How Kites Fly—George Webster

1 Introduction
When I first realised that I was going to write a series of articles that together would be a fairly comprehensive approach to studying the single line kites that might be seen in the sky, I thought that a brief section on tails would be worthwhile. If it were at the end (tail-end, but let it pass), so much the better. That appeared with the last Kiteflier.

I was determined NOT to write on how to make kites, the kit needed to fly them and how kites fly. I've kept the first two resolutions but felt that some treatment of what can go wrong with a kite might be helpful. This links with tails, as they are one of the common methods of dealing with problem kites as well as the main quick-change to the look of the kite which is open to the flier.

But writing on what can go wrong involved me in writing something about "how kites fly". So far so good; I learnt about Bernoulli and the 'Theory of Flight' when I was fifteen. But when I sent it to Ernest Barton to look at, he replied saying did I realise that most of what I had written was now widely thought to be rubbish.

So I did some reading and tried to re-educate myself. What follows in 2 is, I believe, the first treatment of (not so) modern flight in print, which is designed for kite fliers. Some of it is quite difficult and I am not sure how well I have explained what I know. So if something is unclear, do write in. I am sure that many readers know much more than me – let's hear from you.

This article comprises:
1 Introduction
2 How kites fly
3 Bibliography

My objective in all this is not to enable you to design or make a kite but to appreciate the designs which you see and, from this article, to have some helpful knowledge that will assist you in knowing what to do if things seem to go wrong.

My thanks to Ernest Barton for his double contribution to the article – he has done the drawings. Thanks also to Carolyn Swift for more than simply getting scrawl into a computer. The photos are by Malcolm and Jeanette Goodman.

2 So how do kites fly?
For convenience this section is split in two: **2.1 Lift** and **2.2 The Forces on a Kite**. The latter introduces drag even though drag and lift and are interconnected.

2.1 Lift. It is a commonplace understanding that a kite flies for the same basic reason as an aircraft or glider – that moving air generates sufficient lift to counter the weight of the aircraft/kite. Lift is defined as an upward force at right angles to the horizontal direction of flight. The difference is that the aircraft is moved through the air by some sort of engine (or in the case of a glider by using a gentle dive or rising hot air to generate forward movement), while the kite is held in the airstream (wind) by line and bridle.

The theory of flight has been developed to explain how aircraft fly; while its principles apply to kites, there are some obvious differences between the two.

Kites operate at very low wind speeds compared to aircraft. Most kites can fly at 12 mph, some at 4 mph and some as high as 30 mph. Sudden wind gusts can double the speed of airflow across a kite; aircraft try to avoid this.

Most kites are very small in comparison to aircraft. This is important as lift depends on the relationship between the air closest to the surface of the wing and the wing itself and this relationship does not simply scale up or down.

Most kites are single skinned, aircraft wings have an appreciable thickness.

Kites are often flexible in either or both of the frame and the covering.

Kites may have complex shapes compared to an aircraft e.g. a Chinese bird or a Peter Lynn gecko.

Kites fly with, for their size, large rough features (e.g. ties holding spars together) – although a look at some of the underwing armament of ground attack aircraft weakens the comparison.

Some of the flying surfaces of an aircraft can be adjusted in flight by the pilot (or by remote control). Single line kites in flight can be adjusted only by shortening or lengthening the line – which is closer to the pilot's engine control.

We will come back to some of these differences later on, but now lets get into 'the theory'.

Generally in science we want a theory to explain what we observe and, for it to be useful, to predict what will happen if a situation changes. For most thinking kitefliers (that's why you are reading this bit) there could be three approaches.

A) The use of 'real-life' photos and measurement which show us what is happening.
B) A set of formulae and equations (or 'maths') where you put in some figures and the computer then calculates the required result so with a given wing shape etc and angle of attack you can calculate lift.

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C) A logical approach which explains what happens without using maths.

We will be using approach C; although there is some interesting evidence (A) to which we will refer. We will be simplifying the approach found in aeronautics texts, partly because there are issues important for aircraft but not for kites, partly in the hope that a simplified accessible approach is possible. I remember 'it is better to be roughly right than to be precisely wrong'.

In **Bernard & Philpott** (see Bibliography) there is the following statement on page 1;

"Many years ago, someone thought up a convincing, but incorrect, explanation of how a wing generates lift……. it is probably true to say that most of the worlds aircraft are being flown by people who have a false idea about what is keeping them in the air."

