Aircraft Wing

Design Technologies and Configurations

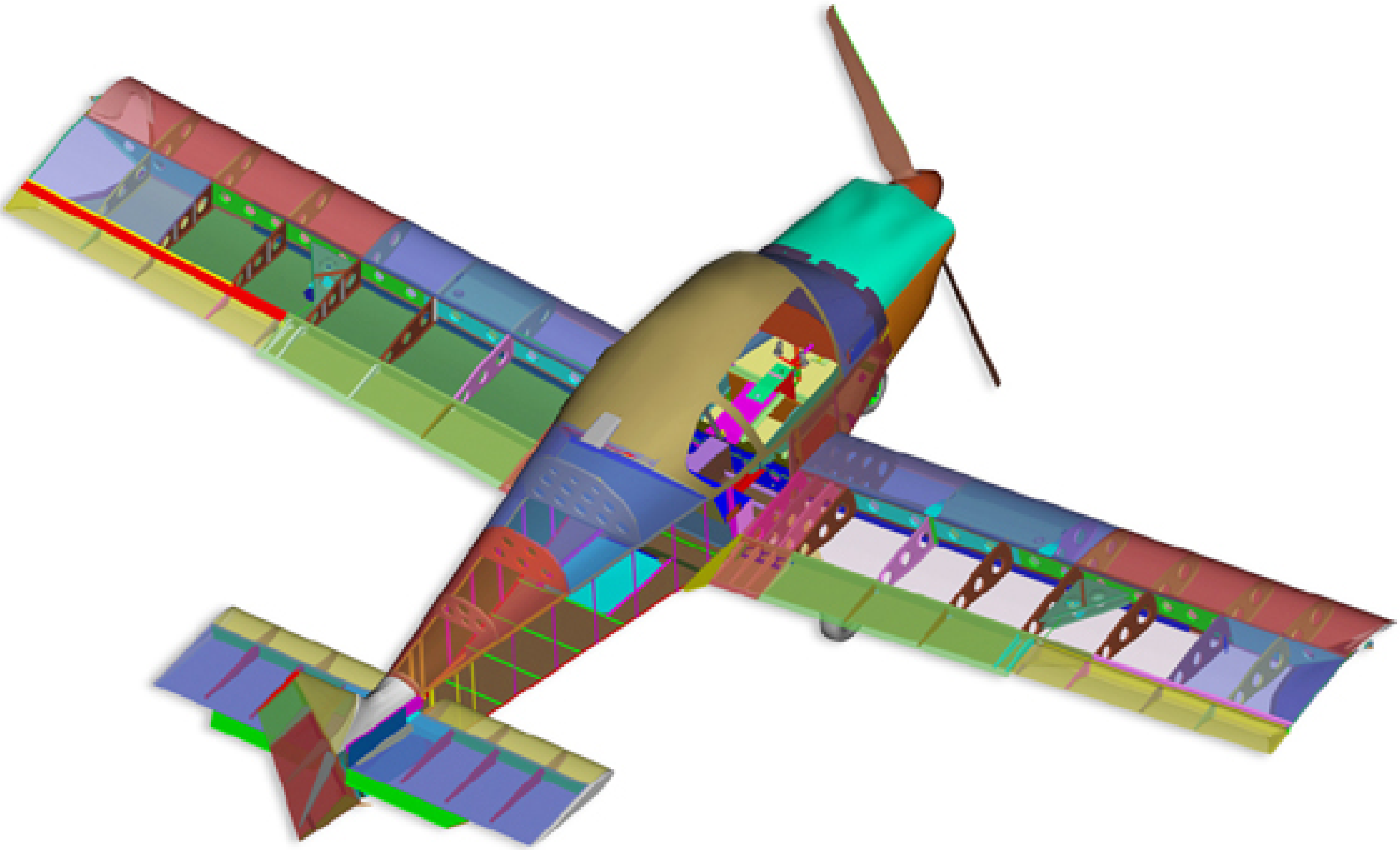

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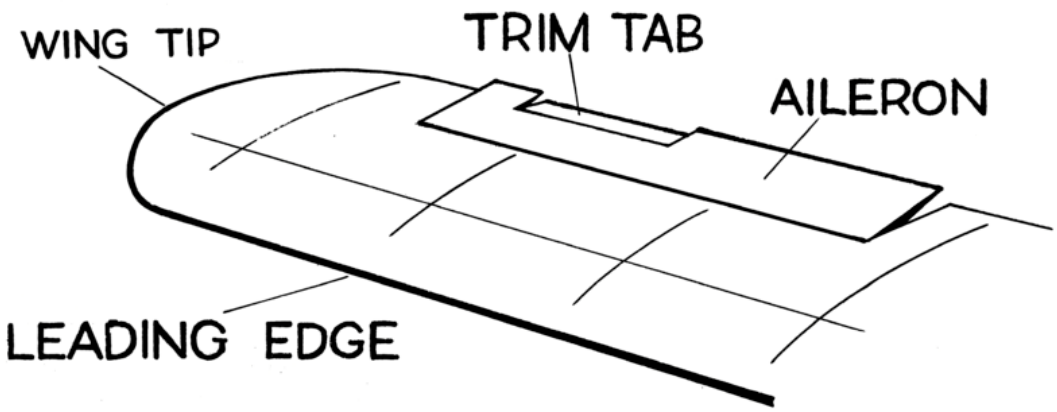
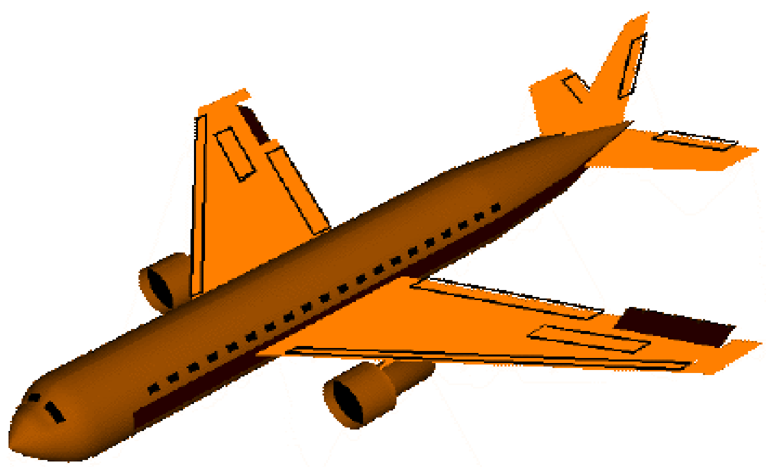
Table of Contents

Chapter 1

Aileron





An aircraft rolling with its ailerons

Ailerons are hinged control surfaces attached to the trailing edge of the wing of a fixed-wing aircraft. The ailerons are used to control the aircraft in roll. The two ailerons are typically interconnected so that one goes down when the other goes up: the downgoing aileron increases the lift on its wing while the upgoing aileron reduces the lift on its wing, producing a rolling moment about the aircraft's longitudinal axis. The word *aileron* is French for "little wing".

An unwanted side effect of aileron operation is adverse yaw—a yawing moment in the opposite direction to the roll. Using the ailerons to roll an aircraft to the right produces a yawing motion to the left. As the aircraft rolls, adverse yaw is caused primarily by the change in drag on the left and right wing. The rising wing generates increased lift which causes increased induced drag. The descending wing generates reduced lift which causes reduced induced drag. The difference in drag on each wing produces the adverse yaw. There is also often an additional adverse yaw contribution from a difference in profile drag between the up-aileron and down-aileron.

Adverse yaw is effectively compensated by the use of the rudder, which results in a sideforce on the vertical tail which opposes the adverse yaw by creating a favorable yawing moment. Another method of compensation is *differential ailerons*, which have been rigged such that the downgoing aileron deflects less than the upgoing one. In this case the opposing yaw moment is generated by a difference in profile drag between the left and right wingtips. *Frise ailerons* accentuate this profile drag imbalance by protruding beneath the wing of an upward-deflected aileron, most often by being hinged slightly behind the leading edge and near the bottom of the surface, with the lower section of the leading edge protruding slightly below the wing's undersurface when the aileron is deflected upwards, substantially increasing profile drag on that side. Ailerons may also be designed to use a combination of these methods.

With ailerons in the neutral position the wing on the outside of the turn develops more lift than the opposite wing due to the variation in airspeed across the wing span, and this tends to cause the aircraft to continue to roll. Once the desired angle of bank (degree of rotation on the longitudinal axis) is obtained, the pilot uses opposite aileron to prevent the angle of bank from increasing due to this variation in lift across the wing span. This minor opposite use of the control must be maintained throughout the turn. The pilot also uses a slight amount of rudder in the same direction as the turn to counteract adverse yaw and to produce a "coordinated" turn where the fuselage is parallel to the flight path. A simple gauge on the instrument panel called the slip indicator, also known as "the ball", indicates when this coordination is achieved.

Ailerons are the trailing-edge control surface nearest the wing tip (although on some airliners they can also be found at the wing root). On this parked Piper Cherokee, the left aileron has deflected downwards, and the right, upwards.

History

Since the need for roll control on aircraft was not as obvious as the need for heading and pitch control, the aileron came into widespread use well after the rudder and elevator. The Wright Brothers used wing warping instead of ailerons for roll control, and initially, their aircraft had much better control in the air than aircraft that used movable surfaces; however, as aileron designs were refined, and aircraft became larger and heavier, it became clear that they were much more effective and practical for most aircraft.

There are conflicting claims over who first invented the aileron. In 1868, before the advent of powered aircraft, English inventor Matthew Piers Watt Boulton patented the first aileron-type device for lateral control via 'flexed' wings. Boulton's patent, No. 392, awarded in 1868 some 40 years before ailerons were 'reinvented', became forgotten until the aileron was in general use. If the Boulton device had been revealed at the time of the Wright Brother's patent filings, they may not have been able to claim priority of invention for lateral control of flying machines.

New Zealander Richard Pearse may have made a powered flight in a monoplane that included small ailerons as early as 1902, but his claims are controversial (and sometimes inconsistent), and even by his own reports, his aircraft were not well controlled.

Robert Esnault-Pelterie, a Frenchman, built a Wright-style glider in 1904 that used ailerons in lieu of wing-warping. Although Boulton had described and patented ailerons in 1868, no one had actually built them until Esnault-Pelterie's glider, almost 40 years later.

The 14 Bis airplane, by Santos Dumont, was modified to add ailerons in late 1906, though it was never fully controllable in flight, likely due to its unconventional wing form.

Henry Farman's ailerons on the *Farman III* were the first to resemble ailerons on modern aircraft, and have a reasonable claim as the ancestor of the modern aileron.

In 1908 U.S. inventor, businessman and engine builder Glenn Curtiss flew an aileron-controlled aircraft. However Curtiss had previously been a member of the Aerial Experiment Association, headed by Alexander Graham Bell. The Association had previously developed ailerons for their aircraft. The AEA members were later dismayed when Curtiss dropped out of their organization, patented their innovation and reportedly sold the patent to the United States Government.

Another contestant includes Dr. William Whitney Christmas of the U.S., who claimed to have invented an aileron in the 1914 patent for what would become the Christmas Bullet, which was built in 1918.

Aileron spades

These are flat metal plates, usually attached to the aileron lower surface, ahead of the aileron hinge, by a lever arm. They reduce the force needed by the pilot to deflect the aileron and are often seen on aerobatic aircraft. As the aileron is deflected upward, the spade produces a downward aerodynamic force, which tends to rotate the whole assembly so as to further deflect the aileron upward. The size of the spade (and its lever arm) determine how much force the pilot needs to apply to deflect the aileron.

Aileron balance weights

To prevent control surface flutter (aeroelastic flutter), the center of lift of the control surface should be behind the center of gravity of that surface. To achieve this, lead weights may be added to the front of the aileron. In some aircraft the aileron construction may be too heavy to allow this system to work without huge weight increases. In this case, the weight may be added to a lever arm to move the weight well out in front to the aileron body. These balance weights are tear drop shapes (to reduce drag) which make them appear quite different from spades, although both project forward and below the aileron.

Types of ailerons

Frise Ailerons

Engineer Leslie George Frise (1897–1979) developed an aileron shape which is often used due to its ability to counteract adverse yaw. The Frise aileron is pivoted at about its 25 to 30% chord line and near its bottom surface. When the aileron is deflected up (to make its wing go down), the leading edge of the aileron dips into the airflow beneath the wing. The moment of the leading edge in the airflow helps to move up the trailing edge, decreasing the stick force. The down-moving aileron also adds energy to the boundary layer by the airflow from the under-side of the wing that scoops air by the edge of the aileron that follows the upper surface of the aileron and creates a lifting force on the upper surface of the aileron aiding the lift of the wing. That reduces the needed deflection angle of the aileron. If the leading edge of the aileron is sharp or bluntly rounded, that adds significant drag to that wing and help the aircraft to yaw (turn) in the desired direction, but adds some unpleasant or potentially dangerous aerodynamic vibration (flutter).

Differential ailerons

By careful design of the mechanical linkages, the up aileron can be made to deflect more than the down aileron (e.g. US patent 1565097). This helps reduce the likelihood of a wing tip stall when aileron deflections are made at high angles of attack. The idea is that the loss of lift associated with the up aileron carries no penalty while the increase in lift associated with the down aileron is minimized. The rolling couple on the aircraft is always the difference in lift between the two wings.

The de Havilland Tiger Moth classic British biplane is one of the best-known aircraft, and one of the earliest, to use differential ailerons.

Combinations with other control surfaces

- A control surface that combines an aileron and flap is called a *flaperon*. A single surface on each wing serves both purposes: used as an aileron, the flaperons left and right are actuated differentially; when used as a flap, both flaperons are actuated downwards. When a flaperon is actuated downwards (i.e. used as a flap) there is enough freedom of movement left to be able to still use the aileron function.
- A further form of roll control, common on modern jet transport aircraft, utilises spoilers in conjunction with ailerons. This is called a *spoileron*.
- In a delta-winged aircraft, the ailerons are combined with the elevators to form an *elevon*.
- Several modern fighter aircraft may have no ailerons on the wings at all, and combine roll control with an all moving tailplane. This is a *stabilator* or a rolling tail.

Research

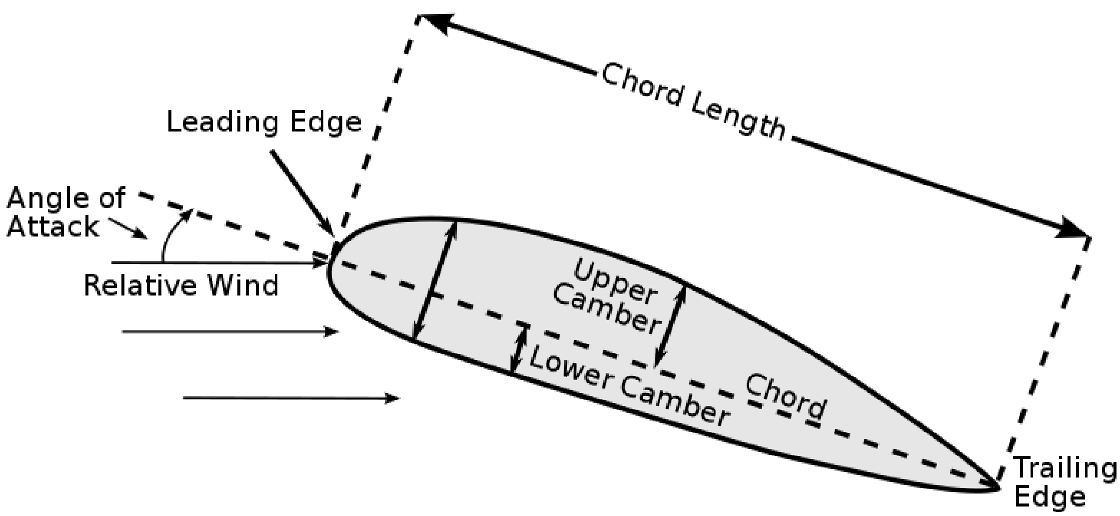
Several technology research and development efforts exist to integrate the functions of aircraft flight control systems such as ailerons, elevators, elevons and flaps, into wings to perform the aerodynamic purpose with the advantages of less: mass, cost, drag, inertia (for faster, stronger control response), complexity (mechanically simpler, fewer moving parts or surfaces, less maintenance), and radar cross section for stealth. These may be used in many unmanned aerial vehicles (UAVs) and 6th generation fighter aircraft. The two main approaches are flexible wings, and fluidics.

In flexible wings, much or all of a wing surface can change shape in flight to deflect air flow. The X-53 Active Aeroelastic Wing is a NASA effort. The Adaptive Compliant Wing is a commercial effort.

In fluidics, forces in vehicles occur via circulation control, in which larger more complex mechanical parts are replaced by smaller simpler fluidic systems (slots which emit air flows) where larger forces in fluids are diverted by smaller jets or flows of fluid intermittently, to change the direction of vehicles. In this use, fluidics promises lower mass, costs (up to 50% less), and very low inertia and response times, and simplicity.

Chapter 2

Airfoil



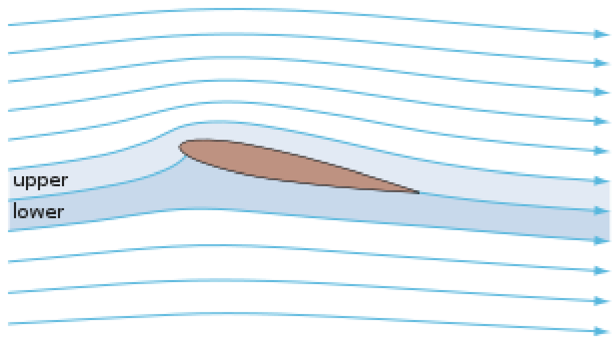
Components of the airfoil

An **airfoil** (in American English) or **aerofoil** (in British English) is the shape of a wing or blade (of a propeller, rotor or turbine) or sail as seen in cross-section.

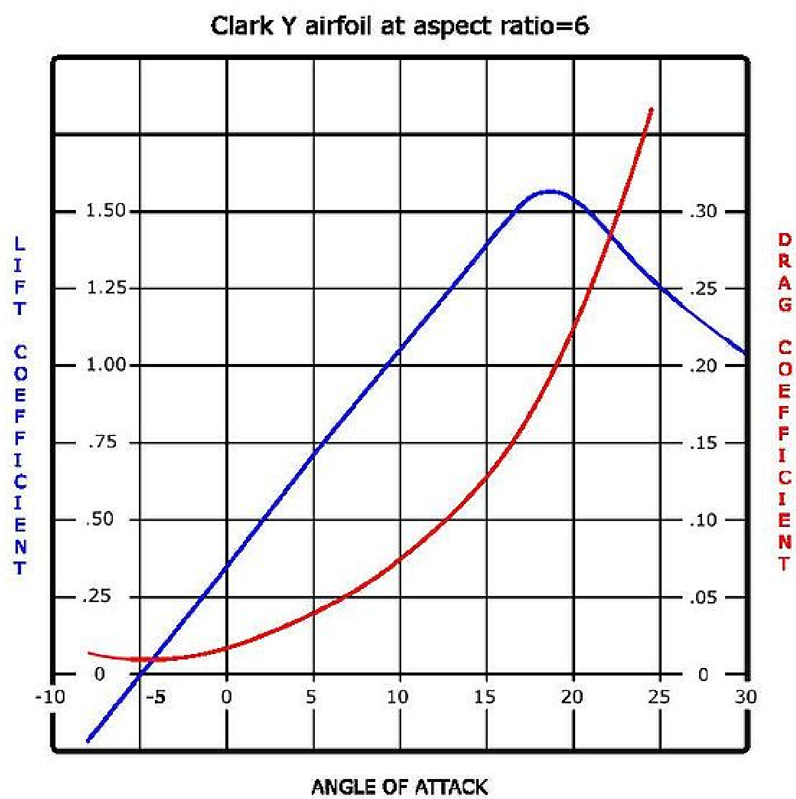
An airfoil-shaped body moved through a fluid produces an aerodynamic force. The component of this force perpendicular to the direction of motion is called lift. The component parallel to the direction of motion is called drag. Subsonic flight airfoils have a characteristic shape with a rounded leading edge, followed by a sharp trailing edge, often with asymmetric camber. Foils of similar function designed with water as the working fluid are called hydrofoils.

The lift on an airfoil is primarily the result of its angle of attack and shape (in particular its camber). When either is positive, the resulting flowfield about the airfoil has a higher average velocity on the upper surface than on the lower surface. This velocity difference is necessarily accompanied by a pressure difference, via Bernoulli's principle for incompressible inviscid flow, which in turn produces the lift force. The lift force can also be related directly to the average top/bottom velocity difference, without invoking the pressure, by using the concept of circulation and the Kutta-Joukowski theorem.

Introduction



Streamlines around a NACA 0012 airfoil at moderate angle of attack



Lift and Drag curves for a typical airfoil

A fixed-wing aircraft's wings, horizontal, and vertical stabilizers are built with airfoil-shaped cross sections, as are helicopter rotor blades. Airfoils are also found in propellers, fans, compressors and turbines. Sails are also airfoils, and the underwater surfaces of sailboats, such as the centerboard and keel, are similar in cross-section and operate on the same principles as airfoils. Swimming and flying creatures and even many plants and sessile organisms employ airfoils/hydrofoils: common examples being bird wings, the bodies of fish, and the shape of sand dollars. An airfoil-shaped wing can create downforce on an automobile or other motor vehicle, improving traction.

Any object with an angle of attack in a moving fluid, such as a flat plate, a building, or the deck of a bridge, will generate an aerodynamic force (called lift) perpendicular to the flow. Airfoils are more efficient lifting shapes, able to generate more lift (up to a point), and to generate lift with less drag.

A lift and drag curve obtained in wind tunnel testing is shown on the right. The curve represents an airfoil with a positive camber so some lift is produced at zero angle of attack. With increased angle of attack, lift increases in a roughly linear relation, called the *slope* of the lift curve. At about 18 degrees this airfoil stalls, and lift falls off quickly beyond that. The drop in lift can be explained by the action of the upper-surface boundary layer, which separates and greatly thickens over the upper surface at and past the stall angle. The thickened boundary layer's displacement thickness changes the airfoil's effective shape, in particular it reduces its effective camber, which modifies the overall flow field so as to reduce the circulation and the lift. The thicker boundary layer also causes a large increase in pressure drag, so that the overall drag increases sharply near and past the stall point.

Airfoil design is a major facet of aerodynamics. Various airfoils serve different flight regimes. Asymmetric airfoils can generate lift at zero angle of attack, while a symmetric airfoil may better suit frequent inverted flight as in an aerobatic aeroplane. In the region of the ailerons and near a wingtip a symmetric airfoil can be used to increase the range of angles of attack to avoid spin-stall. Thus a large range of angles can be used without boundary layer separation. Subsonic airfoils have a round leading edge, which is naturally insensitive to the angle of attack. The cross section is not strictly circular, however: the radius of curvature is increased before the wing achieves maximum thickness to minimize the chance of boundary layer separation. This elongates the wing and moves the point of maximum thickness back from the leading edge.

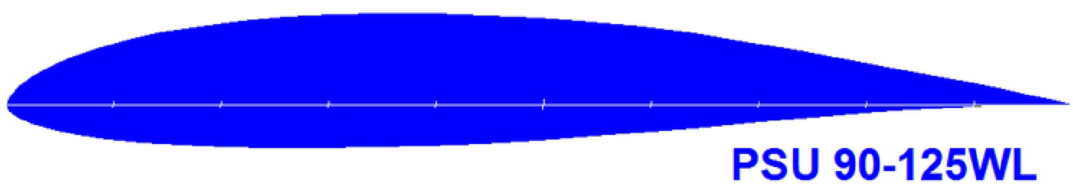
Supersonic airfoils are much more angular in shape and can have a very sharp leading edge, which is very sensitive to angle of attack. A supercritical airfoil has its maximum thickness close to the leading edge to have a lot of length to slowly shock the supersonic flow back to subsonic speeds. Generally such transonic airfoils and also the supersonic airfoils have a low camber to reduce drag divergence. Modern aircraft wings may have different airfoil sections along the wing span, each one optimized for the conditions in each section of the wing.

