CHAPTER 13 *How Kites Fly*

1 Introduction

When I first realised that my series of articles was going to grow into a fairly comprehensive approach to studying single line kites in the sky, I thought that the only addition necessary was a section at the end (tail-end) on tails. I was determined *not* to write on

- how to make kites
- kite equipment
- how kites fly

But I broke my third prohibition and wrote such an article partly because I felt a knowledge on 'how' would help in deciding what to do if a kite wasn't flying well. Then I discovered that the 'Bernouilli' of 'Hump' theory of flight was largely rubbish. Then I tried to explain all this — but didn't do it very well.

So much of this chapter, particularly dealing with lift, is quite different from anything I have written before on the subject.

The chapter comprises

- Section 1: Introduction
- Section 2: Simple kite aerodynamics
- Section 3: Lift
- Section 4: Simple summary of aerodynamics
- Section 5: Back to kites

There are three reasons for my approach:

1) Aerodynamic theory has only a partial application to kites — essentially because kites are not simply tethered gliders. To emphasis this: a kite flies above the source of the line, unlike a glider which is descending throught the airstream. A kite moving forward against the airflow is behaving like a glider and is in most circumstances out of control.

2) There is a lot of very difficult stuff, some of which I don't perfectly understand, and much of which is very hard to explain in simple terms.

3) Anyway, understanding flight theory is not essential to having an appreciation of how your kite is flying and what to do if all is not well.

However, there is a section (3) on Lift largely because I can't bear to think how many kitefliers think they know how aircraft fly — but don't.

2 Simple kite aerodynamics

Let us start off with a kite K which is 'flying stably' at the end of a line GK. Diagram 1 shows the situation in two dimensions.

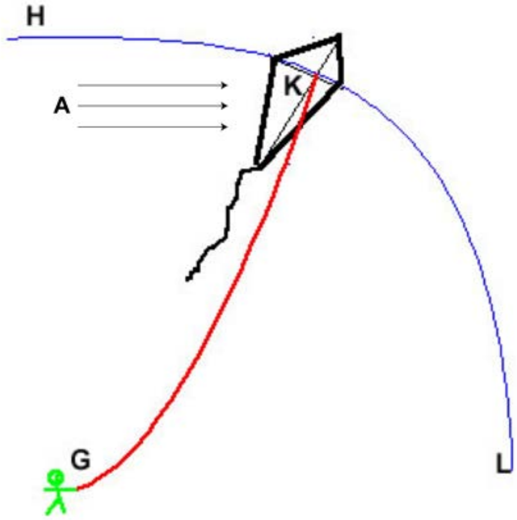

Diagram 1

The kite is a simple flat kite which is flying directly downward of the airflow A. The line GK will never be straight as there will be a downward curve depending on the weight of the line, drag on the line due to A and the 'pull' of the kite (i.e. how tight the line is).

By 'flying stably' is meant that the kite is in balance, i.e. if the forces acting on it don't change it will not change its position. 'Stably' also means that if the forces do change it will seek a new equilibrium position. The kite will have its equilibrium position somewhere on the arc HL. Note that we are in a two-dimensional world, i.e. K can't move off the surface of the page. It is possible that A might change so that there is no longer an equilibrium flying position (e.g. A drops to zero). The kite will always be on HL because the line stops it climbing or drifting downwind. If it moves upwind from HL it is overflying or gliding to the flier G — this occurs when the centre of gravity moves forward of the centre of forces (see the end of this section).

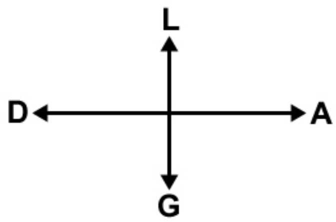

Diagram 2

Diagram 2 identifies the four forces acting on a kite.

G = Gravity. In some kites the centre of gravity is the point at which the kite balances on a finger. In other cases it may not be 'real'; e.g. for a regular 2-cell box it will be halfway between the cells in the middle of the 4 longerons. I don't propose, not even for one moment, to consider the centre of gravity of a Manta Ray.

L = Lift. This is the most difficult force to explain and has its own Section 3 below.

A = Airflow (or wind). It is often said that the airflow across a kite has the same effect as the thrust from an aircraft's engine or that a glider moving at 25 knots equals a kite in a 25 knot airflow.

