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The Laddermill - Innovative Wind Energy from High Altitudes in Holland and Australia

Bas Lansdorp
Delft University, The Netherlands

Paul Williams
RMIT University, Melbourne, Australia

Abstract

The Laddermill is a novel concept to harvest electricity from high altitude winds. The concept's operating principle is to drive an electric generator using tethered kites. Several kites are deployed to altitudes of more than 1 km by means of a single cable that is connected to a drum on the groundstation. The upper portion of the cable is connected to the high altitude kites, whereas the lower portion of the cable remains wound around the drum. The kites are controlled to pull the cable from the drum, which in turn drives a generator. After most of the cable is pulled off the drum at high tension, the kites are controlled to fly down in a configuration that generates significantly less lift than during the ascent, thereby reducing the cable tension. The lower portion of the tether is retrieved onto the drum and the process is repeated. The concept allows very large power outputs from single units. The Laddermill concept is being studied at Delft University of Technology, with additional assistance from RMIT University. As part of this cooperative effort, Delft has gathered significant practical experience, including successful demonstration of a small-scale 2 kW Laddermill, as well as having investigated alternative groundstation designs and other kite concepts. At RMIT, modelling, optimisation, and control design for the system has been studied. This paper presents a summary of some of these achievements and will report on future plans.

1. Introduction

Modern society depends heavily on the availability of efficient energy resources. Currently, Australians, for example, spend approximately $50 billion on energy per year [1]. Unfortunately, the major sources of energy are from depleting nonrenewable reserves such as coal and oil. In the last few decades, awareness of both the environmental side effects of coal, gas, oil and uranium coupled with the limited availability of input resources has caused the Australian government and governments worldwide to invest in so-called clean, renewable energy sources. In fact, the Australian Government is committed to a Mandatory Renewable Energy Target (MRET) under the Renewable Energy (Electricity) Act 2000 [2] to generate 9,500 gigawatt hours of extra renewable electricity per year by 2010 [3]. This amount of electricity would be enough to supply four million people in residential areas with power. Among the possibilities for renewable energy are solar, hydroelectricity, wind, and biomass energy sources. However, many of these new technologies centre on *incremental* improvements to the energy problem, making it difficult to foresee an era when humankind will sever its ties to nonrenewable energy sources.

One source of energy that has received significant attention from humans over the years is wind. The extraction of energy from the wind dates back hundreds of years, and is most commonly associated with windmills for pumping water or grinding grain by generating rotational motion from an array of blades. Typical windmills and wind turbines, beginning with the Hallady-Perry windmill design of the 1920s and 1930s, have been continually refined, altered, and developed over the decades in attempts to improve efficiency. This has often only created small improvements in the system output. These systems have evolved modestly to modern wind turbine systems, which have basically reached the peak of their capability. At best, current ground-based wind turbine technology can only supplement a small fraction of the total energy grid. This is due to a number of contributing factors: 1) the variability of the wind source at low altitudes, 2) the costs of constructing wind farms, and 3) the small power output from individual wind turbines. These three factors combine to give a relatively inefficient power generation method compared to the need for large-scale power production. Furthermore, the size of onshore wind farms is limited by the production of noise [4]. Hence, the need alleviate some of these deficiencies has spawned a significant number of proposals for wind turbines placed at high altitudes where the wind energy source is more powerful and more consistent. The prevalence of wind at altitude is due to the fact that the Earth's surface creates a boundary layer effect so that winds generally increase with altitude according to a power-law at low-altitudes. A typical form of the variation of wind speed with altitude is given by $V = V_r \left(h / h_r \right)^{\alpha}$ where V is the wind speed at altitude h, the subscript r refers to some reference velocity and height, and α is a surface friction coefficient that varies from 0.10 for smooth surfaces such as a lake or ocean to 0.40 for an urban area with tall buildings. However, the true wind patterns depend on a complex interaction of solar flux, the Earth's rotation, and a variety of other factors so that winds at higher altitudes are generally present even when the wind at ground level may be nonexistent. For example, solar radiation and the effects of Earth rotation combine to create two major jet streams: the Sub-Tropical Jet and the Polar Front Jet, each of which are located at latitudes between 30 and 40 deg in each hemisphere [5]. The average wind speed in the jet streams can be on the order of 40 m/s, increasing to even higher values in some parts. This is a significant wind source that is in many respects permanent, which should be contrasted with surface wind speeds on the order of 5 m/s, and which have considerable variations. The power generated by traditional wind turbines does not merely increase linearly with wind speed, but rather by the cube of the wind velocity. Hence, doubling the wind speed increases the available power by eight times. It is this fact that has lead many researchers to propose various concepts for extracting electricity from higher altitudes.

In this paper, one particular concept for extracting the energy available in the high altitude winds is explored. Instead of attempting to locate the wind turbine system at high altitudes, the wind energy is used to mechanically drive a ground-based generator. This is achieved by deploying a series of kites to high altitudes via a cable. The paper is structured as follows: first, a review of proposals for high altitude wind energy extraction is undertaken; next, the central "Laddermill" concept is detailed; the current research status of the concept is described and some recent results are reported; finally, plans for future research are laid down.

2. Some Concepts for Extraction of High Altitude Wind Energy

The idea of using airborne windmills for electricity generation was investigated at least as far back as the 1930s [6,7]. The company Sheldahl, Inc., placed a French-made generator (4-blade, 6.8 ft diameter) on a tethered balloon in the late 1960s and generated about 350 Watts of power. According to Manalis [6,7] several proposals were placed to the National Science Foundation and the Energy Resources Development Administration in the United States in the mid-70s to research the possibility of generating power from an airborne windmill. These were denied because of possible hazards to aircraft and were deemed not to be economical. However, communications aerostats have been placed in a number of areas at high altitudes where air traffic is minimal. M.L. Jacobs produced thousands of aerogenerators between 1930 and 1960 in the U.S., which had very reliable performance for nearly 20 years. Advances in technology, as well as the novelty of the idea, has caused it to persist so that proposals for such systems are still being made.

