Single Line Kite Stability
Peter Lynn, April 2023

I've been trying to understand why kites don't fly, ever since, as a smartarse young engineer, I expected to set the world of kitemaking to rights in short order when I made a kite for our first child in 1973. Ah, hubris! It didn't fly (of course)- setting in motion a life-long obsession with kites that has left my long-suffering wife in despair at times, has had a few successes, but hasn't produced the coherent, predictive understanding of single line kite stability which I thought would take a matter of weeks back then.

Embarrassingly often, fixes for an errant kite come from doing the opposite to what I first try- or something else entirely. Some get put in the naughty corner and never learn to fly.

Just had a terrible thought, what if it's all wrong?---wasted life—Aagh!

But seeing as the dynamic stability of something as simple as a bicycle is not yet fully understood, the stability of single line kites (which is immensely more complex) is probably not going to be analytically defined any time soon. AI's might surprise us in this, except that there's no obvious data set they could use to identify the underlying relationships. There are however some basic relationships which can make the job of kite designing a little more likely to succeed than random forays into the unknown- and can usefully point to changes that are likely to correct various errant behaviours.

The kite maker's challenge is to find combinations that recover from changes in wind speed and direction while keeping sideways movements to a minimum and not getting into positive feedback instabilities. This is especially difficult when the intended design has some graphical imperative- that it must look like some creature for example. There are no formulas for this, just kites that fly and others that don't to learn from, a few qualitative principles, and lots of trial and error.

Back in 1973, to get some handle on what does and doesn't fly, I experimented with simple expanded polystyrene kites- and still use these as test kites when trying to answer specific questions. Their advantage is that they allow lifting and lateral areas to be changed quickly (even while on the kite field, by using contact cement that sticks immediately) and can have multiple-choice line attachment points. That their shape is not wind dependent in the way that fabric skins are, eliminates a major variable.

Polystyrene test kites in 1973- I'm on left, Kirrilee (daughter) on right

From these, I quickly understood the "**First Law**" – that kites fly because their weight acts below and behind where lift forces act, providing a moment arm that points the kite upwards- and began to get some understanding of the effect of lateral area and its disposition.

There are many reasons why kites won't fly. **Leaning over** (when a kite slowly leans off to one side as wind increases, sometimes until it's on the ground) can be caused by an asymmetry but can also be caused by floppy fabric, or too much lateral area towards the front.

D**iving over** (rapid diving over to one side to the ground or near to), is sometimes just a very bad case of **leaning over** (caused by asymmetry or etc) but can also have different, and hard to find causes.

The stability bogeyman is **weaving** instability –figure eighting that gets worse as wind speed increases, culminating in looping out. Weaving can be really difficult to prevent, especially when there are graphical constraints, and can be maddening when a favourite and dependable fix for one style of kite is of no help or even makes weaving worse on a different style. Weaving is indeed where theories of kite stability go to die.

For the last 10 years I've been building single skin single line kites, by far the most difficult kite challenge I've ever taken on. The 100 and something prototypes often with very small differences, have been an excellent test for the various theories of kite stability I've accumulated over the years. Some of these theories have survived, many have been found wanting, and there are a few new insights.

The most confusing concept is how the rate of recovery from a lean relates to kite stability: Kites with very large righting moments (like towed parasails) that recover rapidly from any lean, don't suffer from any of the three main instabilities (leaning over, diving over and weaving). With slower leaning recovery, weaving instability becomes the dominant problem. Kites that have even slower leaning recovery suffer from leaning over and then diving over but not weaving.

Definitions

Aspect ratio: Width relative to length, technically; span squared divided by area.
Angle of attack: angle that the wind strikes a kite's lifting surfaces at.
Apparent wind: Air velocity that a kite experiences (can be more or less than the true wind).
Centre of gravity: Where the sum of a kite's weight forces (including bridles and line) act.
Centre of lift: Where lift forces act- found by sighting up the kite's line.
Chord: a kite's length (excluding tail).
Diving over: High speed dive to the ground, or nearly to, at one side.
Drag: Aerodynamic drag forces that pull a kite in the wind direction
Falling off; collapsing to left or right after stalling.
Lateral area: Keels, flares, fins and other vertical (as opposed to horizontal) area.
Lateral correction. When a kite returns to centre from being laterally displaced.
Leading edge: A kite's front edge
Lean: when a kite is not pointing straight up
Leaning correction: returning to vertical from a lean.
Leaning over: Slowly leaning off to one side or the other- sometimes to the edge of the wind window
Lift: Aerodynamic lift forces that enable kites to fly
Lift to drag ratio: Aerodynamic efficiency**;** tangent of the flying line angle**.**
Luffing: When a kite's leading-edge dips under the wind, causing the kite's line to lose tension.
Righting moment: a kite's weight times the distance between its centre of lift and centre of gravity.
Span: a kite's width
Stalling: When a kite falls back, will not climb, or won't launch- when lift is less than weight.
SSSL: **S**ingle skin, **s**ingle **l**ine kite.
True wind: Actual wind speed at the kite.
Trailing edge. A kite's rear edge.
Weaving: Repeating lateral movements that sometimes builds to looping as wind speed increases.

First Law

Single line kites can only fly if their centre of gravity (where the weight forces act) is behind (and generally below) their centre of lift (where the lift forces act). The weight force pulling downwards against the lift force pulling up, points the kite upwards. If the centre of lift is behind the centre of gravity, the kite will turn over and try to fly down instead.

The '**First Law**" is a necessary condition in the absence of which a kite can't fly. It is not a sufficient condition however, because it doesn't by itself ensure stable flying.

There is a conceptual difficulty with this first law in that a kite, when correcting, does not pivot around the point where its lift forces act but follows a curved path determined by many factors. Nevertheless, the first law is a reliable predicter of kite behaviour. Leaning recovery **is** a function of the righting moment as defined above and no kite with its centre of lift behind its centre of gravity will fly.

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Tails

Kite tails are interesting devices. Considering only ribbon tails for now, they are self-supporting in all except the lightest winds (and will often pull **up** on the rear of a kite in stronger winds. They add drag and shift the kite's centre of gravity (by some functions of their weight and length which diminishes rapidly for longer tails I suspect). Depending on how they are attached (see discussion of this in **Weaving Instability**), tails can usefully improve kite stability and reliability- though "just add more tail' is not the answer to all stability problems, because long tails will often cause leaning**,** and on occasion I have seen tails cause weaving rather than damping it (which is more usual).

Some kitefliers appear to believe that drogues ('buckets of air'), which have negligible weight by comparison to their drag, are the equivalent of tails. They are not. Drogues are only suitable stabilisers for kites that are strongly weaving unstable- and even then, have some negative effects. Any kite that is even slightly inclined to leaning over or diving over will fly worse with a drogue added.

