IOWA STATE UNIVERSITY

QUANTIFICATIONS OF THE TURBULENCE CHARACTERISTICS IN THE WAKE OF AN AIRFOIL BY USING A HOTWIRE ANEMOMETER LABORATORY

AER E 344 - LAB 07 - QUANTIFICATIONS OF THE TURBULENCE CHARACTERISTICS IN THE WAKE OF AN AIRFOIL BY USING A HOTWIRE ANEMOMETER

SECTION 3 GROUP 3

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Abstract

Using the low-speed wind tunnel at Iowa State University, we measured the velocity profile downstream of an airfoil to analyze the turbulent wake region for different angle of attack (AoA). To measure the velocity profile in the wake region, we used a hot wire anemometer positioned downstream of the airfoil. Unfortunately, our results differ wildly from the mathematical and hypothetical predictions. We expect this is caused by a problem in the hot wire setup and configuration.

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Glossary

C_d	Dimensionless coefficient of drag. *(p. 12)*
U/U_e	Normalized air speed. *(p. 11)*
Y/δ	Normalized vertical position of the hot wire anemometer downstream of the airfoil. *(p. 11)*

Acronyms

AoA angle of attack. *(p. i, 3, 5, 8, 9, 11, 12, 18–22)*

FFT fast Fourier transform. *(p. 11)*

MATLAB MATrix LABoratory. *(p. 14)*

RMS root mean square. *(p. 5)*

1 Introduction

The hot-wire anemometer uses a thin wire that passes electric current through it to maintain a constant temperature. As flow passes over the wire, voltage loss is recorded, enabling the anemometer to determine the velocity of the flow. In this experiment, the anemometer is used to track the velocity of flow at various points in the flow behind an airfoil.

Using voltage measurements from the hot-wire anemometer, we will create a profile of the airfoil wake region. We will calculate the coefficient of drag, and compare this to the calculations done for Lab 5 and Lab 6. We will also estimate the boundary layer thickness for the airfoil wake region profiles, and compare these with theoretical values.

2 Methodology

2.1 Apparatus

An airfoil is positioned in the wind tunnel test chamber as seen in Figure 2.1. Downstream of the airfoil is a hot wire anemometer. The data was collected by the data acquisition tool shown in Figure 2.2 which reads the voltage data from the hot wire and saves it to a `.txt` file.

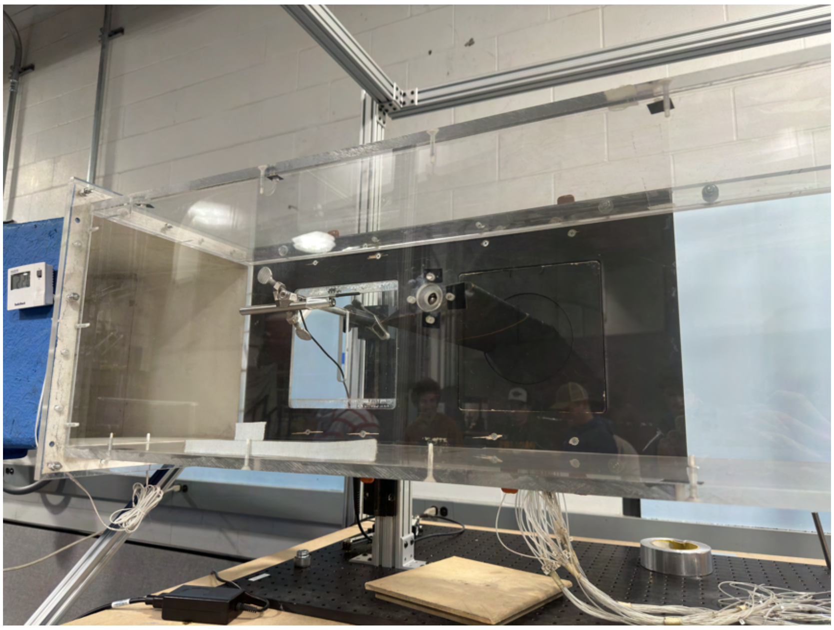

Figure 2.1: *The hot wire anemometer and the airfoil in the wind tunnel test chamber.*

When we collected the data at different heights, and we used the height adjustable knob to change the height as seen in Figure 2.3

2.2 Procedures

1. Set the wind tunnel motor speed to 15 Hz. Wait for the flow to stabilize.
2. Set the AoA to 4°.

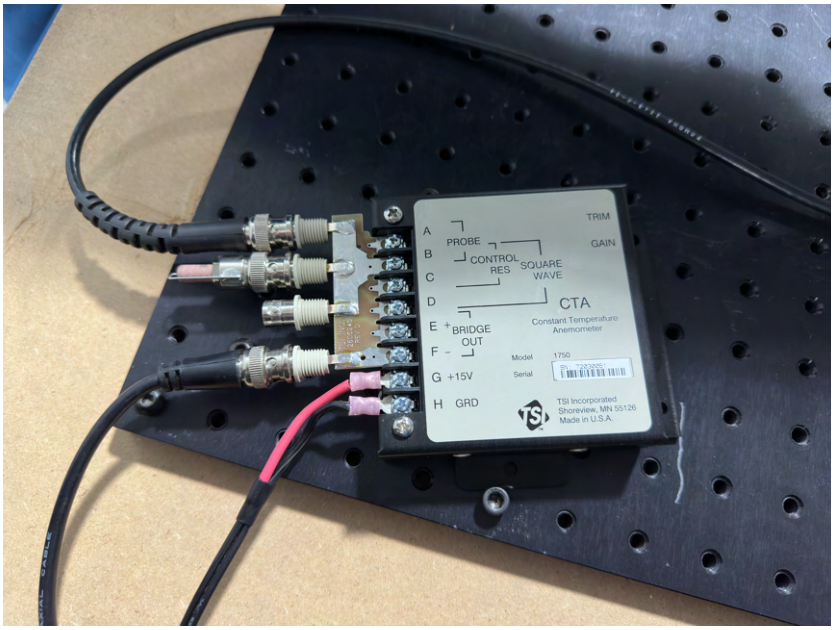

Figure 2.2: *The data acquisition box which is connected to the hot wire anemometer and the data acquisition computer.*

Figure 2.3: *The adjustable knob used to change the angle of attack of the airfoil.*

3. Vertically move the hot wire anemometer from 0 in. to 4 in. in 0.2 in. increments.
4. After each adjustment, acquire and save the data to a `.txt` data file.
5. Repeat Steps 3–4 using the following AoAs: 4, 8, 12 and 16.
6. Save the data to a flash drive for post-lab analysis.

