Aerodynamic Validation of Wind Turbine Airfoil Models in the Virginia Tech Stability Wind Tunnel

NAWEA 2015 Symposium

Matthew Kuester, Kenneth Brown, Timothy Meyers,
Nanyaporn Intaratep, Aurélien Borgoltz, and William Devenport

Virginia Polytechnic Institute and State University

June 9th, 2015

Special Thanks: GE Power & Water

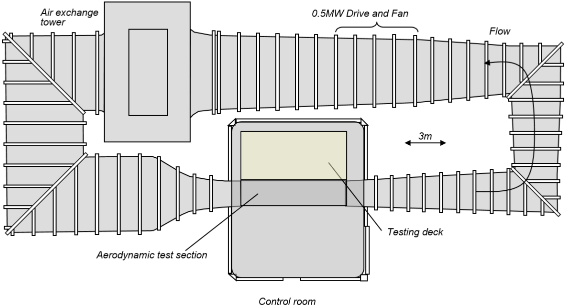
Introduction

- Virginia Tech Stability Wind Tunnel has been used extensively for aerodynamic/aeroacoustic measurements of wind turbine airfoils
- However, comparisons with wind tunnel results from European wind tunnels showed . . .
  - Reduced lift-curve slopes (3.0–5.5% lower for the DU96-W-180)
  - Reduced $c_{l_{max}}$ (0.04–0.12 lower for the DU96-W-180)
- Although differences in lift curve slopes and maximum lift coefficients are not uncommon in wind tunnel testing (McCroskey [1] and Troldborg *et al.* [2]), this was viewed as an opportunity to thoroughly investigate airfoil testing in the Virginia Tech Stability Wind Tunnel.

Objective

- *Goal: investigate and evaluate all aspects of airfoil model testing in the Virginia Tech Stability Tunnel, from model fabrication through data reduction*
- This work has validated the majority of procedures at the Stability Wind Tunnel, but identified three areas that need to be addressed:
  - Model Surface Quality
  - Pressure Tap Diameters
  - Model Deflections Under Aerodynamic Loading

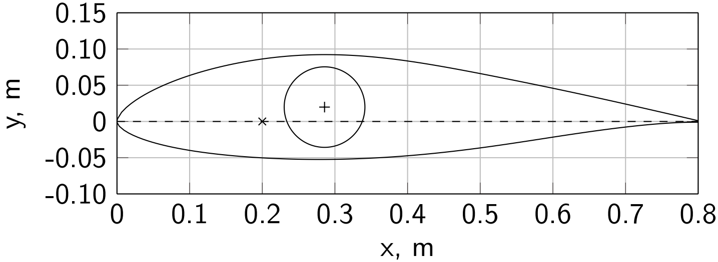
Stability Wind Tunnel



- 6 ft. × 6 ft. × 24 ft. test section
- Two configurations: Anechoic and *Aerodynamic*
- Flow speeds up to 85 m/s
- Turbulence levels below 0.03%
- Airfoil models mounted vertically along the centerline of the test section
- Testing Capabilities
  - Wall & model pressure measurements
  - Phased microphone arrays
  - Pitot-static wake rake
  - Suction system for control of end-wall effects
  - IR thermography
  - Flow visualization
  - Laser diagnostics

DU96-W-180 Model

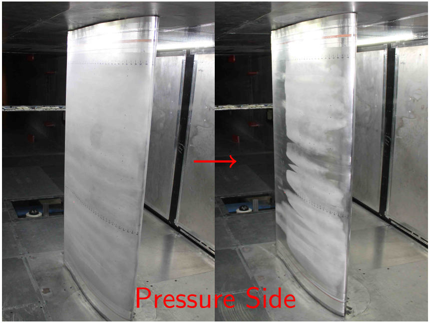
- 0.8 m chord DU96-W-180
- Made from CNC machined aluminum laminates (50 mm wide)
- Laminates stacked, pinned, and held in compression
- Measurements at $Re_c = 3.0$ Million ($U_\infty \sim 60 - 65$ m/s)