Movable high-lift devices, flaps and sometimes slats, are fitted to airfoils on almost every aircraft. A trailing edge flap acts similar to an aileron, with the difference that it can be retracted partially into the wing if not used.

A laminar flow wing has a maximum thickness in the middle camber line. Analysing the Navier-Stokes equations in the linear regime shows that a negative pressure gradient along the flow has the same effect as reducing the speed. So with the maximum camber in the middle, maintaining a laminar flow over a larger percentage of the wing at a higher cruising speed is possible. However, with rain or insects on the wing or for jetliner speeds this does not work. Since such a wing stalls more easily, this airfoil is not used on wingtips (spin-stall again).

Schemes have been devised to define airfoils — an example is the NACA system. Various airfoil generation systems are also used. An example of a general purpose airfoil that finds wide application, and predates the NACA system, is the Clark-Y. Today, airfoils can be designed for specific functions using inverse design programs such as PROFOIL, XFOIL and AeroFoil. XFOIL is an online program created by Mark Drela that will design and analyze subsonic isolated airfoils.

Airfoil terminology



An airfoil designed for winglets (PSU 90-125WL)

The various terms related to airfoils are defined below:

- The *mean camber line* is the locus of points midway between the upper and lower surfaces.
- The *chord line* is a straight line connecting the leading and trailing edges of the airfoil, at the ends of the mean camber line.
- The *chord* is the length of the chord line and is the characteristic dimension of the airfoil section.
- The *maximum thickness* and the location of maximum thickness are expressed as a percentage of the chord.
- For symmetrical airfoils both *mean camber line* and *chord line* pass from centre of gravity of the airfoil and they touch at leading and trailing edge of the airfoil.
- The *aerodynamic center* is the chord wise length about which the pitching moment is independent of the lift coefficient and the angle of attack.
- The *center of pressure* is the chord wise location about which the pitching moment is zero.

Thin airfoil theory

An airfoil section is displayed at the tip of this Denney Kitfox aircraft, built in 1991

Airfoil of Kamov Ka-26 helicopters

Thin airfoil theory is a simple theory of airfoils that relates angle of attack to lift for incompressible, inviscid flows. It was devised by German mathematician Max Munk and further refined by British aerodynamicist Hermann Glauert and others in the 1920s. The theory idealizes the flow around an airfoil as two-dimensional flow around a thin airfoil. It can be imagined as addressing an airfoil of zero thickness and infinite wingspan.

Thin airfoil theory was particularly notable in its day because it provided a sound theoretical basis for the following important properties of airfoils in two-dimensional flow:
(1) on a symmetric airfoil, the center of pressure lies exactly one quarter of the chord behind the leading edge
(2) on a cambered airfoil, the aerodynamic center lies exactly one quarter of the chord behind the leading edge
(3) the slope of the *lift coefficient versus angle of attack* line is 2π units per radian

As a consequence of (3), the section lift coefficient of a symmetric airfoil of infinite wingspan is:

$$c_L = 2\pi\alpha$$

where c_L is the section lift coefficient,

α is the angle of attack in radians, measured relative to the chord line.

(The above expression is also applicable to a cambered airfoil where α is the angle of attack measured relative to the zero-lift line instead of the chord line.)

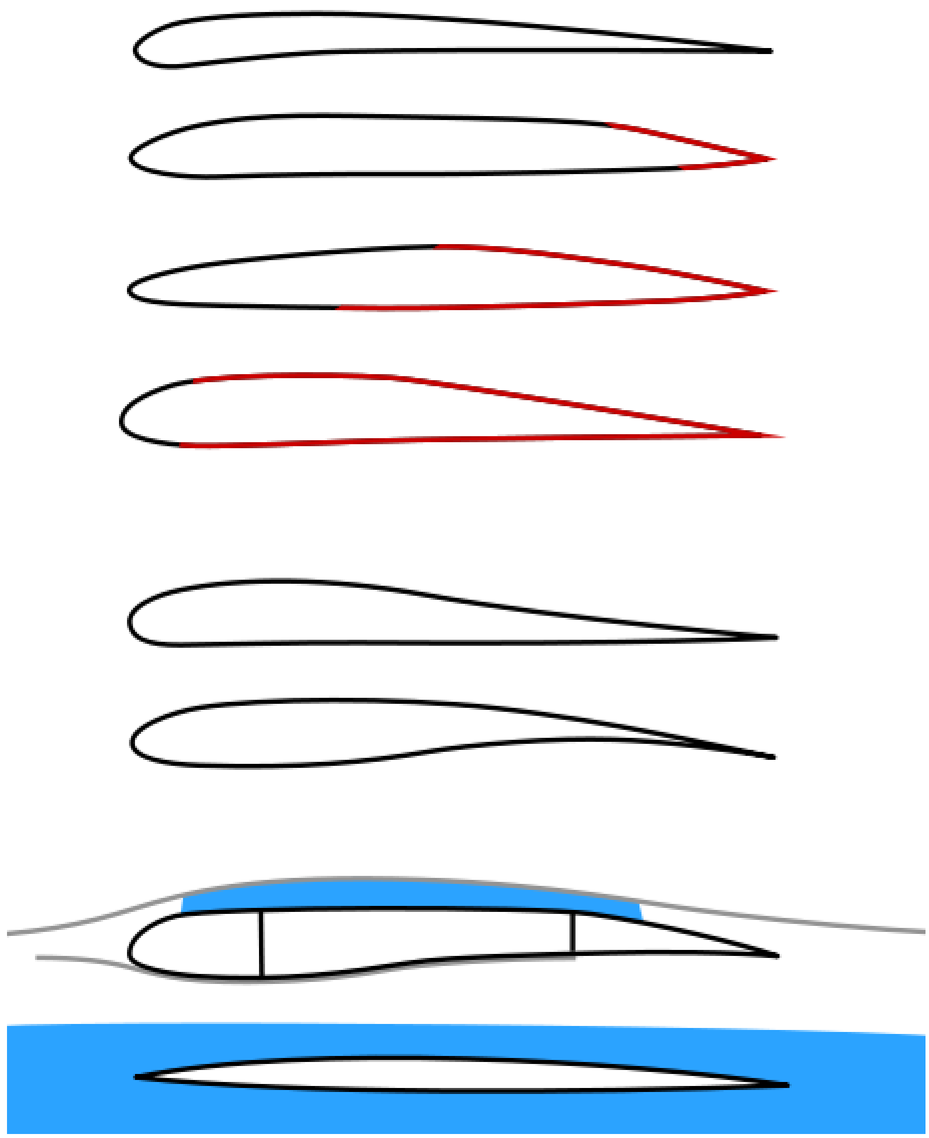
Also as a consequence of (3), the section lift coefficient of a cambered airfoil of infinite wingspan is:

$$c_L = c_{L_0} + 2\pi\alpha$$

where c_{L_0} is the section lift coefficient when the angle of attack is zero.

Thin airfoil theory does not account for the stall of the airfoil which usually occurs at an angle of attack between 10° and 15° for typical airfoils.

Derivation of thin airfoil theory



From top to bottom:

- laminar flow airfoil for a RC park flyer;
- laminar flow airfoil for a RC pylon racer;
- laminar flow airfoil for a manned propeller aircraft;
- laminar flow at a jet airliner airfoil;
- stable airfoil used for flying wings;
- aft loaded airfoil allowing for a large main spar and late stall;
- transonic supercritical airfoil;
- supersonic leading edge airfoil. Colours:
  Black = laminar flow,
  red = turbulent flow,

grey = subsonic stream,
blue = supersonic flow volume

The airfoil is modeled as a thin lifting mean-line (camber line). The mean-line, y(x), is considered to produce a distribution of vorticity $\gamma(s)$ along the line, s. By the Kutta condition, the vorticity is zero at the trailing edge. Since the airfoil is thin, x (chord position) can be used instead of s, and all angles can be approximated as small.

From the Biot-Savart law, this vorticity produces a flow field $w(x)$ where

$$w(x) = \frac{1}{(2\pi)} \int_0^c \frac{\gamma(x')}{(x - x')} dx'$$

where x is the location at which induced velocity is produced, x' is the location of the vortex element producing the velocity and c is the chord length of the airfoil.

Since there is no flow normal to the curved surface of the airfoil, $w(x)$ balances that from the component of main flow V which is locally normal to the plate — the main flow is locally inclined to the plate by an angle $\alpha - dy / dx$. That is

$$V.(\alpha - dy/dx) = w(x) = \frac{1}{(2\pi)} \int_0^c \frac{\gamma(x')}{(x - x')} dx'$$

This integral equation can by solved for $\gamma(x)$, after replacing x by

$$x = c(1 - cos(\theta))/2,$$

as a Fourier series in $A_n sin(n\theta)$ with a modified lead term $A_0(1 + cos(\theta)) / sin(\theta)$

That is $$\frac{\gamma(\theta)}{(2V)} = A_0 \frac{(1 + cos(\theta))}{sin(\theta)} + \sum A_n.sin(n\theta))$$

(These terms are known as the Glauert integral).

The coefficients are given by $$A_0 = \alpha - \frac{1}{\pi} \int_0^\pi ((dy/dx).d\theta$$

and $$A_n = \frac{2}{\pi} \int_0^\pi cos(n\theta)(dy/dx).d\theta$$

By the Kutta–Joukowski theorem, the total lift force F is proportional to

$$\rho V \int_0^c \gamma(x).dx$$

and its moment M about the leading edge to $\rho V \int_0^c x.\gamma(x).dx$

The calculated Lift coefficient depends only on the first two terms of the Fourier series, as

$$C_L = 2\pi(A_0 + A_1/2)$$

The moment M about the leading edge depends only on A_0,A_1 and A_2 , as

$$C_M = -0.5\pi(A_0 + A_1 - A_2/2)$$

The moment about the 1/4 chord point will thus be,

$$C_M(1/4c) = -\pi/4(A_1 - A_2).$$

From this it follows that the center of pressure is aft of the 'quarter-chord' point 0.25 c, by

$$\Delta x/c = \pi/4((A_1 - A_2)/C_L)$$

The aerodynamic center, AC, is at the quarter-chord point. The AC is where the pitching moment M' does not *vary* with angle of attack, i.e.

$$\frac{\partial(C_{M'})}{\partial(C_L)} = 0$$

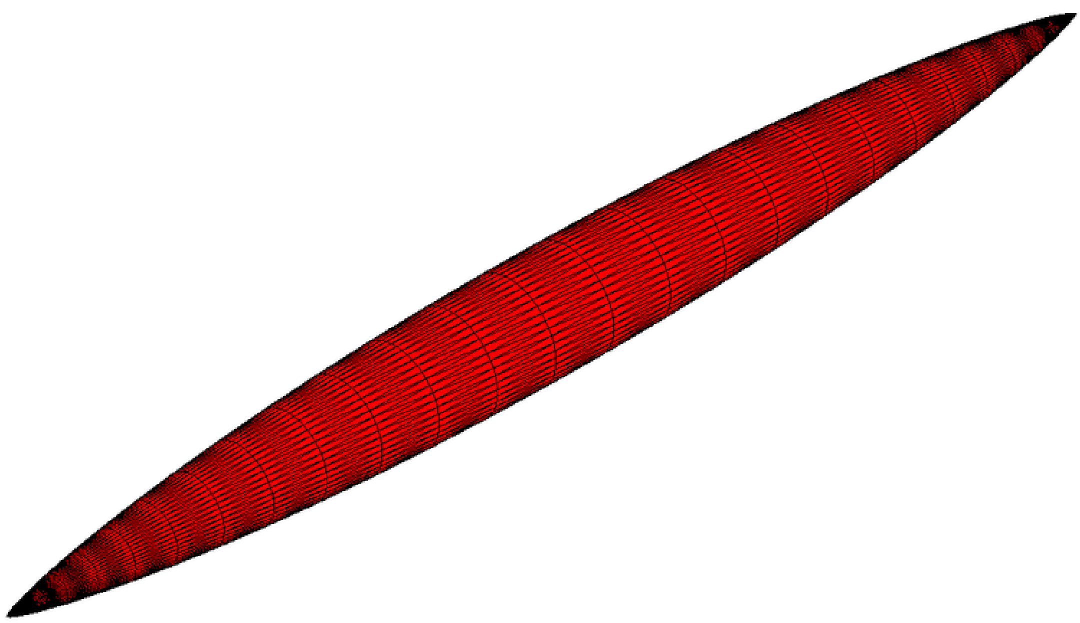
Chapter 3

Area Rule

The **Whitcomb area rule**, also called the **transonic area rule**, is a design technique used to reduce an aircraft's drag at transonic and supersonic speeds, particularly between Mach 0.75 and 1.2.

This is one of the most important operating speed ranges for commercial and military fixed-wing aircraft today, with transonic acceleration being considered an important performance metric for combat aircraft, necessarily dependent upon transonic drag.

Description



The Sears-Haack body shape

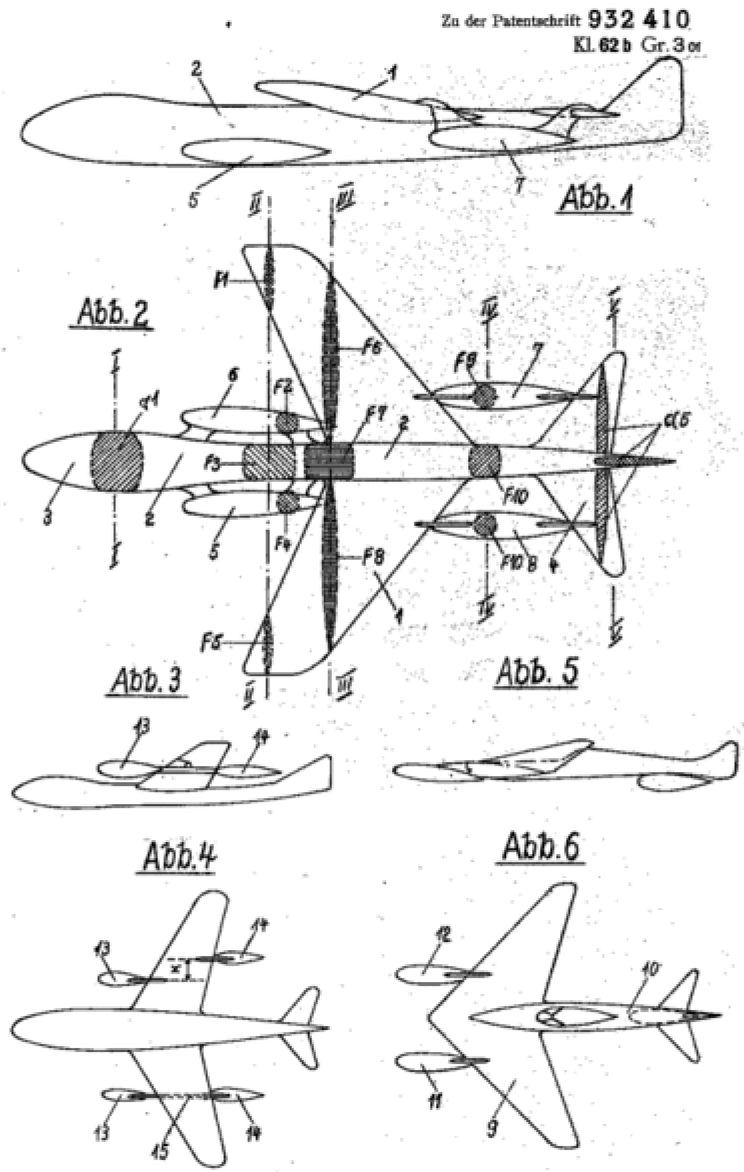
At high-subsonic flight speeds, supersonic airflow can develop in areas where the flow accelerates around the aircraft body and wings. The speed at which this occurs varies from aircraft to aircraft, and is known as the critical Mach number. The resulting shock waves formed at these points of supersonic flow can bleed away a considerable amount of power, which is experienced by the aircraft as a sudden and very powerful form of drag, called wave drag. To reduce the number and power of these shock waves, an aerodynamic shape should change in cross sectional area as smoothly as possible. This leads to a "perfect" aerodynamic shape known as the **Sears-Haack body**, roughly shaped like a cigar but pointed at both ends.

The area rule says that an airplane designed with the same cross-sectional area distribution in the longitudinal direction as the Sears-Haack body generates the same wave drag as this body, largely independent of the actual shape. As a result, aircraft have to be carefully arranged so that large volumes like wings are positioned at the widest area of the equivalent Sears-Haack body, and that the cockpit, tailplane, intakes and other "bumps" are spread out along the fuselage and or that the rest of the fuselage along these "bumps" is correspondingly thinned.

The area rule also holds true at speeds higher than the speed of sound, but in this case the body arrangement is in respect to the Mach line for the design speed. For instance, at Mach 1.3 the angle of the Mach cone formed off the body of the aircraft will be at about $\mu = \arcsin(1/M) = 50.3$ deg (μ is the angle of the Mach cone, or simply Mach angle). In this case the "perfect shape" is biased rearward, which is why aircraft designed for high speed cruise tend to be arranged with the wings at the rear. A classic example of such a design is Concorde. When applying the supersonic area rule, the condition that the plane defining the cross-section meet the longitudinal axis at the Mach angle μ no longer prescribes a unique plane for μ other than the 90 degrees given by M=1. The correct procedure is to average over all possible orientations of the intersecting plane.

History

Germany



Junkers patent drawing from March 1944.

The area rule was discovered by Otto Frenzl when comparing a swept wing with a w-wing with extreme high wave drag working on a transonic wind tunnel at Junkers works in Germany between 1943 and 1945. He wrote a description on 17 December 1943, with the title “Arrangement of Displacement Bodies in High-Speed Flight”; this was used in a patent filed in 1944. The results of this research were presented to a wide circle in March 1944 by Theodor Zobel at the “Deutsche Akademie der Luftfahrtforschung” (German

Academy of Aeronautics Research) in the lecture “Fundamentally new ways to increase performance of high speed aircraft.”

Subsequent German wartime aircraft design took account of the discovery, evident in the slim mid-fuselage of aircraft such as the Messerschmitt Me P.1112, P.1106, and the indisputably wasp-waisted Focke-Wulf Fw 1000x3 type A long range bomber, but also apparent in delta wing designs like the Henschel Hs 135. Several other researchers came close to developing a similar theory, notably Dietrich Küchemann who designed a tapered fighter that was dubbed the “Küchemann Coke Bottle” when it was discovered by U.S. forces in 1946. In this case Küchemann arrived at the solution by studying airflow, notably spanwise flow, over a swept wing. The swept wing is already an indirect application of the area rule.

United States

Wallace D. Hayes, a pioneer of supersonic flight, developed the supersonic area rule in publications beginning in 1947 with his Ph.D. thesis at the California Institute of Technology.

Richard T. Whitcomb, after whom the rule is named, independently discovered this rule in 1952, while working at the NACA. While using the new Eight-Foot High-Speed Tunnel, a wind tunnel with performance up to Mach 0.95 at NACA's Langley Research Center, he was surprised by the increase in drag due to shock wave formation. The shocks could be seen using Schlieren photography, but the reason they were being created at speeds far below the speed of sound, sometimes as low as Mach 0.70, remained a mystery.

In late 1951, the lab hosted a talk by Adolf Busemann, a famous German aerodynamicist who had moved to Langley after World War II. He talked about the difference in the behavior of airflow at speeds approaching supersonic, where it no longer behaved as an incompressible fluid. Whereas engineers were used to thinking of air flowing smoothly around the body of the aircraft, at high speeds it simply did not have time to "get out of the way", and instead started to flow as if it were rigid pipes of flow, a concept Busemann referred to as "streampipes", as opposed to streamlines, and jokingly suggested that engineers had to consider themselves "pipefitters".

Several days later Whitcomb had a "Eureka" moment. The reason for the high drag was that the "pipes" of air were interfering with each other in three dimensions. One could not simply consider the air flowing over a 2D cross-section of the aircraft as others could in the past; now they also had to consider the air to the "sides" of the aircraft which would also interact with these streampipes. Whitcomb realized that the Sears-Haack shaping had to apply to the aircraft *as a whole*, rather than just to the fuselage. That meant that the extra cross-sectional area of the wings and tail had to be accounted for in the overall shaping, and that the fuselage should actually be narrowed where they meet to more closely match the ideal.

Applications

Underside of an A-380. Several area rule-dictated features are visible

The area rule was immediately applied to a number of development efforts. One of the most famous was Whitcomb's personal work on the re-design of the Convair F-102 Delta Dagger, a U.S. Air Force jet fighter that was demonstrating performance considerably worse than expected. By indenting the fuselage beside the wings, and (paradoxically) adding more volume to the rear of the plane, transonic drag was considerably reduced and the original Mach 1.2 design speeds were reached. The culminating design of this research was the Convair F-106 Delta Dart, an aircraft which for many years was the USAF's primary all-weather interceptor.

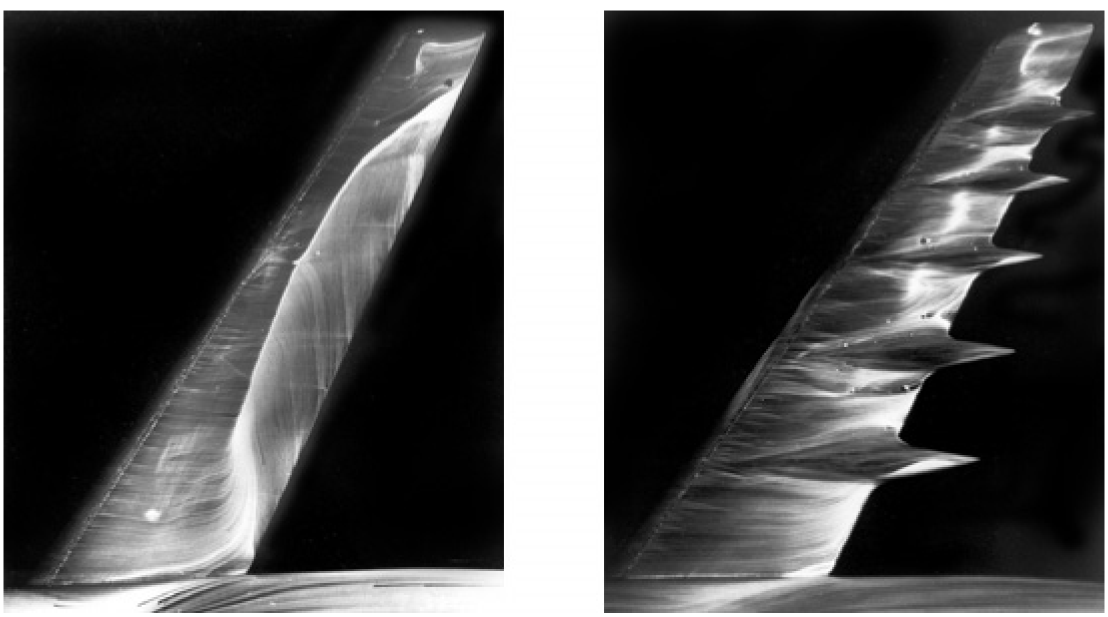
Numerous designs of the era were likewise modified in this fashion, either by adding new fuel tanks or tail extensions to smooth out the profile. The Tupolev Tu-95 'Bear', a Soviet-era bomber, has large bulged landing gear nacelles behind the two inner engines, increasing the aircraft's overall cross section aft of the wing root. Its airliner version has been the fastest propeller-driven aircraft in the world since 1960. The Convair 990 used a similar solution, adding bumps called antishock bodies to the trailing edge of the upper wing. The 990 remains the fastest U.S. airliner in history, cruising at up to Mach 0.89. Designers at Armstrong-Whitworth took the concept a step further in their proposed M-Wing, in which the wing was first swept forward and then to the rear. This allowed the fuselage to be narrowed on either side of the root instead of just behind it, leading to a smoother fuselage that remained wider on average than one using a classic swept wing.

