1 Abstract

Current wind turbines are limited in size because a large base is needed support the wind turbine blades. Low altitude winds are also not consistent, which causes the wind turbines to have high downtime. Higher altitudes have strong winds and are constantly flowing. If these winds can be harnessed, large amount of power will be able to be generated, which could seriously offset our fossil fuel use. New methods of harnessing these high altitude winds have recently been created with the use of tethered kites. These kites can theoretically reach high altitudes and the tension force in the tether can be used to generate power. Our project seeks to further the research for high altitude kites by creating a small scale system that will measure the tension and orientation of an unpowered RC glider that is tethered to the base station. This system does not vary in tether length nor contain a generator, so our project will not generate power, but this system can be used to gain an understanding of the dynamics of tethered flight.

2 Introduction

2.1 Background

Human’s have used fossil fuels to supply our energy needs from the beginning of the Industrial Revolution. Since then, our dependence on this non-renewable resource has only increased despite the drastic changes that have been made to our climate and the ever dwindling supply in the crust of the Earth. In order to curb our consumption of fossil fuels, significant research has been performed on certain methods of harvesting renewable resources. One of the most prominent renewable energies is wind power, which is primarily harvested with wind turbines. Wind turbines, however, are inefficient in harvesting wind energy. They require large bases to support their large blades, limiting their possible altitudes to 200 meters with current technology. Because wind turbines can not achieve high altitudes, the wind that is available to harvest energy from is sporadic and slow. A better method of harvesting wind energy is with high altitude kites. High altitude kites are method of harvesting energy from the wind that flows kilometers in the air. Higher altitude winds are significantly more consistent than low altitude winds and have higher velocities, especially in the polar jet streams.
2.2 Research Objectives

We seek to further research in this field by building a small scale kite model that can perform experimental research. This model will use an unpowered RC plane, which will fly tethered to a base station. The RC plane will be controlled by a nearby pilot and will use some energy for a propeller assisted take off. Once a stable flight path has been established, power will be cut and the glider will remain in the air solely due to wind energy. The flight path will be an ellipse in the vertical plane. The glider is connected to a base station with a tether. This base station is able to measure the tension in the tether and position of the glider using a data acquisition system. Because the tether length does not change, no power can be generated. We are simply performing research to gain a deeper understanding of the influence of each parameter on the system. Our goal for this project is to maintain maximum tension of the tether while sustaining either a horizontal flight path or a vertical flight path. This project will assist in creating automated controls in future projects.

3 Process

3.1 Engineering Specifications

<table>
<thead>
<tr>
<th>Matrix No.</th>
<th>Matrix</th>
<th>Marginal Value</th>
<th>Ideal Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Wingspan</td>
<td>≤ 1.5</td>
<td>&lt; 1 m</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Weight</td>
<td>≤ 6</td>
<td>≤ 4 lb</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>System Cost</td>
<td></td>
<td>&lt; 500 $</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Length of Looping Flight</td>
<td>&gt; 2</td>
<td>≥ 3 min</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>Resolution of Tension Data</td>
<td>≤ 0.1</td>
<td>≤ 0.01 N</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>Resolution of Angular Position Data</td>
<td>≤ 0.5</td>
<td>≤ 0.1 deg</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Typical Sampling Rate</td>
<td>5</td>
<td>3 Hz</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Data Sampling Rate</td>
<td>≥ 100</td>
<td>≥ 500 Hz</td>
<td></td>
</tr>
<tr>
<td>9</td>
<td>Minimal Operational Wind Speed at Ground Level</td>
<td>10</td>
<td>5 m/s</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>Maximum Operational Wind Speed at Ground Level</td>
<td>20</td>
<td>40 m/s</td>
<td></td>
</tr>
<tr>
<td>11</td>
<td>Safe for User and Observer</td>
<td>Yes</td>
<td>Yes</td>
<td>Binary</td>
</tr>
<tr>
<td>12</td>
<td>Number of Looping Trials Demonstrated</td>
<td>≥ 25</td>
<td>≥ 30 Binary</td>
<td></td>
</tr>
<tr>
<td>13</td>
<td>Training Time</td>
<td>&lt; 30</td>
<td>&lt; 20 min</td>
<td></td>
</tr>
<tr>
<td>14</td>
<td>Number of Left Right Horizontal Trials</td>
<td>≥ 25</td>
<td>≥ 30 Binary</td>
<td></td>
</tr>
<tr>
<td>15</td>
<td>Tether Length</td>
<td>≥ 15</td>
<td>≥ 30 m</td>
<td></td>
</tr>
</tbody>
</table>

