

Wind Harvesting via Vortex Induced Vibration

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A Major Qualifying Project Report

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Abstract

There is a need for renewable energy sources to be more feasible. The purpose of this project is to develop a compact device that is able to harvest wind energy and transform it into electrical energy using the concept of vortex shedding. When calibrated correctly, the vortex shedding will induce resonant oscillation. Electricity would be collected from this oscillation using a magnet and coil assembly. This method was proven to work in water, but has not been applied to air currents. This team designed and built a small-scale prototype to be tested in WPI's closed circuit wind tunnel. The wind harvester works at a moderate wind range of 5.4 to 6.6 m/s. Data was collected on the amplitude and frequency of motion of the cylinder during its lock-in condition. Calculations were done to find position, velocity, and acceleration of the system over a complete cycle. The results demonstrate a potential for vortex induced vibration to be utilized with wind to create electricity, however it will be difficult due to the low density of air compared to other fluid mediums, such as water.

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Executive Summary

There is a need for renewable energy sources to be more feasible. They are becoming popular, and their demand is increasing annually. The purpose of this project is to develop a compact device that is able to harvest wind energy and transform it into electrical energy. The process will revolve around the concept of vortex induced vibrations (VIVs). VIVs are motions induced on bodies as a result of periodic irregularities in the downstream flow separation. Normally, vortex induced vibrations are sought to be eliminated in order to prevent mechanical failure. Instead of minimizing the effect of VIVs, as is usual in mechanical engineering projects, our project seeks to maximize vortex induced vibrations to effectively convert wind energy into mechanical energy.

In order to maximize power output, the system is desired to operate at a condition known as “lock in”. Lock-in occurs when the frequency of vortices forming behind the bluff body approach the natural frequency of the system to which it is attached. The synchronization of these frequencies, known as resonance, results in large oscillation amplitudes. The power generated by an object driven by vortex induced vibrations is a function of oscillation amplitude and frequency. The goal of this project was to provide a proof of concept prototype that would convert the oscillation energy to electrical energy.

This team designed and built a prototype to test in WPI’s closed-circuit wind tunnel. This testing environment was chosen, despite its limited available test area, because it was easily controlled. Working within the wind tunnel eliminated weather concerns and as well as provided controllable flow velocity – wind conditions outside would be erratic and unpredictable, creating a poor testing environment for an initial prototype.

Throughout the testing phase, various observations about the behavior of the system were made and the prototype was adjusted accordingly. Major factors of concern included mass of the system and outside forces, such as friction. The initial design did not work, but much was learned

from the testing and an improved prototype was built from which the desired motion was achieved at a range of wind speeds between 3.3 and 4.5 m/s. The only continued downfall was that there could be no energy production because the magnet and coil assembly provided too many weight and interference issues. Because of these unforeseen issues, the magnet and coil assembly was never implemented into the working design.

Based on these results and observations a new prototype was designed to be built and tested in the future. Each lesson learned from testing done throughout the project was taken into consideration in this new design. All calculations indicate a fully functional assembly. Though the constructed prototypes did not lead to electricity generation, they did build on each other's successes and failures to lead to the redesign, which should have the ability to produce electricity.

1. Introduction

In the process of wind harvesting, two primary methods may be considered, rotational wind harvesting and oscillation wind harvesting. Though both allow the transference of wind energy to electrical energy, the mechanical principles behind this transformation differ greatly between the two methods. With any proposed wind harvesting application it is necessary to determine the more appropriate method, a conclusion that will be unique to each scenario based on available space and power generation requirements. Regardless, whether utilizing rotational or oscillation wind harvesting, a comprehensive understanding of the mechanics of the process is necessary to optimize one's wind harvesting device.

Rotational wind harvesting is a principle most easily identified in the form of the common wind turbine. The wind turbine is the most prevalent wind harvesting device today, in large part because of its large scale power generation capabilities and effectiveness in an array. Wind turbines harness wind energy as wind causes the blades of the turbine to rotate. The spinning turbine blades are connected along a center shaft to a gearbox. This gearbox transfers the rotational mechanical energy of the rotors to a generator, which in turn translates the mechanical energy of the wind harvesting device into useable electrical energy. Newer wind turbines also may feature a gearless construction consisting of the rotor blades being connected directly to the generator, which rotates a magnetic field at the same speed as the blades (Capacitance...).

The benefits of rotational wind harvesting lie in the attributes of the wind turbine. Wind turbines have a very large coverage area to base area ratio; in short, meaning that the area covered by their blades far exceeds the ground area necessary to install such a machine. Because of this, wind turbines maximize the available wind energy in a given area, making them an

effective source of wind power. Their drawbacks stem from the same attributes, however, as they are limited by their proximity to airport flight paths, dense population, and avian migratory paths due to their size. Overall, the wind turbine and rotational wind harvesting are benefited by their effectiveness and efficiency at a larger scale, making them the best option for most commercial applications.

Oscillation wind harvesting is, by a substantial margin, the less common of the two methods. To understand why it is less common, one must first examine the attributes of an oscillation wind harvesting device. An oscillation device functions by utilizing what are known as Vortex Induced Vibrations (VIV). VIV are defined as motions induced on bodies interacting with an external fluid flow, produced by periodic irregularities in this flow (Sarpkaya). Essentially, VIV are perpendicular vibrations induced in an object as a fluid, in this case air, flows past it. In oscillation wind harvesting the most geometrically appropriate airfoil shape is the cylinder. The cylinder optimizes the effects of VIV because of its symmetry along its center axis. As a fluid such as air flows past a cylinder positioned horizontally in the flow, VIV cause the cylinder to oscillate vertically at a frequency proportionate to air speed as it is suspended by spring tension. This oscillation can be compared to the rotation of turbine blades in the sense that both are mechanical motions caused by wind flow that must then be transferred to electrical energy. In the case of the oscillation wind harvesting device, the transformation is most commonly done through the use of a magnetic field. As the cylinder oscillates up and down, coils attached to either end move in tandem around magnets. The motion of the coils through the magnetic field generates current, causing voltage, which is then harnessed as electrical energy. This process varies greatly in efficiency based on device scale, spring tension, and the strength of the magnetic field being used to generate electricity.

Oscillation wind harvesting devices are more appropriate for small-scale, wind-based applications due to their mechanical complexity and relative absence from current commercial development. Additionally, it is unclear exactly how such a device will perform in an array, as vortex shedding will affect flow to secondary units. Vortex shedding is an oscillating flow pattern that takes place when a fluid flows past a bluff body. What this means for an oscillation wind harvesting array is that though the first row of devices will receive traditional wind flow, those that are in the second row and beyond will receive extremely turbulent and oscillating flow. This effect varies with wind speed and cylinder properties, complicating the concept of an oscillation wind harvesting array especially in larger scales. However, the optimization of oscillation wind harvesting arrays may lead to exponentially greater power generation if configured correctly. Further examples of oscillation energy harvesting can be found in hydroelectric capacities, which feature steady currents and more predictable operating conditions.

1.1. Overview of Renewable Energy

Renewable energy is any source of energy which can be reused within a human's lifetime. Such energy sources can replenish themselves indefinitely and faster than they can be harvested. There are currently four widely recognized sources of renewable energy: wind, solar, hydro, and geothermal.

In contrast, non-renewable resources are finite and consumed upon use. Most of the United States' energy consumption comes from the burning of various fossil fuels. Fossil fuels exist in several forms, including petroleum, natural gas, and coal. These fuels are the remains of organic life after undergoing a process called anaerobic decomposition. This process takes

millions of years to complete. Currently, fossil fuels are being used faster than they are being created (Doherty).

Fossil fuels are currently convenient for humans to use. They are widely distributed, have a high weight to power density, and can run many devices which are designed to run specifically on fossil fuels. Renewable energy is not currently as efficient or widely used. There is a lot of upfront cost to begin harvesting renewable energy in both research and material costs. Harnessing renewable energy can often be intrusive. For example, dams, wind turbines, solar panels, and other similar structures need adequate space to function. Despite these downsides, the use of renewable energy will eventually have to surpass that of fossil fuels if the United States wants to stay energized.

There are some estimates as to how long fossil fuels will last. Estimates based on current energy consumption and the known fossil fuel reserves state that fossil fuels may be depleted within the next 100 years (The End...). At that point, governments will be forced to develop new sources of energy in order to maintain levels of power consumption and standards of living. As a result of this inevitable situation, many are already looking into various ways to harness renewable resources. The ability to harness these comparably infinite sources of energy is a continuously growing and essential market.

Although the current generation will be capable of relying on non-renewable energy sources for their energy needs, future generations will not. The sooner the world adjusts to renewable energy, the less abrupt it will be when the earth's fossil fuels are depleted. Several nations are taking action to promote renewable energy. Nations like Germany, the United States, and Japan are encouraging both the private and public sectors with financial stimuli (Jordan-Korte). The motivations behind this are to not only wean themselves off of fossil fuels, but to

free themselves financially from the international fossil fuel market, which is controlled by the OPEC cartel.

There are several reasons to begin looking into renewable energy. Changes can be made at both the national and personal level. This project will focus on the harvesting of wind energy with a small, custom generator.

1.2. Different Types of Renewable Energy

Outside of wind energy, which is discussed in more detail in other sections, there are three main types: geothermal, hydro, and solar.

1.2.1. Geothermal

In broad terms, geothermal energy is the thermal energy contained within the earth. It can be used in multiple ways, including electricity generation or direct heating, for which it has been used for thousands of years. As far as electricity generation, there are three types of plants that harvest geothermal energy: dry steam, flash, and binary. In a dry steam plant, high-energy hot steam is tapped from inside the earth and used directly to drive turbines. In flash plants, high-pressure hot water is extracted from deep below the earth's surface and mixed with cool water, and the steam that results is used to drive turbines. The last, and most modern type of geothermal plant, is binary, which takes the same hot water as in flash plants, and passes it by a second fluid with much lower boiling point than water. The resulting heat transfer causes the second fluid to turn to vapor, which then powers turbines (How Geothermal Energy Works).

Overall, geothermal energy harvesting can be a very efficient, environmentally friendly source of energy. It is the most consistent form of alternative energy; however, it does have some drawbacks. For one, it is not guaranteed renewable, as over time areas that are tapped for geothermal energy will cool down. Also, there are some small (relative to fossil fuels)

environmental concerns, including the release of hydrogen sulfide, which has an odor of rotten eggs, as well as toxic materials, which may be contained in small concentrations in geothermal fluids. Also, it requires a decent amount of infrastructure, as one needs to drill deep into the ground to access the high-pressure water and steam. Furthermore, the turbines that it powers are sophisticated, expensive instruments. Though heat pumps make economic sense to many, their expensive initial investment means geothermal energy is not always a viable option for individuals or small communities, but is better for larger operations (How Geothermal Energy Works).

1.2.2. Hydro

Hydro energy is currently the largest source of alternative power, accounting for 16% of the world's power generation. For the most part, hydro energy is harvested by building large dams to keep the flow over turbines relatively constant. There are units that use vortex-induced vibrations, much like our unit does with wind; some have been commercialized, most notably the VIVACE unit developed at the University of Michigan for the Detroit River (Hydroelectric Power Water Use).

Relative to fossil fuels, hydro energy is environmentally friendly. However, it does create some environmental problems, as the large dams that are built to harvest the energy often times are major disruptions to the habitats in which they are built. Furthermore, fish and other aquatic wildlife can get caught in the turbines, and injury and death can result. Also, much like geothermal energy, the large dams and turbines are significant, expensive pieces of infrastructure, and thus are not really feasible for individuals or small communities. Furthermore, nearby water is a necessity for hydropower, and unfortunately is not available in all locations (Hydroelectric Power Water Use).

1.2.3. Solar

Solar power is harvested via solar panels that collect energy from the sun and convert it to electricity. This is done using photovoltaic cells, which are semiconductors whose electrons are knocked loose and allowed to flow freely when struck by light, thus creating a current. On sunny days, the earth can absorb up to 1000 watts of energy per square meter, more than enough to power homes and offices. However, to this point available technology has not been able to harvest 100% of solar energy; panel efficiencies are still low at around 15% for most units (Solar Technology).

The advantages to solar power are obvious, as it is available in pretty much all areas, is quiet, and does not interfere with its environment much relative to other renewable energy devices. Currently, solar is the only alternative energy source that is somewhat feasible for individuals and small communities; however it is still rather expensive, with small units costing in the tens of thousands of dollars before the federal tax credit, putting the expense of solar power installation out of reach for most people. Solar power is still in its early stages, and as solar technology advances it will likely become cheaper and more efficient, but until then it remains a pipe dream for most individuals (Solar Technology).

1.3. Where Our Device Fits

One may inquire why a wind harvesting device, as opposed to other forms of renewable energy harvesting devices, would be chosen to work with. After taking into account the various aspects of different renewable energy sources, our group could clearly see why wind was our best outlet to pursue for harvesting energy. By noticing the limitations of other renewable energy sources, one can see how wind offers the potential for a device with broader options – specifically, but not limited to, location and cost. Geothermal energy harvesting is limited to

areas near tectonic plate boundaries and can be quite expensive. Hydro-power has similar location limitations; the main, and obvious, one being proximity to moving water – i.e. a river or stream. Though there are many waterways in our nation, they are not everywhere and accessible to everyone. Solar radiation is a renewable energy source that can be found everywhere. Therefore, solar power has the greatest likelihood to be our biggest competitor. Harvesting energy through solar power is consistent, but not highly efficient. Our group hopes to achieve at least solar standards, if not better, with our device. Additionally, a goal is to make our device even more affordable than solar products already on the market; solar panels are realistically afforded by individual households, but are still expensive.

Since technology is always moving forward, finding a new and improved way to harvest wind energy would be beneficial to the renewable energy market. More options for renewable energy mean less dependence on fossil fuels (i.e. coal, petroleum, and natural gas) which are nonrenewable – meaning they cannot be renewed at a sufficient rate to sustain demand. The nation, as a whole, is looking for new ways to power our world on the large and small scales.

Wind energy has already proven its value through wind turbines. This project aims to create a new, more versatile, device to expand the wind energy platform. Harvesting energy through wind is not a new idea; our device is the new idea. There are many areas known for their high-wind conditions. A general example is the shoreline. Near the ocean, there is almost always a breeze felt from the water. This would be an example of where our device could be installed. A list was compiled of the top 101 cities (with population 50,000+) with highest average wind speeds. The highest average was 14.3 miles per hour (mph) and the lowest was 10.7 mph. The average from all 101 cities was 11.5 mph (Top 101 Cities...). These measurements are all within

typical working wind speeds for wind turbines. Our device would also be able to use these wind speeds to generate power.

There are places in the United States, and the world, where wind is prevalent at useable conditions for wind turbines. However, not every location which desires a turbine has useable wind conditions. Wind turbines generally need sustained winds at 10 or more miles per hour. To determine if a location is a viable place to install a wind turbine, an extensive study has to be performed. These studies take months and have rigorous standards. The studies collect data on wind speed, direction, and frequency. The large amounts of labor, money, and planning that go into installing a turbine mean installation can only occur in places where the turbine can operate to its best capacity. After a bid is placed for a turbine to be built, and a study is conducted, there is still no guarantee the location will be deemed useable. Desired locations often fail. Our device would aim to widen the range of useable wind conditions, therefore lowering the failure rate for its own studies.

In addition to wind conditions, wind turbines have a large number of other limitations involving placement and operation. These limitations provided the idea to create a new device for wind harvesting. Our project will create a new device with a greater range of reasonable installation locations. By accomplishing that, more places and people could take advantage of wind harvesting as an alternative energy source.

One typical limitation of wind turbines is their size. They are large and intrusive. They cause a height problem and installation must take into account approach and takeoff flight paths for aircrafts. This alone limits the range in which wind turbines can be located. In addition, there would need to be enough land to account for the large size of the structure.

Next, wind turbines can cause a strobe-light effect with sunlight when the sun is rising and setting behind the turbine. These effects can be seen within three miles of the wind turbine. This issue causes strict regulations on how close a wind turbine can be to a population. Therefore, even more locations are taken off the map for possible locations of a wind turbine. Generally, wind turbines need low-density populated areas which are not always near the people actually using their power. When turbines are installed close to populated areas, much thought has to be put into placement to eliminate, or at least minimize, effects from sunlight.

