Project Vortex

A low speed, low cost wind sensor.

ENGN 1735/2735, Vibrations of Mechanical Systems

Submitted: December 10, 2020

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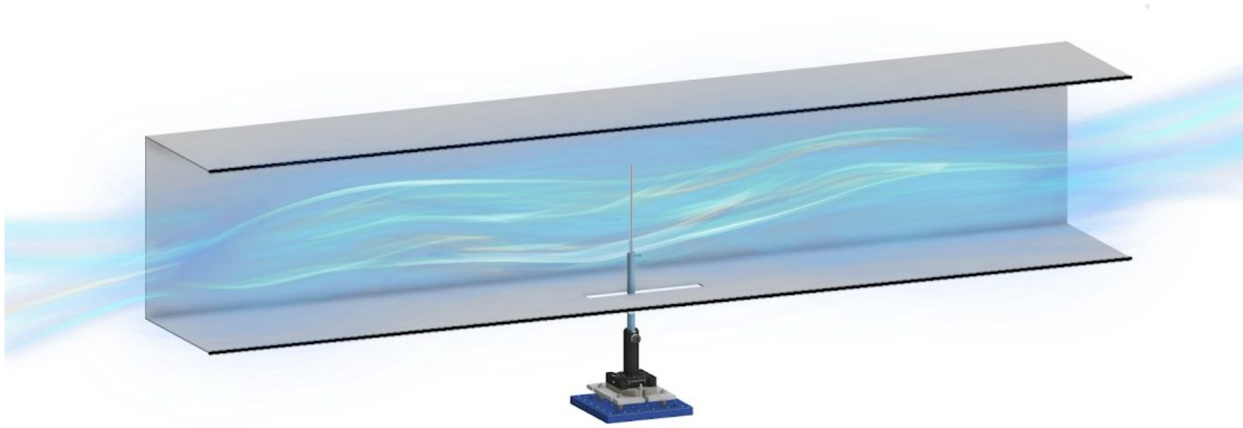


Background and Motivation

In researching low Reynolds number flows, accurate measurements of flow velocity are needed. Methods of measuring flow speed range from simple vane anemometers to pitot tubes to hot wire anemometers, but each can be inadequate when obtaining accurate low free stream velocities. The pitot tube becomes inefficient below ~3 m/s as it is dependent on dynamic pressure, the square of the velocity, to calculate velocity. Therefore, the velocity is either inaccurate at low wind speed or a very sensitive pressure transducer is required to detect such small changes. High sensitivity pressure transducers are expensive, ranging from around $700 to $2000. Vane anemometers often require frequent calibrations, and hot wire anemometers are susceptible to convective heat loss and are expensive (as they range from around $500 to $1500).[1] Without a viable existing low-cost method for accurate flow measurements, the need arises for the development of a new alternative.

A low-speed wind sensor that uses the vortex shedding of a vibrating cylinder was first proposed during ENGN 1860 in the spring of 2020.[2] This design uses the fact that a cylinder in a low Reynolds number flow sheds alternating vortices periodically, forming what is known as the Von Kármán vortex street. The vortices, due to their high velocity, create regions of low pressure. Alternating low-pressure regions on either the bottom or the top of the cylinder create an unsteady periodic lift force.[3] This causes the cylinder to oscillate. The frequency of oscillation is given by the Strouhal number:

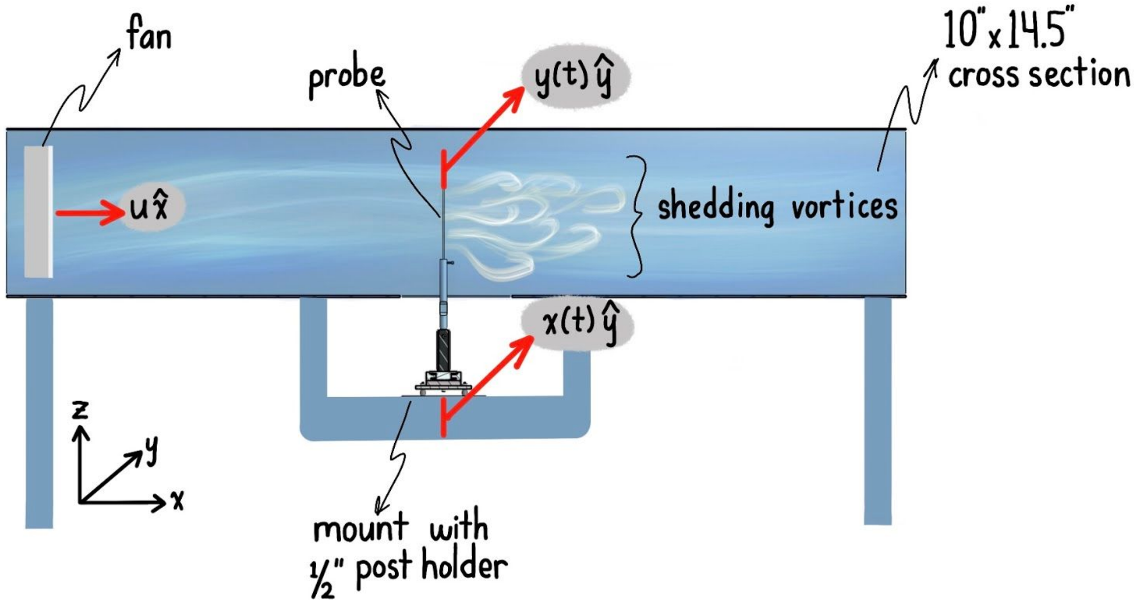
$$St = \frac{fd}{V} \quad (1)$$ [4]

