

Chapter 32

Conceptual Design of Textile Kites Considering Overall System Performance

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Abstract In this paper the authors present basic considerations on conceptual kite design in terms of overall system performance of an airborne wind energy system. This kite design process has been developed at SkySails GmbH for the design of large scale traction kites for sea-going vessels. All aspects are first presented in a brief discussion and then applied to the SkySails kite system. Further examples are provided where applicable. This chapter starts by introducing theoretical approaches for determining maximum system performance and certain other aspects of kite aerodynamics with respect to the SkySails kite system. An overview of the limitations considered during the kite design process is also presented. In the following sections, the influence of kite steering, launch and landing is discussed. Further, structural weight aspects are addressed. The last sections deal with the implications of ground handling on kites.

32.1 Introduction

Within the airborne wind energy community a lot of work has been done to identify various promising concepts for energy production. These concepts often base on a particular patent of the founder or a special idea to harvest energy from altitude winds. Due to the novelty of this young field of research, these ideas often cover the fundamental purpose of the concept, the energy harvesting. The long-time experiences of SkySails with large-scale textile kites for ship propulsion led to some knowledge about the less obvious side effects involved with the systems operation. Some considerations resulted in changes of the kite design which seemed to lower the initial system performance estimate. But on the other hand the systems

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availability and operational time was increased. The output of a system can only be maximized if the whole system is examined and optimized. Output of a system in this context is the physical energy output per unit time in long-term operation, i.e., the long-term average mechanical or electrical output power. This is what we call the *overall system performance*.

This approach does not explicitly deal with lifetime and costs. Reliably estimating the lifetime of a kite is a challenge if the planned mode of operation or scale was never tried before. Simulations and laboratory tests can give first estimates of structural requirements and material properties but only a real application allows assessment of expected system lifetime. Estimation of production and operating costs does not only depend on component lifetimes but also on system specifications which are not necessarily established before actually testing first prototypes. So we chose to develop a functional system first and then improve and mature component lifetime and costs if necessary. Cost and lifetime issues can of course never be neglected but a functional system that is not fully economically profitable in a prototype stage seems to be more useful than a cheap and durable system that does not work. This approach implies that the chosen concept can be developed to an economically viable product at all. That includes that it is technically feasible to achieve a certain lifetime. This is why we put the focus of our kite design process on a functional and robust system and this chapter covers major related considerations. Lifetime and cost in general is of course constantly monitored and improved but this is not covered in this chapter.

This paper discusses the main aspects of kite design in terms of overall system performance optimization. First the theoretical optimum of the wing in crosswind conditions is discussed. The following sections describe the constraints of steering, structure, launch and landing as well as ground handling on overall system performance. Each section starts with a brief discussion of the topic. The way SkySails solved the related challenges for its ship propulsion system is described at the end of each section.

Due to the system's complexity and constantly changing operating conditions some of these findings cannot easily be backed up with measurement data or other scientific proofs. Still the presented considerations reflect the results of numerous simulations, tests and regular operation in small and large scale. It was found that the kite design that matches the requirements for maximum output in operational phase is not necessarily the right kite design for the maximum overall system performance.

32.2 System Performance in Operational Phase

Overall system performance of an airborne wind energy system (AWES) is mainly determined by the system performance in its productive or operational phase. This is therefore a suitable starting point for the kite design process.

Designing an efficient kite for an AWES requires good understanding of the influence of aerodynamic characteristics on the system output (system performance).

A theoretical model of the system in operation is used to derive its dependencies on selected characteristic numbers of kite aerodynamics such as the model described in [2]. This model can be established either analytically or numerically and it should cover all known physical aspects contributing to the output of the complete system.

The derived dependencies can then be used to optimize the aerodynamic characteristics of the kite. Examples for characteristic numbers are glide ratio, lift and drag coefficients or wing loading (load per reference area). To allow for an efficient kite design process, the measurements of characteristic numbers should be considered. For instance, aerodynamic forces can be measured more easily and accurately by means of the total line force instead of lift and drag since the latter requires knowledge of the angle of attack.

In the following, the glide ratio is defined as the quotient of lift and drag (Eq. 32.1) and the total aerodynamic force coefficient as the (vectorized) sum of lift and drag coefficients (Eq. 32.2).

$$E = \frac{C_L}{C_D} \quad (32.1)$$

$$C_R = \sqrt{C_L^2 + C_D^2} \quad (32.2)$$

Some system concepts feature two (or more) distinct flight conditions in the operational phase, such as the retrieval phase of a pumping mode system. In this case, the system performance model could allow for different aerodynamic configurations which vary in at least one characteristic number. Feasibility of the desired manipulation should be evaluated well in advance. The issues involved with actively manipulating aerodynamics are discussed in Sect. 32.3.