Any wing (or kite) moving through an airstream ('flying') does so with the wing having an Angle of Attack α to the wind — see Diagram 3.

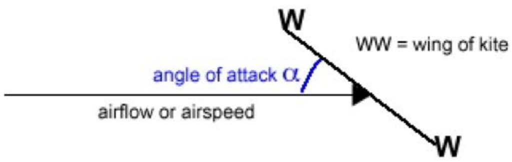

Diagram 3

However (1), pilots can vary the angle of attack of an aircraft, but it is usually very much smaller that that at which kites fly. K's angle of attack will be affected by where it is on HL, with high angles towards L and low angles towards H. Kites may have their angle of attack preset, as when a two-point or other fore-and-aft bridling system is used. But many kites have a single point bridle which may even be, as in the case of some boxes, at their leading edges so that the kite has a 'door hinge' rather than a normal pivot.

However (2), even smooth winds are prone to quick and unforeseen speed variations compared to engine thrust.

However (3), winds are often turbulent and gusty at the low heights at which most kites operate.

D = Drag. Drag is a force which works against A.While it is popularly thought to be caused by projections and roughnesses which interfere with smooth air flow, it is, particularly at the kite's operational windspeed, also partly caused by the process which provides lift, as will be explained later.

Diagram 4 shows the forces operating on a box kite. This is a version of the diagrams in the Glenn Research Centre (www.grc.nasa.gov/WWW/K-12/airplane/bgk.html) which has a more extensive and detailed treatment of kite equilibrium. Very similar diagrams are in Van Veen [3], Wright [4] and the article by Wadsworth *Why Won't it Fly* in Kitelines vol.91 (April 2000).

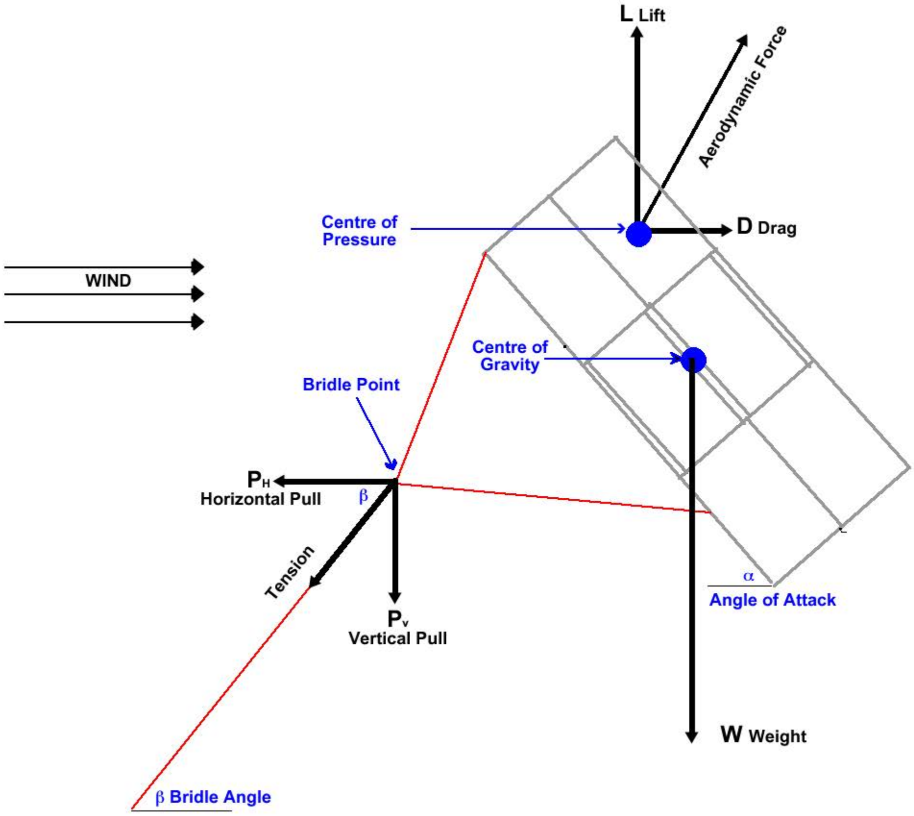

Diagram 4

The kite shown is being flown from one corner and has a very high angle of attack α.