2.3 Derivations

The turbulence intensity is found using the root mean square (RMS) of the velocity fluctuations over the mean velocity. (Hu, 2024) The mean velocity at each position around the airfoil is determined with the voltage data from the anemometer and the calibration polynomial from lab six in the form of Equation 2.1. The full calibration polynomial from lab six is Equation 2.2.

$$\overline{U} = C_0 + C_1\overline{v} + C_2\overline{v}^2 + C_3\overline{v}^3 + C_4\overline{v}^4 \tag{2.1}$$

$$\overline{U} = -10\,248.1714 + 34\,446.6867\overline{v} - 43\,230.9413\overline{v}^2 + 24\,021.8937\overline{v}^3 - 4982.7570\overline{v}^4 \tag{2.2}$$

The derivative of the calibration polynomial equation with respect to the mean voltage multiplied by the manometer voltage RMS will give the RMS of the velocity fluctuations at each position of the manometer around the airfoil (see Equation 2.3). Finally, the turbulence intensity is calculated in Equation 2.4.

$$u_{\text{rms}} = \left.\frac{\partial\overline{U}}{\partial v}\right|_{\overline{v}} = \left[C_1 + 2C_2\overline{v} + 3C_3\overline{v}^2 + 4C_4\overline{v}^3\right] v_{\text{rms}} \tag{2.3}$$

$$TI = u_{\text{rms}}/\overline{U} \tag{2.4}$$

The momentum thickness is related to the coefficient of drag through equation Equation 2.6. However, the momentum thickness must first be calculated through Equation 2.5. In this lab, the integral was determined using the midpoint Riemann sum starting behind the surface of the airfoil and ending at the lowest position of the anemometer. The distance between each anemometer measurement was 0.2in.

$$.\theta = \int_0^Y \frac{u}{U_e}\left(1 - \frac{u}{U_e}\right) dy \tag{2.5}$$

$$C_d = \frac{2\theta}{L} \tag{2.6}$$

The vortex shedding frequency graphs were created by taking the raw voltage data at two positions of each angle of attack, one inside the wake and one outside. A fast Fourier Transform of the raw data with a sampling frequency of 10 000 Hz is used to graph a single-sided amplitude spectrum and in the hopes of finding the vortex shedding frequency.

The following equations (Equation 2.7 and Equation 2.8) are theoretical estimations of the boundary layer thickness at a distance x over a flat plate.

$$\frac{\delta}{x} = \frac{5.0}{\sqrt{\mathrm{Re}_x}} \tag{2.7}$$

$$\frac{\delta}{x} = \frac{0.37}{\mathrm{Re}_x^{\frac{1}{5}}} \tag{2.8}$$

3 Results

Figure 3.1 shows the theoretical boundary layer thickness as a function of the distance from the leading edge of a hypothetical flat plate using Equation 2.7 and Equation 2.8.

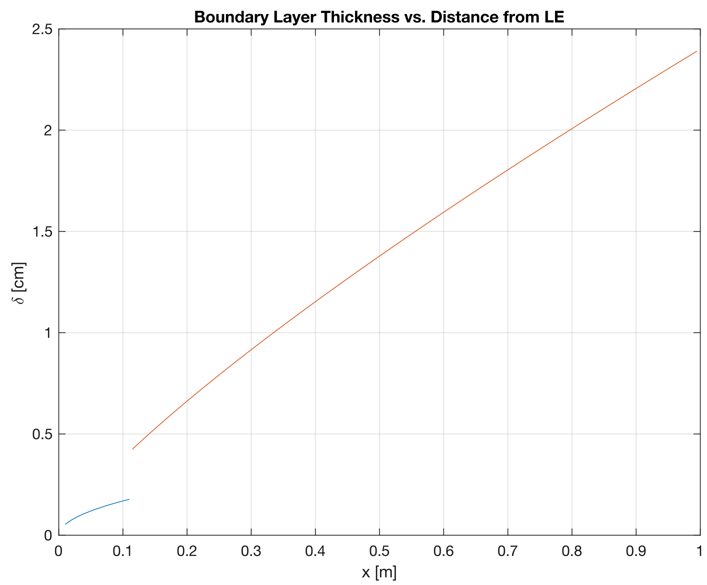

Figure 3.1: *The boundary layer thickness as a function of the distance from the leading edge of a theoretical flat plate.*

Figure 3.2 shows the relationship between fluid velocity normalized against the free stream velocity and the distance away from the surface of the airfoil normalized with the estimated boundary later thickness from Figure 3.3. The minimum normalized fluid velocity is located behind the airfoil surface.

Figure 3.5 shows the single sided amplitude, where the data inside the wake is at a Y/δ of 0 and the data outside the wake is from the lowest possible position by the anemometer below the airfoil.

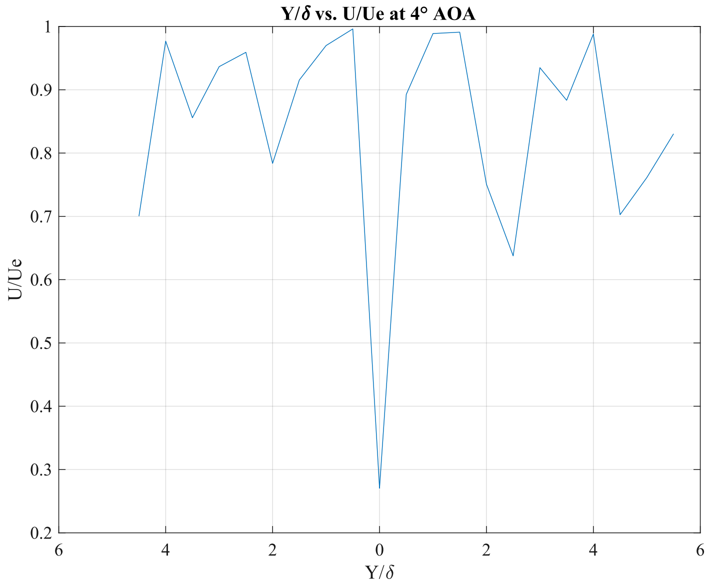

Figure 3.2: *The normalized air speed as a function of the vertical position behind the airfoil at* 4° *AoA.*

