AAE 334L

Lab 4: Supersonic Wind Tunnel
Post-Lab Assignment

Purdue University

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1. Lab Objectives (5)

In 500 words or less, discuss the objectives of this lab and how well they were met and to what extent they were not met. If applicable, discuss reasons why particular objectives were not met during your performance of the lab and how these challenges might be addressed in the future.

The first objective of this lab was to understand how the pressure distribution along the nozzle for the supersonic wind tunnel was measured using a pressure transducer system. In the experiment, we were able to see how the tubes were connected to which pressure channel along the wing tunnel. At the other end, the tubes were connected to the pressure transducer, which is a device taking in the pressure readings from the air flow in the wind tunnel and translates them to a digital signal. Out team did not actually set this up; however, we were able to identify each pressure channels and their purposes by going through the experiment. Thus, we can say that this objective has been fulfilled.

The second objective of this lab was to measure oblique shockwave angles using the schlieren or shadowgraph photography. This objective was sufficed in that we were able to obtain the shadowgraph photos of each bodies in the supersonic wind tunnel as well as their generated shock waves. Along with these shadowgraph images, the LabView software was used to collect the data of the pressures of those generated shockwaves for multiple locations down the wind tunnel. From these pressure values we were able to compute the Mach numbers and the Mach numbers give us the angle of the shock wave using the Prandtl-Meyer function. Thus, we can say that we have satisfied the second objective.

For the third objective, as aforementioned, we were able to obtain the pressure values using the pressure transducer system and these pressure values were for the oblique shock and the expansion fan. Since, we have successfully obtained data for this we can conclude that we have satisfied the objective of collecting the pressure data.

The last objective is also related to the pressure values that we have obtained using LabView. By analyzing the pressure data, we were able to calculate the pressure losses across the normal shock wave formed by a blunt body. This particular trait for the blunt body was clearly examined for the experiment using the body with a round and bullet-like end.

Since we had the time, we were also able to collect data for 3 more bodies which had distinct traits and formed different types of shockwaves due to their geometric differences. We have successfully completed all data acquisitions and were able to conduct additional experimentation. Hence, we were able to end lab4 successfully while fulfilling all objectives.

2. Data Presentation and Analysis (25 points)

2.1 (10 points) Pressure Measurements

- (6 points) For all cases (3 models – wedge, diamond airfoil, and blunt body), plot the measured pressure vs. distance along the wind tunnel and indicate the approximate location of any shock or expansion waves.

By taking the mean for each psi settings (e.g. 40 psi, 45psi, etc.) we can plot the pressure distribution over the pressure tap locations as for each small wedge, diamond, and blunt body as the following.

