Chapter 23
Design and Experimental Characterization of a Pumping Kite Power System

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Abstract The pumping kite concept provides a simple yet effective solution for wind energy conversion at potentially low cost. This chapter describes a technology demonstrator which uses an inflatable membrane wing with 20kW nominal traction power on a single-line tether. The focus is on the innovative and scientifically challenging development aspects, especially also the supervisory control and data acquisition system designed for automatic operation. The airborne hardware includes a Kite Control Unit, which essentially is a remote-controlled cable manipulator, and the inflatable wing with its bridle system allowing for maximum de-powering during the retraction phase. On the ground, the drum/generator module is responsible for traction power conversion while constantly monitoring and adapting the force in the tether. The control software includes two alternating autopilots, one for the lying figure eight maneuvers during tether reel-out and one for the reel-in phase. As a result of monthly test-operation since January 2010, large quantities of measurement data have been harvested. The data acquisition and post-processing is presented and discussed for representative conditions. The power curve of the system and other characteristic operational parameters are determined by a statistical analysis of available data and compared to the results of a theoretical performance analysis.

23.1 Introduction

Using the traction power of a tethered wing for large-scale wind energy conversion was initially proposed by Miles Loyd, an engineer at Lawrence Livermore National Laboratory, during the 1970s energy crisis [10]. His analysis indicates, that a tethered aircraft of 576m² wing surface area would theoretically be capable to generate...
a traction power of 6.7MW when flying crosswind at a background wind speed of 10m/s. Around the same time, space age pioneer Hermann Oberth envisioned kite-lifted wind turbines to access the kinetic energy of high-altitude wind [11]. Two decades later, at the very dawn of the transition towards renewable energies, former ESA astronaut Wubbo Ockels proposed the exploitation of this vast energy potential by means of traction wings [12]. His Laddermill concept is based on a cable loop running several kilometers into the sky with kites attached at equidistant intervals. In the ascending part of the loop the kites are set to a high angle of attack, resulting in a high traction force, whereas in the descending part the kites are set to a low angle of attack, resulting in a low traction force. The resultant traction force in the cable loop is used to drive a generator at a ground station.

With the establishment of a dedicated research group in 2004, development at Delft University of Technology increasingly focussed on a traction power concept operating a single kite in periodic pumping cycles. In order to minimize the aerodynamic performance losses and to allow for high-altitude operation, the system design was based on a remote-controlled wing and a single-line traction tether. The working principle is illustrated in Fig. 23.1. During reel-out of the tether, the traction force and thus the generated energy is maximized by flying the kite in fast crosswind manoeuvres. During reel-in, the generator is operated as a motor and the kite is pulled back towards the ground station. To minimize the amount of energy required for this retraction phase the wing is de-powered by decreasing its angle of attack. A rechargeable battery is used to buffer the energy over the pumping cycles.

Starting from 2kW, the ground station capacity increased to 4kW in 2008 [9] and as of January 2010 a mobile kite power system with 20kW generator capacity is test-operated in monthly intervals [16, 20]. To cover a broad range of wind conditions, kites of 10m² up to 50m² wing surface area can be fitted. The prototype system with its characteristic Kite Control Unit (KCU) is shown in Fig. 23.2 in operation at two different test sites during 2012. The former Dutch Naval Air Base Valkenburg is situated in the proximity of Amsterdam International Airport and is used as regular test site for operation up to 300m altitude. Alternatively the Maasvlakte2 is a recent land extension of the Port of Rotterdam into the North Sea. With a flight permit up to
Fig. 23.2 The 20kW ground station fitted with the regular 25m² kite at the Valkenburg test site (left, photo: Max Dereta) and with a small 14m² kite for peak wind speeds up to 17m/s at the Maasvlakte2 test site (right)

1km altitude the site was used in June 2012 to demonstrate the important technical milestone of automatic operation of the kite power system.

Next to its function as development testbed and technology demonstrator, the prototype is fully instrumented for use in academic education and research. On system level, the research focus is on model development and validation, control and optimization [1, 5, 6, 8, 23, 24]. On component level, the focus is on the structural dynamics, aerodynamics and flight dynamics of the bridled, highly flexible membrane wing [2–4, 7, 17]. The objective is to provide a complete spectrum of simulation tools, ranging from validated real-time capable models up to accurate high-resolution models for computational analysis.