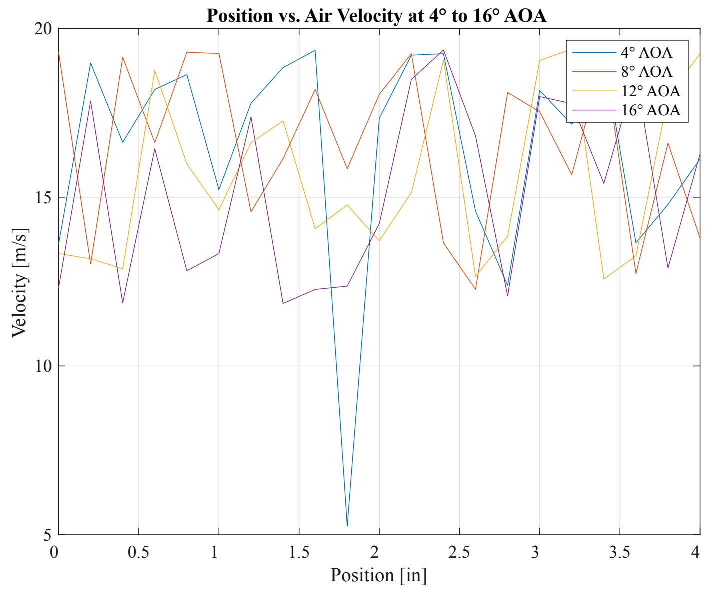

Figure 3.3: *The normalized air speed as a function of the vertical position behind the airfoil at* 4° *to* 16° *AoAs.*

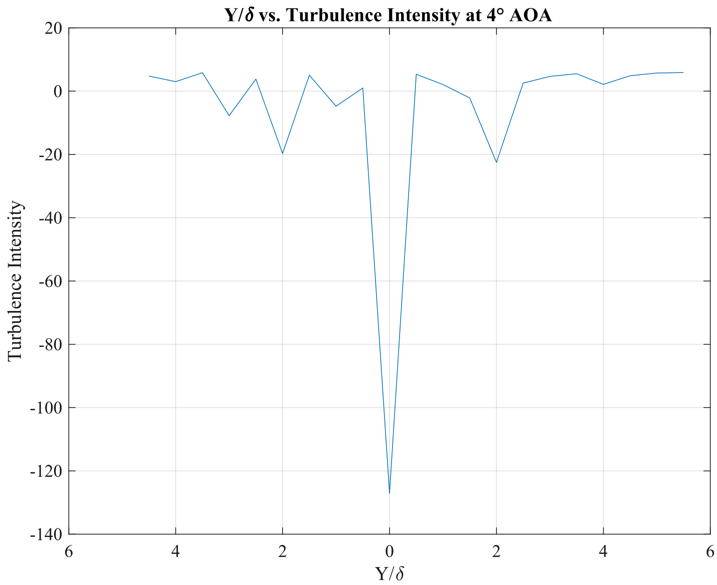

Figure 3.4: *The turbulence intensity as a function of the vertical position behind the airfoil at* 4° *AoA.*

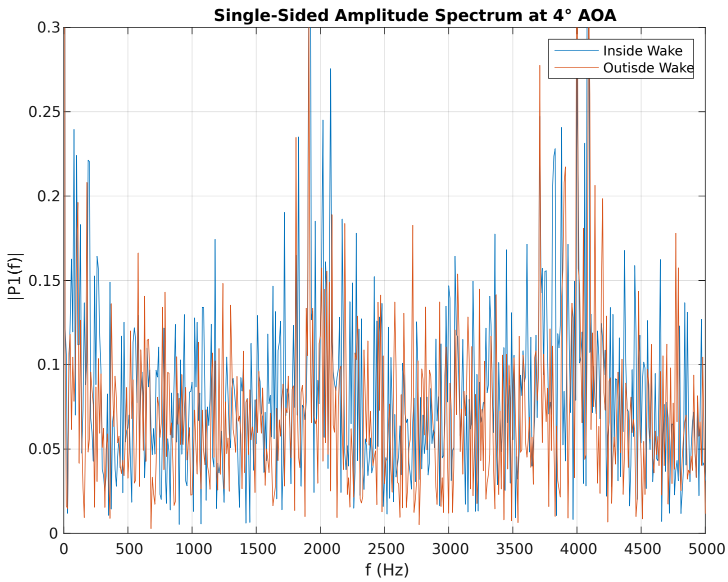

Figure 3.5: *The single-sided amplitude spectrum inside and outside the wake region at a* 4° *AoA.*

The Cd calculated at each angle of attack from Equation 2.6 is as follows:

$$4^\circ = 0.1277$$
$$8^\circ = 0.1371$$
$$12^\circ = 0.1469$$
$$16^\circ = 0.1359$$

Using Equation 3.1 and the subsequent parameters, we find the Reynolds number of about 1.322×10^5 for the airfoil wake measurements.

$$Re = \frac{\rho V L}{\mu} \tag{3.1}$$

$\rho = 1.225\,\mathrm{kg/m^3}$
$\mu = 18.18 \times 10^{-6}\,\mathrm{Pa\,s}$
$L = 0.101\,\mathrm{m}$
$V = 19.4\,\mathrm{m/s}$
$Re = 1.322 \times 10^5$

4

Discussion

4.1 Wake Analysis

The data in our lab is clearly erroneous. The sources of this error are discussed in more detail in Section 4.2. Beginning with the Y/δ vs. U/U_e graph shown in Figure 3.2, we see the shape generally matches our theoretical expectations, although the region outside the wake, where we would expect the flow to be laminar, is far less uniform than we measured in previous labs. This is only exacerbated when we increase the angle of attack as shown in the additional Y/δ vs. U/U_e graphs in Section A.2. At AoAs above 4°, the wake region disappears completely, implying either instrumentation error or that the wake region covers the entire width of measurements gathered. Since the boundary layer thickness we estimated in pre-lab (see Figure 3.1) was on the scale of 0 cm to 2.5 cm, although it is possible, it seems unlikely the wake region exceeded the 0 in. to 4 in. range we measured downstream of the airfoil. As seen in Figure 3.3, the measurements taken with an AoA above 4° seem to have no correlation whatsoever and look more like noise. Even the 4° AoA measurements may have been coincidental noise.