Private land ownership is another issue common to wind turbine installations. Even if an area is deemed useable, people are often unwilling to sell land to allow for turbine placement. Ideally, an agreement could be reached between the land owners and the party hoping to install a turbine, but this is not always the case. Some reasons people say no include: they are an eyesore, the noise can be annoying, they worry about the loss of useable land around the wind farm, they worry the turbine will not cover its cost of manufacturing and installation, they are concerned about impacts to the environment, or they simply are opposed to change (Why Do Some People...). These, and other, reasons are also many of the arguments heard against installation of wind turbines in public areas. The hope is that our new device could lessen these negative outlooks on harvesting wind energy.

Environmental concerns are always an issue when talking about new renewable energy sources. A major concern with wind turbines is their effect on migratory paths of birds. Each day, it is possible wildlife could be lost to these large, rotating blades. Known migratory paths need to be avoided in order to have the best chances of keeping wildlife safe. A new scientific study by government biologists has found “wind farms in 10 states have killed at least 85 eagles since 1997, with most deaths occurring between 2008 and 2012” (‘Alarming’...). This is

alarming to government, the public, and especially wildlife activists. In addition, other wildlife, especially birds, are in danger – not just eagles. A safer alternative would still provide energy while saving wildlife.

Our goal is to create a device that can be used virtually anywhere there is wind. Improving upon wind turbine limitations assures that harvesting wind energy can be done in more areas; safely and with as little disruption to its surroundings as possible. Our device will have an adjustable size. It can be used individually, or in an array. Even in an array, each individual piece would have the option to have its size scaled. Wind turbines do offer these options, but are still large-scale as a whole. Our smaller device may not generate as much power, but could be used in other applications where wind turbines are not useful. Ideally, our device would be able to fit to its surroundings. This would eliminate the need to find an environment that fits to turbine standards. For example, our device would be safer in more confined areas. Our device could easily be placed on the roof of any building, unlike wind turbines. This means multiple people in a city or town, no matter its size and population density, could benefit from harvesting energy from wind, while not impacting themselves or those around them. Wind turbines are large and intrusive. Our aim is to counter that and make wind harvesting attractive and attainable to more people.

There is already a market for wind power. Wind turbines are a popular renewable energy option. However, solar power is the most popular among homeowners. Government programs endorse the use of renewable energy with pay-backs to those who utilize the technology. Our small-scale, relatively low-cost device could target homeowners, giving them another option aside from solar power. Currently, even scaled models of this device could not power an entire house. Where it could be useful is as a supplement. For example, with more work, it could be

used as a back-up generator or to power a part of the house's grid. However, over time, it could be developed to produce more energy and be used for bigger projects. There is a high market potential for renewable energy in consumer, military, and third world applications (Cottone).

1.4. Our Goals

While our group has many ideas in mind for the long-term goals of this device and its potential, the current goals must be more reasonable for our time and resources. The main goal is to make a proof of concept prototype. This prototype will generate power as a small-scale device. Calculations on how to expand the scale and generate even more power will be provided, as well as a general overview and computer-generated study of the device capabilities in an array. Once the concept of harvesting wind energy through VIVs and this device is proven, the ability to adjust this device in size and orientation will expand its possibilities in the future. The device generated from this project can always be improved by future groups as it is only scratching the surface of this concept. Our main goal is to prove that this concept is attainable. Our device will be designed, built, and tested around the VIVs concept.

2. Background

Harnessing the phenomenon of vortex-induced vibrations (VIV) to produce electricity requires the transformation of linear mechanical motion to voltage. This concept has been applied commercially for hydroelectric power generation, where a VIV energy harvesting device is placed in a stream or river of consistent current and allowed to oscillate as flow impacts the hydrofoil. The hydraulic application of VIV devices is made easier by the predictable and singular direction of current in rivers. The device may be oriented in one fixed direction and does not have to be adjusted for changes in direction of fluid flow. This element of simplicity has led to the stark industry favoritism towards the implementation of hydraulic VIV devices as opposed to those that function as airfoils in wind flow. However, with the development of more versatile, efficient, and affordable wind-based VIV devices their application as a common renewable energy device should increase.

In order to harvest substantial amounts of energy from vortex-induced vibration the airfoil must incur sufficient force to cause oscillation. This force is dependent on a number of factors including the shape of the airfoil, orientation of the airfoil, and velocity of fluid flow. The optimization of these factors along with others such as weight, size, and durability will allow for the creation of a feasible VIV wind harvesting device.

The shape of the airfoil determines the magnitude of the force that is generated by airflow. In traditional applications, such as aircraft and land-based vehicles, airfoils are designed to generate force in one direction. This design element allows for the airfoils to be asymmetrical along a vertical cross-section, an attribute that provides the opportunity for maximum lift force generation. Conversely, an airfoil designed for a VIV harvesting device does not offer such a luxury. VIV airfoils function through the generation of lift forces in two directions perpendicular

to airflow. Because of this, the airfoil must be symmetrical when analyzed through a vertical cross-section (Figure 1). The shape most commonly used for this application is a cylinder. The cylinder best utilizes the vortex shedding property of fluid flow that produces oscillation because of its simple, aerodynamic shape. The cylindrical airfoil is also easy to produce, replicate, and work with as a material component.

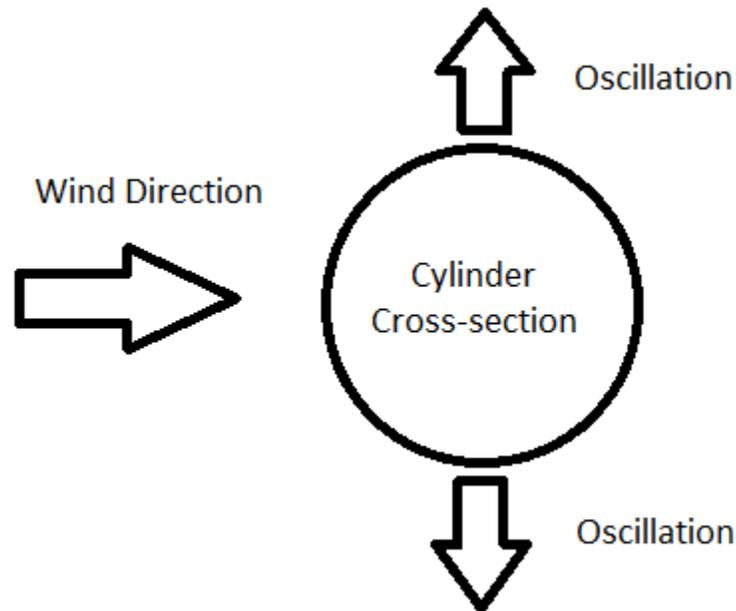


Figure 1: Cylindrical airfoil cross-section

The orientation of the airfoil determines the direction in which the lift force is applied. When horizontal, the lift force is applied vertically, and when the airfoil is vertical the lift force is applied horizontally. The difference between these two orientations is highlighted by the ability for the vertical airfoil to incur lift force from multiple flow directions. Despite this capability, the design of a vertically oriented VIV wind harvesting device yields significant complications, most notably the lack of a feasible medium to turn multi-directional oscillation into electrical energy. Because of this, the horizontally oriented airfoil is a more appropriate design choice. The determination of airfoil orientation drastically affects the nature of oscillation and the power generation capability.

The velocity of fluid flow is an independent variable that must be accounted for in the design of any wind harvesting device. In order for the device to efficiently and consistently maintain mechanical motion, whether rotational or oscillatory, the airfoil must be positioned with its chord length parallel to the fluid flow. In order to accommodate for the unpredictable and inconsistent nature of wind, the VIV device must have the capability to either rotate to face the airflow or generate oscillation from flow in a multitude of directions. This design consideration is unique to wind harvesting VIV devices, as the fixed hydroelectric VIV products would not experience operational wind flow frequently enough to be effective.

Our group will have to consider a multitude of variables when designing and constructing a VIV wind harvesting device. To maximize the efficiency and feasibility of the device, a harmonious equilibrium between dependent variables must be established, accounting for even the most unfavorable of operational conditions. With the evolution and optimization of VIV wind harvesting devices, their energy production can grow to rival the rotational energy generation of wind turbines.

2.1. Fluid Dynamics

To harness vortex-induced-vibrations a conceptual and quantitative understanding of fluid dynamics and vortex shedding was required. Vortex shedding is an oscillatory flow property that takes place downstream of cylindrical bluff bodies. Vortex shedding creates low-pressure vortices which alternate in direction of propagation, and can be harnessed to produce mechanical energy through the use of an airfoil – a cylindrical one, for the scope of this project. The following properties were calculated in the interest of determining numeric specifications about flow conditions in the WPI wind tunnel and for our device.

2.1.1. Reynolds Number

The Reynolds number of a flow indicates the ratio of inertial forces to viscous forces within the flow. This ratio allows flow to be characterized as laminar, transitional, or turbulent, indicating the degree of streamline intersection and dispersion in the flow. Reynolds number is quantified by the following equation:

$$Re = \frac{\rho v D}{\mu}$$

ρ = fluid density

v = flow velocity

D = outer diameter of the cylinder

μ = fluid viscosity

At Reynolds numbers over 1000, the viscosity of the fluid as it flows over the cylinder forms what is referred to as a boundary layer. A boundary layer is defined as the layer of fluid in the immediate vicinity of a bounding surface where the effects of viscosity are significant (Bearman). The formation of a boundary layer around the cylinder is important for creating vortex-induced vibrations, as the boundary layer contributes to an adverse pressure gradient immediately downstream of the cylinder. This pressure gradient allows for vortex shedding to occur in the cylinder's wake and induces airfoil oscillation at the frequency of the shedding.

Figure 2 is a plot of Reynolds number versus flow velocity. Our wind harvesting device is designed to function at flow velocities near 4-4.5 m/s (about 10 mph). According to our plot, at

this flow speed the approximate Reynolds number, for flow over the cylinder is 1.8×10^4 , a definitively laminar environment. Note the linear relationship between Reynolds number and flow velocity.

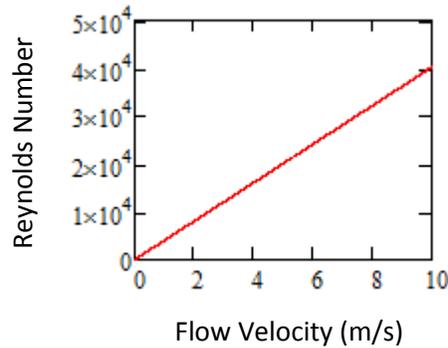


Figure 2: Reynolds Number versus Flow Velocity (m/s)

2.1.2. Strouhal Number

Strouhal number is used as a measure of vortex shedding frequency relative to fluid flow velocity. For this project, the Strouhal number of the flow allowed for the direct relationship between Reynolds number and free stream velocity in the WPI wind tunnel to be quantified (Sunden). The equation for the Strouhal number is as follows:

$$St = \frac{fL}{v}$$

f = vortex shedding frequency

L = cylinder characteristic length (diameter of the cylinder)

v = flow velocity

Reynolds number can also be used to find the Strouhal number. Based on an MIT VIV experiment on cylinders, with Reynolds numbers between $1 \cdot 10^4$ and $7 \cdot 10^4$, the Strouhal number is approximated to be (Resvanis):

$$S_t(v) = -0.0065 * \ln(R_e(v)) + .21$$

$v = \text{variable wind velocity}$

We calculated the theoretical Strouhal number of our experimental flow to be approximately 0.14. The Strouhal number was calculated using the Reynolds number, the equation for which can be seen in detail in the calculations section. The calculated value corresponds to the commonly accepted theoretical plot of Reynolds number vs. Strouhal number, as exhibited in Figure 3.

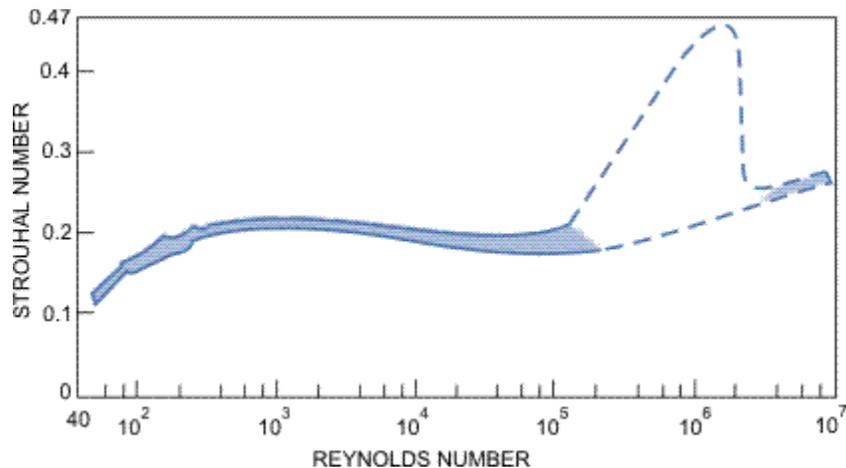


Figure 3: Strouhal Number versus Reynolds Number (Sunden)

The calculation of the Strouhal number was also critical in determining the vortex shedding frequency of the flow. The determination of the vortex shedding frequency in the WPI wind tunnel was necessary for choosing appropriate spring constants so that the natural frequency of the device matched the vortex shedding frequency. The principle through which these frequencies coincide is referred to as lock-in, or lock-in conditions. In lock-in conditions,

the cylinder oscillates at the system's natural frequency, allowing the oscillation to increase in amplitude drastically and maximize the energy produced by the vortex shedding (ME 310: Fluid Dynamics Laboratory).

2.1.3. Vortex Shedding

A primary objective for this project was to create flow conditions that produced vortex shedding at the cylinder and spring assembly resonance frequency. Using the flow Reynolds number and Strouhal number, we were able to calculate the vortex shedding frequency of the cylinder, in the WPI wind tunnel flow. Figure 4 expresses the relationship between vortex shedding frequency and flow velocity for a range of possible velocities. From the graph, it is clear that as the flow velocity increases, so does the frequency of the vortex shedding.

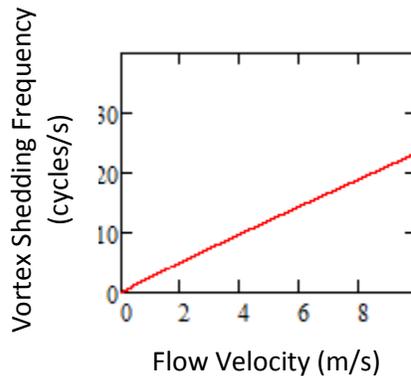


Figure 4: Vortex Shedding Frequency (cycles/s) versus Flow Velocity (m/s)

There are multiple regimes of vortex shedding that may occur around a cylinder, the appearance of each depends on the flow Reynolds number (Bearman). At Reynolds numbers less than 1×10^5 , flow over a cylindrical body is considered laminar. This holds true for the flow over our airfoil. A Reynolds number between 1×10^5 and 5×10^5 indicates transitional flow around the cylinder. At and above a Reynolds number of 5×10^5 the drag force on the cylinder is

significantly reduced as the flow becomes fully turbulent, causing boundary layer flow separation to occur further downstream in relation to the cylinder.

As previously stated, the flow conditions for our tests were laminar. For the purposes of creating vortex-induced-vibrations laminar flow is preferred, primarily because of the decreased degree of flow separation around the curvature of the cylinder (Sakamoto). The degree of flow separation around the cylinder is demonstrated visually in Figure 5:

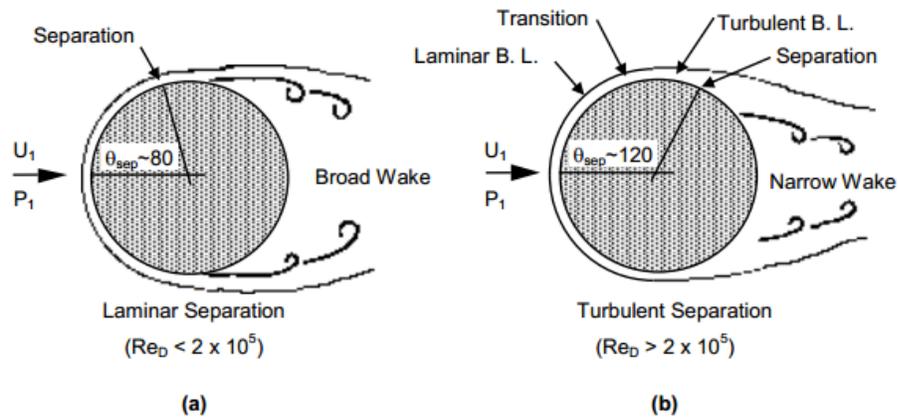


Figure 5: Flow Field Elements about a Cylinder (Sakamoto)

$\theta = \text{degree of flow separation}$

As is evident in Figure 5, laminar flow separation occurs at a smaller degree measure and creates a broader wake downstream of the cylinder. A broader wake allows for vortex shedding of greater magnitude to occur, creating more lift on the cylinder and by extension more power from the device, as discussed below.

