Lab 6 : Measurement of Airfoil Wake Profile and Calibration of a Hot Wire Anemometer

Section 3, Group 1

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Abstract

In this lab, we determined the pressure and drag coefficients of the GA(W)-1 airfoil. To achieve this, we used a pressure rake and measured the momentum change of the air before and after the airfoil. Using the undergraduate wind tunnel with a test section velocity of 21.184 m/s, we found and plotted these coefficients for angles of attack in the range of -4 to 16 degrees in 4 degree increments.

On a seperate flow generating machine, we calibrated a hot-wire anemometer. This anemometer will then be used in future tests of the GA(W)-1 to measure turbulent flow generated by the airfoil. To calibrate the device, we paired it with a pitot-static tube, and measured the pressure differential from the pitot tube and voltage from the anemometer to generate a 4th order calibration curve.

List of Symbols

- C_D = coefficient of Drag [unitless]
- U_∞ = flow velocity [m/s]
- u = wake velocity [m/s]
- Re = Reynolds number [unitless]
- C_p = coefficient of pressure [unitless]
- ρ = density [kg/m^3]
- P = pressure [Pa]
- q = dynamic pressure [Pa]
- K = calibration constant [unitless]
- c = Chord length [meters]
- α = angle of attack [degrees]
- Y = vertical distance measured behind wake [meters]

Introduction

This lab aimed to determine the pressure and drag coefficients of the GA(W)-1 airfoil using a pressure rake. The rake consisted of 46 pressure probes at 2mm spacing. The wind tunnel motor was set to 15 Hz (21.312 m/s test section wind velocity), and the wake pressure distributions were measured from -4 to 12 degrees angle of attack (AOA) in 4 degree increments. By comparing the momentum of the flow before and after the airfoil using the pressure rake, we are able to calculate the pressure and drag on the airfoil.

During this lab, we also calibrated a hot-wire anemometer, which we will use in Lab 7. To calibrate this device, we measured the voltage from the anemometer for a range of flow velocities. To measure this velocity, a pitot-static tube was placed near the anemometer, in such a way that neither device would disturb the airflow around the other. The motor frequency ranged from 0 Hz to 35 Hz in 5 Hz increments. We can relate the dynamic pressure measured at each of these frequencies to the voltage from the anemometer to create a 4th order calibration curve for the anemometer.

Methodology

Setup

<u>Hotwire Anemometer</u>

The setup for the Hotwire Anemometer test was completed by our TA prior to lab. This setup is shown in Figures 1 and 2. The setup included a small-scale wind tunnel, a pitot-static probe, a hot-wire probe, a Mensor digital transducer, a Dantec mini-CTA anemometer, an NI-DAQ board and acquisition PC, and a thermometer. The wind tunnel provided a controlled environment to vary the airspeed to measure the dynamic pressure (from the pitot-static probe) and voltage (from the hot-wire probe) in the test section. The Mensor transducer recorded the dynamic pressure from the pitot probe. The NI-DAQ board recorded the hot-wire anemometer voltage output. The thermometer provided the temperature for ambient lab conditions.

Figure 1: Hotwire Anemometer Setup Frontal View

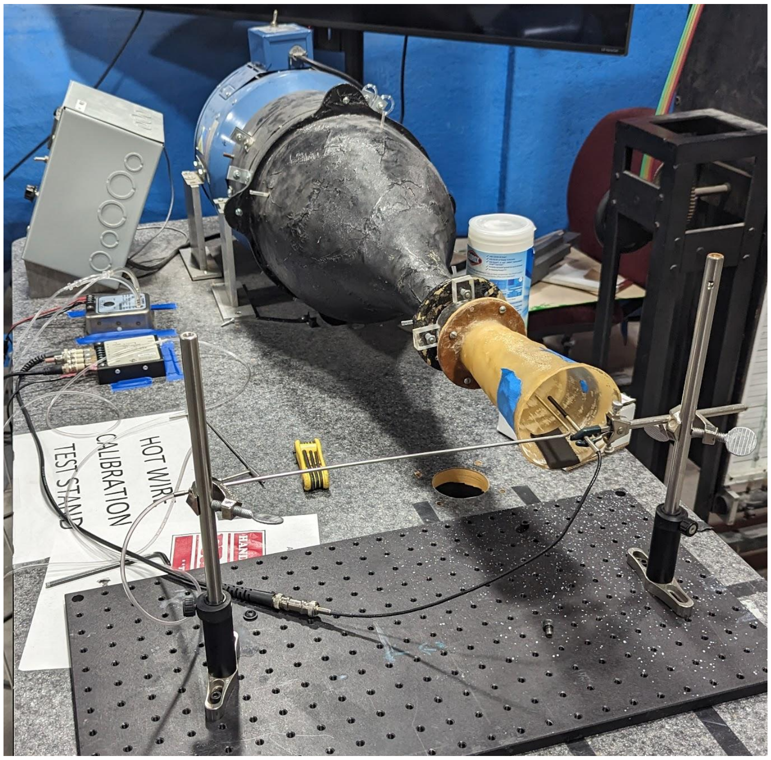

Figure 2: Hotwire Anemometer Setup Side View

<u>Pressure Rake</u>

The setup for the Pressure Rake was also completed by our TA prior to the lab. This setup is shown in Figures 3 and 4. This setup included three 16-channel Scanivalve DSA pressure transducers for 48 pressure probes, a pressure rake containing 46 pressure tubes spaced 2.0 mm apart, a hot-wire probe, a GA(W)-1 airfoil, a data acquisition PC, the undergraduate aerospace wind tunnel, and a thermometer. The Scanivalve pressure transducers will provide pressure readings from the 46 pressure probes in the pressure rake and two additional pressure probes in the wind tunnel. The pressure rake will provide a pressure profile based upon the airfoil. The hot-wire will provide voltage data to be calibrated against the pressure readings. The thermometer will provide ambient lab temperature.

