Aerodynamic Effects of Boundary Layer Trip Strips on the Flow over a DU91W250 airfoil

Aurelien Borgoltz[1]
Virginia Tech, Blacksburg, VA 24061, U.S.A.

Nanya Intaratep[2]
Virginia Tech, Blacksburg, VA 24061, U.S.A.

William J. Devenport[3]
Virginia Tech, Blacksburg, VA 24061, U.S.A.

Abstract

In this lab you will investigate the effects of boundary layer trip geometry on the aerodynamic properties of the DU91W250 profile (typical high lift profile commonly used in wind turbine blades). The experiment takes place in the VT Stability Wind Tunnel. You will measure the mean pressure distribution on the airfoil surface, then integrate it over the airfoil surface to compute the lift coefficient. Note that the confining walls of the wind tunnel have some influence on the pressure distribution on the airfoil compared to flow in "free air". A method is outlined to make the measurement comparable to the free air condition of the computation. You will also run pre-test estimate for the lift curve and pressure coefficient distribution using XFOIL (direct link)

1. Introduction

You will measure the mean pressure distribution on 0.9m-chord DU91W250 airfoil for Reynolds numbers of 1.5 and 3 million and angles of attack ranging from -15˚ to 15˚. You will measure the pressure distribution on the airfoil, from which you determine the profile lift polar (lift versus angle of attack).

Aerodynamics is a key factor in the noise production for onshore wind turbines and is strongly dependent on the flow speed at the wind turbine blade. Thus, noise regulations limit the rotational speed of the rotor and the rotor size for installed wind turbines. Introducing low noise technology allows increasing the rotational speed and/or the rotor size which leads directly to a decrease in the cost of energy.

Wind turbines performance can be dramatically affected by accumulation of bugs and dirt on the leading edge. As seen below, the resulting soiling pattern will cause the flow to transition earlier than it

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[1] Research Associate Professor, Department of Aerospace and Ocean Engineering, 660D McBryde Hall.

[2] Research Assistant Professor, Department of Aerospace and Ocean Engineering, 614 McBryde Hall.

[3] Professor, Department of Aerospace and Ocean Engineering, 660E McBryde Hall.

would on the clean blade and consequently change the performance of the turbine by triggering early stall.

Figure 1. Insect accumulation on the leading edge of a wind turbine blade (Dalili *et. al.*, 2009)

The power produced by the turbine is directly proportional to the blade performance. The change in geometry associated with the soiling pattern can reduce the power output by as much as 50% (see Figure 2 taken from Corten and Veldkamp, 2001).

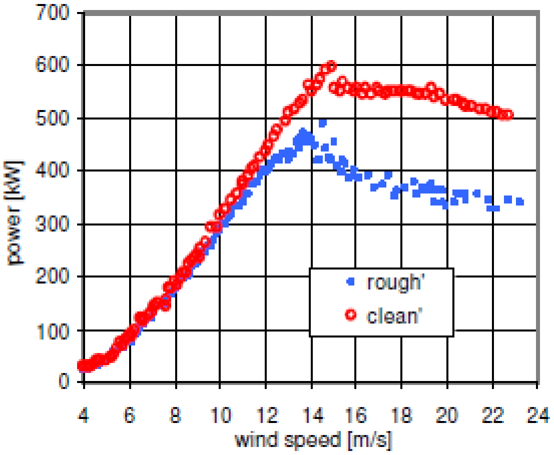


Figure 2. Power output of a wind turbine with clean blades and rough blades (dirt+bugs) (Corten and Veldkamp, 2001)

Stall is the sudden reduction in lift force on an airfoil caused by flow separating from the foil. Since stall is caused by flow separation on the wing, the characteristics of the stall are associated with the initial flow separation location and the manner in which the separation develops as the angle of attack increases.

Controlled, mild wing stall is associated with flow separation that occurs on the upper surface trailing edge, which then moves forward with increasing angle of attack in a gradual, smooth fashion. In the end, it is the airfoil shape that determines stall characteristics.

Typical flow behavior around an airfoil begins as laminar at the leading edge. The flow on the upper side of the airfoil reaches the minimum pressure point. At low Reynolds numbers, a small laminar flow separation often occurs which is then followed by transition to turbulence (bypass transition) and subsequent flow re-attachment as illustrated in **Figure 3**. At higher Reynolds numbers, typically above 500,000, transition occurs due to instabilities in the laminar boundary layer that grow and generate turbulence.

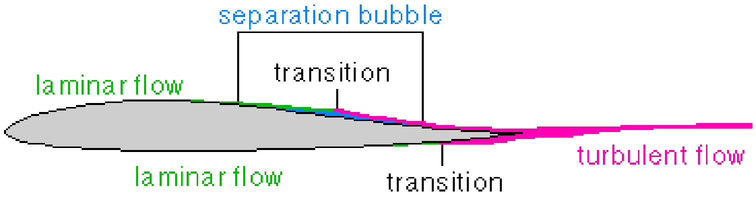


Figure 3. Transition from laminar to turbulent flow over an airfoil (Courtesy of www.mh-aerotools.de)

Poor airfoil performance arises when the flow separates after the transition to turbulence. Depending on the severity of the separation (the fraction of the suction-side surface subject to separation is an indicator of the severity), the airfoil may continue to provide adequate lift or it may be subject to stall. Once an airfoil stalls, a significant portion of the flow is detached from the surface, resulting in major reduction in airfoil lift.

Stall typically occurs when an airfoil is rotated to a large angle of attack. This event might be intuitively predicted since at high angles of attack the flow on the suction surface is more apt to continue along the direction of the freestream velocity rather than turn downwards to follow the airfoil contour at a severe angle. In addition to the angle of attack, the Reynolds number also affects airfoil lift indirectly via influence over the boundary-layer development and thus the stall characteristics. If the surface of the model is contaminated (such as with bugs or dirt accumulation), transition can be triggered early and lead to drastically different performance characteristics.

To simulate the real-world environment of airfoils in turbulent flows, a process known as “tripping” the boundary layer is often employed in wind tunnels. Instead of allowing for natural transition to turbulence in the boundary layer as shown in **Figure 3**, a small layer of tape is applied along the span of the airfoil near the leading edge. An example of a tripped airfoil is shown in **Figure 4**. The lift characteristics of a tripped airfoil are slightly different than those of the clean airfoil. The full onset of stall is usually experienced more gradually on tripped airfoils; however, the maximum lift coefficient reached is lower. Tripping is sometimes used even in real-world applications to lower the abruptness of stall.

Figure 4. Trip applied near the leading edge of an airfoil. The trip strip is indicated by the red arrow.

To illustrate some of the concepts described previously, Figure 5 shows the lift coefficient C_l as a function of angle of attack for tripped and untripped cases on the same airfoil. The airfoil, similar to but not the same as the DU91W250, is shown to experience positive stall at approximately +11° angle of attack and negative stall at approximately -10°. The difference in the tripped and clean airfoil can be seen in the more gradual onset of stall for the tripped case, as well as the lower maximum C_l and lower slope in the linear region of the curve.