Attaching tails (or drogues) by a "Y" bridle can also bring on leaning- because Y bridles limit leaning recovery. With correction slowed too much, kites can lean off a long way to one side or the other before they get around to pointing upwards again.

Long tails can also have a bad effect on kite behaviour. I've done quite extensive testing with tails on some SSSLs and have found, invariably I think, that any longish ribbon tail has a better stabilising effect when it is attached doubled than as one length- and this is true whether a kite is inherently weaving unstable or leaning over unstable (which supports the above theory that a tails' C of G contribution diminishes with its length). If tails are VERY long in relation to a kite's size, they function rather like their end is staked to the ground. Even a tiny wind shift causes a component of the tail's drag to pull the kite sideways, which makes that component larger and so on until the kite is lying on the ground at the side of the wind. This is why Thai snake kites with record attempt kilometre long tails, fly off to one side or the other and lie on the ground.

By a similar mechanism, tails that are heavy by comparison to the kite and attached so as to prevent the head's independent rotation, cause falling off – when the kite falls off to one side or other if the wind drops. For explanation of this see **Falling off** in the kite instability section.

Aspect Ratio

For kites with moderate or minimal lateral area, the effect of aspect ratio **(**span squared divided by area**)** on stability is profound: For kites with aspect ratios exceeding 1.0, the wider a kite is relative to its length the less subject it will be to weaving instability. There are three probable reasons for this.

The first is because the restoring moment is the kite's weight times sine of the angle of lean times a function of the distance between the kite's centre of lift (where an extrapolation of the kite line intersects the kite) and its centre of gravity. As aspect ratio increases, this moment arm's length decreases in relation to the kite's area, causing it to lean less while correcting laterally, which makes weaving less likely to build.

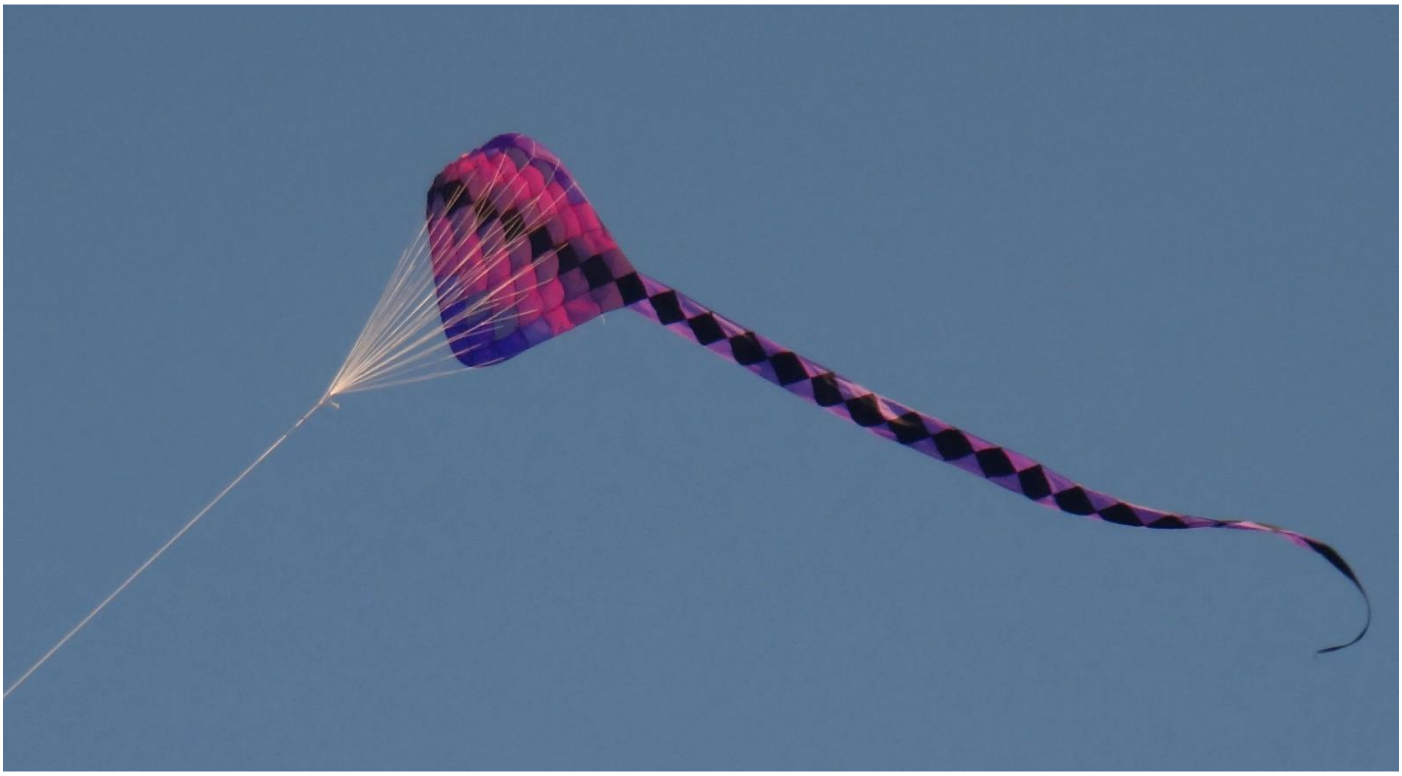
The second is a possible rotational moment of inertia (flywheel) effect, this is something like the reason tight rope walkers carry a pole- it slows things down making wobbles less likely to build up.

The third is that much of the drag price that wings pay for the lift they generate occurs at their tips. Moving the tips further out by increasing the aspect ratio makes the damping effect of this drag more effective in preventing weaving – which is always a function of the speed of leaning correction.

If the aspect ratio is too high, a kite will be likely to lean over rather than weave (and in the extreme, will dive over). There is generally a window between these, but sometimes it's vanishingly small.

Kites with aspect ratios substantially less than one (long in relation to their width) exhibit different behaviour. Long bodies function as lateral area, which tends to keep them in line with the wind. This reduces weaving. But higher restoring moments from having their centre of lift and centre of gravity relatively further apart speeds up leaning recovery which makes weaving more likely, as does having a flexible body (ram air inflated snakes for example).

Because changing a kite's aspect ratio requires a completely new kite, every other tweak is usually tried first. I'm sure that many new kite designs have not succeeded solely because aspect ratio changes were never tried. Tiny changes can have a large effect: Four square metre SSSL Rays with an aspect ratio of 1.21 become weaving unstable from around 30km/hr. With their aspect ratio increased just 8% to 1.31 they are stable through to 60km/hr +. Increasing this further brings on leaning over. An SSSL Ray with an aspect ratio of 1.40 leans over then dives over so badly it is difficult to keep up for long enough to even get a photo.



