IOWA STATE UNIVERSITY

WIND TUNNEL CALIBRATION LABORATORY

AER E 344 - LAB 02 - WIND TUNNEL CALIBRATION

SECTION 3 GROUP 3

MATTHEW MEHRTENS
JACK MENDOZA
KYLE OSTENDORF
GABRIEL PEDERSON
LUCAS TAVARES VASCONCELLOS
DREW TAYLOR

PROFESSOR

HUI HU, PHD

College of Engineering
Aerospace Engineering
Aerodynamics and Propulsion Laboratory

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Abstract

The low-speed wind tunnel at Iowa State University is operated via a remote which controls the frequency of a motor connected to the wind tunnel. Since the motor frequency is not indicative of flow speed, to perform meaningful aerodynamic analyses, we first determined the calibration constant, K—a coefficient that relates the dynamic pressure in the test chamber to the static pressure measured from two ports upstream of the test section. The calibration constant—which we determined to be $K = 1.08$—enables us to convert the static pressure readings from upstream of the test section into the dynamic pressure of the test section and, subsequently, the air velocity in the test section. Our results indicated a linear relationship for both the dynamic pressure vs. static pressure differential relationship and the air speed vs. motor frequency relationship. The K-coefficient determined in this lab will be used to calculate the dynamic pressure and airspeed in future labs.

Contents

List of Figures

List of Tables

Glossary

C	Dimensionless constant that relates the static pressure differential and the dynamic pressure. *(p. 6)*
g	Acceleration due to gravity. *(p. 6)*
H	Height of a liquid in a manometer tube. *(p. 6)*
H_A	Height of water in a manometer tube due to the static pressure at point A. *(p. 7)*
H_E	Height of water in a manometer tube due to the static pressure at point E. *(p. 7)*
H_{ref}	Height of a liquid (usually water) in a manometer tube due to reference or atmospheric pressure. *(p. 6)*
H_{static}	Height of water in a manometer tube due to the static pressure in the wind tunnel test section. *(p. 7)*
H_{total}	Height of water in a manometer tube due to the total pressure in the wind tunnel test section. *(p. 7)*
K	Wind tunnel calibration constant. *(p. i, 2, 6, 7, 9, 11–13)*
P	Pressure. *(p. 6)*
P_0	Total or stagnation pressure. *(p. 6)*
$P_{0,T}$	Total or stagnation pressure in the wind tunnel test section. *(p. 6)*
P_{ref}	Reference or atmospheric pressure. *(p. 6)*
P_T	Static pressure in the wind tunnel test section. *(p. 6)*
q	Dynamic pressure. *(p. 1, 6)*
q_T	Dynamic pressure in the wind tunnel test section. *(p. 6, 7, 9, 11)*
R^2	Coefficient of determination. *(p. 11)*
v_T	Velocity of the air in the wind tunnel test section. *(p. 7, 9, 11)*
V	Velocity. *(p. 1)*
ΔP	Difference in static pressure between point A and point E. *(p. 6, 7, 9, 11)*
ρ	Density. *(p. 1)*
ρ_{air}	Density of air. *(p. 7)*
ρ_{water}	Density of water. *(p. 6)*
ω_{motor}	Frequency of the wind tunnel motor. *(p. 9, 11)*

Acronyms

MATLAB MATrix LABoratory. *(p. 7, 9, 11, 13)*

1 Introduction

One of the least obstructive and most feasible methods of measuring airspeed or flow velocity is by measuring the dynamic pressure of the flow. The dynamic pressure of a flow is related to the velocity via Equation 1.1.

$$q = \frac{1}{2}\rho V^2 \tag{1.1}$$

where q is the dynamic pressure, ρ is the density, and V is the velocity (Hu, 2024b).

Since the dynamic pressure, q, is related to the total and static pressure (see Chapter 2), a pitot tube—which simultaneously measures total and static pressure—is commonly used to calculate q.

