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Leading Edge Erosion
Measurement and Modeling Campaigns

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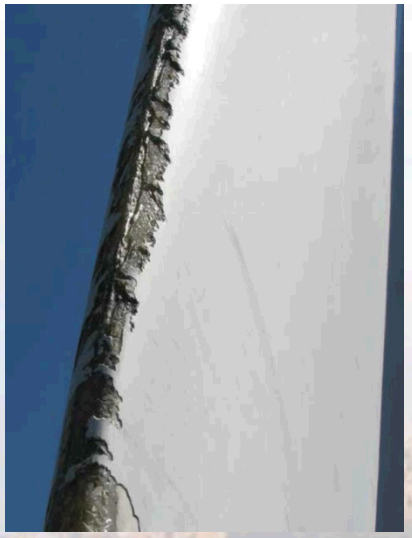
Overview and Motivation

- Historically, wind turbine capacity factors have been overestimated by 15%.[1]
- This is attributed to annual wind intermittency, wind farm topography, and design performance over predictions.



Heavy blade erosion[2]

- One cause of performance loss is leading-edge surface roughness.
- Over time, blades suffer from erosive and additive roughness.

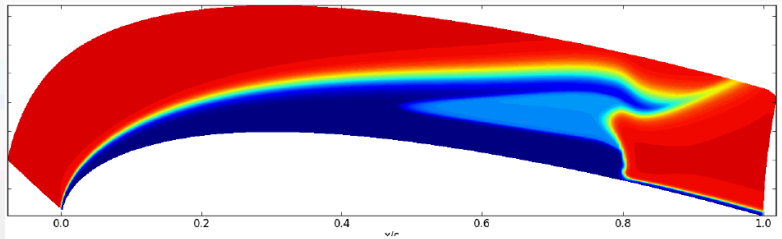
Leading Edge Erosion: Characterization, Measurement, and Modeling

Heavy blade erosion[2]

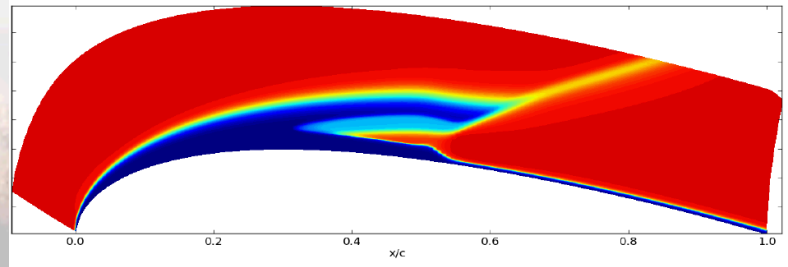
Insect roughness[3]

Leading edge blade erosion[4]

Oran W. Nicks
Low Speed Wind Tunnel

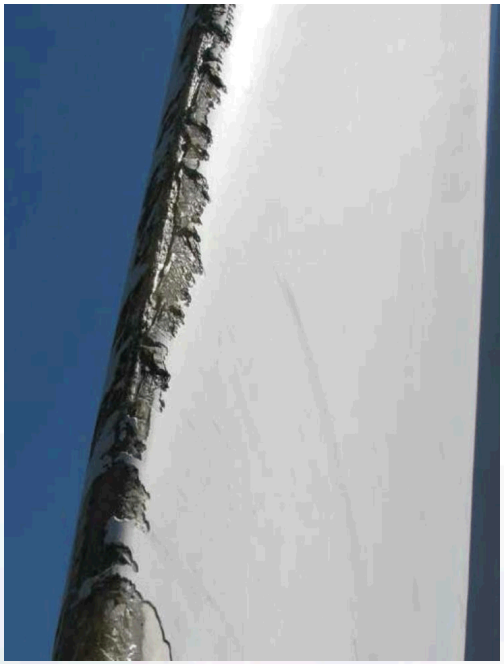


No Roughness

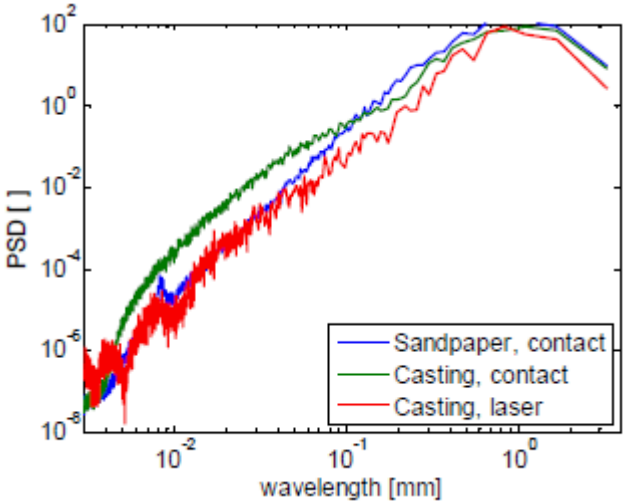


k_s = 350 μm

Types of Surface Roughness



Heavy blade erosion[2]