In case of the SkySails ship propulsion, the system is based on pulling forces of a dynamically operated wing at constant cable length and features a constant aerodynamic configuration in operational phase. The efficiency of such a towing system can generally be optimized by maximizing the achievable line force for given ship speed, apparent wind velocity at the ship and wing size. The maximum line force configuration can be described using Eq. 32.1 and Eq. 32.2 as¹

$$C_{\max} = C_R(1 + E^2) \quad (32.3)$$

Maximizing C_{\max} also gives the minimum sink configuration of a gliding plane. A high glide ratio obviously is very important to increase C_{\max} . However, the polar diagram of a given wing shows that the angle of attack (α) for maximum line force differs significantly from α for maximum glide ratio (see Fig. 32.1). So the optimization of C_{\max} must include α as well (influenced by means of the trim position).

¹ Maximum line force occurs in cross wind situations. Cross wind speed of the kite is $v_c = v_w E$ with wind velocity v_w . Apparent air speed at the kite can then be expressed as $v_a = \sqrt{v_w^2 + v_c^2}$ or $v_a = v_w \sqrt{1 + E^2}$. The tether force can be described as $T = \frac{\rho}{2} v_a^2 A_{\text{ref}} C_R$ with ρ being the air density and A_{ref} being a reference area. Using v_a for the cross wind situation together with C_{\max} according to Eq. 32.3 the maximum tether force equation can be written as $T = \frac{\rho}{2} A_{\text{ref}} v_w^2 C_{\max}$.

If a ram-air kite would be optimized for such an operational phase, it could feature a slim, high camber profile, a high profile rib density (or high cell count), very few bridle lines and maximum aspect ratio. Such a wing would be comparable to a high-performance paraglider in many ways. All of these measures contribute to minimum drag and maximum lift, resulting in maximized glide ratio and C_{\max} (like configuration I in Fig. 32.1).

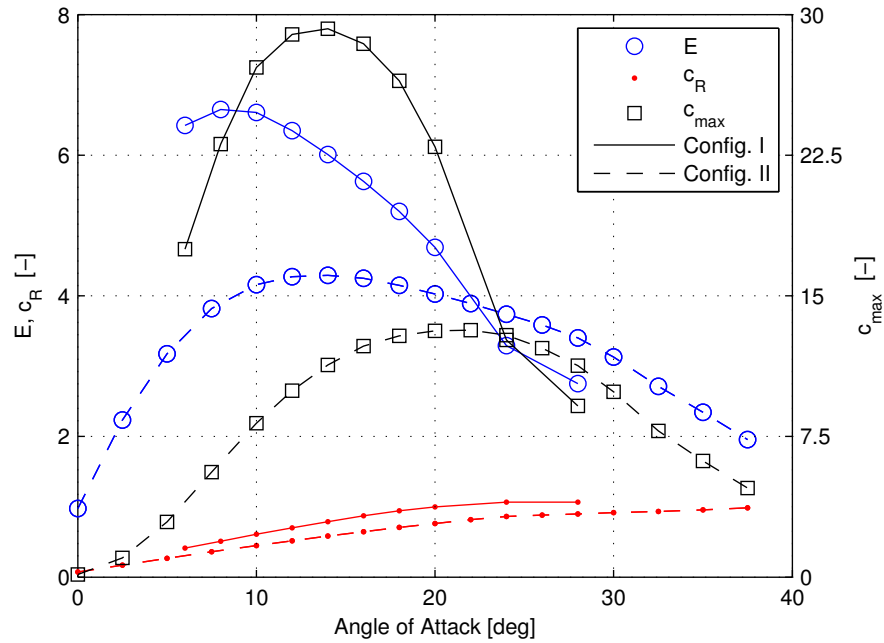


Fig. 32.1 Calculated aerodynamic characteristics of two different wing configurations. (CFD results, with OpenFOAM 2.0.1, solver simpleFoam). Note the angle of attack for maximum C_{\max} . Configuration I represents a kite for high performance in power generation phase while configuration II features a more robust flight behavior in terms of increased resistance against deviations of α but significantly lower C_{\max} . The main difference between the two configurations is the flat aspect ratio (I: $AR = 4.8$ / II: $AR = 2.7$)

32.3 Constraints in Operational Phase

Before a wing can be designed to match the theoretical maximum performance characteristics for the operational phase derived in Sect. 32.2, some constraints need to be considered. Such constraints primarily originate from external conditions (environment), specific issues involved with high glide ratios and certain aspects of

steering mechanisms. They generally shift the optimum aerodynamic configuration towards a lower glide ratio (like configuration II in Fig. 32.1).

