Design and Testing of Power Cycle Concepts for the WPI Kite-Powered Water Pump

A Major Qualifying Project Report Submitted to the Faculty of

WORCESTER POLYTECHNIC INSTITUTE In partial fulfillment of the

requirements for the Degree of Bachelor of Science by:

Jessie Ciulla (ME)

Abdulrahaman Jilani (ME)

Joseph Samela (ME)

John Scarborough (ME)

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Approved: ______________________________

Prof. David Olinger

Abstract

The goal of this MQP project was to continue the design and testing of the Rotary WPI Kite-Powered Water Pump for use in developing nations. This rotary water pump uses the pumping concept for airborne wind energy (AWE) systems where an ascending kite pulls on a tether attached to a rotating wheel, gear mechanism, and water pump axle on the ground. The kite is then retracted to its original altitude using a second kite or separate retraction system. The desired water pump would be low cost, operational under variable wind speeds and for different kites, including for one- or two-kite systems. There were multi-faceted goals for this project. First, we designed a support for the water pump that could be incorporated into the existing A-frame design, which greatly improved the structural integrity of the system. We improved the housing for the power spool to allow for a stall spool and brakes, which will allow for more flexibility in future designs. We improved the vertical pump shaft connecting the windmill pump to the underground pump cylinder, which allowed for more accurate water pumping data. Solidworks, a CAD software, was used to design all parts, and a program was developed to calculate variables within the airborne wind system such as required kite (tether) force at a certain wind speed or spool size. The final design was lab and field tested, and recommendations for future design changes were made.

Acknowledgments

We would like to thank our advisor Prof. David Olinger for his encouragement and guidance during our project. We'd like to thank the staff of the Blue Hills Observatory in Milton, MA for being accommodating and letting us use their facility for testing as well as the Blue Hills director Don McCasland for his ideas and expertise. Additionally, we would like to thank Brookwood Farm in Milton, MA for letting us use their grounds for flight testing.

Authorship

This project and paper represent the equally distributed workload of Jessie Ciulla (ME), Abdulrahaman Jilani (ME), Joseph Samela (ME), and John Scarborough (ME).

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Chapter 1: Introduction

In 2014, The World Health Organization stated that:

> *"More than 700 million people still lack ready access to improved sources of drinking water; nearly half are in sub-Saharan Africa".* (WHO, 2014)

Most people without access to clean drinking water come from impoverished rural communities. One common solution is the installation of a pump to access underground aquifers. These pumps operate electrically, manually, or with wind turbines. In places with limited access to power, electric solutions are not viable. Manual pump operation prolongs the amount of time spent collecting water and detracts from time the operator could spend pursuing a sustainable livelihood. Wind powered pumps don't need electricity and can operate autonomously; however, current designs require turbines that are expensive to construct and maintain.

Many communities lack the financial and technological resources necessary to upkeep the types of water pumps mentioned above. This establishes the niche for a low-cost, wind-powered pump that is simple to construct, operate and maintain. The goal of this Major Qualifying Project (MQP) was to utilize AWE concepts to forward development and construction of a low-cost water pump for communities in underdeveloped nations.

Airborne wind energy, commonly abbreviated as AWE, generates power from the wind by means of a tethered kite or rigid wind glider in favor of stationary turbines. AWE systems have the ability to operate at altitudes much greater than industry's tallest wind turbines (Schmehl, 2013). In addition, AWE systems can operate at variable altitudes, which allow them to move where the wind is strongest. Like stationary turbines, AWE systems can operate autonomously but are less expensive to construct per unit of output energy (Schmehl, 2013).

Companies around the world are pursuing innovation in the AWE space. For example, the Italian company *KiteGen Research*, who specializes in electric power generation, claims AWE is “a radically new and innovative concept that may be the most practical and effective solution…to the world’s energy needs” (KiteGen, 2010). *Makani Power,* another developer of AWE technology, was purchased in 2013 by *Google* now operating as a part of *Google[X]* with the goal of making “energy kites and widespread clean energy a commercial reality” (Makani, 2015). NASA's Langley Research Center developed a working kite-power prototype that achieved the world’s first sustained autonomous flight using only ground-based sensors (D. Quick, 2012).

Groups of students at Worcester Polytechnic Institute led by Professor David Olinger have completed over ten MQPs investigating various aspects of AWE. The work completed by previous MQPs provided a starting point for us to improve upon the current system design. We focused our project on two particular subsystems.

Our final prototype (Figure 1) is made up of the following:

1. An A-frame, modified from a previous MQP project, to support a windmill style pump and house our tether management system.
2. A double spool tether management system with full manual retraction and automated retraction potential designed to withstand the forces associated with sustained flight.

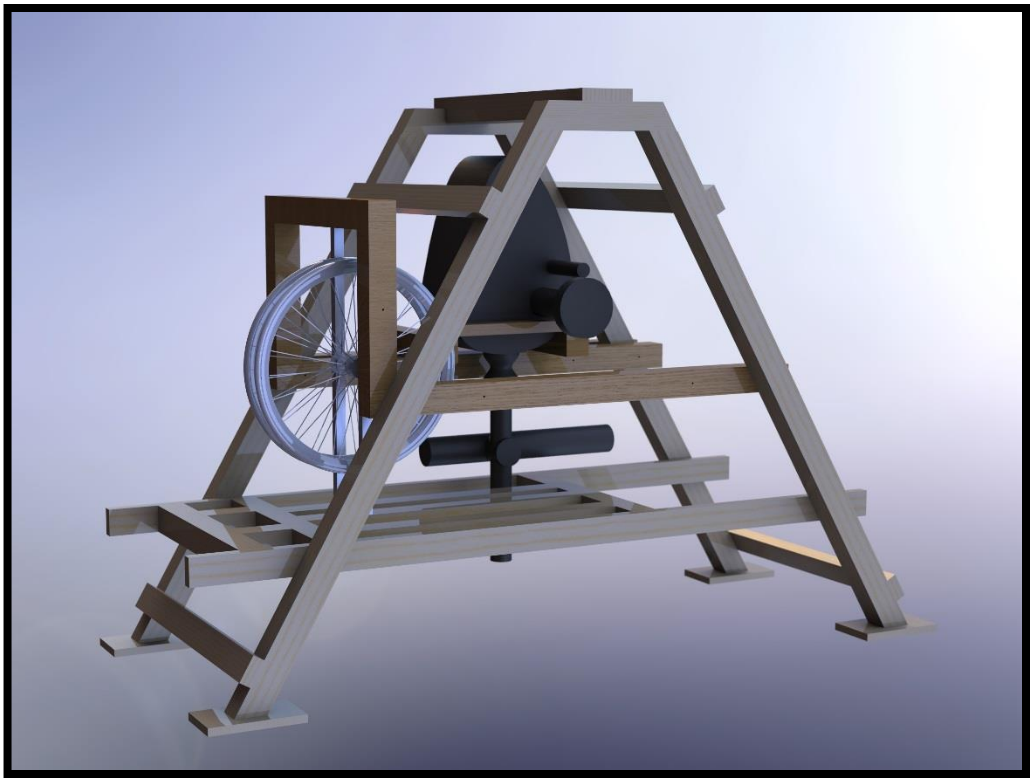


Figure 1: Rotary Kite Powered Pump

In the following chapters, we will discuss the need for AWE as a sustainable and efficient power source, the theory behind our project, our design and testing methods, and the results gleaned from this project.

Chapter 2: Background

The purpose of this section is to identify the need for kite powered water pumps, specifically in Sub Saharan Africa. The section also details the progress of airborne wind energy, both in industry and research. Additionally, the section discusses the previous projects at WPI that focused on airborne wind energy technology.

2.1 Water Need in Sub Saharan Africa

In Africa, 358 million people lack access to drinking water (U.S. Department of Energy, 2015). They rely on government and international aid programs to implement potable water solutions, or consume water that is unsafe to drink. According to the International Food Policy Research Institute, regional water scarcity in Sub-Saharan Africa is due to mismanagement of water resources (U.S. Department of Energy, 2015). This means that there is not always a physical lack of water; rather, areas often do not invest enough in water resources and do not have substantial human capacity to properly meet water demands in areas where the population cannot finance a potable water resource on its own (Manwell, 2010). Oftentimes, impoverished communities do not have the infrastructure or education to implement lasting water collection systems. Systems available to them are expensive or difficult to maintain, and aid programs often fail to create sustainable systems that can be supported by community operators.

For these reasons, communities in Africa need an inexpensive, accessible water solution. Airborne wind energy systems could just that. They are inexpensive compared to ground-based wind turbine pumps, are easy to construct, and do not require a skilled operator.

African Aquifers

Airborne wind energy systems in Sub-Saharan Africa would ideally operate a water pump drawing from an underground aquifer. An aquifer is underground water source, lying in rock, which is large enough to be exported in bulk. After ice sheets and glaciers, groundwater is considered to be the second largest freshwater source. However, aquifers are often underutilized because of their location and inaccessibility (Abramowski et all, 2000). In Sub-Saharan Africa, groundwater is plentiful but education and programs to utilize it are severely lacking (Ahrens, 2013). See figure 2 for a map of Sub-Saharan Africa aquifers.

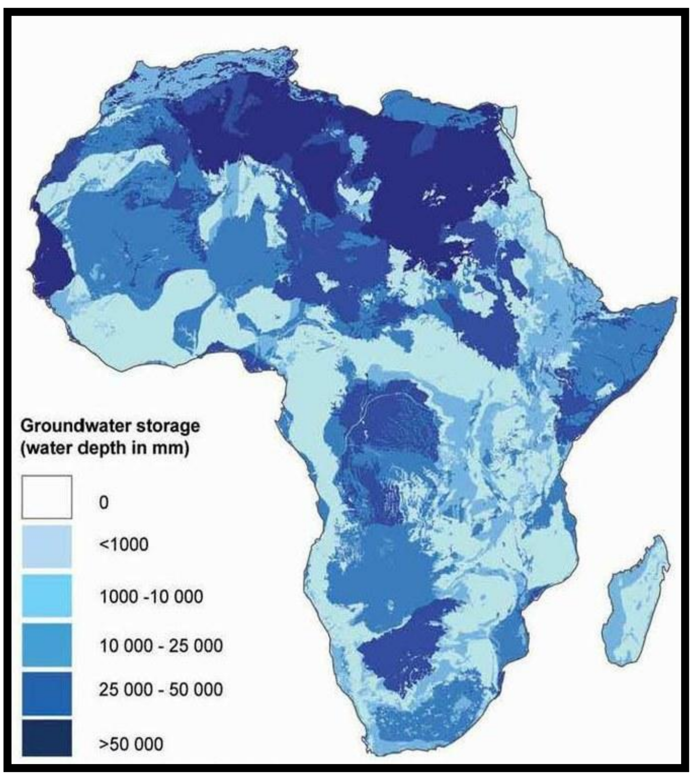


Figure 2: Boundaries of Surficial Geology of Africa, (British Geological Survey, 2011)

With proper development of and investment in airborne wind systems to pump water in Sub-Saharan Africa, the water crisis could be alleviated.

Sub-Saharan Africa Wind Distribution

Wind projects are emerging in Sub-Saharan Africa due to the immense potential for wind-powered generation in the area (Manwell, 2010). These projects are mainly targeting Africa's energy crisis, but are not yet improving the state of the continent's water needs. Existent high winds and open areas provide an excellent ground for the development of airborne wind energy as a resource to aid in collecting potable water. See figure 3 for a map of the average wind speeds in Sub-Saharan Africa.

