Chapter 21
Kite Networks for Harvesting Wind Energy

Roderick Read

Abstract This chapter presents a simple new wind energy concept based on airborne rotary power generation and tensile rotary power transfer to the ground. The inexpensive prototypes use flexible inflatable wings that are arranged on ring kites, similar to how the rotor blades of a wind turbine are arranged on the hub. These autorotating rotary ring kites are stacked and integrated into a tensile structure that transfers the collected rotational power to a ground-based generator. A separate lifting kite provides additional lift to elevate the stack of rotary ring kites. Simulations and prototype testing show that network kite rigging provides the stabilizing benefits of wide tethering to networked individual kites even during fast flight for power generation. Turbulence effects are largely smoothed on individual kites. Stacked rotary ring kites can be integrated into a lattice of interconnected lifting kites, to concurrently run, at close proximity and thus allowing for greater land use efficiency. Solutions for joining the work of multiple ground stations to a single, more efficient generator are discussed. Software for kite network design is discussed. The designs are licensed as open source hardware to encourage engagement.

21.1 Introduction

Wind power as a renewable energy source is desirable. Taller wind turbines can harvest stronger and more persistent winds. However, the upscaling of conventional tower-based concepts has huge material use implications. Searching for innovative system concepts that scale better is thus key for achieving a sustainable and economic electricity generation in the future. Airborne wind energy systems (AWES) can operate at higher altitudes without the need for a tower. The technology can potentially supersede established tower-based wind energy technologies for large scale

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energy generation at lower costs, land use and CO_2 output. Lightweight kite systems scale better and can operate at higher altitudes with a smaller ground footprint. In essence, more wind power can be harvested with less material.

AWES are commonly presented as a further development of conventional wind turbines. Figure 21.1 outlines the derivation of the rotary ring kite and tensile torque transfer concept. The tip of a conventional rotor blade is the fastest moving part,

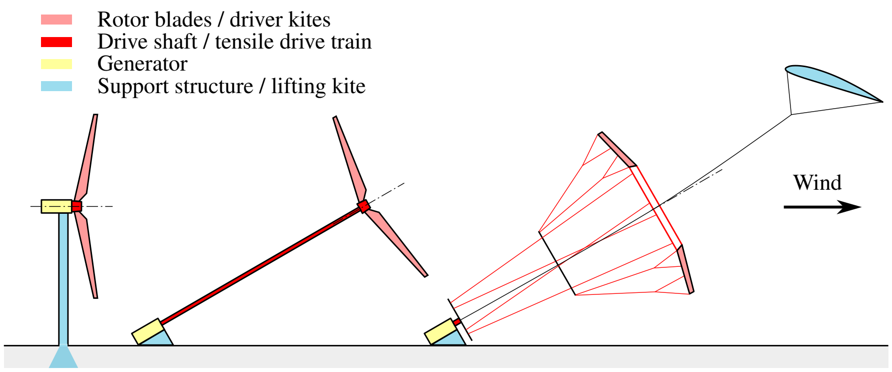

Fig. 21.1 Downwind horizontal axis wind turbine (left), intermediate conceptual step (center) and rotary ring kite and tensile torque transfer concept (right). In the first step, the heavy mast of the HAWT is eliminated by placing the generator on the ground while tilting the drive shaft upwards and extending it to allow unconstrained operation of the now pitched rotor. In the second step, the rigid and heavy rotor blades are replaced by lightweight membrane kites and the inclined drive shaft is replaced by a tensile rotational drive train. An additional lifting kite ensures the inclination of the tensile drive train

sweeping also the largest flow cross section. Although it is the lightest part of the blade it converts most of the wind power. The rigid tower has to support the weight of the rotor and the generator. It is loaded by compression and has to also resist the bending moment that the aerodynamic loading of the rotor generates.

AWES harvest wind energy with fast-flying wings that are connected to the ground by lightweight tethers. The wings use the kinetic energy of the wind and the ground tethering to fly predefined maneuvers and convert some of the wind energy into mechanical or electrical energy. The wing is bridled in such a way that it is inclined with respect to the local relative flow. The generated aerodynamic lift force propels the wing on its flight path and also generates a tensile force in the tether.

The central question is how to convert this aerodynamic force into energy that can be used on the ground and, as a matter of fact, there is a broad variety of different conversion concepts that are currently being developed. Some AWES generate the electricity on the flying wing and transmit it through the conducting tether to the ground. Other AWES use the tether or a tensile structure to transmit mechanical energy to the ground where it is then converted into electricity. This chapter treats only the case of ground-based electricity generation.

Two types of mechanical energy transfer to the ground station can be distinguished. The first one uses cable drums or similar mechanisms on the ground to convert the traction power of kites, defined as product of tether force and reeling velocity, into shaft power, defined as product of torque and angular speed. Most implemented systems operate a single kite [3, 13, 18] or two kites [9] in pumping cycles. A traction kite operated on a linear track has been implemented as a first step towards multi-kite systems that collaboratively generate electricity on a horizontal loop track [1].

The second type uses a tensile structure to directly transfer rotational power from a rotating kite configuration to the ground station. The tensile structure consists of several tethers that are kept separated from each other and tensioned while rotating around a common axis. The working principle of such a concept is illustrated in Fig. 21.1 (right). Similar to the tips of turbine rotor blades, the lightweight driver kites sweep a relatively large flow cross section at high speed. The tensile rotational drive train is optimized to transfer the generated torque at a minimum airborne mass of the structure. An additional lifting kite is used to ensure a stable inclination of the rotary system.

It is unusual in engineering applications to transmit shaft power over long distances and it is even more unusual to do this with a lightweight tensile structure. Using the experimental setup shown in Fig. 21.2 we have successfully demonstrated the working principle of the rotary ring kite concept and the feasibility of tensile torque transfer to the ground. The shaft power available at the ground station can easily be used for continuous electricity generation. The prototype designs have been published under open hardware licensing at [17].

