IOWA STATE UNIVERSITY

AIRFOIL WAKE MEASUREMENTS AND CALIBRATION OF A HOT WIRE ANEMOMETER LABORATORY

AER E 344 - LAB 06 - AIRFOIL WAKE MEASUREMENTS AND CALIBRATION OF A HOT WIRE ANEMOMETER

SECTION 3 GROUP 3

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Abstract

Using the low-speed wind tunnel at Iowa State University, we analyzed the wake distribution of an airfoil using a pressure rake connected to pressure transducers. We collected pressure data from the pressure rake for different angles of attack to create a profile of the airfoil wake region and estimate the coefficient of drag. Our data showed the presence of significant turbulence and vortices at angles of attack greater than 12°. Additionally, to facilitate more precise velocity measurements in future labs, we calculated the fourth order calibration curve of a hot wire anemometer to relate the measured voltage to airspeed.

Contents

List of Figures

List of Tables

Glossary

C Chord length. *(p. 6)*

C_P Dimensionless coefficient of pressure. *(p. iv, 10, 11, 13–17, 20, 21)*

C_d Dimensionless coefficient of drag. *(p. iii, iv, 7, 8, 10, 11, 17, 21)*

K Wind tunnel calibration constant. *(p. 5)*

P_A Static pressure at the inlet of the contraction section. *(p. 5)*

P_E Static pressure at the entrance of the test section. *(p. 5)*

V Voltage. *(p. 7)*

d Distance between pressure taps in the pressure rake. *(p. 6)*

q_∞ Free stream dynamic pressure. *(p. 5)*

v Velocity or air speed. *(p. 7)*

y The vertical position downstream of the airfoil. *(p. 6)*

Acronyms

AoA angle of attack. *(p. iii, 4, 7, 8, 10, 11, 13–17)*

MATLAB MATrix LABoratory. *(p. 10)*

1

Introduction

The Scanivalve DSA 3217, a 16-channel digital pressure transducer, calculates the differences in pressure between the input ports and the calibrated reference pressure. In this experiment, the ports of the pressure transducer are connected to pressure taps on a pressure rake located downstream of an airfoil in the test section of a wind tunnel (see Figure 2.1). Also in this experiment, a hot-wire anemometer is placed in a small wind tunnel for calibration using a pitot-tube connected to a Mensor manometer.

Using pressure measurements from the Scanivalve pressure transducers in conjunction with the data acquisition software, we will measure the pressure due to an airfoil's wake on a pressure rake (see Section B.1). After post-processing using the script in Section C.1, a view of the wake region will be shown (see Chapter 3). The drag coefficients will also be determined from this data and compared to the calculations done for Lab 5 in Chapter 4.

2

Methodology

2.1 Apparatus

2.1.1 Airfoil Wake Measurements

An airfoil is positioned in the wind tunnel test chamber as seen in Figure 2.1. Downstream of the airfoil is a pressure rake consisting of 46 pressure taps, each spaced 2 mm apart. The pressure taps are connected to Scanivalve pressure transducers. A computer with data acquisition software collects measurements from the pressure transducers and stores the data in `.csv` files.

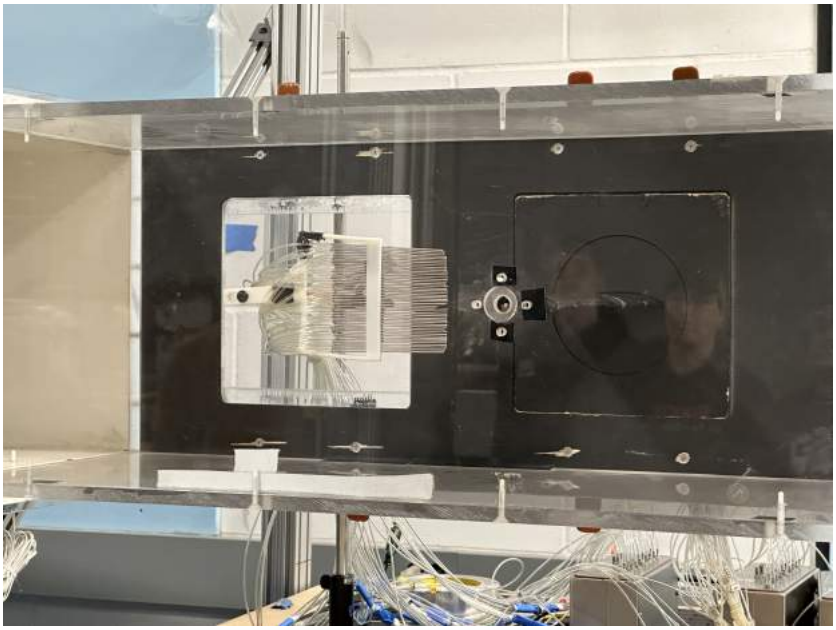

Figure 2.1: *Photograph of the airfoil and the pressure rake in the test section of the wind tunnel.*

2.1.2 Hot Wire Anemometer Calibration

A hot wire anemometer and pitot tube are positioned in the test chamber of a small wind tunnel as seen in Figure 2.2 and Figure 2.3. The pitot tube is connected to a Mensor

manometer. Both the anemometer and Mensor manometer are connected to a computer with data acquisition software to collect measurements and store the data in `.txt` files.