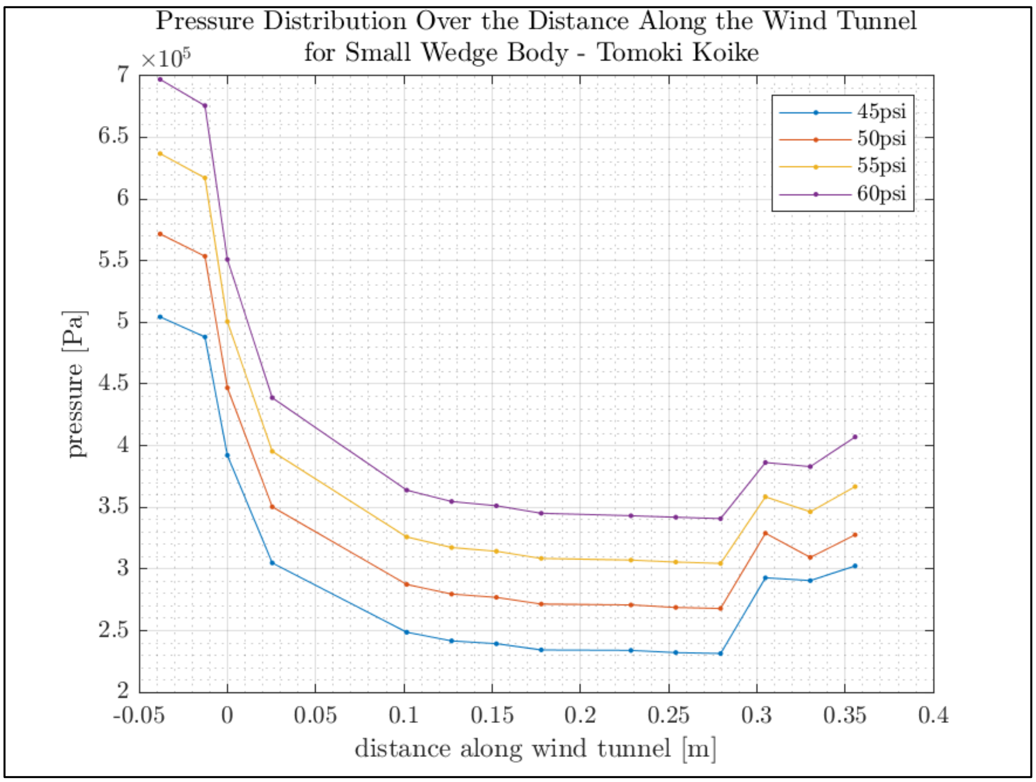

Figure 1: pressure distribution for the small wedge

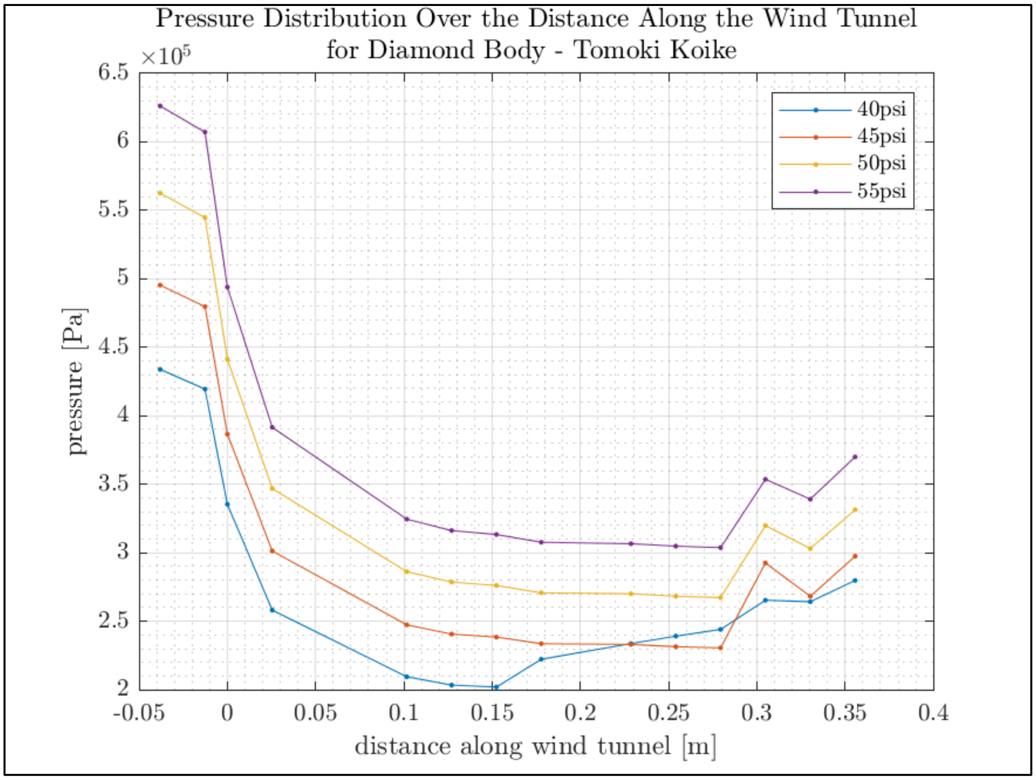

Figure 2: pressure distribution for a diamond body

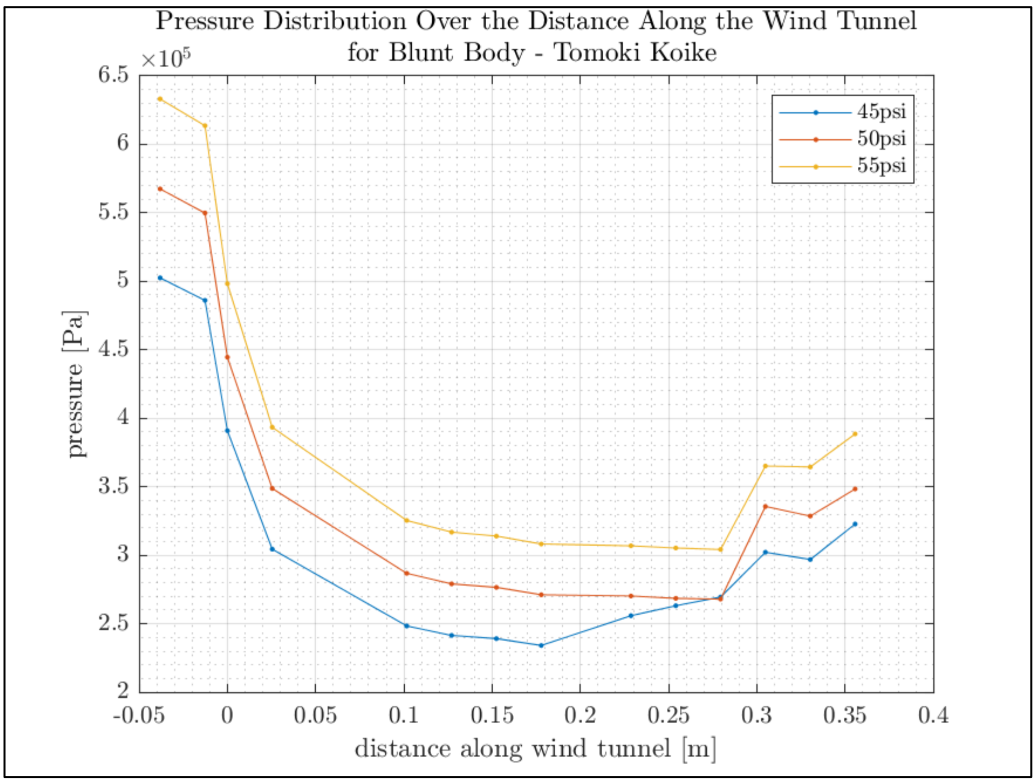

Figure 3: pressure distribution for a blunt body

Since shock waves cause the pressure to increase and the expansion fans cause the pressure to decrease, we can deduce by observing the plots the locations of where the shockwaves and expansion fans occur.

The expansion fans are occurring through the 2^{th} and 6^{th} pressure tap which are located approximately -0.0127 [m] to 0.0762 [m] inward the wind tunnel from the throat. This is because we can see the highest rate of decrease and continuous reduction of pressure at these point for all three bodies.
Whereas, the shockwave is thought to occur through the pressure taps from the 14^{th} to 17^{th} which are located 0.2794 [m] to 0.3556 [m] inward the wind tunnel from the throat. We can say that because there is sharp increase of pressure taking place in those ranges.