This chapter describes the development status of the pumping kite power system of Delft University of Technology. The system design and the various design choices on component level are discussed, focusing on the characteristic features of the prototype. The procedures for data acquisition and post-processing are outlined. Test results of individual pumping cycles are presented as well as statistical data quantifying the power generation characteristics of the system for varying operational parameters and at different wind conditions.

### 23.2 System design

The most characteristic feature of the prototype is the remote-controlled inflatable wing which is operated on a single-line tether. Heavy system components, especially those for the conversion from mechanical into electrical energy, are incorporated in
The basic configuration of the kite power system, including its wireless network, is shown in the schematic of Fig. 23.3.

The use of a soft wing, as opposed to a rigid wing, is motivated primarily by its inherently low hazard potential. Since operational safety is an important topic for Airborne Wind Energy systems it is discussed separately in Sect. 23.2.3. Using a single-line traction tether minimizes system losses due to aerodynamic drag which is particularly important when operating in crosswind mode. Compared to multi-line concepts, which incorporate the steering actuators in the ground station, the single-line design requires remote-controlled steering of the wing. Since actuators can be positioned close to the wing, actuation delays can be minimized, which is important for reliable operation of the kite, especially at larger tether lengths. Also, the separation of wing steering and power conversion at the ground allows for optimized functional designs.

Flight operation in a pumping cycle requires steering of the wing on well-defined crosswind trajectories, as well as changing of its angle of attack to alternate between reel-out and reel-in of the tether. The control system of conventional rigid wing aircraft employs actuated flight control surfaces. For a flexible kite, the choice of control mechanism and actuators depends on type, design and construction of the wing. For example, C-shaped kites such as those used for the prototype, are highly maneuverable due to the span-wise torsion of the wing. Figure 23.4 shows three different combinations of kites and control systems that have been investigated at Delft University of Technology: the inflatable kiteplane with elevator and rudders [17], the ram-air inflated wing with rack-and-pinion actuators [22] and the Leading Edge Inflatable (LEI) tube kite with suspended cable robot [20]. Extensive flight testing has led to a preference for the cable robot suspended below the C-shaped wing. The details of the implementation are described in Sect. 23.2.2 and in [21].

Under nominal conditions, the kite is operated in pumping cycles between 100m and 300m altitude, which corresponds to a variation of tether length between 200m and 400m. In the traction phase, the elevation angle of the tether varies between 25°
and 35°. The highest altitude is reached during the reel in phase. The flight velocity of the kite in this phase is between 20m/s and 25m/s. To maximize the net energy per pumping cycle, the reel-in phase has to be as short as possible with the tension in the tether as low as possible. For operation at a wind speed of 7m/s, the tether force can effectively be lowered from 3kN during reel-out to 0.8kN during reel-in at a reeling velocity of 5m/s.

The Supervisory Control And Data Acquisition (SCADA) system is implemented in the ground control center and the KCU. Several high-performance computers are incorporated in the ground control center, whereas the airborne control unit integrates two embedded systems. The various sensors are indicated in Fig. 23.3 and described in detail in Sect. 23.2.4. The wireless network using three redundant links is outlined in Sect. 23.2.5, the autopilot developed for tracking control of figure eight maneuvers is explained in Sect. 23.2.6 and the ground-based power conversion is presented in Sect. 23.2.7.

### 23.2.1 Traction force generation

The generation of traction power by well-controlled flight operation of the wing is the first step in the conversion process from the kinetic energy of the wind to electrical energy. For efficient energy conversion, the traction force of the wing during reel-out of the tether needs to be high, close to the maximum allowed loading of the tensile membrane structure (for material durability reasons it might be useful to stay well below the maximum wing loading). On the other hand, the reel-in phase requires a maximum reduction of the traction force while ensuring controlled flight. In addition, the reel-out of the tether should be slow while the reel-in should be fast.

The airborne power train includes the wing and the traction tether which are connected by the bridle line system. The design of wing and tether is detailed in the following subsections.
Kite

Realizing a high tether force during the reel out phase can be done in different ways. The fundamental equation for the resultant aerodynamic force \( F_a \) generated by a wing,

\[
F_a = \frac{1}{2} \rho v_a^2 A \sqrt{C_L^2 + C_D^2}
\]  

(23.1)

and the tether force vector \( \mathbf{F}_t \) measured directly at the kite,

\[
\mathbf{F}_t = \mathbf{F}_a + \mathbf{F}_g
\]  

