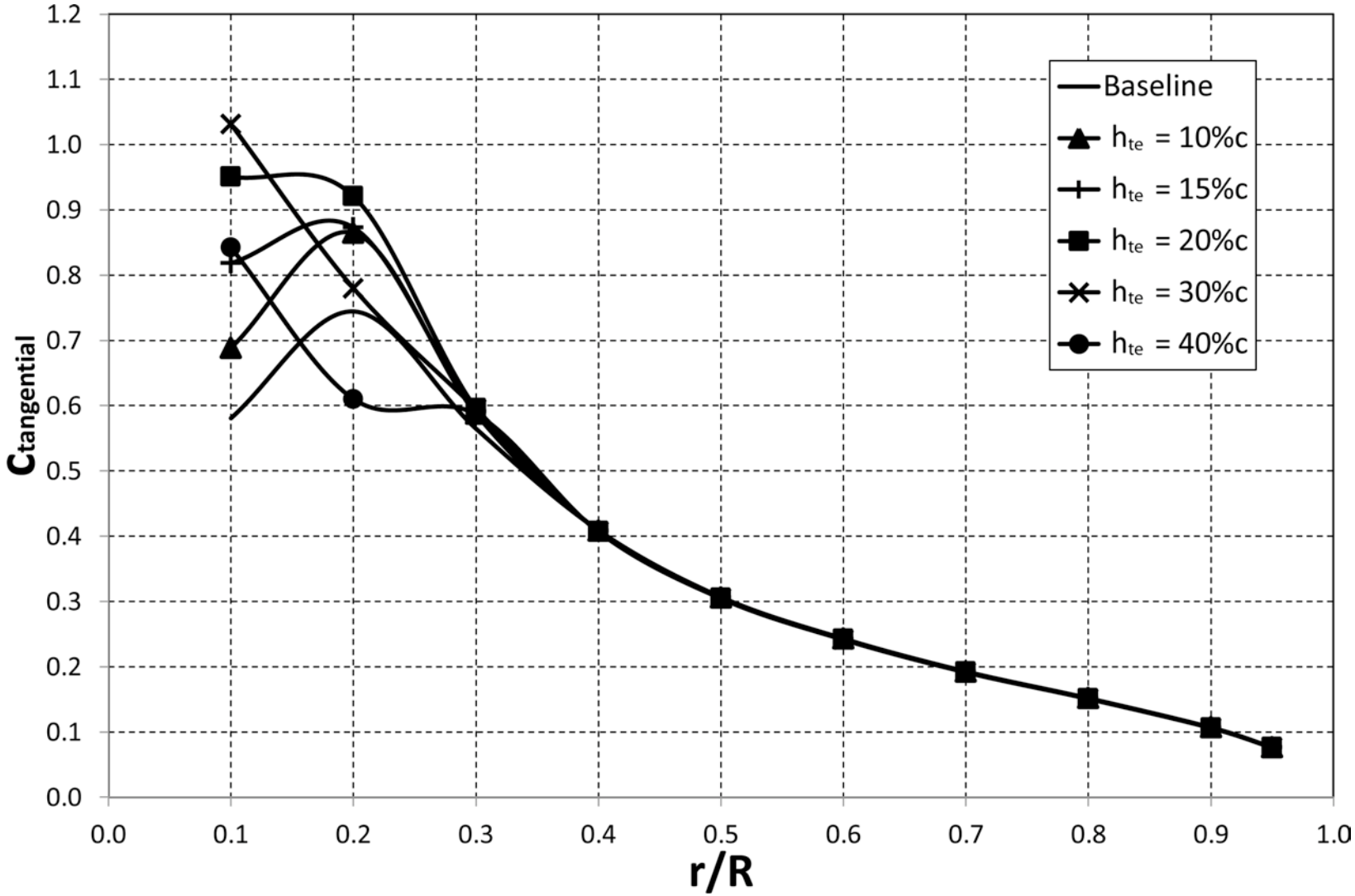
BTE: Change in Power and Thrust



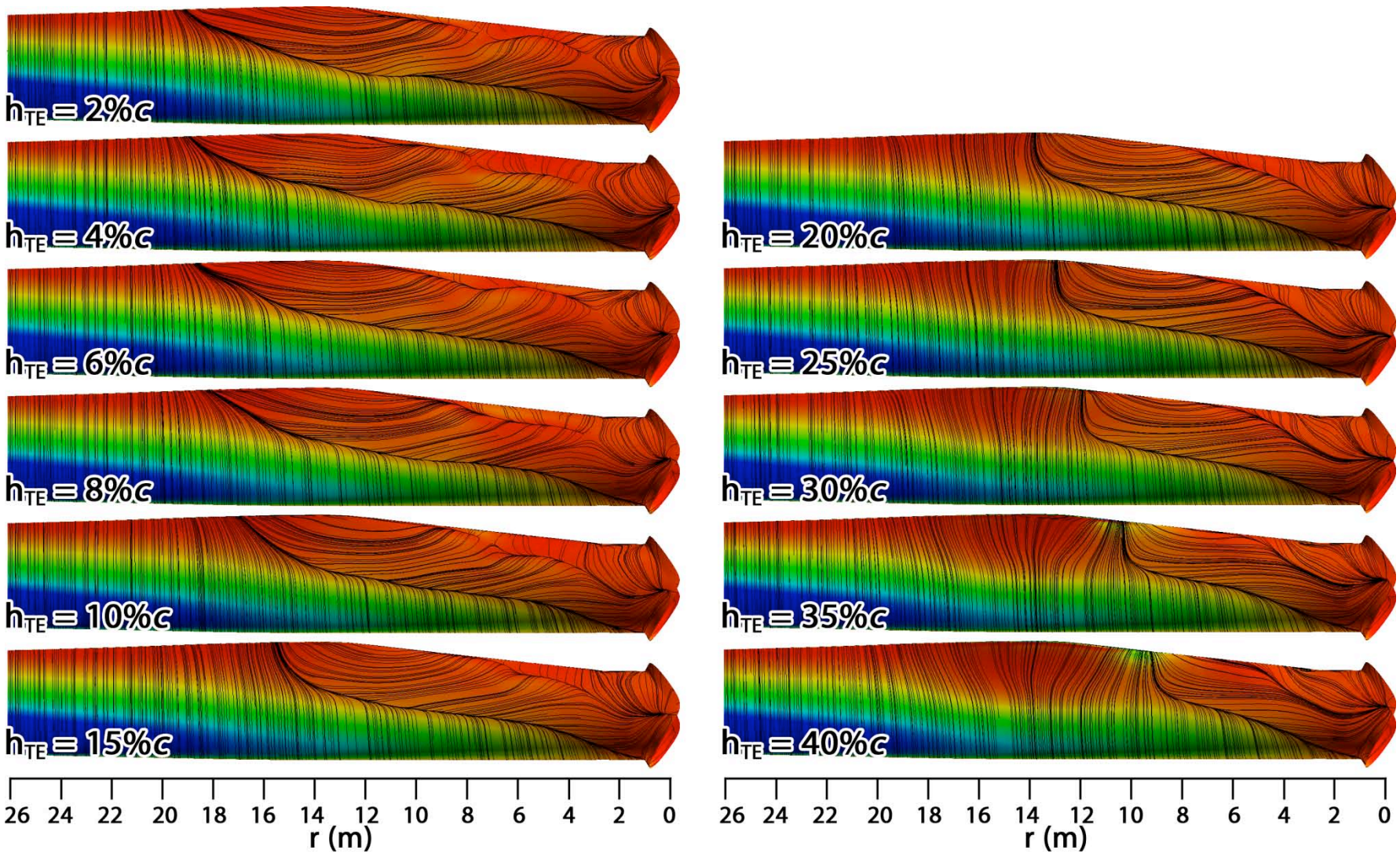
BTE: Spanwise Loading



BTE: Spanwise Loading



BTE: Surface Streaklines & Pressure

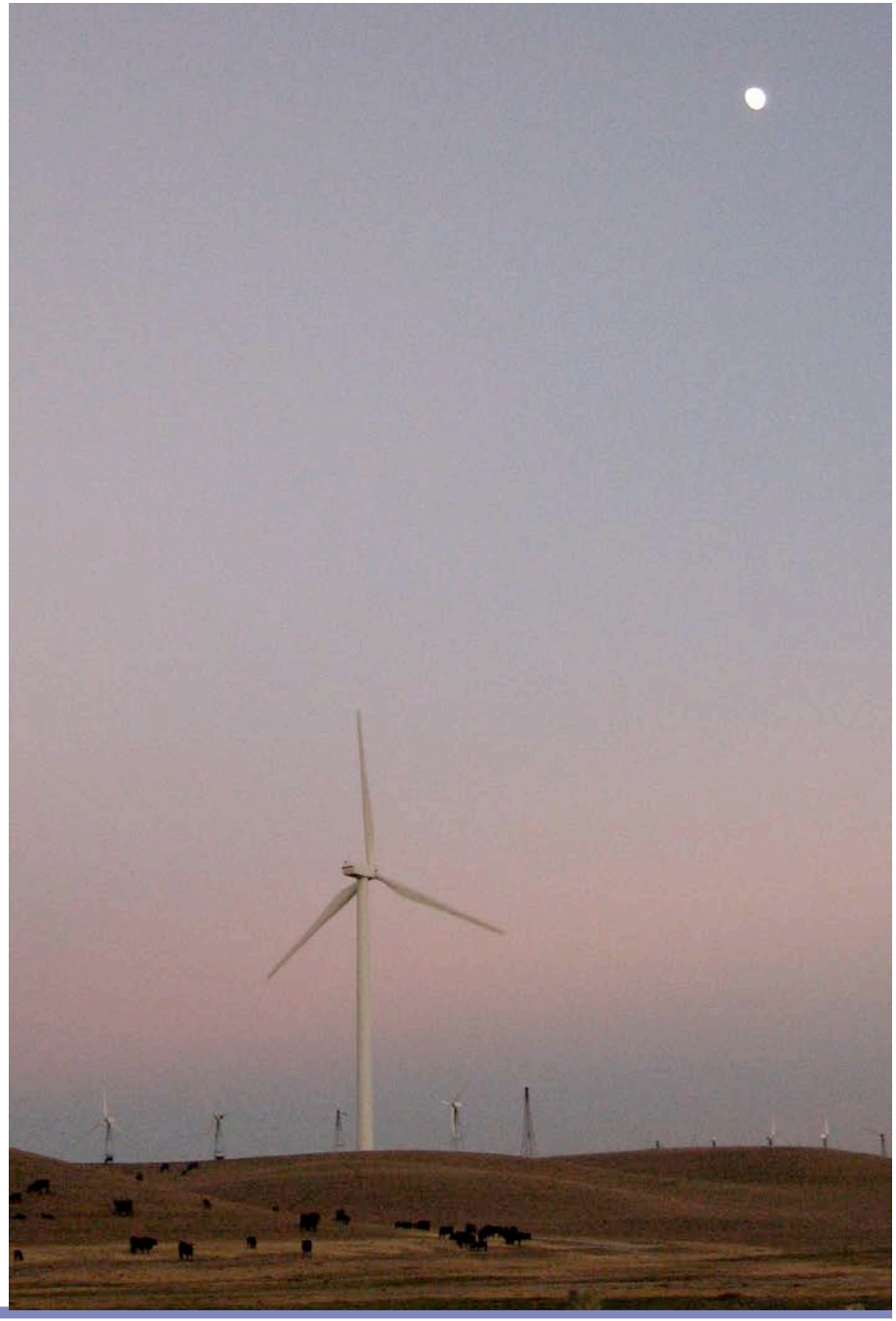


Blunt Trailing Edge Conclusions

- Power increased by nearly 1.6% over a wide range of trailing edge thicknesses (h_{TE} = 10-20%c)
- Thrust increase modest, and isolated over the modified inboard region
- Loading on outboard region unchanged
- Spanwise flow greatly reduced
- Increased cross sectional area
  - Allows for increased structural spar-box
  - Increased structural rigidity
  - Potential to reduce chord size

Final Thoughts

- Computational fluid dynamic (CFD) analyses and design can be:
  - Time consuming
  - Expensive
- But when performed expertly, it can provide detailed insights into:
  - Aero/hydrodynamic performance
  - Aero/hydrodynamic loads
  - Wake characteristics
- Because of all the insights gained, its application in turbine design can lead to reduced turbine life cycle cost
- But beware….coming up with “the answer” instead of “an answer” can be frustrating and require **many** CFD runs



Acknowledgements

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Thank You