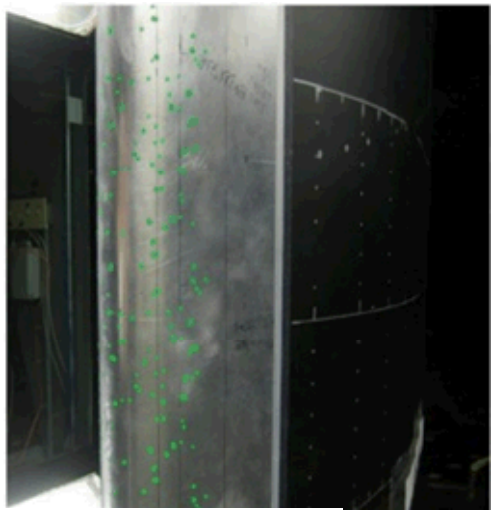
Insect roughness[3]

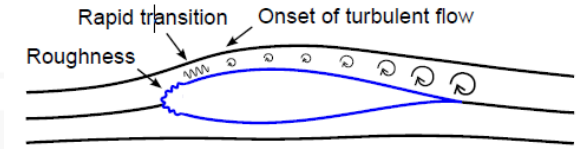
Leading edge blade erosion[4]

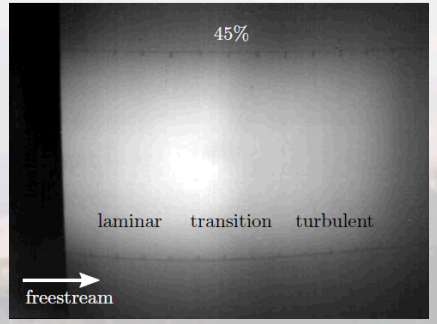
- **Gathered detailed LE erosion measurements from utility scale wind farm**

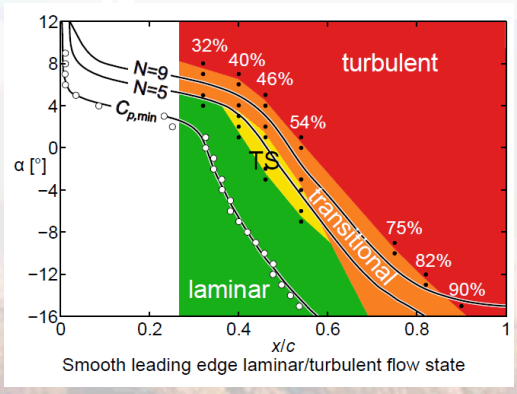
Wind Tunnel Testing

- Measurements from the field used to parameterize roughness
- LE erosion wind tunnel models based on parameterized roughness elements
- Large database of airfoil boundary layer characteristics

