Spring Final Report

Team 9
Power Converting Sub-System of Kite Power Generator

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ABSTRACT

With the growing population and consumption of energy, there is an ever-growing need for clean, renewable energy sources. The purpose of this project is to design, build, and deploy a kite power generator that will power a 40W light bulb. This design will then be scaled to generate 100kW's of power. The scaled kite is a conceptual design. To generate power, the kite is tethered to a permanent magnet within a housing that contains an electric coil. As the kite is subjected to a wind load, the kite pulls the magnet through the coil. When the kite changes its angle of attack, the springs help force the magnet back though the coil. It should be noted, that for demonstration testing, the kite was flown in a figure-8 pattern. Electricity is generated each time the magnet slides through the electric coil via Faradays Law. In an ideal world, the kite would be flown in a straight up and down motion, in order to maximize the forces seen on the tether that would be tied on to the magnet. The expected forces seen by a 1m x 1m kite at our desired altitude of 1000ft are approximated to be 70N-200N, when oscillating between 5^o-15^o. The peak voltage output observed by the team was found to be 0.5V with a frequency of 2Hz, through a displacement of approximately 5in. The expected loss in induced voltage is thought to mainly come from the magnetic springs altering the magnetic field.

ACKNOWLEDGMENTS

Thank you to Jeff Phipps for making himself available through email to answer our questions in regards to this paper and for coming up with the original idea for this project. We would also like to thank Dr. Shih and Dr. Gupta for presenting us with this project and giving the opportunity to execute the desired tasks.

1. Introduction

The idea is to achieve power generation from a water collecting kite in remote island areas. The purpose for this project is to provide affordable power for areas that do not have a major reliable source for power. To harness the energy of the wind without constructing a permanent wind turbine a kite power generator will be used. Conventional wind turbines need a permanent setup and require a high amount of maintenance. Other forms of alternative energy such as solar power can be very costly to initially install and can only generate power when there is direct sunlight.

Kite power allows for more maneuverability and less maintenance due to less mechanical parts. Placing in an area like the Greek Islands, where there are constant prevailing winds also allow for kite to be in the air and generate power at almost all times.

The kite will be of relatively simple design and construction, as to make the product inexpensive and economically appealing. The simplicity of the design will warrant very little service and costs resulting in maximum in-service time. This design will also allow the kite to be retracted at times when necessary, thus making it less intrusive to the surrounding environment.

The kite will generate power by oscillating a magnet inside of an electrical coil. To get the kite to oscillate and still sustain flight, combination gearing and/or cam design will let one end of the kite go while pulling on the other end causing a teeter-totter like motion. This will vary the angle of attack of the kite thus varying the lift force and tension on the string. In combination with the spring connected to the magnet pulling it back down, and the changes in the lift force, the magnet will oscillate. There is also an issue of sustaining equilibrium in the roll axis of the kite.

To achieve this a tail design could be used or another gearing/cam. This, however is outside of the required project scope.

The power generator consists of a housing that has a top and bottom and a hollow interior. The coil will be situated within the housing, where the magnet will consistently pass through. A spring will be fixed on one end to the housing with the other end of the spring connected to the magnet (Figure 1). As the kite is subjected to a wind load, the magnet, connected to the tether of the kite, will be pulled through the coil housing. As the wind load decreases, the spring acts to restore its natural state by forcing the magnet back through the coil housing. The housing is attached to a swivel port, allowing the housing to spin on its axis depending on the direction of the wind and the flight path of the kite.

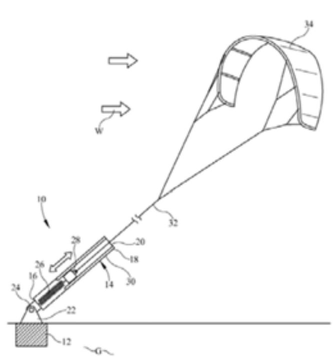

Figure 1. Jeff Phipps Pogo Solenoid Patent [1]

The cycle that the kite will undergo to achieve power generation can be seen in Figure 2. Here the kite will fly in unsteady wind conditions and in a figure-8 like pattern. The figure-8 pattern will be the main source of the oscillation for the magnet, while the springs are meant to assist in the oscillation and keep the magnet bounded inside of the coil. When the magnet is moving through the coil, voltage will be generated via faradays law. B refers to the magnetic strength of the magnet, A is the cross sectional area, N is the number of wraps in the coil, and t is the time it takes for the magnet to travel through the coil. It can be inferred that the voltage, thus the power, that will be generated is directly related to the rate at which the magnet travels through the coil. As the spring is stretched, hooks law will force the magnet back through the coil. Here k is the spring constant, and Δx is the displacement of the spring.

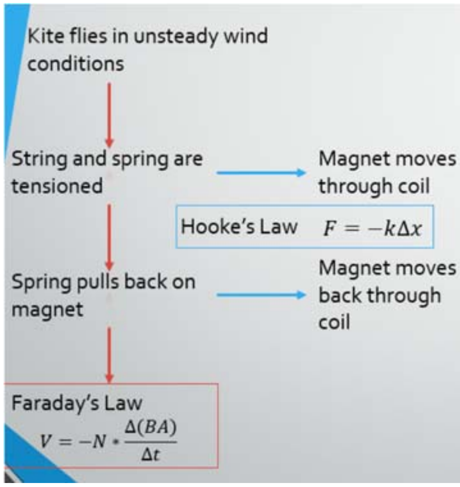

Figure 2. Flow chart of power generation for magnet through coil attached to a spring

2.0 Project Definition

In this section background research, will be presented about various companies and what they have done that is similar to the design goals that are being pursued. It will be important in future endeavors to have reliable reference material to fall back on to check what will work. In addition to the background research, a need statement will be defined, the constraints will be clearly listed, and the methodology of how the project will be approached will be laid out.

2.1 Need Statement

The need statement for this project is as follows:

Design and build the power generating system of a kite power generator, and scale for a 100kW concept kite.

2.2 Background Research

2.2.1 Kiteship

In regards to harnessing power from the wind via the motion of a kite, it is important to take note of other companies who have successfully built such mechanisms. One in particular is Kiteship[2], a company that utilizes sail-kites on freight commercial ships as an aid to pull the ships in their journey across the ocean. The company also holds the world record for the largest kite to pull a land vehicle and largest vessel pulled by a kite. To put things into perspective, a13,000-square-foot kite allows for fuel costs to be decreased by 10-20% on a normal-sized commercial vessel. This directly translates to $400,000 in savings per year. Thus, kite-sails are a more cost-efficient and energy-saving green alternative to transporting traded goods across the world. It can be taken note that the bigger the kite, the more wind energy will be generated and the higher the kite, the stronger the winds. Utilizing this information in further projects will be deemed useful in generating more wind power through the motion of a kite.

2.2.2 Skysails

Skysails[3] is another company that serves as a more efficient and green alternative to utilizing wind power than the conventional sails propulsion systems. The flying towing kites generate 25 times more power than the sails previously used. It works through the control pod which is used to steer the kite in front of the vessel to help pull it in the right direction (Figure 3). The kite and control pod are connected via a towing cable covered by a coat of synthetic fiber that serves as communication for steering between the pod and kite. It is interesting to take note that there is no need for a launching aid such as a balloon filled with helium since the kites are intended to be used in the ocean where there are strong winds. The winds are monitored in direction and velocity to achieve optimal propulsion from the kites.

Figure 3. Skysails used for towing boats so no electricity is used

2.2.3 Strandbeests

Strandbeests[4,5] are giant artistic structures made from PVC piping, wood, and fabric that are self-propelled. Theo Jansen created the first Strandbeest in 1990 and he continues to create them today. Over the years they have evolved into more complex and lifelike creatures. They are self-propelled, using wind power to move around, and have specialized adaptations to help them “survive” on the beach. The Strandbeests have a “spine” that runs down the middle of the structure and acts as a crankshaft for the legs. The legs are designed so that there are always multiple legs supporting the structure at any one time. The more complex Strandbeests (Figure 4) move using wind power and stored up wind energy when necessary. They use sails to initially capture the energy of the wind and use it for movement. Wings are used to power pumps that can pump air into plastic bottles. When these bottles are filled, the air inside can be released and used to move the Strandbeests when there is no wind. The complex Strandbeests also include reflexes to react to certain scenarios. For example, if a Strandbeest detects water, it will turn and go towards high ground or, if it detects high winds indicating an approaching storm, it will stop and anchor itself. Jansen refers to the Strandbeests as animals due to their ability to move on their own and he tours the world showcasing his creations.

