Preliminary design of a high-altitude kite

A flexible membrane kite section at various wind speeds

This is the third paper in a series that began with one titled *A flexible membrane kite section at high and low altitudes*. That paper proposed a kite whose surface is an impermeable flexible sheet, of nylon, say. The sheet is secured at its leading and trailing edges, but it is not stretched by the supports at those edges. Nor is the shape of the sheet determined by ribs. The sheet is left loose and its shape is determined by the airflow. In the first paper, I examined the shape taken on by the free-flying surface, or membrane, when in flight at sea level and at 15,000 feet. To add some realism to the endeavour, I simulated the aerodynamics including a leading edge consisting of a transverse circular tube which formed the leading edge and would be the principal spanwise structural member of the wing.

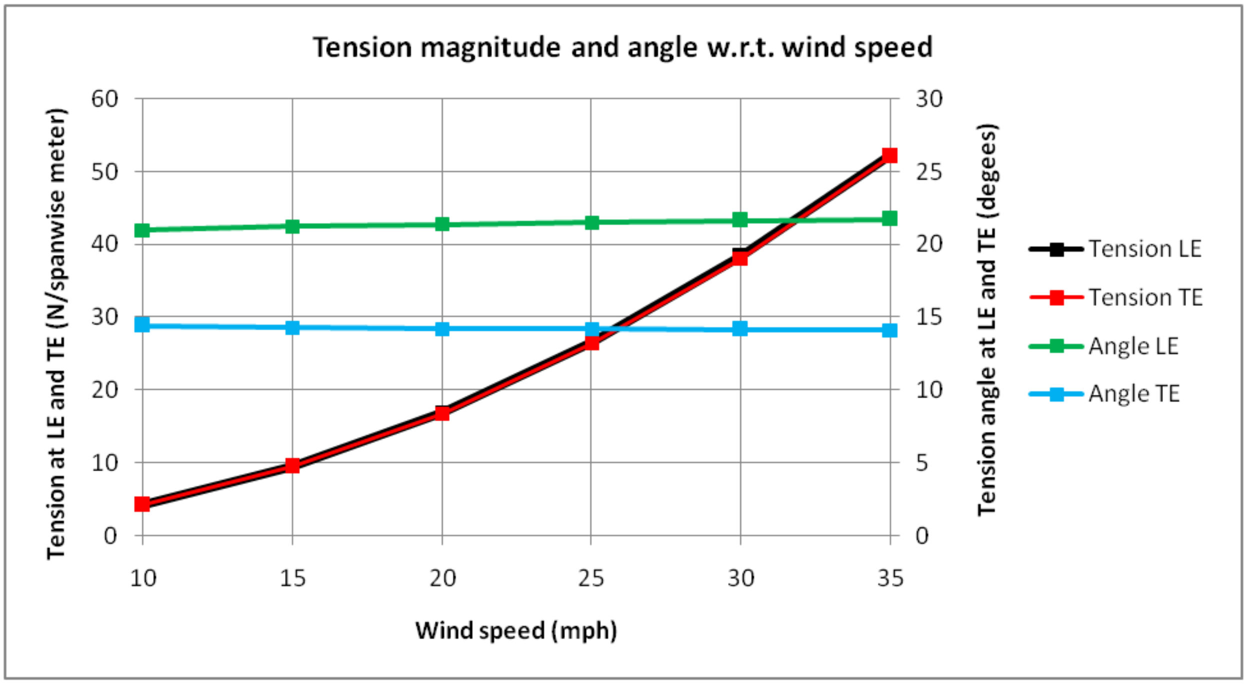
In a subsequent paper titled *A flexible membrane kite section at various angles of attack*, I examined the section through a range of angles of attack at both altitudes. The concept seems promising. There are no signs that the section is unstable.

In this, the third paper, I will examine the effect of wind speed on the shape of the membrane and aerodynamic forces we can expect.

