MEMO TO: Qiuyan Li

FROM: Seth Strayer

DATE: May 28, 2019

SUBJECT: TF2 – Vortex Shedding

On May 22, 2019, Noah Sargent, Aaron Esquino, and I conducted an experiment to understand the turbulence intensity of the wake region behind a cylinder in cross flow and develop a relationship between vortex shedding and speed of flow. Turbulence is an extraordinarily complex phenomenon that many investigators have dedicated their entire careers to understanding. Thus, in performing this study, we hope to gain introductory knowledge in the behavior of turbulence as it relates to flow speed and vortex shedding.

The first part of this experiment involved calibration of the hot-wire anemometer via measuring the voltage output across a range of known input speeds. This is necessary to ensure that the flow velocity may be correctly calculated based on the voltage data for any arbitrary input speed. Ten different trials with wind tunnel input speeds ranging from 15-60 [Hz] (based on the wind tunnel manufacturer data listed in Table 1) were performed. Note that each trial collected data at a sampling frequency of 2 [kHz] over a time of 2 [sec], for a total of 4000 points of voltage data. The average voltage output was then calculated for each input speed and plotted against its corresponding flow velocity. This allowed us to derive an empirical relationship between the flow velocity as a function of the measured average voltage.

Part two of this experiment involved placing a cylinder in the test section and measuring the turbulence intensity and vortex shedding frequency in the wake region of the flow. The flow behavior in the wake region behind the cylinder is dependent upon the magnitude of Reynold's number (Re), given by Equation (1). Thus, eight different speed trials were run at three different wake locations (axial distance from surface of the cylinder), for a total of 24 trials. This data was collected and exported from MATLAB to Excel, where the flow velocity was calculated for each data point based upon the empirical relationship discussed prior. This allowed us to calculate the average and standard deviation of the flow velocity for each trial (*note* that standard deviation was calculated with respect to population rather than a sample, due to the copious amounts of data). From this, the turbulence intensity *(I)* was calculated via Equation (2). Once all trials were run, the turbulence intensity was plotted as a function of flow velocity to determine if there was a clear relationship between the two.

Finally, the vortex shedding frequency can often be characterized by the Strouhal number (*St*), which is a dimensionless parameter described by Equation (3). To determine the frequency of vortex shedding, an FFT analysis was performed on each of the 24 acquired data sets. The average and variance of the Strouhal number were then calculated for each of the 3 measurement locations, and ANOVA was performed to determine whether the *St* values at each of the three positions were statistically different or whether they could be considered equal.

A plot of flow velocity vs. motor input speed is shown in Figure 1. This plot utilized the calibration points based on the wind tunnel manufacturer data and allowed us to determine an appropriate curve fit for flow velocity as a function of motor input speed. I.e., it allowed us to estimate the average flow velocity for any motor input speed which was not explicitly given on the manufacturer's data list. Figure 2 depicts this same flow velocity as a function of the measured, average output voltage. We found that this data followed an exponential curve fit, with an R-squared value of 0.99385. Thus, this fit was fairly accurate in calculating flow velocity for any given voltage measurement. This concluded the calibration analysis for this experiment.

Turbulence intensity was then calculated for each of the 24 trials using methods as previously discussed. Sample data for wake location x = 20 [mm], is listed in Table 2. Similar tables for x = 35, 50 [mm] are provided in the Excel file "TF2 Data.xlsx". A plot of turbulence intensity vs. average flow velocity for each of the three wake locations is shown in Figure 3. It is obvious that the turbulence intensity linearly increases with the average flow velocity. This can be explained by the fact that the flow is becoming increasingly turbulent as flow velocity increases (Eqn. 1) and therefore there are more deviations in the flow velocity. This, in turn, increases the turbulence intensity according to Equation (2). Furthermore, we find that the maximum turbulence intensity decreases with increasing axial distance from the surface of the cylinder. This can be explained by the fact that the flow is stabilizing itself downstream after its initial onset of turbulence from interaction with the cylinder.

