Conference Paper

Team 16: Solenoid Kite Generator

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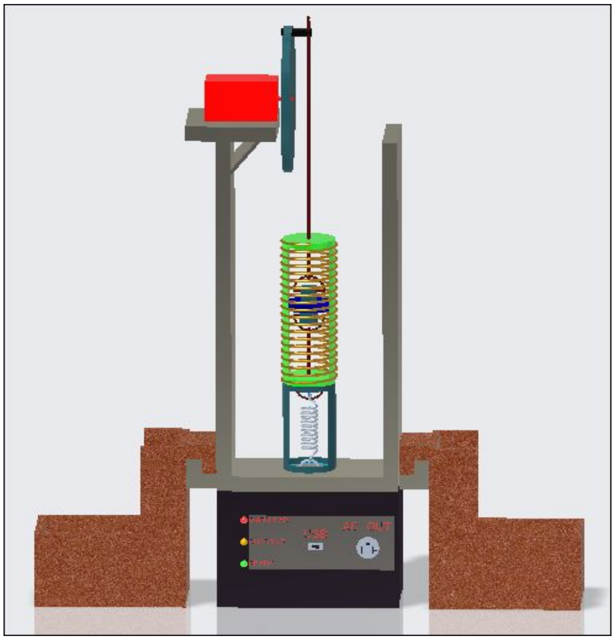
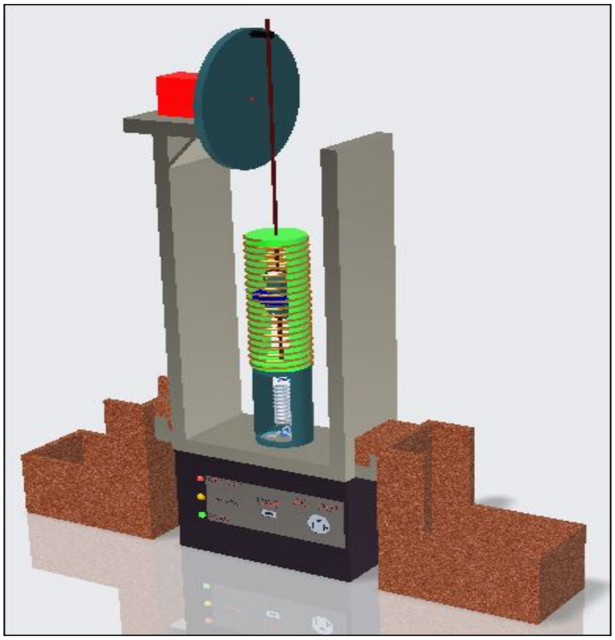

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Abstract

There has been a shift in energy away from fossil fuels to clean energy, with great attention towards wind and solar. With several businesses looking into how to harness this wind energy, this project aims to look at the use of a solenoid kite generator to produce clean wind energy. In a solenoid kite generator, energy comes from the motion of a magnet within a copper layered tube, or solenoid. An oscillating kite provides the motion for the magnet through a tether. This magnet motion is then converted to usable power. The excess power is stored in a battery for later use. One main idea for the study of the solenoid kite generator is that its design will be easy to move and repair when compared to normal wind turbines. The team will build a model of the solenoid kite generator and prove that the power produced depends on the speed of the magnet. The team also plans to research if the solenoid kite generator is practical for the replacement of current wind energy systems. Research will consist of output power, cost, and weight of the total system.

Introduction

Wind is produced from large convection currents in our atmosphere. These currents are driven by the energy given from the sun. This means that wind is a renewable energy source and as long as we have the sun, convection currents will exist. Wind is also a clean source of energy, meaning that no harmful gases are produced during the power production process, unlike burning fossil fuels, natural gases, etc. Wind power has been traditionally harnessed using wind turbines. Though this method is widespread and proven to work, there are some downsides to traditional wind turbines. They are extremely expensive to produce and require significant maintenance. Additionally, once they are installed they are permanently fixed and cannot be relocated. There is a need in the market for a portable, affordable, off-grid wind power generator.

The project sponsor Jeff Phipps, a local entrepreneur, has a patent for a kite generator design utilizing a solenoid base to produce electricity (Patent Number: US 9,013,055 B1). This design consists of a permanent magnet slidably disposed within a housing wrapped in an electrical conducting coil. The magnet is attached to a kite by a tether. The magnet oscillates inside the solenoid, generating an electromagnetic force (EMF) which can be converted to usable energy [1]. Jeff Phipps has a vested interest in the feasibility and practicality of his patent and has contacts within the industry.

There are existing companies prototyping kite generator systems. The most notable among these is Makani, a google owned company with a prototype kite generator rated for 600 kW of power. Their specialized tether and onboard turbines contribute to their unique method of power generation and energy conversion [2]. Other companies implementing kite generators include Skysails, Altaeros Energies, and Kite Power Systems. Skysails is focused on offshore foundations, with underwater support platforms at depths down to 700m below sea level [3]. This allows for the kites to gather untouched wind far away from land. Altaeros Energies uses helium to stay aloft and their kites can reach 600m for consistently higher velocity winds. They also boast their ability to easily transport and install their systems from standard shipping containers [4]. Kite Power Systems utilizes a twin kite system so that when one kite is generating power, the other can be retracted. This ensures a constant generation of power [5]. Our sponsor's patent is unique among these as it is the only design implementing a solenoid.