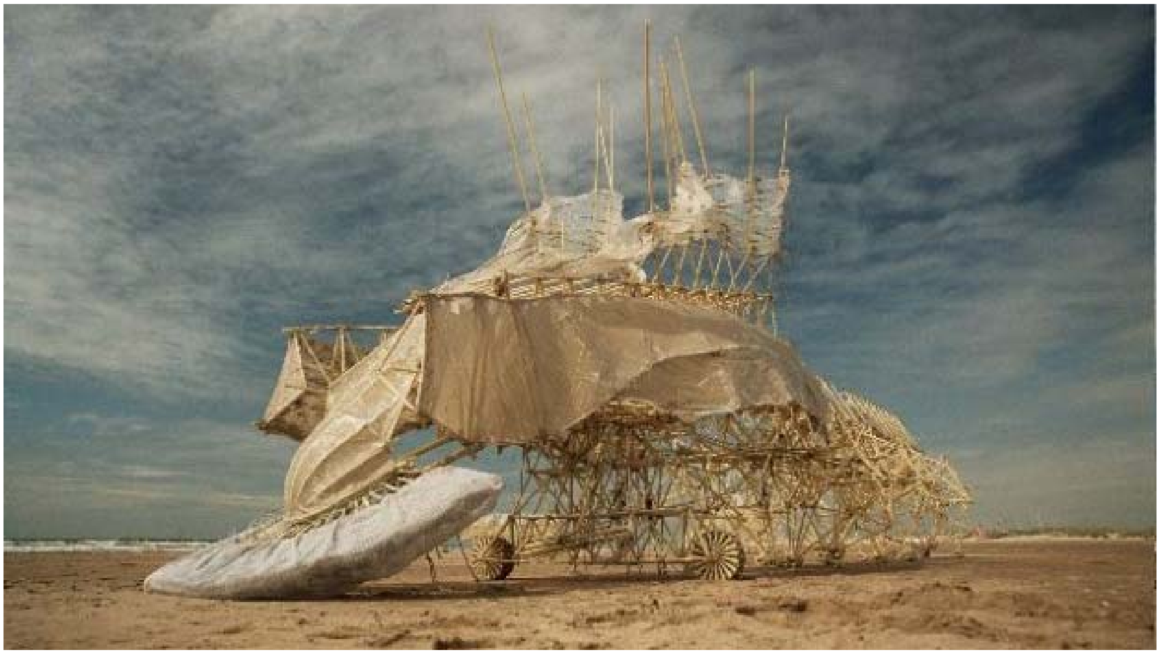

Figure 4. Strandbeest creation that will walk across a beach using only wind power

2.2.4 Kitano

Kitano[6] is a concept yacht that uses a kite as the primary means of propulsion with dual water jets used as secondary propulsion during calm winds. Using a kite as propulsion instead of a sail has advantages that include being able to capture more constant wind speeds at higher altitudes and generating more forward force using less surface area. This means that even a light breeze will provide enough force to propel the yacht to planning speed. The position of the kite can be changed which can be used to counter the force of heeling and the yacht can sail without tilting. This makes for a smoother ride and lessens the chance of the passengers experiencing seasickness. Electric winches are used to control the position of the kite. The autopilot controls the winches to compensate for unexpected changes in wind speed and direction. The kite can also be steered manually by changing the tension in the lines connected to the kite. The position of the hauling point of the kite on the yacht can be changed in the longitudinal and transverse directions depending on the direction of the course. The kite will have helium filled bladders to help support the kite during launch and to keep the profile. As of now, it is just a concept however that will most likely change in the future as sustainable energy becomes more prominent.

2.2.5 Makani

Makani has been recently discovered as it emerged as a brand new product to the kite power generating world. Makani kite power is able to generate 600kW by using energy kites mimicking a wind turbine. This is far more efficient than a wind turbine because it eliminates the tower of the wind turbine and only includes the circular path the blades follow as the wind turbine turns. The edge of the blades is actually where the three-fourths of the energy is generated and the rest of the wind turbine is seen as inefficient to include. Thus, Makani generates this power using less material, less energy input, and for less money by simply using a kite and rotating it in a controlled fashion. In addition, using a kite allows for larger circular paths of a greater radius than those of a wind turbine since it takes less material to allow that. Wind turbines have increased in size to increase efficiency over the years but Makani tackles that problem by offering a more lightweight and cost efficient solution.

3. Methodology

3.1 Goals

The main goals for this project are as follows:

1. Demonstrate that a magnet inside of an electric coil that is oscillated using a kite will generate usable electricity.
2. Come up with an idea that will allow for maximum energy output based on varying wind speeds.
3. Show commercial potential for this product so that it can be taken to the market.

To meet the goals of the project, working together and scheduling out tasks ahead of time plays an important part and ensures that things get done. Every team member is assigned with a position and tasks to complete based on their strengths in the field in order to complete the project as efficiently as possible.

3.2 Constraints

When designing the power generating subsystem of a kite power generator it is important to know what limitations there are for a specific design. For the project that will be executed the power generation will be optimized for altitudes between 500 and 1500 feet. The kite generator will also be optimized for a specific region, the Islands of Greece. The altitude constraint along with the geographic constraint will allow for the design of a kite that a certain nominal wind speed for that region and altitude. The kite must also deliver AC power to the grid so that it is generating usable electricity. The parts that are used in the assembly of the kite power generator must be off the shelf-products to allow for efficient assembly of the system with no manufacturing of custom parts involved. It is important to operate within these constraints to ensure that the concept designs are on target and will achieve the desired function.

3.3 Scheduling

Figure 5 shows the schedule for the project presented in the form of a Gantt chart where it clearly shows the name of each task, the duration of the completion, and the beginning and end date, excluding ME deliverables since they are fixed assignments that will be competed alongside the project.

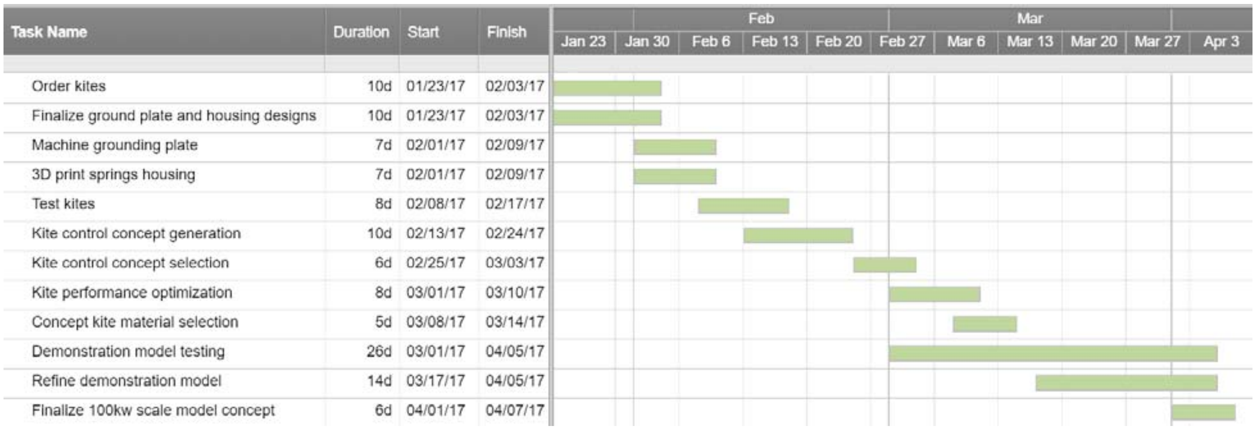

Figure 5. Schedule for the Spring Semester

In reference to the Gantt chart, the first task of the team this semester is to order kites that will be used to perfect the figure-8 pattern in order to generate maximum voltage from the generator. In the meantime, CAD drawings were detailed and finalized of the grounding plate of the generator and the housing for the springs. A week later, the drawings entered the machine shop to be manufactured and 3D printed. Then the team proceeded to generate kite control concept techniques, kite material selection, and compute calculations for maximum kite performance. Once the team has had experience solely flying the kite, the testing of the entire system can begin. Iteration continues for as long as a month until the power generation portion fulfills the needs of the project, which is to power a 40W light bulb. Throughout testing, the team was refining the demonstration model and ordering new parts if need be to fix any issues that may have arose during testing. Once the team met the needs of the project and has finished testing, the concept for the 100kW scale model was generated. In this final step, the team performs the necessary calculations to allow the system to generate 100kW of power in order to show commercial potential. The final concept will allow for maximum power generation since that is a goal of the project. The team also meets every week with the sponsor and advisor to stay on track with the tasks needed to complete the project. The team actively meets every week to work on tasks together, distribute work evenly, and discuss project details to ensure the team stays on track with the Gantt chart.

3.4 Resource Allocation

Every person on the team holds a specific responsibility and is assigned an individual assignment each time a task needs to be completed in order to complete said task on time. The tasks are divided evenly among the team members as shown in Table 1, including ME deliverables.

Table 1. Distribution of workload

Task	Team Member(s) Responsible
Background Research: Kite Power Generation	Denitsa, Zachary
Testing Kite	Andrew, Matthew, Denitsa, Zachary
10 kW parameter calculations	Denitsa
Restated Project Scope	Andrew, Matthew, Denitsa, Zachary
CAD Concept Drawings	Matthew, Zachary
Design for Manufacturing	Zachary
Design Optimization/ Refinement	Andrew, Denitsa, Zachary, Matthew
Economics, Reliability	Denitsa
Engineering Day Poster	Andrew, Denitsa, Zachary, Matthew
Power generation analysis	Denitsa, Zachary
Operations Manual	Andrew
Program motor	Zachary
Order Parts	Denitsa
Final Report	Andrew, Denitsa, Zachary, Matthew
Machine shop	Matthew
Project/ product specifications	Matthew

The table excludes tasks such as team meetings, communications with the sponsor and advisor, and any type of correspondence. Andrew Colangelo handles the communication as Team Leader. He holds the responsibility of delegating tasks based on the team’s strengths while making sure every member gets their assigned tasks completed in time. He also takes the lead in future planning, organizing, and setting up the weekly meetings with the sponsor as well as the team meetings.

Zachary Ezzo is the team’s Lead ME, who manages the mechanical design aspect of the project. He holds the responsibility of being well informed of the design specifications and leading the team through the design process. He presents design options to the team that fall under the project’s design considerations and are within the constraints.

Denitsa Kurteva is the team’s Financial Advisor, who holds the responsibility of managing the project budget and performing costs analyses on the designs chosen for cost optimization. She holds a record of all credits and debits of the project’s account as well as budget adjustments.