Several other interesting characteristics of lift curves are shown in Figure 5. The linear region, as it is called, is the region where there is little to no separation over the airfoil. This region in the figure is roughly -8° to +8°. Numerical flow solvers, which have difficulty modeling the complex flow physics of turbulence, are most useful in this linear region. Also note from Figure 5 that the airfoil experiences no lift at approximately -2.5° angle of attack. This angle of attack is appropriately termed the zero-lift angle of attack.

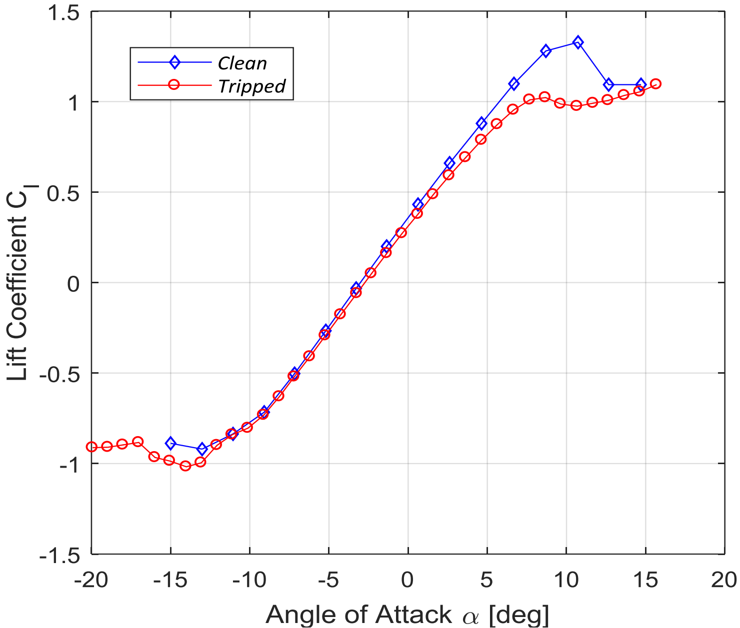


Figure 5. Experimental measurements of lift coefficient as a function of angle of attack for an airfoil similar to the one tested in this experiment.

The experiment you will perform in the Stability Wind Tunnel is common in the sense that aerospace engineers regularly test airfoils and determine aerodynamic characteristics. The ultimate goal is to determine how these trips influence the flow of the wind turbine blade and if they can be designed to replicate realistic tripping scenarios seen in the field.

1.1 Aerodynamic coefficients and flow similarity

When we look at absolute aerodynamic quantities like the lift force or the pitching moment, we find that those quantities depend on a large number of fluid parameters like the density, viscosity and temperature and additionally on the flow speed and model size. That makes it very difficult to apply experimental results to applications. A much better way is to non-dimensionalize the aerodynamic quantities with flow speed and model size and to look at similarity parameters rather than fluid parameters. In our example we are interested in the time average of the lift and moment coefficient for low speed flow (i.e. Mach number smaller than 0.3). It turns out that those coefficients only depend on one single similarity parameter, the Reynolds number, and the angle between free stream velocity and chord line, the angle of attack.

1.1.1 The Reynolds number

The Reynolds number is defined as the ratio of inertial to viscous forces. It is given by

$$Re = \frac{\rho U_\infty c}{\mu} \tag{1}$$

with the density ρ, the flow speed U_∞, the characteristic length (in our case the chord length) c and the dynamic viscosity μ.

1.1.2 The lift coefficient

The lift force is the force acting on the airfoil section perpendicular to the mean flow direction. We measure aerodynamic quantities in the middle of the airfoil section and assume that the flow is approximately two-dimensional. In this special case it is convenient to look at the force and moment per unit span. The section lift, pressure drag and moment coefficients are respectively defined as

$$C_l = \frac{l}{\frac{1}{2}\rho U_\infty^2 c} \tag{2}$$

with l the lift force per unit span.

1.1.3 The pressure coefficient

The non-dimensional surface pressure on the airfoil is given by the pressure coefficient as

$$c_p = \frac{p-p_\infty}{\frac{1}{2}\rho U_\infty^2} \tag{3}$$

where p is the local static pressure and p_∞ denotes the freestream static pressure. The distribution of the pressure coefficient integrated along the airfoil section contour can yield not only the lift, but also the pressure drag and pitching moment coefficient.

1.2 Wind Tunnel Corrections

Obviously the flow field in a wind tunnel with confining walls is not the same as in free flight conditions. For traditional aerodynamic wind tunnels with solid walls, corrections have been developed over the years to make the wind tunnel measurements comparable to free flight. There are several types of corrections that need to be applied here:

- ***Solid blockage***: the area of the tunnel test-section is effectively reduced by the presence of the model. Continuity and Bernoulli's equations require that the flow velocity increases. The effects of solid blockage are functions of the model thickness (its maximum and its distribution) and the overall size, but not of the camber (Barlow et. al., 1999).
- ***Wake blockage***: the wake resulting from the shedding of the viscous layer from the model has inherently a lower mean velocity than the freestream. To maintain continuity, the flow outside of the wake must therefore have a mean velocity higher than the freestream to balance the momentum deficit of the wake.
- ***Streamline curvature***: In free flight conditions, the presence of a lifting body results in streamline deflections far away from the body itself. In the confined space of a test-section, this streamline displacement is limited by the presence of the walls (in our case the side walls). Due to this limitation, the body experiences a higher angle of attack than it is actually set at and therefore appears to have effectively more camber than it actually does. The increased camber results in higher lift and quarter chord moment.

Further description of the physical phenomena behind the blockage corrections and the math (mainly based on vortex images and panel methods) can be found in Barlow *et. al.* (1999) and Allen and Vicenti (1947). While a complete understanding of the calculus involved is beyond the scope of this class, the physical aspect of the blockage corrections should be adequately described in your lab reports.

The pressure distribution data you will obtain from the wind tunnel data acquisition (see Section 3.2 for details) will have been corrected. As such, the pressure coefficient provided is labelled C_{pc} and not simply $\underline{C_p}$ to indicate the correction. Similarly, the lift you will compute from C_{pc} is the corrected lift C_{lc}.

2 Apparatus

2.1 The VT Stability Wind Tunnel

The Virginia Tech Stability Wind Tunnel is a continuous, single return, subsonic wind tunnel with 7.3m long removable rectangular test sections of square cross section 1.83m on edge. The general layout is illustrated in Figure 6.

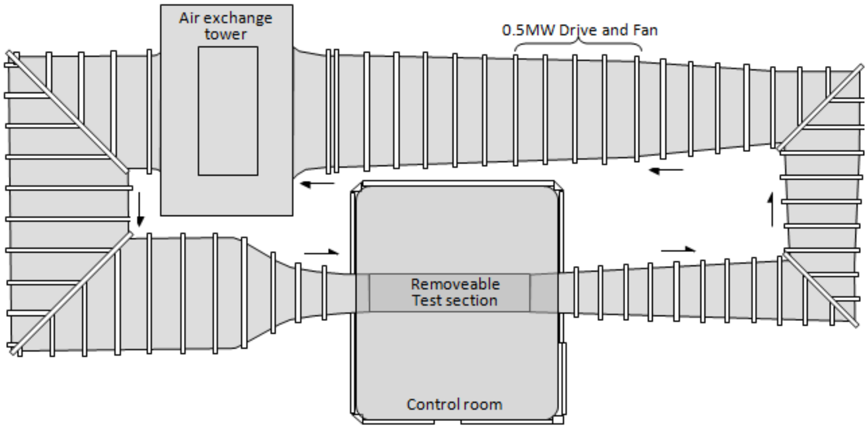


Figure 6. Plan view schematic of the Virginia Tech Stability Tunnel in anechoic configuration.