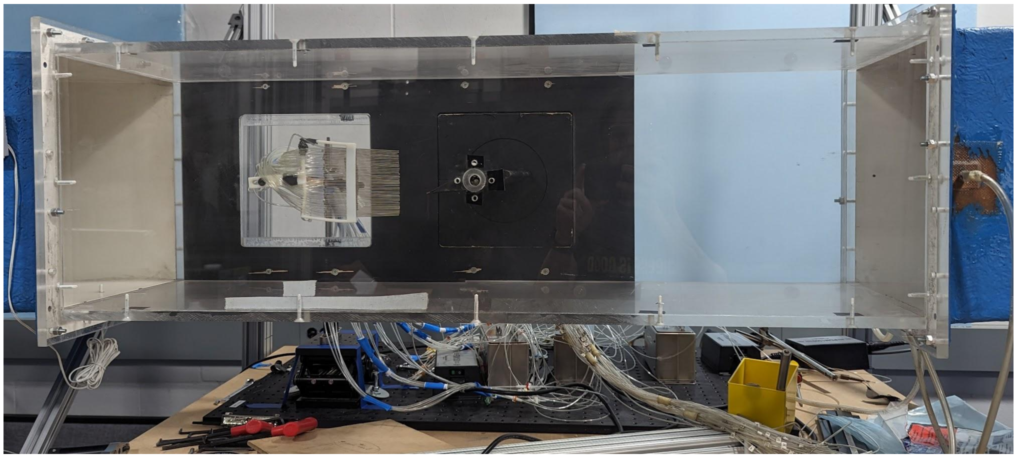

Figure 3: Pressure Rake Setup Frontal View

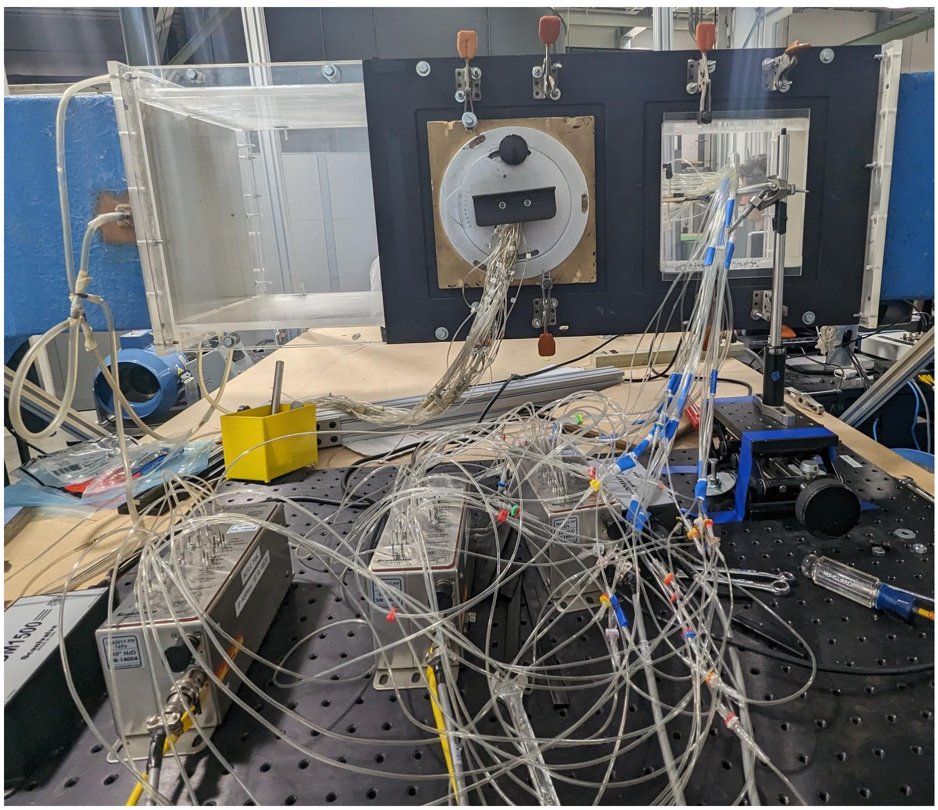

Figure 4: Pressure Rake Setup Rear View

Procedure

<u>Hotwire Anemometer</u>

For the Hotwire Anemometer test, the first step was verifying the setup of the test. Then the motor frequency of the wind tunnel was incremented at 5 Hz intervals from 0 to 35 Hz. At each motor frequency, the voltage from the hot-wire anemometer and the dynamic pressure from the pitot-staic probe was measured using the data acquisition system.

