

The stability of early aircraft

Introduction

In the early years of aviation, much confusion surrounded the question of the stability of aerofoils and aircraft in general. Indeed, some of this confusion still exists in elementary articles on the subject particularly in regard to the question of where exactly on a wing the force of lift acts. For a symmetrical aerofoil the answer is simple. To a very good approximation, the force of lift acts at a fixed point called the *aerodynamic centre* of the wing – but the same cannot be said of the highly cambered, fabric covered aerofoils used in the early years of aviation and the complex aerodynamic behaviour of such surfaces caused the early pioneers of aviation many headaches – both mental and physical!

In this article I would like to clarify the aerodynamic principles involved before going on to discuss the extent to which the pioneers of aviation understood and took account of those principles. All these aviators knew that a moving wing generated lift and drag and that the minimum requirement for an aircraft to fly in a horizontal direction was that the centre of gravity should coincide with the centre of lift, and that a motor was needed to provide sufficient thrust to counteract the drag. What none of them fully appreciated was that it was necessary to balance the *moments* generated by the forces acting on the aircraft as well. Moreover, while efforts were often made to make the aircraft automatically stable in roll and yaw, it was generally assumed that it was the pilots responsibility to control the pitch of the aircraft. The consequence of this assumption was usually disastrous and sometimes even fatal. (Otto Lilienthal died in 1896 as a result of stalling his hang glider 50 feet off the ground.) Since stability in pitch is the most complex and interesting, we shall deal with it first.

Stability in pitch

When an aerofoil moves horizontally through air, it is well known that the resulting force on it can be resolved into two components; a vertical force called *lift* and a horizontal force called *drag*. What is not commonly appreciated is that there is, in general, also a *moment* or turning effect on the aerofoil as well. As the angle of incidence of the wing to the horizontal is varied, all three components will vary, perhaps in some complicated way.

If S is the surface area of the wing, v is the speed with which it is moving and ρ is the density of air, it is usual to write the following three expressions:

$$lift = q S C_L \quad (1)$$

$$drag = q S C_D \quad (2)$$

$$moment = q S C_M \quad (3)$$

where q is the aerodynamic pressure:
$$q = \frac{1}{2} \rho v^2 \quad (4)$$

C_L , C_D and C_M are called the coefficients of lift, drag and moment respectively. Now, in mathematics, a 'coefficient' is a constant but it should be remembered that these coefficients are not constant at all; they are greatly dependent on the angle of incidence. You cannot say that a certain wing has a coefficient of lift of, say, 0.2 because this will only be true at a certain angle of incidence. There will, however, always be a position in which the lift is zero and the angle of incidence α can conveniently be measured from this position.

We shall not be concerned too much about the variation of drag with angle of incidence as we shall assume that we have enough power to cope with these variations. The issue does, however, become

important when discussing the directional control of an aircraft and we shall comment on this later. For the present, we must tackle the vexed question of the variation of the *moment* generated by the aerofoil. Let us get a few basic facts clear.

1) A force by itself does not generate a moment. On the other hand, as soon as you specify an axis of rotation, the force acquires a moment about that axis.

In the context of an aerofoil, the *lift* by itself does not generate a moment. On the other hand, the force will possess a moment about any specified point and the most important point in an aircraft is the centre of gravity. The lift of the wing will therefore, in general, generate a moment about the centre of gravity.

2) A pair of equal and opposite forces is called a *couple* and a couple possesses a moment or turning effect which is independent of the point about which it is measured. A couple is a kind of disembodied moment and it is essential to appreciate that *a wing can generate a couple even if it is not generating any lift*. The total moment generated by a wing about a particular point such as the centre of gravity is the sum of the moment of the lift about the c of g and the couple.

Here comes the tricky bit. The lift and the couple generated by a wing can be calculated by adding up all the forces and moments acting as a result of air pressure on every square cm of the wing. Now it is easy to add up all the forces acting on the wing and the result is the *lift*. But this calculation does not tell you where on the wing the force acts. In order to find out where the lift force acts, we must consider the *moments* generated by adding up the moments of all the air pressures acting on each square cm.

But which point shall we choose as our axis of rotation? The answer is – it doesn't matter. We can choose any point we like. If we know the moment generated by the lift about one point, it is easy to calculate the moment about any other.

Let's invent a very simple situation to see how these calculations are done.

Suppose that our theoretical calculations on a certain aerofoil predict the following distribution of (vertical) forces on a wing which is flying from left to right. Four forces have been calculated on the top and four underneath the wing. The positions of the elements on which these forces act are given in metres measured from the leading edge of the wing.

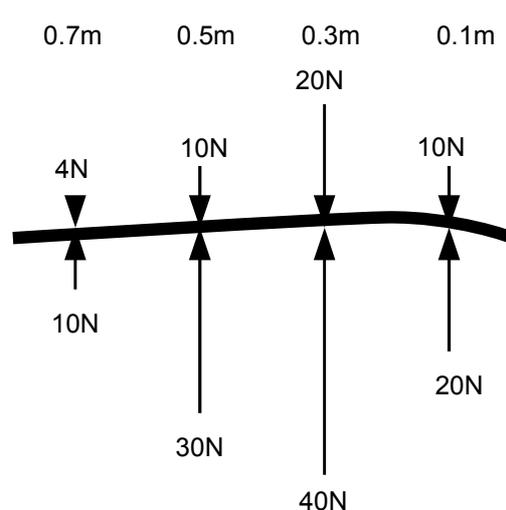


fig 1.

The total lift on this 'wing' is simply $10 - 4 + 30 - 10 + 40 - 20 + 20 - 10 = 56$ N

To calculate the moment on the wing, we need to specify an axis of rotation. In the absence of anywhere better, let's choose the leading edge. Note that, by convention, pitch up moments are counted as positive. And, of course, the moment of a force is equal to the force times its distance

from the axis of rotation so, here we go:

Total moment about leading edge = $(-10 + 4) \times 0.7 + (-30 + 10) \times 0.5 + (-40 + 20) \times 0.3 + (-20 + 10) \times 0.1 = -21.2 \text{ Nm}$.