One interesting outcome of the area rule is the shaping of the Boeing 747's upper deck. The aircraft was designed to carry standard cargo containers in a two-wide, two-high stack on the main deck, which was considered a serious accident risk for the pilots if they were located in a cockpit at the front of the aircraft. They were instead moved above the deck in a small "hump", which was designed to be as small as possible given normal streamlining principles. It was later realized that the drag could be reduced much more by lengthening the hump, using it to reduce wave drag offsetting the tail surface's contribution. The new design was introduced on the 747-300, improving its cruise speed and lowering drag.

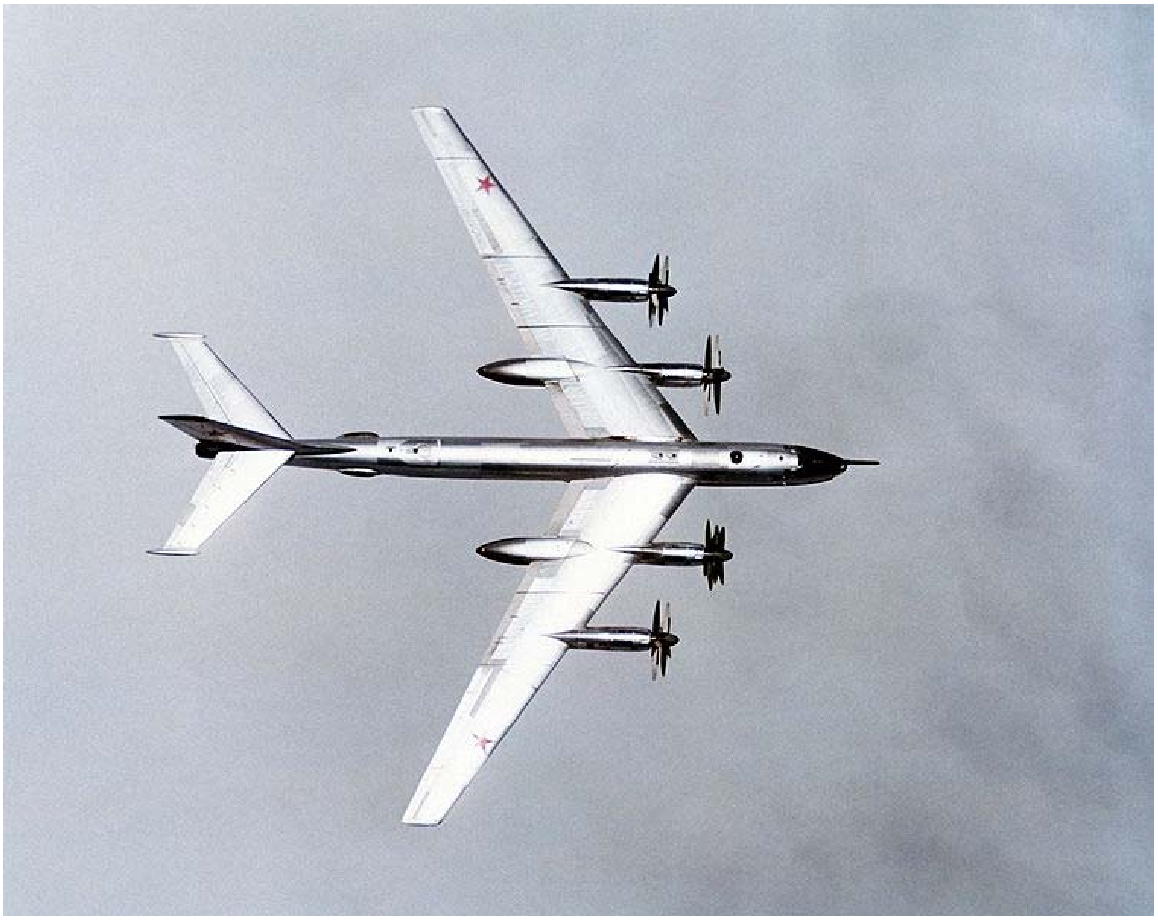
Aircraft designed according to Whitcomb's area rule looked odd at the time they were first tested, (e.g., the Blackburn Buccaneer), and were dubbed "flying Coke bottles," but the area rule is effective and came to be an expected part of the appearance of any transonic aircraft. Later designs started with the area rule in mind, and came to look much more pleasing. Although the rule still applies, the visible fuselage "waisting" can only be seen on a few aircraft, such as the B-1B Lancer, Learjet 60, and the Tupolev Tu-160 'Blackjack' — the same effect is now achieved by careful positioning of aircraft components, like the boosters and cargo bay on rockets; the jet engines in front of (and not directly below) the wings of the Airbus A380; the jet engines behind (and not purely at the side of) the fuselage of a Cessna Citation X; the shape and location of the canopy on the F-22 Raptor; and the image of the Airbus A380 above showing obvious area rule shaping at the wing root, which is practically invisible from any other angle. Antishock bodies are likewise mostly "invisible" today, often serving double-duty as flap actuators, which are also visible on the A380.

The F-106 Delta Dart, a development of the F-102 Delta Dagger, shows the "wasp-waisted" shaping due to area rule considerations

NASA Convair 990 with antishock bodies on the rear of the wings



Oilflow visualization of flow separation without and with antishock bodies

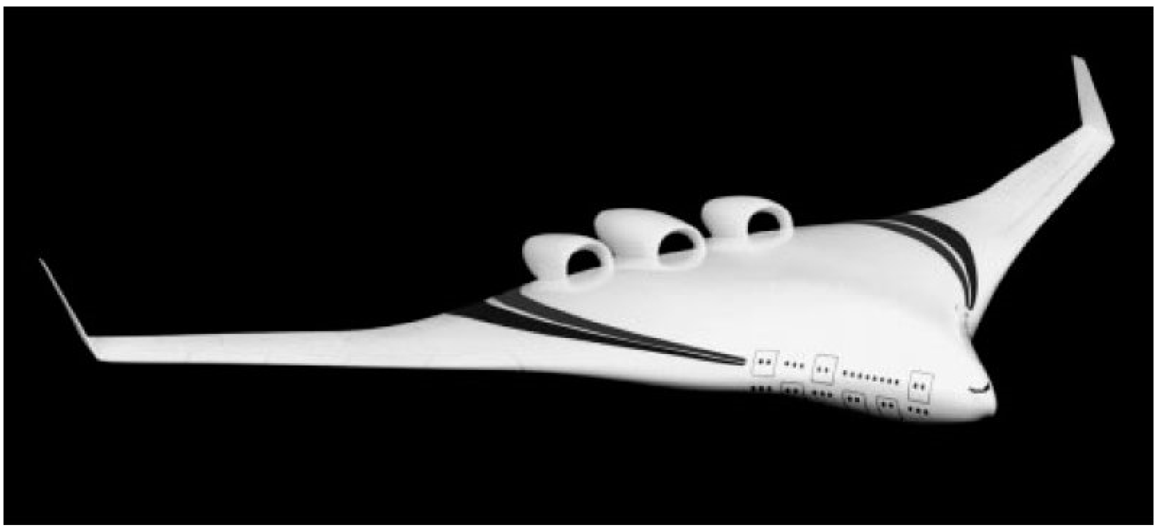


Two large bulged nacelles can be seen behind the engines of this Tupolev Tu-95

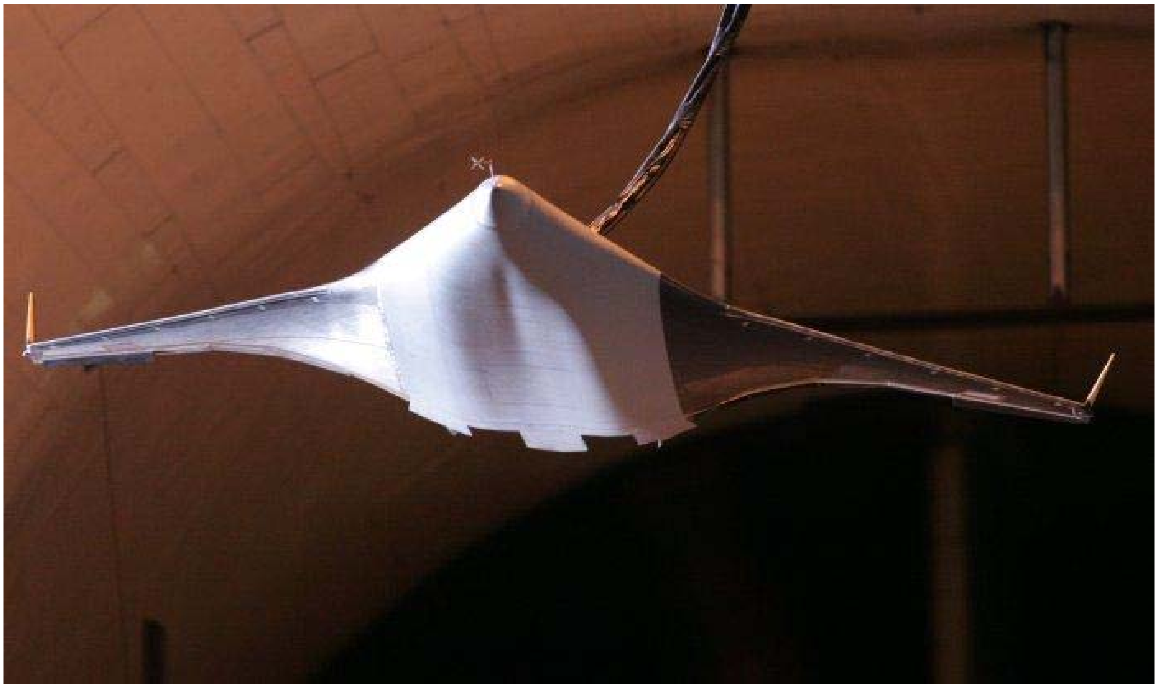
Chapter 4

Blended Wing Body and Blown Flap

Blended wing body



Computer-generated model of the Boeing X-48



NASA's prototype of a Blended Wing aircraft

Blended Wing Body, or BWB, designates an alternative airframe design which incorporates design features from both a futuristic fuselage and flying wing design. The purported advantages of the BWB approach are efficient high-lift wings and a wide airfoil-shaped body. This enables the entire craft to contribute to lift generation with the result of potentially increased fuel economy.

Flying wing designs are defined as having two separate bodies and only a single wing, though there may be structures protruding from the wing. Blended wing/body aircraft have a flattened and airfoil shaped body, which produces most of the lift to keep itself aloft, and distinct and separate wing structures, though the wings are smoothly blended in with the body.

History

An early aircraft exhibiting BWB design principles was the Stout Batwing. The designer William Bushnell Stout, toured the country promoting aircraft of the future would not have fuselages.

The Junkers G.38, flew in 1929. This "super jumbo" airliner of its day, seated thirty-four passengers, six in each of its two meter thick wings, and the balance in the central fuselage. In comparison, a contemporary passenger aircraft, the Ford Trimotor, carried a total of nine passengers in its more traditional wing and box fuselage design. Another example of similar design is Burnelli CBY-3. It had an airfoil shaped fuselage, producing significant part of the total lift. The CBY-3 had however a fairly conventional twin-boom empennage for added stability.

The Miles M.30 "X Minor" of the early 1940s was an experimental aircraft for research blended wing fuselage designs for an envisaged large airliner. Germany was designing blended wing body jet bombers at the very end of World War II.

In some ways, the B-2 Spirit stealth bomber is a design which falls between classic flying wing concepts and the BWB concept. It is usually classified as a flying wing, however, as the protruding body sections are not much larger than the underlying wing shape structure.

Currently, both NASA and Boeing are exploring BWB designs under the designation X-48. Studies suggest that BWB aircraft, configured for passenger flight, could carry from 450 to 800 passengers and achieve fuel savings of over 20 percent. NASA has been developing, since 2000, a remotely controlled model with a 21 ft (6.4 m) wingspan. This research is focused on establishing the base data concerning the lift, stall and spin characteristics inherent in a Blended Wing Body design.

Progression of aircraft design concepts from conventional airliner (1), blended wing-body (2), hybrid flying wing (3), flying wing (4). Note that the progression does not represent either a chronological or technical progression; the YB-49 (4), representing a true flying wing, actually predates all other depicted aircraft, while the "conventional" Boeing 757 (1) is a relatively new and technologically advanced aircraft.

Potential advantages

- Significant payload advantages in strategic airlift/air freight and aerial refueling roles

Blown flap

Blown flaps of the Hunting H.126

Blown flaps are a powered aerodynamic high-lift device invented by the British and used on the wings of certain aircraft to improve low-speed lift during takeoff and landing. The process is sometimes called a **boundary layer control system** (**BLCS**). They were a popular design feature in the 1960s, but fell from use due to their complex maintenance needs. Today a simpler version can be found on military transport aircraft, although the term is not widely used. Additionally, the early concepts have been built upon by modern engineers to create the circulation control wing, a far more effective device with applications in the modern aviation industry.

Mechanism

In a conventional blown flap, a small amount of the compressed air produced by the jet engine is "bled" off at the compressor stage and piped to channels running along the rear of the wing. There, it is forced through slots in the wing flaps of the aircraft when the flaps reach certain angles. Injecting high energy air into the boundary layer produces an increase in the stalling angle of attack and maximum lift coefficient by delaying boundary layer separation from the airfoil. Boundary layer control by mass injecting (blowing) prevents boundary layer separation by supplying additional energy to the particles of fluid which are being retarded in the boundary layer. Therefore injecting a high velocity air mass into the air stream essentially tangent to the wall surface of the airfoil reverses the boundary layer friction deceleration thus the boundary layer separation is delayed.

The effectiveness of wings can be greatly improved by using blow-type flow control, while if the intensity of the blown jet is high enough, even the lift predicted by potential flow theory can be surpassed (i.e. the jet flap effect) due to the initiation of supercirculation. Streamwise blowing however can require large amounts of air and energy thus reducing the overall benefits of the flow control solution itself. At low speeds, the amount of air being delivered by this system can be a significant fraction of the overall airflow, generating as much lift as if the plane were traveling at much higher speeds. This costs little, during landing at least, as the engine power is significantly reduced anyway. During takeoff the trade-off is not so obvious, particularly in conditions of low air density.

Development of the general concept continued at NASA in the 1950s and 60s, leading to simplified systems with similar performance. The *externally-blown flap* arranges the engine to blow across the flaps at the rear of the wing. Some of the jet exhaust is deflected downward directly by the flap, while additional air travels through the slots in the flap and follows the outer edge due to the Coandă effect. The similar *upper-surface blowing* system arranges the engines over the wing and relies completely on the Coandă effect to redirect the airflow. Although not as effective as direct blowing, these "powered lift" systems are nevertheless quite powerful and much simpler to build and maintain.

A more recent and promising blow-type flow control concept is the counter-flow fluid injection which is able to exert high-authority control to global flows using low energy modifications to key flow regions. In this case the air blow slit is located at the pressure side near the leading edge stagnation point location and the control air-flow is directed tangentially to the surface but with a forward direction. During the operation of such a flow control system two different effects are present. One effect, the Boundary Layer Enhancement, is caused by the increased turbulence levels away from the wall region thus transporting higher-energy outer flow into the wall region. In addition to that another effect, the Virtual shaping effect is utilized to aerodynamically thicken the airfoil at high angles of attack. Both these effects help to delay or eliminate flow separation.

In general, blown flaps can improve the lift of a wing by two to three times. Whereas a complex triple-slotted flap system on a Boeing 747 delivers a coefficient of lift of about 2.8, external blowing improves this to about 7, and internal blowing to 9.

History

During the 1950s and 60s, fighter aircraft generally evolved towards smaller and smaller wing planforms in order to have low drag at high speeds. Compared to the fighters of a generation earlier, they had wing loadings about four times as high; for instance the

Supermarine Spitfire had a wing loading of 24 lb/ft^2 (117 kg/m^2) and the Messerschmitt Bf 109 had the "very high" loading of 30 lb/ft^2 (146 kg/m^2), whereas the 1950s-era F-104 Starfighter had 111 lb/ft^2 (542 kg/m^2).

One serious downside to these higher wing loadings is at low speed, when there simply isn't enough wing left to provide lift to keep the plane flying. Even huge flaps could not offset this to any large degree, and as a result many aircraft landed at fairly high speeds, and were noted for accidents as a result.

The major reason flaps were not effective is that the airflow over the wing could only be "bent so much" before it stopped following the wing profile, a condition known as **flow separation**. Effectively, there is a limit to how much air the flaps can deflect overall. There are ways to improve this, through better flap design; modern airliners use complex multi-part flaps for instance. However, large flaps tend to add considerable complexity, and take up room on the outside of the wing, which makes them unsuitable for use on a fighter.

The concept was first tested on the experimental Hunting H.126. It reduced the stall speed to only 32 mph (51 km/h), a number most light aircraft cannot match. The first production aircraft with BLCS was the Lockheed F-104 Starfighter, where after prolonged development problems, it proved to be enormously useful in compensating for the Starfighter's tiny wing surface. It was shortly adopted for North American Aviation's A-5 Vigilante, the F-4 Phantom, the Blackburn Buccaneer and the ill-fated BAC TSR-2. On the TSR-2 it reduced the takeoff distance for this large and highly loaded aircraft from 6,000 feet (1,800 m) without the blowers, to about 1,600 feet (490 m) with them turned on.

In production aircraft, blown-flap systems were found to be a maintenance nightmare. They were continually breaking down due to clogging with dirt, and were generally unreliable. This made blown flaps practically useless as a landing aid on many aircraft. They were removed from later production runs of some aircraft.

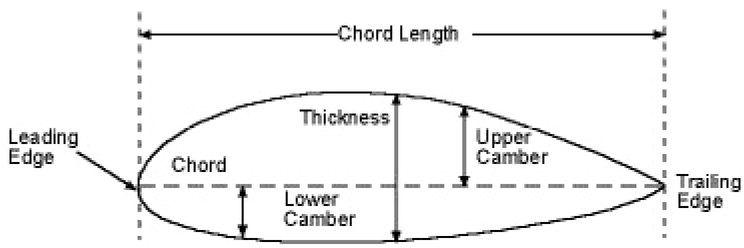
Starting in the 1970s the lessons of air combat over Vietnam changed thinking considerably. Instead of aircraft designed for outright speed, general maneuverability and load capacity became more important in most designs. The result is an evolution back to larger planforms to provide more lift. For instance the F-16 has a wing loading of 78.5 lb/ft^2 (383 kg/m^2), and uses leading edge extensions to provide considerably more lift at higher angles of attack, including approach and landing. Given the problems in service and the better lift from the larger wings, blown flaps have generally disappeared. More recently designed fighter aircraft achieve the same improved low-speed characteristics using the technically more complex swing-wing design.

In the 1970s new methods of constructing blown flaps were designed, with the original system becoming known as **internal blowing**. Two systems of **externally blown flaps** were developed, both using the direct exhaust of wing-mounted engines on otherwise simple flaps. Typical flap designs are split near the engine such that they don't deflect the thrust; however, with sufficiently powered engines, the effect of the flaps being in the path of the exhaust can be tremendous. The Airbus 380, because of its massive size, is one of the few major commercial airliners to use externally blown flaps, which continue behind its engines.

Chapter 5

Camber (Aerodynamics) and Canard (Aeronautics)

Camber



Camber, in aeronautics and aeronautical engineering, is the asymmetry between the top and the bottom curves of an aerofoil. *Camber* in regards to aerofoils passing through the air was discovered and first utilized by Sir George Cayley in the early 19th century in Great Britain.

Overview

Camber is usually designed into an aerofoil to enable it to create "lift", in the jargon of aerodynamics. Note that not all aerofoils are wings: some of them are propellers, etc., and the force that they generate is generally not in the upward direction. Hence, the jargon word "lift" can apply to forces that are horizontal, or even downward or at any angle between straight up and straight down.

The camber of a wing may vary from wing root to wing tip. Camber is not necessary for the generation of lift, and some aerofoils have no camber. Aerofoils with no camber (symmetric aerofoils) do not generate lift at a zero angle of attack, though. Usually, the upper camber of an aerofoil has been greater than the lower, but some recent designs use negative camber. One such design is called the supercritical aerofoil. It is used for near supersonic flight, and produces a more efficient lift to drag ratio at near supersonic flight than traditional aerofoils. Supercritical aerofoils employ a flattened upper surface, highly cambered (curved) aft section, and greater leading edge radius as compared to traditional aerofoil shapes. These changes delay the onset of wave drag and move that drag further aft on the aerofoil.

Adding camber doesn't necessarily increase *lift*; it depends on the aerofoil shape. If too much camber is added, the flow over the aerofoil may not stay attached to the wing even at an angle of attack of zero. When this occurs, we say the flow has separation over the aerofoil; if the entire top of the wing has separation, the wing is stalled. Wings with camber don't, as a result, have the ability to produce more lift in all cases; however, adding moderate camber does generally result in more lift, especially when compared to non-cambered wings at zero angle of attack.

A designer may also reduce the camber of the outboard section of the wings to increase the critical angle of attack (stall angle) at the wing tips. When the wing approaches the stall angle this will ensure that the wing root stalls before the tip—giving the aircraft resistance to falling into a spin by maintaining aileron effectiveness.

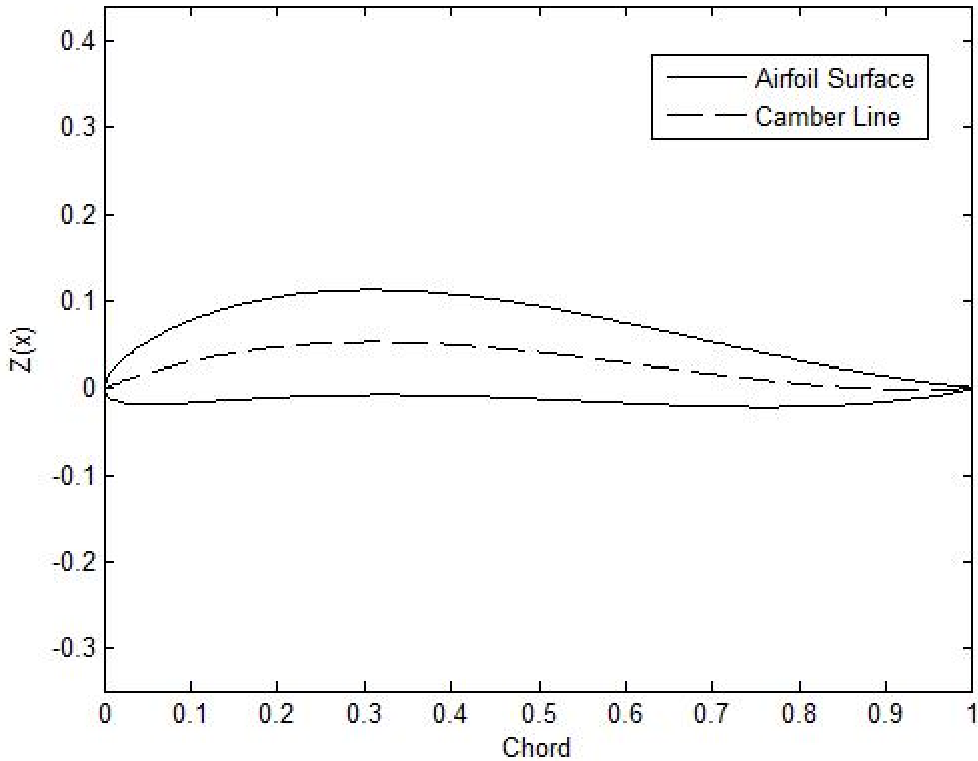
Definition

The camber of an aerofoil can be defined by a camber line, which is the curve that is halfway between the upper and lower surfaces of the aerofoil. Call this function *Z(x)*. To fully define an aerofoil we also need a thickness function *T(x)*, which describes the thickness of the aerofoil at any given point. Then, the upper and lower surfaces can be defined as follows:

$$Z_{upper}(x) = Z(x) + \frac{1}{2}T(x)$$

$$Z_{lower}(x) = Z(x) - \frac{1}{2}T(x)$$

Example - An aerofoil with reflexed camber line



An aerofoil with reflex camber.

