IOWA STATE UNIVERSITY

PIV MEASUREMENTS OF THE UNSTEADY VORTICES IN THE WAKE OF AN AIRFOIL LABORATORY

AER E 344 - LAB 11 - PIV MEASUREMENTS OF THE UNSTEADY VORTICES IN THE WAKE OF AN AIRFOIL

SECTION 3 GROUP 3

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AMES, APRIL 2024

Abstract

Particle image velocimetry (PIV) is a technique that tracks particles within the flow of fluid around an airfoil to map a flow field. This experiment makes use of an airfoil in a wind tunnel, a laser illuminating smoke particles, and a high speed camera that captures the motion of the particles when illuminated by the laser. By taking pictures in extremely short succession, we determined instantaneous velocity vectors for each particle. Then, by analyzing hundreds of frames taken in short succession, we created averaged velocity fields that more accurately represent the flow. This process allowed us to analyze the wake characteristics—like the shape, vorticity, and turbulent kinetic energy. The PIV measurements we analyzed in this lab correctly showed the flow characteristics of an airfoil and generally matched our previous and expected results.

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Glossary

u x-component of the velocity vector data. *(p. 5)*

v x-component of the velocity vector data. *(p. 5)*

x x-component of the position vector data. *(p. 5, 12)*

y y-component of the position vector data. *(p. 5, 12)*

Acronyms

AoA Angle of attack. *(p. iii, 2, 3, 6–11, 16–23)*

MATLAB MATrix LABoratory. *(p. 5, 6)*

PIV Particle image velocimetry. *(p. i, 2–4, 10–12)*

SVG Scalable vector graphic. *(p. 6)*

1

Introduction

Particle image velocimetry (PIV) is a robust technique within fluid mechanics, serving to visualize and analyze flow fields precisely. Its applications span across diverse industries such as aerospace, automotive, environmental engineering, and manufacturing, where a deep understanding of fluid dynamics is crucial for optimization and design.

The fundamental principle of PIV involves illuminating the flow field either with a laser sheet or a pulsing light and then tracking the movement of tracer particles through high-speed camera imaging. A synchronizer coordinates the timing of the laser illumination and the camera acquisition. After taking the images, a PIV software calculates the displacement of particles by comparing consecutive frames. The tracers must be neutrally buoyant, small enough to follow the flow perfectly but big enough to scatter the illumination lights efficiently. If the tracer particles are too big, the gravitational force has a more significant influence on the movement of tracer particles, creating a source of error (Hu, 2024a).

The goal of this experiment is to visualize and analyze the flow around a GA(W)-1 airfoil in a close-circuit, low-speed wind tunnel at different AoA. The PIV system will measure the velocity of the tracer particles along the airfoil. For this experiment, we are using oil droplets that are from 1 μm to 5 μm in diameter. The Nd:YAG laser (NewWave Gemini 200) illuminates using a system of optics and lenses while a high-resolution, high-speed camera captures the images. Both the camera and the laser are connected to a computer via a delay generator, which coordinates the timing between the laser and the camera (Hu, 2024b).

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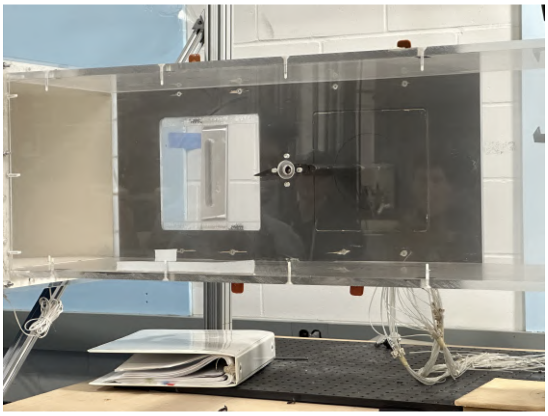
Methodology

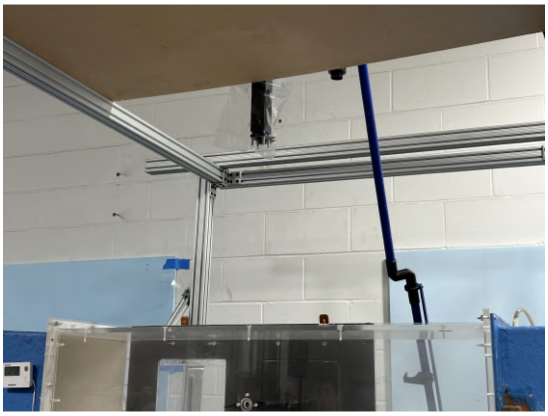
2.1 Apparatus

A PIV system is set up to view flow over an airfoil in a wind tunnel. This system begins with putting an airfoil in a wind tunnel, as shown in Figure 2.1a. Figure 2.1b shows the laser used in this lab, which is reflected off a mirror to illuminate particles in the flow. A smoke machine, such as the one in Figure A.1, is also used to make the particles easier to identify and track. To record data, a high speed camera is used for image acquisition. To control the timing of the camera's photos and the laser illumination, a digital delay generator is used. The camera used can be seen in Figure 2.1c, and the digital delay generator can be seen in Figure A.2. The camera images are collected using data acquisition software on a computer. Figure 2.1d depicts the full PIV system ready for operation.

2.2 Procedure

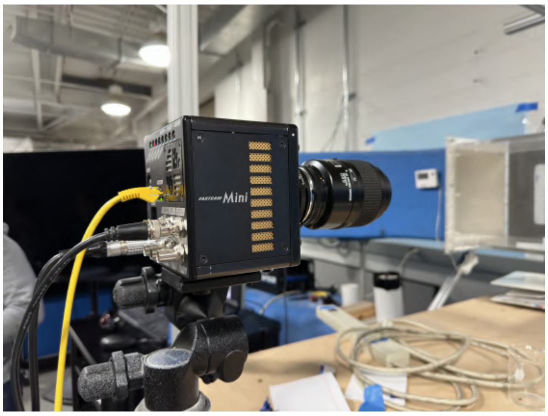
1. Set the wind tunnel to 10 m/s.
2. Set the AoA to 4°.
3. Set up the system as described in Section 2.1.
4. Start recording data using the data collection software.
5. Repeat steps 1 to 4 for 8°, 12° and 16°.

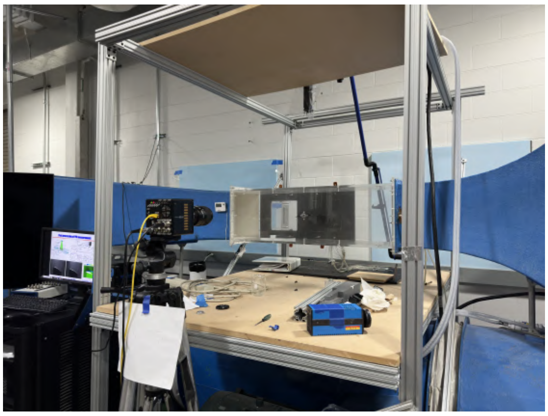




(a) *An airfoil inside the wind tunnel test section.*

(b) *The laser used in PIV measurements.*





(c) *The high-speed camera used to capture PIV frames.*

(d) *Frontal view of the PIV apparatus and the wind tunnel.*

Figure 2.1: *Pictures of the apparatus.*

2.3 Derivations

The PIV Data consists of x and y positions with corresponding x and y velocity, denoted u and v. From the velocity data at each point, vorticity is found using Equation 2.1. This is computed using the `curl` function in MATrix LABoratory (MATLAB) as the k component of the velocity vector is zero and the result is the same.

$$\omega_z = \frac{\delta V}{\delta x} - \frac{\delta U}{\delta y} \tag{2.1}$$

$$\Delta \times Velocity = \begin{bmatrix} i & j & k \\ \frac{\delta}{\delta x} & \frac{\delta}{\delta y} & \frac{\delta}{\delta z} \\ U & V & W \end{bmatrix} = \begin{bmatrix} i & j & k \\ \frac{\delta}{\delta x} & \frac{\delta}{\delta y} & 0 \\ U & V & 0 \end{bmatrix} = (0, 0, \frac{\delta V}{\delta x} - \frac{\delta U}{\delta y}) \tag{2.2}$$

Data at every position over N frames is averaged to get the mean velocity components in the x and y directions (Equation 2.3).

$$U = \sum_{i=1}^{N} \frac{u_i}{N}, V = \sum_{i=1}^{N} \frac{v_i}{N} \tag{2.3}$$

From the mean velocities, the turbulent velocity fluctuations are computed at each position, u_i(Equation 2.4).

$$\overline{u}' = \sqrt{\sum_{i=1}^{N} (u_i - U)^2 / N}, \overline{v}' = \sqrt{\sum_{i=1}^{N} (v_i - U)^2 / N} \tag{2.4}$$

Finally, the turbulent velocity fluctuations are used to find the turbulent kinetic energy distribution, as shown in Equation 2.5.