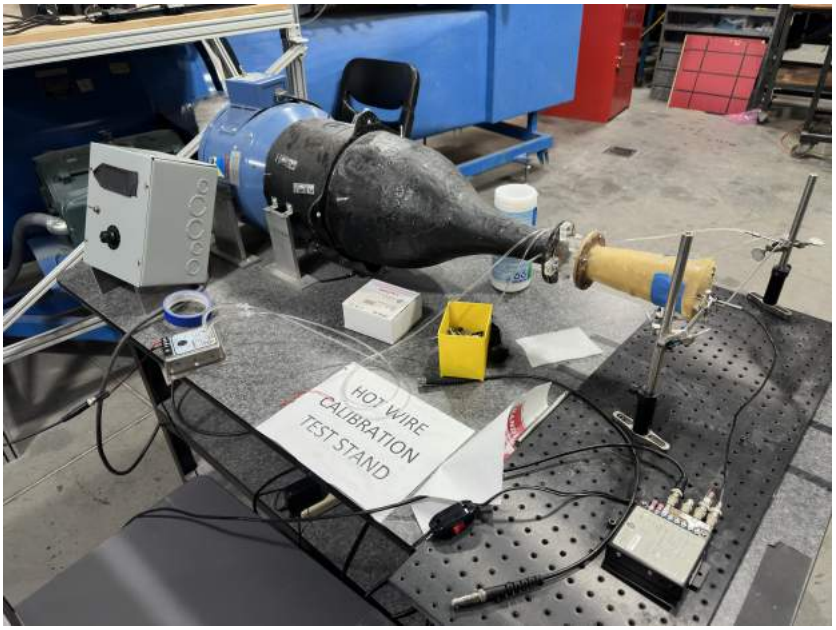

Figure 2.2: *Photograph of the open-loop hot wire calibration wind tunnel.*

2.2 Procedure

2.2.1 Airfoil Wake Measurements

1. Calibrate the instruments with the wind tunnel set to 0 Hz.
2. Set the wind tunnel velocity at 15 Hz. Wait for velocity to become relatively uniform.
3. Set the AoA to 0°.
4. Move the rake to cover the entire wake of the airfoil as necessary.
5. Acquire and save the data to a data file.
6. Repeat steps 3-4 using the following AoAs: 4, 6, 8, 10, 12, 14 and 16.
7. Save the data to a flash drive for past-lab analysis.

2.2.2 Hot Wire Anemometer Calibration

1. Set the hot wire calibration tunnel to 20 % power.
2. Record the voltage data acquired by the data acquisition software and the pressure data from the Mensor digital pressure gauge.
3. Repeat steps 1-2 for 20 % to 60 % power in increments of 4 %.
4. Save the data to a flash drive for post-lab analysis.

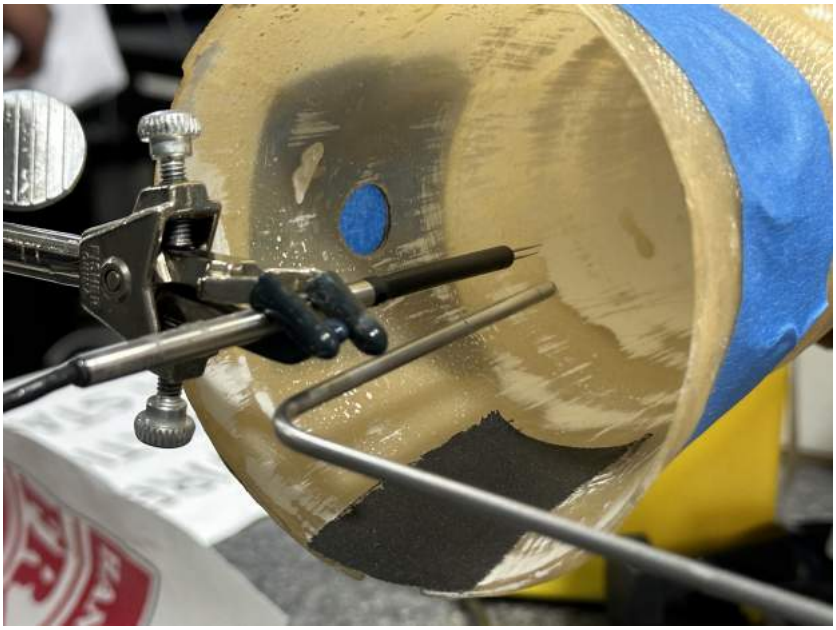

Figure 2.3: *A close-up photograph of the hot wire anemometer and pitot tube in the hot wire calibration wind tunnel.*

2.3 Derivations

The coefficient of pressure is found by normalizing the dynamic pressure measured by the pressure taps with the free-stream dynamic pressure. The difference between the inlet and outlet pressure of the contraction section, P_A and P_E, respectively, along with the wind tunnel calibration constant, K, determines the free-stream dynamic pressure denoted by q_∞.

$$q_\infty = K(P_A - P_E) \tag{2.1}$$

The dynamic pressure at a singular tap from the pressure rake, generically described as the ith tap, is found by subtracting the total pressure measured by the tap with the free-stream static pressure.

$$q_i = P_i - P_E \tag{2.2}$$

Therefore, the coefficient of pressure can be found by dividing Equation 2.2 by Equation 2.1:

$$C_P = \frac{q_i}{q_\infty} = \frac{P_i - P_E}{K(P_A - P_E)} \tag{2.3}$$

To begin calculations on the coefficient of drag, the flow velocity at each pressure tap is found by rearranging the generic dynamic pressure equation, $q = \frac{1}{2}\rho V^2$.

$$U_i = \sqrt{\frac{2q_i}{\rho}} = \sqrt{\frac{2(P_i - P_E)}{\rho}} \tag{2.4}$$

The free-stream flow velocity is found similarly:

$$U_\infty = \sqrt{\frac{2q_\infty}{\rho}} = \sqrt{\frac{2K(P_A - P_E)}{\rho}} \tag{2.5}$$

The coefficient of drag is found by using the fluid momentum change as drag resulting in Equation 2.6, where C is the chord of the airfoil and y is the area downstream of the airfoil (Hu, 2024).

$$C_D = \frac{2}{C} \int \left[\frac{U_y}{U_\infty} \left(1 - \frac{U_y}{U_\infty} \right) \right] dy \tag{2.6}$$

The coefficient of drag can be approximated with the data collected from the pressure rake using a Midpoint Riemann Sum of the pressure taps, where C is the chord and d is the distance between each pressure tap.

$$C_D = \frac{2}{C} \sum_{i=1}^{45} d \frac{\left[\frac{U_i}{U_\infty} \left(1 - \frac{U_i}{U_\infty} \right) \right] + \left[\frac{U_{i+1}}{U_\infty} \left(1 - \frac{U_{i+1}}{U_\infty} \right) \right]}{2} \tag{2.7}$$

3

Results

Figure 3.1 shows pressure distributions at various AoA. Section A.1 has graphs for each of the pressure coefficient distributions.