FFT analysis for each trial was conducted using the MATLAB script "TF2_FFT.m". The analysis for x = 20 [mm] and an input motor speed of f = 57.5 [Hz] is shown in Figure 5, with its original signal given in Figure 4. Figure 5 indicates that the peak magnitude occurred at a frequency of 233.5 [Hz]. This value represents the frequency of the vortex shedding. Using the vortex shedding frequencies, Strouhal numbers were calculated via Equation (3) for each trial and grouped according to their wake location. For each wake location, the average and variance of the Strouhal numbers were calculated and using this information, ANOVA was performed to determine whether the *St* values at each of the three positions were statistically different or whether they could be considered equal. With this approach, the *F-statistic* value was determined to be 42.21. Using a significance value of α = 0.05 (95% confidence), the *F-critical* value was determined to be 3.47. Thus, we conclude that the *St* values *are* statistically different at each of the three measurement locations, to 95% confidence. Note that at a significance level of α = 4.40e-08, it would be possible to conclude that the *St* values *are not* statistically different from each other. However, considering how high of a confidence level this is, it would be unrealistic to assume that the *St* values could ever be considered, statistically, the same. Tabular data for this portion of the experiment is not provided this report but can be found in the Excel file "TF2 Data.xlsx", sheets "FFT Analysis" and "ANOVA".

To recap, Figure 3 indicates that turbulence intensity linearly increases with the flow velocity. This is because Reynolds number increases linearly with flow velocity, creating more deviations in the flow and thus causing turbulence intensity to increase. Based on ANOVA, we conclude that the *St* values at each wake location *are* statistically different, to 95% confidence. This reveals that vortex shedding is dependent upon the wake location.

We may conclude that our results are fairly accurate due to the small amount of error present in this experiment. The largest source of error arises from the curve fit used to calculate flow velocity based on measured average voltage (Figure 2). We note that the fit is an approximation based on a limited number of calibration points, and thus there is some error when calculating flow velocity, given the voltage. Since this is used to calculate the velocity at each voltage data point, this error may accumulate and lead to errors in calculating average flow velocity and the standard deviation of the flow velocity. However, the results correlate to those predicted by literature and thus it follows that measurement error does not have that large of an impact on the accuracy of our results.

Table 1: Calibration Data from Wind Tunnel Manufacturer

Frequency [Hz]	Wind Speed [m/s]	Wind Speed [ft/s]
60	17.01	55.81
55	15.52	50.93
50	14.06	46.11
45	12.71	41.69
40	11.24	36.86
35	9.75	31.99
30	8.28	27.18
25	6.78	22.25
20	5.26	17.27
15	3.72	12.21
10	2.2	7.22
7.5	1.37	4.5
5	0.64	2.12
3	0.43	1.41

Equation to calculate Reynolds number:

$$Re = \frac{\rho V D}{\mu} = \frac{VD}{\nu} \tag{1}$$

Where V is the velocity of the flow, ρ is the density of the fluid, μ and ν are the dynamic and kinematic viscosities, respectively, and D is the characteristic length scale.

Equation to calculate Turbulence Intensity:

$$I = \frac{S_u}{\bar{u}} \tag{2}$$

Where S_u is the standard deviation of the velocity and $\bar{u}$ is the mean flow velocity.

Equation to calculate Strouhals number:

$$St = \frac{fD}{V} \tag{3}$$

Where f is the frequency of vortex shedding, with V and D as defined above for Reynolds number.