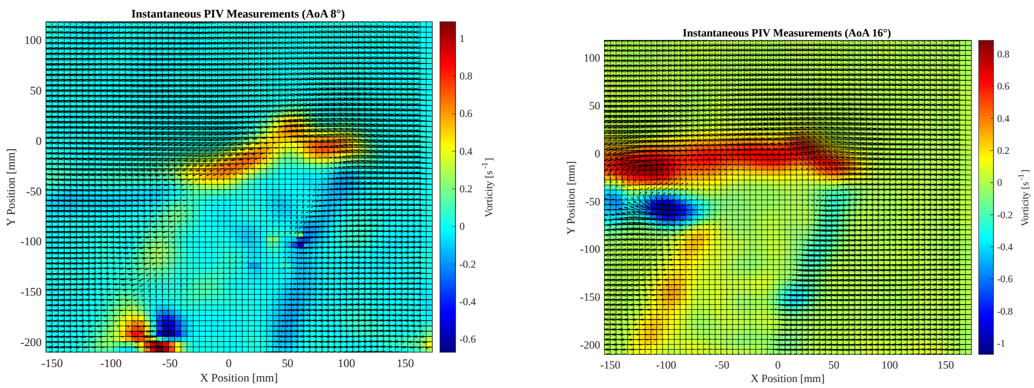
$$TKE = \frac{1}{2}\rho(\overline{u}'^2 + \overline{v}'^2) \tag{2.5}$$

3

Results

The figures in this section were generated from the MATLAB analysis script included in Section B.1. For conciseness and easier comparisons, the graphs have been grouped together according to what they are measuring. Unfortunately, when grouped this way, they are each quite small visually. To address this, each graph included in this document is a Scalable vector graphic (SVG) file, which—if your document viewer allows it—should enable you to zoom in significantly with no loss in resolution. If that is inconvenient, each graph in this section is also included in full-size in Section A.2.

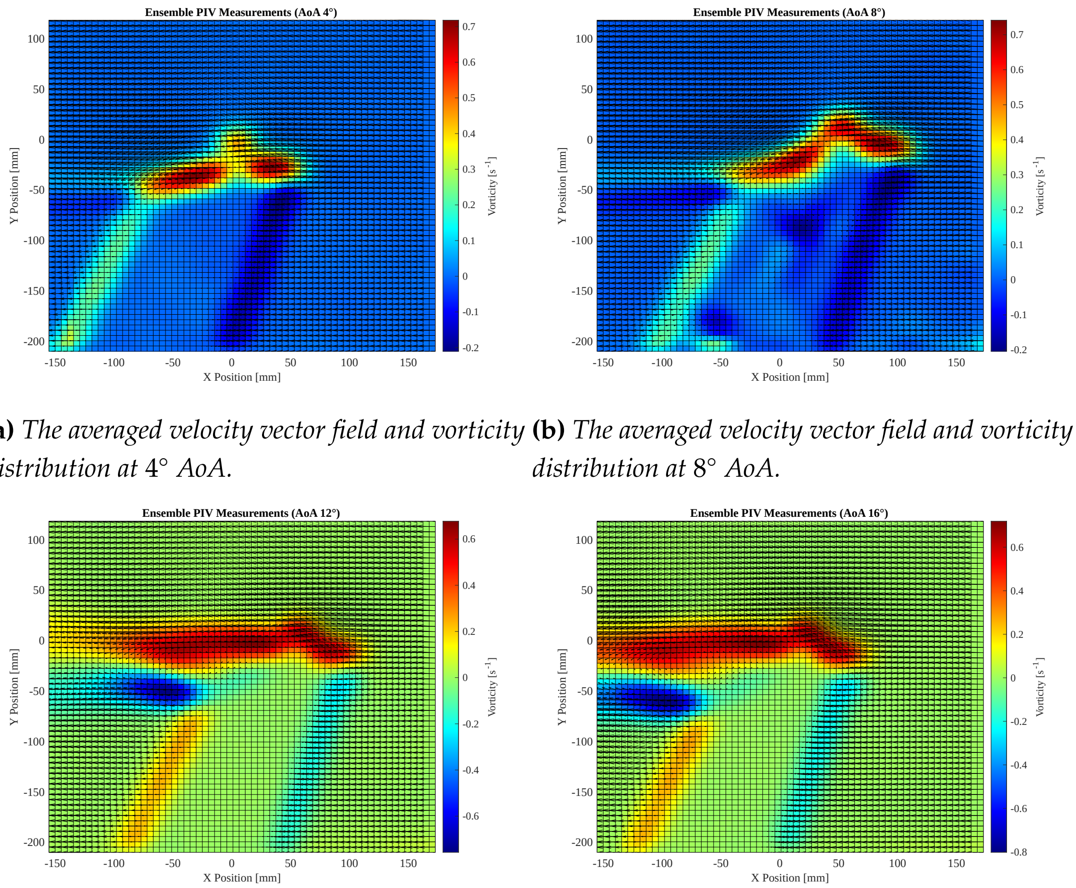
Figure 3.1 shows the instantaneous velocity and vorticity fields for two randomly selected data frames. The first data frame was number 202 at an 8° AoA, and the second data frame was number 245 at a 16° AoA. Figure 3.2, Figure 3.3, and Figure 3.4 show the averaged velocity and vorticity fields, averaged turbulent kinetic energy distribution, and averaged half chord wake profile data, respectively, for a 4°, 8°, 12° and 16° AoA.



(a) *The instantaneous velocity vector field and vorticity distribution for data frame 202 at 8° AoA.*

(b) *The instantaneous velocity vector field and vorticity distribution for data frame 245 at 16° AoA.*

Figure 3.1: *The instantaneous velocity and vorticity fields at two randomly selected AoAs and frames.*



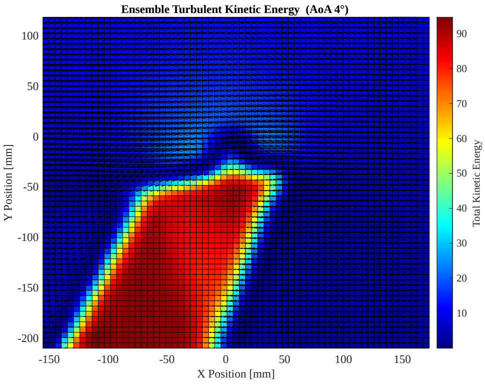
(a) *The averaged velocity vector field and vorticity distribution at* 4° *AoA.*

(b) *The averaged velocity vector field and vorticity distribution at* 8° *AoA.*

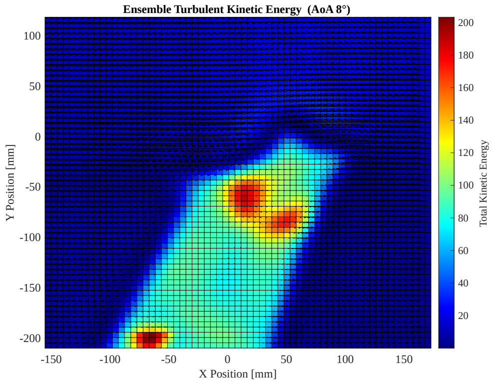
(c) *The averaged velocity vector field and vorticity distribution at* 12° *AoA.*

(d) *The averaged velocity vector field and vorticity distribution at* 16° *AoA.*

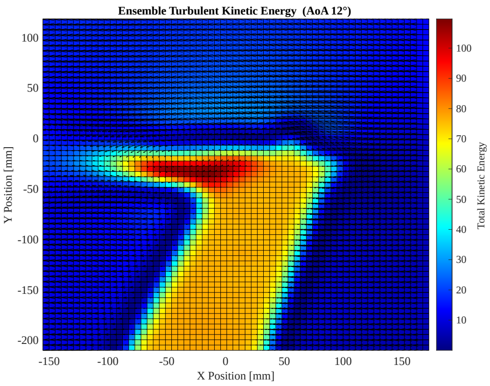
Figure 3.2: *The averaged velocity and vorticity fields for AoAs* 4°, 8°, 12° *and* 16°.