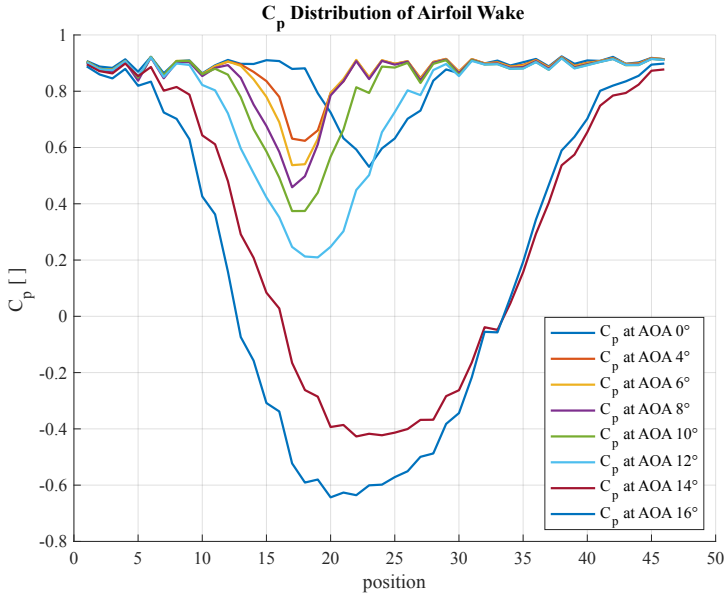

Figure 3.1: *Plot of the pressure coefficient distributions overlaid.*

Figure 3.2 shows the estimated Coefficient of Drag, C_d, over the 0° to 16° AoA we measured with the pressure rake. Figure 3.3 shows the hot wire calibration curve we calculated based on our calibration data. The fourth order polynomial we calculated is shown in Equation 3.1

$$v = -4982.7570V^4 + 24021.8937V^3 + -43230.9413V^2 + 34446.6867V + -10248.1714 \quad (3.1)$$

where v is the air speed and V is the voltage of the hot wire anemometer.

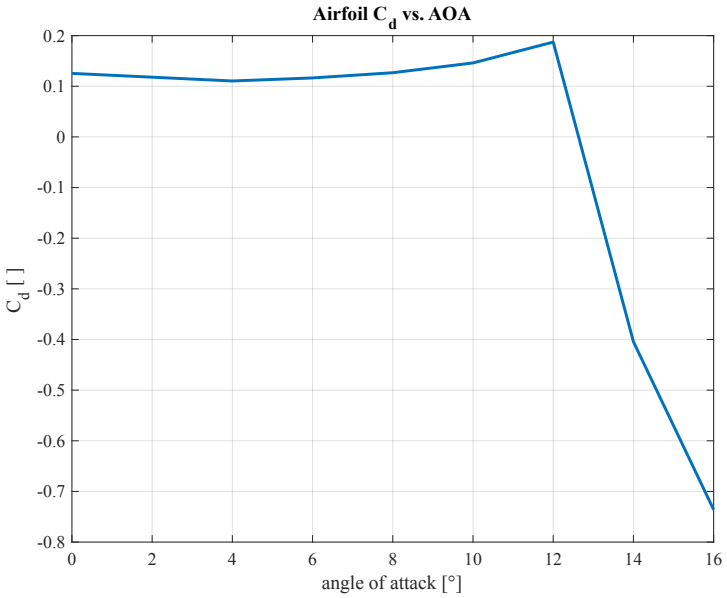

Figure 3.2: *Plot of the C_d in relationship to the AoA.*

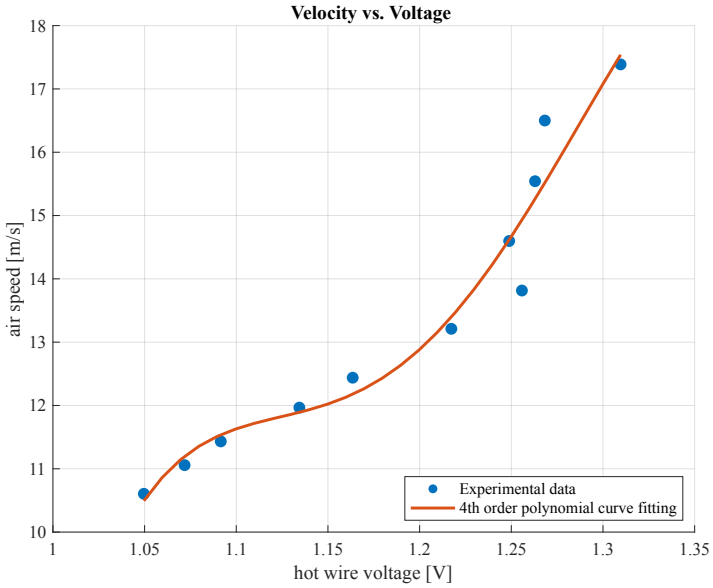

Figure 3.3: *Plot of the air speed vs. the voltage reading from the hot wire anemometer.*

Using Equation 3.2 and the subsequent parameters, we find the Reynolds number of about 1.1×10^5 for the airfoil wake measurements.

$$Re = \frac{\rho V L}{\mu} \tag{3.2}$$

$\rho = 1.225\,\mathrm{kg/m^3}$
$\mu = 18.18 \times 10^{-6}\,\mathrm{Pa\,s}$
$L = 0.101\,\mathrm{m}$
$V = 16.1\,\mathrm{m/s}$
$Re = 1.095\,69 \times 10^5$

4

Discussion

All of the C_P distribution graphs are shown in Section A.1 but Figure 3.1 is more demonstrative. From Figure 3.1, we note that as the angle of attack increases, the wake region becomes wider and more turbulent. Once the AoA reaches 14°, the C_P in the wake becomes negative—denoting the presence of vortices and turbulence that are causing the flow to reverse direction. This aligns with the visual demonstrations we observed in the smoke tunnel during the first lab where significant vortices formed in the wake region of the airfoil as the angle of attack increased.

Using our MATrix LABoratory (MATLAB) script (see Section C.1) and the equations derived in Section 2.3, we calculated and plotted the coefficient of drag, C_d, against the angle of attack as shown in Figure 3.2. For AoA 0° to 12°, the C_d plot generally matches what we would expect from a coefficient of drag graph. For 14° and 16°, however, the C_d turns negative. Although unorthodox, this reaffirms the observations made in the 14° and 16° C_P plots: at very high angles of attack, turbulent vortices are causing the flow in the wake to move in the opposite direction of the free stream flow. If only the magnitude of the drag coefficient is considered (see Figure A.9), the shape of the C_d graph matches what we would expect from an airfoil undergoing low-speed flow.