4sq.m SSSL Ray with Aspect ratio 1.31, stable to more than 60km/hr

This sensitivity is only the case for kites with minimal lateral area and there's nothing magical about an AR of 1.31. For such kites, aspect ratios that are high enough to keep weaving at bay while still low enough not to cause leaning over vary widely. For example, ram air inflated flag kites typically have an aspect ratio of 1.7. In the 8m size they tend towards leaning over**,** especially when flown with a drogue rather than a tail (see **Tails**) but are just on the verge of weaving unstable in the smallest size- see **Scaling.**

Scaling

When scaling kites up or down, the main factors that inform changes in stability are line length, weight, area and air mass (air has no weight but has mass, which resists accelerations). Weight is a factor because of the **first law** (that the weight moment acting behind the centre of lift points the kite upwards). Area is a factor because the aerodynamic forces of lift and drag are functions of area. Therefore, if line length is proportional to other dimensions and weight/area remains constant, kite stability should be independent of size except for air mass influences (which scale with the cube of dimension not the square). And it is:

The smallest ram air flag kite is 0.75 m span, 0.35 sq. m, 0.1kg. The largest (mega flag) is 45m span, 1250 sq. m, 360kg. The mini's weight/area is around 0.28kg/sq. m, the mega's is 0.29kg/sq. m. The mega is therefore more than 3,500 times the mini by area, but they both fly well, with the mini just beginning to exhibit weaving and the mega tending towards leaning in stronger winds. This difference is probably explained by the proportionally greater mass of air larger kites displace when moving laterally or rotationally- which slows correction. To mitigate this mass effect, in very large sizes, ram air kites are made with no internal partitions, using thru cords instead, so that their enclosed air mass (> 3 tonnes for a 1250 sq. m flag kite) can rotate somewhat independently when the kite is correcting. Otherwise, its inertia would slow leaning correction to a problematical extent.

Inside the 1250 sq. m 'Pearl' mega ray showing use of thru cords instead of ribs- and Elwyn and Tory

Framed kites also scale- within limits set by frame strength and rigidity. I've built Nagasaki Hata style fighter kites as small as 200mm across, and as large as 9m. Within this range they fly comparably, with the same technique used to get them to change direction, dive, climb and traverse. The larger sizes take a lot longer to turn and won't fly in light winds because they are proportionally much heavier. The limiting factor is frame weight which increases much faster than by the square of dimension in larger sizes. Above about 15m wingspan, even with carbon fibre, framed kites become either too heavy to fly in a useful wind range, or very fragile.

15m wingspan Hornbill at Bintilu in 2009- about the size limit for practical framed kites

But this is where the wheels fall off scaling theory (that kite stability scales provided weight/area is constant). Single skin kites have the same weight/area when they are scaled up, but they are much less subject to weaving instability in larger sizes. There is no enclosed air mass, scaling with the cube of dimension rather than the square to explain this. If any kite type should scale then SSSLs should, but they don't.

4sq.m SSSL Rays occasionally dive over from around 35km/hr, 10sq.m's from 50 or so and a 20 sq. m never does. And this is with panels and bridles scaled exactly and constant weight/area. Increasing the 4 sq. m's aspect ratio by 8%, lifts their stability to 20sq.m equivalence.

20m SSSL Serpents weave from around 20km/hr, 30m versions from 30km/hr and 60m Serpents are weaving immune to above 60km/hr- panels and bridles exactly scaled.

Fabric stiffness doesn't scale. SSSL kites have no frames, no internal pressure, and no stiffeners. There is nothing except a tiny pressure difference to keep their leading edges in position- and exactly at the leading edge even this drops to nothing.

Indentations of the leading edge, especially when asymmetric, are a prime cause of leaning over and diving over for all SSSLs. Fabric stiffness decreases relatively as kite size increases, so as a possible cause of this scaling anomaly, for SSSL Rays it should have the opposite effect.

Is it possible that by adding drag, leading edge indentation could be making larger SSSL Serpents more resistant to weaving instability? But this can't explain why smaller SSSL Rays dive over, while larger ones don't.

The only plausible explanation for this scaling anomaly is the entrained air mass that attaches to these kites as vortices and boundary layers. This increases with the cube of dimension, not the square. Because of their very high pull/size, SSSLs do drag a lot of entrained air around with them. Possible?

60m SSSL Serpent. Stable to >60km/hr. smaller sizes aren't. Ferocious pull.

There are some other properties of kites that don't scale, but these are trivial I think and are either not relevant or nowhere near sufficient to explain the SSSL anomaly.

There is a non-scaling effect in deflections- that fabric and structures are subject to higher overall loads in larger kites, so will deflect, distort and bend proportionally more. This can be significant for rigid and framed kites. but isn't generally noticeable for ram air or single skin kites within fabric and cording strength limits.

Reynolds number effects: Reynolds number is an indicator of the onset of turbulent flow, which definitely doesn't scale- but seems to be significant only for micro kites in our case as air flow over all the single line kites I've ever flown- down to 100mm even- is clearly turbulent.

Surface roughness doesn't scale (a 20mm bump is significant for a small kite but less relevant on a larger one) - and has some effect I expect. This has been posited as the reason that very large leading-edge inflatable kite surfing kites fly in lighter winds than smaller ones. If significant, large SSSLs would be less stable than smaller ones not more.

At a stretch, it's possible that smaller kites are less stable than larger ones because they are more affected by turbulence- the same reason that A380's are smoother to fly in than Cessna's. Could random turbulence induced leaning be initiating the instabilities that smaller SSSLs are more subject to? This seems ruled out by framed and ram air kites not showing the same sensitivity but could be checked by seeing if smaller SSSL have an appropriately higher instability threshold when tow tested in still air.