At Reynolds number larger than 300, the Strouhal number is approximately constant and equal to 0.2. However, periodic vortex shedding is also seen in the Reynolds number range of 50 to 150, in which the governing equation uses the Roshko number and becomes:

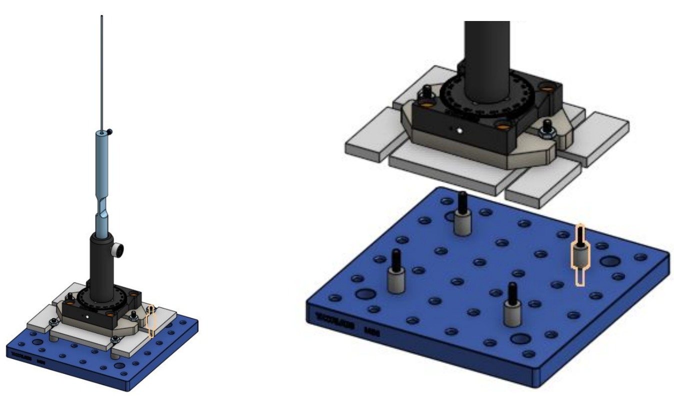
$$\frac{fd^2}{\nu} = 0.212 \, \underline{Vd} \; - 4.5 \quad (2)$$ [5]

where f is frequency, d is the cylinder diameter, **ν** is the kinematic viscosity, and V is the velocity of the flow. Therefore, if the dimensions of the cylinder is known and the vortex shedding frequency is measured from a strain gauge, the velocity of the fluid flow can be obtained.

Experimental Methodologies and Protocols



The schematic above illustrates the experimental parameters defined in our setup. A fan at one end of the tunnel accelerates air at different motor frequencies. As the air flows by the probe at speed U, it experiences vortex shedding and oscillates given by the parameter y(t). Simultaneously, we expect the base of the cylinder mount to experience its own set of vibrations denoted by x(t). The wind tunnel we used in our experiment is located in a larger machine shop which experiences vibrations from the surrounding equipment. In addition, the probe is mounted directly onto the wind tunnel. Due to the range of driving frequencies the motor vibrates at when it is in use, the mount experiences external vibrations. Thus, the vibrations from the surrounding environment and the wind tunnel are accounted for in the term x(t).



Since our goal in this project is to isolate the vibrations experienced as a result of the vortex shedding, we needed to come up with a way to dampen the external vibrations from the motor and environment. To do this we designed a mounting system which incorporates lateral dampeners. The CAD images above depict the final mounting setup. This design incorporates existing wind tunnel materials, ordered parts, and custom fabricated parts. The key aspect of this design is the four sandwich mounts which connect the probe to the base of the wind tunnel. We chose to use vibration dampening sandwich mounts for their ability to counteract lateral and vertical vibrations.

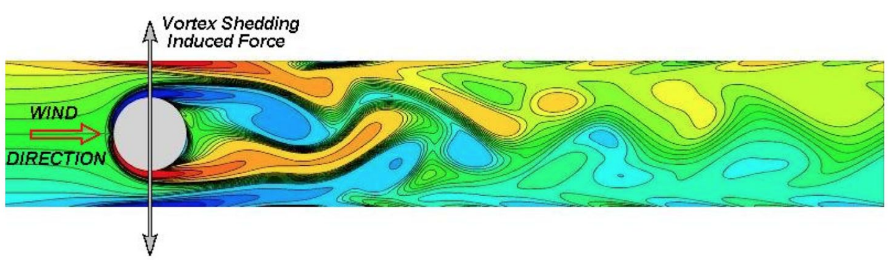
The wind tunnel in the Brown Design Workshop has a preexisting computer and circuit setup with the wind tunnel. Therefore, we were able to utilize the existing equipment and adapt it to our project. The hardware system already in place consists of a half bridge circuit, signal amplifier, and a National Instruments USB 6000 DAq Card connected to a computer.