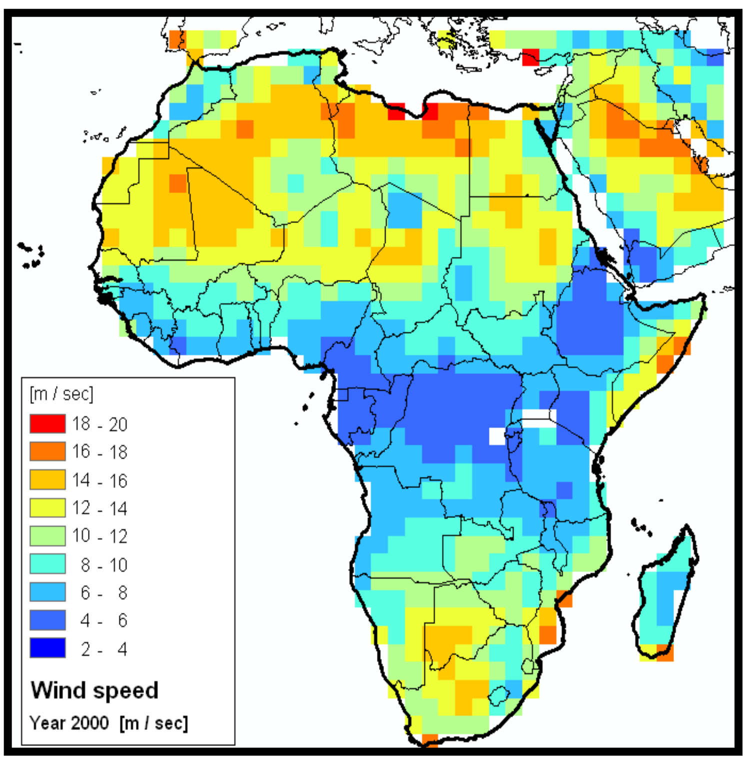


Figure 3: Princeton University: Experimental African Drought Monitor

Airborne wind energy systems can function in wind speeds at or above those seen in the figure above. Additionally, these systems fly higher than traditional wind turbines, so would likely experience higher gusts than this figure shows (Jasper, 2000).

2.2 Airborne Wind Energy

Harnessing Energy from Wind

Wind energy is one of the fastest growing energy sources in the world (U.S. Department of Energy, 2015). It is a form of solar energy, and is a globally available energy source (Manwell, 2013) Harnessing energy from the wind is an attractive method of energy generation because it is a clean, sustainable, cost-effective energy source (U.S. Department of Energy, 2015). Already, many companies are investing research and development for wind energy resources. Due to its benefits, wind energy generation is being investigated in developing countries such as Morocco and Namibia, who are consider the potential of wind energy in their energy profile. However, developing countries often lack the education and resources necessary for successful wind programs (Jasper, 2000).

Wind Energy Generation

There are numerous methods of harvesting energy from the wind. This paper will pursue airborne wind energy (AWE) using a kite. This method flies a kite in a crosswind direction to harness power (Ahrens, 2013). Although stationary wind turbines are traditionally used in wind energy generation, airborne wind energy is advantageous for several reasons. Wind speeds are often significantly higher as altitudes increase. For this reason, airborne wind energy systems excel over traditional ground-based wind turbines because they have a greater range of operational altitudes. In summary, AWE systems have high and variable flight altitudes, are accessible in developing nations, and have greater power generation per dollar than turbines. These benefits make AWE an important technology that has the potential to greatly impact wind power generation.

Airborne wind energy can be harnessed in two ways: on-board and ground-based power generation. While both have advantages and disadvantages, this project chose to utilize ground-based power generation due to the intended application of the system. The intended system does not generate electrical power; rather, it transfers mechanical energy to drive a water pump. For this reason, it is impractical to pursue on-board power generation in the scope of this project. Ground-based generation does not require electrical power transmission from the kite to the ground and uses tension in the kite tether to drive an electric generator. For this design to be operational, the kite tether must be periodically retracted, creating a power cycle during which the tether rotates a spool on the ground[4].

Airborne Wind Energy Industry

Between 1970 and 1980, airborne wind energy developed both technically and conceptually due to the energy crisis that began in 1970. Various engineers made contributions to AWE designs, but after 1980, most wind energy development focused on ground-based, conventional wind power generation.

After 2000, airborne wind energy research gained momentum once again due to advanced tether and control technologies. By 2013, there were about 50 institutions working on airborne wind energy. Amongst these institutions, notable contributors to the advancement of AWE are *SkySails*, which developed the first commercially available kite system; *Makani Power*, who focuses on rigid wing systems with on-board generation; and *KiteGen*, which developed a system based on a dual line surf kite. Additionally, there is an annual conference that meets every year to discuss the growth and development of airborne wind energy. AWE is sustainable and practical, and will ideally be promoted with the dedication of institutions and companies such as those mentioned above.

There are currently no AWE systems attached to the grid for energy production. AWE is not developed enough to produce enough energy, reliably, for access at peak demand. Nevertheless, airborne wind energy devices are becoming more efficient, advanced and less costly to make.

2.3 Previous Projects in Airborne Wind Energy

The study of kite power at WPI began in 2007 and about twelve total projects have worked on the design of low-cost airborne wind energy systems for developing nations. These projects have focused on design improvements, applications, and intensive testing. All have helped make airborne wind energy a more feasible reality for WPI kite power. Summarized in the table below are the major accomplishments from each of the WPI projects pertaining to wind energy, and the students who worked on the projects.

Year	IQP/MQP Title	Main Accomplishments	Author(s)	Reference Citation
2007	Wind Power From Kites MQP	Designed and constructed the basic A - frame structure and rocking arm. Selected kite for use in power generation based on testing and mathematical analysis. Ran simulations based on steady state and dynamic theory of the tested kites.	• Michael Blouin • Benjamin Isabella • Joshua Rodden	Blouin et al. 2007
2008	Kite Power for Heifer International's Overlook Farm IQP	Developed educational exhibits on kite power for use at the Heifer International's Overlook Farm site.	• Gabriel Baldwin • Peter Bertoli • Taylor Lalonde • Michael Sangermano • Nicholas Urko	Baldwin et al. 2008
2008	Design of a One Kilowatt Scale Kite Power System MQP	Completed and tested the demonstrator which was able to generate power as well as autonomously keep the kite aloft for a short period of time. Performed stress analysis in Cosmosworks and ran power generation simulations in MATLAB.	• Ryan Buckley • Christopher Colschen • Michael DeCuir • Max Hurgin • Erik Lovejoy • Nicholas Simone	Buckley et al. 2008
2009	Development of a Wind Monitoring System and Grain Grinder IQP	Designed a balloon mounted wind monitoring system using an anemometer. Implemented a small grain grinder to be attached to the power converter on the kite power system.	• Deepa Krishnaswamy • Travis Perullo • Joseph Phaneuf	Krishnaswamy et al. 2008
2009	Design of a Data Acquisition System for a Kite Power Demonstrator MQP	Designed data collection system for physical attributes of the system as well as for power generation. Designed secondary power generation and oscillation control subcomponents. Further optimized rocking arm and A-frame as well as tested each system and subcomponent.	• Lauren Alex • Eric Restefano, • Luke Fekete • Scott Gary	Alex et al. 2009
2010	Design of a Dynamometer	Designed and built a dynamometer used to measure torque and power.	• Kuthan Toydemir	Toydemir, 2009

	For The WPI Kite Power System MQP			
2010	Re-Design and Testing of the WPI Kite Power System MQP	Modified system: Used a more stable and larger sled kite. Upgraded gear shaft. Built mechanism to change angle of attack of kite. Measured tension of kite tether during testing.	• Adam Cartier • Eric Murphy • Travis Perullo • Matthew Tomasko • Kimberly White	Cartier et al. 2010
2011	Design of a Remote Controlled Tether System for the WPI Kite Power System MQP	Developed wireless system to remotely control trailing edge lines of kite to alter angle of attack and side-to-side motion. Designed a control box with two motors, gear boxes, transmitters, and two spools to control the length of trailing tethers.	• Michael Frewin • Emanuel Jimenez • Michael Roth	Frewin et al. 2011
2012	Design of a Kite Powered Water Pump and Airborne Wind Turbine MQP	Redesigned system to add a mechanical water pump and head simulation valve. Initial design and testing of Airborne Wind Turbine.	• Kyle Bartosik • Jennifer Gill • Andrew Lybarger • Daniel Nyren • John W Wilder	Bartosik et al. 2012
2013	Re- Design of the WPI Kite-Powered Water Pump and Wind Turbine Systems	Altered transfer arm. Modified sliding weight mechanism. Added adjustable weight to rocking arm. Added a ground-tether. Redesigned lightweight, airborne wind turbine.	• Valerie Butler • Jeffrey Corado • Kimberly Joback • Bryan Karsky • Matthew Melia • Robert Monteith • Brandy A Warner	Butler et al. 2013
2014	Optimization of the WPI Kite Powered Water Pump	Performed extensive field testing on the kite system. Created a functioning VI in LabVIEW for data acquisition. Created a simulation using Matlab to model random wind speeds. Design a portable trailer system.	• Aaron Durkee • Christopher Ettis • Dong Kim • David Levien	Durkee et al. 2014
2015	Design and	Designed a new mechanism to transfer	• Caitlin Chase	Chase et al.

	Testing of Kite-Powered Water Pump Concepts	the energy from the kite to the pump using a bike wheel.	• Lindsey DeLuca • Aaron Marshall • Ronald Mazurkiewicz	2015

Figure 4: Table of Previous Projects

Field Testing

Field testing is a crucial part of this MQP to validate the design process and lab testing. While the design may function to specifications in lab, it is entirely different with varying wind speed and direction and without the convenience of an entire lab to improve upon design flaws encounters while testing in the design process and the feasibility assessment of the project.

For this project, all testing was completed at Blue Hills Weather Observatory in Milton, MA and Brookwood Farm in Milton, MA. Both of these locations offer consistent wind speeds and open spaces, and permitting was obtained for testing at both sites. The observatory is at an elevation of 635 feet, which generally provides higher wind speeds than those found at sea level. This location was ideal for testing how the kites flew, and which of the two kites (PowerSled81 or Rokkaku) would be better suited for the project's current application. Brookwood Farm has more space for orienting the trailer and launching the kites from the pump. For both locations, it is pertinent to avoid situating the trailer anywhere that could cause the kite string to become tangled in trees, buildings, or other landmarks. Proper precautions must be taken to ensure that the trailer is oriented such that the kites will fly into the wind and not be obstructed. Both locations allow for trailer storage between test dates.

See below for an image of the pump situated on the trailer during the October 10, 2015 testing date at Brookwood Farm.

Figure 5: WPI students operating Kite-Pump from trailer

Once the trailer is in position, the gates on the trailer are let down. The kite is then walked out to its launching position and laid on the ground. The team connects the kite to the pump, and launches the kite into the wind. Upon a strong gust of wind, the team members holding the kite will let go, and the person holding the line will pull in the direction of the trailer in order to help the kite reach its flight altitude. Once the kite is in stable flight, the team moves to the trailer to view flow rate and overall pump functioning.

Testing Conditions

To ensure successful testing, testing conditions must be taken into consideration. These conditions include wind speed and weather. The day should be clear with no risk of lightening. The wind must be around 15 mph. Too low a wind speed will not allow the kite to fly, while too high a wind speed could damage the kite and pump. Before testing, the team also ensured that the kite was not damaged or ripped in any way.

Safety Precautions

While testing the system, it is important to follow proper safety precautions to avoid accidents or injury. System operators should wear gloves so that they do not get rope burn from controlling the kite's power or stall lines. They should wear proper shoes for launching and recovering the kite on a mountain or uneven field. Operators should also wear protective hats in the event that the kite crashes in their vicinity.

Current Design

The WPI Kite Power project has been under development for many years and is constantly changing design to accomplish various objectives to ensure its success as an airborne wind energy producer. Although the current design goals differ from past designs, it is crucial to understand what considerations were made in the past to ensure a successful and functional design.

Rocking Arm Design

One functional iteration of the system consisted of an A-frame (1.), a rocking arm mounted at the top (2.), a kite, a pump (3.), and a portable trailer (4.). The trailer allows for field-testing in various locations. See figure below for a visual representation of the previous system.