Depending on the output power desired, there are several potential markets for a kite generator to be scaled. The solenoid kite generator could be used for commercial scaled power, putting it in direct competition with the aforementioned companies. Another viable market would be to replace current combustion gas generators with a similarly rated solenoid power generator. These new power generators could be used for areas far removed from the electrical grid or in the event of a collapse of the grid. Applications for use involve disaster relief organizations, individuals interested in boating or camping, and remote military use.

Scope

The purpose of this project is to prove the application of our sponsor's patent and produce a prototype of a solenoid power generator able to utilize wind from a kite without construction of a permanent wind turbine. Conventional wind turbines need a permanent setup and require a high amount of maintenance. Kite power allows for maneuverability and cheaper maintenance due to less complex mechanical parts. Primarily, the project will aim to produce a prototype of the solenoid power generator and to determine the size and feasibility of designs for other applicable markets and power loads.

Functional decomposition

The functional decomposition aims to break down the complex airfoil generator system into smaller sub-sections. Each breakdown describes the desired function of the component in order to achieve the needs of the customer. Below is the overall system decomposition and the component functional decomposition of each component.

In order to satisfy our customer, our overall system decomposition has been condensed to consist of using a motor to simulate the mechanical motion from the wind of a tether attached to a kite and transmitting that energy.

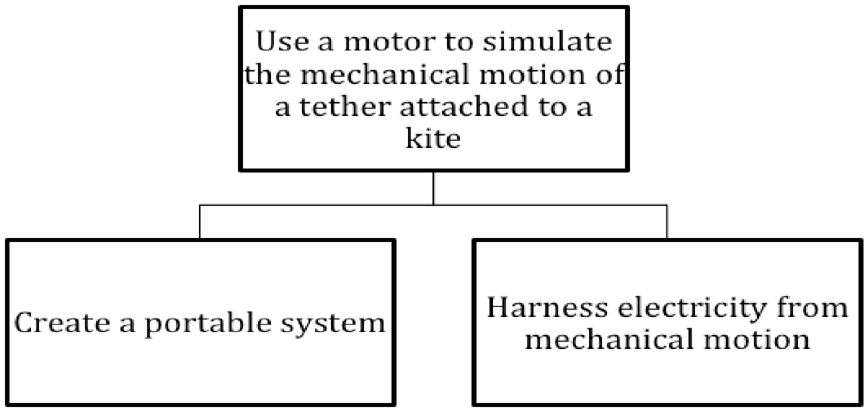

Figure 1: Functional decomposition of system general function.

Base Subsystem

The Base Subsystem is very essential to this project because it can determine the portability and sizing of the whole project. Overall, it could be dramatically simplified through the prototyping of the project. The end project design should keep the housing in mind as a finalized product should incorporate some weatherproof casing and additional features.

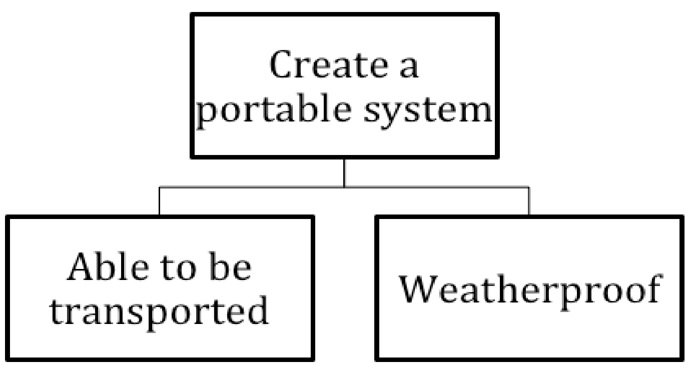

Figure 2: Functional decomposition of base subsystem.

Solenoid Subsystem

The purpose of the solenoid is to be able to create a magnetic field. This magnetic field along with the simulated mechanical motion will cause the magnet to oscillate which will then create an electrical current that can be harnessed.

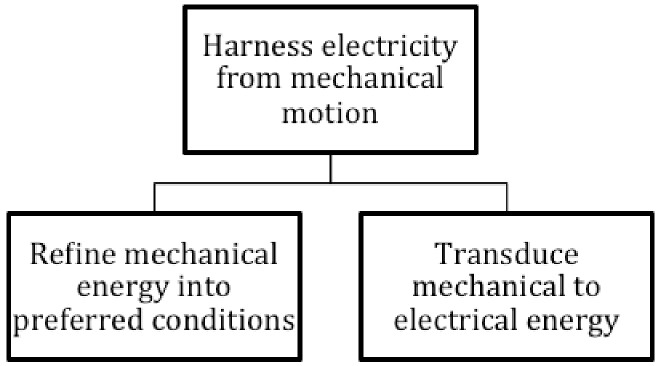

Figure 3: Functional decomposition of solenoid subsystem.