So what does this tell us? The total lift is 56 N and the total moment about the leading edge is a pitch down moment of 21.2 N. This precise situation can be brought about by using any of the following combinations of applied forces and moments:

- a force of 56 N applied to the leading edge plus a pitch down moment of 21.2 Nm
- a force of 56 N applied 0.379 m ($= 21.2 / 56$) behind the leading edge with no added moment
- a force of 56 N applied 10 m behind the leading edge (!) plus a pitch up moment of 539 Nm ($= 56 \times 10 - 21.2$)
- etc. etc. etc

As you can see, the lift force can be applied anywhere you like provided that you adjust the moment appropriately.

On the other hand, there is obviously one rather unique position of application which renders the necessary moment zero and that is 0.379 m behind the leading edge. This position is called the *centre of pressure* and is normally thought of as the point at which the lift force acts. But this is a rather misleading idea. A highly cambered wing can produce such a large pitch down moment that the centre of pressure is *behind* the trailing edge of the wing! Indeed, at zero angle of incidence when the wing is producing no lift at all, the centre of pressure of a cambered wing is infinitely far behind the trailing edge and for a reverse cambered wing it lies infinitely far in front!

Provided that you bear this in mind, it remains true that, except when the lift is zero, you can always reduce the forces on a wing to a single force acting on a particular point. The trouble is, the position of the centre of pressure varies with angle of incidence and in the case of the early fabric covered wings, in a rather nasty way.

The graph below is taken from an article published in Flight magazine in 1910 and it shows the results of experiments carried out by a Mr Sellers in a wind tunnel. It shows how the centre of pressure moves in response to changes in angle of inclination. (NB the leading edge of the wing is on the left of the graph.)

MAY 14, 1910.

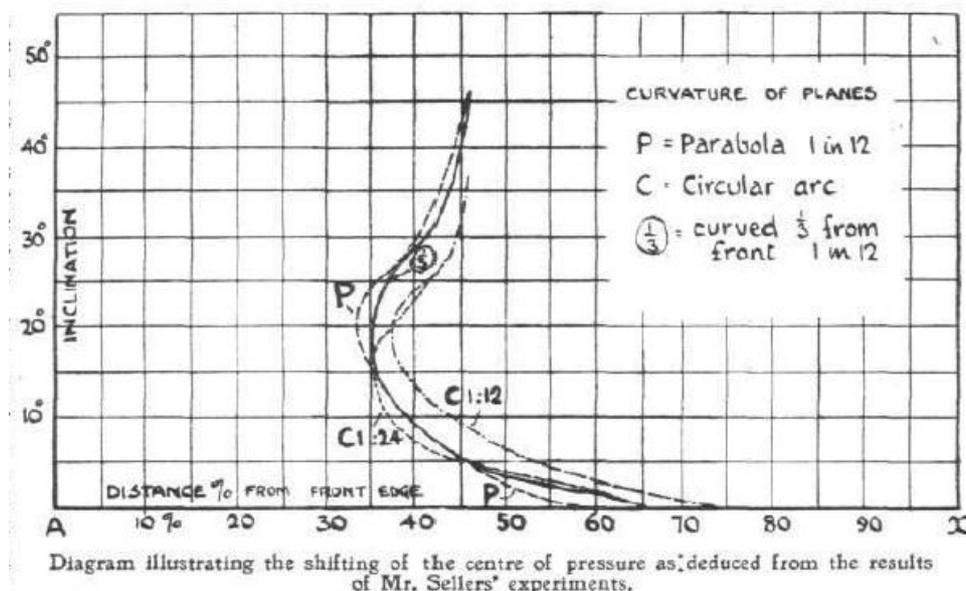


fig 2.

It will be seen that in all the wings considered, the centre of pressure moves forwards rapidly as the angle of incidence increases.

The curve marked  is approximately the aerofoil used by the Wright brothers and shows a rapid forward movement from 65% of the chord to 35% at an angle of incidence of 15° followed by a reverse movement. While it is to be hoped that Wilbur and Orville never got as far as an angle of incidence of 15°, they certainly had trouble with the effect because, in their view, increasing the angle of incidence of the wing moved the centre of pressure in front of the centre of gravity, thus producing a pitch up moment which tended to increase the pitch up attitude still further. Even without the canard, their wing section was inherently unstable in pitch (and, as we shall see, the canard did not necessarily improve matters.)

In 1901 Wilbur Wright wrote:

The balancing of a gliding or flying machine is very simple in theory. It consists in causing the center of gravity to coincide with the center of pressure. But in actual practice there seems to be an almost boundless incompatibility of temper which prevents their remaining peaceably together for a single instant, so that the operator, who in this case acts as a peacemaker, often suffers injury to himself while attempting to bring them together. If a wind strikes a vertical plane, [ie a vertical flat surface] the pressure on that part to one side of the center will exactly balance that on the other side, and the part above the center will balance that below. But if the plane be slightly inclined, the pressure on the part nearest the wind is increased and the pressure on the other part decreased, so that the center of pressure is now located, not in the center of the surface, but a little toward the side which is in advance. If the plane be still further inclined the center of pressure will move still farther forward. and if the wind blow a little to one side it will also move over as if to meet it. Now, since neither the wind nor the machine for even an instant maintains exactly the same direction and velocity, it is evident that the man who would trace the course of the center of pressure must be very quick of mind; and he who would attempt to move his body to that spot at every change must be very active indeed.¹

It is clear from this extract that Wilbur is still thinking in terms of the pilot moving his centre of gravity in order to achieve stability and control. Two years later, at Kitty Hawk, he has realised that control must be achieved with the help of movable surfaces but he is still thinking that, as with riding a bicycle, stability is a secondary issue which can only be achieved dynamically by a skilled pilot.