Fig. 21.2 The "daisy stack" developed by Windswept and Interesting Ltd employs a tensile structure to transmit the rotational power of stacked ring kite configurations (30 August 2017)

This chapter describes prototyping, experimentation and design proposals for rotary ring kite configurations. The “daisy stack” illustrated in Fig. 21.2 integrates rotary ring kites into a tensile rotational drive train that provides continuous positive shaft power to the ground station. Much of the experimentation investigated the rotational power transmission and the application of network designs to kite bridle systems. The daisy stack was the first AWES to win the “100×3 challenge” announced on [17], which had the goal to fly an AWES at an altitude of 100 foot and generating an average of at least $P_{\mathrm{net}} = 100$ W for 100 minutes. Tests in December 2017 with the latest system illustrated in Fig. 21.2 have yielded a net power output of $P_{\mathrm{net}} \approx 600$ W.

The design process at Windswept and Interesting Ltd (W&I) essentially was open trial and error. Experimental designs evolved from experiences with kites, adventure sports and crafts. Occasionally, trails have been dangerous. The work has only been possible with the help of open online forums and the published work of the AWES community [19]. W&I considered many workable AWES schemes. Of those designs, rotary kite network and lift kite network designs are recommended.

Daisy ring kites can be classified as gyrokites that rely on wind-powered autorotation to develop aerodynamic lift in order to fly. By integrating the ring kites into a tensile drive train the rotational power can be transferred to the ground for conversion into electricity. Notable similarity and inspiration is seen in classic kites, like the spin bol, and in the works of Dave Santos [14], Rudy Hardburg on a “Coaxial Multi-Turbine Generator” [8], Bryan Roberts on a “Flying Electric Generator” [12], Doug Selsam on a “Serpentine Superturbine” [16] and Pierre Benhaïem on “Rotating Reeling” [2] and together with Roland Schmehl in Chap. 22 of this book.

Multiple kites bridled together establish a larger meta-kite. Even when only tied to a single arched load line in crosswind direction such a meta-kite will remain in stable flight. Meta-kites accumulate energy from a large harvesting area and can thus be dangerously powerful!

Kite networks with wide spacing and interconnections constrain the freedom of motion of the individual component kites. Kites, which would otherwise fly independently of one another, can work cooperatively flying in a network formation. Kite networks can also be formed into more complex three-dimensional lattice configurations. Networked kites simplify AWES flight control by using bridle network geometries and aerodynamic effects in combination to constrain the possible flight patterns of individual kites. The simple autogyro prototype has no cyclic pitch control. Without power curve profiling nor even controls this prototype is not optimised for rotary power generation yet. It does however provide a smooth continuous generation from inexpensive kites in a range of workable wind conditions. For larger daisy stacks automated controls including launching and landing systems would be preferred for safe operation. Passive control from a network geometry, force alignment and aeroelasticity effects [4] can be used to control a working kite network AWES.

The rest of this chapter focuses on experimentation results and conceptual designs of six key elements of an AWES farming architecture developed by W&I:

- Rotary “daisy” ring kites

- Power over rotating tethers (PORT)
- Stacked ring kite configurations
- Lifting isotropic network kite (LINK)
- Ground control and generation
- Open source design.

Each of these is presented separately in the following as a section. An AWES combining the six elements is then briefly considered at the end of this chapter.

21.2 Daisy ring kites

Rotary ring kites are the central functional elements converting the kinetic energy of the wind into a rotational motion and at the same time providing aerodynamic lift to stay airborne at the operational altitude. In the following we will detail the design principles, motives for the choices of kite components, present options for tuning and control of rotary rings kites and describe experiential results.

21.2.1 Driven ring kite design principle

As illustrated in Fig. 21.3 a set of asymmetric driver kites is mounted along the perimeter of a ring kite and bridled to fly on a circular path much like the blades of a wind turbine rotate around its hub. This analogy is also illustrated schematically in Fig. 21.1. The propulsive power of the driver kites is transferred via the bridle line system into the rotational drive train, which drives the generator on the ground. The radial expansion forces tension the driver kites in spanwise direction and ensure that the bridle line systems of the driver kites and the ring kite are separated. The

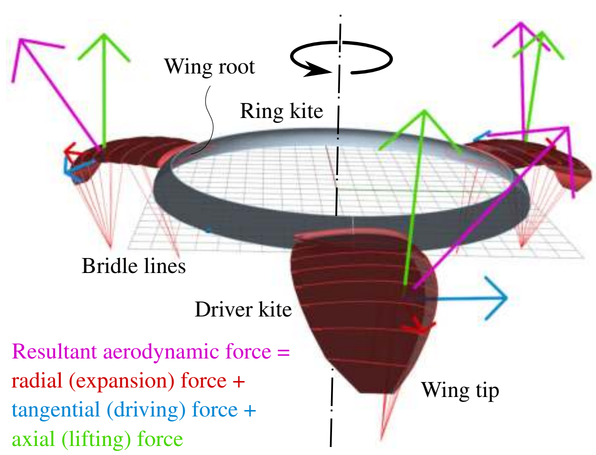

Fig. 21.3 Aerodynamic forces acting on the asymmetric driver kites (blades) mounted along a ring kite (hub). The radial, tangential and axial directions refer to the local reference frame of the entire rotary kite assembly, denoted as "daisy ring kite". For the individual driver kite the radial direction is roughly coinciding with the spanwise direction of the wing while the tangential direction is roughly coinciding with the chordwise direction

resultant axial force of the driver kites constitutes the thrust of the rotary ring kite. In contrast to a horizontal axis wind turbine this thrust force is tilted upwards with the elevation angle and thus has both lift and drag components. Because the presence of a lift component qualifies the rotary assembly as a kite we denote the thrust force in the following as lifting force. As can be seen in Fig. 21.2, the rotary kite assembly is also tethered to a lifting kite, which flies at a higher altitude and provides an additional lifting force which tensions the rotational drive train in axial direction. The tether running along the axis of the drive train up to the lifting kite is denoted in the following as "lifting line".

The tensioning of the drive train by axial and radial forces is essential for maintaining its three-dimensional shape and its capability to transfer rotational power to the ground. The transferable torque increases with the torsion of the drive train up to the point where a beginning constriction starts to impede the capability of torque transfer. The radial aerodynamic force components are caused by the anhedral arc shape of the driver kites and their bank angle [11]. Another radial aerodynamic force component is contributed by the conical shape of the ring kite, which is stabilized by a 3 mm diameter carbon epoxy stiffening rod integrated into the circular leading edge. In newer designs of the system, such as illustrated in Fig. 21.1, the ring kites with conical shape are replaced by rings. An additional radial tensioning is caused by the centrifugal forces acting on the rotating system components.