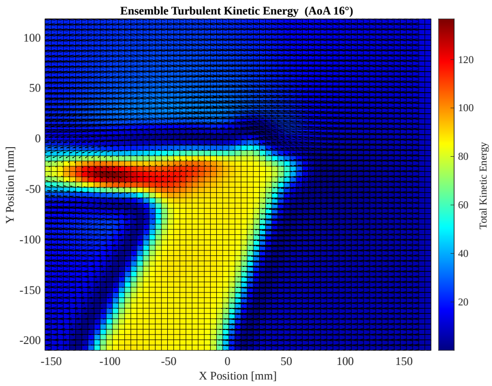
(a) *The averaged turbulent kinetic energy distribution at* 4° *AoA.*



(b) *The averaged turbulent kinetic energy distribution at* 8° *AoA.*

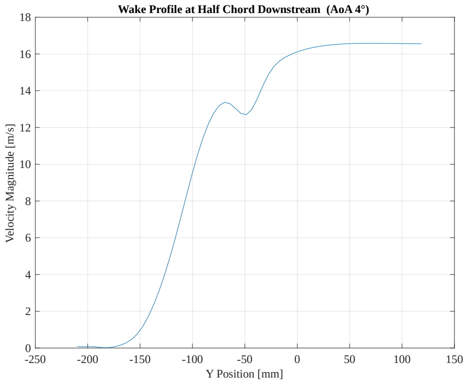


(c) *The averaged turbulent kinetic energy distribution at* 12° *AoA.*

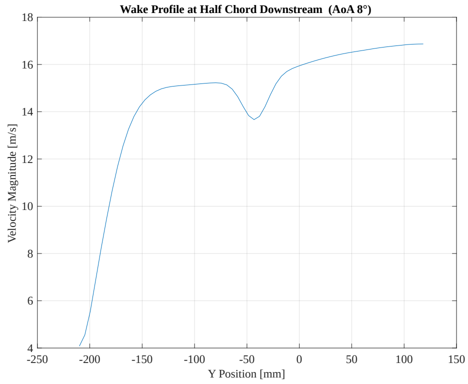


(d) *The averaged turbulent kinetic energy distribution at* 16° *AoA.*

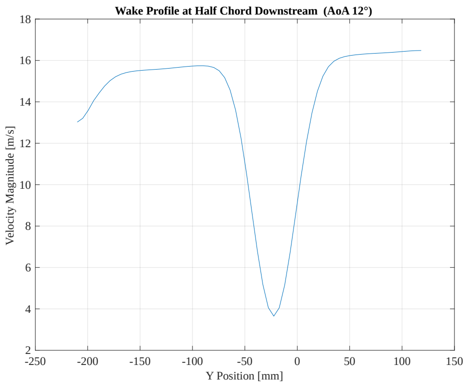
Figure 3.3: *The averaged turbulent kinetic energy distribution for AoAs* 4°, 8°, 12° *and* 16°.



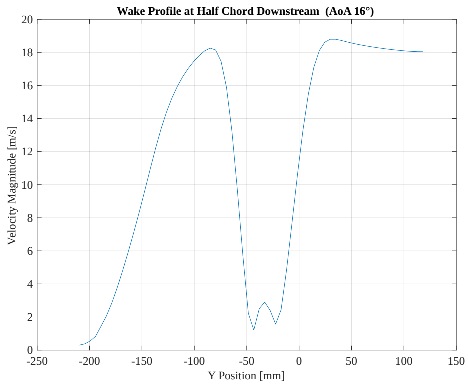
(a) *The velocity magnitude profile at half chord for* 4° *AoA.*



(b) *The velocity magnitude profile at half chord for* 8° *AoA.*



(c) *The velocity magnitude profile at half chord for* 12° *AoA.*



(d) *The velocity magnitude profile at half chord for* 16° *AoA.*

Figure 3.4: *The averaged velocity magnitude profile at half chord for AoAs* 4°, 8°, 12° *and* 16°.

4 Discussion

The flow characteristics and uncertainties are different for instantaneous PIV measurements as opposed to the averaged, or ensemble, measurements. The uncertainty in the velocity field is inversely related to the number of snapshots. More precisely, as the number of instantaneous snapshots increases, the uncertainty decreases. Generating ensemble data smooths out fluctuations and noise in the data, and provides a more representative capture of the flow field's behavior. To show this, examine the difference between Figure 3.1a and Figure 3.2b, the first figure representing an instantaneous velocity and vorticity field and the latter being an averaged velocity and vorticity field for the same AoA.

First, since the instantaneous velocity measurement has a different background color, it is immediately clear that the scale of vorticity is different. In this example, the ensemble data has a *lower* max vorticity and a *higher* minimum vorticity. This is consistent with the hypothesis that the ensemble data will smooth out outliers and momentary fluctuations in the flow—which may not be representative.

Second, note the flow region at approximately $x = -75$ and $y = -200$. In the instantaneous measurement, this area has extremely positive and negative vorticity occurring, perhaps indicating some type of vortex shedding. In the ensemble data, this same region also shows positive and negative vorticity in approximately the same shape, but the absolute difference between the positive and negative vorticity is 25 % the absolute difference of the instantaneous measurement. This demonstrates an important idea: although ensemble data provides a more uniform and consistent characterization of the flow, small nuances in the flow may only be detected by observing instantaneous measurements.

Lastly, since the ensemble data is averaging a number of snapshots, the shape of the ensemble data is much more defined and clear than in the instantaneous measurement. This is particularly helpful in identifying the size and shape of the wake regions.

As shown in Figure 3.1a and Figure 3.1b, there are some regions with high velocity fluctuations or turbulent activity. These regions can be identified by finding local maxima and minima in the instantaneous measurements and comparing those locations to the averaged data. Turbulent flow regions exhibit greater velocity and vorticity variance compared to laminar flows; therefore, turbulent regions like those of wakes, shear layers, or towards the trailing edge at higher AoAs will have higher uncertainty, especially if only observing the instantaneous measurement.

We were unable to compare the PIV wake measurements to the measurements made in the hotwire lab due to erroneous data collection in the hotwire experiment. We were, however, able to compare against our pitot rake measurements in lab six. Our conclusion from the pitot rake data was that as the AoA increases, the wake region becomes wider and more turbulent. Examining Figure 3.4, this seems to generally match our measurements taken in this lab. As the angle of attack increases, the wake region gets wider and more turbulent—as indicated by the higher velocity magnitudes in the wake region.

It should be noted that Figure 3.4a and Figure 3.4b look different from our pitot rake lab data and from our theoretical expectations. The wake region is very narrow and not very turbulent. We think it's likely that we chose an improper point to sample the half chord downstream wake—perhaps we sampled the half chord downstream wake too far upstream.

5

Conclusion

To analyze the aerodynamic characteristics of an airfoil at different angles of attack, a Particle image velocimetry (PIV) system was used to gather a 2D velocity field around an airfoil. The averaged velocity field for each angle of attack was used to find the vorticity distribution and turbulent kinetic energy around the airfoil. A wake profile was constructed by plotting the magnitude of the velocity as a function the y-axis for a given x position one half chord downstream of the trailing edge. The wake profile at each angle of attack shows a similar contour to other means of analysis, such as using a pitot rake or hot wire behind the airfoil. As the angle of attack increases, the vorticity, turbulent kinetic energy, and wake width also increase.

Bibliography

Hu, Hui (2024a). *Particle Image Velocimetry*. URL: https://www.aere.iastate.edu/~huhui/teaching/2024-01S/AerE344/class-notes/AerE344-Lecture-11-Particle-image-velocimetry_CD-Nozzle.pdf.

— (2024b). *PIV Measurements of the Unsteady Vortices in the Wake of An Airfoil*. Iowa State University. URL: https://www.aere.iastate.edu/~huhui/teaching/2024-01S/AerE344/lab-instruction/AerE344L-Lab-11-instruction.pdf.