(23.2)

indicate the three different options for optimization. Here \( \rho \) is the air density, \( v_a \) the apparent wind velocity, \( A \) the reference surface area and \( C_L \) and \( C_D \) the lift and drag coefficients. \( \mathbf{F}_a \) and \( \mathbf{F}_g \) are the aerodynamic and gravitational force vectors. When flying in a crosswind motion \( v_a \) is proportional to the lift to drag ratio \( C_L/C_D \) of the kite [10]. As can be seen from Eq. (2.35) of Chap. 2 the instantaneous power can be maximized by optimizing the following term:

\[
\sqrt{C_L^2 + C_D^2} \left[ 1 + \left( \frac{C_L}{C_D} \right)^2 \right]
\]  

(23.3)

This is done by optimizing the aerodynamic performance of the inflatable wing. Two different methods, experimental and computational analysis, are illustrated in Fig. 23.5. As a third option it is noted that the aerodynamic force can be increased by increasing the lifting area \( A \). As the gravitational force vector \( \mathbf{F}_g \) is added to the aerodynamic force vector and the kite always flies above the ground it can be concluded that mass will in general decrease the tether force. It should be noted, that centrifugal force components can cause the mass to have a positive influence on the tether force \( F_t \). For the presented system operating under nominal conditions, a 20kg kite flying at elevation angle 30° reduces the 300kg traction force by 10kg.
which is roughly 3%. The centrifugal force, while flying at 20m/s, adds roughly 1% to the cable tension.

During the reel-in phase the opposite is true. A low apparent wind velocity $v_a$, a low $C_L/C_D$, a low area, a low $C_L$ and $C_D$ and a large mass result in a reduced tether force. It is not beneficial to fly crosswind, as this only enlarges the apparent wind velocity. A low $C_L/C_D$ can help to prevent the kite from flying in a crosswind motion while it flies towards zenith as it comes out of the reel out phase. Also a low $C_L/C_D$ allows for high reel in velocities while the kite remains at a low elevation angle and thus it reduces losses while transitioning between reel out and reel in. A reduced $C_L$ and $C_D$ is established by pitching the kite in a nose down direction reducing the angle of attack. In the case of a Leading Edge Inflatable kite as used in the described system this means paying out a certain length on the steering lines. The steering lines are attached to the wing tips close to the trailing edge and thus support the load in the trailing edge region. This so-called de-powering however negatively affects the flight stability and steering behavior and in practice, a compromise between achievable de-power and diminished flight authority is required.

Other requirements that have been taken into account are transportability, ground handling during launch and landing and maximum wing loading in both powered and de-powered state. In the early state of development, the ability to crash without any need for repairs has also been taken into account. Altogether, it was decided that the Leading Edge Inflatable kite, as illustrated in Fig. 23.4 (right), provides the best option. This type of kite is affordable, easy to transport and shows a better stability in de-powered state than ram air inflated wings. The stiffness of the pressurized tubes allows for more stability at all angles of attack and a more simple and lower drag bridle.

Tube kites for kite surfing developed quickly over the past few years and many already achieve a large amount of de-power. Delft University of Technology has chosen this concept as a starting point, and in cooperation with industry partners, has further developed it for the kite power application.

Where the low production price could be a large advantage of using leading edge inflated kites, the durability could be a disadvantage. There are indications that the lifetime of a kite could be around 1000h of operation. Yet hardly any knowledge on the lifetime of such kites in this type of operation is available. It is thus advised to put a strong research focus into this direction. Another possible disadvantage could be maintaining pressure through time and while moving through different ambient air pressures at different altitudes. A pressure control and monitoring system will probably be necessary.

The Mutiny V2 kite that is used for the experimental results of Sect. 23.3 has a limited maximum wing loading of 5kN in powered state and about 1.2kN during de-powered state. Exceeding the maximum load causes the wing to collapse in a reversible mode, this means that there is no resulting damage to the material. In most cases the wing recovers while remaining airborne, yet in some cases the structure gets locked and sinks to the ground at low velocity.
Tether

The main cable of the system is a High Modulus Polyethylene rope, made of Dyneema®. It has a diameter of 4mm and a total length of 1km with enough space on the drum to extend to 12km and has a breaking strength of 13.75kN. Dyneema® was highly preferred to other materials because of its high fatigue resistance, low weight (the material is lighter than water) and extreme strength (15 times stronger by weight than steel). During normal operation the cable is only loaded to one third of its breaking strength for safety and longevity reasons. The cable is protected from breaking by a weak link. This weak link will break if the load goes over 6kN. Because of the weak link the spot where the cable breaks is predictable and separation of the kite from the cable in an overload situation is avoided with a safety line. When the weak link breaks a large amount of elastic energy is released from the cable. To prevent that this shock breaks the safety line there is an energy absorber or rip chord built in series with the safety line.