The axis of rotation of the daisy ring kite is approximately coinciding with the lifting line. The fixed path of the driver kites around the lifting line allows stacking of connected rotary rings to incrementally increase the generated power. The lifting kite is a standard kite used in kite displays, normally of a sled design. The customary use of such a kite is for steady lifting of payload, providing a high degree of stability. The lifting kite can be seen in the top of the right photo shown in Fig. 21.4.

Fig. 21.4 A single daisy ring kite with three driver kites using two separated rotating tethers ("torque ladder") to transmit rotational power to a ground-based generator (18 May 2015)

All of the kites align in downwind direction. Ring kites alone generate only a very low lift. Such kite will rest inflated on the ground, occasionally hopping into the air. However, when supported manually in its operating position a rotary ring kite in autorotation generates a significant lift force. Thus, when in operation at nominal position, ring kites require only a small additional lift contribution from the lifting line. Also, the tension provided by the lifting kite helps to guide the entire stack to align in downwind direction. In flight, the continuous motion of the driver kites is approximately in the plane perpendicular to the lifting line. If this line is at a low elevation angle the driver kites are approximately in cross wind operation.

21.2.2 Driver kite choices and reasoning

The cyclical variation of aerodynamic forces generated by the driver kites were not fully accounted for and exploited in the prototypes. Instead simple beginners "forgiving" steerable two-line parafoil kites were used. Such kites can reliably fly loops with small turning radius and at high speed, despite a strongly asymmetric bridle line control input. They are continuously propulsive over a wide range of angle of attack. The kites were arranged so that they would all loop clockwise when seen from the ground.

Parafoils are most powerful when flying crosswind, in the power zone, towards the center of the wind window [7]. A normal two-line parafoil can be controlled to keep looping in the power zone, until excessive friction between the twisting tethers inhibits control. At this point the kite will spin ever lower until it eventually crashes. Mounting parafoil kites on a rotary ring eliminates the problem of twisting tethers, but creates the new problem of how to maintain a looping flight path at altitude. Luckily, it takes very little extra lift to maintain a looping altitude for a parafoil-driven kite ring. It takes very little vertical force from a lifting kite to raise the trailing edge of a ring kite. With a small lifting kite a ring kite can operate deep in the power zone.

The driver kites shown in Fig. 21.4 had their lower leading edge stiffened with a 3 mm diameter carbon rod, to prevent spanwise collapse. The photos also show a forward overdrive rod supporting the driver kites. This 4 mm diameter carbon rod prevented that driver kites collapsed by flying ahead of the daisy ring kite assembly. The rods were unnecessary for the upper kites of a rotary ring kite stack.

21.2.3 Bridle layout, tuning and control

To tune a kite its bridle line system is adjusted to achieve a specific desired flight behavior. The adjustments include the lengths and attachment points of the bridle lines. In the following we propose options for tuning and flight control specifically developed for the rotary kite system.

Static tuning The prototypes have relied on a relatively fixed tuning. The center of bridling of the driver kite is shifted towards the attachment on the ring kite. This bridling increases the tangential component of the aerodynamic force, which causes the rotational motion. As illustrated in Fig. 21.5 the sweep angle is fixed when the root is sewn onto a ring and an overdrive rod fixes the relative positioning of the leading edge. An overdrive rod can be seen in Fig. 21.4 and 21.6.

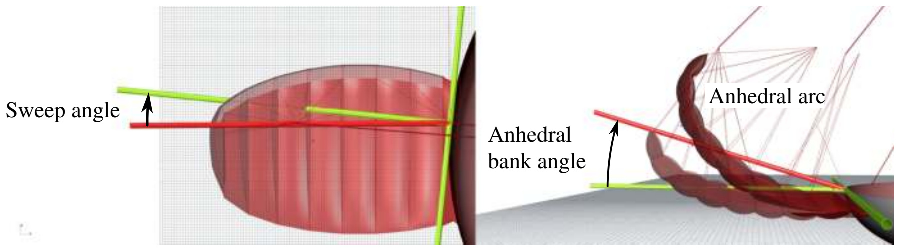

Fig. 21.5 Some tuning parameters for fixed position driver kites

The anhedral bank angle and arc were set by bridling a driver kite to a lower ring kite in the drive train. A spanwise twisting of the wing was achieved by the bridle layout shown in Fig. 21.6. The outer bridle was cascaded onto a tether connecting to the next ring kite towards the ground, slightly forward of the driver kite.

Fig. 21.6 Ring separation distance, the amount of blade twist and forward staggering between ring layers, determines how the static outer bridling cascade has to be tied

Static tuning with two-line driver kites made the manufacturing of prototypes easy. Dynamic tuning, where tethers are bifurcated and connected to match the dynamics of operational force transmission, has improved the performance. Experiments in using reactive and elastic tethering on multi-line kites are being proposed.

Passive-dynamic tuning methods (without active control systems) Rotary kite nets have a workable range of power output. Beyond this range kites and lines will deform and possibly become damaged. A rotary, autonomously generating AWES can adjust its power throughput to the wind conditions by passively stretching some key lines or surfaces. This can extend the workable wind range of the device and mitigate effects of turbulence. Passive-dynamic tuning complements the use of matching ground generation levels to wind conditions. If either method is flawed or failing, the other will help to balance the operation of the system.

Speed regulation by bank angle variation With increasing rotational speed the aerodynamic forces at the wing tip of a driver kite increase more than the forces at the wing root. The tensile membrane structure adjusts to this increasing load imbalance by gradual deformation. Conventional symmetric kites experience a similar aero-elastic deformation effect when flying sharp turns [4]. We can use the mechanism to regulate the rotational speed of the daisy ring kites.

Figures 21.3 and 21.5 (right) illustrate how the tip and the root of a driver kite are supported by two separate branches of the bridle line system. As speed increases, the center of the aerodynamic load shifts radially outwards. In response, the anhedral bank angle of the wing decreases and the tip flexes in axial direction with the load. This passive depowering mechanism is used to limit the rotational speed of the rotary ring kite stack. The flexibility of the wing is greatly influenced by the geometry of the bridle line system and its attachment in the stack. Using a rigid leading edge on the driver kites allows the banking angle to increase to a dihedral to spill wind whilst also maintaining span and inflation [7]. The banking angle can also be used for active speed control.