The first step in our experiment was the setup. We first set up the vibration isolation platform and attached the strain gauge to it. We then attached the wires of the strain gauge to the bridge circuit which then connected to the signal amplifier so the readings would be easier to read since they were low. To run the experiment we turned on the wind tunnel and tested different motor frequencies at initial values, starting at 0 Hz and going all the way to 20 Hz. While the wind tunnel was on, we ran the MATLAB code that drove the DAQ and acquired the data from each test run. We saved the data from each test and ran the test again at a different motor frequency.

Theory and Numerical Calculations

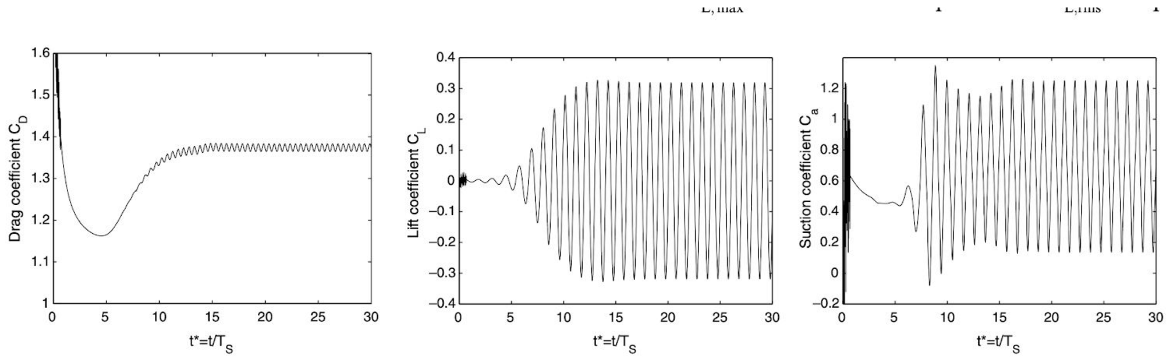
The range of expected frequencies to be measured was first calculated using equations (1) and (2). Assuming a cylinder diameter of 1.5 mm and a range of velocities of 0.5 m/s to 5 m/s, the maximum and minimum Reynolds numbers were found to be 498 and 49.8, respectively. To find the maximum frequency, equation (1) was used with the Strouhal number equal to 0.2, since the maximum Reynolds number is greater than 300. To find the minimum frequency, equation (2) was used, since the minimum Reynolds number is approximately 50. The range of frequencies was therefore calculated as 40.6 Hz to 666.7 Hz.

Vibration isolation theory was then used to design the vibration isolation system. For isolation, $r = \omega/\omega_n > \sqrt{2}$. To have a system that isolates vibration for the entire range of expected measured frequencies, $\omega/\omega_n > \sqrt{2}$ for the lowest expected frequency. Thus, to have isolation at 40.6 Hz, $\omega/\omega_n > \sqrt{2}$ implies that $(2\pi(40.6))/(2\pi f_n) > \sqrt{2}$, or equivalently, $f_n < 28.7$ Hz. The vibration isolation mounts selected for the vibration isolation system thus had a natural frequency below 28.7 Hz.



Vortex Shedding phenomenon induced by wind flowing over a cylinder. [6]

Vortex shedding occurs from the alternating low-pressure regions on either the bottom or the top of the cylinder which create an unsteady periodic lift force.



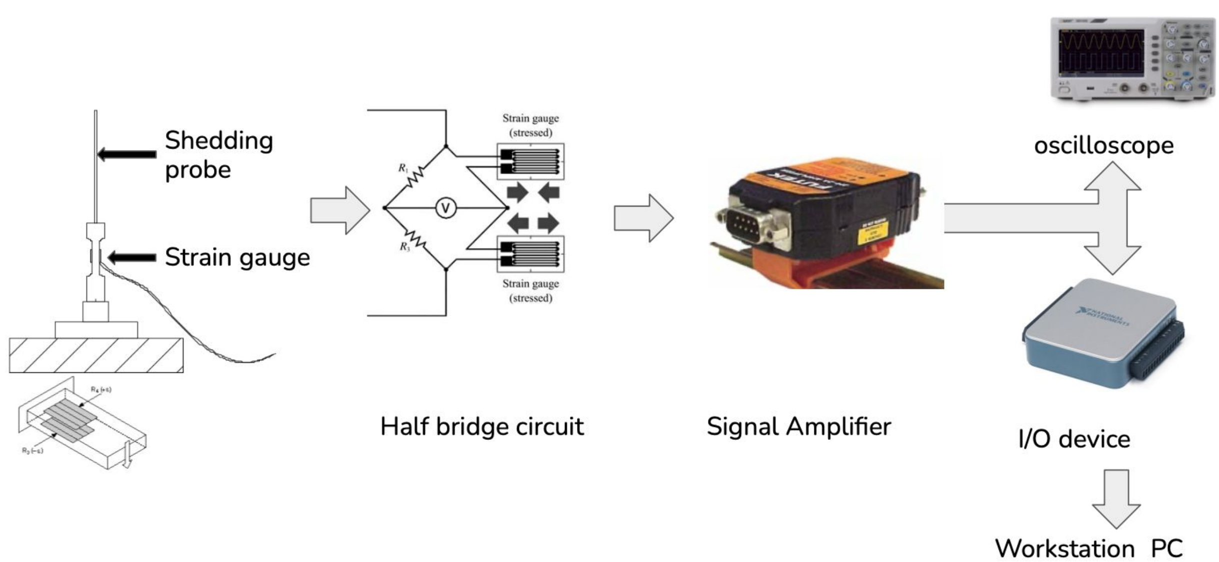
Convergence of the aerodynamic fluctuating coefficients at Re = 100.[7]