Table 1: List of engineering specifications. Marginal value is the value where the project would be declared a success, and ideal value is the desired goal.
3.2 Glider Design

In order to gain a rough estimate of the magnitudes of the tether tension that will be created from our system, a three-dimensional numerical simulation was created in MATLAB. The acceleration of the glider was solved using the momentum balance equations, and a fourth order Runge-Kutta numerical integrator was used to solve for the position and velocities at any time. Once these values were known, the tension, lift, and drag forces were able to be solved. We assumed that the airfoil was a NACA0015 airfoil [1] and that the simulation started in the flight path. Tab. 2 shows the major flight simulation assumptions and how they will effect our predictions.

<table>
<thead>
<tr>
<th>Assumption</th>
<th>Effects of assumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>Side slip negligible</td>
<td>Neglecting side slip assumes that all the flow is going ideally across the wing of the glider, that is perpendicular to the chord. This means the forces that in reality are being generated through side slip are instead being modeled as lift forces.</td>
</tr>
<tr>
<td>Glider is a point mass</td>
<td>Assuming a point mass neglects inertial moments. Instability of the aircraft, which would decrease the glider’s performance, is not factored in.</td>
</tr>
<tr>
<td>Aerodynamic forces calculated based on 3-D glider</td>
<td>Using 3-D lift and drag forces is a more accurate representation of the forces acting on the glider than the simplified 2-D method because it takes into account the surface area of the wing instead of just the chord length.</td>
</tr>
<tr>
<td>Tether is rigid and mass-less</td>
<td>Without this assumption, tether slack and drag would have to be integrated into the simulation. These components act against the performance glider thus the predicted model will yield a greater performance.</td>
</tr>
<tr>
<td>Constant flight conditions</td>
<td>We cannot predict the slight variation in environmental conditions such as density and wind turbulence.</td>
</tr>
<tr>
<td>Glider is orthogonal to the tether line</td>
<td>We cannot predict the slight variations in glider orientation. It is simplest to assume that the glider is fixed with respect to the tether line vector.</td>
</tr>
<tr>
<td>Wind is always horizontal (parallel to the ground)</td>
<td>We cannot predict the slight variation in environmental conditions wind turbulence and velocity changes.</td>
</tr>
</tbody>
</table>

Table 2: List of all major flight simulation assumptions and their effects.
The simulation shows that a 1.4 meter wingspan plane created 1000 pounds of tension force under certain conditions once steady state had been achieved. We found a similar airplane from HobbyKing called the Bixler, Fig 1. Once steady state has been achieved, the tension force is equal to the addition of the aerodynamic forces. We assumed that the aerodynamic forces are distributed evenly across the projected wing area and in the opposite direction of the tether. In order to find an orientation of the tether bridle that allow the glider to support the extremely large forces that are applied, brute force optimization was performed on the tether attachment locations and bridle angle to minimize the largest stress applied on the wings. The tether that was chosen to support the tension was a Dyneema line. This material was chosen because it can support the high stresses, has high visibility, and a small diameter. The line is also designed to break just after 1000 pounds, so it will break before more important components, such as the base station or the glider.

### 3.3 Base Station Design

The glider is attached to a base station for the purpose of anchoring the glider, as well as gathering position and tether tension data during flight. The simulation results for tension were used as the basis for the design of the base station components. Using structural analysis, the base station components were designed using a maximum force of 1000 pounds applied from the tip of the load cell. The following figures depict the progression of the base station design from the initial concept phase to the final construction.
Two tapered roller bearings were used to support the vertical shaft loading (axial and radial) and still allow rotation. Two radial ball bearings were used to support the radial loading on the horizontal shaft. Two potentiometers were connected to the base station, one to the horizontal shaft and one to the vertical shaft to capture the sweep angles. By knowing the length of the tether and these angles at any time instance, the position of the glider can be determined as a function of time. Additionally, a load cell was attached to the horizontal shaft in order to obtain the tether tension which can be compared to the theoretical model.