An aerofoil where the camber line curves back up near the trailing edge is called a reflexed camber aerofoil. Such an aerofoil is useful in certain situations, such as with tailless aircraft, because the moment about the aerodynamic center of the aerofoil can be 0. A camber line for such an aerofoil can be defined as follows (*note that the lines over the variables indicates that they have been nondimensionalized by dividing through by the chord*):

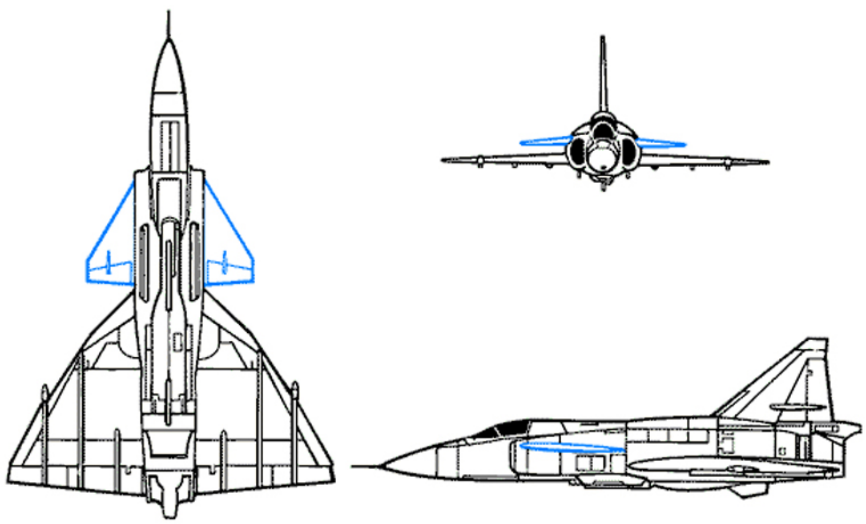
$$\overline{Z}(x) = a\left[(b-1)\,\overline{x}^3 - b\overline{x}^2 + \overline{x}\right]$$

An aerofoil with a reflexed camber line is shown at right. The thickness distribution for a NACA 4-series aerofoil was used, with a 12% thickness ratio. The equation for this thickness distribution is:

$$\overline{T}(x) = \frac{t}{0.2}\left(0.2969\sqrt{\overline{x}} - 0.1260\overline{x} - 0.3516\overline{x}^2 + 0.2843\overline{x}^3 - 0.1015\overline{x}^4\right)$$

Where *t* is the thickness ratio.

Canard (aeronautics)



Canards (blue) on the Saab Viggen

In aeronautics, **canard** (French for duck) is an airframe configuration of fixed-wing aircraft in which the forward surface is smaller than the rearward, the former being known as the "canard", while the latter is the main wing. In contrast a conventional aircraft has a small horizontal stabilizer behind the main wing.

Some early fixed-wing aircraft such as the Brazilian Santos-Dumont 14-bis and French Canard Voisin had tail-first configuration which were seen by observers to resemble a flying duck — hence the name.

General characteristics

Unlike a conventional tailplane, in order to achieve longitudinal stability a canard surface is trimmed to increase lift as speed increases. This equates to a negative coefficient for trim drag.

A canard design tends to be less controllable than a conventional design because ailerons on the main wing may be subject to turbulence from the canards that varies widely at different Angle of attack, leading to conditions of deep stall. If the ailerons were located on the canards, the lever arm would be too short due to the narrow span, and also the twisting motion would be too far forwards of the center of mass.

Canards have poor stealth characteristics because they present large, angular surfaces that tend to reflect radar signals. The Eurofighter Typhoon uses software control of its canards in order to reduce its radar cross section.

Canard classes

Canard designs fall into two main classes: the lifting-canard and the control-canard.

Other classes include the close-coupled type and active vibration damping.

Rutan Long-EZ, with lifting-canard ahead of the cockpit

A deflected control-canard on an RAF Typhoon F2

Canard (yellow) on a Mirage IIIS

Lifting-canard

The first airplane to fly, the Wright Flyer, was a lifting-canard. In this configuration, the weight of the aircraft is shared between the main wing and the canard wing. The pros and cons of the canard versus conventional configurations are numerous and complex, and it is impossible to say which is superior without considering a specific design application.

For example, a lifting-canard generates an upload, in contrast to a conventional aft-tail which typically generates a download that must be counteracted by extra lift on the main wing, which may appear to unambiguously favor the canard. However, the downwash interaction between the two surfaces is unfavorable for the canard, and favorable for the downloaded conventional tail, so the difference in overall induced drag is actually not obvious, and depends on the details of the configuration.

Another example is that the upward canard lift appears to increase the overall lift capability of the configuration. However, pitch stability flight safety requirements dictate that the canard must stall before the main wing, so the main wing can never reach its maximum lift capability. Hence, the main wing must then be larger than on the conventional configuration, which increases its weight and profile drag. Again, the relative merit depends on the details of the configuration and cannot be generalized.

In any case, pitch stability requires that the lift generated by the canard wing is significant, so in order to minimise induced drag on the canard, it is usually of higher aspect ratio and greater airfoil camber than a control-canard. To achieve stability, the change in lift coefficient with angle of attack should be less than that for the main plane.

One way in which this can be achieved is to use the same aerofoil for both planes, but to rig the canard at a higher angle of incidence. This tends to increase drag induced by the foreplane, which may be given a high aspect ratio in order to limit drag.

With a lifting-canard, the main wing must be located further aft of the center of gravity range than with a conventional aft tail, and this increases the pitching moment caused by trailing-edge flaps. Aircraft with lifting canards cannot readily be designed with sophisticated trailing-edge flaps.

Control-canard

In the later control-canard, most of the weight of the aircraft is carried by the main wing and the canard wing is used primarily for longitudinal control during maneuvering. A control-canard mostly operates at zero angle of attack. Combat aircraft of canard configuration typically have a control-canard. In combat aircraft, the canard is usually driven by a computerized flight control system.

One benefit obtainable from a control-canard is avoidance of pitch-up. An all-moving canard capable of a significant nose-down deflection will protect against pitch-up. As a result, the aspect ratio and wing-sweep of the main wing can be optimized without having to guard against pitchup.

Close-coupled canard

In the close-coupled canard, the foreplane is located just above and forward of the main wing. At high angles of attack the canard surface directs airflow downwards over the wing, reducing turbulence which results in reduced drag and increased lift.

The canard foreplane may be fixed as on the IAI Kfir, or have landing flaps as on the Saab Viggen, or it may be moveable and also act as a control-canard during normal flight as on the Dassault Rafale.

A close-coupled canard is very useful for a supersonic delta wing design which gains lift in both transonic flight (such as for supercruise) and also in low speed flight (such as take offs and landings).

A **moustache** is a small, high aspect ratio foreplane of close-coupled configuration. The surface is typically retractable at high speed and is deployed only for low-speed flight. First seen on the Dassault Milan, and later on the Tupolev Tu-144.

Active vibration damping

A large aircraft flying fast at low altitude can experience significant aerodynamic buffeting, leading to crew fatigue and reduced airframe life. Aircraft such as the B-1 Lancer incorporate small canard surfaces as part of an active vibration damping system that reduces these adverse effects.

Examples of canard aircraft

Some aircraft that have employed this configuration are listed below. A few types are listed twice, for example where the foreplane acts as a control-canard during normal flight and as a close-coupled type at high angles of attack.

Lifting-canard types

- AEA Silver Dart
- Beech Starship
- Berkut 360
- Chengdu J-9
- Cozy MK IV
- Freedom Aviation Phoenix
- Gyroflug Speed Canard
- Kyūshū J7W1 *Shinden*
- MacCready Gossamer Albatross
- MacCready Gossamer Condor
- MiG-8 *Utka*
- Miles Libellula
- North American SM-64 Navaho
- North American X-10
- OMAC Laser 300
- Peterson 260SE (a Cessna 182 with an added canard for STOL operations)
- Piaggio P180 Avanti (3 surfaces aircraft with flapped canard for pitch trim)
- Rutan Defiant
- Rutan Long-EZ
- Rutan VariEze
- Rutan VariViggen
- Rutan Voyager
- Rutan Quickie

- Santos-Dumont 14-bis
- Steve Wright Stagger-Ez
- Sukhoi T-4
- Tupolev Tu-144
- Velocity SE
- Velocity XL
- Wright Flyer
- XB-70 Valkyrie
- XP-55 Ascender

Control-canard types

- Atlas Cheetah
- Chengdu J-10
- Dassault Rafale
- Eurofighter Typhoon
- Grumman X-29A
- IAI Lavi
- McDonnell Douglas (now Boeing) F-15 S/MTD
- Pterodactyl Ascender
- Rockwell-MBB X-31
- Saab JAS 39 Gripen
- Sukhoi Su-30 MKI
- Sukhoi Su-33
- Sukhoi Su-34
- Sukhoi Su-27(27M variant)
- Sukhoi Su-37
- Sukhoi Su-47
- Chengdu J-20

Close-coupled canard types

- Atlas Cheetah
- Dassault Rafale
- IAI Kfir
- IAI Lavi
- Saab Viggen
- Tupolev Tu-144
- Novi Avion

Active vibration damping types

- B-1 Lancer

Concept aircraft

Lifting-canard types

- Lockheed L-133

The first powered airplane, the Wright Flyer, used dual, vertically-stacked canards

Eurofighter Typhoon of the Royal Air Force displaying at the Farnborough Airshow, 2006

Dassault Rafale, in service with the French Navy (Marine Nationale) and the French Air Force (Armée de l'Air)

Canards visible on a JAS 39 Gripen at the Farnborough Airshow

Grumman X-29, an experimental aircraft for forward swept wing research

The Rockwell-MBB X-31 Enhanced Fighter Maneuverability Demonstrator Aircraft

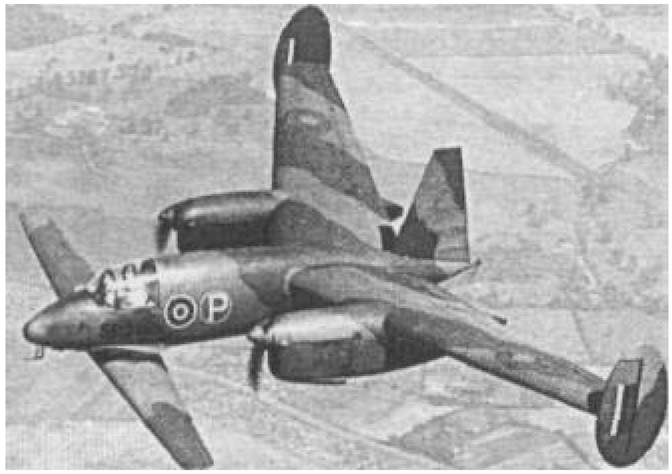
Canards (just behind the flight deck) on the XB-70 Valkyrie experimental bomber aircraft

Closeup of a Piaggio P180 Avanti's canards

The Beechcraft Starship Executive Transport

A Pterodactyl Ascender II+2 showing its canard control surface

Saab 37 Viggen of the Swedish Air Force

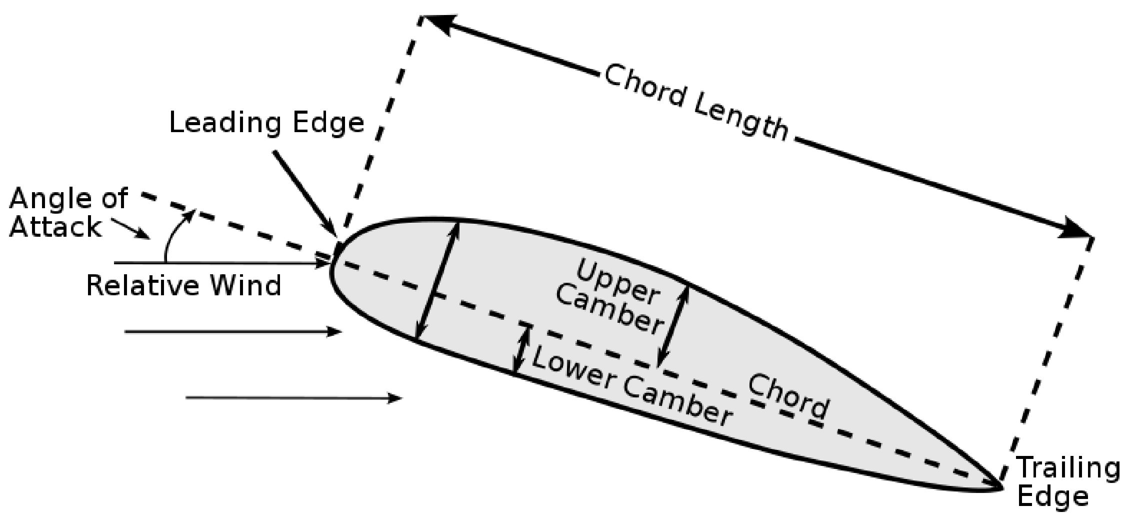


Miles Libellula (1941)

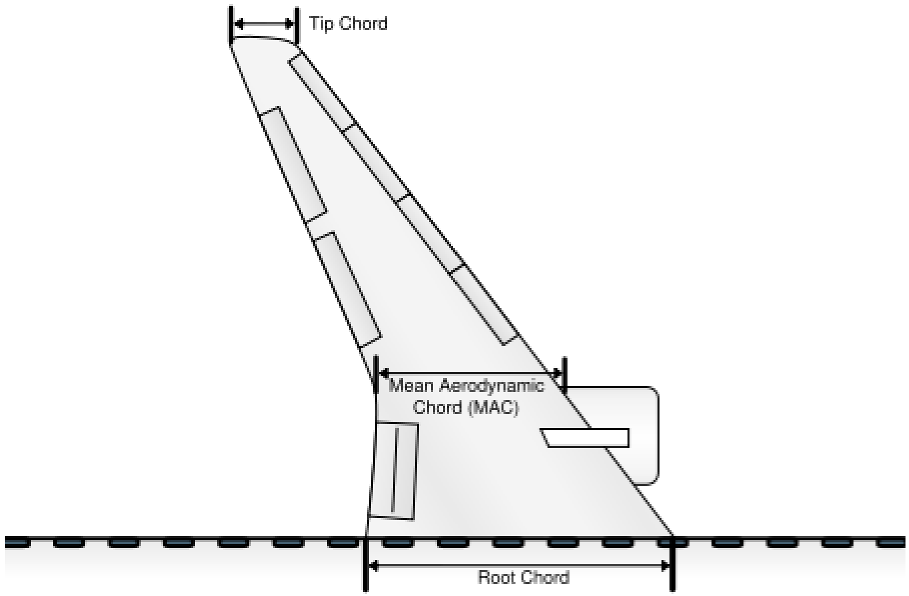
Chapter 6

Chord (Aircraft) and Circulation Control Wing

Chord



Cross section of an airfoil showing chord and chord length



The various chords on the planform of the swept-wing of an aircraft

In aeronautics, **chord** refers to the imaginary straight line joining the trailing edge and the center of curvature of the leading edge of the cross-section of an airfoil. The *chord length* is the distance between the trailing edge and the point on the leading edge where the chord intersects the leading edge.

The wing, horizontal stabilizer, vertical stabilizer and propeller of an aircraft are all based on airfoil sections, and the term *chord* or *chord length* is also used to describe their width. The chord of a wing, stabilizer and propeller is determined by examining the planform and measuring the distance between leading and trailing edges in the direction of the airflow. (If a wing has a rectangular planform, rather than tapered or swept, then the chord is simply the width of the wing measured in the direction of airflow.) The term *chord* is also applied to the width of wing flaps, ailerons and rudder on an aircraft.

The term is also applied to airfoils in gas turbine engines such as turbojet, turboprop, or turbofan engines for aircraft propulsion.

Most wings do not have a rectangular planform so they have a different **chord** at different positions along their span. To give a characteristic figure which can be compared among various wing shapes, the *mean aerodynamic chord*, or *MAC*, is used. The MAC is somewhat more complex to calculate, because most wings vary in **chord** over the span, growing narrower towards the outer tips. This means that more lift is generated on the wider inner portions, and the MAC moves the point to measure the chord to take this into account.

Standard mean chord

Standard mean chord (SMC) is defined as wing area divided by wing span:

$$\text{SMC} = \frac{S}{b},$$

where *S* is the wing area and *b* is the span of the wing. Thus, the SMC is the chord of a rectangular wing with the same area and span as those of the given wing. This is a purely geometric figure and is rarely used in aerodynamics.

Mean aerodynamic chord

Mean aerodynamic chord (MAC) is defined as:

$$\text{MAC} = \frac{2}{S}\int_0^{\frac{b}{2}} c^2 dy,$$

where *y* is the coordinate along the wing span and *c* is the chord at the coordinate *y*. Other terms are as for SMC.

Physically, MAC is the chord of a rectangular wing, which has the same area, aerodynamic force and position of the center of pressure at a given angle of attack as the given wing has. Simply stated, MAC is the width of an equivalent rectangular wing in given conditions. Therefore, not only the measure but also the position of MAC is often important. In particular, the position of center of mass (CoM) of an aircraft is usually measured relative to the MAC, as the percentage of the distance from the leading edge of MAC to CoM with respect to MAC itself.

Note that the figure to the right implies that the MAC occurs at a point where leading or trailing edge sweep changes. **In general, this is not the case.** Any shape other than a simple trapezoid requires evaluation of the above integral.

The ratio of the length (or **span**) of a wing to its chord is known as the aspect ratio, an important indicator of the lift-induced drag the wing will create. In general, planes with higher aspect ratios — long, skinny wings — will have less induced drag, which dominates at low airspeeds. This is why gliders have long wings.

Tapered wing

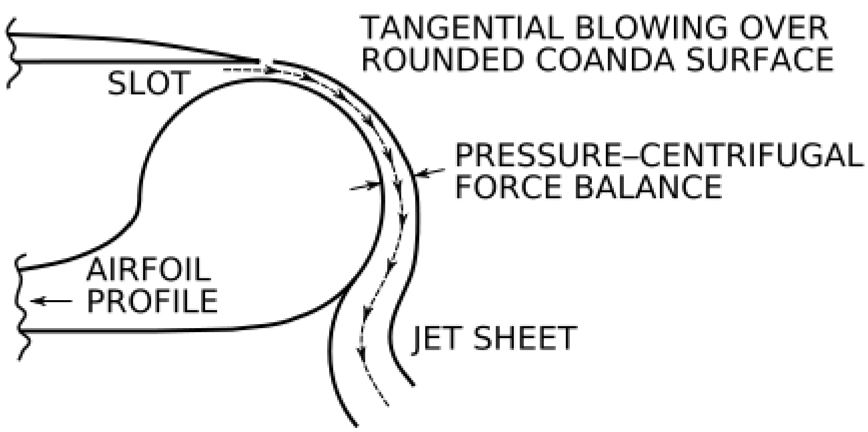
Knowing the area (S_w), taper ratio (λ) and the span (b) of the wing, and whether the wing has sweep or not, the chord at any position on the span can be calculated by the formula:

$$c(y) = \frac{2\,S_w}{(1+\lambda)b}\left[1 - \frac{2(1-\lambda)}{b}y\right]$$

Circulation control wing

A **circulation control wing** (CCW) is a form of high-lift device for use on the main wing of an aircraft to increase the lift coefficient. CCW technology has been in the research and development phase for over sixty years, and the early models were called blown flaps.

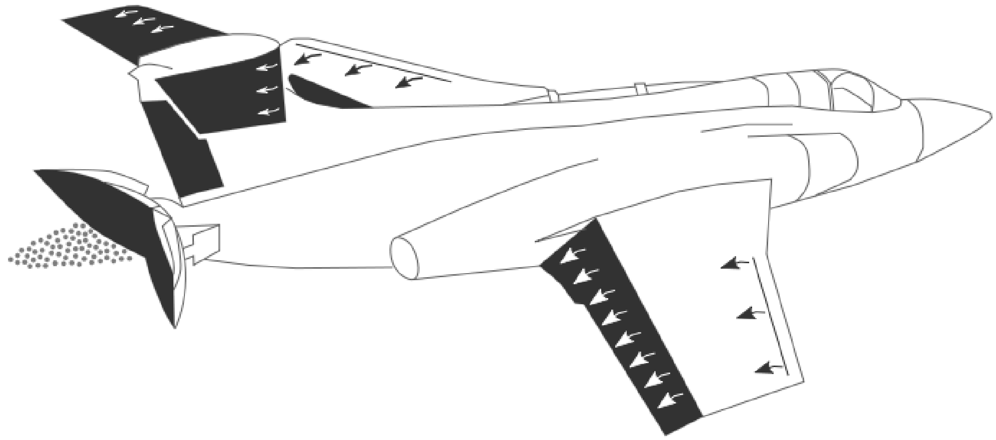
The CCW works by increasing the velocity of the airflow over the leading edge and trailing edge of a specially designed aircraft wing using a series of blowing slots that eject high pressure jet air. The wing has a rounded trailing edge to tangentially eject the air through the Coanda effect thus causing lift. The increase in velocity of the airflow over the wing also adds to the lift force through conventional airfoil lift production.



The trailing edge of a CCW showing the blowing slot and tangential coanda airflow

Purpose

The main purpose of the circulation control wing is to increase the lifting force of an aircraft at times when large lifting forces at slow speeds are required, such as takeoff and landing. Wing flaps and slats are currently used during landing on almost all aircraft and on takeoff by larger jets. While flaps and slats are effective in increasing lift, they do so at a high cost of drag. The benefit of the circulation control wing is that no extra drag is created and the lift coefficient is greatly increased. It is being claimed that such a system could increase the landing coefficient of lift of a Boeing 737 by 150% to 250%, thus reducing approach speeds by 35% to 45% and landing distances by 55% to 75% and that such advances in wing design could allow for dramatic wing size reduction in large, wide body jets.



A Buccaneer pictured with the blowing slots visible on the leading edges. The extended flaps are contributing to the coanda airflow over the wing.

Other uses

Increased maneuverability

At low speeds, an aircraft has reduced airflow over the wing and vertical stabilizer. This causes the control surfaces (ailerons, elevators and rudder) to be less effective. The CCW system increases the airflow over these surfaces and consequently can allow much higher maneuverability at low speeds. However, if one of the CCW systems should fail at low speed, the affected wing is likely to stall which could result in an inescapable spin. Finally, the CCW system could be used on multi-engine aircraft in the result of an engine failure to cancel the asymmetric forces from the loss of power on one wing.

