Airplane Stability and Control, Second Edition

A History of the Technologies That Made Aviation Possible

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CHAPTER 1

Early Developments in Stability and Control

While scientists and mathematicians in the United States and Europe built the foundations of future advances by developing fundamental aeronautical theory, practical aeronautical designers invented and improved the airplane empirically. As recognized by the Wright brothers, solutions to the stability and control problem had to be found. This chapter presents the largely empirical development of airplane stability and control from the precursors of the Wrights through the end of the first World War. It was only then that aeronautical theory started to have an impact on practical airplane design.

1.1 Inherent Stability and the Early Machines

Pioneer airplane and glider builders who came before the Wright brothers recognized the importance of airplane stability. They had discovered that some degree of inherent stability in flight could be obtained with an appropriate combination of aft-mounted tail surfaces (Cayley and Pénaud), wing dihedral angle or lateral area distribution (Langley and Lanchester), and center of gravity location (Lilienthal).

However, very little thought had been given to the problem of control except for the provision of horizontal and vertical rudders (Langley et al.). It was commonly held that an airplane should hold its course in the air while the pilot decided what to do next. Then the pilot would deflect the rudder to steer it, more or less in the manner of a boat. Only the Wrights recognized that (1) an airplane has to be banked to turn in a horizontal plane; (2) an interaction exists between the banking or roll control and the yawing motion of an airplane; (3) excessive dihedral effects hinder pilot control unless sideslip is suppressed and makes the machine unduly sensitive to atmospheric turbulence; (4) wings can be stalled, leading to loss in control; and (5) control can be regained after stalling by reducing the angle of attack.

After the Wright brothers, Blériot and Levavasseur, the constructor and designer of the Blériot and Antoinette machines, respectively, pioneered in developing tractor monoplanes with normal tail surfaces and wing dihedral angles (Figure 1.1). These two airplanes had a fair amount of inherent stability, unlike the Wright biplanes. They had superior speed, which helped establish the aft tail as the normal arrangement. In fact, the Blériot and Antoinette machines were the transitional forms that led from the Wright brothers' biplanes to the famous pursuit airplanes of World War I.

1.2 The Problem of Control

Otto Lilienthal (1848–1896), Sir Hiram Maxim (1840–1916), and Dr. Samuel Pierpont Langley (1834–1906) followed the empirical route, much as did the Wrights, but they failed to demonstrate man-carrying mechanical flight mainly because they underestimated the problem of control. Lilienthal died of a broken back after losing control of his hang glider. Langley's airplane flew stably in uncontrolled flight as a quarter-scale model but broke up twice in full-scale launches. Maxim's steam-driven airplane might have flown, but it broke free of the down-holding rails on its test track and was wrecked.