Although the magnitudes of the drag coefficients in our data vary slightly from the magnitudes of the drag coefficients in lab five, the shape is almost identical—especially when compared to Figure A.9. In both lab five and this lab, the lowest magnitude of the coefficient of drag occurs at 4° to 6° with a clearly defined stall occurring just after 12°.

The fourth order polynomial, Equation 3.1, we calculated for the hot wire calibration curve (see Figure 3.3) using the script in Section C.2 seems to fit well visually. The coefficient of determination was calculated to be 0.95 which shows high correlation. With the data we collected, a third order polynomial may also have fit well, but if we had additional data points between 16.5 m/s and 17.5 m/s, a third order polynomial may have been inadequate.

5

Conclusion

Using the Scanivalve DSA 3217 pressure transducers, we measured pressure from 46 taps on the pressure rake downstream of an airfoil in the wind tunnel for a range of angle of attacks at a constant fluid velocity. The C_P graphs show as angle of attack increases, the wake region increases, resulting in decreasing values of C_P as you move towards the central taps of the pressure rake. The wake region is much larger at AoA larger than the stall angle of 12° as seen in Figure 3.1 due to flow separation and turbulence. The C_d graph is similar to that of lab five as it shows the stall angle and has around the same AoA for the minimum C_d at angles of attack less than the stall angle. However, the magnitude of C_d differs and the behavior of C_d differs at AoA greater than the stall angle.

Bibliography

Hu, Hui (2024). *Airfoil Wake Measurements and Calibration of a Hot Wire Anemometer*. Iowa State University. URL: https://www.aere.iastate.edu/~huhui/teaching/2024-01S/AerE344/lab-instruction/AerE344L-Lab-06-instruction_Wake-Hotwire-caliboration-2024.pdf.