A modern approach to stability

To get any further with our analysis of the stability of early aircraft in pitch, we must apply a bit of mathematics.

We have noted that the coefficient of lift C_L varies with angle of incidence α and we can define α in such a way that the lift (and hence C_L) is zero when $\alpha = 0$. (Note that in most aerodynamic text books, α is usually measured with respect to the line joining the leading edge to the trailing edge of the wing – the wing chord, but for theoretical purposes it is better to define it as I have done.)

Now even if the lift varies in some complicated way over large angles, for *small* angles of incidence (less than about 10 degrees), the lift will be approximately proportional to the angle of incidence and we can write the much more useful equation:

$$\text{lift} = qS \mathbf{C}_L \alpha \quad (5)$$

where \mathbf{C}_L is a true (dimensionless) constant whose value depends solely on the shape of the wing. For a typical cambered wing $\mathbf{C}_L \approx 0.1$ per degree. In other words, for an angle of incidence of one degree, the lift force on the wing is 10% of the dynamic force qS . (Actually, the value of \mathbf{C}_L is equal to 0.1 for pretty well any useful shape of wing including a flat plate so the early obsession

with cambered wings was probably misplaced. A completely flat wing would have produced just as much lift at low angles of incidence without the complication of the moving centre of pressure. While it is true that a cambered wing can produce more lift at high angles of incidence, the real reason that all the early pioneers used it is simply that it is easier to brace and keep taut in a gusty breeze.)

Now what happens to the moment acting on the wing as the angle of incidence is changed?

If you have been reading carefully so far, you will know that the question is meaningless without specifying the axis of rotation we are talking about. Eventually we shall need to know the moment about the centre of gravity but at the moment we are talking about the behaviour of an aerofoil and we have no idea where the centre of gravity will eventually be. We know that if we place the lift at the centre of pressure, the moment will be zero. But we also know that the centre of pressure moves about, so that is not a lot of help.

There is an alternative strategy. We can place the lift at a different point chosen so that the moment generated by the wing is not zero but independent of the angle of incidence. It is not obvious that this is possible and the idea was not widely accepted until the 1930's but it is true none the less, and it applies to all useful wings including those that the early pioneers used. The point about which the moment is constant is called the aerodynamic centre of the wing,

Let us see where it leads us.

Suppose that $lift = qS C_L \alpha$ (equation 5)

and that $moment\ about\ the\ aerodynamic\ centre = qS C_M$ (6)

where C_M is another constant whose dimensions are that of length. (It is often expressed as a fraction, or a percentage of the wing chord.) The moment will vary with the speed of the aircraft but note that there is no α in the equation so the moment does not depend on the angle of incidence.

We can illustrate the situation like this:

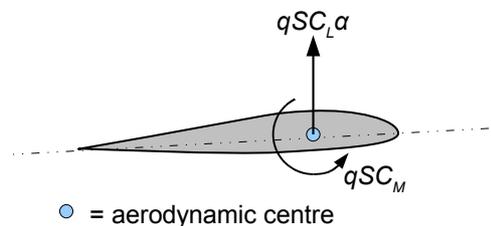


fig 3

but always remember that the aerodynamic centre is NOT the same as the centre of pressure. The centre of pressure is the place where the lift must be applied to make the moment *zero*. Here's a little problem for you. In the situation above with a pitch up moment, will the centre of pressure be in front of or behind the aerodynamic centre? If you are having a bit of difficulty deciding this, imagine taking moments about the leading edge. If you move the lift force backwards towards the trailing edge, what will happen to the moment of this force and how will the pitch up moment have to be changed to compensate? The answer is at the bottom of the page.¹

Now bear with me while we do a little bit of algebra. Suppose the aerodynamic centre is at a distance x_{ac} behind the leading edge and that the centre of pressure is a distance x_{cp} behind the leading edge. We know that

$$-qS C_L \alpha \times x_{ac} + qS C_M = -qS C_L \alpha \times x_{cp} + 0 \quad (7)$$

¹ Moving the lift backwards increases its pitch *down* moment. The pitch up moment will have to be increased to compensate. Therefore, in order to reduce the pitch up moment to zero, the lift must be moved forwards. In this case the centre of pressure is in front of the aerodynamic centre. It should, however be noted that the actual moment generated by conventionally cambered wings is pitch down (ie negative) so for most wings, most of the time the centre of pressure is behind the aerodynamic centre.

(The minus signs are needed because the lift produces a negative pitch up moment about the leading edge.)

If we rearrange this equation so that x_{cp} is the subject

$$x_{cp} = x_{ac} - \frac{C_M}{C_L} \frac{1}{\alpha} \quad (8)$$

Let us pause a minute to see what this equation is telling us.

The first strange thing is that if the angle of incidence α is zero, x_{cp} is infinite! Actually – this is perfectly correct. Do you remember, we said that for a cambered wing, when the lift is zero the centre of pressure could move infinitely far in front or behind the wing? What about a symmetrical wing? Well, when a symmetrical wing is parallel to the airflow, it produces neither lift nor moment. C_M is therefore zero and $x_{cp} = x_{ac}$ for all angles of incidence.

For a cambered wing of the type that the Wright brothers used, C_M is *negative* (because such wings produce a pitch *down* moment when $\alpha = 0$ so the equation has the form

$$x_{cp} = x_{ac} + \frac{k}{\alpha} \quad (9)$$

where K is a constant. A graph of this sort of function looks like this and is called a rectangular hyperbola.