23.2.2 Steering and de-powering

The KCU is attached at the end of the main cable and is suspended about 10m below the kite, as shown in the schematic of Fig. 23.6. The two power lines of the kite carry about 80% of the wing loading and bypass the steering robot. The steering lines of the kite attach to two micro winches in the robot. One of these winches is used for steering, while the other one is used for pitching the kite to control the de-power of the wing. With a mass of only 7kg the KCU takes advantage of the progress that has been made over recent years in Remote Control (RC) technology and micro computers. The two winch motors come from model cars. They are very small and lightweight, yet extremely powerful. One disadvantage of using RC components is that they are designed to be cheap and affordable to meet consumer demands and have a consequently lower quality than industrial components. Industrial motor controllers on the other hand are in general more heavy. Besides controlling the
two winches the KCU also incorporates a pyrotechnic cable cutter that can detach the KCU from the traction tether in case of emergency. This maneuver instantly de-powers the kite to avoid a high speed crash.

The steering robot obtains its power from two Lithium Polymer batteries that allow for about three hours of continuous flight. In the future, the unit will have its own on board power supply from a small on-board wind turbine. The robot has a wired connection to the sensors in the kite.

23.2.3 Operational safety

The important requirements for operational safety can be differentiated as follows: (1) to ensure a reliable operation of the kite power system, (2) to avoid critical load
situations and unstable flight modes that might lead to a crash and (3) to minimize the hazard potential in case that a crash occurs.

With the prototype of Delft University of Technology being operated with the help of students, safety has been of critical importance during the design. Using a soft wing has shown to incorporate a number of safety advantages. Most importantly the use of flexible fabric has resulted in a lightweight construction of only 11.5kg. Due to its flexible behavior the kite is able to deform and absorb the energy that is released in the event of a collision, saving both the colliding object and the kite from major damage. From a safety perspective it is an advantage that the resulting construction is aerodynamically less optimal, as a result the flight velocities will be lower than in the case of using a rigid wing, especially in case of a constructional failure (i.e. canopy or bridle rupture) the kite will loose its performance and come to the ground at a low speed. In the extreme situation where the main cable would break at ground level, the KCU would be detached from the main cable, using a pyrotechnic cable cutter, to prevent the main cable from causing dangerous situations. The KCU would swing below the kite and glide slowly and safely to the ground while still maintaining some steering capability.

23.2.4 Measuring operational data

This section outlines the sensor framework of the prototype and informs about drawbacks and benefits of different choices as well as the background of design decisions. Special focus is on the challenging calculation of the kite position. Table 23.1 groups the most important sensors based on their usage in the system.

**Steering** The KCU steers and de-powers the kite, the position of the relative left steering value and relative power (0-100%) is calculated respectively from the voltage output $u_s$ and $u_p$ of analogue potentiometers which are attached to the winches.
Table 23.1 System-integrated sensors (see Fig. 23.3 for sensor locations)

<table>
<thead>
<tr>
<th>Use</th>
<th>Sensor type</th>
<th>Output</th>
</tr>
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<tbody>
<tr>
<td>Position, orientation</td>
<td>XSens MTi-G</td>
<td>(latitude, longitude, altitude)&lt;sub&gt;k&lt;/sub&gt;, a&lt;sub&gt;k&lt;/sub&gt;, ω&lt;sub&gt;k&lt;/sub&gt;, B&lt;sub&gt;k&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Trimble GNSS</td>
<td>(latitude, longitude, altitude)&lt;sub&gt;k&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Unilog GPS</td>
<td>(latitude, longitude, altitude)&lt;sub&gt;k&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Winch GPS</td>
<td>(latitude, longitude, altitude)&lt;sub&gt;k&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Incremental Encoder</td>
<td>v&lt;sub&gt;k&lt;/sub&gt;, l&lt;sub&gt;k&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Magnetic Encoder</td>
<td>θ&lt;sub&gt;k&lt;/sub&gt;, φ&lt;sub&gt;k&lt;/sub&gt;</td>
</tr>
<tr>
<td>Steering</td>
<td>Steering potentiometer</td>
<td>u&lt;sub&gt;k&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Depower potentiometer</td>
<td>u&lt;sub&gt;p&lt;/sub&gt;</td>
</tr>
<tr>
<td>Wind speed</td>
<td>Pitot tube</td>
<td>v&lt;sub&gt;w,k&lt;/sub&gt;</td>
</tr>
<tr>
<td>Monitoring</td>
<td>Ultrasonic wind sensor</td>
<td>v&lt;sub&gt;w,g&lt;/sub&gt;, temperature</td>
</tr>
<tr>
<td></td>
<td>Load cell</td>
<td>F&lt;sub&gt;k,g&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Miscellaneous</td>
<td>temperature, U, I</td>
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<tr>
<td></td>
<td>Load cell</td>
<td>F&lt;sub&gt;k,g&lt;/sub&gt;</td>
</tr>
<tr>
<td></td>
<td>Miscellaneous</td>
<td>temperature, U, I</td>
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</tbody>
</table>