Configurations for collective as well as individual bank angle control are under investigation.

Proposed speed regulation by twist variation Just as the tips of windsurfing sails twist to spill wind and prevent overloading, the same mechanism can be employed in stiffened versions of the existing model driving blades. Elastic tip response can be set as a function of “mast” stiffness, downhaul tension and panel forming.

Proposed speed regulation by brake and steering Surf kites use leading edge bridling for support of the inflatable tubular frame, to ensure good aerodynamic performance and to allow for full depower. Three- and four-line single skin kites can also be fully depowered. It is expected that cross bridling these more complex driver kites will allow rear edge bridle lines to automatically tension and depower using the same aeroelastic dynamic response mechanism as bank angle variations.

Ground-based cyclic and collective line control This control method has barely been tested on W&I rotary kite nets. We are investigating whether swashplates around the rotation axis can passively or actively set kite attitude from the ground. By completely tilting the ground station ring interface back into the wind a little lift can be induced on ring kites with short tethering. However, kite response on long tethers is always lagging in time and it seems practically unfeasible to use swashplate control of the outer lines to send synchronized control signals to a stack of rotary kites integrated into a long tensile drive train.

A more promising collective control method would be to vary the relative length of the central lifting line with respect to the outer tethers. This signal will propagate up the stack well and it should be simple enough to take steering or power control references for each driver kite from the central line.

Active ground station and wing tuning options Active control both from the ground and in the kites themselves may be more appropriate. Controlling the torque at the ground has a crucial impact on the performance of the rotary ring kite stack and can completely stall the assembly of looping driver kites, stopping rotation if needed. AWES companies have used small, powered onboard actuators to adjust the performance of wings. The whole stack could be actively tuned by shortening or lengthening the central lift line with respect to the outer tethering lines.

Lifting kite tuning The elevation angle and tension of the lifting line directly influence the performance of the rotary ring kite. A low elevation angle keeps the rotary ring kite deep in the power zone but requires a longer drive train to reach a given altitude. Also, with a low elevation angle the higher rings in a stack will operate to a large part in the wake flow of lower rings. A well-tensioned lifting line provides a good working reference for network rigging and dynamic tuning.

A lifting kite, which, like a weathercock, stays aligned with the downwind direction in all wind speeds is desirable. Designing a single line lifting kite that aligns in downwind direction and is stable for a wide variety of winds is challenging without an active control system. For prototyping, we used a simple three-tether (tripod) configuration to stabilize a “Peter Lynn” single skin lifting kite. The main kite line was supplemented by two lightly loaded steering lines, which were set apart, downwind of the main tether. The steering lines attached to the B line bridle points of the first inside ribs [10]. This tethering configuration does not achieve the desired directional stability without ground-based intervention. Tripod lines provide a fail safe rigging. Their usefulness in breakaway prevention has been accidentally demonstrated.

21.2.4 Experimental results for a single rotary kite

The rotary ring kites are remarkably stable in flight without any control input. Driver kites adhered very well to the lead, tail and tether guided path of their ring base. The development of the daisy ring kites has been undertaken on a household budget. No reliable performance data was recorded. The only performance record of single ring setup is from a challenge to make enough energy for a cup of tea for my mother. The challenge was completed in approximately 3 hours of flying at a wind speed $v_w \approx 5.3$ m/s. The generator produced an average power $P_{net} \approx 9.3$ W, which resulted in a net energy $E_{net} \approx 100.8$ kJ. The low power was due mainly to mismatched generator torque demand. The problem was overcome in later tests by stacking ring kites for cumulative torque output and using a multi-tether rotational drive train.

To assess the efficiency of the energy conversion we first determine the available wind power. With a wind velocity $v_\mathrm{w} = 5.3$ m/s and an air density $\rho = 1.3$ kg/m^3 the wind power density evaluates to

$$P_\mathrm{w} = \frac{1}{2}\rho v_\mathrm{w}^3 = 96.8 \text{ W/m}^2. \tag{21.1}$$

Given a driver kite wing span $b = 0.8$ m rotating on a ring radius of $r_\mathrm{h} = 0.9$ m the total swept area in the plane of rotation is $A = 6.53$ m^2. Given that the ring is tilted by an angle of attack $\alpha \approx 35°$, the swept area perpendicular to the wind direction becomes $A\cos\alpha = 5.35$ m^2. This leads to a total wind power passing the flow cross section $P_\mathrm{w}A\cos\alpha = 518$ W and a total conversion efficiency

$$\eta = \frac{P_\mathrm{net}}{P_\mathrm{w}A\cos\alpha} = 0.018. \tag{21.2}$$

It should be noted that the aerodynamics of the rotary ring kite is in general very similar to the aerodynamics of a yawed horizontal axis wind turbine rotor, which is analyzed in more detail for example in [6, Chap. 3].

Given a driver kite total wing surface area $S = 0.9$ m^2 an alternative reference power can be calculated as $P_\mathrm{w}S = 87$ W. The power harvesting factor is evaluated

$$\zeta = \frac{P_\mathrm{net}}{P_\mathrm{w}S} = 0.1, \tag{21.3}$$

which is a quite low value for an AWES [15]. The poor result is however less a consequence of the rotary ring kite design but mainly due to a mismatch of generation equipment used.

For this specific test the rotational power was transferred to the ground by a two-tether rotational drive train, denoted as “torque ladder”, and there converted into electricity by a mountain bike crank connected to a Falco emotors 500W Hxm2.0 hub motor. The lowest bike gear had to be used to overcome torque demands of the motor whilst keeping within the workable tensile rotary power transmission parameter range. Later attempts with stacked rotary kite rings and a multi-tether rotational drive train allowed for much greater torque loading. Both drive train concepts are described in more detail in the following section.

21.3 Power transmission by rotating tethers

Transferring rotational power instead of traction power has certain advantages for AWE applications. The concept allows for continuous power output without the need for the phased generation characteristic of reeling on a drum motor / generator. There is no tether abrasion with rotational power transmission because no tether has to run – it just has to fly and be held by abrasion resistant components. It is easy to add multiple rotor blades to a rotary harvesting mechanism. Power transfer over rotating tethers (PORT) relies on keeping the tensioned tethers apart, at sufficient radial distance, as they rotate around the common axis.