Targets and metrics

Targets of the Generator system are determined for each function of the system. The targets are defined by metrics to measure and achieve the aforementioned functions. Data analysis and customer preference dictate each target and its metrics. As seen in the Target Catalog in below in Table 1, 150 W of power output is set as a suitable target for the generator system to light up a 100-Watt light bulb.

Another key target is to keep the combined weight of all the subsystems under 100 lbs. with each subsystem weighing less than 50 lbs. With the principles of portability in mind, two people should be able to assemble, operate, and disassemble the generator system.

The last notable target was the power to weight ratio of the overall system. The power to weight ratio helps to facilitate comparisons between different forms of sustainable energy as well as other kite generator companies such as Makani. Aiming to produce 150 W of power with a maximum weight of 100 lbs, the power to weight ratio of the whole system calculates to 1.5 W/lb.

Some targets were developed with the help of Physics equations shown below. In the preceding equations, V is voltage (Volt), P is power (Watt), R is resistance (ohm), N is number of wraps, Rho is conductivity, dB/dt is change in magnetic flux over time, A is surface area of moving magnet, and L is the total length of the solenoid [6].

$$P = V^2/R \quad \text{Eq.1}$$

$$V = N * A * (dB/dt) \quad \text{Eq.2}$$

$$R = \frac{Rho*L}{A} \quad \text{Eq.3}$$

From these equations the team concluded that the strength of the magnet, B, as seen in the equation above, has a significant impact on the overall power produced. Based off the facts the group found the strongest magnet on the market, Neodymium, which operates at 1.32 Tesla. Further examining the power equation, the team constrained the length, L, and cross sectional area, A, of the inductor. To comply with the aforementioned targets, the inductor and its wrappings should possess a weight under 50 lbs while covering the largest possible volume. Area and length of the solenoid have initial values of 0.018 m^2 and 1 m, respectively. These values may change following experimental analysis of the induced voltage power generation. This and future experiments will provide the necessary data for confirmation or alteration of the existing targets.

Table 1: *Targets and metrics*

System Component	Function	Target
Overall System	Transmit power	150 W output
	Harness power from mechanical motion	300 W mechanical energy
	Able to be transported	Weight under 100 lbm
	Affordable to the consumer	Cost of system under $2000
Base	Rotate spherically with wind direction	360 degrees of rotation; constant angle of alignment with tether.
	Attach and detach from ground and solenoid	Weight under 100 lbm for both ground and solenoid; non-permanent attachment methods
	Protect power generation equipment	Waterproof housing
Generator	Transduce mechanical to electrical energy	25% efficiency
Electrical System	Maximize magnetic field of solenoid	Use Magnet of 1.32 Tesla

Concept Generation:

To facilitate the concept generation, each member of the group was instructed to find individual background research on the power generation and kite aeronautics. Members were encouraged to perform background research on basic theories and benchmark companies with similar products. Each member then presented his or her own ideas without any interruption or criticism. This technique produced maximum concept generation and respect between members. Following every member's presentation, the group debated the concepts to keep, alter, and discard.

The team utilized the Pugh Matrix Method as a tool for comparing design ideas against design criteria. By doing so we were able to determine which designs were better than others by ranking the overall designs numerically. This method also allowed for certain design criteria to be weighted more highly than others, creating a more accurate evaluation of the design ideas.

To create a reliable Pugh Matrix, evaluations were conducted of all the general variables that affect the power generation. To ensure that the project achieves its best design, these variables must be optimized to provide the highest efficiency at the best cost. To account for this, certain variables are weighted more than others. The priority of the variables was determined by the project scope, customer needs, and functions of the systems. The variables with the greatest influence include size, safety, reliability, efficiency and cost. The Pugh Matrices can be seen in Tables 2-4.

Table 2: *Pugh Matrix Selection of Oscillation Method*

Criterion	**Scale 1-5**	**Oscillation Method**		
		Gravity Forced	Spring Forced	Dual Kite System
Efficiency	5	1	3	5
Weight	5	3	4	3
Power Output	5	1	3	5
Safety	4	2	3	2
Part Standardization	3	3	2	3
Maintenance	4	4	3	2
Cost	2	5	4	1
Score		68	88	**92**

Table 3: *Pugh Matrix Selection of Mechanical to Electrical Energy Conversion Method*

Criterion	Scale 1-5	Energy Conversion Method	
		Solenoid	Alternator
Efficiency	5	2	4
Weight	5	2	3
Power Output	5	2	4
Safety	4	3	3
Part Standardization	3	2	3
Maintenance	4	4	2
Cost	2	2	3
Score		68	**90**

Table 4: *Pugh Matrix Selection of Mechanical Energy Handling Method*

Criterion	Scale 1-5	Mechanical Energy Conditioning	
		Transmission	No Transmission
Efficiency	5	4	2
Weight	5	2	5
Power Output	5	5	2
Safety	4	4	4
Part Standardization	3	4	5
Maintenance	4	2	3
Cost	2	2	3
Score		**95**	**94**

Concept Selection:

There were three primary metrics considered in selecting a design for power generation: method of oscillation, energy conversion method, and mechanical energy conditioning. Design considerations were assessed for each metric based on a list of criteria, resulting in a modular design optimized for overall efficiency. The final design selected included a dual kite system, an alternator, and transmission. The design can be seen in Figure 4 below.