Wind speed The Ultrasonic wind sensor on the ground delivers temperature and ground wind vector v<sub>w,g</sub> at 6 m height relative to the magnetic north. It is located on a beam several meters upwind from the ground station. The Pitot tube in the bridle of the kite can move freely and will align itself to the wind, it measures the apparent wind that the kite experiences v<sub>w,k</sub> as a scalar.

Monitoring Temperature T, current I and voltage U give indications about the status of steering, de-power motors and the batteries of the KCU. T, U and I is measured at the spindle motor, main generator and each battery cell in the ground station. This information is mainly needed for detecting malfunctions and knowing the electrical power in- and outputs. The tether force measured at the kite F<sub>k</sub> is equal to the aerodynamic kite force F<sub>a</sub> subtracted with the combined kite and KCU mass. The resulting force at the ground station F<sub>g</sub> is also measured. It is needed to control the reel-out speed v<sub>t</sub>, for position estimation and to get the mechanical power output of the system.

Position An accurate determination of the kite position is of critical importance to control the kite. At the beginning of 2013, two Global Navigation Satellite System (GNSS) receivers were used to measure latitude, longitude and altitude. The first one is included in the XSens MTi-G inertial measurement unit (IMU), which is located on the center strut of the kite. It uses three additional sensors that allow Kalman based sensor fusion, using 3 axes rate of turn ω<sub>k</sub>, 3 axes acceleration a<sub>k</sub> and the magnetic field B<sub>k</sub>. Fig. 23.9 shows that the XSens GPS data is not always reliable. In general, internal tests concluded that all GPS based sensors have problems during phases of high accelerations. Best results could be achieved with a
high-performance GNSS sensor manufactured by Trimble, which should be able to cope with accelerations up to 8g. The length of the tether $l_t$ which is measured at the ground is compared to the tether length that is calculated based on the GNSS data. Although the Trimble shows better performance it still loses track during accelerations above 5g. Moreover, magnetic encoders are added to the ground station which measure elevation angle $\theta_g$ and azimuth angle $\phi_g$ of the tether. A satellite independent position can be estimated combining this data with tether length $l_t$. By fusing GPS dependent and independent data using double exponential smoothing, which is much faster than a Kalman filter [13]. Fig. 23.9 shows the output of the Positioning sensors and the estimated position at different times during one figure eight. The estimator delivers a reliable position at any point in time, providing double redundancy for failure of one or both GPS systems or the angular potentiometers.

![Figure 23.9](image)

Fig. 23.9 Figure eight flight maneuver recorded on 21-01-2013 at 17:13:21h over a duration of $\Delta t = 44s$. The position data is given in terms of elevation arc length $\theta_g l_t$ and azimuth arc length $\phi_g l_t$.

### 23.2.5 Wireless data transfer

Communication between KCU and ground station can be done in several ways. One can for example use a conducting main cable and pass the control signals through the cable. This increases the cost, weight and diameter of the cable significantly. Another option is to run all controllers on board of the steering robot and only pass changes to the controller setting through a wired or wireless link from the ground. At an early development stage this is not desirable because it puts high demands on the reliability and performance of the controllers and on-board computers. The chosen approach is to send all required sensor data over a wireless link to the ground, process it there to control signals and send those up to the steering robot. In this way all sensor data and the controller performance can be monitored on the ground by the operator.
To ensure redundant wireless communication, a configuration with main, backup and RC link has been implemented [14].

### 23.2.6 Automatic system control

In early 2011 it was found experimentally that the kite can be parked overhead by use of the IMU and GPS sensor data. Controlling the heading of the kite with a simple PID controller to aim at the zenith point (straight above the ground station), proved sufficient to automatically fly the kite towards the zenith and maintain a stationary overhead position.