Riegler and Riedler [8], and Riegler et al. [9] proposed the idea of using a turbine wind generator mounted on a tethered balloon or aerostat. Six symmetrically arranged wind turbines (double-bladed, horizontal axis turbines) were proposed to be attached to the balloon just behind its center of gravity. Tethered aerostats have been proposed for a variety of applications, including atmospheric sensors [10], communications [11], coastal surveillance [12], to support radio telescope receivers [13,14], and so on. Onda and Morikawa [15] investigated using a lighter-than-air platform for telecommunication purposes powered via solar power. They preferred to use an aerostat arrangement over a rigid aircraft-type platform because of the fact that an aircraft tends to increase in weight faster than increases in lift as the size increases.

Tethered aerostats have a long history. The Zeppelin airships of the 1900s were capable of reaching altitudes of approximately 7.5 km [12]. Instead of relying on lift generated via tilted rotors to keep a wind generator aloft, it may be more desirable to keep the system at altitude using lift generated from the aerostat. Tethered aerostats require lift provided by the helium inside the aerostat. In the presence of wind, extra lift is provided due to aerodynamics [16]. To make the design very efficient for generating lift at high altitude, it may also be possible to augment the aerostat with a fixed wing. Krausman [16] presented various design charts for a tethered aerostat for sizes up to 28000 m^3. Tethered aerostats have been used for radar and other electronic payloads, and for applications such as border surveillance and communications. Standard aerostats range from 25 to 71 m in length with volumes between 700 and 17000 m^3. According to Riegler and Reidler [8], balloons up to 200000 m^3 are almost certainly feasible, whereas higher volumes will require further research and development. High altitude airships were studied by the US Navy in two programs: High Altitude Super-Pressure Powered Aerostat, and High Surveillance Platform for Over-the-Horizon Targeting [12]. Colozza and Dolca [12] suggested a high-altitude airship which included horizontal-axis wind turbines for power generation.

There are various factors influencing the design of a high altitude aerostat platform. Grant and Rand [17] discuss the positioning of a tethered platform at an altitude of 20 km using a 14125 m^3 balloon. The tether is a 4.82 mm Kevlar cable (Ultimate strength = 15500 N, mass density = 12.83 gram/m). An analysis of the system was performed corresponding to wind conditions at Hill Air Force Base. Using a dynamic analysis, they suggested that deployment of a tethered balloon to 20 km is feasible using winch control. A winch capable of up to 20 m/s has been designed by French manufacturers. A possible problem in launching the balloon is that large forces are present on the balloon between 9 and 15 km. Possible ways to overcome this are: 1) laying the tether on the ground in the direction of the wind and allowing the balloon to "pick-up" the tether naturally, 2) using a truck to drive in the direction of the wind while reeling the tether out, 3) launching the balloon then dropping the tether. Higher strength materials may now make deployment of the balloon to higher altitudes feasible.

Some important aspects of the wind turbine design are the need to use variable pitch blades to reduce the drag at higher wind speeds [6]. For better performance, the use of variable axis turbines would allow the tilt angle of the rotor to be controlled so that the rotors could be used for autorotation in case of loss of buoyancy of the aerostat. Additional power for control of the system could also be provided via solar power. The performance of the turbine depends on the rotor angle of attack and blade angle, which can be used as the control parameter. The power coefficient of the turbine also depends heavily on its tip speed ratio. The tip speed is limited by blade stiffness and vibration considerations. A potential problem for a tethered aerostat for long term use is the possibility or vortex-induced oscillations of the tether. This can lead to significant increases in drag. To help alleviate this problem, aerodynamic fairings distributed along the cable can be used to help reduce drag [18].

Roberts and Shepard [5] described the concept of a rotorcraft situated near-permanently in the upper atmosphere for generating electricity. The main design utilizes an airframe with two or more identical rotors inclined at a controlled angle to the windstream. The rotors are designed to generate electricity as well as providing lift to support the airframe. The tether would be constructed as an aluminium-Spectra composite. Spectra is a high strength fibre, which is required to withstand the high tensile loads generated in the tether due to drag. Aluminium is necessary for conducting the electricity from the turbines to a ground station. Roberts and Shepard [5] provide an analysis of the system and showed that, on average, at sites in Australia and the U.S., landings would be necessary for about 30 hours per week with more frequent landings in summer due to lack of sufficient wind. Although Ref. 5 is a relatively new reference, the concept dates back to at least 1979 [19]. Fletcher [20] discussed using a system consisting of a platform with rotary wings to provide power from the jet stream. A Kevlar tethering cable was suggested with aluminium conductors for the transmission of power to the ground. In this analysis, the rotary wing concept was suggested to have very high operating costs because of the need to replace the key components frequently. Furthermore, Rye [21] performed a linear stability analysis of the tethered rotorcraft and found that the system is stable for short tether lengths, but unstable for long cables. This implies that active control would be required to stabilize the system at high altitudes. Fry and Hise [22] suggested a tethered system supported by balloons or gliders with wind driven rotors affixed along the length of the tether to generate power. Kling [23] suggested a tethered aerostat carrying at least one gimbal-mounted rotor for generating power. Pugh [24] suggested wind generators at altitude suspended by a kite or similar arrangement. A number of other concepts for extracting wind energy through tethered systems at high altitudes have also been proposed. Many of these concepts also propose to locate the electric generator at altitude [25-29]. Mouton and Thompson [30] suggested a lighter-than-air craft (tubular aircraft) attached to a tether. Power is transmitted mechanically to electrical generators on the ground by power-transmission cables bridging drive sheaves at the turbine wheels and driven sheaves at the generators.

One of the major drawbacks of the aforementioned systems is that the power generator is collocated with the wind energy source. This means that the system must support a significant load in addition to the cable loads. This raises some problems in launching the system to the desired altitude, but more significantly introduces additional costs. An alternative concept was proposed by Ockels [31], where power is generated by a series of high-lifting wings or kites that move a cable through an electric generator. The closed-cable consists of an upside and downside, as shown in Figure 1. The wings on the upside operate at high angles of attack generating high lift and pull the cable upwards, whereas the wings on the downside generate very low lift. The difference in tension at the ground winch causes the cable to be pulled through the generator, generating electric power. It is proposed that the wings would be constructed of light material or inflatable structures so that a soft landing would be assured in case of lulls in the wind. Meijaard et al. [32] developed a mathematical model for the system including the effect of blade dynamics and found that the blade rotation is unstable in the presence of disturbances. Lansdorp and Ockels [33] modified the original Laddermill concept to consist of a single cable with connected wings or kites at the extremity. Rather than continually allowing the system to be pulled around a generator, the cable is moved up and down alternately. It has been concluded that this alternate Laddermill concept is a lighter-weight option. It is also a preferable option from the point-of-view of simplicity. The downside is the alternate power production.