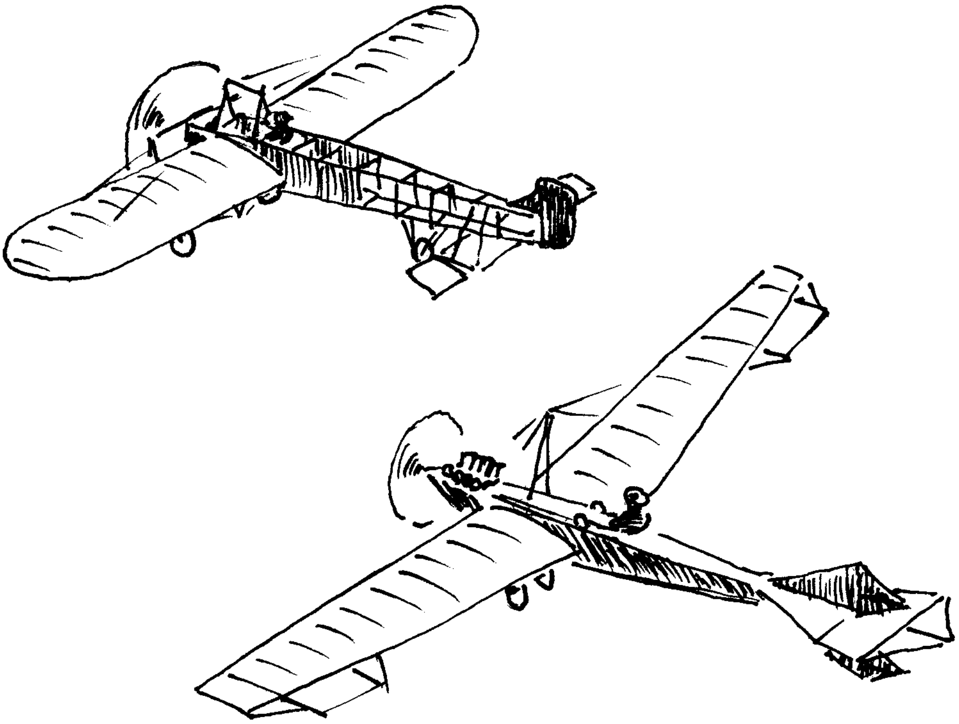

Figure 1.1 Two early flying machines with inherent longitudinal and lateral stability, the Blériot XI Cross-Channel airplane (*above*) and the Levavasseur Antoinette IV (*below*). Both used pronounced wing dihedral, unlike the Wright Flyers.

Maxim's well-engineered failure has had a continuing fascination for modern aeronautical engineers. Bernard Maggin, a noted stability and control engineer with a long career at NACA and the National Research Council, has done extensive research into Maxim's work for the National Air and Space Museum. Another stability and control expert, W. Hewitt Phillips, built and flew a rubber-powered, dynamically scaled, scale model of Maxim's large machine. In unpublished correspondence Phillips reports as follows:

> The model flies fine, despite the lack of vertical tail on the configuration that Maxim used when he ran it on tracks. It flies like a twin pusher, which is what it is. The big propellers aft of the center of gravity give it a marginal amount of directional stability.... Of course, the Reynolds number is far from the full-scale value, but this may not be very important since Maxim used thin airfoils....
>
> My conclusion is that Maxim's airplane would have flown, at least as a giant free-flight model... I feel that Maxim should get more credit for his engineering contributions than has been given by historians.

The Wrights, on the other hand, addressed the control problem head-on. They taught themselves to fly with three experimental biplane gliders, each fitted with warpable wings for lateral control and all-moving foreplanes for pitch control. The third incorporated an all-moving vertical tail coupled to the wing warp for suppression of adverse yaw due to lateral control actuation, and they learned to fly it quite nicely by 1902. They applied for a patent, describing coupled lateral, or roll and yaw, controls.

In 1903 the Wrights built a powered machine based on the 1902 glider, with a four-cylinder gasoline engine geared to turn its two propellers, and they designed and built the engine and propellers too. They flew it first on 17 December 1903. Modern analysis by Professor Fred E. C. Culick and Henry R. Jex (1985) has demonstrated that the 1903 Wright Flyer was so unstable as to be almost unmanageable by anyone but the Wrights, who had trained themselves in the 1902 glider. In 1904 and 1905 the Wrights improved the lateral stability of their 1903 airplane by removing the downward arch of the wings as seen from the front (the so-called cathedral), reduced its longitudinal instability by ballasting it to be more nose-heavy, and improved its lateral control by removing the mechanical roll–yaw control interconnect.

Henceforth, appropriate roll–yaw control coupling would be provided by pilot skill. Finally, the Wrights learned to sense wing stall, especially in turning flight, and to avoid it by nosing down slightly. By practice they became masters of precision flight in their unstable machine. They also received a patent for their control innovations on 22 May 1905. Confident of their skill and achievements, they built two new machines and sent one to France in 1907.

1.3 Catching Up to the Wright Brothers

Two public demonstrations of perfectly controlled mechanical flight in 1908 by Wilbur Wright in France and by Orville Wright in the United States were clarion calls to the rest of the aeronautical community to catch up with and surpass their achievements. The airplane builders – Curtiss, Blériot, Levavasseur, the Voisins, Farman, Bechereau, Esnault-Pelterie, and others – responded; by 1910 they flew faster and almost as well; by 1911 they flew better. However, even after these momentous achievements, neither the Wrights nor their competitors still had any real understanding of aerodynamic theory.