Pressure Rake

After the lab setup was verified, the LabVIEW program on the data acquisition PC was used to calibrate the Scanivalve transducers at zero wind tunnel velocity (wind tunnel was not turned on for this calibration). The wind tunnel motor was then set to 15 Hz which, per previous calibration, corresponds to a wind tunnel velocity of around 21.184 m/s. After the wind tunnel speed was set, wake pressure distributions were acquired for airfoil angles of attack of -4, 0, 4, 8, 12, and 16 degrees. At each angle of attack, the profile was checked to ensure the entire wake of the airfoil was captured by the rake.

Analysis

Hotwire Anemometer

For the Hotwire Anemometer calibration, a plot of wind tunnel velocity versus voltage output of the hot wire anemometer will be produced. At each frequency in the Hotwire Anemometer experiment, the dynamic pressure in the wind tunnel was measured using a pitot probe and the voltage of the hotwire was measured. Equation 1 provides the relation for dynamic pressure, which can be rearranged to give the air velocity (Equation 1.1).

$$q = \frac{1}{2}\rho v^2 \quad (1)$$

$$v = \sqrt{\frac{2q}{\rho}} \quad (1.1)$$

After computing the velocity provided by the pitot probe, the velocity at the given frequency can be plotted against the hotwire anemometer voltage at the given frequency. This will provide a relation between the wind tunnel velocity and the hotwire voltage. A 4th order polynomial fit will be applied to the plot of velocity versus voltage to produce a mathematical relation between velocity and voltage. This relation can be used in later labs to calculate the wind tunnel velocity using the hotwire probe.

Pressure Rake

The Pressure Rake experiment will provide a pressure profile of the airfoil, as shown in Figure 5. From this pressure profile, the coefficient of pressure and coefficient of drag can be calculated.

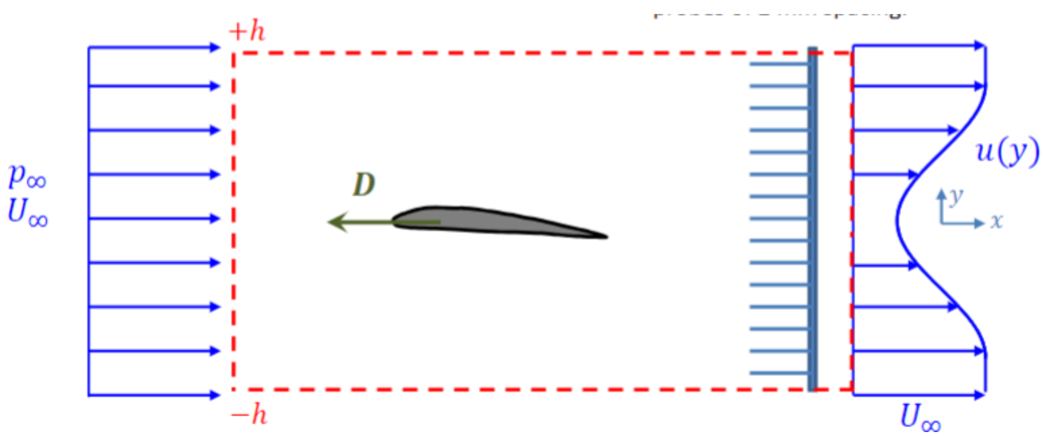

Figure 5: Pressure Profile Across an Airfoil

The coefficient of pressure distribution was determined for each angle of attack based upon the pressure wake. Each pressure tube in the wake measured a dynamic pressure value, and pressure values of the tunnel were also recorded. Equation 2 provides the relation for the coefficient of pressure.

$$C_P = \frac{P - P_\infty}{\frac{1}{2}\rho V_\infty^{\,2}} = \frac{P - P_E}{K(P_A - P_E)} \tag{2}$$

The coefficient of drag of the airfoil can be calculated using Equation 3. Here, the chord length of the GA(W)-1 airfoil is $c = 101\ mm$. The integration is taken from the bottom to top of the pressure profile (-h to +h). The velocity incoming to the airfoil is U_∞ and the velocity in the pressure profile behind the airfoil at vertical position y is $u(y)$, which can be calculated from the dynamic pressure reading from the wake profile at each position. Using Equation 3, the drag coefficient of the airfoil was calculated from the pressure profile at each angle of attack.

$$C_D = \frac{2}{c}\int_{-h}^{h} \frac{u(y)}{U_\infty}\left(1 - \frac{u(y)}{U_\infty}\right)dy \tag{3}$$

Discussion

<u>Hotwire Anemometer</u>

After collecting the necessary data for part one of the experiment, we plotted the velocity, calculated from the pitot tube measurements, against the voltage in order to calibrate the hotwire anemometer. Figure 6. Shows this calibration curve where the blue line indicates the experimental data while the orange line indicates a 4th order line of best fit. This calibration curve provides an equation that relates the voltage of the hotwire anemometer to a specific velocity which will be used in future labs as we calculate the velocity profile in the wake of an airfoil using the hotwire anemometer.