Figure 1.1: *A photograph of a pitot tube available for purchase on* `https://www.ttseries.com`.

For some aerodynamic tests, pitot tubes may be impractical or may obstruct the flow in a significant way. In these situations, an alternative method must be used to measure the airspeed in the test chamber. One solution is to take static pressure measurements at two points upstream of the test chamber and use a constant coefficient to relate the static pressure differential to the dynamic pressure in the test chamber.

In the low-speed wind tunnel, the two static pressure ports are located at point A and point E as shown in Figure 1.2:

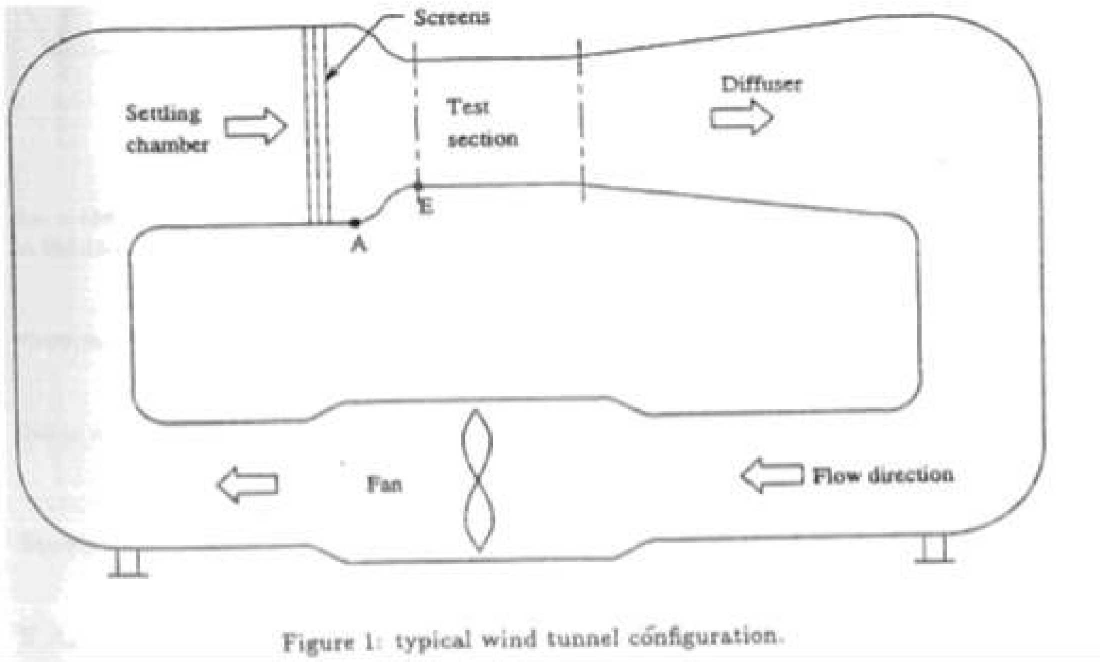

Figure 1.2: *A drawing of the undergraduate wind tunnel, denoting the flow of air and points A and E (Hu, 2024b).*

Once we have calibrated the wind tunnel by following the procedure outlined in Chapter 2 and determined the calibration constant, K, only the static pressure differential measured from points A and E will be required to estimate the velocity in the test chamber.

2

Methodology

2.1 Apparatus

In this experiment, we calibrated the low-speed wind tunnel at Iowa State University, the test section of which is shown in Figure 2.1.