The tunnel is powered by a 0.45MW variable speed DC motor driving a 4.3m propeller at up to 600 r.p.m. This provides a maximum speed in the test section (with no blockage) of about 75m/s and a Reynolds number per meter up to about 5,000,000. The tunnel forms a closed loop, but has an air exchange tower open to the atmosphere to allow for temperature stabilization. The air exchange tower is located downstream of the fan and motor assemblies. Downstream of the tower the flow is directed into a 5.5×5.5m settling chamber containing 7 turbulence-reducing screens each with an open area ratio of 0.6 and separated by 0.15m. Flow exits this chamber through the 9:1 contraction nozzle which further reduces turbulence levels and accelerates the flow to test speed. Flow in the empty test section is closely uniform with turbulence levels of about 0.02%, increasing slightly with speed.

At the downstream end of the test section flow passes into a 3-degree diffuser. Eight 0.16m high vortex generators arranged at intervals of 0.39m around the floor, walls and ceiling of the flow path at the entrance to the diffuser serve to mix momentum into the diffuser boundary layer, minimizing the possibility of separation and the consequent instability and inefficiency. The four corners in the flow path (two between the air exchange tower and settling chamber, and two between diffuser and fan) are equipped with diagonal 6 arrays of shaped turning vanes. Spacing between the vanes is 0.3m except in the corner immediately ahead of the settling chamber where the spacing is 0.076m.

The test-section was remodeled in 2010 and features a 1.83m x 1.83m square cross-section. Interchangeable 0.6m square aluminum panels are used on both the floor and ceiling to maximize model mounting flexibility. On top of the test-section, a turn-table manufactured by Kinematics Mfg. Inc., model number ZE12C-85M-24H01-RC-REV.A, allows the angle of attack of the model to be set with a 0.25° uncertainty. The turn-table is powered by a BK Precision 9123A variable DC power supply. The position of the turn-table is monitored using a LM10 magnetic encoder readhead using a P201 USB interface both manufactured by RLS. The complete system is controlled by a Matlab program.

Flow speed is monitored via wall mounted pressure ports in the settling chamber and contraction. These ports do not sense the pure stagnation and static pressure and thus calibration factors are used to relate these to the true free stream values. Mean surface pressure distributions on the airfoil model and the reference pressures are measured using an Esterline 9816/98RK pressure scanner with a range of ±2.5psi. The system has a rated accuracy of ±0.05% full scale. Temperature in the test section is monitored using an Omega Thermistor type 44004 (accuracy ±0.2°C) and the ambient absolute pressure is determined using a Validyne DB-99 Digital Barometer (resolution 0.01" Hg).

2.2 Airfoil Model and Aerodynamic Measurements

2.2.1 0.9m DU91W250

The normalized profile of the DU91W250 is given in DU91W250.txt (link) (this file is comma separated and provides the 3D coordinates for each point with the first column being chordwise, second along the thickness, and third spanwise) and plotted for the 0.9m model in **Figure 7**. This profile is a wind turbine airfoil that was developed by Delft University in the Netherlands and has been heavily tested and used in wind power over the years. This airfoil is cambered with a 25% thickness and a 3.39% chord leading edge radius.

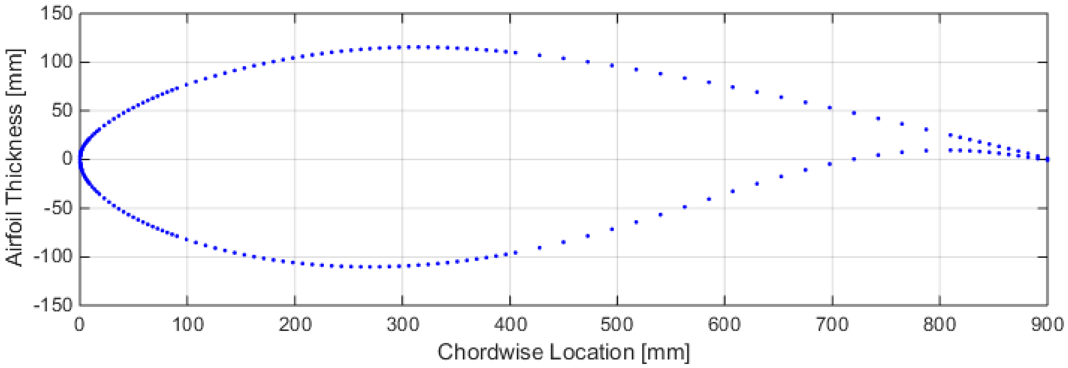


Figure 7. The DU91W250 airfoil profile.

The model, constructed by the AOE Machine shop, was designed to span the complete vertical height of the test section. It has a 1.8m span and 900mm chord and is built around an 88.9-mm diameter steel tube that forms a spar centered on the quarter chord location. The model is made up of 50.8mm aluminum laminates stacked on top of each other via alignment pins. All-thread runs through the length of the model and is bolted at each end to clamp the laminates together. The aluminum tube projects 166mm from the ends of the airfoil and is used for mounting.

The model is instrumented with about 80 pressure taps of 0.5mm internal diameter located near the midspan. The taps are connected internally to 1.6mm Tygon tubing that exits the model through the center of the aluminum tube. Pressure tap locations are given in Table 2 below. This list presents all the ports present on the model. Each port is tested before a tunnel entry to ensure they function properly. If they don’t, their data is disregarded. Therefore, it is likely that the data files you will obtain from this experiment will not include all the ports below.

Table 2: Nominal chordwise locations (x/c) of pressure taps on the suction side and pressure side of the DU91W250 model (note that there is only one port at x/c=0).

0	0.07279	0.269967	0.534121	0.78834
0.001166	0.091515	0.300799	0.568083	0.815544
0.004657	0.112124	0.33256	0.601728	0.841277
0.010458	0.134582	0.365102	0.634898	0.865418
0.018541	0.158723	0.398272	0.66744	0.887856
0.02887	0.184456	0.431917	0.699201	0.908485
0.041394	0.21166	0.465879	0.730033	0.92721
0.056057	0.240208	0.5	0.759792	0.943943
				0.958606

2.2.2 Boundary Layer Trip

To force the transition location on the DU91W250, a serrated tape will be applied to the airfoil at 5% chord on the suction side. The serrated tape is 10mm wide, 0.5mm thick and features 60^{o} serration. It will be applied by the wind tunnel staff over one layer of 0.07mm thick aluminum tape.