Figure 3.4 shows the turbulence intensity profile downstream of the airfoil at an AoA of 4°. Based on the example results we were shown prior to the lab, these turbulence intensity values should have generally been a reflection of the velocity profile—*i.e.*, when the velocity in the wake was at a low, the turbulence intensity should have been at a high—and they should have been positive values in the range of 2 to 3. Figure 3.4 has neither the appropriate shape, magnitude, nor sign, and the turbulence intensity graphs for the higher AoAs (see Section A.2) are no better. Again, the reason for this is discussed in greater detail in Section 4.2, but we suspect this error is compounded by an invalid hot wire calibration polynomial.

The spectrum analysis in Figure 3.5 is equally meaningless. There do appear to be significant spikes around 2000 Hz and 4000 Hz, perhaps implying there was some type of vortex shedding or turbulent behavior occurring. But to assume that were true would ignore the obvious lack of correlation over the entire frequency spectrum. The fast Fourier transform (FFT) looks far more like random noise. In the examples we observed prior to the lab, at low angles of attack, the FFT should have been fairly unexcited, which is obviously not what our data shows.

The Reynolds Number calculation is reasonable considering the free stream velocity value was determined using the lab two motor frequency vs air speed relationship. Despite the unreliable data from the anemometer, the coefficient of drag at each angle of attack almost follows the expected trend. As the angle of attack increases, the C_d would increase. The C_d does increase for angles of attack from 4 ° to 12 °, but then decreases at an AoA of 16°. Since the data is unreliable, as discussed in Section 4.2, this is likely a coincidence.

4.2 Sources of Error

For our data to be this deviant from the theoretical predictions, we must assume there were significant sources of error in the experimental setup, data analysis, or both. While we absolutely cannot vouch for our analysis with complete certainty—we would need more time to validate our calculations on different data sets—we expect the most significant error come from two sources: the hot wire setup and our hot wire calibration polynomial.

Any number of factors could have affected the hot wire data. just to name a few potential sources of error: the electrical wires connected to the hot wire apparatus may have had a loose connection at either terminal; there may have been some type of electromagnetic radiation causing noise or interference on the wires; the hot wire apparatus may have been broken, misaligned, or had a short. It is also possible the data acquisition software was misconfigured, although, we would expect this to result in data of the wrong order of magnitude, not the wrong shape entirely. A mechanical flaw in the apparatus is more likely given the random nature of the data we collected. Throughout the data, there are segments that seem reasonable—*e.g.*, the 4° AoA data—but in general, the data seems to have had significant noise added into it.

In addition to the noisy data, our hot wire calibration polynomial may be invalid for this hot wire anemometer. When exploring potential problems in our analysis script, we tried using the hot wire calibration polynomial calculated by a different group in our section, and we found our turbulence intensity graphs changed shape and magnitude significantly. Although they did not mirror our velocity profiles as expected, they did at least become positive.

4.3 Future Work

Due to the potentially erroneous hot wire data or calibration data, we were unable to analyze the wake region of the airfoil. We also cannot prove definitively the source of our error, but we think it is most likely due to noise in the hot wire anemometer apparatus. To improve our results, we would take the following corrective measures:

1. Test our analysis script on a set of a reliable data and compare the results to the

expected values—fixing bugs and making changes as necessary.

2. Re-calibrate and verify the functionality and accuracy of the hot wire anemometer apparatus.
3. Confirm the settings in the data acquisition software and repeat the experimental data collection.

5

Conclusion

To analyze the flow patterns downstream of an airfoil, we measured the velocity profile downstream of the airfoil using a hot wire anemometer. Due to erroneous data collected from the hot wire anemometer or a misconfiguration of the hot wire anemometer, we were unable to generate a conclusive analysis of the wake region. To rectify this and generate proper results, we would thoroughly review the MATLAB analysis script and, if necessary, validate the functionality and accuracy of the hot wire anemometer before repeating the experiment.

Bibliography

Hu, Hui (2024). *Quantifications of the Turbulence Characteristics in the Wake of an Airfoil by using a Hotwire Anemometer*. Iowa State University. URL: https://www.aere.iastate.edu/~huhui/teaching/2024-01S/AerE344/lab-instruction/AerE344L-Lab-07-instruction_hotwire-wake-meaurement.pdf.