This false explanation uses Bernoulli's Theorem which can be roughly stated as 'for a gas (air) or liquid, higher speed will be associated with lower pressure'. Bernoulli's Theorem is correct and can be demonstrated by the behaviour of shower curtains in a bath. Turn on the water and the flow from the shower causes air each side of it to flow downwards. This faster air pulls in the shower curtain as air pressure is lower inside the bath and the curtains appear to want to stick to the person in the shower. The theory is not sufficiently good to explain why it is more likely to happen in a strange hotel of questionable cleanliness.

How Bernoulli's Theorem produces lift is shown INCORRECTLY in Drawing 1. This shows a fairly typical aircraft cambered wing, i.e. curved top surface, flat lower surface. We visualise flight as being an airflow over the wing from left to right (which easily translates into a stationary kite with a wind). In Drawing 1 look at two particles of air at A which divide, with the top particle at A going over the wing via B before being re-united at C with the particle which went under the wing.

Clearly the particle which went above the wing has further to go and must therefore travel faster to meet at C. Faster speed means lower pressure above the wing therefore lift is the result of such pressure difference and in a sense the wing is 'pulled' up. Persuasive and WRONG.

The first objection and the clearest is seen by looking at Drawing 2. There is no reason why the two particles of air should reassemble above each other after passing around the wing (sometimes called the assumption of Equal Transit Time. The alternative name is Hump Theory). So the upper and lower particles could be in any relationship by point C. Since there isn't a race with the finish at C the upper particle could proceed at the same speed as the lower one and be well behind at C. In fact upper speed **is** faster than below, as Drawing 2 shows **but** we will discover later that this is the **result** of lower pressure not the other way round. Remember Bernoulli's Theorem doesn't state which causes the other, speed or pressure.

Another objection to the Bernoulli Theorem approach comes from looking at real aircraft. Most aircraft can fly upside down, even those with the Hump wings in Drawings 1 and 2. Stunt aircraft often have wings which have symmetrical top and bottom surfaces.

But whichever way up they fly, they do so with an angle between the wing and the airflow which we will call the Angle of Attack (see Drawing 11) sometimes called the Angle of Incidence (drawing 4). Whatever the cross-section of the wing an Angle of Attack is necessary for flight in practice, whereas if Hump Theory worked both drawings in D3 would show a wing producing lift. Thus, even flat wings produce lift at an Angle of Attack.

Apart from observing how aircraft fly, there is other evidence to show that air does not behave in accordance with Hump Theory. There are some 100 year old French photos which show the flow behind a thin wing as being chaotic not à la Hump – I can't find them at the moment but I will get to them in a later magazine.

Secondly, Drawing 4 is a version of one found in Anderson & Eberhardt (see Bibliography) which shows not just faster flows above the wing but some slowing down of the below-the-wing flows (look at the wiggle in the second set).

At this point let us consider an experiment illustrated in several texts and designed to show how the faster airflow over a top surface **produces** lift by reducing pressure. Drawing 5 shows it. Take a thin piece of card, curve it as shown and hinge it (e.g. round a pencil). Hold it close to the mouth. Blow over the top surface as in Diagram A and the card will move upwards which Hump Theory explains by higher speed causing lower pressure.

BUT if you hold the card as before but blow over the **lower** surface as in Diagram B the card does NOT now move downwards in response to the lowered pressure but does what you probably thought would happen before you read this and again it

