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What the Wright Brothers Did and Did Not Understand About Flight Mechanics—In Modern Terms

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ABSTRACT

When the Wright Brothers began their work at the end of the 19th century there were no theories of aerodynamics or of flight mechanics. Data were available for the lift and drag of certain kinds of airfoils, mostly thin and highly cambered imitations of birds' wings. The theory of airfoils began in 1902, but had no practical consequences until World War I, and was unknown to the Wrights and their contemporaries. Similarly, the first publication dealing with flight mechanics, appearing in 1903 was also not known by the Brothers; the subject was not developed usefully until 1911. Thus the Wrights developed their aircraft with repeated tests, keen observations; superb analysis and reasoning; and efficient design. They intuitively understood much of the flight mechanics they observed but there was much they could not understand or explain simply because the basis for understanding did not exist. The purpose of this paper is to trace the Wrights' research and development program and interpret in modern terms their observations and experiences with aerodynamics and flight mechanics.

1. HISTORICAL BACKGROUND

In 1799, twenty-six year old George Cayley (1773–1857) sketched what we now recognize as the familiar conventional configuration of an airplane: a cambered wing having dihedral; an aft vertical tail; and an aft horizontal tail (Gibbs-Smith 1962). Cayley's choice for the airfoil was based on aerodynamical characteristics of airfoils tested by him and his predecessors using a whirling arm apparatus. Cayley himself invented dihedral as a means for maintaining equilibrium in roll. The vertical tail provided directional stability, like the feathers on an arrow, and in Cayley's view, would also be used for steering, as a boat's rudder serves. By analogy, the horizontal tail gave stability in pitch. It turned out later that Cayley was half right on both counts.

Cayley did not formally apply Newton's laws for translational and rotational motions to the airplane. He produced no mathematical descriptions for the motions of an aircraft and therefore has no quantitative basis for designing his flying machines. But he had things right at the level he worked. Already with his first efforts he established the principle that he later explained thoroughly in a series of papers: The means of producing lift to compensate weight must be distinct from the means of generating thrust; a revolutionary idea at the time. He properly shifted attention to artificial flight from simple imitation of birds to development of fixed-wing aircraft.

Those ideas dominated all attempts to invent aircraft in the 19th century. Three predecessors of the Wrights were particularly important to this work. Alphonse Pénaud (1850–1880) in France adopted Cayley's design and flew the first powered mechanical flying machine, a small rubber-powered model. (It was Pénaud's clever idea to use twisted rubber strips as the source of power for a propeller.) In a short paper describing his model, Pénaud gave the first explanation for the action of an aft horizontal tail to provide stability in pitch (Pénaud 1872). In France, the surface became known as the 'Pénaud tail.'

The most important immediate predecessor of the Wrights was Otto Lilienthal (1848–1896). Educated and professionally successful as a mechanical engineer, Lilienthal made his mark following his boyhood ambition to build a successful flying machine. His two most influential contributions were his realization and demonstration, that to build a successful airplane, it was necessary to learn how to fly; and his extensive tests of airfoils, producing the first systematic data for lift and drag of a variety of airfoils. Less well-known is the fact that one of Lilienthal's results also contributed to Kutta's first paper in airfoil theory: he emphasized the property of a good airfoil that the flow should be smooth at the trailing edge. Carrying out his own instruction to fly, Lilienthal built a series of successful gliders having essentially Cayley's configuration. Lilienthal's results were influential particularly because they were widely reported and illustrated and because he wrote his book *Birdflight as the Basis of Aviation*, published in 1889.

Lilienthal inspired four followers: Percy Pilcher (1866–1899), a Scot, who, like Lilienthal, was killed when a gliding test ended in a crash; Octave Chanute (1832–1910), who build several gliders after and Lilienthal's general design; Ferdinand Ferber (1862–1909) who began his gliding tests in 1899; and the Wrights. Ferber's most significant accomplishment was his successful motivation of a group of enthusiastic aviation pioneers in Paris. His contacts with the Wrights eventually led, indirectly, to the agreement the Wrights struck with a French syndicate to fly publicly first in France in 1908.

Octave Chanute was the third predecessor to hold an important position in Wrights' development program, 1899-1905. He provided guidance to the existing literature and accomplishments by others with his important book *Progress in Flying Machines* (1889). Technically, his use of the Pratt truss was adapted by the Wrights as their biplane configuration. Equally important was Chanute's role as a kind of sounding board during the Wright's intensive work from 1900 to 1905. There is no evidence that he provided any technical contributions to their success other than the Pratt truss.

By the end of the 19th century it seemed that much of the basic knowledge was in hand for the invention of powered piloted flight. As a consequence of the progress achieved primarily by Cayley, Pénaud and Lilienthal, a successful configuration had been established. The recent invention of the lightweight internal combustion engine solved the problem of propulsion, although the known propeller designs had efficiencies well below what would soon become available.

But the gap between what was known and what was required for a practical airplane was larger than generally appreciated. Only the Wright Brothers recognized that the great problem of control still remained to be solved. Lilienthal had demonstrated many successful straight glides by swinging his weight to maintain equilibrium in flight. Because his gliders were stable and he did not address the problem of turning, Lilienthal did not require much controllability under his normal flying conditions. The first time he truly needed substantial control in pitch, his method of hang-gliding failed him, causing his death.

Nearly all of the Wrights' predecessors and their contemporaries were preoccupied with constructing intrinsically stable aircraft, essentially large model airplanes. Moreover, none progressed far enough to become concerned with maneuverability and hence controllability was not an issue for them. The sole exception was J.J. Montgomery (1858–1911) who, already in the 1890's, experimented with wing-warping for control in roll (Spearman 1967). His work was not publicized and the Wrights independently invented their method of wing-warping. It's interesting, but not incontrovertible proof of their independence that Wilbur used a biplane design to incorporate warping whereas Montgomery worked only with monoplane gliders. More to the point, Montgomery apparently never considered constructing a powered aircraft and didn't face the general problems of three-axis stability and control.

That is what really distinguishes the work of the Wrights from that of their contemporaries and predecessors. They faced and effectively solved to the extent they required, problems of stability and control about all three axes. A wonderful feature of their style of working is that they meticulously documented their observations and progress. Parts of their diaries and letters read like daily reports of a modern research and development program. That is why we are able to puzzle out how they encountered and reacted to their discoveries of the motions of an unstable powered aircraft. Moreover, by examining closely the problems the Wrights encountered and the solutions they devised, we can clarify the deficiencies in their own understanding of the mechanics of flight and hence of their aircraft. Their stunning invention of the practical airplane placed the Wrights far in advance of their contemporaries. But at the same time, the backward state of the general theory and understanding of flight mechanics hindered them and in fact caused them considerable difficulties.

2. THE GREATEST DEFICIENCY IN EARLY AERONAUTICS

Hindsight is always a satisfying advantage for historical commentary. In the subject of flight mechanics, we now have essentially a complete and closed theory supported as well by decades of experimental and computational results. With all that experience we can review the Wrights' work and appreciate even more deeply the problems they faced, the frustrations they must have felt, and the solutions they fashioned.

It is not an over-simplification to state that ultimately the general problem of achieving mechanical flight is equivalent to the problem of controlling rotations in three dimensions. Any investigation of rotations of an object leads very quickly to considerations of stability and, as a practical matter, control. Newton's laws show that corresponding to the connection between translational motions and forces, rotational motions are the consequences of moments or torques acting on an object.

At the turn of the 19th century, inventors struggling to discover the 'secret' to successful flight understood well translational motions. Steady level flight demands that sufficient lift be generated to compensate the weight $(L = W)$; and that the thrust exactly equals the drag $(T = D)$. They also had an intuitive notion that an airplane will rotate unless the net moment acting is zero. Until the Wrights began their work, would-be inventors were concerned principally with equilibrium (i.e. no rotation) of pitching or longitudinal motions; no rotations in pitch means zero pitching moment $(M = 0)$.

None of the pioneers of flight, including the Wrights, wrote the equation arising from $M = 0$ and therefore had no basis for exploring its implications. Their intuition stopped with the essentially correct conclusion that for equilibrium in pitch, the "center of pressure" must coincide with the center of gravity. Practical problems arise with interpreting and locating the "center of pressure." The statement of coincidence is true if the center of pressure is that of the entire aircraft. Incorrect conclusions follow if only the center of pressure of the wing is understood. Failure to make and understand that distinction caused many difficulties for the aeronautical pioneers.

Because gravity acts in vertical planes, in the first instance it does not affect motions of an aircraft in roll and yaw (heading) away from steady level flight. Hence equilibrium in roll and yaw seemed simpler than equilibrium in pitch. In fact, Cayley realized that stability of equilibrium was the primary matter for both roll and yaw. Stability of equilibrium means that if the aircraft is disturbed from an initial state of equilibrium, aerodynamic forces are naturally generated that tend to restore the equilibrium. Cayley concluded that a vertical tail and dihedral provided the restoring forces in yaw and roll, respectively. His conclusions are correct and apparently solved the problems of roll and yaw motions—until the Wrights recognized that piloted flight required control of roll and yaw, not merely stability.

Nevertheless, despite their brilliant successes, the Wrights never completely understood quantitatively the problem of stability of rotational motions. They shared that deficiency with all their contemporary inventors; for the same reason: they never wrote or considered equations for rotational motions. Without the benefit of that formalism, they could not understand the true essence of stability of rotations. As a practical matter, they could not identify the physical contributions to stability, a failure that had significant consequences for their work:

1) Like their contemporaries, the Wrights could not properly solve the simplest problem of gliding; hence they had only approximate means of designing their gliders;
2) Also like their contemporaries, they did not have the basis for investigating and understanding stability quantitatively;
3) They could not appreciate the importance of zero lift pitching moment and therefore did not realize the problem caused by selecting a highly cambered airfoil;
4) They had no way of estimating the location of the center of pressure of a complete aircraft. Hence they could not understand the significance of the location of the center of gravity.

The point, of course, is not to criticize the Wrights. On the contrary, our admiration for their stunning accomplishments is increased when we understand more completely the contemporary state of aeronautics, the context in which they achieved their success.

3. THE ELEMENTARY PROBLEM OF GLIDING

The Wrights left no notes explaining the details of their calculations relating to the gliding problem. However, it is clear from their letters and entries in their diaries that they (or, rather, most likely Wilbur) determined the sizes of their 1900 and 1901 gliders by quantitative estimates. They used Lilienthal's data and considerations of lift and drag only. Their ignorance of the equation for pitching moments necessarily caused their analysis to be approximate.