A

Appendix A

A.1 Additional Apparatus Pictures

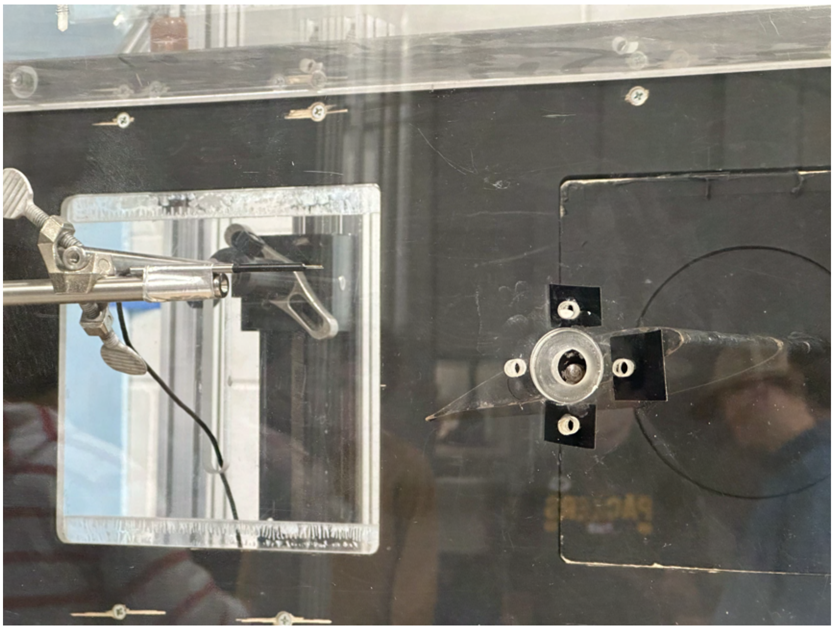

Figure A.1: *Hot Wire Anemometer behind the airfoil in the test section.*

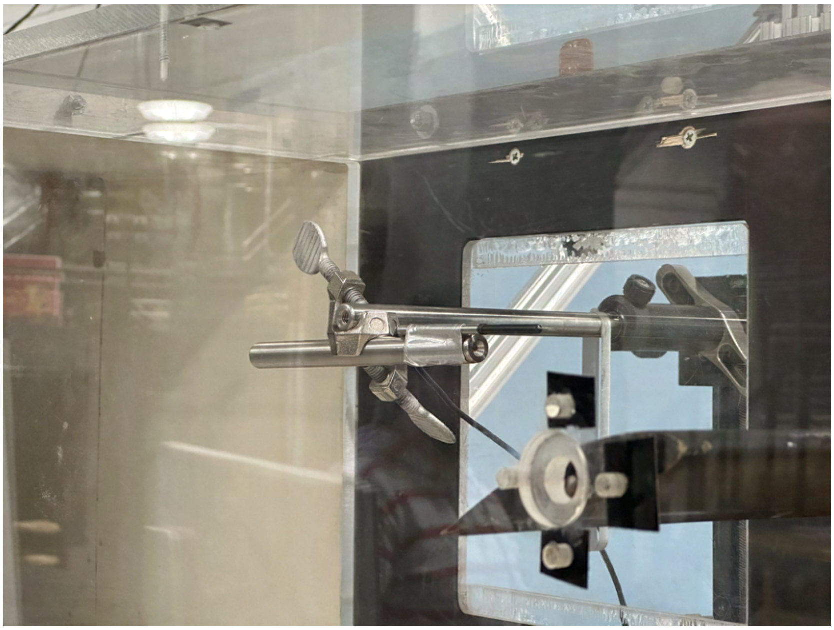

Figure A.2: *Wire Anemometer behind the airfoil in the test section.*

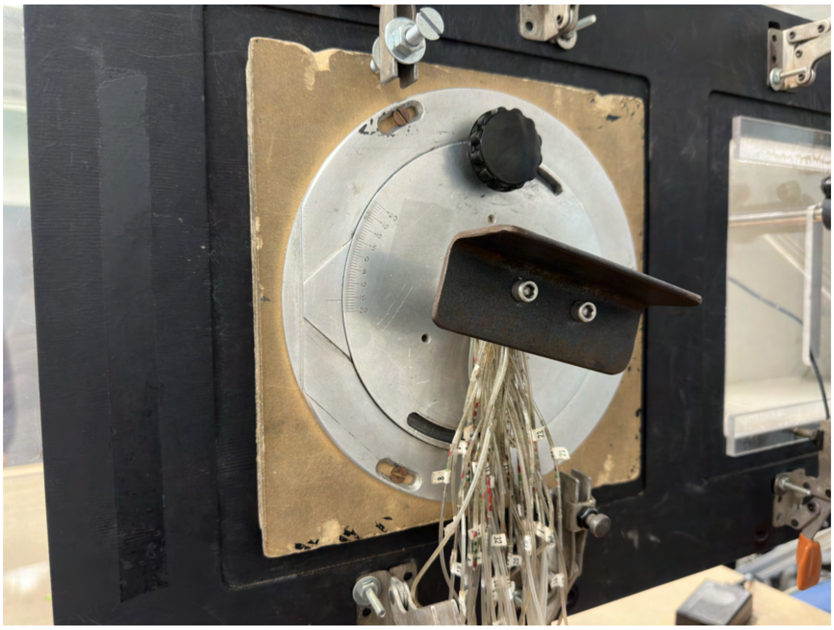

Figure A.3: *Adjustable knob to change the angle of attack of the airfoil.*

A.2 Additional Figures

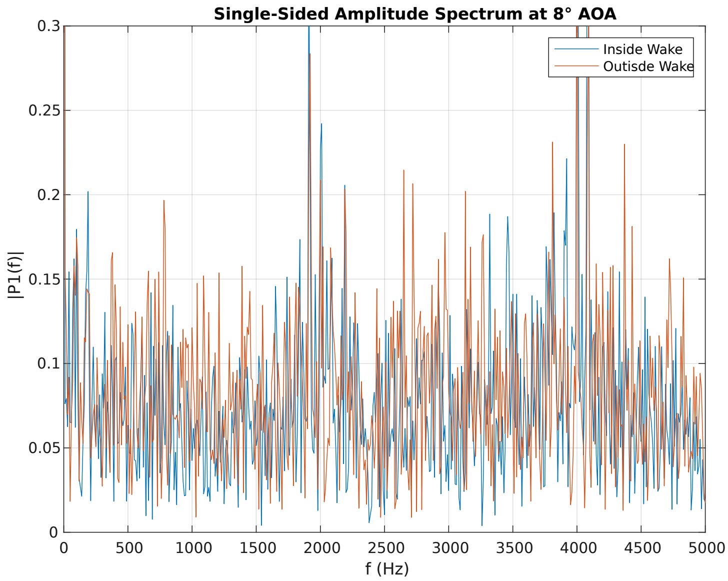

Figure A.4: *The single-sided amplitude spectrum inside and outside the wake region at a* 8° *AoA.*

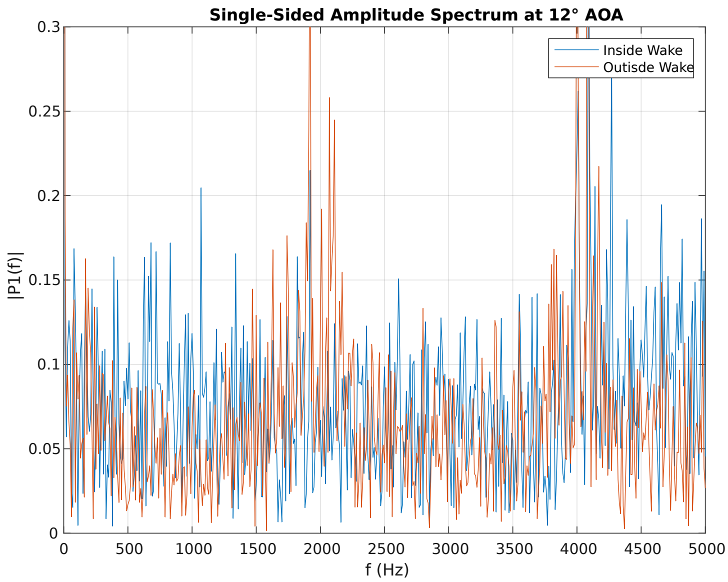

Figure A.5: *The single-sided amplitude spectrum inside and outside the wake region at a* 12° *AoA.*