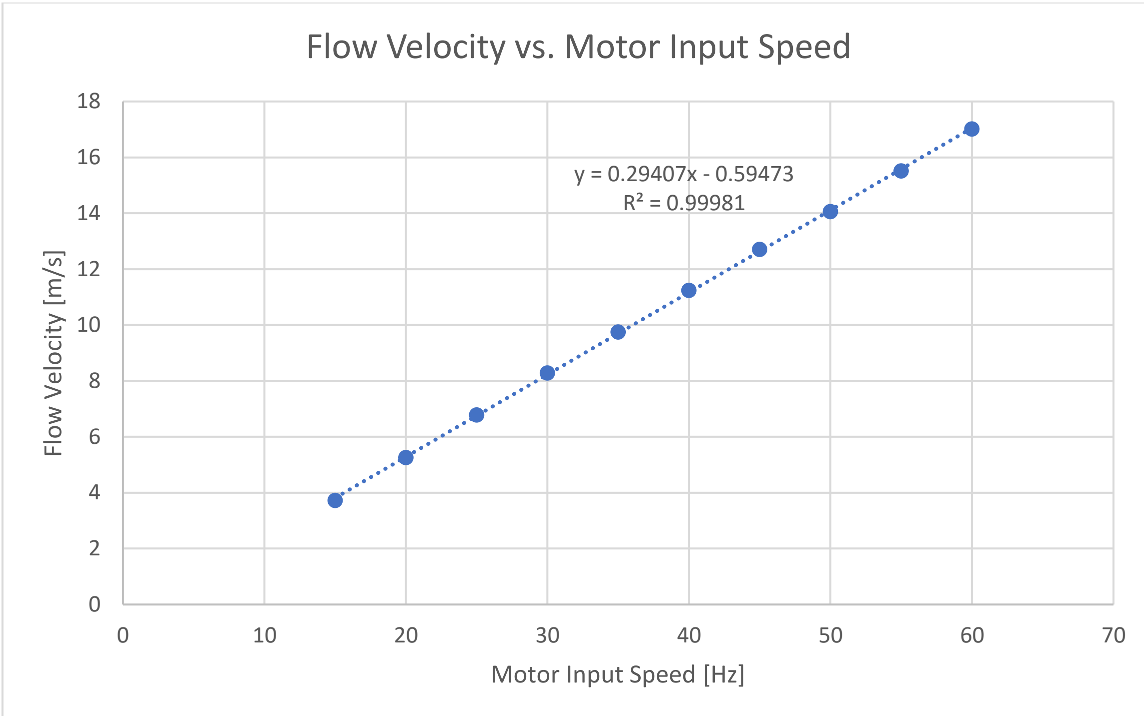

Figure 1: Flow Velocity vs. Motor Input Speed

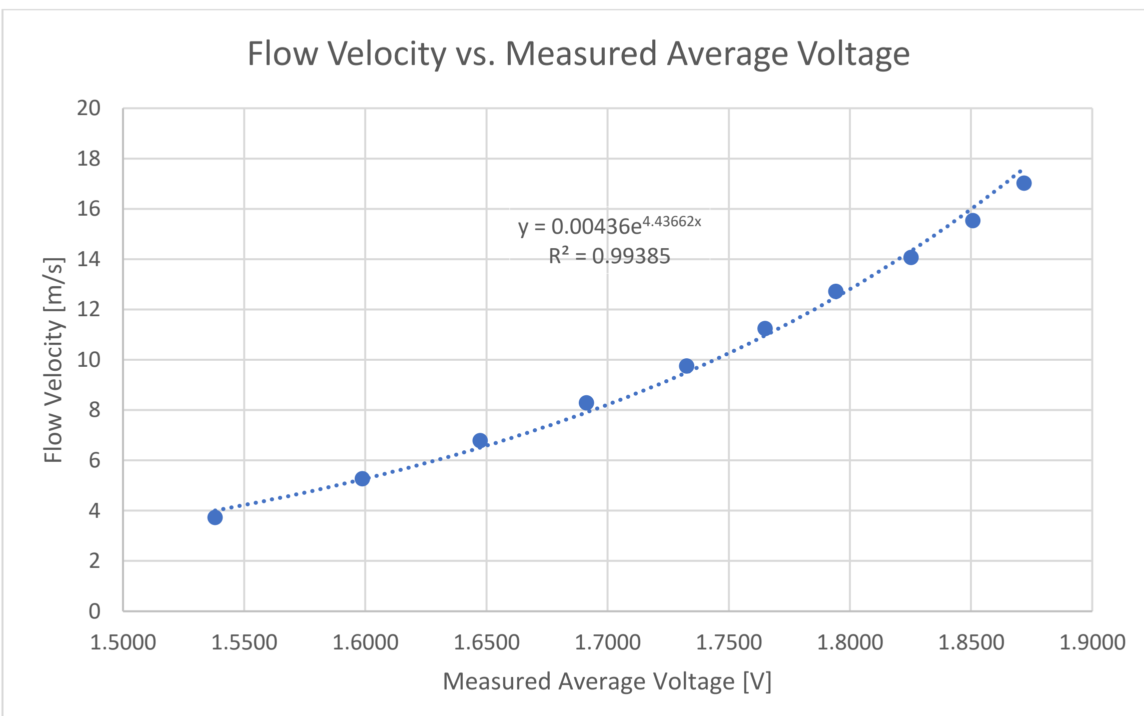

Figure 2: Flow Velocity vs. Measured Average Voltage

Table 2: Sample Flow Data for *x* = 20 [mm]

