Iowa State University

PRESSURE COEFFICIENT DISTRIBUTION ON THE SURFACE OF A CIRCULAR CYLINDER LABORATORY

AER E 344 - Lab 04 - Pressure Coefficient Distribution on the Surface of a Circular Cylinder

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

By measuring the pressure at pressure taps arranged radially around a circular cylinder, we quantified the aerodynamic characteristics of a cylinder for different flow speeds. In the range of 150° to 225°—which corresponds to the side of the cylinder facing the flow—the distribution of the coefficient of pressure, C_P, closely tracks the potential flow theory prediction. Outside this range, the experimental data does not track the theoretical prediction well, and the C_P distribution levels out to approximately -1. Additionally, for each flow speed we calculated the aerodynamic drag coefficient from the pressure measurements and plotted these values as a function of the Reynolds number. The highest coefficient of drag we observed occurred at the lowest flow speed, possibly due to turbulence or viscous effects, which are more significant at lower Reynolds numbers.

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Glossary

C_P Dimensionless coefficient of pressure. *(p. i, iv, v, 5–8, 10, 11, 14, 16–19)*

C_d Dimensionless coefficient of drag. *(p. v, 5, 9–11, 15)*

D Diameter of the cylinder. *(p. 4)*

K Calibration constant for the wind tunnel. *(p. 5)*

L The characteristic dimension for calculating the Reynolds number. *(p. 6)*

P_A Static pressure at the entrance of the contraction section. *(p. 5)*

P_E Static pressure at inlet of test section. *(p. 5)*

P_∞ Pressure of the free-stream flow. *(p. 5)*

P_i Pressure at the ith port. *(p. 5)*

R Radius of the cylinder. *(p. 6)*

Re Reynolds number. *(p. iv, 6, 20)*

V Velocity of air. *(p. 6)*

V_∞ Velocity of the free-stream flow. *(p. 5)*

μ Dynamic viscosity of air. *(p. 6)*

ρ Density of the air. *(p. 5, 6)*

θ Angle of the ports around the cylinder. *(p. 5)*

q Dynamic pressure. *(p. 6)*

1

Introduction

The Scanivalve DSA 3217, a 16-channel digital pressure transducer, calculates the differences in pressure between the input ports and the calibrated reference pressure. In this experiment, the ports of the pressure transducer are connected to pressure taps that wrap radially around a cylinder (see Figure 2.1). The Scanivalve pressure transducer is also measuring the pressure at the inlet and outlet of the contraction section.

Using the Scanivalve pressure transducers in conjunction with the data acquisition software, we will measure the pressure at 20° increments around the cylinder to quantitatively determine the flow characteristics and compare the results to the theoretical flow solution.

2

Methodology

2.1 Apparatus

Figure 2.1 shows the cylinder positioned in the wind tunnel test chamber. The cylinder has pressure taps on the surface—positioned radially in 20° increments—which are connected to a Scanivalve DSA 3217 pressure transducer shown in Figure 2.2. The Scanivalve pressure transducers are connected to a computer running a data acquisition software. After a scan has completed, the data acquisition software stores the 16 pressure samples for each transducer in a `.csv` file.