A

Appendix A

A.1 Additional Apparatus Pictures

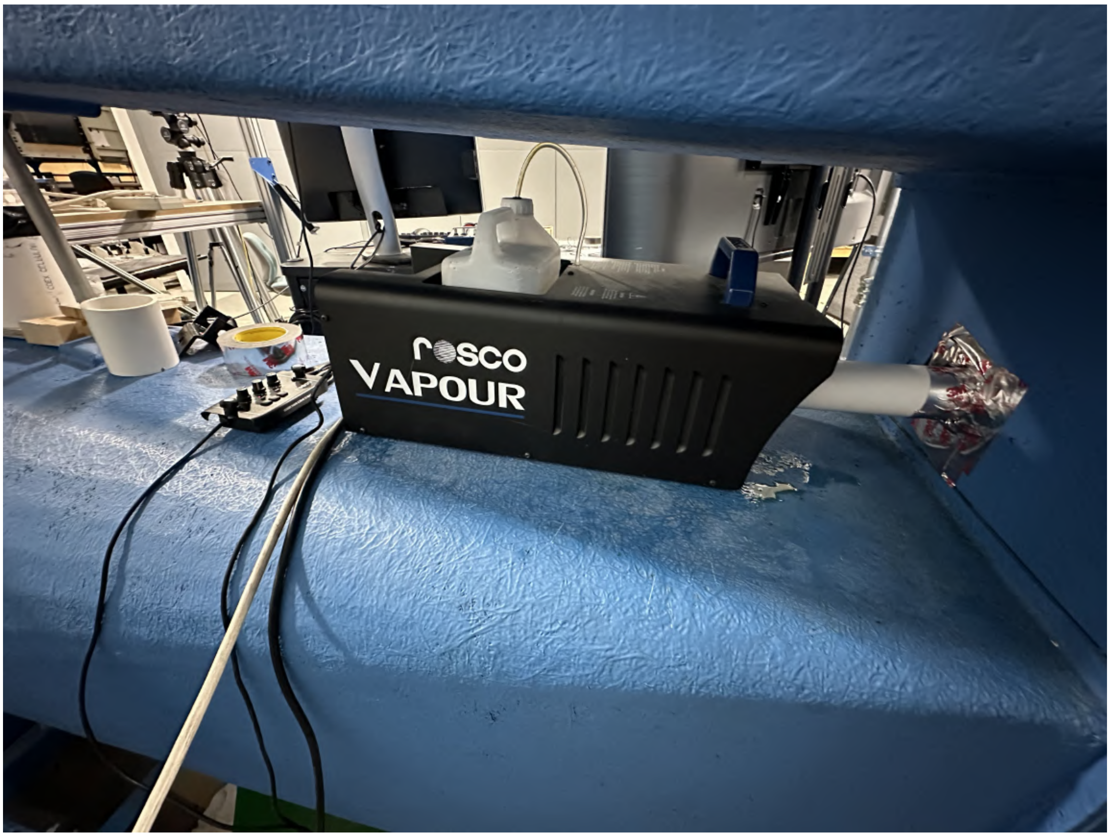


Figure A.1: *The smoke machine.*

Figure A.2: *The delay generator.*

Figure A.3: *The laser generator.*

A.2 Full Size Figures

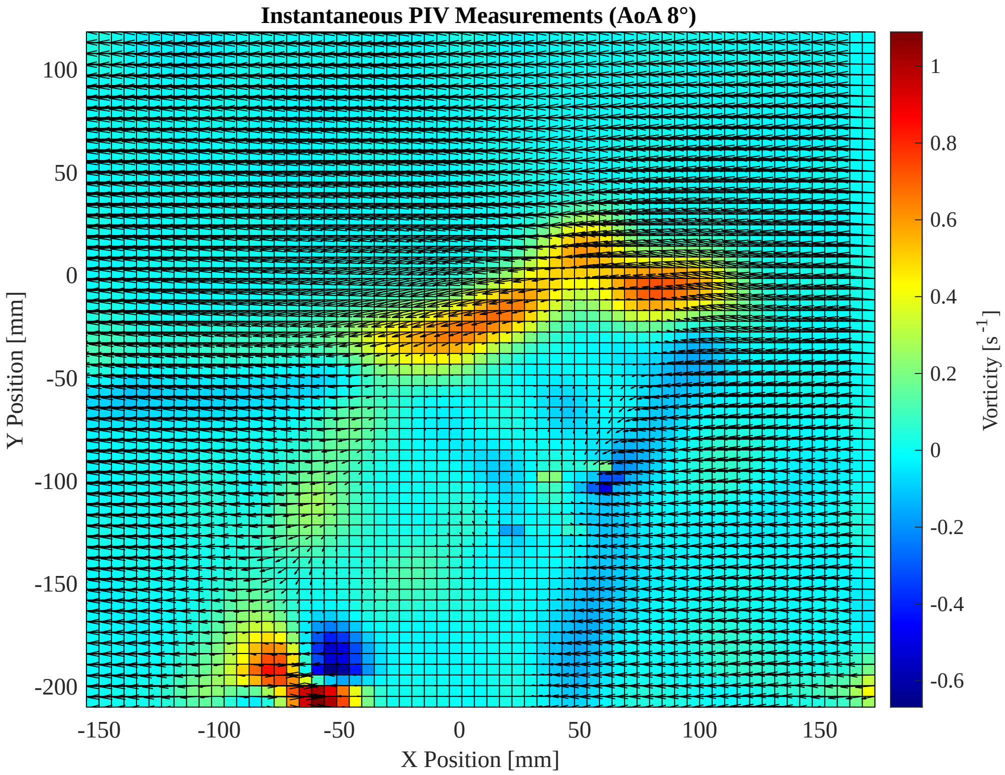


Figure A.4: *The instantaneous velocity vector field and vorticity distribution for data frame* 202 *at* 8° *AoA.*

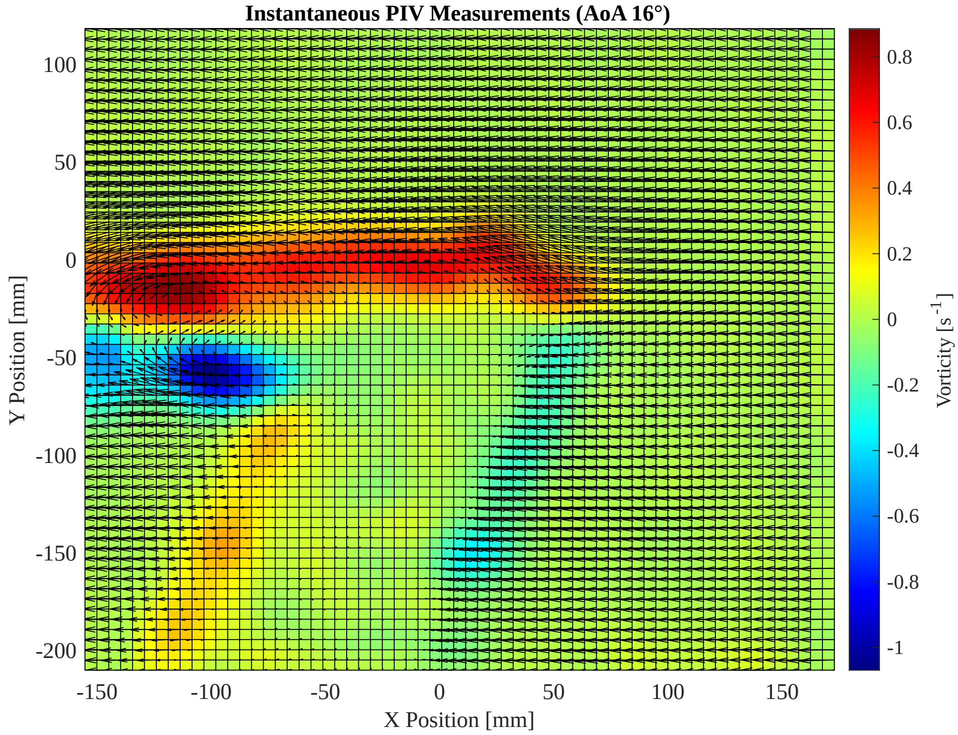


Figure A.5: *The instantaneous velocity vector field and vorticity distribution for data frame* 245 *at* 16° *AoA.*

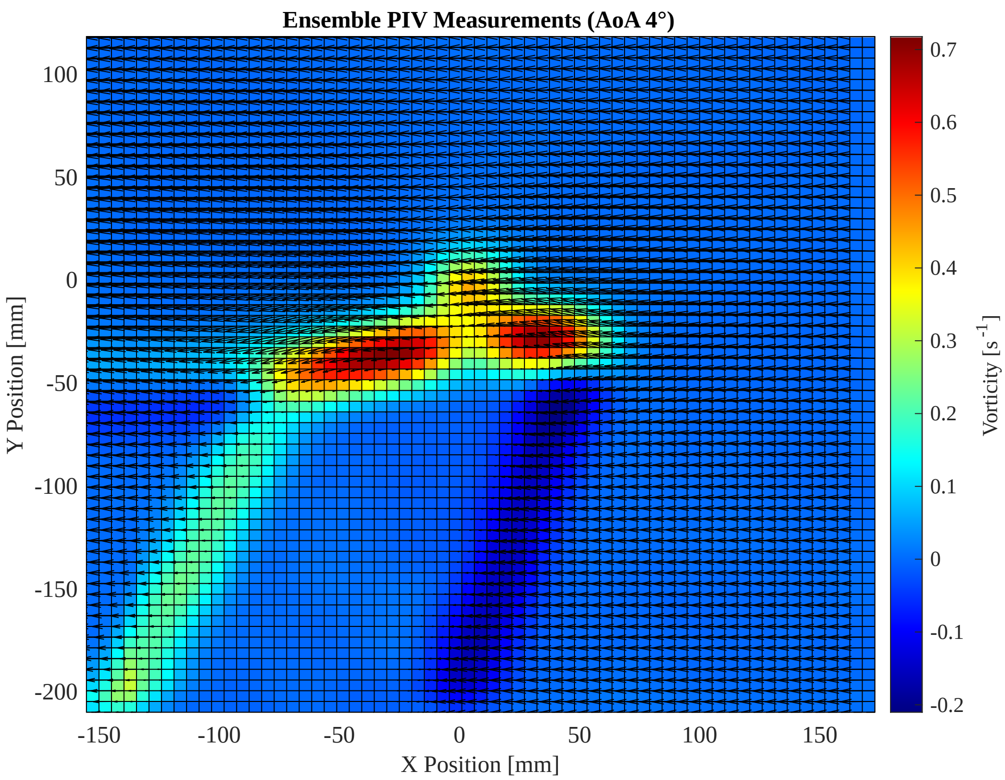


Figure A.6: *The averaged velocity vector field and vorticity distribution at* 4° *AoA.*