The project uses a PowerSled 81 kite, which is attached to the end of the rocking arm by a tether. This functions as the main power line. The kite has three cells that help create lift, and support rods to ensure the kite keeps its shape in flight. There is a stall tether attached to the rocking arm so that when force is applied to this tether, the kite collapses and loses altitude. This feature controls the power phase of the system. The rocking arm is attached to the pump, which pumps as the kite loses and gains altitude. The following figure shows the system design.

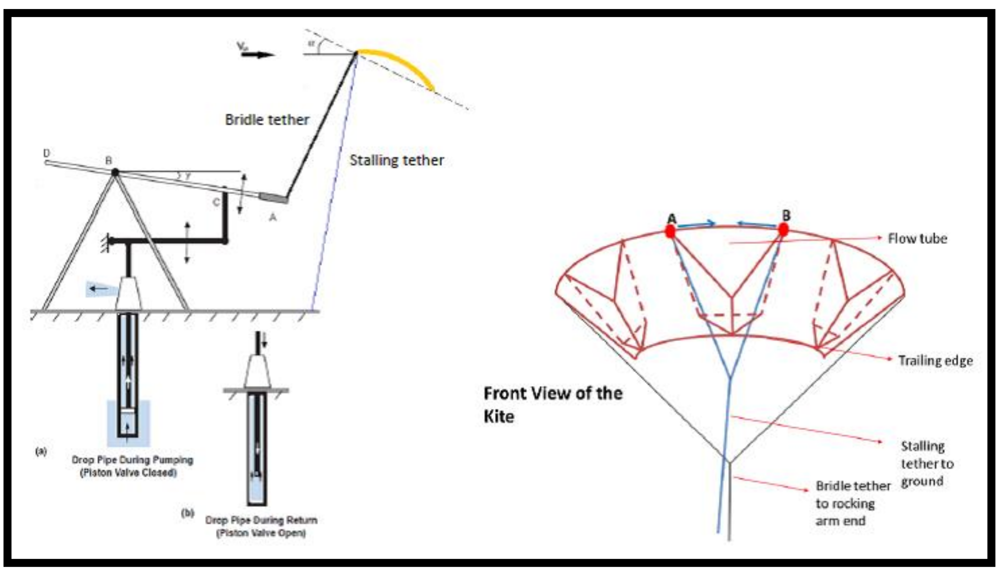


Figure 6: Rocking Arm System Design (Chase et al., 2015)

Rotary Kite-Power Water Pump

A newly implemented system design consists of a kite, spool, A-frame, pump, and trailer. This system differs from the previous system because of the method by which the kite drives the pump. The main tether line of the kite is wrapped around a spool on the A-frame. The kite's stall line tether remains on the ground and is manually manipulated in order to control the kite in flight. In the current design tension on the kite's main tether rotates the spool it is fed from. A gear attached to the spool wheel in turn drives a bicycle chain connected to a gear on the rotary windmill pump shaft. Through this series of mechanical linkages the wind power is transferred into a vertical reciprocating motion of a piston in the shallow well cylinder. In this way each rotation of the rotary pump shaft pumps the displacement volume of the piston within the shallow well cylinder. When the kite has pulled out its maximum length of main tether line where it is stalled by releasing slack in the stall line. This greatly diminishes the lift on the kite and allowed it to be retracted, thereby resetting the cycle.

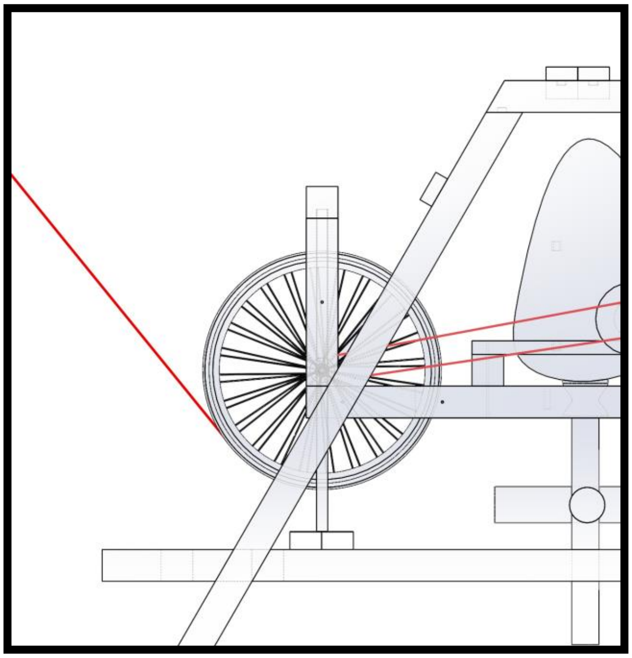


Figure 7: Drawing of Spool Rotary Spool Sub-System

2.4 Specific Project Goals

To continue to develop a low-cost kite-powered water pump for underdeveloped nations, our team developed certain specific project goals. These are:

1. Improve the design on existing WPI kite power system that uses a rotary windmill water pump.
2. Integrate a kite stalling subsystem into the design so that a stall line and spool can induce stall conditions on the kite, thereby substantially decreasing the kite's lift.
3. Design a more stable location for the pump on the A-frame to ensure its stability through testing.
4. Install a manual braking system for power and stall spools.

5. Reconfigure the pump to prevent unnecessary leaking and ensure that the head simulation valve worked effectively.
6. Write a program that can iteratively calculate tether tension, torque, volumetric flow rate with prompts for existing conditions.

With these project goals, our team worked to design, build, and test various parts of the system to ensure its proper functioning.

Chapter 3: Theory

3.1 System Theory and Overview

The kites chosen for use in the pump system have been of the PowerSled and Rokkaku style due to their stability and simple flight characteristics. Other kites which utilize a crosswind kite movement are capable of generating greater power due to the high flight velocities of the kite and their angling relative to the wind. However, cross wind motion requires sophisticated control systems which would be prohibitively expensive, complex, and difficult to maintain in the predicted conditions in which the kite powered pump system would be deployed. The PowerSled and Rokkaku both follow a simpler flight pattern where the power is generated while the kite extends the tether in a near linear path in the wind direction. In this configuration the kite experiences lift and drag forces like a simple airfoil exposed to the freestream flow of the natural winds in the region of the kite's operation. The lift and drag forces acting upon the kite are balanced by a proportional force acting along the tether line which anchors the kite to the pump assembly.

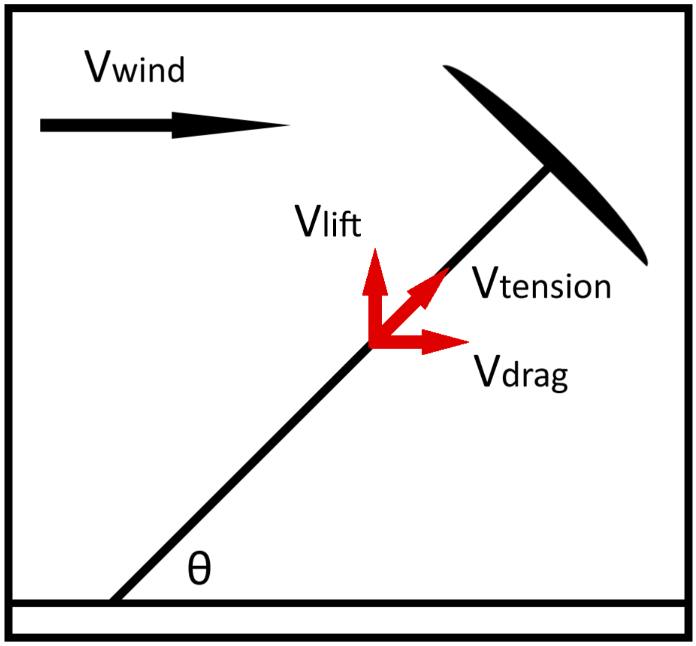


Figure 8: Kite Free Body Diagram

The resultant tension in the tether line induces a torque on the spool assembly. The torque is transferred to the pump via a set of gears attached to the spool and pump respectively and connected via a bicycle chain.

Figure 9: Bicycle Chain Connecting Power Spool to Pump

The torque operating the pump is then converted to forces which induce a linear reciprocating motion of the piston inside the pump cylinder. The reciprocating motion of the pump piston moves the water in the pump cylinder, thereby creating a pressure difference across the piston head. This forces water above the head vertically out of the pump and water from below the head vertically into the pump cylinder. The following sections detail an analysis of each aspect of the system described in detail.

3.2 Tether Tension

In order to appropriately model the flight dynamics of the powersled and rokkaku, a simple kite analysis method was utilized (Loyd, 1982). The following is an outline of the system of equations utilized for calculating the tension in the tether line while the kite is ascending.

First, the optimal tether speed, V_{L}, is derived as one third of the wind speed, V_{W}:

$$V_{\mathrm{L}} = \frac{V_W}{3}$$

The local velocity of airflow over the kite, V_A is calculated with the following relation based off the trigonometric relation between the velocities of wind around the kite:

$$V_A = \sqrt{V_W^2 + V_L^2 - 2V_W V_L cos(\Theta)}$$

Assuming the kite behaves similarly to a flat plate in the airflow, we estimate the coefficient of lift, C_L, based on a flat plate relation for the kite's angle of attack, α:

$$C_L = 2\pi\alpha$$

From the coefficient of lift estimate (C_L), the calculated local velocity (V_A), the known kite area (A) and air density (ρ) we calculate the force of lift (F_L) on the kite:

$$F_L = ½C_L \rho A V_A^2$$

As with the coefficient of lift, we use a known relation for the coefficient of drag (C_D) based on a flat plate relation for the kite's angle of attack:

$$C_D = 1.28\sin(\alpha)$$

From the coefficient of drag estimate (C_D), the calculated local velocity (V_A), the known kite area (A) and air density (ρ) we calculate the force of drag (F_D) on the kite:

$$F_D = ½C_D \rho A V_A^2$$

Next, the available wind power is calculated using the equation laid out in the system for simple kite analysis:

$$P_W = ½\rho V_W^2$$

We utilize the function outlined in Loyd's simple kite analysis to calculate our value for simple kite relative lift power (F_S):

$$F_S = \frac{\left(\frac{V_L}{V_W}\right) \times \left(\sqrt{1 + \frac{1}{(\frac{F_L}{F_D})^2} - (\frac{V_L}{V_W})^2} - \frac{(\frac{V_L}{V_W})}{(\frac{F_L}{F_D})} \right)^2}{\sqrt{1 + \frac{1}{(\frac{F_L}{F_D})^2}}}$$

With the value of F_S, the amount of power harvested by the kite from the total wind power (P) can be calculated with the following relation:

$$P = P_W C_L F_S A$$

Lastly, since the power of the kite can be expressed as $P = V_A T$, Where T is the tether tension and force in the direction of the kite's movement. Therefore, the tension on the tether is:

$$T = \frac{P}{V_A}$$

3.3 Gearing and Torque Transfer

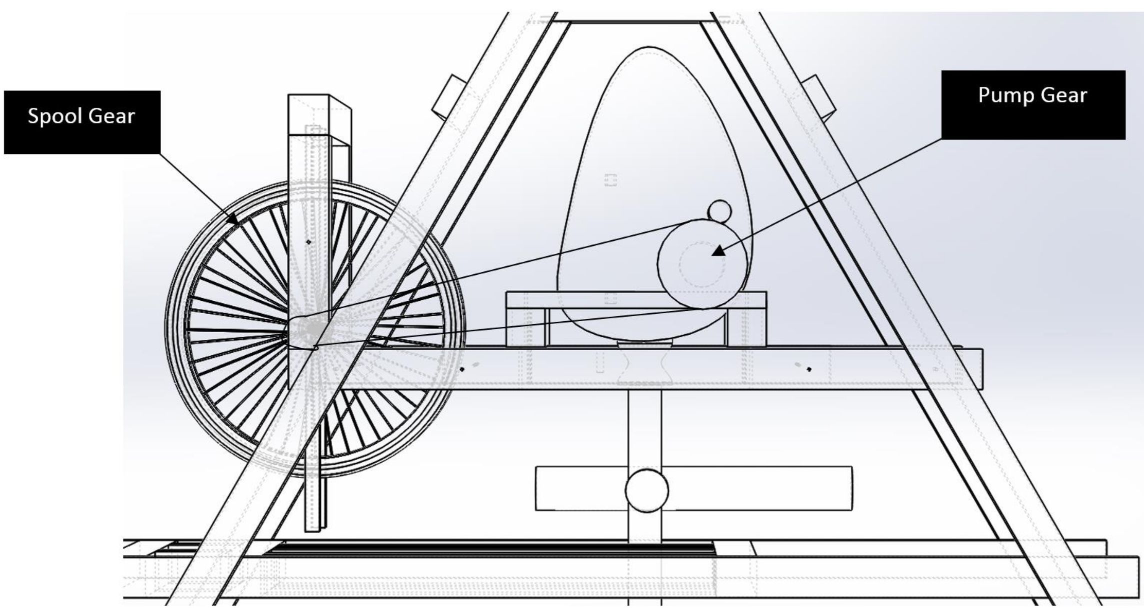
Analysis of the gear system for the transfer of power between the tension applied the power line tether of the kite to the torque applied to the windmill pump assembly is governed by a set of relations between the spool radius, the radius of the gear attached coaxially with the spool, and the radius of the gear attached coaxially with the rotating shaft of the windmill pump. Described below is the set of relations used in calculating the torque delivered to the rotating windmill shaft.