2.1.4. Lift and Drag

At their most fundamental level, lift is the force generated by the flow that acts on the airfoil perpendicular to the flow. By the same logic, drag acts in the direction of the flow. Both

lift and drag are a direct function of flow velocity and airfoil shape. The equations for lift and drag on the cylindrical airfoil as functions of velocity are below:

$$\text{Lift: } L(v) = \frac{1}{2} \rho v^2 A C_l$$

$\rho = \text{fluid density}$

$v = \text{fluid velocity}$

$A = \text{cylinder cross-sectional area}$

$C_l = \text{lift coefficient}$

$$\text{Drag: } D(v) = \frac{1}{2} \rho v^2 A C_d$$

$A = \text{upstream face of cylinder (Diameter x Length)}$

$C_d = \text{drag coefficient}$

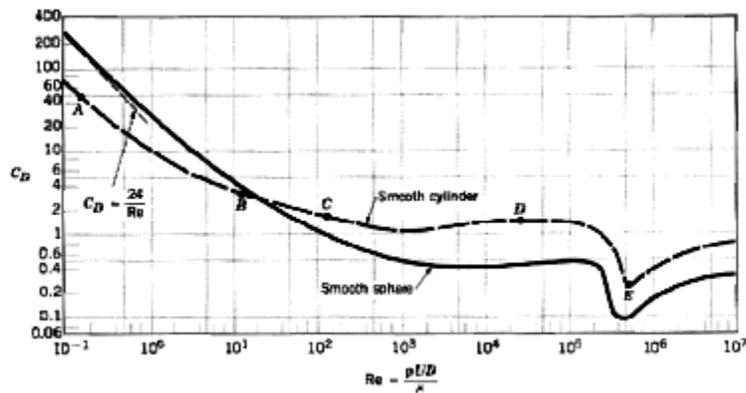


Figure 6: Drag Coefficient for a Smooth Cylinder as a Function of Reynolds Number (Drag of Blunt Bodies...")

In any aerodynamic application it is advantageous to have a high lift-to-drag ratio. This remains true with the VIV cylinder, as the lift force generated from the vortex shedding contributes to the oscillation of the device and the drag inhibits perpendicular oscillation. We were able to mitigate the effects of drag on our device by eliminating any stationary contact points with the cylinder and reducing cylinder diameter. The following graphs exhibit the lift force generated by the flow on our cylinder relative to velocity and the lift force acting on the cylinder as it oscillates through one cycle (approximately 0.1 s). The lift force over one cycle was measured at a flow speed of 4.45 m/s. The lift coefficient of the cylinder varies with oscillatory behavior. In lock-in conditions when the device is engaged in VIV the cylinder lift coefficient is 1. When the cylinder is not in lock-in, the oscillation is inconsistent, thus contributing to an inconsistent lift coefficient (Distler). This inconsistency is demonstrated in Figure 7, which displays lift coefficient of a cylinder as a function of flow time.

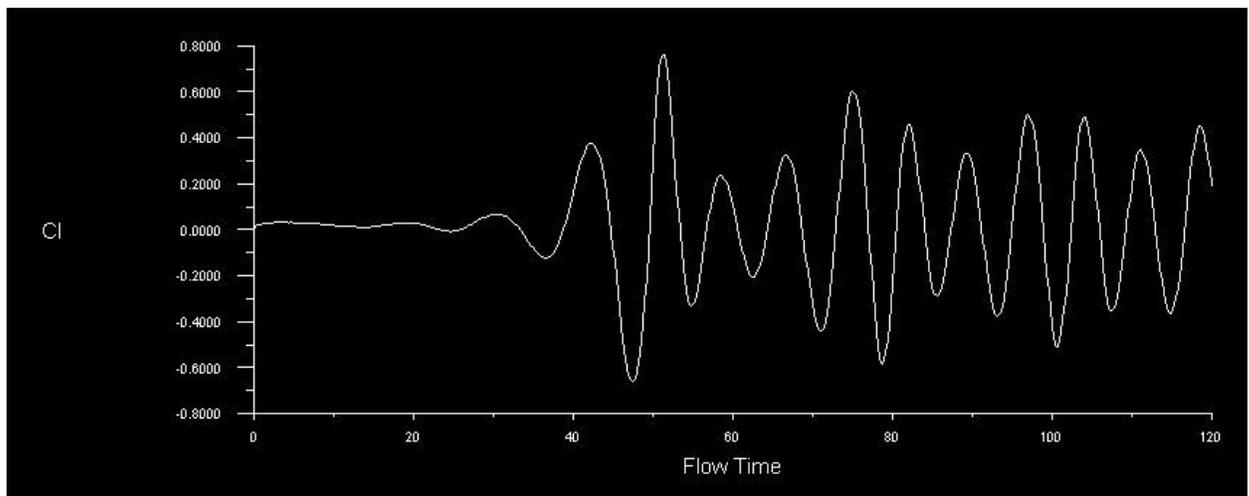


Figure 7: Lift Coefficient of a Cylinder as a Function of Flow Time (Distler)

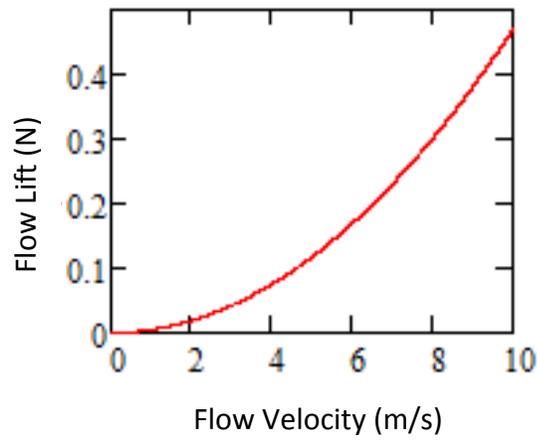


Figure 8: Flow Lift (N) versus Velocity (m/s)

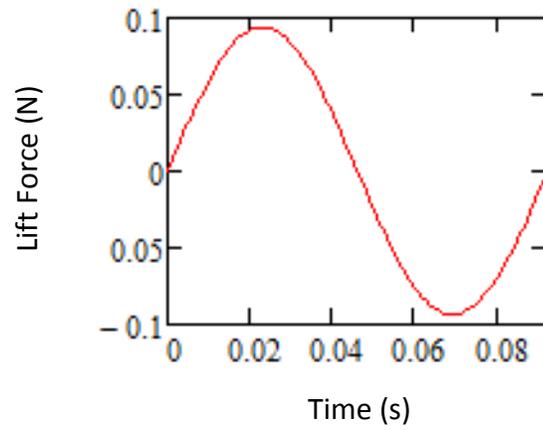


Figure 9: Lift Force (N) Over One Oscillatory Cycle (s)

2.2. Forced Vibrations

Mechanical vibrations occur as a result of energy being supplied to a system. There are two types: free vibrations, which occur as the result of kinetic or potential energy present within the elements of system, and forced vibrations, which occur as a result of work being done by an external source on the system. The VIV Wind harvester device deals mainly with forced vibrations as a result of the wind flow.

The device is designed to take advantage of the periodic vortex shedding of the wind as it passes over the cylinder, causing it to oscillate up and down. The vortex shedding is described by the Strouhal number, which is explained in section 2.1.2.

The Strouhal number for a flow can be found as a function of Reynolds number, and from this the frequency of the shedding, the driving force of the oscillation of the system, can be determined for a given wind speed.

The force driving the device oscillation is given by

$$F(t) = F_L \sin(\omega t + \psi)$$

$$F_L = \textit{lift force}$$

$$t = \textit{time}$$

$$\psi = \textit{phase difference between the function and a purely sinusoidal function}$$

Based on a driving force such as the one described above, the differential equation that describes the oscillation is given as:

$$\ddot{x} + \omega_n^2 x = \frac{F_L}{m} \sin(\omega t + \psi)$$

$$\omega_n = \text{natural frequency of the system} = \sqrt{\frac{k}{m}}$$

$k = \text{spring constant}$

$m = \text{mass}$

$x = \text{displacement}$

When $\omega \neq \omega_n$, the solution to this system is given by

$$x(t) = \left[x_0 - \frac{F_L \sin(\psi)}{m (\omega_n^2 - \omega^2)} \right] \cos(\omega_n t) + \frac{1}{\omega_n} \left[\dot{x}_0 - \frac{F_L \omega \cos(\psi)}{m (\omega_n^2 - \omega^2)} \right] \sin(\omega_n t) + \frac{F_L}{m (\omega_n^2 - \omega^2)} \sin(\omega t + \psi)$$

This solution is shown visually in Figure 10 (Kelly).

For most mechanical systems, it is desired to have $\omega \neq \omega_n$, as when $\omega = \omega_n$ the amplitude increases theoretically without bound (explained below), and this can become very dangerous. Resonance is avoided because it can cause serious damage to the system if the system is not designed to withstand this condition. This device, however, aims for $\omega = \omega_n$, as the increasing amplitude allows for the most energy to be harvested from the system. When $\omega = \omega_n$ as desired, the solution to the equation becomes:

$$x(t) = x_0 \cos(\omega_n t) + \left[\frac{\dot{x}_0}{\omega_n} + \frac{F_L \cos(\psi)}{2 m \omega_n^2} \right] \sin(\omega_n t) - \frac{F_L}{2 m \omega_n} t \cos(\omega t + \psi)$$

This solution is shown visually in Figure 11.

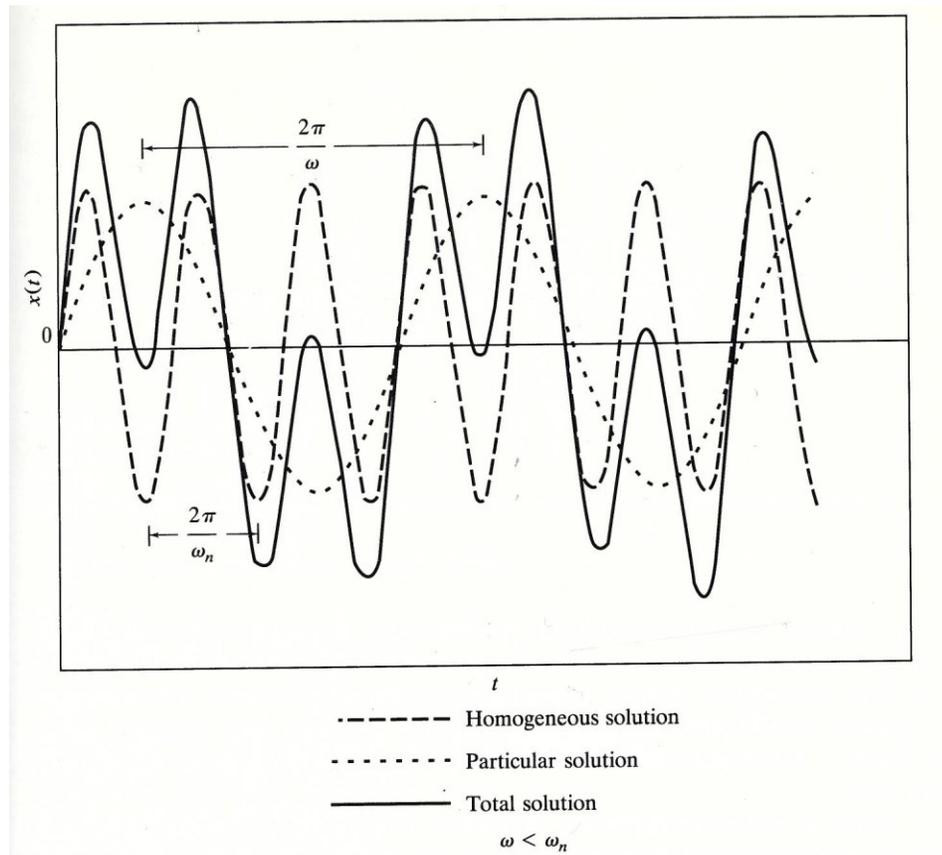


Figure 10: Displacement versus Time for Situation Where $\omega < \omega_n$ (Kelly)

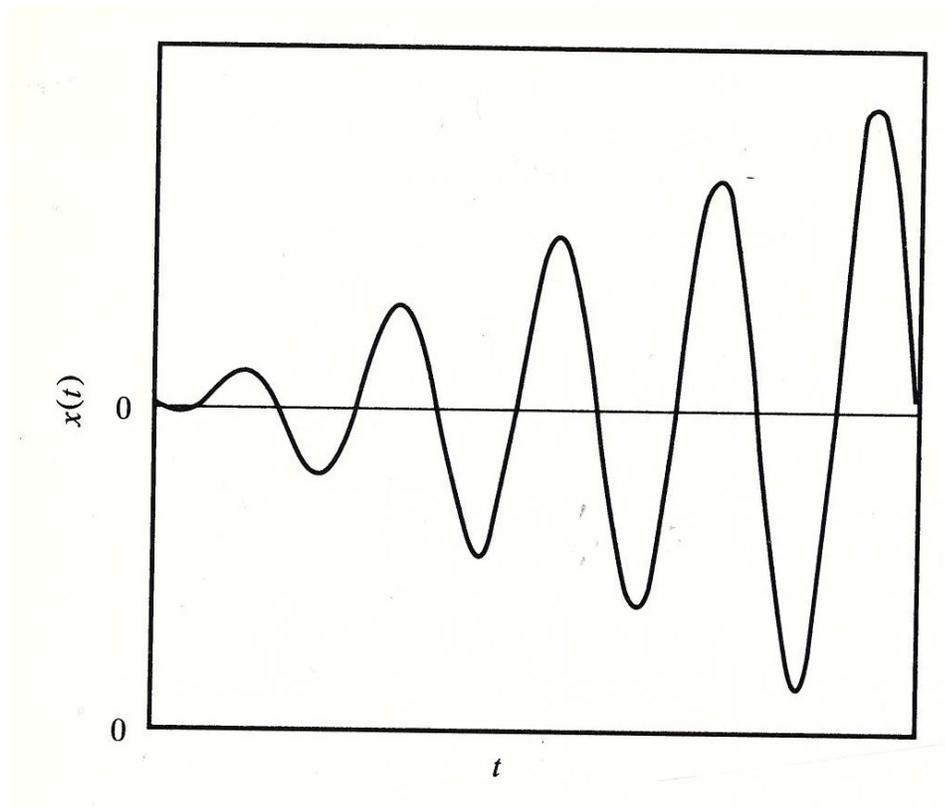


Figure 11: Displacement versus Time for Situation Where $\omega = \omega_n$ (Kelly)

As can be seen from the figure, when the frequency of the vortices is equal to the natural frequency of the system, the amplitude would theoretically increase without bound. However, in the actual system the amplitude is restricted by the height of the device and the springs, and therefore the system will reach a limit based on these factors (Kelly).

The natural frequency of the device is given by the formula

$$\omega_n = \sqrt{\frac{k}{m}}$$

$k = \text{spring constant}$

$m = \text{mass of system}$

It is important to note that the k in this equation is the equivalent spring constant, which is not necessarily equal to the constant of one of the springs in the system. The equivalent spring constant for springs in parallel (Figure 12) is given by the formula:

$$k_{eq} = k_1 + k_2$$

While for springs in series the formula is:

$$\frac{1}{k_{eq}} = \frac{1}{k_1} + \frac{1}{k_2}$$

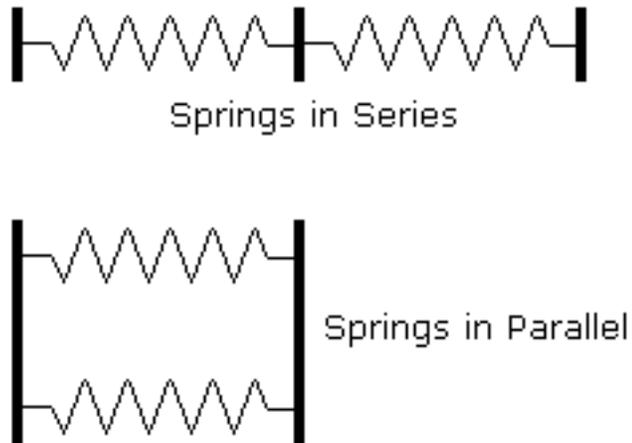


Figure 12: Series versus Parallel Springs

In order to achieve the desired lock-in conditions which occur when $\omega = \omega_n$, we substitute the equation for ω_n into the Strouhal number equation for ω , which yields:

$$St = \frac{\sqrt{\frac{k}{m}} D}{V}$$

Where the Strouhal number is a function of Reynolds number, which is a function of velocity and fluid as described in section 2.1.2. These equations simplify to:

$$\text{St} = -0.0065 * \ln\left(\frac{\rho DV}{\mu}\right) + .21$$

$\rho = \text{fluid density}$
 $\mu = \text{fluid viscosity}$

$$D = \text{characteristic length (diameter of cylinder)}$$

Setting these equations equal to each other and solving for k yields the following:

$$k = \left\{ \frac{\left[-0.0065 * \ln\left(\frac{\rho DV}{\mu}\right) + .21 \right] * V}{D\sqrt{m}} \right\}^2$$

The reason that k is the variable solved for is that it is the easiest to control and change in the system, as it only requires an adjustment to the springs, whereas ρ and μ depend on the fluid medium and V is the wind speed, which are all dependent upon the environment and thus are difficult to control. L and m are dependent on the cylinder, which would require a full redesign to alter, which would be much more difficult than a simple spring change.