- (4 points) Use the pressure measurements or the nozzle area to calculate the Mach number vs. location along the wind tunnel leading up to the model. You need only to do this for one case as the Mach number will always be the same in the test section.

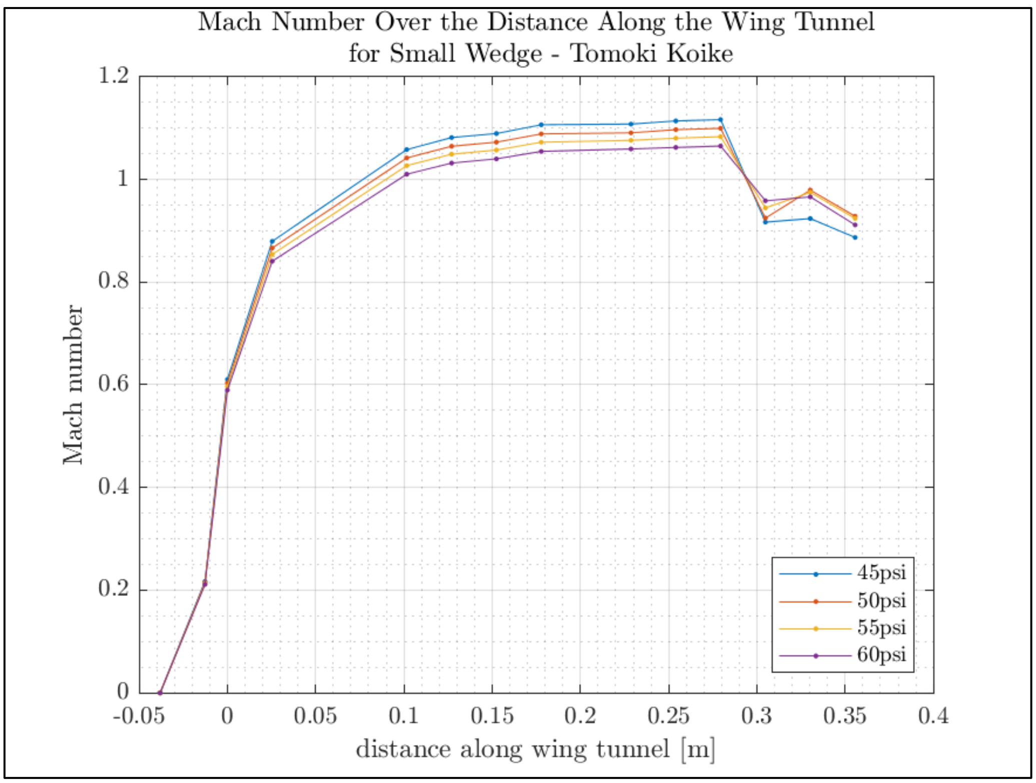

Figure 4: Mach number over the distance for small wedge

2.2 *(10 points) Wedge and Diamond Airfoil*

- (4 points) For the wedge and the diamond airfoil, briefly describe what you observe in the schlieren images.

The shadowgraph photography for the small wedge and the diamond are the following images

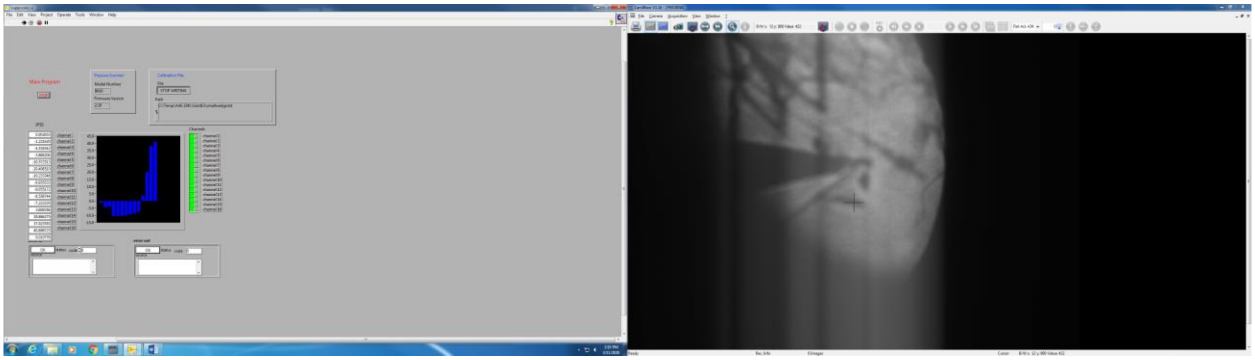

Figure 5: Shadowgraph photography of the small wedge at 60 psi

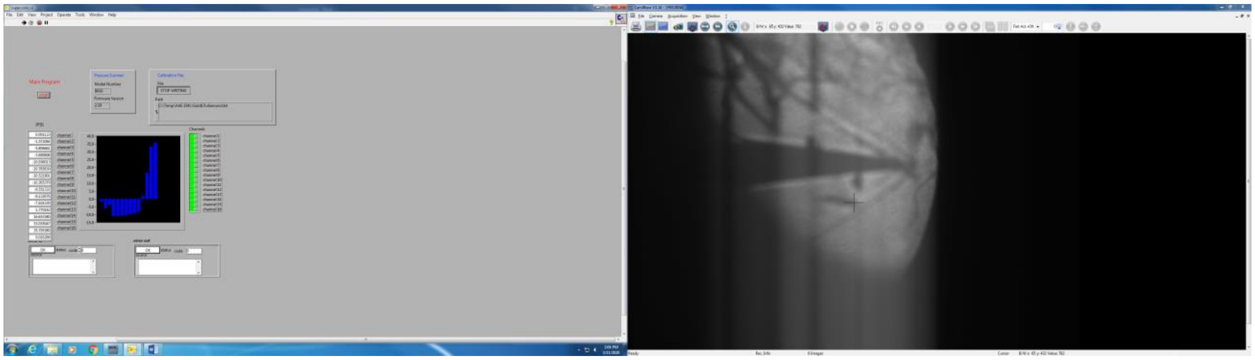

Figure 6: Shadowgraph photography of the diamond body at 55 psi

From the image above we can see an oblique shockwave forming from the tip of the body due to its angle. The clear lines are apparent, and if we look carefully there are also fading subsequent lines following the shockwaves.