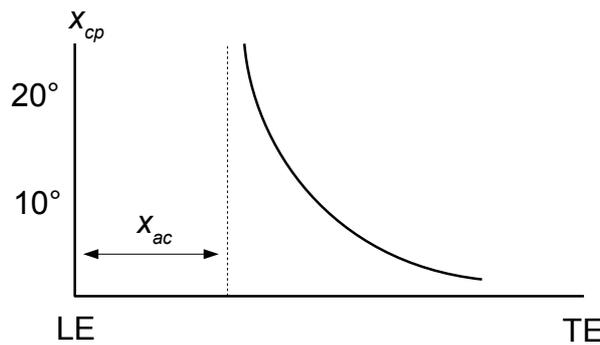


fig. 4

In the following diagram I have superimposed such a curve on Mr Sellers' results of 1910.

MAY 14, 1910.

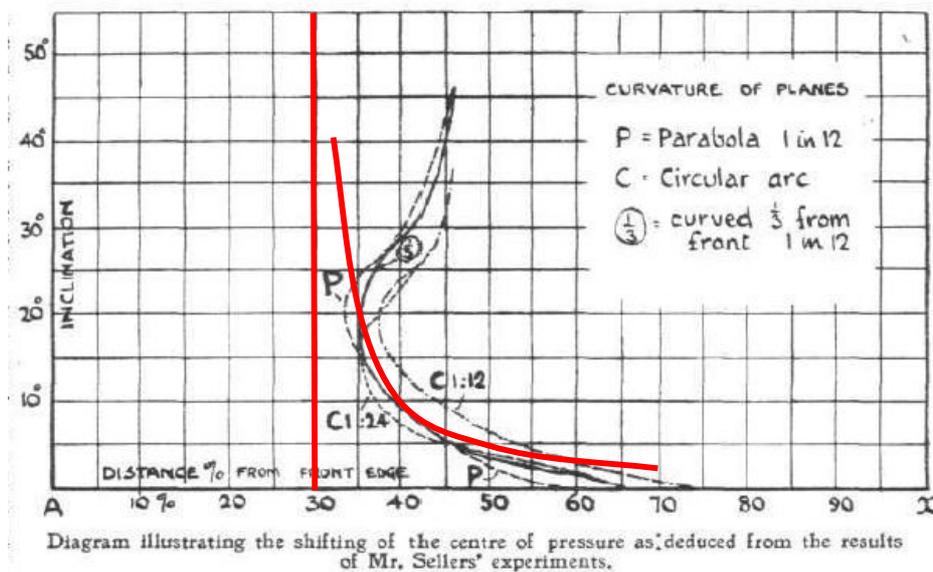


fig. 5

For angles of incidence below 15°, the agreement is pretty good and we can conclude that the following important assumption is justified:

In every wing there exists a special fixed point called the *aerodynamic centre* at which the force of aerodynamic lift can be supposed to act. Lift may be assumed to be proportional to the angle of incidence.

In addition, every wing produces a constant moment (which may be pitch up, pitch down or zero) which is independent of the angle of incidence.

We can now dispense with the idea of the centre of pressure as we now have just two fixed quantities to deal with, namely the position of the aerodynamic centre of the wing x_{ac} (which we can see from the graph is 30% of the chord behind the leading edge) and the moment about the aerodynamic centre (called the *aerodynamic moment*).

We can, in fact estimate the aerodynamic moment coefficient C_M from the graph as well. The constant k is equal to 10% times 10° . Using the fact that $C_L = 0.1 \text{ deg}^{-1}$, we can calculate that for this particular wing $C_M = -10\%$ of the chord. (You will recall that C_M has the units of length and that, for a cambered wing, it is negative.)

We are now in a position to evaluate the Wright brother's wing. The plane that flew on the 17th December 1903 at Kitty Hawk had the following wing dimensions:

Wingspan = 12.3 m

Wing chord = 2.0 m

Total effective surface area of both wings = $1.6 \times 12.3 \times 2.0 = 40 \text{ m}^2$

Total take-off weight = 3400 N (340 kg)

(I have assumed that the effective area of a biplane is 1.6 times the area of a single wing)

Orville Wright was at the controls and then headwind over the dunes was a brisk 11 ms^{-1} . Wilbur was able to run along beside the machine as it took off so we may assume that the effective airspeed over the wing was about 15 ms^{-1} . At this speed, the aerodynamic pressure q is 135 Nm^{-2} . (see equation (4)) and the lift produced by the wing is 5400 N per degree (see equation (5)). In order for the lift to equal the weight, an angle of incidence of 0.63° was all that was needed.

The historic moment was captured in one of the most famous photographs of all time.

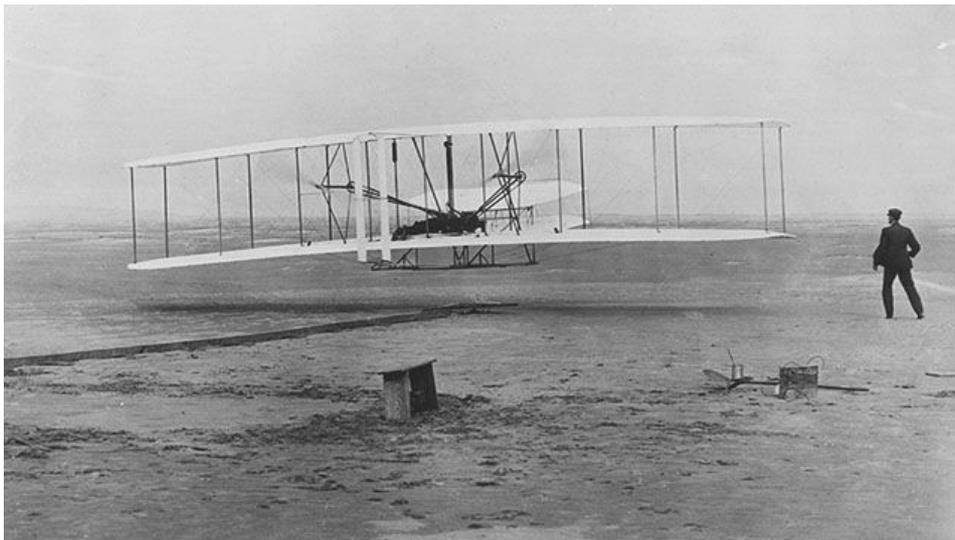


photo. 1

In the photo you can see the tiny rudder at the back, and also the twin surfaced canard wing at the front with which the brothers expected to control the aircraft in pitch. In fact, the canard has a much more important role to play than merely providing a means of control as we shall shortly see.