1.4 The Invention of Flap-Type Control Surfaces and Tabs

Flap-type control surfaces, in which a portion of the wing or tail surface is hinged to modify the surface's overall lift, are at the heart of airplane control. Airplanes designed to fly at supersonic speeds often dispense with flap-type longitudinal controls, moving the entire horizontal surface. Also, some airplanes use spoiler-type lateral controls, in which a control element pops out of the wing's upper surface to reduce lift on that side. Aside from these exceptions, flap-type controls have been the bread-and-butter for airplane control since a few years after the Wright brothers.

It was in 1908 that the aviation pioneer Glenn Curtiss made the first flight of his June Bug airplane, which was equipped with flap-type lateral controls. This was an early, if not the first, advance in lateral control beyond the Wright brothers' wing warping. The Curtiss lateral controls were attached to the interplane struts between the biplane wings and were all-moving. Curtiss evidently saw them as lateral trim devices, since the wheel was connected to the rudder. The French called the flap-type lateral controls *ailerons* – little wings – and the name has persisted in the English language. The Germans call them *querrudern*, or lateral rudders.

The first true flap-type aileron control appears to have been on the French Farman biplane a year or two later. An aerodynamic theory for flap-type controls was needed, but it wasn't until 1927 that Hermann Glauert (Figure 1.2) supplied this need. Control surface tabs are small movable surfaces at the trailing edge, or rear, of a flap-type control. Tabs generate aerodynamic pressures that operate with a long moment arm about the control surface hinge line. Tabs provide an effective way to deflect main control surfaces in a direction opposite to the deflection of the tab itself relative to the main surface.

Figure 1.2 Hermann Glauert (1892–1934). In Glauert's short career he made important airplane stability and control contributions, in control surface, downwash, airfoil, wing, and propeller theory, and in the equations of motion. (From *Obit. Notices of Fellows of the Royal Soc., 1932–1935*)

The tab concept is due to the prolific inventor Anton Flettner, who first applied it to steamboat rudders. One may still find references in the literature to "Flettners," meaning tabs. Flettner received a basic German patent for the tab in 1922. This was for its application to aeronautics. Flettner's patent includes a description of a spring tab device (see Chapter 5), which was promptly forgotten. Glauert's aerodynamic theory for flap-type controls was extended to the tab case in 1928 by W. G. Perrin.

1.5 Handles, Wheels, and Pedals

Before the Wright brothers demonstrated their airmanship, little thought had been given to handles, wheels, and pedals for steering flying machines. Cayley provided his reluctant coachman-aviator with an oar having cruciform blades to "influence" the horizontal and vertical paths of his man-carrying glider. Langley provided Manley, his pilot and engine builder, with a cruciform tail that could be deflected vertically to control pitch attitude and horizontally to turn. Langley expected the dihedral angle of the tandem wings to keep them level, as they had done on his free-flying scale models.

Lilienthal shifted his weight sideways or fore-and-aft on his hang glider to control roll and pitch. This works, but it has limited effectiveness. A roll angle established by a hang glider pilot will make the machine turn if it has weathervane stability, that is, a fixed vertical tail. Hiram Maxim provided his steam-powered airplane with a gyroscopically controlled foreplane to regulate pitch attitude and thought of steering horizontally with differential power to its two independently driven pusher propellers. Fortunately he never had to try this arrangement in flight.

1.6 Wright Controls

In the Wright brothers' 1902 glider and their 1903 Flyer the pilot had a vertical lever for the left hand that was pulled back to increase foreplane incidence. The pilot lay on a cradle that shifted sideways on tracks to cause wing warp. To roll to the left the pilot decreased the incidence of the outer left wings and increased the incidence of the outer right wings. The rudder motion was mechanically connected to the wing warp mechanism to turn the nose left when the pilot wished to lower the left wing, and vice versa for lowering the right wing, thereby overcoming the adverse yaw due to wing warp.

