Chapter 31
Ram-air Wing Design Considerations for Airborne Wind Energy

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Abstract This chapter provides useful reference information for applications using a ram-air wing for wind energy production, from the perspective of a Ram-air parachute background. A limited set of design considerations, as relevant to AWE, are discussed, including wing design guidelines, wing control and handling, scaling, and life of the system. The material herein serves as a reference to an AWE developer or user to educate and inform of additional possibilities using Ram-air wings or to prevent costly and time consuming experiments.

31.1 Introduction

For AWE applications such as those with payout and retract cycles, or those with traction towing, Ram-air wings offer a suitable platform for the reasons that they can be designed to withstand the loads of the application, are relatively light, are steerable, and have a broad existing technical base in which to leverage.

It is useful to define common Ram-air wing components for use throughout the chapter. A Ram-air wing is normally composed of ribs, topskins, bottomskins, lines, and possibly risers. Fig. 31.1 depicts a schematic of a Ram-air wing. Ribs can be loaded if lines attach directly to them, or unloaded, if no lines are attached. Lines are identified by letters starting at A, and increment chordwise from Leading Edge (LE) to Trailing Edge (TE). Upper lines may cascade into lower lines which are often grouped onto risers. For maximum commonality to tube kites, risers are organized into left/right groups. Further subdivisions of risers such as front and rear on each side can provide some level of pitch control. More than two subdivisions are possible, but not shown.

When considering a Ram-air wing for AWE, there are some unique capabilities and limitations related to flying a completely flexible wing. In relative terms, Since

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the Ram-air wing typically has no rigid elements, it can deflect, twist, collapse and fold in ways that the second major flexible wing planform, the tube kite, cannot. Compared to a tube kite, Ram-air kites can be made much stronger and larger, maintain shape under extreme loads, fly in lighter winds, require no pre-inflation, and have no bladders to leak. Another major difference between Ram-air and tube kites is that line lengths determine the wing shape on the Ram-air kites (for fully bridled kites), where the inverse is true for tube kites; the wing shape, which is based on the tube geometry, determines the line lengths.

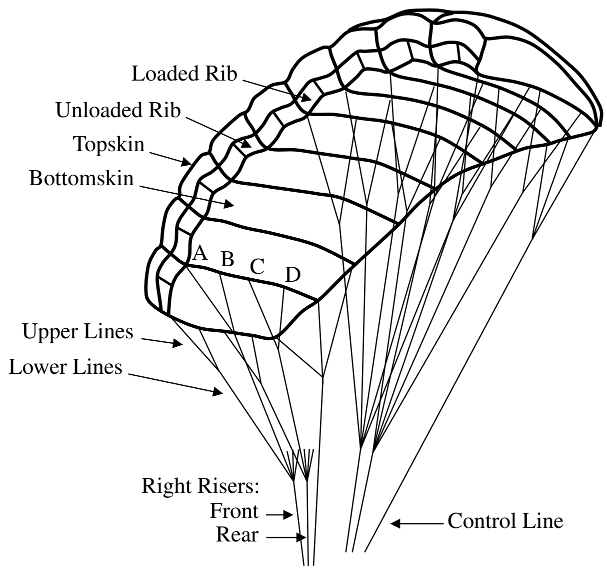

Fig. 31.1 Ram-Air Wing Components

The greatest limitation to Ram-air wings is the need for a stable planform, trim, and anhedral arc (discussed later) to maintain a taught bottomskin and topskin, robustness of flight, and ability to recover after any collapse. Tube kites have the distinct advantage of a much wider range of wing geometry options.

From the perspective of parachute systems design, an engineering discipline nearly a century old, the following useful Ram-air wing design considerations are discussed.

- Planform design options when designing to specification.
- Special considerations pertaining to large scale wings.
- An overview of Ram-air wing control and handling methods, which may assist in the wide range of controls needed for AWE applications.
- A case study into the calculation of the life of a system, which is a key factor in determining commercial viability.

Under these topics, the benefits and limitations of specific parachute concepts and ideas are extrapolated to possible AWE applications for use by an AWE developer or AWE user. However, in considering these benefits, the reader must be familiar with the fundamental differences between parachutes and tethered wings.

Parachutes operate with a fixed mass, are designed for high dynamic pressure environments and deployability, and have trajectories which respond primarily to gravity. AWE wings are operated with essentially an infinite mass, a fixed tether location, a tether load that varies greatly, and trajectories which respond primarily to wind. Further, the restriction of the tether creates a fixed volume in which the wing can operate, dependent on the wind direction and tether length. This fixed volume is generally referred to as the *wind window*, essentially a quarter of a sphere, as shown in Fig. 31.2. The radius of the sphere is the maximum tether length, and the slice planes are tangent to the earth and the plane that is perpendicular to the wind and which passes through the tether anchor point.

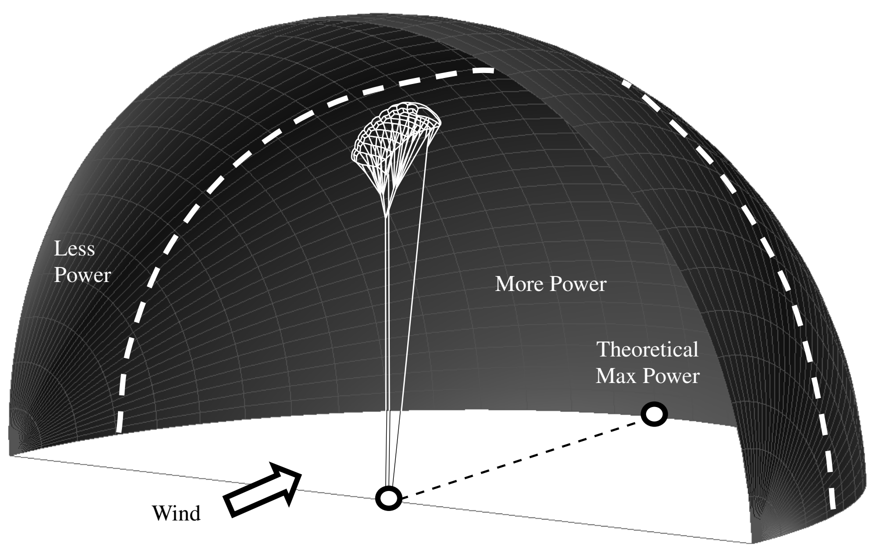

Fig. 31.2 Wind Window

Assuming a constant wind speed, a non-extending tether, and a massless wing and tether, the position directly downwind of the tether attachment point(s) represents the location where the AWE wing is flying the fastest, relative to a ground coordinate system. It is at this point where the wind speed is multiplied by the lift to drag ratio L/D to get the theoretical maximum crosswind velocity. Further information on equations of motion are presented in Loyd [19]. The region around this point can be considered the power zone and is at the back of the wind window. As the wing moves toward the edge of the wind window, the relative airspeed diminishes to eventually equal the wind speed, where the kite then maintains a static position.

At the onset of a Ram-air wing design effort, the AWE developer and or user should establish a list of performance requirements, which should include, at a minimum, wind range, desired flying load, maximum overload, operating volume, wing life, and system weight. Further areas should be defined, based on individual applications, such as depower performance, turning, and handling.

For brevity, full technical details are omitted with the expectation that the reader will explore references provided for more information.

31.2 Airfoil Selection

Airfoil selection, a 2D design input, plays an important role in the overall performance of a wing. However, this is not to undermine the implementation of an airfoil into a 3D wing where selection of aspect ratio, line schematic and trim, wingtip design, cell count, reinforcement structure, and more can have equal or greater impacts. The desired L/D of the wing should be based on an objective operating tether tension, planned operational wind conditions, and expected responsiveness in the control system. When possible, these conditions should be bounded, providing performance envelope limits and thus the driving Design Factors. The following subsections provide guidelines over important airfoil properties to aid in the design or selection of an adequate low-speed root airfoil.