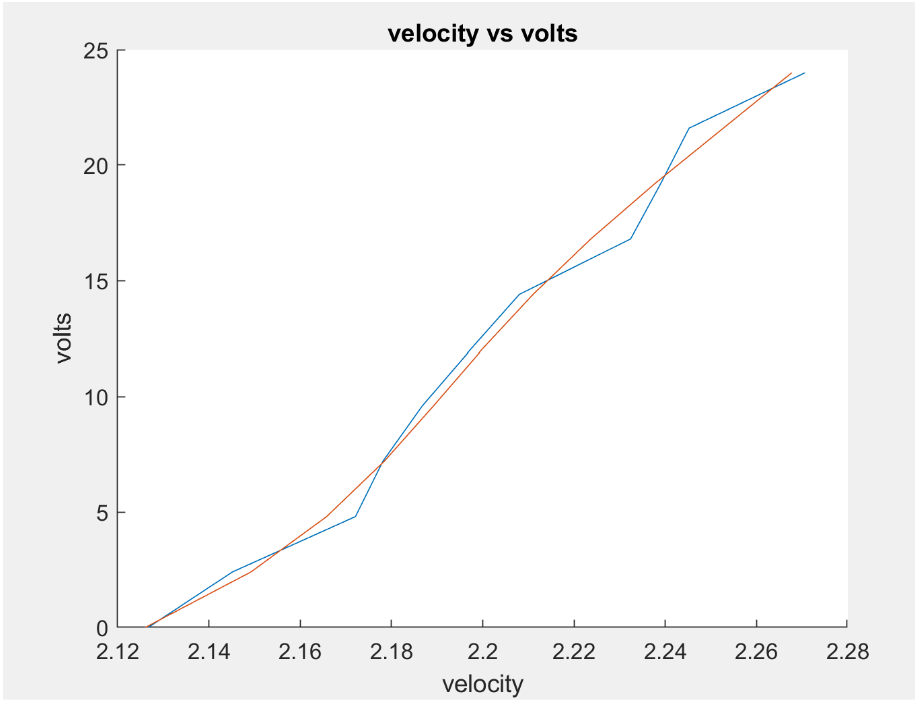

Figure 6: Volts of hot-wire vs Velocity of tunnel

<u>Pressure Rake</u>

Figures 7 through 11 show the graphs of Cp vs y, measured in mm, for each angle of attack. Each graph has a similar shape, symmetric shape about the horiaontal line passing though the minimum Cp value. Both above and below this minimum, the pressure distribution increases to the freestream value of Cp around 0.925. This unique shape is due to the air detaching from the airfoil, causing a boundary layer to form both above and below the airfoil, resulting in a low pressure wake region trailing the airfoil between the boundary layers. When comparing the wake region for each angle of attack, it is apparent that as the angle of attack increases, the wake forms lower with respect to the y axis. Along with this, the minimum Cp value decreases for every increasing angle of attack, and the height of the wake has an increasing trend as the angle of attack increases. This results in a lengthened wake and a stronger Cp differential for higher angles of attack. Figure 11 provides a great example of this widening effect as the angle of attack reaches stalling conditions.