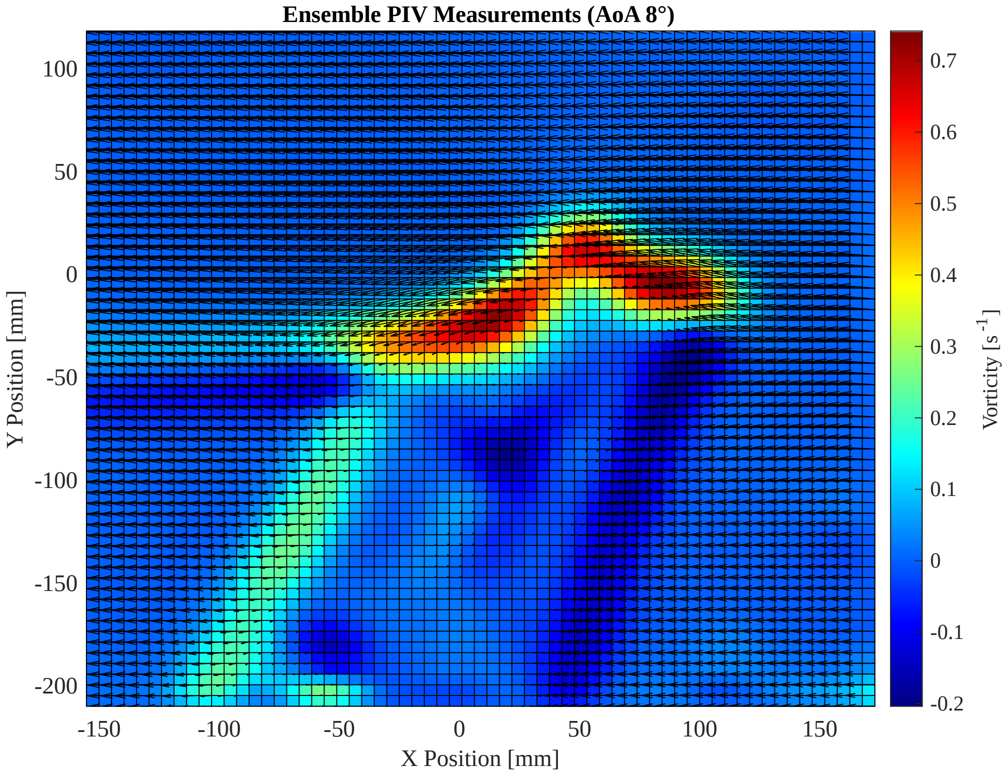


Figure A.7: *The averaged velocity vector field and vorticity distribution at* 8° *AoA.*

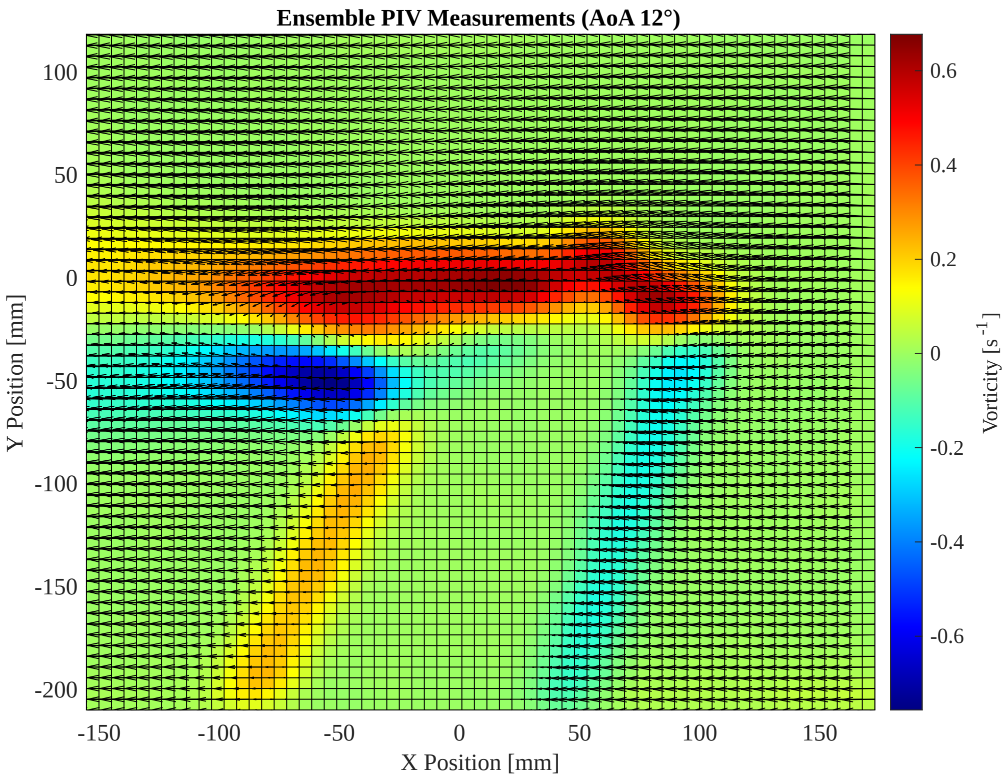


Figure A.8: *The averaged velocity vector field and vorticity distribution at* 12° *AoA.*

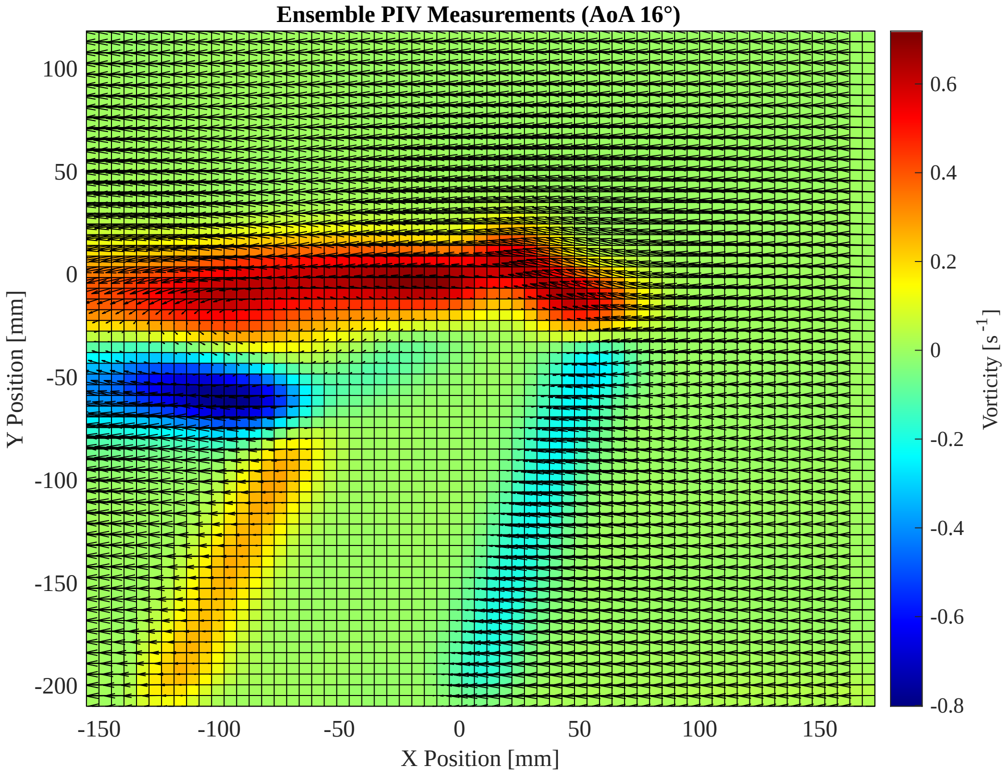


Figure A.9: *The averaged velocity vector field and vorticity distribution at* 16° *AoA.*

