DJO-1401

Simulation of Wind Variation for the WPI Kite-Powered Water Pump

A Major Qualifying Project Report
Submitted to the Faculty of the
WORCESTER POLYTECHNIC INSTITUTE
in Partial Fulfillment of the Requirements for the
Degree of Bachelor of Science
in Aerospace Engineering

by

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October 16, 2014

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This report is an addendum to the previous submitted report, E-project-043014-201241 for MQP Project Code DJO 1401 in May 2014. Sarah Triplett also participated in, and received MQP credit for, Project DJO-1401.

Abstract

This project serves as an addendum to the previously submitted MQP project report, E-project-043014-201241 for Project DJO-1401 on Airborne Wind Energy Systems (AWE). This project discusses various implementation sites for the WPI Kite-Powered Water Pump once field testing is completed. As the WPI Kite-Powered Water Pump is designed to work in rural communities of underdeveloped nations, sites specified in this report include various locations in Namibia, Africa. A MatLab simulation that models the WPI Kite-Powered Water Pump and includes modeling of wind speed variation due to wind gusts was studied. This simulation was used to study variation of key system design parameters to determine how these variations affected the rate of water pumped by the system.

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1.0 Introduction

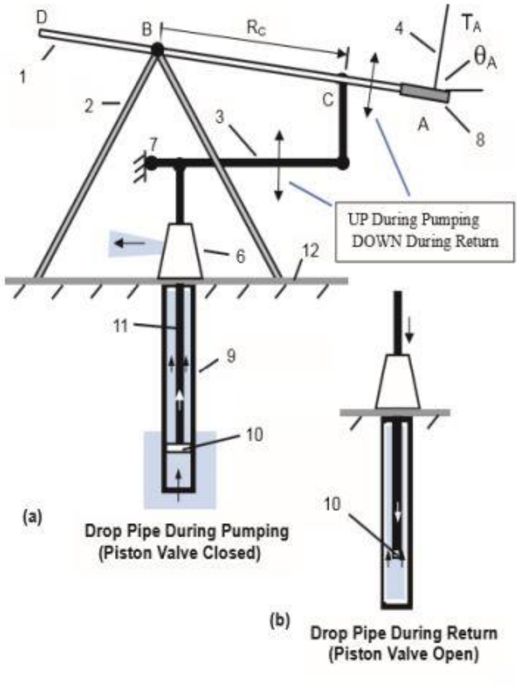

Figure 1 - Diagram of the physical Kite Water Pump System (Olinger et al., 2013)

The goal of this project was to study the available wind data and resources available for the country of Namibia, Africa, and to use an existing MatLab simulation that models the WPI Kite-Powered Water Pump pictured in Figure 1 to study the effect of wind speed variation due to wind gusts on water pump performance. This system is designed to pump water like a hand pump would function, except wind power is utilized instead. The wind power is harnessed by a kite that is tethered to the rocking arm of the pump. The wind is caught by the kite, and this in turn powers the pump.

Using this simulation, several different cases (outlined in Table 1) were tested, varying parameters including kite area, kite weight, tether diameter, tether length, tether weight, well depth, kite aspect ratio, and kite camber. The results of these simulations are discussed in the Results Section of this report.

2.0 Literature Review

An ideal location to look into for the instillation of the completed WPI Kite-Powered Water Pump would be Namibia, Africa. As a nation with several wind farms in place, it is in a good position to test the effectiveness of the WPI Kite-Powered Water Pump in a developing nation setting.

An obstacle that comes up is the current location of these wind farms. Most of them are located on the coast or off-shore, which are not ideal locations to test our WPI Kite-Powered Water Pump. With the hopes of installing our system in areas where people do not have easy access to water, it is more advantageous to look into areas that are not as coastally oriented as most of the wind farms. There are of course exceptions to this. In Walvis Bay, Namibia, there are wind turbines installed in the desert area east of the city, near the Mile 7 reservoir (Reve, 2012). This means that there is significant wind speeds to validate the existence of wind turbines in the desert area outside the coast line of Walvis Bay. As a deserted area, they would be in a prime location to test a WPI Kite-Powered Water Pump water pump, as they are near enough local infrastructure to facilitate a test, while also help local residents have access to the fresh water provided by the pump.

Walvis Bay is really one of the few wind farm sites throughout all of Namibia. The truth is that while many developing nations have access to wind power, they do not have the resources necessary to utilize them. They lack the materials and expertise necessary to operate them efficiently (Abramowski, 2000). This also applies to Namibia. There is the potential to build several wind farms along the coast of Namibia, particularly in the area of Lüderitz, another wind farm site; however there is very limited site specific data on the wind measurements and resources needed. The lack of data is the primary reason why there is a lack of investors in the wind industry in Namibia, because they do not realize the potential of wind resources that is there (von Oertzen, 2009).

That is not to say there is a complete lack of available data in Namibia. There have been regional wind studies done throughout the country and entire southern half of the African continent. In the case of Namibia, the country has an annual average wind speed of 6 to 7 m/s (13.4 to 15.7 mph), including the coast and just off shore of land, which skews the results a bit. Inland averages are closer to 3 m/s, which is about 6.7 mph. There are however some locations on the mid-eastern side of the country that are closer to 4 m/s, which is almost 9 mph. There is even a small area between Lüderitz and Bethanien where inland wind speeds reach an average of 5 m/s, which is about 11.2 mph ("Wind Energy," 2012). Locations between 4 and 5 m/s are ideal for our WPI Kite-Powered Water Pump testing, which requires 4.4 m/s wind speeds to function adequately.

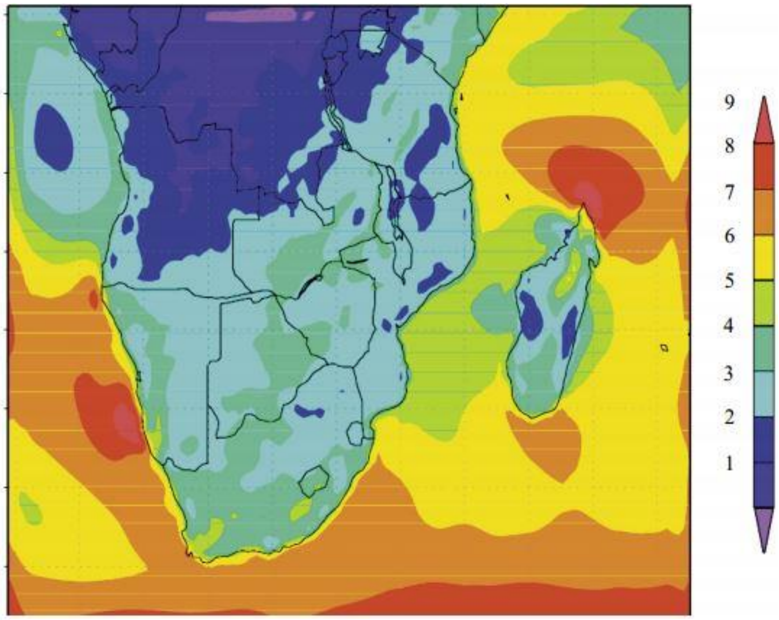

Figure 2 - Average wind speeds in southern Africa, on a meters/second scale.