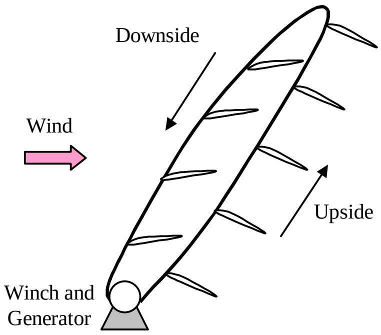

Figure 1: The original Laddermill concept [31].

Recently, Bolonkin [34] presented a number of concepts for extracting wind energy from high altitudes based primarily on the concepts developed in Ref. 5. Bolonkin proposed a system with a high altitude rotor deployed below a stabilized body. He suggested using the rotor as an autogyro if the wind drops below a given threshold. Other designs include a closed-loop cable with forward and backward blades that "rotate" as the cable is driven, which is basically the Laddermill concept, except that it is supported by a balloon. The system would be placed at an altitude of 10 to 12 km at latitudes between 20 and 35 deg. Advances in material make such a system practical using today's technology. For example, the development of Spectra and other fibres that have very high strength to weight ratios means that the cables can withstand much higher loads without adding significant weight to the system. The possibility of utilizing material such as carbon nanotubes, currently being investigated for possible use on the space elevator, would also result in much improved designs.

Loyd [35] noted that kites have been used for hundreds of years for pulling or lifting loads. He suggested that a kite could be used to fly a closed-path downwind of a tether and transverse to the direction of the wind. This type of maneuver increases the crosswind airspeed by a factor of the lift-to-drag ratio of the kite. The lift could then be used to both support the kite and to generate power. He suggested either using the tether tension to "pull a load", or using an air turbine on the kite itself, to generate power. Using conventional 1980s technology, he suggested that a single machine's output would be roughly 3 times that of a ground-based turbine. Studies of the shape of the kite and tether have been performed. Varma and Goela [36] determined the shape of a kite tether under wind loading and showed that it can be significantly different from the standard catenary shape, whereas Jackson [37] derived the optimum shape for tension kites based on lifting-line theory.

Payne and McCutchen [38] suggested different types of tethered "self-erecting" structures (autogyro-helicopter, paramill, sailplane) to extract power at altitude. The energy that is extracted is transmitted to the ground by one of the following: 1) a windmill carried at altitude drives an electrical generator and conducts power to the ground, 2) one or two tethered aircraft are controlled to fly large diameter circles with the tether ends connected to a lever arm on the ground whose vertical axis is fixed to a power generation device, 3) the tethered aircraft are controlled to zig-zag in the wind which rotates a small lever on the ground. Loeb [39] suggested using a tether with a train of parakites or modified parachutes to convert wind energy into rotational energy to allow the line to be pulled off a drum. Using canopy lines, the parakites could be selectively collapsed to allow the tether to be reeled in. The shaft output provides energy either by operation of standard electrical generators or air compressors. Another concept utilizing a sail or buoyant wing was suggested by Lois [40].

Carpenter [41] described a method for extracting energy from the wind using a tethered kite/aircraft. Instead of using a generator on the kite, the tether is pulled off a drum that drives a rotor. The kite is remotely controlled such that its angle of attack is manipulated as a function of position downwind. Three modes of operation were described. In each mode, power is generated when the kite travels downwind pulling the tether off the drum. Upwind travel consumes energy, and the three modes proposed are aimed to reduce the energy expended. The first mode increases the angle of attack at the completion of the downwind journey to cause the kite to increase altitude. The angle of attack is then controlled to cause the kite to move upwind and downward to its starting point. The second mode simply decreases the angle of attack at the completion of the downwind journey, thereby decreasing the tether tension, and the kite is simply reeled back in. The final mode is proposed to alter the surface area of the kite to change the lift and thereby the tension in the tether. The design of a variable surface paraglider was described by Hoisington [42], who also noted that when a paraglider reduces its angle of attack, the wing becomes more likely to collapse. Thus, the variable area concept leads to better stability of the paraglider.

It is apparent from this review of existing proposals that there are two main concepts for extracting energy from high altitude winds. These differ primarily in the location of the generator. Early proposals placed the generator in the upper atmosphere and the electricity is conducted to the ground. Newer proposals locate the generator on the ground, and use the wind to mechanically drive the generator through the tether tension.

3. The Laddermill

The Laddermill concept makes use of lifting bodies, called kites or wings, connected to a cable that stretches into the higher regions of the atmosphere. The lower part of the cable, about 10% of the total length is wound around a drum. The tension that the kite creates in the cable pulls it off the drum, thus driving the generator, as shown in Figure 2.

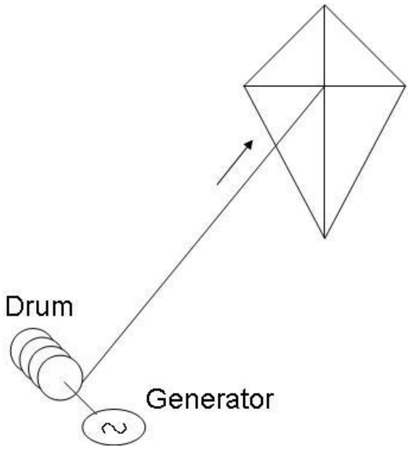

Figure 2: Simple illustration of the Laddermill principle.

A central characteristic of the system is that the kite dynamics must be controlled to generate high and low lift alternately. To cause the kite to ascend, it must operate at a high angle of attack and the forces on the kite must be sufficient to overcome tether drag and the weight of the system. Forces on the kite can be improved dramatically by flying the kite across the wind as shown in Figure 3, which would enable higher tension forces to be created [35].