From [7], the maximum lift coefficient of cylindrical vortex shedding can usually be 0.3 under Re number of 100.

$$C_L = \frac{F_L}{1/2 \rho U_\infty^2 d}$$

Thus we can expect a force fluctuation amplitude of 0.02 N for our setup.

Hardware Setup

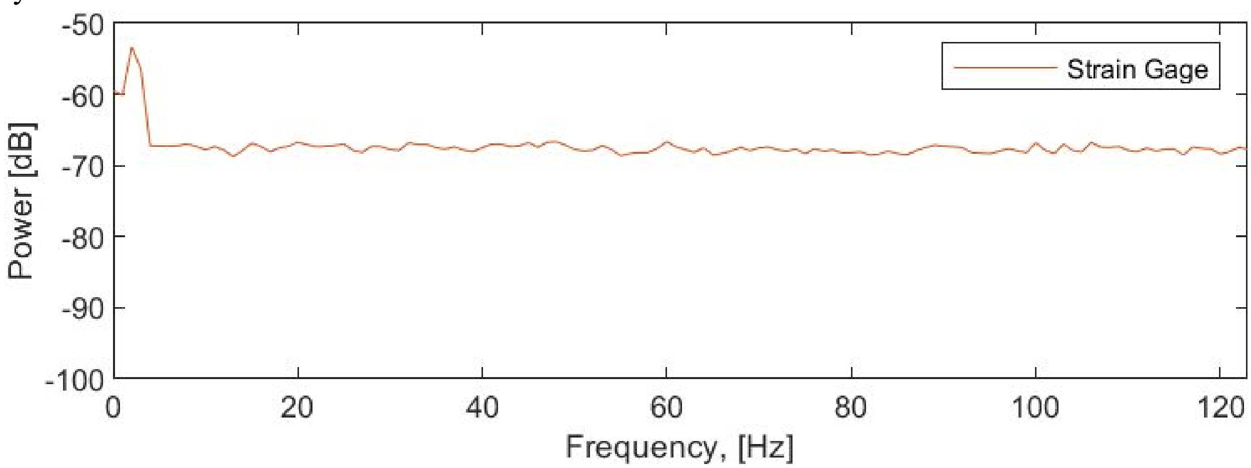


The prototype of the low speed wind sensor is present in the Brown Design Workshop student wind tunnel. The cylindrical wind speed probe is sitting on the sting load cell in the wind tunnel. When there is wind, the vortex shedding will generate vibration on the probe. A single dimension load cell is placed beneath the probe, which can read the bending torque from the vibration on the probe. A half-bridge circuit and a FUTEK CSG110 power amplifier are used to amplify the signal output from the load cell. The National Instrument USB6000 DAq Card is used to transfer the analog signal into a digital signal so that it can be read and analyzed by the workstation. An oscilloscope is also used to monitor the analog signal output.

Signal Validation

Once the hardware is set up, a Matlab code, which can be found in the appendix B., is used to acquire data from the system. The vibration frequency is first picked up by the strain gauge on the dog-bone shaped sting load cell. The voltage signal is then sent to the half-bridge circuit and amplified for the first time. The FUTEK power amplifier will amplify the signal for the second time. This amplified signal is picked up as an analog input to the DAq card and output as a digital signal to be processed by the Matlab.

A simple "swing test" is used to validate the functionality of the system. A 5 g weight is tied on the end of a 10 cm string and hanging about the end of a horizontally placed load cell. The amplitude of the force fluctuation should be just about the value of our vortex shedding estimation. The oscilloscope should be able to show the different signal level when the weight is swinging and the DAq should be able to show the natural frequency of the simple pendulum system.



"Swing test": the natural frequency of the simple pendulum system is captured, a 2 Hz peak can be observed in the power spectrum, which corresponds to the observations.

Results

Vortex Shedding Induced Frequency

To determine the effect of the wind speed on the vortex shedding of the cylinder, tests were performed for a range of motor frequencies. The power spectrums of signals are shown with different driving frequency (Fig. 1). A significant peak associated with wind speed can be identified for two characteristics.

1). The shedding frequency shifts higher with the wind speed and motor driving frequency.

2). The amplitude of the shedding vibration peak increases with the wind speed.