Noise reduction

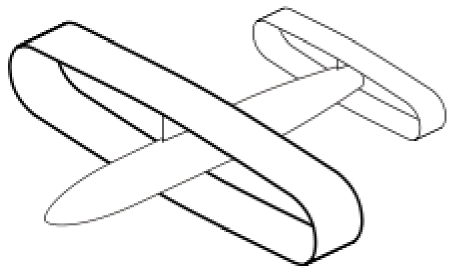
The use of a CCW system eliminates the need for large complex components in the free stream such as flaps and slats, greatly reducing the noise pollution of modern aircraft. Additionally, a much shorter ground roll coupled with steeper climb outs and approaches reduces the ground noise footprint. The blowing slots themselves will contribute very little to the noise of the aircraft as each slot is just a fraction of an inch wide.

Powering the wing

The main problem with the circulation control wing is the need for high energy air to be blown over the wing's surface. Such air is often taken from the engine; however, this drastically reduces engine power production and consequently defies the purpose of the wing. Other options are taking the exhaust gases (which must first be cooled) or using multiple, lightweight gas generators, which are separate from the main aircraft engines.

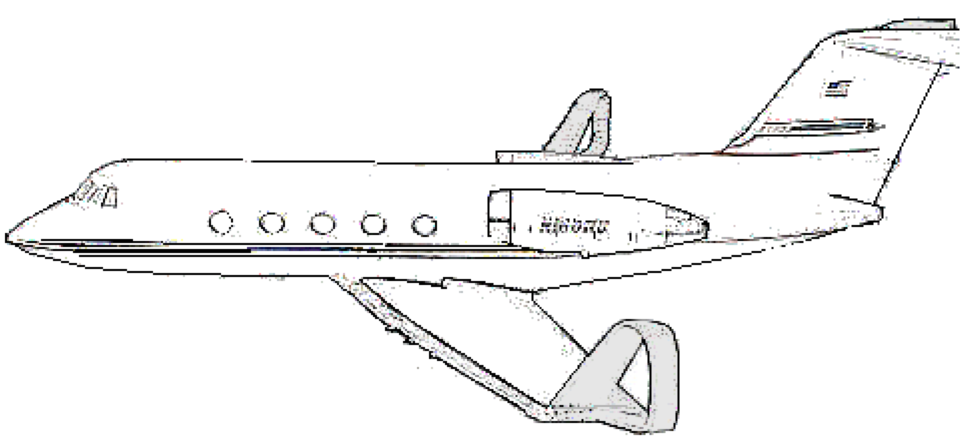
Chapter 7

Closed Wing



A **closed wing** is a non-planar wing planform concept. The term *closed wing* encompasses a number of designs, including the **annular wing** (commonly known as the **cylindrical** or **ring wing**), the **joined wing**, and the **box wing**. A closed wing can be thought of as the maximum expression of a wingtip device, which has the aim of eliminating the influence of the wingtip vortices which occur at the tips of conventional wings. These vortices form a major component of wake turbulence and are associated with induced drag, which negatively affects aerodynamic performance in most regimes. A closed wing surface has no wingtips whatsoever, and thus is capable of greatly reducing or eliminating wingtip drag, which has great implications for the improvement of fuel efficiency in the airline industry.

Performance benefits

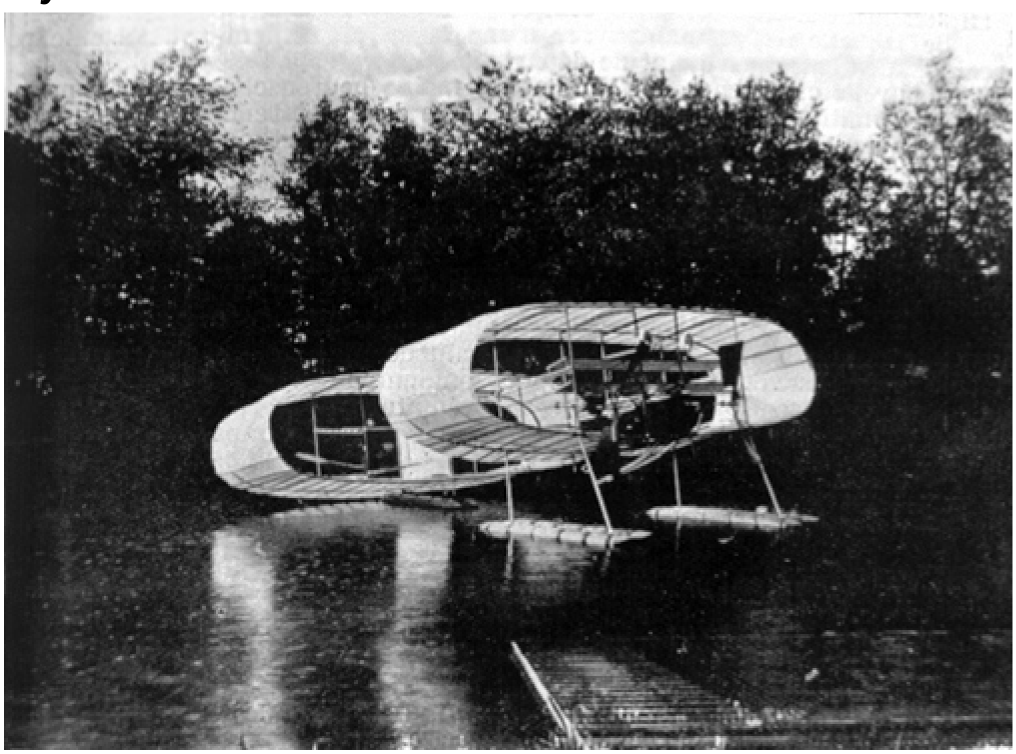


The Spiroid winglet is a closed wing surface attached to the end of a conventional wing

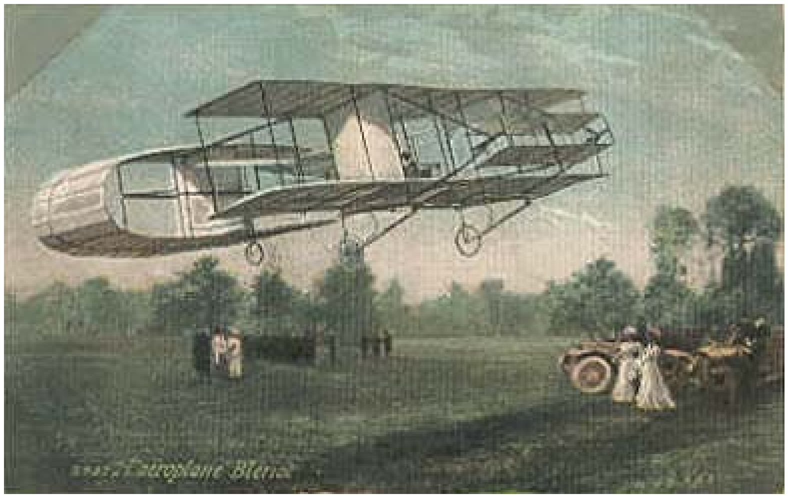
Closed wing surfaces exhibit a number of interesting structural and aerodynamic properties. The boxplane achieves the minimum possible induced drag for a given lift, wingspan, and vertical extent. Annular and joined wings can achieve span efficiencies greater than 1, and the annular wing exhibits half the vortex drag of a monoplane wing of the same span and lift. However, the concept of eliminating the influence of tip vortices through use of closed wings is an ill-conceived notion, according to Dr. Ilan Kroo, Professor of Aeronautics and Astronautics at Stanford University. There appears to be no particular advantage to a fully closed design; despite a decrease in local loading on any given point on the wing, the circulation is constant, thereby causing no change in the wake, and thereby the lift and interference drag associated with the surface. For this reason, closed wings remain mostly confined to the realms of studies and conceptual designs, as the engineering challenges of developing a strong, self-supporting closed wing for use in the large airliners which would benefit most from increases in efficiency have yet to be overcome. The C-wing benefits from many of the drag-reducing benefits of a closed wing design without the downsides of being a fully closed system.

The closed wing concept is also used in the water medium, in surfboard fins also known as tunnel fins.

History



The Blériot III, with its two annular closed-surface wings



The Blériot IV replaced the forward annular wing with a conventional biplane wing

The use of closed wings in aircraft has been explored many times in the past. The oldest known implementation of the surface was the Blériot III aircraft, built in 1906 by Louis Blériot and Gabriel Voisin. The aircraft's lifting structure consisted of two annular wings mounted in tandem, with two tractor propellers powered by an engine mounted inside the diameter of the forward wing. The Blériot IV was a variation on this design, which replaced the forward annular wing with a canard biplane setup similar to the 1903 Wright Flyer. This aircraft was able to leave the ground in a series of small hops before being damaged beyond repair. An aircraft known as the "Kitchen Doughnut" flew in Chicago in 1911; it had two ring wings, one mounted atop the other.

In 1944, the German designer Ernst Heinkel began working on an annular-wing VTOL multirole single-seater called Lerche, but the project was abandoned.

During the 1950s, the French company SNECMA developed an aircraft called the Coléoptère, a single-person VTOL design equipped with an annular wing. Despite the development and testing of several prototypes, the aircraft proved unstable and largely unsafe, and the design was abandoned. Later proposals for closed-wing designs included the Convair Model 49 Advanced Aerial Fire Support System (AAFSS), and the 1980s Lockheed concept known as the "Flying Bog Seat".

The annular wing dates to Terry in 1964.

The boxplane was first proposed by Miranda in 1972.

The modern idea of the joined wing was developed principally by Dr. Julian Wolkovitch in the 1980's, as an efficient structural arrangement in which the horizontal tail was used as a structural support for the main wing as well as a stabilizing surface.

The Spiroid winglet, a design currently under development by Aviation Partners, is a closed wing surface mounted at the end of a conventional wing. Initial testing using a

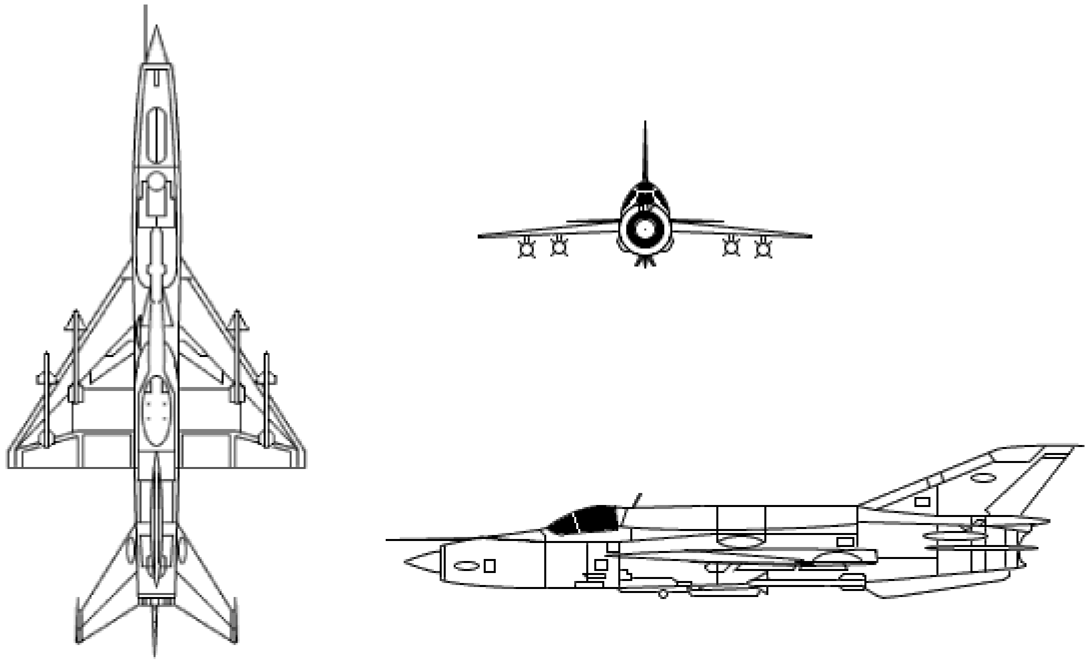
Gulfstream II test aircraft has shown the winglet design to reduce fuel consumption in the cruise phase by over 10%.

Aeronautical engineers in Belarus designed and constructed planes with ellipse wings, which allow the wings size of the plane to be kept small, and with the attached air vortexes on the sides of the wings help increase power by about 30%. The ellipse wings also maintain a sustainable hold on the plane keeping it more firm in all conditions.

Chapter 8

Delta Wing

Eurofighter Typhoon of the German Luftwaffe has a tailless delta wing configuration



MiG-21 had a tailed delta wing configuration (it had a conventional tail)

The delta wing Avro Vulcan bomber

The **delta wing** is a wing planform in the form of a triangle. It is named for its similarity in shape to the Greek uppercase letter delta (Δ).

History

Delta-shaped stabilizers

Between 1529 and 1556 Conrad Haas wrote a book in which he described rocket technology, involving the combination of fireworks and weapons technologies. This manuscript was re-discovered in 1961, in the Sibiu public records (Sibiu public records Varia II 374). His work dealt with the theory of motion of multi-stage rockets, different fuel mixtures using liquid fuel, and also introduced delta-shaped stabilizers.

As the manuscript was discovered only in 1961 until recently the conception of such stabilizers and their name had been suggested in the 17th century by the Polish-Lithuanian military engineer Kazimierz Siemienowicz.

Delta wing

The first practical uses of delta wing came in the form of so called "tailless delta", i.e. without the horizontal tailplane. In fact the designs were at the same time also the first flying wings. It could be argued if 1924 Cheranovsky designs, having one-of-a-kind parabolic planform, fit the category of delta wings. Nevertheless, a triangular wing was pioneered especially by Alexander Lippisch in Germany. He was first to fly tailless delta aircraft in 1931, followed by four improved designs. None of these was easy in handling at slow speeds, and none saw widespread service. During the war Lippisch studied a number of ramjet powered (sometimes coal-fueled) delta-wing interceptor aircraft, one progressing as far as a glider prototype.

After the war, Lippisch was taken to the United States of America, where he worked at the Convair company in California. Some high-ranking Convair engineers became quite interested in his interceptor designs, and they started work on a larger test version known as the Convair XF-92. The prototype—although never put into production—was extensively flight-tested, and its design generated a lot of interest of various airplane manufacturers in several countries. Soon many aircraft designs, particularly interceptors, would be designed around the delta wing. The tail-less delta became a favored design for high-speed use, and was used almost to the exclusion of other designs by Convair and by Dassault Aviation in France. Convair's F-102 was the first fighter with a tailless delta wing in service with any air force anywhere in the world.

Meanwhile, the British also developed aircraft based on the data from Lippisch, notably the Avro Vulcan strategic bomber and the Gloster Javelin fighter. The Javelin incorporated a tailplane in order to rectify some of the perceived weaknesses of the pure delta, to improve low-speed handling and high-speed manoeuvrability and to allow a greater center of gravity range.

The tailed delta configuration was again adopted by the TsAGI (Central Aero and Hydrodynamic Institute, Moscow), to take advantage of both high angle-of-attack flying capability and high speeds. It was used in the MiG-21 (Fishbed) and Sukhoi Su-9/Su-11/15 fighters, built by the tens of thousands in several different communist countries.

More recently, Saab AB used a close-coupled canard foreplane in front of the main wing of the Viggen fighter. The close coupling actively modifies the airflow over the wing, most notably during flight at high angles of attack. In contrast to the classic tail-mounted elevators, the canards add to the total lift, enabling the execution of extreme maneuvers, improving low-speed handling and lowering the landing speed. The design was copied in other aircraft, such as the Eurofighter Typhoon.

Aerodynamic advantages

The primary advantage of the delta wing is that with a large enough angle of rearward sweep the wing’s leading edge will not contact the shock wave boundary formed at the nose of the fuselage as the speed of the aircraft approaches and exceeds transonic to supersonic velocity. The rearward sweep angle vastly lowers the airspeed normal to the leading edge of the wing, thereby allowing the aircraft to fly at high subsonic, transonic, or supersonic speed, while the over wing speed of the lifting air is kept to less than the speed of sound. The delta plan form gives the largest total wing area (generating useful lift) for the wing shape, with very low wing per-unit loading, permitting high maneuverability in the airframe. As the delta's platform carries across the entire aircraft, it can be be built much more strongly than a swept wing, where the spar meets the fuselage far in front of the center of gravity. Generally a delta will be stronger than a similar swept wing, as well as having much more internal volume for fuel and other storage.

Another advantage is that as the angle of attack increases the leading edge of the wing generates a vortex which energizes the flow, giving the delta a very high stall angle. A normal wing built for high speed use is typically dangerous at low speeds, but in this regime the delta changes over to a mode of lift based on the vortex it generates. The disadvantages, especially marked in the older tailless delta designs, are a loss of total available lift caused by turning up the wing trailing edge or the control surfaces (as required to achieve a sufficient stability) and the high induced drag of this low-aspect ratio type of wing. This causes delta-winged aircraft to 'bleed off' energy very rapidly in turns, a disadvantage in aerial maneuver combat and dogfighting.

Additional advantages of the delta wing are simplicity of manufacture, strength, and substantial interior volume for fuel or other equipment. Because the delta wing is simple, it can be made very robust (even if it is quite thin), and it is easy and relatively inexpensive to build - a substantial factor in the success of the MiG-21 and Mirage aircraft.

A canard-delta suffers from a smaller shift in the center of lift with increasing mach number than a wing and tail configuration, but requires a stronger wing in order to provide control inputs that a canard is less effective than a tail at providing.

When used with a T-tail as in the Gloster Javelin the large delta wing could give rise to a "deep stall"; at high angles of attack the wing blanked airflow over the tail and left the aircraft uncontrollable.

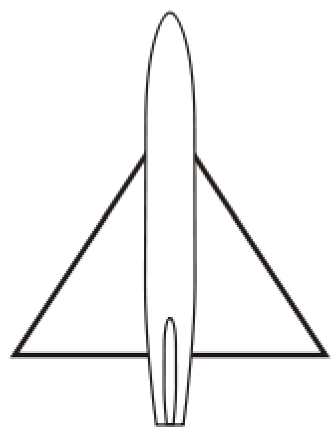
Delta-wing variations

Pure delta-wings fell out of favour somewhat due to their undesirable characteristics, notably flow separation at high angles of attack (swept wings have similar problems), and high drag at low altitudes. This limited them primarily to high-speed, high-altitude interceptor roles.

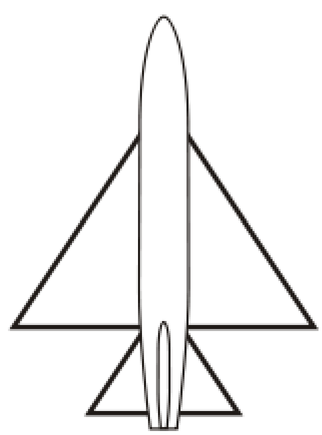
Many modern fighter aircraft, such as the JAS 39 Gripen, the Eurofighter Typhoon and the Dassault Rafale use a combination of canards and a delta wing.

Tailed delta - adds a conventional tailplane (with horizontal tail surfaces), to improve handling. Popular on Soviet types such as the Mikoyan-Gurevich MiG-21. **Cropped delta** - tip is cut off. This helps avoid tip drag at high angles of attack. Used for example in F-16.

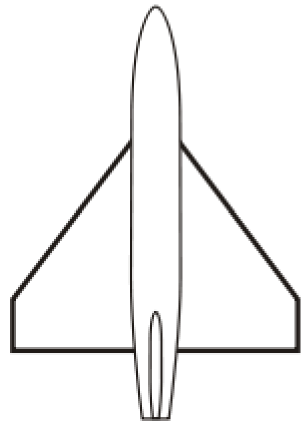
In another variant known variously as **compound delta**, **double delta** or **cranked arrow**, the inner part of the wing has a very high sweepback, while the outer part has less sweepback, to create the high-lift vortex in a more controlled fashion, reduce the drag and thereby allow for landing the delta at acceptably slow speed. This design can be seen on the Saab Draken fighter, the prototype F-16XL "Cranked Arrow" and in the High Speed Civil Transport study. The **ogee delta** (or **ogival delta**) used on the Anglo-French Concorde Mach 2 airliner is similar, but with a smooth 'ogee' curve joining the two parts rather than an angle.



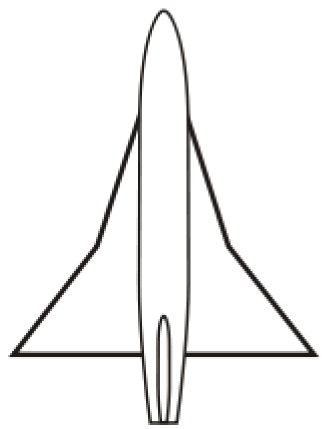
Tailless delta



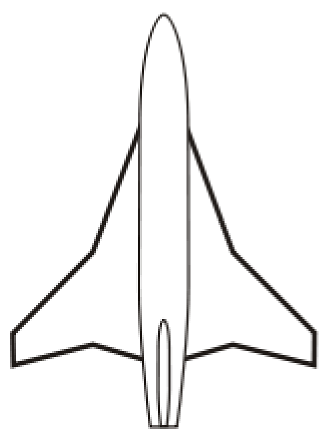
Tailed delta



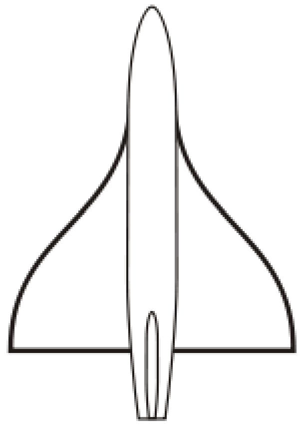
Cropped delta



Compound delta



Cranked arrow



Ogival delta

As the performance of jet engines grew, fighters with other planforms could perform as well as deltas, and do so while maneuvering much harder and at a wider range of altitudes. Today a remnant of the compound delta can be found on most fighter aircraft, in the form of leading edge extensions. These are effectively very small delta wings placed so they remain parallel to the airflow in cruising flight, but start to generate a vortex at high angles of attack. The vortex is then captured on the top of the wing to provide additional lift, thereby combining the delta's high-alpha performance with a conventional highly efficient wing planform.

Chapter 9

Dihedral

The upward tilt of the wings and tailplane of an aircraft, as seen on this Boeing 737, is called dihedral angle

Dihedral angle is the upward angle from horizontal of the wings or tailplane of a fixed-wing aircraft. **Anhedral angle** is the name given to negative dihedral angle, that is, when there is a *downward* angle from horizontal of the wings or tailplane of a fixed-wing aircraft.

Dihedral angle (or anhedral angle) has a strong influence on **dihedral effect**, which is named after it. Dihedral effect is the amount of roll moment produced per degree (or radian) of sideslip. Dihedral effect is a critical factor in the stability of an aircraft about the roll axis (the spiral mode). It is also pertinent to the nature of an aircraft's dutch roll oscillation and to maneuverability about the roll axis.

Longitudinal dihedral is a comparatively obscure term related to the pitch (flight) axis of an airplane. It is the angle between the zero lift axis of the wing and horizontal tail. Longitudinal dihedral can influence the nature of controllability about the pitch axis and the nature of an aircraft's phugoid-mode oscillation.

When the term "dihedral" (of an aircraft) is used by itself it is usually intended to mean "dihedral *angle*". However, context may otherwise indicate that "dihedral *effect*" is the intended meaning.

Dihedral angle and dihedral effect

Dihedral angle is the upward angle from horizontal of the wings of a fixed-wing aircraft, or of any paired nominally-horizontal surfaces on any aircraft. The term can also apply to the wings of a bird. Dihedral angle is also used in some types of kites such as box kites. Wings with more than one angle change along the full span are said to be *polyhedral*.