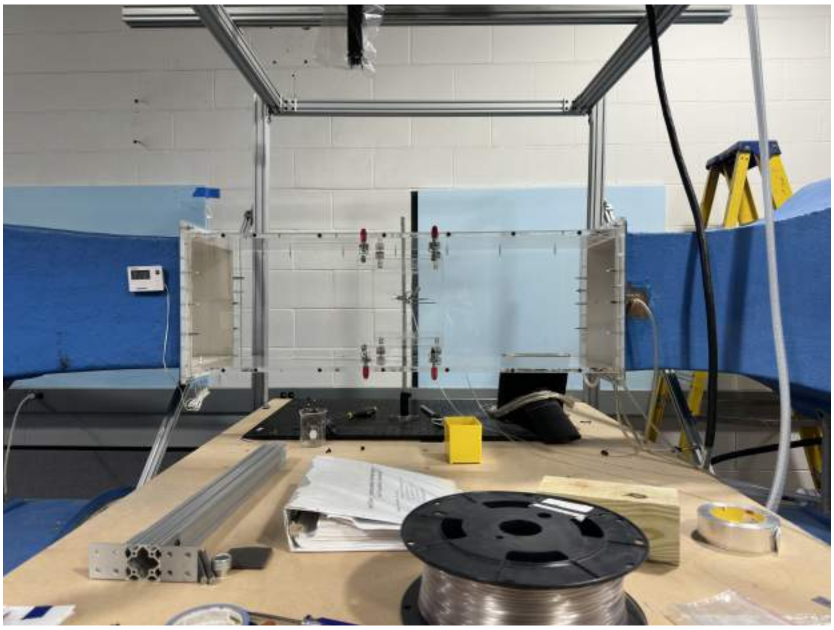

Figure 2.1: *Photograph of the test section in the low-speed wind tunnel at Iowa State University.*

The remote shown in Figure 2.2 is used to control the frequency of the motor that forces air through the closed-loop wind tunnel. To calibrate the wind tunnel and establish a relationship between the frequency of the motor and the dynamic pressure (or velocity) in the test section, a pitot tube was inserted into the middle of the test section, as shown in Figure 2.3. Additionally, two tubes were connected to the static pressure ports at points A and E in the test section. These points are denoted in Figure 1.2 and shown in Figure 2.4.

Four tubes are connected from the wind tunnel to the manometer shown in Figure 2.5. These tubes indirectly measure the

Figure 2.2: *Photograph of the remote that is used to control the low-speed wind tunnel.*

Figure 2.3: *Photograph of the pitot tube used to calibrate the wind tunnel.*

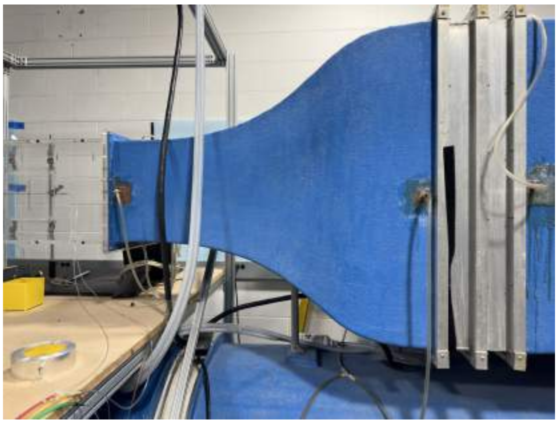

Figure 2.4: *Photograph of the static pressure ports at points A and E.*

- static pressure at point A,
- static pressure at point E,
- total—or stagnation—pressure in the pitot tube, and
- static pressure in the pitot tube.

Additionally, there are a number of tubes not connected to the wind tunnel which are used to measure the reference pressure in the lab. Each graduation marking on the manometer denotes a tenth of an inch.