Consider the elementary problem of steady rectilinear gliding. The machine is treated as a point mass M moving in a vertical plane. Its motion is the result of actions by the forces of lift, drag and gravity; and the pitching moment m. By convention the lift L and drag D act respectively perpendicular and parallel to the direction of motion at velocity V_∞. The velocity lies at the path angle γ to the horizontal. Let x and y be orthogonal axes fixed to the glider as shown in Figure 1, with origin at the center of gravity. For steady gliding, the net force and moment must vanish. In the x-y coordinate system, the three conditions are

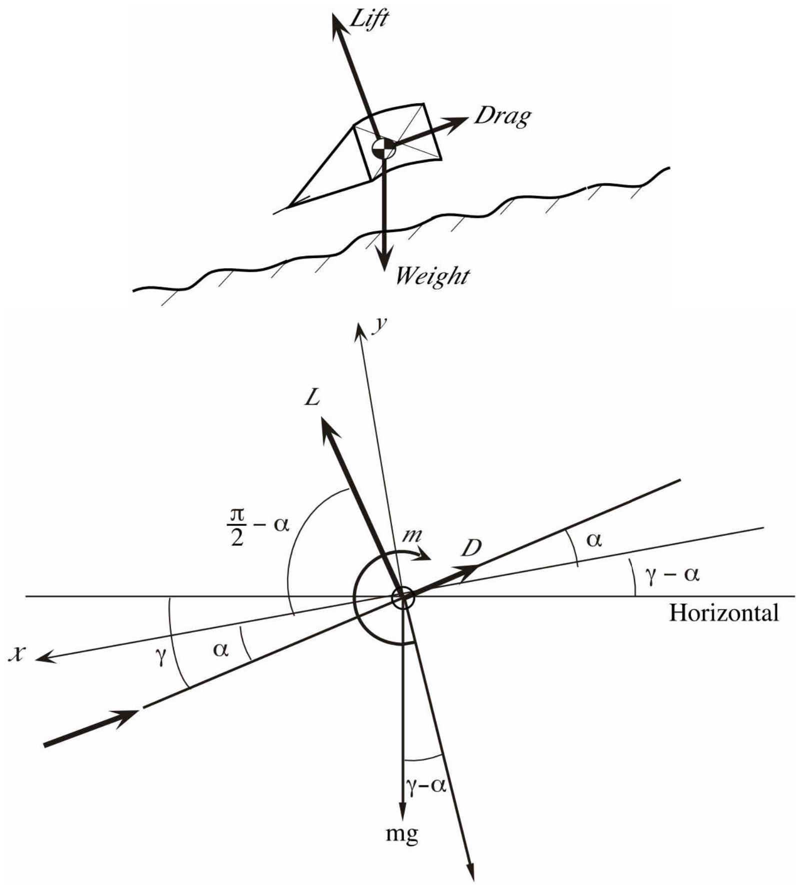


Figure 1. Forces and moment for the elementary gliding problem.

$$\sum^{i} F_{x_i} = 0: \quad L\cos\left(\frac{\pi}{2} - \alpha\right) - D\cos\alpha + Mg\sin\,(\gamma - \alpha) = 0$$

$$\sum^{i} F_{y_i} = 0: \quad L\sin\left(\frac{\pi}{2} - \alpha\right) - D\sin\alpha - Mg\cos\,(\gamma - \alpha) = 0 \qquad \text{(1)a,b,c}$$

$$\sum^{i} m_i = 0: \qquad m = 0$$

For small angles, these equations are

$$\begin{aligned} L\alpha - D + Mg(\gamma - \alpha) &= 0 \\ L - D\alpha - Mg &= 0 \\ m &= 0 \end{aligned} \qquad \text{(2)a,b,c}$$

Let *S* be the wing area, *c* the wing chord, $q_\infty = \frac{1}{2}\rho V_\infty^2$ the dynamic pressure, and divide by $q_\infty c$ to find

$$C_L\alpha - C_D + \frac{w}{q_\infty}(\gamma - \alpha) = 0$$

$$C_L - C_D\alpha - \frac{w}{q_\infty} = 0 \qquad \text{(3)a,b,c}$$

$$C_m = 0$$

where $w = Mg/S$ is the wing loading. The lift, drag and moment coefficients are

$$C_L = \frac{L}{q_\infty},\ C_D = \frac{D}{q_\infty S},\ C_m = \frac{m}{q_\infty Sc} \qquad (4)$$

For the low speeds of gliding, the coefficients C_L, C_D, and C_m depend only on the angle of attack α. Hence for a specific glider, the three equations (3)a,b,c contain three unknown quantities, α, γ, and q_∞ or, for a given density (or altitude) glide speed V_∞. If the moment equation, $C_m = 0$, expressing what is usually called the 'trim condition,' is ignored, one is left with two equations for the three unknowns—path angle γ, angle of attack α and gliding speed V_∞. Solution to that problem doesn't exist.

Evidently the Wrights must have found themselves in that quandary. The only way out is to guess the value of one of the unknown quantities and solve the two equations for the remaining two unknowns. Although we don't know what the Wrights did, it seems that the glide speed is the most reasonable variable to guess. Some of their observations suggests that was their choice and it is also the choice made by Chanute in his article on gliding printed in Moedebeck's handbook (Chanute 1910). That article probably represents the accepted contemporary method for analyzing and 'solving' the problem.

Solution to (2)a,b as part of the design process still requires iteration because the wing loading w is not known initially. Hence we speculate that for designing their gliders in 1900 and 1901, the Wrights might have used the following computational scheme:

1) The functions $C_L(\alpha)$ and $C_D(\alpha)$ are given by experimental results; the Wrights used Lilienthal's data.
2) Choose a value of the glide speed V_∞. The Wrights seem to have sought a ground speed of about 4-6 miles per hour. They chose Kitty Hawk as their testing ground with the expectation of steady wind speeds of 15–20 MPH. Hence $V_\infty \approx$ 20–25 MPH.
3) Select a value of w: = (grossweight)/(wing area). Equations (3)a,b are then nonlinear algebraic equations in α, and linear in q_∞. With some difficulty they can be solved numerically (trial and error if no computer is available) or graphically.
4) For the value of α found from solution to (3)a,b, the lift coefficient and lift can be calculated and compared with the data used in step (1). If the value is too close to the value for stall of the wing, then a new value must be set for V_∞ or w and the process (1)–(3) repeated.

Chanute's article suggests that the Wrights used the above or a comparable method, to estimate a reasonable size for their gliders in 1900 and 1901. In subsequent years their experience probably gave them the basis for estimates without similar calculations.

Part of the point here is to emphasize a difficulty unavoidable if (as the Wrights did) the moment equation is not taken into account. In the correct view of the gliding problem, satisfaction of the condition of zero total moment, equation (3)c, is ensured by appropriate setting of the horizontal tail (or the canard). That is, the moment of the tail lift about the center of mass exactly compensates the moment generated by the lift of the wing imagined to be acting at the center of pressure.

Consistently with ignoring the condition of zero net moment, the Wrights assumed that in equilibrium the canard carried no load and served only as a control device. Hence their view of equilibrium in pitch required that the center of pressure of the wing must coincide with the center of gravity. In practice, it was quite possible that the canard carried a net load, but whether it did or not would likely be obscured by the operational difficulties of piloting an airplane unstable in pitch.

4. THE CENTER OF PRESSURE, AERODYNAMIC CENTER AND NEUTRAL POINT

From the earliest investigations of the force acting on an object in motion, before Newton's *Principia*, it was recognized that the pressure on the object's surface is continuous and nonuniform. The integral of the pressure over the surface is the net force. By analogy with the center of gravity, it is natural to imagine the existence of the center of pressure. If the object is imagined to be supported at the center of pressure, the force generated by the motion causes no rotation: its moment is zero, when the net force is imagined to act at the center of pressure.

In the case of a freely flying wing, the weight is the only other force acting. Thus the "support" is at the center of gravity, and if we neglect drag, there is not net moment on the wing if the center of pressure coincides with the center of gravity. If drag is accounted for, the statement still holds, but as illustrated by Figure 1, the gravity force is decomposed into two components, we compensated by the lifting part of the aerodynamic force, and the other acting as a thrust force compensating the drag.

The practical difficulty with that interpretation of the condition of zero moment is that the position of the center of pressure usually depends quite strongly on the orientation of the wing, i.e. on the angle of attack. Moreover, the motion of the center of pressure with angle of attack causes a destabilizing pitching moment for the usual case of a cambered wing having fixed center of gravity. Figure 2 shows graphs of the center of pressure measured as functions of angle of attack for two airfoils: the Wright 1903 airfoil, the NACA 4412 an airfoil popular for light aircraft (NACA TR 460); and a flat plate. (Engineering Sciences Data, 1970).

Also in Figure 2(b) the dashed line shows the movement of the center of pressure that the Wrights believed to be the case early in their work at least, until gliding tests in 1901. That supposed behavior is based on the following reasoning. When the airfoil (cf. the limit of a flat plate) is placed normal to the stream, the center of pressure is at or close to the mid-chord. As the angle of attack is reduced, the center of pressure evidently moves forward. The Wrights, following the beliefs of previous researchers, assumed that the center of pressure moves forward as α is reduced, reaching the leading edge for $\alpha = 0$. However, in fact, the motion reverses direction and the center of pressure moves aft, in principle, for a cambered airfoil traveling infinitely far downstream as the angle of attack approaches the value for zero lift.