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, 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.

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 (Diagram1) and change its bridle angle – the bridle point being the point around which it swivels.

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. If the centre of gravity was higher than the centre of pressure then the kite would be unstable.

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.

A frequently used term, which can be explained in our two-dimensional world, is Lift/Drag ratio. The kite will move up and down HL (see Diagram 1) depending on its lift/drag ratio. The higher the ratio, the higher the point at which the kite will be in equilibrium. Since a high flying angle (the angle the line make with the ground, measured above the horizontal) is generally though desirable, a high lift/drag ratio is a good design feature. However, the lift to drag ratio is not constant and we know that at stall, lift plateaus or falls while drag increases very quickly. (See Section 4 below.)

3 **Lift** (or the nearest to aerodynamics we are going to get)

3.1 Newtonian theory

The first 'scientific' analysis of lift and drag was made by Newton in the 18th century.

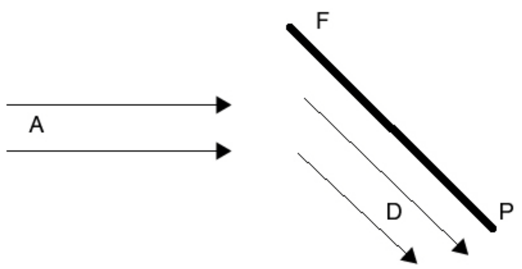

Diagram 5

He considered a measured airflow A hitting an inclined flat plate FP with D being the resultant downwash.

However, his calculations of lift from such a process were too low because

— he ignored the flow of air above FP

— he didn't realise that the area of air affected was greater than the area of his airflow

— he wasn't aware of the Coanda effect (see below)

— he didn't consider the effects on lift of using not a flat plate but a curved or cambered airfoil.

That his calculations of the relationship between A and lift were too low was historically important because it led to the view that an engine could never produce enough thrust (for A) to generate lift greater than the engine's weight and that therefore powered heavier-than-air flight was impossible. Nevertheless the Newtonian approach is still seen as a powerful one in modern aerodynamics.

3.2 post-Newtonian theory

Modern theory –about 100 years old but not readily available to kitefliers– makes use of Lanchester's Vortex System, and the easiest way into that is via the Magnus Effect. Some rotating kites (see Chapter 10) fly by using the effect directly, so at least we can now explain how they do it.

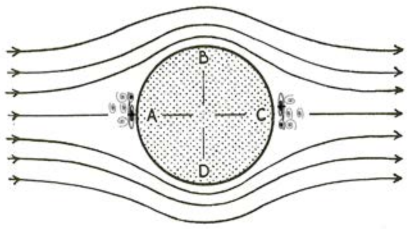

Diagram 6

Consider a solid cylinder fixed across an airstream. What is of interest is the extent to which airstreams follow the edges of the cylinder (e.g. at B and D) before breaking away and continuing the straight flow. There is also an area of chaotic movement at A and C directly in front of and behind the cylinder. In these circumstances, Diagram 6 shows drag but no lift.

Now allow the solid cylinder to rotate clockwise as shown in Diagram 7.

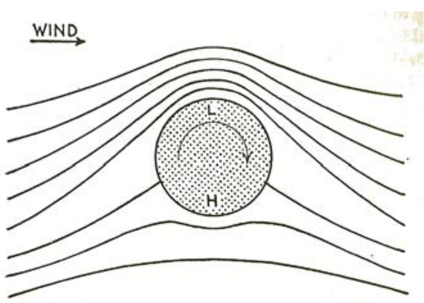

Diagram 7

The speed of the airstreams at L will be increased by the additional forward speed of the rotating surface. Conversely, at H the airstreams would be slowed down by the rearward movement at the surface of the cylinder.

Now there is a 'law' called Bernouilli's Law (or Theorem) which when applied to airflow past a point asserts that higher speed will be associated with lower pressure. Bernouilli's Law is very well established but doesn't claim to explain causality (i.e. whether the speed causes the pressure or the pressure the speed).