Matthew Hedine is the team’s Lead CAD Design who is in charge of all computer modeling. He holds the responsibility and computer modeling the concepts generated and delegating design work, as well as generating design drawings.

4. Concept Generation

In the creation of the design concepts, the major considerations taken included maximum power generation, kite control, maneuverability, ease of deployment and maintenance. A pogo solenoid base was used on each concept design to mock the already patented idea from our teams sponsor, Jeff Phipps.

4.1 Concept Idea 1

To gain control of the kite and generate the maximum possible power from the wind speeds, it is important to consider the angle of attack and its direct correlation with the frequency of the kite's oscillation. In the first concept design generation, four strings are used and attached to the kite on one end and to the magnet on the other end. To optimize the oscillation of the kite to take account varying wind speeds, mechanical winches are added onto each of the four strings that allow for the user to gain control of the kite's angle of attack. One of the benefits of this design is that the winches are close to the ground which allows for easy user access when in operation.

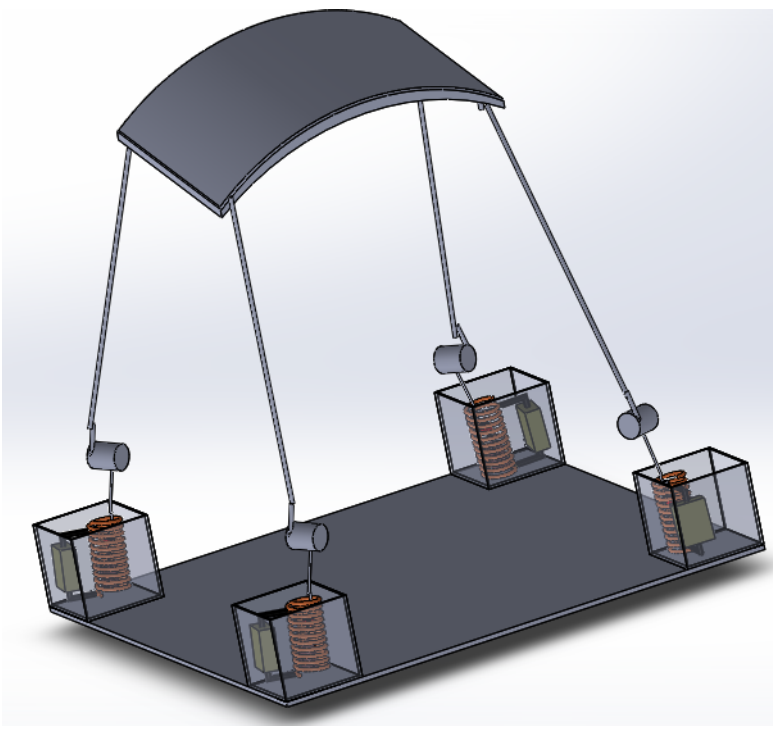

Figure 6. Four-string kite concept idea

In Figure 6 inside the power generation box, the string is attached to the magnet which moves back and forth inside the coil with the kite's oscillation. Thus, the higher the oscillations, the quicker the magnet moves inside the coil and generates power via electromagnetic induction. The AC current that is generated will then go through a rheostat which will convert it into DC. This current will then go through an inverter which will convert the electricity back into AC and allow the electricity to be distributed to the grid. The magnet is attached to a spring that would allow the magnet to oscillate back and forth. As the kite oscillates and pulls the magnet away from the ground, the spring brings it back to keep it inside the area of the coil and can generate a voltage. The stiffness of the spring will depend on the length of the coil since the magnet must stay inside the coil for power to be generated.

This design is beneficial in that it allows the user to easily gain control of the kite from the winches that are close to the ground. This would allow full control of the oscillation of the kite which in turn would in theory generate the maximum power possible. However, while four strings allow for maximum control of the kite, it is important to consider the energy loss from using multiple strings. The vibrations in the system from the kite’s oscillation would be distributed over four strings, thus not providing enough tension in each string to generate maximum power.

4.2 Concept Idea 2

Figure 7 shows the two-string kite design is a condensed version of the four-string kite design. This design relies on two kite tethers attached to either side of the kite and connected to the ground. The advantage of having two less kite tethers is that more tension is created in the remaining two tethers. The lift force due to the wind load is now dispersed to only two tethers rather than four. This allows for a higher spring tension which in effect will cause more oscillation. The weight of the kite will also be much less, allowing the kite to easily remain in the air when wind speeds begin to diminish. Having two tethers on either side of the kite still allows for moderate control of the kite. This design will not allow for full control of the kite as does the four-string kite, however, the kite’s angle of attack would still be able to be altered with minimal energy input. Also, with the two-string kite design, the mechanical components will be on the ground making it easy for repair and maintenance when necessary. Containing the mechanical components either in the housing or near the ground helps to avoid the issues caused from the natural elements.

Figure 7. Two String kite concept idea

4.3 Concept Idea 3

Figure 8 the in-air winch design differs significantly from the previous two designs. This design will incorporate only one kite tether attached to the ground to generate power. Utilizing only one tether maximizes the tension resulting in greater oscillation. This design uses a single housing to generate power. This is beneficial in that there is less surface area needed to deploy the kite as well as less hardware that can break down. However, if the housing does break down, the kite will then cease to generate power until the housing is repaired.

The in air winch design, as it states, has the winch in the air near the kite, rather than near the ground or housing. Having the winch connected in the air near the kite creates a focus on the single tether coming down to the housing. This prevents any tangling of tethers as the wind loads fluctuate as well as a smaller of a chance of interference to the surrounding environment.

Figure 8. In-Air winch concept idea

4.4 Selection Matrix

Through the background research and deliberation, the concept ideas were presented as potential ideas to use going forward. In an effort to narrow the focus of the project a single design was chosen using the Pugh Matrix seen in Table 2.

Table 2. Pugh Matrix used to compare concept ideas

Criterion	Baseline	Weight	4-String Kite	2-String Kite	In-Air Winch
Power Generation	0	6	0	0	1
Kite Control	0	5	1	0	-1
Ease of Deployment	0	3	-1	1	0
Mobility	0	2	-1	0	1
Maintenance	0	1	-1	1	-1
Cost	0	4	-1	0	1
Sum	0	-	-5	4	6

The decision was made to move forward with concept idea 3 which is the in-air winch design. This decision was partially based on the Pugh Matrix and partially based on discussion with the sponsor and the advisor to the project.

4.5 Kite Stabilization Concepts

Concept idea 3, the in air winch, will be the concept that will be used moving forward. However, a challenge with this concept is the stabilization of the kite. It is thought that this concept will have little yaw control, which is rotation around the vertical axis. Therefore, stabilization will most likely have to be added to the kite in order to increase stabilization and control.

4.5.1 Kite Tails

The first concept involves kite tails for stabilization. Figure 9 below shows the In-air winch concept model with kite tails. The kite tails would be placed on the back of the kite in order to create a drag force. This drag force will stop any unwanted yaw rotation by providing an evenly distributed force on the back of the kite. The tails would be long and thin so as to minimize their weight while maximizing the amount of drag force they can generate. The drag force should be large enough to prevent the yaw rotation yet not enough to simply pull the kite backwards and make it fall out of control. This concept is the simplest of the 3 and provides the most effective stabilization but it does not provide additional control over the kite.

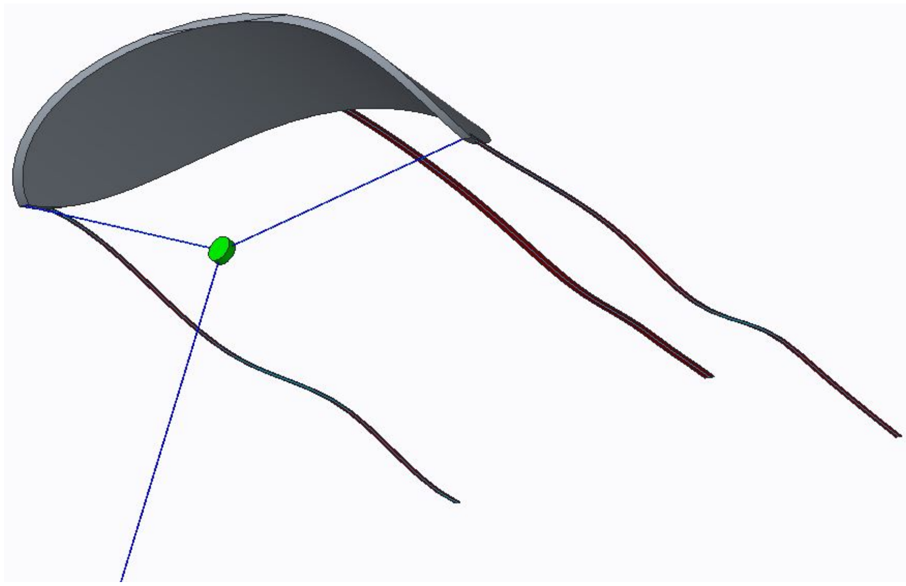

Figure 9: Kite Tails Stabilization Concept

4.5.2 Kite Rudder

The second concept has a single large rudder that hangs from the kite itself. This rudder would act similar to the tail of an airplane. Figure 10 shows a detailed depiction of the tail of an airplane.

