# Wing mill Energy Harvesting

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**The wing mill experiment was conducted to demonstrate the feasibility of capturing low velocity, turbulent airflow using an oscillating wing system, as opposed to traditional wind turbines, for wind energy harvesting. Two pairs of NACA 0015 airfoils are coupled to a central shaft using four bar linkage mechanisms, placed 90 degrees out of phase, resulting in a coupled, rocking oscillation of each pair. This oscillation is induced by altering each wing's angle of attack via a passive control mechanism, to generate the lift needed to push the wings up and down. Experimentation consisted primarily of outdoor testing - placing the wing mill in variable, turbulent low speed winds (10-20 mph). The data collected and analyzed includes the torque produced at the output shaft, the shaft's angular speed, each airfoil's angular position, and wind speed. The data will allow for fine tuning and better understanding of the device for future iterations. In this paper we present the wing mill's development as well as testing aimed at characterizing its potential power generation.**

## Nomenclature

| | | |
|---|---|---|
| $P$ | = | power output |
| $F$ | = | force registered by load cell |
| $\omega$ | = | rotational velocity of crankshaft |
| $l$ | = | length of de Prony brake lever arm |
| $Cy$ | = | force coefficient in the $y$ direction |

## I. Introduction

THE wing mill is an experimental wing oscillator designed to convert wind energy to usable electrical power. The primary reason to investigate the feasibility of a heaving-wing mechanism as an alternative form of energy conversion to the traditional horizontal axis wind turbine (HAWT) is to expand the reach of wind energy beyond the concept of large commercial wind farms. Traditional turbines require laminar wind flow possible only at certain altitudes and thus are very tall; in addition, minimum tower height of a wind turbine must be far above all nearby obstructions. In fact, turbine blades alone can extend up to 150 feet long. The significant space considerations of a traditional wind turbine restrict wind farms that generate significant amounts of energy to more rural areas.

The wingmill was designed to circumvent these limitations: it is more compact than a HAWT and has the ability to operate at lower wind speeds and higher turbulence. Its advantages are conducive to placement on top of existing structures in an urban environment. Thus, the wing mill has the potential to act as an effective supplement to traditional wind turbines.

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## A. Previous Research

The wing mill was designed taking into consideration previous research on plunging wing mechanisms. The initial concept was created after reading papers by McKinney and DeLaurier[*], Jones and Platzer[†], Lindsey[‡], and Davids[§].

### *1. McKinney and DeLaurier*

The origin of the wing mill project was McKinney and DeLaurier's proof of concept wing mill. They used a harmonically oscillating single wing to harvest energy from the wind. Their paper presented a starting point for our own design; however, our final product was quite different and much of the analysis and results presented in their study could not be directly applied. A vertically translating wing was replaced by a wing flapping about a pivot at one end of its span. McKinney and Delaurier focus on the effect of the phase angle between pitch and roll on the efficiency; this is not a meaningful parameter of the new design. The new design concentrates on the dimensions of our novel four-bar linkage based mechanism instead. Their paper did demonstrate that a wind mill can produce power with efficiency comparable to a wind turbine, and that the lift on the wing dominates power production.

### *2. Jones and Platzer*

Jones and Platzer built on McKinney and Delaurier's work with a hydropower generator. They researched the efficiency and motion of a similarly designed wing mill in water and investigated the effects of the increased viscosity of water as well as other changes related to the different medium. Rotational motion was converted from plunging motion via a rocker-arm assembly. Again, their design and focus was dissimilar enough from the current wing mill that no direct comparison could be made. The decision to have coupled pairs of wings stemmed from this report. Jones and Platzer's work validated McKinney and Delaurier's results.

### *3. Lindsey*

Lindsey combined Jones and Platzer's experimental results with a numerical simulation to examine the potential for commercial use of wing mills to generate power. He found large discrepancies between experimental and numerical results, which could be explained by the simplifications models must use to be effective; however, he confirmed that numerical simulations can provide useful insight. Lindsey concluded that while wing mills have limited potential, there is a potential market for them as small-scale environmentally friendly generators, especially if they can be refined to match the maximum output predicted by the numerical results.

### *4. Davids*

Davids' report used computational and experimental methods to investigate the potential of a wing mill design. He used approximately the same design as McKinney and DeLaurier but was interested in finding the parameter configuration that gave the maximum efficiency. Using both water and air as the working fluid, he found that the maximum theoretical efficiency was 30%. The experimental performance trends matched his numerical results sufficiently to believe that an optimized mechanical system could achieve comparable efficiencies. This again confirms the feasibility of wing mills as an electrical energy producer.