A

Appendix A

A.1 Additional Figures

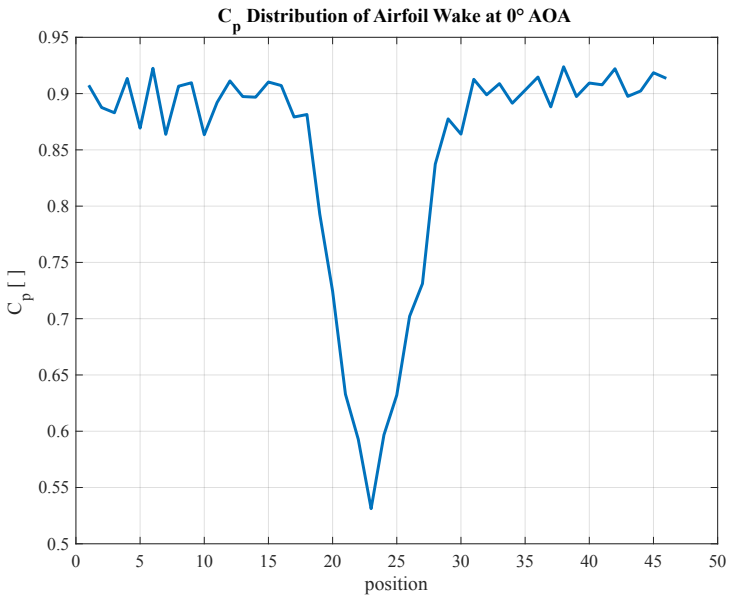

Figure A.1: *Plot of C_P distribution vs the Airfoils wake at an AoA of* 0°

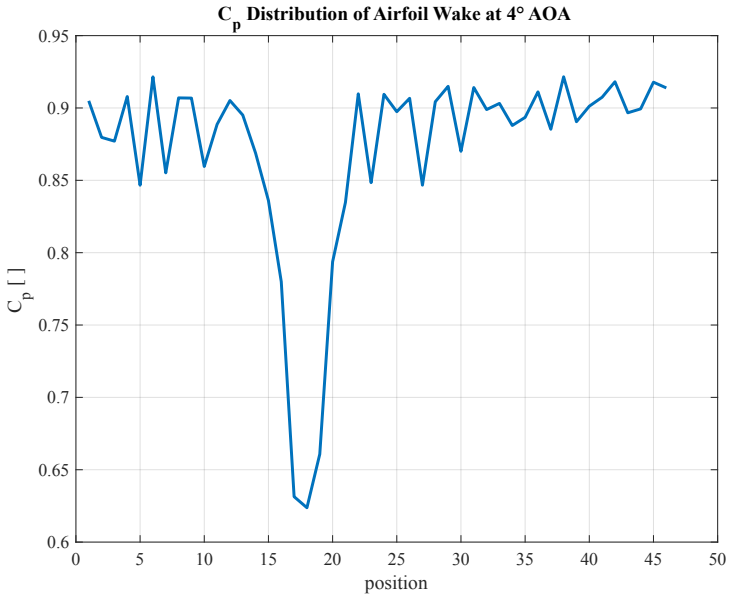

Figure A.2: *Plot of C_P distribution vs the Airfoils wake at an AoA of* 4°

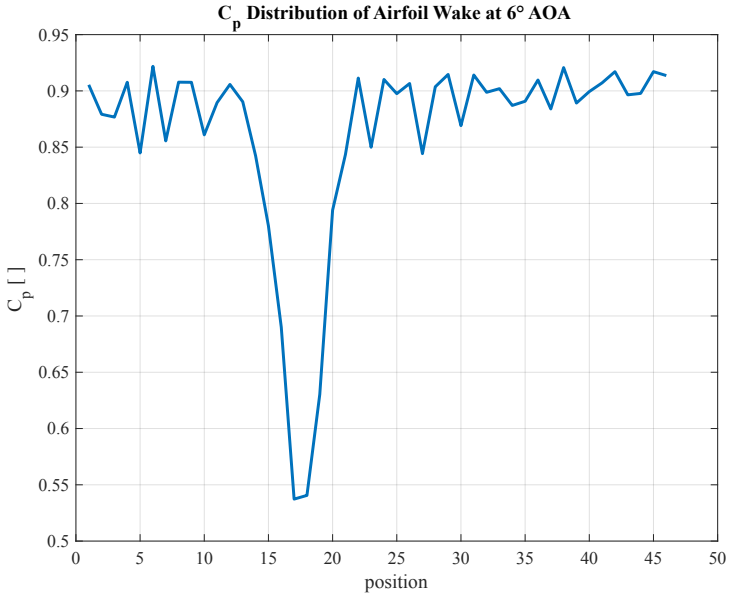

Figure A.3: *Plot of C_P distribution vs the Airfoils wake at an AoA of* 6°

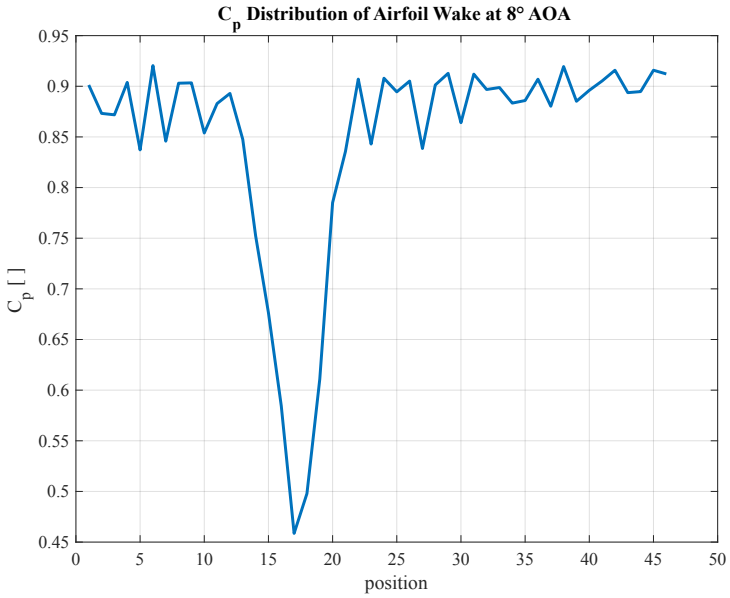

Figure A.4: *Plot of C_P distribution vs the Airfoils wake at an AoA of* 8°

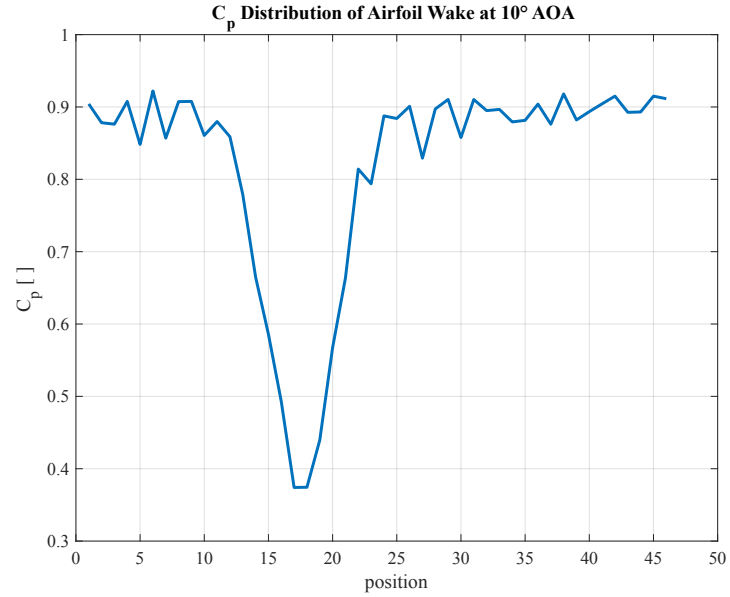

Figure A.5: *Plot of C_P distribution vs the Airfoils wake at an AoA of* 10°

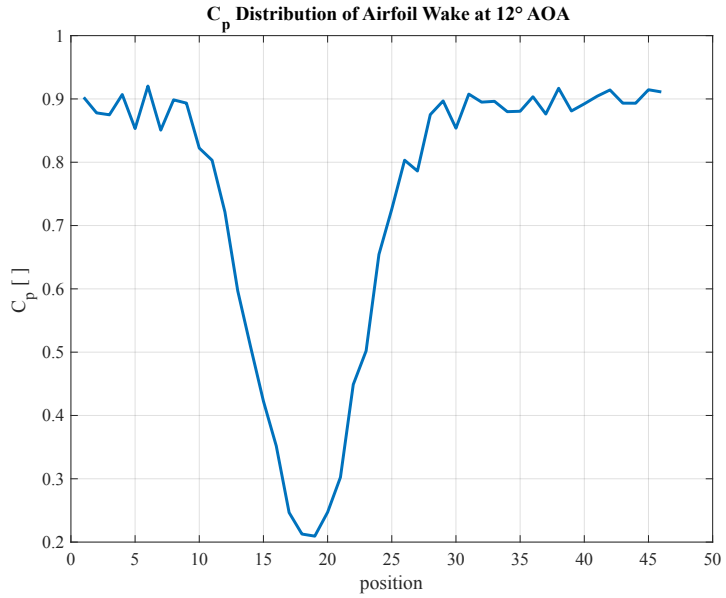