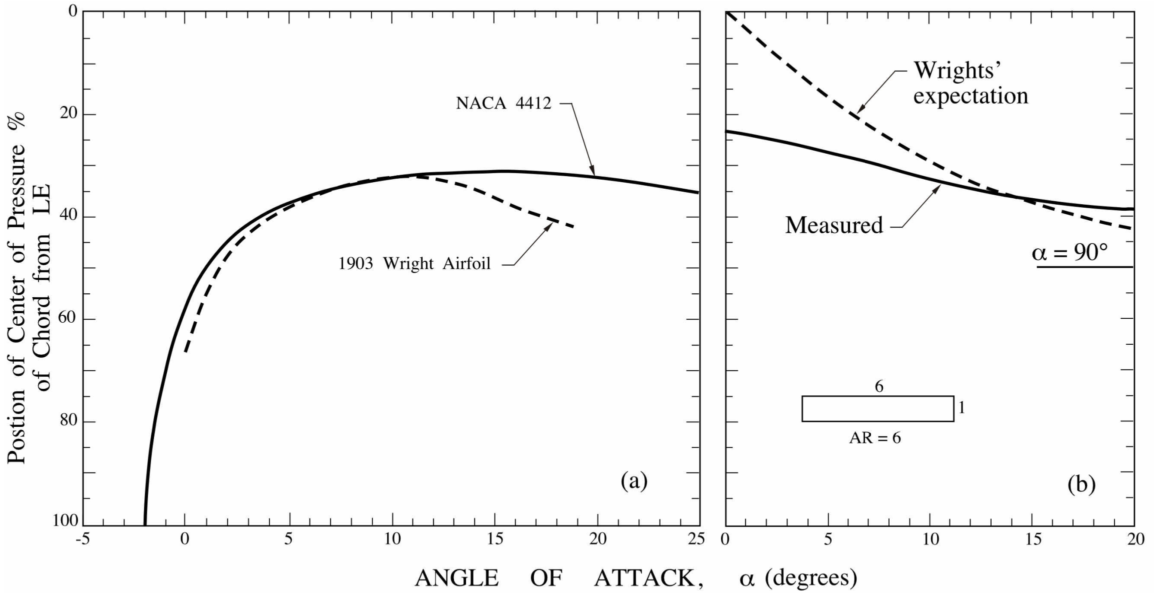


Figure 2. (a) Centers of pressure for the Wright 1903 Airfoil, and the NACA 4412. (b) Measured center of pressure for a flat plate and according to an early belief (- - - -).

Problems with controlling pitch, while gliding in 1901 and some tests of the glider as a kite, led Wilbur to conclude that his previous notion of continuous forward motion of the center of pressure was wrong. What he didn't realize was that the most forward location of the center of pressure occurs when the airfoil is stalled and has maximum lift. Hence, the correct view is that under normal flying conditions the center of pressure moves continuously forward as the angle of attack (and lift) increases up to the value for stall, where reversal of the motion occurs.

The particular way in which the center of pressure moves with change of angle of attack depends on the shape of the airfoil: there is no universal representation. Even if the Wrights, or anybody else had investigated use of the moment equation for pitch, they would therefore have encountered certain detailed complications. In fact those complications are apparent in the literature of flight stability until the late 1930's when the distinguished British applied aerodynamicist Gates introduced the idea of the **neutral point** for an aircraft. The neutral point is the **aerodynamic center** for a complete aircraft.

Tchaplygin and later, independently, von Mises (1920) discovered that every airfoil possesses an aerodynamic center having location fixed as the angle of attack changes. It's a remarkable property valid for incompressible steady flow if the airfoil has fixed shape and if the Kutta condition (smooth flow at the trailing edge) is satisfied. The aerodynamic center (ac) is defined as that point on an airfoil such that if the net lift is imagined to act at the ac, the aerodynamic moment about the axis passing through that point is independent of angle of attack. For the airfoils normally used in practice, the aerodynamic center is close to the quarter-chord. Also, for the usual airfoil having camber line convex upward, the moment about the aerodynamic center is negative in the conventional sense, acting to rotate the leading edge down.

As a practical matter in writing the equation of pitching moment for an aircraft, existence of the aerodynamic center for a lifting surface means that surface is simply represented by the lift acting at its aerodynamic center, a pitching moment (or better, a pitching moment coefficient C_{mac}) independent angle of attack. The difficulty associated with accounting for the motion of the center of pressure is eliminated. In fact the forward movement of the center of pressure as the lift increases towards its maximum is a direct consequence of the existence of the aerodynamic center.

The definition of the neutral point is the extension of the idea of the aerodynamic center, for a single surface, applied to an array of surfaces. Thus the aerodynamic forces and moments acting on the various parts of an aircraft can be replaced by a single force acting at the neutral point and a moment about the neutral point that is independent of angle of attack.

It is an immediate consequence of the definition of the neutral point that as the angle of attack is increased the additional lift can be imagined to appear at the neutral point. And the most important consequence of that behavior is that for static stability of an aircraft, the center of gravity must lie forward of the neutral point. That property is easily established with the help of Figure 3.

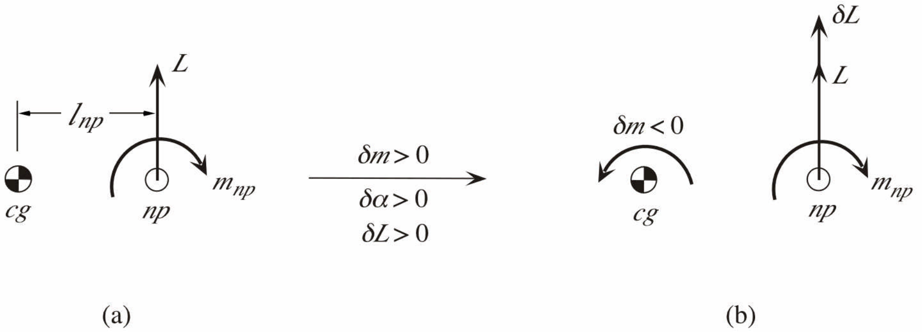


Figure 3. Intrinsic stability when the center of gravity lies forward of the neutral point.

Assume that the neutral point does exist (we have not proved it is true) having the property that the aerodynamic moment m_{np} about the neutral point is constant as the angle of attack changes. In Part (a) of Figure 3, the aircraft is assumed to be in equilibrium in level flight so $Ll_{np} = m_{np}$. Now suppose that the aircraft receives a disturbance causing the nose to rise, a change of pitching moment $\delta m > 0$ according to the usual sign convention, and the angle of attack is also increased: $\delta\alpha > 0$. Hence the lift also is increased, producing a negative (nose down) moment, $\delta m = - \delta L l_{np}$, tending to restore the aircraft stability if the center of gravity lies ahead of the neutral point.

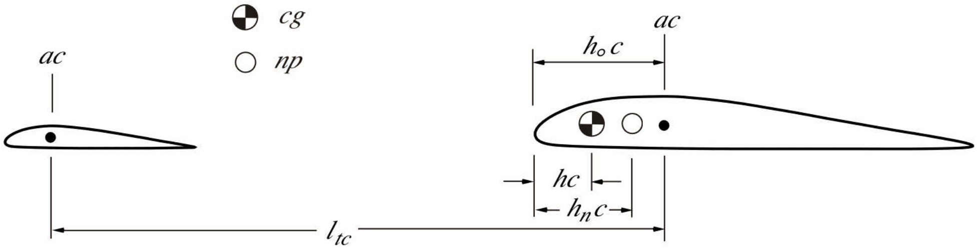
This is a perfectly general result of which the Wrights were unaware—and couldn't be. In fact no one knew this simple argument until more than thirty years later, although the stabilizing effect of moving the center of gravity forward was already known with the work of Bryan and Williams (1904) and Bryan (1911).

In 1904, the Brothers decided to try to reduce the amplitude of pitching oscillations ('undulations') they encountered by moving the center of gravity. Actually, they may have been dealing with a situation in which the oscillating motion was stable, but combined with a second motion exponentially unstable with a growth rate troublesomely rapid (Section 8 here). In any case, they first moved the center of gravity aft—exactly the wrong direction—by moving the engine. One flight was enough to reveal the error. For the remainder of their work with canard configurations, the Wrights carried ballast as far forward on the canard as they could, as much as 70 pounds.

5. RELATIVE STABILITY OF CANARD AND AFT TAIL CONFIGURATIONS

Much has been written about the Wrights' problems of stability, or rather instability, of their canard aircraft. With Wilbur's tests of his 1899 kite (a biplane having a single smaller surface giving control in pitch) and their 1900 kite/glider, the Brothers knew that the machines would fly with the tail forward or aft of the main lifting surfaces. How much they had learned of the relative stability of the two configurations is not known. What is fairly clear is that Wilbur chose to use the canard configuration for two reasons: Lilienthal was killed because of inadequate control of his conventional configuration, and Wilbur thought he would have better control with the canard; and it was comforting to see the control surface during flight. Because the theoretical basis was not yet established to understand the importance of forward location of the center of gravity, the Wrights simply had to deal with the serious pitch instabilities of their canard aircraft. Contrary to the view that has appeared in some accounts, there is no evidence that the Wrights intentionally designed their aircraft to be unstable—they just turned out that way. In fact, without paying attention to rotational motions in some detail—and that means understanding about moments—no one could have a firm grasp of what stability is really about. The first paper on the subject of aircraft stability was given by Bryan and Williams (1904) who showed that for the center of gravity fixed relative to the larger surface, the configuration having a smaller surface aft is relatively more stable than that with a smaller surface forward. The paper was unknown to those constructing aircraft at the time and of course appeared after the Wrights' commitment to the canard.

Elementary analysis of the wing/tail configuration may be found in standard texts of applied aerodynamics. The main results needed for present purposes are given in Table 1. For simplicity we treat a single wing and ignore corrections for the biplane.



CANARD **AFT TAIL**

MOMENT ABOUT CG

CANARD:
$$C_{mCG} = C_{mac} + C_{L_t}\overline{V}_t - C_L(h_0 - h)$$

AFT TAIL:
$$C_{mac} = C_{m0} + C_{L_t}\overline{V}_t + C_L(h_0 - h)$$

POSITION OF NEUTRAL POINT

CANARD:
$$h_n = h_0 - H$$

AFT TAIL:
$$h_n = h_0 + H$$

$$H = V_t \frac{dC_{Lt}}{dC_L}$$

Table 1. Some results for canard and conventional configurations.

The coefficients of lift, C_L, and pitching moment about the aerodynamic centers are weighted values for the wing/tail configurations:

$$C_L = C_{Lw} + \eta_t \frac{S_t}{S} C_{Lt}$$
$$C_{mac} = C_{macw} + \eta_t \frac{c_t S_t}{cS} C_{mact} \tag{5)a,b(}$$

where subscripts ($)_w$ and ($)_t$ refer to the wing and tail. An efficiency, η_t is defined equal to actual dynamic pressure at the surface divided by q_∞. Locations relative to the leading edge of the wing are denoted by the symbols *h*, distances divided by the wing chord. Thus h_0 is the dimensionless distance of aerodynamic center of the wing from its leading edge; and *h* is the dimensionless distance of the center of gravity from the leading edge, being positive for an aft location. Thus $h_0 - h > 0$ means that the center of gravity of the aircraft is forward of the aerodynamic center of the wing.