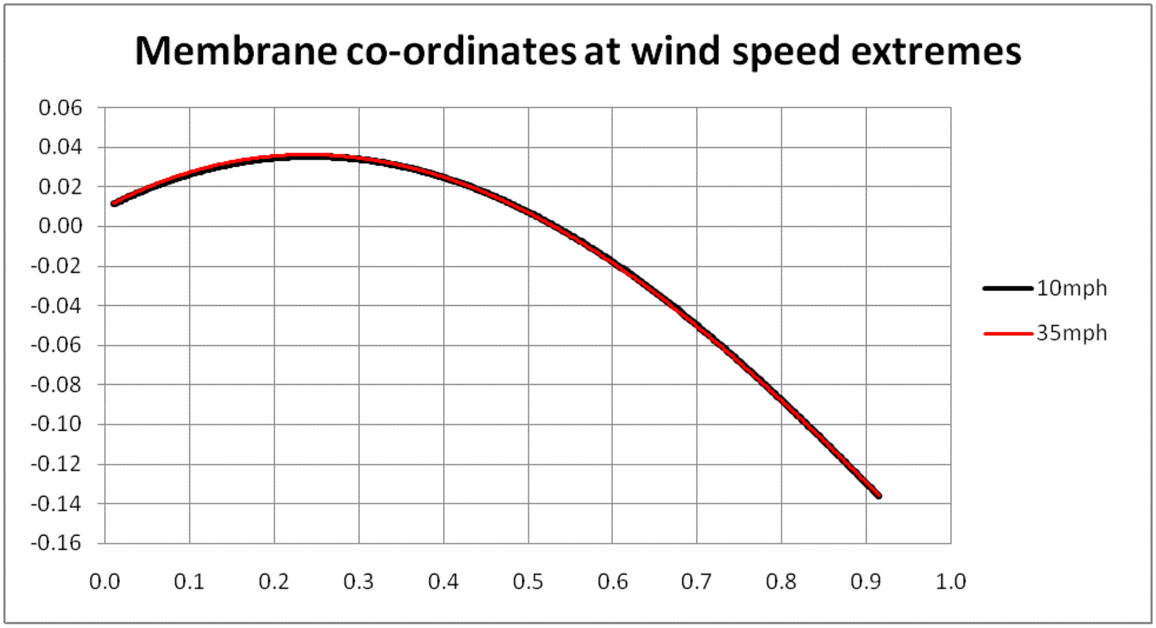
In all of the aerodynamic simulations so far, the section has been subjected to a two-dimensional analysis, and all quantities expressed "per meter of span". That will be the basis for the analysis in this paper, too. Many of the numerical examples so far have been based on the following parameters:

- Angle of attack 9°
- Wind speed 20 mph
- Altitude 15,000 feet

I will use the 9° angle of attack and the characteristics of air at 15,000 feet as the starting point for this study. The following graph shows how the magnitude of the tension, and the angle the tension vector makes with respect to the reference chord, at both the leading and trailing edges of the free-flying part of the membrane, change as the wind speed changes.