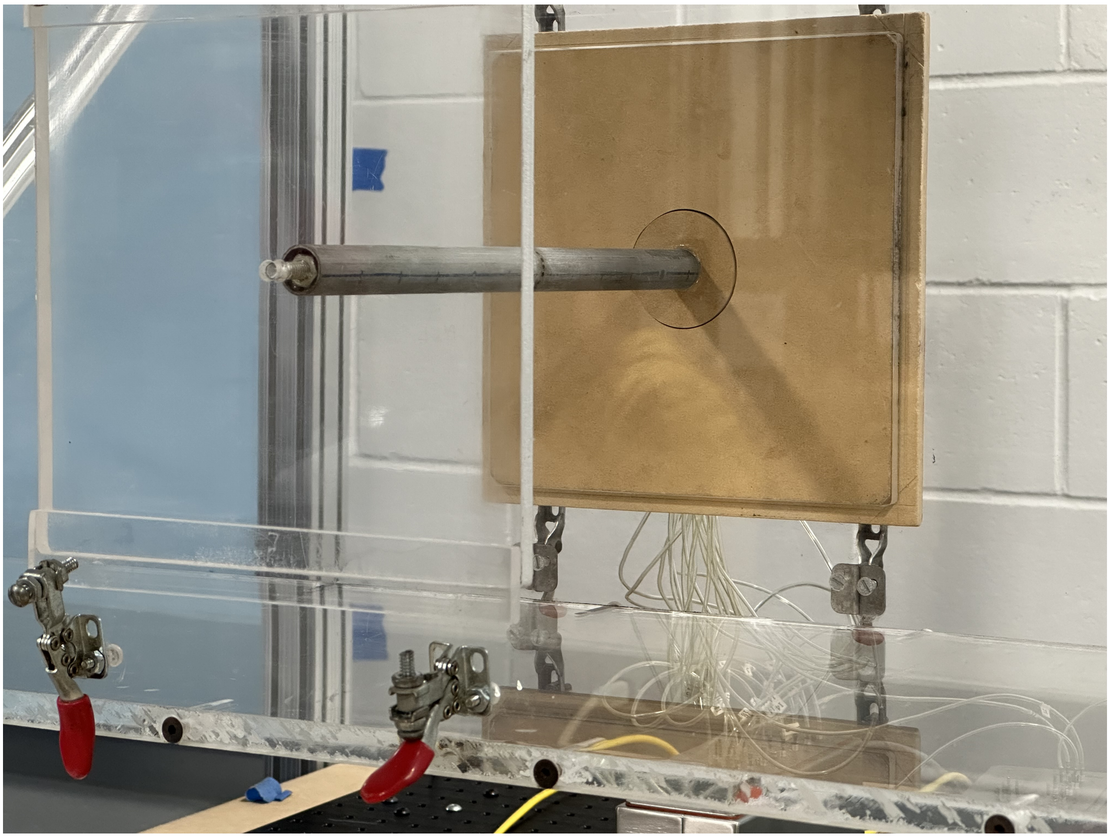

Figure 2.1: *Photograph of the Cylinder in the Low-Speed Wind Tunnel.*

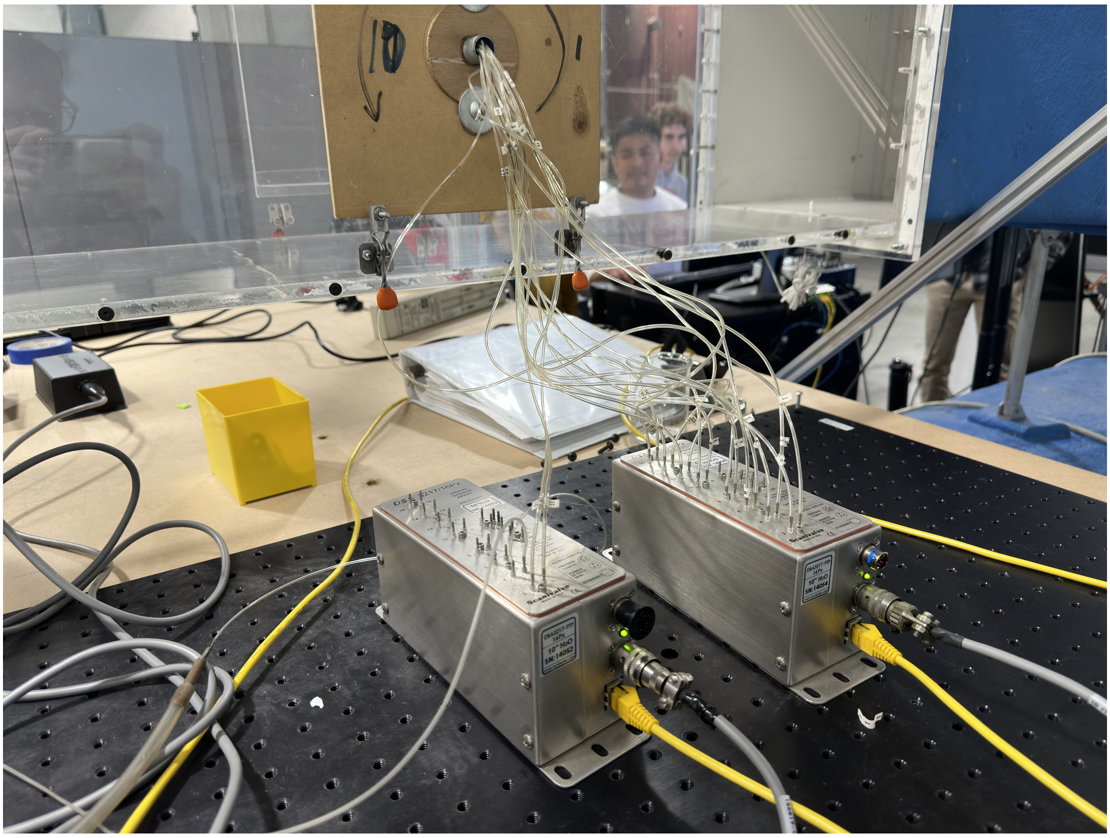

Figure 2.2: *Photograph of Scanivalve Pressure Transducers.*

2.2 Procedures

1. Measure the following data:
   (a) Temperature in the wind tunnel
   (b) D, the diameter of the cylinder
2. When the wind tunnel is not running, press the calibrate button in the data collection software.
3. Set the wind tunnel to 5 Hz.
4. Once the motor has stabilized, press the "Start Data File" button and save the file.
5. Press the "Start" button to begin data collection.
6. Once data collection is complete, press the "Stop Data File" button.
7. Repeat Steps 4 to 6 for each of the frequencies specified in the lab manual, up to 35 Hz.

2.3 Derivations and Calculations

2.3.1 Calculating the Pressure Coefficient

To calculate the drag coefficient, C_d, we start with the equation for the coefficient of pressure, C_P, at each tap:

$$C_{P,i} = \frac{P_i - P_\infty}{\frac{1}{2}\rho V_\infty^2} \tag{2.1}$$

where P_i is the pressure measurement at the ith pressure port, P_∞ is the pressure of the free-stream air, ρ is the density of air, and V_∞ is the velocity of the free-stream air.

Using the calibration constant, K, which was determined in Lab 2 to be $K = 1.1$, we can substitute the expression for dynamic pressure, $\frac{1}{2}\rho V^2$, as shown in Equation 2.2:

$$C_{P,i} = \frac{P_i - P_E}{K\left(P_A - P_E\right)} \tag{2.2}$$

where P_E is the static pressure at the entrance of the wind tunnel and P_A is the static pressure at the opening of the contraction section of the wind tunnel (Hu, 2024).

2.3.2 Calculating the Drag Coefficient

The coefficient of drag, C_d, is defined in Equation 2.3:

$$C_d = -\frac{1}{2}\int_{-\pi}^{\pi} C_P \cos\theta d\theta \tag{2.3}$$

where θ is the angle of the C_P measurement. θ is defined as shown in Figure 2.3 (Borgoltz et al., 2024).

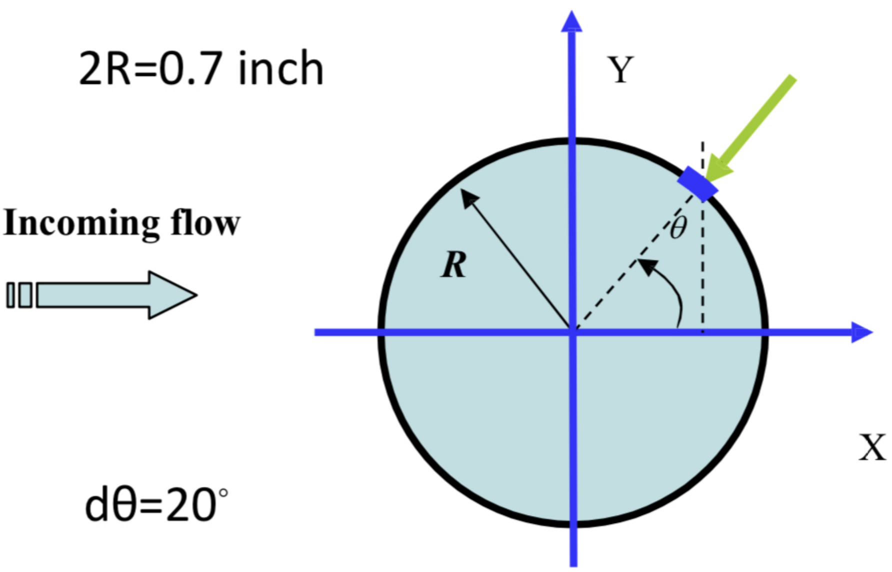

Figure 2.3: *Diagram of the cylinder with sign conventions and flow direction.*

Since we do not have a continuous expression for C_P about the cylinder, we can use numerical integration to solve the integral in Equation 2.3. We start by defining a value, f_i:

$$f_i = C_{P,i} \cos\theta \tag{2.4}$$

Using a Riemann's sum, we then substitute the integral in Equation 2.3 as shown in Equation 2.5:

$$C_D = -\frac{\Delta\theta}{2}\left[f_1 + f_2 + f_3 + \cdots + f_n\right] \tag{2.5}$$

By evaluating and summing all the f-values and subsituting this sum into Equation 2.5, we can find the dimensionless coefficient of drag for a specific motor frequency (Hu, 2024).

2.3.3 Calculating the Reynolds Number

From the Lab 4 manual, the Reynolds number, Re, is a dimensionless value defined as

$$Re = \frac{\rho V L}{\mu} \tag{2.6}$$

where ρ is the density of air, V is the velocity of air, L is the characteristic length, and μ is the dynamic viscosity of air. Since we are evaluating the Reynolds number of a cylinder, the characteristic length is $2R$, where R is the radius of the cylinder.