For reference, Fig. 31.3 depicts the basic features of a Ram-air airfoil.

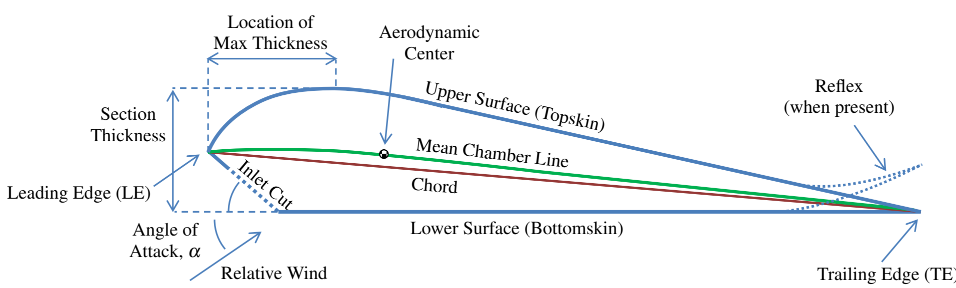

Fig. 31.3 Basic Parachute Ram-air Airfoil Diagram; Paraglider LE's are typically more rounded with a shallower inlet cut, made possible using stiffeners such as Mylar or flexible rods. Often, the lower surface has curvature upward near the inlet cut.

Lift and Drag At a desired tether tension, priority should be given for an airfoil with high lift coefficient, C_L, and a smooth transition to stall if possible. The drag coefficient, C_D, however, could be adjusted to moderate airspeed and provide ease of control. Approximate Reynolds Numbers for the broad range of AWE applications could be 750,000 to 25,000,000. The wide range is based on a generic range of wing chords from 3 to 7m at assumed airspeeds ranging from 5 to 50 m/s to account for all positions in the wind window. E.g. A 3 m chord wing flying in a 5 m/s wind at the edge of the wind window would be characterized by Re = 750,000. A 7 m chord wing with an L/D of 5 flying in a 10 m/s wind at the back of the wind window would be characterized by Re = 25,000,000. It would be desirable to select the wing based on the larger Re at the back of the wind window, as this is where power generation is at maximum potential. Ram-air parachute Reynolds Numbers vary somewhat less, from about 1,000,000 to 10,000,000.

Section Thickness As suggested in [21, Chap. 7], thicker sections typically yield a higher $C_{L,max}$, but make only small increases on C_D. The Ram-air parachute industry therefore often uses relatively thick 14 to 16% section thicknesses (thickness over chord) compared to general aviation.

Location of Maximum Thickness The location of maximum thickness for most Ram-air airfoils is forward of the quarter chord, making the airfoil a front loaded section. Using the established general guideline that the aerodynamic center is at $1/4$ chord, a maximum thickness forward of the $1/4$ chord results in a nose-up pitching moment corresponding to a positive moment coefficient. Accordingly, a maximum thickness aft of the aerodynamic center results in a nose-down moment and a negative moment coefficient. Both will fly, but the negative moment wing will be more susceptible to nose-under collapses. Negative moment coefficients are seen in some high L/D and high speed paragliding wings, however these wings often require additional nose structure. A wing has a positive moment if at the onset of a gust, the wing pitches down, and a negative moment, if at the onset of a gust, the wing pitches up. From a survey of various wings and applications, the most common location of maximum thicknesses of Ram-air airfoils is 18 to 21% of chord of constructed dimensions. AWE applications may accommodate thicknesses located further back since nose-under risk is primarily at the edge of the wind window, where the wing is expected to spend a minimum of operational time.

Camber Generally speaking, the addition of positive camber yields increased lift at a specific Angle of Attack (AOA) [21, Chap. 7]. Drag changes also exist, dependent on AOA. However, at common Ram-air wing AOA's, the combined effect is a higher L/D. Except for paragliders with targeted nose reinforcements, wings with reflex (negative camber at the TE), and a limited number of hobby kites, Ram-air wings have a flat bottom from leading edge cut to tail, resulting in significant positive camber.

Stability In-flight dynamic stability is desired across the range of AOA anticipated for a given AWE system. Stability can be quantified somewhat in terms of a minimum of center-of-pressure travel, a positive pitch moment, and a stagnation point location within a generous leading edge inlet cut (size of cut). These features reduce the frequency and severity of wing collapses. A wing with a wide center-of-pressure travel could result in more pitch forward and aft relative to the line confluence point when transitioning to different AOA's, making maneuvers more dynamic. A positive pitch moment is more tolerant to sudden changes in wind magnitude. A smaller inlet cut reduces the acceptable AOA range which results in the stagnation point lying in the inlet cut area.

Manufacturability Consideration should be given to make the wing easy to manufacture. Advanced airfoil designs may increase cost of manufacture for improvement in performance. Designs with additive nose structure and airfoils with extensive curved lengths should be traded against cost. A lower cost wing would have no reinforcement in the nose and minimized total curved length (topskin and bottomskin seams) making sewing operations quicker and higher quality.

Modifications The airfoil shape must be modified to be implemented into a 3D wing. In the Ram-air wing, the airfoil component is the rib, which requires hole provisions for cross venting of air between cells to equalize internal pressure (if desired), diagonal reinforcements to carry the load from the line attachment points to the topskin, added structure at the LE to maintain desired aerodynamic shaping, seam allowances to permit construction to the other wing components, and other design features for specific performance attributes.

Inlet Cut The selection of inlet size, angle, number of cells with cut, and location should be made to ensure the stagnation point is captured across the desired AOA range across the span of the wing. If the cut of inlet is too shallow, wrinkles result from stagnation pressure against the nose during flight. The topskin material often wraps over the leading edge cut improving the leading edge aerodynamics, however, at the compromise of a reduced inlet size and longer inflation time, which is not desirable for emergency parachute inflations. Common LE cut angles for parachute Ram-air airfoils range from 27 to 45 degrees from the lower surface. Refer to Fig. 31.3 for cut location.

Leading Edge Reinforcements The addition of reinforcements or leading edge shape enhancers can improve the aerodynamics of the normally blunt leading edge. These reinforcements also enhance recovery and inflation of restricted leading edge inlets by maintaining a presentation of the inlet to the anticipated airflow.

Reflex Reflex, as indicated in Fig. 31.3, is useful for tailless aircraft in providing stabilizing pitch moments. It is not required for Ram-air wings due to the bridled structure and pendulum center of gravity. However, it still provides increased positive pitch moment, resulting in increased stability in turbulence, and a potential delay in stall. Note, if the particular AWE application is nominally flying with trailing edge deflection in control lines, reflex is lost and thus not necessary in the cells used to steer.

It is noted that almost any airfoil could be made to fly. While different airfoils will have varying capabilities of speed, efficiency, controllability, and stability, the selection of an airfoil is second to the combined effects of the methods used to implement the airfoil into a 3D wing. Given this, it is recommended to not depart far form established Ram-air airfoils as development time and funds may be spent more effectively in other areas.