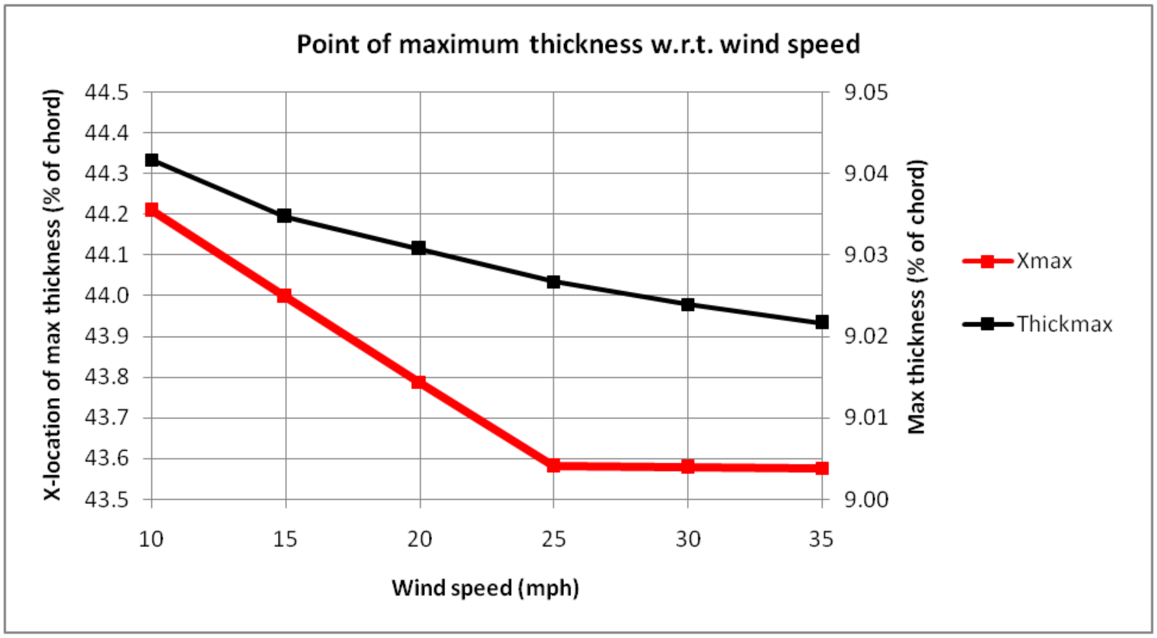


The tension in the membrane varies aggressively with the wind speed, perhaps something like the square of the wind speed. The angles which the membrane makes with the reference chord show very little dependence on wind speed. This is a clue that the shape of the membrane is largely independent of the wind speed. The following graph illustrates this. It shows the actual shape of the membrane at the two extreme wind speeds, 10 mph and 35 mph.



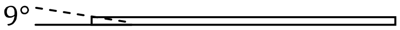
The vertical and horizontal scales are not laid out at the same scale, so the membrane seems more highly curved than it really is. The horizontal axis extends through a range of one meter; the vertical axis covers only 20 centimeters. The two shapes shown are those for the highest and lowest wind speeds examined. Even so, the shapes are very close. In fact, to make them distinguishable on the graph, I had to make the black line (10 mph) thicker so that it would stand out behind the red line (35 mph).