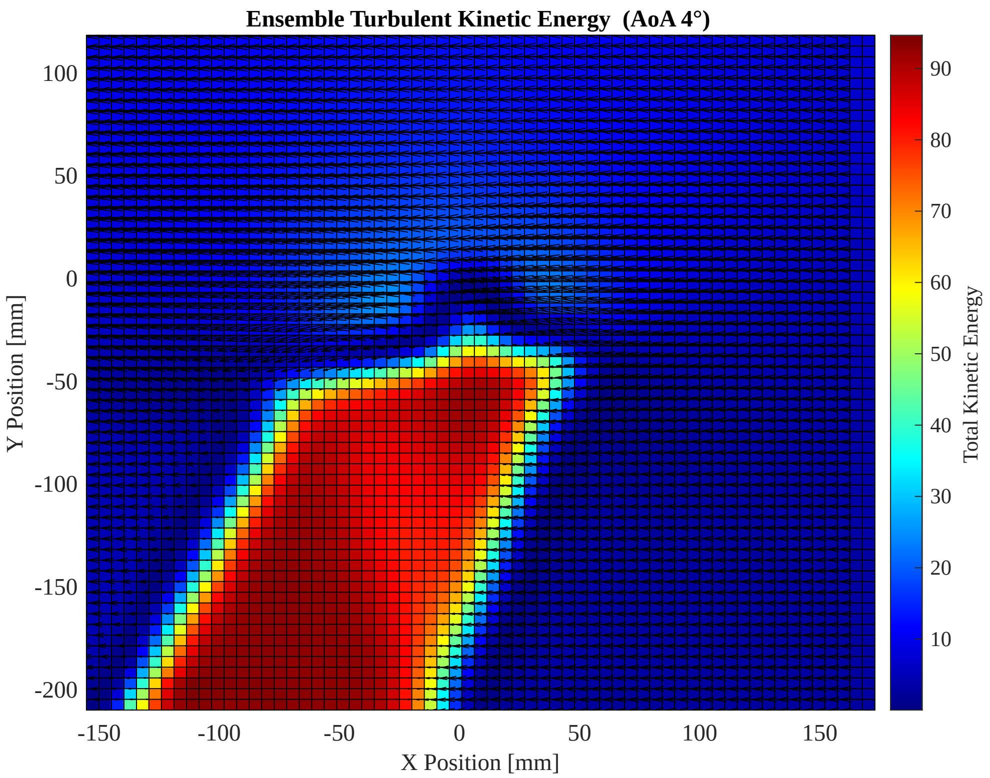


Figure A.10: *The averaged turbulent kinetic energy distribution at* 4° *AoA.*

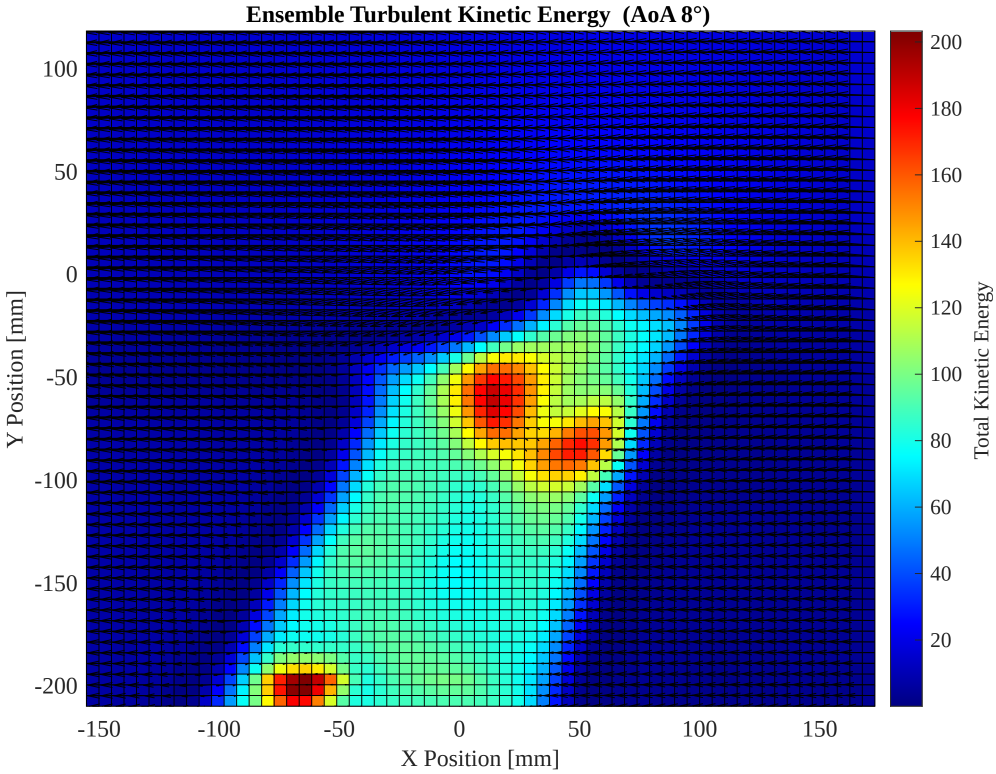


Figure A.11: *The averaged turbulent kinetic energy distribution at* 8° *AoA.*

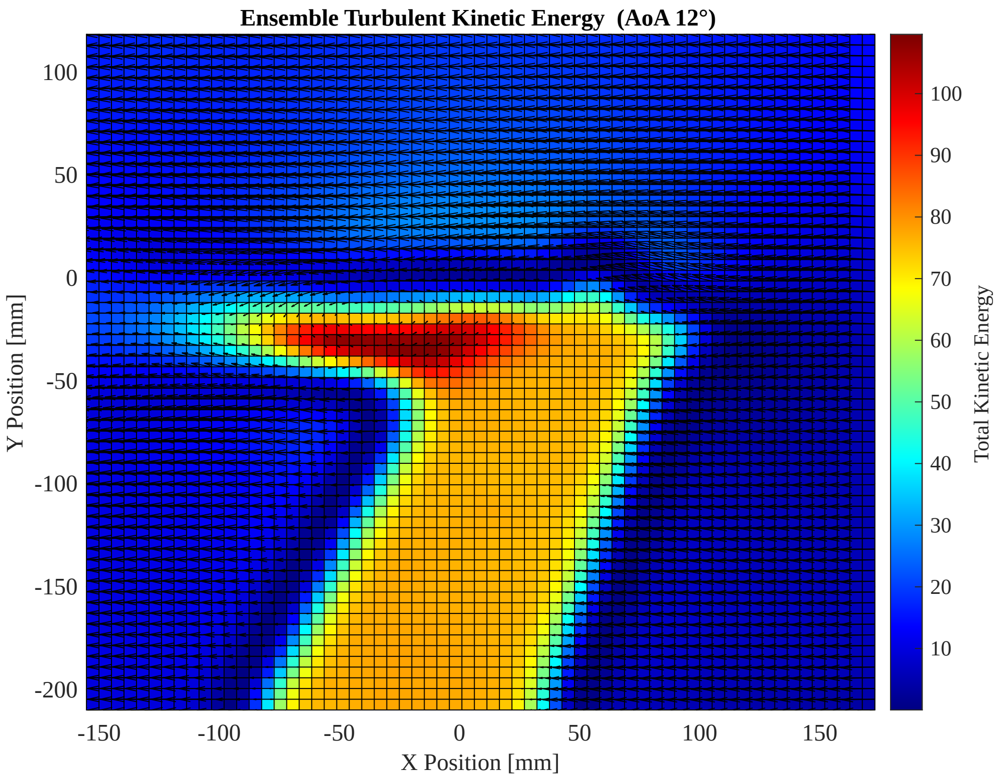


Figure A.12: *The averaged turbulent kinetic energy distribution at* 12° *AoA.*

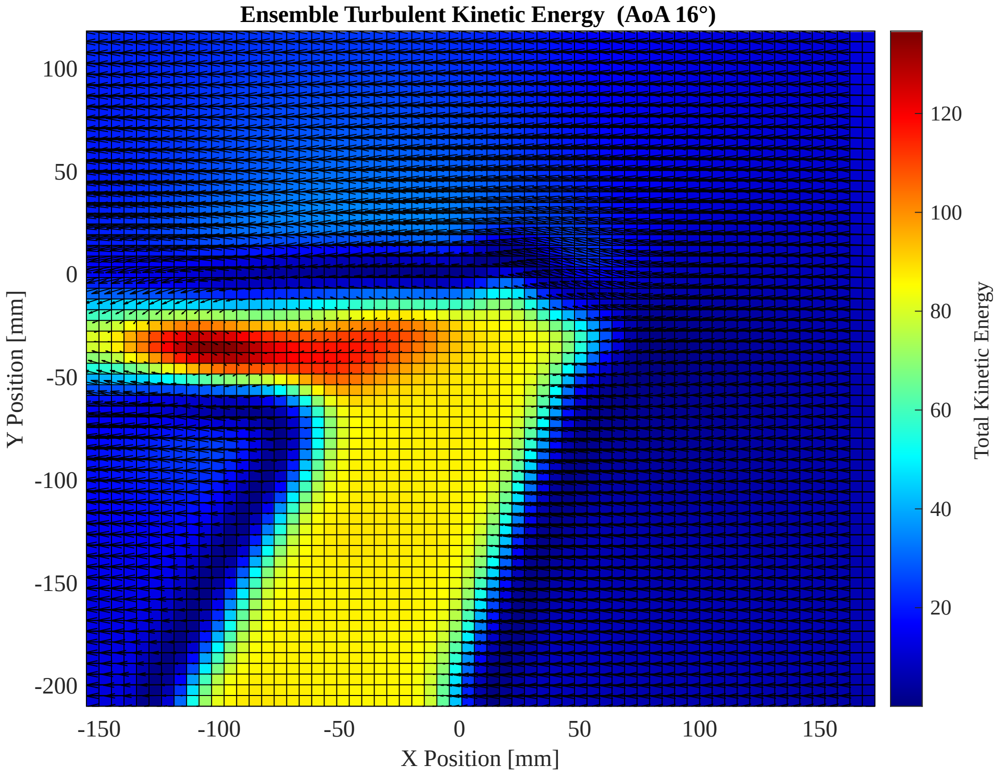


Figure A.13: *The averaged turbulent kinetic energy distribution at* 16° *AoA.*

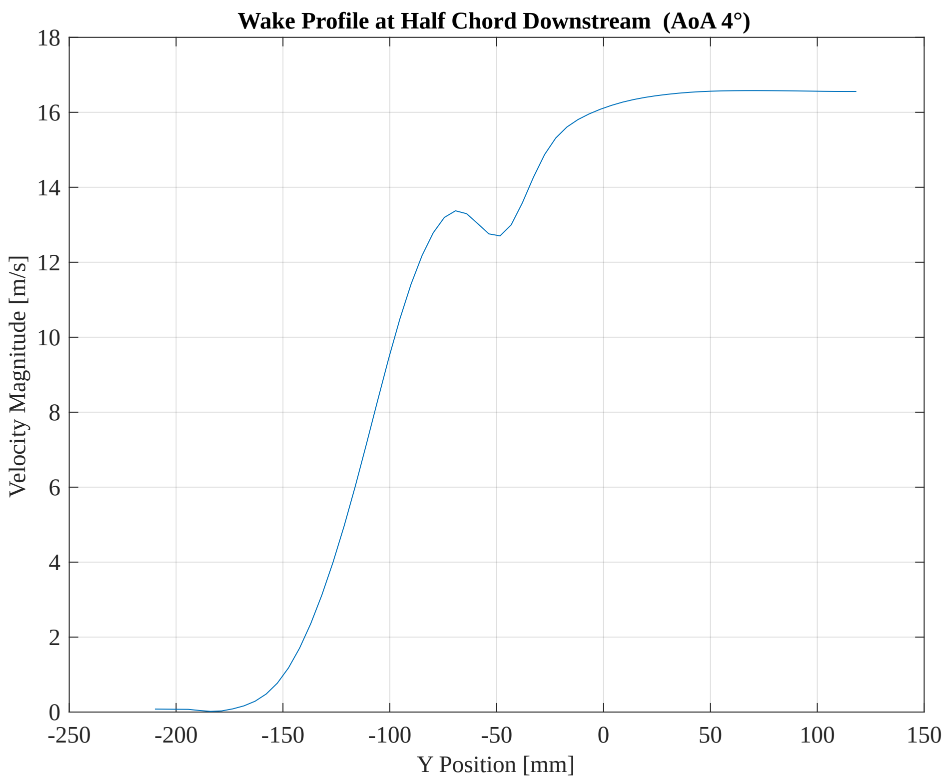


Figure A.14: *The velocity magnitude profile at half chord for* 4° *AoA.*

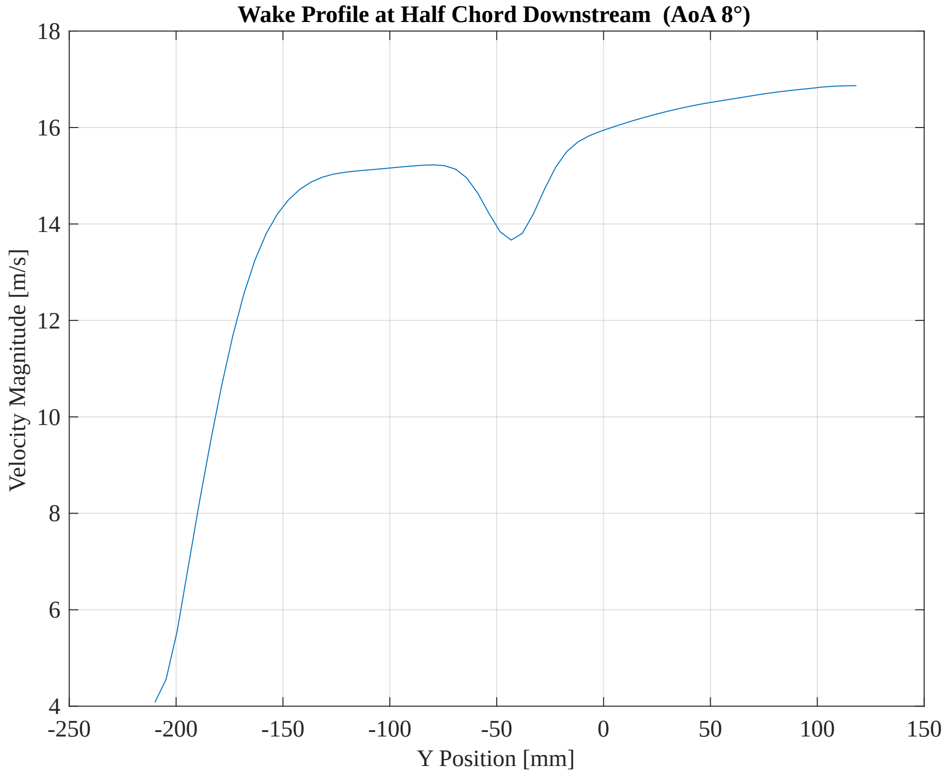


Figure A.15: *The velocity magnitude profile at half chord for* 8° *AoA.*

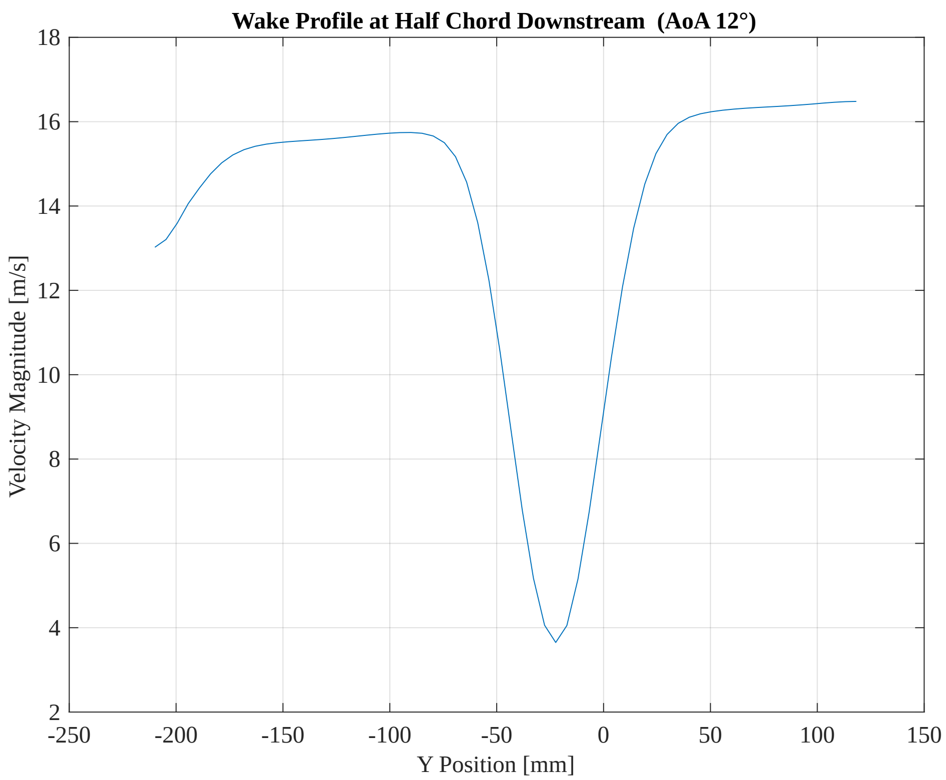


Figure A.16: *The velocity magnitude profile at half chord for* 12° *AoA.*

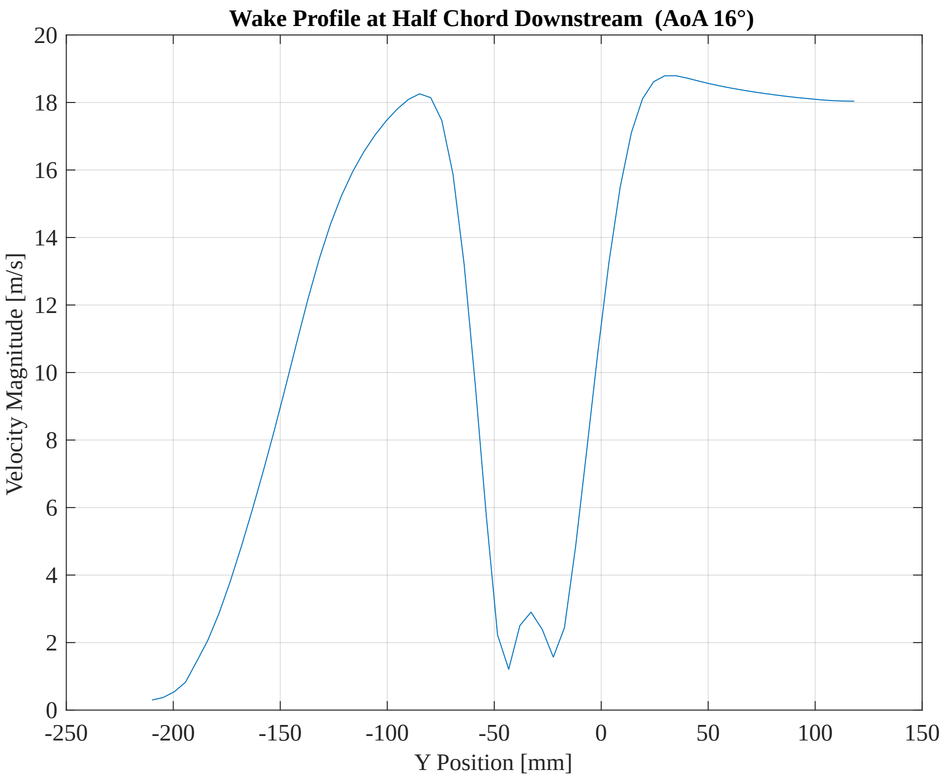


Figure A.17: *The velocity magnitude profile at half chord for* 16° *AoA.*

B

Appendix B

B.1 Lab11Analysis.m

```
% PIV Data Analysis
% AER E 344 Spring 2024 - Section 3 Group 3
clear; clc; close all;

%% Constants
rho = 1.225; % [kg/m^3]
figure_dir = "../Figures/";
data_dir = "./Data/";
zip_dir = "./Data/AER E 344 PIV LAB 11 Data.zip";
file_dir = "./PIV LAB/";
space = 5.209344;
chord = 101; % [mm]

%% Instantaneous PIV Measurements
instant_title = ["B00202.dat","B00245.dat"];
source = ["AOA8","AOA16"];
source_title_str = ["AoA 8°","AoA 16°"];
for t = 1:length(instant_title)
    data = readtable(data_dir+instant_title(t),"VariableNamingRule", ...
        "modify","NumHeaderLines",3);
    data.Properties.VariableNames = {'x','y','Vx','Vy'};
    % Initalize matrices for vorticity calculations.
    X = min(data.x):space:max(data.x)+1;
    Y = max(data.y):-space:min(data.y)-1;
    U = zeros(64,64);
    V = zeros(64,64);
    % Put .dat columns into matrix format with 1,1 in the top left
    count = 1;
    for i = 1:64
        for j = 1:64
            U(i,j) = data.Vx(count);
            V(i,j) = data.Vy(count);
            count = count +1;
        end
```

```
    end
    % Plot velocity field on top of vorticity
    figure;
    colormap("jet");
    [curlz,cav] = curl(X,Y,U,V);
    pcolor(X,Y,curlz);
    hold on;
    quiver(data.x,data.y,data.Vx,data.Vy,"Color","black","AutoScale", ...
        "off");
    title_str = "Instantaneous PIV Measurements";
    title(title_str + " (" + source_title_str(t) + ")");