When extruding a 2D airfoil into a 3D wing, there is a loss in root airfoil performance. The maximum L/D of a root airfoil for a common parachute is greater than 20, and sometimes much more, depending on Re, and is based on an infinite wingspan. Adding necessary Ram-air wing characteristics, such as a finite wingspan (induced drag), crude inlet cut (reduced lift coefficient, increased drag coefficient), construction imperfections from sewing (reduction of area via shrinkage, distortion of patterns), anhedral arc (changes in lift vectors), presence of lines (parasitic drag), and other imperfections, as well as the differences between inflated shape vs. model shape (section thickness midway between ribs can be up to 50% thicker than ribs), it is not surprising to see 3D wing L/D as low as 2.5 to 3.0. Top-end paragliding wing L/D's claim to be just over 10, which can be attributed to a better optimization of the implementation process. A Leading Edge Inflatable (LEI) tube kite would be expected to retain closer to the 2D performance due to the superior inflated shape retention and reduced line count.

31.3 Planform Features

After having selected the root airfoil, extruding this to a wing planform involves the selection of a wing shape and aspect ratio. For the purposes of this section, the term planform is generalized, and meant to encompass wing shape and internal wing support structure. Wing shape can be characterized by aspect ratio, geometric shape, and wing sweep.

Aspect Ratio Aspect ratio AR is defined as the wingspan squared divided by the wing area. An AR greater than 1 infers a wingspan wider than the chord. Aspect ratio AR $\gg$ 1 infers a very wide wingspan and a very narrow chord, but there is no inference to wing shape or wing area. Fig. 31.4 depicts two planforms with AR = 3.

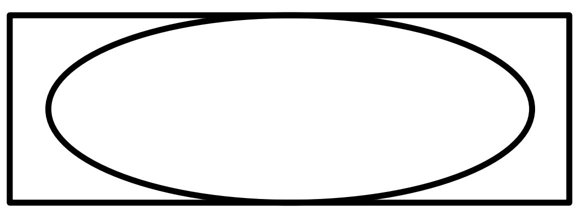

Fig. 31.4 Similar Aspect Ratio, Rectangle and Ellipse Shapes.

As a general physical rule, the higher the aspect ratio, the greater the system L/D and the closer to the performance of the root airfoil (which is normally based on infinite wingspans). This is the reason sailplanes have such large spans. However, anhedral arc, stability, and line length (and associated parasitic drag) will at some point, result in a point of diminishing returns when considering further increases in aspect ratio.

Roughly speaking, for the purposes of tethered wings for AWE applications, a nominal L/D can be achieved that is about equal to the AR, from an AR of about 2 to 7, subject to additional performance enhancements. Using a more elliptical planform shape, specialized low-vortex-drag wingtip designs, a low-drag line rigging scheme, LE shaping reinforcements, structural reinforcements to permit a reduced number of line attachments (such as 3-line paragliders), and other methods, can increase the L/D above the AR by a factor up to about 1.5. For example, a top-end paraglider with a constructed AR of 7 could achieve an L/D of 10.5 using many design enhancements.

Geometric Shape At one end of the wing shape spectrum is a rectangular shape where the chord is equal in length for every rib, and at the other end, an elliptical shape, where each rib can be a different length, if only slight. In between are polygon shapes with various levels of taper.

Parachutes do not have a sufficient cell count to graduate the ellipse shape across so few a number of panel patterns. Top-end parachutes normally have an elliptical base, but are truncated at the wingtips. Most top-end paragliders are nearly fully elliptical in shape. Fig. 31.5 illustrates generic rectangular (constant chord), polygonal (constant chord with tapered wingtips), semi-elliptical (variable chord), and elliptical planform shapes for identical wingspans. In each of these images the quarter chord position as a function of span forms a straight line.

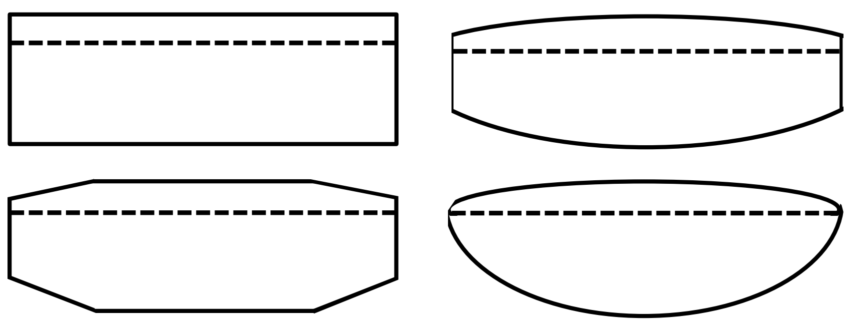

Fig. 31.5 Planform Shapes: Rectangular, Polygonal, Semi-elliptical and Fully Elliptical.

Wing Sweep Sweep is the shape characteristic defining how much the wingtips are angled backward or forward of the wing center cells. A generic swept elliptical wing is shown in Fig. 31.6. This, along with anhedral arc, are the two primary axes of rotation of a wing. Ram-air wings may have some very slight sweep backward or forward during construction to compensate for wingtip flying speeds different from the center cell flying speed. Wingtips may over or under-fly the wing center cells, depending on the combined effects of wingtip drag, different trims at the wingtips, and reduced wingtip drag area (smaller chord at wingtips). Some designs seek to reduce or eliminate sweep curvature of the quarter chord of the in-flight shape (as opposed to the constructed shape). Other designs deviate from this to reduce drag or to obtain a specific desired handling quality. Wing sweep used on Ram-air wings normally does not result in a concave leading edge or trailing edge, as stability issues would need to be addressed.

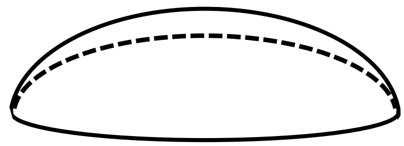

Fig. 31.6 Swept Elliptical Wing.

Internal Structure Another major design decision is what cell structure should be used. A cell is defined as the fabric between two adjacent ribs (and volume contained). Wing structures have been demonstrated that have between 0 to 3 unloaded ribs between loaded ribs. In addition to the selection of number of ribs, the addition of crossbracing may be desired. Crossbracing elements are effectively ribs constructed on diagonals, as visible in Fig. 31.7, where the use of which reduce the ballooning effect of an inflated Ram-air wing. The crossbracing diagonal ribs are load bearing ribs and need similar modifications to permit venting of air between cells to equalize pressure.

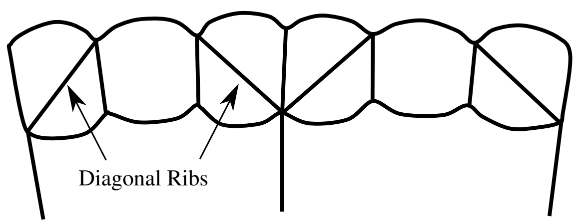

Fig. 31.7 Crossbracing Construction.

31.4 Anhedral Arc

For Ram-air wings, the anhedral arc is the curvature of the shape of the wing as looking from front or back. Figure 31.8 illustrates this geometric parameter for a parachute and a paraglider. Large radii make lightly anhedral arcs and small radii make highly anhedral arcs. A wing can have different radii at different span stations.

The arc of a wing can be a composite of multiple arcs and is designed, in conjunction with the line length and center of gravity (CG), for flying efficiency, performance in turning, and stability in turbulence, turning, and spiraling, among other handling features. Ram-air parachutes are rarely dihedral since the convex shaping provides no spanwise tension, necessary to keep the entire wing inflated. The internal pressure alone is not enough to hold a wing shape. Some powered paraglider

Fig. 31.8 Example Anhedral Arcs in a Parachute and Paraglider, Lightly and Highly Anhedral Arcs, Respectively.

wings have a slight dihedral in the very center of the wing due to very wide riser attachments and near constant length of the A-lines.

The anhedral angle metric, shown in Fig. 31.9, is a method to quantify the total anhedral arc of a wing. This is the angle between the horizon and a line between the bottom skin center cell (at A-line attachment) and the wing tip bottom skin. Calculations for anhedral arc impact to Ram-air wing performance can be found in [18].