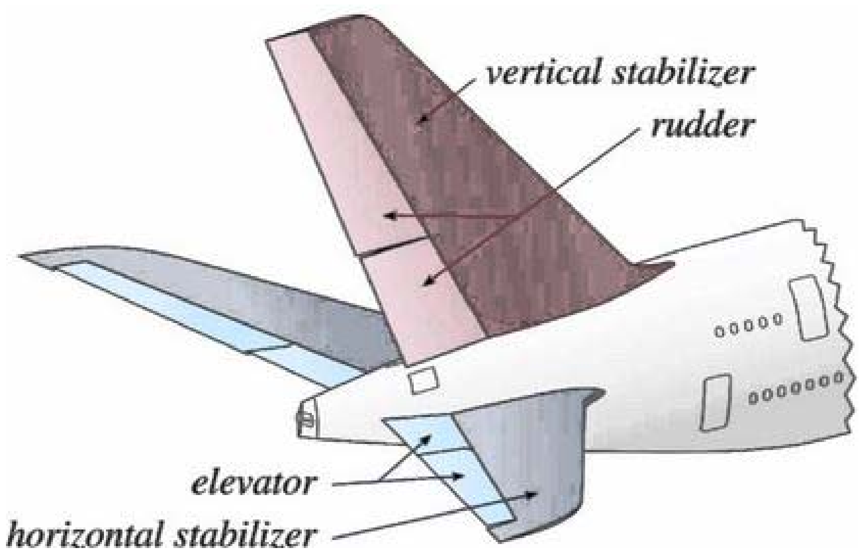

Figure 10. Detailed View of Airplane Stabilizer

As seen in the figure, the tail has a vertical stabilizer that has rudders which provide yaw stability and control. The tail also has a horizontal stabilizer that also has a rudder. This provides longitudinal stability and control. This method of stabilization allows for control of the yaw and pitch of the kite. However, the stabilizer would need to be constantly analyzing the position of the kite and the wind speed and direction in order for it to correctly move the rudders so the kite stays on the correct path. This would require additional components to the system which will make it more complicated and expensive. There is also little research to show the effectiveness of this method.

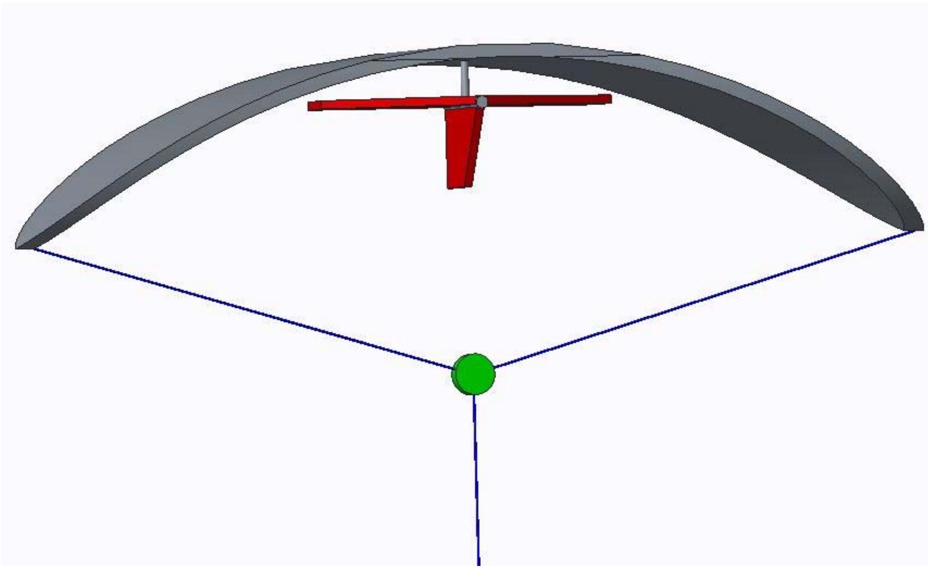

Figure 11. Kite Rudder Stabilization Concept

4.5.3 Double Winch Stabilizer

The third concept adds a second winch to the In-Air Winch conceptual design. The idea behind it is that the first winch will be attached to the strings connected to the sides of the kite. This will allow the winch to change the roll of the kite and make it turn left or right. The second winch will be attached to the string connected to the front and back of the kite. This will allow the winch to control the pitch of the kite and make it go up or down. It can also change the amount of drag the kite is generating and increase the stability if needed. This method would allow for the most kite control of the three concepts. As for stability, it would require additional components to measure the position of the kite and the wind speed and direction, much like the second concept. This adds additional complications in terms of maintenance and repairs the will be required as well as the overall complexity of the system. It would also increase the cost.

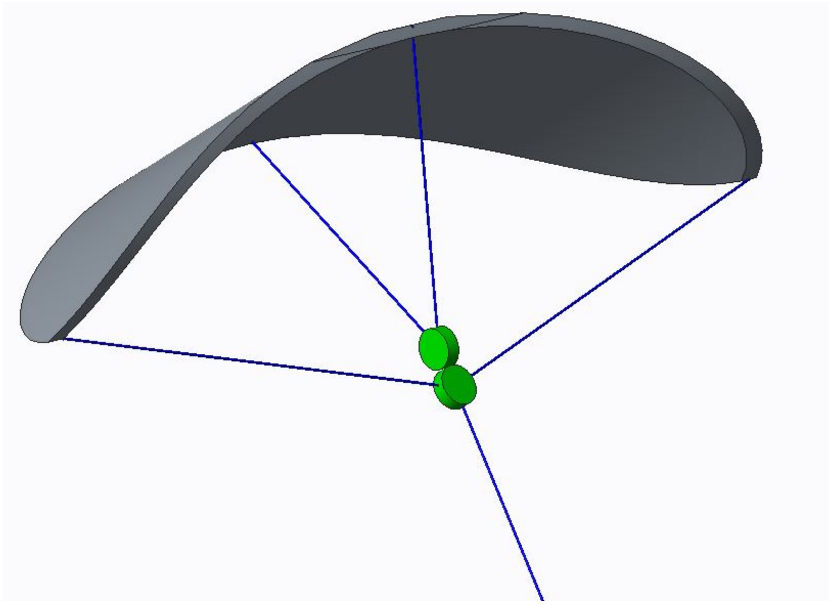

Figure 12. Double Winch Stabilization Concept

4.5.4 Evaluation of Stabilization Concepts

The scope of the project was narrowed down in order to focus on power generation but maximizing power involves the control and stabilization of the kite. The kite will fly in a figure 8 pattern so as to create oscillation of the magnet. The stabilization ideas are strictly concepts to try and figure out viable ways to control and stabilize the kite in the scaled up concept model. The stabilization conceptual designs were all based on the In-Air winch design because that was chosen to be the best design.

4.6 Oscillation Concepts

4.6.1 Motorized Stiffness Variation

Figure 13 shows the motorized spring stiffness variation device. This design would utilize two mechanical shafts on either side of the spring. The spring, in blue, would be either compressed or elongated by the rotation of the mechanical shafts depending on the necessary spring stiffness needed. This allows for a greater variation in spring stiffness as well as a precise measurement. However, this also requires power input and defeats the purpose of a power generation device.

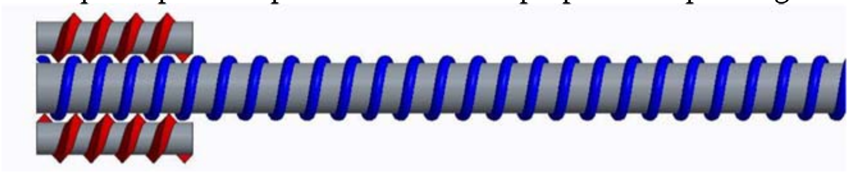

Figure 13. Motorized Spring Stiffness Variation

4.6.2 Pulley System

Figure 14 shows the pulley system design that was considered. The pulley system is connected to both the solenoid coil and the magnet. Therefore as the magnet is being pulled in one direction, the solenoid is being pulled in the opposite direction. This allows for a greater relative velocity between the two creating a higher magnetic flux. However with this design comes a lot more complexity.

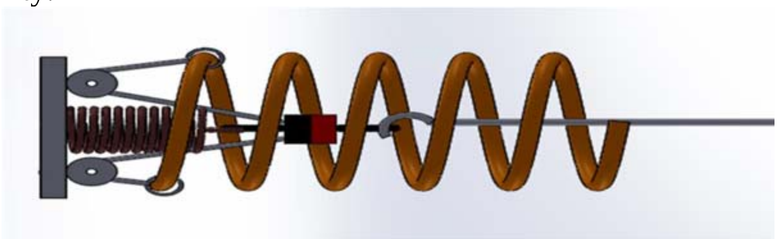

Figure 14. Pulley System

4.6.3 Concentric Springs

This design incorporates three concentric compression springs. The springs are attached to the top of the housing and vary in length and spring stiffness coefficients. This allows for no power input as well as a high safety factor. This also allows for a step response in the spring stiffness coefficients. This was a fairly simple design and provided the team with a variation in the spring coefficients therefore it was chosen for the final design.

4.7 Kite Design Concepts

4.7.1 Traction Kite

The traction kite that was tested was a two string airfoil design. This kite allowed for more lift, higher control, and slower movements. It provided a good amount of force throughout the strings due to its large size. Figure 15 shows the traction kite that was used.

Figure 15. Traction Kite Tested

4.7.2 Stunt Kite

The stunt kite that was tested was a two string prism design. This kite provided less lift, faster maneuverability, and was far less stable when compared to the traction kite. The quick jerking and less force in the strings proved it more difficult to fly. Figure 16 shows the stunt kite that was used.

Figure 16. Stunt Kite Tested

5. Final Design

5.1 Demonstration Model

Figure 17 shows the dimensioned drawing of the model that is being used. Figure 18 shows how the parts of the model are assembled and shows each component in more detail.