The canard wing

A cambered wing with a straight leading edge can never be stable on its own because, in order to counteract the pitch down aerodynamic moment generated by the wing, the centre of gravity must be behind the aerodynamic centre.

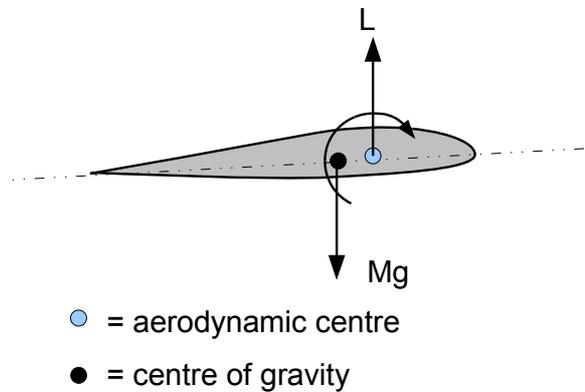


fig. 6

It is obvious that if the angle of incidence increases due to some disturbance, the lift L will increase causing the angle of incidence to increase still more. (This is essentially the same argument that was used in the discussion on the centre of pressure.)

The addition of a second, independently controllable wing surface, either in front of or behind the main wing, changes all this because instead of having to adjust the centre of gravity to achieve the required balance of moments, the centre of gravity can be placed anywhere you like (within limits of course) and the balance of moments can be achieved by adjusting the angle of attack of the control surface.

In the case of a canard, the pitch down moment generated by the main wing must be counteracted by a pitch up moment which implies that the canard must have a positive angle of attack. In fact, this can be clearly seen in the photo of the Wright Flyer. The canard is obviously pitched up at an angle of several degrees and is clearly contributing to the overall lift. The dimensions of the canard were as follows

Surface area = 4.5 m^2
Forward projection of the canard = 3.0 m

At last we are now in a position to ask ourselves the crucial question. Was the 1903 Wright Flyer stable in pitch? Here is a simplified diagram of the forces and moments acting on the flyer.

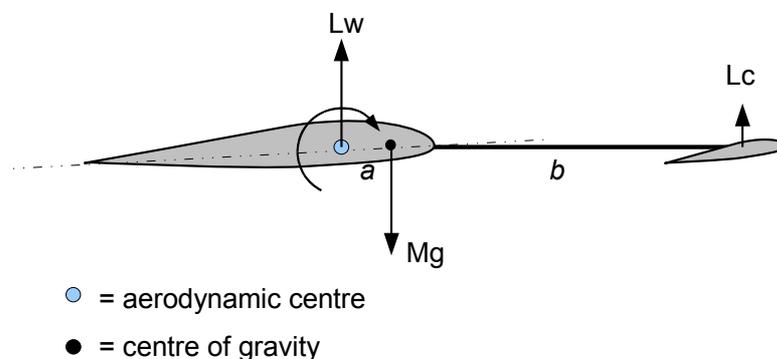


fig. 7

You will note that the extra lift generated by the canard has enabled the centre of gravity to be positioned in front of the aerodynamic centre of the main wing. This, in itself does not confer stability on the configuration but it is an essential feature because we need to show that if the angle

of incidence of both surfaces is increased by a small amount, the extra lift generated by the main wing will more than compensate for the extra lift generated by the canard. The details are a bit messy but it is actually quite easy to show that the product of the surface area of the wing and the distance a must be greater than the product of the surface area of the canard and the distance b .

i.e.
$$S_{wing} \times a > S_{canard} \times b \quad (10)$$

Now we can calculate the distances a and b which will produce neutral stability as follows. $a + b = 3.0$ m; $40 \times a = 4.5 \times b$. Solving these equations gives $a = 0.3$ m and $b = 2.7$ m .

Since the chord of the main wing was 2 m and x_{ac} for the wing was 30%, the aerodynamic centre was 0.6 m behind the leading edge of the wing. This puts the neutral point (the position of the centre of gravity which results in neutral stability) 0.3 m behind the leading edge – a perfectly possible position for the c of g. The question therefore boils down to whether or not the Wright brothers managed to move the centre of gravity this far forward. Wilbur and Orville did experiment with the position of the centre of gravity and discovered the dangers of a rearward c of g at first hand. The following extract is taken from a lecture given by Wilbur Wright describing the brothers experiences with gliders in 1901ⁱⁱ. It repays careful study.

The machine was completed and tried for the first time on the 27th of July [1901] in a wind blowing about 13 miles an hour. The operator having taken a position where the center of pressure was supposed to be, an attempt at gliding was made, but the machine turned downward and landed after going only a few yards. This indicated that the center of gravity was too far in front of the center of pressure. [It seems likely from this, and the earlier passage quoted above, that the brothers started out with the assumption that their machine would fly best when the centre of gravity coincided with the centre of pressure and that the canard (here called the 'rudder') would have zero angle of incidence, only being used to control the pitch] In the second attempt the operator took a position several inches farther back, but the result was much the same. He kept moving farther and farther back with each trial, till finally he occupied a position nearly a foot back of that at which we had expected to find the center of pressure. [While it is true that the tendency to pitch down could be interpreted in terms of the centre of gravity being in front of the centre of pressure, what the brothers did not realize at this time was just how far back the centre of pressure was at the low angles of incidence used. In modern terms we would prefer to think in terms of a strong pitch down moment acting on the wing. Instead of trying to move the c of g backwards, they should have increased the angle of attack of the canard in order to move the combined centre of pressure forward.] The machine then sailed off and made an undulating flight of a little more than 300 feet. To the onlookers this flight seemed very successful, but to the operator it was known that the full power of the rudder [elevator] had been required to keep the machine from either running into the ground or rising so high as to lose all headway. [In other words, the glider was unstable in pitch.] In the 1900 machine one-fourth as much rudder action had been sufficient to give much better control. It was apparent that something was radically wrong, though we were for some time unable to locate the trouble. In one glide the machine rose higher and higher till it lost all headway. This was the position from which Lilienthal had always found difficulty to extricate himself, as his machine then, in spite of his greatest exertions, manifested a tendency to dive downward almost vertically and strike the ground head on with frightful velocity. In this case a warning cry from the ground caused the operator to turn the rudder to its full extent and also to move his body slightly forward. The machine then settled slowly to the ground, maintaining its horizontal position almost perfectly, and landed without any injury at all. This was very encouraging, [It was also extremely fortunate!] as it showed that one of the very greatest dangers in machines with horizontal tails had been overcome by the use of a front rudder. [It would appear that the Wright brothers were seriously disturbed by the fact that Lilienthal had been killed as a result of a stall in a glider stabilised with a rear tail and all the brothers' early gliders and aircraft were canards.]