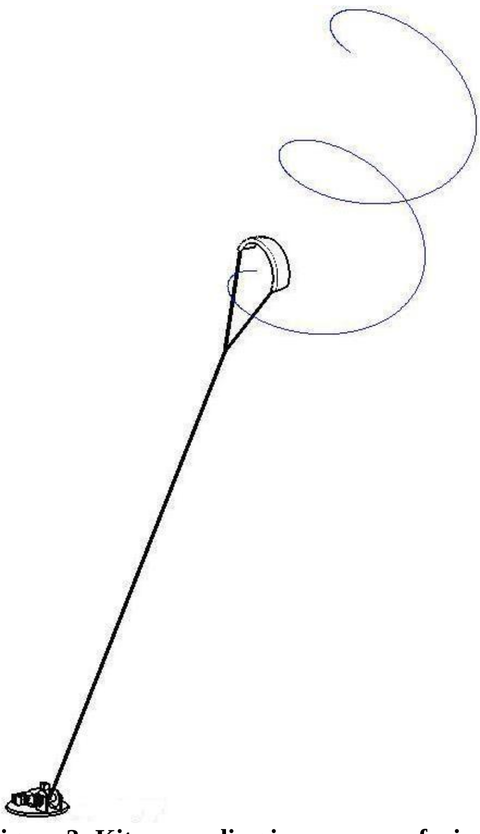

Figure 3: Kite ascending in presence of wind.

Once the cable has been pulled off the drum, the cable must be retrieved. In order to generate a surplus of energy per cycle, the lift of the kite has to be reduced, thereby reducing the tension in the cable. This can be achieved by lowering the angle of attack of the kite. One possibility for a complete maneuver of the kite resembles a figure-of-eight, where the descent of the kite corresponds to a reduced kite angle of attack, as illustrated in Figure 4. This flight pattern differs from the ascending/descending circular motion (helical) illustrated in Figure 3. One aspect of this research is to determine the types of trajectories that result in the optimal net average power produced per cycle.

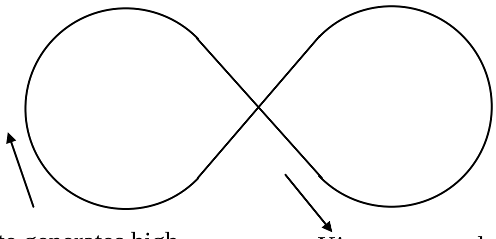

Figure 4: Projection of possible ideal kite trajectory for generating power.

A high ratio between the cable tension when ascending and the cable tension when descending will increase the power output and efficiency of the Laddermill. Only the lower ~10% of the cable will be payed out and retrieved, although optimised full-scale trajectories still need to be explored. The rest of the cable with the kites/wings attached will always remain airborne during normal operation. In the case of insufficient wind, the whole Laddermill will need to be retrieved. Preliminary simulations with wind data from "de Bilt" in Holland show this will occur about 40 times per year, but precise calculations must be performed for particular locations around the world.

The actual Laddermill will have several wings connected in the upper section of the cable. An artist impression of the Laddermill is shown in Figure 5. The installed power of a Laddermill can be higher than that of conventional windmills. Since the wings are high up in the air, their size is not limited like the blades of a conventional windmill. Large controllable kites are thus an enabling technology for the Laddermill. Preliminary results with remotely controllable kites exist [43]. Higher installed power will lead to a larger cable diameter and a larger, ground-based generator. Larger single-unit outputs are expected to decrease the cost per kWh.

Figure 5: Artist impression of the Laddermill.

4. Laddermill Research Status

4.1. Preliminary Modelling and Trajectory Control

In order to understand the behavior of a tethered kite system deployed into high altitude winds, it is necessary to begin by studying the dynamics and control of a simplified system. Such a simple model is useful for trajectory design and optimisation, as well as the design of a feedback controller. The simplest model of a tethered kite system is to treat the tether as inelastic and straight. Although this may seem very crude, this type of model has been used extensively for the design of controllers for tethered satellite systems [44, 45] and aerial-towed systems [46]. For trajectory design purposes, the actual kite dynamics are not considered, and the forces on the kite are modelled purely as lift and drag, whose magnitudes are functions of the kite angle of attack. Three-dimensional control is achieved by tilting the lift vector in the desired direction. The coordinates of the tether tip are described by the spherical coordinates (r,θ,ϕ), where r approximates the tether length, θ describes the angle from the winch to the kite in the $x-z$ plane, and ϕ describes the angle from the winch to the kite in the cross-wind direction, i.e., $x-y$ plane (see Figure 6). In other words, the Cartesian coordinates of the kite can be represented by $x = r\sin\theta\cos\phi$, $y = r\sin\phi$, $z = r\cos\theta\cos\phi$.

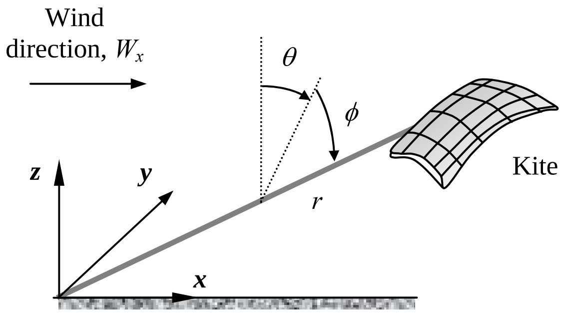

Figure 6: Simplified tethered kite model for trajectory design.

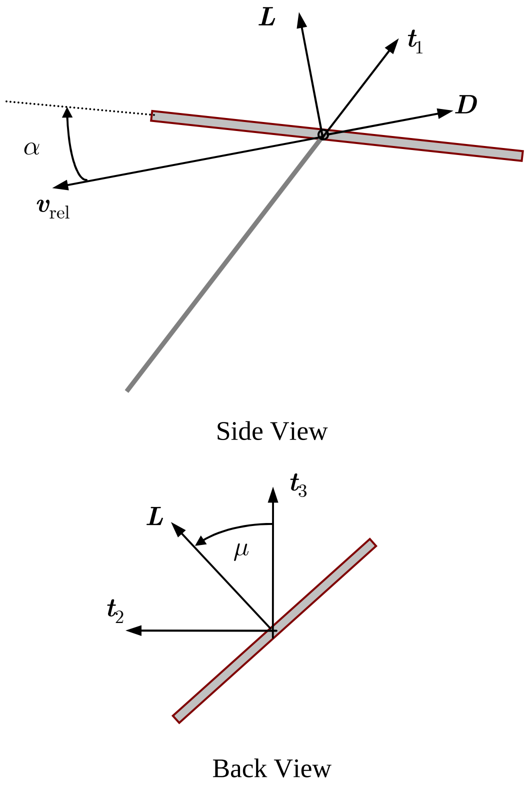

Figure 7: Assumed lift and drag forces on kite.