Figure A.6: *Plot of C_P distribution vs the Airfoils wake at an AoA of* 12°

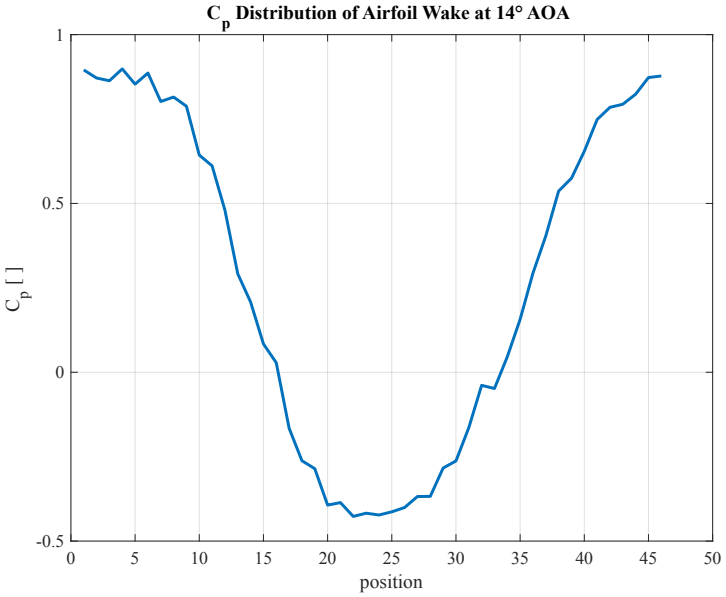

Figure A.7: *Plot of C_P distribution vs the Airfoils wake at an AoA of* 14°

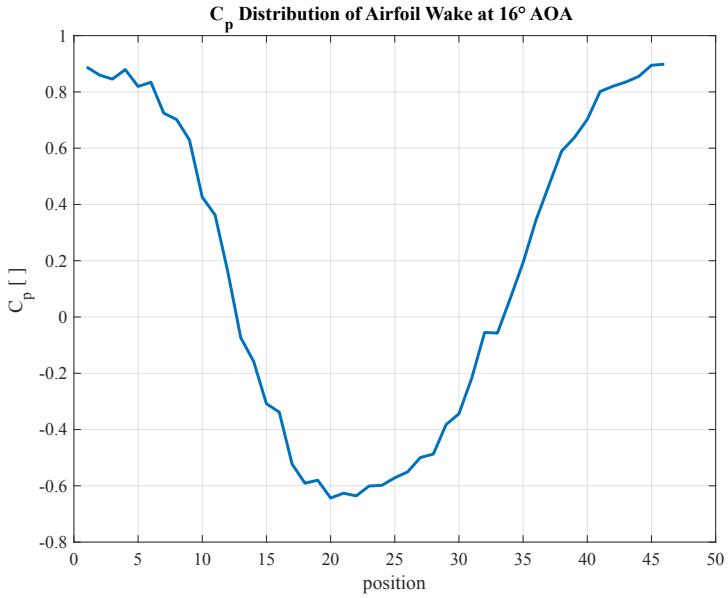

Figure A.8: *Plot of C_P distribution vs the Airfoils wake at an AoA of* 16°

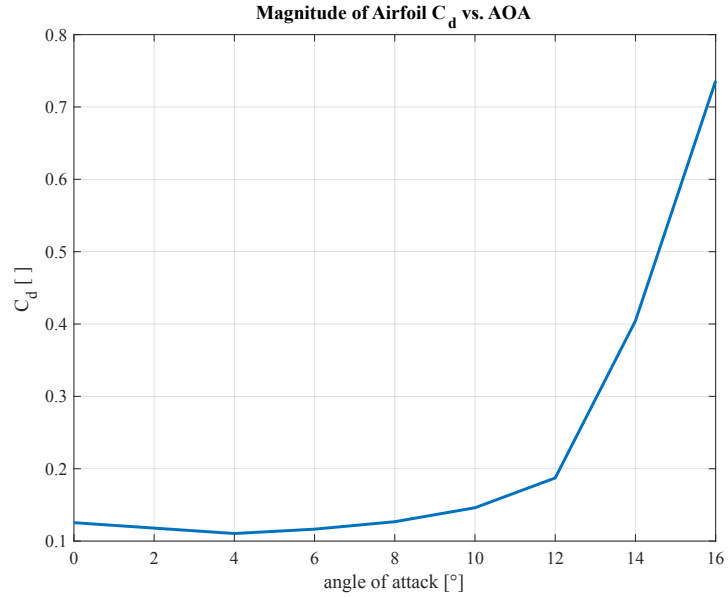

Figure A.9: *Plot of the magnitude of the airfoil's C_d vs. the airfoil's AoA.*

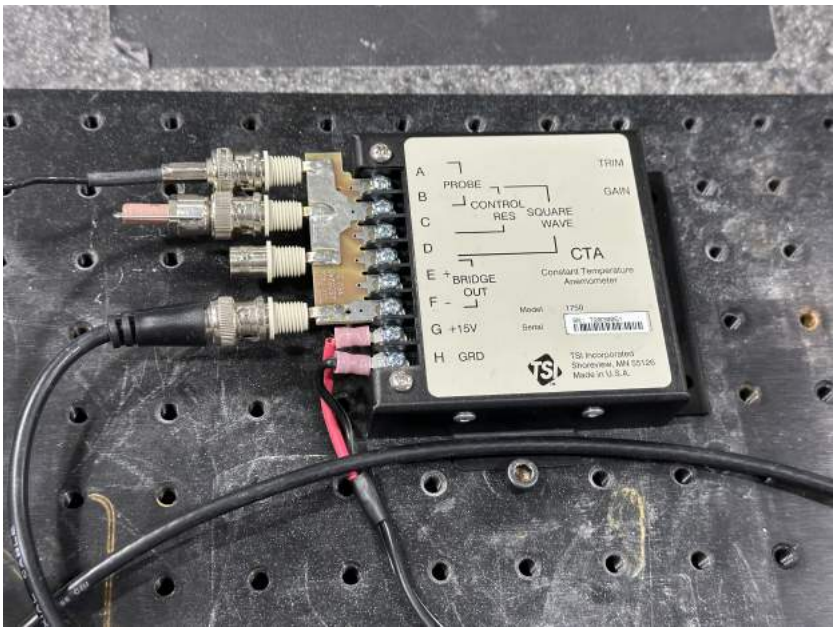

Figure A.10: *Image of the Hot Wire data collection computer.*

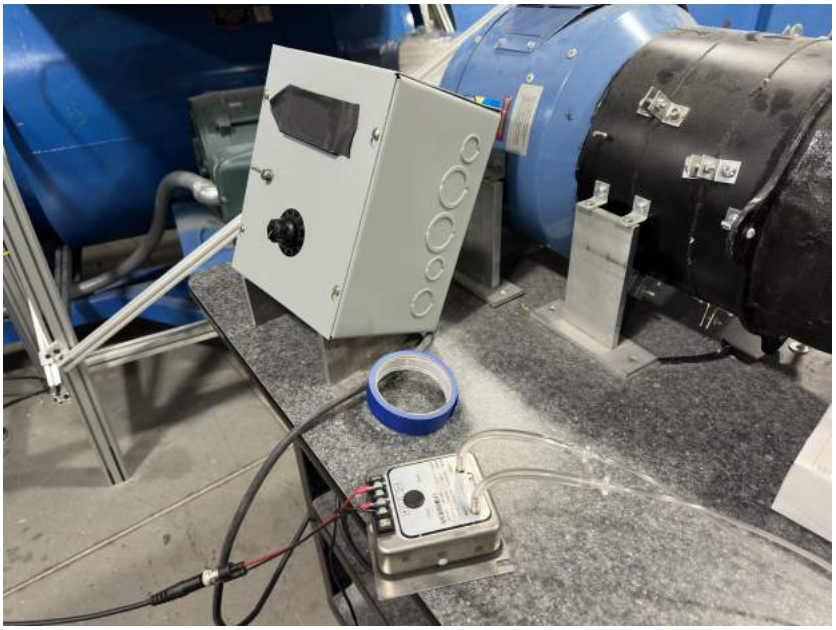

Figure A.11: *Open loop wind tunnel speed controller and the Mensor manometer*

Figure A.12: *Image of the Hot Wire Anemometer inside of open Circuit wind tunnel.*