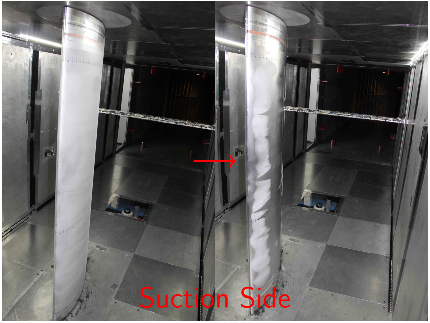


Naphthalene Transition Visualization

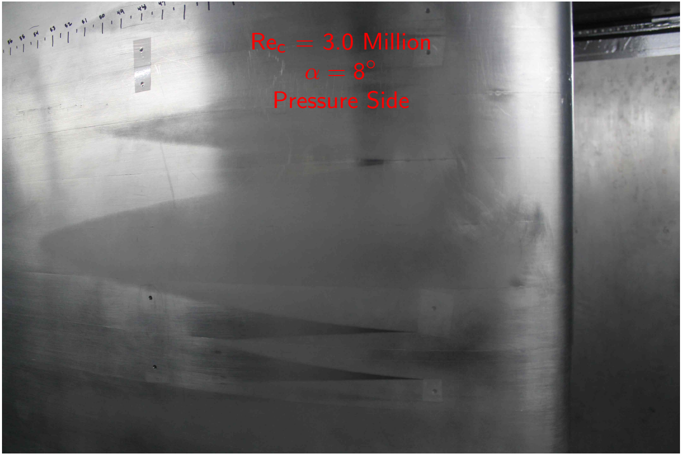
- Typically use IR thermography for transition detection → model is covered in thin insulative material
- Naphthalene visualization shows the effect of surface quality on boundary layer transition on the clean surface
- Sublimation rate is proportional to shear stress → naphthalene sublimates quickly in turbulent boundary layers

$$\mathrm{Re_c} = 3.0 \text{ Million}, \ \alpha = 8^\circ$$



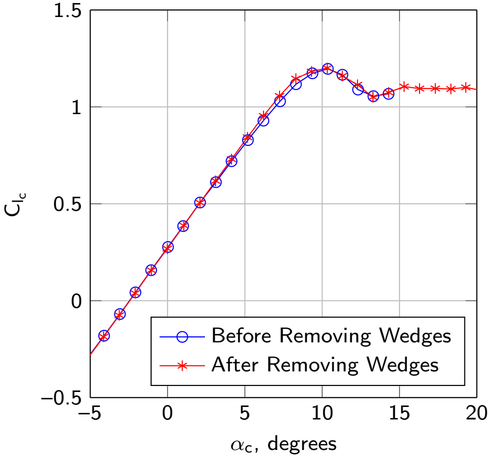


Turbulent Wedges From Surface Defects



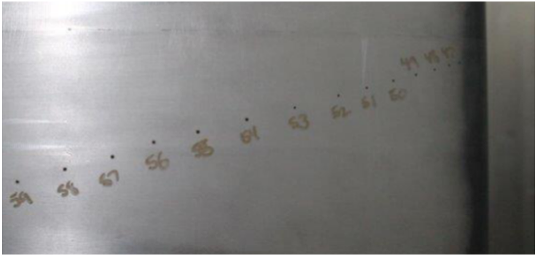
Turbulent wedges caused by tape (40 μm) and defects at laminate edges.

Effect on Lift Curve Slope



- All tape was removed, and holes were filled/sanded.
- Surface was systematically sanded/polished after each naphthalene run.
- Eliminating turbulent wedges, particularly on the suction side, led to a 3.1% increase in lift curve slope.
- Issue with models that are taken apart and reassembled several times → defects on laminate edges.