2.2.3 Measurement System

Pressure ports measure the pressure at a given point on an airfoil; no flow moves through them once their pressure reaches a steady-state value. One end of the port is attached to a pressure transducer and the other is open to the flow. The pressure felt by the pressure transducer is the same as that felt by the surface of the airfoil in the region just around the given pressure tap. In the Stability Wind Tunnel, pressures are measured using an Esterline 9816/98RK pressure scanner with a range of ±2.5 psi. The system has a rated accuracy of ±0.05% full scale. Additionally, flow speed is monitored via wall mounted pressure ports in the settling chamber and contraction. These ports do not sense the pure stagnation and static pressure and thus calibration factors are used to relate these to the true free stream values. Temperature in the test section is monitored using an Omega Thermistor type 44004 (accuracy ±0.2 °C) and the ambient absolute pressure is determined using a Validyne DB-99 Digital Barometer (resolution 0.01" Hg).

3 Objectives and Procedures

In this experiment, you will acquire surface pressure data in the form of pressure coefficients as a function of angle of attack. You will perform measurements at 2 Reynolds number (1.5M and 3M).

a. Evaluate the effects of angle of attack and Reynolds number on the surface pressure distribution plots
b. Evaluate the impact of the boundary layer trip on the pressure distribution.
c. Determine the effects of Reynolds number on the lift curves.
d. Determine the zero-lift angle of attack (note that you may need to interpolate the data to get the exact angle for which the lift coefficient is 0.
e. Evaluate the effects of Reynolds number and boundary layer trip on the lift curve and zero-lift angle of attack

3.1 Measurement Procedure

It is strongly suggested to bring your own digital camera when you do the experiment and take pictures of the wind tunnel test section and the airfoil model!

For this lab, Group 1 will measure the pressure distribution on the DU91 airfoil at two Reynolds numbers, 1.5 and 3 million, over a range of angle of attacks from -15 degrees to 15 degrees for either a clean or tripped airfoil. This measurement will be used in conjunction with data from the second group of your lab session to study the effects of tripping on the airfoil. Group 2 will then perform measurements at 1.5 and 3 million for angles of attack between -15 and 15 degrees for whichever surface condition group one did not test. The boundary layer trip will be applied to the model by wind tunnel staff during the change-over between the two teams.

Therefore each lab will have a data set containing 4 polars (at Reynolds numbers of 1.5 and 3 million for both the clean and tripped airfoil surface conditions).

The team responsibilities are as follows:

Task **in chronological order**	**Group 1**	**Group 2**
1	Arrives at the start of the lab period	Arrives 1h30 after the beginning of the lab period
2	Performs a polar for two Reynolds numbers on either a clean or tripped airfoil	Performs a polar for two Reynolds numbers on the remaining surface condition for the airfoil

Prior to the experiment:

- Read the manual online.
- Perform XFOIL lift curve and pressure coefficient estimates for the 4 combinations of boundary layer trip and Reynolds number you will be testing (see Appendix A for a detail of XFOIL commands). You can download XFOIL here. You can run your estimates at every degree between -15 and 15 degrees. Using standard atmospheric conditions and knowing the airfoil chord (900mm), you will need to determine the speed needed to run the wind tunnel at 1.5 and 3M. The tunnel staff will ask you to provide those estimates.
- Develop a Matlab program that will read in the pressure tap location and pressure coefficient matrices (see Section 3.2 below) and compute the lift through numerical integration. Validate this code by computing the lift from the pressure distribution produced by XFOIL and comparing your value of the lift coefficient to XFOIL's. You will need this code during your lab to plot your lift curves as you obtain them.
- Assign a task to each member of the team (it is paramount that each assignment be efficiently executed so the test goes smoothly):
    - Logbook (bring your own laptop; responsible to enter information about the run (atmospheric conditions, speed, Reynolds number, trip condition etc… as well as processing and analyzing data)
    - Tunnel operator (will control the speed of the flow during testing)
    - Data acquisition (a computer is provided; responsible to run the acquisition code and ensure data is recorded correctly)

During the experiment:

- You will perform an angle of attack sweep at the following angles (given using Matlab vector notation): [-15:2:15]:
- At each point: you will measure the pressure distribution on the airfoil.
- At each point, the tunnel operator will have to adjust the flow speed so that it stays constant. You will need to keep the Reynolds number within ±5%.
- You will need to take several pictures. Figure 8 through Figure 10 are the type of photos that are **suggested** for this experiment (you will need to add your own labeling). You are welcome (and encouraged) to take extra as you see fit. Note that due to the presence of a wake rake , you will not be able
- You should process data as soon as a run is completed and import the data in your logbook. This means you should have a Matlab code(s) that produces plots of *Cl*c vs α_c and compare it to XFOIL predictions you would have made before the lab. Generating those plots should be a matter of seconds, which leaves time to analyze those plots and make initial comments and on the agreement (or lack of) between experimental and XFOIL data.

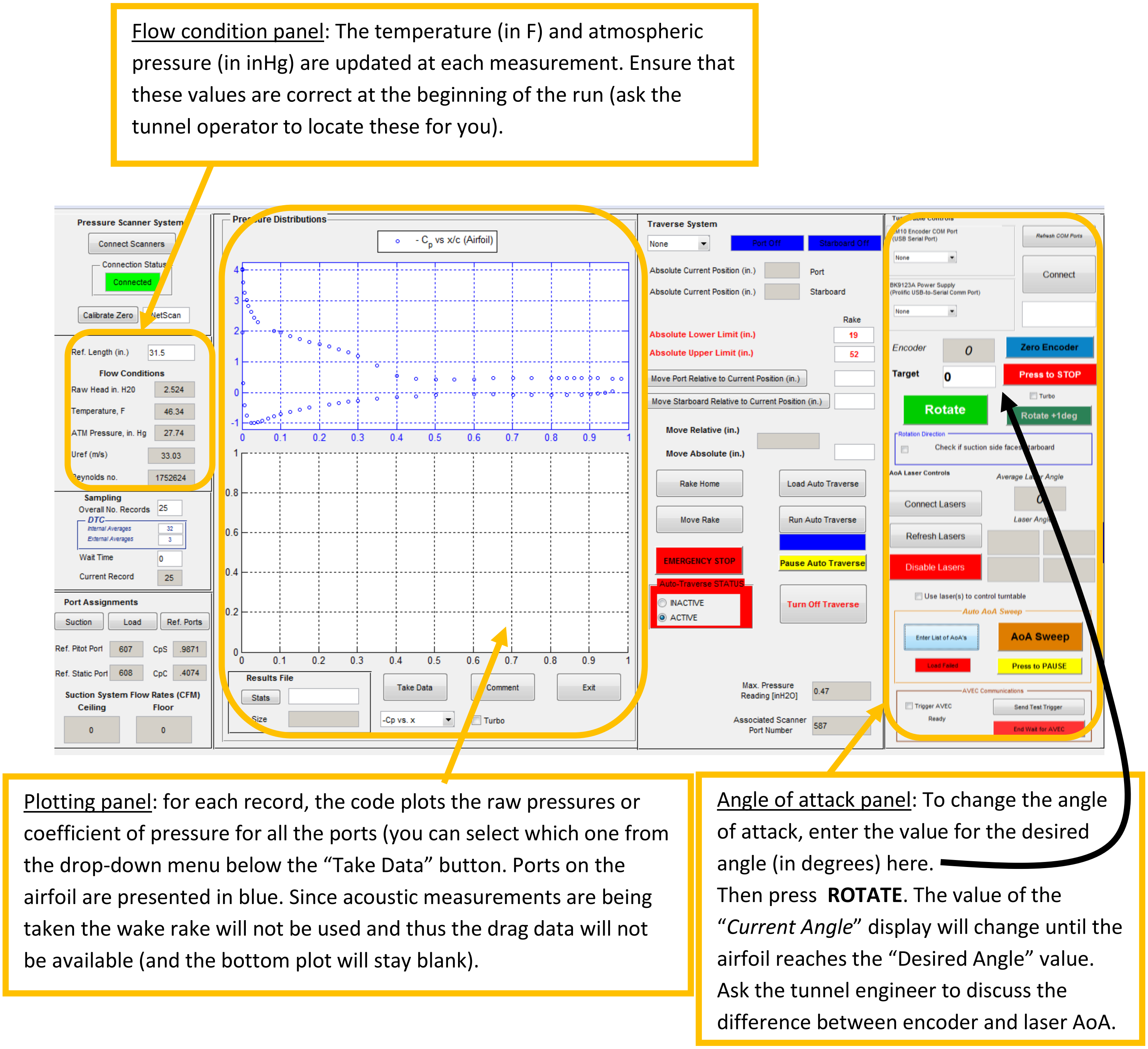
Figure 8. Wind turbine blade section model fitted with boundary layer trip (overall view)