- (6 points) Use the schlieren images to estimate the oblique shock angles. How do the measured shock angles compare with the theoretical shock angle (calculated based on upstream Mach number and wedge angle)?

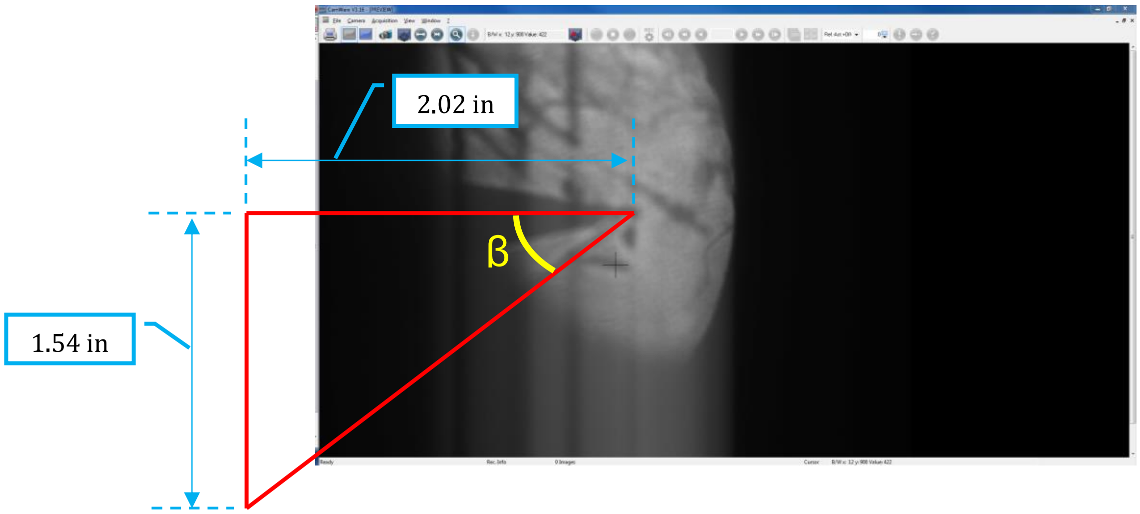

Figure 7: demonstration of measuring the angle of the shockwave for diamond body

From the demonstration we can calculate the shockwave angle to be

$$\beta_{exp} = \arctan\left(\frac{2.02\ in}{1.54\ in}\right) = 0.6514\, rad = 37.3210\ deg$$

Now since the wedge angle θ ≅ 0.2793 rad ≅ 16 deg, and using the following formula

$$\cot\beta = \tan\theta\left[\frac{(\gamma+1)M^2}{2(M^2 sin^2\beta - 1} - 1\right]$$

and by solving this function for β we can obtain the shockwave angle. For Mach number we will use the Mach number calculated from the data of pressure tap 15. This is because the pressure increases sharply at that point which is in the test section. This is for the diamond object at 55 psi.

$$\text{now since } M = 0.5922,\ \gamma = 1.4,\ \theta = 0.2793 \text{ rad}$$

we get the following numerical solution computed from MATLAB

$$w = -1.6137 + 1.1250i$$

By taking the argument/arg(w) of this complex number we can obtain the angle.

$$\beta' = atan2(1.1250, -1.6137) = 145{,}1159\ deg$$

Since,

$$\tan(-\varphi) = -\tan(\varphi) = \tan\,(\pi - \varphi)$$

Thus,

$$180° - 145.1159° = 38.8841°,\ \ and\ \ -\tan(38.8841°) = \tan\,(180° - 145.1159°)$$

$$\beta = 38.8841°$$

And as a result, the percent error of the experimental and theoretical values for the angle is

$$error\% = |37.3210 - 38.8841|/38.8841 * 100 = 4.0199\%$$

From this, we can say that we have a considerably accurate result for the experimental result.

2.3 (5 points) Blunt Body

- (2 points) Briefly describe what you observe in the schlieren images.

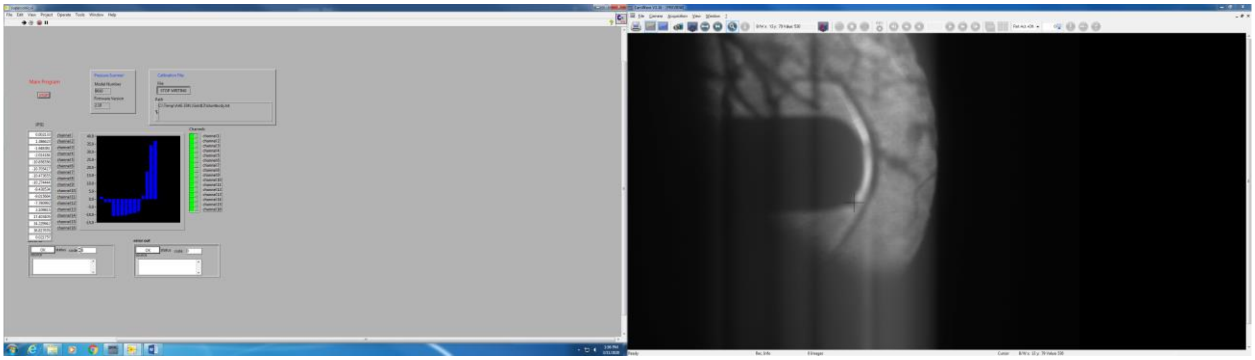

Figure 8: shadowgraph photography for a blunt body at 50 psi

The image shows that for a blunt body the shockwave is not a angled in the way the wedge and diamond demonstrates due to its rounded body geometry. However, the distinctive trait for this shockwave is that it is curved in the way the blunt body is shaped, called a bow shock, and shows a much more clear shockwave than the other two bodies.