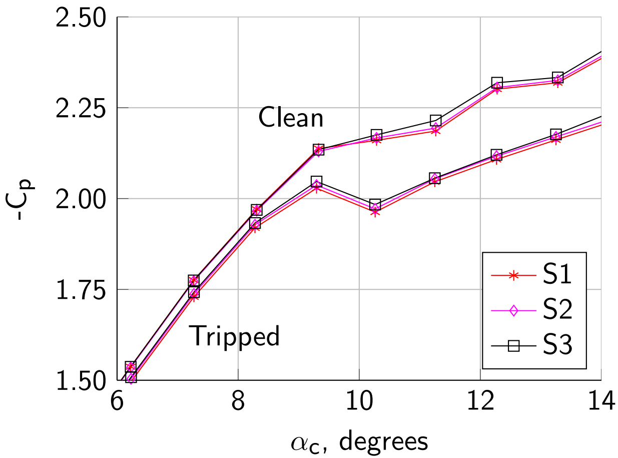
Additional Pressure Taps



- DU96-W-180 model has 79 pressure taps (1.0 mm ID)
- Additional taps were added to investigate tap diameter effects

Tap	Side	z/span	x/c	Tap Diameter
S1	Suction	0.361	0.050	1.0 mm
S2	Suction	0.369	0.050	0.5 mm
S3	Suction	0.353	0.050	0.3 mm

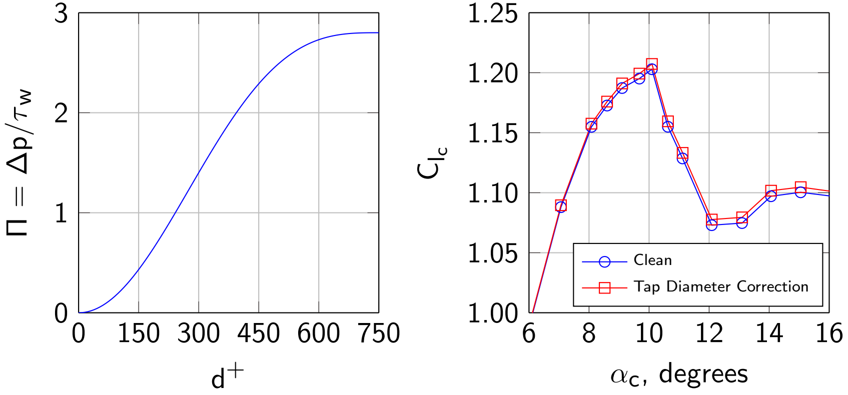
Additional Pressure Taps



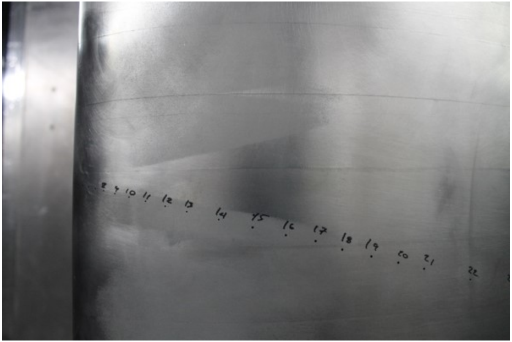
- Comparison of clean and tripped cases shows that increased ΔC_p spread occurs in turbulent boundary layers
- ΔC_p spread ordered according to tap diameter
  - S1: 1.0 mm ID $\rightarrow$ highest pressure
  - S2: 0.5 mm ID
  - S3: 0.3 m ID $\rightarrow$ lowest pressure

Tap Diameter Corrections

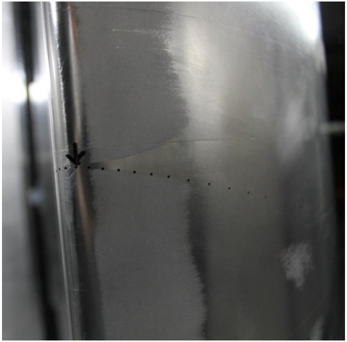
- Used skin friction estimates from XFOIL and a turbulent pressure tap diameter correction from Shaw [3] to correct measurements downstream of transition
- 0.8 m chord model, $Re_c = 3.0$ Million, 1 mm taps $\rightarrow d^+ = 50\text{–}300$
- Small correction to maximum lift (0.004)