To find V, we use the definition of dynamic pressure:

$$\begin{aligned} q &= \frac{1}{2}\rho V^2 \\ V &= \sqrt{\frac{2q}{\rho}} \end{aligned} \tag{2.7}$$

where q is the dynamic pressure. Using the calibration constant determined in Lab 2, we determine that

$$V = \sqrt{\frac{2K(P_A - P_E)}{\rho}} \tag{2.8}$$

Once V is evaluated, it can be substituted into Equation 2.6 in conjunction with the standard density and dynamic viscosity of air to determine the Reynolds number for a given motor frequency.

3

Results

3.1 Coefficient of Pressure Distribution

Figure 3.1 shows the coefficient of pressure, C_P, around the cylinder at motor frequencies of 5 Hz to 35 Hz. The C_P for each motor frequency was calculated at 20° increments around the cylinder using Equation 2.2 from data measured with the Scanivalve DSA 3217 and collected using the data acquisition software (see Section 2.2). The theoretical solution was calculated using the equation:

$$C_P = 1 - 4\sin^2\theta \tag{3.1}$$

To demonstrate the uniformity of the flow at higher velocities, Figure 3.2 excludes the pressure distribution curves for the 5 Hz to 15 Hz motor frequencies.

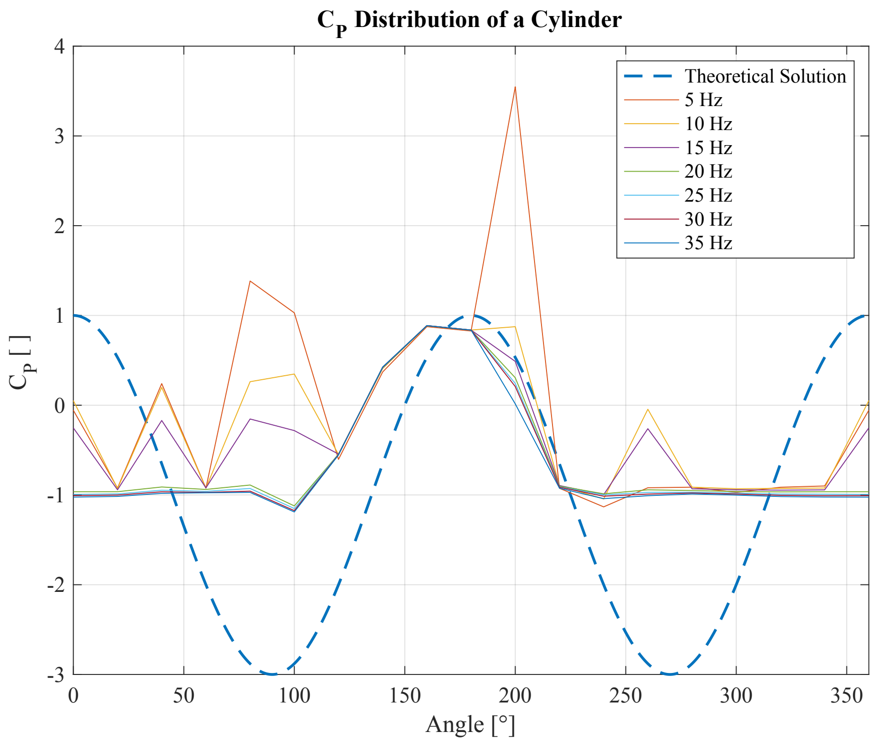

Figure 3.1: *Plot of the C_P distribution at different angles around the cylinder with the theoretical solution*

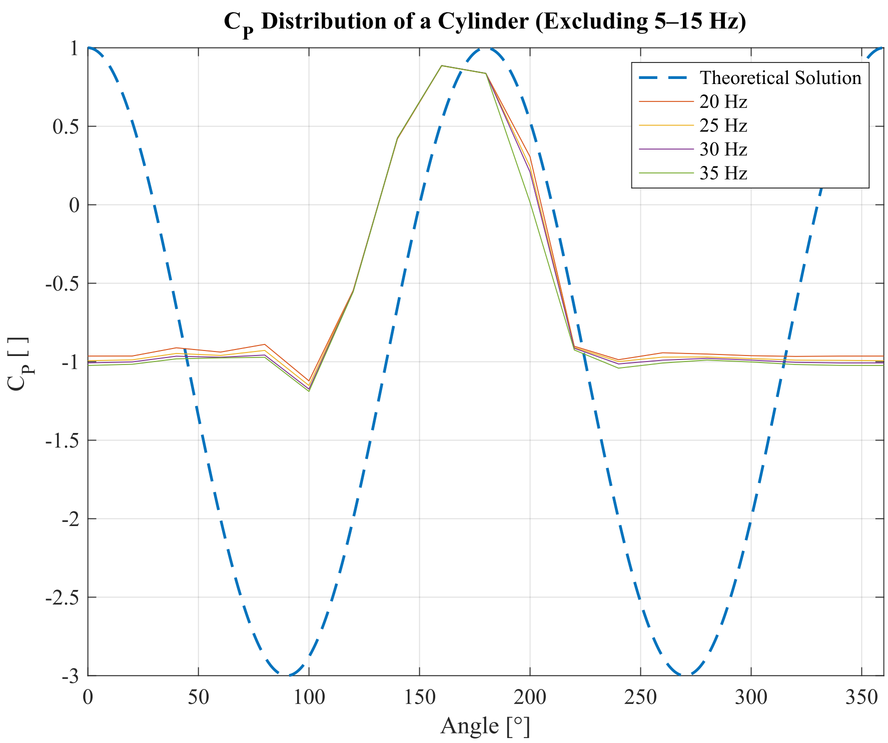

Figure 3.2: *Plot of the C_P distribution at different angles around the cylinder with the theoretical solution, excluding 5-15 Hz motor speeds*

3.2 Coefficient of Drag

Figure 3.3 shows the relationship between C_d and the Reynolds number. Equation 2.6 is used to calculate Reynolds number at the different fluid velocities.