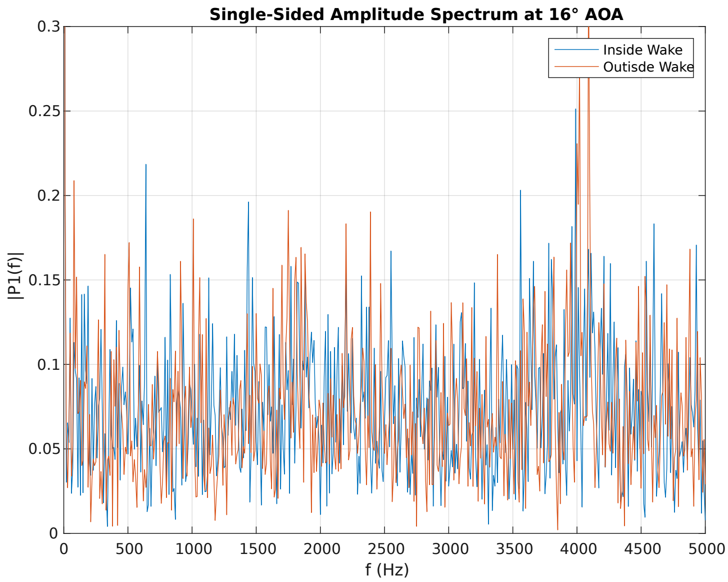

Figure A.6: *The single-sided amplitude spectrum inside and outside the wake region at a* 16° *AoA.*