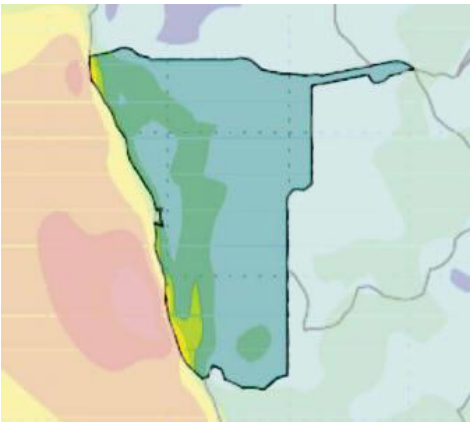

Figure 3 - Namibia wind data, using the same scale as Figure 1.

Wind pumps happen to be the most common use of wind energy in Namibia with about 30,000 in operation, though not using our WPI Kite-Powered Water Pump model. Wind pumps currently in Namibia are set up like large pinwheels with many more blades than a wind turbine would use. The blades turn to lift a piston in the ground to pump water through attached pipes. The pumps run on an engine during windless months. These pumps also require regular maintenance as many things tend to interfere with the operation of the pump, such as sticking gears ("Wind Energy," 2012).

3.0 Methodology

After field work was performed with the existing WPI Kite-Powered Water Pump, various factors were tested using a MatLab simulation of the system. The simulation is the same code that was used in the previous MQP (E-project-043014-201241 for MQP Project Code DJO 1401) related to this work. This code models varying wind velocities with time. Within this code, several different constants can be changed, including kite area, tether density, and aspect ratio. A complete list of these factors can be found in Table 1 of this report. The code allows for comparison of water pump outputs based on these varying parameters.

Each simulation run from this code shows data over a 30 second time span which is sufficient time to establish steady-state system operation. Graphs which show the kite motion, rocking arm angle, kite tether force, rate of water pumped, and wind speed vs time are produced. By varying the parameters in Table 1, we can determine how the rate of water pumped, among other results, varies with the changes made to these variables.

4.0 Results

4.1 Simulation Results

Using a simulation based on the physical WPI Kite-Powered Water Pump, the following results have been found by running eighteen test cases though MatLab. With the first case being the control, the following cases were run by changing variables as shown in the table below. Each change in variable was made to determine the effect it would have on the rate of water pumped by the WPI Kite-Powered Water Pump.

Case	**Wind Velocity (m/s)**	**Kite Area (m^2)**	**Kite Weight (N)**	**Tether Length (m)**	**Tether Diameter (m)**	**Tether Density (kg/m)**	**Well Depth (m)**	**Kite Aspect Ratio**	**Kite Angel of Zero Lift (deg)**
0 (base line)	6	10	22	250	0.001	0.0075	120	4	-4
1	**5**	10	22	250	0.001	0.0075	120	4	-4
2	**7**	10	22	250	0.001	0.0075	120	4	-4
2 retest	**6.7**	10	22	250	0.001	0.0075	120	4	-4
3	6	**8**	22	250	0.001	0.0075	120	4	-4
4	6	**12**	22	250	0.001	0.0075	120	4	-4
5	6	10	**20**	250	0.001	0.0075	120	4	-4
6	6	10	**25**	250	0.001	0.0075	120	4	-4
7	6	10	22	**200**	0.001	0.0075	120	4	-4
8	6	10	22	**300**	0.001	0.0075	120	4	-4
9	6	10	22	250	**0.0005**	0.0075	120	4	-4
10	6	10	22	250	**0.002**	0.0075	120	4	-4
10 retest	6	10	22	250	**0.001275**	0.0075	120	4	-4
11	6	10	22	250	0.001	**0.001**	120	4	-4
12	6	10	22	250	0.001	0.0075	**60**	4	-4
13	6	10	22	250	0.001	0.0075	**200**	4	-4
14	6	10	22	250	0.001	0.0075	120	**3**	-4
14 retest	6	10	22	250	0.001	0.0075	120	**3.5**	-4
15	6	10	22	250	0.001	0.0075	120	**5**	-4
16	6	10	22	250	0.001	0.0075	120	4	**-2**
17	6	10	22	250	0.001	0.0075	120	4	**0**

Table 1 - Simulation Cases

The following figures were produced after each case.

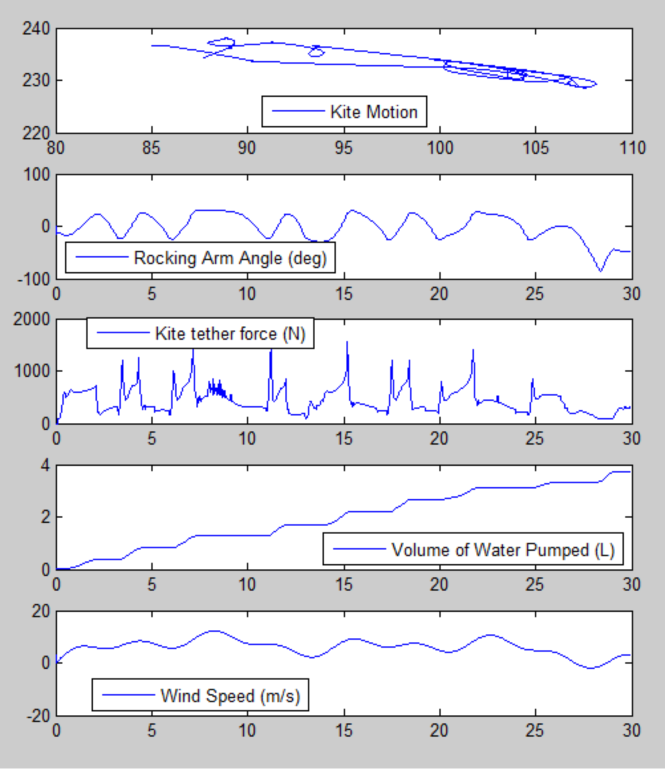

Figure 4 - Case 0 (Base Line)

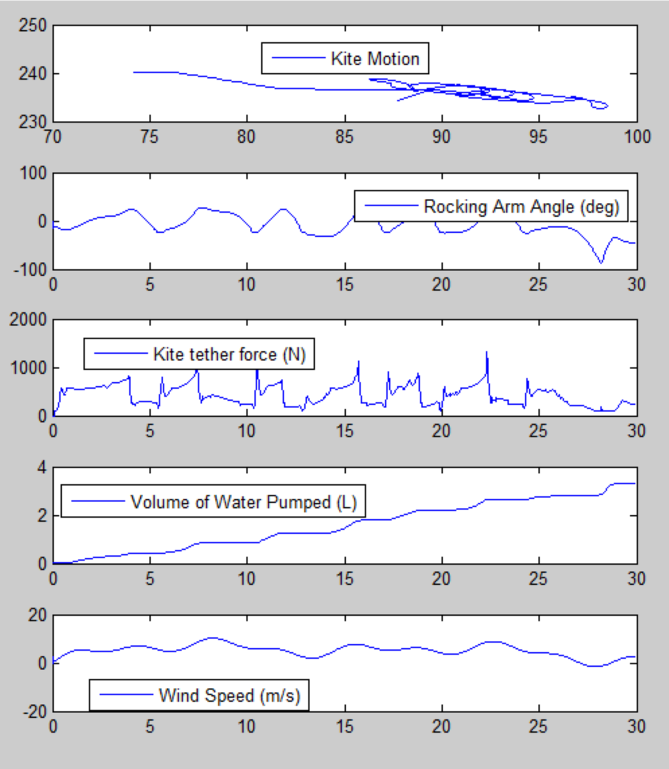

Figure 5 - Case 1 (Wind Velocity = 5 m/s)