3.4 Flight Experiments

Due to the complexity of the experiments and the difficulty to fly an RC plane in windy conditions, multiple practice experiments were performed during the course of the design process. Originally, the gliders were flown untethered in both windy and low wind days, and eventually were tethered during second phase of our practices. The tethered flights added a new challenge to flying the plane, because the glider would lose control and crash when the tether became taut. After attempting to enter a flight path in different methods, we discovered ways to retain stability when the tether became taut. When there was minimal wind, the glider was flown in increasingly large circles until the tether just became taut. The glider would smoothly reorient itself into the flight path. When there was large amounts of wind, it became too difficult to fly the plane smoothly into a flight path. We discovered that it was more beneficial to enter the flight path as soon as possible. We would try to gain altitude and become taut quickly. The plane would lose stability when the tether becomes taut, but with enough altitude, the pilot may regain control before crashing.

Another challenge we encountered after entering the flight path was that the glider would not gain altitude with any control surface inputs. We first thought that this would be fixed by increasing the rudder area. While this did increase the controls entering the flight path, we still did not gain altitude after the tether became taut. After viewing our flight videos, we realized with a symmetric bridle caused the lift forces to be horizontal to the ground. In order to make our glider gain altitude, we reoriented the bridle so that the lift force would be pointed towards the center of our flight radius.

3.5 Data Acquisition

Fig. 5: Complete DAQ System Showing All Stages
This data acquisition (DAQ) consists of three sensors (one load cell and 2 potentiometers) that record all the required data. The load cell is a Phidgets Micro Load Cell (0-50kg), see Fig. 6. The signal is measured in volts and converted to pounds. The potentiometers used are three turn potentiometers. They are used to measure the vertical and horizontal angles of the attached aircraft. The potentiometers are mounted with aluminum L-brackets and flexible couplings to avoid binding see Fig. 7.

![Fig. 6: Load Cell Mount](image)

![Fig. 7: Potentiometer Mount](image)

A bridge amplifier amplifies the sensor signal so it may then be recorded by the system. The device used is a Logos Electromechanical Bridge Amplifier v2. The load cell is wired into the bridge and the resulting output is connected to the DAQ device for measuring and recording. The data is recorded with the DAQ device, the computer, and the LabVIEW code. The DAQ device used is a NI USB-6210 module. It is a 16-bit device capable of 250 kS/s. This produces a load cell resolution of 0.008 N and a potentiometer resolution of 0.016 degrees. Each sensor has a noise range that must be taken into account when recording. All three sensors are wired to the DAQ device which is connected to the computer via USB. The computer is responsible for supplying the DAQ device with power, which then supplies +5V to each sensor.

4 Results and Discussion

Significant progress was made towards the desired end result however there is still room for improvement and refinement. The Bixler v1.1 RC plane proved to be a worthy plane to prototype. The base station design also proved to be a strong concept and provides an adequate means of collecting position and tension data from the system.

4.1 The Bixler

The Bixler’s price, durability, and simplicity of design led to a rapid flying learning curve, short down time in between flights for repairs, and ease of modification. The EPO foam from which the glider is made was sturdy, resilient, and withstood a significant number of hard crashes as we were learning how to fly the glider both in normal flight and in looping flight. In total, 3 Bixler gliders were purchased. The first was lost due to lack of flying experience and high winds. The second was retired due to damage. The third is operational as of this writing. Foam glue was great for assembling the glider but we quickly learned that extra structural reinforcement was necessary in critical areas. The Bixler’s wings were not held to the fuselage well and could not withstand
the harsh crashes. In hard nose-first impacts, they would pull out of the fuselage and showed an inclination to rip apart from leading edge towards the trailing edge near the wing root. To overcome this we glued the wings to the fuselage and applied tape to the wing near the root of the wing. This worked until the glue holding the wings and fuselage together failed. We chose to just use duct tape to hold the wings together. This wasn’t the best solution because the wings could wiggle slightly but it was effective for a quick repair. Other failure points were the control surface joints tearing and the narrow portion of the fuselage would break. We used duct tape to fix these; however, it severely limited the range of motion of the control surfaces. The tail (vertical and horizontal stabilizers) was also a weak point as it was a major joint on the Bixler. Duct tape and glue were constantly applied to maintain a solid connection. A critical note for the duct tape reinforcements is the amount of weight it adds to the glider. The balance between rigidity and weight is delicate as proven by our second glider. The second glider was forced to be retired because it became too heavy to fly at about 750 g, just under 100 g of addition weight in tape.