Figure 9. Boundary layer trip fitted on the wind turbine blade section model (side view)

Figure 10. Boundary layer trip fitted on the Wind turbine blade section model (3/4 view as seen from upstream)

Data Acquisition:

1. When you arrive in the lab, the tunnel engineer should have the Matlab data acquisition code open (ask the wind tunnel engineer to bring it up otherwise). You will see a screen similar to
2. **Figure 11**.



Flow condition panel: The temperature (in F) and atmospheric pressure (in inHg) are updated at each measurement. Ensure that these values are correct at the beginning of the run (ask the tunnel operator to locate these for you).

Ref. Length (in.) 31.5

Flow Conditions

Raw Head in. H20 2.524

Temperature, F 46.34

ATM Pressure, in. Hg 27.74

Uref (m/s) 33.03

Reynolds no. 1752624

Sampling

Overall No. Records 25

DTC

Internal Averages 32

External Averages 3

Wait Time 0

Current Record 25

Port Assignments

Ref. Pitot Port 607 CpS .9871

Ref. Static Port 608 CpC .4074

Suction System Flow Rates (CFM)

Ceiling 0 Floor 0

Traverse System

None

Rake

Absolute Lower Limit (in.) 19

Absolute Upper Limit (in.) 52

Auto-Traverse STATUS

○ INACTIVE

● ACTIVE

Max. Pressure Reading [inH2O] 0.47

Associated Scanner Port Number 587

M10 Encoder COM Port (USB Serial Port) None

BK9123A Power Supply (Prolific USB-to-Serial Comm Port) None

Encoder 0

Target 0

☐ Turbo

Rotation Direction

☐ Check if suction side faces starboard

Average Laser Angle 0

☐ Use laser(s) to control turntable

☐ Trigger AVEC

Ready

Plotting panel: for each record, the code plots the raw pressures or coefficient of pressure for all the ports (you can select which one from the drop-down menu below the "Take Data" button. Ports on the airfoil are presented in blue. Since acoustic measurements are being taken the wake rake will not be used and thus the drag data will not be available (and the bottom plot will stay blank).

Angle of attack panel: To change the angle of attack, enter the value for the desired angle (in degrees) here.
Then press **ROTATE**. The value of the "*Current Angle*" display will change until the airfoil reaches the "Desired Angle" value.
Ask the tunnel engineer to discuss the difference between encoder and laser AoA.

Figure 11. Screenshot of the Matlab data acquisition and control program

3. Zero calibration.
    a. Press “Calibrate Zero”. The fan of the wind tunnel has to be switched off at this moment. The zero calibration compensates for the internal offset of the pressure scanner.
    b. Set number of records in the menu “Sampling” to 10 and make a measurement by pressing the button “Take Data”.
    c. Check in the graph that all ports measure roughly 0inH2O. A deviation of 0.1inH2O is tolerable. You might have to choose “pressure vs port” in the drop down menu below the graph to visualize the pressure. Note channels with an offset in your measurement log.
4. The port location file should be loaded ask the wind tunnel engineer to verify this.
5. Final check.
    a. Tell the lab technician to set the wind speed to 10m/s.
    b. Take a measurement by pressing “Take data”.
    c. Check that the raw head in the menu “Flow Conditions” shows the same value as “Q” on the screen for the wind tunnel control.
    d. When the lab technicians tells you that the flow is stable, check that the flow temperature and the ambient pressure (make sure that the unit is in. Hg) in the fields “Temperature F” and “ambient pressure” are correct. You can read these values from the wind tunnel control screen (ask the tunnel technician)

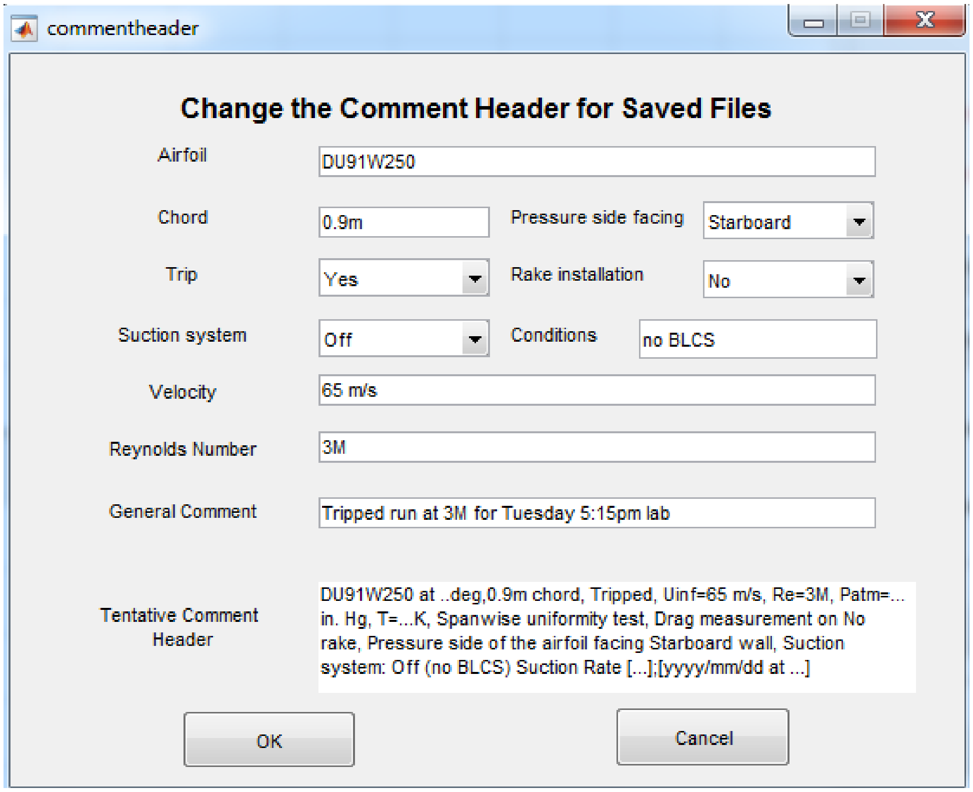
If your last check was positive you have set up the data acquisition system correctly and can proceed with the measurement.