Note that the lift curve slope of the tail $dC_{Lt}/d\alpha$ is computed with respect to the angle of attack of the wing, it is better interpreted as

$$\frac{dC_{Lt}}{d\alpha} = \frac{dC_{Lt}}{d\alpha_t}\frac{d\alpha_t}{d\alpha} \tag{6}$$

in which $dC_{Lt}/d\alpha_t$ is the actual lift curve slope of the tail (approximately 2π reduced by the effect of aspect ratio according to lifting line theory); and $d\alpha_t/d\alpha$ is due to the downwash for an aft tail and upwash for a canard:

$$\frac{d\alpha_t}{d\alpha}\begin{cases} < 0 & \text{aft tail} \\ > 0 & \text{canard} \end{cases} \tag{7}$$

If we assume that the wing and tail have lift curve slopes nearly the same, we can approximate *H* by the formula

$$H \approx \bar{V}_t \frac{d\varepsilon_t}{d\alpha}\begin{cases} < 0 & \text{aft tail} \\ > 0 & \text{canard} \end{cases} \tag{8}$$

where $\bar{V}_t = \frac{l_{to} S_t}{cS}$ is the dimensionless tail volume, l_{to} is the distance between the aerodynamic centers of the wing and tail, and ε_t is the conventional symbol for upwash or downwash. With (7), the formulas in Table 1 then give the results for the positions of the neutral point:

$$h_n = h_0 - H = \begin{cases} h_0 + |H| & \text{aft tail} \\ h_0 - |H| & \text{canard} \end{cases} \tag{9}$$

Hence the neutral point for a conventional configuration lies **aft** of the wing's aerodynamic center but the neutral point of a canard lies **forward**. That is the explicit realization of Bryan and Williams' conclusion that the aft tail configuration is relatively more stable than the canard of the same surfaces are used. The more forward is the neutral point, the more difficult it is in practice to get a stable aircraft: the natural tendency is for the cg to lie further aft than desirable.

The Wrights' choice of the canard configuration was therefore already leading to a possible problem with pitch stability. That is a consequence of the aerodynamics. A canard can of course be designed to be intrinsically stable if the center of gravity is far enough forward. In the case of the Wrights' canard, the problem is particularly difficult because of the mass distribution dictated by their design: the large weights (biplane cell, engine and pilot) are all located such that their center of gravity are close together and aft of the leading edge.

In the 1903 *Flyer*, the center of gravity is about 3/10 of the chord aft of the leading edge and the neutral point is close to the leading edge. The aft vertical tail is already light and has little effect on the location of the center of gravity. There are only two ways to shift the center of gravity significantly: add ballast to the canard; and move the engine and pilot as far forward as possible on the wing. Estimates suggest that nearly 40% of the gross weight carried as additional ballast will move the center of gravity to the leading edge of the 1903 *Flyer* if the positions of the pilot and engine are not changed.

When ballast is added, the flying speed of the aircraft increases and more power is required. By trial and error the Wrights did as much as they could so far as moving the center of gravity is concerned. They simply accepted their *Flyers* as unstable aircraft (later models in 1908–1909 had the center of gravity about 15% of the chord aft of the neutral point according to Hooven, 1978). Hence their emphasis or control was an absolute necessity if their canards were to succeed.

6. IMPORTANCE OF THE ZERO LIFT PITCHING MOMENT, C_m

Consideration of the formulas for the pitching moment about the center of gravity leads to a pleasing graphical interpretation of the rule that for stability the center of gravity must lie forward of the neutral point. Simultaneously we will find that the pitching moment at zero lift has special importance not anticipated with the discussion in the preceding section.

From Table 1, the coefficient for the pitching moment about the center of gravity of a canard is

$$C_{mCG} = C_{mac} + C_{Lt}V_t - C_L(h_0 - h) \tag{10}$$

The lift coefficient C_{Lt} of the canard depends on the setting (deflection) of the surface and, due to upwash created by the wing, on the lift coefficient of the aircraft. In general it cannot be taken equal to zero, because for trim $(C_{mCG} = 0),$ the condition must be satisfied

$$C_{Lt}\overline{V}_t = C_L(h_0 - h) - C_{mac} > 0 \qquad \text{(stable canard)} \tag{11}$$

Because C_{mac} is normally negative, $C_{Lt}\overline{V}_t$ is positive for a stable canard.
The slope of the moment curve is

$$\frac{dC_{mCG}}{dC_L} = \frac{dC_{Lt}}{dC_L}\overline{V}_t - (h_0 - h) = -\left(h_0 - \overline{V}_t\frac{dC_{Lt}}{dC_L}\right) + h = -(h_n - h) \tag{12}$$

For stability, reasoning similar to that accompanying Figure 3 shows that the slope must be negative for stability in pitch. Hence the moment curve for a stable canard is like that sketched in Figure 4. (The line C_{mCG} versus C_L is straight only if the lift coefficient of the tail is constant.)

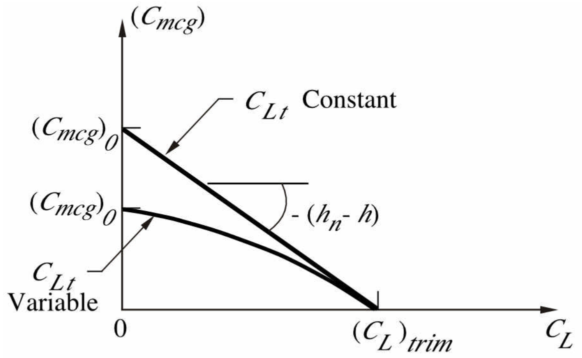


Figure 4. Moment curve for a stable aircraft.

Equation (10) gives the value for the moment coefficient at zero lift.

$$(C_{mCG})_0 = C_{mac} + C_{L_{t_0}}\overline{V}_t \tag{13}$$

In order to have a stable moment curve with a trim condition $\left(C_{mCG}\right)_0$ must be positive. Note that the moment curve is a straight line, as drawn in Figure 4, only if the lift coefficient of the tail is fixed at the trim value, $\overline{C}_{Lt}$. In any case, $\left(C_{mCG}\right)_0$ cannot be negative, for that would cause the curve to cross the axis a second time. The second intersection represents an unstable trim condition, not allowed under the circumstances enforced here.

Table 2 shows some estimated results for trim of 1903, 1905 and 1909 *Flyers*, using the measured (Bettes and Culick 1982) values $C_{mac} = -0.14$ and assuming $\overline{C}_L = 0.6$.

Flyer	1903	1905	1909
$\overline{V}_t$	0.096	0.26	0.24
$-\dfrac{C_{mac}}{\overline{V}_t}$	1.46	0.54	0.58
$-\dfrac{\overline{C}_L}{\overline{V}_t}\left(h_0 - h\right)$	-0.31	-0.23	-0.30
$\overline{C}_{Lt}$	1.15	0.307	0.283

Table 2. Canard lift coefficient for trim of the *Flyers*, equation (11).

The results for $\overline{C}_{Lt}$ show that the 1903 *Flyer* could not be trimmed because the canard would stall before reaching the lift coefficient 1.15. Due to their larger tail volumes, the 1905 and 1909 *Flyers* could be trimmed, although the equilibrium states would be unstable.

7. THE WRIGHTS DISCOVER LONGITUDINAL DYNAMICS

A rigid aircraft has six degrees of freedom. For small departures from a state of steady flight; the time varying motions of a symmetrical aircraft can be separated into two uncoupled types: longitudinal motions in the plane of symmetry, and lateral motions out of that plane. The variables for the longitudinal motions are two translational velocities (*u*, *v*) in the forward (*x*) direction and in the vertical (*z*) direction measured downward; and one rotational velocity (*q*) for pitching motions.

7.1 NORMAL MODES FOR LONGITUDINAL MOTIONS

Stability of the translational motions is guaranteed by the presence of aerodynamical damping. If the aircraft is also stable in pitch—the center of gravity lies ahead of the neutral point—then the aircraft possesses two oscillating
phugoid’ or long period (low frequency) mode; and the short period mode. If a conventional aircraft is rendered unstable, by improper distribution of the payload, the common case is that the short period mode degenerates to two exponential motions, one of which is unstable while the phugoid remains. That is the case for the 1903 Wright *Flyer*.

To a good first approximation, the phugoid oscillation is a slowly decaying oscillation having frequency equal to $2\pi\sqrt{\dfrac{\overline{u}}{g}}$ where $\overline{u}$ is the average forward translational velocity. For an unpiloted airplane, it is a relatively slow undulating motion involving periodic exchange of kinetic and potential (gravitational) energy. The angle of attack remains nearly constant. During a phugoid oscillation, the aircraft normally undergoes noticeable oscillations of altitude.

In contrast, a stable short period motion normally takes place with little change of altitude and is independent of the phugoid motion. During a short period motion, the nose bobs up and down and the change of pitch angle relative to the horizon equals the change of angle of attack.

Probably the most common way in which the phugoid oscillation is observed is by making a change of altitude. The slow oscillation may be excited and cause some difficulty in trimming to the new altitude, particularly if the new altitude is higher than the initial altitude. Unless abrupt changes of the elevator are made, the short period oscillation is not likely to be apparent. On the other hand, flight through choppy air will easily excite the short period oscillation.

However, the pilot will always notice an unstable short period oscillation. The growth of the unstable exponential part requires active control. If also the phugoid happens to be excited, then the aircraft will execute oscillations superposed on the growing exponential; the result could be interpreted as an unstable oscillation.

7.2 THE WRIGHTS' EXPERIENCE WITH LONGITUDINAL DYNAMICS: 1901–1903

During their flying seasons 1900–1903 the Wrights no doubt encountered longitudinal motions of their unstable gliders and powered aircraft. In 1900, the kite/glider was flown mostly as a kite, so the behavior just described is not relevant. Their total free-flying time was of the order of ten seconds or so, and the Wrights recorded only general observations. There is inadequate information to comment on their experiences with the longitudinal modes of motion. It does seem that the glider was probably unstable, requiring the pilot's constant attention even for such short flying times. In fact, the Wrights drew two main conclusions from their tests in 1900: their design of pitch and roll controls work well; and the lift and drag they measured were less than the values they had predicted with Lilienthal's data and formulas.

1901 was a different story. In respect to technical matters, this was the most significant of the Wrights' flying seasons before their powered flights in 1903: they discovered the basic problems they had to solve, and before their flying in 1902, they had either solved them, or nearly so. With one exception (adverse yaw) their discoveries were all related to longitudinal motions.