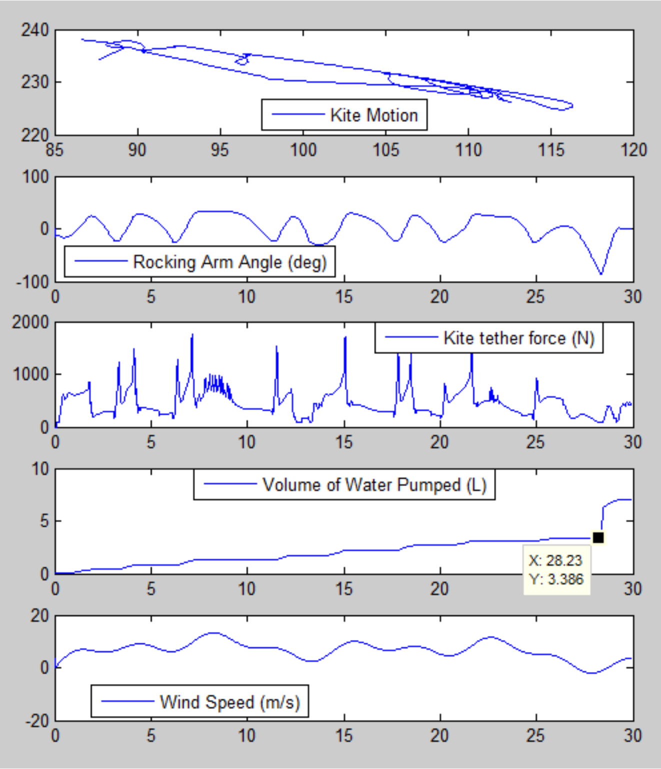

Figure 6 - Case 2 retest (Wind Velocity = 6.7 m/s)

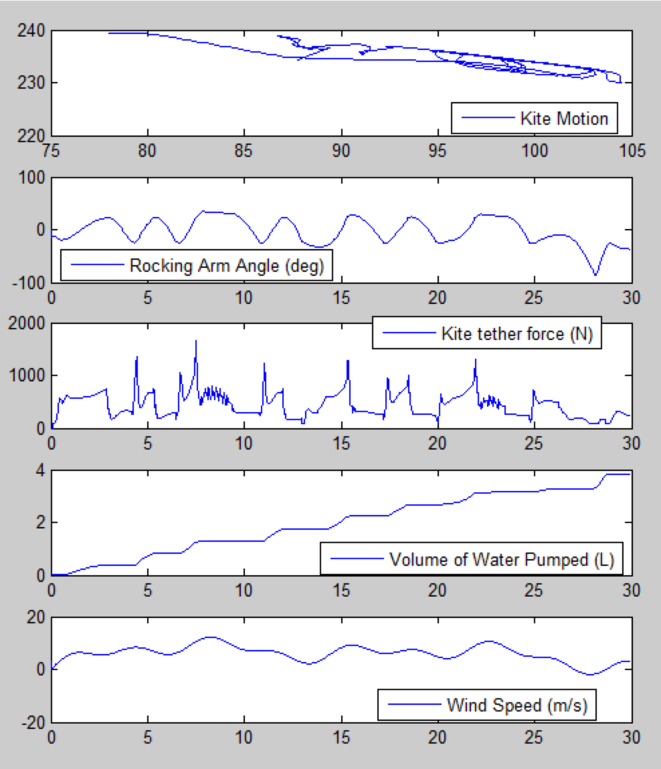

Figure 7 - Case 3 (Kite Area = 8 m^2)

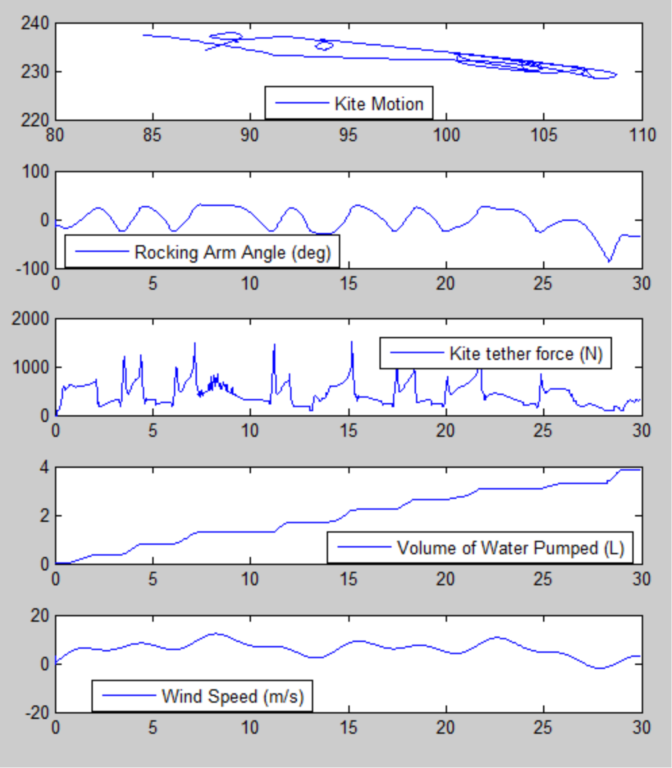

Figure 8 - Case 4 (Kite Area = 12 m^2)

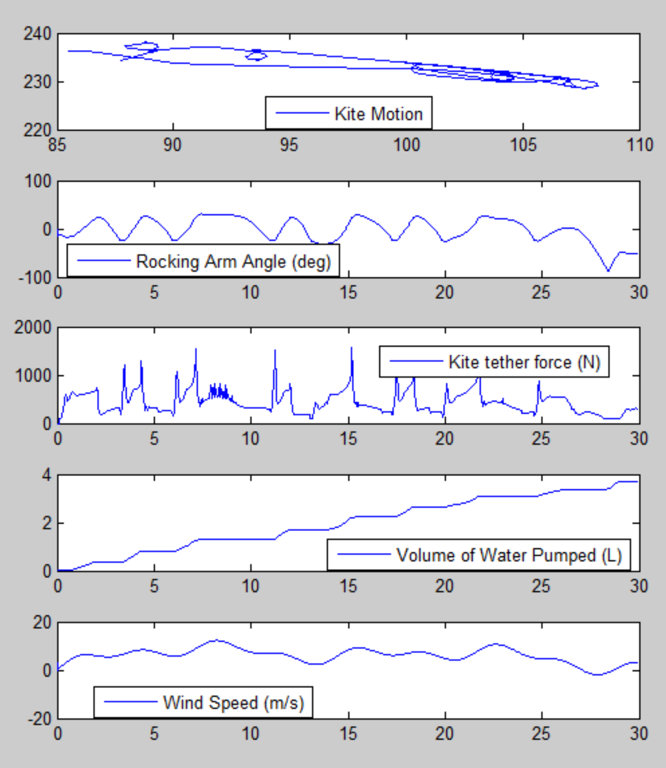

Figure 9 - Case 5 (Kite Weight = 20 N)