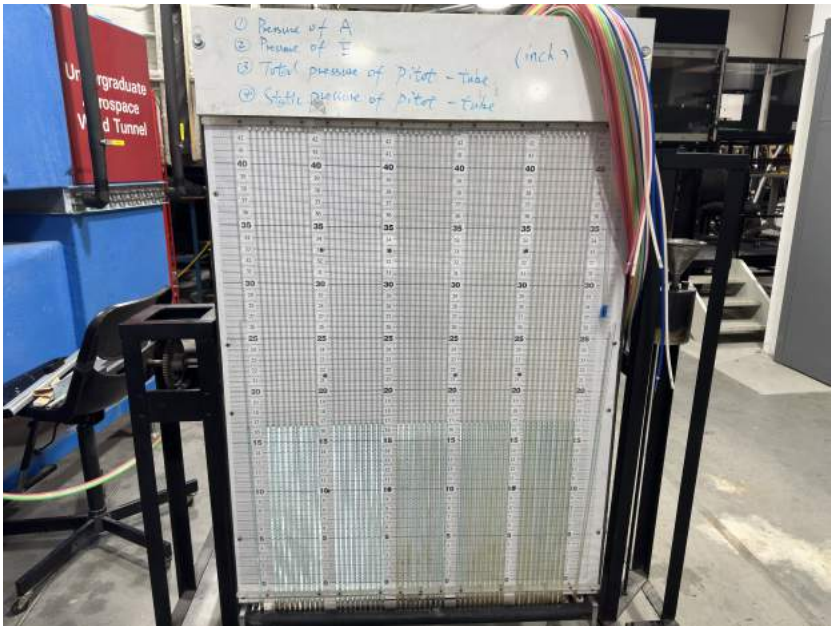

Figure 2.5: *Photograph of the manometer used to measure the pressure at different points in the wind tunnel.*

2.2 Test Procedure

To determine the relationship between the dynamic pressure in the test section and the static pressure differential at points A and E, we measured the heights of each active tube in the manometer for a number of different motor frequencies. This is the procedure we followed:

1. With the wind tunnel motor turned off, measure and record the height of the liquid in each active tube and the reference tube.
2. Increase the motor frequency by 5 Hz and wait for the liquid in the manometers to stabilize.
3. Record the new heights of the liquid in each active tube and the reference tube.
4. Repeat step 2 and step 3 for frequencies 5 Hz to 40 Hz.

The data collected from these steps are recorded in Table A.1.

2.3 Derivations

From the lab two manual, we are given

$$\Delta P = C q_t \tag{2.1}$$

where ΔP is the static pressure differential between points A and E, C is a dimensionless constant, and q_T is the dynamic pressure of the test chamber (Hu, 2024b). Equation 2.1 can then be rearranged to

$$q_T = \frac{1}{C}\Delta P \tag{2.2}$$

Since the calibration constant, K, is defined as

$$K = \frac{1}{C} \tag{2.3}$$

we can substitute Equation 2.3 into Equation 2.2 to get

$$q_T = K\Delta P \tag{2.4}$$

2.3.1 Quantifying Dynamic Pressure

To find K, we must first use the data collected from the experiment to calculate q_T and ΔP. To quantify q_T, we start by using the equation of total pressure,

$$P_0 = P + q \tag{2.5}$$

where P_0 is the total or stagnation pressure, P is the static pressure, and q is the dynamic pressure. From Equation 2.5, we can derive an expression for q_T:

$$q_T = P_{0,T} - P_T \tag{2.6}$$

where $P_{0,T}$ is the total pressure in the test chamber and P_T is the static pressure in the test chamber (Hu, 2024b).

$P_{0,T}$ and P_T were measured indirectly using a manometer. From the lab manual, we are given the following manometer equation:

$$P = P_{ref} - \rho_{water} g \left(H - H_{ref}\right) \tag{2.7}$$

where P is the pressure being measured, P_{ref} is the reference pressure, ρ_{water} is the density of water, g is the acceleration due to gravity, H is the height of the water in the active manometer tube, and H_{ref} is the height of the water in the reference manometer tube (Hu, 2024b). Using Equation 2.7, we can define expressions for $P_{0,T}$ and P_T:

$$P_{0,T} = P_{ref} - \rho_{water} g \left(H_{total} - H_{ref}\right) \tag{2.8}$$

$$P_T = P_{ref} - \rho_{water} g \left(H_{static} - H_{ref}\right) \tag{2.9}$$

where H_{total} is the height of the water in the manometer tube connected to the total pressure port of the pitot tube and H_{static} is the height of the water in the manometer tube connected to the static pressure port of the pitot tube.