When they began to fly sitting up in 1905, the Wrights retained the left-hand vertical lever for foreplane incidence but added a right-hand vertical lever for wing warp and rudder. They moved the new right-hand lever to the left for left wing down and forward for nose-left yaw. The right-hand lever was moved to the right for right wing down and aft for nose-right yaw. Turn coordination required the pilot to phase control motions, leading with yaw inputs. These unnatural control motions had to be learned and practiced on dual control machines or simple simulators. Bicyclists to the last, they never used their feet for control. They retained this scheme until 1909. Since wing warping involved considerable elastic deformation of the wing structure, they later changed the fore-and-aft motion of the right-hand lever to wing warp and mounted a new, short lever on its top for side-to-side movement to control the rudder. When the Wrights abandoned the all-moving foreplane array for an all-moving rear horizontal tail in 1911, the left-hand lever still controlled its incidence, but now reversed.

The Wrights' patent was for mechanically linked roll and yaw controls. Other airplane builders, notably Curtiss, built airplanes with ailerons, rudders, and elevators, providing independent three-axis control. Curtiss and others asserted that the Wright machine now had independent three-axis control, but U.S. courts upheld the Wright patent against them. The courts maintained that the coupling of roll and yaw controls in the Curtiss machines existed in the mind of the aviator and was essential to the art of flying. Therefore, the Curtiss independent three-axis control infringed on the Wright patent!

1.7 Blériot and Déperdussin Controls

Louis Blériot devised what has become the standard stick and rudder cockpit controls for small airplanes. A central stick between the pilot's legs is moved forward for nose down, aft for nose up, to the left for left wing down, and to the right for right wing down. The pilot's feet rest on a rudder bar from the ends of which a pair of cables run straight back to the rudder horns. Thus left foot forward deflects the rudder to the left and turns the machine to the left (Figure 1.3). Blériot fitted a nonrotatable wheel to the top of the control stick, perhaps to give the pilot a firmer grip for wing warping.

The Blériot rudder pedal convention, now quite standard, is just the opposite of bicycle or "Flexible Flyer" sled steering, where operators turn the handlebars or hand grips in the direction of the desired turn. Igor Sikorsky thought that the Blériot convention was backward. Sikorsky crossed the rudder wires on all of his airplanes, to make them steer like bicycles. He warned conventionally trained pilots not to try to fly these particular machines.

Before the war, the company Société pour Avions Déperdussin (SPAD) produced a series of military airplanes and racers that were designed by Bechereau. These streamlined airplanes were fitted with Blériot-style rudder bars and a vertical wheel that could be moved fore and aft for pitch and turned sideways for wing warp. The wheel's increased mechanical

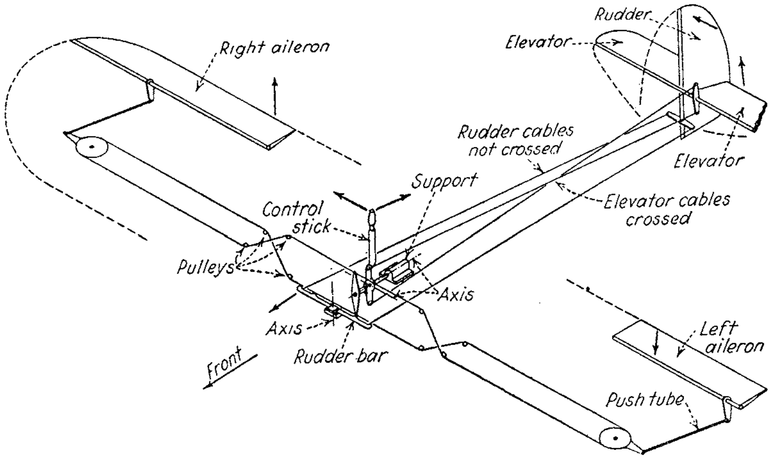

Figure 1.3 Diagrammatic sketch of a simple airplane control system. When the controls are moved as shown by arrows on the stick and rudder bar, the surfaces move as shown by the arrows. (From Chatfield, Taylor, and Ober, *The Airplane and Its Engine*, McGraw-Hill, 1936)

advantage as compared with levers was needed to warp wings of increased torsional rigidity. The Déperdussin wheel is the ancestor of modern control yokes.