The equations of motion for the simplified kite system are given in the form

$$\left(m_{kite}+\tfrac{\rho_c r}{3}\right)r^2\left[\ddot{\theta}\cos^2\phi-2\dot{\theta}\dot{\phi}\sin\phi\cos\phi\right] +2\left(m_{kite}+\tfrac{\rho_c r}{2}\right)r\dot{r}\dot{\theta}\cos^2\phi -\left(m_{kite}+\tfrac{\rho_c r}{2}\right)rg\cos\phi\sin\theta=Q_\theta \qquad (1)$$

$$\left(m_{kite}+\tfrac{\rho_c r}{3}\right)r^2\ddot{\phi}+2\left(m_{kite}+\tfrac{\rho_c r}{2}\right)r\dot{r}\dot{\phi} +\left(m_{kite}+\tfrac{\rho_c r}{3}\right)r^2\dot{\theta}^2\sin\phi\cos\phi -\left(m_{kite}+\tfrac{\rho_c r}{2}\right)rg\sin\phi\cos\theta=Q_\phi \qquad (2)$$

$$\begin{aligned}&(m_{kite}+\rho_c r)\ddot{r}+\frac{1}{2}\rho_c\dot{r}^2\\&-\left(m_{kite}+\tfrac{\rho_c r}{2}\right)\left(r\dot{\phi}^2+r\dot{\theta}^2\cos^2\phi\right)\\&+(m_{kite}+\rho_c r)\,g\cos\phi\cos\theta=Q_r\end{aligned} \tag{3}$$

where m_{kite} is the mass of the kite, ρ_c is the cable density, g is the gravitational acceleration, and Q represent the generalised forces acting on the system (distributed tether drag, kite lift and drag). The generalised forces are derived elsewhere [47]. The kite forces are assumed to be dependent on the kite angle of attack α and the velocity roll angle μ, as shown in Figure 7.

Cross-wind control of the kite is achieved by tilting the lift vector via the velocity roll angle. To conduct a preliminary analysis of the control of such a system, an inverse dynamics approach is used. The angle of attack and velocity roll angle can be used as inputs, and the equations of motion can be propagated forward in time to determine the evolution of the θ and ϕ angles. This "forward" approach is difficult due to the sensitivity of the system to these variables. Alternatively, by specifying the variations of θ and ϕ, the position of the kite is assured. The task is then to compute the required kite control angles to maintain the specified motion. The θ and ϕ angles are two equations in the two unknowns, which can be solved via a Gauss-Newton algorithm at a particular instant of time. If one examines the equations of motion, assuming that the length is specified as a function of time, then the r-equation uniquely defines the variation in tension over time. Thus the power generated by the system can be calculated from the resulting solution.

A genetic algorithm is used to maximize the average power gained by the system

$$\min J=-\tfrac{1}{T_p}\int_0^{2T_p} T\dot{r}\,\mathrm{d}t \tag{4}$$

subject to the constraints

$$T\geq 0 \tag{5}$$

$$-10\leq\alpha\leq 20 \text{ deg} \tag{6}$$

$$-65\leq\mu\leq 65 \text{ deg} \tag{7}$$

where T is the tether tension, and $2T_p$ is period of the power generation cycle. These constraints are appended to the cost function via penalty functions for optimization using the genetic algorithm. The genetic algorithm must be executed multiple times to ensure that the solution is in the vicinity of the optimum. The process is described in more detail in [47]. The resulting trajectory is one which maximizes power generation, and which is periodic.

Once a trajectory is designed for a particular system altitude and mean wind speed, a PID feedback controller is designed via a linear receding horizon approach. This feeds back errors in the kite position and velocity measurements $\delta\theta,\delta\dot{\theta},\delta\phi,\delta\dot{\phi},\int\delta\theta,\int\delta\phi$ to adjust the angle of attack and velocity roll angle. The controller needs to be robust to gusts and uncertainties in particular system properties, like aerodynamic parameters.

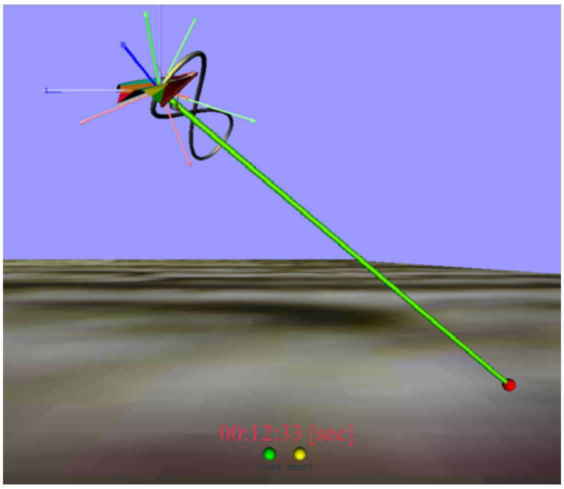

Figure 8: Example optimal periodic trajectory for generating power.

Figure 8 shows an example of an optimal periodic trajectory for extracting energy from the wind using the system (1 km long tether). This image was captured from a virtual reality animation of the trajectory. As can be seen, the trajectory is a figure-of-eight inclined to the wind direction.

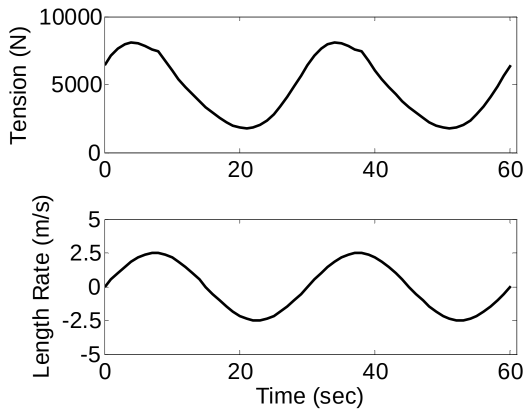

Figure 9: Tension variation and length rate for optimal power extraction.

Figure 9a shows the tension in the tether is quite significant for this maneuver, and varies by several thousand Newtons as the system cycles. The corresponding length rate is shown in Figure 9b, which shows peaks on the order of 2.5 m/s. The power generated by this maneuver is much greater than that generated by keeping the kite in a single plane (energy = 208390 J), due to the significant tension in the tether. Figure 9b shows, in general, that the tether is reeled in when the tension is lower than the maximum, and pulled out when the tension is large.