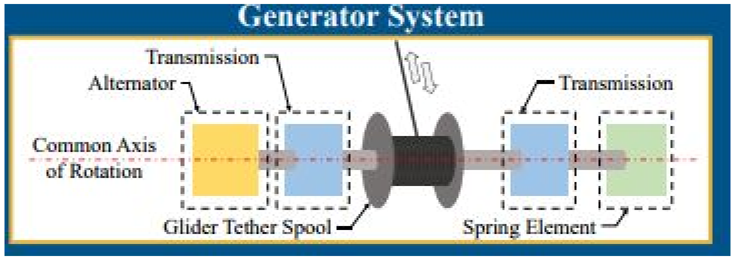

Figure 4: Generator system.

After discussing our selected design and all alternate designs with our sponsor, the team decided to go in a different direction with the concept selection. Because of the sponsors invested interest in this project, it was deemed necessary to follow the path of the customer's patent and prove the feasibility of it because it is one of a kind, something that is not already on the market. With that being said, the design selected is a permanent magnet solenoid generator which can be seen below in Figure 5.

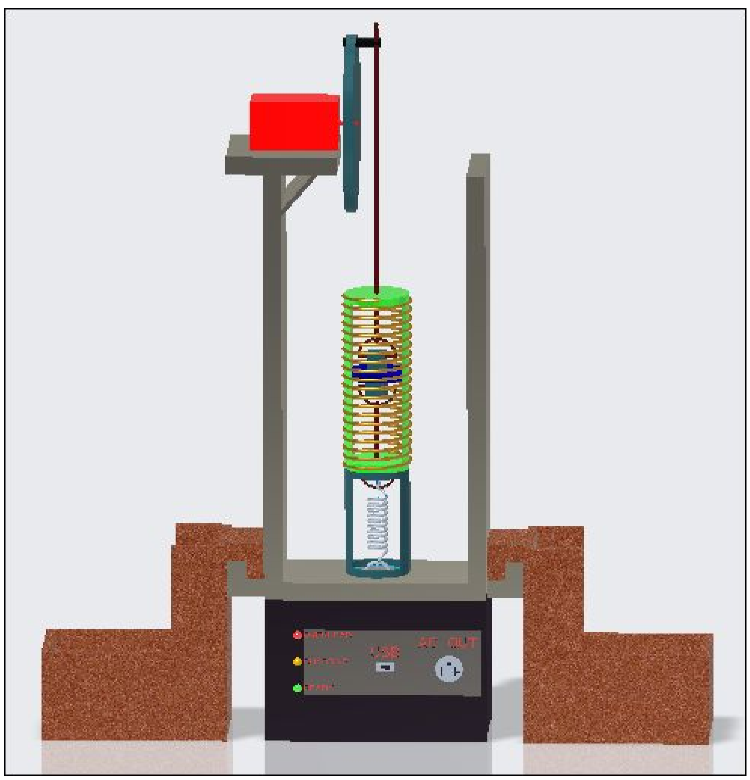

Figure 5: Computer Model of Detailed Design.

In the event that the team was ahead of schedule and could connect the solenoid subsystem to the kite subsystem, the team measured variables from a previously purchased kite

(Tantrum 220 Prism Kite) so that the project had the potential to be completed in its entirety this year.

In order to analyze and design various components for the solenoid, a relationship was developed between the motion of the kite and the motion of the magnet. As evident in equation 2, the power induced from a solenoid is dependent upon the change in magnetic flux. The change in magnetic flux increases with higher velocities from the magnet. As a result, the team began to develop a single relationship from the kite down to the solenoid.

The first step for developing the relationship involved measuring the dimensions of an existing kite: Tantrum 220 Prism Kite. The team selected this kite for sizing in the event that the team was ahead of schedule and could connect the solenoid subsystem to the kite subsystem. Using aerodynamic equations and principles, the coefficients of lift and drag could be obtained for various suitable angles of attack. To determine the forces of lift and drag acting on the kite, the team needed to find a way to produce a wind velocity dataset. Luckily, the team was able to find a wind velocity dataset from the German Climate Computing Center (GCCC /DKRZ) [7]. The dataset takes the average of wind velocity every six minutes and yields a range of average wind speed from 2-15 meters per second.

Several boundary conditions were drawn to aid in the development of the relationship. For example, the minimum velocity for flight is found when the lift is equal to the weight of the kite. By taking the difference between the maximum velocity found in the dataset and the minimum velocity for flight, the team was able to determine the greatest relative change in velocity the kite may experience. With the maximum change in velocity determined, the forces of lift and drag could be found and approximated. Below are the initial results from aerodynamic analysis. It should be noted that these values represent the extremes, low and high that could possibly act on the kite.