Rotational power is generally transferred over tubular drive shafts that can sustain large shear stresses. Using ropes or net tubes initially seems unfeasible. We know that an applied torque leads to twisting and compression of flexible fiber materials. There has not yet been a need for a tensile rope rotational power transmission system. Meaningful rotational power can only be transferred when a constriction of the drive train – a geometric singularity at which the tethers pass through the axis of rotation – can be avoided. Accordingly, the axial and radial tensioning of the drive train by aerodynamic forces is essential for rotational power transfer.

Excessive torsion of the tensile drive train causes lines to overtwist and cross (hockle) if the lines are long enough. Hockled (overtwisted) lines will not transfer torque effectively. In general, longer and closer tethers need more tension to avoid hockling, while short and well-separated tethers can easily transfer torque without much line tension.

21.3.1 Two-tether rotational drive train

In the most simple configuration of a tensile rotational drive train, two rods are connected at each end by tethers of equal length. One rod is fixed at its center to the axis of a generator and is perpendicular to this axis. When tensioning the tethers by pulling the second rod in axial direction and at the same time turning this rod around the axis, the first rod and the connected generator are also forced to turn. Both rods must maintain a common rotation axis to work efficiently and avoid tangling. The torque is transferred by the tangential components of the tether forces, while the axial components are required for the tensioning of the system.

This unit setup can be extended into a "torque ladder", which is illustrated in Fig. 21.7. The testing has revealed, however, that this double helix "ladder" structure was impractical. It was prone to hyper coiling when line tension in the system

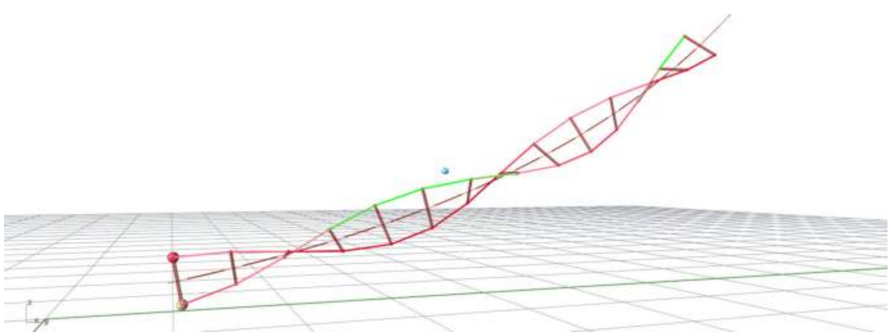

Fig. 21.7 Simulation of a two-tether rotational drive train "torque ladder" with additional guiding lifting line

dropped. Rungs easily got caught inside the tethers. The central guiding lifting line was used to align the rods along a common axis of rotation. Yet, power transfer was jerky given any misalignment.

21.3.2 Multi-tether rotational drive train

A smoother, more resilient transmission method uses multiple tethers connecting a stack of rings to form a tubular tensile structure, as illustrated in Fig. 21.8. Us-

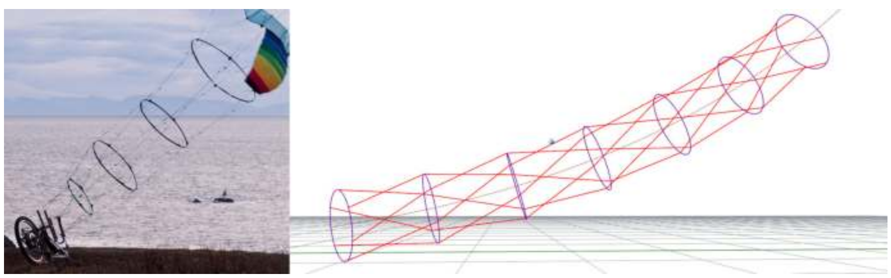

Fig. 21.8 Ring-to-ring transmission of rotational power employs multiple tethers forming a tensile tubular drive train. Power transmission is smooth despite of the misalignment of the crank at the ground to the lift-normal plane in this prototype and model. Also this setup makes use of a central guiding lifting line

ing ring-to-ring rotational power transmission is in fact analogous to torque transfer with inflatable beams. Experiments have shown that the transferable torque increases with the diameter of the inflated beam [5]. Relatively stiff and wide rings, connected at close distance will not lead to hockling of the tethers, even at full propulsion with no axial tension.

The most basic dynamic description of the system assumes that the resultant aerodynamic force and torque contributions of the rotary ring kites will be available at the ground ring. However, this lossless force and torque transmission ignores effects of gravity due to the mass of rings and tethers, aerodynamic line drag and friction in bearings. A full dynamic analysis of rotational power transmission over separated tethers is now being conducted through PhD research by Oliver Tulloch at the University of Strathclyde.

The experimental tests have shown that the ring-to-ring method is well-suited for torque transmission and that it is fail safe and "fail soft". If a component were to break the system continues to run in a diminished condition. Ring-to-ring transmission allowed easier launching of the AWES. The rotary ring kites were evenly pretensioned, inflated and inspected on the ground before being allowed to ascend.

21.4 Stacked rotary ring kite nets

Integrating rotary ring kites with a multi-tether rotational drive train leads to a systematic modular design. By stacking rotary rings the power output of the system can be incremented in discrete steps. This requires an adjustment of the drive train and lifting kite dimensioning, taking into account the increasing gravitational and aerodynamic drag effects. Exactly how many rotary ring kites of a given size a lifting line with given tension can reliably support is still unknown, however.