A feedback control algorithm was designed to track the optimal trajectories. Simulations were carried out for two power cycles, with the maximum wind strength normally distributed around the mean of 15 m/s with a standard deviation of 4 m/s. The "gusts" are simulated with 0.5 sec duration. In addition, there is a difference in the simulated cable drag coefficient to simulate uncertainty in the system.

Figure 10 shows the closed-loop simulation for the response of the tether angle measured to the vertical, and Figure 11 shows the out-of-plane angle, both of which combine to locate the position of the tether tip in spherical coordinates. It is evident from these plots that the feedback controller is able to keep the system flying very close to the desired trajectory over the entire simulation. In particular, the roll angle shows almost no disturbance away from the reference trajectory. One might be tempted to suggest that this is because the disturbances are not large enough to create significant perturbations. However, Figure 12 and Figure 13 illustrate that the required control corrections are indeed relatively large compared to the reference trajectories. Figure 12 shows that the angle of attack is more sensitive to changes in the wind speed than the roll angle. This is because the angle of attack directly influences the lift of the kite, whereas the roll angle only alters the direction of the lift force in the cross-wind direction. Figure 12 also shows that the kite angle of attack remains within the original bounds imposed on the trajectory. Finally, Figure 14 shows the time history of the wind strength used for these simulations. Although the mean wind strength remains constant, it is evident that the maximum and minimum wind speeds are significant fractions of the mean strength. Thus, it appears that it is possible to follow the desired trajectories quite well, even in the presence of large wind variations. It will be necessary to validate these findings using more detailed simulation models of the tether and kite.

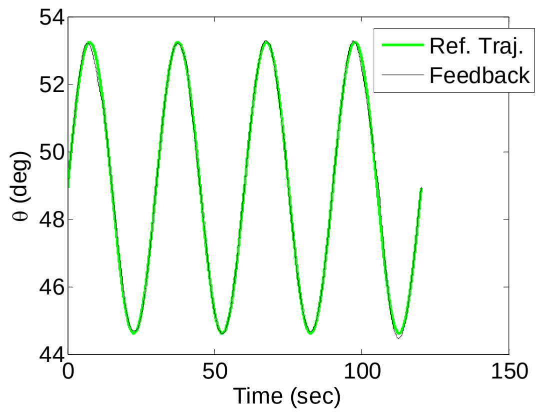

Figure 10: Closed-loop simulation of tether angle to the vertical.

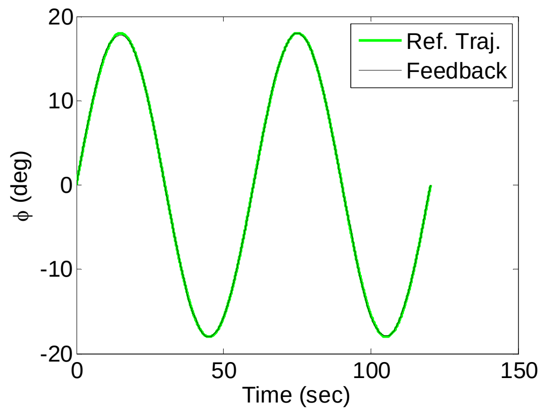

Figure 11: Closed-loop simulation of out-of-plane tether angle.

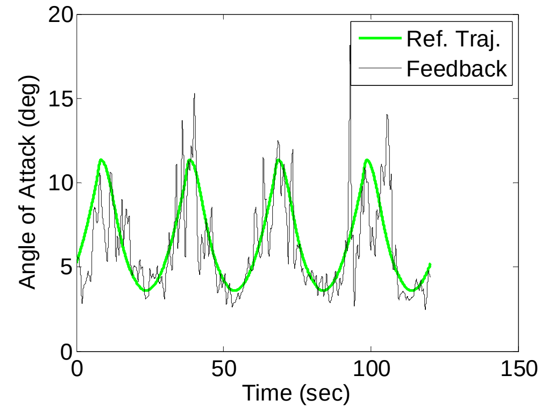

Figure 12: Kite angle of attack during feedback controlled maneuver.

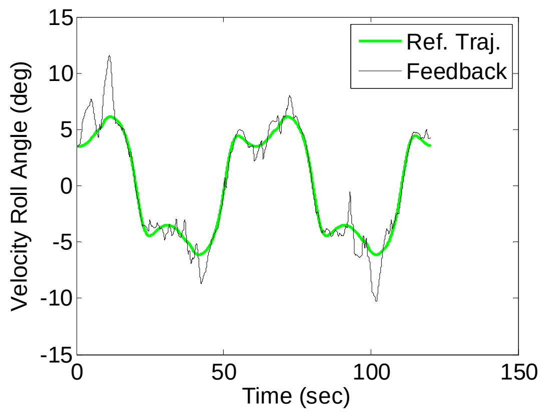

Figure 13: Kite velocity roll angle during feedback controlled maneuver.

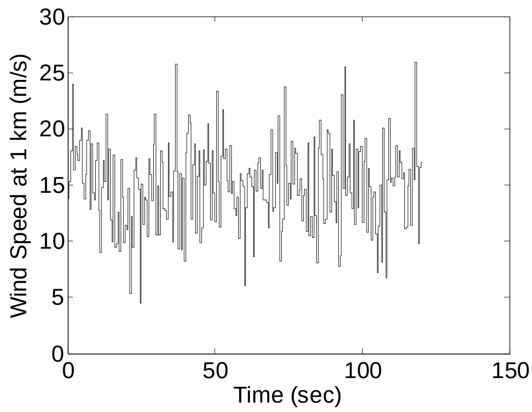

Figure 14: Simulated wind speed for closed-loop response.

4.2. Detailed System Modelling

Simulations using a simplified system model demonstrate the possibilities of being able to generate power, as well as being able to control the trajectory of the kite around the reference trajectory. However, much more detailed simulation work and modelling must be undertaken to fully understand the complexities of the system. Dynamic models of flexible cables in the atmosphere have been fully developed, which allow for deployment and retrieval simulation. In general, the cable can be discretized by two methods: (1) the finite segment method or (2) the lumped parameter method.