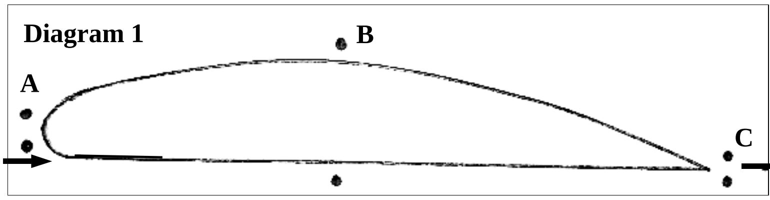


Diagram 1

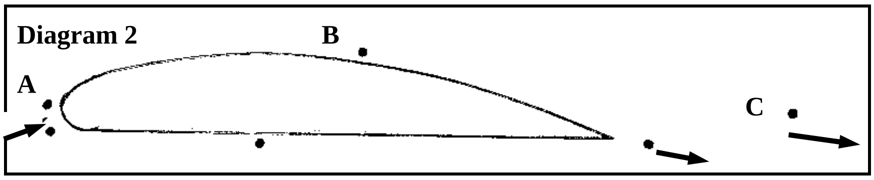


Diagram 2

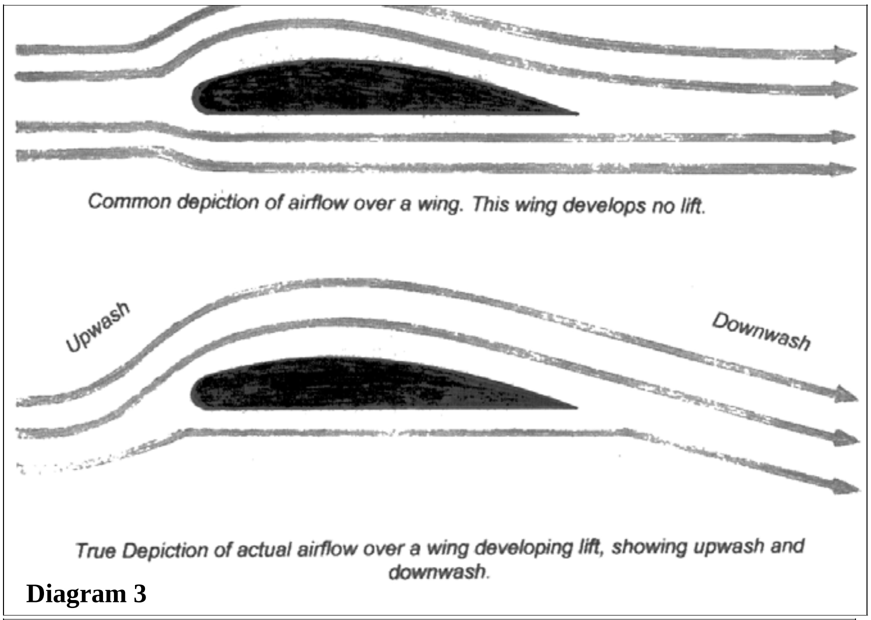
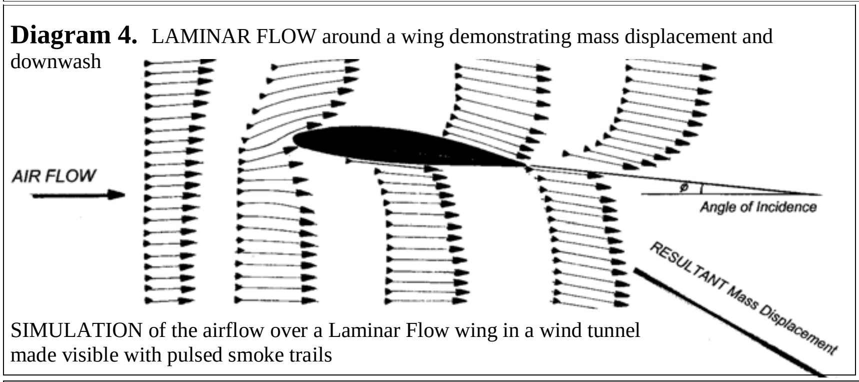


Diagram 3

Diagram 4. LAMINAR FLOW around a wing demonstrating mass displacement and downwash



SIMULATION of the airflow over a Laminar Flow wing in a wind tunnel made visible with pulsed smoke trails