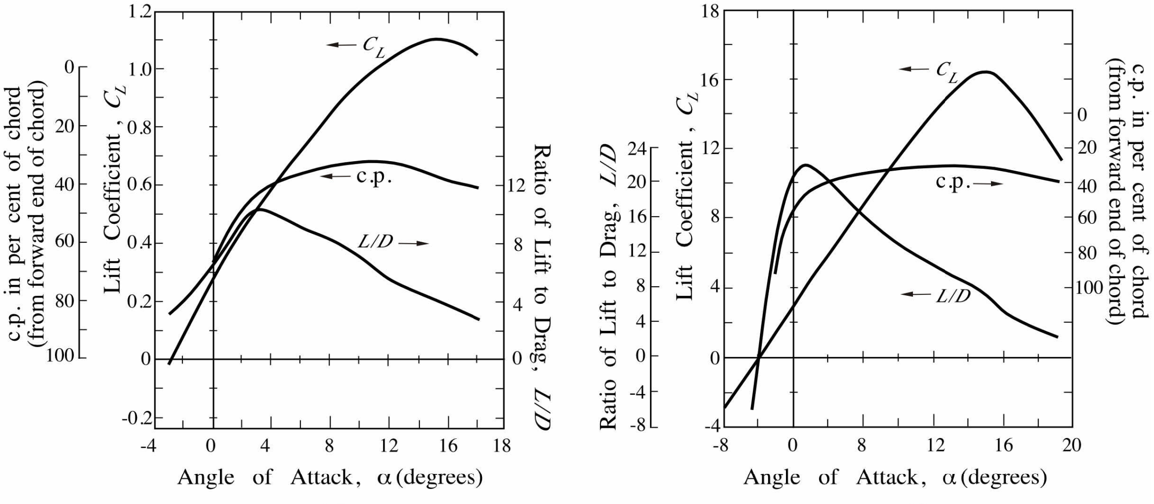
With a combination of flight tests, and particularly testing their biplane cell as a kite with spring scales to measure forces in the restraining lines, the Brothers deduced the values of lift and drag on their wings. They concluded correctly that their values were (again) much-less than those predicted with Lilienthal's results. That conclusion caused them to carry out their intensive series of wind tunnel tests in the fall of 1901. When the work was done, they could explain the differences between their results and Lilienthal's. Moreover, they had collected virtually all the data they needed for their designs for the next ten years.

We understand now that there were two serious deficiencies in the Wrights' airfoil tests, both flowing, as explained in Section 2 and 4, from their ignorance of the importance of pitching moments and the quantitative aspects of pitching motions. First, although their idea of equilibrium in pitch was founded in the idea that in equilibrium the centers of pressure and gravity of the airplane must coincide, they made no measurements of the center of pressure. (They later made a few in 1905). Secondly, they were content to find the optimal slope of a highly cambered airfoil. If they had realized the trouble that the large negative zero-lift pitching moment would cause them for trim and stability (Section 6), they would likely have investigated other shapes with less camber.

During early gliding tests in 1901, Wilbur had serious problems controlling the glider in pitch. All tests at this stage were straight ahead with no attempts to turn. The problems probably arose from his attempts to extend the glides by raising the nose, by deflecting the canard. As explained here in Section 4, he anticipated that the center of pressure would move continuously forward as the angle of attack is reduced. It was fundamental to his flying technique that he should know the direction of motion for that determined how he would respond with canard deflection to try to maintain coincidence of the centers of pressure and gravity.

Contrary to his expectation, what he found during flight that as he reduced the angle of attack, the center of pressure move **aft** thus reinforcing the nose-down motion. He had to interpret that as reflecting a reversal of the *cp* motion at some angle of attack. That behavior caused him much more serious difficulties on at least two occasions when he was flying near stall. If initially he was flying just below stall and raised the nose to counter a disturbance, the center of pressure would move forward and if the angle of attack continued to increase, the wing would stall, lift would decrease, the nose would begin to mush and drop. The center of pressure would then move aft, causing the nose to drop further. The sequence was, to say the least, puzzling and unsettling, causing the airplane to mush to the surface on the two occasions cited.

Thus the Wrights' ignorance of the phenomenon of stall was responsible for dangerous episodes in their flight tests. They never did understand stalling and its origins. In particular, they seem not to have connected stalling (loss of lift) and the reversal of motion of the center of pressure. Figure 5 shows two examples: the Wright 1903 airfoil and the NACA 4412 airfoil. However, they had discovered the existence of stalling in 1901, recognized its importance and later learned how to avoid it operationally. It's interesting that already during his last flights in 1901, Wilbur began trying to turn. (Orville did not fly in 1901—it was Wilbur's flight test program.) He did not have success with turns but he did have a genuine success with his brief trials: he discovered the fundamental phenomenon now called **adverse yaw**. This was his second great discovery as a test pilot, the first being the motion of the center of pressure and stalling.



(a)

(b)

Figure 5. Lift, lift/drag ratio and center of pressure.
(a) Wright 1903 Airfoil (Eiffel); (b) NACA 4412.

Cayley and others before the Wrights, Montgomery being the sole exception, assumed that turning in flight could be achieved by use of the vertical tail or rudder, in exactly the same way a boat is turned. Probably from his observations of birds in flight, Wilbur knew better. His correct idea was that to generate the centripetal force required to set the airplane on a circular path, the airplane should be rolled to tilt the lift force (perpendicular to the wing surface) so that part of the lift would act towards the center of the intended circle. What he did not recognize until later, was that to cause the nose to turn in the direction of the desired turning motion, there must be a vertical tail to cause rotation in **yaw**. Without it, the airplane would begin to execute a circular path, but the nose would continue to point in the initial direction initially. But the situation is worse as Wilbur discovered in his first attempts. To roll the airplane, the lift on one wing is increased, and decreased on the other, in Wilbur's case by warping the structure. That control generates a roll moment. But the drag on a wing has a part proportional to the lift. Hence one wing has greater drag than the other. The differential drag causes the aircraft to yaw, the nose actually swings in the sense opposite to that desired in the turn. That is what Wilbur discovered, a very keen observation indeed.

Thus when the symmetry of the aircraft is broken, by warping the wing, lateral motions are induced. After 1901, the Wrights were forced to address problems of lateral motions as well as those of longitudinal motions.

All evidence suggests that the 1902 glider did not present serious problems of longitudinal stability and control. The lightweight structure and the relatively favorable position of the pilot favored a position of the center of gravity that probably gave a machine that was only mildly unstable in pitch. Several replicas have been made and successfully flown repeatedly during the past twenty-five years or so.

On the contrary, when the Wrights scaled-up their 1902 design and added a propulsion system, the behavior in flight was quite different. The best evidence we have for the sorts of dynamics the Wrights must have encountered with their 1903 *Flyer* rests on analyses reported by Culick and Jex (1984) and Jex and Culick (1985). Using wind tunnel data acquired in sub-scale wind tunnel tests, the writers calculated both longitudinal and lateral dynamics of the *Flyer*, open loop and closed loop with a pilot exercising proportional control. Their root locus, Figure 6, shows the presence of the lightly damped pitch oscillation originating in the phugoid mode, and the exponentially unstable motion, associated with the degenerate short period mode, for the airplane alone (open loop). For simple proportional control exercised by the pilot, the lightly damped oscillation remains and the exponential is stabilized.

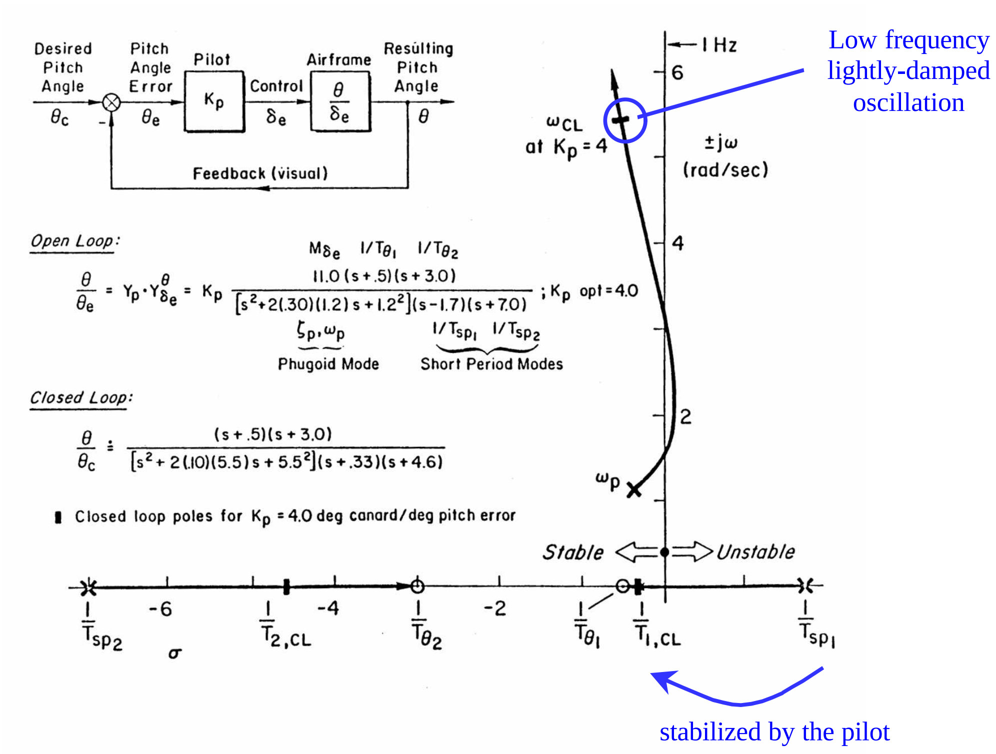


Figure 6. Locus of dynamic roots for longitudinal motion of the 1903 Wright *Flyer*; Pilot control law: canard deflection proportional to pitch angle error (Culick and Jex 1984).

8. THE WRIGHTS DISCOVER LATERAL DYNAMICS

The three lateral degrees of freedom are translation along the y-axis perpendicular to the plane of symmetry; rotation in roll; and rotation in yaw. It's the presence of two rotations that make lateral motions seem somewhat more complicated than the longitudinal motions. The translational velocity is v and the two rates are p, r in roll and yaw respectively.

8.1 THE NORMAL MODES FOR LATERAL MOTIONS

For a rigid aircraft there are usually three distinct normal modes: the roll subsidence; the spiral mode; and the lateral or 'Dutch roll' oscillation. All three generally have components of motions in the three lateral degrees of freedom, but some simplifications are possible and often give acceptably accurate results.