In our case it means that the rotating cylinder in Diagram 7 will have lower pressure above (higher airspeed = lower pressure) and higher pressure below (lower airspeed = higher pressure); so the two effects added together will produce lift. This is the Magnus effect, named after the German physicist Heinrich Magnus who described it in 1852 (though Newton had observed it and correctly inferred the cause in 1672). (Note that a rotating cylinder in a steady airstream is the same as fixed cylinder in an airstream which is made to rotate round it; this will become important later.)

Let us now introduce the idea of a 'boundary layer' — the phenomenon that close to any surface which has air passing by it, the air closest to the surface will behave differently. It is easiest to think of this as a layer which sticks to the surface, to an extent dependent on the nature of the surface and the viscosity of the air. The boundary layer is very thin, no more than 2.5cm. on a large aircraft wing.

This is related to the Magnus effect in a number of ways.

(1) The relationship between air on the surface of the cylinder and the rest of the airflow. We don't need to go into this except to note that roughness and irregularities are not necessarily a bad thing. Thus dimpled golf balls fly further than smooth ones. Providing lift by backspin to a tennis ball is helped by the hairy surface. There is a lot of information now available on the importance of the seam on swinging cricket balls.

(2) Then there is the Coanda effect, named after Henri Conda who survived a nasty accident in Paris in 1912 when flames followed along the surface of an aircraft which he had designed. He later became the Chief Engineer of the Bristol Aeroplane Compaany. In Diagram 7 the effect of air movement close to the surface will be related to the length of contact (as shown in Diagram 6). Air behaves in a similar way to water — Diagram 8 shows how a stream of water falling on the side of a glass is deflected by the Coanda effect.. Or slowly overfilling a wine glass will result in the liquid running down the side instead of cascading. We can think of an airstream even in a Newtonian situation (Diagram 9a) as being deflected yet still following the surface. The effect will be much greater if the surface is curved (cambered) and so by giving the air less sharp corners it will be less likely to break away (Diagram9b).

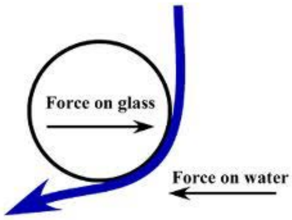

Diagram 8

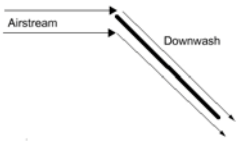

Diagram 9a

Diagram 9b

(3) We have the drag caused by the chaotic airflow behind the cylinder. Some turbulence in the airflow as it meets with the boundary layer (golf balls) is desirable as it helps the Coanda effect.

Another relevant concept or measure sometimes introduced at this point is the Reynolds Number. This measures the tendency of airflow to develop turbulence as it passes a smooth surface. Without going into the actual formula, one result is relevant to kitefliers. The length of the path of the flow/surface contact is important and thus some kite designs cannot be scaled up or down by a large factor without adversely affecting the aerodynamic performance.

While George Cayley (1773-1857) knew of the pressure differences above and below an airfoil, there have been two approaches after Newton's to explain how it occurs, and why the effect is greater than Newton calculated.

Fiirstly we find what is often called 'Bernouilli' or 'Hump' theory. Diagram 10 shows how two particles of air T and U, which are above each other, encountering an airfoil will have travelled different distances before being reunited behind it at T_1 and U_1. The particle going over the 'hump' will have travelled further and therefore must have been moving faster. Higher speeds means lower pressure above the airfoil, and this results in lift. Despite being a favourite in kite books, this is unconvincing in many ways.

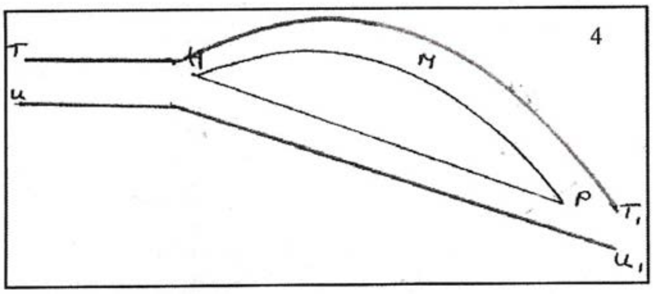

Diagram 10

Why should the two particles rearrange themselves one above the other at the end of the airfoil? If they don't, no speed difference and no lower pressure.