Finite segment methods: In the finite segment approach, the cable is divided into a series of finite segments. Each segment may be either straight and rigid, straight and extensible, or curved [48]. The rotational inertia of each segment is usually taken into account, and the distributed effects of external forces are applied at the ends of each segment (called nodes). The finite segment method is very versatile once the construction of segment and force models is complete. Coupling usually exists in segment accelerations at the nodes, which means that a complete mass matrix must be assembled and inverted. If the mass of the cable is constant in time, then the mass matrix only has to be inverted once. However, due to the effect of added hydrodynamic mass (for underwater cables), the mass matrix does not remain constant. Hence, matrix inversion must take place at each time step resulting in significant increases in computation time.

Lumped parameter methods: In a similar manner to the finite segment method, the lumped parameter method divides the cable into a series of line segments. The mass and forces present on each segment are lumped at the end of the respective segment (or half is taken from two adjoining segments). Lumped parameter models are able to overcome the difficulties of inter-element coupling inherent in finite element methods because the inertia properties of each element are lumped to a single point. In addition, since each segment is usually assumed to be extensible, the constitutive relation for the material provides the longitudinal constraint force within each segment. The result is that the motion of each node may be determined uniquely at each time step.

A lumped parameter model of aerial tethers has been developed for detailed simulations of the tethered kite system. Figure 15 shows a snapshot of a simulation of the deployment of a 1 km long tethered kite system using the developed model.

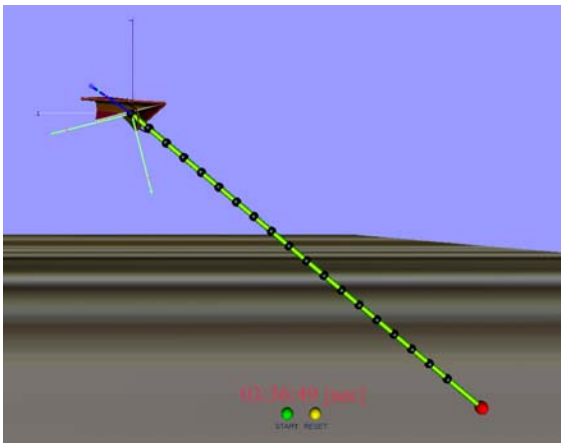

Figure 15: Simulated deployment of a 1 km long tethered kite.

4.3. Kite control actuator developments

Remote control of kites is an important enabling technology for the Laddermill. Research is focusing on commercially available surfkites, because they are readily available. In parallel several kites that are optimized for Laddermill use are being developed. Up to date, three control mechanisms for adjusting the attitude of the kite have been tested. The first control system uses a small servo to activate drag flaps on the side of the kite, as shown in Figure 16. This control mechanism only works on a stable kite because the force generated is quite small. The drag force creates a deviation from the equilibrium, causing the kite to yaw.

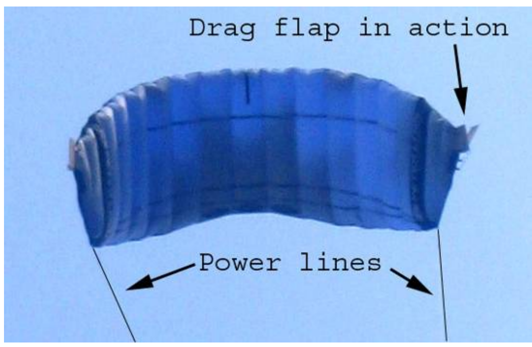

Figure 16: Drag flap control mechanism

The second control mechanism uses a winch servo to increase the angle of attack of the kite wingtip. This causes additional drag on that side together with a (lift) side force, causing the kite to yaw. The mechanism is shown in Figure 17.

Figure 17: Wingtip AoA control

The third and latest control mechanism steers by changing the attachment point of the power line on the kite. The slide mechanism is shown in Figure 18 and Figure 19.

Figure 18: Slide mechanism on kite.

Figure 19: Slide mechanism.

The slide mechanism has been demonstrated to work very well on many different types of surf kites. Currently, efforts are ongoing to control the slide mechanism by means of a computer.

4.4. Laddermill groundstation

The Laddermill groundstation is where the tension and motion created by the kites is transferred into electrical energy. A 2 kW groundstation was constructed in 2004, mainly from recycled parts. The 2 kW groundstation is shown in Figure 20. It features a stationary drum with a traversing mechanism on top to nicely reel the cable. The drum is about 15 cm in diameter and 40 cm wide.

Figure 20: 2 kW groundstation.

The main lessons learnt from this design can be summarised as:

1) Storing the cable on a layer wound drum will damage the cable because of cutting.

2) The layer wound drum will result in microslip occurring between the top layer of cable and the one below. The cable stretches over a certain length while it is still on the drum, as shown in Figure 21, where α is the angle over which the slip occurs. For Dyneema with a large difference between N^+ and N^-, the angle will be more than a full revolution.

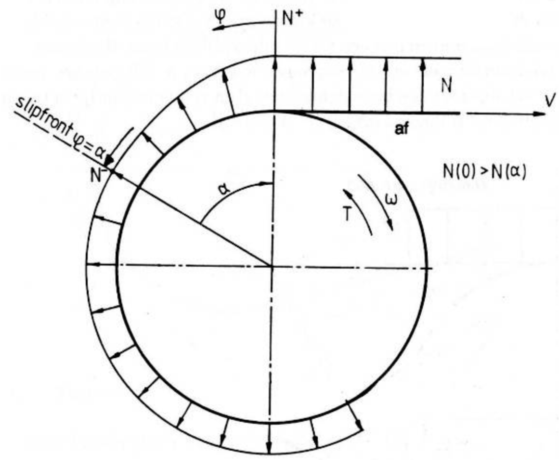

Figure 21: Microslip because of alternating stress.

3) Normal slip occurs when the kite flies in geometric patterns. During retraction, the traversing mechanism keeps the cable straight above the drum, shown in Figure 22.

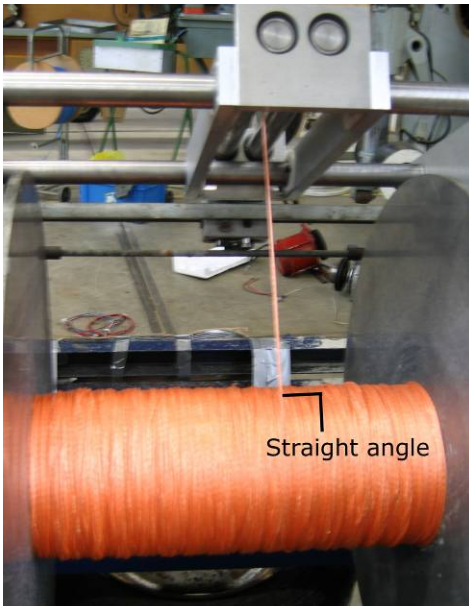

Figure 22: Cable leaving the drum – straight angle.

