IOWA STATE UNIVERSITY

PRESSURE TRANSDUCER CALIBRATION LABORATORY

AER E 344 - LAB 03 - PRESSURE TRANSDUCER CALIBRATION

SECTION 3 GROUP 3

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Abstract

To measure the dynamic pressure and velocity distribution of the low-speed wind tunnel at Iowa State University, we first had to calibrate the pressure transducer we would use to measure the pitot tube pressures in the wind tunnel. By using a plenum chamber and a reference pressure gauge, we calculated the calibration coefficient of our Omega pressure transducer to be $C = 623.3\,\mathrm{Pa/V}$. We then used this calibration coefficient and the Omega pressure transducer to measure the dynamic pressure at distances of 0 cm to 16 cm from the wall of the wind tunnel test chamber. This dynamic pressure data was used to calculate and plot a velocity distribution of the low-speed wind tunnel, which can be used to determine how far objects should be from the wall of the test chamber to avoid boundary layer effects.

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Glossary

C	Electronic manometer calibration constant. *(p. 6, 9, 11)*
K	The wind tunnel calibration constant. *(p. 2, 11)*
L	The distance from the test chamber wall in cm. *(p. 9, 10)*
R^2	The coefficient of determination. *(p. 11)*
V	Voltage measured from the electronic manometer. *(p. 6, 8)*
V_0	Voltage at zero pressure. *(p. 6)*
ρ	Ambient air density of the wind tunnel. *(p. 6)*
p	Pressure. *(p. 2, 6, 8)*
p_0	Stagnation Pressure . *(p. 2)*
q	Dynamic pressure of the wind tunnel test chamber. *(p. 2, 6, 9)*
v	Velocity of the wind tunnel test chamber. *(p. 6, 10)*

Acronyms

MATLAB MATrix LABoratory. *(p. 2, 6)*

1 Introduction

The Omega pressure transducer is a tool used to measure the difference in pressure between its main port and its secondary port. It converts this difference in pressure to a voltage output which is recorded by the data acquisition software. Because of its dual port configuration, the Omega pressure transducer paired with a pitot is well-suited to measure dynamic pressure. Since, by definition,

$$q = p_0 - p \tag{1.1}$$

where q is the dynamic pressure, p_0 is the total or stagnation pressure, and p is the static pressure, the dynamic pressure can be recorded by connecting the stagnation pressure tube to the main port and the static pressure tube to the secondary port on the Omega pressure transducer.

Without proper calibration, however, we cannot directly convert voltage to pressure. To determine the pressure as a function of the voltage output by the Omega pressure transducer, we use a reference pressure gauge and a plenum chamber to find a calibration constant K.

Once we collected the calibration data to find K, we connected the Omega pressure transducer to a pitot tube in the wind tunnel test chamber and recorded the dynamic pressure at distances of 0 cm to 16 cm from the wall of the test chamber.

Once all the data was collected, we used a MATrix LABoratory (MATLAB) script to convert the voltage readings into dynamic pressure. Then, we converted the dynamic pressure into velocity and plotted the velocity distribution of the wind tunnel test chamber.

Finding the velocity distribution of a wind tunnel is useful in that it determines the useful width of the wind tunnel. Due to viscous boundary layer effects, the flow near the wall of the wind tunnel will have more turbulence and a decreased flow speed. Determining where this boundary layer begins and ends is crucial to ensure the optimal placement of models and to ensure the wind tunnel is not used to analyze objects that are too wide.

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Methodology

2.1 Apparatus

In this experiment, we calibrated the Omega pressure transducer in the Iowa State University wind tunnel laboratory, shown in Figure 2.1.