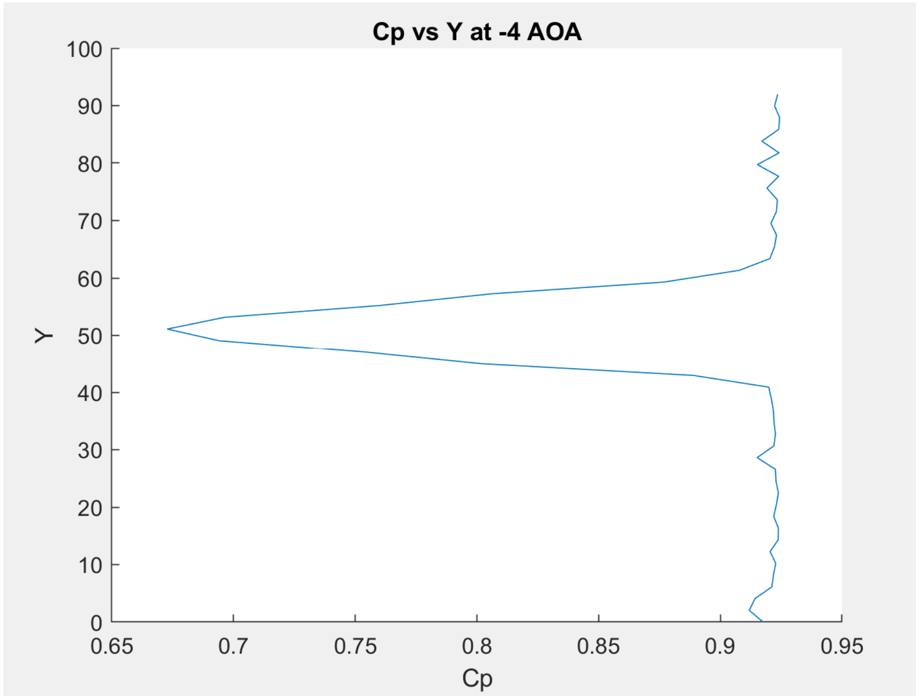

Figure 7: Coefficient of Pressure across the wake when angle of attack is -4

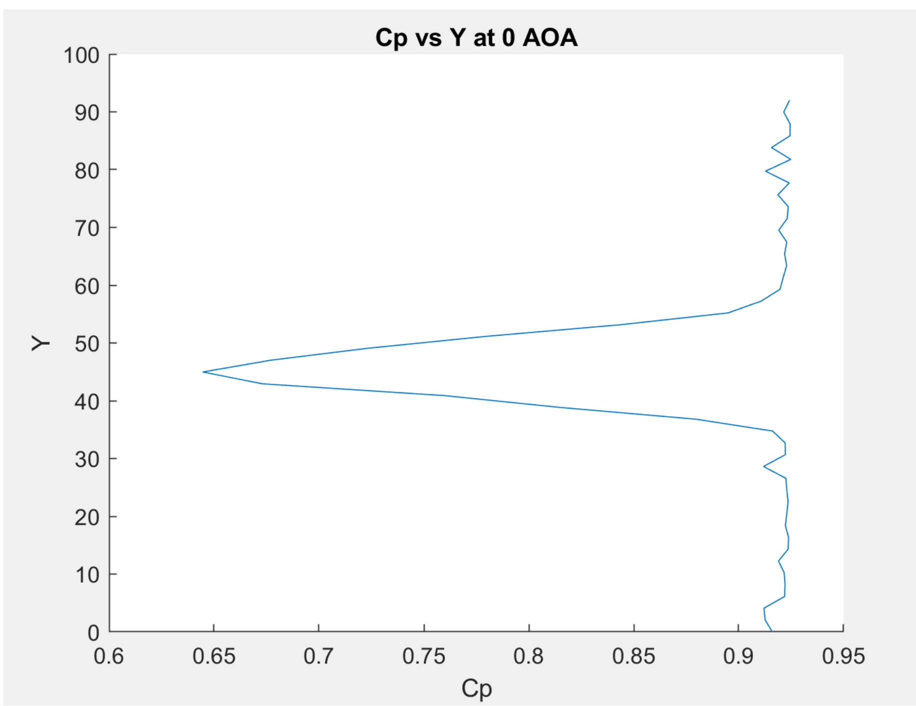

Figure 8: Coefficient of Pressure across the wake when angle of attack is 0

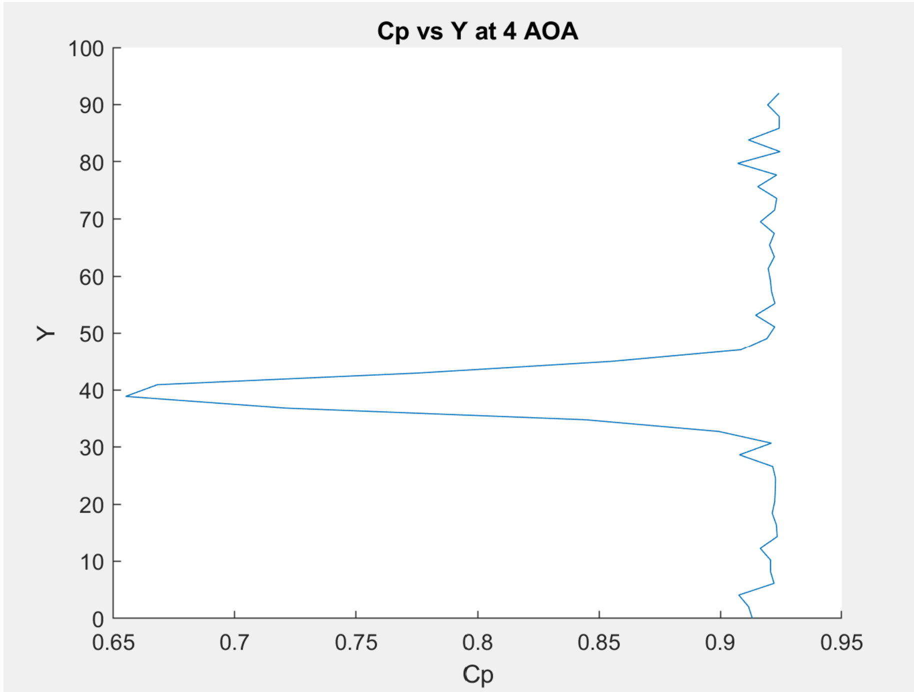

Figure 9: Coefficient of Pressure across the wake when angle of attack is 4

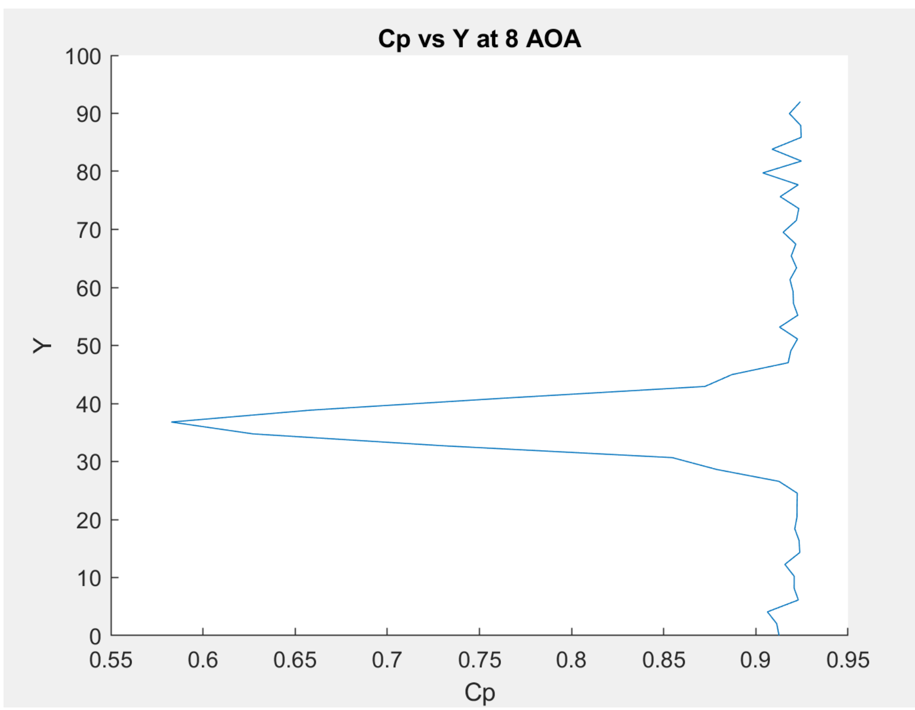

Figure 10: Coefficient of Pressure across the wake when angle of attack is 8

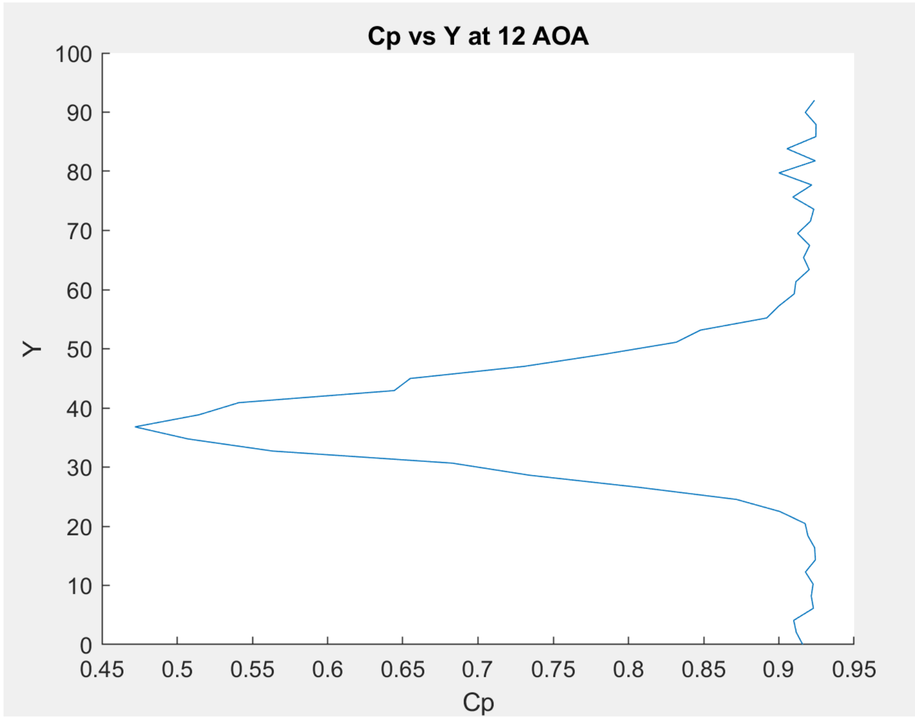

Figure 11: Coefficient of Pressure across the wake when angle of attack is 12

Once all the Cp values were computed for each angle of attack, we integrated them with respect to the freestream Cp values in order to create the Cd vs angle of attack graph in Figure 12. As we can see, there is a general trend towards greater Cd values for higher angles of attack, correlating to the larger wake regions discussed previously in regards to Figures 7 through 11. When comparing this Cd graph to the Cd graph obtained in Lab 5 from the pressure distribution around the airfoil, the Cd graph obtained in this lab is not quite accurate as the values for Cd fluctuate up and down slightly for lower angle of attacks. For the higher angles of attack, the graphs are very similar, with a large increase between angles 8 and 12. This error is most likely due to the nature of the experiment and the difficulties in measuring the Cp values of a turbulent region within the wake. It is much easier to accurately measure Cp values along the surface of an object than to measure them across a flow profile.