Beneath 8 Hz or approximately 2.5 m/s, it is still hard to identify a shedding induced peak from the power spectrum with current setup. At above 20 Hz of driving frequency, the shedding induced vibration pattern can even be visually observed on the probe.

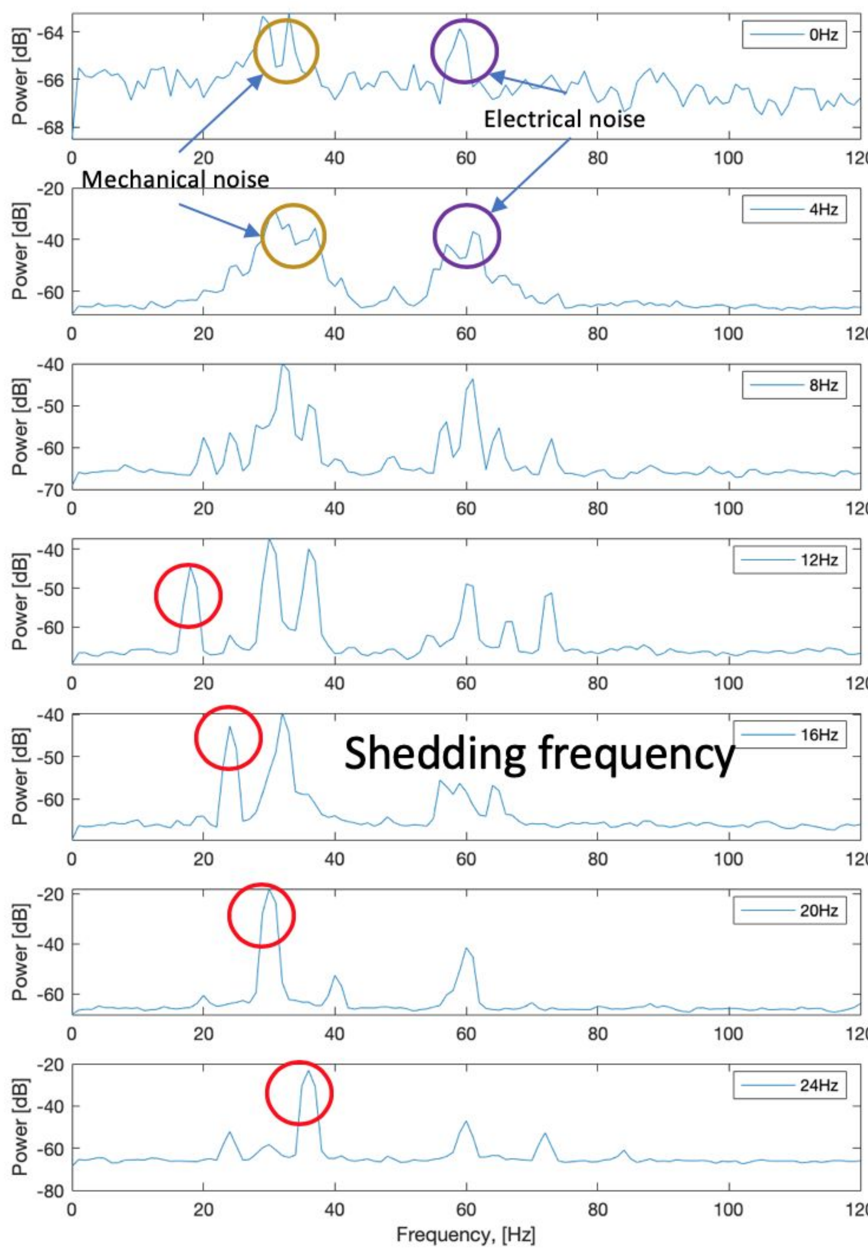


Figure 1. Although the power spectrums still show significant noise at 8 Hz and below, by 12 Hz a clear shedding frequency peak can be seen that increases as the motor frequency increases.

A shifting of shedding induced vibration frequency can be clearly observed above 8 Hz of motor driving frequency.The amplitude of the shedding induced vibration also increases with wind speed. At 20 Hz motor driving frequency it merges with a mechanical noise peak, which makes it look higher than expected.

Wind Speed Calibration

A simple wind speed calibration is performed with pitot tube readings in the wind tunnel, which shows the relationship between shedding frequency and wind speed. One may use this chart as a rough guideline for further calibration or usage on the wind sensor (Fig. 2).