Why are some wings symmetrical above and below their centre line — surely this would mean no net lift?

Why can almost all aircraft fly upside down, when the hump would be the wrong way?

Why do all airfoils need a positive angle of attack to produce lift? Hump theory doesn't need this.

Measurements to establish how much extra distance would be needed for the path of the upper of the two well-behaved particles to generate enough lift for an actual aircraft require extremely 'thick' humps. For eample Craig [7] shows that for his Cessna aircraft at a minimum airspeed of 60 knots the upper surface path would need to be more than twice that of the lower path to produce lift in this way; in his case the actual measurements differ by less than 2%.

Far better is what is sometimes called 'Modern Theory' arising from Lanchester's Vortex System, as developed by Prandtl, Kutta and Joukowski (for those who like to google). I'll look at a simple view of Lanchester's insight that an airfoil moving through air creates a system of vortices. Then I'll sum up what we need to know about lift.

I'll start by considering the side view of an airfoil as an aircraft moves forward and starts to generate lift. The airfoil is drawn in the typical conventional shape with an angle of attack to the airflow. A wing section which had a curved profile was known in the late 19th century but at that time cross-sections were thin as it was thought that the 'cambered' shape had to have a curved lower edge. I'm still simplifying by imagining that the wings are infinitely wide (wing tips are introduced below).

As the wing moves forward in Diagram 11, the airflow will produce for a short time an area of stagnant air just above the trailing edge. Air will move round towards it from the underside — towards higher pressure (slow-moving air). In turn, this causes a vortex, or rotary air system, which will quickly be shed from the trailing edge (and this is the start of the turbulence behind the wing of an aircraft, associated with drag). That first vortex is inevitably associated with a vortex in the reverse direction –that is how vortices operate (conservation of angular momentum)– which will take the form of circulation around the airfoil. This is the Magnus effect and causes lift.

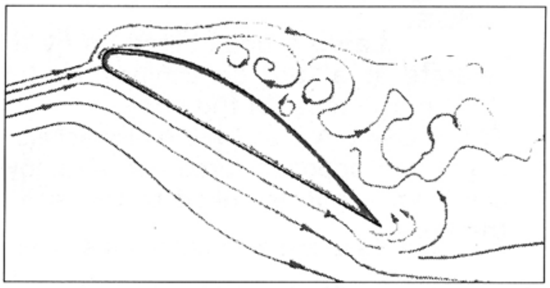

Diagram 11

Finally I'll relax the assumption that the airfoils (wings) are infinitely wide. Lanchester realised that air moving from high pressure to low pressure would do this at the wing tips by vortices, with the twin results of reducing lift from part of the wing and increasing drag. See Diagram 12.

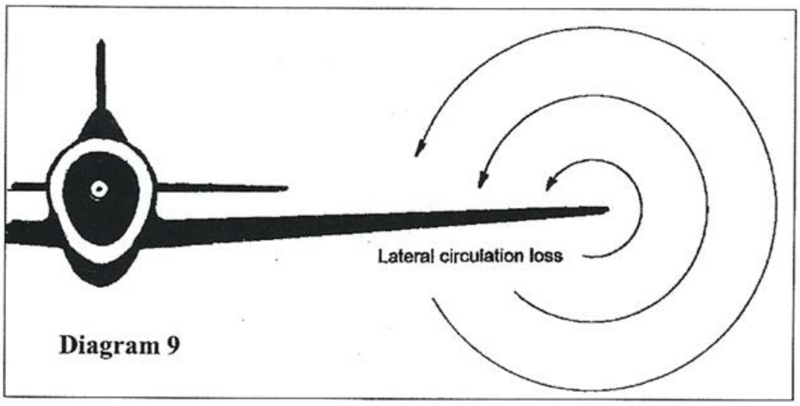

Diagram 12

Some examples of this are:

'Ground effect' when an aircraft lands and, just before touching down, experiences increased lift as the vortices can't form because of lack of space below the wings. Those of us who fly deltas will know that when they glide in a very low wind they will sometimes skim the grass for several metres glorying in the absence of vortices.

There are other ways of trying to reduce the impact of wing-tip vortices. Soaring birds have wing feathers which protrude at the tip to break up the vortices. Some aircraft have fillets near the wing tips.