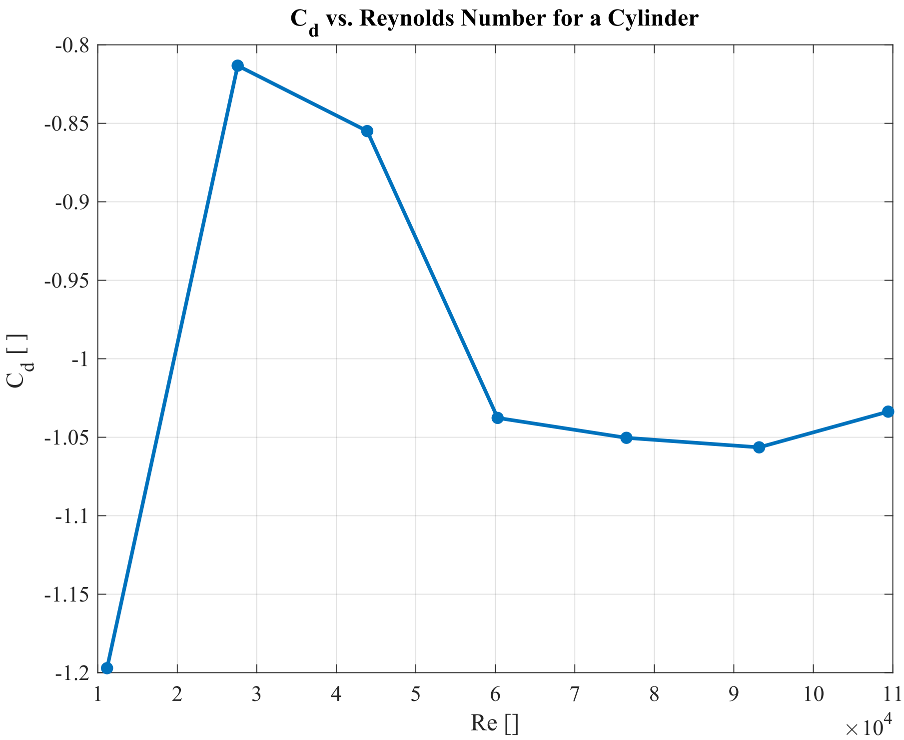

Figure 3.3: *Plot of the coefficient of drag vs. Reynolds number.*

4

Discussion

4.1 Coefficient of Pressure Distribution

Figure 3.1 shows all the coefficient of pressure distributions plotted over the theoretical solution for the pressure distribution over a cylinder (see Section B.1 for all the individual pressure distribution graphs). All the pressures distributions but the 5 Hz pressure distribution track the theoretical solution well in the range of 150° to 225°. The phase shift in the high pressure part of the pressure distribution is likely due to a slight rotation of the cylinder in the wind tunnel (see Figure 2.1). Outside the range 150° to 225°, the pressure distribution tracks the theoretical solution more poorly, but this is due to a limitation in the type of pressure measurement being taken. We noted that the pressure distributions all level out at a C_P of approximately -1, which is the center of the theoretical sinusoid.

If we exclude the 5 Hz to 15 Hz pressure distributions as shown in Figure 3.2, the pressure distributions track the theoretical solution better and become more uniform. This seems to indicate a significant amount of turbulence and separation is occurring in the 5 Hz to 15 Hz flows. At around 20 Hz and above, the flow becomes more uniform.

4.2 Coefficient of Drag

Examining Figure 3.3, we see that the highest drag coefficient magnitude occurs at the lowest Reynolds number, when the motor frequency is at 5 Hz. We assume this larger drag coefficient is due to viscosity effects on the surface of the cylinder which are more significant at lower speeds. We suspect the large jump in C_d between 15 Hz and 20 Hz is due to turbulence and separation effects.

5

Conclusion

Using the Scanivalve DSA 3217 pressure transducers, we measured the pressure from 18 ports around a cylinder at a range of velocities. We used the data acquired by the Scanivalve pressure transducers to calculate the C_P distribution around the cylinder. Once the C_P distribution was evaluated, we then determined the coefficient of drag, C_d, and plotted it against the Reynolds number. In the range of 150° to 225°, our experimental data tracked the theoretical pressure distribution well. The data collected when the motor frequency was between 5 Hz and 15 Hz had several significant outliers and generally did not act as uniform compared to the higher velocity flows—likely due to turbulence or viscous effects.

Bibliography

Borgoltz, Aurelien, William Deveneport, and Nanya Intaratep (Aug. 24, 2024). *Experiment 3 - Flow Past a Circular Cylinder*. Virginia Tech. URL: `https://borgoltz.aoe.vt.edu/aoe3054/manual/expt3/index.html`.

Hu, Hui (2024). *Pressure Transducer Calibration*. Iowa State University. URL: `https://www.aere.iastate.edu/~huhui/teaching/2024-01S/AerE344/lab-instruction/AerE344L-Lab-04-instruction.pdf`.

A

Appendix A

A.1 Raw Data

Table A.1: *Raw pressure measured from the pressure ports on the cylinder. Data in this table is the pressure at each pressure port in units of Pascals.*

	Frequency [Hz]						
Port	5	10	15	20	25	30	35
1	−7.808	−38.54	−165.9	−592.6	−969.9	−1463	−2037
2	−19.34	−118.2	−307.6	−592.5	−966.7	−1457	−2028
3	−3.862	−26.64	−148.9	−572.1	−941.1	−1424	−1983
4	−19.35	−117.9	−303.3	−582.7	−949.1	−1430	−1976
5	11.35	−21.47	−145.5	−563.6	−929.1	−1417	−1971
6	6.632	−14.53	−172	−654	−1069	−1618	−2249
7	−15.09	−87.29	−225.8	−430.2	−691.7	−1040	−1438
8	−2.129	−9.566	−28.16	−56.12	−86.35	−136.6	−186.7
9	4.581	29.17	68.28	124.8	203.2	291.9	402.5
10	3.939	25.26	58.23	105.8	172.2	245.9	339.2
11	40.13	28.32	−13.64	−100.2	−198.6	−337.3	−710.7
12	−19.37	−115.6	−297.9	−568.3	−917.4	−1377	−1911
13	−22.13	−127.7	−318.8	−601.6	−973.3	−1469	−2059
14	−19.3	−46.4	−167.7	−584.4	−955.7	−1447	−2017
15	−19.21	−117	−305.3	−587.6	−955.2	−1436	−1993
16	−19.99	−118.4	−307.6	−591.6	−961.5	−1447	−2009
17	−19.22	−118.1	−308.4	−593.4	−967.7	−1460	−2030
18	−19.03	−117.7	−307.8	−592.6	−968.5	−1463	−2036
19	5.036	31.12	72.95	133.8	217.6	312.3	431.4
20	−7.059	−42.75	−113.9	−218.8	−349.9	−529.9	−729.7

A.2 Calculated Data

Table A.2: *Coefficient of Pressure, C_P, at an angle around the cylinder. Data in this table is the dimensionless C_P around the cylinder.*

	Frequency [Hz]						
Angle [°]	5	10	15	20	25	30	35
180	−0.056 31	0.051 73	−0.2531	−0.9639	−0.9933	−1.007	−1.024
160	−0.9228	−0.9286	−0.9425	−0.9637	−0.9881	−1.001	−1.016
140	0.2403	0.1982	−0.1704	−0.9112	−0.9472	−0.9648	−0.9817
120	−0.9238	−0.9246	−0.9217	−0.9385	−0.96	−0.9714	−0.9755
100	1.384	0.2618	−0.1536	−0.8893	−0.9279	−0.9574	−0.9718
80	1.029	0.3473	−0.2829	−1.122	−1.152	−1.174	−1.189
60	−0.6035	−0.5482	−0.5448	−0.5452	−0.5476	−0.5504	−0.5546
40	0.3706	0.4084	0.4171	0.4193	0.4221	0.4245	0.4251
20	0.8749	0.8851	0.8864	0.8858	0.886	0.8871	0.8865
0	0.8267	0.837	0.8375	0.8368	0.8363	0.8374	0.8369
−20	3.547	0.8747	0.4878	0.3058	0.2423	0.2078	0.014 82
−40	−0.9256	−0.8965	−0.8954	−0.9013	−0.9092	−0.914	−0.9249
−60	−1.133	−1.045	−0.997	−0.9871	−0.9988	−1.014	−1.041
−80	−0.9199	−0.044 95	−0.2617	−0.9429	−0.9705	−0.99	−1.008
−100	−0.9133	−0.9134	−0.9311	−0.9509	−0.9698	−0.9785	−0.9892
−120	−0.9716	−0.9306	−0.9427	−0.9615	−0.9798	−0.9896	−1.001
−140	−0.914	−0.927	−0.9465	−0.9661	−0.9898	−1.004	−1.018
−160	−0.9	−0.9229	−0.9436	−0.964	−0.9911	−1.008	−1.023