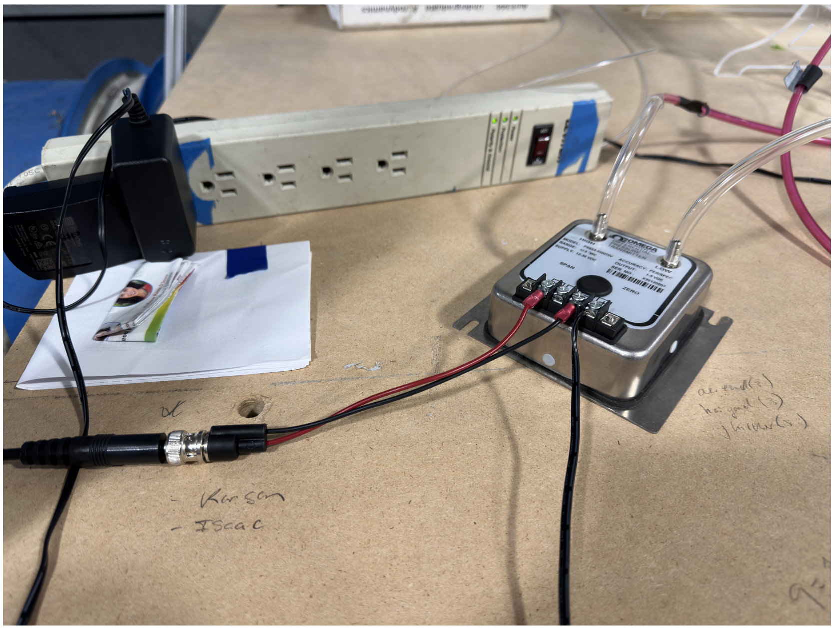

Figure 2.1: *Photograph of the Omega pressure transducer*

In Figure 2.1, we connected the tubing to two ports on the Omega pressure transducer. The first port served as the main port, receiving the total pressure, while the second port was the reference pressure port. The Omega pressure transducer then outputted the dynamic pressure by calculating the difference between the main and reference ports.

In Figure 2.4, we used the wind tunnel, a pitot tube, and the Omega pressure transducer to find the relationship between the dynamic pressure and the distance from the wall. This enabled the determination of the flow speed in the test section as a function of the distance away from the wall.

Figure 2.2: *Photograph of the Mensor Digital Pressure Gauge*

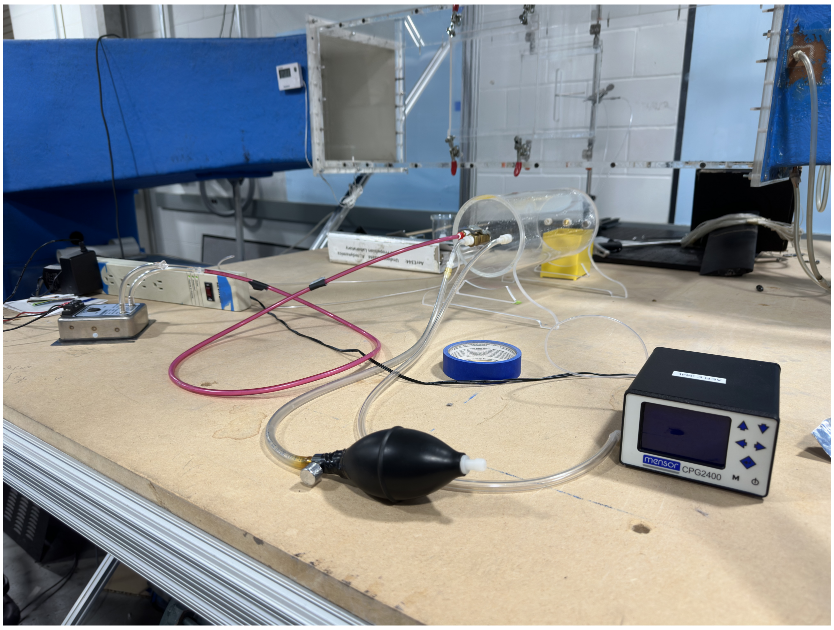

Figure 2.3: *Photograph of the setup that we used to calibrate Omega pressure transducer*