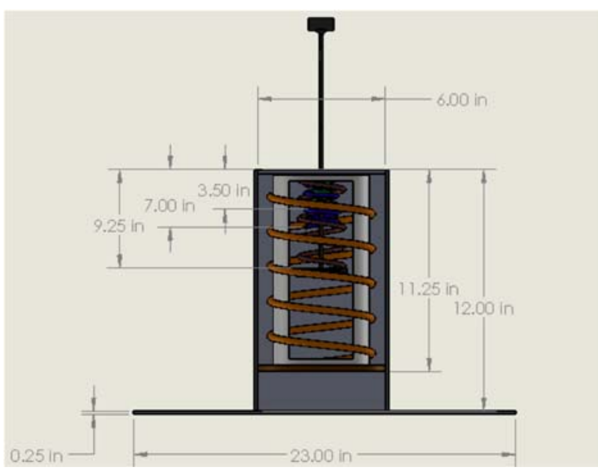

Figure 17. Dimensioned drawing of demo model

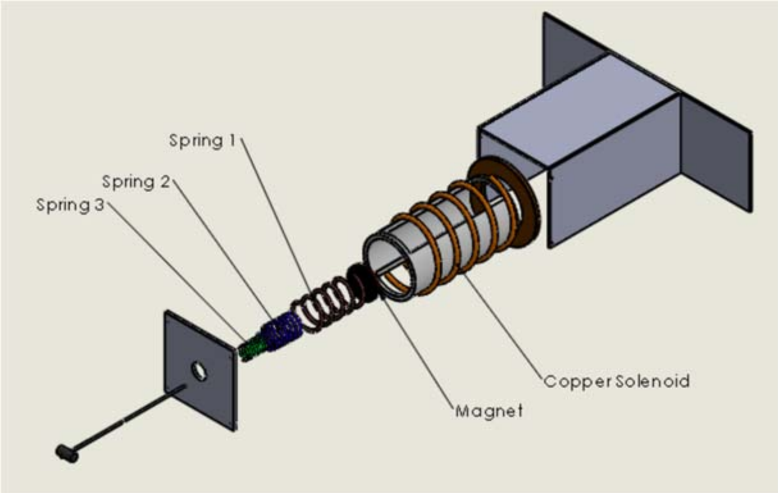

Figure 18. Exploded view of demo model

As can be seen in Figure 18, the final design that was chosen involved three concentric springs of 9.25, 7, and 3.5 inches in length. This allowed for the spring stiffness coefficients to vary depending on the force exerted. As well, the neodymium magnet was used and was connected to the first spring via a strong adhesive. The springs and magnet were all located within a 3D printed housing that was wrapped with copper wire. This prevented any loss in friction due to no contact between the magnet and the outer solenoid. All of these parts were contained in an aluminum enclosure open on one end. The edges were all welded together to provide a strong connection between the plates. The top was made removable via 1/4” screws allowing for easy access and maintenance. Figure 19 shows the constructed demonstration model with the motor attached allowing for testing of the power generation without the need of a kite or hand crank.

Figure 19. Demonstration Model with Motor

5.2 Safety and Reliability

A very important aspect of the design of this system is the reliability as a whole as well as its individual components. It is critical that the system function successfully without failing in order to minimize downtime and maximize usage. In terms of reliability, nothing went wrong during the multiple test runs that were performed with the demonstration model. However, assuming that the conditions are optimal for testing, the demonstration model should be able to perform many test runs before any issues arise. Some of these issues could include, but are not limited to, the adhesive holding the springs to the roof of the base housing possibly coming undone or the kite string could possibly fray or even break due to friction against the aluminum base housing. Also, the kite itself could tear due to the experience of repeated tension forces. Other issues with the system could include the copper wire coming unwrapped off of the solenoid housing and the base housing disconnecting from its grounds and being lifted up due to the forces of the kite in a strong gust of wind. It is impossible to tell how long it will take for these issues to arise, it could take 100 test runs or 10,000 but they will eventually arise and need to be addressed. The main reliability concern would be the kite or kite string breaking. This would be a major failure which would stop all testing and would require a completely new kite and/or string to be ordered to continue operation. The other major concern would be the base housing becoming ungrounded 3 and lifted up because this would be a huge safety hazard. These issues can be addressed by performing regular inspections to make sure that there is no concerning wear and tear on the kite or the kite string and checking to make sure that everything is safe and secure before undergoing operation of the system. Regular inspections would also be effective at preventing the other issues that could arise. Table 3 shows the FMEA that was done for the kite powered generator system.

Table 3. FMEA for demonstration model of kite powered generator

Process Step/Input	Potential Failure Mode	Potential Failure Effects	SEVERITY (1 - 10)	Potential Causes	OCCURRENCE (1 - 10)	Current Controls	DETECTION (1 - 10)	RPN	Action Recommended	Resp.
What is the process step or feature under investigation?	In what ways could the step or feature go wrong?	What is the impact on the customer if this failure is not prevented or corrected?		What causes the step or feature to go wrong? (how could it occur?)		What controls exist that either prevent or detect the failure?			What are the recommended actions for reducing the cause?	Who is responsible for making sure the actions are completed?
Kite catches strong wind	Kite string snaps	Kite falls to the ground	9	Knots on 3rd string aren't tied correctly	2	Visual Inspection	4	72	Replace kite string/ retie knots	senior design team
Tether pulls hard on springs	housing unglues/ top breaks	electricity stops being generated	8	Housing not glued correctly or strong winds	3	Visual Inspection	4	96	Glue properly/ use durable material	senior design team
Flying the kite in strong wind conditions	Housing lifts up from the ground	possible injury/ model breaks	9	housing not grounded/ strong winds	2	Visual Inspection / manually holding it down	5	90	Enough testing and practice using the housing	senior design team

5.3 Risk Assessment

Using this raw demonstration model to test the kite can come with a few risks that the team has to consider and plan for. With such a powerful magnet being used for the demonstration, there is the possibility of crushing a finger without proper caution of using the magnet. The users will need to be wearing gloves when handling the magnet in that case. Misuse of a magnet has been documented to wipe phones or computers. To avoid these accidents, it is imperative to enforce a certain distance that electronics are allowed to be near the magnet. There is also the possibility that a force is exerted on the demonstration that is higher than the safety mechanism and could damage the user or machine or that the model will not be correctly grounded and can potentially lift from the ground damaging the users. In this case, the team will need to keep their distance and do an inspection each time before flying the kite to ensure the machine is durable and properly grounded.

During the demonstration, the tether that is used to pull the magnet through the coil could snap and pose a risk of injury for the user. To avoid a worn tether from snapping during operation of the model, the plan would be to routinely check the tether to make sure that there is no wear or tear. Additionally, if the leads are put on backwards on the battery there is the risk of a spark. To avoid this, the leads will be color coated to prevent attaching them to the wrong ends.

5.4 Operating the Demonstration Model

5.4.1 Operational Instruction

1. Check that the springs are properly attached to the housing with a strong adhesive
   - If the springs are not attached, use strong metal adhesive to attach the springs is concentric order to the roof of the housing

2. Check that the magnet is attached to the largest spring, and that the kite line is secured to the magnet
   -If the magnet is not attached to the springs, use a strong metal adhesive to attach the magnet to the longest spring
   -Feed the center kite string though the cut out on the top of the housing and through the center of the springs, down through the center of the magnet
   -Tie kite string to the support bar on the bottom the magnet securely

3. Make sure that the ends of the copper coil are either tied to a voltmeter or connected to whichever device you would like to power

4. Secure the housing to the ground by standing on it, or adding weights to the side panels of the housing

5. Unravel the kite and kite strings, being careful not to tangle the lines

6. Once the kite strings are unraveled, grab hold of the kite control bar
   -If you do not have experience flying the kite, familiarize yourself with basic kites before flying the generator kite

7. Have a friend grab hold of the kite while kite strings are tensioned and untangled

8. When suitable wind is present, throw the kite into the wind, and fly the kite using the control bar

9. Watch as power is generated when the magnet moves through the coil

10. *****If the motor is used to simulate the kite motion follow direction below******

11. Repeat steps 1-3 using a line that is tied off on the shaft of the motor

12. Have at least two feet of slack to wrap around motor shaft

13. Select motor speed and simulated wind speed using the microcontroller

14. Repeat step 8

5.4.2 Troubleshooting

Potential problems with this kite may involve but are not limited to; 1) Kite string tangling 2) adhesive failing between the springs and the housing 3) Kite tearing 4) Magnet coming lose 5) Copper coil coming unraveled 6) Kite string breaking.

If the kite strings become tangled, the user should use care in untangling the lines to not further tangle them or damage the lines. If the adhesive fails between the springs and the housing, or the springs and the magnet, the user should use a strong metal adhesive and reattach the components until a more reliable mount is created. If the kite is torn, that kite should be decommissioned and a new kite will need to be purchased for the system to work as designed. If the copper coil comes unraveled, the user should rewrap the coil making tight loops, and secure both ends of the coil. If the kite string shows signs of tearing or wear, new strings should be used to prevent tearing. It is important to fly the kite in a safe area, away from people and power lines. If the kite strings do break, retrieve the kite where it lands and determine the cause of the tear. Prevent this from happening at all costs.

5.4.3 Regular Maintenance

Maintenance should be performed on the kite weekly if it is being flown continuously. The kite strings and kite itself should be inspected carefully for signs of wear. If there are signs of wear and tear, the kite strings and kite should be replaced immediately to prevent the kite from breaking lose and flying away. The adhesive holding the springs to the housing should also be inspected weekly to make sure that there is no breaking where they are connected. If there is cracking seal, apply more adhesive or redo the seal. If the springs show any sign of deformation, replace them at the earliest convenience.