Pressure Tap Tripping



$\alpha = 8^\circ$

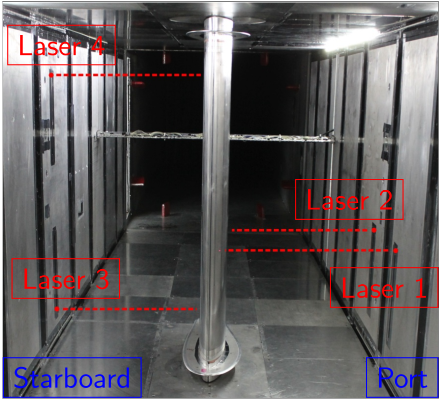


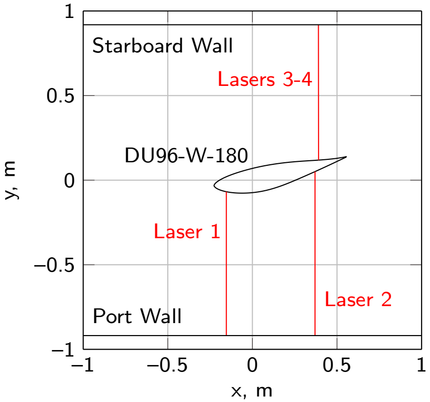
$\alpha = 11^\circ$

- Turbulent wedge from leading edge pressure taps appears on the suction side for $\alpha > 6^\circ$
- Wedge was not removed by lightly sanding around the leading edge taps
- Naphthalene tests on another model with 0.5 mm taps did not show a wedge from the leading edge taps
- Use 0.5 mm ID taps on all new models

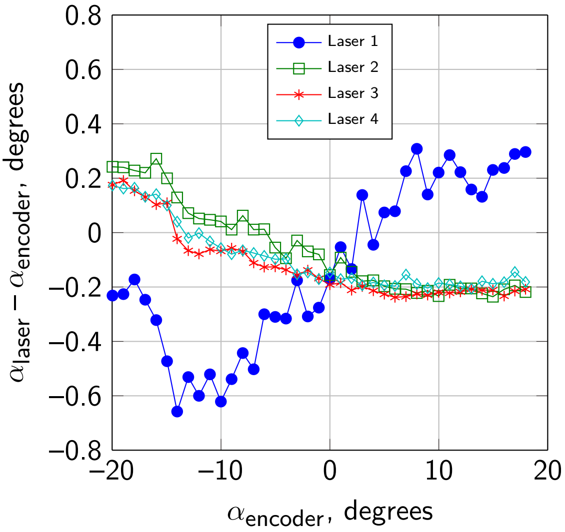
- Calibration using α_{encoder} with flow off to calculate laser position & orientation relative to the C.O.R.
- Distance reading is used to calculate the position of the model, assuming the C.O.R. is fixed

- Calibration accuracy: $\pm 0.07°$ for laser 1, $\pm 0.02°$ for lasers 2-4
- Single laser installed in the anechoic test section (looking down through an optical panel in the ceiling)



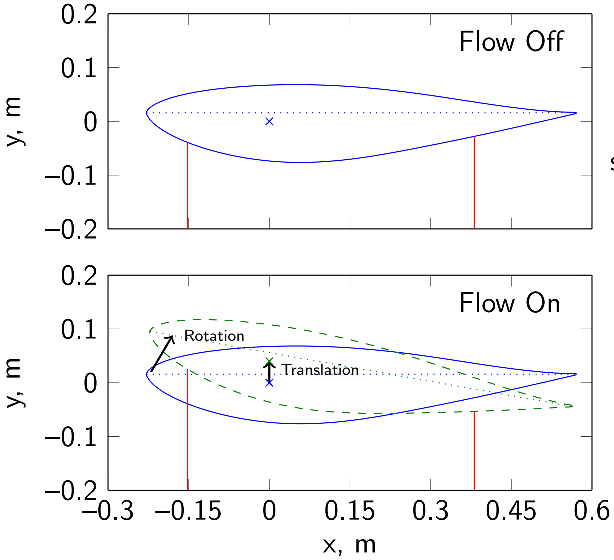


Additional Laser Measurements



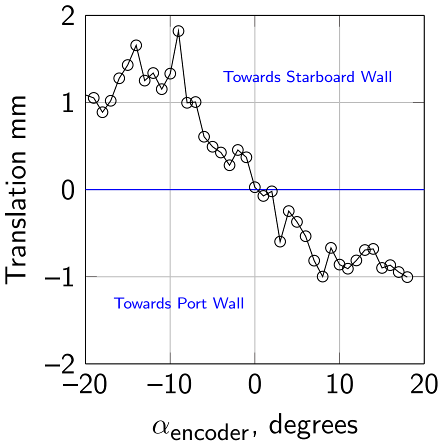
- Analysis computes α_{laser} assuming . . .
  - Profile shape remains constant
  - *Center of rotation remains fixed*
- Laser 1 is is 6" upstream of the C.O.R.
- Lasers 2-4 are 14"-15" downstream of the C.O.R.