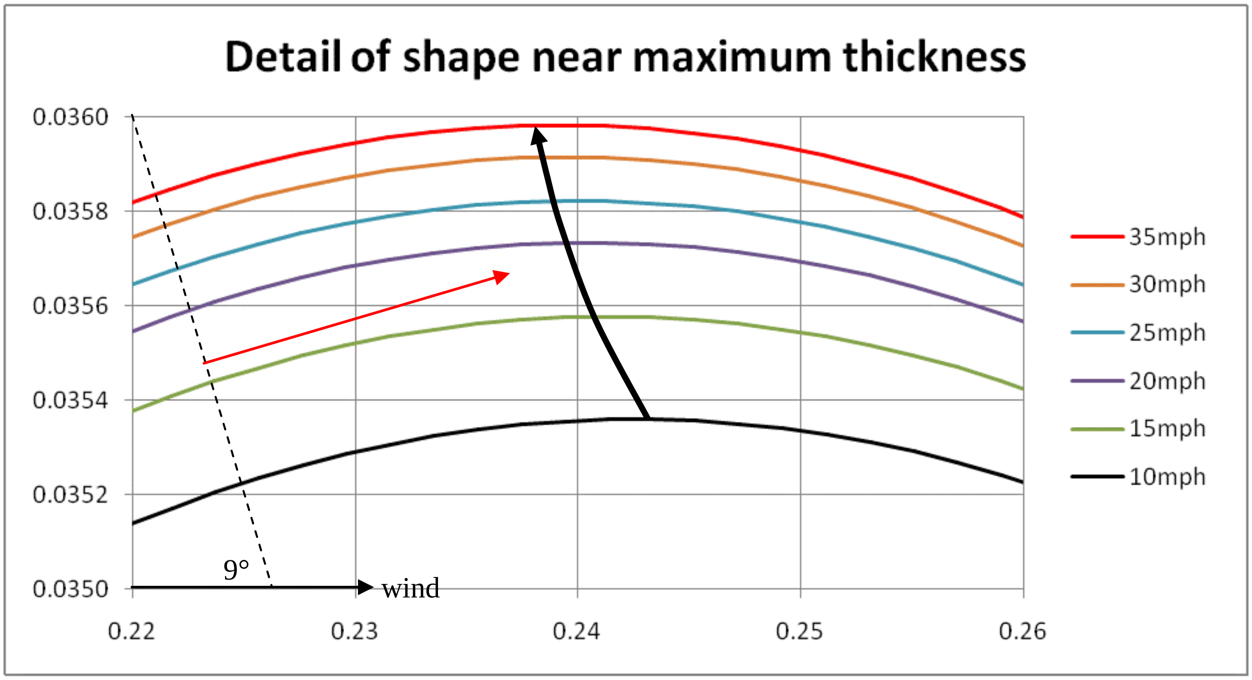
Two important characteristics used to compare shapes like these are the maximum amount of camber and the location of the point of maximum camber along the reference chord. In this study, I have been calling these two quantities the maximum thickness and the point of maximum thickness. The following graph shows how they vary as the wind speed varies. Each distance is expressed as a fraction of the length of the reference chord, which is approximately one meter.



The maximum thickness is approximately 9% of the reference chord length, with an extremely small tendency to decrease with increasing wind speed. The point of maximum thickness is at about 44% of chord. A little more noticeably, the point of maximum thickness moves forward as the wind speed increases. This is counter-intuitive – one would think that a higher wind speed would "blow" the point of maximum thickness towards the rear. The top-versus-bottom pressure differential, and the constraint imposed by the increasing tension in the membrane as the wind speed increases, conspire to draw the point of maximum thickness forwards. Indeed, the entire thought that the point of maximum thickness would be forwards from the midpoint of the chord may seem counter-intuitive, but it is so.

I was troubled by the discontinuity which occurs at a wind speed of 25 mph. What happens to stop the forward creep of the point of maximum thickness? I looked more closely at the membrane near the point of maximum thickness. The following figure shows a very small region of the membrane. The axes extend through a range of four centimeters in the horizontal direction and one millimeter in the vertical direction. At a 1:1 scale with respect to the size of this page, the region shown in the graph is only this big:



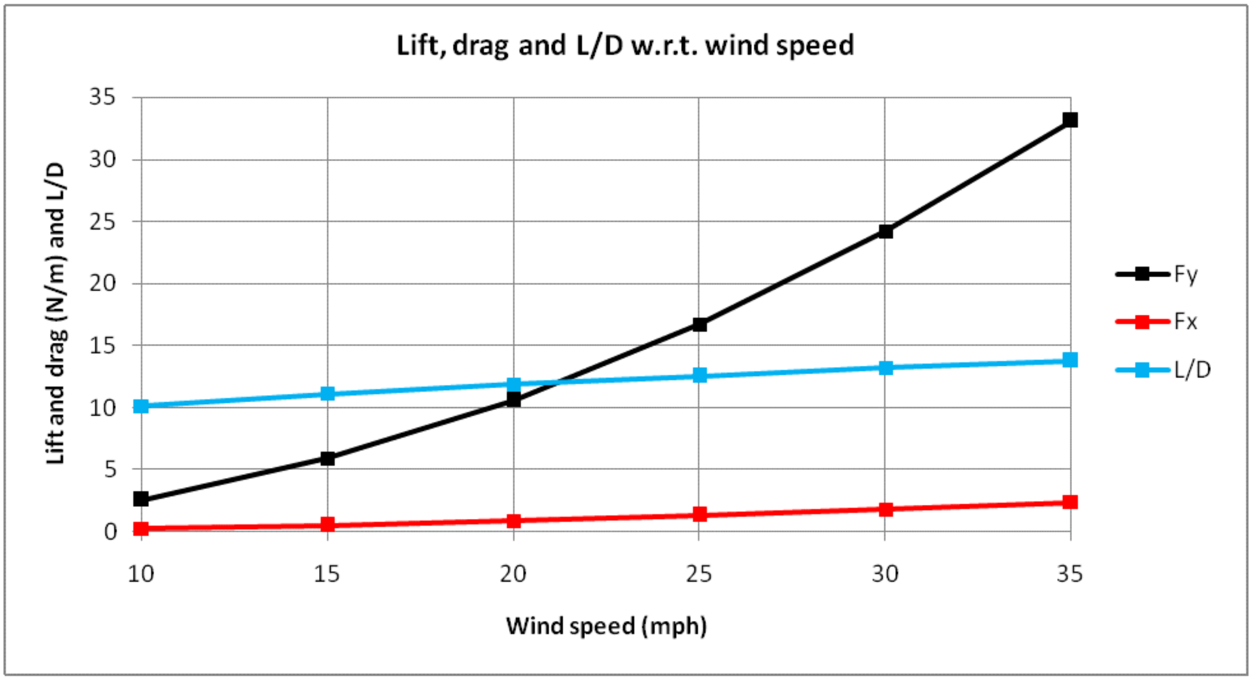


I have used a heavy black arrow to connect the points at which the membrane reaches its "highest" point at the different wind speed. "Highest" needs to be defined. The plot shows the shape of the membrane in the OpenFoam frame of reference, that is, with the horizontal axis being parallel to the ground and to the prevailing wind speed. Since the kite is flying at a 9° angle of attack, the reference chord is actually inclined to the horizontal axis. It slopes downwards from the upper left to the lower right. In the small rectangle depicted above the plot, which shows the plot area at 1:1 scale, the reference chord is the dotted line. Since that rectangle is rendered to scale, the 9° angle of attack appears to be correct.

The reference chord is also shown as a dotted line in the graph. Since the scale of the vertical axis is so much smaller than the scale of the horizontal axis, the 9° angle of attack appears to be greatly exaggerated. The thin red arrow shows the direction in which the maximum thickness is measured; this red arrow is perpendicular to the reference chord.

With this explanation, it is now easer to see why the maximum thickness is the same for the three highest wind speeds. Yes, it is true that the membrane's shape becomes more peaked as the wind speed rises. It is also true that the point of maximum thickness continues to more forward as the wind speed rises. But the geometry is such that the perpendicular distance from the reference chord to the point on the surface with maximum thickness does not appear to change at all. This explains the apparent discontinuity.

The following graph shows how the total lift, drag and lift-to-drag ratio change with the wind speed.



The total lift increases with wind speed at very close to the quadratic rate predicted by theory. As an example, compare the lift at 30 mph with that at 15 mph:

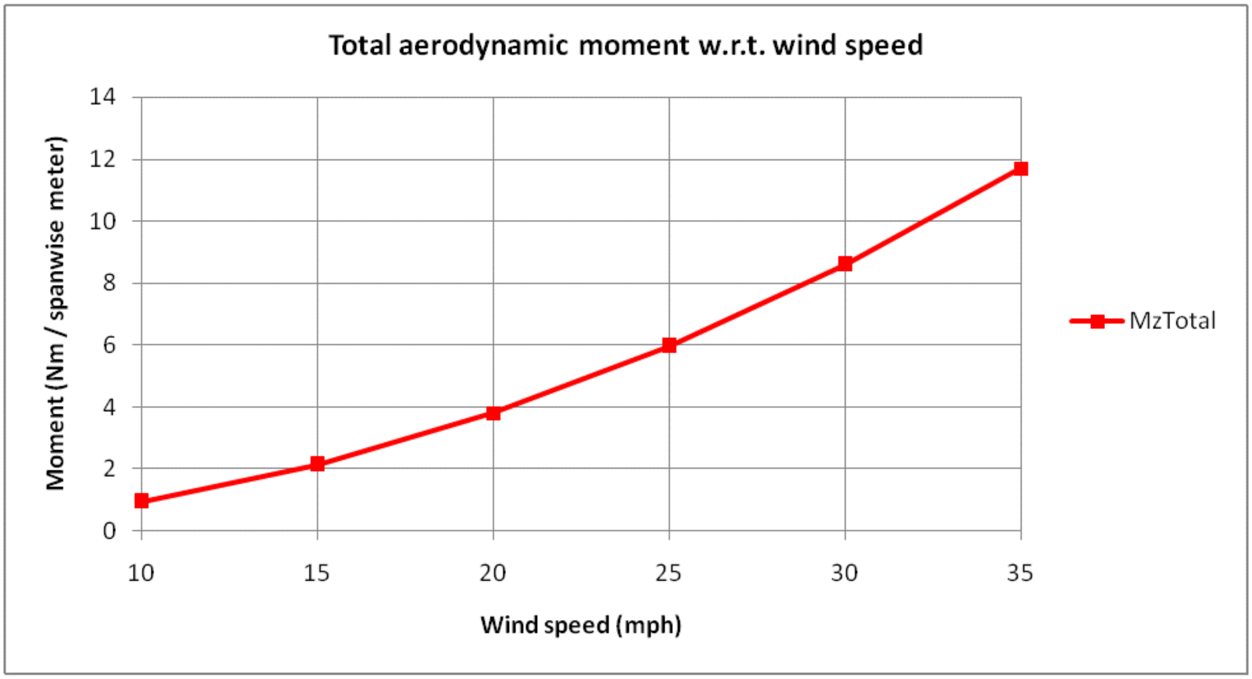
$$\frac{L_{30\text{ mph}}}{L_{15\text{ mph}}} = \frac{24.193\text{ N/m}}{5.916\text{ N/m}} = 4.09 \cong \left(\frac{30\text{ mph}}{15\text{ mph}}\right)^2$$

The total drag increases at slightly less than a quadratic rate:

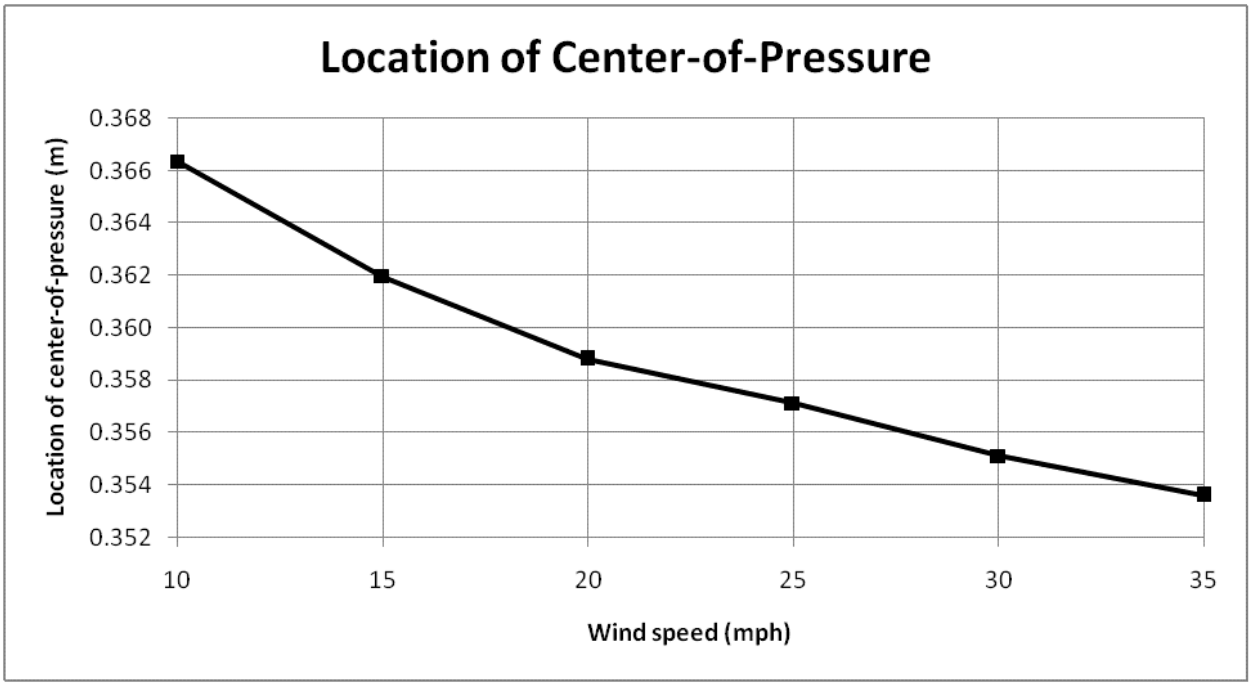
$$\frac{D_{30\text{ mph}}}{D_{15\text{ mph}}} = \frac{1.834\text{ N/m}}{0.532\text{ N/m}} = 3.45 \cong \left(\frac{30\text{ mph}}{15\text{ mph}}\right)^{1.78}$$