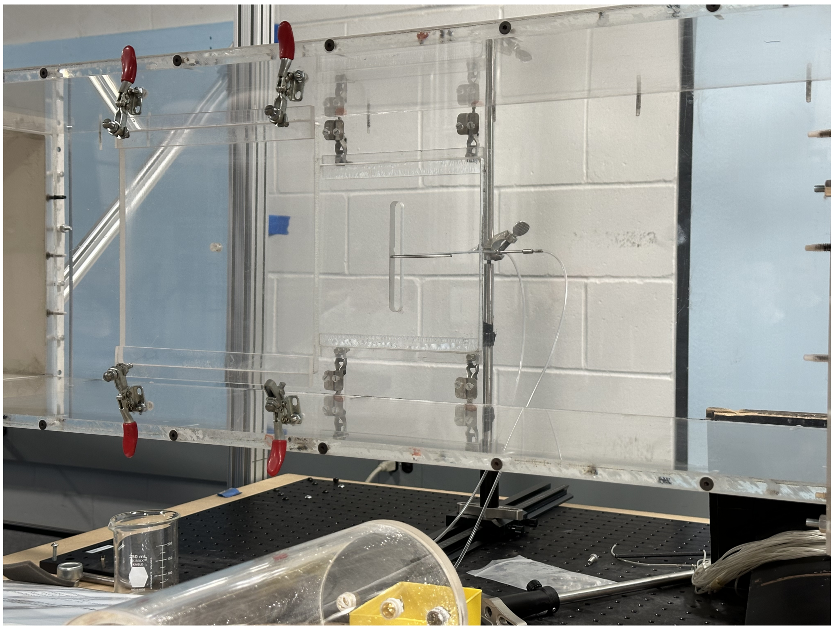

Figure 2.4: *Photograph of the pitot tube that we used in the second part of the lab.*

2.2 Procedures

2.2.1 Electronic Manometer Calibration

1. Measure the voltage with 0 inH_2O of pressure in the chamber.
2. Pressurize close to 5 inH_2O and record the voltage.
3. Open the chamber valve and release about 0.5 inH_2O of pressure.
4. Wait for the pressure to stabilize and record the voltage.
5. Repeat Steps 3–4 until the pressure is 0 inH_2O. Take at least 10 data points. If you reach 0 inH_2O pressure before you have 10 data points, re-pressurize to 5 inH_2O and repeat the process until you have acquired enough data.

2.2.2 Wind Tunnel Dynamic Pressure Distribution Mapping

1. Set the wind tunnel to 15 Hz
2. Start the pitot tube at the wall and sample the voltage from the electronic manometer. Save the file.
3. Move the pitot tube in from the wall 1 cm. and sample the voltage from the electronic manometer. Save the file.
4. Repeat for Step 3 for 15 locations, until the pitot tube should be in the middle of the test section.

2.3 Derivations and Calculations

2.3.1 Reading Data from the Electronic Pressure Transducer

As described in Chapter 1, the Omega pressure transducer must be calibrated before it can be used to measure pressures. The calibration procedure is described in Section 2.2.1. To determine the calibration coefficient, C, we use the equation

$$p = C(V - V_0) \tag{2.1}$$

where p is the difference between the main port pressure and the secondary port pressure, V is the voltage reading from the pressure transducer, and V_0 is the zero-pressure voltage reading of the pressure transducer (Hu, 2024).

When an acquisition is performed with the Omega pressure transducer, it samples the pressure at 1000 Hz for 10 s resulting in 10 000 samples per acquisition. The resulting data file for each acquisition is averaged into a single voltage value. The difference of each averaged voltage value, V, and the zero-pressure voltage, V_0, is related to a known pressure, p, measured from a calibrated digital pressure transducer. A line of best fit can be found for p vs. $V - V_0$, the slope of which is C, as shown by Equation 2.1.

Once C is known, the voltage samples taken from the pitot tube in the wind tunnel test chamber (see Section 2.2.2) can be plugged into Equation 2.1 to determine the dynamic pressure, q, in the wind tunnel test chamber.

The definition of dynamic pressure is

$$q = \frac{1}{2}\rho v^2 \tag{2.2}$$

where q is the dynamic pressure, ρ is the density of air, and v is the flow speed. Equation 2.2 can be rearranged to solve for v as shown below:

$$v = \sqrt{\frac{2q}{\rho}} \tag{2.3}$$

2.3.2 Lab Analysis Script

To analyze the data collected, we wrote an analysis script in MATrix LABoratory (MATLAB), the entirety of which can be found in Appendix B. The key functions are described below:

- The script begins by unzipping the file `data.zip` which contains all the files collected by the data acquisition software. Upon completion of the script, these unzipped data files will be removed.
- We use a `for` loop to open each data file and extract the voltage data. This voltage data is averaged for each data file.
- The `polyfit` function is used to calculate a linear line of best for the pressure vs. voltage differential data. The slope of this linear regression is C.

- Once C has been defined, we calculate the dynamic pressure and velocity of air in the wind tunnel test chamber using the acquired voltage data.
- The line of best fit for the dynamic pressure and velocity distribution graphs was calculated as a piece-wise function. The first two data points are fit with a quadratic line of best fit to simulate the viscous boundary layer effects. After the second data point, a third order polynomial is used to fit the remaining data.
- All the data is plotted with the lines of best fit shown underneath the data. Finally, the graphs are saved to an `.svg` file.