Substituting Equation 2.8 and Equation 2.9 into Equation 2.6, we can simplify the expression for q_T as follows:

$$\begin{aligned} q_T &= \left[P_{ref} - \rho_{water} g \left(H_{total} - H_{ref}\right)\right] - \left[P_{ref} - \rho_{water} g \left(H_{static} - H_{ref}\right)\right] \\ &= -\rho_{water} g H_{total} + \rho_{water} g H_{static} \\ &= \rho_{water} g \left(H_{static} - H_{total}\right) \end{aligned} \tag{2.10}$$

Equation 2.10 was used in our MATrix LABoratory (MATLAB) script (see Appendix B) to calculate q_T for each of the motor frequencies we tested.

2.3.2 Quantifying the Static Pressure Differential

An equation for the static pressure differential, ΔP, can be derived in a similar fashion to q_T. For more details see Section 2.3.1. Furthermore, the equation for ΔP is

$$\Delta P = \rho_{water} g \left(H_E - H_A\right) \tag{2.11}$$

where H_E is the height of the water in the manometer tube connected to the static pressure port at point E and H_A is the height of the water in the manometer tube connected to the static pressure port at point A. Equation 2.11 was used in our MATLAB script to calculate ΔP for each of the motor frequencies we tested.

2.3.3 Determining the Calibration Constant

Once we calculated the values of q_T and ΔP for each of the motor frequencies, we used MATLAB to plot q_T vs. ΔP (see Figure 3.1). We used the `polyfit()` function to calculate the coefficients of a linear line of best fit. Since K is the slope of Equation 2.4, it follows that the slope of the line of best fit is approximately K.

2.3.4 Calculating the Test Chamber Velocity

Since we have already calculated the values of q_T at for each of the motor frequencies we tested, we can use Equation 1.1 to derive an expression for the velocity of the test chamber:

$$v_T = \sqrt{\frac{2q_T}{\rho_{air}}} \tag{2.12}$$

where v_T is the velocity of air in the test chamber and ρ_{air} is the density of air. Using Equation 2.12 and our MATLAB script, we calculated the velocity of air in the test chamber for each of the motor frequencies and created a plot of test chamber airspeed vs.

motor frequency (see Figure 3.2). Finally, we used the `polyfit()` function once more to calculate a linear line of best fit for the velocity vs. motor frequency relationship.

3 Results

Figure 3.1 shows the dynamic pressure in the test chamber, q_T, as a function of the pressure differential, ΔP, between the static pressures measured at points A and E. The slope of this graph, defined as the calibration constant, K, is 1.08.

Figure 3.2 shows the airspeed in the test chamber, v_T, as a function of the motor frequency, ω_{motor}. This plot can be used to determine the approximate test chamber airspeed for a given motor frequency. By using the `polyfit()` function in MATLAB (see Section 2.3.4), we calculated the linear regression to be