The roll subsidence is nearly a pure rolling motion that can be excited by a step change of aileron setting. Small yaw and lateral translational motions may be generated due to the action of lateral cross-derivatives. In any event, the roll subsidence is heavily attenuated due to the large damping-in-roll provided by the wings.

A second mode, the spiral mode, also usually has behavior exponential in time. It is either lightly damped or weakly unstable. The spiral mode for the 1903 *Flyer* was seriously unstable, causing the Wrights so much trouble that they eventually made the modifications necessary to stabilize the mode.

The third lateral mode is the lateral oscillation which always involves contributions from the three degrees of freedom. It is most obviously a coupled yaw/roll oscillation but also involves oscillatory translational or slipping motions perpendicular to the forward motion. Usually the frequency of the lateral oscillation lies in the range where it is easily excited during flight through turbulent air or by appropriate periodic manipulation of the controls. Otherwise it is hardly noticeable in normal flight of conventional aircraft.

8.2 THE WRIGHTS’ EXPERIENCE WITH LATERAL DYNAMICS: 1901–1905

It was Wilbur’s observation of adverse yaw in 1901 that first caused the Brothers to pay attention to motions in yaw. Eventually they also noticed a slipping motion subsequent to rolling their aircraft, an observation confirming that they encountered the spiral mode.

When they returned for flight tests at Kitty Hawk in 1902, their new glider was larger and heavier than the 1901 machine, but had the same wing loading (0.84 pounds per square foot). More significantly, it sported a fixed double vertical tail intended to compensate adverse yaw when the aircraft was rolled to turn.

During the first part of their flying season in 1902, the Brothers concentrated on learning how to turn. Because they were flying close to the slopes of the hills—they probably rarely reached altitude greater than a wingspan or two—they never completed, or even attempted circles. Rather, it seems clear that they were trying to figure out the mechanics of the turn. They encountered two problems that demanded small changes of their design. Or perhaps they were two manifestations of the same problem, caused by adverse yaw.

During the early gliding tests, both Brothers encountered an annoying form of the response to gusts. Up to this time, all the gliders had positive dihedral effect, following Cayley’s idea to provide intrinsic stability to disturbances in roll. If one wing drops—or what is the same aerodynamically—the aircraft is exposed to a side gust, then positive dihedral causes the airplane to right itself in the sense indicated in Figure 7. In particular, for example, a gust from the right causes the airplane to roll to the right—i.e. the left wing is rotated downward. That was troublesome to the Wrights for the following reason.

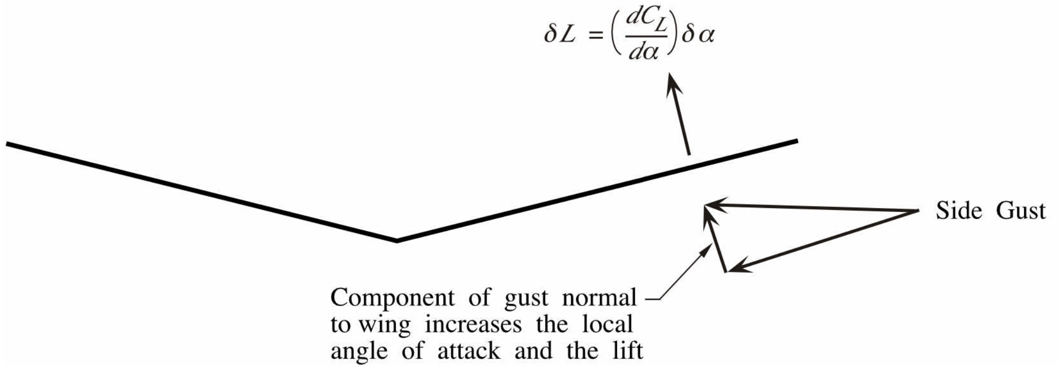


Figure 7. Illustrating the dihedral effect

The Wrights were gliding down a slope into the wind. Most gusts occurred in the direction of the wind, i.e. up the hill. When they attempted to turn, or for some other reason they were not flying directly into the wind, a gust would cause the uphill wing to drop (positive dihedral effect), occasionally striking the slope. That happened sufficiently often that Brothers decided to truss the wings for negative dihedral (also called ‘
lower than the center.

With or without anhedral, the glider having fixed tail also several times exhibited a second problem associated with adverse yaw. As a gentle turn, having relatively small roll angle, was being connected to level flight, the outer wing of the turn dropped and struck the ground. The Brothers called this event “well-digging.” Wald (1999) has best explained the cause of the problem. Suppose the glider is turning to the left, say, and the wings are warped, the trailing edge of the left wing warped downward to increase its lift and stop the turn. Due to adverse yaw the wing is slowed, the lift is reduced and the wing actually drops. If the glider is sufficiently close to the ground, the tip of the wind would strike the sand.

In 1902 the new vertical tail, because it provided directional stability, did help the aircraft turn. But also because it was fixed it had a serious shortcoming—it was effective only if the aircraft had translational motion laterally, i.e. slipping. When a turn was initiated, adverse yaw swung the aircraft such that the lift (to the side) generated by the tail would correctly compensate the swinging motion. But apparently the correction was too large under some circumstances, causing the glider’s nose to swing too far into the turn; the beginning of motion that we now know as the spiral mode.

Orville (McFarland 1953, p. 470) later testified that their glider having "cathedral angle [anhedral] with fixed rear vertical tail and adjustable wing type was the most dangerous…." The negative dihedral caused the spiral mode to be seriously unstable so any attempted turn would lead to a crash unless corrected very quickly.

Those unsatisfactory results with the glider having fixed tail convinced the Brothers they need to modify the design. It was Orville who suggested that the vertical tail be made controllable. In the interest of simplifying the pilot's workload, Wilbur proposed connecting the rudder control to the warp control. From then until September 1905, the Wrights flew their aircraft with roll and yaw controls interconnected. They were the last to have two-axis control until Fred Weick invented the Europe in the late 1930's.

However, not realizing the consequences of giving an unstable spiral mode, the Wrights also retained the negative dihedral until November 1904. They finally realized that it was causing problems when they attempted turns and removed the anhedral in early November.

9. MORE TROUBLE WITH DYNAMICS: 1904

After installing anhedral and a moveable vertical tail, the Brothers spent the remainder of the 1902 season learning how to fly their glider. At most they seem to have attempted only gentle turns. They continued that kind of practicing for two months in 1903 while they prepared the powered aircraft. It seems a fair assessment to characterize this period of their flying as a process of learning how to fly more-or-less straight and level in the presence of disturbances or gusts. They did not expose any new problems of flight dynamics.

In that context, the first powered flights were really powered and sustained level gliding flights following take-offs. The 1903 *Flyer* was larger than the 1902 glider (span 40'40" compared with 32'1") and heavier (750 pounds compared with 257 pounds) and had wing loading increased from 0.84 to 1.47 pounds per square foot. Hence the 1903 airplane surely offered more difficult handling qualities, but with only straight flights, the Brothers did not report new dynamical problems. If new dynamical problems did appear they were likely not easily identified, being obscured by the Brothers' vigorous efforts to keep the airplane in the air.

It became a different story in 1904. They began with a new airplane having the same design as the 1903 *Flyer* but with a larger engine producing about 25-30 HP compared with the 12-16 HP of the earlier aircraft. From the beginning of the 1904 tests the Brothers had trouble. In the light or calm winds and higher density altitude (Combs 1979) take-offs were difficult and often failed, even with the longer take-offs rail. Orville stalled the machine shortly after one of his first flights and Wilbur imitated him. They first used the term 'stall' in their report of those flights.

More distressingly, they continuously fought the pitching undulations that were likely present in the 1903 flights. In an effort to correct the problem they moved the engine, its water tank and the pilot aft, exactly the wrong direction. One test flight was enough to show them that they really needed to move the center of gravity forward. Two weeks of repairs were required.

They made no further changes to the airplane in 1904 but they did devise their catapult apparatus to ease their take-off problem (Figure 8). They were forced continually to cope with the dynamics of taking off. Many trials ended in minor crashes before flying speed was reached. And even when take-off was successful it seems that they were always flying very close to the stalled condition. Although they knew they had to maintain some minimum speed, in the vicinity of 27-28 MPH, the fact that they really didn't understand the phenomenon of stalling and why it occurred, probably hindered their progress. They seem not to have been aware that the canard could stall as well, with consequent loss of control power in pitch.

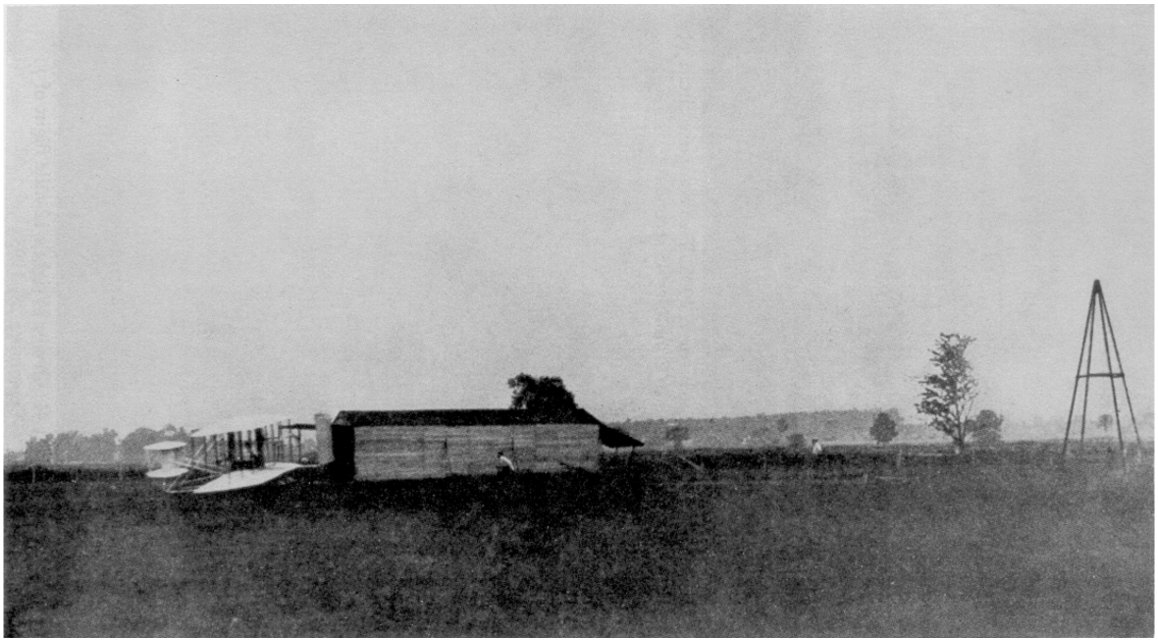


Figure 8. The Wrights' catapult launching apparatus at Hoffman Prairie, August 1904.