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Results

3.1 Calibration Data

Figure 3.1 shows the relationship between pressure [Pa] and voltage [V]—specifically the voltage reading from the Omega pressure transducer less the zero-pressure voltage. The slope of this line is the calibration coefficient, $C = 623.3$. The pressure values were manually logged using the Mensor digital pressure gauge whereas the voltage readings were recorded automatically via the data acquisition software (see Section 2.2). The line of best for this figure is shown in Equation 3.1

$$p = 623.3(V - V_0) \tag{3.1}$$

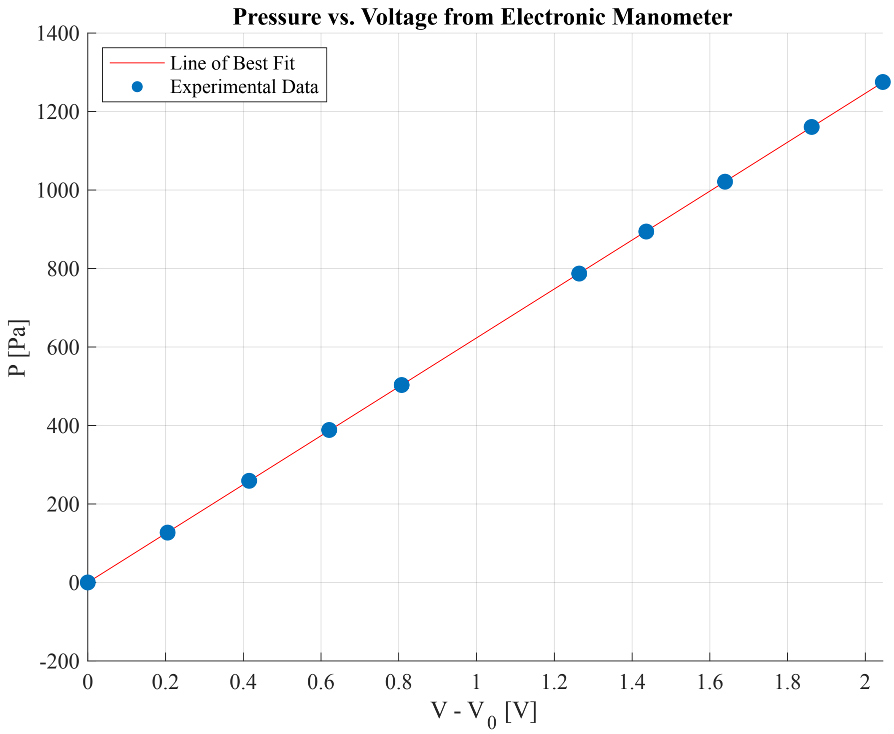

Figure 3.1: *A plot of the pressure, p, vs. the voltage measured from the electronic manometer, V.*

3.2 Dynamic Pressure Distribution Data

Figure 3.2 shows the dynamic pressure [Pa] in the test chamber as a function of the distance [cm] the pitot tube was from the wall of the test chamber. The distance, L, was manually adjusted for each experiment by using a graduated slider with a mounted pitot tube. The pressure values were calculated using the voltage recorded from the data acquisition software and the calibration coefficient, C. The line of best fit is a piece-wise function, defined in Equation 3.2.

$$q = \begin{cases} -17.44L^2 + 55.51L & 0 \leq L < 1 \\ 0.01316L^3 - 0.4481L^2 + 5.095L + 33.13 & 1 \leq L < 16 \end{cases} \tag{3.2}$$