$$v_T = 1.32\omega_{motor} - 0.431 \tag{3.1}$$

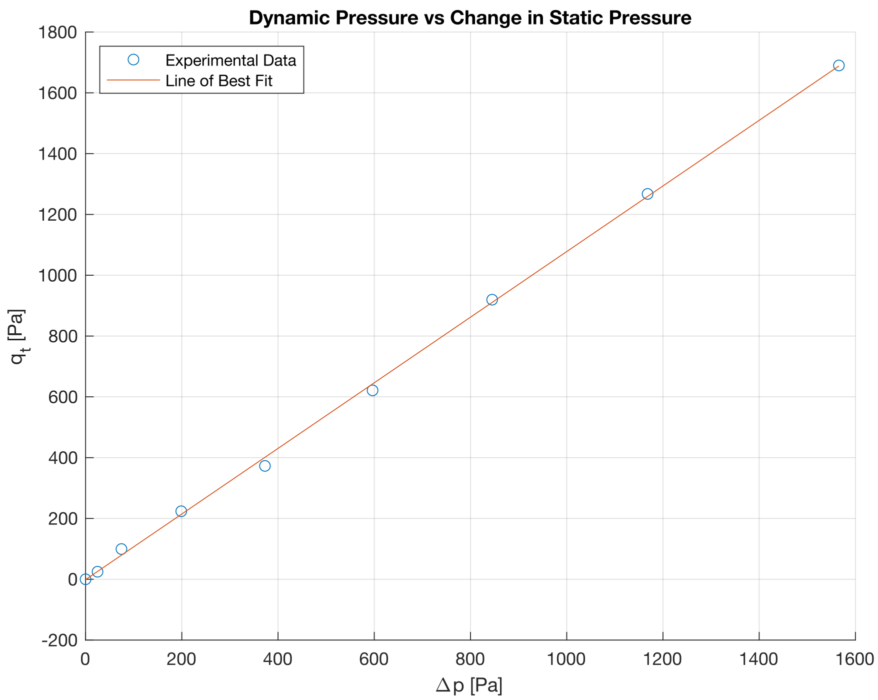

Figure 3.1: *Plot of the dynamic pressure in the test chamber, q_T, vs. the pressure differential, Δp, between the static pressures measured at points A and E. The units of both axes are pascals.*

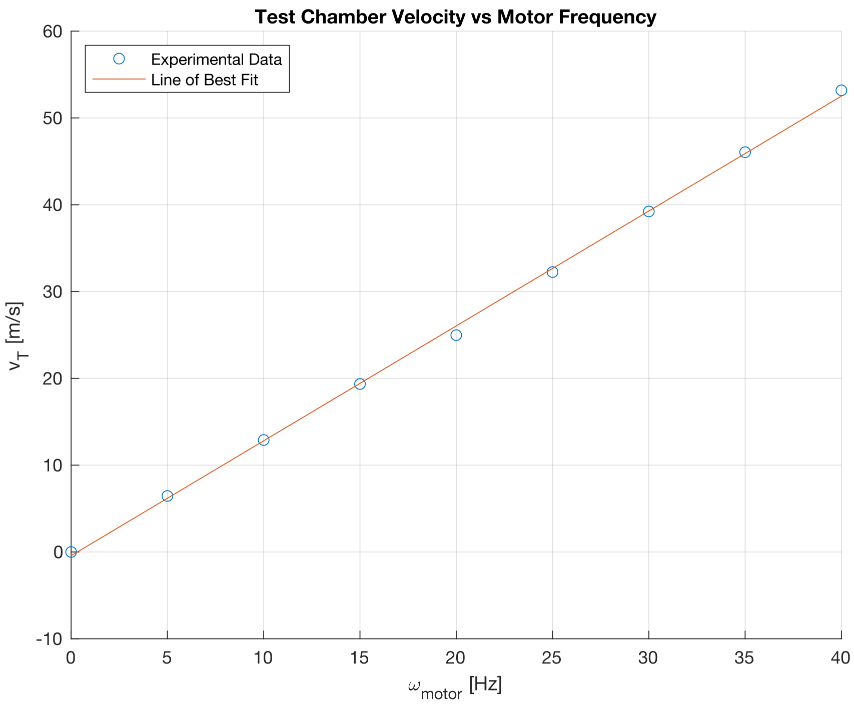

Figure 3.2: *Plot of the test chamber velocity, v_T, vs. the motor frequency, ω_{motor}.*

4

Discussion

From inspection of Figure 3.1, the relationship between q_T and ΔP is very linear, suggesting a direct relationship between the dynamic pressure in the test chamber, q_T, and the change in pressure from points A and E, ΔP. After calculating a linear regression on this data using the `polyfit()` function in MATLAB (see Section 2.3.3), we confirmed that there is a strong direct relationship since the coefficient of determination, R^2, is 0.9993. From the linear regression, we were also able to determine the K-coefficient, defined in Equation 2.3. This coefficient allows us to calculate the dynamic pressure—and furthermore, the flow speed—in the test chamber given only the static pressure readings from points A and E.

