Simulink® modelling of a kite wind generator

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Abstract

This paper presents the simulation of a tethered lifting device for wind power generation using Simulink®. An explanation of the underlying power extraction methodology will precede a description of the mathematical model. Heuristic controls are then developed to demonstrate net power generation using a tethered aircraft. This work serves as an in principal demonstration of wind power generation using a tethered aircraft.
Keywords: tether, winch, control, kite, generator, renewable, energy, wind, glider, altitude.

1 Introduction

Reclining fossil fuel reserves, increasing carbon emissions and increasingly fast climate change are profound reasons to pursue renewable, environmentally friendly sources of energy. Wind energy is a well-known alternative to non-renewable energy and usually brings the image of a windmill or wind turbine to mind, a beautiful structure pointing out from the earth with large blades rotating majestically about the hub. In this work however we look at harnessing high altitude wind energy due to the fact that it is much more consistent and is of much higher potential [1].

There have been several proposed methods of extracting high altitude wind energy. The work of Fletcher et al. [2] explored several variants of tethered turbine generators with Fletcher and Roberts exploring high altitude wind energy resources in earlier work [1]. The crux of their ideas was to place a turbine at altitude, tethered to the ground with energy travelling down a conductive cable. Lloyd proposed the flying of closed loop orbits to increase the apparent wind and hence available power for a kite based generator either as a towing device or with on board turbines [3].

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Ockels invented the concept of the Laddermill [4], which works on the principal of a chain of lifting bodies with a high lift (up going) and low lift (down going) half in a loop about a ground-based generator. The high lift half of the loop pulls the chain up, down wind of the low lift half on which the lifting bodies are coasting toward the ground. This idea was later developed into the pumping mill that is essentially half a Laddermill. The pumping mill works on the premise that high and low lift cycles are combined with unreeling and retrieval (respectively) to generate net power [5]. This system has been shown theoretically more efficient in terms cost per unit power generation. Williams has published a number of works on the optimal control of tethered lifting bodies for power generation [6, 7].

At RMIT University there has been work on developing and modelling a tethered glider variant of the Pumping Mill. The focus of this work is in developing methods of control for optimal power generation from a tethered glider system, modelling the system and virtual design tools to aid future development of the concept.

In this work we focus on the initial modelling and virtual testing of a tethered aircraft.

2 System modelling

In this paper an existing aircraft model is utilised and modified to represent a tethered aircraft. The original model was taken from the 'AeroSim Blockset' [8] for Simulink® and the force equations were then replaced with a pendulum model with three degrees of freedom. The pendulum is free to rotate about the ground attachment point and the length is be controlled by either direct acceleration control or direct tension application. The aircraft model used is the Aerosonde® UAV model included in the Aerosim Blockset [8]. The pendulum model is as described in equation (1).

$$\begin{aligned}
\ddot{l} &= \left((\mathbf{F}_{A_g} + [0 \quad 0 \quad -mg]) \cdot \frac{\partial \mathbf{v}}{\partial \dot{l}} - T \right) \left(\frac{1}{m} \right) + l\dot{\phi}^2 + l\dot{\theta}^2 \cos^2 \phi \\
\ddot{\phi} &= \left(\left((\mathbf{F}_{A_g} + [0 \quad 0 \quad -mg]) \cdot \frac{\partial \mathbf{v}}{\partial \dot{\phi}} \right) \left(\frac{1}{m} \right) - \left(2l\dot{l}\dot{\phi} + l^2 \dot{\theta}^2 \sin\phi \cos\phi \right) \Big/ l^2 \right) \\
\ddot{\theta} &= \left(\left((\mathbf{F}_{A_g} + [0 \quad 0 \quad -mg]) \cdot \frac{\partial \mathbf{v}}{\partial \dot{\theta}} \right) \left(\frac{1}{m} \right) - \left(2l\dot{l}\dot{\theta} \cos\phi - 2l^2 \dot{\phi}\dot{\theta} \cos\phi \sin\phi \right) \Big/ l^2 \cos^2 \phi \right)
\end{aligned} \tag{1}$$

where,

l is the tether length

ϕ and θ are the tether rotations

$\dot{l}, \dot{\phi}$ and $\dot{\theta}$ are velocities and

$\ddot{l}, \ddot{\phi}$ and $\ddot{\theta}$ are accelerations

m is the mass

g is acceleration due to gravity

T is the applied tension.

When assuming direct control over tether acceleration equation (1) is reduced to two equations, with the expression for cable length being defined by the control input. This equation is then written into a custom Simulink® block for integration with the existing aircraft model (Figure 1).