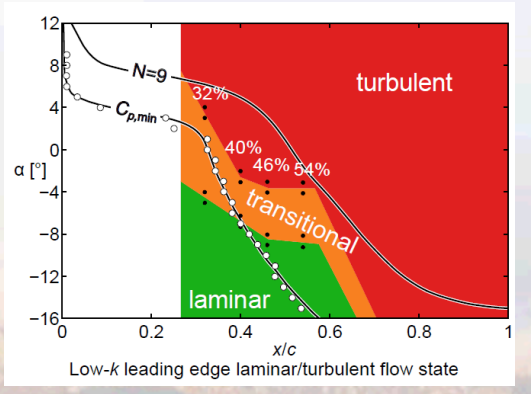








Smooth leading edge laminar/turbulent flow state



Low-*k* leading edge laminar/turbulent flow state

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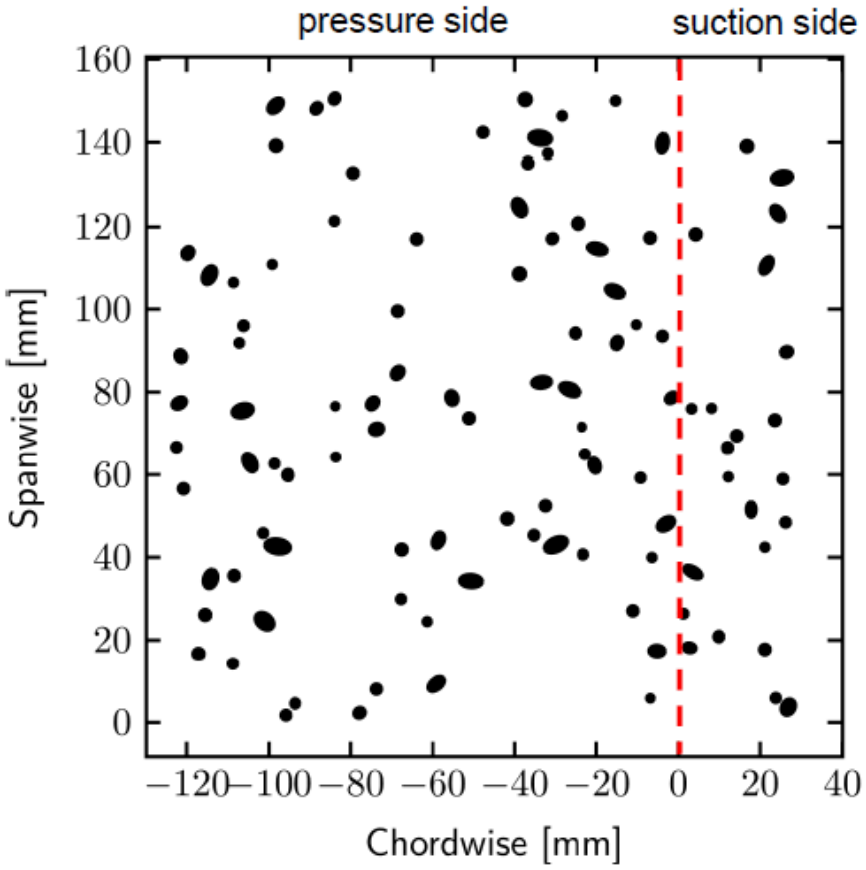
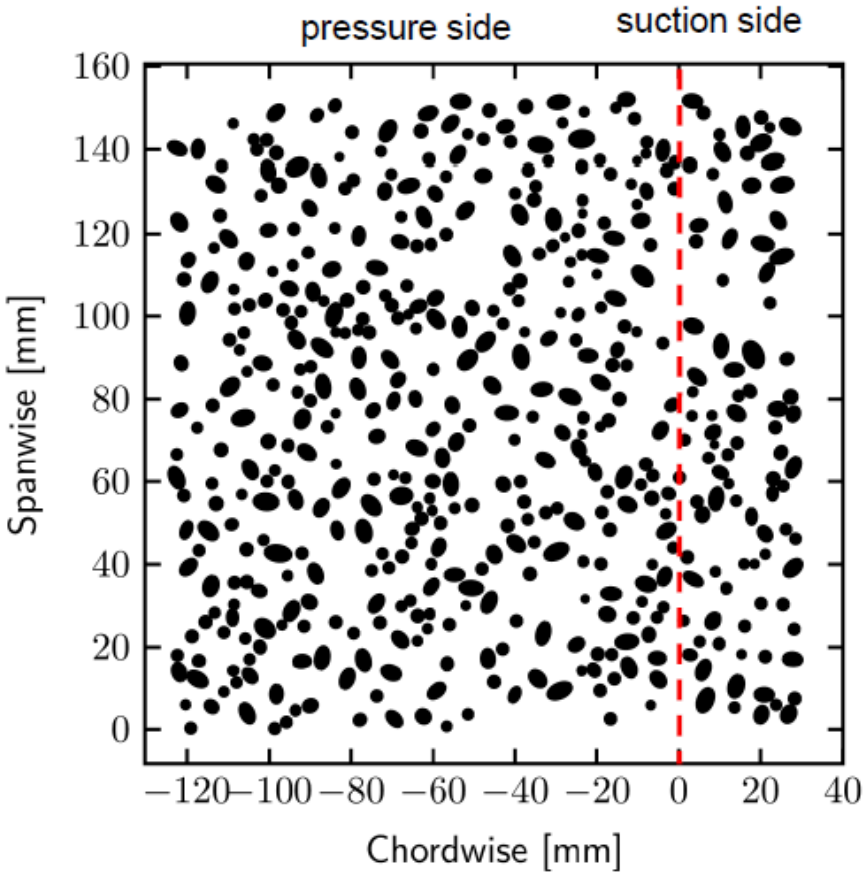
Distributed Roughness



Random insect distribution with 3% coverage.



Random insect distribution with 15% coverage.