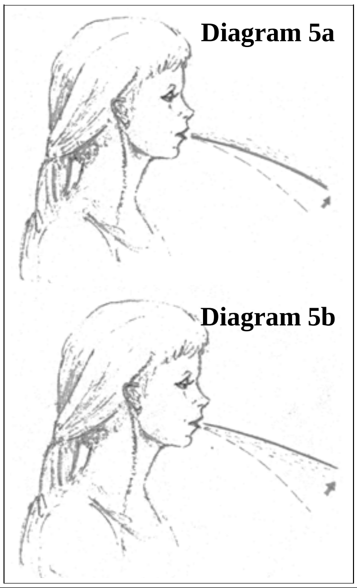


Diagram 5a

Diagram 5b

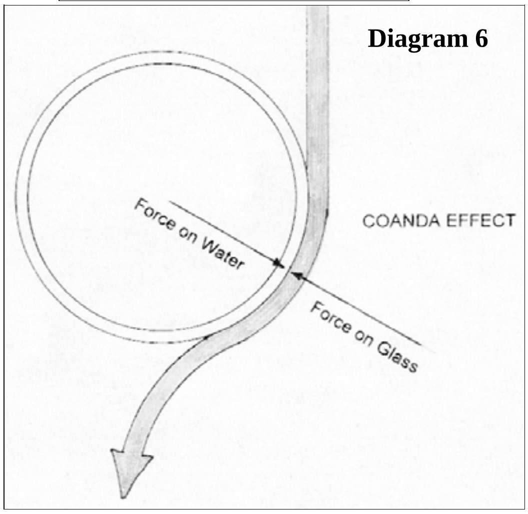


Diagram 6

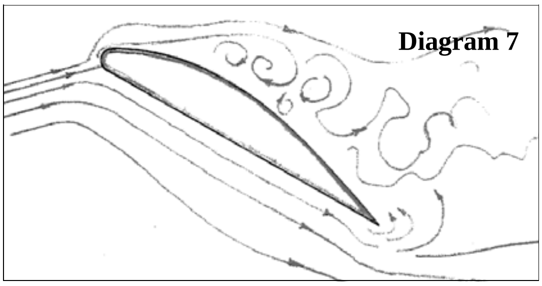


Diagram 7

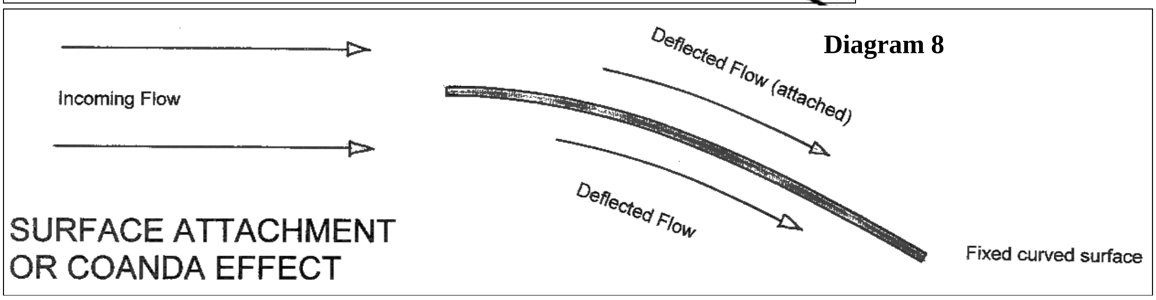


Diagram 8

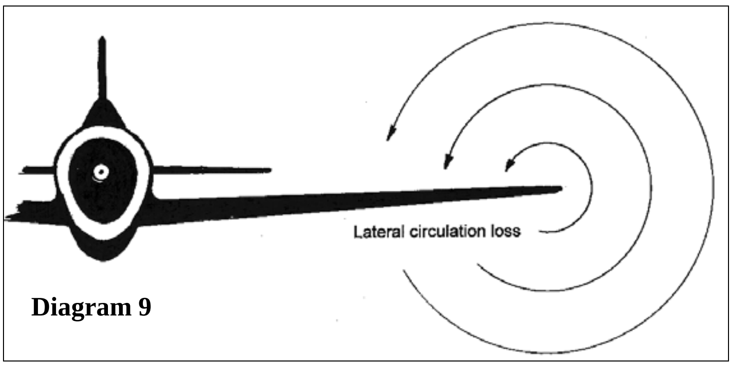


Diagram 9

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moves upwards.

One last relevant piece of evidence. If you measure pressures at points several feet above and below an aircraft wing in flight, the lower pressure above extends several feet above the wing (I believe 18 feet in the case of a large aircraft). The low pressure is not a local feature close to the wing. Aircraft shift large quantities of air downwards (causing the pressure drop).

They have to do that to produce lift as big as their weight. Kites with their very light weight can be ineffective compared to aircraft, they don't have to generate much lift.

The Newtonian Approach
Now for the CORRECT explanation. To explain what happens when air hits a wing we simply need to go back to Newton's Laws and to add something called the Coanda effect. Oh, and consider the effect of vortices and why soaring birds have separate strong feathers on their wing tips.