    xlabel("X Position [mm]");
    ylabel("Y Position [mm]");
    fontname("Times New Roman");
    fontsize(12, "points");
    c = colorbar;
    c.Label.String = "Vorticity [s^{-1}]";
    saveas(gcf, figure_dir + title_str + " - " + source(t) + ".svg");
    %% Slide 30 Method (does not look right compared to TecPlot)
    % figure
    % [PartialVx,PartialVy] = gradient(V,space,-space);
    % [PartialUx,PartialUy] = gradient(U,space,-space);
    % w = PartialVy - PartialUx;
    % pcolor(X,Y,w);
end

%% Ensemble Average Measurements
unzip(zip_dir);
dirs = ["AOA4","AOA8","AOA12","AOA16"];
aoa_str = ["AoA 4°","AoA 8°","AoA 12°","AoA 16°"];
for d = 1:length(dirs)
    sum = table(data.x,data.y,zeros(4096,1),zeros(4096,1),zeros(4096,1));
    sum.Properties.VariableNames = {'x','y','U','V','TKE'};
    % Iterate through all 250 frames to get ensemble average
    for f = 1:250
        filename = file_dir+dirs(d)+"/B00"+num2str(f,"%03d")+".dat";
        data = readtable(filename,"VariableNamingRule","modify", ...
            "NumHeaderLines",3);
        data.Properties.VariableNames = {'x','y','Vx','Vy'};
        sum.U = sum.U + data.Vx;
        sum.V = sum.V + data.Vy;
    end
    sum.U = sum.U/250;
    sum.V = sum.V/250;
    count = 1;
    for i = 1:64
        for j = 1:64
            U(i,j) = sum.U(count);
            V(i,j) = sum.V(count);
            count = count +1;
        end
```

```
    end
    % Plot ensemble average data
    figure;
    colormap("jet");
    [curlz,cav] = curl(X,Y,U,V);
    pcolor(X,Y,curlz);
    hold on;
    quiver(sum.x,sum.y,sum.U,sum.V,"Color","black","AutoScale","off");
    title_str = "Ensemble PIV Measurements";
    title(title_str + " (" + aoa_str(d) + ")");
    xlabel("X Position [mm]");
    ylabel("Y Position [mm]");
    fontname("Times New Roman");
    fontsize(12, "points");
    c = colorbar;
    c.Label.String = "Vorticity [s^{-1}]";
    saveas(gcf, figure_dir + title_str + " - " + dirs(d) + ".svg");

    %% Turbulence Distributions
    avg_U = mean(sum.U);
    avg_V = mean(sum.V);
    prime = table(data.x,data.y,zeros(4096,1),zeros(4096,1));
    prime.Properties.VariableNames = {'x','y','u','v'};
    for f = 1:250
        filename = file_dir+dirs(d)+"/B00"+num2str(f,"%03d")+".dat";
        data = readtable(filename,"VariableNamingRule","modify", ...
            "NumHeaderLines",3);