The traversing mechanism is not strong enough to deal with the sideways pointing force in the cable. Therefore, it is decoupled during the power generation phase, causing the cable to leave the drum at an inclined angle, shown in Figure 23.

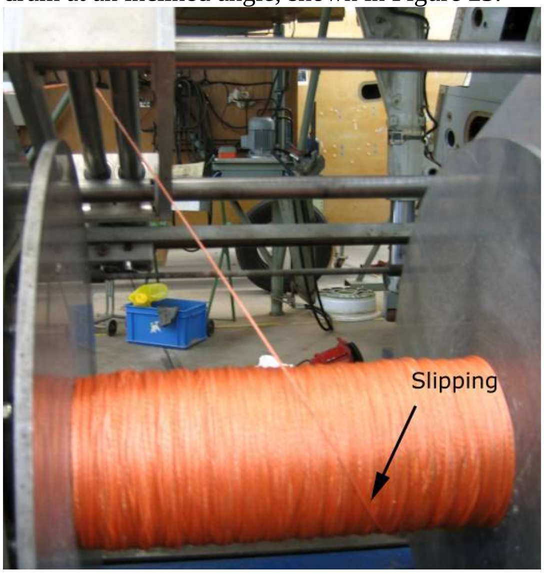

Figure 23: Cable leaving the drum - wrong angle

After taking these lessons learnt into account, a new groundstation was designed that is currently under construction, shown in Figure 24.

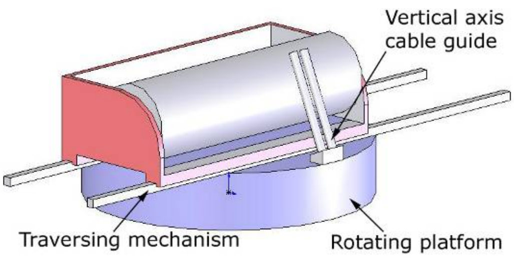

Figure 24: Rotating platform concept.

The large drum stores the Dyneema cable in a single layer. About 200 m of cable can be stored on the drum. The platform rotates freely, such that the vertical cable guides will always point the drum into the direction of the cable. This copes with geometric pattern flying of the kite and changing windspeed directions. The whole drum traverses under the vertical cable guides such that the cable always leaves the drum perpendicular to the axis of rotation.

4.5. Power production

The Laddermill groundstation of Figure 20 has been tested successfully in several tests, one of them shown in Figure 25, with a maximum electric output of about 1 kW. Although this flight test demonstrated the Laddermill principle, the 2 kW groundstation was not efficient enough to result in net power production. To solve this issue, the 4 kW groundstation of Figure 24 is currently being built. Optimisation of the kite flight path and its implementation is another aspect that must be fully explored. This is the focus of some of our future research efforts to bring the system into realisation.

Figure 25: Testing the Laddermill groundstation.

5. Future work

The current status of tethered kite research for generating power is very promising. However, there is still a long way to go before a practical system can be flown autonomously. With sufficient funding, the following actions seem to be necessary:

1) Development and validation of computer simulation models of variable geometry aerial tethers and flexible tension kites and their coupling (including deployment and retrieval of the cable with explicit modelling of the cable winch, as well as bending and torsional effects of the cable). The model will incorporate advanced aerodynamic features such as vortex-shedding oscillations of the cable, variable attachment points on the kites, and ability to simulate trains of kites on a single cable. The models developed will allow direct, high-fidelity simulation of a wide variety of potential system arrangements.

2) Implementation of measurement techniques for the kite motion, such as the tension and directional sensor shown in Figure 26. In conjunction with this, filter design and parameter estimators for various kite properties needs to be undertaken.

Figure 26: Kite tension and direction sensor

3) Testing the new groundstation resulting in a solid demonstration of net energy production over several cycles. This will be performed using manual piloting of the system via remote control.

4) Development of powerpoint tracker software for the groundstation.

5) Investigation of the major competing designs for kite power generation using high-fidelity computer simulations and development of a preliminary evolutionary algorithm for optimally sizing the tethers, kites, and winches for extracting energy. The design algorithm will utilise Monte Carlo type analysis to provide dynamic loads during the lifetime of a kite system for sizing the system rather than static loads. The horizontal/vertical configurations will be sized for generating various average power output levels and compared on a cost and efficiency basis. A large-scale dynamic stability analysis of the various systems designed will also be undertaken.

6) Development of real-time nonlinear control strategies for controlling the three-dimensional motion of a train of kites and/or multiple tethered kites for optimally extracting energy from the wind. Control of the attitude of the kites via flaps and other variable geometries will be investigated. A wind modelling and prediction tool for a local kite station will be developed to help estimate short-term wind loading on the cable, allowing better trajectories to be generated.

7) Development of a real-time navigation, guidance, and feedback control algorithm for intelligently maneuvering a train of kites to extract energy from the wind. The system will be capable of adapting rapidly to changes in the environment, such as the steady wind speed and gusts, and be robust to large parameter fluctuations and potential failures of one or more kites. If wind strength drops too low, the system will be capable of controlling itself to a safe, gentle surface landing. Techniques for deploying the kites to the desired altitude with minimal assistance will be investigated. The system will operate without user intervention. A new optimisation approach will be developed that utilises the previously developed models and control architectures to simultaneous optimise the system arrangement and control system to best reduce system drag and weight.

8) Studies of cable-generator interaction (wear).

6. Conclusions

A potential technique for extracting high altitude wind energy is currently being explored by Delft University, with some assistance from RMIT University. Mathematical simulations of the system have been developed which verify the potential for generating net energy by maneuvering the kite in an optimal manner. Furthermore, simulations also show that it is possible to control the kite around the desired trajectory in the presence of large wind gusts. Design and testing of control actuators for the kites has demonstrated that it is possible to remotely control the attitude of the kites. The design of a suitable groundstation has also been successful. It is expected that a preliminary demonstration system could be flown autonomously shortly.

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