First, the torque applied along the axis of the spool wheel is calculated as the cross product of the radius of the spool and the tension from the kite power line, which is applied tangentially to the outer circumference of the spool wheel

$$T_{spool\ wheel} = R_{spool} \times F_{tension}$$

Since the spool gear is attached to the spool wheel and they share an axis, the torque applied to the spool gear is the same as the torque applied to the spool wheel

$$T_{spool\ gear} = T_{spool\ wheel}$$



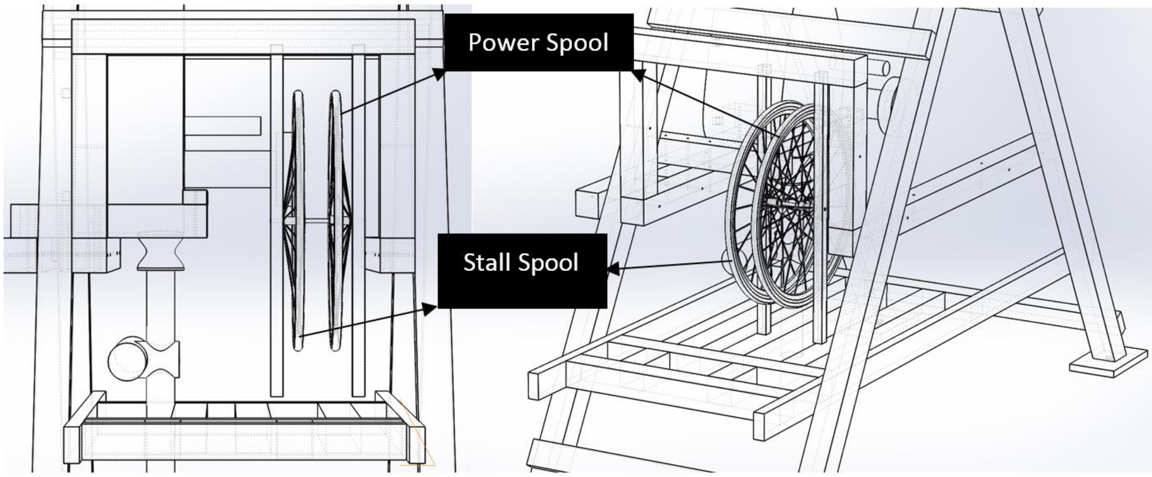


Figure 10: Perspective Drawings of Rotary Pump

The same is true for the pump gear and the pump shaft because they are also coaxial. Therefore the torque applied to the pump gear is the same as the torque applied to the pump shaft.

$$T_{pump\ gear} = T_{pump\ shaft}$$

As a result, the torque delivered to the pump shaft is the product of the torque applied to the spool gear and the ratio of the radii of the pump gear and the spool gear.

$$T_{pump\ shaft} = T_{spool\ gear} \times \frac{R_{pump\ gear}}{R_{spool\ gear}}$$

This formula can also be expressed in terms of its most basic components as:

$$T_{pump\ shaft} = (R_{spool\ wheel} \times F_{tension}) \times \frac{R_{pump\ gear}}{R_{spool\ gear}}$$

3.4 Minimum Tension for Operation

In order to calculate estimates for the minimum tension required to induce sufficient torque to overcome resistance in the pump shaft for a given set of gear sizes used on the spool and pump the following relation was used.

$$F_{min\ tension} = \frac{T_{required} \times R_{spool\ gear}}{R_{pump\ gear} \times R_{spool\ wheel}}$$

Please note that $T_{required}$, the minimum torque required to rotate the pump shaft, was determined through testing for the tangentially applied force required to begin rotating the pump shaft at a known distance away from the axis of the shaft's rotation. This testing was conducted with a with a hand held force gauge.

3.5 Pump Volumetric Flow Rate

From the previously listed analysis methods it is possible to estimate whether the kite in a given set of wind conditions will produce enough tension in the power line in order to operate the pump as well as the speed at which the tether will be retracted from the spool. Using relations between the sizes of the spool wheel, spool gear, and pump gear it is possible to estimate the rate of rotation of the pump shaft. For each complete revolution of the pump shaft the piston inside the pump cylinder will displace a specific volume of water. The volume of the displaced water correlates to the area of the pump piston head and the linear displacement of the piston within the pump cylinder. Outlined below is the process for estimating the volumetric flow rate of water from the system using these principles.

As described in the kite dynamics analysis laid out in Lyod's "Crosswind Kite Power" paper, the velocity of the kite will be approximately one third of the absolute speed of the wind the kite is operating in. The speed of the tether will be equal to the speed of the kite.

$$V_{tether} = V_{\text{kite}} = \frac{V_{Wind}}{3}$$

The release of the tether results in the rotation of the spool at a rate determined by the tether speed and the circumference of the spool. Since the spool wheel and spool gear are attached and share an axis of rotation, the rotational velocity of the spool gear will be equal to that of the spool wheel.

$$\omega_{spool\ wheel} = \frac{V_{tether}}{2\pi R_{spool\ wheel}} = \omega_{spool\ wheel}$$

The rotation of the spool gear moves the bicycle chain therefore introducing a rotation in the pump gear. The difference between the gears' rates of rotation will be proportional to the difference in their circumferences. Since the pump gear and pump shaft are attached and share an axis of rotation, the rotational velocity of the pump shaft will be equal to that of the pump gear.

$$\omega_{pump\ gear} = \omega_{spool\ gear} \times \frac{2\pi R_{spool\ gear}}{2\pi R_{pump\ wheel}} = \omega_{pump\ shaft}$$

or

$$\omega_{pump\ gear} = \omega_{spool\ gear} \times \frac{R_{spool\ gear}}{R_{pump\ wheel}} = \omega_{pump\ shaft}$$

The volume of water pumped per rotation of the pump shaft is the displacement volume of piston within the pipe cylinder. The piston has a head of radius R_{piston} and displaces a distance X_{piston} along the pump cylinder.

$$V_{per\ rotation} = X_{piston} * 2\pi(R_{piston})^2$$

Since the pump displaces the volume of one piston displacement per revolution of the pump shaft, the volumetric flow rate of water through the pump, Q, can be estimated using the formula below.

$$Q = V_{per\ rotation} \times \omega_{pump\ shaft}$$

The theory equations developed in the previous sections will be used to calculate system performance in the later Results & Analysis section. Sample calculations are also presented in Appendices B and C.

Chapter 4: Methodology

The goal of this project was to continue development of the WPI kite-powered rotary water pump system by improving upon the designs and methods of previous iterations of the Kite Power MQP. In the following sections we will discuss the methodologies used to; identify areas of improvement, our design process, methods for implementing designs, testing methods and data collection/analyses.

4.1 Identification of System Updates

Before beginning work on the project, the team made an assessment of the state of the prototype pump and shop conditions. This included becoming familiar with the previous MQP group's work and taking inventory of tools and materials available in our workspace. This was an important step because the type and quantity of resources at our disposal affected our final designs. After our assessment of the current system we identified two areas of the pump that we would focus our attention.

The first area was structural support for the pump. Initially the pump unit was suspended in the rough center of the A-Frame by ratchet-straps and webbing. It was clear that this method of attachment was never meant to be permanent and in order to prepare the prototype for field-testing, a secure structure was needed to support the pump. The team prioritized this subsystem because it was felt the pump was the most central component of our project and other systems should be build around it.

The second area was the spool housing and tether management systems. The A-Frame was originally constructed with the purpose of accommodating a “rocking arm” pump system has since been retrofit with temporary tether management system. This temporary tether management system consisted of two wooden risers spanned by a 4ft threaded rod that held the bicycle-wheel spools. The weight of the empty spools caused a bend in the rod and upon closer inspection the whole unit was in no way attached to the A-Frame. The team felt that for the Kite Power project to pursue a spooling kite power design the A-Frame needed a spool housing that could withstand the forces it will experience under load.

It is worth noting that in addition to the main subsystems mentioned above we made numerous small-scale improvements to the condition of the A-Frame. The A-Frame has been used as a testing platform for many years and has begun to deteriorate over this time. Many of these improvements include bracings to prevent wobbling, tightening screws and bolts, removing vestigial hardware, and rearranging components to lower center of mass and prevent tipping. The culmination of these improvements greatly increased the performance of the A-Frame as a testing platform and will increase its operational lifespan for future projects.

4.2 Design Process

To properly design our subsystems, our team went through various stages of planning and testing. To better separate our tasks, we divided into two groups, each focusing on one subsystem: pump design and spool design.

The first step of the development process was to create CAD models of major components that we'd be working with. These models included the A-Frame and pump, and ended up being important assets that supported our design process. It is important to note that when creating CAD models everything was done in a way that would make it easier for future groups to use these models for their own projects. This included, organizing all the parts and assemblies logically with descriptive naming and zipping together finished assemblies. See the initial model of the A-Frame that was used to generate designs for the pump and spool structures in the figure below.

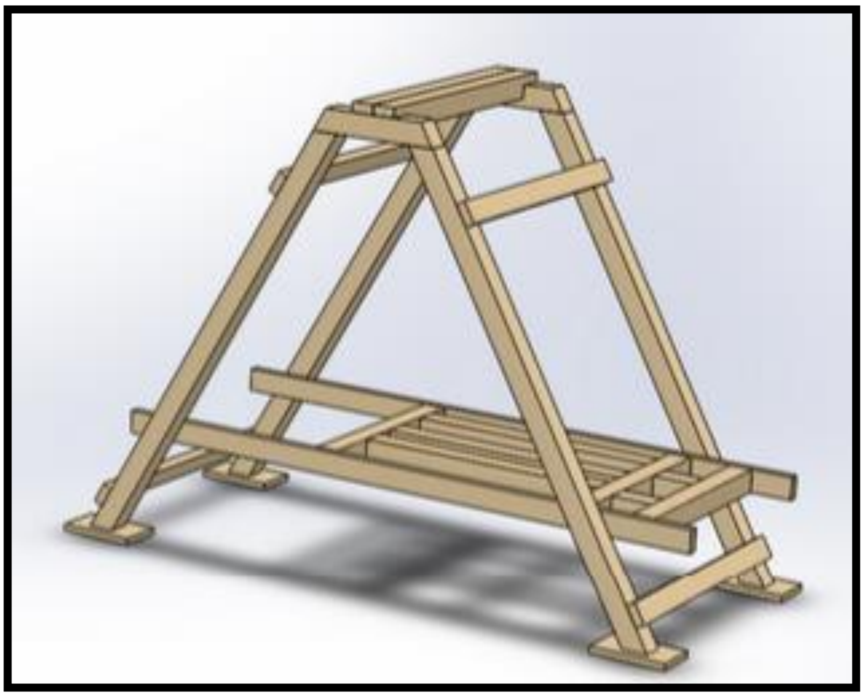


Figure 11: CAD Model of A-Frame

A primary example of CAD models supporting the design process was the pump support structure. The team worked together to generate two designs, discussed the pros and cons of each and then decided on a final design. See the two design iterations in the figure below.