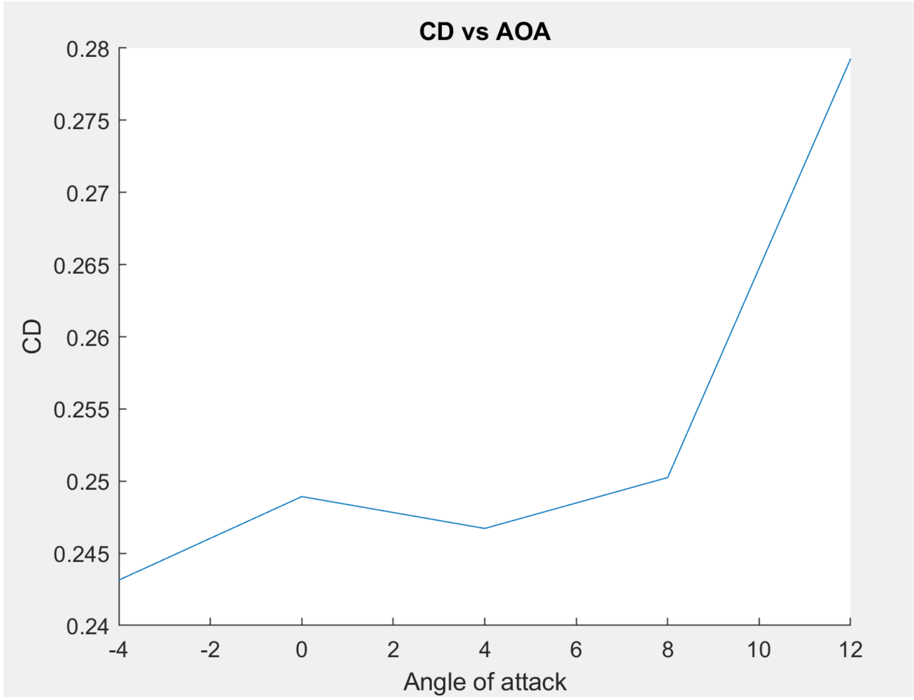

Figure 12: Wake drag coefficient vs angle of attack of the airfoil

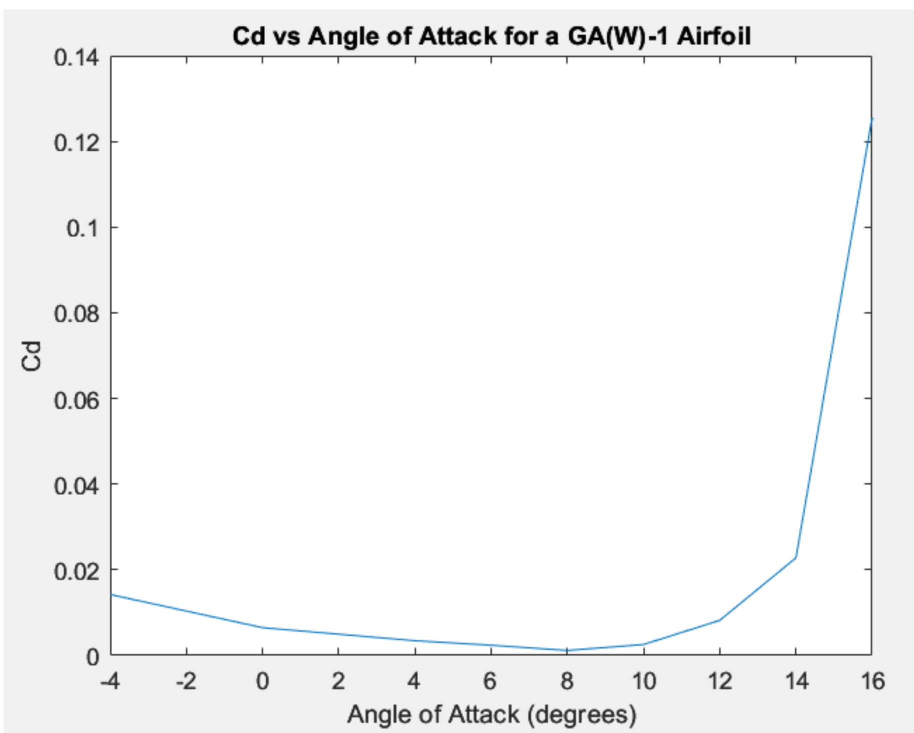

Figure 13: Drag coefficient vs angle of attack (from lab 5)

Conclusion

This lab contained two parts: calibrating a hot-wire anemometer and measuring an airfoil's wake profile. In the calibration of the hot wire, we used a small-scale wind tunnel, a pitot tube, and a hot wire to measure the pressure and voltage. The pressure and voltage were measured at each motor speed, which increased in increments of 5 Hz from 0 Hz to 35 Hz. From the pressure measurements, the flow velocity was calculated from equation 1.1. From graphing the velocity versus voltage, the relationship between the two was shown to be a linear relationship. This graph will be used in the next lab to calibrate the hot-wire anemometer.

For the second part of measuring the airfoil's wake profile, there was an airfoil in the wind tunnel with a pressure rake behind the airfoil. The pressure rake would measure the pressure at 15 Hz. The angle of attack was increased by 4 degrees from -4 to 16 degrees. Equations 2 and 3 were used with the pressure measurements, and velocity was calculated from equation 1.1 to find the coefficient of pressure and drag. From there, the pressure coefficient was plotted over the wake for each angle of attack. Then, the drag coefficients were plotted over all the angles of attack. It was found that as the angle of attack increases, the pressure behind the wake decreases, and the drag increases.