Another solution is to design very wide wings with proportionately small wing tips, i.e. having a high Aspect Ratio (roughly wing span/chord or breadth of wing, as used in gliders). It is well known that such kites have the best light wind lift performance (e.g. Genkis).

4 Simple Summary of Aerodynamics

Lift is a process which clearly shifts the airflow downwards with Newtonian effects. For the pressures involved in kite flight, air is considered incompressible. When air is accelerated over the top of the leading edge and down, it must be replaced. So some air must be shifted around the wing (below and forward, and then up). At the same time the pressure differences rely on the circulation or flow of air close to the wing surface. Diagram 13 shows a heavily simplified view of the circulation and vortices arising from an airfoil AA producing lift.

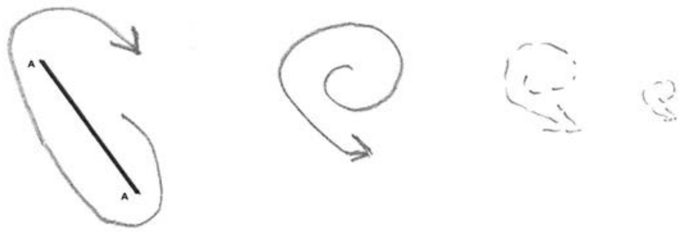

Diagram 13

In all the diagrams in this chapter the airfoil, wing or kite operates with an angle of attack (Diagram 3). This is physically necessary for the Newton and Lanchester accounts, but whatever the theory, the practice is very clear: no angle of attack, no lift.

Considerable work has been done on the relationship, for any given airfoil, between A (windspeed), α (angle of attack) and L (lift/drag ratio). In general, increasing α from a very low number will lead to an increase in L up to a point at which there is sudden and considerable loss of lift. This is the point at which it stalls. In some cases, going beyond this point will lead to L increasing once more and it is said that some kites will fly above the stall angle.

Similarly, varying A will give a stall speed. Aerodynamic stalling occurs when the flow of air around the wing breaks up through too large a change in direction, meaning that circulation and smooth downwash no longer occur.

If you are still a believer in simple Hump Theory then consider this.

A helicopter flies by getting lift, and forward motion, from rotating wings which produce enormous downdraft. If the important effect was a Bernouilli loss of pressure above then they would be designed with a circular plate equal in diameter to the rotors and fitted below them to stop the downdraft which causes problems for the hair and hats of those who stand near to them.

Although kites are rather removed from the world of machines which are usually bigger, move in greater airspeeds and have lift/weight rations unncessarily large for kites, yet the basic aerodynamic forces are just the same. Our problem is that kites really are unimportant compared to aircraft and have attracted rather little recent scientific work.

5 Back to Kites

5.1 in two dimensions

In our two-dimensional world shown in Diagram 1, the kite could only move up or down and this could be caused by

– a change in A leading to a change in lift/drag ratio
– a change in angle of attack α due to movement along H–L.

A special case is where the line length GK is altered by the flier. Shortening has the effect of increasing A and thus is used as a way of moving up a new arc HL; and in addition even the lower weight of line can be critical. Lengthening the line lowers the wind speed.

For a given kite, holding α constant, changes in A will cause the equilibrium point on the arc of the line AL to change. There will be a limit to A when its speed produces instability through imperfections becoming significant and by drag. Holding A constant and changing α will have a similar range of effects.

The equilibrium point will of course be the result of lift (and drag) versus gravity or weight. As mentioned earlier, a kite's angle of attack can be changed on the ground and may be changed in the air by the pivoting of a single point bridle. For most kites it is α which is of critical importance for lift.

5.2 in three dimensions

Now let our kite move from side to side, i.e. become three dimensional. The kite may move simply because the smooth airstream (A in Diagram 1) has shifted or because A is unsteady or has several sideways shifts. But kites have to deal with an airstream which may move quickly and unsteadily in three dimensions.

The kite can yaw, i.e. move from side to side (i.e. rotate slightly around a vertical axis) or roll (i.e. rotate slightly around a horizontal axis in the direction of the airstream) — see Diagram 14. A special case of roll is where a side by side bridle may hold the kite in a tilted position.