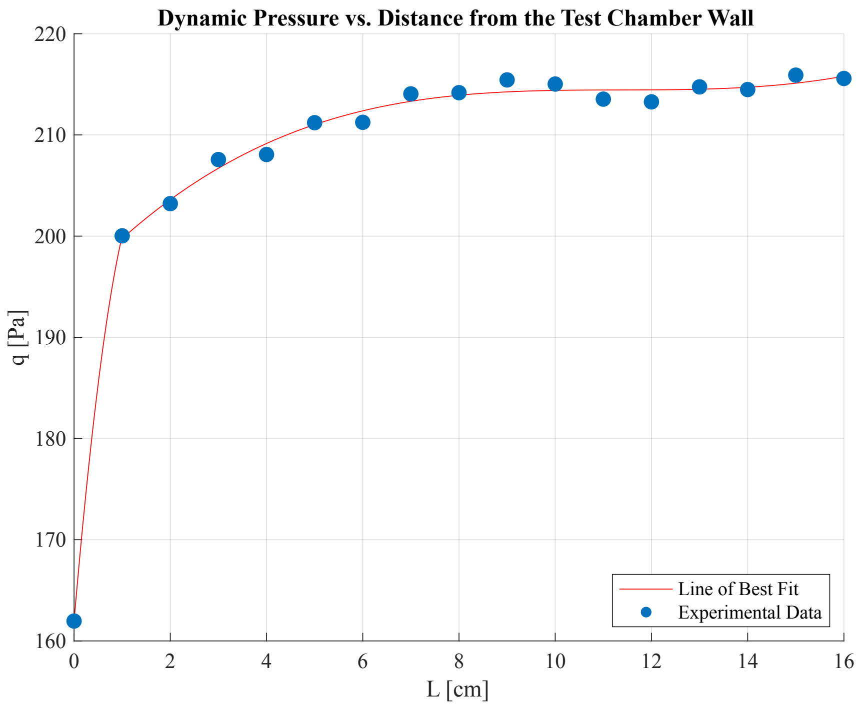

Figure 3.2: *A plot of the dynamic pressure, q, vs. the distance from the test chamber wall, L.*

Figure 3.3 shows the flow velocity [m/s] in the test chamber as a function of the distance [cm] the pitot tube was from the wall of the test chamber. The distance, L, was manually adjusted for each experiment by using a graduated slider with a pitot tube mounted to it (see Figure 2.4). The velocity data was calculated using the dynamic pressure data and Equation 2.3. The line of best fit is a piece-wise function, defined in Equation 3.3.

$$v = \begin{cases} -3.780L^2 + 11.66L & 0 \leq L < 1 \\ 0.001297L^3 - 0.04385L^2 + 0.4923L + 7.419 & 1 \leq L < 16 \end{cases} \tag{3.3}$$

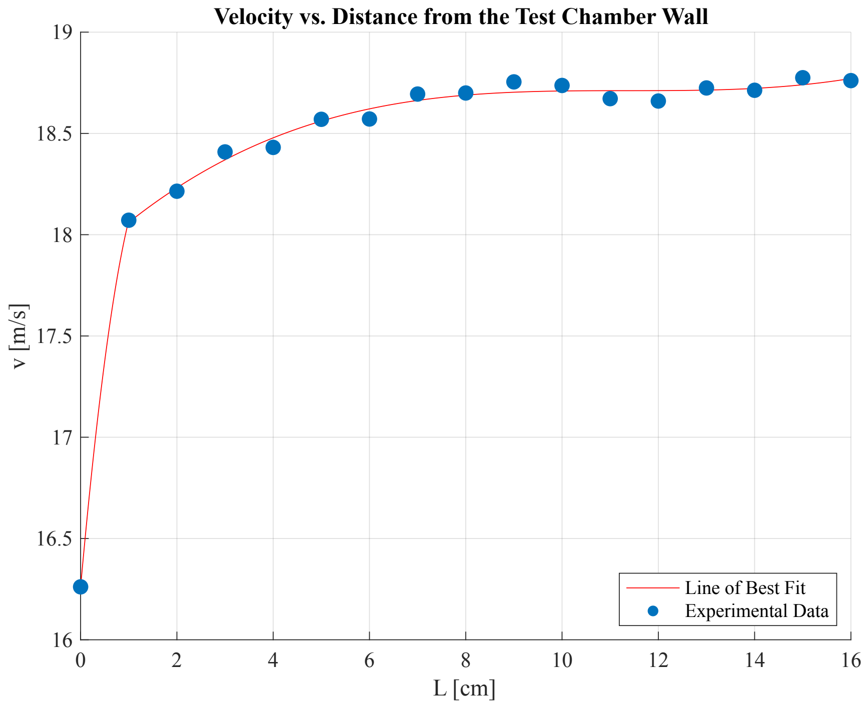

Figure 3.3: *A plot of the velocity, v, vs the distance from the test chamber wall, L.*

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Discussion

Figure 3.1 shows the relationship between known pressure values and the voltage output of the Omega pressure transducer. The coefficient of determination, R^2, was extremely high: $R^2 = 0.999997$. This extremely precise correlation is due to the accuracy and precision of the Omega pressure transducer. This R^2 value *does not* mean our calibration coefficient, C, is accurate to the same degree. Since the pressure values were logged manually and the Mensor digital pressure gauge would not consistently settle to a certain pressure, the calibration constant may be inaccurate. See Appendix C for a discussion on the calibration constant error.