Lateral Area

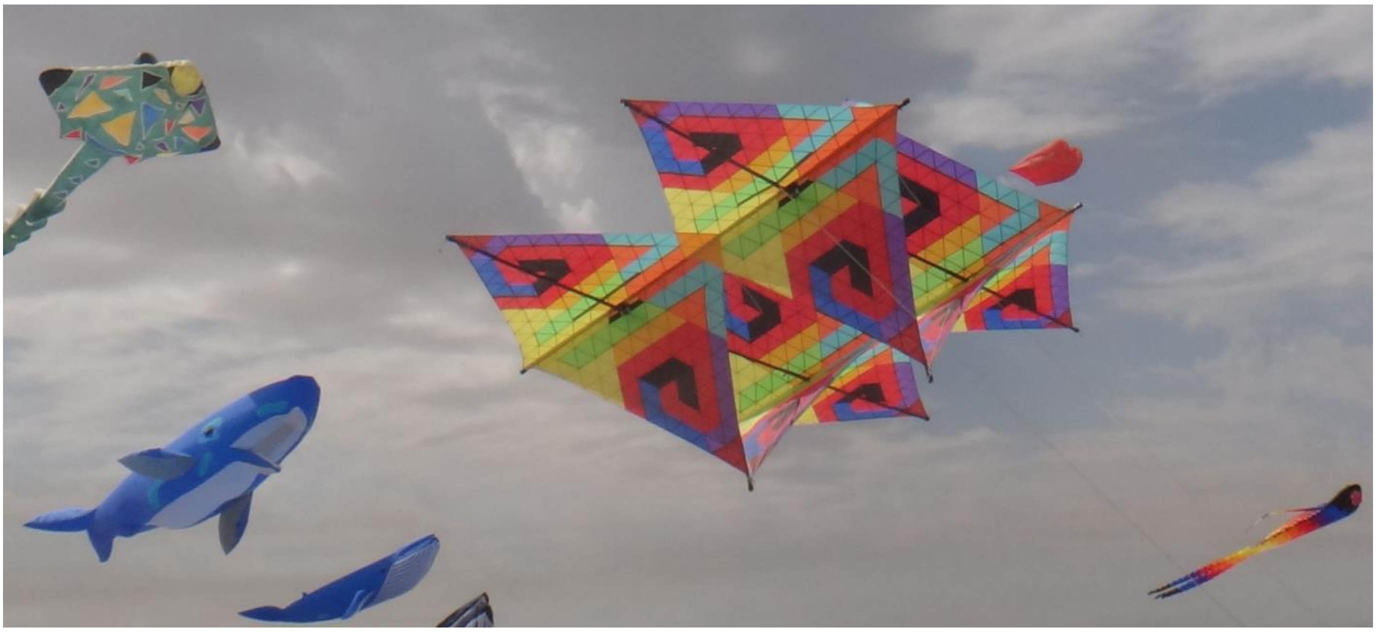
Lateral area is not only vertical surfaces such as keels, fins, flares and side plates, but also dihedral, anhedral and the side area of body elements- the projected lateral area of the kite. By area, keels and etc are more effective.

Some kites have more lateral area than lifting area and some have almost none. All can fly, other things being supportive. But how much lateral area there is, and how it's disposed chordwise has profound effects on stability.

At the minimalist end, a small amount is necessary to prevent side slip and spinning. Fighter kites and the like are often completely flat until there is some line tension- with lateral area then being progressively provided by frame deflection as wind speed increases. Letting out line at the same speed as the wind returns them to flat which causes them to spin – the mechanism by which they are directionally controlled.

Kites with lateral area similar to their lifting area are quite resistant to weaving instability. My guess is that this is because lots of lateral area keeps a kite aligned with the wind and generally doesn't allow it to get too far away from the vertical. Provided a kite stays central and steady- which kites with lots of lateral area tend to do, it can't develop much of a lean. Wind direction is not a good proxy for up and down though, so such kites can still get into weaving and looping when apparent wind takes over.

They can also thrash around a lot when flown on a short line. This is because the lateral component of line tension is greatest when the line is short and reacts with the lateral area to cause rapid and repeated overcorrections. Cody man lifters (a style of box kite) are renowned for this, requiring skill to get then to ground without damage.



6m PLT Box kite in Kuwait 2023- high lateral area ratio, no weaving instability

When there's a wind shift, a sideways component of wind direction striking a kite's lateral area pushes it back towards alignment while a sideways component of line tension is pulling it the same way. If there's as much lateral area as lifting area than these corrective forces are initially equal.

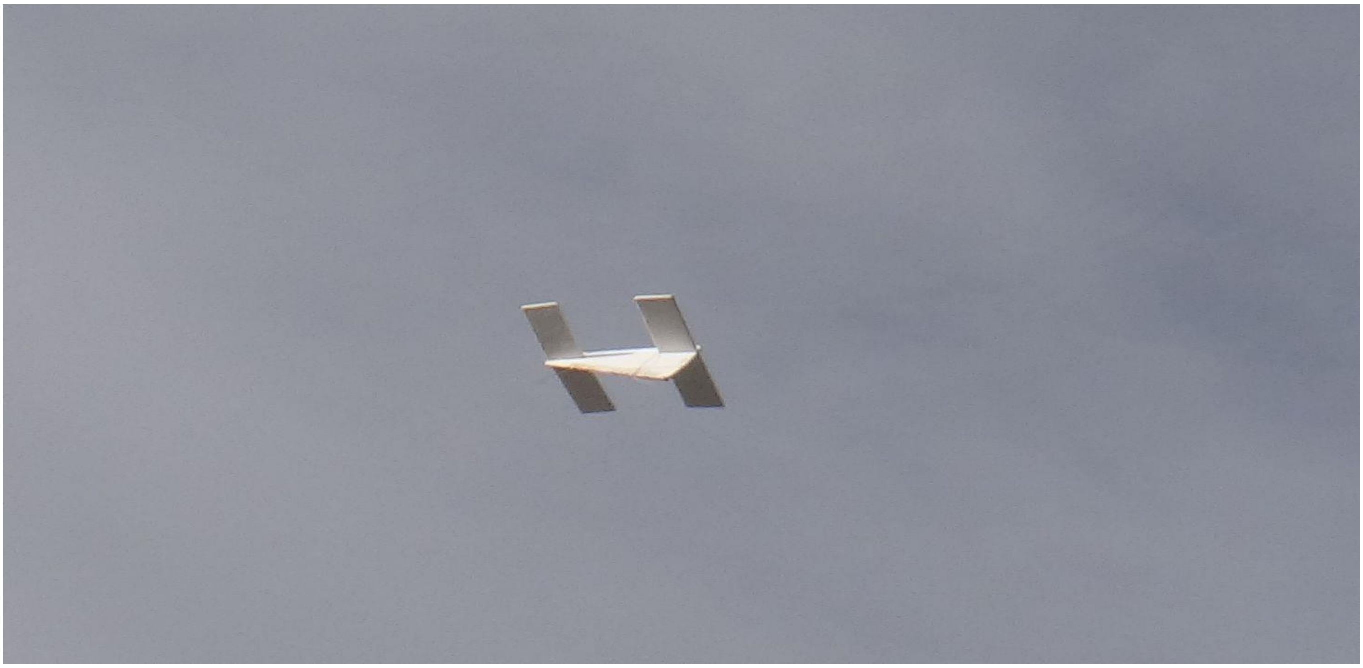
The longer its flying line is, the further a kite can move sideways before these corrective forces pull it back into alignment (or try to). The magnitude of the line tension component is line tension times sine of the angle by which it's out of alignment in plan view. The magnitude of the corrective force applied by wind striking lateral area is a function of the angle of the kite to the apparent wind at that moment.