So with an airplane they knew to be unstable in pitch, always plagued with the familiar pitch undulations, the Wrights pressed on to learn how to fly circles. Wilbur flew their first complete circle on 20 September 1904, a grand achievement with 1903 design. As they continued practicing turns, both Brothers encountered a new serious problem that they characterized as “unable to stop turning,” those flights sometimes terminated by crashes. Evidently the cause was one now familiar: stalling of the inner wing of the turn due to its slower speed and higher angle of attack. The Wrights sensed the cause and correctly eased the problem by adding seventy pounds of steel ballast to the canard, a move that reduced the amplitude of the pitch undulations, and also caused them to fly faster.

Moreover, they also correctly concluded that the anhedral was causing them difficulties. Nowhere do they mention any feeling that the airplane seemed to have a tendency to tighten turns, but that was surely a factor. In a turn, the presence of their unstable spiral mode was bound to be felt because of its short (~0.8s) doubling time. In late October, the Brothers finally removed the anhedral, Figure 9. That was the airplane for their last tests of 1904.

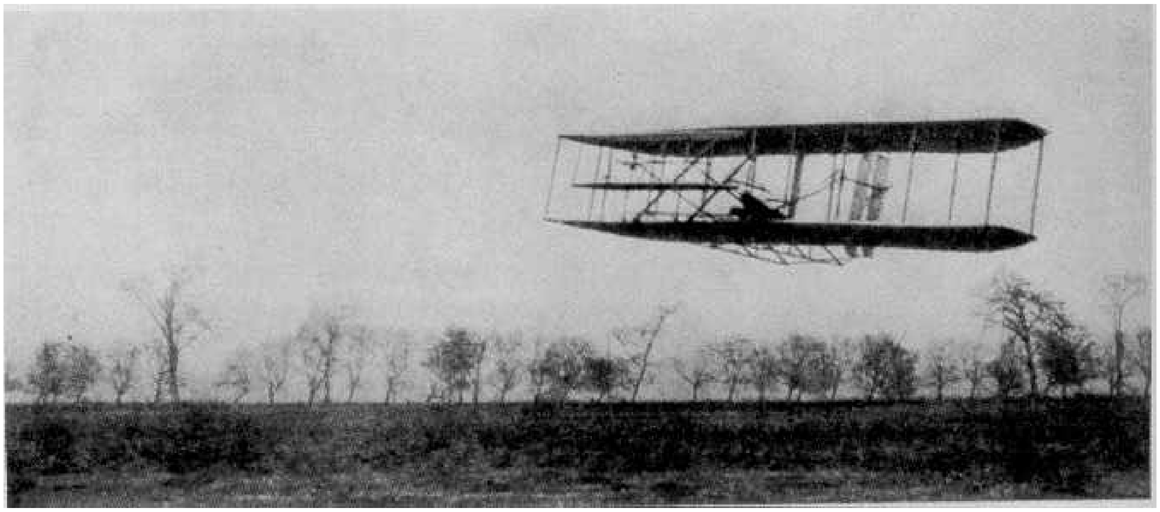


Figure 9. The *Flyer* on 16 November 1904: the 1903 design with a larger engine and no anhedral.

10. 1905: FLIGHT TESTS LEAD TO THE FINAL DESIGN OF A PRACTICAL AIRPLANE

In a court deposition (Wrights vs. Herring-Curtiss), Wilbur (McFarland 1953, p. 469) explained clearly that while they had progressed considerably in 1904, the Brothers were still left with a puzzle: “on a few occasions, the machine did not respond promptly (to action taken to restore lateral balance) and the machine came to the ground in a somewhat tilted position.” That is, the pilot could not cause the transition from a turn to level flight and the aircraft crashed. The airplane was unreliable and certainly not yet a practical machine.

The Wrights eventually solved the ‘puzzle’ when they discovered the correct flying technique, in the last days of September, 1905. Before they reached that point they made some important modifications in their design, relating to both lateral and longitudinal dynamics.

When they began flying again in June 1905, the Brothers still had essentially the 1903 design but with some detailed structural changes for improved strength and a larger engine, now producing more than thirty horsepower. For some reason, they re-installed a small amount of anhedral. They also, inexplicably, add small vertical vanes to the canard, that came to be called ‘blinders’. Those surfaces mainly reduced the directional stability and in the absence of explanation it is not clear why the Wrights thought they would help ease their steering problems; evidently they believed they would reduce the problem of slipping when the aircraft has a lateral translational velocity. That in turn reduces a roll motion in a sense depending on the dihedral effect (positive or negative).

On 14 July, Wilbur noted that at a higher flight speed he had trouble once again with the undulations in pitch and crashed. When they made repairs, the Brothers increased the area of the canard by about 73% and moved its hinge line forward from about six and a quarter to ten and a quarter feet. That’s an interesting modification reflecting again the Wrights’ lack of understanding of stability and, probably, their central concern for control. The larger tail volume of the canard causes the neutral point to lie further forward, a destabilizing effect.

On the other hand, the larger tail volume increases the damping in pitch, giving substantial improvement in controllability by reducing the frequency and amplitude of the oscillations. Also the more forward placement of the canard reduces a destabilizing influence of upwash from the wing. Recent tests with ground simulations (Test Pilot School, Edwards Air Force Base 2001) have confirmed the advantage of increased damping in pitch. Technically, it causes the maneuver point to move aft, a favorable result for controlling accelerated motions, including undulations. The Wrights clearly found that to be a good modification, although in their 1907-09 models the canard was made smaller and moved further forward, a 3.8% decrease in tail volume from the value in 1905. Nothing in their diaries gives a specific reason for the details of these changes.

While those repairs and modifications were being made, the Brothers made some measurements of the center of pressure on their airfoil, the first such data they had taken, Figure 10. Apparently those tests were done as a direct response to the July crash. However, there is no evidence in their diaries (McFarland 1953) about their interpretation of their results or what influence the tests may have had on their design changes. Their decisions about changes in the geometry affecting behavior in flight continued to be restricted by their inattention to the moments acting on the aircraft.

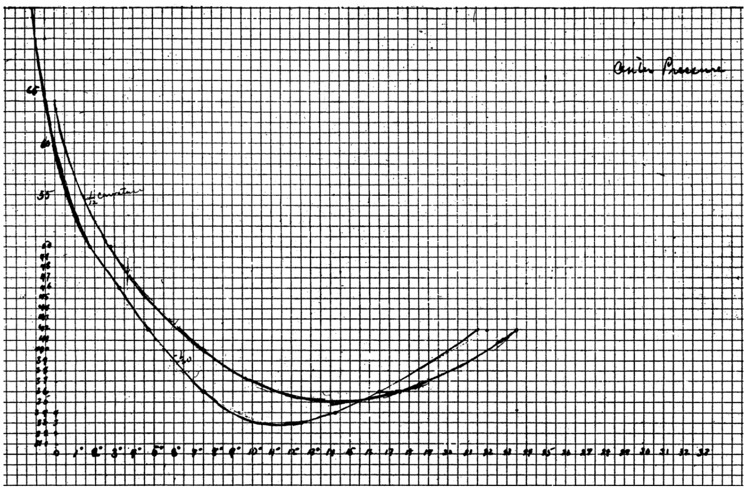


Figure 10. The Wrights data for the center of pressure on two of their airfoils.

While they modified the canard they also enlarged the vertical tail. They had finally concluded that the tail was too small to give the control they required. From 1903 to the final design in 1905 the tail area and the distance between the wing and the tail were increased. The increase of dimensionless tail volume gave comparable increases in the directional stability and control power.

Installation of the larger vertical tail initially caused a handling problem. Wilbur commented that Orville's first flight with the new tail was "a very comical performance." Apparently the difficulty arose because the hinge line was too far aft, behind the center of pressure. No change was made at that time, but in the 1907–09 machines flown publicly, the vertical tail was hinged at the leading edge.

For the remainder of the 1905 season, all of September and for the first two weeks of October, only minor structural changes were made; the Brothers concentrated mainly on learning to turn. On September 7 Wilbur flew four circles consecutively, but then two days later, with larger propellers installed, he stalled the airplane twice. Again on the 12th he stalled while turning and on the 15th he was "unable to stop turning." A week later they removed the anhedral they had been keeping since the beginning of the season, an indication that they were bothered by slipping in turns.

On the 26th of September Orville executed sixteen circles in one flight, remaining aloft eighteen minutes until his fuel supply was exhausted. The Brothers' performance remained erratic, however. On the following day, Wilbur noted that the "machine at low speed could not be stopped from turning." On the 29th, Wilbur made 14 circuits in 19 minutes; but on October 3 he was "unable to stop turning." The last was a mistake he understood, for on September 28 he finally isolated the source of the problems both he and Orville had been having: failure to maintain sufficient speed while turning, causing the inner wing to stall. They had been fighting what remains a cause of many accidents, stall/spin out of a turn. Wilbur explained the matter as well as anyone could today:

> "… When it was noticed that the machine was tilting up and sliding toward the tree, the operator then responded promptly to the lateral control. The remedy was found to consist in the more skillful operation of the machine and not in a different construction. The trouble was really due to the fact that in circling, the machine has to carry the load resulting from centrifugal force, in addition to its own weight, since the actual pressure that the air must sustain is that due to the resultant of the two forces. The machine in question had but a slight surplus of power above what was required for straight flight, and as the additional load, caused by circling, increased rapidly as the circle became smaller, a limit was finally reached beyond which the machine was no longer able to maintain sufficient speed to sustain itself in the air. And as the lifting effect of the inner wing, owing to its reduced speed, counterbalanced a large part of the increased lift resulting from the greater angle of incidence on that wing, the response to lateral control was so slow that the machine sank to the ground, usually before it had been brought back to the level again. … When we had discovered the real nature of the trouble, and knew that it could always be remedied by tilting the machine forward a little, so that its flying speed would be restored, we felt that we were ready to place flying machines on the market."
>
> [McFarland, 1953, pp. 520–521]

With their identification of the stall/spin problem and Wilbur's discovery of its solution, the Wrights announced they had a practical airplane. They ceased flying to turn all of their efforts to selling their invention.