Table A.3: *Coefficient of Drag, C_d, and Reynold's number around a cylinder for the different wind tunnel motor frequencies.*

Frequency [Hz]	C_d	Re
5	-1.207	1.117×10^4
10	-0.8042	2.76×10^4
15	-0.8991	4.389×10^4
20	-1.206	6.029×10^4
25	-1.224	7.649×10^4
30	-1.232	9.319×10^4
35	-1.212	1.094×10^5

B

Appendix B

B.1 Figures

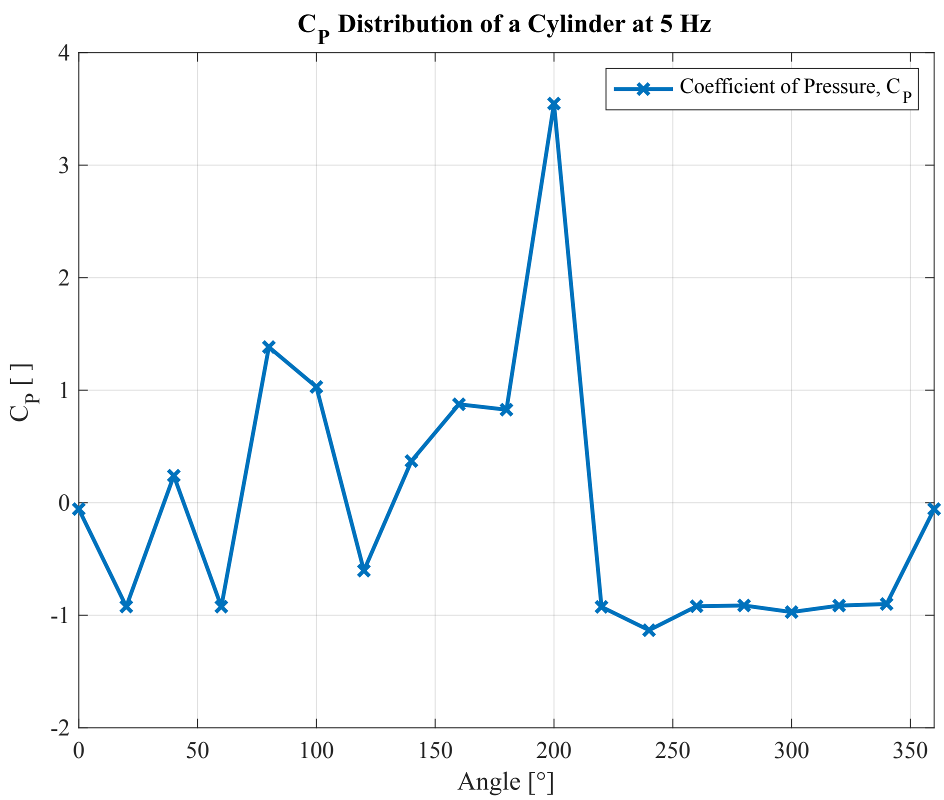

Figure B.1: *Plot of the C_P distribution around a cylinder at* 5 Hz.