The most important environmental constraints are precipitation and strength and quality of wind. The smaller a wing's specific weight (weight per reference area) and the slower its air speed, the more sensitive it can be to rain. This is most significant for textile wings, as the very low specific weight is easily affected by the increased weight of a wet wing, though the use of highly hydrophobic materials can reduce this effect. High performance aerodynamics are also affected by boundary layer effects due to small droplets on the wing's surface. Low temperatures together with wet conditions impose the additional risk of icing, especially to rigid wings.

Quality of wind is a significant constraint for overall system performance optimization. Wind generally varies over time in speed and direction (horizontally and vertically) and with position, mainly altitude (layering and shear). Wind quality and strength is usually less favorable in the lower atmospheric boundary layer during launch and landing, though at operating altitude (at least up to 300 m) the system is still exposed to significant disturbances. The change in wind speed or direction generally changes the kite's α or its side slip angle β .

While the kite is operated at high air speeds, changes of the apparent wind angles are comparably small. Then the most significant threats are overload situations (system load above safe working load) due to increased α (resulting in increased C_R), increased air speed and/or trajectory deviations. Overload can potentially be avoided if a quick system response either allows to pay out the tether (reducing apparent wind speed at the kite's position) or to reduce C_{\max} .

While the air speed is low deviations of α or β become more significant. If a tolerance range is exceeded, the wing will collapse (mainly for textile and bridled kites) or stall, both with potentially severe consequences. A high tolerance of disturbances of α is the key to a robust static flight behavior.

As described above, a high glide ratio is a powerful parameter for increasing system performance. A higher glide ratio allows reaching a kite's design load at lower wind speeds but imposes drawbacks on aerodynamic robustness. Some of the issues to be considered with high glide ratios are:

- Risk of overload due to disturbances such as gusts or ground station motion
- Reduced flight stability in low air speed situations, such as static flight especially in decoupled flight situations (free flight) and at short tether lengths

If a higher glide ratio would lead to an increased nominal airspeed (due to a lower C_R , for example), some steering related topics need to be considered (see also next section for steering considerations):

- High precision trajectory planning and steering system required
- Higher steering power required (same steering motion in less time)
- A textile kite's lifetime could be affected due to higher steering intensity (same kite deformation in less time).

As described above, there are good reasons to consider an adjustable aerodynamic configuration. System performance in operational phase could be optimized

for maximum efficiency while launch and landing or static flight could be more robust if for instance the glide ratio could be actively adjusted. Also overload protection could be implemented if this system is sufficiently fast. On the downside of such an additional system stands increased airborne system weight and most of all increased complexity.

In case of the SkySails system, the general operation is at constant cable length which limits the possibilities to use the winch to compensate any disturbances. There are very significant disturbances due to the ship motion (more than 2 m/s ground station motion in tether direction was measured during operation of the system²). The kite features a comparably low projected aspect ratio of less than two. This results in a rather small glide ratio ($E < 5$) which reduces the risk of overload as a result of gusts and ship's motion in high airspeed situations. In addition to this an adjustable winch brake passively limits the tether load to a safe level. The low aspect ratio also greatly increases the wings tolerance range regarding a change in α . Profile nose shape and thickness trade in maximum glide ratio for an improved robustness against the risk of collapses and persisting stall. This is especially important during launch and landing (see Sect. 32.5).

The specific weight of 160 to 320 m² kites is around 0.5–0.6 kg/m². This is a compromise between low minimum air speed and little weight gain in wet conditions. Despite hydrophobic treatment of the materials used for the kites, weight gain in wet conditions can be significant and is known to affect minimum wind speed for launch. Operation is limited to non-freezing conditions to reduce the risk of icing of structures and sensors.

Another aspect which is specific for a towing system like the marine propulsion system is the pulling direction with respect to the ship's keel line. Usable pulling force is towing line force projected into ship's longitudinal axis. A ship sailing downwind (wind astern) in strong wind requires a kite with low glide ratio to allow flying the kite at low elevation in the wind window.

32.4 Kite Steering

Most kite systems rely on some kind of steering mechanism. The steering system must be fully functional in all phases that rely on active steering, e.g., active and static flight at various tether lengths including launch and landing. The steering precision required strongly depends on the dynamics of the kite system. The higher its airspeed, the more precise the steering system must be in order to avoid overload due to trajectory deviations.

