**Lab Report 1: Voltage Calibration Curves and Turbulent Vortex Frequency Analysis**

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**Nomenclature**

= freestream velocity

= dynamic pressure

= density of air

= corrected voltage

= wire temperature

= reference temperature from wind tunnel

= acquired temperature measurement

= acquired voltage measurement

= standard deviation of freestream velocity

= mean freestream velocity

= Strouhal number

= frequency of vortices

= diameter of cylinder

= Reynolds number

= dynamic viscosity of air

1. **Introduction**

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HIS report covers two experiments performed in the subsonic wind tunnel on the dates \_ and \_, respectively. Each lab used Constant Temperature Anemometry (CTA) system to gather information on the flow. In the first experiment, a calibration curve was generated for the hot wire anemometer that measured the speed of the airflow by analyzing the change in voltage that was required by the hot wire anemometer to maintain its temperature. Turbulence percentage was also calculated as part of the first experiment using the calibration curves. The second experiment focused on the calculation of the frequency of vortices shed behind a cylinder, which was accomplished through combining the calibration curves from the first lab and Fast Fourier Transforms (FFT). The data was then used to calculate Strouhal number and compare it the local Reynolds number of the pitot tube that was located behind the cylinder. In each laboratory session, three sensor positions were tested and analyzed.

1. **Flow Diagrams**

Below are the flow diagrams for each experiment. They are similar as experiment two builds off of experiment one, but with the additional element of the cylinder obstruction.

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| **Figure 1. Experiment 1 Flow Diagram.** *A hot-wire probe provided temperature readings to the CTA anemometer system that returned the variables necessary for data processing, excluding the thermocouple and pitot-static tube measurements that are included in every wind tunnel experiment.* |

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| **Figure 2. Experiment 2 Flow Diagram.** *The flow diagram for the second experiment is the same as the first, with the addition of the cylinder used to obstruct the flow and create vortices, labelled as flow interference in the diagram.* |

1. **Calculations**

Freestream velocity in the subsonic wind tunnel was calculated using the dynamic pressure measured by the pitot tube with the equation below.

|  |  |  |
| --- | --- | --- |
|  |  | (1) |

Instrumentation provided temperature readings from the hot-wire anemometer as well as the voltage reading, but this voltage was corrected to provide an accurate voltage reading from the reference temperature. This is described by Eq. 2, below.

|  |  |  |
| --- | --- | --- |
|  |  | (2) |

Percentage turbulence was calculated through a relationship between the standard deviations of velocity and the mean of the same velocity. Each position had a different velocity and thus resulted three turbulence percentages. The equation below represents the relationship used in the calculation.

|  |  |  |
| --- | --- | --- |
|  |  | (3) |

The Strouhal number was necessary to fully describe the oscillations in the flow and was calculated using of Eq. 3.

|  |  |  |
| --- | --- | --- |
|  |  | (4) |

Reynolds number, the ratio of inertial forces to viscous forces, was also used to describe the flow, and was calculated using the diameter of the cylinder as the reference length.

|  |  |  |
| --- | --- | --- |
|  |  | (5) |

|  |  |  |
| --- | --- | --- |
|  |  |  |

1. **Results**

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| **Figure 3. Position 1 Calibration Curve.** Both the positive and negative data points and fifth-degree polynomial fits are presented here for position 1*.* |

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| **Figure 4. Position 2 Calibration Curve.** *The position 2 data is represented here and is comparable to the position 1 data.* |
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| **Figure 5. Position 3 Calibration Curve.** *Position 3 varied slightly more, but the differences were negligible.* |

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|  |
| **Figure 6. Position 2 Turbulence Percentage vs. Velocity.** *The relationship between the turbulence percentage and velocity is shown here, with a higher velocity generally correlating to a lower percent turbulence.* |
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| **Figure 7. Laminar Strouhal Number vs. Reynolds Number.** *Laminar S vs Re data was slightly higher than.* |
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| **Figure 8. Turbulent Strouhal Number vs. Reynolds Number.** *Turbulent data shown to be slightly less than laminar data.* |
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| **Figure 9. Laminar Strouhal Number vs. Reynolds Number against Reference Plot.** *Here the collected data is shown against the reference data and does not show an equivalent trend.* |
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1. **Discussion**

The calibration curves show almost no hysteresis as the increasing (POS) and decreasing (NEG) data sets were compared through polynomial curve fitting. Polynomials of the fifth degree were used due to the residual no longer decreasing significantly from an increase in polynomial degree. Each position shows that the corrected voltage increases with airspeed velocity, as the anemometer must provide more energy to maintain its constant temperature.