Figure 3.1 and Figure 3.3 both show the general shape and trends we expected. At the wall of the wind tunnel, $L = 0$, the flow velocity is significantly lower than the rest of the test chamber due to viscous boundary layer effects. Further from the wall, the velocity levels out to the expected flow speed. By using the wind tunnel calibration constant, K, that we calculated in lab two, we determined that the air speed in the wind tunnel for a 15 Hz motor frequency should be approximately 19.4 m/s. Figure 3.3 shows the velocity in the wind tunnel near the center of the test chamber was close to the expected velocity. The approximate 1 m/s difference is likely due to inaccuracy in our pressure transducer calibration coefficient, C, as discussed in Appendix C.

This data is useful to determine the useful width of the wind tunnel if an object with finite width is being measured. Examining Figure 3.2, it is clear that any object or probes placed within 6 cm of the test chamber walls will experience unrepresentative flow conditions compared to the center of the test chamber.

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Conclusion

In conclusion to this lab 3, we found that the relationship between the pressure and the voltage was a linear relationship. This then allowed us to assess the uncertainty associated with the measurements that we collected in the lab. This was a vital part of the lab because we then took that data to calculate the dynamic pressure map for the wind tunnel. As a result, we were able to create an illustration of the dynamic pressure distribution within the test section of the wind tunnel. By incorporating the calibrated measurements, we were able to gain valuable insights into the variations in dynamic pressure across different regions of the test section. This approach not only allowed us to visually see how the air flow moves through the test section, but it also allowed us to ensure the accuracy of our experiment.

Bibliography

Hu, Hui (2024). *Pressure Transducer Calibration*. Iowa State University. URL: https://www.aere.iastate.edu/~huhui/teaching/2024-01S/AerE344/lab-instruction/AerE344L-Pre-Lab-03.pdf.

A

Appendix A

A.1 Calibration Data

Table A.1: *Averaged calibration data.*

p [inH_2O]	p [Pa]	V [V]	$V - V_0$ [V]
0.00	0.00	2.97	0.00
0.51	0.13	3.17	0.205
1.04	0.259	3.38	0.415
1.56	0.389	3.59	0.621
2.02	0.503	3.77	0.807
3.16	0.787	4.23	1.26
3.59	0.894	4.40	1.44
4.10	1.02	4.61	1.64
4.66	1.16	4.83	1.86
5.12	1.28	5.01	2.05

A.2 Wind Tunnel Dynamic Pressure Distribution Data

Table A.2: *Averaged data from the wind tunnel dynamic pressure distribution measurements.*

L [cm]	V [V]	$V - V_0$ [V]	q [Pa]	v [m/s]
0.0	3.226	0.000	0.00	0.00
1.0	3.287	0.061	38.1	7.88
2.0	3.292	0.066	41.2	8.21
3.0	3.299	0.073	45.6	8.63
4.0	3.300	0.074	46.1	8.68
5.0	3.305	0.079	49.2	8.97
6.0	3.305	0.079	49.3	8.97
7.0	3.309	0.084	52.1	9.22
8.0	3.310	0.084	52.2	9.23
9.0	3.312	0.086	53.5	9.34
10.0	3.311	0.085	53.1	9.31
11.0	3.309	0.083	51.6	9.18
12.0	3.308	0.082	51.3	9.15
13.0	3.310	0.085	52.8	9.28
14.0	3.310	0.084	52.5	9.26
15.0	3.312	0.087	53.9	9.38
16.0	3.312	0.086	53.6	9.36