From the experience with automatic parking it was decided to use this simple control algorithm to start flying in a crosswind motion by changing the target point through time. Where attempts were already made by our and other groups to control the kite on a strictly defined path it was found that it could be more elegant to give the kite a certain freedom to find its own path while tracking from one point to the other. Also it was seen as a useful experiment to find if a control algorithm as simple as this one, would be sufficient to control the kite in a crosswind motion. A controller was developed where a number of points defined by their elevation and azimuth were used as attraction points. For each point a boundary was defined as a criterion to switch from one attraction point to the other. As a first step the single point parking mode could be extended to a two point switching mode. Great circle navigation theory was used to compute the preferred heading towards the next point. At high elevation angles the shortest path to the other point is always over the top of the sphere. This naturally results in an uploop figure eight motion. It was found that this mode is especially useful in strong winds, where the uploop figure eight results in a more constant and easy to control cable tension than the later described four point mode. On the other hand, in lightwind conditions, the downloop figure eight, as shown in Fig. 23.10, has proven to be the more efficient shape.

A further step has been the use of three attraction points to control the kite in a downloop figure eight motion. The third point was placed in the center at low elevation to force the kite down, but with the gravitational force causing the kite to underfly the attraction points there was no certainty that the kite would change direction in a downloop fashion. The three point mode was concluded to be of limited use.

Using four points has shown to be more successful in achieving a downloop motion. With two points above each other at each side of the wind window, the upper point number one in Fig. 23.10, will attract the kite to the side of the wind window. Crossing a defined azimuth limit will switch attraction to the lower point, indicated by number two, and force the kite to dive down. Passing a certain elevation angle will then switch attraction to the upper point number three on the other side. Passing the azimuth limit on the right side makes the kite dive towards number four. As the kite passes below the elevation limit again the figure eight is closed by switching to attraction point one again. This process continues until the maximum
cable length is reached. In order to switch to the reel in phase the kite is depowered and attraction point five causes the kite to fly towards zenith.

An unexpected but favorable effect of the four point algorithm has been that in the case where the kite is unable to climb over the elevation threshold, for whatever reason, the lower points two and four are automatically skipped. As such the kite is forced into an uploop figure eight and prevented from hitting the ground.

Both heading (where the nose points towards) and course (where the kite is moving towards) were used as control parameters. The kite has shown the most stable response to heading control, especially in parking and reel in mode as in those modes the angular velocities are minimal.

In the work of Jehle [8] a more sophisticated control algorithm was developed. This later algorithm has shown to be capable of controlling the kite in a more controlled and more constant shaped figure eight motion.

### 23.2.7 Power conversion

The ground station of the demonstrator has been designed to be reliable and robust and to enable the development of other key aspects of the technology, it was not designed to be as efficient as possible.

The ground station incorporates an industrial 3-phase asynchronous motor/generator that is connected to a cable drum by a belt drive. The drum can hold about 20km of 3mm cable or about 12km of 4mm cable. Drum and generator are mounted on a
A sled that is moved perpendicularly to the incoming tether by a spindle and a spindle motor. This configuration ensures that the cable always exits the winch at the same location. The spindle motor takes care that the cable is spooled evenly onto the drum. At the cable exit point there is a small mast that houses the load cells for measuring the cable tension and a swivel. The swivel is an arrangement of bearings and pulleys that allows the cable to be deployed in all directions. This is illustrated in Fig. 23.11.

Communication with the ground station and processing of all signals goes through a Programmable Logic Controller (PLC). The PLC communicates with a laptop on the user side and with the two motor controllers on the winch side. The winch stores energy in a Lithium-Iron-Phosphate (LiFePO₄) battery with a dedicated battery monitoring system. The battery consists of 104 LiFePO₄ cells in series with a nominal voltage of 333V and 60Ah capacity, resulting in a total capacity of 20kWh.

Power for control computers and any other electrical equipment on site comes from an auxiliary power system that is powered from the main battery of the ground station. This auxiliary power system transforms the DC power from the main battery into 240VAC.

The main battery is charged by the pumping operation of the kite. Because of the pumping operation the 18.5kW generator can be overloaded up to 30kW. During the reel-in phase power is drawn from the main battery to retract the kite. The net energy produced during such a cycle is enough to power all computers of the system and to charge the main battery. This means that the full system works on the energy produced by the kite with the access power available for consumption. A future step could be to feed the obtained access power into the grid or make it available for an end user that is not connected to the grid.
23.3 Experimental Characterization

In this section the system level performance of the described demonstrator is presented. Results are compared to the theoretical framework presented in Chaps. 2 and 14.