Follow the list below to start the **lift polar measurements**:

1. Check that the reference length in the field “Ref. Length” is set to 35.43 in. (the chord length of the DU91W250 model).
2. Press “Stats” in the “Results File” panel and you will be asked for the file name in which your data will be stored. Name the file ***DU91W250_x_Config_D_T.stat*** where **x** is the Reynolds number times 10 (has to be one of the following: ***15M or 30M – DO NOT USE DOTS IN THE FILENAME***), **Config** is the surface treatment either ***TRIPPED*** or ***CLEAN***, ***D*** is the day of the week (**Monday**, **Tuesday**…), and **T** is the time of your team arrived in the tunnel followed by **am** or **pm**. ***<u>Do not include any spaces or slashes in the file name</u>***. Therefore the very first measurement for the first group of week 1 should be:
   DU91W250_15M_Tripped_Monday_330pm.stat

3. A new window will pop-up asking you to enter information about your run (this information will be saved as a header each time you press the “Take Data” button or load a file containing a specified range of Angle of Attacks). A sample screenshot is shown in Figure 12. You will need to enter the information that is pertinent to **YOUR configuration under Trip, Velocity, Reynolds Number, and General Comment**. Default values for the rest should be:

a. “Pressure Side Facing”: Port
b. “Rake Installation”: A
c. “Suction System”: Off
d. “Conditions”: No BLCS

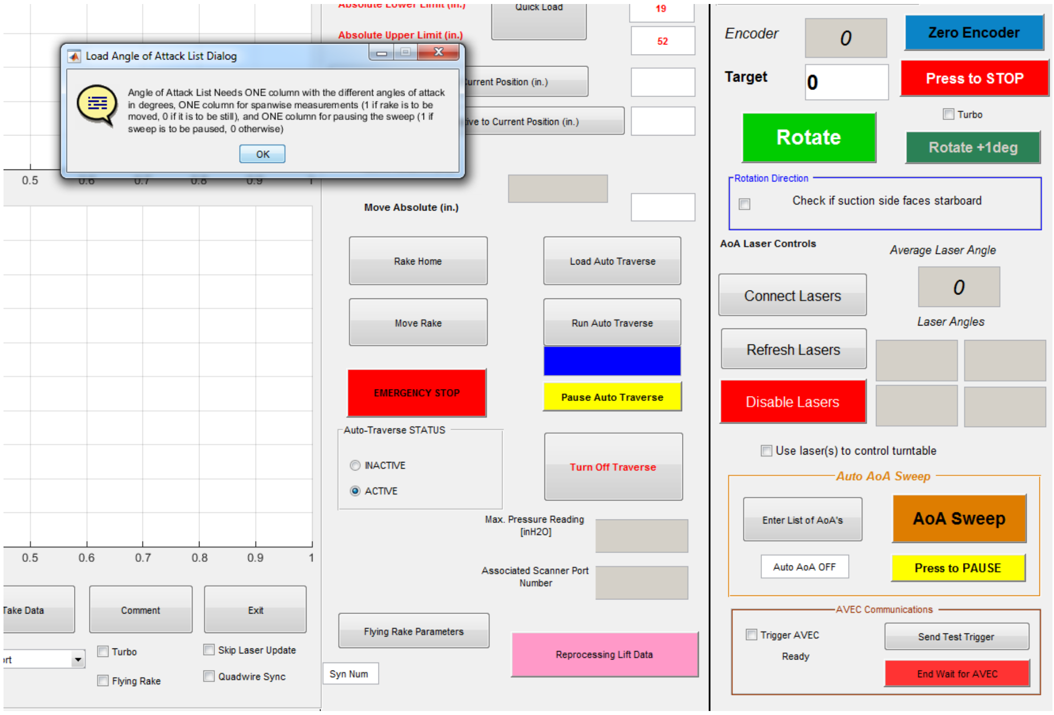


Change the Comment Header for Saved Files

Airfoil: DU91W250
Chord: 0.9m
Pressure side facing: Starboard
Trip: Yes
Rake installation: No
Suction system: Off
Conditions: no BLCS
Velocity: 65 m/s
Reynolds Number: 3M
General Comment: Tripped run at 3M for Tuesday 5:15pm lab
Tentative Comment Header: DU91W250 at ..deg,0.9m chord, Tripped, Uinf=65 m/s, Re=3M, Patm=... in. Hg, T=...K, Spanwise uniformity test, Drag measurement on No rake, Pressure side of the airfoil facing Starboard wall, Suction system: Off (no BLCS) Suction Rate [...];[yyyy/mm/dd at ...]

Figure 12. Screenshot of the data acquisition program with comment input

4. With the lab technician consent, set the wind tunnel to your desired velocity/Reynolds number and set the model to the desired angle of attack.
5. Enter 20 in the field “No. Records” to acquire 20 samples (gives good accuracy of the mean value).
6. Press “Enter List of AoAs” on the right hand-side of the program window. A dialog window (Figure 13) will pop-up, click OK.


Load Angle of Attack List Dialog

Angle of Attack List Needs ONE column with the different angles of attack in degrees, ONE column for spanwise measurements (1 if rake is to be moved, 0 if it is to be still), and ONE column for pausing the sweep (1 if sweep is to be paused, 0 otherwise)

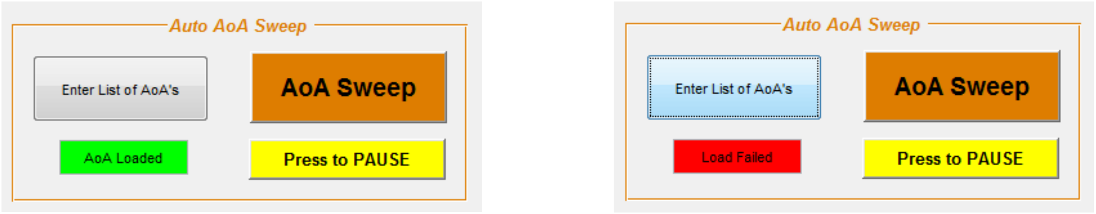
Encoder: 0

Target: 0

Average Laser Angle: 0

Figure 13. Screenshot of the data acquisition program with the angle of attack list dialog

7. Select the angle of attack list associated with your particular run (AOE3054_FullSweep.txt for the main test – ask the tunnel engineer to assist you as needed). If the angle is successfully loaded, the indicated above the "AOA Sweep" button will turn green as in Figure 14 (ask the tunnel staff to confirm you have done this properly).