## B. Design Evolution

The current manifestation of this research project is an evolution of the Laboratory for Intelligent Machine Systems' original prototype. A new system of pitch articulation was implemented and the data acquisition system was expanded and improved. With its rudimentary pitch-changing mechanism, the first iteration of the wing mill was designed to confirm that a heaving-wing mechanism was able to convert wind energy to a rotational motion at a large scale. The new iteration is suitable for data collection and first concrete results from a wing mill.

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[*] McKinney, W. and DeLaurier, J., "The Wing mill: An Oscillating-Wing Windmill," Journal of Energy, Vol. 5, No. 2, March-April 1981, pp. 109-115.

[†] Jones, K. D. and Platzer, M. F., "Numerical Computation of Flapping-Wing Propulsion and Power Extraction," AIAA Paper No. 97-0826, Reno, NV, January 1997.

[‡] Lindsey, K., "A Feasibility Study of Oscillating-Wing Power Generators", Master's Thesis, Naval Post Graduate School, Monterey, CA, September 2002.

[§] Davids, S.T., "A Computational and Experimental Investigation of a Flutter Generator", Master's Thesis, Naval Post Graduate School, Monterey, CA, June 1999.

## II. Design

### A. Wing Heaving

Using a heaving wing design presented numerous technical difficulties: the wing needs to be able to repeatedly heave in a vertical direction, control its angle of attack in order to achieve the desired movement, and if a standard motor or generator is to be used the heaving motion must be translated into a rotational motion. While there are many solutions to these requirements, finding one that would be simple enough to manufacture within our budget was challenging. Our novel solution was to create a mechanism that changes the pitch of each wing based on its position within the heaving cycle. When one of the left wings is pitched downwards, the paired right wing is pitched upwards, causing the pair to heave counter clockwise. In order to transmit this heaving motion into rotational motion, from which energy can more easily be produced, we used a Grashof four bar linkage.

This consists of the arm located directly underneath the pivot point of the wing, oriented perpendicular to the span of the wing and a connecting rod from the crank arm to a point along the span of the wing. The frame connecting the axis about which the wing heaves to the crankshaft and the wing spar make up the third and forth "bars" in the four bar mechanism. The pitch changing mechanism has been calibrated to work with the heaving motion of the wings. When correctly calibrated, the wings pass through a 0 degree angle of attack as the crank reaches top or bottom dead center, and begin to move in the opposite direction.

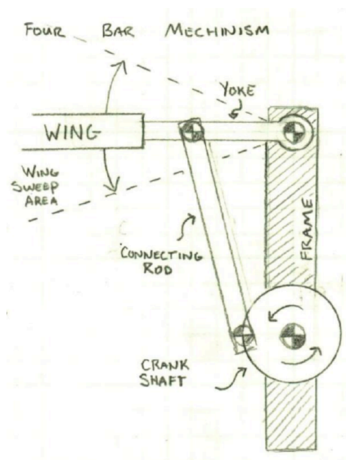


**Figure 1. Four-bar linkage**

Initially, the wing mill would have had two pairs symmetrically flapping wings. However, the decision to use an axial oriented crank made this symmetry nearly impossible; since a crank goes through a period of zero power transmission, wings moving symmetrically cause wings on both sides to go through their zero power transmission phase at the same time causing a large dip in the power output of the device during each crankshaft rotation. Additionally, having both wings simultaneously heave in the same direction creates a force on the frame that could possibly rock the entire frame of the wing mill. Based on these physical constraints we decided to use two pairs of heaving wings with phases offset by 90 degrees, ensuring that the wings are never at top or bottom dead center at the same time.