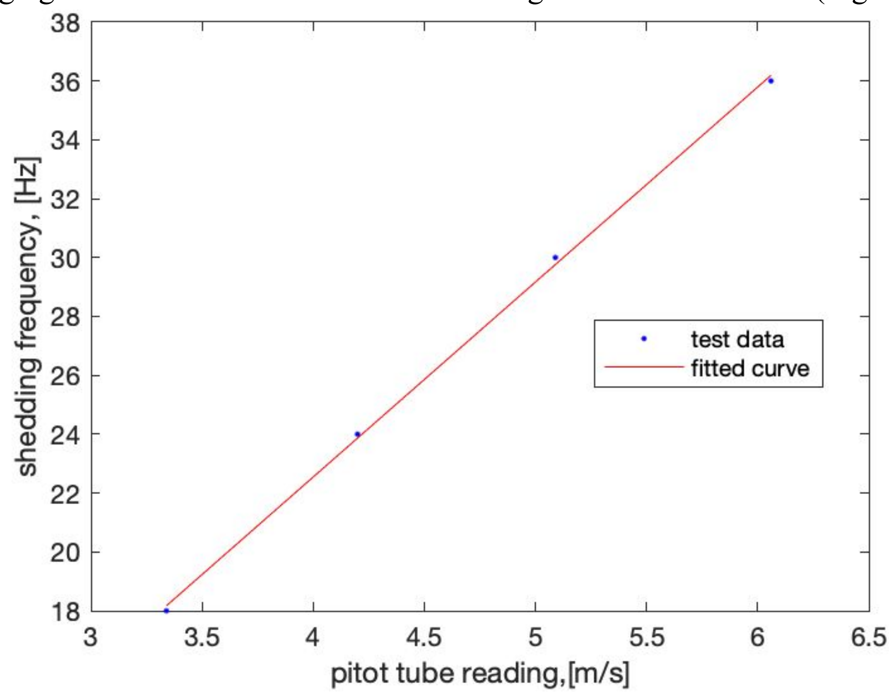


Figure 2. This calibration curve can be used to roughly determine the vortex shedding from the pitot tube reading.

Noise isolation

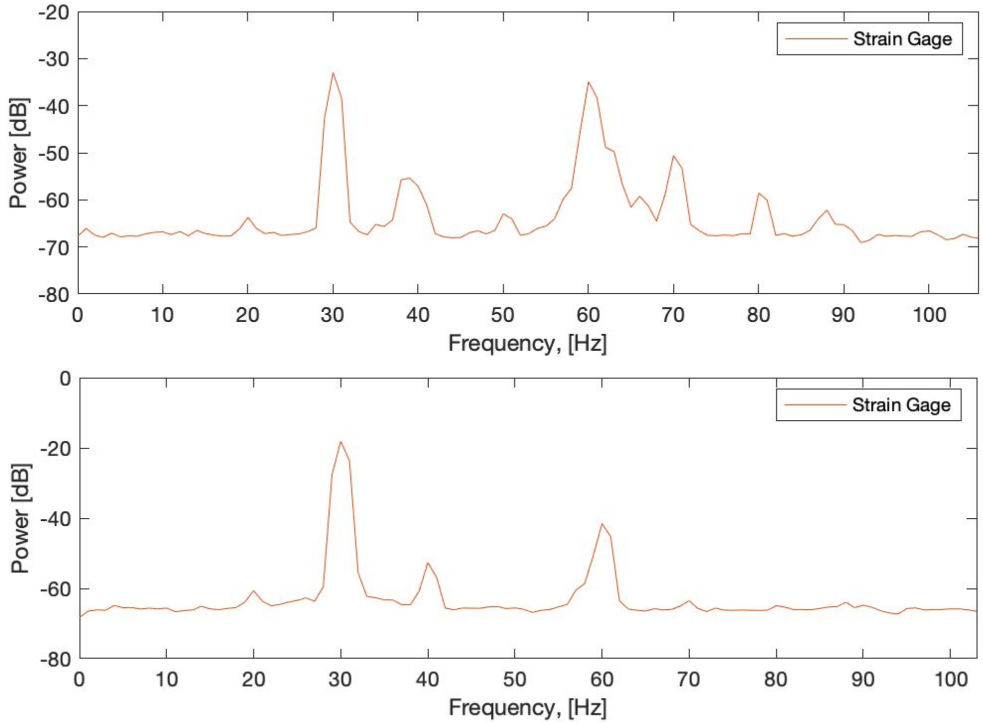


Figure 3. At a motor frequency of 20 Hz, more peaks can be seen without the vibration isolation mount (top) than with the vibration isolation mount (bottom).

A vibration isolation system was designed and installed to isolate the mechanical noise that was transfering from the base to the cylinder system. To validate the effect of the vibration isolation mount, tests were run both with and without the vibration isolation system (Fig. 3). Although the vibration isolation is not absolute, as a peak at 60 Hz which results from electrical noise still occurs, it is significant. The number of peaks is greatly reduced with the vibration isolation system, especially at frequencies greater than 60 Hz.

Current Status

The current status of the project is functional. It produces a clear peak that scales with motor frequency when the motor frequency is greater than 8 Hz. However, below a motor frequency of 8 Hz a clear peak is still not seen and therefore additional functionality needs to be added to this device for it to measure very low speeds. This can be done by increasing the vibration isolation of the mount and by increasing the sensitivity of the load cell. Additional functionality can also be added by using both a more robust, commercial level strain gauge (as the current one is prone to breaking) and a more sensitive strain gauge to better measure the oscillations of the cylinder.