1.8 Stability and Control of World War I Pursuit Airplanes

By 1917 trial and error during the first World War had established the wire braced biplane with aft-tailed surfaces as the normal configuration. Diagonal brace wires between the wing struts and fuselage and within the wing frames made a torsionally rigid structure that resisted twisting and instability failure in high-speed dives. The heavy engine in front and the generous tail surfaces behind tended to keep the fuselage and wings aligned with the velocity of flight. The pilot could apply roll control by aileron deflection, yaw control by rudder deflection, and pitch control by elevator deflection – all independently. Aerodynamic hinge moments tended to center the controls. By ground adjustment of wing, fin, and tailplane rigging the airplane could be made to maintain level flight with cruising power in calm air for a minute or so.

Violent maneuvering in combat was provided mainly by the elevator, which had sufficient authority to bring the airplane to a full stall. Horizontal turning flight required rolling the airplane about its longitudinal axis quickly, which was most often accomplished by combined rudder and aileron deflection. The rudder-induced sideslip produced an unsymmetric stall and a snap or flick roll that could be checked at the desired angle by relieving stick back pressure and centering the rudder and ailerons.

The ailerons were difficult to deflect at combat speeds but could be used to produce a slow or barrel roll. An important use of the ailerons was to produce a cross-controlled (e.g., right rudder and left stick) nonrolling sideslip for glide path control while landing. The glide angle could be steepened appreciably by sideslipping in a steep bank, incidentally giving the pilot a good view of the touchdown point.

A dangerous aspect of stability and control of the otherwise benign World War I airplanes was inadvertent stalling and spinning at low altitudes, the so-called arrival and departure stalls (and spins). Moderate sideslip at stall would provoke a snap roll, which rapidly developed into the dreaded tail spin, or spinning nose dive. Generally there was insufficient room for recovery before ground contact.

Arrival stalls are still produced in modern airplanes by attempting to rudder the airplane around to the proper heading on final approach at a low speed without banking. The inner wing stalls and drops. The pilot attempts to pick it up with aileron deflection, which aggravates the situation. The airplane stalls and spins into the intended turn. The pilot who survives complains that the ailerons did not work.

Departure stalls are more spectacular. The pilot takes off from a small field. As the obstacles at the end of the field get near, with the engine at full power, the pilot rolls with the ailerons to a steep bank angle and turns away. The airplane has insufficient power to climb in steeply turning flight, so the pilot applies top rudder to hold up the nose. The resulting sideslip stalls the top wing, and the airplane performs an over-the-top snap roll and spin entry, followed by a fiery crash at full power.

Because of the stall–spin propensity of World War I airplanes, student pilots were given flight instruction on spin entry and recovery in airplanes with generally docile behavior. However, some airplanes, notably the Sopwith Camel, killed many student pilots because of its particularly vicious stalling characteristics. The Camel's main fuel tank was behind the pilot, and the fully loaded center of gravity was so far aft that the airplane was unstable in pitch just after takeoff. Constant pilot attention was required to keep it from stalling.

Not only that, but, like many other World War I airplanes, the Camel's vertical tail was too small. Any stall automatically became a snap roll spin entry, even without intentional rudder deflection. Finally, once spinning, the Camel required vigorous rudder deflection against the spin to stop the motion. A well-behaved airplane, on the other hand, has to be held in a spin; letting the controls go free should result in automatic recovery. Directional instability was so common among World War I airplanes that the Royal Air Force (R.A.F.) resisted closed cockpits for years so that pilots could use wind on one cheek as a sideslip cue.

Another dangerous feature of World War I airplanes was the gyroscopic effect of rotary engines. According to Gibson (2000), engine gyroscopic effect in the Sopwith Camel required left rudder for both left and right turns and caused a departure if full power was used over the top of a loop at too low an airspeed. Pilots were warned to attempt their first hard right turns only above 1,000 feet.

1.9 Contrasting Design Philosophies

Comparison of the 1917 British (Royal Aircraft Factory) S.(scouting) E.(experimental)-5 and the Fokker D-VII shows an interesting contrast between the design philosophies of the Royal Aircraft Factory designers, who had been exposed to primitive airplane stability theory, and Anthony H. G. Fokker and his co-worker, Reinhold Platz, neither of whom had any formal technical training. Platz had been trained in the art of acetylene gas welding, which he applied to the construction of steel tube airplane fuselages, while Fokker was an experienced craftsman, pilot, and small boat sailor with an instinct for aerodynamics.