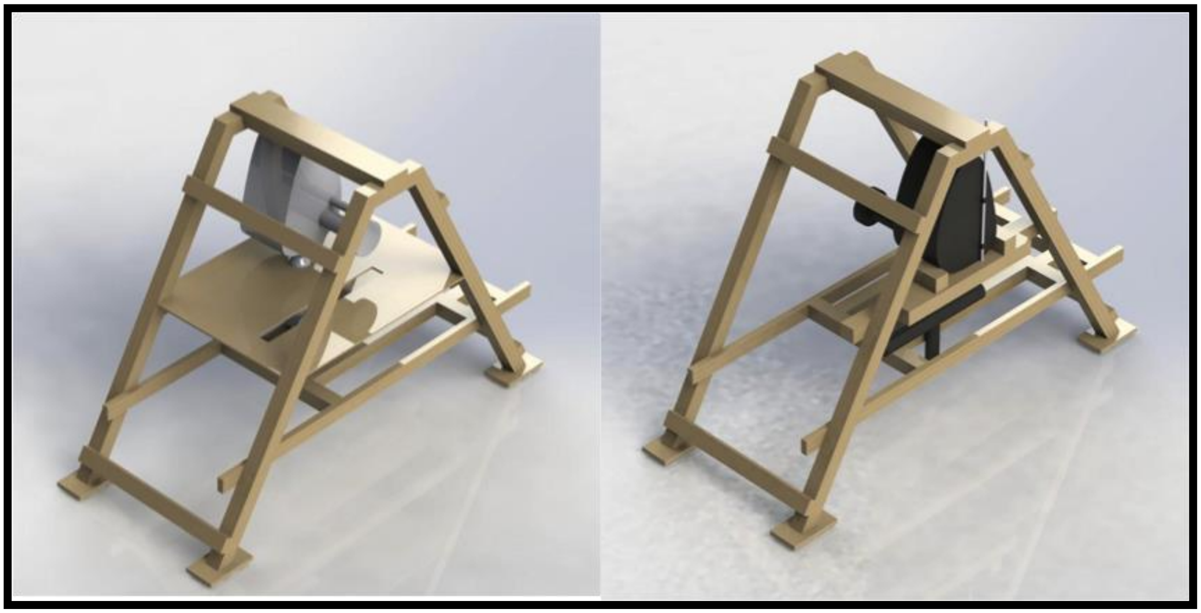


Figure 12: Pump Table Support (left) vs. Pump Beam Support (right)

The design to the left had the main feature of a table that supports the pump. The cut-outs in the table give access to parts such as chain and pump-shaft. The design to the right features a support beam that cradles the weight of the pump with two blocks on either side to prevent the pump from twisting in its mount. The team discussed the two designs and generated the simple matrix below highlighting aspects of each design.

	Advantages	**Disadvantages**	**Decision**
Pump Beam Support	a. Low cost. b. Manufacturable.	a. Less secure.	This concept was implemented
Pump Table Support	a. More secure. b. Stronger/more durable.	a. Hard to make. b. High cost.	This concept was *not* implemented.

The other major subsystem the team designed were the spools that transfer work from the kite to the pump. A rough prototype had been created by the previous group, pictured below, which served to demonstrate the basic idea. However, this new design needed a second spool for managing the additional "stall line" common on more powerful kites. We began designing by making the following considerations.

First, we needed to decide what the intended flight pattern for the kite would be because this would have the greatest affect of our design. We conducted research and discussed with our expert at the Blue Hills Observatory and decided on a single kite with manual retraction with the option for later addition of the two-kite system. Our final list of specifications included:

1. A manual brake for the power spool.
2. Proper resting houses for both the power and stall lines.
3. A system for linking/unlinking the power and stall spools.
4. Housing for the spools to immobilize the system.

With these considerations, our team iteratively designed subsystems. We focused on cost, manufacturability, and the ability to redesign based on feedback and performance.

At first the team had the idea of using bicycle frame components as the major parts of the spool structure as illustrated below.

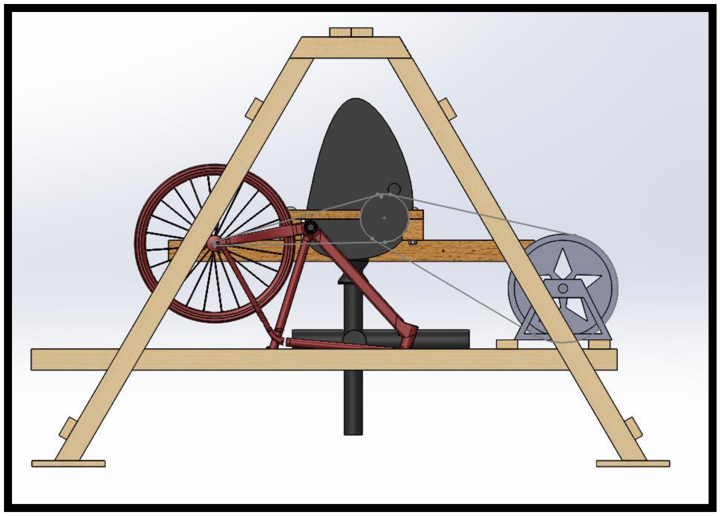


Figure 13: Illustration of Bicycle Design

At first glance it appears a bike already has many of the aspects required in our final design including, a securely mounted spool (wheel), brakes, retraction system (pedals), not to mention a variable gearing system. However, the more the team investigated this option it became clear that getting off the shelf bicycle components to work within the constraints of the A-Frame was too difficult and a custom built system was needed.

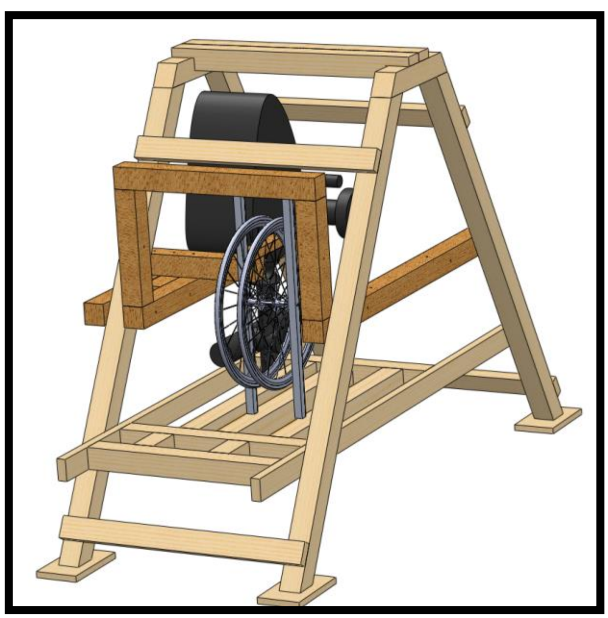


Figure 14: Model Showing Custom Spool Mounts

The new frame that was designed to hold the two wheels in the same axis pictured above. This design promoted the use of tabs to control whether the spools spin independently or not. Progress on the tab design was put on hold to expedite testing of the single kite system. Likewise, the team also considered automated retraction systems including spring loaded spools to counteract the force of the power line pulling upward. This design would have featured a commercial strength hose spring to retract the stall and, subsequently, power line after a predetermined power phase. While this design could have been effective, it was an expensive solution that, for the sake of expediting the design process, was never implemented.

4.3 Software Based Simulation

The calculations derived for estimating the performance of the kite and pumping system as outlined in section 3 only represent a specific set of field conditions in any given moment of the kites operation. Due the natural variations in wind conditions throughout the operation period of any system reliant on wind as a power source, the estimates need to be made across a large array of potential wind speeds. By having those estimates conducted across a range of potential field conditions it is easier to predict what operating conditions will allow the system to operate acceptably as well as what condition sets are likely to be ideal. If the ideal operating conditions of a given system configuration are known it becomes easier to target design changes which can optimize the system for the specific wind conditions of the location it will be deployed to.

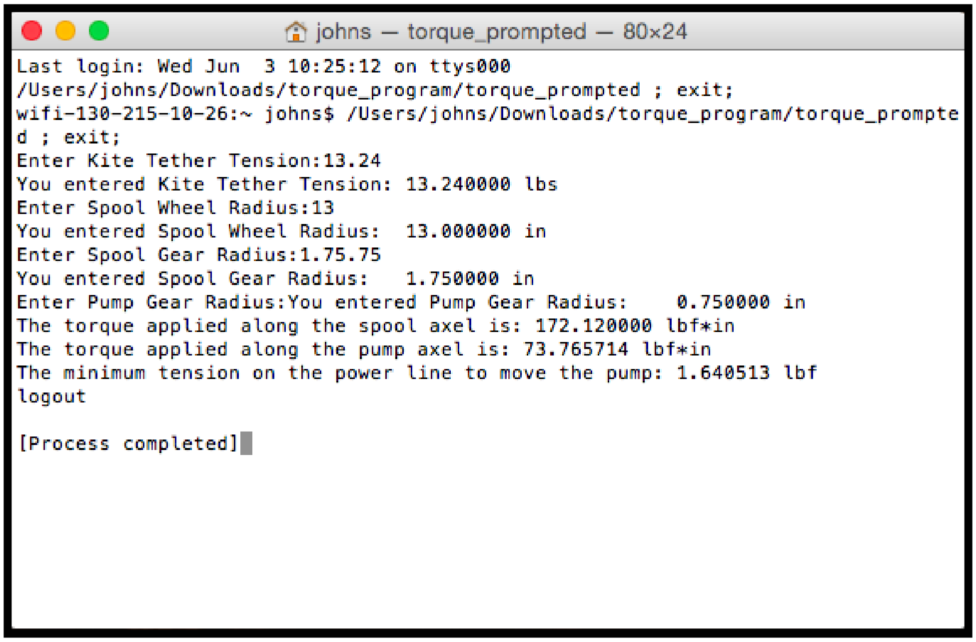


Figure 15: Sample Torque Simulation Results

Rather than doing the calculations individually in order to generate a series of estimates, a program was written which was capable of solving those sets of calculations quickly and iteratively across a range of varying input values. This program, which is detailed further in the appendices, allows simulation of varying conditions and system configurations in four main aspects of the system. The results of each set of simulation calculations are written to delimited text documents capable of being imported to spreadsheet programs, thereby facilitating easy graphing and analysis of results. The simulations the program is currently capable of performing are outlined below.

Tether Tension

The program is capable of running sets of calculations to determine the like tether tension for given flight conditions of the kite. Each of the input variables can be set to a range in which all values for that variable will be run through the full set of calculations at user defined increments in order to give the user an understanding of how that variable affects the resultant tether tension in the system during operation. The variables which can input and varied are freestream wind speed, tether line angle relative to the ground, density of the ambient air, surface area of the kite being used, and the angle of attack of the kite relative to the freestream wind velocity.

Gearing and Torque Transfer

As with the tension calculations, the torque delivered to the pump's main shaft can be simulated across varied values for the size of the main power line's spool wheel, the size of the gear attached to the spool wheel, the size of the gear attached to the pump shaft, and the tether tension delivers tangentially to the main spool wheel. Study of simulation data from these calculations is capable of assisting the optimization of the gearing in order to deliver the minimum torque required for pumping while maximizing the rotation rate of the pump shaft therefore delivering the highest volumetric flow rate of water from the pump for a given set of wind conditions.