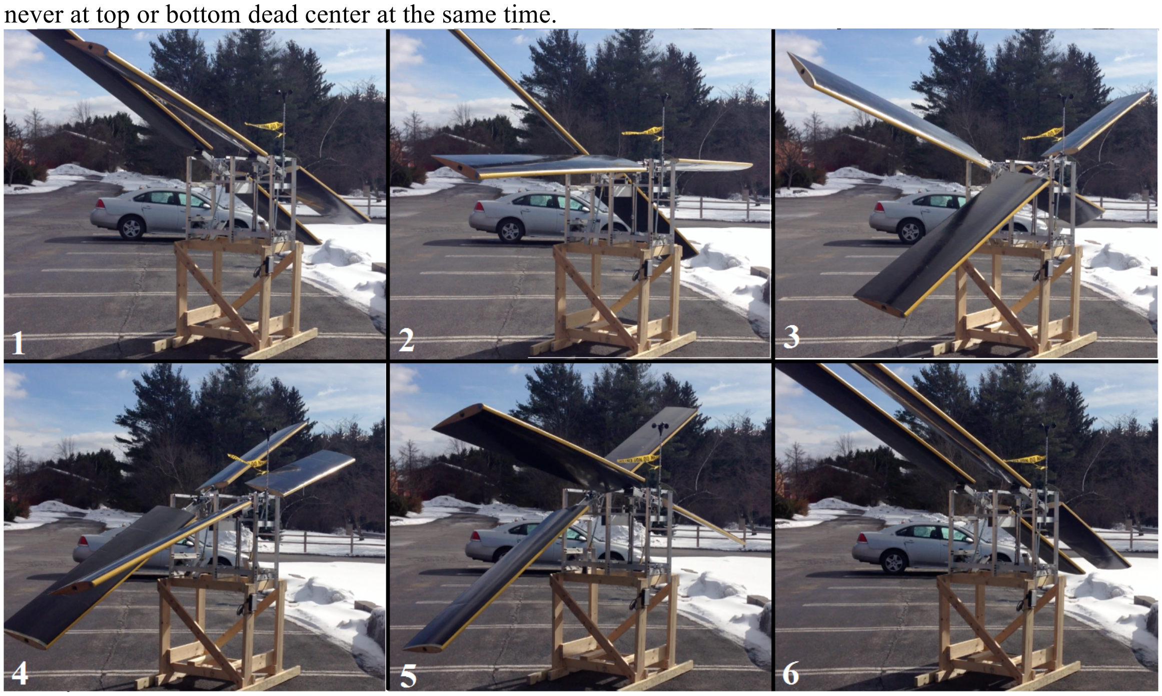


**Figure 2. Motion of wing mill through one cycle. –** *(1)The wing mill begins with a slight angle of attack, the wind pushes the front wing downwards(2). In (3), the wing has reached the bottom of the cycle and its wings are pitched to create lift(4,5) and move back to its original position (6). The rear wing is 90 degrees out of phase .*

### B. Sweep

Another parameter that affects of the performance of the wing mill is the sweep of the wings. We use sweep to denote the angle between the top and bottom dead center positions of a wing. The sweep is determined by the lengths of the wing mill linkages. Using MATLAB, we defined values for the crank and ground linkages from construction requirements, while allowing the rocker and coupler to vary.

Possible values for sweep were 15-60 degrees. Greater angles are difficult to achieve, since the wing mill would have to be raised quite high to prevent the wings from hitting the ground. Smaller angles require the rocker and coupler linkages to be very long. For instance, at 12 degrees the rocker link would be 5.5 in. and the coupler link would be 6.2 in., which is more than twice as long as the ground link. Figure 3 plots the efficiency against the sweep. The efficiency decays asymptotically with the greatest output at the minimum sweep of 15 degrees.

From the data above, one would assume that the sweep angle should be minimized, however a smaller sweep angle reduces the transmission angle between the coupler and rocker links. This drawback was taken into account in a second simulation. Figure 4 also uses a wind speed of 11 m/s, but a minimum load torque was added. When the sweep is less than 25 degrees, the link lengths become too long and can no longer transmit enough torque from the wings to move the crank. This is a concern if the finished wing mill were to be connecting to a generator with a non-negligible minimum torque. This would increase the cut-in speed, which is the minimum wind speed at which power would begin to be generated. Based on the results of the revised MATLAB simulation below, we designed the wing mill with a sweep of 30 degrees.