Fig. 4 illustrates that an increase in velocity for position two resulted in a decrease in the percentage of turbulence, meaning that faster flow was less turbulent than the slower flow around the sensor. The drop from the minimum tested velocity to the maximum tested velocity is initially steep, then gradual, but significant at around twenty-five percent, almost akin to an inverse exponential relationship between the two properties.

The figures of the Stouhal number against the Reynolds number for the second experiment does not compare well with the reference data, indicating an error in the analysis. The cylinder diameter used in this experiment is slightly less than that used for the reference data, but that should only be shown as a slight variation. It was expected that the figures from this experiment would show an equivalent trend, with Strouhal values and Reynolds numbers only slightly lower, as compared to the dramatic difference displayed in Fig. 9. Errors in the method of the FFT or velocity calculations likely could have resulted in this discrepancy in the trends, but it is still possible that the trend of Strouhal number versus Reynolds number breaks down at lower Reynolds numbers. Regardless, there is an error in the calculations that has caused the discrepancy, at least to some extent, if not entirely.

To maintain a pressure range of one to nine pounds per square foot while increasing the Reynolds number, the diameter of the cylinder must be increased as it varies directly with the Reynolds number. This direct variation can be seen in Eq. 5. The density and dynamic viscosity are properties of the fluid, so if the working fluid is changed to a denser one, this could also cause an increase in the Reynolds number. As the pressure range directly influences the velocity, this variable cannot be manipulated to increase the Reynolds number.

1. **Appendix**

%% Experimental Aerodynamics III: Lab 1 and 2

% include folders for lab 1 and lab 2

%% Lab 1

% string names for file names

filenames1 = {"instrumentation\_data\_Q\_", "voltage\_time\_history\_Q\_"};

% Constants

rho = 1.14; % kg/m^3

%% Load in data

inspos = cell(1,10);

insneg = inspos;

vthpos\_loc = cell(10,3);

%vthpos\_loc2 = vthpos\_loc1;

%vthpos\_loc3 = vthpos\_loc1;

for i = 1:10 % number of readings

% Positive instrumentation data

inspos{i} = importdata(filenames1{1} + "POS" + i + ".dat"); % gets pos123 etc.dat

% Negative instrumentation data

insneg{i} = importdata(filenames1{1} + "NEG" + i + ".dat");

% Positive voltage time history data (there is no neg)

for j = 1:3

vthpos\_loc{i,j} = importdata(filenames1{2} + "POS" + i + "\_position\_" + j + ".dat"); % vth data pos1 loc 1

%vthpos\_loc2{i} = importdata(filenames1{2} + "POS" + i + "\_position\_2.dat");

%vthpos\_loc3{i} = importdata(filenames1{2} + "POS" + i + "\_position\_3.dat");

end

end

%% Calculations

% Instrumentation data files, 3 rows (3 positions)

% Position Qtrans Qpitot Tacq Twire Tref Eacq

% vinf, vinf\_standard\_deviation, vinf\_mean

%eacq\_vth = {};

for i = 1:10

for j = 1:3 % (each position)

dynP = inspos{i}(j,3);

dynPneg = insneg{i}(j,3);

twire = inspos{i}(j,5); %+ 273.15; % (not) corrected to kelvin

twireneg = insneg{i}(j,5);

tref = inspos{i}(j,6); %+ 273.15; % (not) corrected to kelvin

trefneg = insneg{i}(j,6);

tacq = inspos{i}(j,4);

tacqneg = insneg{i}(j,4);

eacq = inspos{i}(j,7);

eacqneg = insneg{i}(j,7);

eacq\_vth{i,j} = vthpos\_loc{i,j}(:,2); %eacq from vth data for the turb%

%eacq\_vthneg{i,j} = vthneg\_loc{i,j}(:,2);

t\_vth{i,j} = vthpos\_loc{i,j}(:,1); % time from vth data for use in plot

%vinf = sqrt(2\*dynp/dens) dynp is p02 (Qpitot)

vinf(i,j) = sqrt(2\*dynP / rho);

% eCorr

eCorr(i,j) = sqrt((twire - tref)/(twire - tacq))\*eacq;

eCorrneg(i,j) = sqrt((twireneg - trefneg)/(twireneg - tacqneg))\*eacqneg;

%eCorrvth{i,j} = sqrt((twire - tref)/(twire-tacq)).\*eacq\_vth;