When looking at overall system performance, the steering system's power supply must be considered, too. An airborne steering actuator being integrated close to the kite's canopy requires a power supply through the traction cable or potentially heavy airborne power generators. This reduces system efficiency not only due to its power

² Logfile 20110615_113820

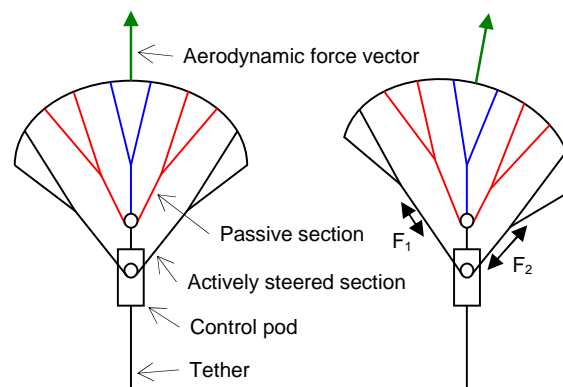
consumption but also as a result of increased drag and weight. Steering the kite from a ground station potentially affects steering precision at long tethers and/or during static flight phases.

Another important point to be considered when discussing the steering mechanism of a kite system is the negative effect of steering intensity (expressed by means of steering frequency and amplitude) on a textile kite's durability. Commonly applied steering mechanisms are based on some kind of canopy deformation deflection or a span wise shift of a tether coupling point (lateral trim). Steering deformations can significantly affect material properties and lifetime of textile structures.

In case of the SkySails system, the kite is controlled by an airborne steering unit (control pod). It contains sensors, controllers and actuators which allow for precise automatic control over a wide range of operating conditions [1]. The kite remains stable and controllable during slack line situations as the airborne system's center of gravity is well below the canopy's aerodynamic center. Without coupling to the ground station, the kite dynamics become similar to a free flying paraglider.

The control pod deflects the canopy by pulling in one tip and releasing the other (see Fig. 32.2). Together with a set of passively balanced sections the canopy is basically rotated around its roll axis, thereby tilting the lift vector to one side. This steering concept causes little additional drag in turns, since both profile and induced drag are not increased significantly.

Fig. 32.2 Schematic drawing of SkySails steering system. The control pod only needs to compensate the force difference between both wing tips, that is, the steering forces are the difference of F_1 and F_2 . Deformation is generally reduced to a minimum and profile ribs are almost not affected which significantly contributes to the kite's lifetime



As the control pod has direct access to the canopy with negligible steering line slack, the steering forces can be well balanced and close to neutral allowing for low energy demand over one steering cycle. This also allows for unstable steering forces (the control pod is pulled towards full deflection) which can significantly improve steering efficiency though precision potentially suffers as improved turn rates are a result of unstable deflection of passive sections.

Electrical power for the control pod is supplied from the ground station through wires embedded within the traction cable. This helps keeping the take-off weight as low as possible but limits the maximum potential line length due to increasing towing line weight and drag.

Since the SkySails kite system features a low glide ratio and high C_R , required steering speeds as well as peak and average steering power contribute to a comparably small and light weight control pod.

A 320 m^2 kite designed to provide a pull of up to 320 kN (design load) has a mass of about 250 kg , the appropriate control pod adds 70 kg and the towing line another 0.9 kg/m . Thus the specific weight of the airborne system at launch is about 1.0 kg/m^2 while it rises to about 2.0 kg/m^2 (or about 50 daN/kg pulling force to mass ratio) at its operating point at a tether length of about 360 m . The control pod is designed for steering forces up to 12 kN though measured forces usually stay below 2.5% of towing line forces.