Appendix B

B.1 Lab3Analysis.m

```
% AER E 344 Spring 2024 Lab 03 Analysis
% Section 3 Group 3
clear, clc, close all;

figure_dir = "../Figures/";
data_zip = "./data.zip";
u = symunit;
rho_air = 1.225; % [kg/m^3]

% Unzip the data file
unzip(data_zip);

%% Import Calibration Data
pStrings = ["0" "0.51" "1.04" "1.56" "2.02" "3.16" "3.59" "4.10" ...
    "4.66" "5.12"]; % [inH_2O]
p = str2double(pStrings); % [inH_2O]
p_pa = double(separateUnits(unitConvert(p .* u.inH2O, u.Pa))); % [Pa]
V = zeros(1, length(p)); % [V]

for i = 1 : length(p)
    dataFile = fopen(strrep(pStrings(i), ".", "") + ".txt", "r");
    dataFormat = "%*s %*s %f";
    V(i) = mean( ...
        cell2mat(textscan(dataFile, dataFormat, "HeaderLines", 5)));
    fclose(dataFile);
end

V_0 = V(1); % [V]

%% Import Wind Tunnel Data
L = 0 : 16; % [cm]
V_q = zeros(1, length(L)); % [inH_2O]

for i = 1 : length(L)
```

```
    dataFile = fopen("p2_" + string(L(i)) + ".txt", "r");
    dataFormat = "%*s %*s %f";
    V_q(i) = mean( ...
        cell2mat(textscan(dataFile, dataFormat, "HeaderLines", 5)));
    fclose(dataFile);
end

V_q_0 = V_0;

%% Calculate Calibration Coefficient
[C_regress, S] = polyfit(V - V_0, p_pa, 1);
C = C_regress(1); % [Pa/V]
R_sq = 1 - (S.normr/norm(p_pa - mean(p_pa)))^2;

fprintf("Calibration Values:\n");
fprintf("V_0 = %g V (zero pressure voltage)\n", V_0);
fprintf("C = %g Pa/V (calibration constant)\n\n", C);
fprintf("Setra electronic manometer calibration curve:\n");
fprintf("\tP = %g(V - V_0) [Pa]\n\n", C);
fprintf("R^2 = %f\n\n", R_sq);

%% Calculate Dynamic Pressure and Velocity
q_tunnel = C .* (V_q - V_q_0); % [Pa]
v_tunnel = sqrt(2 .* q_tunnel / rho_air); % [m/s]

%% Calculate Line of Best Fit for Dynamic Pressure Graph
q_regress_1 = polyfit(L(1:3), q_tunnel(1:3), 2);
q_regress_2 = polyfit(L(2:end), q_tunnel(2:end), 3);

fprintf("Wind Tunnel Mapping:\n");
fprintf("V_0 = %g V (zero pressure voltage)\n\n", V_q_0);
fprintf("q = %gL^2 + %gL + %g [Pa] for 0 <= L < 1\n", q_regress_1);
fprintf("q = %gL^3 + %gL^2 + %gL + %g [Pa] for 1 <= L < 16\n\n", ...
    q_regress_2);

%% Calculate Line of Best Fit for Velocity Graph
v_regress_1 = polyfit(L(1:3), v_tunnel(1:3), 2);
v_regress_2 = polyfit(L(2:end), v_tunnel(2:end), 3);

fprintf("v = %gL^2 + %gL + %g [m/s] for 0 <= L < 1\n", v_regress_1);
fprintf("v = %gL^3 + %gL^2 + %gL + %g [m/s] for 1 <= L < 16\n", ...
    v_regress_2);

%% Display Data
V_x = 0 : 0.01 : (V(end) - V_0) * 1.15;

figure(1);
h = scatter(V - V_0, p_pa, 75, "filled");
fontname("Times New Roman");
fontsize(12, "points");
title("Pressure vs. Voltage from Electronic Manometer");
```

```
xlabel("V - V_0 [V]");
ylabel("P [Pa]");
hold on;
plot(V_x, polyval(C_regress, V_x), "red");
hold off;
xlim([V(1) - V_0, V(end) - V_0]);
uistack(h, "top");
legend("Line of Best Fit", "Experimental Data", "Location", "northwest");
grid on;
saveas(gcf, figure_dir ...
    + "Pressure vs Voltage from Electronic Manometer.svg");

q_x_1 = L(1) : 0.01 : L(2);
q_x_2 = L(2) : 0.01 : L(end);

figure(2);
h = scatter(L, q_tunnel, 75, "filled");
fontname("Times New Roman");
fontsize(12, "points");
title("Dynamic Pressure vs. Distance from the Test Chamber Wall");
xlabel("L [cm]");
ylabel("q [Pa]");
hold on;
plot(q_x_1, polyval(q_regress_1, q_x_1), "r");
plot(q_x_2, polyval(q_regress_2, q_x_2), "r");
hold off;
uistack(h, "top")
legend("", "Line of Best Fit", "Experimental Data", ...
    "Location", "southeast");
grid on;
saveas(gcf, figure_dir ...
    + "Dynamic Pressure vs Distance from the Test Chamber Wall.svg");

v_x_1 = L(1) : 0.01 : L(2);
v_x_2 = L(2) : 0.01 : L(end);

figure(3);
h = scatter(L, v_tunnel, 75, "filled");
fontname("Times New Roman");
fontsize(12, "points");
title("Velocity vs. Distance from the Test Chamber Wall");
xlabel("L [cm]");
ylabel("v [m/s]");
hold on;
plot(v_x_1, polyval(v_regress_1, v_x_1), "r");
plot(v_x_2, polyval(v_regress_2, v_x_2), "r");
hold off;
uistack(h, "top")
legend("", "Line of Best Fit", "Experimental Data", ...
    "Location", "southeast");
grid on;
```

```
saveas(gcf, figure_dir ...
    + "Velocity vs Distance from the Test Chamber Wall.svg");

delete *.txt
```