Future Work

A question that remains is how the material and length of the cylindrical probe affect the measured peaks. In this project, only one cylinder was explored and so there is room for additional work to determine the optimal cylinder conditions for the best measurement results.

Additional future work to pursue if the project was to continue would also be to integrate an MCU based system and make the system less reliant on the expensive I/O daq devices.

Appendix

A. Materials

Bill of Materials

- Strain Gauge (350Ω)
- Vibration Damping Sandwich Mount with Studs
- 1.5 mm OD Hollow Rod
- NI DAQ USB
- NI DAQ USB MATLAB Code
- 1/4" Acrylic
- Thorlabs 1/2" OD Post Holder
- ThorLabs 2" OD Metric Manual Rotation Stage
- ThorLabs Breadboard with 8-32 taps
- 3/8" Polypropylene Sheet
- Wind Tunnel with Computer Setup (example)
- 1/2" OD x 7" Aluminum Rod
- 2 X 8-32 1" Screws
- 4 X M6 1/2" Screws
- 6 X 8-32 Hex Nuts
- 1 X 5-40 1/2" Screw

Tools

- Laser Cutter
- Mill
- Wire Cutters
- Band Saw
- MATLAB Software
- Computer
- 0.4", 1/4" End Mill Bits
- 0.15", 1/8", 1/4" Drill Bits
- 5-40, M6 Taps