2.3. Sociocultural Viability

Aside from mechanical function and power grid viability renewable energy generation devices face polarizing sociocultural standards as well. Consumers desire cheap, sustainable electrical power instantaneously available for their use. With non-renewable energy production methods, such as coal burning or nuclear fission reactors, the exothermic processes harnessed to generate electricity are control variables. This control allows for specific energy production rates to be achieved, with the volume of power generation being based on average hourly demand

(Understanding Base Load Power). The ability to control the rate of energy production to align with consumer demand allows for the power grid to operate as efficiently as possible, which helps to ensure the profitability of the power generation economic sector. These factors contribute positively to the public perception of non-renewable energy production and are current hurdles for renewable energy sources to overcome in their development.

Wind harvesting devices and other renewable energy sources face unique operational challenges when competing with non-renewable sources for market share and sociocultural acceptance. Primarily, wind harvesting devices rely on an independent variable as an energy source in wind. Whereas a coal plant can control the rate at which coal is burned wind can gust in any direction, at any velocity, and for any amount of time. This uncertainty makes wind difficult and inefficient to harvest, a significant drawback for wind harvesting's societal viability as a major contributor to the energy grid. Consumers expect optimized infrastructure which provides them with convenient, high quality goods or services on demand (Introduction to Marketing). Non-renewable energy sources have been used to generate electrical power for over a century, and the processes used to do this have been iterated to optimum efficiency. Wind harvesting devices, though existent as prototypes for decades, have only recently become a substantial portion of global energy production (Lars Kroldrup). This difference in time of operation has led many to the conclusion that non-renewable energy sources remain the most cost-effective method to mass produce electrical power. As wind harvesting devices continue to improve in design and operational efficiency, it will become easier to market the devices to municipalities looking to lessen their dependency on fossil fuels. Until then, the challenge of selling a less efficient product to consumers will remain for wind harvesting entrepreneurs.

An additional facet of efficiency posing a challenge to the continued sociocultural integration of renewable energy sources is device size. The most common wind harvesting device in use globally today is the wind turbine (New Zealand Wind Energy Association). Wind turbines vary greatly in height, generator type, and blade length, with power production relatively proportionate to these attributes. In order to output the same amount of power that a traditional power plant may produce, wind turbines must be installed in array-based fields. These fields require significant geographical area, and are limited to locations with consistent and predictable wind flow such as coastal regions. Consumers are rather outspoken about the unsightliness of a large field of wind turbines and have vetoed the installation of such arrays in a multitude of locations. The rotation of wind turbine blades also creates a flickering effect with sun rays, a phenomenon that can cause someone visual discomfort as far as three miles from the turbine (Wind Energy Frequently Asked Questions). Non-renewable energy source power plants also require large acreage for their installations; however they often have less specific locational requirements and can be placed miles away from residential epicenters. The ability to locate power plants strategically to prevent their interference with residential development is a powerful sociocultural advantage over wind harvesting devices.

The above considerations were taken into account for the development of our VIV wind harvesting prototype. As with wind turbines, our device would have to be appropriately sized and potentially assembled in an array to produce the type of power associated with power plants. The device would have to be located in an area with highly consistent wind flow to achieve lock-in natural frequency oscillation, a stipulation that severely limits the locations at which it may be installed. The issue of efficiency is in fact even more profound with a VIV wind harvesting device than with a wind turbine, as our device will only function properly at its design natural

frequency. This natural frequency exists at a specific wind velocity, the alteration of which prevents proper oscillation and by extension inconsistent electrical power generation. At present, the VIV oscillation wind harvesting device prototype we have produced is not socio-culturally viable. Even at great physical size and operating in an array or group, our device will not produce electrical power with the consistency or reliability necessary to depend upon it as the sole power source. It would often have to be located in areas of considerable population density, would require regular maintenance at these locations, and in times of extreme weather would not operate at all. Non-renewable energy production is still the most reliable and cost-effective process to sustain the power grid, and until wind harvesting devices can compete with these criteria non-renewable energy sources will continue to be the most socially and culturally viable.

2.4. Comparable Product Analysis

Multiple products, which utilize similar technology to our wind harvester, were researched to help aid in our design process.

2.4.1. Windbelt

Windbelt technology was invented by Shawn Frayne. He noticed a need for small-scale wind power to provide energy to devices such as LED lamps or radios in the homes of the poor. Frayne was inspired by the 1940 collapse of Washington's Tacoma Narrows Bridge (Ward). This bridge collapsed due to vibrations cause by the wind, resulting in the phenomena called aeroelastic flutter. Aeroelastic flutter is a dynamic instability of an elastic structure in a fluid flow. The force exerted by the fluid flow causes the body to deflect. From this deflection, there is a destructive vibration, generally perpendicular to the body's length. Structures, such as bridges and skyscrapers, are designed to avoid flutter (Aeroelasticity). Instead, Windbelt uses those vibrations for good.

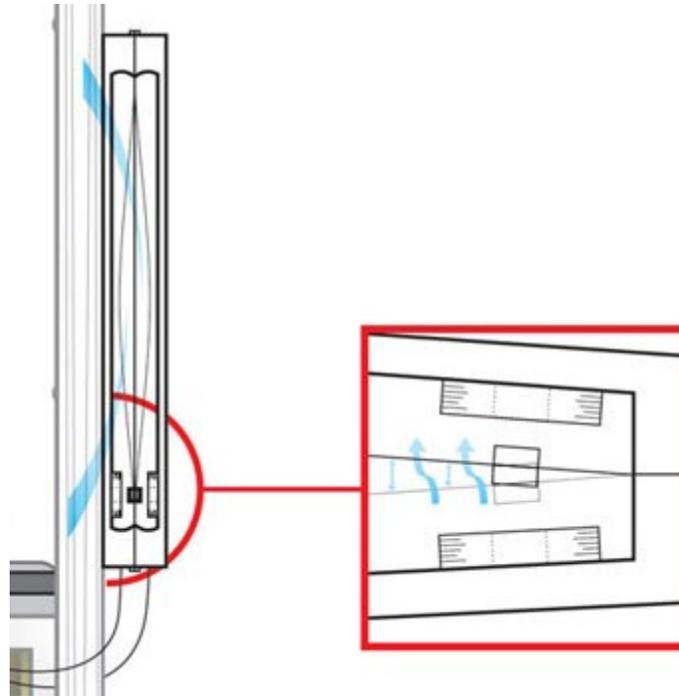


Figure 13: Sketch of Windbelt, Depicting Membrane, Magnets, and Coils (Ward)

Frayne's design uses a taut membrane, made of Mylar-coated taffeta, and a pair of magnets which oscillate between metal coils (Figure 13). The potential cost for Frayne's device is a few dollars. He hopes it can replace kerosene lamps in Haitian homes – instead of the flammable kerosene lamps, Haitian's could instead use LED lamps powered by the Windbelt.

Frayne is confident in his device because its technology is unlike that of conventional wind turbines. The Windbelt's biggest asset is that it can scale down well – something conventional wind turbines cannot do well because of friction. Already, Frayne's prototype can generate 40 milliwatts of electricity in 10 mph, sporadic winds. This is 10 to 30 times as efficient as the best microturbines (Ward).

In a video where Frayne demonstrates his Windbelt's abilities, he powers LEDs, a standard analog clock, and a small radio on the spot. He explains that it can replace batteries, for example, in temperature and humidity sensors in buildings (Ward).

As this project expands, the goal is to tap into 3 m/s to 12 m/s wind speeds. To give an idea of what those speeds represent, a 3 m/s wind speed is defined as a “gentle breeze – enough to make twigs on a tree branch sway” (Windbelt – Reinventing). The Windbelt will be designed to flutter at the lowest threshold, but maintain flutter even in higher speeds, without retensioning. Built on these ideals, Frayne’s first device, the Windcell, is approximately 1 meter in length and typically produces .2 kWh per month (enough electricity to power 10 energy saving light bulbs). His powerful device can be placed on bridges and the sides of skyscrapers – places turbines cannot go (Windbelt – Reinventing). The Windcell was developed for applications needing .1 kWh to 1 kWh of energy per month. It is modular and individual units can be combined together for larger installations to generate more total power (Windbelt Innovation: Medium).

The ability of this device to be scaled opens even more doors for its potential use. The microBelt is a device, also developed by Frayne, which fits in the palm of your hand. Its cut-in wind speed is 6 mph. It has operational wind speeds of 6 to 20 mph, with constant power output. A single microBelt has the energy potential equivalent to dozens to hundreds of AA batteries. Estimated over a 20 year lifetime, with a 10 mph average airflow and 30% operating time, the microBelt can produce about 100 to 200 Wh. This scenario was chosen because it replicates that of an HVAC duct. Frayne believes the microBelt’s main use will be to provide power to data sensors. It can use the air flow in a duct within a building to power HVAC temperature sensors and air quality sensors. It could also be placed on the underside of bridges to power stress monitoring devices. Using the microBelt in these areas would mean not having to replace billions of batteries every year (Windbelt Innovation: Micro).

Frayne’s device was designed to use a typically destructive phenomenon in a productive way. Wind is a renewable and widely available source – it can be found anywhere. By designing

a device to use low, average wind speeds to produce electricity, Frayne has opened doors to new possibilities in the area of renewable energy. More specifically, he has widened the area where wind energy can be harvested. Since the Windbelt can be placed in areas turbines cannot – i.e. bridges, buildings, HVAC ducts – the potential market widens. By also minimizing the cost of the device, Frayne creates an even wider market – homeowners and even third-world countries can purchase and use the Windbelt to their advantage. The Windbelt is a true advancement in the area of renewable energy via wind.

2.4.2. “Piezo-tree” Concept

Inspired by nature, Cornell University began research into a new way to generate electricity through wind. The idea was to imitate swaying tree branches (Energy). Piezoelectrics would be utilized for their ability to convert mechanical pressure into electrical signals – electricity (Manmadhan). The structure Cornell University created would replicate a real-life tree. Polyvinylidene Fluoride (PVDF) is a flexible piezoelectric material that was chosen because it could withstand the unpredictable wind strengths it would encounter.

The leaf stems on the tree would be piezoelectric, utilizing the PVDF material. One edge of PVDF stem would be left free to move while the other edge was connected to a cylindrical, bluff body. This bluff body, for the purpose of this invention, would replicate the tree branches. As wind passes over the branches, their bluff nature would create vortex-shedding. The shedding would then move the PVDF stems and create electrical energy that would be stored in a capacitor (Energy). However, an issue was soon found.

The “piezo-tree” generated about 100 pW of electricity. This small amount of power could not even light an LED. This low electrical generation was thought to be due to the weak piezoelectric strain coefficient of PVDF. More motion in each PVDF stem would result in more

electricity being produced. Leaves were found to make the difference. These flexible leaves would flutter and oscillate like a leaf in the wind on a tree found in nature. There was a 100 times increase in power when a plastic film (a “leaf”) was added to the free ends of the PVDF stems. Cornell utilized attachments of various shapes, areas, densities, and flexibilities. They tried plastic and polymer films. Various arrangements resulted in varying levels of power generation. The best combination was found to be vertical stalks (stems) and horizontal leaves (Energy).

The goal of the research is to build plant-like devices with hundreds or thousands of piezo-leaves (Energy). The more the wind blows, the more the leaves move (frequency increases), and the more the piezo generators (PVDF) are stimulated to make even more energy (Manmadhan). Multiply this by hundreds or thousands of leaves, and you have a man-made tree that will generate power from a renewable energy source – the wind. Already, Cornell University’s research has shown that cost appears to be low and the device is easily scalable (Energy). Other pros include the fact that these devices will be no more intrusive than a tree is already and can be placed close to homes, businesses, and any other populated areas.

The vortex-shedding concept that the piezo-tree uses is similar to the VIV wind harvester created by this group. In addition, it utilizes flutter on the leaves, like Frayne’s Windbelt design. Combining the two, usually destructive, wind-motion concepts proved to be an excellent and positive idea for Cornell. They provided another alternative for wind energy generation.

2.4.3. Vortex Hyrdo Energy

In 2004, at the University of Michigan, a doctoral student, Kamal Raghavan, created a new means of harnessing natural energy to convert it to electrical energy. The device is the Vortex Induced Vibration for Aquatic Clean Energy converter (VIVACE converter). Michael Bernitsas, a University of Michigan Professor in Naval Architecture and Marine Engineering and

the Director of the Marine Renewable Energy Lab, was another mastermind behind this technology. He started Vortex Hydro Energy, a company to further develop and deploy the technology of the VIVACE converter, with backing from the Office of Technology Transfer of the University of Michigan (Bernitsas).

VIVACE is meant to be long cylinders suspended in water, perpendicular to a current flow. It uses the physical phenomenon of vortex induced vibration, just like this group's device (Vortex). The difference is in scale and fluid medium – VIVACE is larger than the VIV wind harvester and designed for water while the VIV wind harvester is currently small-scale and designed for wind. VIVACE is made up of boxes with cylinders placed on the bottom of the river. As current passes over these cylinders, it creates vortices in the current and causes the cylinders to bob up and down. The bobbing cylinders move a magnet up and down along a metal coil, creating DC current. This DC current is then converted to AC current and sent to shore (Vortex). Figure 14, taken from the Vortex Hydro Energy website, depicts this explanation. The use for their specific example is to light a new wharf between the Renaissance Center and Hart Plaza. Its location is in the Detroit River.

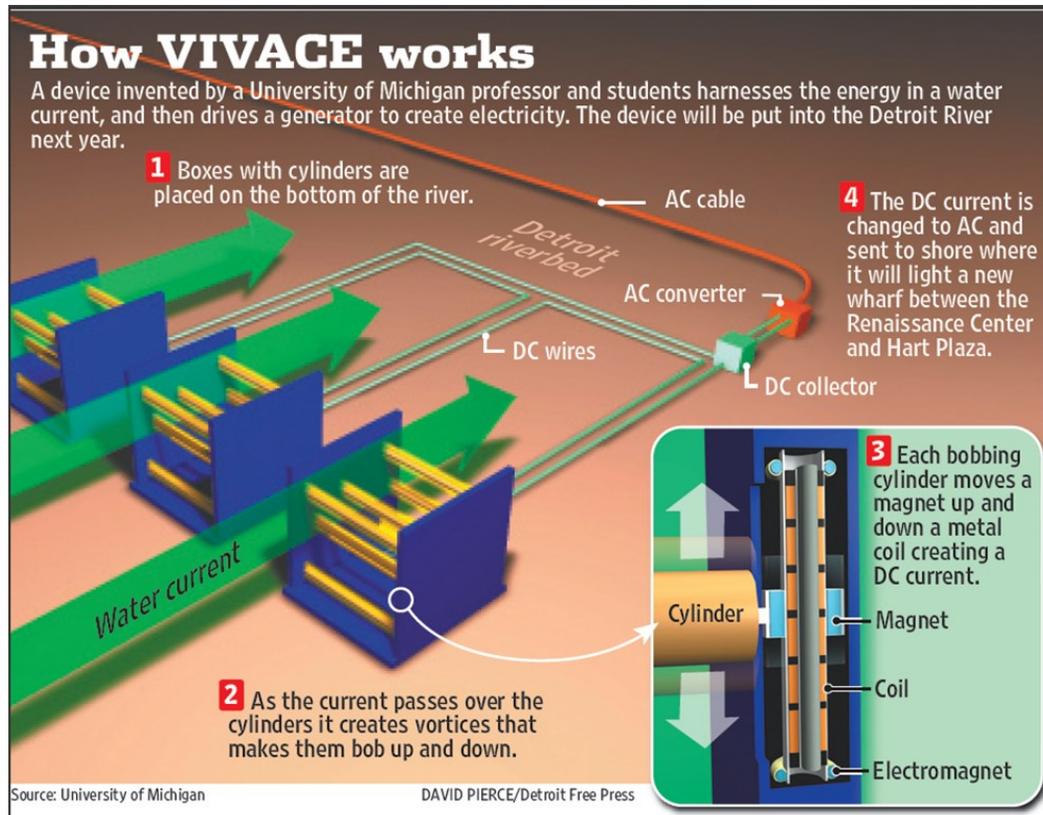


Figure 14: How VIVACE Works (Vortex)

VIVACE provides clean and renewable electric power. It is also environmentally compatible. VIVACE can utilize water currents as slow as 2 to 4 knots. This fact is important because a majority of river and ocean currents in the United States are slower than 3 knots. VIVACE takes advantage of these naturally occurring currents to generate useful electricity (Vortex). In addition, VIVACE does not impede nature. Instead, it allows water to continue to flow freely (Bernitsas). VIVACE will not be bothersome to aquatic creatures, either. The cylinder oscillations are slow – about a cycle per second – and create no direct physical threat to fish. Fish, and other aquatic wildlife, can navigate safely around the cylinders (Vortex).