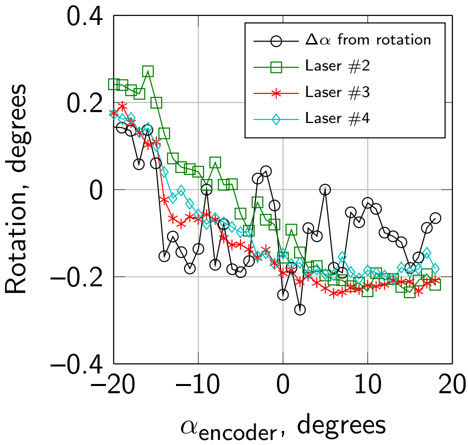
Rotation/Translation Analysis



Lasers 1 & 2 are at the same spanwise location. Laser distance measurements from flow off and flow on conditions at matching α_{encoder} yields translation of the C.O.R. and $\Delta\alpha$.

Rotation/Translation Analysis





- Noise generated by slight mismatches in α_{encoder} between flow-on and flow-off
- C.O.R. shifting up to 2 mm in the lift direction
- Lasers 2-4 track the change in rotation angle to $\sim \pm 0.1^{\circ}$
- *Rotation accounts for 1.6% reduction in measured lift curve slope*

Airfoil Model Loading Rig

- Models mount to steel structure that is nearly identical to tunnel mounting system
- Three pistons are attached to loading bar that applies spanwise uniform load at desired chord location (up to 3000 lbs.)
- Multiple laser distance sensors are traversed along the span of the model to measure shape profiles
- Preliminary results have shown deflection in both the models and the mounting system

Airfoil Model Loading Rig

- Models mount to steel structure that is nearly identical to tunnel mounting system
- Three pistons are attached to loading bar that applies spanwise uniform load at desired chord location (up to 3000 lbs.)
- Multiple laser distance sensors are traversed along the span of the model to measure shape profiles
- Preliminary results have shown deflection in both the models and the mounting system

Conclusions

- Naphthalene visualizations showed tape and defects at laminate edges were tripping the boundary layer, resulting in a $\sim$3% reduction in lift curve slope.
- 1.0 mm diameter pressure taps create a slight pressure bias in turbulent boundary layers ($\Delta C_p < 0.02$ at $Re_c = 3.0$ Million, resulting in a 0.004 reduction in measured maximum lift.)
- Pressure taps at leading edge created a turbulent wedge on the suction side for positive angles of attack.
- Laser distance sensors installed in the wind tunnel walls identified multiple modes of model deflection, including a rotation effect that reduced the measured lift curve slope by 1.6%
- Laser distance system defines effective angle of attack to within $\sim 0.1^\circ$, including uncertainty due to model bending/translation.

Continuing Work

- Create new instrumented laminates with 0.5 mm diameter taps
  - Tap diameter effects
  - Leading edge tripping
- Use the model loading rig to further diagnose model deflections
  - Comparisons to laser deflection data with DU96-W-180
  - Corrections for past datasets
  - Redesign of airfoil mounting system

References

[1] McCroskey, W., “A critical assessment of wind tunnel results for the NACA 0012 airfoil,” Tech. rep., DTIC Document, 1987.

[2] Troldborg, N., Bak, C., Aagaard Madsen, H., and Skrzypinski, W. R., “DAN-AERO MW: Final Report,” Tech. rep., DTU Wind Energy, 2013.

[3] Shaw, R., “The influence of hole dimensions on static pressure measurements,” *Journal of Fluid Mechanics*, Vol. 7, 4 1960, pp. 550–564.