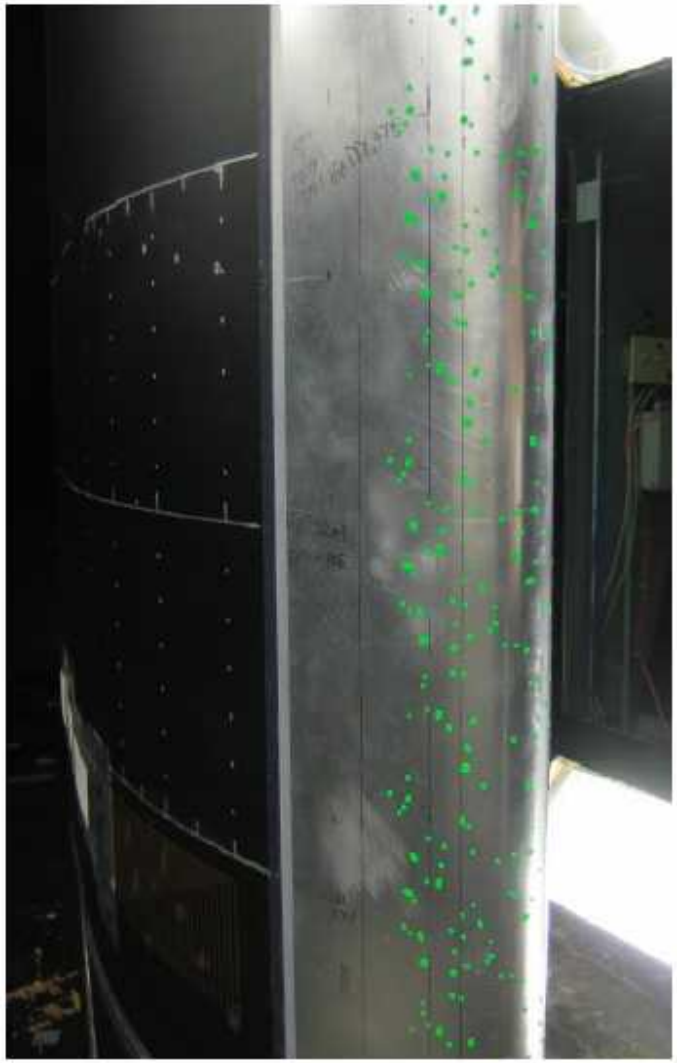
Wind Tunnel

- Oran W. Nicks Low Speed Wind Tunnel at Texas A&M
- Closed return tunnel
- Test section 7 ft × 10 ft
- Maximum velocity of 90 m/s
- Blockage of 4.8%
- Turbulence intensity of 0.25%
- Maximum $Re_c = 3.6 \times 10^6$ based on $c_{l,max}$ loading
- Maximum $Re_c = 5.0 \times 10^6$ to $\alpha = 4°$