VIVACE creators chose water as a medium to work with for a few reasons. One reason is that “ocean currents and river flows are much more predictable and reliable than waves, wind, or solar activity” (Bernitsas). These water flows are always in one direction and relatively steady,

unlike wind which is inconsistent and has variable direction. Bernitsas also mentions an immediate observation: wind begins with a clear disadvantage because, compared to flowing water, wind has a low power density. Water is 784.1 times denser than air, resulting in more force for VIV and better motion. Water's higher density also leads to a higher power density and, therefore, produces significantly more power than a similar device in wind. In addition, wind devices need careful location selection to exploit favorable wind conditions. VIVACE just needs flowing water, which is consistent within a river (Bernitsas).

The VIVACE converter uses the same technology as this project's VIV wind harvester. It is a proven idea, and can be easily scaled. However, there are major differences between working with water and working with wind. With more work, a VIV wind harvester is attainable. However, the VIVACE converter exemplifies the benefits to working with water, a denser and better medium.

3. Methodology

3.1. Design Goals

A few preliminary design ideas were created. In order to choose one idea a design matrix was created. The parameters for the device needed to be reasonable for the time and resources available. The main goal is to make a proof of concept prototype. This prototype should be able to generate power as a small-scale device. Theoretical power output calculations will be compared to the actual output. The most limiting factors need to be determined so the device can be designed around them.

The greatest limitations to the project were the facts that the device needs to demonstrate electrical energy output, fit in the wind tunnel, and the material costs need to be less than \$640. These conditions could not be worked around. The purpose of the project was to see if gathering electricity from vortex induced vibrations is feasible, so this became a primary factor. In order to test the device, a controlled environment was needed. The wind tunnel allows the experimenters to control the wind speed, so the device was built to function in the wind tunnel. A budget of \$640 was granted to the group, so this was the limit of the funds.

Table 1: Design Matrix

| Design Matrix | | | | | | |
|---|----------------|---------------------------------------|-------------------------------------|---|--|---|
| | Weighted Value | Horizontal Cylinder (magnet and coil) | Horizontal Cylinder (piezoelectric) | Vertical Cylinder (piezoelectrics on outside at ends) | Vertical Cylinder (frame through middle, piezoelectrics on inside at ends) | Vertical, Piezoelectric Cylinder (frame through middle) |
| Generates electricity | 0.9 | 5 | 3 | 3 | 3 | 3 |
| dimensions smaller than 1ft ³ (fit in wind tunnel) | 1 | 5 | 5 | 5 | 5 | 5 |
| Weighs less than 25lbs (manageable) | 0.5 | 5 | 5 | 5 | 5 | 5 |
| material costs less than ~\$600 total | 1 | 5 | 4 | 4 | 4 | 2 |
| Able to collect wind from 2+ directions by itself | 0.4 | 4 | 4 | 5 | 5 | 5 |
| Feasibility in an array | 0.8 | 3 | 3 | 3 | 3 | 3 |
| Able to work in wind speeds from 1 to 25 mph | 0.5 | 4 | 3 | 2 | 2 | 2 |
| Durability in weather conditions | 0.4 | 4 | 3 | 3 | 3 | 3 |
| Feasibility within time constraint (3 terms) | 0.8 | 5 | 4 | 2 | 2 | 2 |
| Totals | | 28.6 | 24.1 | 22.4 | 22.4 | 20.4 |

| Scale | |
|-------|----------|
| 5 | Good |
| 4 | |
| 3 | Moderate |
| 2 | |
| 1 | Bad |

From the parameters discussed above and presented in Table 1, two more limiting factors were established. Friction and mass greatly damped the oscillating system. The initial design had to be modified to reduce the friction and weight on the moving cylinder. The support rods were removed because the friction between them and the cylinder was greater than the lift force from the wind and prevented the cylinder from moving. This friction came from the drag force on the cylinder pushing the cylinder against the rods, producing friction that, when added to the mass of the system, was too great for the lift force to overcome. The material of the cylinder was changed

from PVC to cardboard. This made the cylinder 86% lighter. This reduced its inertia, or resistance to change in motion of an object. This was important because the cylinder needs to be able to change direction rapidly in response to the wind vortexes. If the system is damped in anyway, it will suffer from destructive interference and will not be able to reach its natural frequency. For this reason, the coils and leads could not be attached to the cylinder. They added too much mass. For future iterations, the electricity will need to be gathered using a different setup.

3.2. Selected Design

The VIV wind harvesting device features a hollow PVC cylinder of 2” nominal diameter and 5” length as the airfoil (seen in Figure 17). A cylinder was chosen as the airfoil because of its ability to harness an equal amount of lift force in both the positive and negative directions along the vertical axis. The cylinder is suspended at equilibrium by four springs positioned along the cross-sectional midline of the cylinder. Each spring has an approximate un-stretched length of 1.5” and a maximum operable stretched length of approximately 6.28”. Two additional support rods flank the springs and run through the cylinder along its midline. These support rods are of lesser diameter than the holes through which they run, only making contact with the cylinder if excessive drag force causes deviation from its path of vertical oscillation; in this case, they are meant to act as rails for the device and keep it from twisting or moving under the excessive drag force.

Extending outward from each end of the cylinder is a wire coil assembly. Each coil is constructed of magnet wire wound approximately 100 times to form a uniform cylindrical coil. This coil is then attached to the cylinder by a support rod.

There are two threaded rods, one at either end of the PVC tube. These serve as primary structural support components between the base and top, as well as an attachment point for the magnet assembly. The magnets will be held in their desired position by hex-nuts. These support rods and the smooth support rods within the cylinder are all attached to an acrylic base and top each of 0.5" thickness. The threaded rods are held in place by additional hex-nuts positioned to hold the acrylic together with the appropriate clearance. The smooth rods are held in place by scissor clamps. The sketches for ideation are shown in Figure 15 and Figure 16.

The acrylic pieces are 21" in length and 9" in width. They are made to fit as the top and bottom of the wind tunnel. Holes were drilled directly through these pieces for all support rods and also for attachment points for the springs. This design was created so the PVC device could be easily observed while tested in the wind tunnel.

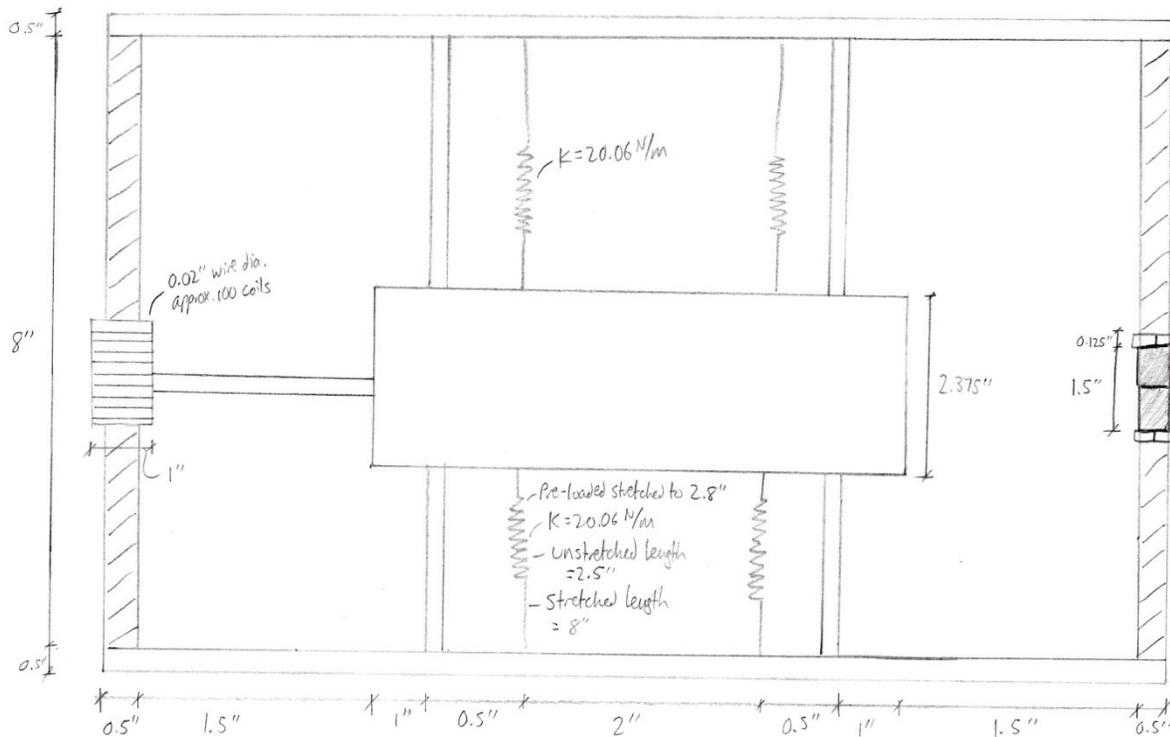


Figure 15: Sketch of Initial Design, Front View

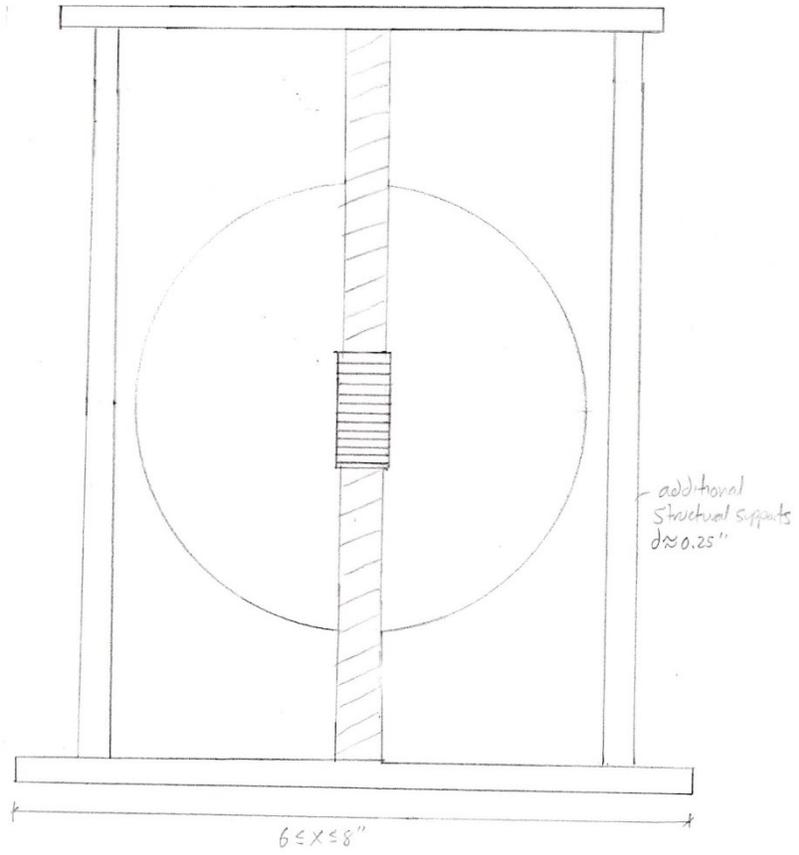


Figure 16: Sketch of Initial Design, Side View

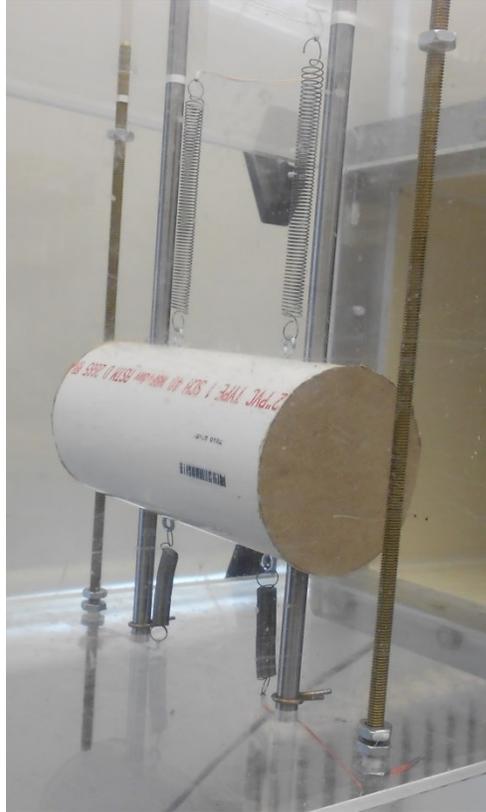


Figure 17: Original Design, Once Built, In Wind Tunnel

As the cylinder oscillates at an arbitrary frequency and amplitude, the wire coils move in unison along with it. The magnet coils are centered around the threaded support rods which contain the magnet assembly. The magnet assembly consists of two cylindrical magnets stacked together along the rod. The magnets are centered at the equilibrium point of the cylinder and wire coil and supported on each end by hex-nuts. As the wire coil on each end oscillates with the amplitude and frequency of the airfoil, it passes back and forth over the magnet assembly. This continuous movement of the coil over the magnets generates a current in the coil, which is then harvested to create electricity.

3.3. Calculations

This section will go through the calculations used to predict how much voltage could be generated from wind using the system. Values were either researched or chosen by the experimenters. To start, the dimensions associated with the cylinder were found.

The nominal area of the cylinder is calculated by multiplying the length of the cylinder by its diameter. The length and diameter were selected based on available materials and space limitations within the wind tunnel.

$$1. A_c = \text{Cross sectional area of the cylinder} = l * d = 76.6\text{cm}^2$$

$$l = \text{length of the cylinder} = 12.7\text{cm}$$

$$d = \text{diameter of the cylinder} = 6.03\text{cm}$$

The mass of the cylinder is calculated using a researched weight to length ratio of PVC piping, given by the Engineering ToolBox.

$$2. m_c = \text{mass of the cylinder} = l * \frac{w}{l} = 0.14\text{kg}$$

$$l = \text{length of the cylinder} = 12.7\text{cm}$$

$$\frac{w}{l} = \text{weight per unit length} = 0.011 \frac{\text{kg}}{\text{cm}}$$

The diameter of the coil will be slightly larger than that of the magnet which is $\frac{3}{4}$ " (0.01905 m). There are currently 100 coils, but this value may be increased to improve output.