Because the lift increases slightly faster than the drag, the lift-to-drag ratio increases slightly as the wind speed rises. I confirm that the lift and drag figures include the effect of the leading edge tube, and include both pressure-induced and viscosity-induced effects.

The following graph shows the total aerodynamic moment, measured nose-down around the leading edge (the foremost part of the leading edge tube in line with the carbon fibre straight ribs), as it varies with wind speed.



Like the lift force, the total aerodynamic moment has very nearly a quadratic dependence on the wind speed. We can therefore expect that the location of the center-of-pressure will be nearly constant across the range of wind speeds shown. This is confirmed in the following graph.



It looks like the center-of-pressure moves through a total range of only 1.5 centimeters, with the CP creeping forward as the wind speed rises.

In the earlier paper, we showed that the kite should have pitch stability at a 9° angle of attack in a 20 mph wind. (Or, at least, the kite enjoys a positive restoring moment in those conditions.) The calculations done in the earlier paper had the center-of-gravity at approximately one-quarter chord. So long as the center-of-pressure stays with the bounds of the graph, pitch stability should not be put at risk.

The principal benefit of a higher wind speed is, of course, greater lift. This is particularly useful at high altitudes, where it can offset the effects of less dense air. The best flight conditions are those with a moderate wind speed on the ground and a higher wind speed aloft. If the increase in wind speed with altitude is just right, the kite could actually experience constant lift at all altitudes.

In the earlier paper, I mentioned that I envision a kite with a six-meter span. At an altitude of 15,000 feet with a 20 mph wind speed, the total lift (uncorrected for wingtip effects) would be about 6 m × 10.6 N/m = 63.6 Newtons. With a 30 mph wind speed, the gross lifting capacity of the kite woule be increased to 6 m × 24.2 N/m = 135.2 Newtons. Using the rough conversion factor of four Newtons per pound, this is equivalent to gross lift of 34 pounds.

The next step in the design is to estimate how much of this lift will actually be available if the wing is three-dimensional, and has a finite span. All of the simulations I have done up to this point have treated the wing as if it had exactly the same pattern of airflow at each spanwise location. That would be true if a wing had an infinite span. When the span is finite, the low pressure air on the top surface and the high pressure air along the bottom surface have another alternative way to get together; they can flow towards and then over the wing tips. I will examine these wing tip effects in the next paper.

Jim Hawley
September 2014

An e-mail setting out errors or omissions would be appreciated.