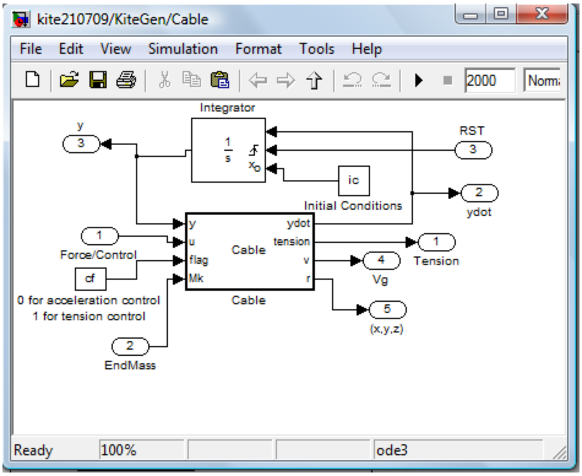

Figure 1: Simulink® custom block.

3 Stability control

Once the system model was constructed it was noted that the tethered aircraft was unstable and hence some form of control was necessary. Using the control models already built within the Aerosonde demos available with the AeroSim Blockset [8] stability was achieved with simple manual tuning. These controls are a PID controller for pitch using the elevator control, a PI controller for the roll using the ailerons and a simple proportional controller for heading. By regulating the roll and heading angles to zero the aircraft remains flying into the wind. The pitch controller is used to regulate the aircraft pitch about a set point and therefore control the lift generated by the aircraft. The only other necessity for stability is that pitch and cable acceleration inputs are changed smoothly and sufficiently slowly.

4 Power generation

Power generation is achieved by coupling cable deployment with high lift conditions and cable retrieval with low lift conditions. In this work cable deployment speed and pitch settings were chosen in an experimental nature as a proof of concept and a validation of the modelling. Logically the cable deployment speed must be lower than the wind speed powering the system by an appropriate factor such that the apparent wind is still sufficient to generate lift.

Further, since the aircraft uses linearised aerodynamic models the angle of attack must be limited within the range of applicability.

5 Results

Throughout this section the simulated results are presented and discussed. Due to the two dimensional nature of the simulation, i.e. there is negligible movement transverse to the wind only the relevant variables and results are shown. Three-dimensional motions of the aircraft are much more complicated and due to their high degree of non-linearity heuristic control is more difficult to implement.
The important parameters for this experiment are given in table 1.

Table 1: Simulation parameters.

Parameter	**Value**	**Parameter**	**Value**
Aircraft mass	8.5kg	Cable Linear Density	0.003kg/m
Wind Speed	22m/s	Wing Area	0.55m^2
Wing Span	2.89m	C_{L0} (zero angle of attack)	0.23
C_{D0} (minimum drag)	0.043	L/D	~6

Figure 2 shows both altitude and downwind position of the aircraft with time for the simulation. During deployment the aircraft climbs and moves downwind as one would expect. As the cable is slowed and the pitch reduced the aircraft climbs a little more but stops moving down wind. During retrieval the aircraft rapidly moves upwind until it again reaches a quasi-equilibrium state, due mainly to the change in apparent wind direction and the wing loading and hence drag. Moving into the second deployment phase the aircraft rapidly moves down wind as the pitch is increased and the cable begins to move outward. Generally

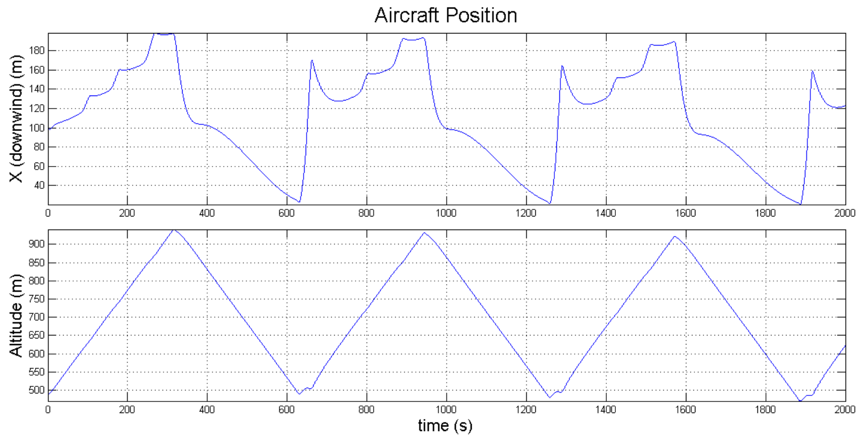

Figure 2: Aircraft position vs. time.

speaking, lift is related to pitch and the increased lift has a corresponding increase in drag. Higher drag means the equilibrium position of the aircraft is further downwind. (Conceptually similar to a heavier aircraft flying slower due to lift induced drag.)