Sir Isaac Newton (d.1727) formulated laws of motion which are still valid and can be stated as:

First Law: The velocity of an object (which could be zero i.e. at rest) changes only when acted on by a force.
Second Law: A body acted on by a force will accelerate at a rate determined by the size of the force of the mass of the body.
Third Law: A mass will resist acceleration with an equal and opposite force (we all know that the recoil from a gun is linked to the size and speed of the bullet).

Newton made his own estimates of the upward force (lift) which would result from air striking an inclined plate (e.g. a flat wing with an angle of attack) but he seriously underestimated the lift, basically for two reasons. Firstly he thought that only a narrow stream of air would be affected rather than the deep flows moved by an aircraft's wing.

Secondly he didn't know of the Coanda Effect. Drawing 6 shows the Coanda Effect (the tendency of fluids to follow a curved surface) which can be demonstrated by running a thin stream of water over a tumbler and watching how it follows at least part of the curve. At a stronger flow it will at some point 'break away'.

Applied to aeronautics and put simply, air - like water – has a viscosity or 'stickiness' when it comes into contact with a surface. You could try to explain it in an approximate way by saying that whereas Newton envisaged air as a series of pebbles which could bounce from an angled wing, air in practice bends and sticks to the wing's surface and will follow the downward pointing trailing edge and so greatly adds to the lift.

Back to the airflow over a cambered wing. If we were able to look at the flow at a low angle of attack we would find that the air parts just below the leading edge so that some moves forward and up and over it. However the main bulk of the top of wing flow follows the slope downwards at the trailing edge. This downward flow, by Newton's Laws, has an upward reaction which pushes up the wing (lift) so the wing mainly diverts air downwards for lift. There is then a cycle of downwash at the trailing edge and air speeding up into the area of curved airflow above the surface.

The angle of attack is important. As it is increased there will come a point (drawing 7) at which the top flow is asked to bend too much and breaks away into chaos – with a sudden reduction of lift and increase in drag called a stall. For some wing shapes if the angle of attack is increased still further the turbulence dies down and once 'through the stall' the lift rises again and might even be at its highest. It is said that many kites fly above the stall. Certainly many kites fly at 20/30 degrees angle of attack whereas 5 – 15 degrees is more normal for wings before they stall.

For a given wing cross section (or shape), lift depends on the angle of attack and airspeed. What about 'thin' or single surface wings as are common with kites? Well Drawing 8 shows how a curved plate may be very efficient at producing downwash at the trailing edge and many singled skinned kites curve in the wind. But even those which are made of a rigid material or are strongly tensioned will divert the air necessary for lift – early aircraft wings were thin. Incidentally this made them weak structures (sometimes with fatal results) and promoted bi-planes (ex box kites) which enabled inter-wing bracing.

Before leaving wing cross-sections remember that aircraft with the cambered wings of Drawing 1 can fly upside down. They simply fly at such an angle that the inverted wing has an angle of attack (even though the Hump Theory says the air should take longer over the lower surface). I am reminded of Flexifoils which have a section that can look 'upside down'.

As we know, the downward flow of air from the rear edge of a wing is associated with lower pressure. This causes a movement forwards from air

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just below the leading edge which reduces lift and by giving forward thrust is a major component of drag. However the major effect of this air movement is at the outside edge of each wing in an aircraft (Drawing 9). At these points air from below seeks to move inboard along the top of the wing. This produces the vortices shown in the drawing. These are sometimes seen behind wing tips at air displays (they are NOT the vapour trails from engines at high altitude).

Because they reduce the amount of the wing producing downward thrust and lift they are undesirable. The simplest way to reduce their proportionate effect is to have wings which are wide but narrow. Such wings have a High Aspect Ratio. Aspect Ratio is measured by span divided by chord. Aircraft design, like any other man made object, is a series of compromises. High aspect ratio is found in sail planes and high altitude ultra long-distance aircraft where high speed is not required and the problems of making such wing strong are not so acute. Generally the higher the speed the lower the aspect ratio. This works for birds; those which soar, glide and cover great distances have high aspect ratio wings (buzzards, condors and albatrosses) whereas sprinters have short stubby wings (e.g. grouse and ducks). I am aware that swallows are fast flyers but they also fly for long periods of time and use swept back wings – outside this section's scope. Incidentally there are very few swept wing single line kites.