- (3 points) Briefly discuss how you might estimate the pressure drop across the detached bow shock wave 1) near the nose of the blunt body and 2) far from the blunt body.

For the pressure drop near the nose of the blunt body we can estimate the pressure drop by hypothesizing multiple layers of oblique shocks and each with small angles. Though it takes many steps, by computing with small angles and integrating all the layers we can account for the curved and detached trait of a bow shock. For the downstream, we can assume it to be a normal shock to obtain the pressure loss.

3. Appendix

3.1 Shadowgraph photography

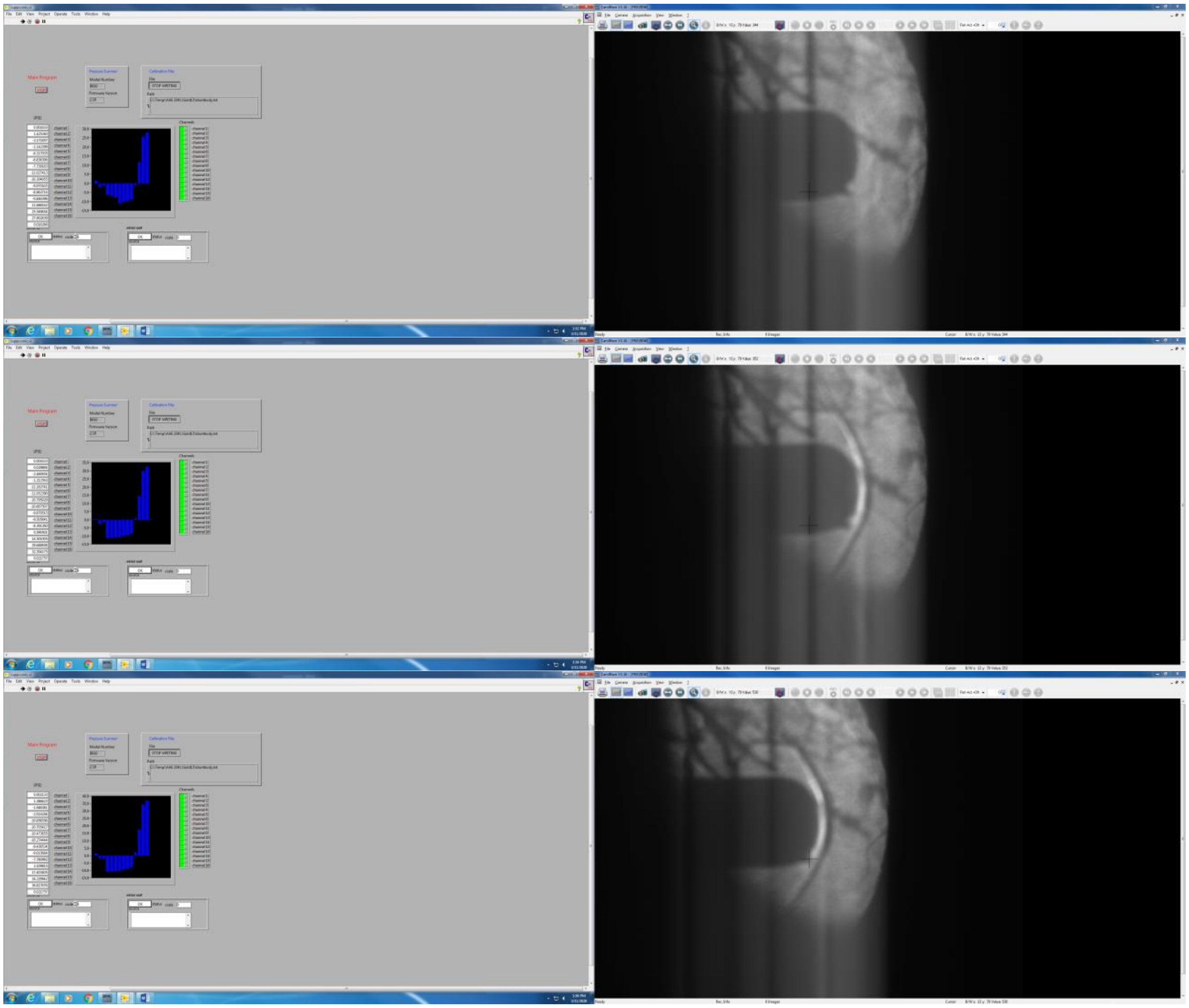

Figure 9: shadowgraph photography for blunt body for 45, 50, 55 psi

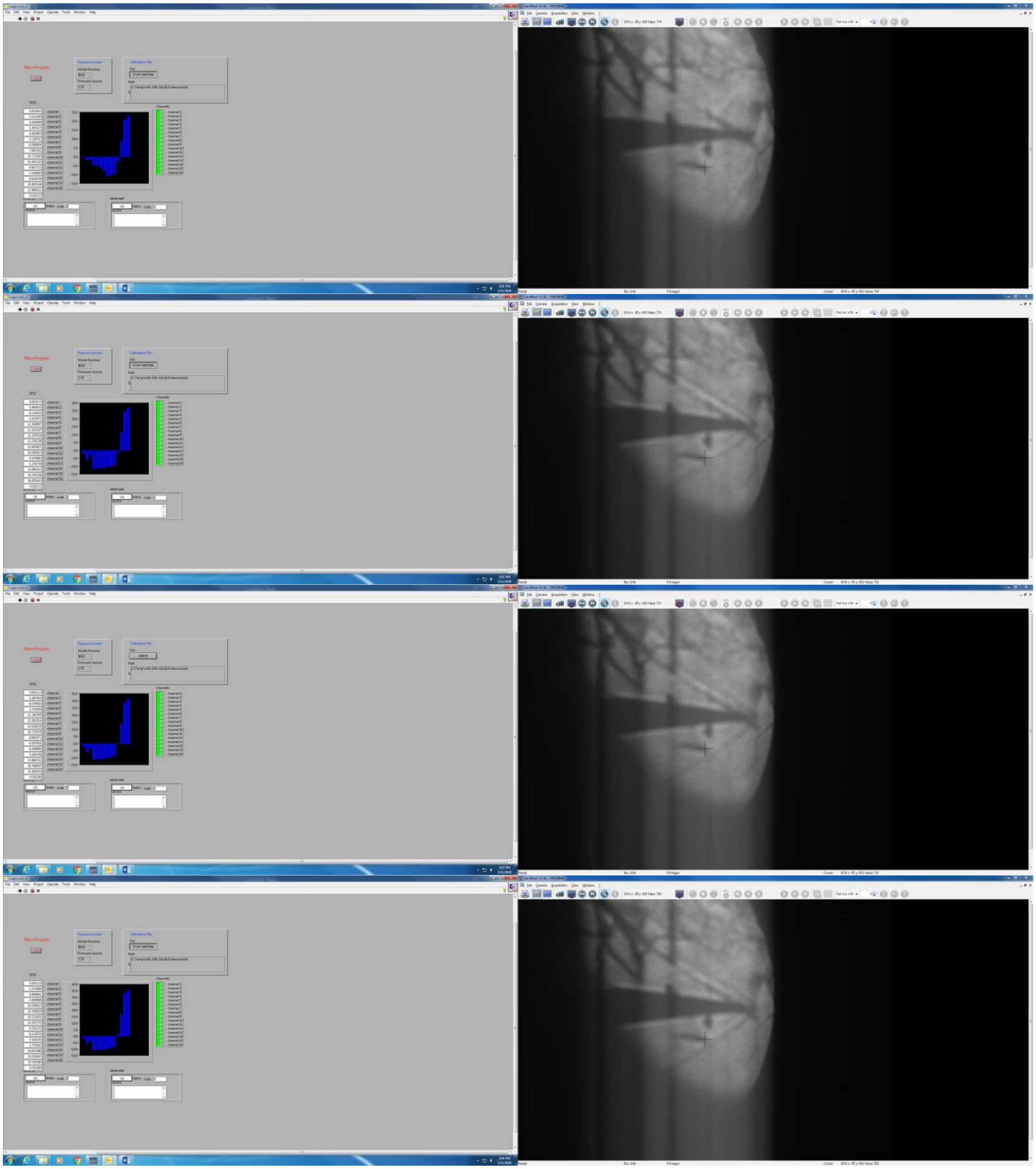

Figure 10: shadowgraph photography of diamond body for 40, 45, 50, 55 psi

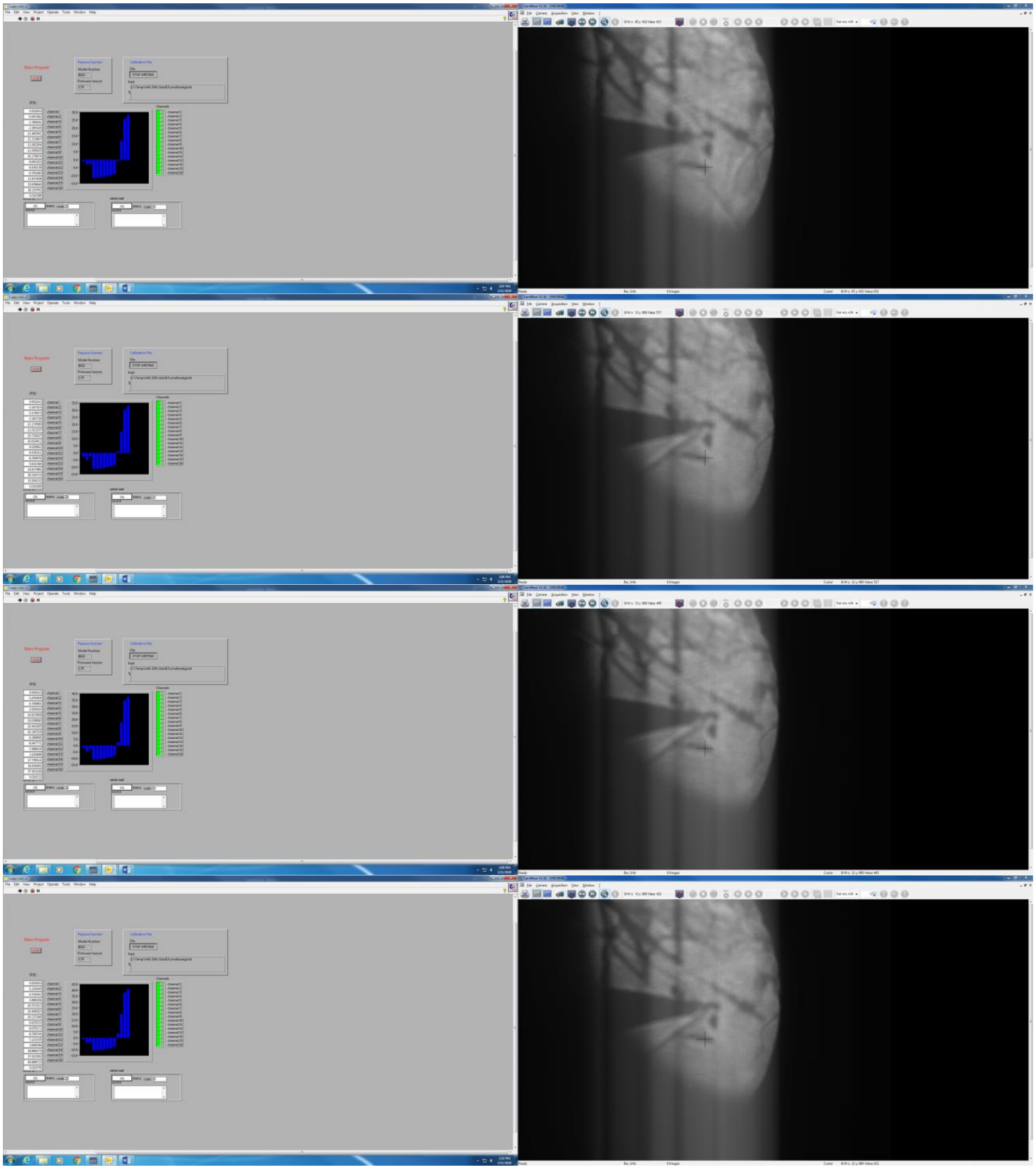

Figure 11: shadowgraph photography of small wedge for 45, 50, 55, 60 psi