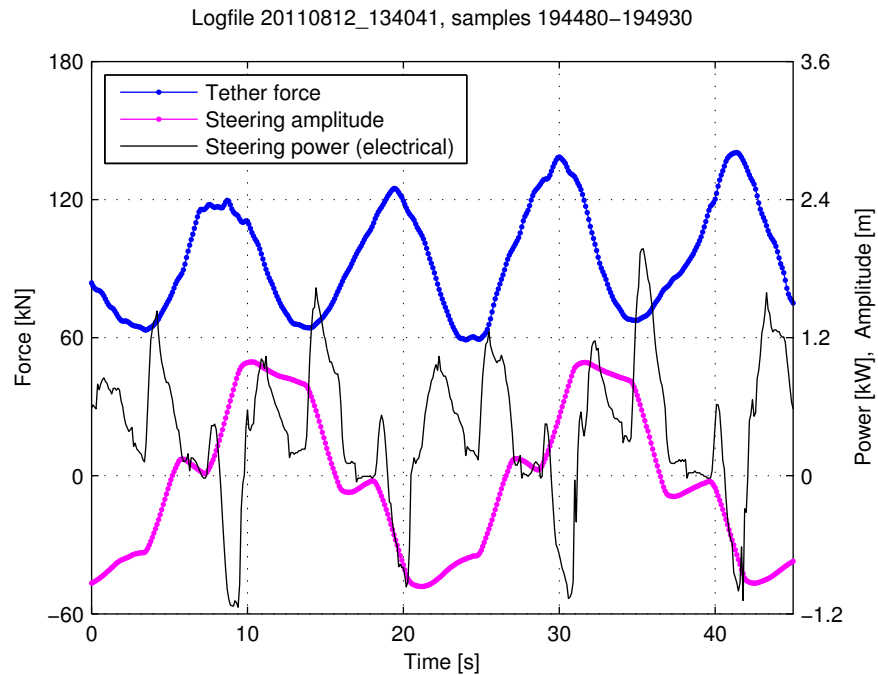


Fig. 32.3 Steering data of a $225\text{ m}^2/160\text{ kN}$ -Kite. Note that this steering system has unstable characteristics, so increasing deflection can provide power to the steering drive resulting in negative steering power. Average control pod power demand for this period is 403 W . The control pod and its power supply system are able to continuously provide 1 kW of electrical power

32.5 Transition

This section covers the launch and landing phases. The launch begins when the system is ready for take-off and actuators are handed over to the flight control. The

system will then be released from its launch and landing unit. At this point three main launching principles can be distinguished. All have in common that the airborne system has to be carried up to stronger winds at altitude in a reliable and reproducible manner.

1. A simple static-flight launching concept that relies on the lift of the airborne system (either aerodynamic or lighter-than-air) without applying additional forces or requiring dynamic flight.
2. A dynamic launching concept that additionally uses the system's capability for dynamic flight. Therefore the wing is accelerated by an external force (e.g., winch launch of gliders or propeller) which leads to a higher apparent wind at the wing. For this reason the kite can achieve a higher lift than in static operation.
3. Yet another approach is the combination between a static launching concept and an external force. Here the static lift can for instance be supported by a propeller in vertical take-off operation or by a mechanism to pull-up the airborne system (e.g., by mast or a parent ship).

To achieve the maximum flight time the main objective of kite-design for the transition phase is to lower the minimum wind velocity ($v_{a,min}$) at which the airborne system can generate sufficient lift. Since the idea is to harvest winds at altitude, a bottleneck in wind velocity in the lower boundary layer of the atmosphere would limit the overall system performance. Launching principles 2 and 3 aim for lowering $v_{a,min}$ by indirectly or directly increasing the lift-to-weight-ratio of the system. This can help to reduce $v_{a,min}$ for take-off.

While the launch can be scheduled relatively well in terms of weather conditions (no need to launch without wind or during thunderstorms), the most common reasons to land the airborne system are insufficient or extreme winds. In particular, all systems relying on wind for launch necessitate the ability to reliably landing the system without wind on the first approach.

In most concepts of tethered flight it is possible to generate apparent wind at the airborne system by paying-in the tether. However, this motion adds an additional wind vector along the tether axis which tilts the wind window. The kite could then access positions outside of the static wind window. This would make the kite collapse once the winch stops, e.g., when approaching the landing position. The higher the glide ratio of the kite, the more significant is this effect.

Depending on the launch and landing concept a number of different problems can arise. Compact launch and landing units (compared to the wing size) generally include a flight phase at short tether. This situation is difficult to control since even small disturbances result in high angular accelerations within the wind window resulting in high variations of angle of attack. To compensate such disturbances a precise and fast steering concept is needed. The combined effects of turbulence, shear, layering, gusts and lulls, motion of ground station, and precipitation makes a reliable control of launching and landing a challenge. Kite design can contribute to a reliable launch and landing process at demanding environmental conditions and short tether length. A wing designed and/or trimmed to a low glide ratio can promote flight stability by increasing its tolerance against deviations of angle of attack.

Other methods of stabilizing the wing include the application of passive mechanisms such as a reflexed trailing edge which can prevent collapses. Auto-stable kites (kites which tend to turn upwards when steering is neutral) can ease the requirements for steering actuators and flight control. But dynamics of auto-stability strongly depend on tether length and wind velocity. Beyond the means of kite design, external forces can be applied to stabilize the system at short tether by restricting the degrees of freedom.