Compared to aircraft, kites have low aspect ratios – often in the range 1:1 to 2:1. Some deltas are 2.8:1, Genkis 3:1 plus. The limit to the aspect ratio of a delta is probably the engineering problem of finding a wing cover which can cope with the spreader bar to leading edge low angle rather than the problems of instability.
The important effect of vortices explains why very low aspect ratio (or columnar) kites are difficult to design and fly – a high proportion of their lift is destroyed by vortices.

Lastly, soaring birds not only have a high aspect ratio but prominent stiff wing feathers (for some reason usually three, always an odd number) which serve to break up the vortex and may even be adjusted so as to provide forward thrust.

The term 'ground effect' is sometimes used by kite flyers as referring to the uneven rolling wind frequently found in the first few metres of a kite's launch. In aeronautics it has a different and quite specific meaning viz. the observable fact that an aircraft at its last stage before touch down suddenly develops greater lift and will glide with a very low rate of decent when very close to the ground. I have noticed that when deltas glide in on low wind speeds they will sometimes float above the grass for several metres. Ground effect is caused by the vortices illustrated in Drawing 9 being interrupted by the ground. No vortices results in more lift.

2.2 The forces operating on a kite
So far we have concentrated on lift and have rarely mentioned drag – which is the horizontal force on a kite in the same direction as the wind. While it is popularly thought to be caused by projections and roughnesses which interfere with smooth air flow, it is, particularly at the kites operational windspeed, largely **induced**.

By this is meant that the process of moving air round a wing close to its surface, with stickiness, means that there will be forward movements just under the leading edge as well as the vortices. A forward movement is drag and is induced by lift

However the Lift to Drag ratio is not constant and we know that at stall, lift plateaus or falls while drag increases very quickly. Drawing 10 shows the forces operating on a box kite.

The kite shown is being flown from one corner and has a very high angle of attack. This is a version of the diagrams in the Glenn Research Centre material which has a more extensive and detailed treatment of kite equilibrium. Very similar diagrams are in Van Veen , Wright and Wadsworth (see Bibliography 4).

For our purposes the important points are these:

The aerodynamic force on the kite is a combination of L (vertical lift) and D (horizontal drag). They operate through the Centre of Pressure. Its location for our kite together with L and D depends on airspeed and the angle of attack given by the bridle position.

W (weight) is a vertical downwards force which acts from the Centre of Gravity.
Where kites differ fundamentally from aircraft is the flying line. (Occasionally you hear of someone seeking to invent a kite without line. Impossible. Quite simply: no line, no kite). The line is connected to the bridle and at that point, which determines the equilibrium flying angle of the kite (see Drawing 10), there are two forces, horizontal pull (P_H) and vertical pull (P_V).
For the kite to be in stable flight the external forces must balance each other out, by Newton's First Law.