3.2 MATLAB code

AAE334L Lab4 Postlab MATLAB CODE

```
clear all; close all; clc;
fdir = 'C:\Users\Tomo\Desktop\studies\2020-Spring\AAE334LAB\matlab\outputs\lab4';
set(groot, 'defaulttextinterpreter',"latex");
set(groot, 'defaultAxesTickLabelInterpreter',"latex");
set(groot, 'defaultLegendInterpreter',"latex");
```

SETUP

```
% Defining necessary constants
gamma = 1.4;


% Defining the vector with the pressure tap locations
p_tap = inch2m([14 13 12 11 10 9 7 6 5 4 1 0 -0.5 -1.5]);


% Reference pressures
P_ref_40 = psi2Pa(40);  % 40 psi [Pa]
P_ref_45 = psi2Pa(45);  % 45 psi [Pa]
P_ref_50 = psi2Pa(50);  % 50 psi [Pa]
P_ref_55 = psi2Pa(55);  % 55 psi [Pa]
P_ref_60 = psi2Pa(60);  % 60 psi [Pa]


% Importing data
% Small wedge
data_SW = readmatrix("inputs\lab4\small_wedge.xlsx");
data_SW = psi2Pa(data_SW);  % converting units from psi to Pa
% Diamond
data_DM = readmatrix("inputs\lab4\diamond.xlsx");