The strong dihedral (5 degrees) of the S.E.-5 wings (Figure 1.4) is evidence of an attempt to give the airplane inherent spiral stability. On spirally stable airplanes, if the pilot establishes a banked turn, the rudder and elevator have to be held in a deflected position to continue the turn. If the pilot centers the rudder bar and control stick, a correctly rigged airplane will automatically, but slowly, regain wings-level flight.

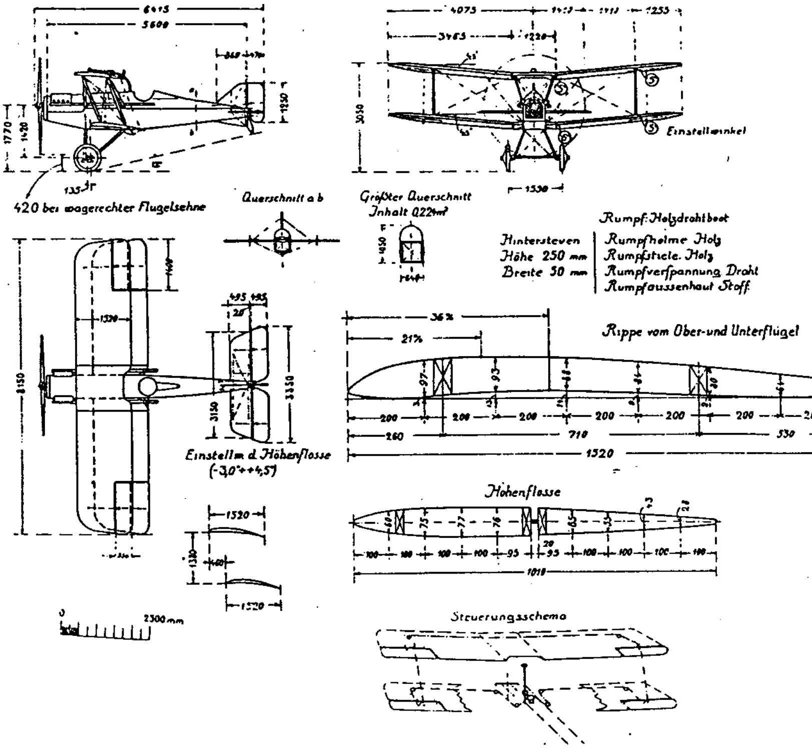
6415
5600
4075
3050
420 bei waagerechter Flugelsehne
Querschnitt a b
Größter Querschnitt
Inhalt 0,22m²
Einstellwinkel
Rumpf: Holzdrahtboot
Rumpfholme Holz
Rumpfstiele Holz
Rumpfverspannung Draht
Rumpfaussenhaut Stoff
Hintersteven
Höhe 250 mm
Breite 50 mm
Rippe vom Ober- und Unterflügel
36%
21%
200
260
710
1520
530
120
Einstellw. d. Höhenflosse
(-3,0°+4,5°)
Höhenflosse
1010
1520
2300 mm
Steuerungsschema

Figure 1.4 The British paid attention to inherent spiral stability during World War I days, building 5 degrees of dihedral into the S.E.-5. (From Jane's *All the World's Aircraft*, 1919. Jane's used a German source for these drawings since the S.E.-5 was still classified in Britain in 1919.)

The S.E.-5's control surfaces had no aerodynamic balance and were difficult to move at diving speeds. Thin wing sections were used. The designers also had embraced a whim for numerology; the wings had 250 square feet of area and 5-foot chords; they were set at 5 degrees with respect to the thrust line, and so on.

Modern flight tests of World War I fighters (using the Shuttleworth Collection) give the S.E.-5A high ratings. Ronald Beaumont says this airplane was

> perhaps the best handling fighter on either side, with excellent pitch and yaw control and inherent stability on both axes, and with light and responsive ailerons up to the quite high speed of 130 mph.