% tuPerc

%tuPerc(i,j) = (vinf\_std/vinf\_mean)\*100;

% Polyfits and polyvals

x = vinf(:,j);

y = eCorr(:,j);

yneg = eCorrneg(:,j);

xvalrange{j,1} = linspace(min(x),max(x));

p{j,1} = polyfit(x, y, 5); % cubic fit

pneg{j,1} = polyfit(x,yneg,5);

vals{j,1} = polyval(p{j,1}, xvalrange{j,1});

valsneg{j,1} = polyval(pneg{j,1}, xvalrange{j,1});

end

end

voltmat = cell2mat(eacq\_vth'); % matrix of vth voltages, cols are pos, might want to transpose

%vlotmatneg = cell2mat(eacq\_vthneg');

velvals = interp1(y,x, voltmat,'linear','extrap'); % linear interp for velocities from voltages

velvalsneg = interp1(yneg,x,voltmat,'linear','extrap');

%stdvelvals = std(velvals);

%meanvelvals = mean(velvals);

% Position 1

velvals1 = velvals(1:10000,:);

stdvelvals1 = std(velvals1);

meanvelvals1 = mean(velvals1);

% Position 2 is row values 10001:20000

velvals2 = velvals(10001:20000,:);

stdvelvals2 = std(velvals2);

meanvelvals2 = mean(velvals2);

% Position 3

velvals3 = velvals(20001:end,:);

stdvelvals3 = std(velvals3);

meanvelvals3 = mean(velvals3);

tuPercVals = stdvelvals2./meanvelvals2.\*100; % for pos 2

%% Plots

% Create calib curves for each position

% Plots

figure(1) % pos 1, calib curves and scatter data

plot(vinf(:,1),eCorr(:,1),'o') % scatter data pos 1

hold on

plot(xvalrange{1,1}, vals{1,1})

plot(vinf(:,1),eCorrneg(:,1),'sq') % neg data

plot(xvalrange{1,1}, valsneg{1,1},'--')

hold off

xlabel('V\_inf')

ylabel('E\_C\_o\_r\_r')

title('Position 1 Calibration Curve')

legend('Data points (POS)','Line of best fit (POS)', 'Data Points (NEG)', 'Line of best fit (NEG)')

figure(2) % pos 2

plot(vinf(:,2),eCorr(:,2),'o') % pos 2

hold on

plot(xvalrange{2,1}, vals{2,1})

plot(vinf(:,2),eCorrneg(:,2),'sq') % neg data

plot(xvalrange{2,1}, valsneg{2,1},'--')

hold off

xlabel('V\_inf')

ylabel('E\_C\_o\_r\_r')

title('Position 2 Calibration Curve')

legend('Data points (POS)','Line of best fit (POS)', 'Data Points (NEG)', 'Line of best fit (NEG)')

figure(3) % pos 3

plot(vinf(:,3),eCorr(:,3),'o') % pos 3

hold on

plot(xvalrange{3,1}, vals{3,1})

plot(vinf(:,3),eCorrneg(:,3),'sq') % neg data

plot(xvalrange{3,1}, valsneg{3,1},'--')

hold off

xlabel('V\_inf')

ylabel('E\_C\_o\_r\_r')

title('Position 3 Calibration Curve')

legend('Data points (POS)','Line of best fit (POS)', 'Data Points (NEG)', 'Line of best fit (NEG)')

figure(4) % tuPerc vs velvals

plot(meanvelvals2,tuPercVals)

title('Turbulence Percentage (Position 2) vs. Velocity')

xlabel('Velocity')

ylabel('Tu(%)')

%% Hysteresis check

% plot vel from up data and vel from down data against eachother, do visual

% check and also can get polynomial fit, do percent difference on the fits

%% LAB 2

mu = 1.962e-5; % dynamic viscosity kg/ms

d = 0.1016; % cylinder diameter, m

% Use fast Fourier transform (matlab fft) to get shedding frequencies

%S = f\*d/vinf Strouhal number

%Re = rho\*vinf\*d/mu

% Load in data

Q = {'0.5', '1.0', '1.5', '2.0', '2.5', '3.0', '3.5', '4.0', '4.5', '5.0', ...