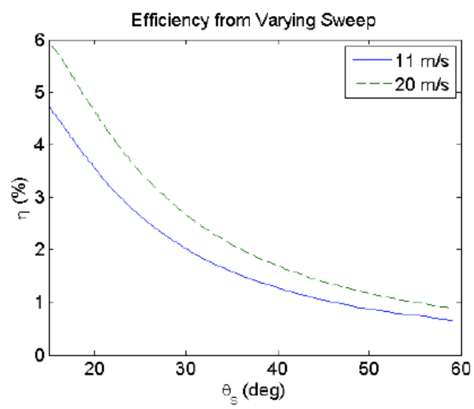


**Figure 3. Efficiency from Varying Sweep**

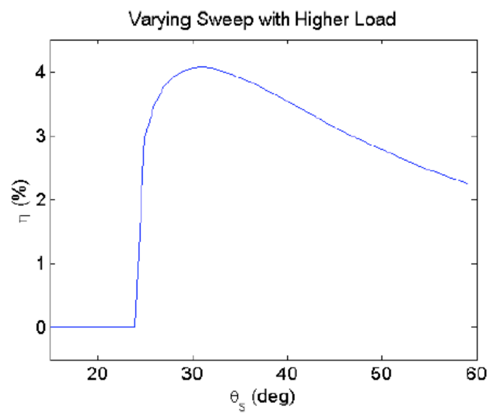


**Figure 4. Varying Sweep with Higher Load**

### C. Pitch Control

An essential element to the proper function of the wing mill is control over the angle of attack of each wing relative to its paired wing and to the other set of wings. The ideal orientation of the wings at the top and bottom of their heave is flat – an angle of attack of zero – while they should be at their maximum angle (positive or negative) while travelling between these two extremes. Previous work and testing on a scaled model of the wing mill has proven that the wings' angular position cannot be reliably determined by the wind. Thus, a more robust control mechanism was desired. As a result of research into various mechanisms, we decided to implement a four-bar linkage to couple the pitching

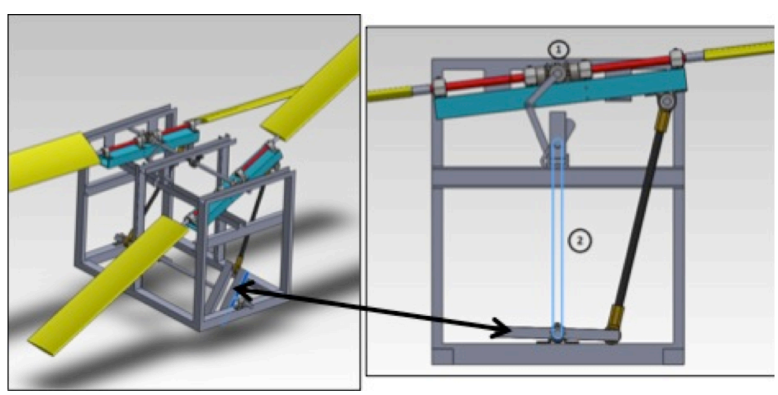


**Figure 5 (a),(b). Entire wing mill (left) and a cross-section highlighting the parasitic mechanism. (1) is where the oscillating output of the small four bar is output to the wings via miter gears. (2) is the chain driving the smaller four bar.**

motion of the wings to their heaving motion.

The lower arm of the four-bar linkage, “the crank,” is parasitically driven off of the main crankshaft of the wing mill (indicated by the double-headed arrow in Fig. 5). In order to reduce the size of the pitching mechanism, sprockets and a chain (represented by blue lines in Fig. 5) were used to transmit the rotation of the main crankshaft to a secondary shaft, which directly drives the crank. The rocker is directly attached to a shaft in the same plane as the wings (indicated by a ‘1’ in Fig. 5), which uses miter gears to transmit the reciprocation of this shaft to the wings’ spars.

Since the wings’ miter gears are being driven by the central miter gear as well as rotating about them due to their heaving motion, a simulation was necessary to understand the epicyclical nature of the gearing validate the design of this mechanism as well as choose appropriate lengths for the components of the four-bar linkage.

The equations provided in Fig. 6 are given in *Norton’s Design of Machinery*[**]. In our mechanism, the crankshaft angle is the angle dictated by the wing mill’s main crankshaft, plus or minus a phase difference set by the sprockets. The output angle is the angle that the gear is swept through. In order to ensure that the crank link was able to make the complete 360 degree revolution, the Grashof condition was checked for each linkage variation.

$$\text{Shortest link} + \text{Longest link} = b + c \tag{1}$$

In our case, the longest link was the ground link, marked as ‘d’ in Fig. 6 and the shortest link was the crank, marked as link ‘a’.In order to account for the inherent epicyclical nature of the gear train shown, the position of the wings was needed as well. Fortunately, the wings’ heaving motion is only the result of another four bar linkage, similarly proportioned. Using the same equations as above and accounting for the gear position, we arrive at a relatively simple expression:

$$\alpha_{wings} = \theta_{4,S} + \theta_{4,B} \tag{2}$$

Simulating these equations using MATLAB, various parameters - such as linkage length and sprocket phase - could be iterated through in order to see their effects on performance. The wing’s angular position is plotted along with the main crankshaft’s angular position for the successful design in the plot in Fig. 8, and a plot of actual wing pitching position in Fig. 11.