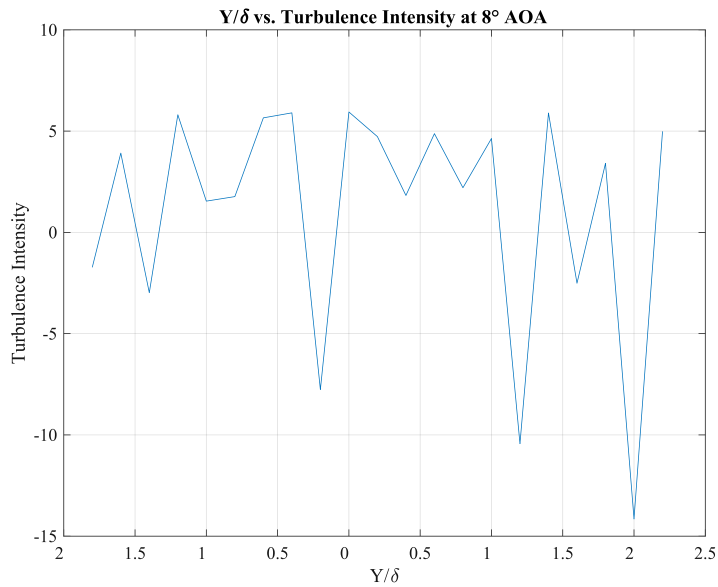

Figure A.7: *Turbulence intensity at a* 8° *AoA.*

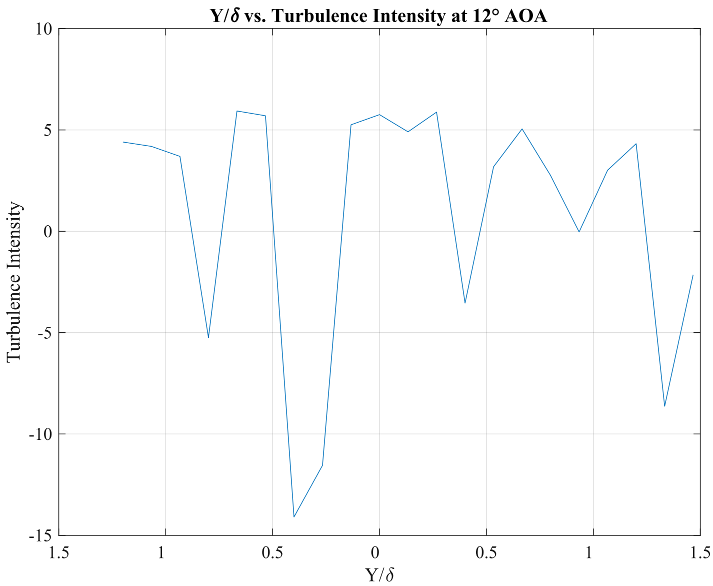

Figure A.8: *Turbulence intensity at a* 12° *AoA.*

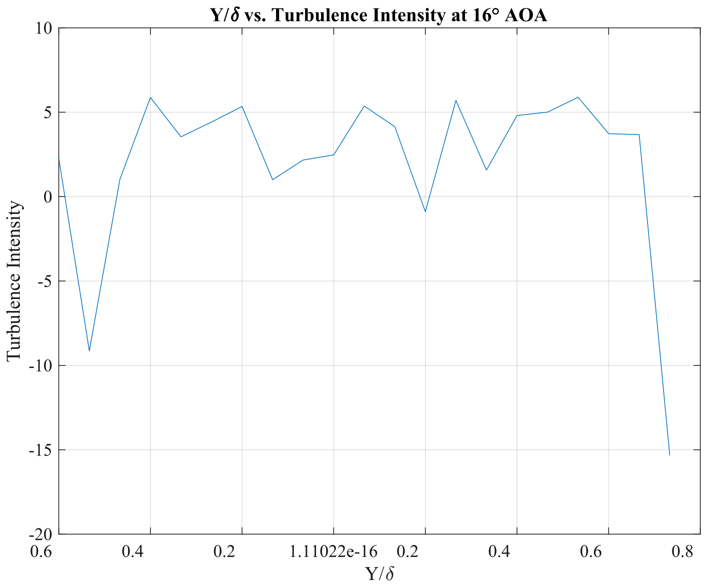

Figure A.9: *Turbulence intensity at a* 16° *AoA.*

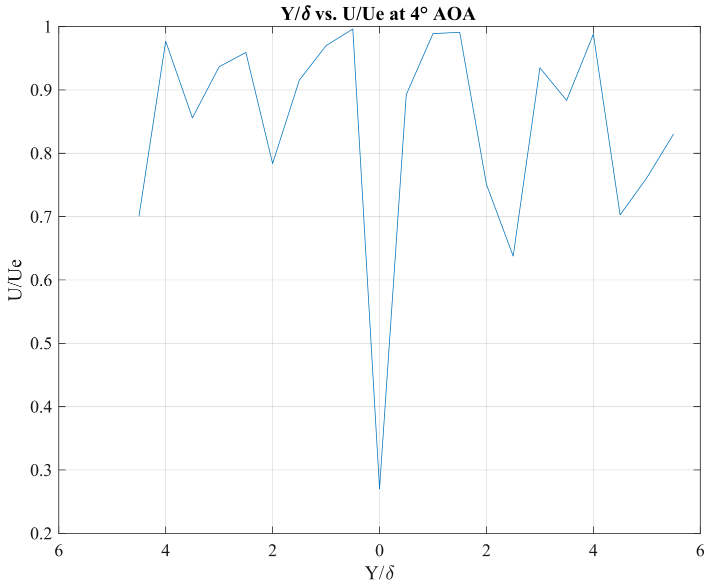

Figure A.10: *Velocity at a* 8° *AoA.*

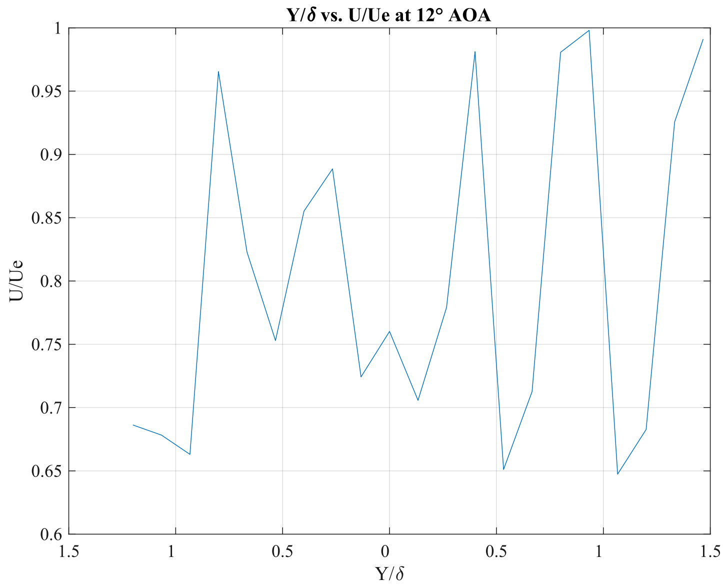

Figure A.11: *Velocity at a* 12° *AoA.*

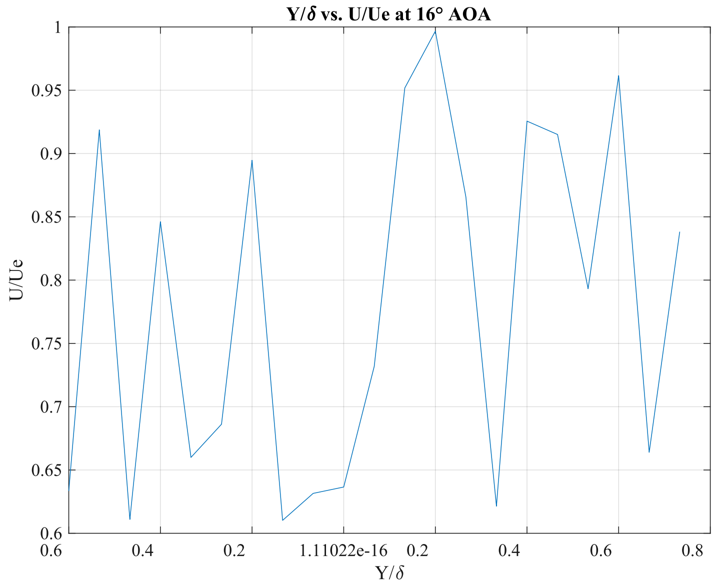

Figure A.12: *Velocity at a* 16° *AoA.*

B

Appendix B

B.1 Lab7Analysis.m

```
% AER E 344 Spring 2024 Lab 04 Analysis
% Section 3 Group 3
clear, clc, close all;

figure_dir = "../Figures/";
data_zip = "./data.zip";

%% Parameters
aoa = 4:4:16;
pos = 0:0.2:4;
figure_count = 1;

%% Constants
% 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]
L = 0.101; % [m]
% Curve fit equation for voltage (x) vs air speed (y) from Lab 6
v_vs_U = @(x) -4982.7570*x.^4 + 24021.8937*x.^3 + -43230.9413*x.^2 + 34446.6867*x +
  ↪ -10248.1714;
Cf = [34446.6867 -43230.9413 24021.8937 -4982.7570];
% v_vs_U = @(x) (6553.11832)*x^4 + (-30178.43731)*x^3 + (52087.72644)*x^2 +
  ↪ (-39881.78843)*x + (11425.60699);
% Cf = [-39881.78843 52087.72644 -30178.43731 6555.1183];
row = length(aoa);
col = length(pos);
volt = zeros(row, col); % [V] voltage
U = zeros(row, col); % [m/s] velocity
Ue = 1.32372*(15) -0.430966; % [m/s] Freestream velocity estimated from Lab 2
d_m = .2*.0254; % [m] Distance between measurements

%% Reynolds Number
```

```
Re = rho_air * Ue * L / mu_air;

%% Find avg. Voltage and Air Speed
unzip(data_zip);
for i = 1 : row
    for j = 1 : col
        name = "./" + aoa(i) + "/" + pos(j) + "in.txt";
        temp = readmatrix(name);
        volt(i, j) = mean(temp(4:1003,2));
        U(i, j) = v_vs_U(volt(i, j));
    end
end

%% Position vs. Velocity Graph
figure(figure_count)
figure_count = figure_count+1;
for i = 1:row
    plot(pos, U(i,:));
    hold on
end
fontname("Times New Roman");
fontsize(12, "points");
title_str = "Position vs. Air Velocity at 4° to 16° AOA";
title(title_str);
xlabel("Position [in]");
ylabel("Velocity [m/s]");
grid on;
legend(aoa + "° AOA");
xticks = get(gca, 'XTick');
abs_xticks = abs(xticks);
set(gca, 'XTickLabel', abs_xticks);
saveas(gcf, figure_dir + "Position vs. Air Velocity at 4 to 16 AOA.svg");

%% Position vs. Voltage Graph
% figure(figure_count);
% figure_count = figure_count+1;
% for i = 1:row
%     plot(pos, volt(i,:));
%     hold on
% end
% fontname("Times New Roman");
% fontsize(12, "points");
% title_str = "Position vs. Anemometer Voltage at 4° to 16° AOA";
% title(title_str);
% xlabel("Position [in]");
% ylabel("Voltage [V]");
% grid on;
% legend(aoa + "° AOA");

% Boundry Layer determined from graph estimations (looking/making it up)
delta = [0.4, 1, 1.5, 3]; % [in]
```

```
delta_pos = 1.8; % [in] try to make position centered at wake
y_right = .2 : .2 : max(pos) - delta_pos;
y_left = min(pos) - delta_pos : .2 : 0;
y_pos = [y_left,y_right];

%% Normalized Position vs. Normalized Velocity Graph
y_delta = zeros(row,col);
U_Ue = zeros(row,col);
for i = 1:row
    figure(figure_count)
    figure_count = figure_count+1;