Figure 3 shows the behaviour of tether tension, pitch and the amount of cable deployed over the simulated experiment. The correlation between pitch and cable tension is clearly visible. Care must be taken when designing an experiment to ensure that cable tension remains positive, as a flexible cable cannot support negative tension conditions, hence invalid. This simple experiment shows the aircraft ranging between approximately 500 and 1000 meters altitude and a similar figure for cable deployment. This suggests at maximum altitude the aircraft is approximately directly overhead of the ground station and similarly for minimum altitude.

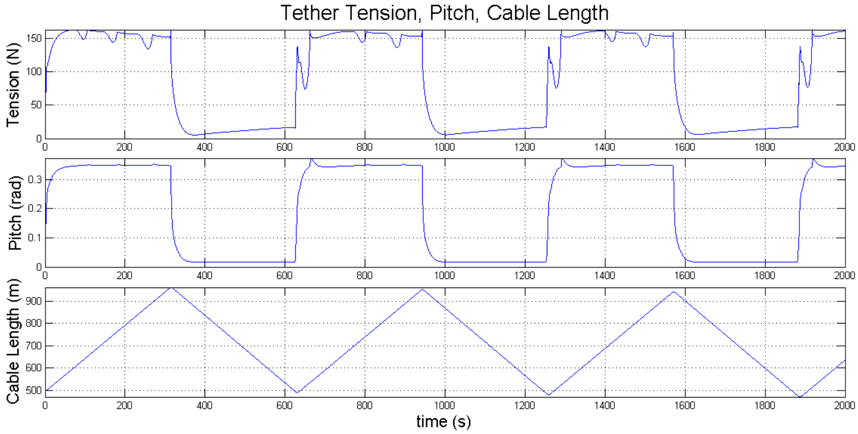

Figure 3: Tether tension, pitch and cable length with time.

Figure 4 shows the power generation and work done over the simulation time. The average power generation for this experiment is approximately 100W. By examining the work done it is possible to estimate the amount of energy storage that is necessary so that retrieval is possible before the next deployment phase.

The simulation performed here shows that with very basic control and a sub-optimal aircraft design 100W can be generated. There are many areas for improvement that would yield a greater average power generation with an aircraft of this size. Firstly optimal control (assuming appropriate winching control is possible) could reduce retrieval time significantly, reduce the transient time in between successive cycles and could increase the power generated during deployment. Further by using a model that does not have a propulsion system sitting idle the mass could be suitably reduced leaving much more lifting force for generating power.

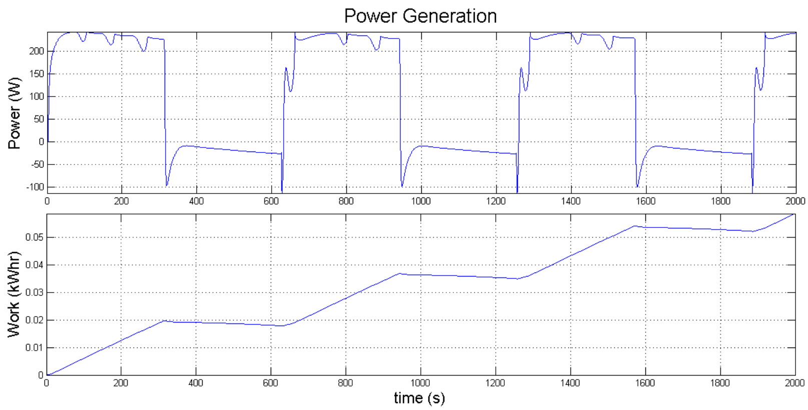

Figure 4: Power generation during simulation time.

There are however many factors that need to be investigated; the effects of aerodynamic drag on the cable needs to be studied along with cable flexibility. Further, work has been done investigating how the aircraft structure and performance is affected by the increased wing loading. There are also many interesting problems related to variability in wind resources and how to manage them.

6 Conclusions

This work has presented a model of a tethered aircraft and simulated its response to heuristic controls. A significant net power generation has been demonstrated despite the many sub-optimal natures of the control. This simple system, showing significant power generation, leaves the door open to many improvements that would see significant increases in power generation. While there is much room for model refinement it is thought that this work is demonstrative of the real capabilities of using tethered aircraft for wind power generation.

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