Now it is of great interest to calculate what is the required angle of incidence of the canard which will result in neutral stability. Equation (3) tells us that the pitch down moment generated by the

main wing = qSC_M which evaluates to $135 \times 40 \times 0.1 \times 2.0 = 1080 \text{ Nm}$. Now a bit of simple algebra tells us that the required lift on the canard

$$L_c = \frac{\text{Weight} \times a + \text{pitch down moment}}{a + b} \quad (11)$$

Putting the figures in that we know, we get:

$$L_c = \frac{3400 \times 0.3 + 1080}{3} = 700 \text{ N} \quad (12)$$

Using equation (5) again, we can calculate that the angle of incidence of the canard must have been $700 / 135 / 4.5 / 0.1 = 11.5^\circ$ - a result which would appear to be rather excessive. In fact, with an angle of incidence of the canard this big, the canard would be in great danger of stalling with catastrophic results. A glance at the photograph reproduced above clearly shows that the canard does indeed have a very significant angle of incidence but it is impossible to tell exactly what the angle was. My feeling is that, on these first flights at any rate, the canard was unable to produce enough lift to enable the c of g to be moved forward as far as the neutral point and that the 1903 Wright Flyer was unstable in pitch.

The Wright Flyer III, built in 1905 was the world's first practical aircraft and with it the Wright brothers were able to make flights whose duration was limited only by the amount of fuel it could carry. This machine used essentially the same wing as the 1903 flyer but had a canard whose surface area was 7.5 m^2 with a forward projection of about 4.4 m. Repeating the same calculation as before with these new figures, we find that neutral stability in pitch can now be achieved with an angle of incidence at the canard of less than 8° - a much more likely figure.

Here is a picture of the 1905 flyer:

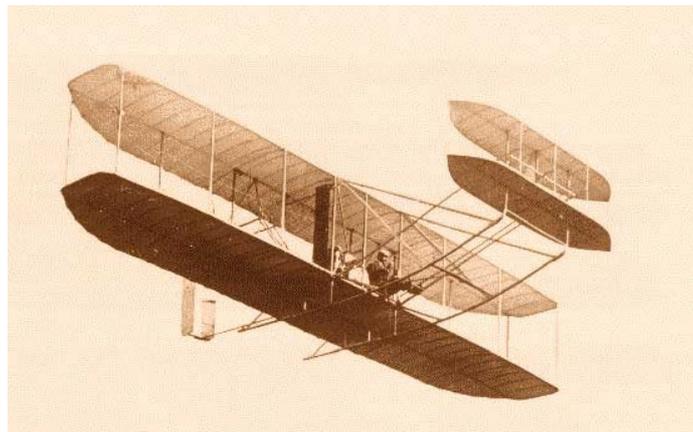


photo. 2

and here is a comparison of the 1903 and 1905 flyers in plan:

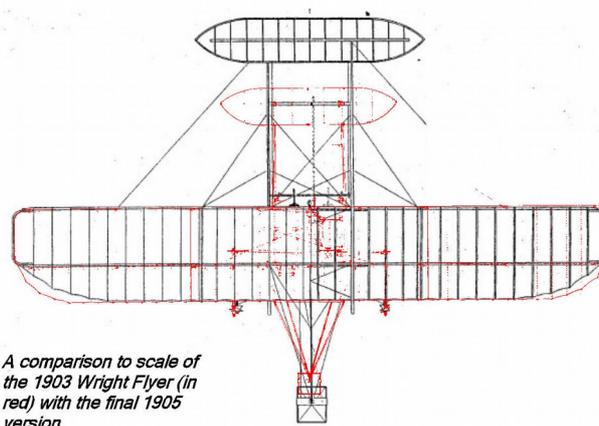
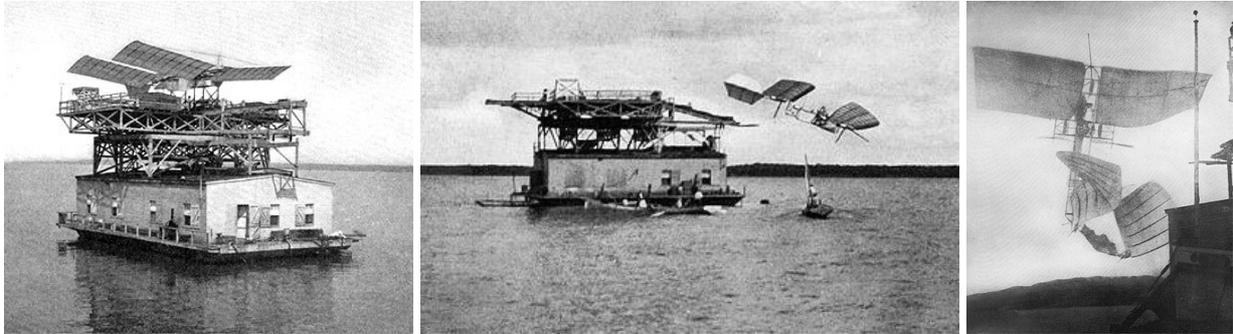


fig. 8

Langley's 'Aerodrome'

Just a few weeks before the Wright brothers' successful flights in 1903, another design was being tried out by Samuel Langley on the Potomac river in Washington. His design was a 'tandem wing' – ie it had two, approximately equal area wings, one fore and one aft. Langley had already built several successful powered free-flight models and versions of the design were successfully flown in later years but the two occasions on which he attempted to launch a full sized, man carrying machine ended in disaster. The pictures below tell the whole sad story.