Plotting the test chamber velocity, v_T, with respect to the frequency of the motor, ω_{motor}, resulted in Figure 3.2. Once more, we calculated the linear regression (see Section 2.3.4). The coefficient of determination was 0.9992 and the subsequent line of best fit is shown in Equation 3.1.

Equation 3.1 allows us to directly determine the flow speed in the test chamber given only the frequency of the motor. Similarly, reversing this equation, $\omega_{motor} = 0.755 * v_T + 0.326$, allows us to determine the appropriate motor frequency for a given velocity. For example, if the tester wanted to set the wind tunnel to 15 m/s, they would set the wind tunnel motor frequency to $\omega_{motor} = 0.755 * 15 + 0.326 = 11.7\,\text{Hz}$.

This calibration process is necessary to accurately estimate the airspeed in the test chamber, a critical value in wind tunnel testing. In many instances, inserting a pitot tube near the model or putting holes in the model could result in different flow characteristics (Hu, 2024a). Even if a pitot tube or pressure transducer were inserted further upstream in the wind tunnel—far enough that any turbulent effects due to the obstruction had dissipated by the time the flow reached the test chamber—the energy and dynamic pressure loss due to the boundary layer effect near the walls of the wind tunnel could lead to inaccurate estimates. By determining the calibration constant, K, pressure transducers need only be inserted normal to the flow at points A and E, minimizing adverse effects on the flow without sacrificing accuracy.

In future experiments, to increase the accuracy and precision of the pressure readings, an electronic manometer could be connected to the static pressure ports at point A and

E. Assuming the port at point A was connected to the main port of the manometer and the port at point E was connected to the secondary port of the manometer, the resulting voltage would be the pressure differential between points A and E. Using the value of K calculated in this lab, the dynamic pressure in the test chamber for a given pressure differential could be estimated trivially by multiplying the pressure differential by K. If desired, the corresponding airspeed could be calculated using Equation 2.12.

5

Conclusion

Using a pitot tube and a manometer, we recorded pressure data from the low-speed wind tunnel. By analyzing this data in MATLAB and utilizing a polynomial fit function, we calculated the calibration coefficient, K. This calibration coefficient relates a static pressure differential to the dynamic pressure in the test chamber, which can further be evaluated to find the airspeed in the test chamber. The calibration coefficient and relationships we derived will allow us to more accurately estimate the airspeed in the wind tunnel during future experiments.

Bibliography

Hu, Hui (2024a). *Lecture #04 Pressure Measurement Techniques and Instrumentation*. URL: https://www.aere.iastate.edu/~huhui/teaching/2024-01S/AerE344/class-notes/AerE344-Lecture-04-Pressure-Instrument.pdf.

— (2024b). *Wind Tunnel Calibration*. Iowa State University. URL: https://www.aere.iastate.edu/~huhui/teaching/2024-01S/AerE344/lab-instruction/AerE344L-Lab-02-instruction.pdf.