(a) (b)

Figure 14. AOA indicator showing AOA list was loaded (a) successfully and (b) unsuccessfully.

8. Check one last time that the acquisition is set-up correctly. With the tunnel engineer permission, bring the wind tunnel up to speed and press the "AOA sweep" button only when the target speed has been reached. Once you start the sweep, the program will automatically go through all the angles of attack listed in the AoA list file and take data at each of them.
9. Make sure to check the acquisition code at every angle of attack for the following:
   a. Shape of the pressure distribution
   b. Flow temperature, pressure, and dynamic pressures match the tunnel values
   c. Angle of attack is increasing by 2° steps as described before.

10. When the sweep is completed, the AOA indicator (below the “Enter List of AoA’s” button) will switch back to white.
11. At that point, Press “Stats” to save the file.
12. Ask the tunnel operator to show you how to process the .stat file to obtain the .mat file with the data for the run and move on to your next objective.
13. While you are running the following sweep, one student should start importing the data in your logbook and compute the lift. Perform some basic analysis (plot Cl_c vs α_c, determine stall angle if possible, zero-lift angle, compare all these to XFOIL etc…). Be as efficient as possible.
14. **As runs are completed, you will be able to download your data files from the following website: https://www.dept.aoe.vt.edu/~boetjens/tests/AOE3054_2018/. This is also where you will access the data for the other team in your lab (i.e. the other trip condition).**

3.2 Processing of the Measured Data

The data will be processed for you for each run and you will be given the pressure coefficient corrected for blockage C_{pc} obtained at every angle of attack. The .mat file will contain the following variables:

Table 3: Description of variables obtained from the pressure distribution processing code.

Variable	**Description**	**Size**
airfoilName	Airfoil Designation	string
alphaC	Corrected angle of attack in degrees (**N angles in total**)	N x 1
Chord	Airfoil chord in inches	1 x 1
Cpc_suction	Corrected surface pressure coefficient distribution for the **M suction side pressure ports** at the N angles of attack	N x M
Cpc_pressure	Corrected surface pressure coefficient distribution for the **Q suction side pressure ports** at the N angles of attack	N x Q
Prof	Array containing the normalized profile of the airfoil (first column is x/c, second column is y/c) at **P points**.	P x 2
Rec	Corrected Reynolds number based on the chord for each of the N angles of attack	N x 1
Rho	Flow density (kg/m^3) for each of the N angles of attack	N x 1

Testsection	Test-section type in which test was performed (aerodynamic in your case)	string
Tf	Flow temperature in Kelvin for each of the N angles of attack	N x 1
Trip	String describing whether boundary layer trip is used	string
Urefc	Freestream velocity in m/s for each of the N angles of attack	N x 1
X_suction	Chordwise location of the M suction side pressure taps on the airfoil, normalized by the chord.	1 x M
X_pressure	Chordwise location of the Q pressure side pressure taps on the airfoil, normalized by the chord.	1 x Q
Y_suction	Thickness location of the M suction side pressure taps on the airfoil, normalized by the chord.	1 x M
Y_pressure	Thickness location of the Q pressure side pressure taps on the airfoil, normalized by the chord.	1 x Q

Note that since the boundary layer trip will cover part of the model surface, some of the pressure taps near it will be covered and data will not be available for them. When plotting the C_{pc} distribution this should be kept in mind and you are encouraged to comment on the effects of these missing ports on the accuracy of the lift integration.

A sample data file is provided here to allow you to validate your processing code.

3.3 Presentation of your Results

In plotting and presenting data, normalize x (chordwise distance) with the chord length of the airfoil model. Present the profile polar C_{lc} vs. α_c for various Reynolds numbers and trip conditions. Plot some of the C_{pc} vs. x/c distributions. **Note** that plots of experimental data should consist of symbols – no curves between points.

3.4 Report Expectations

1. Introduction
2. Apparatus and Technique
    a. Describe the wind tunnel and airfoil model (use the information provided in this document and pick out the most important things, write in your own words!)

    b. Make a 2D sketch of the airfoil in the wind tunnel with the most important dimensions
    c. Label the photos of the trip installed on the airfoil (locations, spanwise extent, flow direction etc…)
    d. Describe the data acquisition system and the pressure measurements
    e. Discuss the calibration procedure of the pressure measurement system
    f. Describe the test conditions (Reynolds number and angle of attack)
3. Results of Experiment and computations
    a. C_{pc} distribution plots at (at least) 2 angles of attack (zero-lift and just before stall) with explanation of shapes, comparison to XFOIL.
    b. Clc vs angle of attack with description of variation, comparison to XFOIL, and effects of boundary layer trip (compared to baseline).
    c. Comment on the overall airfoil performance: how is C_{lmax} affected by Reynolds number? By the trip? Same questions for the slope. What impact would you expect leading edge soiling to have on the performance of this airfoil?
4. Conclusions
    a. Brief description of the tests
    b. Repeat major findings

References

Allen, H. J. and Vicenti, W. G., "Wall interference in a two-dimensional flow wind tunnel, with consideration of the effect of compressibility", NACA Report No. 782, 1947.

Barlow, J.B., Rae, W.H. jr. and Pope, A., "Low-Speed Wind Tunnel Testing", 3rd Edition, John Wiley & Sons Inc., 1999.

Corten G.p., and Veldkamp H.F., 2001, "Insect Cause Double Stall", EWEC Copenhagen, ftp://ecn.nl/pub/www/library/report/2001/rx01052.pdf

Dalili N., Edrisy A., Carriveau R., 2009, "A review of surface engineering issues critical to wind turbine performance", Renewable and Sustainable energy Reviews, Volume 13, Issue 2, p. 428-438.

Appendix A: Pre-test estimates using XFOIL

You will use XFOIL (download here) to perform free-flight computations to compare to the measurement results. XFOIL's inviscid formulation is based on potential flow theory. The airfoil geometry is described via a source panel method, and the boundary layer and wake of the airfoil are neglected in this formulation. In the viscous formulation of XFOIL, boundary layers and wake are modeled with a two-equation lagged dissipation integral boundary layer formulation. The transition from laminar to turbulent flow is modeled via the standard e^N-criterion. The incompressible inviscid flow outside the boundary layer and wake region is solved in the same way as the flow field in the inviscid formulation.

Accurate predictions of the transition from laminar to turbulent boundary layer flow are extremely difficult. The e^N-criterion used in XFOIL is a greatly simplified way to describe reality. Additionally, there is also uncertainty in the choice of the N-factor. N depends mostly on the turbulence level of the flow around the airfoil section, but other factors such as the airfoil shape also play a role. For the Stability Wind Tunnel, the correct N factor is between 10 and 11. You may choose either one for your calculations.