In place of the hollow foam and plastic cockpit that is included with the glider, we created a similarly shaped solid piece of EPP foam. We had a portion of the foam fit snug inside the glider, and was held in place with duct tape. This addition was needed to protect the nose of the glider from direct impacts. The foam is thin and vulnerable here so the added EPP foam helped to significantly minimize structural damage to the glider. Based on the impacts the nose of the third glider withstood compared to the second glider, it is clear that this addition was valuable.

The Bixler v1.1 was a good choice for a first RC glider but an EPP foam glider would have been a better one. It would have been more resilient and less duct tape would have been needed for reinforcement.

4.2 The Tether

Dyneema was a great choice for the tether. It is flexible, bright orange, and strong. We were able to easily use it as a bridle and adjust it as necessary. Initially marking off the tether at 5 meter increments helped us keep a consistent tether length across the tests.

4.3 The Base Station

The base station’s design is robust yet still compact. The most vulnerable part of it is the exposed load cell and vertical potentiometer however any impact damage to these components would remain localized. The rest of the base station is made of steel, aluminum, or half-inch plywood. The ball bearings used for the vertical potentiometers provide a smooth range of motion. The tapered roller bearings provide smooth range of motion for the horizontal potentiometer while dissipating the vertical loads that are applied. Preliminary testing shows that tracking occurs by the base station with approximately 2 lbs of tension on a 1 m tether.

While the base station works well, it was difficult to manufacture for inexperienced machinists. After consulting with professional machinists, the parts were re-machined to a higher degree of precision. This greatly improved the bearing alignment resulting in minimal turning resistance. Installing the base station in a field was very easy. The auger installation is simple and is secure when in the ground. A rod is used to attach the auger to two hooks on the underside of the base
station. The three adjustable legs are used to level the base station with the aid of a 2D bubble level.

4.4 The Coupled System

When flying with the glider attached to the base station it is recommended to videotape both the glider’s flight and the base station. While not a requirement for the data acquisition, we found it valuable for identifying whether the base station was acquiring accurate data throughout the test. One loop of looping flight was captured via the data acquisition system. The loop had minimal tension (the load cell was not operational at the time of data capture) and captured data featured a lot of noise. With only one data sample to analyze, a credible conclusion can’t be made. More data must be collected via either successful looping flights or by designing a controlled experiment to test the potentiometer’s performance in similar conditions to what is predicted.

5 Conclusions and Recommendations

5.1 Recommendations for Future Designs

The Bixler v1.1 was a good choice for a first RC glider but an EPP foam glider would have been a better one. It would have been more resilient and require less duct tape for reinforcement. Changing the tether’s small markers to larger streamers might also be useful. When testing, it is sometimes difficult to see the tether. On video, it is nearly impossible. The streamers can help identify the location of the tether and indicate any slack in the line. A light material will be needed to avoid adding more tether drag.

5.2 Recommendations for Future Testing

Our tests showed that the glider was losing altitude while performing loops even when there was significant wind. We believe that this is caused by the bridle setup; i.e. the bridle caused the glider to be oriented so that the lift force component was downward when at the top of the flight path. This can be fixed by changing the bridle to a two-point bridle where the tether connects to the fuselage at two points. The ailerons can control the roll of the glider while in the flight path so that the lift force component always is in the positive vertical direction. This may be too difficult to be human controlled so a future project may need to automate the process. A new glider may be need to be designed for this specific purpose in mind.

References


May 8, 2014