'6.0', '7.0', '8.0', '9.0', '10.0', '11.0', '12.0'};

Qnums = [0.5 1 1.5 2 2.5 3 3.5 4 4.5 5 6 7 8 9 10 11 12].\*47.88; % psf to Pa

vthlam = importdata("voltage\_time\_history\_Q\_1.0\_lam\_position\_1.dat");

%vthlam = importdata(filenames1{2} + num2str(Q(i)) + "\_lam\_position\_1.dat");

vthlam = {};

vthturb = {};

parfor i = 1:length(Q) % number of Q's tested

vthlam{i} = importdata(filenames1{2} + Q{i} + "\_lam\_position\_1.dat");

vthlam\_volt{i} = vthlam{i}(:,2);

vthturb{i} = importdata(filenames1{2} + Q{i} + "\_turb\_position\_1.dat");

vthturb\_volt{i} = vthturb{i}(:,2);

end

% Calculate freestream velocity

vinf2 = sqrt(2.\*Qnums./rho);

% Calculate vel from vth data using interp

% MIGHT only need to get v\_inf from Qtrans as says in handout

%vthvel\_lam = interp1(polyval(p{3,1},linspace(min(y),max(y),17)),vinf2, cell2mat(vthlam\_volt),'linear','extrap'); % vels separated by dynp

vthvel\_lam = interp1(y,x, cell2mat(vthlam\_volt),'linear','extrap'); % vels separated by dynp

vthvel\_turb = interp1(y,x, cell2mat(vthturb\_volt),'linear','extrap');

% Calculate Reynolds number

Re\_lam = rho.\*d.\*vthvel\_lam./mu;

Re\_turb = rho.\*d.\*vthvel\_turb./mu;

%Re\_both = rho.\*d.\*vinf2./mu;

% FFT for shedding frequencies

% FFT

freq = [];

for i = 1:length(Q)

voltage = vthturb{i}(:,2);

%voltage = vthvel\_turb(:,i);

%voltage = vthvel\_turb(:,i); % if need to do vel

fastft = fft(voltage); % fft of voltages

L = length(voltage); % length of signal

Fs = 1000; % sampling frequency (samples in 1 sec)

% One sided

P2 = abs(fastft/L);

P1 = P2(1:L/2+1);

P1(2:end-1) = 2\*P1(2:end-1);

f = Fs\*(0:(L/2))/L; % frequency domain

%plot(f,P1);hold on

P1\_aug = P1(f >= 3); % augmented to only include frequencies within wanted domain

freq(i) = f(P1\_aug == max(P1\_aug)); % frequency of vorticies

end

% Calculate Reynolds number

%Re\_lam = rho.\*d.\*vinf2/mu;

%Re\_turb = ;

% Calculate Strouhal number

%S = freq .\* d ./ vinf2; % wrong

S\_lam = freq .\* d ./ vthvel\_lam;

S\_turb = freq .\* d ./ vthvel\_turb;

%% Plot S vs. Re

%

%mean(abs(Re\_lam))

%{

figure(3) % wrong

plot(mean(abs(Re\_lam)), S, '\*')

hold on

plot(mean(abs(Re\_turb)), S, 'o')

hold off

%}

% Reference image coplotting

X = mean(Re\_lam); Y = mean(S\_lam);

%X = Re\_both; Y = S;

px = [107, 890];

py = [88, 746];

Xlim = [10^4, 10^6]; Ylim = [0, 0.5];

plotx = px(1) + X.\*diff(px)./diff(Xlim);

ploty = py(1) + Y.\*diff(py)./diff(Ylim);

figure(5);

Fig = flip(imread('refplot.jpg'), 1);

[stdby1, stdby2, ~] = size(Fig);

imshow(Fig);

set(gca, 'YDir', 'normal')

line(plotx, ploty, 'color', 'r', 'lineWidth', 2);

title('Laminar S vs. Re against Reference Plot')

%%

figure(1) % laminar s vs. re

plot(mean(Re\_lam), mean(S\_lam), 'sq')

xlabel('Mean Re');

ylabel('Mean S');

title('Laminar S vs. Re');

%figure(3)

%plot(Re\_both, S)

figure(2) % turbulent s vs. re

plot(mean(Re\_turb), mean(S\_turb), 'o')

xlabel('Mean Re');

ylabel('Mean S');

title('Turbulent S vs. Re');

1. **References**

1Narsipur, Shreyas. “MAE 451 – Experimental Aerodynamics III General Information and Lab 1 (CTA)”. *NCSU,* September 10, 2019.

2Narsipur, Shreyas. “MAE 451 – Experimental Aerodynamics III Lab 2 – Cylinder Vortex Shedding Analysis”. *NCSU,* September 17, 2019.