Model installed in wind tunnel

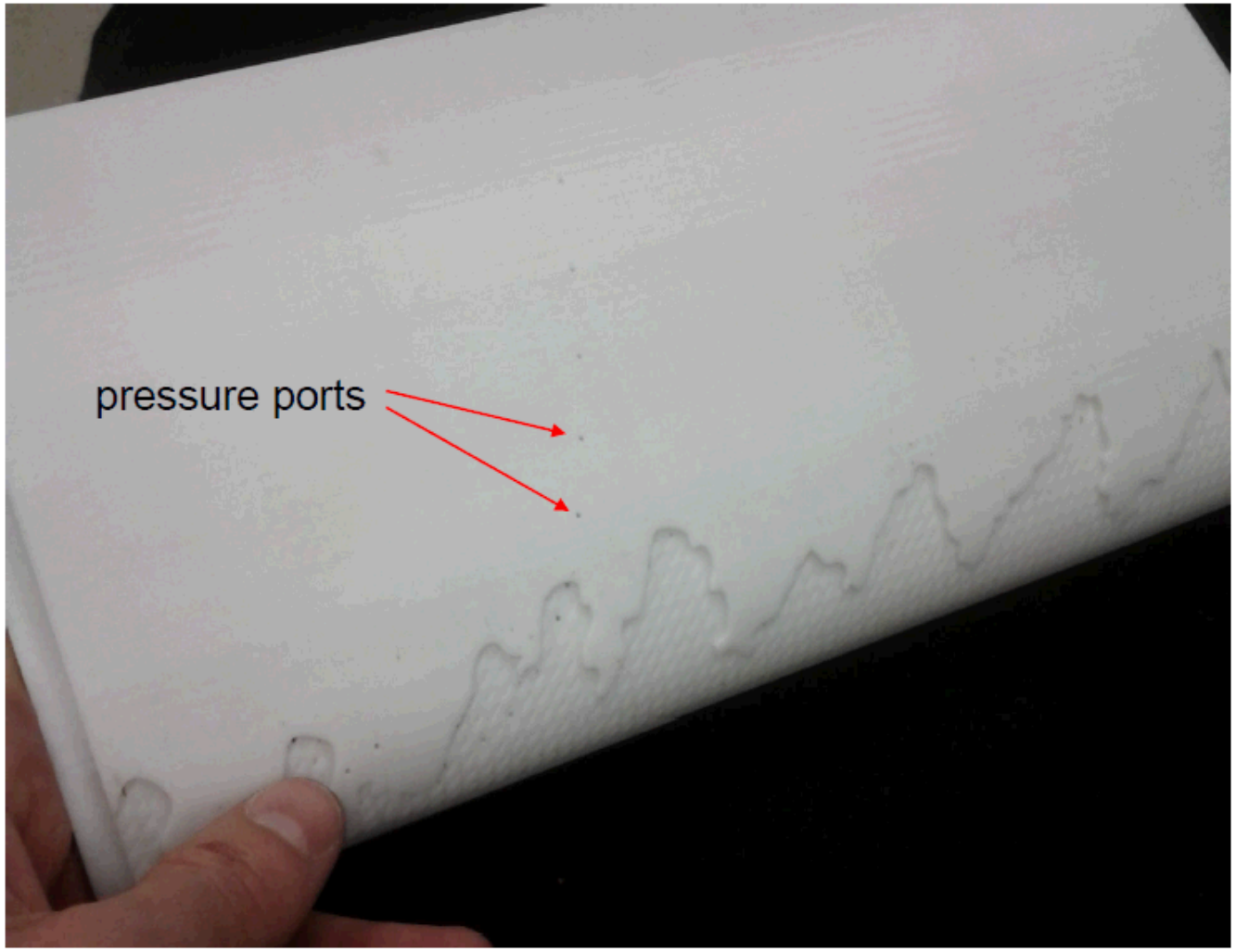
Configurations

- Clean
- Tripped
- Forward Facing Steps
  - Chipped paint 157μm
  - Straight step 157μm
- Distributed Roughness
  - 100 μm, 3, 9, 15% coverage
  - 140μm, 3, 6, 9, 12, 15% cov.
  - 200μm, 3% cov.
  - Distributed and 2D roughness