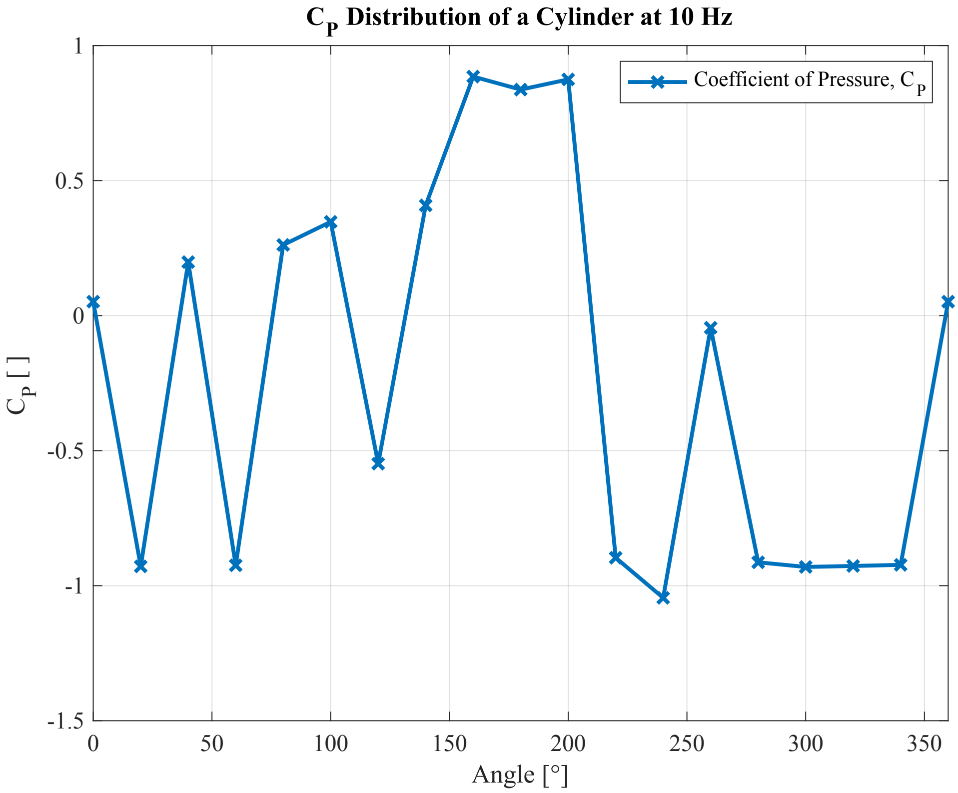

Figure B.2: *Plot of the C_P distribution around a cylinder at* 10 Hz*.*

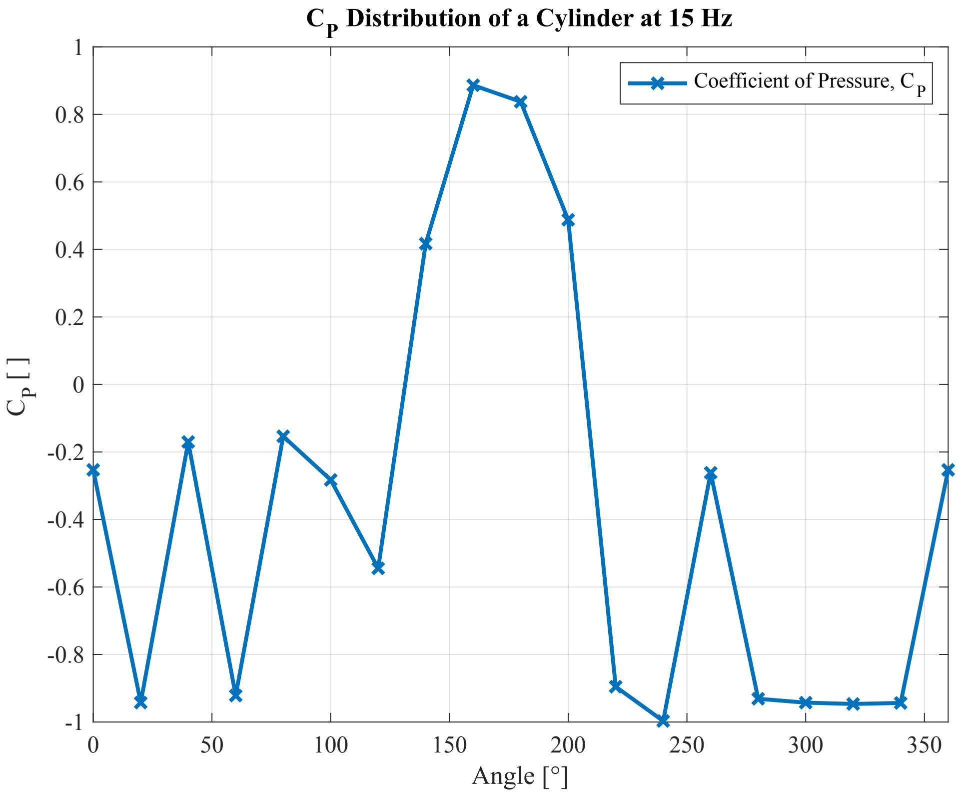

Figure B.3: *Plot of the C_P distribution around a cylinder at* 15 Hz*.*

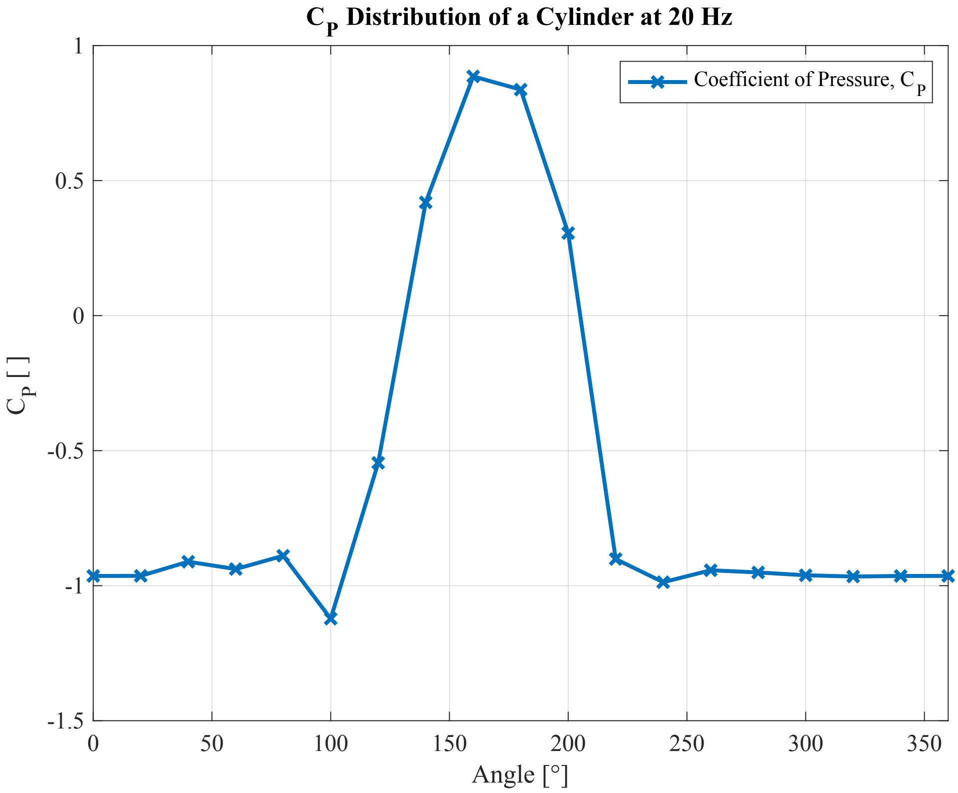

Figure B.4: *Plot of the C_P distribution around a cylinder at* 20 Hz*.*

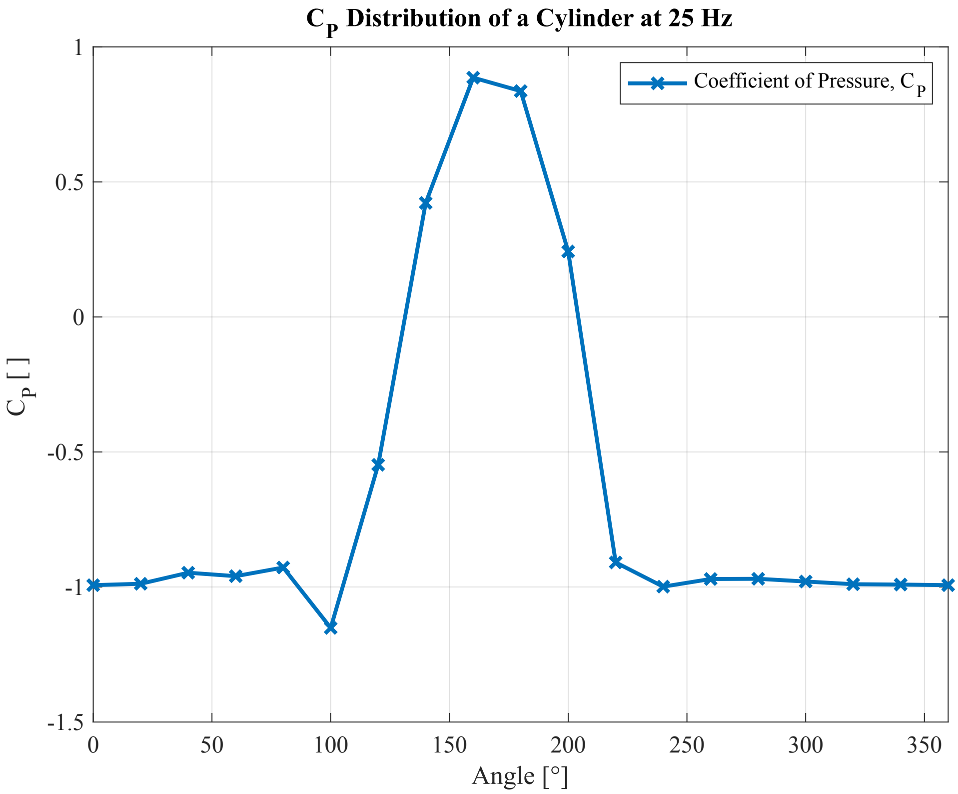