21.4.1 Design considerations and vision

The extension of the single rotary ring kite illustrated in Fig. 21.3 to a setup of four stacked rings is shown in Fig. 21.9. The drawing indicates how the tethers of driver

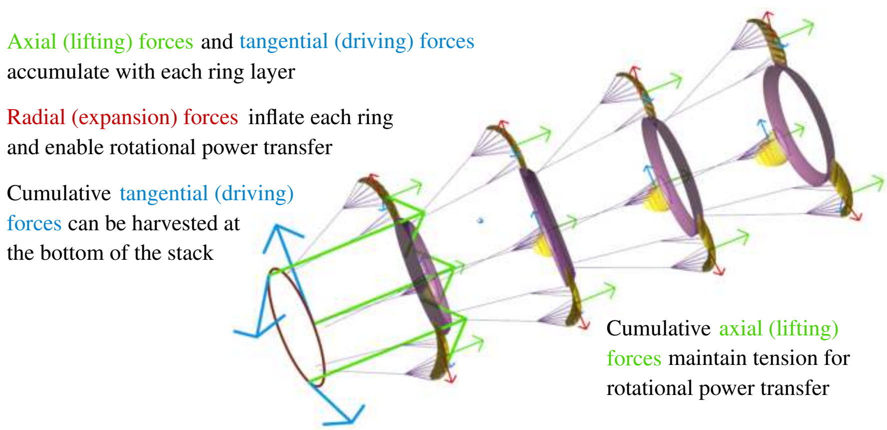

Fig. 21.9 Integration of rotary ring kites with a multi-tether rotational drive train. Lifting and propulsion forces generated by the rings kites are cumulative through the stack

kites attach to the respectively lower ring in the stack. Because of the networked tethering, the rings rotate all at the same angular velocity, each contributing to the resultant torque of the stack, while using the generated radial expansion forces to tension the ring structure and the generated axial lifting force to tension the entire drive train. The energy harvesting varies along the perimeters of the rotary rings. In general, the upward going kites are facing a stronger apparent wind speed and hence generate a larger line tension. Furthermore, the bottom parts of the rings operate in the wake flow of their upstream neighbors, while the top parts penetrate into the free stream. Because the wake effects decrease with increasing elevation angle of the net the amount of wind energy available for harvesting increases with increasing elevation angle. However, because of the low solidity and large spacing between rotary ring kite layers the impact on the power output seems to be practically unaffected by the elevation angle.

For the investigated prototype each rotary ring kite has its axis of rotation inclined by an angle $\alpha \approx 35^\circ$ with respect to the horizontal wind velocity. A variance in α along the stack can occur due to the sagging of the tensile drive train as a result of gravitational loading, aerodynamic drag and conditions leading to low lifting line tension.

The driver kites of each rotary ring kite are tethered to a upwind ring base, that is lower in the stack. Tethering of a driver kite to a wider ring base generally improves the structural stability of the bridled ram air wing compared to a tethering to a narrower ring base. As can be seen from Fig. 21.5 the bridle attachment angle depends also on the bank angle of the wing. Tethering of the driver kites to a wider ring also increases the generated torque of the rotary ring. Driver kites on wider orbits travel faster and by that make the conversion system more efficient. More rigid and larger driver kites will be suited for such wider orbits. Rings with different properties can be flown to complement each other. Further design details are listed in Fig. 21.10.

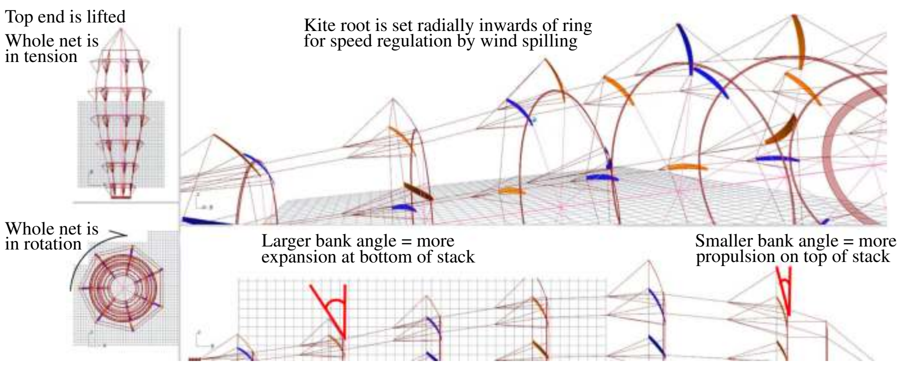

Fig. 21.10 Driver kites at higher ring levels are set flatter, with a smaller bank angle, and fly faster for overall net dynamic

All AWES are affected by the aerodynamic drag of tethers and bridle lines and reducing this important loss factor by design is one of the key goals of current development efforts. In a stack the tethers of the individual kite are very short and therefore the drag loss per driving kite area is greatly reduced. However, line thicknesses should progressively increase with tension and torsion toward the bottom of the stack.

The daisy stack prototype is fail safe and “fail soft”. It is fail safe in the way that each component is prevented from breaking away as it links to at least two other components. It is “fail soft” in the way that if something breaks the failing stack has less lift and less power and will eventually bring itself to ground.

We think that the research into rotary kite power networks should be intensified and propose open testing and development to cover the following aspects

- Single skin soft kites for use in hugely scaled arrays

- Rigid kite "blades" with high aerodynamic efficiency
- Short tethered hybrid stiff and flexing tip wings
- Asymmetric parafoils specifically for rotor work
- Active and cyclical control of the angle of attack
- Flying controlled wings outward from the ring surface
- Buoyant or sinking kite configurations for tidal electricity generation
- Optimizing the blade count (solidity) based on ring diameters and blade profile
- Elastic anhedral to dihedral stack models for smoother operation
- Dynamic model of tensile rotary power transmission
- Mixed-function soft and rigid ring layers for generation and transmission needs
- Parametric system optimization

Manual launching and landing the rotary ring kite stack has been mostly easy, only occasionally dangerous in strong winds. Automated launching and landing, particularly of larger systems, would be desirable. The current launch method could easily be mechanized but does not scale well. Concepts for modular attachment of new ring layer parts on live systems have been suggested, but no such device has yet been made. A complete ground handling solution is desirable for high end versions of rotary ring kite nets.

21.4.2 Experimental results for a rotary ring kite net

Test data from the "100×3 challenge" [17] is used for the following analysis. This data is based on the 2016 daisy stack prototype using a ground generator adapted from an e-bike. More detailed results based on the latest prototype illustrated in Fig. 21.2, which has peaked at $P = 616$ W so far, is due to be published through the PhD research of Oliver Tulloch at the University of Strathclyde.