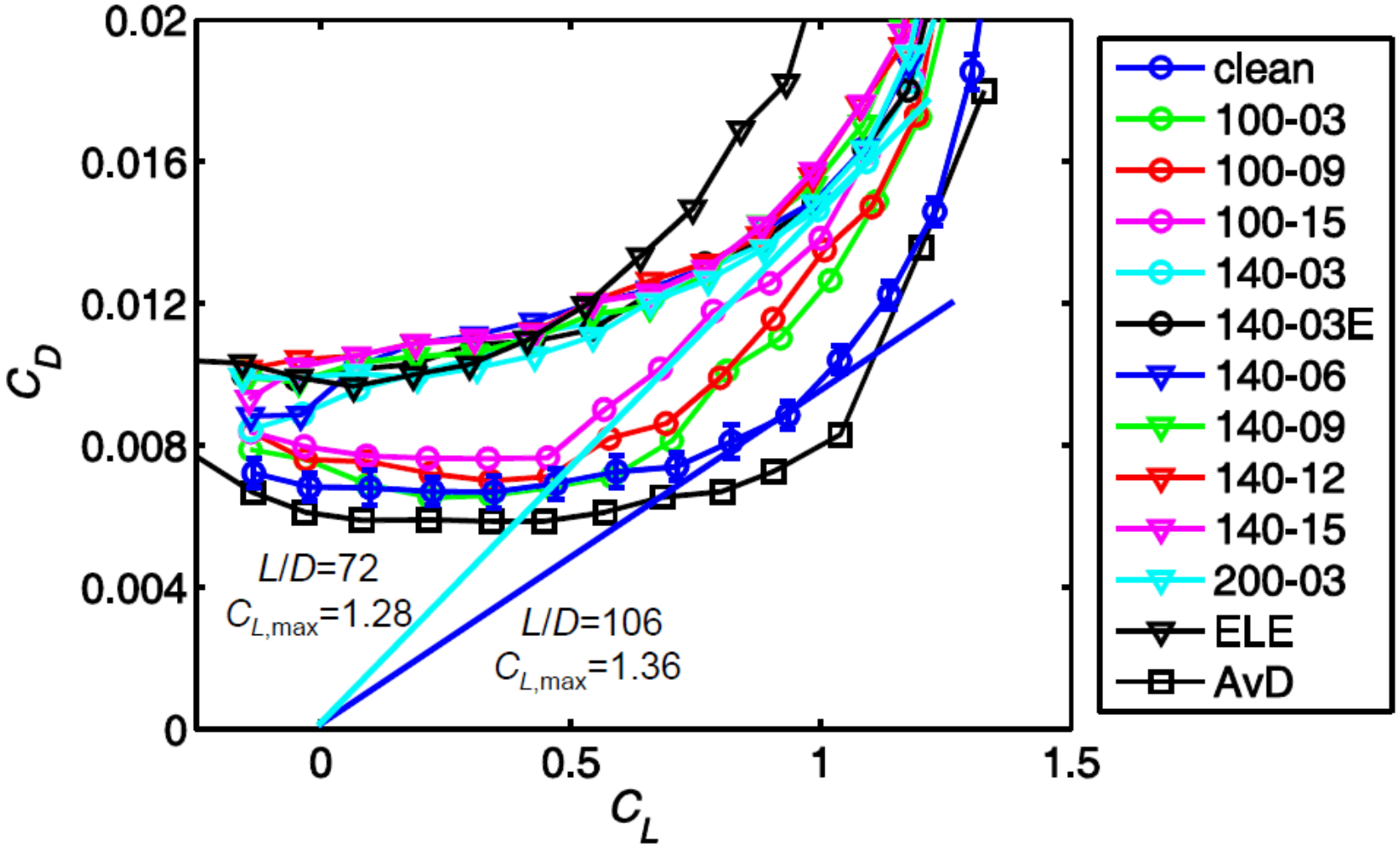


Simulated insect roughness (140 μm, 3% coverage) on NACA 63_3-418.

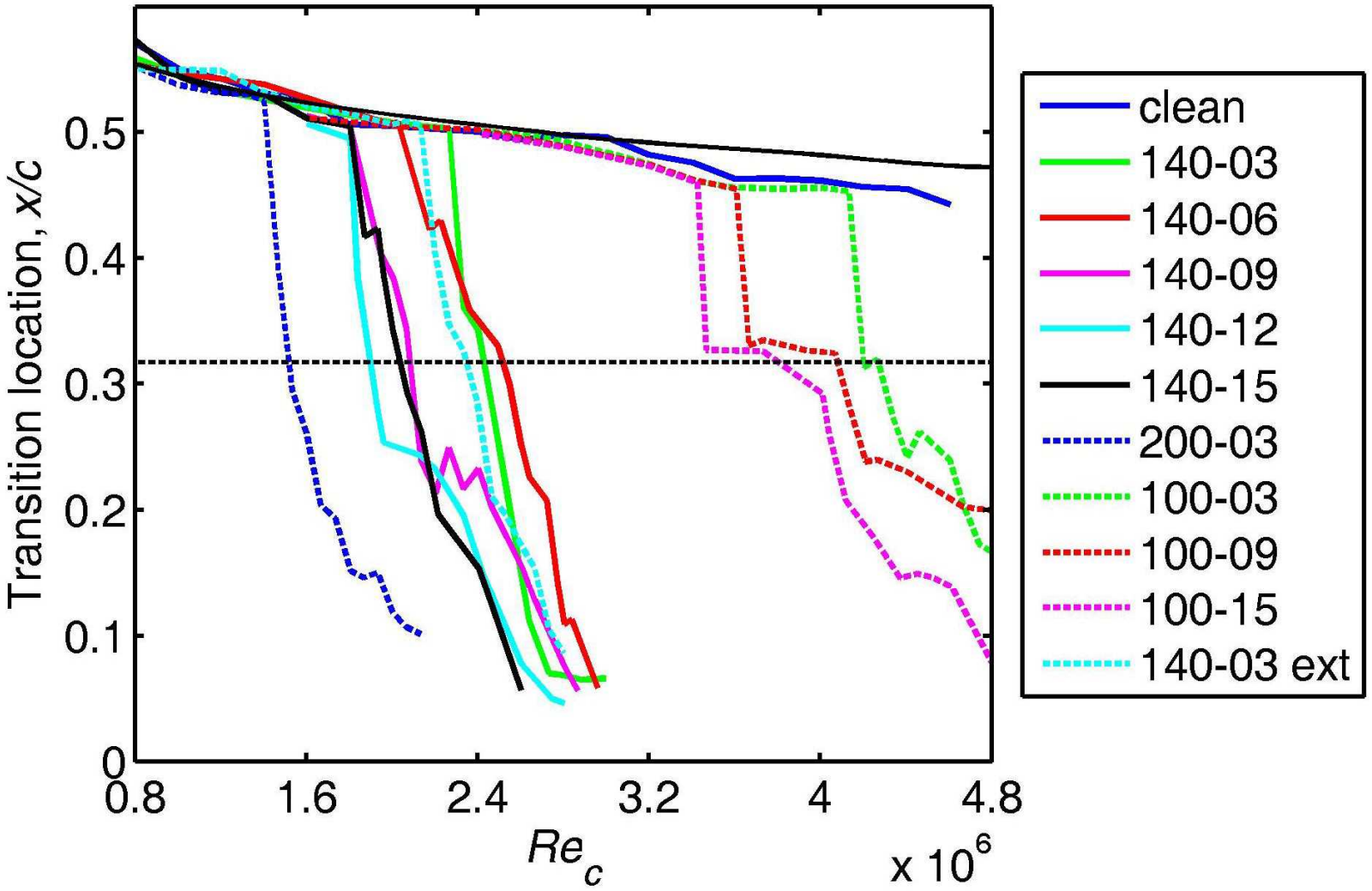
Eroded Leading Edge (ELE)