B

Appendix B

B.1 Data

Table B.1: *Coefficient of Pressure, C_P, at taps 1-23 on the pressure rake at different angles of attack.*

Tap	0°	4°	6°	8°	10°	12°	14°	16°
1	0.907	0.905	0.905	0.901	0.904	0.902	0.895	0.888
2	0.888	0.880	0.879	0.873	0.878	0.878	0.871	0.860
3	0.883	0.877	0.877	0.872	0.876	0.875	0.863	0.846
4	0.913	0.908	0.908	0.904	0.908	0.907	0.898	0.879
5	0.869	0.847	0.845	0.837	0.848	0.853	0.853	0.819
6	0.922	0.921	0.922	0.920	0.922	0.920	0.886	0.834
7	0.864	0.855	0.856	0.846	0.857	0.851	0.802	0.724
8	0.907	0.907	0.908	0.903	0.907	0.899	0.815	0.702
9	0.910	0.907	0.908	0.903	0.908	0.893	0.788	0.629
10	0.863	0.860	0.861	0.854	0.861	0.822	0.643	0.426
11	0.892	0.889	0.890	0.883	0.880	0.803	0.611	0.362
12	0.911	0.905	0.906	0.893	0.859	0.721	0.480	0.159
13	0.897	0.895	0.890	0.848	0.779	0.597	0.292	−0.074
14	0.897	0.869	0.842	0.753	0.665	0.508	0.208	−0.158
15	0.910	0.836	0.780	0.676	0.586	0.423	0.084	−0.308
16	0.907	0.780	0.690	0.584	0.493	0.352	0.028	−0.338
17	0.879	0.631	0.537	0.459	0.374	0.247	−0.166	−0.523
18	0.881	0.624	0.541	0.498	0.374	0.213	−0.262	−0.591
19	0.793	0.661	0.630	0.611	0.440	0.209	−0.285	−0.580
20	0.724	0.794	0.794	0.785	0.567	0.247	−0.393	−0.643
21	0.633	0.835	0.844	0.836	0.664	0.302	−0.386	−0.626
22	0.593	0.910	0.911	0.907	0.814	0.449	−0.427	−0.636
23	0.531	0.848	0.850	0.843	0.794	0.502	−0.417	−0.601

Table B.2: *Coefficient of Pressure, C_P, at taps 24-46 on the pressure rake at different angles of attack.*

Tap	0°	4°	6°	8°	10°	12°	14°	16°
24	0.597	0.909	0.910	0.908	0.888	0.654	−0.423	−0.598
25	0.632	0.897	0.898	0.894	0.884	0.726	−0.413	−0.571
26	0.702	0.907	0.907	0.905	0.901	0.803	−0.401	−0.551
27	0.731	0.847	0.844	0.839	0.829	0.786	−0.368	−0.499
28	0.837	0.904	0.904	0.901	0.897	0.875	−0.368	−0.487
29	0.878	0.915	0.915	0.913	0.910	0.897	−0.284	−0.382
30	0.864	0.870	0.869	0.864	0.858	0.854	−0.263	−0.344
31	0.913	0.914	0.914	0.912	0.910	0.908	−0.164	−0.217
32	0.899	0.899	0.899	0.897	0.895	0.895	−0.039	−0.055
33	0.909	0.903	0.902	0.899	0.897	0.896	−0.048	−0.057
34	0.891	0.888	0.887	0.883	0.879	0.880	0.046	0.066
35	0.903	0.894	0.891	0.886	0.882	0.881	0.157	0.194
36	0.915	0.911	0.910	0.907	0.904	0.903	0.294	0.344
37	0.888	0.885	0.884	0.880	0.876	0.876	0.404	0.467
38	0.924	0.922	0.921	0.919	0.918	0.917	0.537	0.589
39	0.897	0.890	0.889	0.885	0.882	0.881	0.575	0.638
40	0.909	0.901	0.899	0.896	0.894	0.892	0.654	0.702
41	0.908	0.907	0.907	0.905	0.904	0.904	0.749	0.801
42	0.922	0.918	0.917	0.916	0.915	0.914	0.785	0.820
43	0.898	0.897	0.896	0.894	0.893	0.893	0.794	0.835
44	0.902	0.899	0.898	0.895	0.893	0.893	0.824	0.855
45	0.919	0.918	0.917	0.916	0.915	0.915	0.873	0.895
46	0.914	0.914	0.914	0.912	0.911	0.911	0.878	0.898

Table B.3: *C_d at different airfoil angles of attack.*

	0°	4°	6°	8°	10°	12°	14°	16°
C_d	0.125	0.110	0.116	0.127	0.146	0.187	0.309	0.297

Table B.4: *Manometer pressure, anemometer voltage, and flow velocity values at different percents of wind tunnel motor maximum frequency.*

Percent of Max Freq.	Pressure [in H_2O]	Voltage [V]	Velocity [m/s]
20%	3.005	1.050	10.605
24%	3.028	1.072	11.057
28%	3.048	1.092	11.432
32%	3.078	1.134	11.966
36%	3.106	1.163	12.438
40%	3.154	1.217	13.211
44%	3.193	1.256	13.815
48%	3.246	1.249	14.598
52%	3.315	1.263	15.542
56%	3.388	1.268	16.501
60%	3.461	1.310	17.388