Table 4: Dependence of N factor on turbulence intensity according to the XFOIL vpar menu.

n_{cr}	Tu [%]
4	0.563
5	0.371
6	0.245
7	0.161
8	0.106
9	0.070
10	0.046

You will perform viscous computations with the XFOIL code for the DU91W250 airfoil and for a range of angles of attack from -15˚ to 15˚ in steps of 1˚ at Reynolds numbers of 1.5×10^6 and 3×10^6 (It's OK if your code does not converge for every angle, but you should have results for most angles). Using standard atmospheric conditions and knowing the airfoil chord (900mm), you will need to determine the speed needed to run at 1.5 and 3M. It is also necessary to calculate the Mach number of the flow for XFOIL. You will need to compute the speed of sound based on ideal gas law.

Make a viscous calculation with XFOIL using the Reynolds number and Mach number you computed and with the same tripped/clean condition as tested (5% on suction side for the tripped case). Select the N factor between either 10 or 11 to get a good agreement between the XFOIL results and the measurements. The agreement will not be perfect, and differences will be analyzed in the report. Typically, XFOIL tends to overestimate both the lift-curve slope and the maximum lift coefficient. Once the final N value is selected, run a full sweep of angle of attack from -15˚ to 15˚ in steps of 1˚ to be used in the report. While comparing XFOIL and experimental results, you are encouraged to cover the following:

- Compare the lift curves for the XFOIL and experimental data sets identifying what regions of the lift curve the data best agree and for what regions they do not agree. What region of the curve would you rely on experimental data over numerical results?
- What is the overall effect of Reynolds number on the lift curve behavior?
- Instead of only looking at lift coefficient as a function of angle of attack, we also are often interested in examining the pressure coefficient along the airfoil. Typically we examine the pressure coefficient by plotting $-C_{pc}$ as a function of x/c, where x/c represents the chordwise distance, x, normalized with the chord length, c, of the airfoil model. Plot two of the $-C_{pc}$ vs. x/c distributions, one near 0° angle of attack and one just before stall and comment on the plots (note that the '.out' file containing the pressure distributions can be opened in Excel and the values displayed are C_p rather than $-C_p$). Which part of the data corresponds to the suction side and which to the pressure side of the airfoil? Why does an airfoil near stall produces more lift according to these pressure data?

Be aware that neither the XFOIL program nor the wind tunnel experiments are perfect. You will not get THE ANSWER from one of them. Keep that in mind when you interpret your results!

To run XFOIL:

Copy the XFOIL application *xfoil.exe* and the file containing the airfoil coordinates *(we will assume it is DU91W250.txt)* to your working directory. Open Matlab and browse to your working directory. In the command window, type "system('xfoil.exe')". This is the equivalent to running a DOS command while staying within the Matlab environment.

Alternatively, you could open a DOS window[4] directly and go to the path of your working directory or simply open *xfoil.exe*. Follow the commands given below, hitting enter after each command.

Note: once you are in Xfoil, by pressing enter before entering a command, you move from a sub menu to the next higher level. ***When there are blank lines in the command structure below, this means you should hit enter before moving on to the next command*.**

Note: Comments are indicated below in green for clarification and should **not** be included in the batch file (see the next page about batch processing). If a line needs to be left intentionally blank, "Leave this line blank" will appear on the left hand side in the text below.

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[4] If you don't know how to get a DOS window, this link should help: http://www.computerhope.com/issues/chdos.htm

Batch File Line Number	**Batch File Line Code**	**Comment**
1	*load DU91W250.txt*	! loads the airfoil and displays airfoil geometry data
2	DU91	!provides name for the airfoil
3	*pane*	! smoothes the airfoil geometry
4	*ppar*	! show/change paneling (a plot will pop up. Click back to original window).
5	*n*	! command to enter a new number of panels
6	*161*	! number of panels
7	*LEAVE THIS BLANK*	
8	*LEAVE THIS BLANK*	
9	*oper*	! go to menu to choose operation mode (viscous/inviscid)
10	*visc*	! viscous mode
11	***2.50E+06***	! Enter the value of the Reynolds number for your run
12	*mach*	! command to enter the mach number
13	***0.15***	**! Mach number that you will need to compute**
14	*vpar*	! go to the change boundary layer parameter menu
15	n	! command to enter the N factor of the transition criterion
16	***10***	! N factor for computing transition location
17	*LEAVE THIS BLANK*	
18	*vpar*	! go to the change boundary layer parameter menu
19	*xtr*	! fix the laminar-turbulent transition location xtrip/chord. **Use 1.0 for suction and pressure for the clean (natural transition) case with no trip. Use your trip location otherwise (e.g. x/c = 0.05 for suction and x/c = 0.10 for pressure)**
20	***1***	! forced transition location x/c on the suction side
21	***1***	! forced transition location x/c on the pressure side
22	*LEAVE THIS BLANK*	
23	pacc	! enables point accumulation for polar calculation
24	*DU91_polar.dat*	! file name in which polar data is stored
25		**!** see Note below about how to easily run a sweep without pressure distribution
26	*alfa*	! prescribe angle of attack for first calculation point*
27	***0***	! value of the angle of attack in deg.
28	*cpwr*	! Output Cp vs x/c to file at specified calculation point
29	*cp_DU91_AOA00.out*	! name of file in which x vs Cp is stored
30	*alfa*	
31	***2***	
32	*cpwr*	
33	cp_DU91_AOA02.out	! you must specify a new file name for every alfa. (…etc. if you want pressure distributions for every angle of attack, continue with this pattern (alfa, value, cpwr, filename). See Note below for a one line command to get the lift and drag coefficients for a range of angles)
34	*pacc*	! turn off point accumulation
35	*LEAVE THIS BLANK*	
36	quit	! quit XFOIL

*Note that if you only want to run a sweep of angle of attack to look at lift and drag (and don't need the pressure distributions), you can replace the entire section that starts with the first "alfa" and ends with "cp_DU91AOA02.out" (lines 26 to 33) with a single line: "aseq -15 15 1". That command will run a sweep of angle of attack from -15° to 15° in steps of 1°. This command should be useful on the prelab assignment.

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You can save the list of commands above into a batch file (let's assume it is *DU91.inp*). If you open xfoil with the following command line it will execute and perform calculations for all the angles listed in the batch file:

```
xfoil<DU91.inp
```

<u>Note:</u> You have to start a separate DOS command window and navigate to your directory (where XFOIl.exe is located) to open xfoil with the above command. If you open xfoil.exe directly, you will be in the program already and can't run in batch mode.

Now the coefficients of lift, moment, and drag are stored in *DU91_polar.dat* and each of the pressure distributions are stored in *cp_DU91_AOAXX.out*. You can open any of the .out or .dat in Notepad or Excel or Matlab.

<u>Note:</u> You probably will have to first run notepad (or Excel), then select open from the file drop down and finally select these files in order to read them. Double clicking on the file will probably not open it (unless you have already set your system to have notepad or Excel open files with these particular extensions).

*If you have further interest in XFOIL or run into errors with it, there is a manual provided in the file *xfoil_doc.txt* and you can find a nice XFOIL tutorial on the web page:

https://engineering.purdue.edu/~aerodyn/AAE333/FALL09/HOMEWORKS/FinalProject/tutorial.doc