With these simulations, it was easily seen that the parameters mentioned earlier varied the output motions dramatically. The amplitude, shape, phase and relative velocities of the output motions could all be changed through the link lengths and the sprocket phase difference. MATLAB was essential to understanding the motions and understanding trends in parameter variations.

$$\theta_4 = 2\tan^{-1}\left(\frac{-B \pm \sqrt{B^2 - 4AC}}{2A}\right)$$
$$A = \cos(\theta_2) - k_1 - k_2\cos(\theta_2) + k_3$$
$$B = -2\sin\theta_2$$
$$C = k_1 - (k_2 + 1)\cos(\theta_2) + k_3$$
$$k_1 = d / a$$
$$k_2 = \frac{d}{c}$$
$$k_3 = \frac{a^2 + c^2 + d^2 - b^2}{2ac}$$

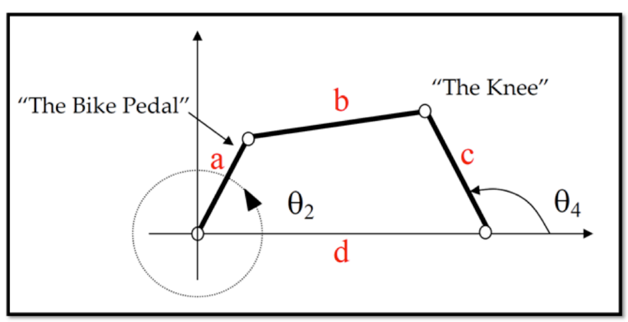


**Figure 6. Four-bar linkage and its governing equations**

From analysis of the governing equations for 4 bars and their combination, it can be seen that producing a pure sinusoid may only be possible for special cases. In light of this, finding link ratios that could closely approximate a sinusoid was a determining important factor when iterating through designs.

[**] Norton, R. L. (2004). Design of Machinery 3rd Ed : An Introduction to the Synthesis and Analysis of Mechanisms and Machines. Worcester, Mass. : McGraw-Hill

The mechanism's desired output angle – 20 degrees – was found through a simple analysis, similar to the calculations investigating downwash on an airfoil. Assuming that the wings are oscillating at a constant frequency of 1 Hz, we can find roughly what the expected angular velocity of the heaving airfoil could be.

We begin with the relative wind-speed, the vector sum of the incoming wind velocity and the wing heave velocity. Using trigonometry we can solve for the angle of the relative wind speed, θ.

$$\theta = \tan^{-1}\left(\frac{-\dot{h}_W}{U}\right) \quad \textbf{(3)}$$

Here, the h term is the heaving position (The derivative term being velocity),

$$\dot{h}_W = r\,\dot{\beta}_W \quad \textbf{(4)}$$

Where heaving angular velocity is

$$\dot{\beta}_W = \frac{47\pi^2}{180}\cos(\pi t) \quad \textbf{(5)}$$

The constant term being the maximum heaving angle of the wings.

Assuming that the wind is blowing parallel to the ground and that we are concerned with the velocity of the wingtip, we can reduce this heaving velocity to its components. In using the velocity at the wingtip, the effective stall angle we find will apply for the entire airfoil, given that the wingtips are the fastest moving portion of the wing. Using the maximum velocity on the wing (at the tip) and combining that with an estimate of the expected wind speeds we arrived at an estimate for the angle of the relative velocity.

Using the angle, we can solve for the effective angle of attack of the wing while in motion. The two angles combined was used as a design goal for the output of the four bar linkage.