data_DM = psi2Pa(data_DM);  % converting units from psi to Pa
% Blunt body
data_BB = readmatrix("inputs\lab4\blunt_body.xlsx");
data_BB = psi2Pa(data_BB);  % converting units from psi to Pa
```

```
% Assigning variables for the acquired pressure data
% Small wedge
% 45 psi
P_SW_45  = P_ref_45 + mean(data_SW(1:7,2:15));
% 50 psi
P_SW_50  = P_ref_50 + mean(data_SW(9:18,2:15));
% 55 psi
P_SW_55  = P_ref_55 + mean(data_SW(20:32,2:15));
% 60 psi
P_SW_60  = P_ref_60 + mean(data_SW(34:46,2:15));
```

```
% Diamond
```

```
% 40 psi
P_DM_40  = P_ref_40 + mean(data_DM(1:12,2:15));
% 45 psi
P_DM_45  = P_ref_45 + mean(data_DM(14:24,2:15));
% 50 psi
P_DM_50  = P_ref_50 + mean(data_DM(26:34,2:15));
% 55 psi
P_DM_55  = P_ref_55 + mean(data_DM(36:45,2:15));
```

```
% Blunt body
% 45 psi
P_BB_45  = P_ref_45 + mean(data_BB(1:8,2:15));
% 50 psi
P_BB_50  = P_ref_50 + mean(data_BB(10:21,2:15));
% 55 psi
P_BB_55  = P_ref_55 + mean(data_BB(23:34,2:15));
```