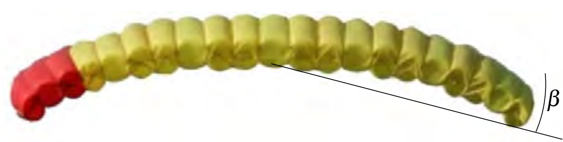

Fig. 31.9 Anhedral Angle.

31.4.1 Minimum Anhedral Arc

For parachutes, which must inflate from a freefalling condition, it is necessary that the wingtip lines should be approximately the same length as the center lines, or shorter, giving positive spanwise inflation characteristics. It is not uncommon to see Ram-air wings with the same length A-lines across all ribs. For a given wingspan, the minimum anhedral arc possible for a given Ram-air wing is then dependent on the line length which determines the anhedral arc radius. Longer lines give a larger radius and lower anhedral arc. This rule holds true for other Ram-air wing applications such as paragliding and kitesurfing, however in these applications, rarely is the minimum arc used.

On a given wing there is a trade in line drag versus lift working against the tether axis. Increased anhedral angle results in lift forces that contribute less to the tether tension, as shown in Fig. 31.10. There should be an optimal rigging length for each given application, however handling considerations may warrant alternative rigging schemes.

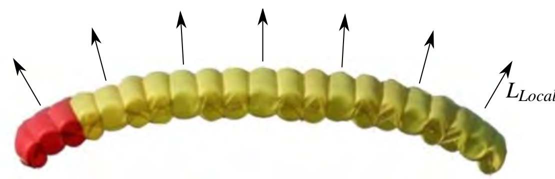

Fig. 31.10 Local Lift Vectors.

31.4.2 Maximum Anhedral Arc

Maximum arc is more difficult to define a limit. Notably, once the wingtips have curved into the tether direction, any further curvature would generate lift acting with the tether and working against the primary lift in the center of the wing. As the anhedral angle increases, lateral lifting forces increase, wing weight vs. tether tension also increases, and drag increases. A limit on maximum arc would thereby be based on design objectives, such as a desired lateral lift, or a particular turning responsiveness or handling quality.

Four-line Ram-air wings probably represent the most extreme case of anhedral arc. The shape of these wings are nearly semi-circular, with an approximate 45 degree anhedral angle.

31.4.3 Important Factors of Arc Design for AWE

As related to anhedral arcs for AWE applications, the following factors should be considered at a minimum.

Efficiency Objective of Wing Efficiency, such as the flying L/D is dependent upon many inputs, however, attention should be paid to the lightness of anhedral arc of the primary lifting section (inner third of the wing), the taper ratio at the wingtips, and the tightness of the local anhedral arc at the wingtips for reduction of and relocation of wingtip drag and effects of vortices. Changes in local radii of the anhedral should be smooth to prevent local sensitivities to turbulence, and AOA. A larger aspect ratio wing with more spanwise line attachment points provides for more arc options as well as greater control over the shape of the arc.

Lateral Lift Using control input, AWE Ram-air wing applications should be able to provide enough delta in lateral lift, left to right, to counter the weight of the wing at the edge of the wind window by the ground at the lowest operating wind speed.

Line Length Line lengths for bridles of AWE applications should be relatively short for reduced line drag. The wingtip A-lines should be the shortest lines of the wing. The center section length should be chosen based on amount of anhedral arc desired for the application. Lines that attach to ribs between the center cell and the wingtip cells can be longer than both the center lines and the wingtip lines, resulting in a flatter profile, and a more efficient use of the wing lifting surface acting against the tether. Parachutes normally have a ratio of A-line length to constructed span of 0.5 to 0.6, where constructed span is the wingtip to wingtip distance when laid flat.

Stability Since AWE implies a tether, the CG is therefore located very, very low below the wing, fixed in space. This results in a very stable wing with respect to pitch and roll. Using control lines, all turning is primarily due to yaw. Using control via a left right asymmetry in line length, yaw and roll are contributing factors. The stability characteristics of anhedral arc design matter greatly in applications of paragliding and parachutes, but due to the tether these are secondary design qualities for AWE and are not discussed further.

31.5 Line Rigging

Lines are needed on Ram-air wings to maintain a desired inflated shape, to hold trim, to allow a means of making control inputs, and to support the load generated by the wing. The rigging design should first take into account the line requirements or constraints.

Spanwise Constraints Achieving a smooth shape of the selected anhedral arc will require a minimum number of spanwise stations, at the discretion of the designer. The strength of materials used in the wing such as topskin and ribs will require the load to be supported at a calculated maximum spacing, usually based on area of wing supported. The spacing of lines is also restricted based on the need for a smooth LE. Typically, the cell width is less than the chord thickness, where narrower widths result in better wing shaping (less ballooning). This represents one of the underlying fundamental challenges in Ram-air wing design – balancing line usage against accuracy of leading edge shape. The number of cells between spanwise line stations (loaded ribs) is usually 1 or 2, and with crossbracing, 3 and sometimes 4.

Chordwise Constraints The spacing of lines chordwise must also adhere to the maximum spacing for structural reasons, but also for the necessary control over wing trim. Common to personnel parachutes or paragliders, there are usually A, B, C, D, and TE control lines. Trim can be maintained with just A, B, C, and TE control lines, but these wings carry greater risk (and consequences) of collapse or other flying anomalies, even with stiffening reinforcements.

Since lines create parasitic drag, they are a major factor in the system performance, such as L/D, and responsiveness, such as turning. The amount of drag slows the wings flight, and the location of the drag below the wing results in the wing overflying the lines (and tether) and consequently achieving a pitch down flying trim, which may or may not be surmountable using control inputs.

Key to obtaining an optimized lining arrangement is a compromise between line drag and the conflicting influences of strength requirements, resultant flying shape, and robustness to turbulence, aggressive flying maneuvers, or off-nominal flight events.

Line arrangements can be continuous, spanwise cascaded, streamwise cascaded (Fig. 31.1), or some combination of these. Continuous lines obviously have the greatest line drag area, but offer strength, damage tolerance, and convenience in rigging changes for early prototypes. Cascaded solutions offer reduced drag area and require stronger lower lines than upper lines, and are used on the majority of products available. Bergeron et al. [6] studied the aerodynamic effects of spanwise versus streamwise cascading, although for a parachute braided line with an oval section. This showed that the spanwise drag was additive, as expected, but that the streamwise had some improvements due to wake sharing, especially near the insertion point of the cascade.

Line rigging has been demonstrated with cascades ranging from 1:2 to 1:4, as well as sequential cascades resulting inupper, middle, and lower line groups. The joining of lines to risers should be selected to enable the desired control options.

A limit on the shortness of line lengths will be the compressive forces of the sine's of the load in adjacent lines attaching to the bottomskin, overcoming the internal pressure, and resulting in a poor wing shape. A typical cascade angle or cone angle between adjacent lines is less than 30 degrees. This is equivalent to a line-to-bottomskin angle of 15 degrees. Depending on sequential cascading, the angle may be greater.

Trim Ram-air wings are built with a trim that is nose down. In parachutes, the trim angle, or rigging angle, is the built-in angle of the bottomskin (assumed flat) and a horizontal plane, when the quarter-chord is directly over the CG tether, as seen in [18]. Generically, a flat trim, <5-6 degrees, is close to stall, while a steep trim, >12-13 will have low lift performance, and be more sensitive to frontal collapse nose under. The rigging angle is different from conventional AOA in that the AOA is normally measured from the chord line LE-to-TE where the rigging angle is measured from the lower surface line.