In case of the SkySails system, flight control at short tether is strongly affected by the quality and intensity of the apparent wind as well as wave induced motions of the launch and landing unit. For such an offshore application compensation of ground station movements to optimally launch and land the system is as essential as the systematic damping of the wing reactions and an appropriate steering control. The towing winch is used to compensate the wave induced motions along the tether axis by paying-in and -out. Motion of the coupling point perpendicular to the tether direction cannot be compensated, though. As described in Sect. 32.3, the wing features a low aspect ratio and is trimmed to a high α to maximize stability against collapses and avoid collisions with the ship's structures. Collisions of the textile structure of the wing with solid components do not necessarily result in damages. The high α can not reduce the risk of stalls. Stall situations at short tether can safely be recovered by tightening the line which is used to guide and dock the kite to the mast top.

32.6 Structure

This section covers basic considerations about the correlation between strength, weight, and size of an airborne system.

Structural strength is determined by the aerodynamic forces of the wing. Due to a potentially high load variance a sufficient safety margin has to be included to safely operate the system. The safe working load (SWL) is a relevant design parameter and can be used as one part of the correlations on structural issues.

Increasing strength always leads to a weight gain. To operate the heavier airborne system, a higher wind velocity is needed. The weight of the wing is therefore represented by the minimum wind velocity for operations $v_{a,min}$. The system's weight has to be compensated by the aerodynamic force component contrary to gravity.

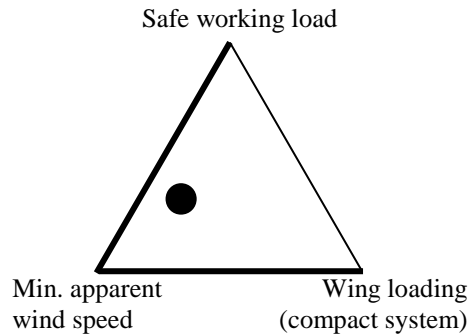
Different methods of how to generate lift for the launch and landing phase were discussed in Sect. 32.5. For launching concepts that completely depend on the available apparent wind at the ground station, the operation time is limited by $v_{a,min}$. Depending on the site conditions, a high $v_{a,min}$ potentially reduces the flight time significantly.

The minimum wind speed varies for static and dynamic flight mode. The $v_{a,min}$ required for the static case is usually higher than for the dynamic. The difference is, that the kite's movement leads to higher apparent wind speeds and therefore to higher tether forces. Much of this higher tether force is in horizontal direction, but

(if the elevation is not too low) the vertical component is still higher than the lift in static flight.

One method to avoid a limitation of flight time due to a high $v_{a,min}$ is to reduce the wing loading (WL) of the kite at constant design load (SWL). This allows for a larger kite with lighter materials resulting in a lower specific weight. Thus the wind range can be shifted to fit the site conditions. Side effects of a lower wing loading are a more difficult handling or possibly a higher sensitivity to rain. In Fig. 32.4 the relationship between $v_{a,min}$, SWL and WL is illustrated.

Fig. 32.4 The conflict between $v_{a,min}$, SWL and WL can be visualized by a trade-off triangle. If the design point of the airborne system is optimized for one feature the other aspects usually get worse. The main conflicts involve the minimum apparent wind speed. A high SWL and high WL are both possible if the specific weight is completely neglected



It is not possible to achieve an optimum for all parameters in one system. The optimum design point depends on the external circumstances like, e.g., expected weather conditions or wind distribution.

If reducing the wing loading does not shift the minimum apparent wind speed to an acceptable level, an external energy supply mechanism could improve the lift-weight-ratio. For example, a classic glider winch launch would work for lower winds than a static launch. Still, the winds at altitude need to be strong enough to keep the kite in operation. Such an external energy can partially break the described trade-off triangle and new relations can be associated.

In case of the SkySails marine system the target configuration is already indicated in the figure as a dot. At the expense of a compact wing a kite is used that has a low $v_{a,min}$ and a moderate SWL to be able to even launch in light wind conditions. Though exact numbers for minimum wind speed depend on the level of turbulences and ship motion. In perfect conditions, a launch can easily be considered at about 5 m/s while rough sea and bad weather might require 10 m/s. As already mentioned in Sect. 32.3, the specific weight of such a kite is around 0.5 kg/m² (without control pod and tether) at a mean wing load of ≈ 0.7 kN/m² at design load.

The use of textile kites for ship propulsion is partially motivated by the need for stowing (see Sect. 32.7). Heavy rigid structures are expected to be rather unhandy and difficult to stow or integrate into the regular operation of the ship.