The system was operated in a variety of weather conditions which allows a broad overview of its performance. The analysis focuses on the conversion of wind energy into mechanical energy as a function of the measured wind velocity. To give a clear and compact overview it was decided not to address the conversion from mechanical to electrical energy. This is the focus of Chap. 14.

23.3.1 Data Acquisition and Post Processing

ZeroMQ messages containing Google Protocol Buffers define the message delivery and the message type protocol, which are standards that ensure a universal and flexible network wide interprocess communication and data logging. This communication is hardware, programming language and platform independent. All messages that are send through the network (e.g. sensor data from the KCU, steering commands from the autopilot) are collected and recorded. The result can be filtered and relevant data can be extracted. Creating statistics covering data from all test flights and getting time specific data with a granularity of $1/5s$ are just two possible uses. Fig. 23.12 shows the trajectory of a pumping cycle.

23.3.2 Data Selection

To give an accurate and complete overview of the performance of the demonstrator system, a selection was made of six data sets coming from six different testing days. This allows for a presentation of the experimental results over a broad range of operating conditions. With the wind velocity having a large influence on the system performance, a range of wind velocities from 2m/s to 11m/s could be covered. A selection of representative cycles was made. In the selected data two leading edge inflated kites have been used, a 25m$^2$ with a projected area of 16.7m$^2$ in light wind conditions and a 14m$^2$ with a projected area of 10.2m$^2$ in stronger wind.

Four average cycles are selected from the data and presented in Fig. 23.13. The average mechanical power as well as the obtained energy are displayed. The pumping operation is visible in both the power and the energy plot. It can be seen that in this example about 18kW is produced during the reel out phase. With a maximum of 7kW consumed during the reel in phase the average power production comes down to 5.7kW. The energy data illustrates how the produced amount of energy gradually increases.
23.3.3 Cycle Analysis

Generally a cycle consists of 60 to 180s of reeling out followed by 60 to 90s of reeling in, all depending on the wind conditions. To analyze the performance of the system the data will be divided into cycles. The conversion performance can then be quantified for the individual cycles. The deployed tether length is used to separate the data into cycles.

First a definition of the cycle starting point is required. For comparing the cycles to each other it is important that each cycle starts and ends at the same tether length.

### Table 23.2
Selection of data sets. The wind speed was measured at 6m above the ground, the airborne mass consists of the kite with sensors and the KCU.

<table>
<thead>
<tr>
<th>Data set</th>
<th>Wind speed [m/s]</th>
<th>Date</th>
<th>Kite type</th>
<th>Kite Area [m²]</th>
<th>Airborne mass [kg]</th>
<th>Time [min]</th>
<th>Cycle count</th>
<th>Autopilot control</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.8</td>
<td>22-5-2012</td>
<td>V2</td>
<td>25</td>
<td>25</td>
<td>22</td>
<td>12</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>4.4</td>
<td>20-1-2011</td>
<td>V2</td>
<td>25</td>
<td>21</td>
<td>26</td>
<td>11</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>6.6</td>
<td>22-9-2011</td>
<td>V2</td>
<td>25</td>
<td>21</td>
<td>42</td>
<td>25</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>7.4</td>
<td>31-5-2012</td>
<td>V2</td>
<td>25</td>
<td>25</td>
<td>26</td>
<td>20</td>
<td>Yes</td>
</tr>
<tr>
<td>5</td>
<td>8.0</td>
<td>23-6-2012</td>
<td>V2</td>
<td>25</td>
<td>21</td>
<td>31</td>
<td>20</td>
<td>No</td>
</tr>
<tr>
<td>6</td>
<td>10.0</td>
<td>23-6-2012</td>
<td>Hydra</td>
<td>14</td>
<td>18</td>
<td>29</td>
<td>15</td>
<td>Yes</td>
</tr>
</tbody>
</table>
Fig. 23.13 Traction power and energy over four consecutive pumping cycles. The wind speed was 7.4m/s at 6m altitude.

As the data contains cycles with different maximum and minimum tether lengths, starting each cycle on either a maximum or a minimum would affect the performance figures. It is therefore decided to take the average value of all maxima and minima in a data set and use the upward crossing with this average tether length as the starting criterion for each cycle. In general the transitions to change the reeling direction take between 1 and 5s, the time stamp of these maxima and minima is defined by the first sample that reaches the extreme.