B.2 Lab3Uncertainty.m

```
% AER E 344 Spring 2024 Lab 03 Analysis
% Section 3 Group 3
clear, clc, close all;

data_zip = "./data.zip";
u = symunit;
rho_air = 1.225; % [kg/m^3]

% Unzip the data file
unzip(data_zip);

%% Import Calibration Data
pStrings = ["0" "0.51" "1.04" "1.56" "2.02" "3.16" "3.59" "4.10" ...
    "4.66" "5.12"]; % [inH_2O]
p = str2double(pStrings); % [inH_2O]

% uncertainty added due to rising values from manometer during sampling
rng(1234,"twister")
uncertainty = rand(1,length(pStrings))*.15;
p = uncertainty + p; % [inH_2O]
% Zero-pressure reading settled before sampling; no uncertainty added
p(1) = 0;

p_pa = double(separateUnits(unitConvert(p .* u.inH2O, u.Pa))); % [Pa]
V = zeros(1, length(p)); % [V]

for i = 1 : length(p)
    dataFile = fopen(strrep(pStrings(i), ".", "") + ".txt", "r");
    dataFormat = "%*s %*s %f";
    V(i) = mean( ...
        cell2mat(textscan(dataFile, dataFormat, "HeaderLines", 5)));
    fclose(dataFile);
end

V_0 = V(1); % [V]

%% Import Wind Tunnel Data
L = 0 : 16; % [cm]
V_q = zeros(1, length(L)); % [inH_2O]

for i = 1 : length(L)
```

```
    dataFile = fopen("p2_" + string(L(i)) + ".txt", "r");
    dataFormat = "%*s %*s %f";
    V_q(i) = mean( ...
        cell2mat(textscan(dataFile, dataFormat, "HeaderLines", 5)));
    fclose(dataFile);
end

V_q_0 = V_q(1);

%% Calculate Calibration Coefficient
[C_regress, S] = polyfit(V - V_0, p_pa, 1);
C = C_regress(1); % [Pa/V]
R_sq = 1 - (S.normr/norm(p_pa - mean(p_pa)))^2;

fprintf("Calibration Values:\n");
fprintf("V_0 = %g V (zero pressure voltage)\n", V_0);
fprintf("C = %g Pa/V (calibration constant)\n\n", C);
fprintf("Setra electronic manometer calibration curve:\n");
fprintf("\tP = %g(V - V_0) [Pa]\n\n", C);
fprintf("R^2 = %f\n", R_sq);
```

C

Appendix C

C.1 Error in the Calibration Constant

One possible point of error in calculating the Calibration Constant, C, involves the settling of the Mensor Manometer readings used as the standard during Part 1 of the lab. When air was released from the plenum chamber, the value on the manometer would drop before slowly increasing. Data was recorded when the rate of the increasing value slowed; however, the manometer reading continued to increase during the 10s recording period and never seemed to settle completely. Only during the zero-pressure reading was the value stable. We noticed the reading increased up to 0.15 inches of H20 during the recording periods. Assuming bias uncertainty and adding 0.15 to all of the manometer readings would not affect the value of the Calibration Constant since the relationship between the voltage and the pressure reading is linear.

Increasing the manometer readings by random values between 0 and 0.15 may provide insight into more accurate values of the Calibration Constant. This was done in Section B.2 using the $rand()$ function in Matlab where the Calibration Constant was estimated to be 631.937 Pa/volt.

$$\frac{|C_{estimated} - C|}{C} = \frac{|631.937 - 623.286|}{623.286} = 1.38\% \tag{C.1}$$

The percent error between our estimated value of C with random uncertainty values and the calculated value of C using the pressure readings at the start of the recording period is small. Therefore, the increasing pressure readings during the recording period do not seem to affect the value of C greatly.

Comparing our calculated value of C to the reference Calibration Constants provided in the Lab Manual shows a much larger percent error.

$$\frac{|C - C_{Setra1}|}{C_{Setra1}} = \frac{|623.286 - 746.52|}{746.52} = 16.53\% \tag{C.2}$$

This difference in Calibration Constants could be due to the different pressure transducers provided during the lab against what was described in the lab manual. The lab transducer was made by Omega while Setra transducers were described in the manual.