Motor Input Speed [Hz]	Average Voltage [V]	Average Velocity [m/s]	Standard Deviation	Intensity
22.5	1.6299	6.142	1.095	0.178
27.5	1.6702	7.417	1.586	0.214
32.5	1.7064	8.766	2.073	0.236
37.5	1.7361	10.082	2.638	0.262
42.5	1.7653	11.535	3.195	0.277
47.5	1.7822	12.598	3.928	0.312
52.5	1.8053	14.086	4.699	0.334
57.5	1.8219	15.326	5.471	0.357

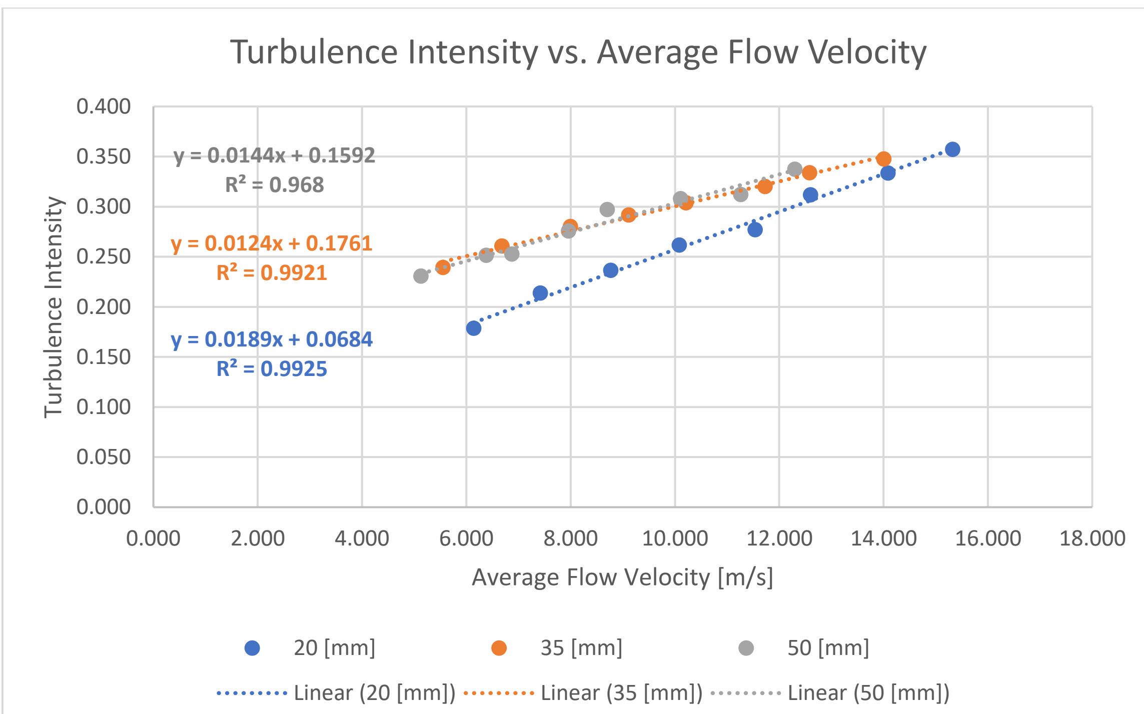

Figure 3: Turbulence Intensity vs. Average Flow Velocity for each Wake Location

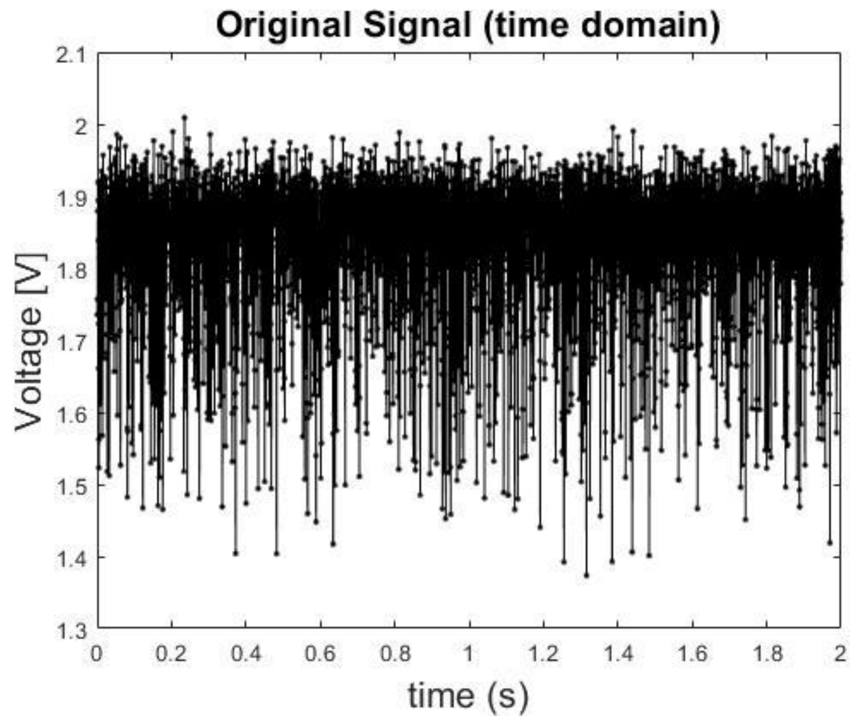

Figure 4: Original Voltage Signal for x = 20 [mm] and f = 57.5 [Hz]

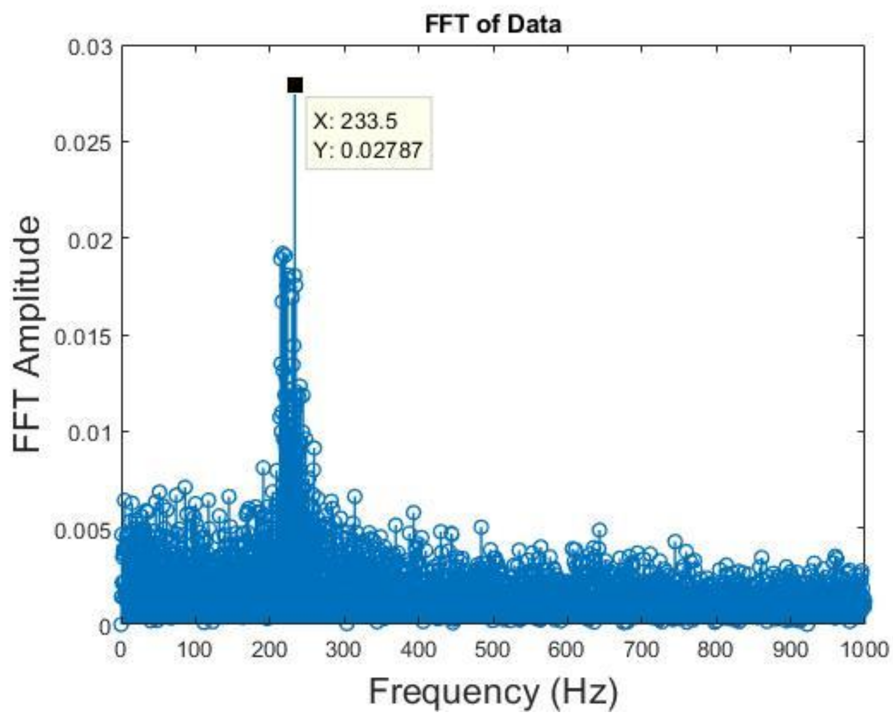

Figure 5: FFT for x = 20 [mm] and f = 57.5 [Hz]