Table 5: *Aerodynamic and Kite analysis*

Minimum wind speed	**0.49 m/s**
Maximum wind speed	**15.2 m/s**
Maximum speed change	**14.6 m/s**
Maximum Resultant Force	**650 N**
Average Solenoid Length	**0.25 m**

Since the magnet and kite are linked through a tether, it was assumed that the motion of the kite and magnet must be similar. The team assumed that there were no energy losses in the entire system i.e., elasticity of the tether, inertial effects at the high and low peaks of motion. In doing so, the team could conglomerate all the relationships developed into one through the work-energy theorem. Using the force interactions of the kite with the obtained wind velocity data set over varying times allowed the team to determine the optimal length of the solenoid. With a solid approximation for the length of the solenoid the team could now move forward with selecting the best wire diameter for wrapping the solenoid. Sizing the solenoid utilizes the equations found in the targets and metrics sections as well as a simple understanding of how the wire will be wrapped and layered on circular pipe [6].

The team evaluated the power generated by the solenoid for varying AWG wire diameters for a fixed weight of copper wire. Evaluating the aforementioned equations, the team found that it would be best to use a large diameter wire that is short in length. The weight of copper was adjusted so that it the number of layers was an even integer so that the lead in and lead out of wire were at the same end of the solenoid. The team was also informed about the fabrication of square wire instead of traditional circular/stranded electrical wire. Comparing the two proved that square wire is always better for the application of generating power and carrying an electromotive force shown in the plot below. The subsequent table breaks down the square wire diameter selected and its electrical specifications.

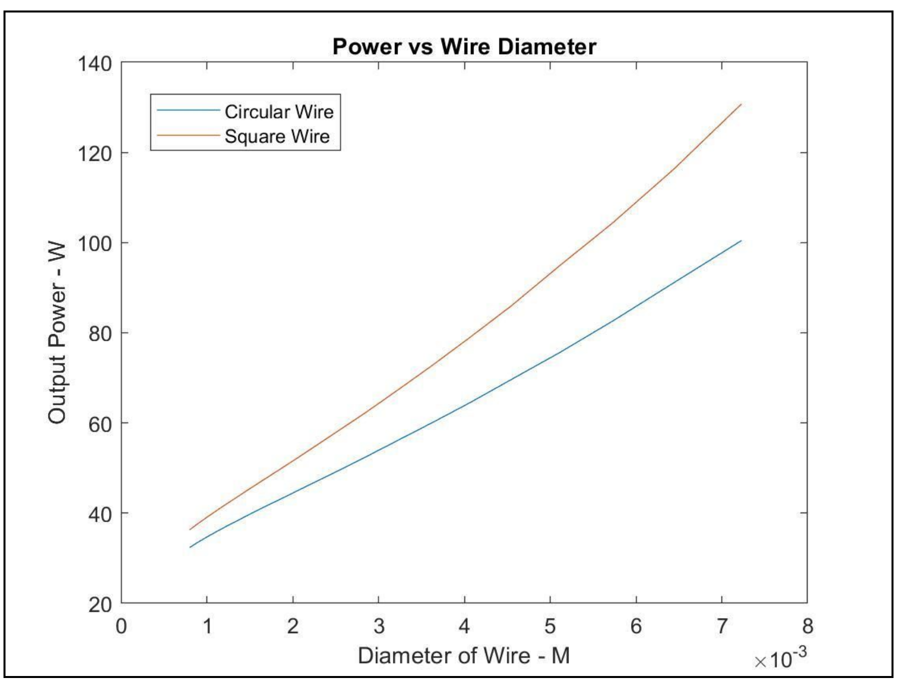

Figure 6: Solenoid power output - square vs. circular wire.

Table 6: *Initial solenoid electrical specifications*

Wire Diameter	**7.35 mm**
Voltage	**0.97 V**
Current	**136.98 A**
Resistance	**7.10 mΩ**
Wrappings per layer	**17**
Layers	**4**
Total Wrappings	**68**
Projected Power Output	**133 Watts**

With all the information gathered, the team purchased all of the necessary materials in order to construct the CAD generated prototype. Some items were either personally manufactured, 3D printed, or purchased. Below is a table of the parts used and purchased.

Table 7: *Cost Breakdown of Prototype*

Part	Cost	Form of Fabrication
3” Neodymium Magnet	Free	Previous Year
DC Motor	Free	Previous Year
Tantrum 220 Prism Kite	Free	Previous Year
26 Pound AWG 1 Magnet Wire	$310	Purchased
11 Pound AWG 18 Magnet Wire	Free	Exchanged AWG 1 Magnet wire with MAGLAB
Sch 40: 3” x 2’ PVC Pipe	$8	Purchased
Solenoid Machining Frame	$30	Purchased/Self Fabricated

Multimeter	$50	Purchased
Springs (x5)	$150	Purchased
Wood Plates	Free	Donated
Fiberglass Rods	$5	Purchased
Crankwheel	Free	3D Printed
Square Eye Plates	$5	Purchased
Shipping & Handling	$125	Purchased
Approximate Total Budget Spent	$683	-
Approximate Total Budget Remaining	$1317	-