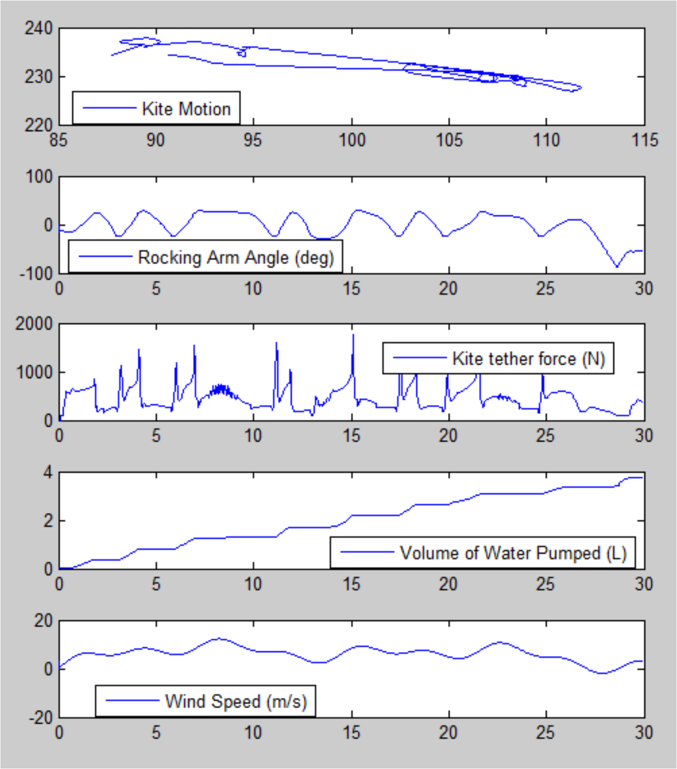

Figure 10 - Case 6 (Kite Weight = 25 N)

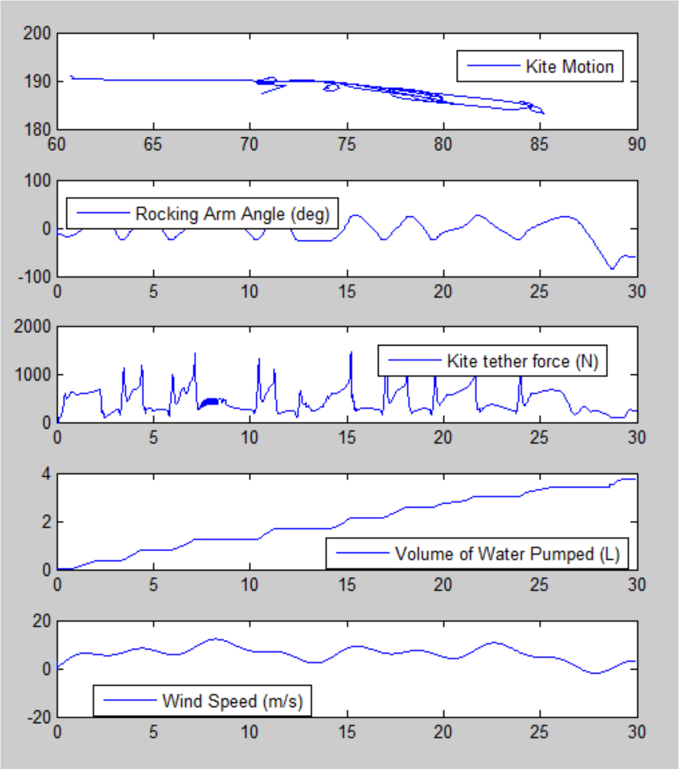

Figure 11 - Case 7 (Tether Length = 200 m)

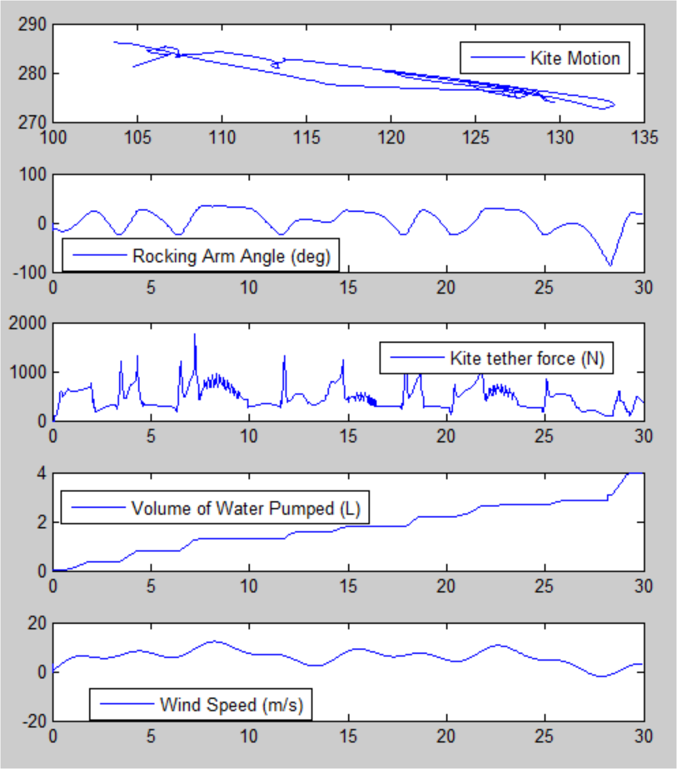

Figure 12 - Case 8 (Tether Length = 300 m)

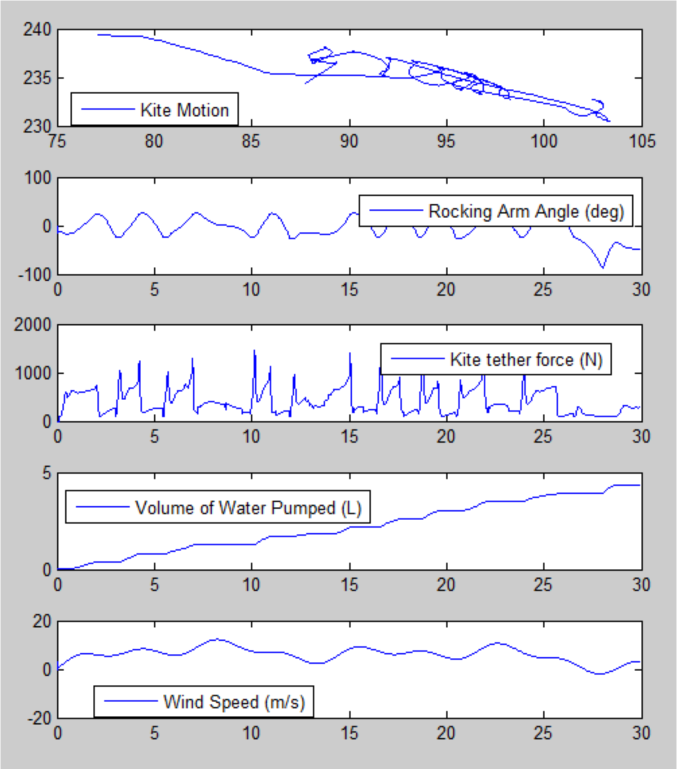

Figure 13 - Case 9 (Tether Diameter = 0.0005 m)