23.3.4 Power Curve

This section gives an overview of the mechanical power that is produced with the described system. It needs to be noted that through the selected testing days different flight control algorithms and winching strategies have been tested. Even modifications were made to the control unit. While this can be a reason for an increased spread in the data, it is found that the differences in hardware have been minimal and the data still provides an interesting and representative illustration of the performance of the demonstrator. Also it must be noted that, as the wind velocity is measured at 6m altitude, there remains a significant uncertainty in the wind velocity at the altitude of the kite. Using the theoretical framework explained in Chaps. 14 and 2 a theoretical power curve is established and compared to the presented experimental data. The model estimates the expected average power over a full cycle for given wind velocity $v_w$, wing surface area $A$, $C_L$, $C_D$, elevation angle $\beta$, reel out fac-
tor $f$ and tether thickness $d$. The reel out and reel in power is calculated separately. Experimental results show that the elevation angle can be reasonably assumed constant during the reel out phase and that the elevation angle constantly changes during the reel in phase. To account for this the reel in power is estimated using a dynamic model. Similar to the reel in algorithm used by the winch, the reeling velocity is adapted to keep the tether force constant. The model parameters used for the theoretical analysis are listed in Table 23.3. They have been derived by statistical analysis of the measurement data [15].

<table>
<thead>
<tr>
<th>Projected area</th>
<th>$L/D$ reel-out</th>
<th>$L/D$ reel-in</th>
<th>$C_L$ reel-out</th>
<th>$C_L$ reel-in</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.7 m$^2$</td>
<td>5.0</td>
<td>2.0</td>
<td>1.0</td>
<td>0.14</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Max reeling velocity</th>
<th>Force reel-out</th>
<th>Force reel-in</th>
<th>Mass kite &amp; KCU</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.0 m/s</td>
<td>3200 N</td>
<td>800 N</td>
<td>20 kg</td>
</tr>
</tbody>
</table>

Table 23.3 Parameters used for modeling.

Figure 23.15 shows that the highest mean mechanical power is achieved over a range of wind velocities roughly between 6 m/s and 10 m/s. The reason is that at 6 m/s the system starts to run into its reeling velocity (max. 8 m/s) and force (max. 5 kN) limits. This is illustrated in Figs. 23.16 and 23.17. During operation the reel...
out force is controlled at 3.2kN while the reel in force is set to 800N. It can be seen in Fig. 23.16 that the reel out velocities increase up to around 7m/s, after which peak velocities that reach the maximum allowable velocity frequently appear and prevent safe operation at higher average velocities.

Figure 23.16 indicates how the reel out velocity increases with increasing wind velocity. It is also noted that as the wind reaches above 6m/s the generator is approaching its limit of 8m/s. Optimizing the model under the known constraints shows that the operation has been close to optimal for the system’s constraints.

Figure 23.17 shows how the average cable tension reacts to changing wind velocities. While the generator is able to control the reel out force close to 3kN the peak loads clearly increase as the 25m² kite is starting to become too large. The reel in force is kept slightly below 1kN in all tested conditions.

As presented in Chap. 14 the duty cycle represents the ratio between the time the system is in useful reel-out mode and the complete cycle time. Looking at the system’s duty cycle in Fig. 23.18 it is noted that as the wind increases the duty cycle becomes lower. This is understandable as the system is force controlled. As the wind increases it is mostly the reduction in reel in velocity but also an increase in reel out velocity that has a reducing effect on the duty cycle. Using a smaller kite in stronger winds under the same force controlled settings results in an increase of the duty cycle.
Fig. 23.16 Reeling velocities for different wind velocities. Each marker represents an average over the indicated part of the cycle. Open marker: 25m² Filled marker: 14m².

Fig. 23.17 Cable tension for different wind velocities. Open marker: 25m² Filled marker: 14m².

23.4 Conclusions

The Kitepower demonstrator of Delft University of Technology has been described and experimental results have been presented. The developed model and the ex-
Fig. 23.18 Duty Cycle for each completed power cycle. Open marker: 25m² Filled marker: 14m².

Experimental data show good resemblance. This provides some confidence to extend further model based analysis outside the range of the experimental setup. The model can thus be used for investigating scaling and sensitivity analysis for the improvement of system components. A better estimate of the wind velocity at the altitude of the kite would enable a more accurate model validation.

Looking at both modeling and experimental results it is concluded that the demonstrator runs into its operational limits already around 7m/s of wind velocity at ground level. Further research should indicate how the kite and the generator should be dimensioned with respect to each other to come to an optimal balance.

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