Minimum Tension for Operation

The minimum tether tension will change with changes to the gearing ratio between the spool wheel and the pump shaft. The program is capable of calculating the minimum required tension for varied spool wheel size, spool gear size, and pump shaft gear size in order to ensure that a new gear system configuration will not reduce the torque so low that the system will no longer pump water.

Pump Volumetric Flow Rate

Since purpose of the kite pump system is to move enough water to supply the operators of the pump on a daily basis, the program also includes the calculation of estimated volumetric flow rate of water from the pump system. The water flow rate is a function of the freestream wind speed, spool wheel size, spool gear size, pump gear size as well as the pump piston head area and length of displacement. Each of these variables can be incremented in the calculations in order to measure their effects on flow rate and optimize them to the anticipated system operating conditions.

4.4 Testing Methods

In order to quantify the performance of our design it was necessary to perform a series of tests in the lab. We searched previous Kite Power project reports for a standardized benchmark we could perform to compare our performance to previous iterations of the project to no avail. In the following section we will detail our testing methods and results. Our hope is that project groups after us will repeat these experiments and their continued use will be used to show an increase in performance as they improve upon our designs. Our testing methods include:

Unit Tether Length/Volume Pumped

The goal of this test is to pump water by driving the power spool with a tether of known length. By measuring the amount of water collected and the tether length used; the proportion Tether-Length per US Gallon can be reported. For example, our best result was 177ft/1Gal. It was decided that a lower number indicated better performance because more water will be pumped for each spool revolution. This number is expected to increase dramatically when future projects optimize spool/pump gear ratios.

Minimum Required Tether Force

This test is designed to show the sum of internal forces in the system. In our tests this force mostly includes internal pump friction and inertia of the spools. When future project groups add additional subsystems this test will indicate their contributed effect. Decreasing this number indicates better performance because less work is lost to internal forces.

For further information on the tests conducted look in section 5.2.

Chapter 5: Results & Analysis

This chapter will present and discuss the results gathered from the items mentioned in the Methodology.

5.1 Kite Powered Water Pump Design

The current kite powered water pump is an iteration of the previous projects in kite power at Worcester Polytechnic Institute as well as research into kite power in industry and research. As described in the methods and background of this project, our team explored various design considerations and models. Below is a rendering of our finalized design and a description of our team's contribution to each of the individual parts.

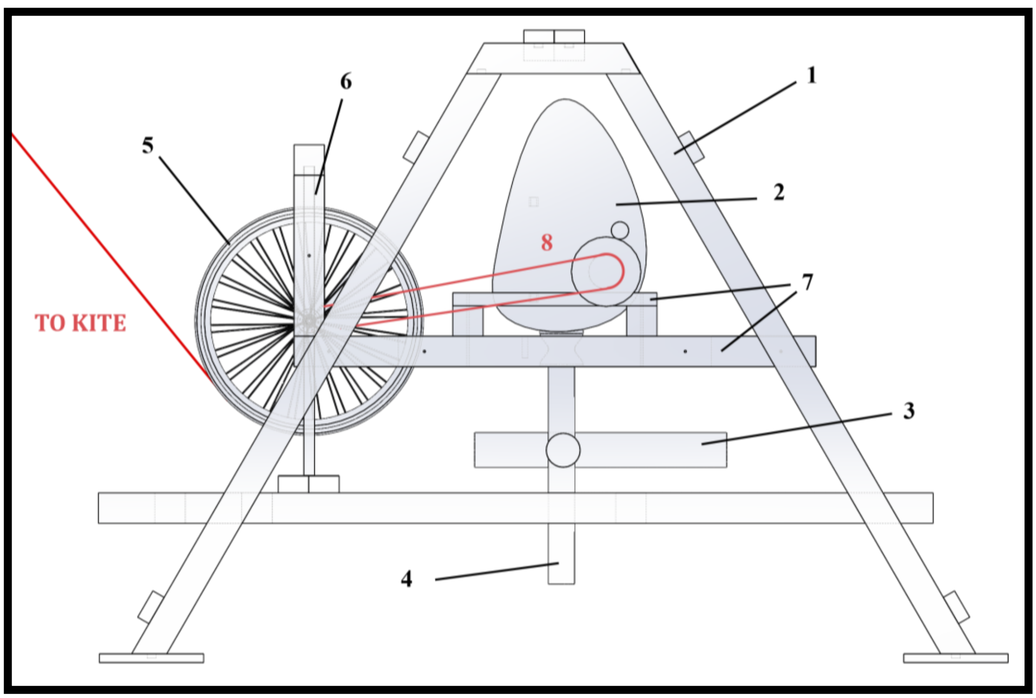


Figure 16: Rotary System Identification

1. A-Frame
2. Windmill Water Pump
5. Double Spool Tether Management
6. Spool Housing

3. Pump Head Simulator
4. Pumping Column
7. Pump Supports
8. Bicycle Chain

A – Frame

The A – Frame has been a component of the kite powered water pump since its inception. Four our part, we reinforced the entire structure to increase structural stability and durability. We added supports where needed and tightened any loose components. In addition, we ensured that the bottom supports held the frame high enough off the ground so that the pump component did not run into the ground. In order to improve upon the A frame in the future, it would be beneficial to lower its center of gravity. Earlier iterations of the project used a rocking arm to control the mechanical motion of the pump. This design is no longer in use, yet the rocking arm is still mounted to the top of the frame. For the frame to be transported more easily to and from testing locations, it would be more beneficial to have no rocking arm.

Windmill Water Pump

The water pump currently used in this project is from an old windmill pump. It has been repurposed for this project, and is driven by the kite pulling out from the power spool. At the current conditions, we have calculated that the pump can project 1 gallon of water per 180 feet of kite string pulled from the power spool. Although the pump is effective for its current purpose, its gearing is set slightly off center, so it is difficult to obtain meaningful test results. Some phases of its turning cycle require more force to rotate the pump than others, so it is difficult to properly calculate the wind speed needed to maintain a power cycle as well as the force needed to brake the power phase and begin retracting the kite. For design purposes, we measured that the maximum force needed to rotate the pump was 16 lb, and based all tensioning and power phase calculations on this number.

Pump Head Simulator

In order to simulate pumping water from a well at a certain depth, our design includes a pump head simulator. When we initiated our part of the project, the simulator was not functioning; it did not change the simulated pressure of the pump. To fix this, our team took it apart and reinstalled the spring system to ensure that it was properly constructed. The inside of the simulator functions as such:

1. Pressure gauge display: Displays the simulated pressure in the device based on how the spring is tensioned.
2. Water chamber: Based on how tightly the spring is tensioned affects the rate at which water can pass through the chamber, creating a simulated pressure head.
3. Spring: Allows head pressure simulator to be tensioned.
4. Simulator casing: Contains all internal parts of head simulator.
5. Rod: Connects hardware inside tensioning system.

While this simulator needed to be fixed so that tests could accurately reflect varying well depths, more testing should be done at various simulated head pressures.

Pumping Column

The pumping column passes water through from the well to an exit located higher up the pump. Inside of the column is a metal rod that is attached to the gears inside the pump. As the pump gears turn, they drive the rod which in turn pulls water through the column. At the bottom of the column is a dividing wall that allows water to pass into and out from the column. Our team worked to replace the lowermost part of the column and to identify fittings that minimized the length of the column. The intention was to have a short column that would not require the A-frame to be elevated off the ground any higher than it already was. To best accommodate this objective, our team focused on using PVC connectors, which allowed us to effectively construct a working column that was far shorter than that used with previous MQPs. Additionally, our team focused on improving the integrity of the column. At the start of the project, water could pass freely up through the column and into the gearing of the water pump. As a consequence, water was flowing from the water pump and not through the designed exit. To fix this, we installed a rubber stopper in the neck of the column. The stopper is made of ___ material, and does not allow water to pass up to the pump. It allows for the rods vertical movement so does not affect pump operation. Finally, we secured the column to the A-frame to reduce unwanted movement during operation.

Double Spool Tether Management

Ideally, the kite powered water pump will operate autonomously with little operator input. In this scenario, the kite would need to initiate and stall its power phase while maintaining operation. To accommodate for this design specification, our team designed a double spool tether management system. One spool houses the stall line and the other, the power line. When the kite is initially launched, both the power and stall lines freely unspool until the kite is at a maximum operating height.

At this height, the operator can apply the brakes to the system and stop the stall line from pulling out any further. This break in the stall line will force the kite to stall and lose altitude. At this point, the operator or retracting mechanism will mate the power and stall spools and begin reeling the kite tethers back in. Then, at the lower altitude range of the power cycle, the operator would undo the mating of the two spools and allow both tethers to extend back to the maximum altitude.

Spool Housing

To construct the double spool system on the existing A-frame, our team used iterative CAD drawings and tested with various materials. Finally, we constructed two spools from bicycle wheels and plastic tubing secured with screws and washers. These are attached to a metal rod and can be manually positioned with two sets of bolts. The spools are housed by a wooden and metal frame which supports the metal rod, and limits any motion that the force of the kite might induce on the spools.

Pump Supports

Another aspect of our project was to ensure the stability of the pump within the A-frame. Initially, it was supported with straps and did not stand freely. To amend this, we constructed a table for the pump to rest on and build wooden supports to limit movement from the torque of the bicycle and pump gears. The supports are designed to hold the shape of the pump and keep it restricted in a certain position. Unfortunately, this does not alleviate all problems with potential pump movement. The pump’s center of gravity is still higher than the center of gravity of the A-frame, which makes it a risk to transport to testing sites. For this reason, the pump is removed from the support while it is in transit.

Bicycle Chain

The bicycle chain connects the power spool to the water pump. It drives the gearing in the water pump which allows water to be pumped. Although there is currently only a single gear ratio, more could be added to this aspect of the project to achieve variable gear ratios. Additionally, a tensioning system would help, as the bike chain is often not as taut as it needs to be.

5.2 Simulated Results

Using the program described in section 4.3 a number of simulations were conducted in order to provide estimates for what operating conditions are likely to be required during operation.

Minimum Wind Speed

By comparing the results of a tether tension simulation of a single kite in varying wind speeds to the minimum tension required to operate the pump an estimate for the minimum required wind speed could be made. The wind speed simulation assumed the kite was of the Rokkaku style with a surface area of 36 square feet (3.3445m^2), at an angle of attack of 45 degrees to the wind, and with the tether line forming a 35 degree angle with the ground. The minimum tether tension was calculated using the diameters of the spool wheel (26 inches), spool gear (3.5

inches), and pump gear (3.5 inches) as currently configured on the pump system. Figure 16 displays the results of both calculation sets plotted together.

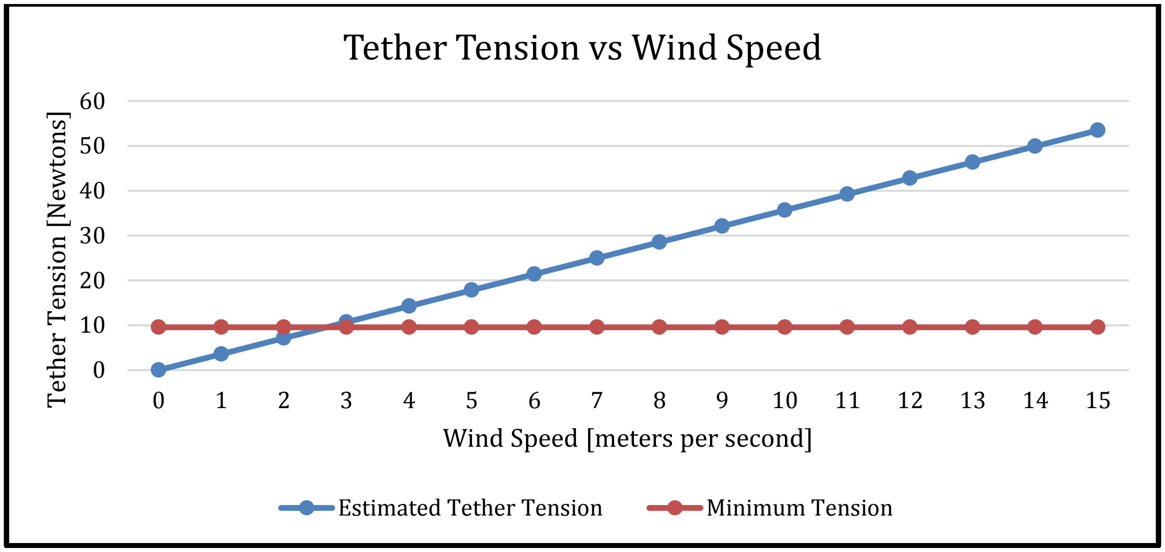


Figure 17 Tether Tension vs Wind Speed Plot

In figure 16 all wind speeds at which the estimated tether tension exceeds the minimum tether tension are likely going to be sufficient for the pump system to operating in field testing so long as field conditions are similar to the assumptions made in the simulations calculations as outlined above. The location along the horizontal axis where the two lines intersect represents the wind speed at which the torque applied to the pump via the tether and gear system matches the maximum torque resisting motioning within the pump due to friction and water pressure. This point occurs when the wind is traveling at a velocity of approximately 2.75 meters per second. It can therefore be assumed that consistent wind speeds greater than 2.75 meters per second must be present for pump operation in this configuration.