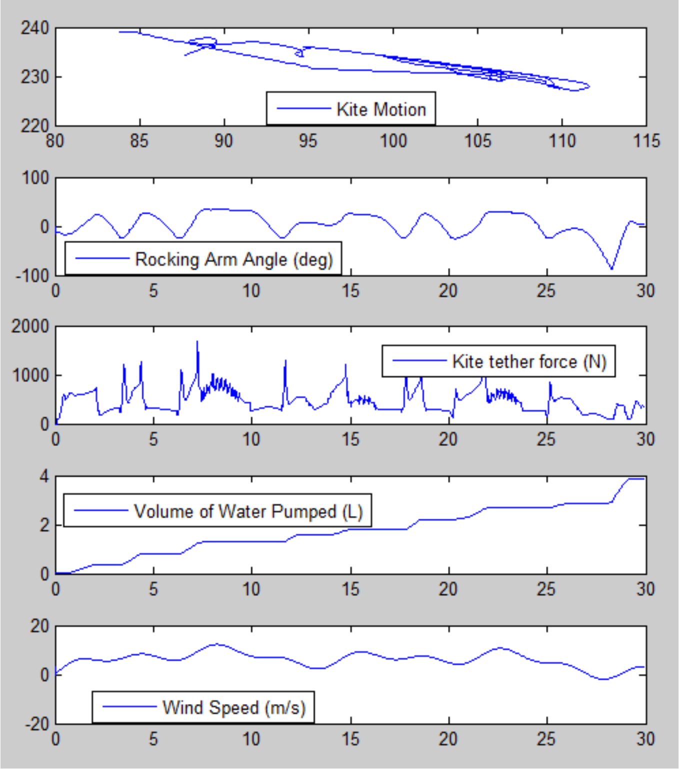

Figure 14 - Case 10 (Tether Diameter = 0.002 m)

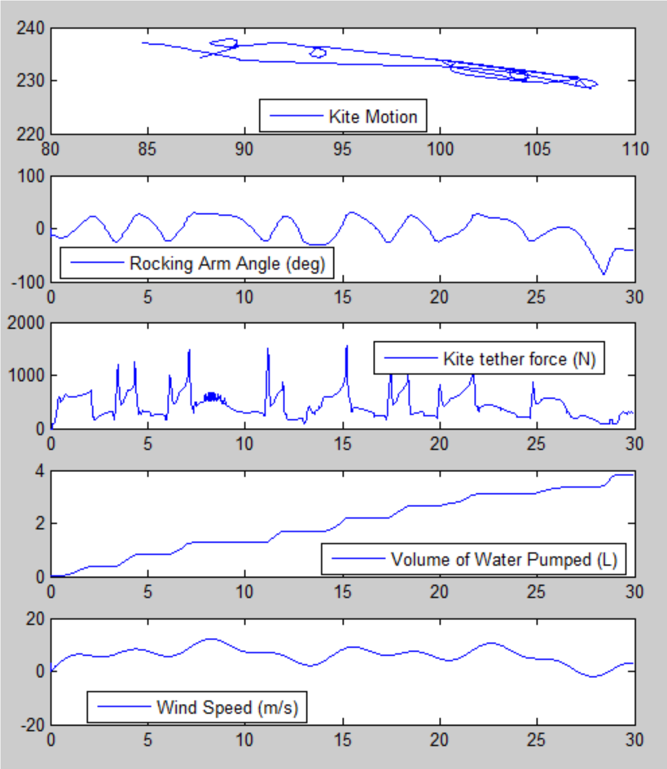

Figure 15 - Case 11 (Tether Density = 0.001 kg/m)

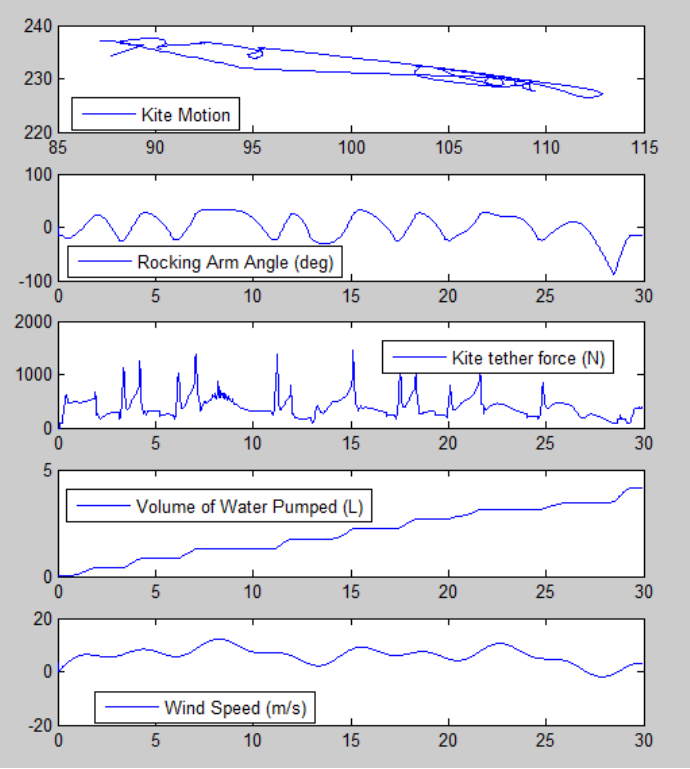

Figure 16 - Case 12 (Well Depth = 60 m)

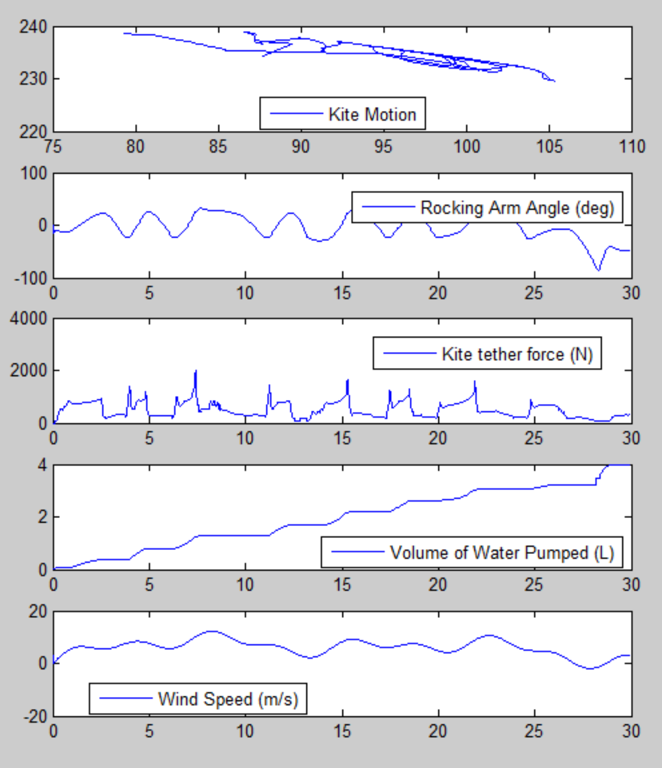

Figure 17 - Case 13 (Well Depth = 200 m)