When the lateral component of line tension kicks in it will pull the kite over into a lean towards the new wind direction. This is like when a bicycle with its front wheel at right angle is pulled sideways- it will turn towards the pull. The angle of this lean is a critical factor in kite stability and is a function of the disposition of lateral area- how much is forward and how much to the rear- and of inertial forces.

Of course, if all of a kite's lateral area is forward of a kite's axis of rotation then obviously the kite will not fly, because as soon as it veers off one way or the other, wind forces striking this forward area will push it even further off straight. This is easiest to understand by thinking of a kite's lateral area as a wind vane– if a kite has proportionally too much lateral area towards its front, it will attempt to turn around and fly tail first.

Nor is it only a matter of how much lateral area and where it is centred. A single large but short fin doesn't provide much directional control compared to a long fin or one fin at the front and another to the rear that have the same total area.

To test the influence of lateral area disposition on a representative kite style with significant righting moment, I tried two polystyrene test kites, identical except for the disposition of their lateral area. One had a parallel full-length keel, the other's keel was wedge shaped (and it could be flown from either end). The version with parallel keel became weaving unstable in quite light winds. The wedge keel version flown with lateral area to the front was unstable, spinning uncontrollably even in light wind. Flown with lateral area to the rear it was stable through to strong wind. They both had lateral area equal to 65% of their lifting area. Kites of this style with parallel keels and lateral area equal to 100% of lifting area are stable in a wide wind range.



Polystyrene test kite with rear distribution of lateral area- stable through to strong winds

Kites that have only rear lateral area can be inclined to diving over**:** A 2019 3 sq. m SSSL Serpent head with all its lateral area towards the rear would not fly straight for even a second; it dived over to one side or the other immediately on launching, requiring quick reactions even to get a photo. Probably this was because its rear lateral area acted like the back wheel of the bicycle above, and because the lateral area disposed as a fin to either side at the rear provided almost no resistance to spinning- unlike if the lateral area had been rearward but on the kite's centre line. It also had a very short righting moment. With the rear flares cut away and side bridles shortened to create some lateral area disposed more to the front, it flew stably, and centrally, even without a tail in very light winds- until it was accidentally left on the beach at Lytham St Annes when a storm hit.

An observation here is that kites with too much rear lateral area will not launch from lying on their side- they go nose down rather than nose up. This may be a useful check for diving over susceptibility.

Underneath view of 3sq.m SSSL Serpent head with rear flares- dived over, wouldn't fly at all.

Lightweight kites with small righting moments (centre of lift and centre of pressure quite close together), and substantial rear lateral area will often hang off to one side or other in light winds. The yellow pilot kite in the following photo **leans over** to the right with the rear parts of both flares holding the kite's trailing edge up. It would **lean over** to the left just as happily. This is only a problem for these pilots in very light winds.

Ram air pilot kite leaning off because of rearward lateral area disposition. Sarawak, August 2009

For kites with substantial righting moments (longer narrower kites for example), if their rear area (keels or body) gets twisted by wind forces this can build by parametric resonance until they thrash around quite alarmingly (Trilobites with insufficient tail drag for example). Long tube-shaped kites can also be subject to an effect which causes repetitive sideways swinging of their after-body by the same phenomenon that causes tall chimneys to swing in the wind like an upside-down pendulum. Called the von Karman effect, it can be prevented by interrupting the airflow with suitably placed spoilers or fins.

Megabite in Bangkok showing rear body twisting – unstable parametric resonance.

22sq.m 4 bridle Pilot kite with effective lateral area disposition.

For kites with lateral area less than say 25% of lifting area, a starting point is to balance this area around the centre of lift (where an extrapolation of the flying line would intersect the kite's surface), and to make it as long, chordwise, as is convenient.

Disposition of lateral area is a common and often unrecognised cause of kite misbehaviour, especially for kites with not much lateral area and small righting moments.

Specific Single Line Kite Instabilities

Although there are many causes of kite instability there are just 3 main manifestations:

Leaning over: Slowly leaning off to one side or the other- sometimes to the edge of the wind window

Diving over: High speed dive to the ground, or nearly to, at one side.

Weaving: Repeating lateral movements that sometimes builds to looping as wind speed increases.

There is a fourth; **swinging** (when a kite behaves like a pendulum), but this has very specific causes and rarely if ever causes a kite to come down. There is also **falling off,** which is not an instability but the annoying way that some kites slide off to one side instead of falling straight down when the wind drops.

Falling off (collapsing to left or right after stalling) is exactly that and only occurs when the apparent wind drops below a kite's minimum flying speed, when most kites fall gently back to earth directly downwind from their line anchoring point. SSSL kites, especially those with tails do not always do this. Some of them fall off to one side or the other, often by as much as 45 degrees from the wind direction. When a kite stalls, one side usually drops first which can cause the head to lean over and slide off to that side as it descends. If there's a tail, this then keeps the kite leaning over as it falls off to the side of the wind window. SSSL Serpent**s** are a devil for this, only partly mitigated by automatic bridles that make stalling less likely. I have seen the same behaviour in some ram air inflated and framed kites, and it seems to correlate with minimal lateral area, having a tail and rearward centre of lift (say at 35% or more of chord).

At some wind speed, all kites fail- if not by structural damage, then by some type of instability.
But **how** they become unstable is important.
The most benign instability is leaning over, because diving over and especially weaving cause an increase in apparent wind speed**,** which can increase line pull by as much as nine times (for the case of a kite with a lift/drag ratio of 3, by the rule that apparent wind speed ='s true wind speed times the kite's lift/drag ratio, line tension being a function of wind speed squared). This can be very dangerous, breaking lines and causing anchor failure- not to mention an aerial experience for anyone who happens to get caught up in the line. The goal therefore is to avoid diving over and weaving, while contriving for the upper wind limit to be set by leaning over, and at the maximum achievable wind speed. This should preferably be above 70km/hr, the practical upper limit for most kite events. Unfortunately, even if a kite is perfectly stable at 70km/hr there will still be times, even at organised events when the wind will unexpectedly exceed this- which is why it's important that the eventual failure mode is as benign as possible. Ram air pilot kites are an example of the success of this approach- they have been developed so as to always fail by leaning over rather than by going crazy and is, I think the main reason that kite festival flying with large kites has such a good safety record.

Leaning Over

(Slowly leaning off to one side or the other- sometimes to the edge of the wind window)

Leaning over can have causes such as significant asymmetry in the kite, and too much lateral area in front of the centre of lift or can be a symptom of extremely slow recovery from a lean.