    y_delta(i,:) = y_pos/delta(i);
    U_Ue(i,:) = U(i,:)/Ue;
    plot(y_delta(i,:), U_Ue(i,:));
    fontname("Times New Roman");
    fontsize(12, "points");
    title_str = "Y/\delta vs. U/Ue at "+ aoa(i)+"° AOA";
    title(title_str);
    xlabel("Y/\delta");
    ylabel("U/Ue");
    grid on;
    xticks = get(gca, 'XTick');
    abs_xticks = abs(xticks);
    set(gca, 'XTickLabel', abs_xticks);
    saveas(gcf, figure_dir + "Ydelta vs. UUe at " + aoa(i) + " AOA.svg");
end

%% Normalized Position vs. Turbulence Intensity
turb_i = zeros(row,col);
for i = 1:row
    v_rms = zeros(1,col);
    for j = 1:col
        % find rms of raw data at each position
        name = "./" + aoa(i) + "/" + pos(j) + "in.txt";
        temp = readmatrix(name);
        v = temp(4:1003,2);
        v_rms(j) = rms(v);
    end
    v_ = volt(i,:);
    u_rms = (Cf(1) + 2*Cf(2)*v_ + 3*Cf(3)*v_.^2 + 4*Cf(4)*v_.^3).*v_rms;
    turb_i(i,:) = u_rms./U(i,:);

    figure(figure_count)
    figure_count = figure_count+1;
    plot(y_delta(i,:), turb_i(i,:));
    fontname("Times New Roman");
    fontsize(12, "points");
    title_str = "Y/\delta vs. Turbulence Intensity at "+ aoa(i)+"° AOA";
    title(title_str);
    xlabel("Y/\delta");
    ylabel("Turbulence Intensity");
```

```
    grid on;
    xticks = get(gca, 'XTick');
    abs_xticks = abs(xticks);
    set(gca, 'XTickLabel', abs_xticks);
    saveas(gcf, figure_dir + "Ydelta vs. Turbulence Intensity at " + aoa(i) + " AOA.svg");
end

%% Vortex Shedding Frequency
for i = 1:4
    figure(figure_count)
    figure_count = figure_count+1;
    % Inside Wake
    name = "./" + aoa(i) + "/" + pos(10) + "in.txt";
    temp = readmatrix(name);
    y = temp(4:1003,2);
    Fs = 10000;
    n = length(y);
    Y = fft(y);
    P2 = abs(Y/n); % Compute the two-sided spectrum
    P1 = P2(1:n/2+1); % Compute the single-sided spectrum
    P1(2:end-1) = 2*P1(2:end-1);
    f = Fs*(0:(n/2))/n; % Define the frequency domain
    % Plot the single-sided amplitude spectrum inside wake
    plot(f,P1);
    hold on

    % Outside Wake
    name = "./" + aoa(i) + "/" + pos(1) + "in.txt";
    temp = readmatrix(name);
    y = temp(4:1003,2);
    Fs = 10000;
    n = length(y);
    Y = fft(y);
    P2 = abs(Y/n); % Compute the two-sided spectrum
    P1 = P2(1:n/2+1); % Compute the single-sided spectrum
    P1(2:end-1) = 2*P1(2:end-1);
    f = Fs*(0:(n/2))/n; % Define the frequency domain
    % Plot the single-sided amplitude spectrum inside wake
    plot(f,P1);

    title_str ="Single-Sided Amplitude Spectrum at "+ aoa(i)+"° AOA";
    title(title_str);
    xlabel('f (Hz)');
    ylabel('|P1(f)|');
    ylim([0,.3]);
    legend({'Inside Wake', 'Outisde Wake'})
    grid on;
    saveas(gcf, figure_dir + "Single-Sided Amplitude Spectrum at " + aoa(i) + " AOA.svg");
end
```

```
%% Momentum Thickness
theta = zeros(1,row);
C_D = zeros(1,row);
for i = 1:row
    for j = 10:20
        f1 = U(i,j)/Ue*(1- U(i,j)/Ue);
        f2 = U(i,j+1)/Ue*(1-U(i,j+1)/Ue);
        theta(i) = theta(i) + d_m*((f1 + f2)/2);
    end
    C_D(i) = 2 * theta(i) / L;
end

%% Delete unzipped data
dirs = {'4', '8', '12', '16'};
for i = 1:length(dirs)
      rmdir(dirs{i}, 's');
end
```