11. THE WRIGHTS' TRANSITION FROM CANARD TO AFT TAIL

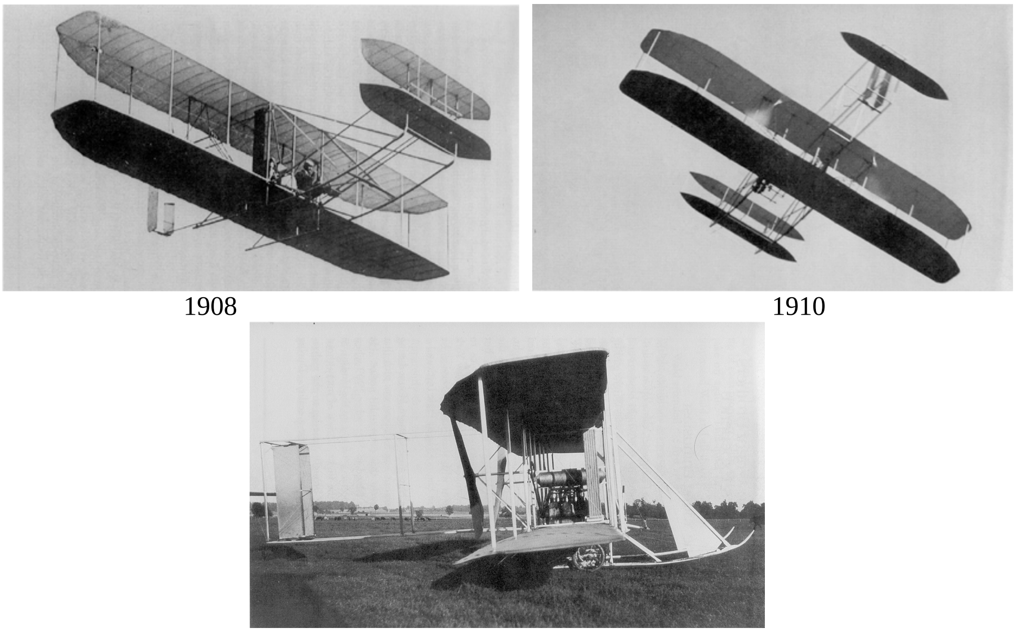
Wilbur initially settled on his canard configuration to avoid (he expected) the inadequate pitch control that Lilienthal had with his aft tail. Combined with the biplane cell containing, eventually, 94% of the machine's gross weight, the canard presents a very difficult problem of designing for trim and stability. It was difficult to shift the center of gravity far enough to give a positive static margin. The choice of airfoil then becomes a crucial matter nearly as important as the location of the center of gravity. An airfoil having a large negative zero lift moment may give an aircraft that has a stable moment curve but cannot be trimmed; or can be trimmed but has an unstable moment curve. Moreover, in the second case the trim condition may require lift from the canard that cannot be reached because the surface already stalls at a lower angle of attack. In practice there are really only two certain ways out of this situation: use a drastically different airfoil, even one having a reflexed camber line; or change the configuration from canard to aft tail.

The Wrights learned from flight tests some of the nasty consequences of their 1903 design. They were severely handicapped in understanding the problems they discovered because they were not aware of methods based on analyzing the moments acting on the aircraft in flight. Moreover, neither experimental nor theoretical investigations had progressed to the stage where anybody could understand the dependence of aerodynamic pitching moment on the shape of the camber line. All-in-all, then, the state-of-the-art (which in fact had been developed by the Wrights themselves!) was such that it was difficult for them to understand any technical reasons to justify changing their canard design.

No other designers contemporary with the Wrights suffered the same commitments to the canard. The French in particular were not so concerned with control as the Wrights were, and so they did not share the same fear of the aft tail. In fact, because it was Pénaud's tail, the French for the most part were biased, if not even prejudiced, to that configuration. As a result, the Wrights' sought a controllable airplane, even if unstable, and they got it; the French sought an intrinsically stable airplane design, and got it, but at the expense of paying too little attention to the fundamental problem of control.

After their two-year flight test program the Wrights had finally gotten rid of their lateral instability. Their observations demonstrated repeatedly that the unstable spiral mode interfered with circling—so they removed the anhedral initially installed to solve a problem peculiar to their glide tests close to the ground. Their tests also showed them that the intensity of the pitch instability was reduced by carrying ballast to move the center of gravity forward. Geometrical restrictions raised serious obstacles to making their canard stable and they were satisfied with an unstable but controllable aircraft.

But following the Wrights' first public flights in 1908, when their contemporaries finally grasped the significance of control, advantages of conventional configurations became increasingly apparent. The Wright aircraft were undoubtedly more difficult to learn to fly, a distinct shortcoming at the time when the new businesses of flying schools and aircraft manufacturing were growing rapidly in many countries of Europe. Conventional aircraft slowly gained a reputation for being safer. The Wrights were effectively pressured to relax their commitment to their canard design. Possibly at the suggestion of a German customer they relented. Their first step was simply to add a fixed horizontal tail to their existing design, in 1910. The improvement in handling qualities must have been immediately evident. Few pictures of the airplane exist (Figure 11) and within a year the Wrights removed their canard surfaces. That indeed their use of the configuration which had been their invention and had served them well for a decade. Despite their commitment to that form of the airplane, original with them, the Wrights didn't try to patent it. The basis for their patent, granted in 1906 and never broken, was their two-axis control of lateral motions, in general, not for their particular aircraft design.



1908

1910

1911

Figure 11. The transition from canard to aft tail conventional aircraft.

12. CONCLUDING REMARKS

Justification exists for the position often taken that somebody would have invented the airplane in the early years of the 20th century. Bleriot was closest to having all of the practical pieces in place by 1908—except for three-axis control which he learned from the Wrights. In fact, Bleriot owes an earlier debt to the Brothers, for their achievements motivated Ferber to initiate the "rebirth of aviation in Europe" (Gibbs-Smith 1970), the activity in France that attracted Bleriot to the problem of mechanical flight.

Bleriot's approach of largely uninformed trial and error (his successful monoplane that was his first real success, later crossing the English Channel, was his eleventh design) contrasts stunningly with the Wrights' systematic research and development program centered on the evolution of one design. Everybody began with the same history and known results at the end of the 19th century, but the Wrights brought with them the revolutionary idea of roll control; willingness gained from their experiences with bicycles, to accept an unstable, but controllable, machine; and especially their own original style, now recognized as a modern 'research and development program'.

That style was central to the ability of the Wrights to develop their airplane in such a relatively short time without benefit of the understanding and guidance later provided by theories of aerodynamics and flight mechanics. Had those theories been developed earlier, it seems certain that the Wrights would have avoided the problems caused by their highly cambered airfoil and their canard configuration. Their systematic progress to solutions to those problems is clearly shown by the sequence of side-views of their aircraft, Figure 12.

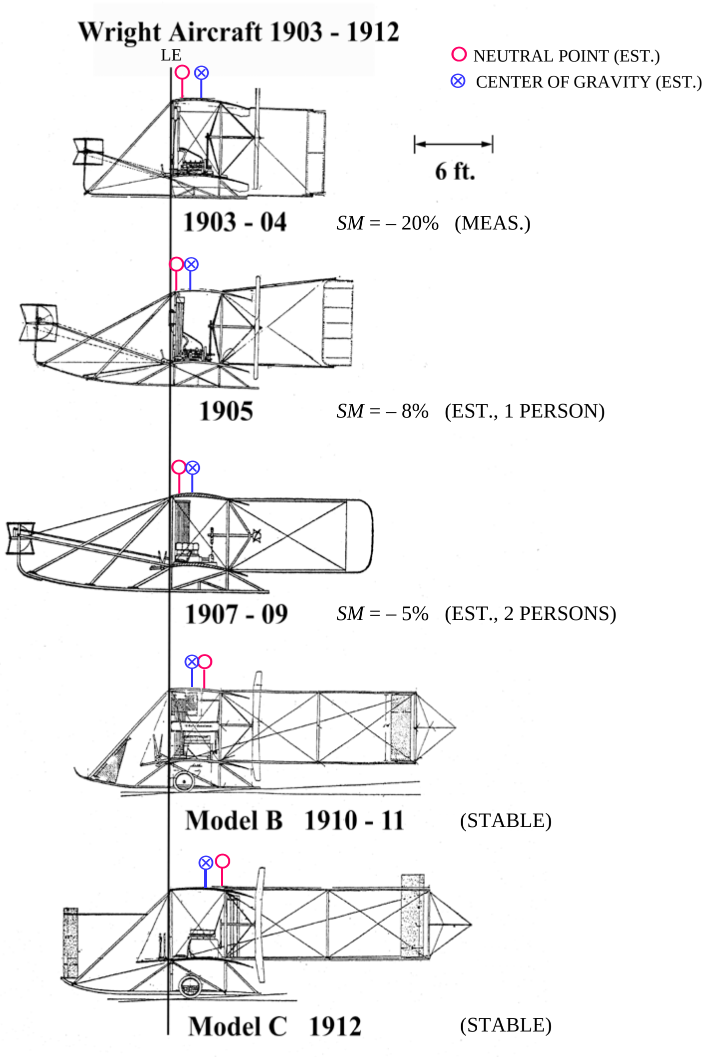


Figure 12. Summary of Wright aircraft, 1903-1912.

The summary given in Figure 12 is really a pictorial progress report of a successful flight test program. While the biplane cell remains practically unchanged, and most of the weight is concentrated between the wings, the change of the size and location of the secondary horizontal surface finally produced a stable aircraft in 1911. The forward displacement of the center of gravity from 1903 to 1905 was important, but insufficient to provide longitudinal static stability.

At the beginning of their program, the Wrights estimated that in all his gliding tests, Lilienthal had been in the air perhaps five hours—too little, they felt, to reach his goal of having a powered flying machine. They set out to do better, the chief reason they selected Kitty Hawk, a place known to have steady strong winds during most of the times they planned to be there. In fact, the Brothers themselves accumulated between them less than six hours gliding experience from 1900 to 1903.

What is truly surprising is that when they were satisfied they had their practical aircraft, the two together had attempted about 150 take-offs, of which 115–120 were successful but only 100 led to successful landings. *In toto* they had less than six hours experience with their powered aircraft. What a testament to their ability to observe and act accordingly to improve their design!

A modern student pilot has perhaps 8-12 hours' dual flying experience before soloing. In about the same time the Wrights both learned how to fly and invented their airplane.

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