The Fokker D VII (Figure 1.5) had wooden-frame cantilever wings, almost without dihedral, with a thick airfoil section, an early result of Prandtl/Lanchester circulation theory. David Lednicer reported (2001) that the D VII wing airfoil was close to the Göttingen 418. The D VII had a steel-tube–welded fuselage and tail assembly. Horn balances (called elephant ears) were provided to lessen the pilot effort to deflect the ailerons, elevators, and rudder.

When Fokker flew the first version he realized he had created a dangerous airplane. Before the German Air Ministry officials could get a good look at it, he rebuilt it secretly in the hangar, moving the wings aft to make it less unstable, lengthening the fuselage, and modifying the vertical tail to incorporate a fixed fin. As a result of the D VII's long tail moment arm; blunt-nosed, cambered airfoil sections; and mechanically limited up elevator

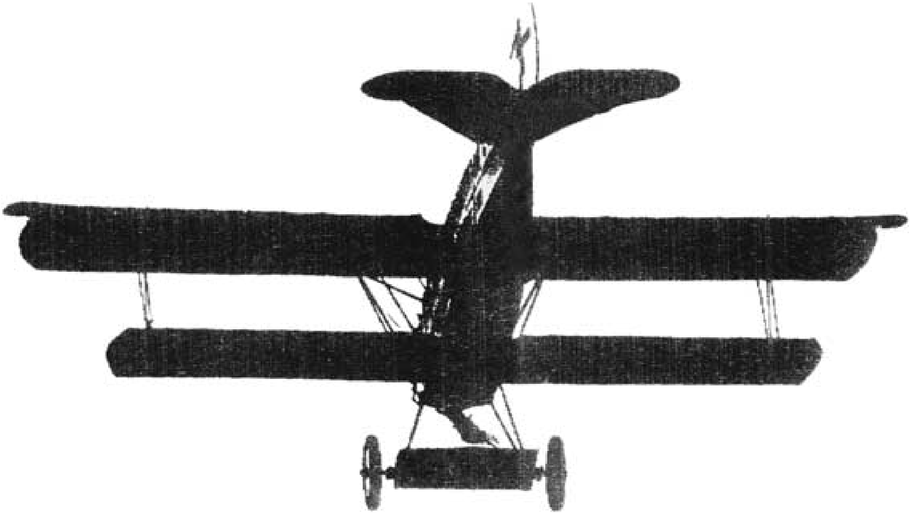

Figure 1.5 The Fokker D-VII, built without wing dihedral, showing no concern for spiral stability. This machine had horn aerodynamic balances at the tips of all control surfaces, to reduce control forces. (From *Progress in Airplane Design Since 1903*, NASA Publication L-9866, 1974.)

deflection, stability and control at low speeds and climb rate were quite good. In its final form it pleased everyone so much that it was mentioned in the Treaty of Versailles as a military airplane that had to be surrendered to the Allied authorities, the only one so designated.

1.10 Frederick Lanchester

Airplane stability and control theory in the modern sense began with Frederick William Lanchester. Lanchester was not really a theoretician but a mechanical engineer who devoted most of his effort to the construction of very innovative motor cars. He performed aeronautical experiments with free-flying gliders. He speculated correctly on the vortex theory of lift and the nature of the vortex wake of a finite wing but was unable to give these ideas a useful mathematical form. His free-flying gliders were inherently stable and exhibited an undulating flight path, which he analyzed correctly in 1897. He misnamed the motion the “phugoid,” intending to call it the “flying” motion; actually he called it the “fleeing” motion, having forgotten that the Greek root already existed in the English word “fugitive.”

Lanchester published two books, *Aerodynamics* in 1907 and *Aerodonetics* in 1908, which expressed his views and the results of his experiments. He even talked with Wilbur Wright, evidently to no avail, because Wilbur had no understanding of inherent stability in flight, already demonstrated by Pénaud, Langley, and Lanchester on a small scale.