1-a

```
% Plotting the pressure over the location of the pressure tap
% Small wedge
fig1 = figure("Renderer","painters");
    plot(p_tap,P_SW_45,'.-')
    title({'Pressure Distribution Over the Distance Along the Wind Tunnel',
['' ...
        'for Small Wedge Body - Tomoki Koike ']})
    xlabel('distance along wind tunnel [m]')
    ylabel('pressure [Pa]')
    hold on
    plot(p_tap,P_SW_50,'.-')
    plot(p_tap,P_SW_55,'.-')
    plot(p_tap,P_SW_60,'.-')
    hold off
    grid on; grid minor; box on;
    legend('45psi','50psi','55psi','60psi')
saveas(fig1, fullfile(fdir,'p_dist_SW.png'))


% Diamond
fig2 = figure("Renderer","painters");
    plot(p_tap,P_DM_40,'.-')
    title({'Pressure Distribution Over the Distance Along the Wind Tunnel',
['' ...
        'for Diamond Body - Tomoki Koike ']})
    xlabel('distance along wind tunnel [m]')
    ylabel('pressure [Pa]')
    hold on
    plot(p_tap,P_DM_45,'.-')
    plot(p_tap,P_DM_50,'.-')
    plot(p_tap,P_DM_55,'.-')
    hold off
```

```
    grid on; grid minor; box on;
    legend('40psi','45psi','50psi','55psi')
saveas(fig2, fullfile(fdir,'p_dist_DM.png'))


% Blunt body
fig3 = figure("Renderer","painters");
    plot(p_tap,P_BB_45,'.-')
    title({'Pressure Distribution Over the Distance Along the Wind Tunnel',
['' ...
        'for Blunt Body - Tomoki Koike ']})
    xlabel('distance along wind tunnel [m]')
    ylabel('pressure [Pa]')
    hold on
    plot(p_tap,P_BB_50,'.-')
    plot(p_tap,P_BB_55,'.-')
    hold off
    grid on; grid minor; box on;
    legend('45psi','50psi','55psi')
saveas(fig3, fullfile(fdir,'p_dist_BB.png'))
```

1-b

```
% Calculating the Mach numbers
% Small wedge
M_SW_45 = MachNum_from_p(P_SW_45(14),P_SW_45(1:14));
M_SW_50 = MachNum_from_p(P_SW_50(14),P_SW_50(1:14));
M_SW_55 = MachNum_from_p(P_SW_55(14),P_SW_55(1:14));
M_SW_60 = MachNum_from_p(P_SW_60(14),P_SW_60(1:14));


% Diamond
M_DM_40 = MachNum_from_p(P_DM_40(14),P_DM_40(1:14));
M_DM_45 = MachNum_from_p(P_DM_45(14),P_DM_45(1:14));
M_DM_50 = MachNum_from_p(P_DM_50(14),P_DM_50(1:14));
M_DM_55 = MachNum_from_p(P_DM_55(14),P_DM_55(1:14));


% Blunt body
M_BB_45 = MachNum_from_p(P_BB_45(14),P_BB_45(1:14));
M_BB_50 = MachNum_from_p(P_BB_50(14),P_BB_50(1:14));
M_BB_55 = MachNum_from_p(P_BB_55(14),P_BB_55(1:14));
```

```
% Plotting
fig4 = figure("Renderer","painters");
    plot(p_tap, M_SW_45,'.-')
    title({'Mach Number Over the Distance Along the Wing Tunnel',[' for
Small' ...
        ' Wedge - Tomoki Koike']})
    xlabel('distance along wing tunnel [m]')
    ylabel('Mach number')
```

```
    hold on
    plot(p_tap,M_SW_50,'.-')
    plot(p_tap,M_SW_55,'.-')
    plot(p_tap,M_SW_60,'.-')
    hold off
    grid on; grid minor; box on;
    legend('45psi','50psi','55psi','60psi','Location','southeast')
saveas(fig4, fullfile(fdir,'Mach_SW.png'))


fig5 = figure("Renderer","painters");
    plot(p_tap, M_DM_40,'.-')
    title({'Mach Number Over the Distance Along the Wing Tunnel',[' for
Diamond' ...
        ' Body - Tomoki Koike']})
    xlabel('distance along wing tunnel [m]')
    ylabel('Mach number')
    hold on
    plot(p_tap,M_DM_45,'.-')
    plot(p_tap,M_DM_50,'.-')
    plot(p_tap,M_DM_55,'.-')
    hold off
    grid on; grid minor; box on;
    legend('40psi','45psi','50psi','55psi','Location','southeast')
saveas(fig5, fullfile(fdir,'Mach_DM.png'))


fig6 = figure("Renderer","painters");
    plot(p_tap, M_BB_45,'.-')
    title({'Mach Number Over the Distance Along the Wing Tunnel',[' for
Blunt' ...
        ' Body - Tomoki Koike']})
    xlabel('distance along wing tunnel [m]')
    ylabel('Mach number')
    hold on
    plot(p_tap,M_BB_50,'.-')
    plot(p_tap,M_BB_55,'.-')
    hold off
    grid on; grid minor; box on;
    legend('45psi','50psi','55psi','Location','southeast')
saveas(fig6, fullfile(fdir,'Mach_BB.png'))
```

2-a

```
% Calculating the theoretical shockwave angle numerically
syms beta
theta = 0.1396;  % half angle of wedge [rad]
M1 = M_DM_55(12);  % Mach number after shockwave for dimaond @
a1 = (gamma + 1)*M1^2/(2*(M1^2*(sin(beta))^2 - 1));
eqn = cot(theta) == tan(beta)*(a1 - 1);
res = solve(eqn,beta)
res = double(solve(eqn,beta))
```

```
beta = rad2deg(angle(res))


% percent error
err = abs(37.3210 - 38.8841)/38.8841 * 100
```

FUNCTIONS

```
function M = MachNum_from_p(P0,Pi)
    %{
      inputs:  (1) Pi: pressure for the static pressures
                       (vector or scalar input)
      outputs: (1) M:  mach number for isentropic relations (vector
                       or scalar)
    %}

    gamma = 1.4;  % constant of heat capacity ratio
    % Calculating the mach number
    a1 = 2/(gamma - 1);
    a2 = (gamma - 1)/gamma;
    a3 = (P0./Pi).^a2 - 1;
    M = sqrt(a1.*a3);
end
```