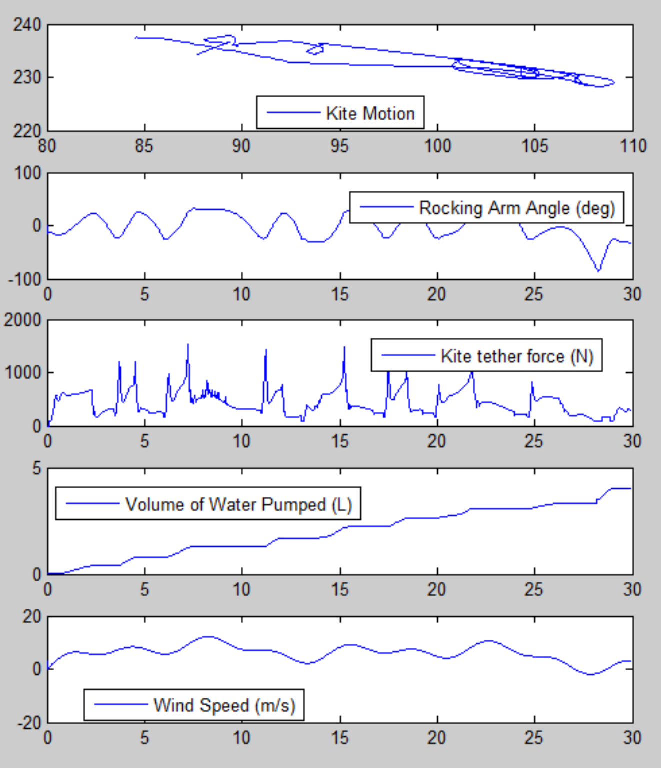

Figure 18 - Case 14 (Kite Aspect Ratio = 3.5)

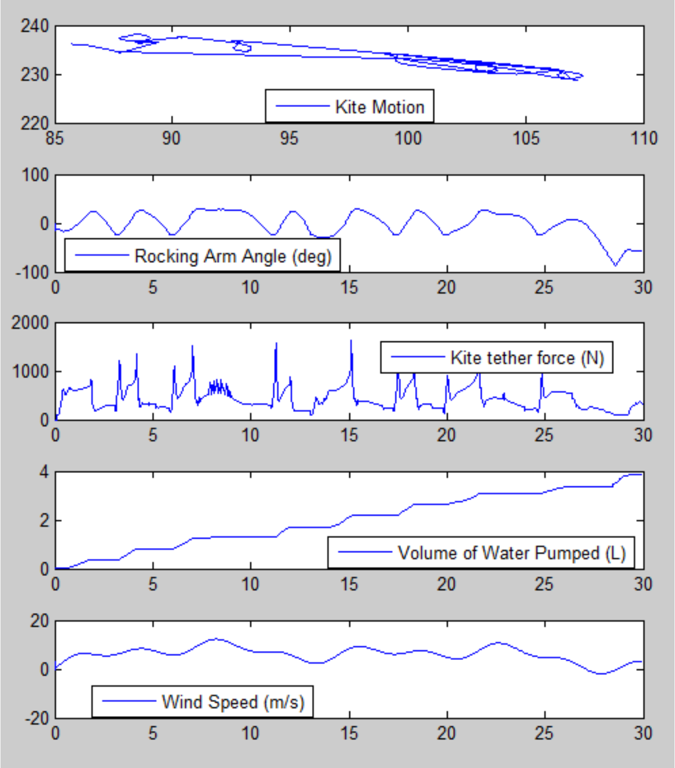

Figure 19 - Case 15 (Kite Aspect Ratio = 5)

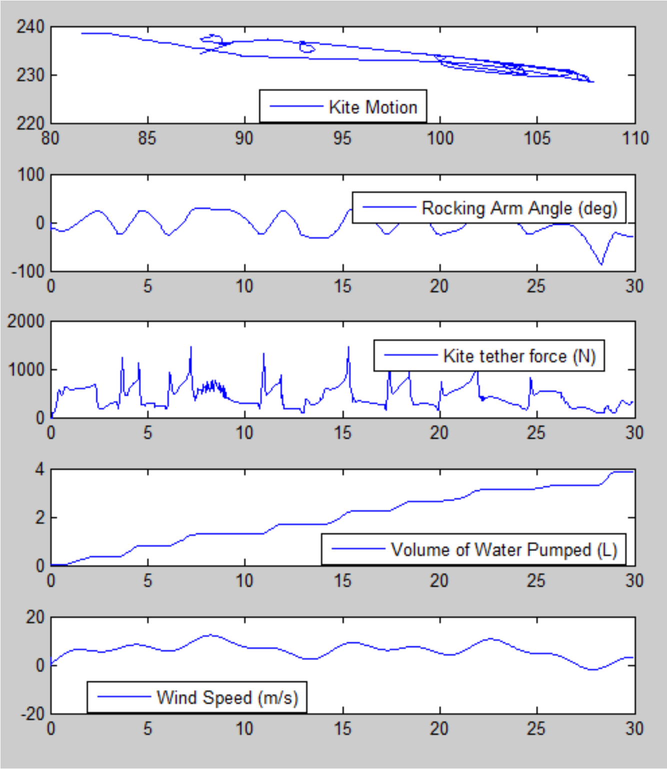

Figure 20 - Case 16 (Kite Angle of Zero Lift = -2°)

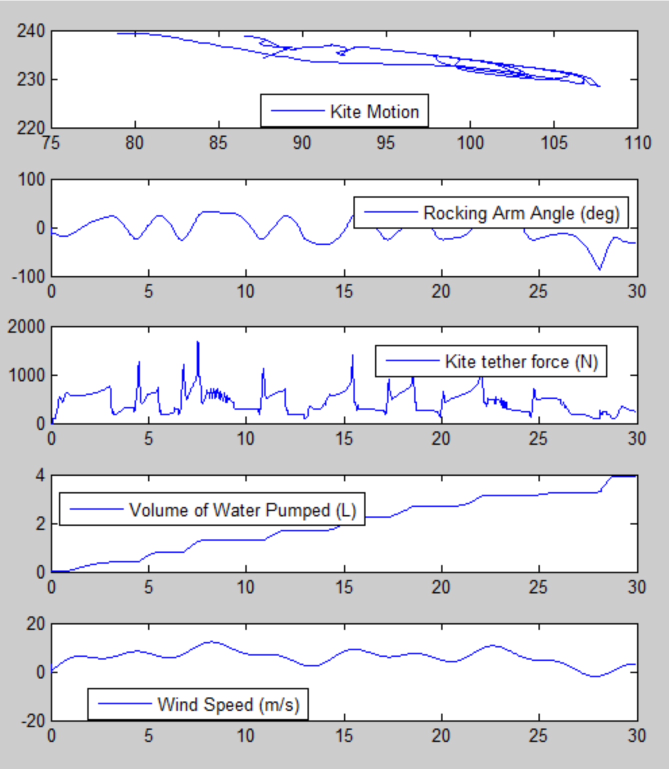

Figure 21 - Case 17 (Kite Angle of Zero Lift = 0°)

4.2 Discussion of Results

Each case produced a rate of water pumped during a 30 sec time span. These values were then compared to the control test (Case0) and their corresponding variable runs to produce the graphs seen in this section. Some cases were not able to run at the variable specified in the above table, and these cases will be mentioned throughout this section along with their graph.

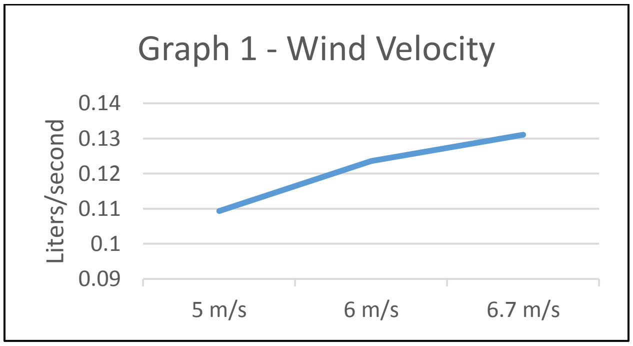

Figure 22 - Variation of rate of water pumped based on the changed variable 'wind velocity.' Shows Cases 1, 0, and 2.