5.4.4 Spare Parts

Spare parts needed for extended run time of this power generating device can be found in Table 4 below. The springs are needed in case of plastic deformation from increased and continuous loading on them. The kite is needed in case any damage is done to the kite that is in operation, and the kite strings are needed in case the lines sustain any damage during operation.

Table 4. Summary of spare parts

Spare Parts List	
1	Replacement initial spring
2	Replacement second spring
3	Spare kite string to replace kite lines
4	Extra kites

5.5 Product Specifications

The assembly of the demo model consists of three concentric compression springs of different lengths and stiffness coefficients. These are connected to the top of the housing with a strong adhesive. The solenoid is a 3D printed piece of plastic that surrounds the three compression springs and is connected to the top of the housing with the same strong adhesive. Copper wire is then wrapped meticulously around the solenoid as to not come into direct contact with any of the moving parts. A string is tied to the bottom of the magnet and fed through the solenoid and springs then attached to the kite.

The specs for the kite that is used can be found in Table 5. Table 6 describes the specifications of the magnet that was selected for this model. Table 7 shows the specifications for the springs that were used in the model throughout testing. The old spring configuration was selected based on the notion of hand cranking the magnet though the coil. Since it was later decided that the device would in fact be driven by a kite, new springs needed to be used based on lower forces provided by the kite. Figure 20 shows the specification of the motor that will be used for simulating the kite's motion when desired.

Table 5. Kite specification that is flown in figure-8 pattern

Tantrum 220 Prism	
Weight (lbs)	1.5
Wing Span (in)	86.5 x 98.5
Wind Range (mph)	5 to 25
Kite String Length (ft)	85

Table 6. Selected magnet specifications

Neodymium Magnet	
Diameter (in)	3
Thickness (in)	1/2
Hole (in)	1/4
Strength (tesla)	1.32

Table 7. Specifications for new and old springs that are used in model

	Springs	Length (in)	Stiffness (lbs/in)	Outer D (in)	Inner D (in)	Solid Height (in)
Old	1	9.00	13.00	3.00	2.62	1.54
	2	6.88	9.00	1.50	1.25	1.88
	3	3.50	153	1.00	0.68	2.11
New	1	9.25	2.20	2.25	2.01	1.68
	2	7.00	1.70	1.55	1.37	1.61
	3	3.50	153	1.00	0.68	2.11

rpm @ Continuous Operating Torque	3,000 rpm @ 21 in.-oz.
Starting Torque	159 in.-oz.
Maximum rpm	3,456
hp	0.06
DC Voltage [Nom]	12 Volts DC
Amps @ Full Load	4.9
Electrical Connection	Lug Terminals
Lug Terminals	
Width	0.187"
Thickness	0.02"
Motor Type	Brushed Permanent Magnet
Service Factor	1
Efficiency	68%
Enclosure Type	TENV
Enclosure Material	Steel
Bearing Type	Ball
Overall	
Length	4 3/4"
Width	2 1/4"
Height	2 3/4"
Shaft	
Diameter	0.250"
Length	1"
Center to Base (A)	1.06"
Mounting Orientation	Any Angle
Mounting Holes	
Thread Size	6-32
Quantity	4
Bolt Circle Diameter	1.53"
Insulation	
Class	F
Maximum Temperature	311° F

Figure 20. Specifications for motor used to simulate kite motion

5.6 Testing Results

Tests were run using three different methods. Initial testing involved hand cranking the motor using a tether that was tied to the magnet. The second method of testing was done using a kite, flown in a figure-8 patters to drive the oscillation of the magnet. The third method of testing, involved the use of a motor that was run at different frequencies, and ranges of displacement, in order to see the results of the induced voltage. A voltmeter was used to make these measurements, and was set to the AC voltage setting, in the mV range.

Hand cranking the motor yielded the highest induced voltage values of 0.5V. During these test, the magnet was oscillated at a rate of approximately 2Hz, over a range of 5in. Hand cranking was first done on the demo model using the setup seen in Figure 21.

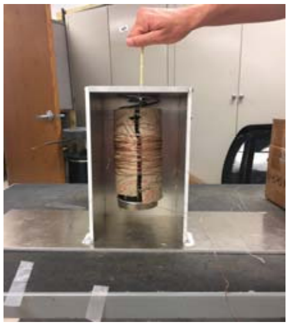

Figure 21. Initial demonstration model with cardboard housing

Here a cardboard cylinder was used as the housing for the electric coil. Knowing that this would not be a permanent setup, the coil was not neatly wrapped around the housing, and there were significant gaps between some wraps. Using this setup, the max voltage output was found to be 20mV.

To improve this output voltage, a 3D printed housing for the electrical coil was used. For this housing, a permanent coil was made, that had more wraps, in a much smaller area. This meant that there were tighter wraps, with less overlap between them. Using the same method of hand cranking described above, the voltage output was found to 0.5V. This was more than 10x the observed induced voltage during preliminary testing using the cardboard cylinder. The setup used for testing from this point on can be seen in Figure 22.

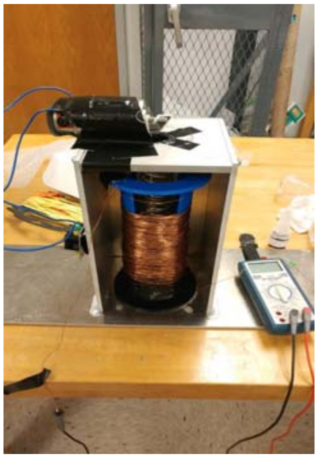

Figure 22. Updated and final demonstration model

Modifications were made to both the demonstration model seen in Figure 22, and to selected traction kite, to allow for kite driven power. Using the junction points on the left and right hand span of the kite, where the control lines of the kite meet, two strings (one on each side) were tethered. These lines then met at a ‘quick clip’ where a single line came down, and was attached to the magnet and housing. This configuration is better illustrated in Figure 23.

Figure 23. Image showing how kite lines were attached

While flying the kite in a figure-8 pattern, the maximum voltage output was found to be 0.4V, similar to that of the hand crank tests. This was not however, able to be sustained. When the kite was flown to its peak altitude, and the springs were put into tension, pulling back on the kite, the kite folded and fell to the ground. The kite would then catch wind and ascend rapidly, however this motion was not consistent. Eventually the kite would crash into the ground. At one point, the kite ascended rapidly and broke the string that was tethered to the magnet.

Because the kite was not able to be flown in the desired figure-8 path with any consistency, a motor was used to simulate this kite motion. The motor was used to spool the line connected to the magnet around its shaft, till a desired compression length was reached, and then released so that the magnet would oscillate inside of the electrical coil. Before these tests were run, more wraps were added to the coil, thinking that it would increase the induced voltage. The opposite proved to be true. The total resistance of the coil was increased due to the increase in the total length of the wire, and a lower induced voltage was generated. The motor was programmed to oscillate at three different displacements, and three different speeds. The highest induced voltage was found to be 50mV, at high displacement and high speeds.

5.7 Calculations

One factor that was thought to cause potential issues with the kite power generator were elastic losses due to the kite string stretching. It order to determine the potential load on the strings, the wind speeds at 1000ft above sea level were found using Eqn. 1. Here, a is the Hellmann exponent [13] and depends on the coastal location and shape of the terrain. This value was taken to be 0.27 based on the coastal region of the Greek Islands. v_{10} is the velocity at 10 meters off the ground, and h is the altitude of interest.

$$v_h = v_{10} * \left(\frac{h}{10}\right)^a \qquad \text{Eqn. 1}$$

Based on these wind speeds, the pressure distribution along the kite was found using the panel method [14]. Figure 24 shows this pressure distribution for 5 degrees angle of attack, and 15 degrees angle of attack. It is important to note, that although the kite is not a perfect airfoil, the shape of the kite was taken to be a NACA 0012 airfoil, which is symmetric about the chord line.

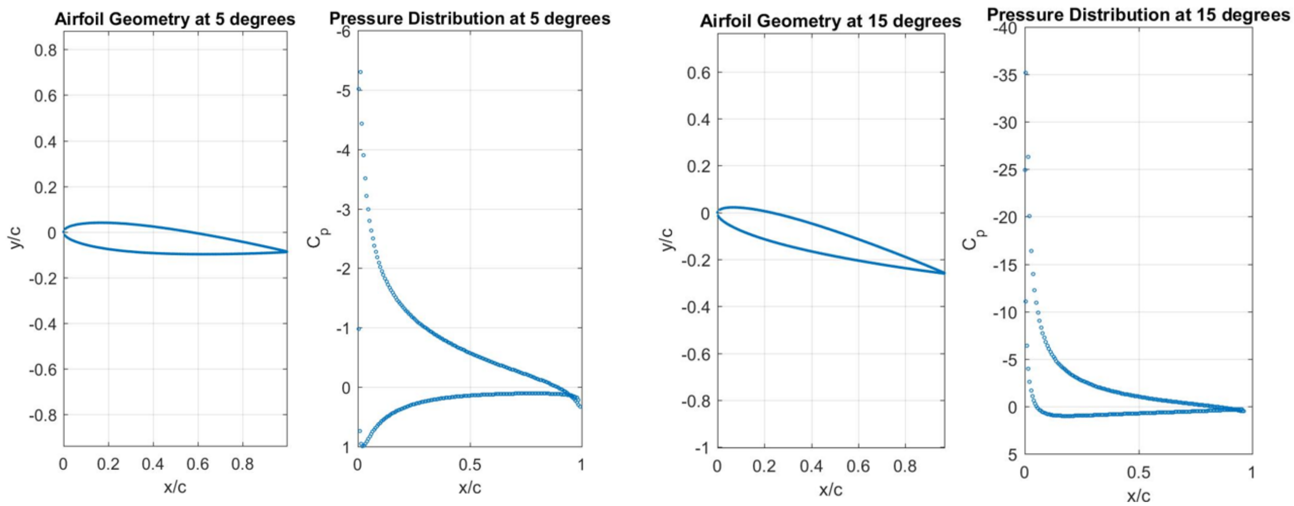

Figure 24. Pressure distribution along airfoil kite at 5 and 15 degrees

The kite was also taken to be a 1mx1m area. The forces on the kite were found to be 15lbf, and 45lbf of lift for 5 and 15 degrees respectively. It is also important to consider the drag force on the kite, as a kite's main role is to catch wind. The drag force for 5 degrees was found to be 1.5lbf, and for 15 degrees, it was found to be 5lbf. These numbers are considerably low, because the kite shape was taken to be a streamlined airfoil, however if another geometry were to be tested, new coordinates could be plugged into the MatLab code found in the Appendix.