With the availability of all of the parts mentioned above, construction of the prototype began. Through multiple resources and recommendations at the FAMU-FSU College of Engineering, the team was referred to Lee Marks, and his team of engineers at the coil winding shop in the National High Magnetic Lab (Maglab). With the help of Mr. Marks and his team, the solenoid was able to be fitted for machining. Upon the initial meeting, it was found that the AWG 1 wire purchased was not machinable with a PVC pipe core. The solid AWG 1 was solid and rigid, and machining said wire would exert too great of a stress on the PVC pipe causing rupture. Mr. Marks and his team recommended that in order to use AWG 1 wire, the team would need a solenoid core of stronger material that is either non-ferrous and non-conductive material or change the diameter of the solenoid core.

The team either needed to redesign the solenoid core or utilize different magnet wire. For the sake of time and cost, the senior design team and the machine winding shop agreed that using a smaller wire that was more flexible. While a smaller diameter wire conflicts with the goal of maximizing generated power, the team decided to move forward with construction of the prototype to validate Mr. Phipps patent and its proof of concept. Additionally, Mr. Marks offered to trade available AWG 18 wire for the already purchased AWG 1 wire. Machining consisted of a lathe spinning the PVC pipe with the magnet wire fed through a mechanical arm. At each turn of the lathe, the arm would tick over by the preset diameter of the wire to ensure the wire would assemble neatly and that the number of wraps were maximized. The table below shows the new wire diameter, wraps and electrical specifications.

Table 8: *Solenoid electrical specifications*

Wire Diameter	**1.016 mm**
Voltage	**33.48 V**
Current	**1.04 A**
Resistance	**32.2 mΩ**
Wrappings per layer	**244**
Layers	**6**
Total Wrappings	**1,464**
Projected Power Output	**35 Watts**

With the solenoid properly wrapped up, the team began to assemble to remaining parts of the prototype. The team started with the wood baseplates, carefully attaching them to the existing solenoid. The motor, flywheel, and spring were then mounted on the base plates producing the final prototype shown below.

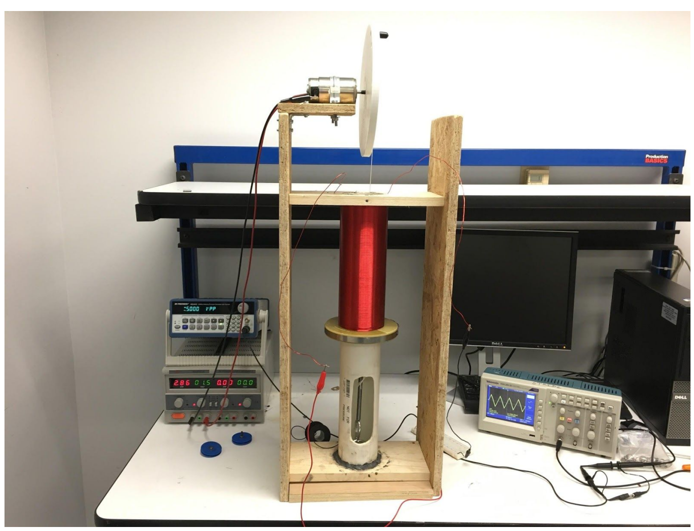

Figure 7: Solenoid prototype connected to oscilloscope for experimentation.

Results

The team initially designed the prototype so that the DC motor could simulate the mechanical motion of the kite. The current team assumed that when the previous design team used the motor and magnet, the motor was strong enough to lift the magnet. Unfortunately this was not the case when evaluating the output power of the motor and the weight of the magnet. Additionally the team believes that the 3D printed flywheel does not carry enough rotational momentum to keep the magnet in any oscillatory pattern. As a result, the team has to develop alternative methods to determine what magnitude EMF the solenoid could produce.

The following two experiments were developed: 1) a magnet was oscillated through a flywheel pendulum 2) forced oscillation by manual input at different rates. The flywheel pendulum began with the magnet connected to the flywheel, held at the topmost position and subsequently released to begin its motion. The magnet oscillated back and forth displaying an exponential decay of motion. For the other experiment, a metronome acted as a timer for the frequency of oscillations for the experimenter moving the magnet. Both of these experiments were measured via an oscilloscope as seen in the figure 8 above. The motor stalling forced a change in experimental design, increasing the margin of error and irregularity of experimentation. It should also be noted that the magnet used in these experiments was at roughly half its original size due to an accident during construction of the prototype. Nonetheless, the experiment produced valid results shown in the tables and plots below.