Figure B.5: *Plot of the C_P distribution around a cylinder at* 25 Hz*.*

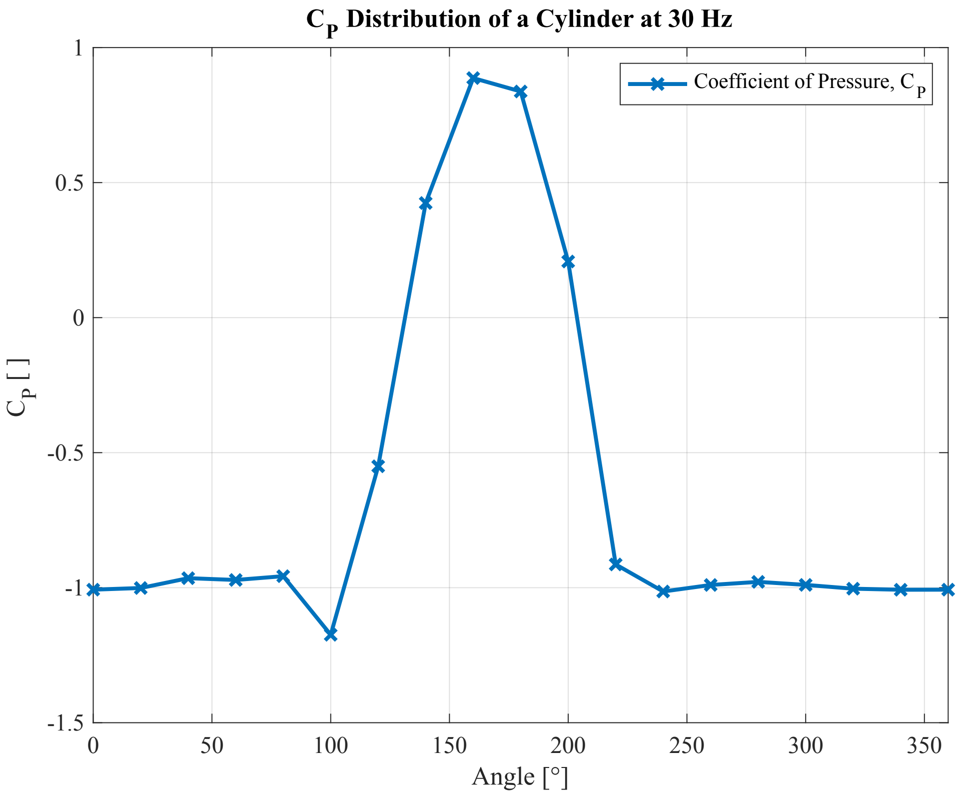

Figure B.6: *Plot of the C_P distribution around a cylinder at* 30 Hz.

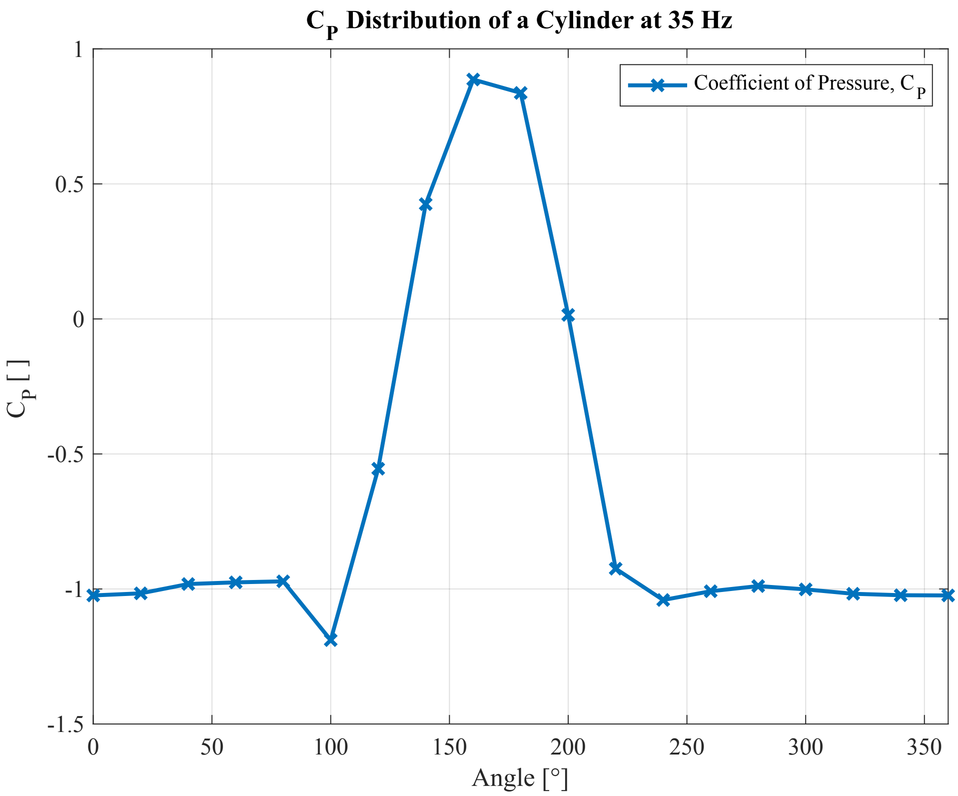

Figure B.7: *Plot of the C_P distribution around a cylinder at* 35 Hz.

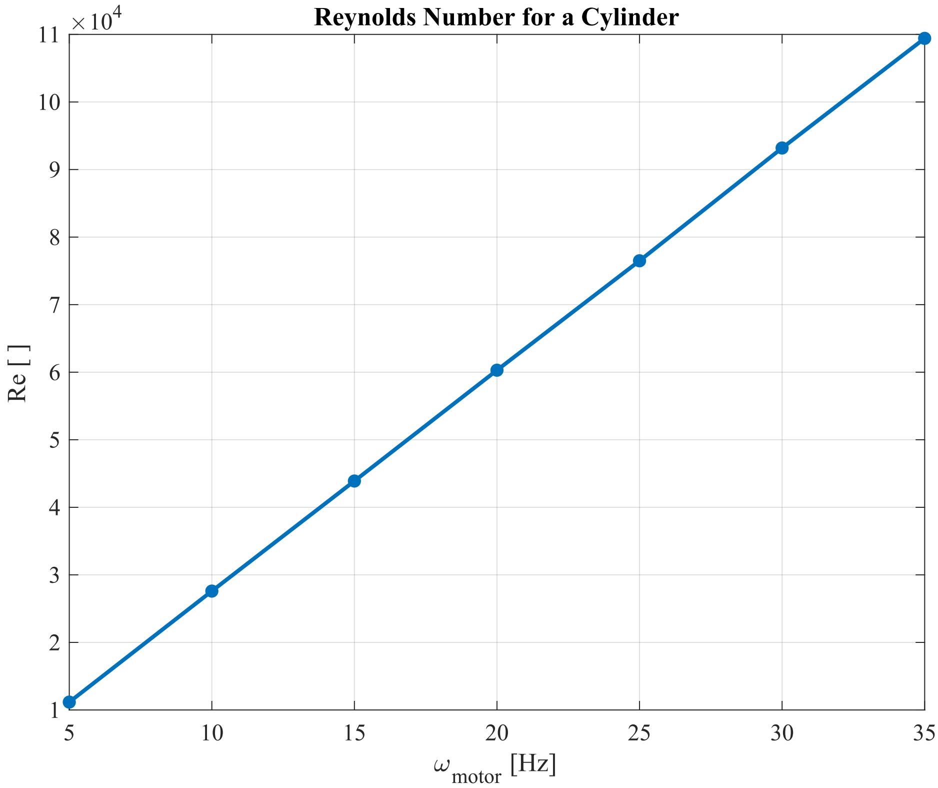

Figure B.8: *Plot of the Reynolds's Number Re vs motor frequency* Hz.