1.11 G. H. Bryan and the Equations of Motion

The mathematical theory of the motion of an airplane in flight, considered as a rigid body with 6 degrees of freedom, was put into essentially its present form by Professor George Hartley Bryan (frontispiece) in England in 1911. In an earlier (1903) collaboration with W. E. Williams, Bryan had developed the longitudinal equations of airplane motion only. Bryan’s important contribution rested on fundamental theories of Sir Isaac Newton (1642–1727) and Leonhard Euler (1707–1783). Today’s stability and control engineers are generally

$$
\begin{aligned}
W\left(\frac{du}{gdt}+\frac{qw}{g}-\frac{rv}{g}\right) &= W\sin\theta + H \quad - X \quad . \quad . \\
W\left(\frac{dv}{gdt}+\frac{ru}{g}-\frac{pw}{g}\right) &= W\cos\theta\cos\phi \quad - Y \quad . \quad . \\
W\left(\frac{dw}{gdt}+\frac{pv}{g}-\frac{qu}{g}\right) &= -W\cos\theta\sin\phi - Z \quad . \quad . \\
A\frac{dp}{gdt} - F\frac{dq}{gdt} + (C-B)\frac{rq}{g} + F\frac{pr}{g} &= \quad - L \quad . \quad . \\
B\frac{dq}{gdt} - F\frac{dp}{gdt} + (A-C)\frac{pr}{g} - F\frac{qr}{g} &= \quad - M \quad . \quad . \\
C\frac{dr}{gdt} \quad + (B-A)\frac{pq}{g} - F\left(\frac{p^2-q^2}{g}\right) &= -Hh - N
\end{aligned}
$$

$$
\begin{aligned}
p &= \dot{\phi} + \dot{\psi}\sin\theta \\
q &= \dot{\theta}\sin\phi + \dot{\psi}\cos\theta\cos\phi \\
r &= \dot{\theta}\cos\phi - \dot{\psi}\cos\theta\sin\phi
\end{aligned}
$$

Figure 1.6 G. H. Bryan's modern-looking 6-degree-of-freedom equations of airplane motion, supplemented by the Euler angular rate equations. For NASA symbols interchange Y and Z, M and N, q and r, and v and w. A, B, and C are moments of inertia about NASA's X-, Y-, and Z-axes, respectively. (From Bryan, *Stability in Aviation*, 1911)

$$
\begin{aligned}
W\frac{du}{gdt} &= W\epsilon\cos\theta_0 + \delta H - uX_u - vX_v - rX_r \\
W\left(\frac{dv}{gdt}+\frac{rU}{g}\right) &= -W\epsilon\sin\theta_0 \quad - uY_u - vY_v - rY_r \\
C\frac{dr}{gdt} &= -h\delta H \quad - uN_u - vN_v - rN_r
\end{aligned}
$$

$$
\begin{aligned}
W\left(\frac{dw}{gdt}-\frac{qU}{g}\right) &= -W\phi\cos\theta_0 - wZ_w - pZ_p - qZ_q \\
A\frac{dp}{gdt} - F\frac{dq}{gdt} &= \quad - wL_w - pL_p - qL_q \\
B\frac{dq}{gdt} - F\frac{dp}{gdt} &= \quad - wM_w - pM_p - qM_q
\end{aligned}
$$

Figure 1.7 The perturbation form of Bryan's equations of airplane motion. The longitudinal equations are above, the lateral equations below. Note the absence of control derivatives. (From Bryan, *Stability in Aviation*, 1911)

astonished when they first see these equations (Bryan, 1911). As his book's (Bryan, 1911) title indicated, he focused on airplane stability, not control. Aside from minor notational differences, Bryan's equations are identical to those used in analysis and simulation for the most advanced of today's aircraft (Figures 1.6 and 1.7).

Not surprisingly, at this early date he does not cover in detail control force and moments, nor does he treat the airplane as an object of control. The perturbation equations in Fig. 1.7 include stability but not control derivatives. The influence of external disturbances such as gusts is also not addressed, although he recognizes this and other problems by presenting a summary of questions not covered in his book that set an agenda for years of research.

Bryan calculated stability derivatives based on the assumption that the force on an airfoil is perpendicular to the airfoil chord. W. Hewitt Phillips points out that while this theory is not the most accurate for subsonic aircraft, it is quite accurate for supersonic aircraft, particularly those with nearly unswept wings, such as the Lockheed F-104. Thus, Bryan might be considered even more ahead of his time than is usually acknowledged.