Volumetric Flow Rate

The volumetric flow rate of water for a given system configuration is linearly related to the tether velocity when the gear and spool sizes are held constant. As described in section 3 the tether speed will be the same as the speed of the kite which is approximately one third of the wind speed. Using the program the volumetric flow rate can be calculated across a range of wind speeds. Figure 17 shows the simulated volumetric flow rate of the current system across the same set of wind speeds as the tether tension estimates of figure 16.

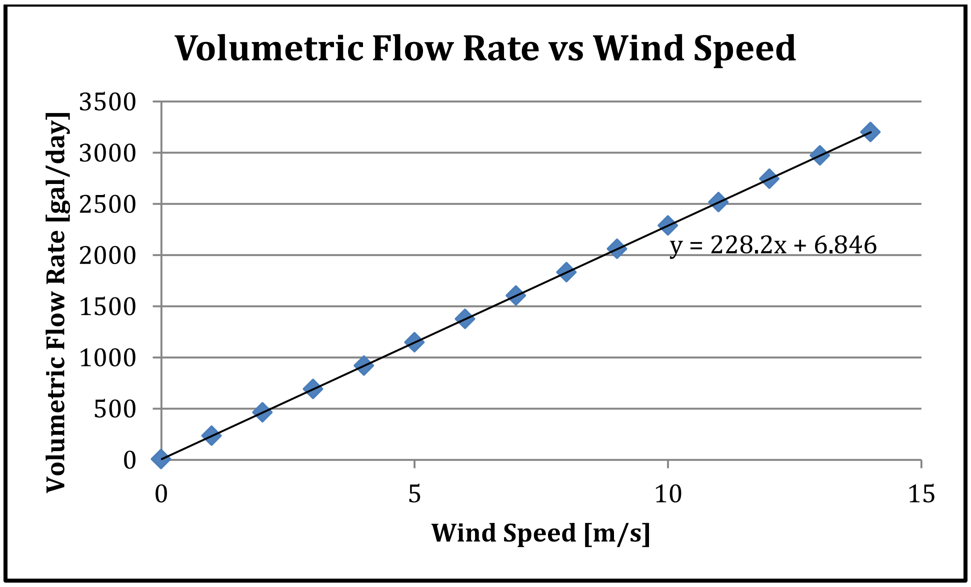


Figure 18 Volumetric Flow Rate vs Wind Speed

Using the estimated minimum required wind speed of 2.75 meters per second for the given system configuration we can estimate the operational minimum flow rate. By interpolating between the flow rate values at 2 and 3 meters per second the minimum flow rate value is estimated at approximately 0.000038 cubic meters per second. The volumetric flow rate increases by 0.00001 cubic meters per second for every 1 meter per second increase in wind speed.

Gear Train Optimization

If the wind conditions have low variance in the planned area of operation for the pump system then it is possible to use simulations to optimize the gear ratio so that the volumetric flow rate will be maximized without causing the torque transferred to the pump shaft to be too low for a significant portion of the annual operating time of the pump. In the same way the gear train can be optimized to be able to pump at lower wind speeds and tether tension while forgoing maximal flow rates at higher wind speeds. These optimizations will need to be tailored to the exact operating conditions of the kite and the needs of the operators. For example, If the operate has ample water storage capabilities and the wind variance is low then a system optimized to the most probable wind speed would be favorable. Other operators without storage and more highly varying wing speeds may need the pump gearing optimized to provide water even when wind speeds are significantly lower.

5.3 Testing Results

The process for gathering results during lab and field testing routinely followed the procedures discussed in chapter 4. During lab testing we iterated our performance benchmarks and the results we gathered were as follows.

Unit Tether Length/Volume Pumped

For this benchmark we conducted a total of 4 trials and the result of each was in the ballpark of 180ft/gal. This number is much greater than its ideal calculated value. Our pump cylinder has a maximum stroke of 10" but our pump only has a stroke of 6" so the volume pumped per stroke is:

*Length of stroke * Cross-sectional area of cylinder = Volume per stroke*

The cylinder is rated for 0.136 gal/stroke, but ideally we would get:

$$6" \times \pi 1.25^2 = 30in^3 = 0.127 \frac{gal}{stroke}$$

By iterating this benchmark we've determined that the pump operates much lower than this, in lab we pumped 2Gal with 60 turns (gear ratio is 1:1) so 1 turn = 1 stroke:

$$\frac{2gal}{60strokes} = 0.333 \frac{gal}{stroke}$$

This raises the question, 0.333 gal/stroke is much less than the ideal 0.127gal/stroke, where is all the extra water going? Most of the water is being pushed up into the pump or leaking out of the head-simulator. The team manufactured and installed a custom bushing to prevent the pump from filling with water but the fit is not perfect.

One sub-system that would greatly improve the results of this benchmark is the addition of a variable gearing system. Actively changing gear ratios during flight would allow the kite operator to maximize performance in variable wind conditions.

Minimum Required Tether Force

This test is designed to show the sum of internal forces in the system. In our tests this force mostly includes internal pump friction and inertia of the spools. For this benchmark the system currently requires 12lb 10oz to begin from a dead stop at the top of a stroke. Fortunately, once the pump is primed and started it requires much less force to continue working.

Field Testing

The primary objective of field testing was to visually assess the performance of the system under real-world use conditions. This included not only the kite powered pump system but the trailer used to transport the system, environmental factors and operator skill. The major testing took place at Brookwood Farm on October 8, 2015 in an open field. The day was clear, but average wind speeds were 0 mph. However, there was a recorded gust of 11 mph. During testing, our team was able to get the kite to fly on four occasions. During these times, the kite pumped water into a basin under the A-frame, proving that the design worked. To launch the kite, two members of the team held the kite downwind from the A-frame, while a third held the power line about 10 m from the kite. During a gust, the third member would indicate for the first two to release the kite, and then run upwind to launch the kite. The fourth team member monitored the power spool to ensure that the line was not tangling. This operating system was effective and allowed for the successful field testing of the design. For a visual aid, please see the Field Testing video uploaded to the WPI Library project site which was recorded by Joseph Samela during testing. There were small improvements that could be made that we enumerate in our recommendations section 6.2 but by and large field testing showed that low-cost rotary spool based kite power for pumping water is feasible.

Chapter 6: Conclusions & Recommendations

In this chapter we draw conclusions from the results discussed in the previous chapter and present a series of recommendations for the future of kite power at WPI.

6.1 Conclusions

Upon the completion of any project it is important to look back and evaluate the impetus of your efforts. For our MQP we must ask, is kite power still a good idea? What we have designed and built to support the idea of spool based kite power worked, a fact corroborated by the successful tests of our prototype. With continued development this method of kite power will only continue to improve.

The following question would be, why should more resources be dedicated to AWE opposed to sustainable alternatives? We discussed the many benefits of AWE over traditional wind systems in our introduction but, turbines, solar, geothermal, etc. technologies can be implemented NOW. The inevitable advance of these technologies *will* bring costs down and make them more widely accessible. So why continue to invest in AWE?

The AWE industry is new and it is growing fast, WPI research is leading in this growing industry However, more importantly, like any technology it needs to be developed. The work of our MQP has brought WPI closer than ever to AWE success and progress will continue with the efforts of each new MQP group. In this regard, the future of kite power at WPI remains bright.

In the following section we will present a series of recommendations for future developments of kite power at WPI.

6.2 Recommendations

Future MQPs

Since the 2014 kite power team redesigned the spool system from scratch, future MQPs should develop the new system to make it more efficient. Some of the ideas the group have will be discussed in depth in this section. As of now, the whole system is in good shape but some modifications can be applied to enhance the overall performance.

Gearing system

A good improvement which will benefit the spool system would be a gearing system. This system can allow different gear ratios between the pump the power spool based on the amount of torque required by the operator. The operator will be responsible for shifting between gears. This would make the gear system optimizations outlined in section 5.2 redundant.

Braking system

Currently the team developed a beta version of the braking system. The system now only brakes the power wheel. The current system needs to be modified to produce more braking strength. An addition of a new braking system to the other wheel should also be put into consideration. The overall functionality of the current system is in good shape.

Redesigned structure

The A-Frame was designed for a pervious MQP, where a rocking arm was the source of the pump movement. With the new spool system, the A-Frame could be changed. A new structure designed from scratch specifically to fit the new spool system should be much smaller and lighter. Also the pump should be located in the middle of the new structure to give it more stability.

New pump

An investment in a new pump will benefit the whole system in a couple of aspects. First, new pumps are smaller, lighter and more efficient, which will give the system the ability to be smaller and produce more output that using the current pump. Since the current pump is old, its internal components are mostly rusted, water pumped with it will need to go through a filtration process before it can be used. This will make it costly for the people who will be using it.

New head pressure gage

The current pressure gage is not in a good working condition, a replacement for it is highly recommended. If the decision was made to purchase a new pump, a new pressure gage should also be purchased. If not, the group highly suggests to replace the current gage to get better reads and data of the system performance.

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Appendices

Appendix A: Software Simulation Package Instructions

KiteDynSimV7 README

-------*Authorship*-------
Developed by John Scarborough for Professor David Olinger's WPI Kite Wind Power Major Qualifying Project Team of E-Term 2015

-------*Purpose*-------
This program performs iterative calculations across ranges of specified values to estimate the tether tension, generated torque, minimum required tension, and volumetric flow rate of a simple kite motion power water pump system like that of the WPI Kite Wind Power Major Qualifying Project.

-------*Installation and Running*-------

###Windows###
1) Open the "KiteDynSimV7" folder
2) Right Click "KiteDynSimV7.exe"
3) Select "Run as Administrator" (this allows the program to store simulation results to a text file for export to spreadsheets)
4) Follow the prompts and guides within the program to conduct simulations [type help for a list of options at a prompt]

###Mac OSX###
1) Move the "KiteDynSimV7" folder to your documents folder and open the "KiteDynSimV7" folder.
2) Double click the file named "KiteDynSimV7_install.command" to compile the program
3) Double click the file named "KiteDynSim_Launch[with file output].command"
[You will be prompted to enter the password for your local account on your computer in order to grant the required permissions for the program to write the results of program to a text file, if you do not need results to be saved in a text file then double click "KiteDynSim_Launch.command" instead]
4) Follow the prompts and guides within the program to conduct simulations [type help for a list of options at a prompt]

###Linux###
You should know what to do
...
...

...
but if not:
1) Move the “KiteDynSimV7” folder to your documents folder.
2) Open a terminal window
3) type “cd Documents”
4) type “cd KiteDynSimV7”
5) type “make” to compile
6) to run the program type “./KiteDynSimV7”
7) Follow the prompts and guides within the program to conduct simulations [type help for a list of options at a prompt]

-------*The LD alternatives*-------
The files ending in the suffix “LD” work the exact same way in installation and running but conduct the calculations using an alternative method in which lift and drag coefficients are calculated based off the tether angle of the kite in flight rather than the flat plate relations used in the standard version of the program. This may be useful for alternative styles of kites were this method is more applicable.