Slow recovery is usually (always?) because the righting moment is small in relation to the mass it needs to swing or displace to afford correction or in relation to lateral area that's resisting correction.

To correct a strong wind leaning problem, the first thing to look for is asymmetry. After this, the changes to try are lateral area and its disposition (especially too much forward lateral area), and then the righting moment (centre of lift position relative to centre of gravity).

Aspect ratio strongly influences the righting moment but is usually inconvenient to change (needs to be decreased in this case), so a much easier (but not costless) way to increase the righting moment is usually tried first. This is to shift the line attachment point towards the kite's leading edge, usually by changing relative bridle lengths. Shifting the centre of lift forward while the centre of gravity remains where it was, gives the kite's weight more leverage to point it upwards again. This will reduce leaning. A cost is that it will almost always also increase a kite's propensity to weaving instability. Another cost is that it may cause luffing.

Smooth tailed high aspect ratio Ray, terminal leaning over as a fly alone- but some use as shade.

Many attempts by myself and others to develop a ram air inflated Ray that will fly by itself without pilot kite support and not require a bucket tail for extra stabilising drag have failed. With high enough aspect ratio to resist weaving, they lean over, and even dive over in strong winds. Such a kite should be possible, but to date, a window between these instability modes has not yet been found for this kite type.

Diving Over

(High speed dive to the ground, or nearly to, at one side.)

Diving over can also have various causes:

One is asymmetry, which it shares with leaning over when an asymmetry becomes severe enough to cause a dive rather than just a lean as wind speed increases.

Ram air inflated and single skin kites are especially vulnerable to diving over when there is asymmetrical buckling in of the leading edge. This can onset suddenly and unpredictably as wind speed increases.

Framed kites, especially those with wood or bamboo members are prone to diving over when their structure deforms asymmetrically. If buckling occurs, this can also onset quite suddenly rather than as a slowly increasing lean.

Bridle stretch can also cause diving over- and is often difficult to identify. If bridle loads are greater on one side of a kite than on the other (because of a wind gust for example), then that side's bridles will stretch a bit. If this stretch is enough, it can cause the kite to turn away from that side, increasing the speed, the loads and therefore the stretch even more in a positive feedback loop that will culminate in a dive or looping.

Lastly there is centre of pressure migration. Ram air inflated and single skin kites have their flying line attached to bridles some distance from the kite's surface. As the angle of attack decreases in strong winds and for high flying line angle, the centre of lift will generally move rearward- facilitated by the kite rocking around the bridle point. This decreases a kite's righting moment, sometimes until it is no longer sufficient to keep the kite pointing upwards, resulting in a lean or even a dive. A kite's centre of lift is at the point on the kite identified by sighting up the line and for some SSSLs this point can be observed migrating back to near where the kite's centre of gravity is as the kite climbs to maximum height- then dives.

Weaving Instability

(Repeating lateral movements that increase with windspeed, sometimes to looping out.).

Because the driving force behind weaving instability is lift while drag provides the major stabilising affect, weaving instability is at some fundamental level a function of lift/drag ratio.

Weaving instability is a complex dynamic relationship between a kite's weight force moment (the righting moment), line pull, inertial reactions, and aerodynamic forces. It establishes when righting moment-initiated recovery and the lateral component of line tension, sends a kite back past centre in a repeating sequence of increasing amplitude. As a kite corrects laterally, it moves faster than the true wind speed. This is called its apparent wind speed. The increase in lift force generated by this extra speed is a function of apparent wind squared minus true wind squared and is maximum every time the kite passes centre, driving the parametric resonance which is weaving instability.

If, as a kite recovers laterally from a wind shift, it continues to point upwards it will just drift from side to side in response to changes in wind direction, and weaving will not establish because there is no significant increase in apparent wind speed. No such kite quite exists of course but nevertheless, this perspective is useful by defining what **doesn't** cause weaving. Minimising leaning in response to wind shifts and turbulence will reduce the likelihood of weaving developing or at least shift its onset to higher windspeeds. This is because the less a kite leans over, the slower its lateral movement will be- and fast lateral movement is what drives weaving.

To test this theory, I flew various kites from two lines, one of them anchored, the other hand-held. By pulling each kite off a defined distance to one side with the second line, then releasing it, the amount of lean that developed during correction could be easily seen.

The results from this are unequivocal. Kites that are inclined to weaving instability (such as 30m SSSL Serpents) lean by as much as 45 degrees while re-aligning, fly fast while doing so- and overshoot. Kites that are not susceptible to weaving instability (like 10 sq. m SSSL Rays) remain much more vertical- don't build much apparent wind while recovering and overshoot by very little if at all.

Kites that have very large righting moments don't ever lean enough from the vertical for weaving to establish. Towed parasails – parachutes with people hanging below them- that are often an attraction at tourist beaches are an example of this. The person's weight is so great in relation to the canopy's weight, and they hang so far below (giving their weight huge leverage) that these 'kites' don't ever point anywhere much except straight up. Hence, they are not susceptible to weaving instability (though they can swing like a pendulum, a different phenomenon). Some rigs used for kite photography also work this way.