Table 9: *Experimental Results from Variable Frequency Tests*

Parameters	**0.60 Hz**	**0.75 Hz**	**1 Hz**	**Drop**
Energy Produced (J)	**0.218**	**0.204**	**0.329**	**0.173**
Energy Expected (J)	**3.418**	**1.897**	**2.932**	**0.570**
Efficiency	**6.37%**	**10.77%**	**11.21%**	**30.35%**
Max Peak to Peak Voltage (V)	**4.00**	**5.16**	**6.28**	**7.76**

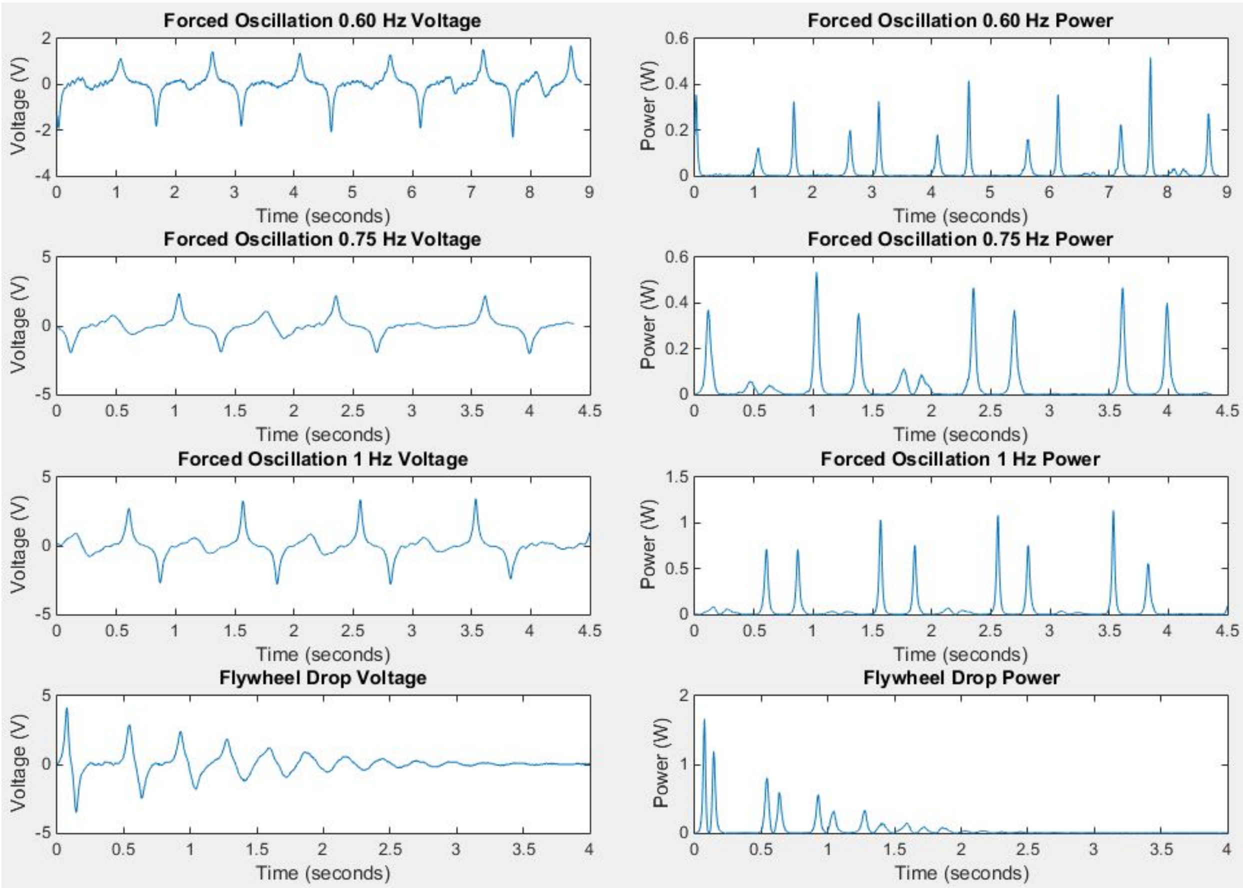

Figure 8. Voltage (left) and Power (right) curves for variable frequency experimental tests.

The table above shows the experimentally determined work of the magnet (Energy Expected) and the output energy from the solenoid (Energy Produced) to ultimately find an efficiency of this prototype solenoid generator. The table also shows the maximum peak to peak sinusoidal voltage produced by the working magnet which can also be seen in figure 8. It should be noted that the total time period of all experiments varied in length and attributes as to why some parameters have a higher expected energy vs system efficiency. When analyzing the data from the forced oscillation experiment, one particular trend that was obvious was the effect of the frequency to the max voltage produced and efficiency of the solenoid. The greater the frequency of the moving magnet, the greater the voltage, output power, and efficiency.

This consistent data trend proves the hypothesis from the team before experimentation that is, the velocity of the magnet is proportional to the power output which can also be seen in the pendulum experiment. This can also be mathematically understood in equation 3 where the EMF generated is proportional to the change in magnetic flux with respect to time. A rapidly moving magnet would be inducing a greater change in magnetic flux vs a slower moving magnet. When evaluating the drop experiment, the overall efficiency was found to be 30.35%.