Apart from the use on board of a ship, the perceived safety that is emanated from a light textile kite can be important in terms of public acceptance, even if the technical safety (e.g., in the form of controllability) might be lower. The tradeoff

is that the aerodynamic efficiency of textile or extremely light weight structures is limited due to design restrictions (e.g., no bending stiffness) and unwanted load depending deformations.

32.7 Ground Handling

Ground handling covers the processes in between flights. When an approaching airborne system of an AWES reaches its landing position the ground handling begins. Due to the requirement that an AWES should operate automatically, a handling process should be aimed for which can be done by machines. Human handling is possible with small systems like the demonstrators shown by various projects. But with increasing power, the forces the systems generate will increase by magnitudes. The high forces lead to a heavy and large airborne system that cannot be handled by humans.

Especially for R&D systems, a machine supported handling system is a good starting point for the process development. In this case a human operator controls or observes the processes. But the forces to move the landed system around are applied by mechanical actuators.

In the future and especially for offshore or remote-use, systems have to work almost autonomously. This is an important contribution to the overall system performance of an AWES.

The major challenge in the ground handling process is the transfer of the airborne system from its landing position to a sheltered stowing position. The shelter is necessary to prevent damage of the airborne system in extreme weather conditions. For example, strong wind, precipitation, and lightning could seriously harm an unsheltered system. When thinking of offshore application spray and wash have to be considered, too. The landing and stowing position can be the same if a shelter moves around the airborne system after landing.

Currently there are mainly two different types of wings structures. One concept is rigid and the other is flexible. In terms of ground handling there are the following requirements to the wing concepts:

- process repeatability
- reliable automation
- robustness against damage
- compactness
- small weight of the handled parts
- deliverability (shipping)

Roughly, process repeatability and automation is the advantage of rigid wings as their geometry is always well defined. Robustness, compactness, weight, and deliverability are the benefits of flexible wings.

In conceptual and early prototype stage the focus is on proofing operational performance in flight. The development of ground handling processes is postponed to

later project stages. It is important to have it in mind when making decisions about a wing concept. A good compromise has to be found between aerodynamic efficiency and handling.

In case of the SkySails system, a textile flexible wing is used, which can be reefed and de-reefed in a short time. The Ram-air inflatable kite features span-wise reef lines which squeeze the air out of the kite volume.

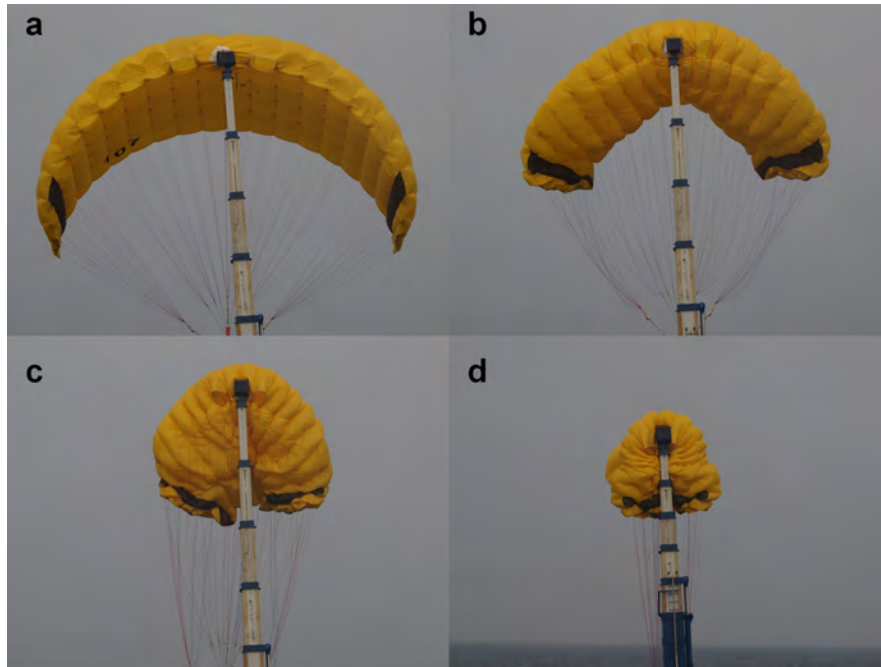


Fig. 32.5 Reefing process of a SkySails kite: **a)** Inflated kite, **b),c)** Internal reef lines contract the kite and squeeze the air out of the intakes, **d)** After reefing the mast retracts. The projected span of this 160 m^2 kite is about 14 m

Compared to, e.g., Leading Edge Inflatable tube kites, the ram-air kite is only inflated with the actual dynamic pressure. At landing position the dynamic pressure is relatively low and it is possible to reef the kite. Beside the reefing system and its ground mounted actuator no other subsystems are needed to reduce the volume. A telescopic mast brings the reefed kite down from its landing position toward the stowing compartment.