Dihedral angle has important stabilizing effects on flying bodies because it has a strong influence on the dihedral effect.

Dihedral effect of an aircraft is a rolling moment resulting from the vehicle having a non-zero angle of sideslip. Increasing the dihedral angle of an aircraft increases the dihedral effect on it. However, many other aircraft parameters also have a strong influence on dihedral effect. Some of these important factors are: wing sweep, vertical center of gravity, and the height and size of anything on an aircraft that changes its sidewards force as sideslip changes.

Longitudinal dihedral

Dihedral angle on an aircraft almost always implies the angle between two *paired* surfaces, *one on each side of the aircraft*. Even then, it is almost always between the left and right *wings*. However, dihedral in math means the angle between *any* two planes. So, in aeronautics, in one case, the term "dihedral" is applied to mean the difference in angles between two *front-to-back* surfaces:

Longitudinal dihedral is the difference between the angle of incidence of the wing and angle of incidence of the horizontal tail.

Longitudinal dihedral can also mean the angle between the zero lift axis of the two surfaces instead of between the root chords of the two surfaces. This is the more meaningful usage because the directions of zero-lift are pertinent to longitudinal trim and stability while the directions of the root chords are not.

History

In geometry, dihedral angle is the angle between two planes. Aviation usage differs slightly from usage in geometry. In aviation, the usage "**di**hedral" evolved to mean the positive, up angle between the left and right wings. While usage with the prefix "an-" (as in "**an**hedral") evolved to mean the negative, down angle between the wings.

The aerodynamic stabilizing qualities of dihedral angle were first described by Sir George Cayley in 1808-1809.

Uses of dihedral angle and dihedral effect

Aircraft stability analysis

In *analysis* of aircraft stability, dihedral effect is also a stability derivative called $\mathbf{C_{l\beta}}$ (pronounced "see-ell-beta") meaning the change in rolling moment coefficient (the "$\mathbf{C_l}$") per degree (or radian) of change in sideslip angle (the "β").

Provision of stability

The purpose of dihedral effect is to contribute to stability in the roll axis. It is an important factor in the stability of the *spiral mode* which is sometimes called "roll stability". It is important to note that dihedral effect does not contribute *directly* to the restoring of "wings level", but that its action is *indirect*. It indirectly helps restore "wings level" through its effect on the spiral mode (as described below).

Wing clearance

Aircraft designers may increase dihedral angle to provide increased clearance between wing tips and the runway. The increased dihedral effect caused by this may need to be compensated for by one or more other means, such as decreasing the dihedral angle on the horizontal tail.

Using dihedral angle to adjust dihedral effect

During the design of a fixed-wing aircraft (or any aircraft with horizontal surfaces), changing dihedral angle is usually a relatively simple way to adjust the overall dihedral effect. This is to compensate for other design elements' influence on the dihedral effect. These other elements (such as wing sweep, vertical mount point of the wing, etc.) may be more difficult to change than the dihedral angle. As a result, differing amounts of dihedral angle can be found on different types of fixed-wing aircraft. For example, the dihedral angle is usually greater on low-wing aircraft than on otherwise-similar high-wing aircraft. This is because "highness" of a wing (or "lowness" of vertical center of gravity compared to the wing) naturally creates *more* dihedral effect itself. This makes it so less dihedral angle is needed to get the amount of dihedral effect needed.

Common Confusions

Dihedral effect is defined simply to be the rolling moment caused by sideslip and nothing else. Rolling moments caused by other things that may be related to sideslip have different names.

Dihedral effect is not caused by *yaw rate*, nor by the *rate of sideslip change*. Since dihedral effect is noticed by pilots when "rudder is applied", many pilots and other near-experts explain that the rolling moment is caused by one wing moving more quickly through the air and one wing less quickly. Indeed, these are actual effects, but they are not the dihedral effect, which is caused by being *at* a sideslip angle, not by getting to one. These other effects are called "rolling moment due to yaw rate" and "rolling moment due to sideslip rate" respectively.

Dihedral effect is not roll stability in and of itself. Roll stability is less-ambiguously termed "spiral mode stability" and dihedral effect is a contributing factor to it, but dihedral effect is not any kind of stability by itself.

How dihedral angle creates dihedral effect and stabilizes the spiral mode

The following discusses how dihedral angle creates dihedral effect and how dihedral effect contributes to stability of the *spiral mode*. A *stable* spiral mode will cause the aircraft to eventually return to a nominally "wings level" bank angle when the angle of the wings is disturbed to become off-level.

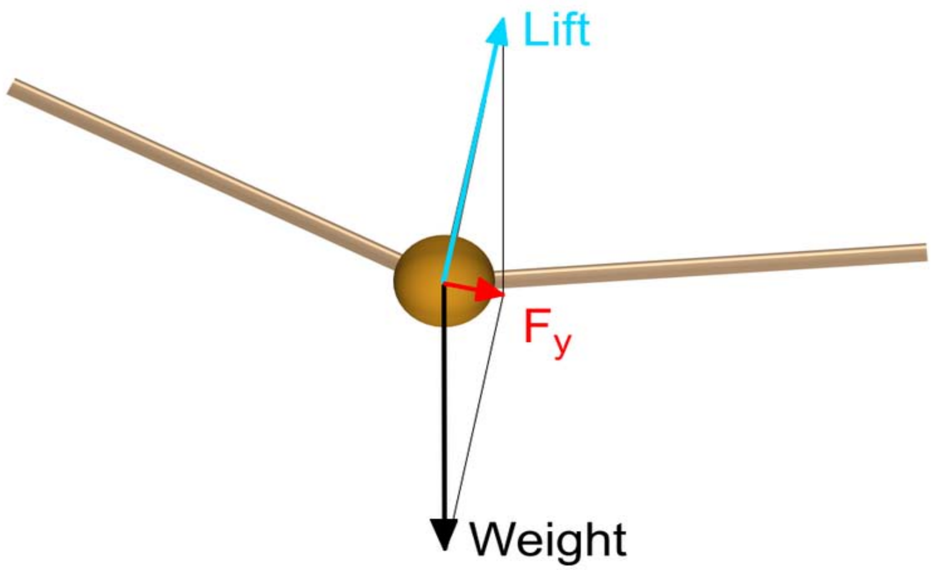


Fig. 1: Uncompensated lift component produces a side force F_y, which causes the aircraft to sideslip.

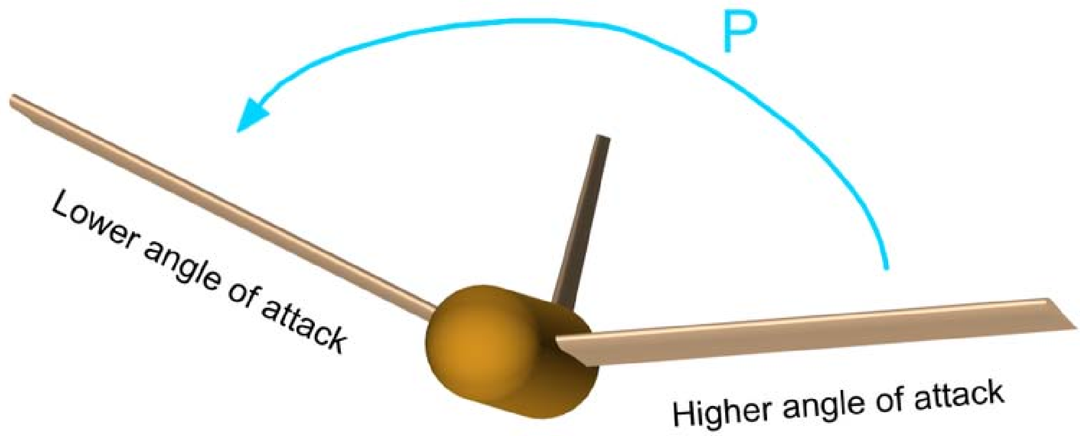


Fig. 2: Non-zero sideslip sets the lower, upwind wing to a higher angle of attack, resulting in stabilising roll moment P.
The aircraft is shown flying towards the viewer.

If a disturbance causes an aircraft to roll away from its normal wings-level position as in Figure 1, the aircraft will begin to move somewhat sideways toward the lower wing. In Figure 2, the airplane's flight path has started to move toward its left while the nose of the airplane is still pointing in the original direction. This means that the oncoming air is arriving somewhat from the *left* of the nose. Because of this, the airplane now has *sideslip* angle in addition to the bank angle. Figure 2 shows the airplane as it presents itself to the oncoming air.

How dihedral angle creates rolling moment from sideslip (dihedral effect)

In Figure 2, the sideslip conditions (not the roll angle which is also shown) make the dihedral angle *geometrically* produce greater angle of attack on the forward-yawed wing and smaller angle of attack on the rearward-yawed wing. This alteration of angle of attack by sideslip is visible to the eye in Figure 2. Since greater angle of attack makes greater lift, the forward wing will have more lift and the rearward wing will have less lift. This difference in lift between the wings is a rolling moment, and since it is caused by sideslip, it is dihedral effect (or more correctly, it is a *contribution* to the total dihedral effect of the aircraft).

How dihedral effect stabilizes the spiral mode

The rolling moment created by the sideslip (labeled as "P") *tends* to roll the aircraft back to wings level. More dihedral effect tries to roll the wings in the "leveling" direction more strongly, and less dihedral effect tries to roll the wings in the "leveling" direction less strongly. Dihedral effect *helps* stabilize the spiral mode by *tending* to roll the wings toward level in proportion to the amount of sideslip that builds up. It's not the whole picture however. At the same time that angle of sideslip is building up, the vertical fin is trying to turn the nose back into the wind, much like a weathervane, minimizing the amount of sideslip that can be present. If there is no sideslip, there can be no restoring rolling moment. If there is less sideslip, there is less restoring rolling moment. So, yaw stability created by the vertical fin *fights* the tendency for dihedral effect to roll the wings back level by *not letting as much sideslip build up*.

The spiral mode is the tendency to slowly diverge from, or the tendency to slowly return to wings level. If the spiral mode is stable, the aircraft will slowly return to wings-level, if it is unstable, the aircraft will slowly diverge from wings-level. Dihedral effect and yaw stability are the two primary factors that affect the stability of the spiral mode, although there are other factors that affect it less strongly.

Other factors contributing to dihedral effect

The CG of a paraglider is very low, making a strong contribution to dihedral effect

Factors of design other than dihedral angle also contribute to dihedral effect. Each increases or decreases total aircraft dihedral effect to a greater or lesser degree.

Sweepback

Wing sweepback also increases dihedral effect. This is one reason for anhedral configuration on aircraft with high sweep angle, as well as on some airliners, even on low-wing aircraft such as Tu-134 and Tu-154.

Vertical position of the center of mass

The center of mass, usually called the center of gravity or "CG", is the balance point of an aircraft. If suspended at this point and allowed to rotate, a body (aircraft) will be balanced. The front-to-back location of the CG is of primary importance for the general stability of the aircraft, but the vertical location has important effects as well.

The vertical location of the CG changes the amount of dihedral effect. As the "vertical CG" moves lower, dihedral effect increases. This is caused by the center of lift and drag being further above the CG and having a longer moment arm. So, the same forces (lift and drag) that change as sideslip changes produce a larger moment about the CG of the aircraft. This is sometimes referred to as the pendulum effect.

An extreme example of the effect of vertical CG on dihedral effect is a paraglider. The dihedral effect created by the *very* low vertical CG more than compensates for the negative dihedral effect created by the strong anhedral of the necessarily strongly downward curving wing.

Effects of too much dihedral effect

A side effect of too much lateral stability, caused by excessive dihedral among other things, can be yaw-roll coupling (a tendency for an aircraft to dutch roll). This can be unpleasant to experience, or in extreme conditions it can lead to loss of control or can overstress an aircraft.

Other Dihedral-related terminology

Anhedral on the wings and tailplane of an RAF Harrier GR7A

Anhedral

Military fighter aircraft often have near zero or even negative dihedral angle. This reduces dihedral effect, reducing the stability of the spiral mode. A too-stable spiral mode decreases maneuverability and is undesirable for fighter-type aircraft.

Anhedral angles are also seen on aircraft with a high mounted wing, such as the BAe 146 and Lockheed Galaxy. In such designs, the high mounted wing is above the center of gravity which confers extra dihedral effect due to the pendulum effect also called the keel effect, so additional dihedral angle is often not required. In fact, such designs can have excessive dihedral effect and so be excessively stable in the spiral mode, so the anhedral angle is added to cancel out some of the dihedral effect to ensure that the aircraft can be easily maneuvered.

Polyhedral

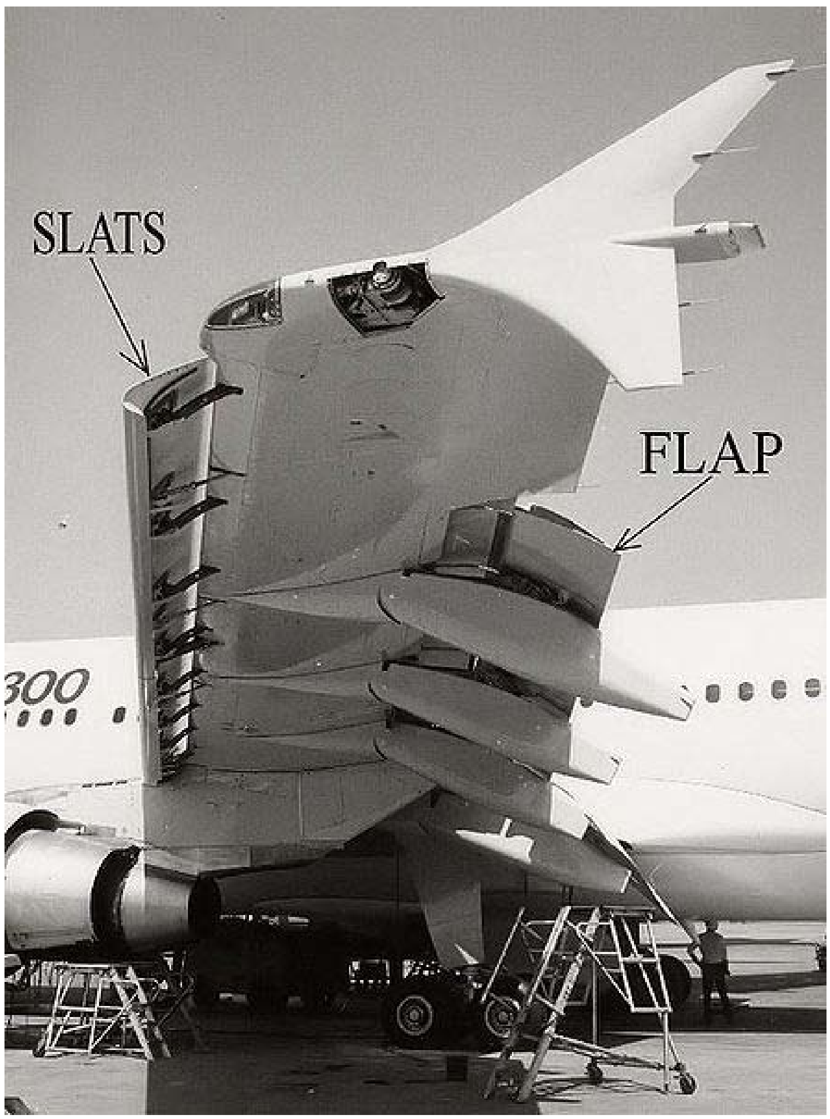
McDonnell Douglas F-4 Phantom II showing polyhedral wing and anhedral tail

Most aircraft have been designed with planar wings with simple dihedral (or anhedral). Some older aircraft such as the Vought F4U Corsair and the Beriev Be-12 were designed with gull wings bent near the root. Modern polyhedral wing designs generally cant upwards near the wingtips, increasing dihedral effect without increasing the angle the wings meet at the root, which may be difficult to alter for some other reason.

Polyhedral is seen on gliders and some other aircraft. The McDonnell Douglas F-4 Phantom II is one such example, unique among jet fighters for having dihedral wingtips. This was added after prototype flight testing (the original prototype of the F-4 had a flat wing) showed the need to correct some unanticipated spiral mode instability - angling the wingtips, which were already designed to fold up for carrier operations, was a more practical solution than re-engineering the entire wing.

Chapter 10

Flap



The position of the trailing edge flaps on an airliner (Airbus A310-300). In this picture, the flaps are extended, note also the drooped leading edge slats.

Triple-slotted trailing-edge **flaps** and leading edge Krueger (unslotted and slotted) flaps fully extended on a Boeing 747 for landing.

An Air France jet with flaps fully extended as it reduces speed before landing

A British Airways Boeing 757-200 lands with flaps extended

Flaps are hinged surfaces on the trailing edge of the wings of a fixed-wing aircraft. As flaps are extended, the stalling speed of the aircraft is reduced, which means that the aircraft can fly safely at lower speeds (especially during take off and landing). Flaps are also used on the leading edge of the wings of some high-speed jet aircraft, where they may be called Krueger flaps

Extending flaps increases the camber of the wing airfoil, thus raising the maximum lift coefficient. This increase in maximum lift coefficient allows the aircraft to generate a given amount of lift with a lower speed. Therefore, extending the flaps reduces the stalling speed of the aircraft.

The wing of an Easyjet Airbus A319-100. The three (orange) canoe-shapes are flap track fairings to hide and streamline the flap driving mechanisms. The flaps (two on each side, on the A319) lie directly above the flap track fairings.

Extending flaps also increases drag. This can be beneficial in the approach and landing phase because it helps to slow the aircraft. Another useful side effect of flap deployment is a decrease in aircraft pitch angle. This provides the pilot with a greater view over the nose of the aircraft and allows a better view of the runway during approach and landing.

A fully extended flap before landing

Some trailing edge flap systems increase the planform area of the wing in addition to changing the camber. In turn, the larger lifting surface allows the aircraft to generate a given amount of lift with a lower speed, thus further reducing stalling speed. Although this effect is very similar to increasing the lift coefficient, raising the planform area of the wing does not itself raise the lift coefficient. The Fowler flap is an example of a flap system that increases the planform area of the wing in addition to increasing the camber.

Physics explanation

The general airplane lift equation demonstrates these relationships:

$$L = \frac{1}{2}\rho V^2 S C_L$$

where:

- L is the lift,
- ρ is the air density,
- V is the true airspeed of the airplane
- **S** is the planform area of the wing and
- C_L is the aircraft lift coefficient

Here, it can be seen that increasing the area (S) and lift coefficient (C_L) allow a similar amount of lift to be generated at a lower airspeed (V).

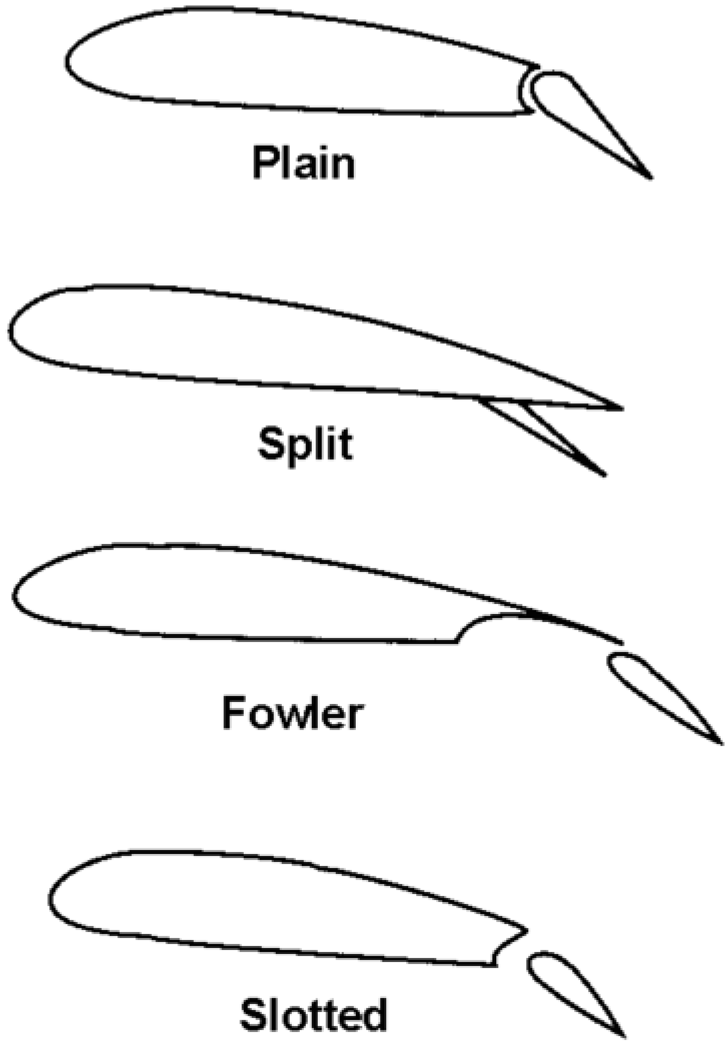
Extending the flaps also increases the drag coefficient of the aircraft. Therefore, for any given weight and airspeed, flaps increase the drag force. Flaps increase the drag coefficient of an aircraft because of higher induced drag caused by the distorted spanwise lift distribution on the wing with flaps extended. Some flaps increase the planform area of the wing and, for any given speed, this also increases the parasitic drag component of total drag.

Depending on the aircraft type, flaps may be partially extended for takeoff. Especially with general aviation aircraft, the use of flaps for takeoff may be optional. This depends on the manufacturer's procedures in the Airplane Flight Manual for a specific takeoff method (e.g., short field, soft field, normal, etc.). Flaps may be partially extended on takeoff to increase the amount of lift generated at a given airspeed, as well as to reduce the stalling speed of the airplane. Together, these two effects help an airplane lift off in a shorter distance at a lower drag penalty than that incurred by a full flap deflection.

Flaps are usually fully extended for landing to give the aircraft a lower stalling speed so the approach to landing can be flown more slowly, allowing the aircraft to land in a shorter distance. The higher lift and drag associated with fully extended flaps allows a steeper and slower approach to the landing site. This demonstrates the combined benefit of the higher lift and drag coefficients of fully extended flaps.

Some gliders not only use flaps when landing but also in flight to optimize the camber of the wing for the chosen speed. When thermalling, flaps may be partially extended to reduce the stalling speed so that the glider can be flown more slowly and thereby turn in a smaller circle to make best use of the core of the thermal. At higher speeds a negative flap setting is used to reduce the nose-down pitching moment. This reduces the balancing load required on the horizontal stabilizer, which in turn reduces the trim drag associated with keeping the glider in longitudinal trim. Negative flap may also be used during the initial stage of an aerotow launch and at the end of the landing run in order to maintain better control by the ailerons.

Types



Four types of flaps

Types of flap systems include:

- Krueger flap: hinged flap on the leading edge. Often called a "droop".
- Plain flap: rotates on a simple hinge.
- Split flap: upper and lower surfaces are separate, the lower surface operates like a plain flap, but the upper surface stays immobile or moves only slightly.
- Gouge flap: a cylindrical or conical aerofoil section which rotates backwards and downwards about an imaginary axis below the wing, increasing wing area and

chord without affecting trim. Invented by Arthur Gouge for Short Brothers in 1936.

- Fowler flap: slides backwards before hinging downwards, thereby increasing both camber and chord, creating a larger wing surface better tuned for lower speeds. It also provides some slot effect. The Fowler flap was invented by Harlan D. Fowler.
- Fairey-Youngman flap: moves body down before moving aft and rotating.
- Slotted flap: a slot (or gap) between the flap and the wing enables high pressure air from below the wing to re-energize the boundary layer over the flap. This helps the airflow to stay attached to the flap, delaying the stall.
- Blown flaps: systems that blow engine air over the upper surface of the flap at certain angles to improve lift characteristics.