Twist Sometimes it is advantageous to have the wingtips with a different trim angle than the center section (also true for aircraft and hang gliders). Pitch down twist results in faster turning wingtips and a delayed stall of the wing tips (i.e. the center section stalls first). Pitch up twist can result in a stall sooner on the wingtips, especially during control inputs. Pitch up twist is a less frequently added feature. Alternatively, camber can be added to the wingtip sections to aerodynamically achieve the effect of physical trim twist without modifying line trim.

31.6 Scale

The Ram-air wing planform has been scaled and manipulated broadly across a range of applications. It has been used to make small toy kites and very large military delivery systems, from square to highly elliptical, from flat to highly anhedral, and more. Concerning AWE, scale is of interest in terms of size of wing and load generated. Special considerations when building Ram-air wings of increased capability include additional design features as a result of increased load and size, logistics in manufacturing, handling characteristics, and trimming and rigging. The scale of many Ram-air wing systems is being pushed aggressively by Precision Aerial Delivery Systems (PADS) [5] and AWE systems, such as Skysails, which is discussed in other chapters in this handbook.

Design Features for Large Ram-air Wings Fortunately, most construction techniques are scalable at the component level, substituting stronger materials or simply adding more stitches to withstand the necessary loads. Proven line spacing can be maintained in the larger sizes (i.e. same ratio of square meters per line), only the addition of more lines is required toaccommodate the increased wing area. Instead of A, B, C, D and control lines, one may need A through E, F, G, H, or more and control lines. The maximum spacing between loaded ribs is still determined by the topskin material strength – one can use the same material when scaling up, just by adding more cells and making cells longer. Weight can be saved by using lighter weight materials in the back $2/3$ of the topskin, since this area is stressed less.

Compared to parachutes, AWE wings can have a bottomskin material of a lower strength. Typical Ram-air parachutes must have a strong bottomskin to survive the relatively high dynamic pressure during opening (35-70 lb/ft^2, 171-342 kg/m^2). Compare this to the relatively low 1.25 lb/ft^2 (6.1 kg/m^2) at 20 knots when the bottomskin is presented broadside at the back of the wind window.

It is wise to consider additional reinforcements throughout the canopy to prevent small damage from propagating into catastrophic damage. Figure 31.11, shows the parachute system "Screamer", manufactured by Strong Enterprises, that has a rectangular shaped planform and which has demonstrated wing loadings of 15 lb/ft^2 (73 kg/m^2). The 78 m^2 system with 4535 kg suspended can be seen with spanwise reinforcements across the topskin to catch any runaway tears.

Fig. 31.11 Highly Loaded Screamer Ram-Air Wing (Photos by Steve Tavan, US Army).

Other features are required to prevent the sheer number of parts from making the system cumbersome. Most importantly is that modularity needs to be designed into the system. This will save time handling the system and cost when replacing as just the failed component must be exchanged. Attention should also be given to the design of confluence points where loads converge. Designs where components such as lines can be removed or replaced easily will benefit the system. Airborne Systems used a line attachment bar for the confluence where individual lines could be easily removed and replaced [11].

Manufacturability A Ram-air wing is conventionally manufactured using cutting tables and sewing machines. The fact that one of the heaviest wings ever manufactured weighed 600 kg was a challenge when one considers it needed to fit under a sewing machine. Modularity can help tremendously, and a maximum weight of about 115 kg for any one subassembly is recommended [11]. Custom material handling bins may be required to shuttle the Ram-air wing to the various manufacturing stations. Alternatively, the manufacturing stations can be moved to the canopy.

Controllability Large Ram-air wings typically have a reduced turning responsiveness than smaller-scaled similarly designed wings. One metric for quantifying this effect is the ratio of the mass of the wing plus the mass of the air inside the wing to the load. This term is commonly called the Mass Ratio, and is detailed in Lingard [18]. Lingard shows a method to analytically predict a symmetric deflection response based on this ratio, but omits the mass of the wing. For asymmetric deflection, where the mass of the wing is a contributor to the moment forces involved in turning, one should add the mass of the wing to the air mass for this calculation.

Ground Handling When testing or flying operationally, larger foils will have a greater logistical burden to recover and pack away. This may be a concern when, for example, winds increase beyond acceptable limits for the control unit and or wing. Safety should be considered as people will need to get in close proximity to collect the Ram-air wing. For this reason, it is desirable for the modular design to be something that can be disengaged readily. On the Megafly from Airborne Systems [11], a textile link between sections was severable with a knife which permitted expedited recovery.

When a wing needed to be recovered in moderate winds, the approach taken was to retract the control lines collapsing the canopy. However, due to the limited amount of trailing edge deflection on some of the wings, this was not always successful. Occasionally, a truck was needed to continue pulling the trailing edge into wind, collapsing the parachute. Pulling by hand was not an option. Line tension can be very high and the movement of the lines can be dangerous. A safer more automated system would be required for bridled Ram-air wings for AWE purposes, such as the Skysails mast concept, or some form of front riser release mechanism. Four-line Ram-air wings could be recovered using the approach of wing flagging, as demonstrated in [23].

Trimming and Rigging On large systems with many lines, the rigging schematic should be simple, as any one desired change (such as trim) will involve an extensive amount of repetitive operations. Cascading lines more than once is recommended, and cascading 1:4 has also been proven, such as when two adjacent spanwise lines plus two adjacent chordwise lines are joined, forming a pyramid. Often changes can be made in just the lower portion of the line resulting in a reduced number of operations for an uncomplicated trim change. It is useful to hang, either the canopy or the line confluence to perform initial assembly. This can require a very large space or a space with a very high ceiling. The lines of the Megafly were initially limited to the height of the Yuma Proving Ground parachute hanging tower, as this is where the systems were rigged and packed.

A prime example of the scaling process is documented nicely in the X-Fly family of Ram-air precision cargo delivery systems from Airborne Systems North America [9, 11]. The development originated as an Advanced Concept Technology Demonstrator research program from Natick Soldier Systems, whereby iteratively heavier weight requirements were levied (0.25 ton, 1 ton, 2.25 tons, 4.5 tons, 13.5 tons, and finally 19 tons). The wing sizes were 36 m^2, 102 m^2, 250 m^2, 350 m^2, 900 m^2, and 1,040 m^2, respectively. After a given weight could be reliably flown and landed precisely, a heavier requirement was set. The technology evolved to be modular, stackable, and scalable, using the root airfoil throughout. The 1,040 m^2 wing, made possible by modularity, was simply a swap-out of wider wingtips from the 900 m^2 wing. It is noted that as the wing became larger, a heavier wing loading was used.

A basic comparison of planform span and chord for some of the Airborne Systems sizes mentioned are shown in the shadow chart of Fig. 31.13.

Another large Ram-air wing scaling program was the NASA X-38, which had individual prototypes scaled and wind tunnel tested. While this program had less overall flight testing, iteration, and tolerance for failure, it performed significantly more analysis which has been documented extensively. A starter reference is a paper on the design and development of the parafoil recovery system [4].

31.7 Wing Control and Handling

For Ram-air wings, there are a wide range of control methods used to achieve desirable flight results. This section discusses conventional or other previously documented methods used for steering, depower, and launch and landing of Ram-air systems. Where appropriate, both fully bridled and Four-line Ram-air wing configurations will be detailed.

31.7.1 Steering

For AWE applications, since the tether restricts roll motion, all turns are achieved in yaw only. A yaw turn results primarily when there is a change in drag or drag-

Fig. 31.12 Various Airborne Systems X-fly Large Ram-Air Systems (Photos by Steve Tavan, US Army).