Appendix

```
clear,clc, close all

% Read the data from the spreadsheets into sets of matrices
voltdata = readmatrix('HotWire Student Data.csv');
data_n04 = readmatrix("-4.csv");
data_00 = readmatrix("0.csv");
data_04 = readmatrix("4.csv");
data_08 = readmatrix("8.csv");
data_12 = readmatrix("12.csv");

%Pull data into columns
voltdata_pressure = voltdata(:,2);
voltdata_volt = voltdata(:,1);
voltdata_hot = voltdata(:,3);

% get velocity from the pressure readings, convert percentage of volts to
```

```
% find the actual volts, and create a polynomial fit of four degrees for
% the plot
v_vel = sqrt((2.*voltdata_pressure)./1.22);
volts = (voltdata_volt./100).*60;
[p] = polyfit(volts,v_vel,4);
v = polyval(p,volts);

% Read data from the pressure values and take the average of each point at
% each angle of attack
i = 1;
while i <= 48
pmean_n04(1,i) = [mean(data_n04(:,i))];
pmean_00(1,i) = [mean(data_00(:,i))];
pmean_04(1,i) = [mean(data_04(:,i))];
pmean_08(1,i) = [mean(data_08(:,i))];
pmean_12(1,i) = [mean(data_12(:,i))];
i = i+1;
end

% Create y vector
y = linspace(0,92,46);

%Define a matrix of Cp values at each point in the wake for each AoA
%By using the formula, Cpi = (Pi-PE)/[k*(PA-PE)
i = 1;
while i <= 46
Cp_n04(1,i) = (pmean_n04(i)-pmean_n04(48))/(1.1*(pmean_n04(47)-pmean_n04(48)));
Cp_00(1,i) = (pmean_00(i)-pmean_00(48))/(1.1*(pmean_00(47)-pmean_00(48)));
Cp_04(1,i) = (pmean_04(i)-pmean_04(48))/(1.1*(pmean_04(47)-pmean_04(48)));
Cp_08(1,i) = (pmean_08(i)-pmean_08(48))/(1.1*(pmean_08(47)-pmean_08(48)));
Cp_12(1,i) = (pmean_12(i)-pmean_12(48))/(1.1*(pmean_12(47)-pmean_12(48)));

i = i+1;
end

% Use the formula v = (sqrt(2*q)/1.22) to calculate the average velocity at
% each data point for each angle of attack
i = 1;
```

```
while i <= 46
v_n04(1,i) = sqrt((pmean_n04(i)*2)/1.22);
v_00(1,i) = sqrt((pmean_00(i)*2)/1.22);
v_04(1,i) = sqrt((pmean_04(i)*2)/1.22);
v_08(1,i) = sqrt((pmean_08(i)*2)/1.22);
v_12(1,i) = sqrt((pmean_12(i)*2)/1.22);

i = i+1;
end



%Define velocity of the wind tunnel, change in y, and chord length
V = 21.184;
dy = 0.002;
c = 0.101;

% Takes the velocity reading that were just made and plugs them into the
% equation to get CD for the wake for each data point at each angle of
% attack
i = 1;
while i <= 46
   CD_n04(1,i) = (2/c)*(v_n04(i)/V)*(1-(v_n04(i)/V))*dy;
   CD_00(1,i) = (2/c)*(v_00(i)/V)*(1-(v_00(i)/V))*dy;
   CD_04(1,i) = (2/c)*(v_04(i)/V)*(1-(v_04(i)/V))*dy;
   CD_08(1,i) = (2/c)*(v_08(i)/V)*(1-(v_08(i)/V))*dy;
   CD_12(1,i) = (2/c)*(v_12(i)/V)*(1-(v_12(i)/V))*dy;
   i = i +1;
end

% Sums the previous loop to get a CD for each angle of attack
CD_n4 = sum(CD_n04);
CD_0 = sum(CD_00);
CD_4 = sum(CD_04);
CD_8 = sum(CD_08);
CD_12 = sum(CD_12);

% Creates the vectors for angle of attack and coefficient of drag to be
% plotted against each other
```

```
AOA = [-4 0 4 8 12];
CD = [CD_n4 CD_0 CD_4 CD_8 CD_12];

% Plots the velocity of the flow vs the voltage with a polynomial line of
% best fit
figure(1)
hold on
plot(v_vel,volts)
plot(v,volts)
title('velocity vs volts')
xlabel('velocity')
ylabel('volts')

% Plots the coefficient of pressure across the wake at -4 angle of attack
figure(2)
hold on
plot(Cp_n04,y)
title('Cp vs Y at -4 AOA')
xlabel('Cp')
ylabel('Y')

% Plots the coefficient of pressure across the wake at 0 angle of attack
figure(3)
hold on
plot(Cp_00,y)
title('Cp vs Y at 0 AOA')
xlabel('Cp')
ylabel('Y')

% Plots the coefficient of pressure across the wake at 4 angle of attack
figure(4)
hold on
plot(Cp_04,y)
title('Cp vs Y at 4 AOA')
xlabel('Cp')
ylabel('Y')

% Plots the coefficient of pressure across the wake at 8 angle of attack
```

```
figure(5)
hold on
plot(Cp_08,y)
title('Cp vs Y at 8 AOA')
xlabel('Cp')
ylabel('Y')

% Plots the coefficient of pressure across the wake at 12 angle of attack
figure(6)
hold on
plot(Cp_12,y)
title('Cp vs Y at 12 AOA')
xlabel('Cp')
ylabel('Y')

% Plots the coefficient of drag for each angle of attack
figure(7)
hold on
plot(AOA,CD)
title('CD vs AOA')
xlabel('Angle of attack')
ylabel('CD')
```