Drag Polar, $Re_c = 3.2 \times 10^6$



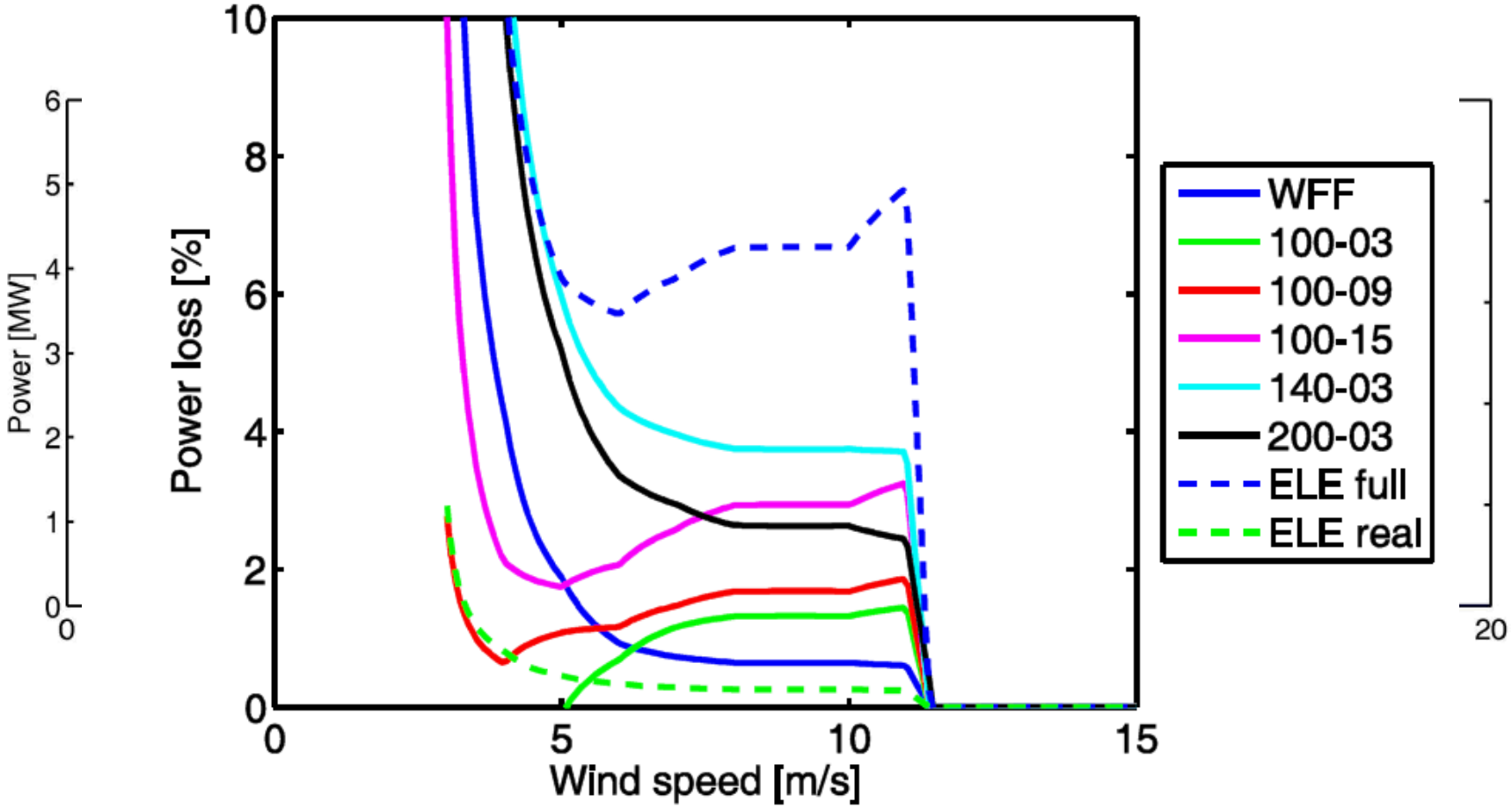
Transition, $\alpha = 0^\circ$



Performance at $Re_c = 3.2 \times 10^6$

Configuration	$dC_L/d\alpha$	L/D_{max}	$C_{L,max}$	$Re_{k,crit}$
Clean	6.71/rad	106	1.36	-
100-03	-0.3%	-18%	-3.4%	316±12
100-09	-1.6%	-24%	-4.8%	271±13
100-15	-3.1%	-32%	-6.0%	254±13
140-03	-3.4%	-35%	-4.0%	240±19
140-03ext	-2.8%	-37%	-5.6%	222±19
140-06	-3.7%	-37%	-5.6%	207±19
140-09	-3.6%	-39%	-7.4%	178±18
140-12	-3.6%	-40%	-7.8%	178±18
140-15	-3.7%	-41%	-8.7%	178±18
200-03	-2.7%	-35%	-0.6%	227±28
ELE	-7.3%	-52%	-16.9%	-

NREL 5 MW AEP Loss



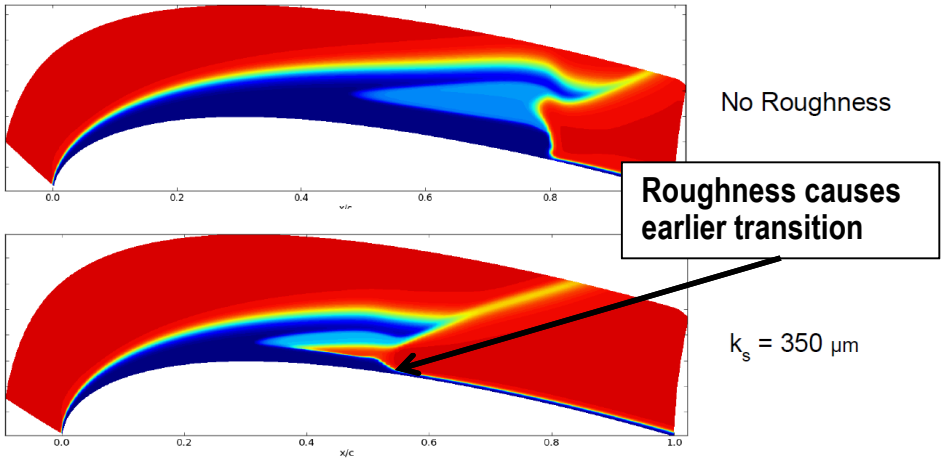
AEP Loss