A ¼'' diameter nylon string was selected as the material to be used for the kite strings. This material was chosen because of its excellent strength to weight ratio, and that it is mold and mildew resistant. Table 8 shows the properties of the nylon string that was chosen.

Table 8. Nylon Rope properties

Nylon Rope Properties	
Modulus (Gpa)	3.9
Breaking Strength (lbf)	1804
Weight of rope (lbm/ft)	0.016

The string was found to only stretch 0.5'', which led to negligible potential energy losses. This value was found using Eqn. 2 and 3 found below.

$$T = \frac{\lambda x}{l}$$ Eqn. 2

$$E = \frac{l x^2}{2l}$$ Eqn. 3

Here, T is the tension in the string, x is the displacement of the string, l is the natural length of the string, and λ is the modulus of elasticity. E is the potential energy that is stored in the tensioned spring.

5.8 Budget Summary

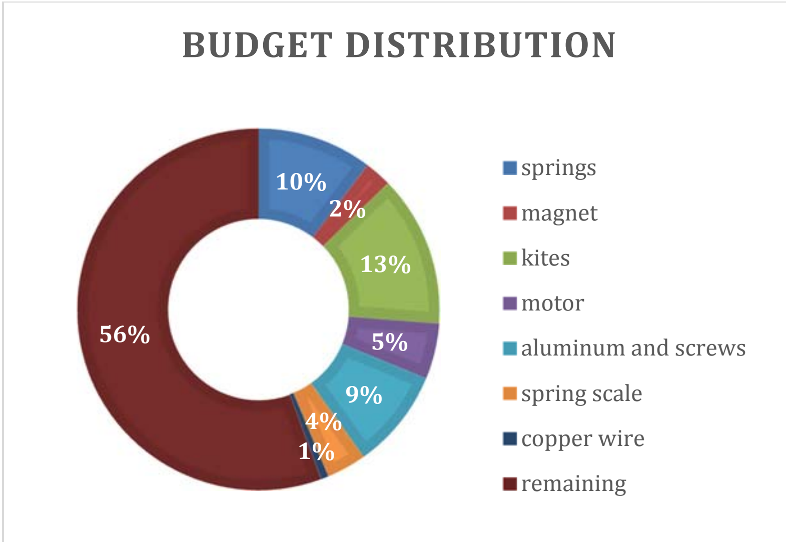

Figure 25. Budget Distribution

The entire demonstration model costs roughly $887 altogether. The power generation portion of the project cost roughly $267 and that includes the magnet, springs, and the electrical copper coil. The prototype was built out of aluminum and was screwed together, which cost about $179. Kites were purchased to examine which kite will generate more lift and thus generate more power, which collectively were $270. Additionally, a motor was purchased at a price of $100 to mimic the kite motion in the event that the kite does not produce enough power for a 40 W light bulb.

Table 9. Budget Distribution

Items	**Cost (USD)**
3 springs	129.44
Magnet	48.26
2 kites	270.27
Al sheet	162.93
Copper ire	13.2
Spring scale	71.13
Screws	16
New springs	76.69
Acrylic rod	351
DC motor	99.53
TOTAL:	**1,238.45**

It can be seen from Table 9 that the total is actually $1,238.45, not $887. This is because the team purchased an acrylic rod for $351 to be cut in the machine shop for the solenoid housing. However, the material was not used since the machine shop deemed 3-D printing the part would be more time-efficient. Thus, due to a time constraint, the housing was 3D printed and the acrylic rod is in the process of being returned. The remaining money is the majority of the budget, thus this design is fairly affordable. The largest part of the pie chart of the budget that is already used is taken up mainly by the springs and kites. The springs take up a large part of the budget because the team bought 2 sets of 3 springs to refine the test model as they ran into problems while testing the design. Also, multiple kites were purchased so that the team had options to choose from and see which kite gave the best oscillation which will be used to generate maximum power. Thus, the design can be repeated for less than the budget used since the design has been refined.

5.9 Proposed Improvements

As seen from our results, the demonstration model was not able to produce 40 watts of electricity to power a standard light bulb. There are possible ways to increase that through improvements in the design. One way would be to get a larger magnet and increase the cross sectional area, which will in turn increase the voltage generated via Faraday's Law. Another way is to increase the magnetic field of the magnet which can be done in several ways such as simply purchasing a stronger magnet or multiple magnets. By having multiple magnets, the team could stack them together with glue, tape, or a string and create a stronger magnetic field. In addition to modifying the magnet, it can be easily seen that the weight of the magnet plays an important in the kite's oscillation. The magnet is directly attached to the third string that is tethered to the kite. Thus, a heavy magnet can act as a force pulling the kite down as it is attempting to reach higher altitudes. Not only does it prevent the kite from getting higher but it also yanks down on it when it is oscillating, thus preventing steady oscillation.

It can be noted that if a lighter magnet is used, then a smaller kite can be attached to it rather than a large one since it will create greater oscillation. The type of kite also plays a large role in this design. The kite used for the demonstration model is a traction kite which did not have any support and was pure nylon. As the third string finally began moving the magnet and creating oscillation, the kite would be yanked down and in the process folded over. As it folded, the kite lost its shape to stay aloft and fell to the ground each time. To avoid this, a suggested improvement is to purchase a stiff winged kite that has a frame since it would keep the kite aloft in varying wind speeds. One drawback to this design is the extra weight of the kite frame. However, if a smaller kite is purchased along with the lighter magnet, then this loss would be insignificant.

The wraps in the copper coil also play an important part in the power generation aspect of the design. It is ideal to have enough wraps in the coil for the magnet field to cross since it directly impacts the voltage generated. Thus, adding more wraps in the coil with tighter spacing is optimal and can always be improved in the design. Faraday's Law clearly states that the greater the number of wraps, the greater the voltage. If the same solenoid housing is used and the number of wraps need to be greater, then it would be worth it to invest in thinner wire. However, using thinner and longer wire for more wraps will increase the resistance. This will directly limit the flow of current it can output since the cross sectional area of the wire is smaller. Thus, there must be a balance between the number of the wraps the coil needs and the diameter of the wire.

5.10 Scaling for 10kW Concept Kite

The scale for the 10 kW model will involve a lot of assumptions. Powering a 40 W light bulb will involve producing 120 volts for the given standard light bulb. In order to make the correct modifications on this specific kite power generator design, certain power specifications will remain the same such as the current flowing through the copper wire. If the current remains the same and the power changes to roughly 250 times the power needed for the light bulb, then the voltage will change. The power needed is 10 kW, or 10,000 W, thus the voltage that needs to be generated is going to be 30,000 V as it can be seen from Table 10.

Table 10. Power Generation Parameters

Power (W)	10,000
Voltage (V)	30,000
Magnet radius (inches)	6
Magnet velocity (windings/second)	100
Number of windings	3116

By using Faraday's Law, it can be seen that the rate of the magnet field is needed in order to carry out the calculation. The magnetic field rate depends on the cross section of the magnet being used and the magnetic field. The magnetic field of the magnet chosen for the demonstration model is relatively high as it is a rare earth magnet with a magnet field of 1.32 T. Thus, if the cross sectional area is increased then that will contribute to the over voltage generation. The cross sectional area is chosen to be 6 inches in diameter, which is much bigger than the magnet used for the demonstration. Another parameter that could be changed with the design is the magnet velocity inside the solenoid housing. The faster the velocity of the magnet, then the faster the rate of the magnetic field as it is crossing over each copper winding in the solenoid. The parameter for the velocity is changed to 100 windings per second. After plugging in those changed values, it can be seen that the number of coil windings needed for this solenoid is roughly 3116.

Thus, if the diameter of the magnet is increased and the velocity at which it moves inside the solenoid directly affects the voltage generated via Faraday's Law. It can be concluded that using those parameters outputs 10 kW of power for a larger system that can be used for the grid.

6. Conclusion

The design of the concept model kite involved a much bigger kite than the traction kite that was used for testing. It also had a method of kite stabilization to make the system autonomous. Multiple methods of stabilization and oscillation were created and evaluated for the design.

Through background research and deliberation a final demonstration model was selected along with the concentric spring set that will be a major part of the system. The demonstration model consisted of three concentric springs. The first and second spring work in combination to provide resistance, while the third spring is meant to be the safety mechanism. The safety mechanism is there so that no plastic deformation is done to the springs to extend the life of the mechanism. The magnet must travel at 50 wraps/second in order to achieve the necessary power generation.