The drag force on the cylinder is calculated using the following equation:

$$3. F(v) = A_{\text{cyl}} * \frac{\rho}{2} * v^2 * C_d$$

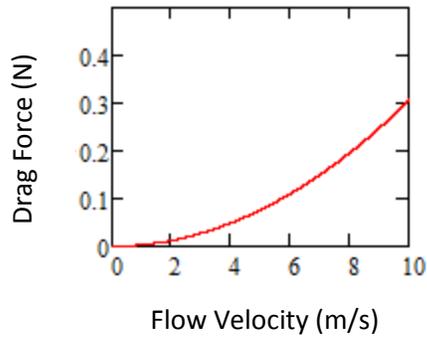


Figure 18: Drag Force (N) versus Flow Velocity (m/s)

$v =$ the variable velocity of wind

$A_{cyl} =$ The cross sectional area of the cylinder = 76.6cm^2

$\rho =$ the density of air ($1.225 \frac{\text{kg}}{\text{m}^3}$ at STP)

$C_d =$ Coefficient of drag over a cylinder
(1, in this case: based on geometry and Re , see Figure 6)

For a wind velocity of 4.47 m/s (10 mph), the drag force is calculated to be.

$$F\left(4.47 \frac{\text{m}}{\text{s}}\right) = 0.061 \text{ N}$$

Reynolds Number is calculated using the following equation:

$$4. \quad R_e(v) = v * d/v$$

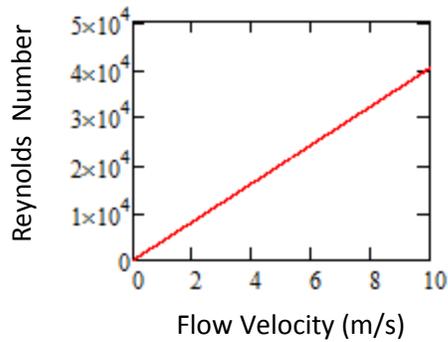


Figure 19: Reynolds Number versus Flow Velocity (m/s)

$v = \text{variable wind velocity}$

$d = \text{diameter of the cylinder} = 6.03\text{cm}(2.375\text{ in})$

$\nu = \text{kinematic viscosity of air} = 15 \times 10^{-6} \frac{\text{m}^2}{\text{s}}$

For a wind velocity of 4.47 m/s (10 mph), the Reynolds number is calculated to be.

$$Re\left(4.47 \frac{\text{m}}{\text{s}}\right) = 1.8 \times 10^4$$

Reynolds number is used to find the Strouhal number. The Strouhal number is approximated to be (Resvanis):

$$5. S_t(v) = -0.0065 * \ln(R_e(v)) + .21$$

$v = \text{variable wind velocity}$

For a wind velocity of 4.47 m/s (10 mph), the Strouhal number is calculated to be.

$$S_t\left(4.47 \frac{\text{m}}{\text{s}}\right) = 0.146$$

The Strouhal number is needed to find the frequency of the vortex shedding in the following equation:

$$6. \quad f(v) = S_t(v) * v/d$$

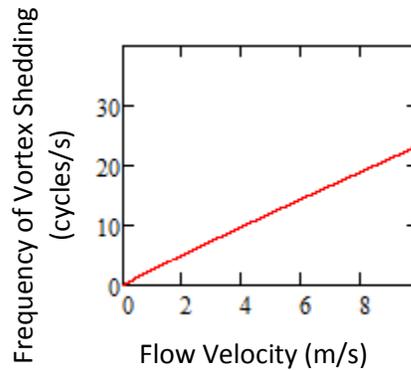


Figure 20: Frequency of Vortex Shedding (cycles/s) versus Flow Velocity (m/s)

$v = \text{variable wind velocity}$

$d = \text{diameter of the cylinder} = 6.03 \text{ cm (2.375 in)}$

For a wind velocity of 4.47 m/s (10 mph), the frequency is calculated to be.

$$f\left(4.47 \frac{m}{s}\right) = 10.8 \frac{\text{cycles}}{s}$$

The frequency represents the number of times the cylinder is expected to oscillate per second. In order to maintain this oscillation, the system needs to yield a simple harmonic motion.

The following equation for natural frequency is rewritten to solve for k, the spring constant.

$$7. \quad f_n = \sqrt{k/m}$$

$k = \text{spring constant}$

$m = \text{mass of the cylinder}$

This gives:

$$8. \quad k(v) = (f(v))^2 * m$$

An expected range of wind velocities (10 to 15 mph) are entered in as v in the frequency equation.

$$k(10\text{mph}) = 16.4 \frac{\text{kg}}{\text{s}^2}$$

$$k(15\text{mph}) = 35.7 \frac{\text{kg}}{\text{s}^2}$$

These values are compared to values from the equation:

$$9. \quad k = F_{\text{max}} / (L_{\text{max}} - L_{\text{min}})$$

$F_{\text{max}} = \text{maximum force the spring can withstand without deforming} = 2.09\text{N}$

$L_{\text{min}} = \text{the length of the unstretched spring} = 3.8\text{cm}$

$L_{\text{max}} = \text{the length of the spring when } F_{\text{max}} \text{ is applied} = 16\text{cm}$

$$k = 17.2 \frac{\text{kg}}{\text{s}^2}$$

F_{max} , L_{max} , and L_{min} are all taken from spring specifications on McMaster Carr. Several iterations were done, changing the actual spring dimensions based on available springs, to obtain a spring with a k value that was within the range of possible k values found from equation 9. The k value 17.2 kg/s^2 is close to the k value of a 10 mph wind, 16.4 kg/s^2 . Using the k value of the spring above, the expected natural frequency will be:

$$f_n(k = 17.2 \frac{kg}{s^2}) = 11.1 \frac{cycles}{s}$$

The total force on the cylinder needs to be calculated from the sum of the lift force and the springs. The lift force is calculated using the following equation:

$$10. L(v) = \frac{1}{2} * \rho * v^2 * A_{cyl} * C_L$$

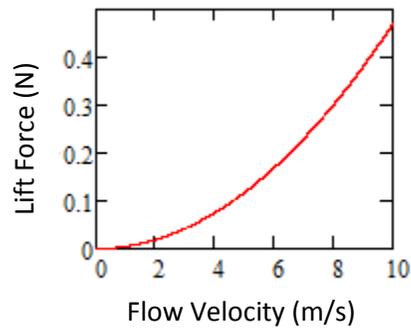


Figure 21: Lift Force (N) versus Flow Velocity (m/s)

$$\rho = \text{density of air at STP} = 1.225 \frac{kg}{m^3}$$

$$v = \text{variable wind velocity}$$

$$A_{cyl} = \text{The cross sectional area of the cylinder facing the wind} = 7.661 \times 10^3 \text{ m}^2$$

$$C_L = \text{Coefficient of lift for a cylinder (1: based on geometry and Re)}$$

(Lift coefficient is found similar to the drag coefficient. For a smooth cylinder in cross flow, the lift and drag coefficients will both equal 1 (Sunden). The drag coefficient was found above, and the graph of C_D relative to Reynolds number can be seen in Figure 6.)

For a wind velocity of 4.47 m/s (10 mph), the lift force is calculated to be:

$$L\left(4.47 \frac{m}{s}\right) = 0.094N$$

Lift force ($L(v)$) is the maximum force applied by the wind. This force changes direction depending on the frequency of the cylinder's oscillation, which is also a function of velocity. The variable lift force with respect to velocity and time is then noted as:

$$11. L_t(t, v) = L(v) * \sin(2 * \pi * f(v) * t)$$

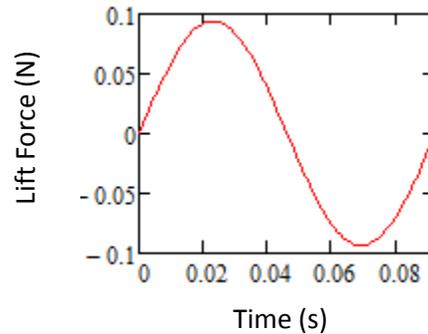


Figure 22: Lift Force (N) over Time (s)

$$L(v) = \text{lift force}$$

$$v = \text{variable wind velocity}$$

$$f = \text{shedding frequency}$$

$$t = \text{variable time in seconds}$$

This equation uses the lift force as the amplitude to the sinusoidal shedding frequency.

The amplitude of the oscillation may need to be calculated to find how far the coils need to be placed from the magnets. By combining the following equations:

$$L(v) = m_c * a_{max}$$

$$a_{max} = (2 * \pi * f(v))^2 * A$$

The amplitude can be found by solving for the maximum acceleration (a_{\max}) and setting them equal to each other:

$$12. A(v) = \frac{L(v)}{m_c * (2 * \pi * f(v))^2}$$

$L(v) = \text{Lift force as a function of } v$

$m_c = \text{mass of the cylinder} = 0.14\text{kg}$

$f(v) = \text{frequency of oscillation of the cylinder as a function of } v$

$v = \text{variable wind velocity}$

For a wind velocity of 4.47 m/s (10 mph), the amplitude is calculated to be:

$$A\left(4.47 \frac{\text{m}}{\text{s}}\right) = 0.014\text{cm}$$

A change in magnetism of a coil of wire will cause an induced voltage or electromotive force (emf). A change in magnetism is caused by adding or removing a magnetic field from the coil. The relationship between the voltage created and the changes in a magnet and coil are represented in the Faraday Lenz equation:

$$13. \varepsilon = -N \frac{\Delta\Phi_B}{\Delta t}$$

$\varepsilon = \text{emf} = \text{electromotive force (V)}$

$N = \text{number of coils} = 100$

$\Delta\Phi = \Delta(B * A) = \text{change in magnetic flux}$

$B = \text{magnetic field} = 1.48\text{T to } 0\text{T}$

The magnetic field will be the variable that changes in the system. It will range from 0 to 1.48T as the cylinder cycles in the system. When the magnet is in the coil, B will equal its max value. When the magnet is out of the coil, B will equal 0T. This causes the magnetic flux which results in voltage.

$$A = \text{cross sectional area of the coil} = \pi * r^2 = 2.85\text{cm}^2$$

$$r = 0.952\text{cm}\left(\frac{3}{8}\text{in}\right)$$

The cross sectional area is the area of the coils perpendicular to the motion of the magnet. For our coils, it is the area of the circle they create, using the coils radius as the characteristic dimension.

$$\Delta t = \text{change in time} = \frac{1}{f(v) * 4}$$

Δt is the time that it takes the cylinder to reach the amplitude from its equilibrium position. It is equal to one quarter of the cylinder's period. This is the amount of time it takes the magnet to be fully entered or removed from the coil.

By utilizing this relationship, the VIV wind harvester will be able to convert mechanical energy into electrical. By changing the distance of the magnetic field from the coil, the magnetism in the coils will vary from 0T to 1.48T over 0.023s. This change in magnetic flux over time will yield a voltage. The calculation for theoretical voltage for a 4.47 m/s wind velocity follows:

$$\varepsilon\left(4.47\frac{\text{m}}{\text{s}}\right) = -1.83\text{V}$$

It is sinusoidal with respect to the oscillation of the cylinder and creates an AC voltage. This can be graphed for a specific wind velocity with the equation:

$$14. V\left(t, 4.47 \frac{m}{s}\right) = \varepsilon\left(4.47 \frac{m}{s}\right) * \sin\left(f\left(4.47 \frac{m}{s}\right) * 2 * \pi * t\right)$$

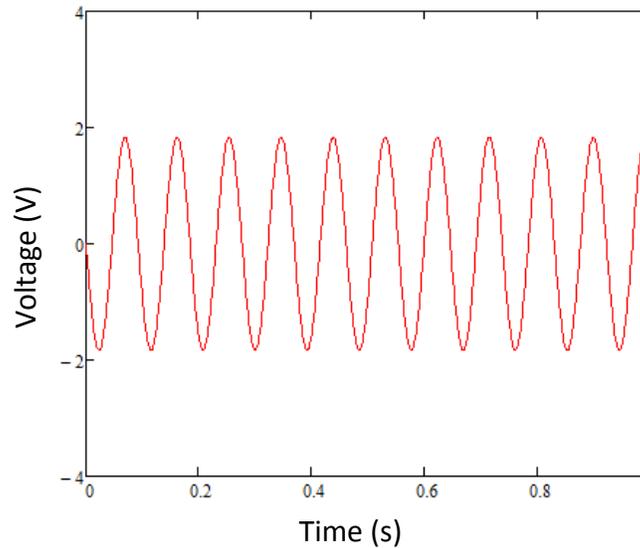


Figure 23: Theoretical Voltage Output (V) over Time (s) (for the 100 Turn Coil System Explained Above)

The diameter of the coils (d_{coil}) and magnetic force (B) are constrained by space and materials. The number of coils (N_{coil}) can be changed in future testing. By increasing the number of coils, the amount of volts will increase.

3.4. Testing and Design Iterations

Throughout the testing phase of the project, a multitude of different set-ups at a range of wind speeds were tested in an attempt to achieve lock-in conditions and thus maximum energy output. In this section each test will be described, along with the successes and failures of each.

The first test was with the initial design, using a 2.375-inch diameter PVC cylinder with vertical support rods inserted to limit displacement parallel to the wind flow due to the drag force. In this test periodic motion was not achieved, and observations indicated this was due to friction between the supports and the cylinder due to contact made as a result of the drag force. After the initial test, the support rods were removed in an attempt to eliminate friction. With this setup, tests were run at wind speeds up to 21 m/s in the wind tunnel. The desired motion was still not achieved at any wind speed. In fact, only slight motion occurred as a result of the removal of the access hatch on the wind tunnel, which introduced extra turbulence to the flow. This, however, was not the anticipated motion based on calculations. It was also not the same as a VIV induced motion – it was more of a shake than an oscillation.

After conducting the tests with the PVC cylinder, it became clear a lighter weight material was needed. Cardboard was chosen as the material to use because of its ease of attaining and ease of creating the desired shape and size. Tests were done using this cylinder at wind speeds ranging from about 3.33 to 5.83 m/s. The support rods were not used (as seen in Figure 24). After this cylinder was proven to work, the copper coils were attached to the ends of the cylinder so that electrical power could be generated. 100-turn coils were made first, with leads that came out of the wind tunnel so that the generated power could be measured. These coils were too heavy and, therefore, incrementally scaled back to reduce the effect of the extra weight until 10-turn coils were found to be a viable option. The leads, however, still caused hindrance of

motion. Much like with the coils, the length of the leads was gradually trimmed, going from about one foot down to no leads. This was done in one-inch increments. The desired motion was not achieved until the leads were removed completely. Based on these results and observations the final, filmed test was the cardboard cylinder with no attachments. From the high-speed film the team was able to determine the amplitude and frequency of the oscillation, from which a theoretical voltage that could be generated from the coils and leads, if they could be attached without affecting the motion, was calculated. These tests were done with wind speeds between 3.33 and 5 m/s, taken in .17 m/s increments. These values and increments were chosen because the wind tunnel operates in Hertz settings, with every .1 Hz equal to about .085 m/s. Tests were done with .2 Hz increments.



Figure 24: Iterated Design, In Wind Tunnel

Overall, these tests provided valuable information regarding the actual behavior of the system as opposed to the theoretical behavior. They allowed the team to determine the effects of adding the electrical components and friction, which were not accounted for in the initial design. The knowledge of these effects allowed them to be taken into consideration for the redesign, which is described in section 5.

4. Results and Data Analysis

The improved design consisted of a lighter cylinder and no guide rods. This reduced mass and removed friction. As a result of these changes, the cylinder was able to oscillate. The oscillating cylinder moved so fast for the frequency to be counted by the human eye. A high speed camera was used to record the cylinder's motion at 240 fps. The video allowed the experimenters to count the number of cycles per second and measure the amplitude of the system. The values were recorded and compared to the calculated results in Table 2.

Table 2: Wind Tunnel Testing Data

| Wind Speed (m/s) | Initial, Calculated Amplitude (cm) | Lock-in Amplitude (cm) | Predicted Frequency (cycles/s) | Experimental Frequency (cycles/s) |
|------------------|------------------------------------|------------------------|--------------------------------|-----------------------------------|
| 3.33 | 0.043 | 2.25 | 11.1 | 8.51 |
| 3.75 | 0.044 | 3.5 | 12.4 | 8.45 |
| 3.92 | 0.044 | 3.25 | 13 | 8.48 |
| 4.17 | 0.044 | 2.75 | 13.7 | 8.51 |
| 4.58 | 0.044 | 0.75 | 15 | 8.33 |

The prediction for the amplitude is much smaller than the actual amplitude. The predicted values are representative of the amplitude the system will achieve at the onset of lock in conditions. When the cylinder reaches lock in frequency, the amplitude will increase until constrained by the spring forces. This was not accounted for in the calculations. However, it can be seen in the experimental results, proving lock in was achieved. A graph of amplitude versus wind speed can be seen in Figure 25.