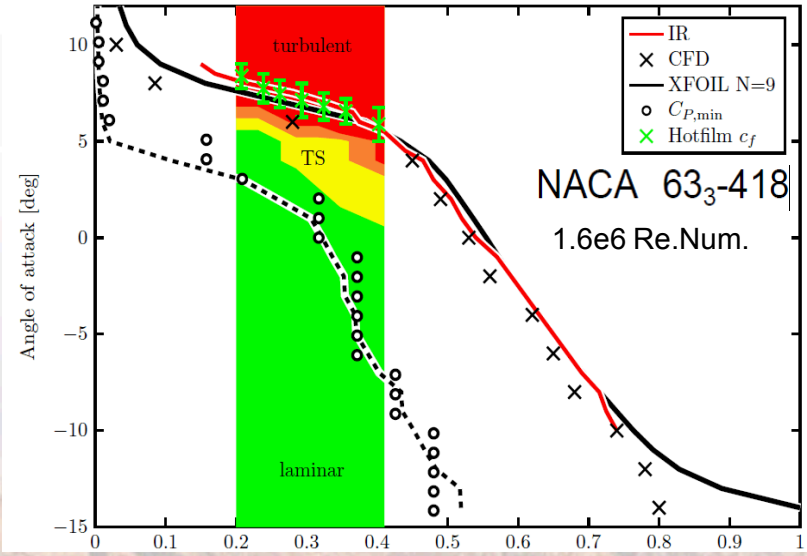
Configuration	IEC II [%]	Annual Earning* [thousands $]
Clean	20.9 GW-hr	1,046
100-03	-0.6	-6
100-09	-0.8	-8
100-15	-1.3	-14
140-03	-1.9	-20
140-03ext	-2.2	-23
140-06	-2.0	-21
140-09	-2.2	-23
140-12	-2.3	-24
140-15	-2.3	-24
200-03	-1.4	-14
ELE full	-3.2	-33
ELE real	-0.1	-1

*Assuming $0.05 kWh

Model Development

- Created CFD model of leading edge erosion
- Tight interaction between modelers and experimentalists
- Detailed calibration and validation of model





Direction

Future Work:

- Create publicly accessible database
- Expand tests to thicker sections
- Modify model to capture stall through addition of pressure gradient terms

Thank You.