In Graph 1, Cases 1 and 2 were tested against the control, Case 0, and varied the wind velocity as the experimental variable. In this set, Case 2 was originally set to run with a wind velocity of 7 m/s, however there was an error in the simulation, so the number 6.7 m/s was used. The results of these runs physically make sense. As the wind velocity increases, the rate of water volume pumped increases in a linear fashion. This works until the simulation tried to do a wind speed higher than 6.7 m/s. At this point, the simulation was unable to complete its run. This is likely because the increased wind velocity caused a portion of the WPI Kite-Powered Water Pump to fail, such as the tether breaking, or so much force on the Rocking Arm that is was unable to cycle back down to complete the pumping motion. Both of these situations were observed during field testing. As such, there is a clear window where the WPI Kite-Powered Water Pump will function at its finest. If the wind velocity is too slow, there will not be enough water pumped through the system. If the wind velocity is too high, the system will break or cease to function correctly.

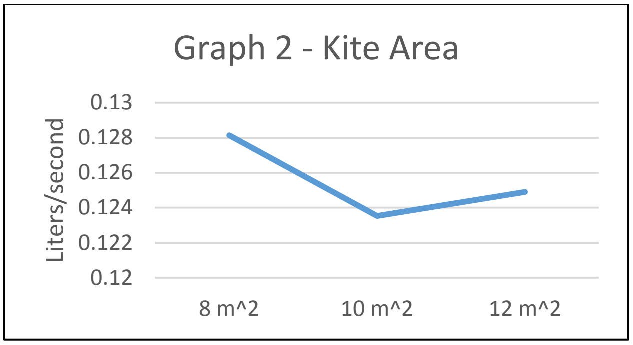

Figure 23 - Variation of rate of water pumped based on the changed variable 'kite area.' Shows Cases 3, 0, and 4.

Graph 2 shows changes in the kite area, tested by Cases 3 and 4. In this graph, there appears to be a parabolic trend to the data. The data shows higher rates of water volume being pumped with a kite area of 8 m^2 compared to the control of 10 m^2, and the second case of 12 m^2 is also higher than the control case. Within these cases the data makes sense because a lesser kite area would also mean lesser weight, so the rocking arm wouldn't be burdened with the extra weight. With a larger kite area, there is more surface area for the kite to catch the wind, which also validates the data produced from this run. Logically, going beyond either of these extremes would probably produce lesser water pumping rates. If the kite is too small, it won't be able to catch enough wind to lift the rocking arm, and if the kite is too large, it would be too heavy to lift the rocking arm. This is true even if the kite weight is kept the same. If the kite is too small yet keeps the weight of the original kite, it would be too dense and wouldn't catch the wind as well as lift the arm properly. If the kite is too large and keeps the weight of the original kite, the kite would be too fragile and would run the risk of tearing.

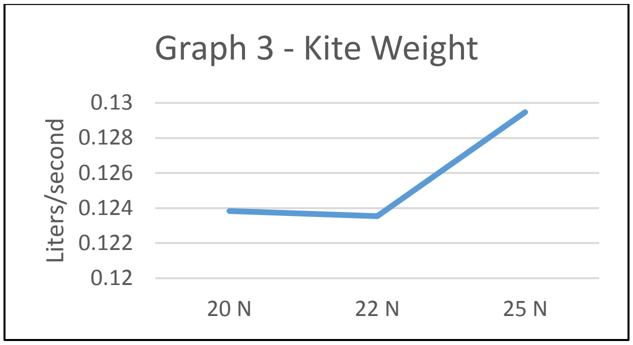

Figure 24 - Variation of rate of water pumped based on the changed variable 'kite weight.' Shows Cases 5, 0, and 6.

Graph 3 looks at the opposite variable to Graph 2. Rather than varying the kite area, this test studies the variation of the kite weight. The first two points of data in this graph make sense, with the lighter weight of Case 5 having a slightly better rate of water pumped verses the control case. With Case 6 however, the rate of water pumped is significantly higher than the control. At first reaction, this result wouldn't make sense, because the higher density of the kite should weigh it down and reduce efficiency. But this quality is also fairly beneficial. At higher wind speeds, the rocking arm wouldn't cycle through the pumping motion because the force from the wind in the kite was too high. A kite with higher density may balance this overwhelming force and allow the system to function more smoothly.

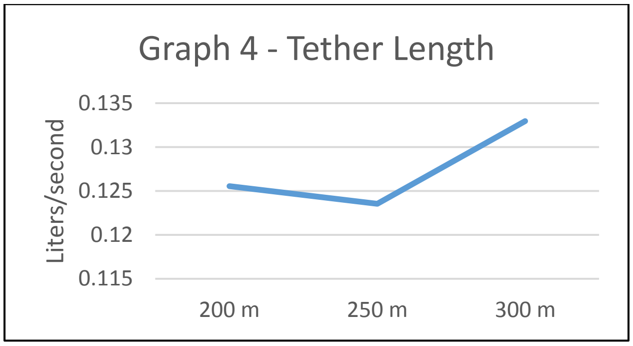

Figure 25 - Variation of rate of water pumped based on the changed variable 'tether length.' Shows Cases 7, 0, and 8.

The next three Graphs shift focus from the kite to the tether of the kite. Graph 4 shows Cases 7 and 8, which varied tether length. The changes in tether length do make sense. This parabolic trend shows that both shorter and longer tether lengths based on the control are more advantageous to the WPI Kite-Powered Water Pump's operation. With a shorter length tether, less force is needed to keep the tether taught, thus the wind energy is converted to the pump more efficiently. Conversely, the longer tether would also produce a higher rate because there are faster wind speeds at higher altitudes. Taking away the wind velocity factor, there are less obstructions to wind at higher altitudes, so the kite would be catching a more constant current rather than rapid changes in direction due to tree lines or other obstructions.

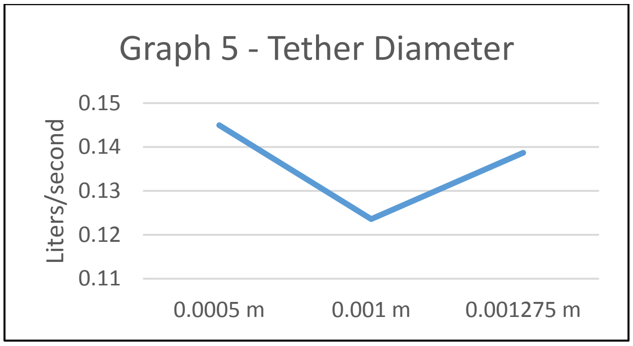

Figure 26 - Variation of rate of water pumped based on the changed variable 'tether diameter.' Shows Cases 9, 0, and 10.