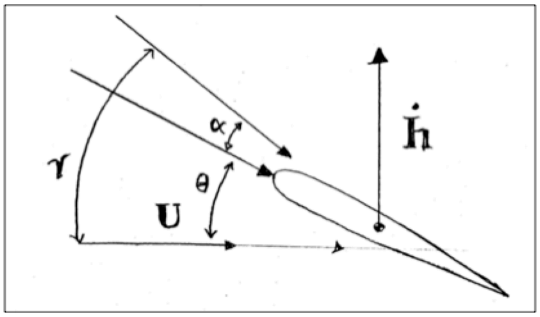


**Figure 7. Angle of attack variables**

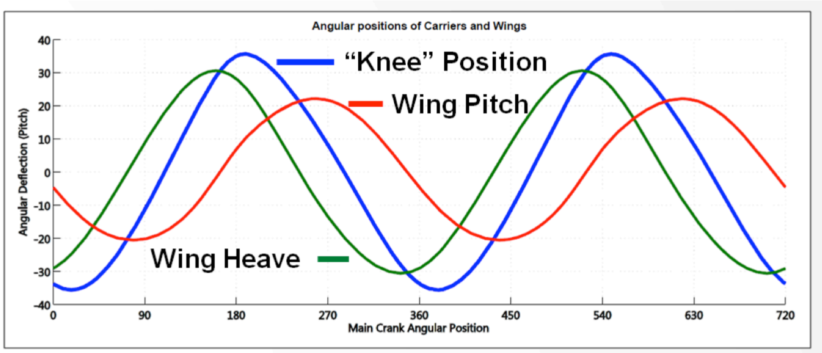


**Figure 8. Angular positions of Carriers and Wings**

## III. Fabrication

### A. Wings

The wings were constructed using a NACA0015 camber profile. To achieve this shape, guides were cut from particleboard and attached to a plank. Sections of foam were then placed in this plank and cut to size – one side at a time. The foam sections were shaped using a hot wire following the guides. The two sides were placed together to make a 4"x24"x22" section of the wing. A total of four sections of wings were attached together, with a 6-foot aluminum spar running the length of it. After sanding, the foam was then prepped for fiberglass.

The foam core was then wrapped with fiberglass, and covered in resin. A thick Mylar sheet that had been spray-painted black was placed over the fiberglass; the paint transfers during the vacuum process to achieve a smooth surface finish. A layer of peel ply was then placed over the Mylar, followed by the breather. This was all placed in a fabricated vacuum bag and kept under -27 psi-$_{ga}$ for 5 hours. After the curing period, the bag and layers were removed. The final step was cutting off excess material, and spray painting the leading edge.

### B. Pitching Mechanism

The pitching mechanism was driven by means of the four bar linkage designed. The linkage itself consisted of a shaft collar that the pitching gears were attached to, an adjustable rocker link for the collar, a coupler bar, and a crank arm that connected to the ancillary axle. To construct this most of the components were machined out of Al 6061 – T6 . Members of the project primarily using a basic mill and lathe machined all of these parts. The most difficult aspect of construction the pitching mechanism was securing the bearings in the linkage to the pins connecting each bar. A total of four different systems were attempted, with the final system involving machined pins out of steel that threaded into the fork of the coupler bar and for the crank arm a steel pin with a groove was placed through the bearings and secured with a wire.

## IV. Data Collection and Instrumentation

To evaluate the performance of the wing mill quantitatively, the system was wired with a series of data acquisition devices. The instrumentation was used to correlate the wind speed and wing pitch with the power output of the crankshaft in real time.

The wind speed was measured with a Type #41 anemometer from Maximum Weather Instruments. The device produced an AC voltage with a frequency that varied proportionately with wind speed. The anemometer was attached to an extendable pole that placed it about 0.6 meters over the frame of the wing mill to make sure that it did not interfere with the flow of air over the airfoils.

Attached to each pair of wings was a potentiometer. The TT Electronics Rotary Potentiometer was attached via a stiff wire to one of the wings and is rotated proportional to the wing's angle of attack. The change in resistance was calibrated in our software to output the current angle of the airfoils in real-time. Only one potentiometer is located on each wing pair because the wings were coupled; by knowing the pitch of one, we know the pitch of the other.
There was an optical encoder on the crankshaft that measures the rotational velocity of the shaft. The HB6M hollow bore optical encoder was chosen because it features 2500 counts per rotation and fits snuggly on the shaft. The result was high-precision accurate data.