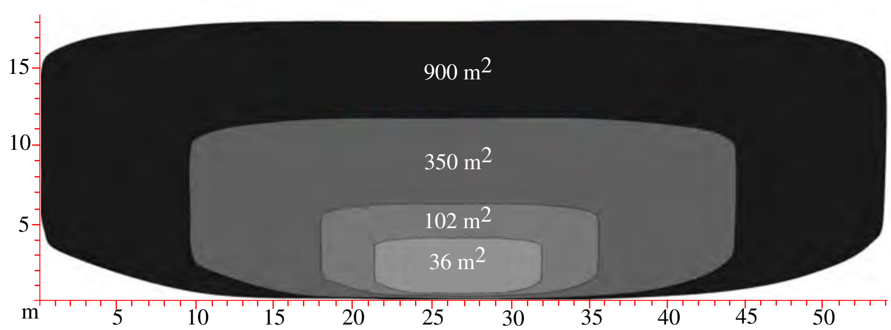

Fig. 31.13 Basic Planform Comparisons of Various Airborne Systems X-fly Ram-Air Wings.

due-to-lift symmetry, producing a moment force. Asymmetry could be generated by a physical change to just one half of the wing, such as trailing edge deflection, local pitch change, or controlled collapse (like big ears in paragliding), or use of a mechanism that disrupts the normal flow over or under the wing on one side, or a change in CG left right under the wing, to name a few.

Conventionally, steering is normally performed by one of two means; asymmetry in left/right riser lengths, a *riser shift*, or asymmetrical deflection of the trailing edge via a control line. Both options produce yaw effects and normally require a dedicated control mechanism.

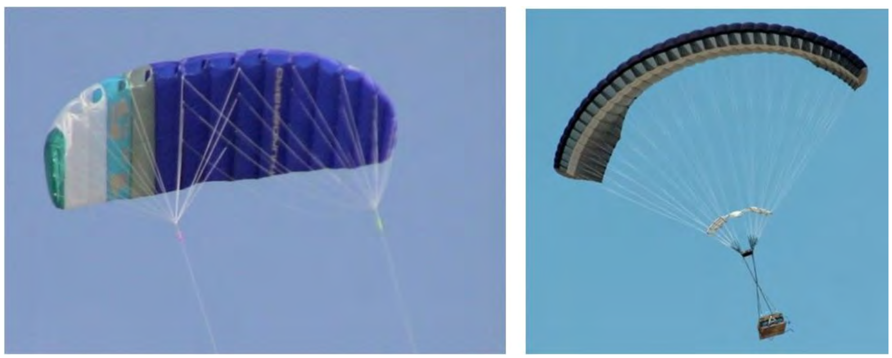

Fig. 31.14 Images of Steering via Left Right Asymmetry and Steering via Control Lines (Left Photo by Storm Dunker, Right Photo by Steve Tavan, US Army).

The control system for AWE can be either a suspended guidance unit or a ground guidance unit, whereby the actuation of the control inputs occur either in the air at a natural confluence point, or at a ground station, as indicated by the examples shown in Fig. 31.15. Steering control of the suspended guidance unit is very similar to that used for PADS, which is a relatively mature industry with worldwide production of large systems (> 100 m^2) in the thousands.

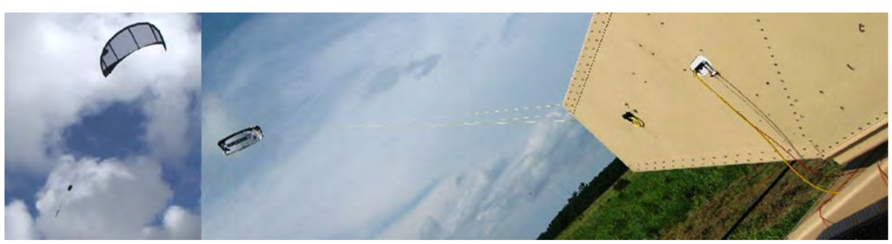

Fig. 31.15 Images of a Suspended Control Unit and a Ground-Based Control Unit (Left Photo by Delft University of Technology, Right Photo by Windlift LLC).

Whole riser shifts can consume a significant amount of energy without mechanical leverage or a spool with continuous coupling between left and right risers. Larger motors and additional structure may be required to effect such turns. Empirically, a riser shift will need to be able to overcome about 50% of the load experienced on the wing at the time of command. A half riser shift must be able to overcome about 15% of the load if it is the rear half of the riser or about 35% of the canopy load if the front half. It may, therefore, be more advantageous to use a spool with continuous coupling, where a delta load between the left right risers of just a few % can achieve turning. Distribution of lift is commonly about 65-85% on the forward half of the chord and 15-35% on the rear half, but ultimately depends on planform rigging and trim [1, 2].

Trailing edge deflection is a lower energy method to effect a turn in a given wing, especially on large wings. Pulling down on a control line will increase drag on that side of the wing, simultaneously effecting a positive local angle of attack (AOA) change. Oversimplifying, the additional drag created causes the non-deflected side to over-fly the deflected side, resulting in a turn. Yaw occurs, and roll will as well, if the system were untethered, as on PADS. The amount of trailing edge deflection, and the distance from the canopy center, can be thought of as a moment force about the canopy mid-section.

An even lower energy method to effect turning is using top skin bleed-air actuators, similar to the upper spoilers shown in Fig. 31.16 in the following section, except deflected asymmetrically [8]. This method required inputs of only a few kg.

On larger systems that use control lines, it can be seen that only a small section of the trailing edge is deflected at the wingtip, providing an efficient moment force for turning Fig. 31.14. If turn rate is not a critical performance parameter, one could optimize guidance unit weight by reducing the strength capability of the control system, which is important if it is a suspended guidance unit.

31.7.2 Depower Options

Early AWE system development has experimented with Ram-air wings as a source of generating energy from wind and have found difficulty in the retraction phase as the wing has limitations to the ability to depower. This section seeks to present perceived limits of Ram-air wing depower to either assist in optimizing a retraction cycle or to prevent needless attempts of Ram-air wing depower.

31.7.2.1 Glide Control Changes

In recent years, the parachute industry has investigated wider L/D ranges for a fully bridled Ram-air wings, especially low end L/D, in pursuit of accurate landings by unmanned cargo delivery systems. Lessons from these investigations could provide some improvements in Ram-air wing depower, which will need low end glide performance to reduce the retraction cycle burden. In the methods of glide modulation mentioned below, the addition of an electro-mechanical control system has been required, adding weight and complexity to the system.

Gavrilovski et al. [14] at the Georgia Institute of Technology found that they could extend the controllable glide range for a Ram-air wing with a nominal L/D of 3.8 down to 1.75 with the implementation of topskin spoilers (Fig. 31.16). They also found that with a bottomskin spoiler, they could expand the positive end from 3.8 to 4.3, before stalling, which resulted in a drop to about 1.25.

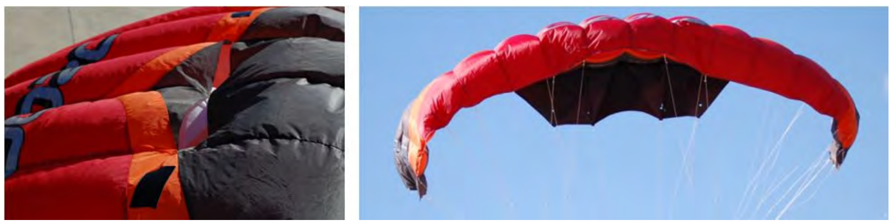

Fig. 31.16 Topskin and Bottomskin Spoilers Used to Explore Glide Modulation.