Appendix B: Sample Calculations

For testing, the team is using a PowerSled 81 kite. For all lift calculations, the team must determine the kite planform area. Only the area of one side of the kite is used in lift calculations.

$$A = 81ft^2 \ (known) = \ 7.53m^2$$

With this dimension, the tether tension can be calculated using the equation

$$F_L = \frac{1}{2}\rho v^2 A C_L$$

Assuming Sea Level Conditions,

$\rho = air\ density = 1.225\ kg/m^3$

$v = wind\ velocity\ at\ Blue\ Hills = 14\ mph = 6.26\ m/s$

$A = 7.53\ m^2$

$C_L = 1$

$$F_L = \frac{1}{2} * 1.225 * 6.26^2 * 7.53 * 1 = \mathbf{180.74\ N}$$

However, this calculation does not consider the drag force on the kite. Assuming a lift-to-drag ratio of 10 for the kite, the drag force is calculated as

$$\frac{F_L}{F_D} = 10$$

$$F_D = \frac{F_L}{10} = \frac{180.74}{10} = \mathbf{18.07\ N}$$

With this drag force, the kite tether angle can also be calculated using trigonometric principles.

$$\Theta = \tan^{-1}(\frac{F_L}{F_D}) = \tan^{-1}\left(\frac{180.74}{18.07}\right) = \mathbf{84.29°}$$

Accounting for both the lift and drag forces on the kite, the new tether tension is

$$F_T = \frac{F_L}{\sin(\Theta)} = \frac{180.74}{\sin(84.29)} = \mathbf{181.64\ N}$$

Figure 1 details the lift, drag, and tether forces on the kite at flying at angle Θ.

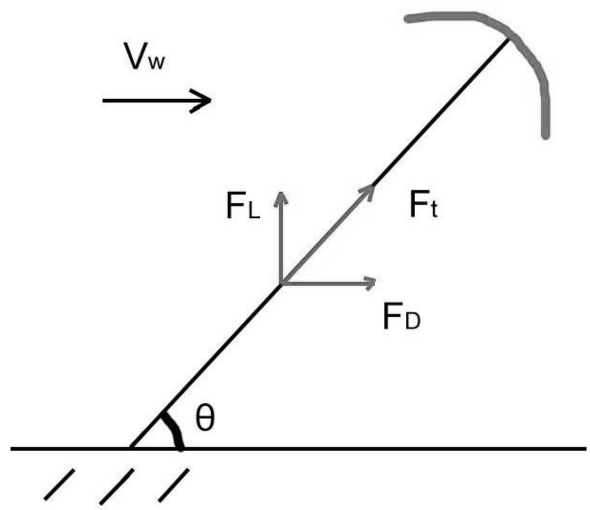

Figure 19: Forces on Kite

To determine the lift and dag forces as well as tether tension at high wind velocities, the same calculations were made using the maximum gust speed recorded at Blue Hills Testing site during testing on May 20, 2015.

$\rho = air\ density = 1.225\ kg/m^3$

$v = maximum\ gust\ at\ Blue\ Hills = 35\ mph = 16.65\ m/s$

$A = 7.53\ m^2$

$C_L = 1$

$$F_L = \frac{1}{2} * 1.225 * 16.65^2 * 7.53 * 1 = \mathbf{1129.09\ N}$$

Calculating the drag force on the kite, again using a lift-to-drag ration of 10, yields

$$\frac{F_L}{F_D} = 10$$

$$F_D = \frac{F_L}{10} = \frac{1129.09}{10} = \mathbf{112.91\ N}$$

This allows the tether angle to be calculated using

$$\Theta = \tan^{-1}(\frac{F_L}{F_D}) = \tan^{-1}\left(\frac{1129.09}{112.91}\right) = \mathbf{84.29}°$$

This is the same value as before because the lift-to-drag ratio was not changed. Using these values, the tether tension at the maximum gust is

$$F_T = \frac{F_L}{\sin(\Theta)} = \frac{1129.09}{\sin(84.29)} = \mathbf{1134.72\ N}$$

Appendix C: Sample Calculations

In the current system configuration, the water pump operates as the kite gains altitude. It pulls a tether, the power line, from the bike wheel spool, which drives the pump. It has been shown (Loyd, 1980) that a kite creates maximum power when:

$$V_T = \frac{1}{3} V_W$$

Where V_T is the tether reel-out velocity, and V_W is the wind speed. For the purpose of this project, we will assume that the wind speed is 7 m/s. At this speed, the optimal tether velocity is:

$$V_T = \frac{1}{3} * 7 = \mathbf{2.33\ m/s}$$

From this velocity, the rotation rate of the bike wheel in the pumping system can be calculated using the equation:

$$V_T = r * \omega$$

$$\omega = \frac{V_T}{r}$$

In the current system, the bicycle wheel radius is 0.345 m, so using that value for r and the optimal tether velocity for V_T,

$$\omega = \frac{2.33}{0.345} = 6.8 \frac{rad}{s} = \mathbf{64.94\ rpm}$$

Using this rotation rate, the amount of kite tether that must be stored on the bicycle wheel in order for it to have a power phase time period of t = 30 seconds, 60 seconds, and 5 minutes can also be determined using the equation:

$$Tether\ Length\ (L_T) = V_T * t$$

For t = 30s,

$$L_T = 2.33 * 30 = \mathbf{70\ m}$$

For t = 60s,

$$L_T = 2.33 * 60 = \mathbf{140\ m}$$

For t = 5 min,

$$L_T = 2.33 * 300 = \mathbf{700\ m}$$

The power phase is the time period that the kite is reeling out the tether from the bicycle wheel and turning the water pump. These lengths represent the amount of tether needed to sustain such power phases.

In addition to the length of tether needed to pump water at various power phase time periods, it is also important to know the kite lift force when the kite is reeling out the tether. Knowing this value helps ensure that the tether is strong enough to withstand this force. The following equation is used to determine the kite lift force (F_L),

$$F_L = \frac{1}{2}\rho v^2 A C_L$$

Where

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

$$v = V_{Relative} = V_R = V_T - V_W = 7 - 2.33 = 4.67\ m/s$$

$$A = Area\ of\ PowerSled81 = 7.53\ m^2$$

$$C_L = lift\ coefficient = 1$$

Calculated at a tether angle of 0°,

$$F_L = \frac{1}{2} * 1.225 * 4.67^2 * 7.53 * 1 = \mathbf{100.56\ N}$$

Thus, the tether must be able to withstand a lift force of 100.56 N, or 22.6 lb.

However, these values must also be calculated at an angle the kite would realistically fly. Using a flight angle of 40^{o} from the horizontal, as observed at Blue Hills, the optimal tether velocity can be recalculated using the same equation as before. However, the component of the wind that the kite will experience at 40^{o} is

$$V_{W,\theta} = 7\cos(40) = \boldsymbol{5.36\ m/s}$$

Using this wind velocity,

$$V_T = \frac{1}{3} * 5.36 = \boldsymbol{1.787\ m/s}$$

To find the rotation rate of the bike wheel in the pumping system at this velocity,

$$\omega = \frac{1.787}{0.345} = 5.181\frac{rad}{s} = \boldsymbol{49.475\ rpm}$$

At this rotation rate, the amount of kite tether that must be stored on the bicycle wheel in order for it to have a power phase time period of t = 30 seconds, 60 seconds, and 5 minutes is:

For t = 30s,

$$L_T = 1.787 * 30 = \boldsymbol{53.61\ m}$$

For t = 60s,

$$L_T = 1.787 * 60 = \boldsymbol{107.22\ m}$$

For t = 5 min,

$$L_T = 1.787 * 300 = \boldsymbol{536.10\ m}$$

Finally, recalculating the kite lift force at this angle yields

$$F_L = F_L = \frac{1}{2} * 1.225 * (5.36 - 1.787)^2 * 7.53 * 1 = \boldsymbol{58.88\ N}$$

Figure 1 diagrams the kite flying at this angle and the various forces it is exposed to.

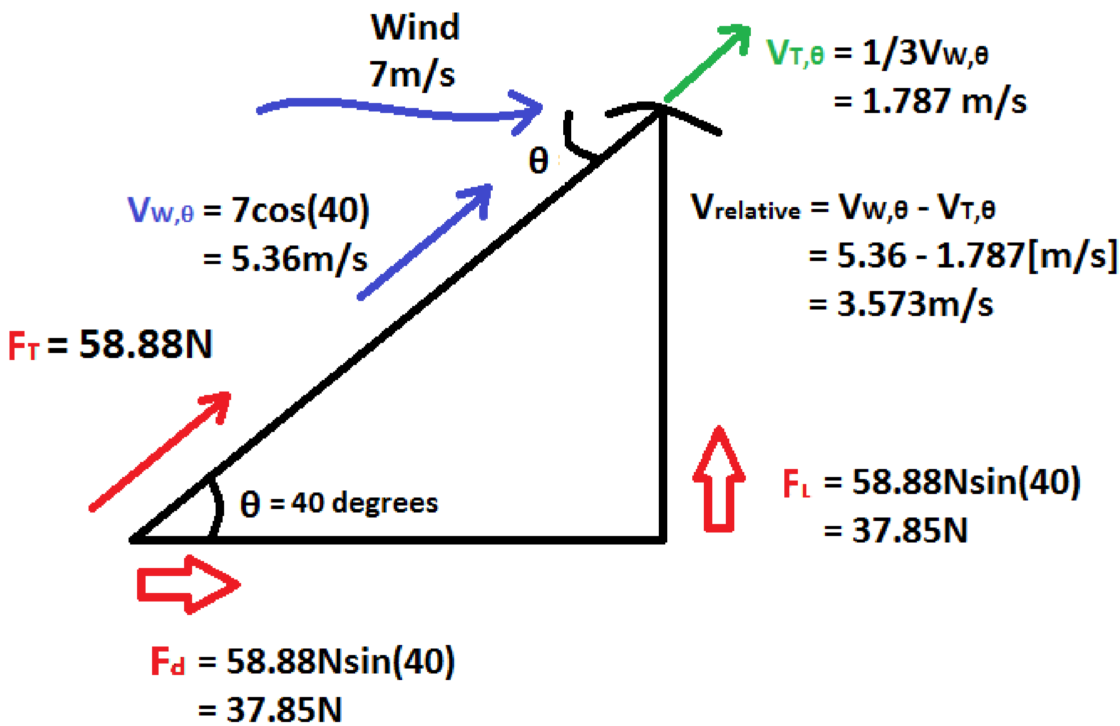

Figure 20: Kite at 40°

The amount of water pumped per RPM can be translated to amount of water pumped per unit time to determine system output in operation. In our system,

$Outer\ Circumference\ of\ Pump\ =\ \mathbf{10.75in}$

$Estimated\ Inner\ Circumference\ of\ Pump: \mathbf{C}\ =\ \mathbf{10.0in}$

$Stroke\ Length: H\ =\ 6in$

$Displacement\ Volume\ of\ Pump: \mathbf{V}\ =\ A * H\ =\ \pi r2 * H\ =\ \boldsymbol{\pi(C/2\pi)2 * H}$

Thus,

$$\mathbf{V}\ =\ \pi(10in/2\pi)2 * 6in\ =\ 47.75in3\ =\ \mathbf{0.78L}$$

By testing the pump system we found that the spool must be rotated 3 times for each complete cycle of the pump to be completed. Therefore:

$Pump\ Flow\ Rate$: $\boldsymbol{Q}$

$Rotation\ Speed\ of\ Spool$: $\boldsymbol{\omega}$

$$\boldsymbol{Q} = \frac{\omega}{3} * V = \frac{49.475}{3} * 0.78 = 12.86\ L/min$$