A de Prony brake was fabricated to fit on the crankshaft to measure torque output. The brake has a Teflon collar that clamps to the shaft with adjustable force, allowing measurements at different shaft velocities and different simulated loads on the system. The brake has a lever arm of 9.525 cm (3.75 in), so the torque could be calculated by measuring the load at the end of the arm. A Loadstar iLoad Pro Digital integrated load cell was mounted at the end of the lever arm to measure the force exerted by the crankshaft to high precision. The output of the load cell and the length of the de Prony brake lever arm were combined with the output of the optical encoder during post-processing to determine the power output of the wing mill. Equation (6) shows the relation between the power output and datapoints.

$$P = Fl\omega \tag{6}$$

All the instrumentation connects to a U.S. Digital USB4 Encoder Data Acquisition Device. The optical encoder, potentiometers, and anemometer all feed into the DAQ, which then connects to a computer via a USB cable. The load cell connects directly to the computer using its own USB cable. All the data was then compiled on the computer and analyzed using special software.

National Instruments LabVIEW data acquisition software was chosen because of familiarity with its functions. The DAQ came with its own software, but it was judged not to be superior to LabVIEW in its capability. A custom virtual instrument was designed to visually show the outputs of all of our instruments as well as right them to an .LVM file for additional processing.

The wing mill was tested outdoors in a variety of wind conditions and environments. This approach was selected partially because it gives realistic data and also due to the lack of a wind tunnel large enough to test the device in controlled conditions. The main issue with testing outdoors is the unpredictability of the wind. The wind sometimes died down in the middle of testing, or it was too strong to set up the prototype without fear of damaging it. However, the benefits are that the wing mill experiences a range of low-speed, turbulent winds, in which it is designed to operate. The wind tunnel would not be able to provide the same variety of fluctuations as present outdoors.

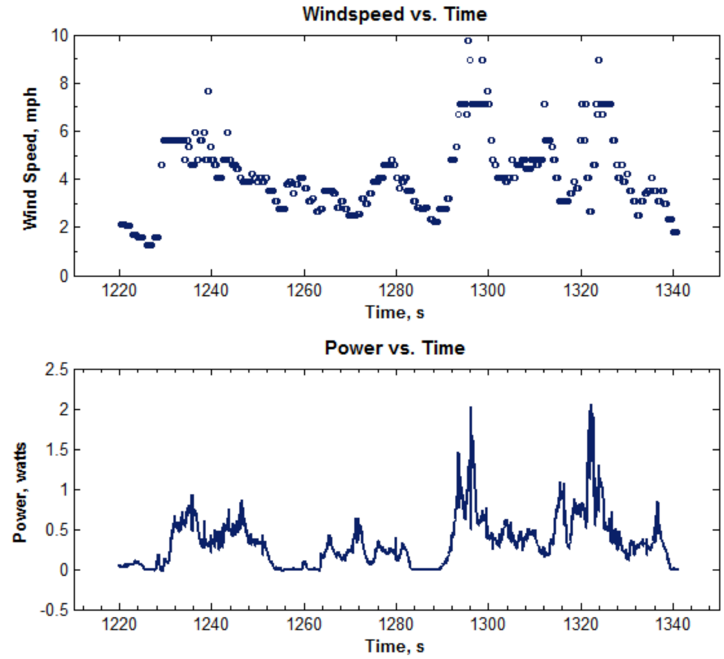


**Figure 9. Power output with low brake loading compared to wind speed**

## V. Results

The wing mill was tested at different brake settings to observe the effect of different loading situations. The figures below compare wind speed to power output. Figures 9 and 10 show lower and higher brake loadings. In the raw data taken from the load cell, once static friction is broken and steady wind assumed, output at the load cell is relatively constant. This behavior is expected from the idealized model of friction. The variable nature of the plots showing power output is therefore a result of variations in the angular speed of the main crank. This variation is present during both brake settings and is a result of irregular heaving of the wings.

An interesting and expected phenomenon observed is the change in wind start up speeds between the two tests. In the low brake loading scenario the start up speed is around 3.5mph (1.6 m/s), and in the high brake loading scenario the startup speed increases marginally to 4.5mph (2 m/s). However, the power output is much higher at similar windspeeds.