B. Matlab Code

```
% Measure three channels in the student wind tunnel over a bunch of speeds
%
% We assume that channel 0 is the pitot tube pressure transducer, which
% outputs a voltage from 1-5 volts, corresonding to 0-1" H20.  This channel
% is used to accurately compute the speed from the Pitot tube.
%
% channels 1 and 2 are called "hot wire" and "strain gage", but could be
% any channel that outputs a voltaqe between -10 and 10
%
% Kenny Breuer, Feb 2020
%
%% Set parameters for experiment
Nspeed = 1;       % Number of speeds to loop through
Npts = 50000;      % Total number of points on each channel to measure
DigRate = 1000;   % Digitizing rate, in Hz
NI_DEV = 'Dev3';  % Name of the NI-DAQ box attached to the computer
D = 1.5e-3%12.7e-3; %
%2.38e-3; %Diameter
%% Dont change stuff here on down

% Add path for temperature and pressure c0odes
addpath 'C:\Users\Public\Documents\ENGN0810';

% Set up the NI-DAQ
s = daq.createSession('ni');
s.NumberOfScans = Npts;
s.Rate = DigRate;
Re = zeros(Nspeed);
ideal_freq = zeros(Nspeed);
addAnalogInputChannel(s, NI_DEV, 'ai0', 'Voltage');  % Pitot Tube voltage
addAnalogInputChannel(s, NI_DEV, 'ai1', 'Voltage');  % Hot Wire
addAnalogInputChannel(s, NI_DEV, 'ai2', 'Voltage');  % Strain gage

% Time array
time = (1/(s.Rate))*(1:Npts);

% Measure temperature and pressure
disp('Measuring Temperature and Pressure')
```

```
Temperature = WindTunnelTemperature;  % Temp in Kelvin
Pressure =  WindTunnelPressure;  % Pressure in Pa
Density = 1000*Pressure /((273 + Temperature) * 287);
Visc = 1.458*10^-6*(Temperature+273)^(3/2)/(Temperature+110.4+273);
fprintf('Temp: %6.2f [C]; Pressure: %6.3f [kPa], Density: %5.3f [kg/m^3]\n', ...
   Temperature, Pressure, Density);
fprintf('Each speed will take approx %d seconds\n', round(Npts/DigRate));

% Zero out the arrays
freq    = zeros(1,Nspeed);
ch1_ave = zeros(1,Nspeed);
ch1_std = zeros(1,Nspeed);
ch2_ave = zeros(1,Nspeed);
ch2_std = zeros(1,Nspeed);
ch3_ave = zeros(1,Nspeed);
ch3_std = zeros(1,Nspeed);
vel     = zeros(1,Nspeed);
pitot   = zeros(Npts, Nspeed);
hotwire = zeros(Npts, Nspeed);
strain  = zeros(Npts, Nspeed);
clear spec1 spec2;

% Loop through the speeds
for ispeed = 1:Nspeed,
   fprintf('Set wind tunnel to speed: %d/%d: ', ispeed, Nspeed);

   Pitot_Pressure = input('Enter Pitot Tube pressure [in-H20]: ' );
   freq(ispeed)   = input('Enter motor frequency [Hz]: ' );
   vel(ispeed) = sqrt(2*248.84*Pitot_Pressure/Density);
   fprintf('   Estimated Velocity [from visual reading of DP]: %6.3f m/s\n', vel(ispeed))

   % Measure ADC
   data = startForeground(s);

   % This will measure from the Phidget strain gage
   % [t,data] =  Phidget_Bridge(Npts);

   ch1_ave(ispeed) = mean(data(:,1));
   ch1_std(ispeed) =  std(data(:,1));
```

```
ch2_ave(ispeed) = mean(data(:,2));
ch2_std(ispeed) =  std(data(:,2));

ch3_ave(ispeed) = mean(data(:,3));
ch3_std(ispeed) =  std(data(:,3));

% Update the speed based on the accurate measure from the Pitot tube
Pitot_Pressure = (ch1_ave(ispeed) - 1)/4;  % in-H20
vel(ispeed) = sqrt(2*248.84*Pitot_Pressure/Density);

fprintf('   True speed (from Pitot tube reading):   %6.3f m/s\n', vel(ispeed));
fprintf('   Pitot tube:  %6.3f +/-%5.3f [V]\n', ch1_ave(ispeed), ch1_std(ispeed));
fprintf('   Hot Wire:    %6.3f +/-%5.3f [V]\n', ch2_ave(ispeed), ch2_std(ispeed));
fprintf('   Strain gage: %6.3f +/-%5.3f [V]\n', ch3_ave(ispeed), ch3_std(ispeed));

figure
subplot(2,1,1)
plot(time,detrend(data(:,2:3)))
xlabel('Time [sec]')
ylabel('Hot Wire Voltage [Volts]')
legend('Hot Wire', 'Strain Gage')

% seg = 500 gives 2 Hz resolution
% seg = 1000 gives 1 Hz resolution
seg = 1000;  % Length of FFT - at 1000 Hz

fs = 1/(time(2)-time(1));
[pxx f] = pwelch(detrend(data(:,2:3)), seg, seg/2, seg, fs);
subplot(2,1,2)
plot(f,10*log10(pxx))
xlabel('Frequency, [Hz]')
ylabel('Power [dB]')
legend('Hot Wire', 'Strain Gage')

% Save the data and the spectra
spec1(:,ispeed) = pxx(:,1);
spec2(:,ispeed) = pxx(:,2);

pitot(:,ispeed)   = data(:,1)';
hotwire(:,ispeed) = data(:,2)';
```

```
    strain(:,ispeed)  = data(:,3)';
    Re(ispeed) = Density*vel(ispeed)*D/Visc;
    ReTest(ispeed) = Density*(0.256+0.304*freq(ispeed))*D/Visc;
    ReTestSting(ispeed) = Density*(0.256+0.304*freq(ispeed))*1.27e-2/Visc;
    ideal_freq(ispeed) = (.212*Re(ispeed)-4.5)*Visc/Density/D^2;
    ideal_freqTest(ispeed) = (.212*ReTest(ispeed)-4.5)*Visc/Density/D^2;
    ideal_freqTestSting(ispeed) = (.212*ReTest(ispeed)-4.5)*Visc/Density/1.27e-2^2;
    fprintf('Reynolds Number = %f\n ; Re Sting = %f\n',ReTest(ispeed),ReTestSting(ispeed))
    fprintf('Ideal frequency (Pitot Value) = %f, Ideal frequency (Approximate) =
%f\n',ideal_freq(ispeed),ideal_freqTest(ispeed))
    fprintf('Approx low Freq ideal = %f \n',ideal_freqTestSting(ispeed))
end

%% Plot the average and rms vs speed
% figure
% subplot(3,2,1)
% plot(vel, ch1_ave, 'o')
% xlabel('Speed [m/s]')
% ylabel('Pitot Tube [V]')
%
% subplot(3,2,2)
% plot(vel, ch1_std, 'o')
% xlabel('Speed [m/s]')
% ylabel('Pitot Tube RMS [V]')
%
% subplot(3,2,3)
% plot(vel,ch2_ave, 'o')
% xlabel('Speed [m/s]')
% ylabel('Hot Wire Voltage [V]')
%
% subplot(3,2,4)
% plot(vel,ch2_std, 'o')
% xlabel('Speed [m/s]')
% ylabel('Hot Wire RMS [V]')
%
% subplot(3,2,5)
% plot(vel,ch3_ave, 'o')
% xlabel('Speed [m/s]')
% ylabel('Strain gage Voltage [V]')
%
```

```
% subplot(3,2,6)
% plot(vel,ch3_std, 'o')
% xlabel('Speed [m/s]')
% ylabel('Strain gage RMS [V]')

%% reset the DAQ
daqreset
```

C. CAD and Laser Cutting Files, Step by Step Building Instructions

See the linked instructables post for downloadable files, as well as step by step directions to build this device: https://www.instructables.com/editInstructable/edit/EKOAMNPKIAA29FF
Laser Cutting Files: Step 1
CAD Files: Steps 2, 4

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