Changes in tether diameter are shown in Graph 5. This particular graph shows a much more distinct parabolic trend, with the control case being close to the minimum value in the trend. Case 9 has a significantly higher pumping rate compared to the control, while Case 10 is not quite as high, but still better than the control. This test group does not make sense physically when all of the other variables are applied. If the tether diameter is too small, it runs the risk of snapping at high wind speeds. If you can get a smaller diameter tether with the same strength as the control, the higher rate does make more sense. The smaller diameter would produce less drag against the wind, thus making the system more efficient and allowing for more of the wind energy to be transferred to the rocking arm. A larger diameter tether on the other hand does not make much sense physically. In terms of the test case, just the diameter grew, so the weight of the tether stayed the same. With the increased diameter, the tether would be able to withstand higher wind speeds, and the danger of the tether snapping would reduce. Realistically, this increased diameter would add weight overall if the density remained the same, or the density would reduce allowing the weight to remain the same, but the tether would have a reduced strength. In addition, there would be an added drag on the tether. It is worth noting that the original Case 10 called for a diameter of 0.002 m, however the simulation would not run, likely due to the errors caused by a tether with a too large diameter, thus the case was run with a value of 0.001275, the highest working value in the simulation.

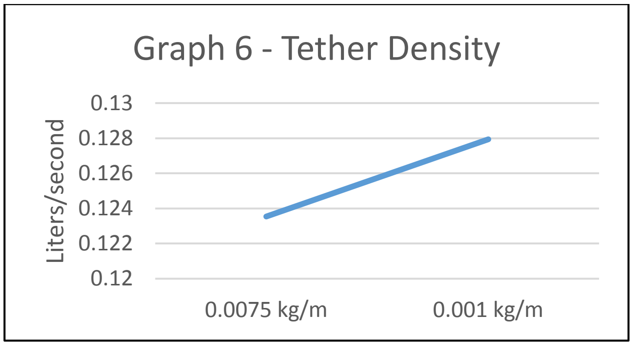

Figure 27 - Variation of rate of water pumped based on the changed variable 'tether density.' Shows Cases 0 and 11.

Graph 6 is the only graph that only shows two Cases, the control and Case 11. This is because this test group tested a change in tether density, and it would not have made sense to test a lesser density because there are already strength issues with the current density of tether. Further reducing the density would only result in more frequent tether failures. Therefore, it makes sense that increasing the tether density in Case 11 would result in a higher rate of water pumped. The increased density would result in less tether failures, as well as counterbalance the kite in the air. Of course, this would only be true to a certain point. Eventually, a tether density that is too high would eventually weigh down the kite to the point where no water would be pumped.

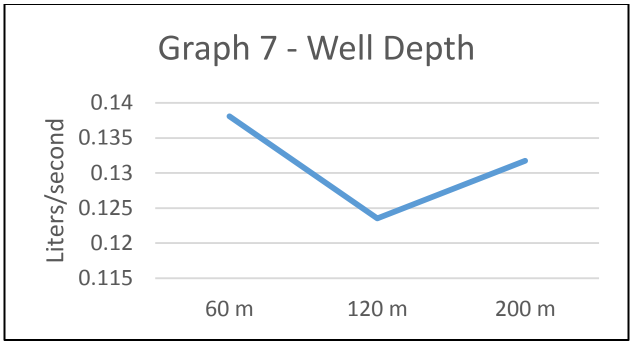

Figure 28 - Variation of rate of water pumped based on the changed variable 'well depth.' Shows Cases 12, 0, and 13.

The changes in well depth are shown in Graph 7. The depth of the well where the water is being pumped is a big effect on the rate at which the water is pumped. With this in mind, the results of this test group don't necessarily match what would be theorized. With no other variables changed, a smaller well depth should result in more water pumped, because less energy is spent pumping the water up the length of the in-ground pipe. This is proven between Case 12 and the control, as the rate of water pumped decreases significantly as the depth increases. What doesn't necessarily make sense about this group is Case 13, where the well depth further increased to 200 m. Logically, the increased depth should result in a lower rate of water pumped, yet the graph shows the rate increasing again after the control.

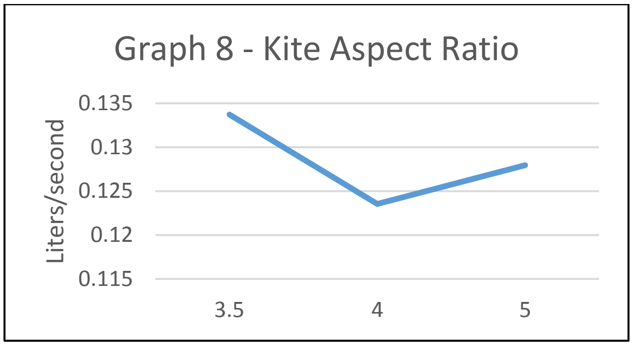

Figure 29 - Variation of rate of water pumped based on the changed variable 'kite aspect ratio.' Shows Cases 14, 0, and 15.

Graph 8 shows the kite aspect ratio. The graph shows that the control aspect ratio of 4 performs worse than that of Case 14 and 15, with ratios of 3.5 and 5 respectively. Simply put, aspect ratio is the $\text{span}^2/\text{area}$. In a standard wing or airfoil, it would make sense that a higher ratio would result in better performance. However, kites are difficult to apply this logic to because they are three dimensional, and are subject to other forces and factors. For instance, a wing is attached to a solid body whereas a kite is only attached to an unstable tether. This difficulty with kites is reflected in the graph. Though the graph shows that a ratio of 3.5 or 5 is better than the control of 4, this does not necessarily represent a trend. A ratio of 2 or 6 may perform better or perhaps worse than the control, it is hard to say for sure without testing. In this particular test, the original Case 14 ratio of 3 was unable to run in the simulation, so it stands to reason that values below this would not work in the simulation anyway.

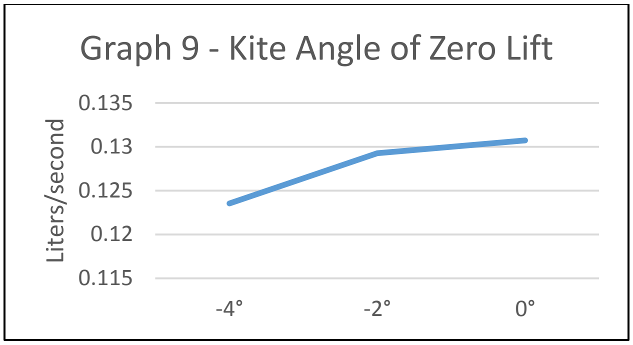

Figure 30 - Variation of rate of water pumped based on the changed variable 'kite angle of zero lift.' Shows Cases 0, 16, and 17.

Finally, Graph 9 shows changes to the angle of zero lift for the kite. As with Graph 6, this graph shows two cases to one extreme of the control rather than one increase and one decrease. This is because a positive angle of lift would be counteractive to the pull on the rocking arm, and there would be a reduced pull from the wind on the rocking arm. The graph shows an exponential trend that suggests reducing the angle increases the rate of water pumped by the system, though this increase slows as you get closer to 0 degrees. Beyond the 0 degree point, there would likely be a kite failure that would either result in the kite falling or just a failure to move the rocking arm.

5.0 Conclusions and Future Work

Each of these graphs show that in no situation is the control case the ideal situation. That being said, the other cases do not necessarily factor in their variables effect on other variables. It stands to say that further tests could be done to test what a change in each of these variables would do while simultaneously changing other variables. For instance, would increasing the kite area while also increasing the kite weight result in an increase in rate of water pumped? These combined variable tests would have to be done in another case set, and would probably require more cases to run than the eighteen run in this test.

6.0 References

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