When compared with the fastest forced oscillation, the pendulum proves to be nearly triple in its efficiency. While this data may seem to counter-intuitive, it's important to analyze how the experiment was performed. The magnet used in the experiment was moved by a threaded string. Since it is not possible to push a string, it can be inferred that there is some energy lost through an inelastic bounce of the magnet when the direction of motion is quickly changed. In the pendulum experiment, the magnet was allowed to move more freely once it reached the base of the solenoid as its potential energy was not as greatly disturbed compared to the forced oscillation experiment. The undisturbed natural decay of the voltage generated allowed for an overall greater efficiency.

Discussion & Future Work

Although this project involves both a kite and power generation, there was only enough time to design and optimize one subsystem of the patent. Mr. Phipps expressed his preference for the solenoid generator, prioritizing proof of concept and the overall feasibility of his patent. Analysis has been performed on the kite through modeling but with the timeline given and the sponsor's prioritization of the generator, the kite and tether were not connected to the rest of the system.

From the data collected on the experiment of the solenoid power generator, the results definitely warrant further investigation. The moving magnet ultimately was able to produce a voltage in all methods of experimentation. Additionally, there was a noticeable positive trend in magnet velocity, efficiency, and peak voltage generated. This noticeable trend calls for more experiments for optimal development of a solenoid power generator. The first would be to improve upon the initial form of testing. The team recommends that the experiment be performed with a solid, non-damaged magnet with a consistent magnetic field. Furthermore, the team recommends finding a better system for simulating the kite motion. The implementation of a stronger motor with higher torque, a flywheel that will carry efficient rotational momentum and a rigid linkage for the moving the magnet are a start. However, the idea of integrating a completely new system for kite simulation maybe more beneficial. A device that can generate the fastest motion of the magnet with the least amount of inelastic losses should be considered.

Another experiment that should be considered is comparing two solenoids of the same weight but at different wire diameters. The two solenoids will differ in all electrical parameters and will allow for confirmation that wire diameter affects power output. Additional work needs to continue on how to model the interacting magnetic fields when the magnet is moving. From *Lorentz,* the result of generating a voltage induces a magnetic field. In the case of the solenoid, the magnetic field opposes the motion of the magnet. Determining how that variables at play for the net magnetic field will further confirm results from experimentation.

When true understanding of the solenoid design is achieved and efficiency of the magnet motion is increased, future work should focus on the development of the kite. The current solenoid prototype is designed for eventual integration of the kite subsystem. In the event that future teams continue to directly connect the tether to the magnet, the spring system is already accounted for. The future team will need to find additional methods to secure the solenoid to the ground when the connected system is operational. Ultimately, the design of the kite will dictate the power generated. An optimally designed kite could potentially increase the forces of lift and drag on the tether, providing a larger resultant force which will result in a faster moving magnet. Testing of either the Tantrum 220 Prism Kite or future purchased kites should be modeled through a wind tunnel to maximize the analysis of the output resultant force. To enhance the overall design, attention should be employed on reducing friction/drag, and maximizing the mechanical motion of the magnet within the solenoid. Future work of the overall system also includes the integration of an electrical subsystem. This subsystem will provide the generator the ability to convert from ±AC to +DC power with the potential to incorporate a battery storage system if that is an interest of the customer. Once these modifications are implemented, additional analysis should be performed in order to fine tune and increase the overall system efficiency.

<u>Conclusion</u>

The team was able to achieve the project goal of producing a working prototype using sponsor Jeff Phipps' patent, proving that oscillating a magnet in a solenoid induces a voltage. Even though the project was successful, the experimental findings warrant further investigation. More test would be necessary in order to attain a wider range of data. Calculated efficiencies from the forced oscillation experiments (6% - 11%) indicate that this design may prove to be a viable clean energy production method. Current efficiencies of traditional wind turbines (24%) are still significantly higher than the current model of the solenoid generator. However, the greatly increased portability and reduced cost of the solenoid kite generator makes up for the loss of efficiency. Some modifications would be necessary in order to make this design competitive in the marketplace. Namely, the efficiency of a solenoid generator is inferior to that of a transmission and alternator, especially in power production and energy conversion. Depending on the intended scale, the current model may not provide sufficient power for the needed cost and work input. The team would recommend further testing and analysis of scaled models in order to more accurately evaluate the scalability and marketability of the sponsor's patent.

References

1. Phipps, Jeffrey Sterling. Kite System for Generating Electricity. Phipps, assignee. Patent 9,013,055. 21 Apr. 2015. Print.
2. "Makani Kites: Airborne Wind Energy." *Makani,* Google, x.company/makani/.
3. "Skysails: A Compelling Technology." *Skysails,* skysails.info/english/power/power-system/
4. "Altaeros Technology". *Altaeros Energies,* altaerosenergies.com/technology.html
5. "The height of wind energy." *Kite Power Systems*, http://www.kps.energy/technology/
6. "Magnetic Field/Magnetic Interaction Electromagnetism Introduction". Haplo Sciences, http://onlinephys.haplosciences.com/magnetism.html
7. DKRZ long term archive. (n.d.). Retrieved February 27, 2018, from https://cera-www.dkrz.de/WDCC/ui/cerasearch