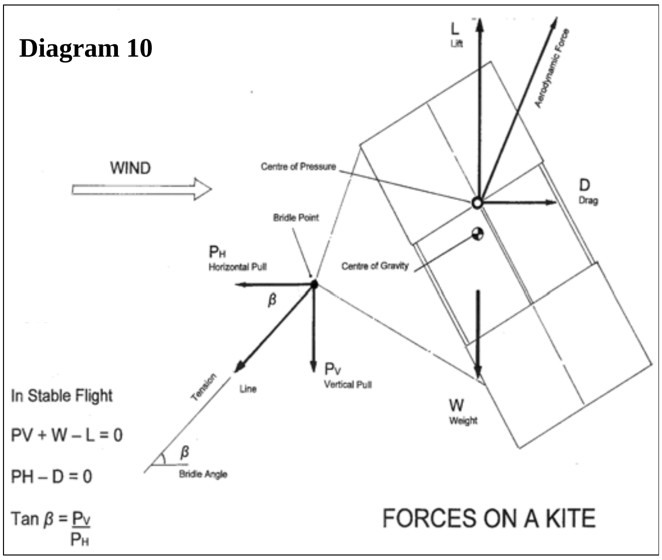

Diagram 10

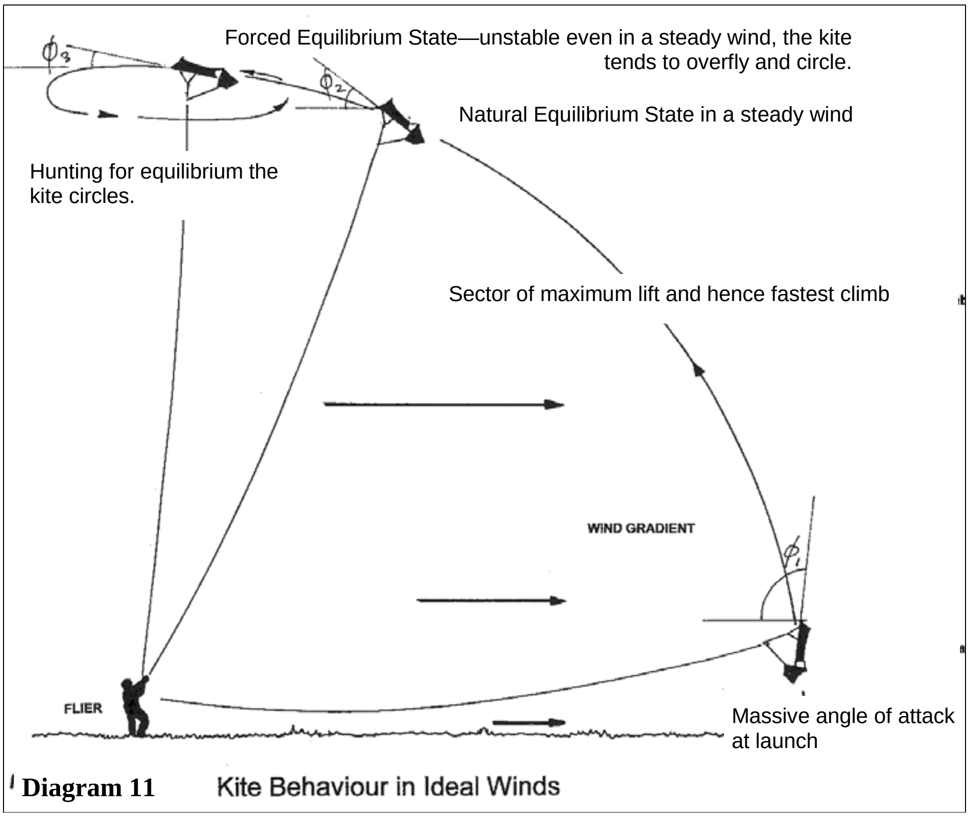

Diagram 11

So vertically the vertical pull is equal to lift minus weight.

or $P_V + W - L = 0$

Horizontally the horizontal pull will equal the drag.

or $P_H - D = 0$

What happens when the wind rises? Unless the kite is at its maximum flying angle the effect will be to increase L & D. The kite will rise as L is greater than W (weight) and the P_V. Line tension increases as increased D produces more P_H. The kite will move up its arc (Drawing 11) and change its bridle angle – the bridle point acting like the hinge on a trap door.

Notice that the centre of gravity of the kite doesn't change but the centre of pressure might. The importance of this is that for a kite to behave as we want the centre of pressure must be in front of the centre of gravity. If it is the other way round then the kite's nose will drop, the flier's control goes and it will glide. Many model gliders can be flown as kites – so long as the centre of gravity can be moved back. With kites if we want to deal with changes in lift through wind changes we alter the bridle point and thus the angle of attack.

2.3 Observation and some final thoughts

I've almost finished all I want to say about flight and the flying characteristics of kites. Early in 1, I mentioned the lack of visual evidence of what happens to airflows around kites. Basically aeronautics is not concerned with anything as small and slow as a kite and there aren't enough resources for much testing. There have been some UK tests of performance; Paul Chapman has reported somewhere about wind tunnel tests of Codys which had them flying in winds up to 60 mph.

Hopefully you can now look at kites in the sky with greater understanding e.g. why hexagons need tails, why Genki's fly in light wind, why bird kites work so well.

Look at the patterns made by lightweight streamers on the tips of a delta. Nicholas Wadsworth showed me an interesting experiment at Petworth this year. He thought of it, but you could reproduce it, perhaps on a different kite design. He took a white ripstop delta which was quite transparent in the air and pinned small (5 x 2cm) tabs of very light black polybag to the top surface. In flight the tabs close to the leading edge pointed forwards.