C

Appendix C

C.1 Lab6Analysis.m

```
clear; clc; close all;

%% Knowns
figure_dir = "../Figures/";
data_dir = "./Data/";
% Viscosity calculated at 21.2°C
% https://www.engineeringtoolbox.com/air-absolute-kinematic-viscosity-d_601
% .html
mu_air = 18.18e-6; % [Pa*s]
rho_air = 1.225; % [kg/m^3]
V_inf = 19.4; % [m/s] V
K = 1.1; % Calibration Constant
chord = 0.101; % [m] Chord of airfoil
d_taps = 0.002; % [m] Cistance between taps

%% Part 1 Airfoil Wake
aoa = [0 4 6 8 10 12 14 16];
n_aoa = length(aoa);
wake_files = dir(data_dir + '*deg.csv');
% Columns containing pressure values from raw data
range = cat(2,(2:17),(35: 50),(68: 81));
n_taps = length(range); % number of taps
position = (1:n_taps); % position of taps
PA_idx = 82;
PE_idx = 83;
C_p = zeros(n_aoa, n_taps); % Initialize matrix for pressure data
U_p = zeros(n_aoa, n_taps); % Initialize matrix for velocity data
C_D = zeros(1,n_aoa);
U_inf = zeros(1,n_aoa);
for a = 1:n_aoa % Iterate through files
    % Read file & find average of columns
    temp = mean(readmatrix(data_dir+wake_files(a).name));
    count = 1;
    PA = temp(PA_idx);
```

```
    PE = temp(PE_idx);
    q = K *(PA - PE); % Dynamic Pressure
    U_inf(a) = sqrt(2 * q / rho_air ); % Freestream velocity
    for i = 1 : width(temp) % Iterate through data
        if ismember(i,range) % Take columns with pressure data
            % Velocity at each tap
            U_p(a,count) = sqrt(abs((temp(i) - PE)) * 2 / rho_air);
            if temp(i) - PE < 0
                U_p(a, count) = -U_p(a, count);
            end
            C_p(a, count) = (temp(i)-PE) / q ; % Cp at each tap
            count = count + 1;
        end
    end
    % C_P Graphs
    figure;
    plot(position, C_p(a,:), "LineWidth", 2);
    fontname("Times New Roman");
    fontsize(12, "points");
    title_str = "C_p Distribution of Airfoil Wake at " + aoa(a) +"° AOA";
    title(title_str);
    xlabel("position");
    ylabel("C_p [ ]");
    grid on;
    saveas(gcf, figure_dir + title_str + ".svg");

% midpoint rule for approx integral
    for i = 1:n_taps-1
        f1 = U_p(a, i)/U_inf(a) * (1 - U_p(a, i)/U_inf(a));
        f2 = U_p(a, i+1)/U_inf(a) * (1 - U_p(a, i+1)/U_inf(a));
        C_D(a) = C_D(a) + d_taps*((f1 + f2)/2);
    end
    C_D(a) = C_D(a) * 2 / chord;
end

figure;
hold on;
for a = 1:n_aoa % Iterate through files
    plot(position, C_p(a,:), "LineWidth", 1.5);
end
hold off;
fontname("Times New Roman");
fontsize(12, "points");
title_str = "C_p Distribution of Airfoil Wake";
title(title_str);
xlabel("position");
ylabel("C_p [ ]");
legend("C_p at AOA " + aoa + "°", "Location", "southeast");
grid on;
saveas(gcf, figure_dir + title_str + ".svg");

```

```
% C_D Graph
figure;
plot(aoa, C_D, "LineWidth", 2);
fontname("Times New Roman");
fontsize(12, "points");
title_str = "Airfoil C_d vs. AOA";
title(title_str);
xlabel("angle of attack [°]");
ylabel("C_d [ ]");
grid on;
saveas(gcf, figure_dir + title_str + ".svg");

figure;
plot(aoa, abs(C_D), "LineWidth", 2);
fontname("Times New Roman");
fontsize(12, "points");
title_str = "Magnitude of Airfoil C_d vs. AOA";
title(title_str);
xlabel("angle of attack [°]");
ylabel("C_d [ ]");
grid on;
saveas(gcf, figure_dir + title_str + ".svg");
```

C.2 Lab6HotWire.m

```
% AER E 344 Spring 2024 Lab 06 Part 2 Analysis
% Section 3 Group 3

clear, clc, close all;
figure_dir = "../Figures/";
% Initialize arrays
pitotTube_inH2O = [];
hotWireV = [];

% Loop through files
for fileIndex = 20:4:60
    % Generate filename
    filename = sprintf('Data/%d.txt', fileIndex);

    % Read the file
    data = readtable(filename, 'HeaderLines', 5, 'Delimiter', '\t', 'Format',
    ↪  '%s%f%f', 'ReadVariableNames', false);

    % Extract columns 3 and 4 from the data table
    column3 = data.Var2;
    column4 = data.Var3;

    % Calculate mean values and append to arrays
```

```
    meanColumn3 = mean(column3);
    meanColumn4 = mean(column4);
    pitotTube_inH2O = [pitotTube_inH2O, meanColumn4];
    hotWireV = [hotWireV, meanColumn3];


end

% Display pitotTube_inH2O and hotWireV arrays
disp('Mean Values for Pitot Tube Pressure [inH2O]:');
disp(pitotTube_inH2O);
disp('Mean Values for Hot Wire Voltage [V]:');
disp(hotWireV);

% Variables
rho_air = 1.195; % [kg / m^3]

%Estimating the pitot tube V when the motor is off
motorFreqPercentage = 0.2:0.04:0.6; % % of max motor frequency
P1 = polyfit(motorFreqPercentage, pitotTube_inH2O, 1);
pitotTube_inH2Oat0 = P1(2); % pitot tube V when the motor is turned off

%Calculate v_pt
q_pt = (pitotTube_inH2O - pitotTube_inH2Oat0) .* 248.84; % [Pa]
v_pt = sqrt(2 .* q_pt ./ rho_air); % [m/s]

%Display v_T array
disp('Flow velocity [m/s]:')
disp(v_pt)

%Calculate and display curve fitting
P3 = polyfit(hotWireV, v_pt, 4);
x = hotWireV(1):0.01:hotWireV(11);
curveFit = P3(1) * x.^4 + P3(2) * x.^3 + P3(3) * x.^2 + P3(4) * x + P3(5);
fprintf('4th order polynomial curve fitting formula: \n   %.4fx^4 + %.4fx^3 + %.4fx^2
↪  + %.4fx + %.4f \n\n', P3(1), P3(2), P3(3), P3(4), P3(5))

%Plot Hot Wire Voltage vs. Air speed
scatter(hotWireV, v_pt, 64, "filled");
hold on
plot(x, curveFit, "LineWidth", 2);
fontname("Times New Roman");
fontsize(12, "points");
title_str = "Velocity vs. Voltage";
title(title_str);
xlabel('hot wire voltage [V]')
ylabel('air speed [m/s]')
legend('Experimental data', '4th order polynomial curve fitting', 'Location',
↪  'SouthEast')
grid
saveas(gcf, figure_dir + title_str + ".svg");
```