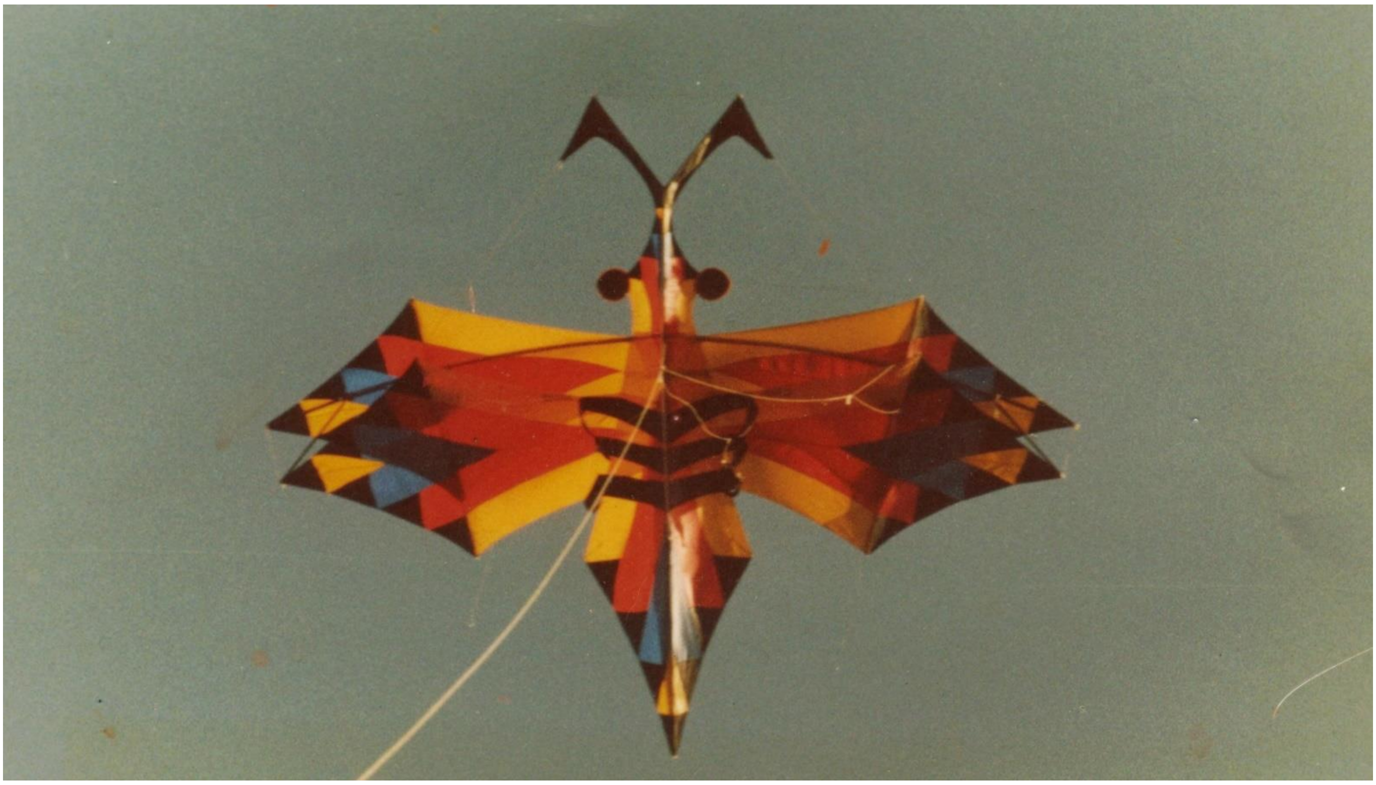
The only other kites I've see that take this approach to stability are conventional diamond kites with weights tied to their tails (I sometimes did this as a kid). These are a little different in that their line goes directly to the kite not to a weight hanging underneath, but their flying characteristics are similar.

Towed parasail: Righting moment is very high, weaving can't establish- but swinging can.

Hanging a big weight below a kite is not practical for most kite types- not least because such kites fly at low line angles and require a lot of wind. Fortunately, there are various other ways to limit weaving instability.

Consider a kite as it corrects from a wind shift. Before it starts correcting, the kite is vertical. A lateral component of line tension then starts it moving back towards centre. At the same time, a component of wind striking the kite's lateral area also pushes it back towards centre (both these corrective forces diminish as the kite gets closer to centre). Because the line pull is necessarily above the kite's centre of gravity, it will cause the kite to lean towards the direction it is moving in. Minimising this angle of lean is the key to preventing weaving instability.

One way to reduce leaning is to move the line pull to a point further down the kite. This gives the lateral component of line pull on the front of the kite less leverage- so the lean it causes will be less. The 'arm length' of this leverage is the distance between a kite's centre of lift and its centre of gravity, sort of. That a kite rotates around its centre of gravity, is not always true as this can be influenced by tails and the disposition of lateral area. But regardless, moving the line pull down does reduce its leverage. Usually accomplished by lengthening the kite's front bridles or shortening the rear ones, it's a widely known and invaluable technique which I've been using since my earliest remembered kite flying days. For much of this time I did not understanding why it works. Unfortunately, it also increases line pull, which is not always desirable, and it costs some light wind performance, which never is.



9m wingspan Dragonfly kite 1984, violent weaving reduced by moving the bridle point down.

I'm uncertain about this, but maybe another way to reduce leaning is to increase a kite's rotational moment of inertia (flywheel effect). This does resist the lateral component of line tension and result in less of a lean, but it also resists recovery from whatever lean there is after the kite passes centre. Is the net effect to slow the kite's apparent wind and therefore to de-power weaving?

Assuming it is, changing aspect ratio is a useful way to change rotational inertia, which is minimum when the aspect ratio is 1.0. Making a kite longer than it is wide increases the rotational inertia but also increases its righting moment, which will increase its propensity to weaving. In most (all?) such cases the increase in righting moment dominates**.**

For kites with aspect ratio greater than 1.0. increasing aspect ratio increases rotational inertia **and** reduces the righting moment- so will be useful in combatting weaving irrespective of any rotational inertia effect.

Ram air inflated Ray kites- resistant to weaving by judicious use of aspect ratio and tail drag

Most of the weaving inhibiting effect of increasing aspect ratio comes not by a theorised flywheel effect but because it moves the drag generated by a kite's wing tips further from the kite's centre line. In weaving behaviour, kites follow a curved path with one side wing therefore travelling faster than the other. Drag is a function of speed squared, so drag at the tip slows the faster wing by a lot and damps weaving.

Instead of increasing aspect ratio, extra drag to damp weaving can be provided by, for example, affixing tails to the tips. A common enough sight at kite events, wingtip ribbons are often added to kites for decorative rather than stabilising reasons but can be beneficial. If overdone however, they will cause leaning over.

Quilt kites with wingtip drag tubes that inhibit weaving. Nordeney 2003

What stops weaving better than adding drag elements to wing tips is to use shape changes caused by increasing wind speed to increase the drag and decrease the lift at the tips. Delta's and many other styles of framed kites use wind induced frame bending to do this. For a delta kite flying in light winds, all the wing area will be providing lift, but as windspeed increases, the leading-edge struts bend back. This causes the fabric towards the tips to flare out and not contribute to lift, while still contributing drag. By this mechanism, delta kites can fly without weaving or any other type of instability across a very wide wind range. Too much frame bending, especially if its asymmetric, will cause leaning over or diving over**,** so a key to delta kite design is in getting the frame flex exactly right.

Delta style framed kite- wings flare back in stronger winds to prevent weaving.

Rokaku kites have a different and ingenious way of using frame flex to damp out weaving over a wide wind range. When a Rokaku flies on a curved path (like when weaving is beginning to establish), aerodynamic forces on the faster side cause that side's camber to increase (increasing its drag) , while the fabric on the slower side tightens up (decreasing its drag). This acts promptly to straighten the kite's flight and stop the weaving.

Unfortunately, using frame flex as a stability aid is not available for ram air inflated and single skin kites.

Rokaku's have a clever trick to damp weaving.