Leading edge slats, usually found at the leading edge (frontmost part) of the wing where it meets the air first, have a similar function as the trailing-edge flaps. Note that a Krueger flap and a leading-edge slat differ in how they are extended. A slat allows a separation from the rest of the wing for energized air to pass from the bottom of the surface to the top, delaying boundary layer separation, whereas a Krueger flap does not because it only increases the wing area and wing curvature.

Research

Several technology research and development efforts exist to integrate the functions of aircraft flight control systems such as ailerons, elevators, elevons, and flaps, into wings to perform the aerodynamic purpose with the advantages of less: mass, cost, drag, inertia (for faster, stronger control response), complexity (mechanically simpler, fewer moving parts or surfaces, less maintenance), and radar cross section for stealth. These may be used in many unmanned aerial vehicles (UAVs) and 6th generation fighter aircraft. The two main approaches are flexible wings, and fluidics.

In flexible wings, much or all of a wing surface can change shape in flight to deflect air flow. The X-53 Active Aeroelastic Wing is a NASA effort. The Adaptive Compliant Wing is a commercial effort.

In fluidics, forces in vehicles occur via circulation control, in which larger more complex mechanical parts are replaced by smaller simpler fluidic systems (slots which emit air flows) where larger forces in fluids are diverted by smaller jets or flows of fluid intermittently, to change the direction of vehicles. In this use, fluidics promises lower mass, costs (up to 50% less), and very low inertia and response times, and high simplicity.

Chapter 11

Flying Wing

Graphic rendering

A **flying wing** is a tailless fixed-wing aircraft which has no definite fuselage, with most of the crew, payload and equipment being housed inside the main wing structure.

A flying wing may have various small protuberances such as pods, nacelles, blisters, booms, vertical stabilizers (tail fins), or undercarriage. Some aircraft have no fuselage but do have a separate horizontal stabilizer surface mounted on one or more booms; these are also commonly referred to as flying wings, although this is not strictly correct. An example of such a design is the Northrop X216H.

Theoretically the flying wing is the most efficient aircraft configuration from the point of view of aerodynamics and structural weight. It is argued that the absence of any aircraft components other than the wing should naturally provide these benefits. However in practice an aircraft's wing must provide for flight stability and control; this imposes additional constraints on the aircraft design problem. Therefore, the expected gains in weight and drag reduction may be partially or wholly negated due to design compromises needed to provide stability and control.

History

Northrop YB-49 flying wing

The US-produced B-2 Spirit, a strategic bomber capable of intercontinental missions.

Tailless aircraft have been experimented with since the earliest attempts to fly. But it was not until the deep-chord monoplane wing became practicable after World War I that the opportunity to discard any form of fuselage arose and the true flying wing could be realised.

Hugo Junkers patented a wing-only air transport concept in 1910. He saw it as a natural solution to the problem of building an airliner large enough to carry a reasonable passenger load and enough fuel to cross the Atlantic in regular service. He believed that the flying wing's potentially large internal volume and low drag made it an obvious design for this role. In 1919 he started work on his "Giant" JG1 design, intended to seat passengers within thick wings, but two years later the Allied Aeronautical Commission of Control ordered the incomplete JG1 destroyed for exceeding post-war size limits on German aircraft. Junkers conceived futuristic flying wings for up to 1,000 passengers; the nearest this came to realisation was in the 1931 Junkers G-38 34-seater *Grossflugzeug* airliner which featured a large thick-chord wing providing space for fuel, engines and two passenger cabins. However, it still required a short fuselage, ending in a double tail, and containing the crew and additional passengers.

The flying wing configuration was studied extensively in the 1930s and 1940s, notably by Jack Northrop and Cheston L. Eshelman in the United States, and Alexander Lippisch and the Horten brothers in Germany.

Soviet designers such as Boris Ivanovich Cheranovsky started research independently and in secret under Stalin after the 1920s. With significant breakthrough in materials and construction methods, aircraft such as the BICh-3, BICh-14, BICh-7A and so on became possible. Men like Chizhevskij and Antonov also came into the spotlight of the communist party by designing aircraft such as the tail-less BOK-5 (Chizhevskij) and OKA-33 (the first ever built by Antonov) which were designated as "motorized gliders" due to their similarity to popular gliders of the time. The BICh-11 by Cheranovsky in 1932 was competing with the Horten brothers H1 (and Adolf Galland) at the Ninth Glider Competitions in 1933, but did not demonstrate in the 1936 summer Olympics in Berlin. The BICh-26 was one of the first attempts at a supersonic jet flying-wing aircraft, ahead of its time in 1948 the airplane was not accepted by the military and the design died with Cheranovsky.

Early examples of true flying wings include:

- The Soviet Boris Ivanovich Cheranovsky built and tested tailless flying wings, from 1924 gliders, eventually also powered BICh-3.
- The French Charles Fauvel designed the AV3 glider, successfully flown in 1933, featuring a self-stabilizing airfoil on a straight wing.
- The German Horten H1 glider flown with partial success in 1933, and the subsequent H2 flown successfully in both glider and powered variants.
- The American Freel Flying Wing glider flown in 1937.
- The American Northrop N-1M of 1940
- The British Armstrong Whitworth A.W.52G of 1944, a glider test bed for the later Armstrong Whitworth A.W.52 jet-powered version.
- The German Horten Ho 229 of 1945 - the world's first twin jet engine pure flying wing

Several late-war German military designs were based on the flying wing concept (or variations of it) as a proposed solution to extend the range of the otherwise very short-range jet engined aircraft. Most famous of these would be the Horten Ho 229 fighter. This aircraft, first flown in 1944, combined a flying wing, or *Nurflügel*, design with twin jet engines. The surviving prototype remains in storage at the Smithsonian Institution in an unrestored state.

After the war, a number of experimental designs were based on the flying wing concept, but the known difficulties remained intractable. Some general interest continued until the early 1950s, when the concept was proposed as a design solution for long range bombers. Such trends culminated in the Northrop YB-35 and YB-49, which did not enter production. Those designs did not necessarily offer a great advantage in range and presented a number of technical problems, leading to the adoption of "conventional" solutions like the Convair B-36 and the B-52 Stratofortress.

Interest in flying wings was renewed in the 1980s due to their potentially low radar reflection cross-sections. Stealth technology relies on shapes which only reflect radar waves in certain directions, thus making the aircraft hard to detect unless the radar receiver is at a specific position relative to the aircraft - a position that changes continuously as the aircraft moves. This approach eventually led to the Northrop B-2 Spirit stealth bomber. In this case the aerodynamic advantages of the flying wing are not the primary needs. However, modern computer-controlled fly-by-wire systems allowed for many of the aerodynamic drawbacks of the flying wing to be minimised, making for an efficient and stable long-range bomber.

Due to the practical need for a deep wing, the flying wing concept is most practical for designs in the slow-to-medium speed range, and there has been continual interest in using it as a tactical airlifter design. Boeing continues to work on paper projects for a Blended Wing Body Lockheed C-130 Hercules-sized transport with better range and about 1/3 more load, while maintaining the same size characteristics. A number of companies, including Boeing, McDonnell Douglas and de Havilland, did considerable design work on flying-wing airliners, but to date none have entered production.

Design issues

A Northrop N-1M on display at the National Air and Space Museum's Steven F. Udvar-Hazy Center

A clean flying wing is theoretically the most aerodynamically efficient (lowest drag) design configuration for a fixed wing aircraft. It also offers high structural efficiency for a given wing depth, leading to light weight and high fuel efficiency.

Because it lacks conventional stabilizing surfaces or the associated control surfaces, in its purest form the flying wing suffers from the inherent disadvantages of being unstable and difficult to control. These compromises are difficult to reconcile, and efforts to do so can reduce or even negate the expected advantages of the flying wing design, such as reductions in weight and drag. Moreover, solutions may produce a final design that is still too unsafe for certain uses, such as commercial aviation.

Further difficulties arise from the problem of fitting the pilot, engines, flight equipment and payload all within the depth of the wing section. A wing that is made deep enough to contain all these elements will have an increased frontal area, when compared to a conventional wing and fuselage, which in turn results in higher drag and thus slower speed than a conventional design. Typically the solution adopted in this case is to keep the wing reasonably thin, and the aircraft is then fitted with an assortment of blisters, pods, nacelles, fins and so forth to accommodate all the needs of a practical aircraft.

Directional stability

For any aircraft to fly without constant correction it must have directional stability in yaw.

Flying wings lack the long fuselage which provides a convenient attachment point for an efficient vertical stabilizer or fin. The fin must attach directly on to the rear part of the wing, giving a small moment arm from the aerodynamic center, which in turn means that to be effective the fin area must be large. This large fin has weight and drag penalties, and can negate the advantages of the flying wing. The problem can be minimized by increasing the leading edge sweepback, as for example in a low-aspect-ratio delta wing, but most flying wings have gentler sweepback and consequently have, at best, marginal stability. In the so called ruptured duck configuration, the wing tip sections are angled sharply downwards (anhedral), increasing the area at the rear of the aircraft when viewed from the side.

Yaw control

In most flying wing designs, the stabilizing fins are so far forward that any control rudders mounted on them have little effect, thus alternative means for yaw control must be provided. The only practical solution is differential drag: the drag near one wing tip is artificially increased, causing the aircraft to yaw in the direction of that wing. Typical methods include:

- Split ailerons. The top surface moves up while the lower surface moves down, to create an air brake effect.

- Spoilers. A spoiler surface in the upper wing skin is raised, to disrupt the airflow and increase drag. This effect is generally accompanied by a loss of lift, which must be compensated for either by the pilot or by complex design features.
- Spoilerons. An upper surface spoiler which also acts to reduce lift (equivalent to deflecting an aileron upwards), so causing the aircraft to bank in the direction of the turn - the angle of roll causes the wing lift to act in the direction of turn, reducing the amount of drag required to turn the aircraft's longitudinal axis.

A consequence of the differential drag method is that if the aircraft manoeuvers frequently then it will frequently create drag. So flying wings are at their best when cruising in still air: in turbulent air or when changing course, the aircraft may be less efficient than a conventional design.

Borderline cases

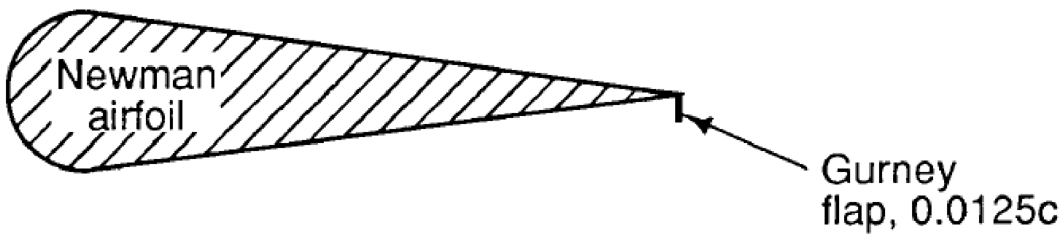
Some aircraft have no fuselage but do have a horizontal stabilizer mounted on one or more booms. Strictly, these are not flying wings although they are usually referred to as such. An example is the Northrop X-216H, which has a tail stabilizer mounted on two tail booms but is regarded as Northrop's first flying wing type.

Many hang gliders and microlight aircraft are tailless. Although often referred to as flying wings, these types carry the pilot (and engine where fitted) below the wing structure rather than inside it, and so are not true flying wings.

An aircraft of sharply-swept delta planform and deep center section represents a borderline case between flying wing, blended wing body and/or lifting body configurations.

Chapter 12

Gurney Flap

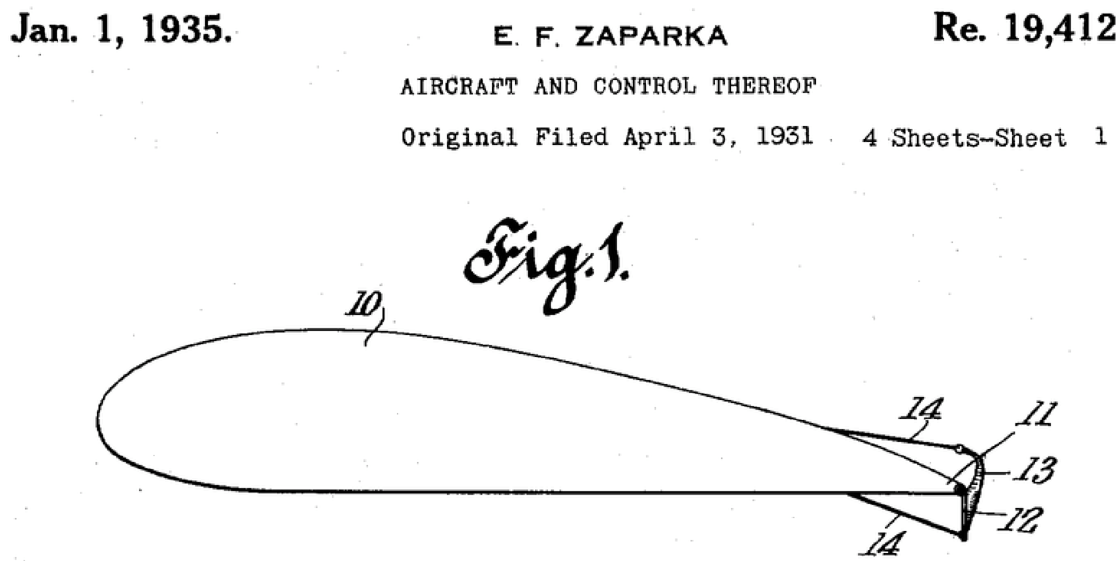


A gurney flap shown on the underside of a Newman airfoil (from NASA Technical Memorandum 4071).

The **Gurney Flap** (or **wickerbill**) is a small flat tab projecting from the trailing edge of a wing. Typically it is set at a right angle to the pressure side surface of the airfoil, and projects 1% to 2% of the wing chord. This trailing edge device can improve the performance of a simple airfoil to nearly the same level as a complex high-performance design.

The device operates by increasing pressure on the pressure side, decreasing pressure on the suction side, and helping the boundary layer flow stay attached all the way to the trailing edge on the suction side of the airfoil. Common applications occur in auto racing, helicopter horizontal stabilizers, and aircraft where high lift is essential, such as banner-towing airplanes.

History



The "variable lift airfoil" shown in Figure-1 of the 1935 E.F. Zaparka patent, U.S. Patent Re19,412. It is a movable microflap, similar to the fixed Gurney flap.

A Gurney flap on the trailing edge of the rear wing of a Porsche 962.

The original application, by automobile racing icon Dan Gurney, was a right-angle piece of sheet metal, rigidly fixed to the top trailing edge of the rear wing on his open wheel racing cars of the early 1970s. The device was installed pointing upwards to increase downforce generated by the wing, improving traction. He field tested it and found it allowed a car to negotiate turns at higher speed, while also achieving higher speed in the straight sections of the track.

The first application of the flap was in 1971, after Gurney retired from driving and began managing his own racing team full-time. His driver, Bobby Unser, had been testing a new Gurney designed car at Phoenix International Raceway, and was unhappy with the car's performance on the track. Gurney needed to do something to restore his driver's confidence before the race, and recalled experiments conducted in the 1950s by certain racing teams with "spoilers" affixed to the rear of the bodywork to cancel lift. (At that level of development, the spoilers were not thought of as potential performance enhancers—merely devices to cancel out destabilizing and potentially deadly aerodynamic lift.) Gurney decided to try adding a "spoiler" to the trailing edge of the rear wing. The device was fabricated and fitted in under an hour, but Unser's test laps with the modified wing turned in equally poor times. When Unser was able to speak to Gurney in confidence, he disclosed that the lap times with the new wing were slowed because it was now producing so much downforce that the car was understeering. All that was needed was to balance this by adding additional downforce in front.

Unser realized the value of this breakthrough immediately and wanted to conceal it from the competition, including his brother Al. Not wanting to call attention to the devices, Gurney left them out in the open. To conceal his true intent, Gurney deceived inquisitive competitors by telling them the blunted trailing edge was intended to prevent injury and damage when pushing the car by hand. Some copied the design, and some of them even "improved" it by pointing the flap downwards, which actually hurt performance.

Gurney was able to use the device in racing for several years before its true purpose became known. Later, he discussed his ideas with aerodynamicist and wing designer Bob Liebeck of Douglas Aircraft Company. Liebeck tested the device, which he later named the "Gurney flap," and confirmed Gurney's field test results using a 1.25% chord flap on a Newman symmetric airfoil. His 1976 AIAA paper (76-406) "On the design of subsonic airfoils for high lift" introduced the concept to the aerodynamics community. The Gurney flap is the first aerodynamic development made in automobile racing that has been successfully transferred to aircraft engineering.

Gurney assigned his patent rights to Douglas Aircraft, but the device was not patentable, since it was substantially similar to a movable microflap patented by E.F. Zaparka in 1931, ten days before Gurney was born. Similar devices were also tested by Gruschwitz and Schrenk and presented in Berlin in 1932.

The Gurney flap has also been implemented on the rear spoiler of the 2010-2011 Shelby Mustang GT500.

Theory of operation

The Gurney flap increases the maximum lift coefficient ($C_{L,max}$), decreases the angle of attack for zero lift (α_0), and increases the nosedown pitching moment (C_M), which is consistent with an increase in camber of the airfoil. It also typically increases the drag coefficient (C_d), especially at low angles of attack, although for thick airfoils, a reduction in drag has been reported. A net benefit in overall lift to drag ratio is possible if the flap is sized appropriately based on the boundary layer thickness.

The Gurney flap increases lift by altering the Kutta condition at the trailing edge. The wake behind the flap is a pair of counter-rotating vortices that are alternately shed in a von Kármán vortex street. In addition to these spanwise vortices shed behind the flap, chordwise vortices shed from in front of the flap become important at high angles of attack.

The increased pressure on the lower surface ahead of the flap means the upper surface suction can be reduced while producing the same lift.

Helicopter applications

Double Gurney flaps on a Bell 222U helicopter

Gurney flaps have found wide application on helicopter horizontal stabilizers, because they operate over a very wide range of both positive and negative angles of attack. At one extreme, in a high-powered climb, the negative angle of attack of the horizontal stabilizer can be as high as -25°; at the other extreme, in autorotation, it may be +15°. As a result, at least half of all modern helicopters built in the West have them in one form or another.

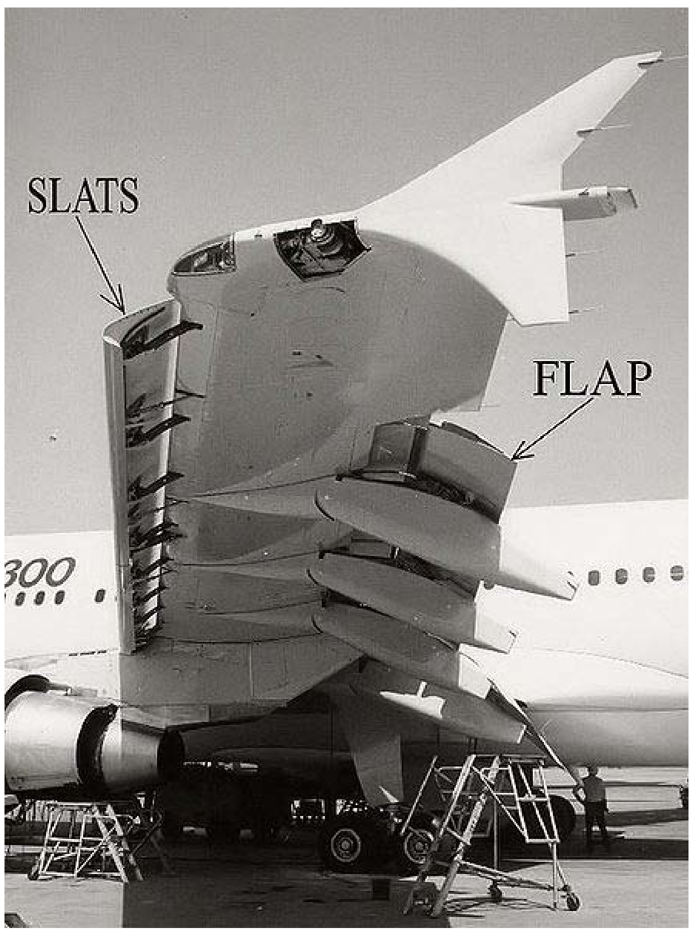
The Gurney flap was first applied to the Sikorsky S-76B variant, when flight testing revealed the horizontal stabilizer from the original S-76 did not provide sufficient lift. Engineers fitted a Gurney flap to the NACA 2412 inverted airfoil to resolve the problem without redesigning the stabilizer from scratch. A Gurney flap was also fitted to the Bell JetRanger to correct an angle of incidence problem in the design that was too difficult to correct directly.

The Eurocopter AS355 TwinStar helicopter uses a double Gurney flap that projects from both surfaces of the vertical stabilizer. This is used to correct a problem with lift reversal in thick airfoil sections at low angles of attack. The double gurney flap reduces the control input required to transition from hover to forward flight.

Chapter 13

Leading Edge Slats

Slats are aerodynamic surfaces on the leading edge of the wings of fixed-wing aircraft which, when deployed, allow the wing to operate at a higher angle of attack. A higher coefficient of lift is produced as a product of angle of attack and speed, so by deploying slats an aircraft can fly more slowly or take off and land in a shorter distance. They are usually used while landing or performing maneuvers which take the aircraft close to the stall, but are usually retracted in normal flight to minimize drag.



The position of the leading edge slats on an airliner (Airbus A310-300). In this picture, the slats are drooped, note also the extended trailing edge flaps.

Slats on the leading edge of an Airbus A318 of Air France

The Fieseler Fi 156 *Storch* had permanently extended slots on its leading edges (fixed slats).

The wing of a landing bmi Airbus A319-100. The slats at the leading edge and the flaps at the trailing edge are extended.

Types

Types include:

- Automatic - the slat lies flush with the wing leading edge until reduced aerodynamic forces allow it to extend by way of springs when needed.
- Fixed - the slat is permanently extended. This is sometimes used on specialist low-speed aircraft (these are referred to as slots) or when simplicity takes precedence over speed.

- Powered - the slat extension can be controlled by the pilot. This is commonly used on airliners.

Operation

The chord of the slat is typically only a few percent of the wing chord. The slats may extend over the outer third of the wing, or they may cover the entire leading edge. Many early aerodynamicists, including Ludwig Prandtl believed that slats work by inducing a high energy stream to the flow of the main airfoil thus re-energizing its boundary layer and delaying stall. In reality, the slat does not give the air in the slot high velocity (it actually reduces its velocity) and also it cannot be called high-energy air since all the air outside the actual boundary layers has the same total head. The actual effects of the slat are :

- The slat effect: The velocities at the leading edge of the downstream element (main airfoil) are reduced due to the circulation of the upstream element (slat) thus reducing the pressure peaks of the downstream element.
- The circulation effect: The circulation of the downstream element increases the circulation of the upstream element thus improving its aerodynamic performance.
- The dumping effect: The discharge velocity at the trailing edge of the slat is increased due to the circulation of the main airfoil thus alleviating separation problems or increasing lift.
- Off the surface pressure recovery: The deceleration of the slat wake occurs in an efficient manner, out of contact with a wall.
- Fresh boundary layer effect: Each new element starts out with a fresh boundary layer at its leading edge. Thin boundary layers can withstand stronger adverse gradients than thick ones.