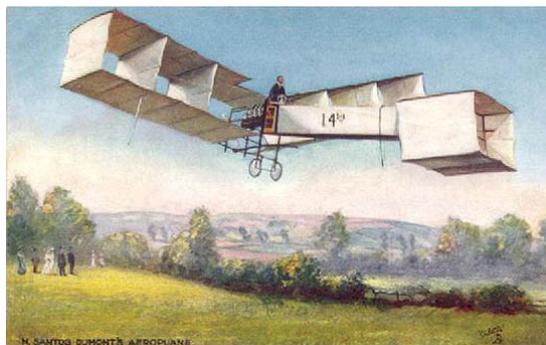
The first picture shows Aerodrome A sitting on its catapult on top of a houseboat in the Potomac river. Its two, equal size tandem wings are clearly visible. The second picture shows the results of the first launch on October 3rd 1903. It was said at the time that the machine was 'nose-heavy' and therefore plunged into the river head at an angle of 45°. This is not strictly true. In order to achieve stability, it is essential that an aircraft is 'nose-heavy'. But this means that the forward wing must support more than half the weight of the aircraft and must have an appropriate angle of incidence. A glance at the second photograph shows that this was far from the case.

Having fished the wreckage (and his long-suffering employee, Charles Manly) out of the river, Langley tried again on a freezing cold day in December. The results were even more spectacular and Manly nearly lost his life (see the third photograph). Perhaps in the light of the previous experience, Langley increased the angle of attack of the fore wing, or, more likely, he mistakenly moved the centre of gravity backwards. In any event, on leaving the catapult the machine pitched up violently, hanging on its propellers for a moment before falling backwards into the river, the rear wing collapsing as it did so.

The newspapers ridiculed the poor man and he retired from aviation. There is, however, nothing the matter with a tandem design and many such aircraft, including a modified 'Aerodrome A'. The principles remain the same. To achieve pitch stability with two wings of equal area, the centre of gravity must be forward of the mid point. That is all.

Santos-Dumont

On 23rd of October 1906, before a large crowd of sightseers and journalists, the Brazilian inventor Santos-Dumont took off and flew for about 60m in the most unlikely looking aircraft called the 14-bis.



It is not so much the box-kite wings that make it look so weird, it is the fact that the aircraft in the picture is flying from left to right! Look closely at the way the pilot is looking!

The aircraft is, in fact, a canard and one can see that the pilot is having great difficulty in maintaining the pitch attitude because the canard is already at its maximum pitch-up angle. The machine was probably highly unstable, both in pitch and yaw.

While it is true to say that this strange machine was the first powered heavier-than-air machine to take off unassisted in public, it is not surprising that Santos-Dumont quickly abandoned the design and by the time that the Wright brothers demonstrated their mastery of the air in front of a French audience in 1908, Santos-Dumont was already experimenting with a much more successful series of monoplanes with a much more conventional design, the Demoiselle.



photo. 5

Voisin and Farman

On 13th January 1908, Henri Farman won an important prize for being the first European to fly a 1 km course in a closed circuit, demonstrating that his machine, built by Gabriel Voisin, was capable of controlled turns, albeit very flat ones.



photo. 6

It is not clear whether the machine he actually used possessed the side curtains illustrated in the photo above; many later photos do not show these. What is clear, though, is that the Voisin-Farman I had both a canard elevator and a rudder enclosed within a box-kite stabilizer at the rear.

Louis Blériot

Between 1906 and 1909, the year in which he flew across the channel, Louis Blériot designed and built dozens of aircraft. Blériot V was a canard; Blériot VI was a tandem design; Blériot VII was a thoroughly modern looking monoplane with a tractor propeller at the front, elevator and rudder at the rear.



photo. 7

While it cannot be said to have been anything like as successful as the Wright Flyer 3, it proved to be the way forward in the end. By 1909, Bleriot had perfected a design with which he was able (just) to fly across the channel – the Bleriot XI



photo. 8

So why was the conventional 'poisson'² configuration with the tail at the rear not adopted right from the start?

The answers are complex and have as much to do with prejudice and fashion as aerodynamics but, for what it is worth, here is a list of pros and cons.

- In the canard, the pilot and engine are placed amidships, close to the expected centre of pressure. The fore and aft structures can be relatively lightly constructed. In a poisson, however, the engine must be placed at the front of the main wing and in consequence, the fuselage has to be much stronger.
- In a crash, the canard can absorb much of the impact whereas the pilot and engine are much more vulnerable in a poisson.
- The canard acts as a sort of artificial horizon which helps the pilot maintain his sense of orientation.
- The canard provides useful lift whereas the tail of a poisson is either neutral or produces negative lift.

² The term is my own invention. It is, of course, French for 'fish' as opposed to 'canard' which is French for 'duck'.

Stability in roll and yaw

A glance at the previous photographs will show that early aviators had very mixed ideas about the necessity for and methods of achieving stability in roll and yaw. Langley's Aerodrome had no rudder at all and while some machines were given a pronounced dihedral, the Wright brothers used a perfectly straight wing.