Compared to its unfolded volume a textile wing can be packed in a much smaller space. For example, a 225 m^2 traction ram-air kite with a working load of 160 kN has an internal volume of about 200 m^3 (CAD geometry data). The packed volume is about 3 m^3 and smaller. This allows a relatively small stowing compartment and therefore a compact ground station. Replacing a kite can be done safely and quickly inside the shelter.

Fig. 32.6 A cone (tubing and textile mesh) close above the stowing hatch helps to further compress the kite volume. Below the cone the reefed kite has the right dimension to slide into the stowing compartment. When the hatch is closed the airborne system is inside the robust shelter and therefore safe. The components outside the shelter withstand all ambient conditions



For the stowing process the kite has to be as robust as possible. Sharp edges, abrasion, grease, and oil can harm the fabric. A fabric which is able to withstand numerous cycles of stowing and re-launching has to be comparably heavy, strong, and tear resistant. A heavy fabric contributes to the system weight, though. This works against the ability to start the system at light winds (see Sect. 32.6).

A way to use heavier fabric without gaining too much weight is to reduce the number of cells. When reducing this number the stress level in the fabric increases, but also the specific weight reduces because less fabric is consumed. To keep the same SWL the fabric has to be stronger. The weight gain due to the stronger and heavier fabric is almost the same as the reduction due to less material. The result is a slightly heavier kite featuring better mechanical robustness and UV resistance. A positive side effect of reducing the number of cells appeared to be an enhanced flight stability in static flight.

32.8 Take-off Position

An airborne system of an AWES needs a position where the launch begins. Depending on the launching principle the take-off position can either enable a free flight of the wing or being a position where the launching process with an additional energy starts. (see Sect. 32.5).

In case of the SkySails system the kite gets pulled out of the stowing compartment by the telescopic mast. The mast goes up until the de-reefing and take-off

height is reached. To enhance the reliability of the de-reefing process an adequate bridle handling is necessary. The reefing system ensures that all bridle lines have minimum slack during the hoisting process (see Fig. 32.5d). This prevents entangled lines which are a main reason for de-reefing problems.

Fig. 32.7 The system is ready for take-off when the kite is fully inflated, checked and the mast is in take-off position. A challenge is the kite check after inflation. An automated check for lines and canopy is difficult to develop. A possible solution is a camera which can be used by a human operator. Then a control center does not necessarily have to be at the same location as the AWES



32.9 Conclusion and Outlook

In this chapter we presented basic considerations on conceptual kite design in terms of overall system performance on the example of the SkySails marine system. The system fulfills the special requirements for the operation on a seagoing vessel. However, some aspects such as pulling direction and handling on the forecastle differ from an AWES for electrical power production.

As a result, the optimization of a 160 kN system led to a ram-air-inflatable kite with the following specifications:

- Nominal working load of 160 kN
- Flat size of 225 m²
- Kite weight with lines of 120 kg (without control pod and tether)
- 22 cells (see Fig. 32.5a)
- Fabric weight of slightly above 100 g/m²
- Compact shape with a projected aspect ratio lower than 2 (see Fig. 32.7)
- Glide ratio between 4 and 5
- Measured average steering power 0.5 kW (Figure eight flight at nominal load)

This design is far away from being an aerodynamically optimized solution. But as a kite for pulling cargo ships it leads to a higher overall system performance since it increases availability (in terms of flight time), mechanical robustness, and

propulsion force in ship direction. Comparisons with former systems with higher aerodynamic efficiency have shown that the gain in availability overcompensates the loss in aerodynamics. Numbers cannot easily be calculated. But since this kite design was established we were able to operate the system in real world conditions.

For other concepts and environments, e.g., land based AWESs, the emphasis on the single design topics can be very different. For instance, a land based platform does not move like the forecastle of a vessel and a continuously operated pumping-cycle system might be able to avoid many overload situations. But other restrictions will emerge which might reduce the system performance below initial theoretical optimum estimates.

The topic lifetime and the corresponding costs have not been covered explicitly as this is beyond the scope of this paper. We know that fatigue issues for textile wings and ropes are a limiting factor for economic success, a main part of the current development work is dedicated to this topic. So far the work on material lifetime does not conflict with the presented considerations for the conceptual kite design.

References

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