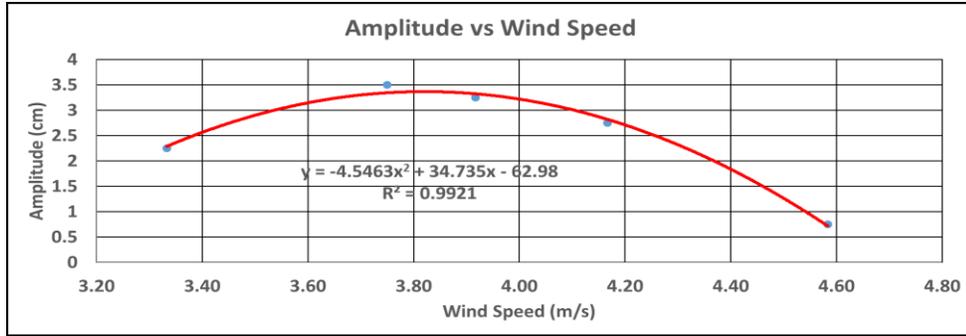


Figure 25: Graph of Measured Amplitudes over Range of Flow Velocities

In Table 2, the predicted frequencies are in the same order of magnitude as the experimental frequencies, but they are linear. This is because the actual data is limited by the fact that the same spring constant is used at every flow velocity. The spring constant is one of the factors that determine the lock in velocity. The predicted frequencies assume that an idealized k value is used at every flow velocity. Unfortunately this is not the case, springs have one k value and springs cannot be changed every time velocity is changed. It would also complicate the system, making it harder for potential users if it was commercialized. Instead, a single spring constant was used that would produce voltage within a limited range of flow velocities. This would simplify the system without sacrificing too much power.

From the experimental data, the displacement of the cylinder was graphed by inserting the observed frequency and amplitude into the basic equation for a sinusoid.

$$y(t) = A * \sin(2 * \pi * f * t)$$

$$y(t) = \text{vertical displacement of the cylinder}$$

$$t = \text{variable time in seconds}$$

$$A = \text{observed amplitude} = 3.25\text{cm at flow velocity of } 3.92 \frac{\text{m}}{\text{s}}$$

$$f = \text{observed frequency} = 8.48 \frac{\text{cycles}}{\text{s}} \text{ at flow velocity of } 3.92 \frac{\text{m}}{\text{s}}$$

The displacement graph for a flow velocity of 3.92 m/s can be seen below:

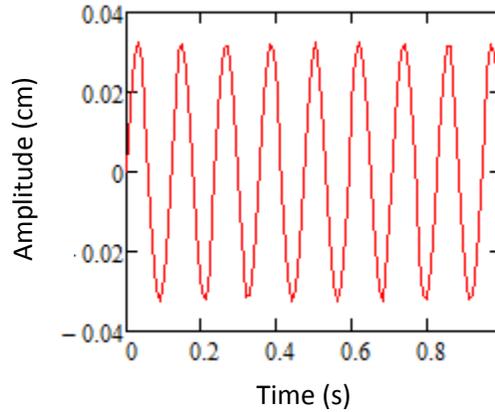


Figure 26: Amplitude (cm) over Time (s)

With this displacement equation, the velocity of the cylinder can be found by taking the derivative:

$$y_v(t) = A * 2 * \pi * f * \cos(2 * \pi * f * t)$$

$$y_v = \text{velocity of the cylinder}$$

$$t = \text{variable time in seconds}$$

$$A = \text{observed amplitude} = 3.25\text{cm at flow velocity of } 3.92 \frac{\text{m}}{\text{s}}$$

$$f = \text{observed frequency} = 8.48 \frac{\text{cycles}}{\text{s}} \text{ at flow velocity of } 3.92 \frac{\text{m}}{\text{s}}$$

To find the maximum voltage that could be produced, the change in magnetic field strength over change in time needs to be calculated. Using the max amplitude as the distance

covered for the magnetic field to reach its greatest distance a magnetic field per distance can be found.

$$\frac{B}{A} = \frac{\text{magnetic field}}{\text{observed amplitude}} = 0.615 \frac{T}{m}$$

This can be multiplied by the velocity to get a change in tesla per second. The peak velocity occurs at zero seconds.

$$v_{max} = y_v \left(\frac{1}{4 * f} \right) = 1.73 \frac{m}{s} \text{ for flow velocity of } 3.92 \frac{m}{s}$$

With these values the voltage can be found.

$$V_{max} = -N * A_{coil} * \frac{B}{A} * v_{max} = \pm 0.03 V \text{ at flow velocity of } 3.92 \frac{m}{s}$$

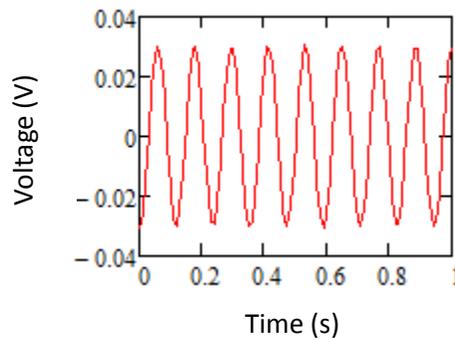


Figure 27: Voltage (V) over Time (s)

$$N = \text{number of coils} = 100$$

$$A_{coil} = \text{cross sectional area of the coils} = 2.85 \text{cm}^2$$

This is the expected voltage graph from the observed motion of the cylinder.

5. Redesign

5.1. Airfoil Material Selection

The material from which the cylindrical airfoil is formed directly correlates to device performance. The most important attributes to this project are material density, rigidity, surface finish, availability, and cost. As there are a myriad of composite materials that could theoretically be formulated to better suit the needs of this specific airfoil, it was necessary to limit the options to those that are readily obtainable.

5.1.1. Fiberglass

Fiberglass is a composite material of glass cloth and polyester resin (Fiberglass). When using this material the fabrication process involves the construction of a foam replica figure, the formation of a basic mold around the replica, and finally the application of the resin and glass cloth to produce the desired shape. Constructing a cylindrical airfoil out of fiberglass is an intriguing option because of its low density and ease with which to fabricate. As the weight of the airfoil directly correlates to the force required to induce movement, fiberglass would require less lift force, allowing for the airfoil to reach natural frequency oscillation at lower flow velocities. Additionally, fiberglass is reasonably affordable, does not require specialized machinery to work with, and can be molded to replicate most geometric shapes, contributing to its feasibility as an airfoil material.

Though fiberglass has generally favorable material characteristics for the fabrication of an airfoil for this device, it fails to satisfy one important criterion; surface finish. After the application of the resin and glass cloth, the fiberglass must be left to set in place. The resin is viscous; however it does settle around the glass cloth strands forming an uneven surface finish

(Fiberglass). The material surface finish is an important characteristic to consider for fluid flow applications. In laminar flow conditions, airfoil surface roughness can contribute to a transition to more turbulent flow should the degree of surface inconsistencies be great enough. In turbulent flow conditions, airfoil surface roughness plays a far more important role; Additional surface roughness on the airfoil will compound the inconsistencies found in turbulent flow, causing an increase in Reynolds Number and greater flow turbulence. In the WPI wind tunnel flow conditions are nearly laminar, diminishing any significant effects of surface roughness on aerodynamic performance. Conversely, in outdoor applications wind flow will be turbulent, and a smooth airfoil surface finish will be required to facilitate proper aerodynamic performance. If left with the unfinished surface, the airfoil may not be aerodynamically efficient and achieving lock-in conditions may be considerably more difficult. Commonly fiberglass components are sanded down to a smooth surface and then finished with a glossy resin. This process is rather labor intensive and requires some basic craftsmanship to achieve a truly uniform finish. Should the finishing process not appear daunting, fiberglass is an appropriate choice for an airfoil assembly material.

5.1.2. Moldable Plastics

Moldable plastics are most commonly found in pellet form, and are heated to a critical temperature (about 140° F) at which the pellets begin to congeal and become ‘moldable.’ Like fiberglass, moldable plastics are lightweight, affordable, and strong enough to withstand the stress of operating as the airfoil in this device. Ease of fabrication is the most valuable asset of moldable plastics. Moldable plastic pellets simply must be heated to their specified critical molding temperature and then formed into the desired shape either by hand or with tools. This is advantageous when compared to fiberglass or other fabrication materials as moldable plastics

require no chemicals or equipment, and can be heated with any available heat source capable of achieving the necessary temperature. Once the shaping process is complete, moldable plastics may be painted, dyed, machined, or carved, making them by far the most versatile fabrication material available at reasonable cost (About). Out of the materials researched and discussed here, moldable plastics are the most feasible option for the creation of a lightweight and aerodynamically sound cylindrical airfoil.

5.1.3. Carbon Fiber

Carbon fiber is a much more ambitious material to use for the cylindrical airfoil than the aforementioned options. In general, carbon fiber is one of the lightest and strongest fabrication materials currently available. It is formed by weaving miniscule strands of carbon together to form a woven 'sheet'. These strands have a diameter of approximately 5-8 micrometers, and millions are required to form even a small piece of woven carbon fiber (What). As one may conclude, the assembly process for such a material requires specialized machinery and is far more expensive than the other two options listed here. Because of this, the viability of carbon fiber as a fabrication material for the cylindrical airfoil is low. Despite its relative cost, carbon fiber remains a necessary consideration for this purpose because of its significant durability and commercial implications. A carbon fiber airfoil would require minimal lift force to achieve natural frequency oscillation, withstand all but the most extreme weather elements, and remain intact without required maintenance for a longer duration than either of the other two materials. This material longevity and reliability is crucial for the commercial mass production of any product, especially one which is located outside and would undergo immense normal and shear stresses. Though it is not the most feasible, a carbon fiber cylindrical airfoil would undoubtedly be an effective airfoil for this application.

5.2. Summary

The performance of the airfoil in this device hinges upon the material from which it is crafted. The materials discussed above all offer substantial operational benefits with few shortcomings. Based on this analysis the conclusion can be drawn that a moldable plastic material would be the most appropriate choice for this application. That being said, these materials could all be optimized within this system, as the airfoil will ultimately have to be calibrated as part of the mechanical system regardless of material composition.

5.3. Magnet and Coil Assembly

One ongoing problem with the original design was the magnet and coil assembly. Initial problems started with too much weight being put on the cylinder, and later problems involved lead interference and attachment issues. In the original design, the coils would be attached to the oscillating cylinder and the magnets would remain stationary on guide rails. This design was implemented so that a larger, heavier, and stronger magnet could be chosen to work with without adding too much weight to the system. The size of the coils could be varied until something that worked was found. However, regardless of coil size, the leads from the coils caused problems because they added too much weight to the system and caused resistance to the motion from their stiffness. Overall, the coils and their leads would not work while attached to the oscillation cylinder.

5.3.1. New Design

After analyzing other designs, it became clear a reversed design should be implemented – the magnet should be attached to the oscillating cylinder and the coils held stationary. The Windbelt and VIVACE converter both move magnets while keeping the coils stationary. The Windbelt connects its magnets directly to the taut membrane that flutters. The coils are placed

above and below the magnets so that as the membrane flutters the magnets move in and out of the coils. This assembly is placed near the end of the belt, so it is out of the way (Ward). The VIVACE converter uses hollow, cylindrical magnets attached directly to the ends of the cylinders. The coil runs through the middle of these magnets as the cylinders bob (Vortex).

Both magnet-moving methods have been demonstrated in working designs. Therefore, the redesign is going to attach the magnets to the cylinder and make the coils stationary. A small but powerful magnet (.589 grams, .2748 gauss) was chosen, and the coils are now free to be made as large or small as desired – they will not add any unnecessary weight to the oscillating cylinder and their leads will not impede any motion as the coils will be stationary. Of course, a slightly heavier and stronger magnet could be chosen, but starting with a light-weight design and increasing weight from there, if workable, is suggested.

The magnets produce the desired magnetic force, but lack the desired geometry needed to reach into the coil. The magnets are too short to dip in and out of a coil as the cylinder oscillates. The magnet can be seen in Figure 28. The attachment peg would hit the edge of the coil. This could be remedied by adding more magnets to create a column, but that would also



Figure 28: Magnet Used for Redesign (K&J Magnetics)

add more mass. Instead, a material called magnetic shielding foil will be used. It is a lightweight, ferrous material that is easily magnetized (Popovic). By shaping the foil into a hollow cylinder, the desired shape can be reached by adding less than a gram. This set-up can be seen in Figure 29. The foil absorbs the magnetic field from the magnet and redirects it through the foil. This property will be used to extend the magnetic field throughout the desired geometry (Magnetic).

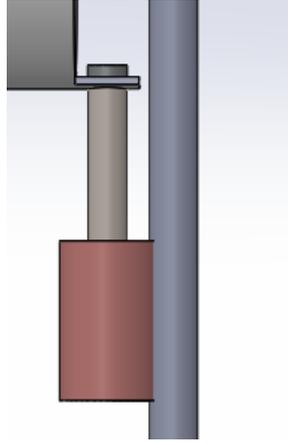


Figure 29: New Magnet and Coil Assembly, with Magnetic Sheilding Foil

5.4. Sketches

Figure 30 and Figure 31 are new sketches of the final redesign. Figure 32 is a CAD model of the complete set-up of the final redesign. It reflects what the built model would look like. The setup is virtually the same as the original design, with the exception of the magnet and coil assembly and support rods. Aside from the setup, the most important change was to the cylinder material – choosing something lighter than PVC and more durable than the cardboard used for testing. The chosen material may be heavier than cardboard, but a slight weight increase is acceptable in order to provide the necessary durability to the system. For example, the moldable plastic cylinder is 4 times heavier than the cardboard cylinder, but still 6 times lighter than the PVC cylinder. Most dimensions are relatively constant from start to finish, and any minor changes are negligible and only effect calculations. These minor changes were not redesign considerations, but instead varied based on availability of material at the time (for example, the cardboard tube diameter changed from the PVC diameter to be the diameter of the tube it was created from).