        data.Properties.VariableNames = {'x','y','Vx','Vy'};
        prime.u = prime.u + ((data.Vx - avg_U).^2)/250;
        prime.v = prime.v + ((data.Vy - avg_V).^2)/250;
    end
    prime.u = sqrt(prime.u);
    prime.v = sqrt(prime.v);
    sum.TKE = .5 * rho * (prime.u.^2 + prime.v.^2);
    TKE = zeros(64,64);
    % RE = zeros(64,64);
    % Put .dat columns into matrix format with 1,1 in the top left
    count = 1;
    for i = 1:64
        for j = 1:64
            TKE(i,j) = sum.TKE(count);
            %RE(i,j) = sum.tau(count);
            count = count +1;
        end
    end
    figure;
    colormap("jet");
    pcolor(X,Y,TKE);
    hold on;
    quiver(sum.x,sum.y,sum.U,sum.V,"Color","black","AutoScale","off");
    title_str = "Ensemble Turbulent Kinetic Energy";
```

```
    title(title_str + "  (" + aoa_str(d) + ")");
    xlabel("X Position [mm]");
    ylabel("Y Position [mm]");
    fontname("Times New Roman");
    fontsize(12, "points");
    c = colorbar;
    c.Label.String = "Total Kinetic Energy";
    saveas(gcf, figure_dir + title_str + " - " + dirs(d) + ".svg");

    %% Reynolds Stress (add tau column to sum table)
    % sum.tau = -rho* prime.u .* prime.v;
    % figure;
    % colormap("jet");
    % pcolor(X,Y,RE);
    % hold on;
    % quiver(sum.x,sum.y,sum.U,sum.V,"Color","black","AutoScale","off");
    % title_str = "Reynold"s Stress Distribution (" + dirs(d) + ")";
    % title(title_str);
    % colorbar;

    %% Wake Profile at 1/2 chord downstream
    figure;
    % Estimating half chord is at x position of 0 (about index 31)
    % Half Chord downstream is about -100 millimeters (about index 11)
    plot(Y,sqrt(U(:,11).^2 + V(:,11).^2));
    title_str = "Wake Profile at Half Chord Downstream";
    title(title_str + "  (" + aoa_str(d) + ")");
    xlabel("Y Position [mm]");
    ylabel("Velocity Magnitude [m/s]");
    fontname("Times New Roman");
    fontsize(12, "points");
    grid on;
    saveas(gcf, figure_dir + title_str + " - " + dirs(d) + ".svg");

    %% Write to File
    filename = "./Data/Ensemble/"+dirs(d)+".dat";
    fid = fopen(filename, "wt");
    fprintf(fid, 'TITLE = "%s"\n',dirs(d));
    fprintf(fid, 'VARIABLES = "x", "y", "Vx", "Vy", "TKE"\n');
    fprintf(fid, 'ZONE T="Frame 0", I=64, J=64\n');
    fclose(fid);
    writetable(sum, filename,"Delimiter","\t","WriteVariableNames", ...
        false,"WriteMode","append");
end

%% Clean Up
rmdir(file_dir,"s");
```