C

Appendix C

C.1 Lab4Analysis.m

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

%% Constants
u = symunit;
figure_dir = "../Figures/";
data_zip = "./data.zip";
K = 1.1; % []
% 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]
p_A_idx = 19;
p_E_idx = 20;
delta_theta = deg2rad(20);
angles = 180 : -20 : -180; % [°]
angles_shortened = 180 : -20 : -160; % [°]
D = double(separateUnits(unitConvert(0.7 * u.in, u.m))); % [m]

%% Import Calibration Data
unzip(data_zip);
freq = 5 : 5 : 35; % [Hz]
freq_str = strings([1 length(freq)]);
for i = 1 : length(freq_str)
    freq_str(i) = freq(i) + " Hz";
end
%{
Pressure Matrix Structure:
Each row is a different frequency corresponding to the values in the freq
array. Each column is a different pressure tap. For example, to get the 6th
pressure tap for 10 Hz, you would call pressure_matrix(2, 6).
%}
```

```
p = zeros([length(freq) 20]); % [Pa]
% defines the columns we actually want to parse
column_mask = [0 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 1 0 0 0 0 0 0 0 0 0 0 0 0 0 ...
    0 0 0 0 0 0 1 1 1 1];

for i = 1 : length(freq)
    data = readmatrix(sprintf("%02dHz.csv", freq(i)));
    counter = 1;
    for j = 1 : length(column_mask)
        % Only find the mean of certain columns
        if column_mask(j)
            p(i, counter) = mean(data(:, j)); % [Pa]
            counter = counter + 1;
        end
    end
end
clear data;

%% Calculations
C_p = zeros([length(freq) 18]);
C_d = zeros([1 length(freq)]); % []
Re = zeros([1 length(freq)]); % []
for i = 1 : length(freq)
    C_p(i, :) = (p(i, 1:18) - p(i, p_E_idx)) ...
        ./ (K .* (p(i, p_A_idx) - p(i, p_E_idx))); % []
    C_d(i) = -delta_theta ./ 2 ...
        .* sum(C_p(i, :) .* cosd(angles_shortened)); % []
    V = sqrt(K * (p(i, p_A_idx) - p(i, p_E_idx)) * 2 / rho_air);
    Re(i) = rho_air * V * 2 * D / mu_air; % []
end

% Make the data symmetrical
C_d_trap = zeros([1 length(freq)]); % []
for i = 1 : length(freq)
    C_p(i, 19) = C_p(i, 1); % []
    C_d_trap(i) = -delta_theta / 2 * trapz(C_p(i, :) .* cosd(angles)); % []
end

theta_theoretical = 0 : 0.01 : 360; % [°]
C_p_theoretical = 1 - 4 .* (sind(theta_theoretical).^2); % []

%% Plot
% Plot the individual C_p graphs
figure_cnt = 1;
for i = 1 : length(freq)
    figure(figure_cnt);
    plot(0 : 20 : 360, C_p(i, :), "-x", "MarkerSize", 8, "LineWidth", 2);
    fontname("Times New Roman");
    fontsize(12, "points");
    title_str = ...
        sprintf("C_P Distribution of a Cylinder at %d Hz", freq(i));
```

```
    title(title_str);
    xlabel("Angle [°]");
    ylabel("C_P [ ]");
    legend("Coefficient of Pressure, C_P");
    xlim([0 360]);
    grid on;
    figure_cnt = figure_cnt + 1;
    saveas(gcf, figure_dir + title_str + ".svg");
end

% Plot a cumulative C_p graph
figure(figure_cnt);
p = plot(theta_theoretical, C_p_theoretical, "--", "LineWidth", 1.5);
hold on
for i = 1 : length(freq)
    plot(0 : 20 : 360, C_p(i, :))
end
hold off;
fontname("Times New Roman");
fontsize(12, "points");
title_str = "C_P Distribution of a Cylinder";
title(title_str);
xlabel("Angle [°]");
ylabel("C_P [ ]");
legend(["Theoretical Solution" freq_str]);
xlim([0 360]);
uistack(p, "bottom");
grid on;
figure_cnt = figure_cnt + 1;
saveas(gcf, figure_dir + title_str + ".svg");

% Plot a cumulative C_p graph without 5-15 Hz
figure(figure_cnt);
p = plot(theta_theoretical, C_p_theoretical, "--", "LineWidth", 1.5);
hold on;
for i = 4 : length(freq)
    plot(0 : 20 : 360, C_p(i, :));
end
hold off;
fontname("Times New Roman");
fontsize(12, "points");
title_str = "C_P Distribution of a Cylinder (Excluding 5-15 Hz)";
title(title_str);
xlabel("Angle [°]");
ylabel("C_P [ ]");
legend(["Theoretical Solution" freq_str(4 : end)]);
xlim([0 360]);
uistack(p, "bottom");
grid on;
figure_cnt = figure_cnt + 1;
saveas(gcf, figure_dir + title_str + ".svg");
```

```

% Plot the C_d graph
figure(figure_cnt);
plot(freq, C_d, ".-", "MarkerSize", 20, "LineWidth", 3);
hold on;
plot(freq, C_d_trap, ".--", "MarkerSize", 20, "LineWidth", 2);
hold off;
fontname("Times New Roman");
fontsize(12, "points");
title_str = "C_d of a Cylinder";
title(title_str);
xlabel("\omega_{motor} [Hz]");
ylabel("C_d [ ]");
legend("Riemann Sum", "Trapezoidal Integration");
grid on;
figure_cnt = figure_cnt + 1;
saveas(gcf, figure_dir + title_str + ".svg");

% Plot the Reynold's graph
figure(figure_cnt);
plot(freq, Re, ".-", "MarkerSize", 20, "LineWidth", 2);
fontname("Times New Roman");
fontsize(12, "points");
title_str = "Reynolds Number for a Cylinder";
title(title_str);
xlabel("\omega_{motor} [Hz]");
ylabel("Re [ ]");
grid on;
figure_cnt = figure_cnt + 1;
saveas(gcf, figure_dir + title_str + ".svg");

% Plot C_d vs Reynold's
figure(figure_cnt);
plot(Re, C_d, ".-", "MarkerSize", 20, "LineWidth", 2);
fontname("Times New Roman");
fontsize(12, "points");
title_str = "C_d vs. Reynolds Number for a Cylinder";
title(title_str);
xlabel("Re []");
ylabel("C_d [ ]");
grid on;
figure_cnt = figure_cnt + 1;
saveas(gcf, figure_dir + title_str + ".svg");

delete *.csv
```