Indeed, it is not at all obvious that stability in roll or yaw is either necessary or desirable. Birds do not have vertical stabilizers and the moment of inertia of an aeroplane about its longitudinal axis is so large that a pilot generally has plenty of time to react to unanticipated rolls.

Where the issue becomes important is the way in which the pilot is supposed to steer the aircraft. Langley seems to have given this matter little or no thought at all. Santos-Dumont, in placing the rudder at the front, probably thought that he would steer his craft in the same way the a cyclist steers a bicycle. In the event, the 14-bis was only capable of short, straight hops. Henri Farman was able to make flat turns with the use of rudder alone. The side curtains placed between the main surfaces would have been useful in counteracting the inevitable slide-slip that would result. Only the Wright brothers realised that, in order to steer an aircraft successfully, the aircraft must be banked into the turn, like a cyclist, and to achieve this, the pilot must have complete control over both roll and yaw. Here is what the brothers had to say in 1908 in respect of their early experiments with wing warpingⁱⁱⁱ.

We also discovered that in free flight, when the wing on one side of the machine was presented to the wind at a greater angle than the one on the other side, the wing with the greater angle descended, and the machine turned in a direction just the reverse of what we were led to expect when flying the machine as a kite. The larger angle gave more resistance to forward motion, and reduced the speed of the wing on that side. The decrease in speed more than counterbalanced the effect of the larger angle. The addition of a fixed vertical vane in the rear increased the trouble, and made the machine absolutely dangerous. It was some time before a remedy was discovered. This consisted of movable rudders working in conjunction with the twisting of the wings.

To put it another way, if it was desired to turn left, the wings would be warped in such a way as to cause the right wing to increase its lift. This caused so much increase in drag on that wing that the machine actually turned right! The solution was to add a rudder which was initially coupled to the wing warping mechanism so that the correct amount of left rudder was automatically applied. In later models, when the importance and usefulness of the rudder was fully appreciated, the pilot was given independent control. This also enabled the pilot to prevent the machine side-slipping into the ground when making turns at low altitude.

A closely related issue is the question of whether the main wings should have any dihedral. As with other pioneers, the Wright brothers initially thought that stability in roll would be achieved by means of a low centre of gravity and/or a pronounced dihedral.

The balancing of a flyer may seem, at first thought, to be a very simple matter, yet almost every experimenter had found in this the one point which he could not satisfactorily master. Many different methods were tried. Some experimenters placed the center of gravity far below the wings, in the belief that the weight would naturally seek to remain at the lowest point. It was true, that, like the pendulum, it tended to seek the lowest point; but also, like the pendulum, it tended to oscillate in a manner destructive of all stability. A more satisfactory system, especially for lateral balance, was that of arranging the wings in the shape of a broad V, to form a dihedral angle, with the center low and the wingtips elevated. In theory this was an automatic system, but in practice it had two serious defects: first, it tended to keep the machine oscillating; and, second, its usefulness was restricted to calm air.^{iv}

In point of fact, neither a low centre of gravity, nor a pronounced dihedral has any direct effect on roll stability because if the two wings produce the same amount of lift, the resultant lift force always

passes through the centre of gravity and therefore produces zero moment about it.

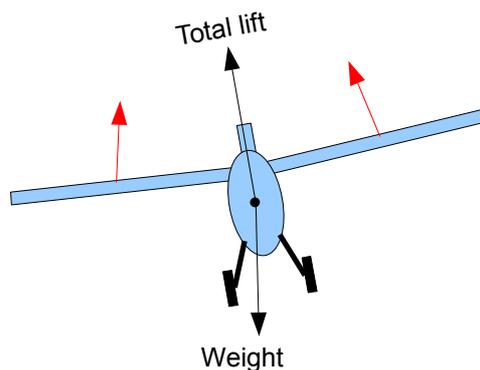


fig. 9

(There is, however, an indirect effect because the resulting sideways force will cause the aircraft to slip sideways, increasing the lift on the lower wing.)

It is clear that the Wright brothers were seriously concerned, not without reason, that a sideways gust of wind would get underneath one of the wings and flip the machine over. They therefore gave the 1903 Flyer a pronounced negative dihedral angle as can be seen from photo. 1.

After considering the practical effect of the dihedral principle, we reached the conclusion that a flyer founded upon it might be of interest from a scientific point of view, but could be of no value in a practical way. We therefore resolved to try a fundamentally different principle. We would arrange the machine so that it would not tend to right itself. We would make it as inert as possible to the effects of change of direction or speed, and thus reduce the effects of wind-gusts to a minimum. We would do this in the fore-and-aft stability by giving the aëroplanes a peculiar shape; and in the lateral balance, by arching the surfaces from tip to tip, just the reverse of what our predecessors had done. Then by some suitable contrivance, actuated by the operator, forces should be brought into play to regulate the balance . . . A happy device was discovered whereby the apparently rigid system of superposed surfaces, invented by Wenham, and improved by Stringfellow and Chanute, could be warped in a most unexpected way, so that the aëroplanes could be presented on the right and left sides at different angles to the wind. This, with an adjustable, horizontal front rudder, formed the main feature of our first glider.^v

Here the brothers make quite clear that, in their opinion, stability was not even desirable – let alone necessary. As cyclists, they knew that a skilled human could turn the instability of the machine to his advantage. What they desired above all else was control – and it was at least 5 years before anyone else got even close to achieving the same object.

The Wright Flyer was, in more senses than one, the first fly-by-wire aircraft.

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- i SOME AERONAUTICAL EXPERIMENTS. Mr. WILBUR WRIGHT, Dayton, Ohio.
[Presented to the Western Society of Engineers September 18, 1901.]
<http://www.wright-house.com/wright-brothers/Aeronautical.html>
- ii ibid
- iii THE WRIGHT BROTHERS AËROPLANE by Orville and Wilbur Wright
Century Magazine, September 1908
<http://www.wright-house.com/wright-brothers/Century.html>
- iv ibid
- v ibid