The traction kite that was selected for testing was tied to the magnet inside the demonstration model. Tests involving the kite pulling the magnet only yielded 0.4V whereas hand cranking the demonstration model yielded 0.5V. The goal for power generation was not met and can be attributed to a number of reasons as to why. Possible improvements to the system to increase the power generation include strengthening the magnetic field and adding more wraps of copper coil.

References

[1] Phipps, Jeff. "Patft » Page 1 of 1." *Patft » Page 1 of 1*. Uspto, 20 Jan. 2014. Web. 30 Sept. 2016.

[2] Doan, Abigail. "POWER YOUR BOAT WITH KITES: Wind Power by KiteShip."*Inhabitat Green Design Innovation Architecture Green Building*. Inhabitat, 23 Oct. 2007. Web. 30 Sept. 2016.

[3] "POWERFUL - UNLIMITED - FREE." *SkySails GmbH - SkySails Propulsion for Cargo Ships*. N.p., n.d. Web. 30 Sept. 2016.

[4] "Mini Beasts | Books Beast Photos Events Theo Jansen Contact."*STRANDBEEST*. N.p., n.d. Web. 30 Sept. 2016.

[5] "Strandbeest: The Dream Machines of Theo Jansen." *Exploratorium Blog*. N.p., 16 Sept. 2016. Web. 30 Sept. 2016.

[6] Yacht, Kite Sailing. *KITANO* (n.d.): n. pag. *Princess of Style*. Kitano. Web.

[7] "U.S. Energy Information Administration - EIA - Independent Statistics and Analysis." *EIA Projects 48% Increase in World Energy Consumption by 2040*. N.p., n.d. Web. 21 Oct. 2016.

[8] "Fresh Water Resources - Greece - Climate Adaptation." *Fresh Water Resources - Greece - Climate Adaptation*. N.p., n.d. Web. 21 Oct. 2016.

[9] "Disadvantages Of Solar Energy - Conserve Energy Future."*ConserveEnergyFuture*. N.p., 17 Aug. 2015. Web. 21 Oct. 2016.

[10] Windfinder.com. "Windfinder.com - Wind Forecast Map Greece."*Windfinder.com*. N.p., n.d. Web. 21 Oct. 2016.

[11] "Key Points."Highaltitude Wind Technology Innovative Renewable Energy Wind Energy Kitenergy. N.p., 17 Dec. 2014. Web. 21 Oct. 2016.

[12] "High-altitude Wind Energy from Kites!" *Saul Griffith:*. N.p., n.d. Web. 21 Oct. 2016.

[13] soliton.ae.gatech.edu/people/lsankar/AE2020/Panel.Method.doc

[14] *Elastic Strings - Mathematics A-Level Revision*. N.p., n.d. Web. 19 Apr. 2017.

Appendix

```
% Vortex panel method
clear all;
tic

% Add folder search path for airfoil coordinates
%    addpath([cd '/Airfoil Coordinates']);
clc
clear all
% Freestream velocity [m/s]
   U =15;
% Angle of attack of freestream velocity vector [radians]
   alpha = 5*pi/180;
% Angle of attack of airfoil geometry [radians]
   aoa = alpha;
% No. panels desired
   Nopanels = 100;

   rho = 1.15 ;

%% NACA

% Import airfoil surface coordinates
% Must already be in order from lower TE CW to upper TE
% D is (x,y) coordinates, Nl is index of 0,0
   [D, Nl] = NACA00xx(.12,1);
   %Naca 6412
   %[D, Nl] = project_Coordinates;

   x = D(:,1).*cos(-aoa)-D(:,2).*sin(-aoa);
   y = D(:,1).*sin(-aoa)+D(:,2).*cos(-aoa);


% **** Cosine coordinate spacing having issues at LE - Need to fix *****

% % % %% Generate more panels at LE and TE
% % %
% % %
% % % % No. points
% % %     Npts = Nopanels+1;
% % %
% % % % Cosine spacing for increased resolution at LE and TE
```

```
% % %     for i = 1:Npts/2
% % %        xli(i) = 1/2*(1-cos(((i-1)*pi)/(Npts/2-1)));
% % %        xui(i) = xli(i);
% % %     end
% % % % Spline fit
% % %     % Lower surface
% % %        yli = pchip(D(1:Nl,1),D(1:Nl,2),xli);
% % %     % Upper surface
% % %        yui = pchip(D(Nl:end,1),D(Nl:end,2),xui);
% % % % Combine upper and lower coordinates
% % %     Ds = [fliplr(xli(2:length(xli)))' fliplr(yli(2:length(yli)))';
% % %          xui' yui'];
% % % % Angle of attack coordinate transformation
% % %     x = Ds(:,1).*cos(-aoa)-Ds(:,2).*sin(-aoa);
% % %     y = Ds(:,1).*sin(-aoa)+Ds(:,2).*cos(-aoa);



 %%

% No. of panels
  N = length(x)-1;

% Preallocate
  xbar = zeros(N,1);
  ybar = zeros(N,1);
  l = zeros(N,1);
  r = zeros(N,N+1);

%% Geometric paramaters

for i = 1:N

  % x-coordinate panel midpoint
    xbar(i) = (x(i)+x(i+1))/2;
  % y-coordinate panel midpoint
    ybar(i) = (y(i)+y(i+1))/2;

  % Distance from midpoint of ith panel to jth node
  for j = 1:N+1
    r(i,j) = sqrt((xbar(i)-x(j))^2+(ybar(i)-y(j))^2);
  end

  % Length of each panel in the x direction
```

```
    t1 = x(i+1) - x(i) ;
  % Length of each panel in the y direction
    t2 = y(i+1) - y(i) ;
  % Length of each panel
    l(i) = sqrt(t1*t1+t2*t2) ;



  % ith panel inclination rel. to global coordinates
    theta(i) = atan2(y(i+1)-y(i),x(i+1)-x(i));


  % ith panel inclination rel. to jth panel
  for j = 1:N

       beta(i,j) = atan2((ybar(i)-y(j+1))*(xbar(i)-x(j))-...
         (xbar(i)-x(j+1))*(ybar(i)-y(j)),(xbar(i)-x(j+1))*...
         (xbar(i)-x(j))+(ybar(i)-y(j+1))*(ybar(i)-y(j)));
      % Approach panel from outside of airfoil
      if i == j
        beta(i,j) = pi;
      end

  end

end

figure
plot(xbar,theta,'o')

A = zeros(N+1,N+1);

%% Matrix A, for Aq = b

% Matrix elements 1:N,1:N
for i = 1:N

    for j = 1:N

      A(i,j) = 1/(2*pi)*(sinld(theta(i),theta(j))*log(r(i,j+1)/r(i,j))+...
           cosld(theta(i),theta(j))*beta(i,j));

    end
```

```
   b(i) = U*sinld(theta(i),alpha);
end

% Matrix elements 1:N,N+1
for i = 1:N

   for j = 1:N

         a1(j) = 1/(2*pi)*(-sinld(theta(i),theta(j))*beta(i,j)+...
               cosld(theta(i),theta(j))*log(r(i,j+1)/r(i,j)));

   end

   A(i,N+1) = sum(a1);

end

% Matrix elements N+1,1:N
for j = 1:N


   a2 = 1/(2*pi)*(sinld(theta(1),theta(j))*beta(1,j)-...
                 cosld(theta(1),theta(j))*log(r(1,j+1)/r(1,j)));
   a3 = 1/(2*pi)*(sinld(theta(N),theta(j))*beta(N,j)-...
                 cosld(theta(N),theta(j))*log(r(N,j+1)/r(N,j)));

   A(N+1,j) = a2+a3;


end


% Matrix element N+1,N+1
for j = 1:N
   a4(j) = 1/(2*pi)*(sinld(theta(1),theta(j))*log(r(1,j+1)/r(1,j))+...
                  cosld(theta(1),theta(j))*beta(1,j));
   a5(j) = 1/(2*pi)*(sinld(theta(N),theta(j))*log(r(N,j+1)/r(N,j))+...
                  cosld(theta(N),theta(j))*beta(N,j));

end

A(N+1,N+1) = sum(a4+a5);

b(N+1) = -U*cosld(theta(1),alpha)-U*cosld(theta(N),alpha);
```

```
%% Solve system of equations

q = A\b';

% Circulation to satisfy Kutta condition
   gamma = q(N+1);

% Tangential velocity at midpoint of each panel
for i = 1:N

   for j = 1:N

      a5(j) = q(j)/(2*pi)*(sinld(theta(i),theta(j))*beta(i,j)-...
                   cosld(theta(i),theta(j))*log(r(i,j+1)/r(i,j)));

      a6(j) = gamma/(2*pi)*(sinld(theta(i),theta(j))*log(r(i,j+1)/r(i,j))+...
                   cosld(theta(i),theta(j))*beta(i,j));

   end


   Ut(i) = sum(a5)+sum(a6)+U*cosld(theta(i),alpha);

end

% Pressure coefficient
    Cp = 1-(Ut./U).^2;

Cl = (2*gamma/U)
L = rho*U*gamma

%% Figures
figure
   subplot(1,2,1)
   plot(x,y,'.','MarkerSize',5); axis equal
   xlabel('x/c')
   ylabel('y/c')
   title('Airfoil Geometry at 15 degrees' )
   grid on
  %xlim([-.05 5]);

% figure
```

```
subplot(1,2,2)
plot(xbar,Cp,'o','MarkerSize',2)
xlabel('x/c')
ylabel('C_p')
title('Pressure Distribution at 15 degrees')
set(gca,'YDir','reverse')
grid on
%xlim([-.05 1]);
```