A

Appendix A

Table A.1: *Raw data collected from this lab.*

ω_{motor} [Hz]	H_{ref} [in]	H_A [in]	H_E [in]	H_{total}[in]	H_{static} [in]	T_{tunnel} [°C]
0	16.7	16.7	16.7	16.7	16.7	22.1
5	16.7	16.7	16.8	16.7	16.8	22.1
10	16.7	16.6	16.9	16.6	17.0	22.1
15	16.7	16.4	17.2	16.4	17.3	22.1
20	16.7	16.1	17.6	16.1	17.6	22.1
25	16.7	15.7	18.1	15.7	18.2	22.1
30	16.7	15.2	18.6	15.2	18.9	22.1
35	16.7	14.6	19.3	14.6	19.7	22.1
40	16.7	13.9	20.2	13.8	20.6	22.1

B

Appendix B

```
% AER E 344 Spring 2024 Lab 02 Analysis
% Section 3 Group 3
clear, clc, close all;

figure_dir = "../Figures/";
u = symunit;

%% Import Data
data_sheet = readtable('AER E 344 Lab 02 Data Sheet.xlsx', ...
    'VariableNamingRule', 'preserve');
omega_motor = data_sheet.("Motor speed [Hz]").'; % [Hz]
H_ref = double(separateUnits(unitConvert( ...
    data_sheet.("H_ref [in.]").' * u.in, u.m))); % [m]
H_A = double(separateUnits(unitConvert( ...
    data_sheet.("H_A [in.]").' * u.in, u.m))); % [m]
H_E = double(separateUnits(unitConvert( ...
    data_sheet.("H_E [in.]").' * u.in, u.m))); % [m]
H_total = double(separateUnits(unitConvert( ...
    data_sheet.("H_total [in.]").' * u.in, u.m))); % [m]
H_static = double(separateUnits(unitConvert( ...
    data_sheet.("H_static [in.]").' * u.in, u.m))); % [m]
T_tunnel = data_sheet.("T_tunnel [deg C]").'; % [°C]

%% Variables
% https://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html
% Calculated @ 22.1°C
rho_water = 997.74; % [kg / m^3]
% https://www.engineeringtoolbox.com/water-density-specific-weight-d_595.html
% Calculated @ 22.1°C
rho_air = 1.195; % [kg / m^3]
% https://physics.nist.gov/cgi-bin/cuu/Value?gn
g = 9.80665; % [m / s^2]

%% Calculate q_T & delta_p
% q_T = P_0T - P_T
q_T = rho_water .* g .* (H_static - H_total); % [Pa]
delta_p = rho_water .* g .* (H_E - H_A); % [Pa]
```

```matlab

%% Calculate q_t vs. delta_p Regression
regress_1 = polyfit(delta_p, q_T, 1);
K = regress_1(1); % []
regress_1_x = delta_p(1):0.1:delta_p(end); % [Pa]
regress_1_y = K * regress_1_x + regress_1(2); % [Pa]

fprintf("K = %g []\n", K);

%% Plot q_t vs delta_p
figure(1);
scatter(delta_p, q_T);
title("Dynamic Pressure vs Change in Static Pressure")
xlabel("{\Delta}p [Pa]")
ylabel("q_t [Pa]")
hold on;
plot(regress_1_x, regress_1_y);
hold off;
legend("Experimental Data", "Line of Best Fit", "Location", "northwest");
grid on;
saveas(gcf, ...
    figure_dir + "Dynamic Pressure vs Change in Static Pressure.svg");

%% Calculate v_T
v_T = sqrt(2 * q_T / rho_air); % [m/s]

%% Calculate v_T vs omega_motor Regression
regress_2 = polyfit(omega_motor, v_T, 1);
regress_2_x = omega_motor(1):0.1:omega_motor(end); % [Hz]
regress_2_y = regress_2(1) * regress_2_x + regress_2(2); % [m/s]

fprintf("v_T = %G * omega_motor + %g\n", regress_2);

%% Plot v_T vs omega_motor
figure(2);
scatter(omega_motor, v_T);
title("Test Chamber Velocity vs Motor Frequency");
xlabel("\omega_{motor} [Hz]");
ylabel("v_T [m/s]");
hold on;
plot(regress_2_x, regress_2_y);
hold off;
legend("Experimental Data", "Line of Best Fit", "Location", "northwest");
grid on;
saveas(gcf, figure_dir + "Test Chamber Velocity vs Motor Frequency.svg");
```