Three rotary ring kites as described in Sect. 21.2.4 are operated in a stack, amounting in a total swept area in the plane of rotation of $A = 19.6$ m^2 and, with a tilting by an angle of attack $\alpha \approx 35°$, the swept area perpendicular to the wind direction becomes $A\cos\alpha = 16.06$ m^2. With a wind velocity $v_\mathrm{w} = 5.5$ m/s and an air density $\rho = 1.3$ kg/m^3 the wind power density evaluates to

$$P_\mathrm{w} = \frac{1}{2}\rho v_\mathrm{w}^3 = 108.1 \text{ W/m}^2. \tag{21.4}$$

This leads to a total wind power passing the flow cross section $P_\mathrm{w}A\cos\alpha = 1736$ W. Measuring an average power $P_\mathrm{net} = 111$ W with this setup, the total efficiency is

$$\eta = \frac{P_\mathrm{net}}{P_\mathrm{w}A\cos\alpha} = 0.064. \tag{21.5}$$

Given a total wing area of $S = 2.7$ m^2 an alternative reference power can be calculated as $P_\mathrm{w}S = 291$ W. The power harvesting factor becomes

$$\zeta = \frac{P_{\mathrm{net}}}{P_{\mathrm{w}} S} = 0.38. \tag{21.6}$$

This value for three rotary rings is significantly larger than the value for the single rotary ring, given in Eq. (21.3), despite the additional losses due to wake effects on downstream rotary rings. This improvement is most likely due to the better match between the torque available from the stack and the torque demands of the generator. In this recorded test the rotational power transmission worked well throughout the tensile drive train. By applying the brake at the ground ring interface it was possible to stop the rotation of the entire stack on demand.

Experimentation and accident showed that leading edge stiffening and the forward overdrive rods are not necessary when flying driver kites on wide diameter stacked rings. This has positive implications for scaling. The driver kites have survived harsh treatment in testing, repeatedly showing how soft blades can handle crashing over the ground when the lifting kite tension drops. The Peter Lynn single skin lifting kite, as used in prototyping, was stabilized with two spread tag lines, anchored downwind of the full stack. Realigning the lifting kite to windward, is unnecessarily time consuming. A more reliable networked lift system with monitoring and control is recommended before risking hitting rigid blades on the ground. A host of improvements have been proposed for future models. Given the power return on the minuscule model cost, we are confident this system can be useful in a range of markets.

Stacked rotary ring kites guided by a lifting line can be arranged in a dense array because rotary drive trains can be operated in parallel both across and down wind. Lifting kite lines can also be conjoined across the entire array to achieve network stability and, therefore, improve land use efficiency. Stacked ring kites have also been suspended from solid structures. It is supposed that stacked ring kites could be set on three-dimensional lattice work to fill the void between mountain gaps whilst generating electricity. Again this would improve land use efficiency. Various floating networks for AWES deployment and channel rope networks for tidal energy generation have been suggested.

21.5 Lifting isotropic network kites

A lattice of interconnected lifting kites can stay airborne in wind from any direction. Because of its network layout and mutual stabilization of the member kites such a lifting meta-kite is generally resilient towards local fluctuations of the wind field. A computational simulation of a lifting isotropic network kite (LINK) exposed to a turbulent wind field is shown in Fig. 21.11.

Simulation and prototype testing has confirmed the stabilizing effect of a wide outer anchoring and wide net tethering of a LINK. A method for steering individual kites by line through network nodes has been demonstrated experimentally. Methods

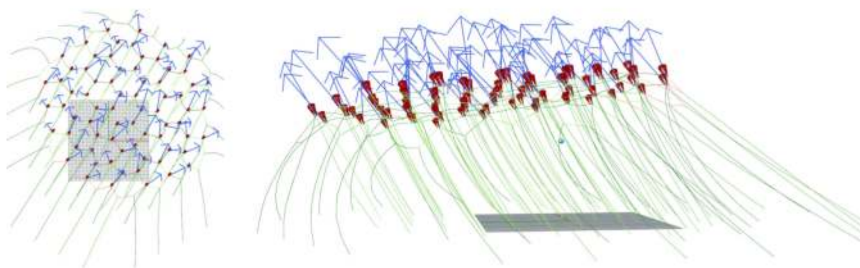

Fig. 21.11 Model representation of a lifting isotropic network kite (LINK). The resultant aerodynamic force vectors from turbulent wind acting on the individual lifting kites are displayed as blue arrows. Line tension varies from high (red) to low (green). The central lifting lines are held apart and aligned to the average downwind direction despite the action of turbulence on the individual kites

to align kite flight with its nodal network normal plane to maintain the deployment of the meta-kite have been suggested and are currently being investigated.

Although networking of kites provides additional stability it would be dangerous to build large power projects without automatic monitoring and control. The system design and performance of a LINK can be improved by controlling the tether length of the individual lifting kites. An example is illustrated in Fig. 21.12. Because the top part of the meta-kite is generally stable due to its exposure to the free stream multiple lift lines can be kept sufficiently apart for safe and dense ring kite farming applications.

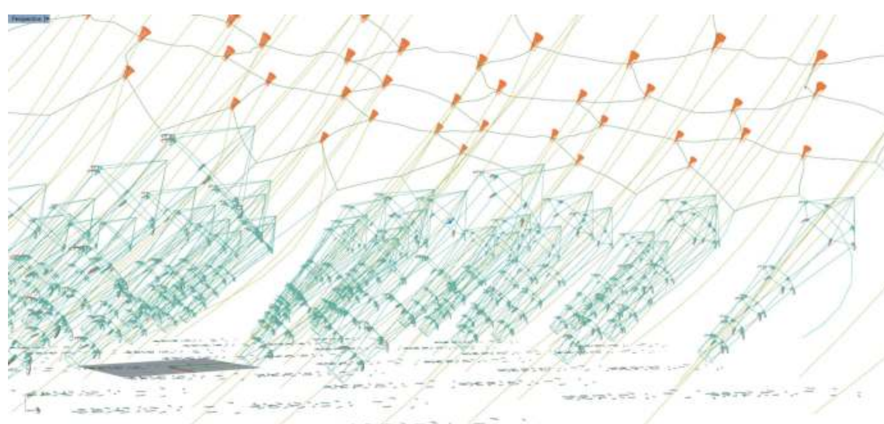

Fig. 21.12 Meta-kite concept to collaboratively farm with large numbers of rotary ring kites

Using a LINK to suspend rotary ring kite stacks would simplify the operation and reduce costs. Algorithms and geometric patterns suitable for stacking LINK layers into a taller three-dimensional energy harvesting lattice are being developed.