They also found with a rigging scheme that allowed trim modulation via motor, a range in glide was possible from 2.5 to 4.9 on a wing with 3.4 aspect ratio and 2.9 to 4.4 for a wing with 2.8 aspect ratio [25]. At a pitch-down attitude, there is serious risk in a frontal collapse as the stagnation point moves too high on the nose of the Ram-air wing. Therefore, a bottom-end limit was not investigated in this study. One should consider handling and gust robustness if pitch modulation is applied to an AWE application. This control method is similar to trim tabs and speed bars on paragliding, however, since paraglider wings are much more efficient and have a higher L/D, the low end L/D performance is still significant, even if similar max to min L/D ratio were possible. As a further note, APCO Aviation have experimented with a one-way valve located at the LE, called the HIT Valve, which may permit the stagnation point to travel further around the nose and allow even steeper angles of attack.

A US Army Precision Aerial Delivery System, AccuGlide, is another system that has adaptive trim [7]. This system operates with a mechanically controlled trim angle of -5 to -17 degrees, similar in functionality to paraglider trim tabs and foot accelerators. Using a combination of conventional Ram-air wing brakes and the mentioned trim control, the stable glide range for this 1.8 aspect ratio canopy is from 1.5 to 2.7, however, a quasi-stable deep sink mode is achieved for up to 10 seconds, where the L/D can be reduced to 0.2 – 0.3. After this time, a full stall is realized. Depending on the rate of tail deflection and angle of incidence change, the entry into stall can be less dynamic.

However, for AWE applications with extension and retraction cycles, one of the greatest challenges is to reduce lift significantly while adding minimum drag or, more preferably, reducing drag. Depending on the application, pitch change alone may not achieve the desired return cycle power consumptions.

31.7.2.2 Stall / Collapse

An unlikely method for depower is a stall or collapse of the wing in a manner which can be controlled and recovered after a desired retract phase. This has been attempted with a Ram-air Four-line wing by KiteGen, whereby one half of the kite had all tension removed, resulting in the Ram-air wing becoming deflated and flapping like a flag. For recovery, the flagging side would be re-tensioned and the wing would begin flying again. Among other things, challenges would exist in flagging wear, maintaining line continuity, heading, and positive pressures during retract, and timing of reversal from retract operation to traction operation. Delft University of Technology employs a similar technique in landing their 50 m^2 Ram-air wing [23]. See Fig. 31.17 for reference.

Within skydiving, a canopy style, termed Accuracy, is designed to be very docile and controllable for the purpose of low speed precision maneuverability. These canopies have a very thick section ($> 16\%$) and low aspect ratio (< 2.0), relative to other skydiving canopies, as shown in Fig. 31.18. What is unique about these planforms, is that in the stalled condition, the bottom skin remains an inflated bluff body, as if a single surface round parachute. Lift is nearly lost and drag is the paramount balancing force remaining. In this stalled state, the parachute is still maneuverable using slip (Newtonian glide) forward or backward, as desired, by adding less or more TE control input, respectively. The resultant glide in this configuration is more Newtonian than Bernoulli, in that the action of air mass deflection causes the reaction of glide in the parachute, rather than differences in pressure generating a net lift (inviscid flow).

Naturally, the descent rate of the skydiver increases in this condition, however it is not intended to land in this mode. Also common to this canopy are oversized vanes and stabilizers, fabric panels protruding down from the bottom skin, which purportedly help maintain heading during stall and near stall maneuvers. The AccuGlide system mentioned previously uses such a canopy, however this system does not employ these full stall techniques. An AWE retraction cycle utilizing this stall would not result in the wing overflying the ground station.

On wider aspect ratios, approximately ratios > 2.0, wingtip convergence occurs (or attempts to occur) and the bottom skin does not remain stably inflated. Wingtip convergence can be described as when the left and right wingtips attempt to make contact behind the wing. This is true for both control line stalls and rear riser stalls, however, the effect is more pronounced with the control line stalls [10]. Both of these configurations have a loss of primary lift and drag becomes the dominant force.

In the control line stall image in Fig. 31.19, the pilot chute used to deploy the parachute is actually forward of the nose, indicating flight in the reverse direction.

Fig. 31.17 Flagging of a Four-line Ram-Air wing, Mid-process (Photo by Delft University of Technology).

Presumably a paragliding style full B-line stall is possible via a guidance unit, but it may require paraglider-like aspect ratios and extensive customized rigging. Fig. 31.20 shows Brad Gunnuscio of the US Paragliding Team demonstrating the B-line stall with good heading control and stable behavior [15].

All stalls illustrated by the various references were intentional, and required no reserve parachute by the pilot. In this sense, the entry and exit from stall are controllable. In relative order of controllability during stall, from both observation and first-hand experience, they are Accuracy, B-line, rear riser, and control line. Further, the latter two stalls types are the most sensitive due to the fact that they are typically performed at much higher wingloadings. Lower wingloading would reduce the entry and recovery dynamics.

Fig. 31.18 Classical Accuracy Canopy (Photo by US Army).

Fig. 31.19 Images of Rear-Riser Stall (left) and Control Line Stall (right) in a Parachute (Photos Niklas Daniel).

Fig. 31.20 Demonstration of a B-Line Stall in a Paraglider

31.7.2.3 Reduced Projected Area

Yet another way of reducing lift of a wing in the tether direction is to reduce the projected area via some mechanism or rigging solution. Flysurfer Ram-air wings operate in such a way, pulling the wingtips down and inward [13]. The surface area of the kite does not change significantly, rather the change in shape of the wing results in less of the lifting forces acting in the tether direction. Under this concept, only small changes in total wing drag occur since the wing cross-sectional area changes are minimal.

Fig. 31.21 Flysurfer Change in Projected Area (Photo Copyright by Flysurfer).

The Fastwing system, also a PADS, changes projected area incrementally in an accordion like fashion, to inflate in stages, but does not contract [26]. They have, however, demonstrated that flight of their wing was stable, predictable, and repeatable, spurning promise that accordion controlled span is theoretically possible. Under this concept, both net lift and drag are reduced. Assuming a constant AOA across the wing (which is not likely the case), the glide would remain approximately the same in both contracted and expanded configurations. Note some lines would go loose if the contracted cells have different trim.

Another form of reduced projected area, practiced in paragliding, is the big-ears maneuver. Actuated by pulling down on the outermost A lines, this maneuver collapses the outer wingtip sections, approximately 30% of the wing in total. It is noted that trailing edge deflection controls would be largely disabled during this flight mode.

31.7.2.4 Increased AOA range

Another option for increased depower is by designing-in an increased AOA range of a ram-air wing by selection of a symmetrical airfoil with shallow pitch / trim angle. A research project successfully achieved a high airspeed / low lift flight in this configuration. For this application, an air inlet cut was made at near 90 degrees to the chord, cutting off the tip. This wing was capable of approximately 45 m/s kited behind a small vehicle.

31.8 Designing for the Life of the System

An AWE system using a Ram-air wing must be able to prove commercial viability which dictates that a wing must have a minimum life, presumably in flight hours. The life of a system is a function of the operating conditions, storage conditions, time, materials, and wear limitations. Assume manufacturing quality is perfect, the life of a system would be determined by the point when the first subcomponent fails to perform its intended purpose. For example, when the topskin material has lost enough strength due to a combination of exposure to the elements and fatigue that it tears during an above nominal loading event such as a high gust, launch, or other flying load anomaly.

The wing life for a known wing can be calculated in the following general manner. A stress analysis should be performed to identify the maximum load in each individual component type, i.e. rib, topskin, bottomskin, each type of reinforcement, suspension line, etc. Following this, the applicable Load and Degradation Factors for the given application should be identified. Values for the factors should then be determined by reference or test, making special note of which are time or exposure dependent.