Lateral area is a sure remedy for lean induced weaving when it's available (an octopus kite with fins is no longer an octopus kite). It seems to work best when disposed around the centre of lift (that is, where the line pull acts). I assume this is because it then resists the top of the kite being pulled over into a lean by the lateral component of line pull when the kite is out of alignment with the wind. Adding just 0.1 sq. m of lateral area (by shortening 3 bridles each side of the head 75mm) lifted the onset of weaving for a 20m SSSL Serpent from 20km/hr to above 30km/hr. This additional lateral area amounted to less than 5% of its 3 sq. m head size.

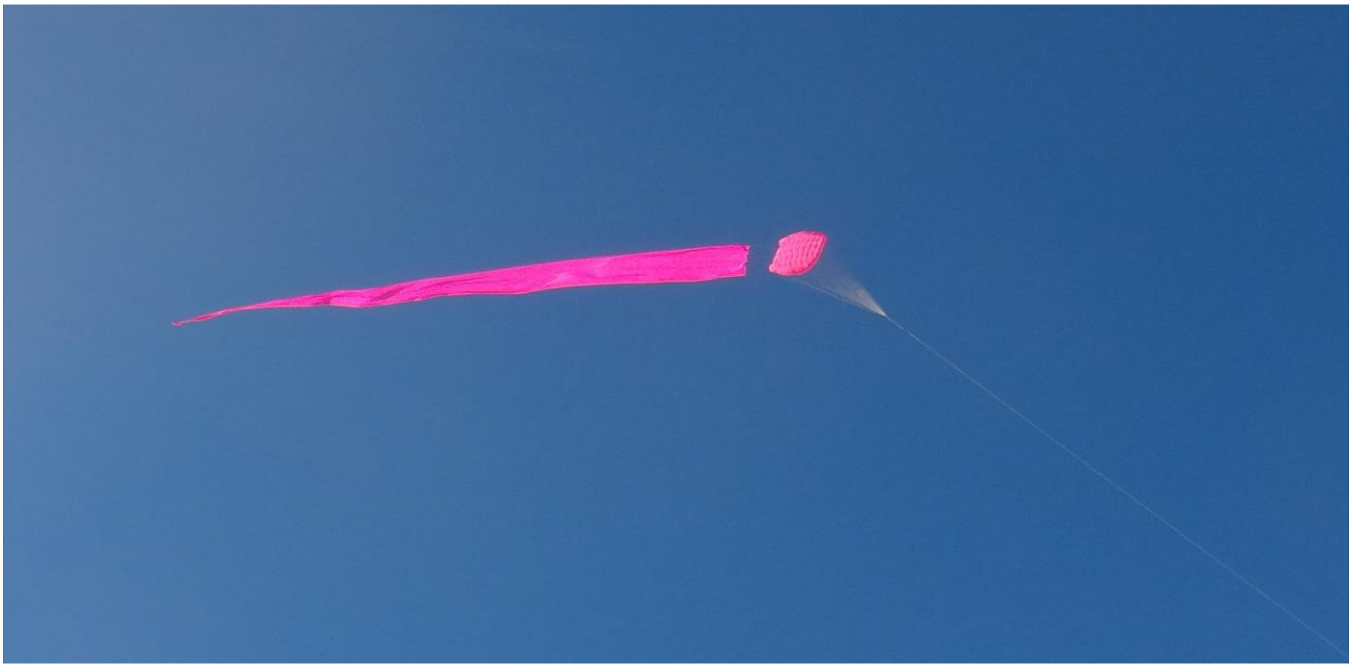
There is another mechanism by which lateral area resists weaving which comes into play when lateral area is a more substantial fraction of the lifting area. When a kite habitually flies fairly steadily and centrally, wind direction combined with line pull (as a vector) can be a useful proxy for vertical orientation. In this case, changes in wind direction cause such a kite to immediately re-align with the new wind direction without also developing a significant lean. This, I think, is why box kites, corner kites, even circle flexes are largely immune to weaving instability.

20m SSSL Serpent: just 0.1 sq. m increase in lateral area dealt to weaving instability.

Tails are also a time-honoured weaving remedy. Probably they work by limiting the angle that a kite can lean to by keeping it aligned with the wind- rather like for lateral area. If weaving threatens to establish- just add more tail. Tails are a little different from lateral area in that they don't apply directional correction to a kite until there is a few degrees of misalignment, after which the effect of their corrective drag increases rapidly. This can be advantageous by allowing the kite some rotational independence- which makes leaning over less likely. The 20m Serpent above, with its tail attached half width to allow some rotational independence is weaving resistant even without extra lateral area. I surmise that this is because, with its tail attached full width the kite goes a long way sideways before it straightens up from even a small lean because the entire kite and tail must rotate as one unit. As evidence for this theory, when this kite with its tail attached half width gets to one side of a figure eight, the head appears to straighten up before the tail follows.

20m Serpent with tail attached half width- significantly higher weaving instability onset.

To check that this improvement isn't because of a flow effect at the head's trailing edge, it was then tried with the same tail attached full width but with a 1.2m gap. This had the same weaving onset speed as for the tail attached full width without a gap. Allowing the head some independence **is** therefore the reason for the stability gain.



20m Serpent with gap to tail- no weaving improvement over no-gap full width attachment.

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A "Y" bridle can be used to attach a tail so that the degree of rotational independence allowed to the kite is adjustable. This is particularly useful when trying to find a window between weaving and leaning over. For many kite types, allowing no rotational independence can cause leaning over and even diving over in strong winds.

Summary (caveats apply):

Single line kites can only fly if their centre of gravity is below and behind where the lift forces act. The weight force pulling downwards against the lift force pulling up, points the kite upwards.

Kites scale provided their weight/area remains fairly constant- except for SSSL's.
Kites with substantial lateral area are resistant to **weaving** instability.
Kites with VERY large righting moments are resistant to all types of instability.
Weaving instability is a function of lean – a kite that remains vertical will not weave.
Short tails cause less **leaning over** than do long tails with the same weight and drag.

Kites with small righting moments and little lateral area:

Will tend to **dive over** if their lateral area disposition is rearward,
Will tend to **lean over** if lateral area disposition is forward.
Will **lean over** if their aspect ratio is too high.
Will be **weaving** unstable if their aspect ratio is too low.
Will be less **weaving** instable if tails are attached to allow some rotational independence.

This is my understanding of single line kite instability at present. I've noted uncertainties and doubts and I'll revise it when I find inconsistencies and get new insights. Critiques are welcome, especially examples of kite behaviour that don't fit- because this is how theories improve. More experimenting is needed to verify some bits- which I'm doing all the time- and inevitably some of the theories above are likely to be wrong or at least incomplete.

Peter Lynn, June 2023

PS: Why do Chinese dragon kites fly? Aagh!.

Multi cell Chinese dragon kite- is it one kite or many?