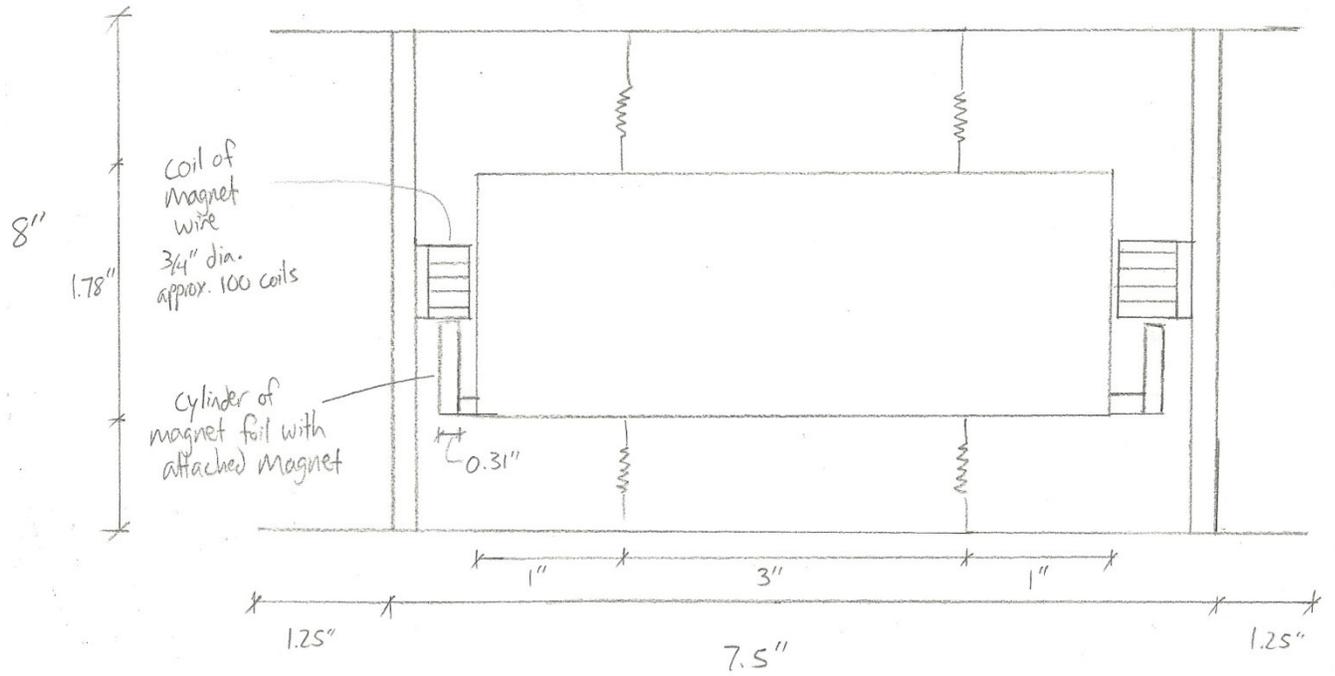


Figure 30: Sketch of Final Redesign, Front View

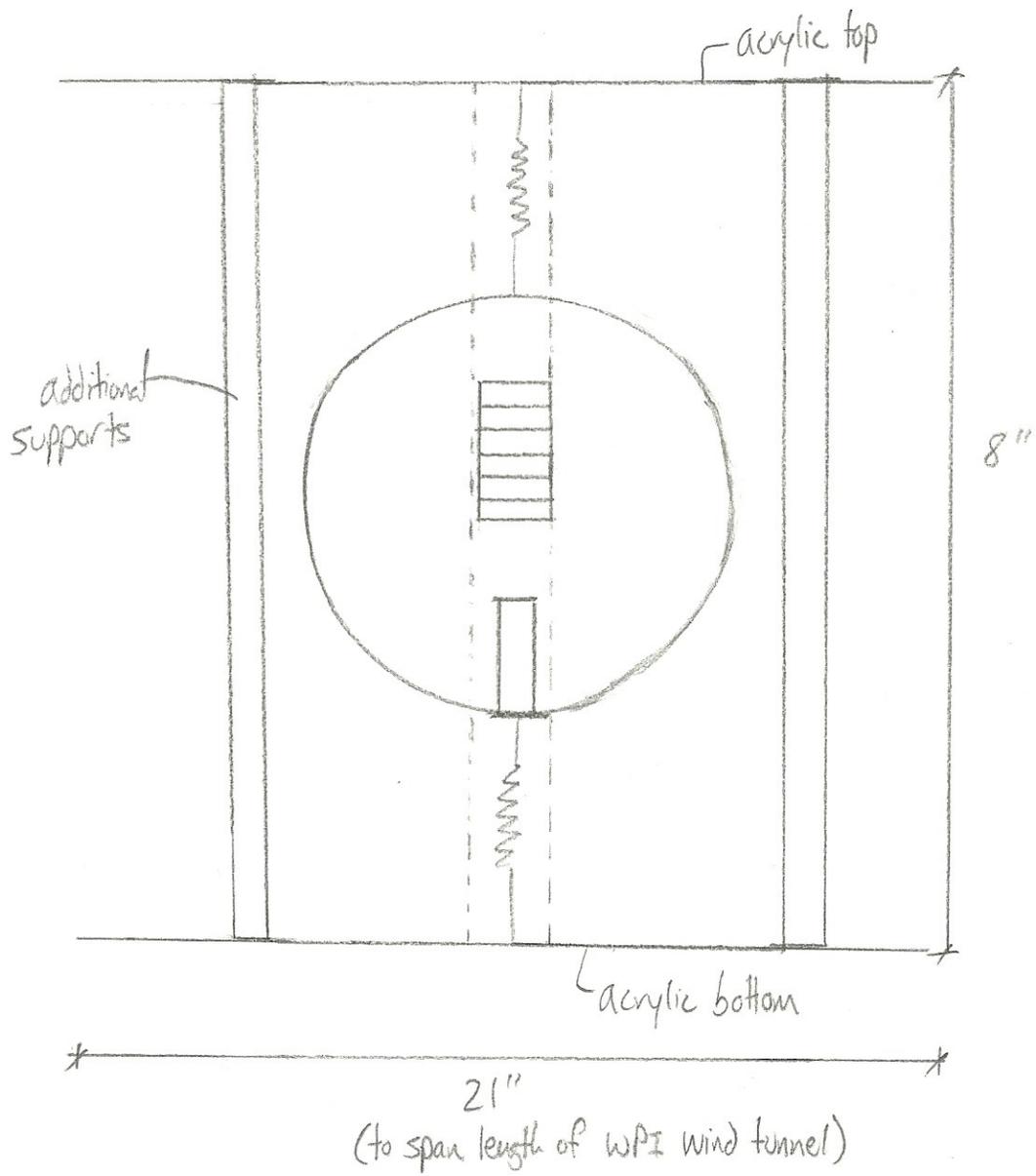


Figure 31: Sketch of Final Redesign, Side View

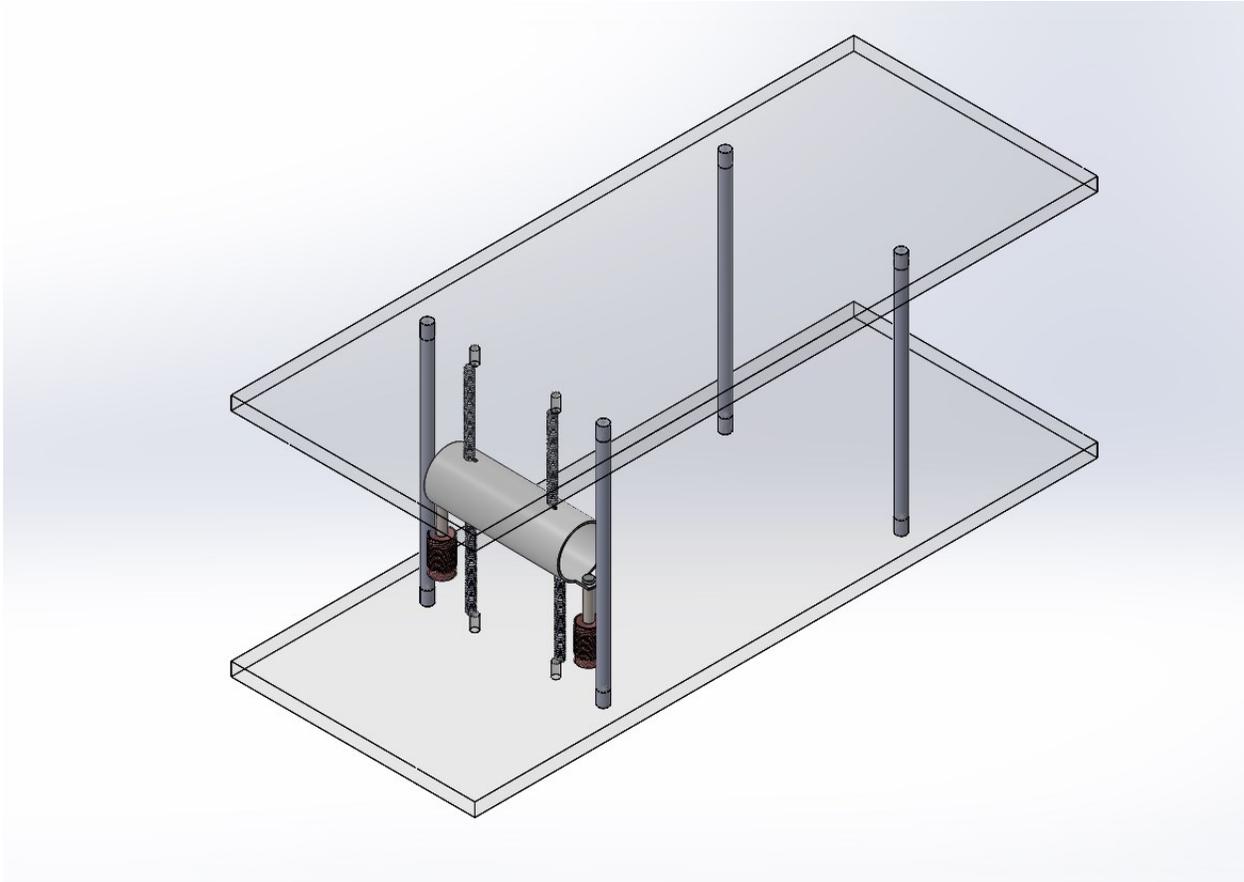


Figure 32: CAD Model of Final Redesign

5.5. Calculations for the New System

The biggest differences between the improved and the new system are its mass, the magnetic force, and the way that the coil and magnet are attached to the rest of the system. Moving the magnet to the cylinder instead of the coil has no effect on the calculated data. In both cases, the magnet and coil are moving relative to one another. It does not matter which one is moving relative to the rest of the system. However, after experimenting, it is now known that having a light magnet connected to the cylinder is better than having the coils with leads. The magnet has less inertia and leads to the coils can remain stationary.

Because of these simple changes, the same equations can be used as before. Some values will need to be changed. The new values are:

$$m_{sys} = \text{mass of the moving system (cylinder, magnets, foil)} = 0.074\text{kg}$$

$$B = \text{magnetic force} = 0.2748\text{T}$$

Using these new values in the equations used in section 3.3, new values can be solved for. At 4.47 m/s (10 mph), the drag force was:

$$F\left(4.47\frac{\text{m}}{\text{s}}\right) = 0.046\text{N}$$

At 4.47 m/s, the Reynolds number was:

$$R_e\left(4.47\frac{\text{m}}{\text{s}}\right) = 1.35 * 10^4$$

At 4.47 m/s, the Strouhal number was:

$$St\left(4.47\frac{\text{m}}{\text{s}}\right) = 0.148$$

At 4.47 m/s, the frequency was:

$$f\left(4.47\frac{\text{m}}{\text{s}}\right) = 14.7\frac{\text{cycles}}{\text{s}}$$

The k value needed for a natural frequency at 4.47 m/s is 16.3 N/m. The springs used previously had a k value of 17.2 N/m. These are close to the desired value, but some testing will need to be done to find the true lock in flow velocity.

At 4.47 m/s the lift force was:

$$L\left(4.47\frac{m}{s}\right) = 0.07N$$

At 4.47 m/s the amplitude was:

$$A\left(4.47\frac{m}{s}\right) = 0.011cm$$

A single period of the cylinder's height position over time at a 4.47 m/s wind speed is modeled by Figure 33:

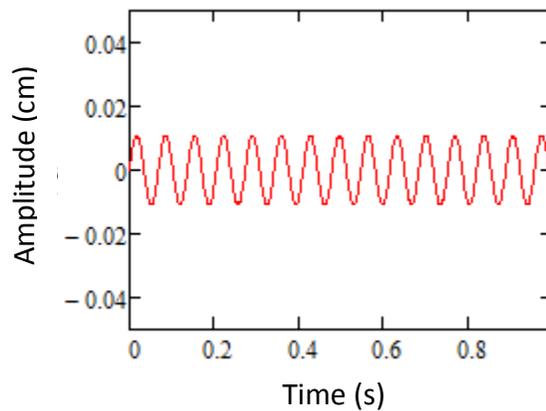


Figure 33: Amplitude (cm) over Time (s)

This motion can be used to describe the AC nature of the voltage generated. As the magnetized material is moved into the coils, a negative voltage is generated. When the magnetic field is removed from the coil, a positive voltage is generated. As the cylinder repeats its sinusoidal motion, the voltage will be created with the same sinusoidal frequency. This alternating voltage from positive to negative at a frequency of 14.7 times per second will result in an alternating current (AC).

With the new frequency and magnetic field, the calculated max voltage at 4.47 m/s will be:

$$V_{emf} = \pm 0.459V$$

This is the maximum value of the AC current generated with a 14.7 cycle/s frequency.

5.6. The Effect of Cylinder Length

The original device was built based on the dimensions of WPIs closed-circuit wind tunnel, which is an 8" by 8" rectangular area perpendicular to the direction of flow. This is a rather small area to be restricted to, so while the redesigned device is still based on this size, it is strongly recommended that future groups try to find a larger wind tunnel or test area, and apply any increase in available length to the cylinder length. The reason for this is it will increase the total lift force on the cylinder and device, thus helping to reduce the effects from friction and the weight of the system.

The total lift force is defined by the following equation:

$$L = \frac{1}{2} * C_l * \rho * v^2 * A$$

$$\rho = \text{density of air}$$

$$C_l = \text{lift coefficient}$$

$$v = \text{flow velocity}$$

$$A = \text{cross sectional area}$$

C_l is a constant for a given shape and A is the cross-sectional area of the cylinder facing the flow, i.e. the diameter times the length. Based on this equation, it can be seen that the total lift force is directly proportional to the length of the cylinder. Also, the drag force is defined by a

similar equation using C_d instead of C_l and thus will increase proportionately with the length as well.

Now, consider that the weight of the cylinder will increase with an increased length. In fact, it will also increase in direct proportion with an increase in length, as the weight can be calculated as:

$$W = \rho * V * g$$

$$\rho = \text{density of material}$$

$$V = \text{volume of material}$$

$$g = \text{gravitational constant}$$

The volume of a hollow cylinder such as the one in this design is:

$$V = \frac{OD^2 - ID^2}{4} * \pi * L$$

$$OD = \text{outer diameter}$$

$$ID = \text{inner diameter}$$

$$L = \text{length of cylinder}$$

This is directly proportional to length, thus making the weight of the cylinder directly proportional to length as well. However, this does not describe the weight of the entire system, which is defined as the weight of the cylinder plus the weight of the power generation attachments, which are not in any way affected by cylinder length. When dealing solely with the cylinder, the original design achieved the desired motion. It was when the attachments were

added that the weight became too much for the lift to overcome. Therefore, by increasing the length of the cylinder, the effect of the added weight of the attachments should be minimized, and hopefully the desired motion can be achieved with the attachments on the device and the electric power can be measured directly.

6. Conclusions

The goal of this project was to create a proof-of-concept prototype in order to research and develop a device for harvesting wind energy. This goal was met. The winder harvester device did produce VIV oscillation, working best at a lock-in wind condition. In addition, it performed within a small range of wind speeds (3.3 m/s to 4.6 m/s). From this prototype, lessons were learned about what conditions work best for a device of this nature. Overall, the project was useful as a tool for learning and expanding a new concept – utilizing VIV wind harvesting to produce electricity.

The VIV concept was developed at WPI through previous MQPs utilizing water flow as the driving force behind the motion. This project was the first to utilize air as the fluid medium at WPI. Transitioning to air proved difficult. Air is less dense than water, leading to challenges with small lift forces unable to induce motion if weight of the system is too large. Water, the previously used medium, is 781 times denser than air. This results in more force for VIV and better motion. However, to expand the potential to harvest energy through VIVs, using air as a medium, in addition to water, would be beneficial. This idea of expansion is the motivation behind this project.

One area where the design struggled was in mass of the system. A system in air must be lightweight, meaning have minimal mass. PVC was used in previous projects where the fluid medium was water. Therefore, this material was chosen to work with because it had been used before. However, it soon became obvious that mass was an issue in air. Since motion was not achieved with the PVC cylinder, other, easily accessible, materials were sought. The cheapest and most readily available material to use was cardboard. The new, lightweight cylinder

performed much better, actually achieving VIV and lock-in frequency – something the PVC cylinder never did.

Mass became an issue again when adding the coils to the system. The additional mass was too much for the system. The small lift force could not overcome the weight of the system to initiate motion. Motion could only be achieved with small coils with no leads. Having no leads meant there was no way to measure the voltage that was being produced. Also, larger coils would produce more voltage. Limiting the size and number of turns in the coil limits the potential voltage output. Proving the potential to produce electricity was the purpose of this project, and this could no longer be achieved with measurable results. Instead, the proof-of-concept was in the fact that VIV motion could be achieved in air and that a magnet and coil assembly, once fine-tuned, would produce voltage. The future design addresses the weight issue in both areas – it looks at lighter, yet still durable, materials for the cylinder and has a redesign of the magnet and coil assembly that ensures minimal mass is added to the moving part of the system.

Another important design constraint involved friction. Originally, support rods were added to the system to negate effects from drag force. However, the drag force created friction between the cylinder and the rods. This friction dampened the system and no motion was achieved. After removing the support rods and changing to a lighter-weight cylinder, it was found that there was no issue from the drag force. The slight horizontal movement was negligible. In addition, there was no twisting about a vertical axis, as was incorrectly predicated. The conclusion drawn was that friction was a bigger problem than undesired motion (which was not occurring at the low wind speeds being used). Any outside forces, such as the friction between the cylinder and support rods, will dampen the system and negate possible motion.

This device was design to be tested in WPI's closed-circuit wind tunnel. Using the wind tunnel was great for testing. It provided a controlled wind speed and environment. However, calculations show a longer cylinder would be better, and this project did not have the option to add any length. This severely limited the scale of the device. It had to fit within the 8 inch span of the wind tunnel test area interior. In the end, the result was a scaled down prototype, not a fully operational or marketable design. Though this was never the main goal of the project, it was something to aim for, if possible. Instead, a scaled-down VIV wind harvester was produced with theoretical, not actual, power.

In the end, this project did provide valuable lessons about VIV energy harvesting through wind. The initial design did not perform as desired, but iterations that were improved through testing and observations lead to an operable prototype. The importance of minimizing outside forces, such as friction, was discovered. In addition, the necessity of minimizing the system's weight while maximizing its length was learned. From these findings, the team was able to design a future model with necessary improvements to achieve even better results. The proof-of-concept prototype proved a potential, though difficult, possibility for VIV wind harvesting.

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