The wing life in operating hours then equals the time when first time-dependent Margin Of Safety (MOS) becomes negative.

Where:

$$MOS = \frac{\text{Material Strength}}{\text{Component Load}} \times \frac{1}{\text{Design Factor}} - 1$$

Where:

$$DesignFactor = \frac{\text{Load Factor}_n \times \text{Load Factor}_{n+1}}{\text{Degradation Factor}_n \times \text{Degradation Factor}_{n+1}}$$

Any number of factors n can be used. However, a basic set of applicable AWE Degradation Factors could include Joint Efficiency, Abrasion (with itself / ground / obstacles), Fatigue (bending, stretching, fluttering, aging material), Moisture and Ultraviolet (UV) Exposure. Additional factors may be needed depending on specifics of an individual application.

It is highly recommend, when funding and schedule afford, to collect values for all factors from testing dedicated for this purpose. Generalizations exist for many factors, but experience typically shows variations are larger than expected.

Applicable AWE Load Factors could be Safety Factors, Dynamic Load Factors, Asymmetrical Load Factors, and Statistical Deviation Factors.

31.8.1 Example Life Calculation

For the purposes of an example life calculation, consider the oversimplified case of a two component wing (topskin and suspension lines). Note this example is not representative of any AWE system. In this example, the topskin is Nylon 6/6 (one of the two main classes of Nylon textiles) and the suspension lines are High Modulus Polyethylene (HMPE). Nylon is used in this example as there is a wide range of data available, which helps in producing a more realistic result. Table 1 presents a conservative set of Degradation Factors from parachute applications [17], supplemented with additional considerations for AWE. Specifically, for AWE, UV Exposure is added, and estimates for Abrasion, Fatigue, and UV are given as a function of time. UV, Abrasion, and Fatigue values should be based on actual values for a given material, when possible. Since time of year, location, and weather have significant impacts to UV exposure, UV impacts should be collected using standardized accelerated weather tests, such as American Society for Testing and Materials (ASTM) G155 [24] or International Organization for Standardization (ISO) 4892 [20].

Component	Raw Strength	Material	Joint Efficiency	Abrasion	Fatigue	Moisture	UV EXposure
Topskin	175 N/cm	Nylon 6/6	0.80	0.90	0.90	0.95	0.70
	Est. Operating Hours			500	250		1080
Suspension Line	4,448 N	HMPE	0.80	0.90	0.75	1.00	0.80
	Est. Operating Hours			500	1000		1050

Table 31.1 Example Set of Degradation Factors.

In the table above, Nylon UV data comes from the study Age-Life Prediction of Nylon 6/6 Parachute Materials [12] and assumed 10 hrs / day sunlight, HMPE UV data is from [27], and HMPE fatigue data comes from a Barry Cord cycles test [3] with the assumption of five figure-eight maneuvers per minute (10 turns/cycles).

Many strength loss measurements have been published for materials common to parachutes and AWE, and they vary significantly. One study had found Nylon to degrade (without UV inhibitors) by 50% in just over 1 week exposure [22], which is an extreme case. This reinforces the need to perform individual testing. Most time dependent values will vary significantly with weave type, denier, resin and UV inhibitors, and thickness of woven good. Kenney and Abbott [16] illustrates a variance in strength degradation of the same base material as a result of weave thickness, which after 200 hours of accelerated weather, showed a 14% strength loss on the thinnest material tested, but just a 1.2% loss on the thickest material tested.

Taking the above material example further, the load factors and an arbitrary component load are showcased in Table 31.2.

The Safety Factor and Dynamic Load Factor are taken from [17], while the Asymmetric Factor is an estimate. The Statistical Factor is omitted at this time.

Component	Raw Strength	Material	Safety Factor	Dynamic Factor	Asymetric Factor	Example Component Load
Topskin	175 N/cm	Nylon 6/6	1.50	1.10	1.20	52 N/cm
Suspension Line	4,448 N	HMPE	1.50	1.10	1.20	1,334

Table 31.2 Example Component Load Factors.

Using the load factors and the time variant degradation values with assumed linear trend (for simplicity), the relationship of Design Factor with time is achieved, as shown for the Suspension Line example in Fig. 31.22 below.

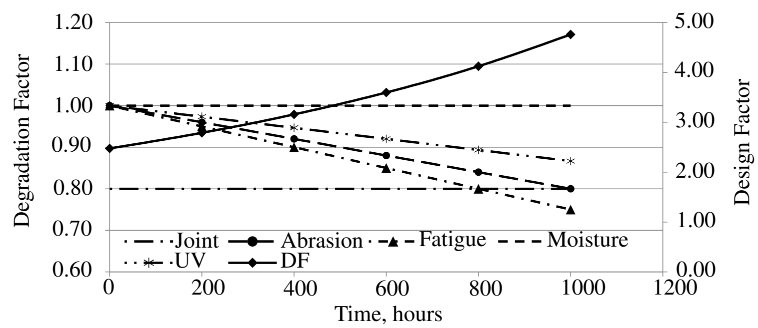

Fig. 31.22 Example of Suspension Line Degradation Factors and Resultant Design Factor (DF).

Comparing the MOS's for both example materials, the life of the example wing is then 265 hours as shown in Fig. 31.23.

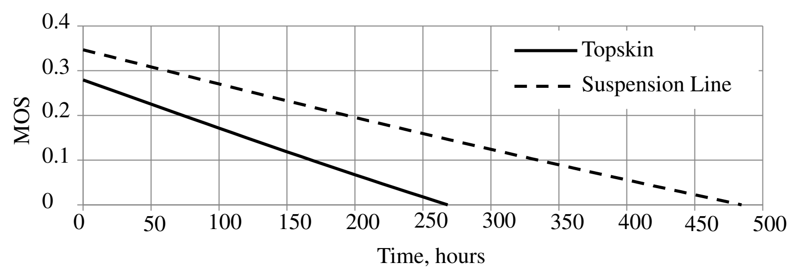

Fig. 31.23 Example Ram-Air Wing Margins of Safety (MOS).

A detailed life analysis review of a given existing wing could reveal the weakest links in the system, if not already known, highlighting the components or areas most needing improvement. Alternatively, if the fault tolerance for an application is moderate, a wing life may be reached when a certain number of components fail, or when a key critical component fails.

31.9 Conclusion

This chapter has provided an overview of Ram-air wing design and handling tailored to anticipated AWE system needs from a parachute design perspective, as well as an analytical method to evaluate system life for the purposes of determining commercial viability. This material should serve as a reference to an AWE developer or user to educate and inform of additional possibilities using Ram-air wings or to prevent costly and time consuming experiments. Numerous references have been provided with the intent that the reader will investigate further any specific content of interest. Attention should be given, however, to investigate if any in-life patents exist for any of the concepts presented, if intended to use one in any AWE application.

With any Ram-air wing, there are numerous dimensional discrepancies present resulting from the construction process, such as shrinkage and stiffness, which ensures that a constructed wing does not exactly meet the CAD form. Further, the resultant wing shape from flight, with internal pressure and surface tension added, also differs from the base CAD form. For these reasons, iterations of line trim and possibly wing shaping are likely required to meet a set of requirements. Accordingly, the development of a Ram-air wing for any AWE system is an important necessary process. While the AWE machine design drives the wing performance requirements, the wing often needs more design emphasis than normally given, especially when considering budget and development effort.

It is recommended that a developer plan for three iterations minimum of Ram-air wing design to meet a new requirement specification, which could be line changes, wing shape changes, or both. Development should also include seam an joint testing for structural suitability and material endurance testing for calculating system life.

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