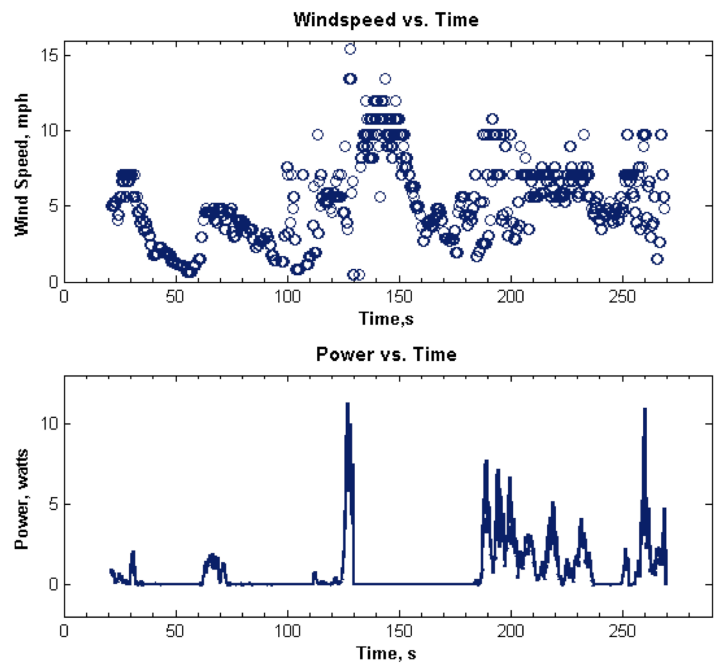


**Figure 10. Power output with high brake loading compared to wind speed**

The power outputs seen here are relatively low compared to a similarly sized traditional windmill, but this inefficiency is likely due to a limitation of the brake and other nonoptimized components we used. With the low brake setting, we achieved a maximum power output of 2 watts at roughly 10 miles per hour. With the higher brake setting, we see a higher power output of 11 watts achieved, albeit at a higher wind speed. The power output is roughly an order of magnitude larger despite the slightly higher startup speed.

In Fig. 10 many of the same trends exist as in Fig. 8. In addition to a higher wind start-up speed, a greater sensitivity to changes in windspeed is noticeable. A comparison of the wing mill's torque output to time shows that with the higher brake loading, torque output is much more sensitive to changes in wind speed. Looking at both plots, however, a key takeaway is the time the wing mill takes to reach a steady state. This is hard to see given that the wind was never truly steady. Later in the data, we have what appears to be more than a gust and the power output follows accordingly.

In Fig. 11, we see a validation of the models used to design and develop the pitch articulation mechanism.

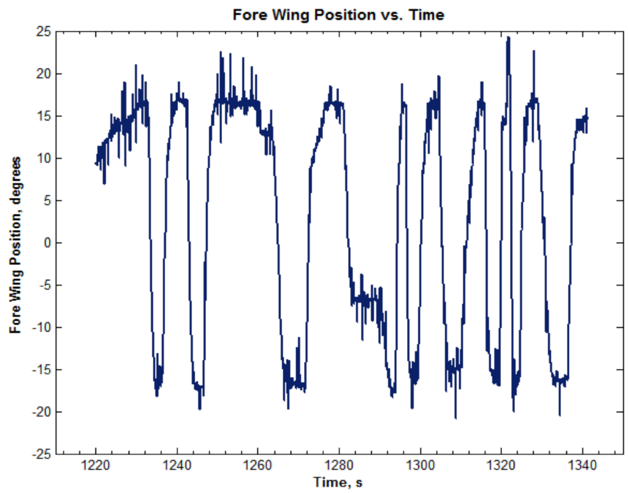


**Figure 11. Wing angular position**

Looking at the plot, we can see that the wings pitch approximately ±17 degrees. This is very close to the intended output angle of ±20 degrees. The discrepancy could arise from a multitude of possible manufacturing errors such as installation imperfections and backlash.

## VI. Conclusion

The wing mill has proven to be a viable energy harvest for small scale generation. The preliminary test results show that although the power output is low, a reciprocating wind harvester has potential. The prototype has much room for improvement, yet our results justify further development of the design. In the future, further tests will be conducted under more stable wind conditions, allowing us to pinpoint system inefficiencies. The system developed in order to pitch the wingmills has also proved its viability

## Acknowledgments

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## References

Norton, R. L. (2004). Design of Machinery 3rd Ed : An Introduction to the Synthesis and Analysis of Mechanisms and Machines. Worcester, Mass. : McGraw-Hill

Bryant, M., Mui, C., Shiff, J., Smead, A., Chisolm, M., Herrera, C. (2011). Wingmill: Novel Wind Energy Capture, Fall 2011 Report. Ithaca, NY. Cornell University