Methods have been suggested to extract useful power from coordinated or even harmonic meta-kite motions. Openly proposed ideas for meta-kite swaying, swirling and pumping energy extraction models have been briefly considered, as have coordinated fields of meta-kites working against each other. The control and actuation needed for these designs seems complex and beyond the current work scope.

21.6 Ground control and generation for ring kite stacks

For the sake of minimal airborne mass the generation equipment and kite controls, including launching, landing and storage equipment, is placed on the ground. Because the axis of rotation of the rotary ring stack is tilted from the vertical into the wind direction also the ground ring, to which the tensile drive train attaches, needs to be tilted. We have tested generator mounting with both gimbal and following wheel configurations to follow the lifting line axis.

The earlier prototype illustrated in Figs. 21.4 and 21.8 (left) used an e-bike as a ground station, operating the rotating ring kite stack through the crank. In the latest development version shown in Fig. 21.13 a custom-made ground station is used.

Fig. 21.13 Rotary ring kite stack in operation, generating $P_{\text{net}} = 600$ W, showing the portable tracking ground station, the new ring configuration and the force scale (1 December 2017)

The photographic footage depicted in Fig. 21.4 shows that some daisy ring kite prototypes have the coaxial generator-crank assembly not well aligned with the wind direction and kite elevation. That was not too problematic at such a small scale, however, it is clear that better and more controllable alignment will improve system performances.

For an efficient rotational power transfer the track of the rotating tethers on the ground ring interface will have a diameter closely matching the connected airborne ring. This is illustrated by the concept design shown in Fig. 21.14.

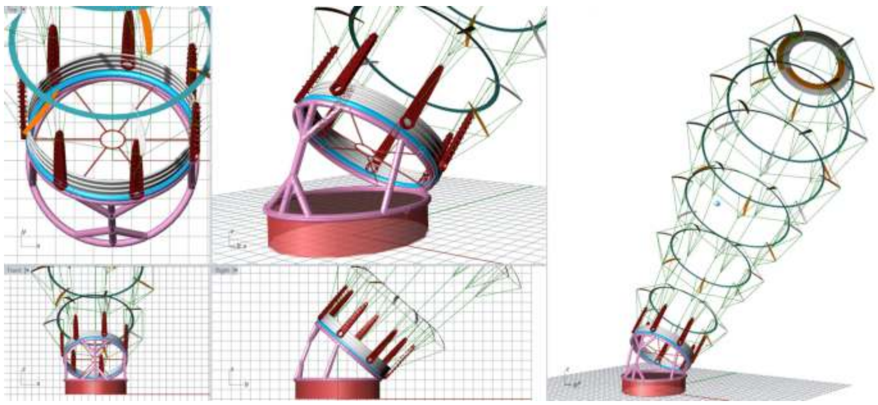

Fig. 21.14 Concept sketch of an all-in-one tracking ground control and generation system

It seems unlikely that a rotary ring kite deployment and recovery system or a cyclical tether tension control will feature on small scale ring kite stacks soon. However, at larger scales manual handling and intervention with rotary ring kites will not be safe and as consequence automated systems will be required. Solutions are being designed for these utility sector device scenarios.

For rotary ring kite stacks operated in lattice configurations it might be desirable to combine the rotational power of several stacks to jointly drive a generator. We produced simple freewheel collection and field arrangement algorithms, to match network spaced rotary power outputs to a central generator.

21.7 Open source design

Windswept and Interesting Ltd has released all of our core design work to date as open source hardware because we believe that it is a better way to start a technology. We are convinced that better work comes from the design integrity of open source hardware. Obtaining funding for open source hardware projects is challenging, but the benefits are obvious. Your right to patent novel components relating to these designs is not affected.

Our company develops three-dimensional AWES models using parametric algorithm design software. Collections of kites and their parameters can be rapidly reconfigured this way. Parametric designs are particularly suited for evolutionary development of design algorithms. The number and variety of parameters, which govern a kite network algorithm, is large. Parametric designs can be automatically evaluated, restructured and optimized with evolutionary iterations of Artificial Intelligence (AI) software. An AI system can evaluate large numbers of combinations of the parameters governing a network kite to derive AWES optimization models, which will otherwise take years to derive experimentally.

AWES, is the kind of complex and valuable design challenge where multiple objective optimization solvers can be applied to great effect. The required tools are openly available. The current work will benefit greatly from a more organized implementation of AI architecture. AWES design should therefore embrace AI.

21.8 Conclusions

Rotary ring kite stacks can work together in networks, harvesting energy continuously and autonomously. The tethering geometry of lifting and rotary kite networks stabilizes the flight of individual kites. A lifting kite can guide working rotary ring kites into suitable operational positions. The rotational power of ring kite stacks can be collected and transferred to the ground by a tensile drive train. Combinations of complementary lifting and rotary kites can be arranged to harvest wind energy in three-dimensional wind farming arrays. Kite and line fatigue has been very low. The performance of an exceptionally inexpensive airborne wind energy prototype improved with upscaling.

The practical prototyping approach left little verifiable data. More accurate measurements are being performed in the frame of a University of Strathclyde study. Improvements in kite performance as well as practical operations such as launching, landing and ground handling routines will soon be tested and published openly. Many areas for performance improvement have been identified. A specially commissioned asymmetric soft wing is currently being discussed.

A more comprehensive and thorough approach to the full working scope of Windswept and Interesting Ltd is being sought. Universities have expressed interest in analyzing the dynamic and optimization challenges posed by the kite methods demonstrated. The potential of using larger diameter rings has been shown. There appears to be large potential for soft, rigid and hybrid kite rotor turbine networks but this potential is mostly unverified.

Business models are being considered for a next iteration daisy kite AWES. Manufacturers have been able to produce kite ring parts remotely. A simple ground generator torsion control based on measurements of line tension and the ring spacing dynamic is likely to be built soon. The open source hardware design methods used are available for anyone to improve. The parametric design software used will be suitable for artificial intelligence development. The methods are very promising. There is scope and reason to vastly increase the work being done on this project.

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