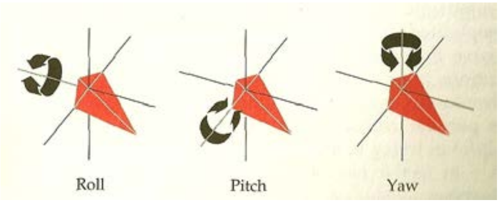

Diagram 14

Pitch (i.e. rotation around a horizontal axis perpendicular to the airstream) does not normally occur in kites unless the wind is turbulent and can be constrained by tension on the line.

We will look again at these in the context of faults and actions in Chapter 13, but there are some aerodynamic points to be made first.

While kites are designed to eliminate yaw and roll, the aerodynamics is complicated by the fact that they are often combined (e.g. wing tilts up (roll) and causes kite to yaw). A simple example: as a kite yaws, one wing moves forward compared to the other, has more A and thus changes lift which may produce roll. Lift is realted to A^2, whereas weight is constant. So the effect is magnified. If this causes the kite to move sideways then, since the kite is on a line, the weight force will shift in relation to lift (Diagram 15).

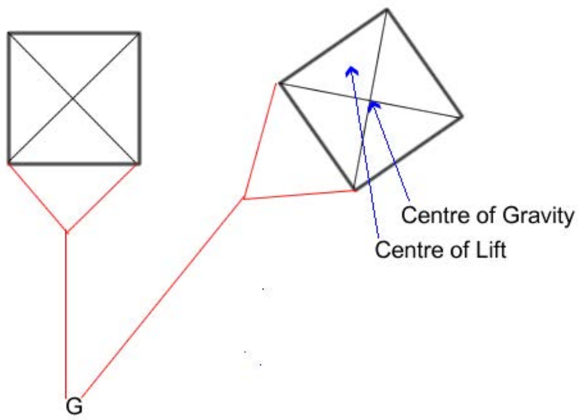

Diagram 15

How this relates to yaw and roll will obviously be complicated — see Nick Wadsworth's article in *Kiteflier* vol. 91 (April 2000).

A major simplification is to ignore timing. The forces sketched in here do not all happen instantly in reality. A single example is that gravity is constant but variations in lift take time to operate.

A final complication for the aerodynamics of a kite is that many designs have two or more lifting surfaces fore and aft, e.g. 2-cell boxes, rollers. The design has to consider the disturbed airflow which will usually be experienced by the rear cell. Why have a second cell (for example)? Single cell boxes will fly but on balance it is preferable to have the fore-aft stabilising factor (pitch and yaw) of the second cell.

6 Bibliography

6.1 General kite books

Pelham [9] has a good section on lift and stability

Maxwell Eden [10] has a chapter on aerodynamics and another on correcting problems.

6.2 Kite books on the theory of flight etc .

See the books by Dunford [5], Ito & Makura [6], Van Veen [3] and Wright [4].

6.3 Articles in Kite Magazines

Nicholas Wadsworth 'Why Won't it Fly' *Kitelines* no. 91 (April 2000).

Good on forces which affect a kite with an emphasis on the importance of weight.

6.4 Aeronautics

See the books by Bernard & Philpott [1], Anderson & Eberhardt [2] and Craig [7] and [8]. The best general reatment I know is Sutton [11].

6.5 Two from the Web

Glenn Research Center 'Beginners Guide to Aerodynamics' by Tom Benson http://www.grc.nasa.gov/WWW/K-12/airplane/bga.html. 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.

6.6 Book list

[1] Bernard, R. and Philpott, D. (1989*) Aircraft Flight.*

[2] Anderson, D. F. and Eberhardt, S. (2009*) Understanding Flight.*

[3] van Veen, H. (1996*) The Tao of Kiteflying.*

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.

[4] Wright, C. (1998*) Kite Flight, Theory and Practice.*

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.

[5] Dunford, D. (1977*) Kite Cookery.*

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.

[6] Ito, T. and Komura, H. (1983*) Kites, the Science and the Wonder.*

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.

[7] Craig, G. M. (1997*) Stop Abusing Bernouilli.*

[8] Craig, G. M. (2002*) Introduction to Aerodynamics.*

[9] Pelham, D. (1976) *Kites*.

[10] Eden, M. (1989) *Kiteworks.*

[11] Sutton, G. (1965) *Mastery of th Air.*