In the late 1970's Don Dunford (of Dunford Flying Machine fame) produced the Dixie, a 2-line kite roughly similar in shape to the Peter Powell. As he wrote (European Kiteflier May 1979) he wind tested the kite and found an airflow moving forwards up the centre back of the kite. He then put a piece of card on the top surface at right angles to the axis to benefit from the flow (Newton again) and found the performance improved.

Some final thoughts on why kites fly. A kite has to be able to achieve equilibrium in the set of forces shown in Drawing 10. The most difficult of these forces to understand is that of lift. Lift is the result of downward flow of air. I think the easiest way of accepting this is by considering the helicopter. A helicopter gets lift from its rotor which is a rotating wing. Like all wings this produces lift by directing

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air downwards with wing shape, cross section and angle of attack all important. Whether or not we have flown by helicopter we all know, because we have seen it on TV and film, that helicopters produce a strong downdraft – grass flattened, people holdings hats etc. Measure all that pressure downwards and you are measuring lift. If you could hover a helicopter over a giant weighing machine then the downward air, or lift, would measure the weight of the helicopter.

Secondly, you will know of the unusually shaped soft kites which have been designed. Does air travel further over the top than the bottom of Peter Lynn's Black and White Cat? Look at the photo of Anke Sauer's Jack-in-the-Box kite. Surely only diverted downward flowing air can explain its flight?

Finally, remember what we expect of a kite's flight. We require it to have an equilibrium point in the sky i.e. a position from which it will not deviate unless there is a change in the forces acting on it. Principally this will be the wind – its speed, smoothness etc., although it could be line pressure (line being let out or pulled in).

As we have seen working the line may be necessary to help the kite stabilise. Indian Fighter Kites can be moved around the sky using only line pressure.

We expect a kite not only to have equilibrium but within certain limits to be stable if there has been a change in a force i.e. to find a new equilibrium. In most cases we require the kite not to be too particular in its requirements e.g. not to only find stability in a narrow range of windspeeds.

Some of these issues will be looked at in the next section.

3 Bibliography
General kite books

Pelham has a good section on lift and stability
Maxwell Eden has a chapter on aerodynamics and another on correcting problems.

Kite books on the theory of flight etc
Don Dunford 'Kite Cookery' Cochranes 1977
The only book with a prime aim of enabling you to design a kite. Written by the inventor of the Dunford Flying Machine. Details of how to make 4 kites – this was the age of tape and plastic.
Ito T. and Makura H. 'Kites, the science and the wonder.' Tokyo 1983
Some of the maths and geometry is very difficult, strange terms are used and the practical value of the conclusions is small. Much of the book is devoted to 21 animal shaped kites which actually look more Chinese than Japanese and don't closely resemble western kites.
Van Veen H. 'The Tao of Kite Flying……' Aeolus Press 1996
Interesting, brief and difficult, published by the Kitelines team. Has a famous Stabilising Feature Table. Particularly good on the implications of changing the size of a design.
Chris Wright 'Kite Flight. Theory and Practice' Middlesex V.P. 1998
Difficult (face it; this is inherent in the subject). Has a very complete 'fault chart'. Some odd views (e.g. on deltas). A good range of things to do to get a kite to fly better.

Articles in Kite Magazines
Nicholas Wadsworth 'Why Won't it Fly' Kiteflier No 91. Good on forces which affect a kite with an emphasis on the importance of weight.

But I don't know of much else. Do you have any suggestions?

Aeronautics
Bernard R. and Philpott D. 'Aircraft Flight'. Longman 1989 Chapters 1-4.
Craig G.M. 'Stop abusing Bernoulli'. How airplanes really fly. Regenerative Press 1997
Craig G.M. 'Introduction to Aerodynamics' Regenerative Press 2002

Glenn Research Center 'Beginners Guide to Aerodynamics' by Tom Benson http://www.lerc.nasa.gov.
Can be followed into kite applications
The Physical Principles of Winged Flight http://regenpress.com
Soon gets difficult but the best simple statements of Newton vs. Bernoulli.
A Physical Description of Flight by D Anderson and S Eberhardt. http://www.aa.washington.edu/faculty/hardt/lift.htm