The slat has a counterpart found in the wings of some birds, the alula – a feather or group of feathers which the bird can extend under control of its "thumb".

History

Slats were first developed by Gustav Lachmann in 1918. A crash in August 1917, with a Rumpler C aeroplane on account of stalling caused the idea to be put in a concrete form, and a small wooden model was built in 1917 in Cologne. In 1918, Lachmann presented a patent for leading edge slats in Germany. However, the German patent office at first rejected it as the office did not believe in the possibility of increasing lift by dividing the wing..

Independently of Lachmann, Handley-Page Ltd in Great Britain also developed the slotted wing as a way to postpone stall by reducing the turbulence over the wing at high angles of attack, and applied for a patent in 1919; to avoid a patent challenge, they reached an ownership agreement with Lachmann. That year a De Havilland D.H.9 was fitted with slats and flown. Later a D.H.4 was modified as a monoplane with a large wing fitted with full span leading edge and back ailerons (ie what would later be called flaps) that could be deployed in conjunction with the leading edge slats to test improved low speed performance. Several years later, having subsequently taken employment at the Handley-Page aircraft company, Lachmann was responsible for a number of aircraft designs, including the Handley Page Hampden.

Licensing the design became one of the company's major sources of income in the 1920s. The original designs were in the form of a fixed slot in the front of the wing, a design that was found on a number of STOL aircraft.

During World War II German aircraft commonly fitted a more advanced version that pushed back flush against the wing by air pressure to reduce drag, popping out when the airflow decreased during slower flight. Notable slats of that time belonged to the German Fieseler Fi 156 *Storch*. These were similar in design to retractable slats, but were fixed non-retractable slots. The slotted wing allowed this aircraft to take off into a light wind in less than 45 m (150 ft), and land in 18 m (60 ft). Aircraft designed by the Messerschmitt company employed leading-edge slats as a general rule.

In the post-war era slats have generally been hydraulically or electrically operated.

Slats are one of several high-lift devices used on airliners, such as flap systems running along the trailing edge of the wing.

Chapter 14

Wing Configuration

This chapter summarizes the **wing configurations** of fixed-wing aircraft, popularly called aeroplanes, airplanes or just planes.

Here we, provides a breakdown of types, allowing a full description of any aircraft's wing configuration. For example the Spitfire wing may be classified as a *conventional low wing cantilever monoplane with straight elliptical wings of moderate aspect ratio and slight dihedral*.

Sometimes the distinction between types is blurred, for example the wings of many modern combat aircraft may be described either as cropped compound deltas with (forwards or backwards) swept trailing edge, or as sharply tapered swept wings with large "Leading Edge Root Extension" (or LERX).

All the configurations described have flown (if only very briefly) on full-size aircraft, except as noted.

Some variants may be duplicated under more than one heading, due to their complex nature. This is particularly so for variable geometry and combined (closed) wing types.

Number and position of main-planes

Aircraft can have different numbers of wings:

- No wings at all.
    - **Lifting body** - relies on air flow over the fuselage to provide lift.
    - **Powered lift** - relies on downward thrust from the engines to stay airborne.

- **Monoplane** - one wing. Most aeroplanes have been monoplanes since before the Second World War. The wing may be mounted at various heights relative to the fuselage:
    - **Low wing** - mounted on the lower fuselage.
    - **Mid wing** - mounted approximately half way up the fuselage.
    - **High wing**- mounted on the upper fuselage.

        - **Shoulder wing** - a high wing mounted on the upper part of the main fuselage (as opposed to mounting on the cockpit fairing or similar).
    - **Parasol wing** - mounted on "cabane" struts above the fuselage.


Low wing

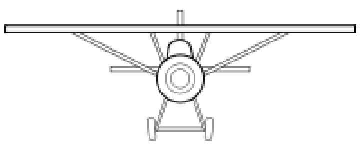

Mid wing

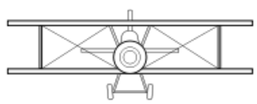

Shoulder wing

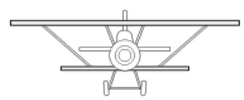

High wing

A fixed wing aircraft may have more than one wing plane, stacked one above another:

- **Biplane** - two planes of approximately equal size, stacked one above the other. The most common type until the 1930s, when the cantilever monoplane took over.
    - **Sesquiplane** - literally "one-and-a-half planes" is a variant on the biplane in which the lower wing is significantly smaller than the upper wing. **Inverted sesquiplanes** have smaller upper wings.


Parasol wing

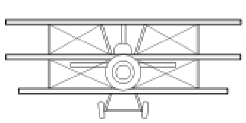

Biplane

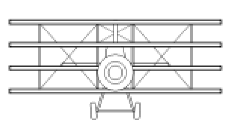

Sesquiplane

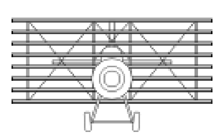
- **Triplane** - three planes stacked one above another. Triplanes such as the Fokker Dr.I enjoyed a brief period of popularity during the First World War due to their small size and high manoeuvrability as fighters, but were soon replaced by improved biplanes.

- **Quadruplane** - four planes stacked one above another. A small number of the Armstrong Whitworth F.K.10 were built in the First World War but it never saw operational military service.

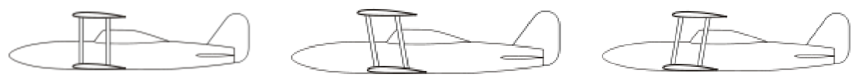
- **Multiplane** - many planes, sometimes used to mean more than one or more than some arbitrary number. The term is occasionally applied to arrangements stacked in tandem as well as vertically. No example with more than four wings has ever flown successfully: the nine-wing Caproni Ca.60 flying boat was only airborne briefly before crashing.


Triplane


Quadruplane


Multiplane

A **staggered** design has the upper wing slightly forward of the lower. This helps give stability to stacked wings, and is usual on successful designs. Backwards stagger is also seen in a few examples such as the de Havilland D.H. 5, Sopwith Dolphin, and Beechcraft Staggerwing.



Unstaggered biplane   Forwards stagger   Backwards stagger

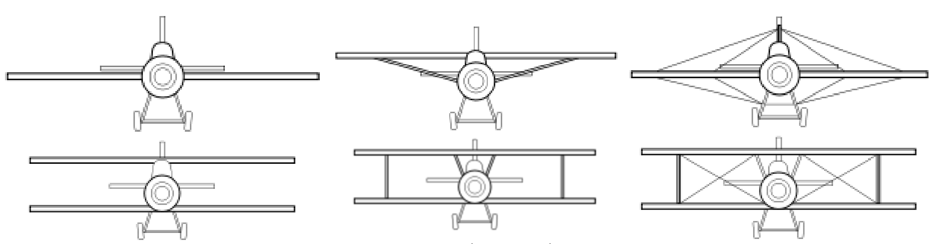
A **Tandem wing** design has two similar-sized wings, one behind the other. Some early types had tandem stacks of multiple planes.

Wing support

To support itself a wing has to be rigid and strong and consequently may be heavy. By adding external bracing, the weight can be greatly reduced. Originally such bracing was always present, but it causes a large amount of drag at higher speeds and has not been used for faster designs since the early 1930s.

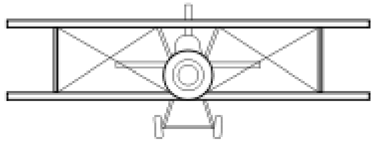
The types are:

- **Cantilevered** - self-supporting. All the structure is buried under the aerodynamic skin, giving a clean appearance with low drag.
- **Braced**: the wings are supported by external structural members. Nearly all multi-plane designs are braced. Some monoplanes, especially early designs such as the Fokker Eindecker, are also braced to save weight. Braced wings are of two types:
    - **Strut braced** - one or more stiff struts help to support the wing. A strut may act in compression or tension at different points in the flight regime.
    - **Wire braced** - alone, or in addition to struts, tension wires also help to support the wing. Unlike a strut, a wire can act only in tension.

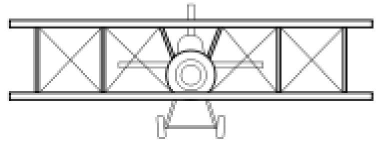


Cantilever   Strut braced   Wire braced

A braced multiplane may have one or more "bays", which are the compartments created by adding interplane struts; the number of bays refers to one side of the aircraft's wing panels only. For example, the de Havilland Tiger Moth is a single-bay biplane where the Bristol F.2 Fighter is a two-bay biplane.

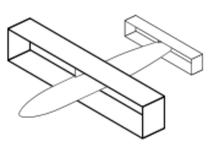


Single-bay biplane

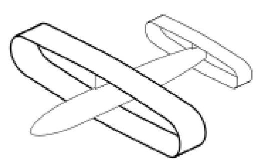


Two-bay biplane

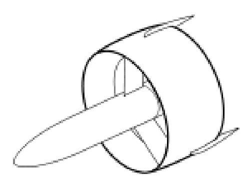
- **Combined** or **closed wing** - two wings are joined structurally at or near the tips in some way. This stiffens the structure, and can reduce aerodynamic losses at the tips. Variants include:
    - **Box wing** - upper and lower planes are joined by a vertical fin between their tips. Some Dunne biplanes were of this type. Tandem box wings have also been studied.
    - **Rhomboidal wing** - a tandem layout in which the front wing sweeps back and the rear wing sweeps forwards such that they join at or near the tips to form a continuous surface in a hollow diamond shape. The Edwards Rhomboidal biplane of 1909 failed to fly. The design has recently seen a revival of interest where it is referred to as a **joined wing**. The Small Diameter Bomb, a smart guided bomb, has a rhomboidal wing.
    - **Annular** or **ring wing** - may refer to various types:
        - **Flat** - the wing is shaped like a circular disc with a hole in it. A Lee-Richards type was one of the first stable aircraft to fly, shortly before the First World War.
        - **Cylindrical** - the wing is shaped like a cylinder. The Coléoptère took off and landed vertically, but never achieved transition to horizontal flight. Another plane with this design is the Heinkel Lerche, but it was never produced.
        - A type of box wing whose vertical fins curve continuously, blending smoothly into the wing tips. An early example was the Blériot III, which featured two annular wings in tandem.



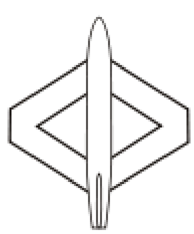
Box wing



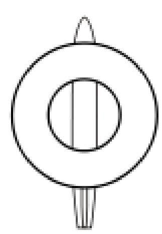
Annular box wing



Cylindrical wing



Rhomboidal wing



Flat annular wing

Wings can also be characterised as:

- **Rigid** - stiff enough to maintain the aerofoil profile in varying conditions of airflow.
- **Flexible** - usually a thin membrane. Requires external bracing or wind pressure to maintain the aerofoil shape. Common types include Rogallo wings and kites.

Wing planform

The wing planform is the silhouette of the wing when viewed from above or below.

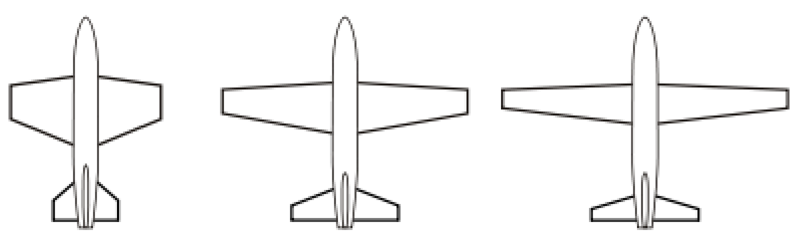
Aspect ratio

The aspect ratio is the span divided by the mean or average chord. It is a measure of how long and slender the wing appears when seen from above or below.

- **Low aspect ratio** - short and stubby wing. More efficient structurally, more maneuverable and with less drag at high speeds. They tend to be used by fighter aircraft, such as the Lockheed F-104 Starfighter, and by very high-speed aircraft (e.g. North American X-15).

- **Moderate aspect ratio** - general-purpose wing (e.g. the Lockheed P-80 Shooting Star).

- **High aspect ratio** - long and slender wing. More efficient aerodynamically, having less drag, at low speeds. They tend to be used by high-altitude subsonic aircraft (e.g. the Lockheed U-2), subsonic airliners (e.g. the Bombardier Dash 8) and by high-performance sailplanes (e.g. Glaser-Dirks DG-500).



Low aspect ratio Moderate aspect ratio High aspect ratio

Most Variable geometry configurations vary the aspect ratio in some way, either deliberately or as a side effect.

Wing sweep

Wings may be swept forwards or back for a variety of reasons. A small degree of sweep is sometimes used to adjust the centre of lift when the wing cannot be attached in the ideal position for some reason, such as a pilot's visibility from the cockpit. Other uses are described below.

- **Straight** - extends at right angles to the line of flight. The most efficient structurally, and common for low-speed designs, such as the P-80 Shooting Star.
- **Swept back** - (references to "swept" often assume swept back). From the root, the wing angles backwards towards the tip. In early tailless examples, such as the Dunne aircraft, this allowed the outer wing section to act as a conventional tail empennage to provide aerodynamic stability. At transonic speeds swept wings have lower drag, but can handle badly in or near a stall and require high stiffness to avoid aeroelasticity at high speeds. Common on high-subsonic and supersonic designs e.g. the English Electric Lightning.
- **Forward swept** - the wing angles forwards from the root. Benefits are similar to backwards sweep, also at significant angles of sweep it avoids the stall problems and has reduced tip losses allowing a smaller wing, but requires even greater stiffness and for this reason is not often used. A civil example is the HFB-320 Hansa Jet and in military Sukhoi Su-47.

Some types of **variable geometry** vary the wing sweep during flight:

- **Swing-wing** - also called "variable sweep wing". The left and right hand wings vary their sweep together, usually backwards. Seen in a few types of combat aircraft, the first being the General Dynamics F-111. Another is the Grumman F-14.
- **Oblique wing** - a single full-span wing pivots about its mid point, so that one side sweeps back and the other side sweeps forward. Flown on the NASA AD-1 research aircraft.

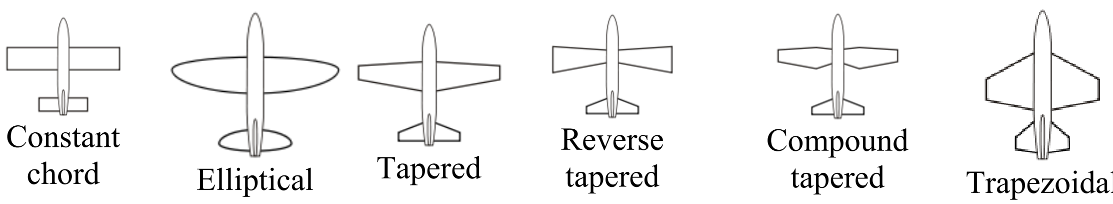
Planform variation along span

The wing chord may be varied along the span of the wing, for both structural and aerodynamic reasons.

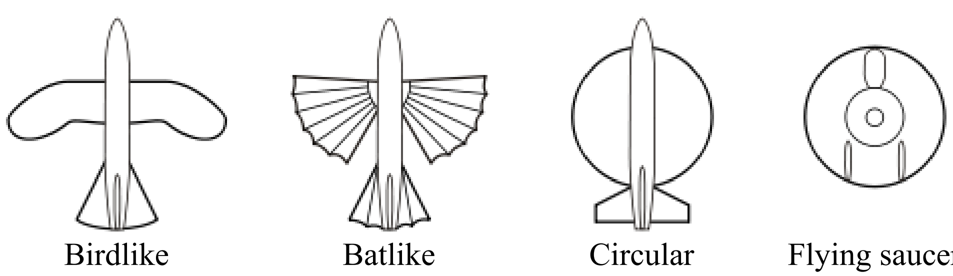
- **Constant chord** - leading and trailing edges are parallel. Simple to make, and common where low cost is important, e.g. in the Short Skyvan.
- **Elliptical** - wing edges are parallel at the root, and curve smoothly inwards to a rounded tip, with no division between the edges and the tip. Aerodynamically the most efficient, but difficult to make. Famously used on the Supermarine Spitfire.
- **Tapered** - wing narrows towards the tip, with straight edges. Structurally and aerodynamically more efficient than a constant chord wing, and easier to make

than the elliptical type. One of the most common types of all, as on the Hawker Sea Hawk.

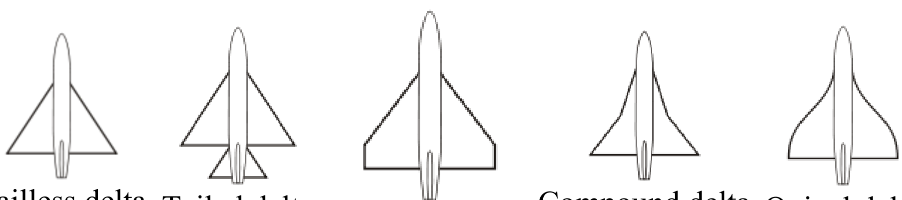
- **Reverse tapered** - wing widens towards the tip. Structurally very inefficient, leading to high weight. Flown experimentally on the XF-91 Thunderceptor in an attempt to overcome the stall problems of swept wings.
- **Compound tapered** - taper reverses towards the root, to increase visibility for the pilot. Typically needs to be braced to maintain stiffness. The Westland Lysander was an observation aircraft.
- **Trapezoidal** - a low aspect ratio tapered wing, having little or no sweep such that the leading edge sweeps back and the trailing edge sweeps forwards. Used for example on the Lockheed F-22 Raptor.



- **Bird like** - a curved shape appearing similar to a bird's outstretched wing. Popular during the pioneer years, and achieved some success on the Etrich Taube.
- **Bat like** - a form with radial ribs which was used for some early designs, especially if the wings were foldable. The Whitehead No. 21 of 1901 is sometimes claimed as the first powered aircraft to fly, over two years before the Wright Flyer.
- **Circular** - approximately circular planform. The Vought XF5U attempted to counteract the large tip vortices by using large propellers rotating in the opposite sense to the vortices.
    - **Flying saucer** - tailless circular flying wing. The Avrocar demonstrated the inherent instability of the design, while the Moller M200G uses computer control to achieve artificial stability in hover mode.
    - **Flat annular wing** - the circle has a hole in, forming a closed wing. A Lee-Richards type was one of the first stable aircraft to fly, shortly before the First World War.

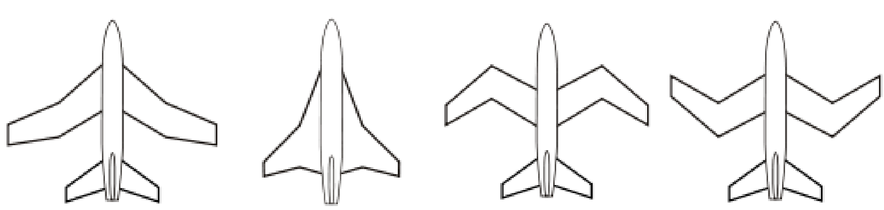


- **Delta** - triangular planform with swept leading edge and straight trailing edge. Offers the advantages of a swept wing, with good structural efficiency. Variants are:
  - **Tailless delta** - a classic high-speed design, used for example in the widely built Dassault Mirage III series.
  - **Tailed delta** - adds a conventional tailplane, to improve handling. Popular on Soviet types such as the Mikoyan-Gurevich MiG-21.
  - **Cropped delta** - tip is cut off. This helps avoid tip drag at high angles of attack. At the extreme, merges into the "tapered swept" configuration.
  - **Compound delta** or **double delta** - inner section has a (usually) steeper leading edge sweep e.g. Saab Draken. This improves the lift at high angles of attack and delays or prevents stalling. Seen in tailless form on the Tupolev Tu-144. The HAL Tejas has an inner section of reduced sweep.
  - **Ogival delta** - a smoothly blended "wineglass" double-curve encompassing the leading edges and tip of a cropped compound delta. Seen in tailless form on the Concorde supersonic transports.



The angle of sweep may also be varied, or cranked, along the span:

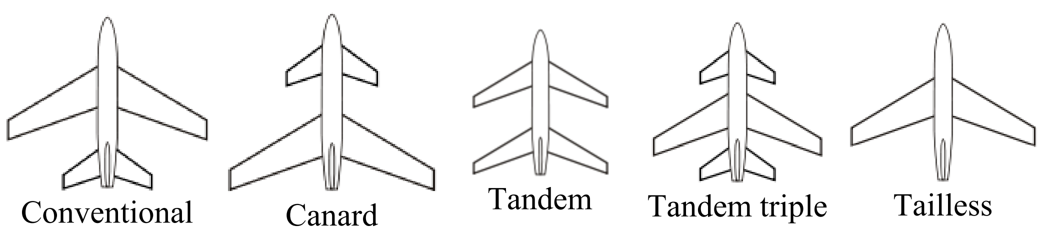
- **Crescent** - wing outer section is swept less sharply than the inner section. Used for the Handley Page Victor.
- **Cranked arrow** - similar to a compound delta, but with the trailing edge also kinked inwards. Trialled experimentally on the General Dynamics F-16XL.
- **M-wing** - the inner wing section sweeps forward, and the outer section sweeps backwards. The idea has been studied from time to time, but no example has ever been built.
- **W-wing** - the inner wing section sweeps back, and the outer section sweeps forwards. The reverse of the M-wing. The idea has been studied even less than the M-wing and no example has ever been built.



Horizontal stabilizer

The classic aerofoil section wing is unstable in pitch, and requires some form of horizontal stabilising surface. Also it cannot provide any significant pitch control, requiring a separate control surface (elevator) elsewhere. The elevator may be hinged to a fixed horizontal stabiliser, or the whole stabiliser may pivot to double as the elevator.

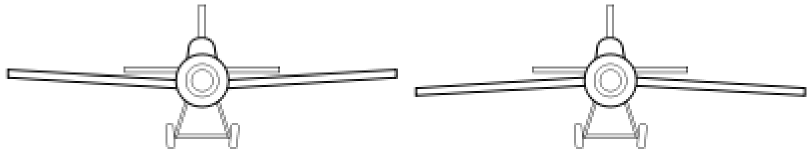
- **Conventional** - "tailplane" stabiliser at the rear of the aircraft, forming part of the tail or empennage.
- **Canard** - "foreplane" stabiliser at the front of the aircraft. Common in the pioneer years, but from the outbreak of World War I no production model appeared until the Saab Viggen.
- **Tandem** - two main wings, one behind the other. The two act together to provide stability and both provide lift. An example is the Rutan Quickie.
- **Tandem triple or triplet** - having both conventional and canard stabiliser surfaces. This may be for manoeuvrability, or the canard surfaces may be used for active vibration damping, to smooth out air turbulence giving the crew a more comfortable ride and reducing fatigue on the airframe. Popularly (but incorrectly) referred to as a **tandem triplane**.
- **Tailless** - no separate stabilising surface, at front or rear. Either the lifting and horizontal stabilising surfaces are combined in a single plane, or the aerofoil profile is modified to provide inherent stability. The Short SB.4 Sherpa used wingtips which could be rotated about the wing's major axis to act as either ailerons and/or elevators. Recently, aircraft having a tailplane but no vertical tail fin have also been described as "tailless".



Dihedral and anhedral

Angling the wings up or down spanwise from root to tip can help to resolve various design issues, such as stability and control in flight.

- **Dihedral** - the tips are higher than the root as on the Boeing 737, giving a shallow 'V' shape when seen from the front. Adds lateral stability.
- **Anhedral** - the tips are lower than the root, as on the Ilyushin Il-76; the opposite of dihedral. Used to reduce stability where some other feature results in too much stability thus making manoeuvering difficult. A popular choice in modern fighters since the configuration makes them more agile in battle. In level flight, computers assist the pilot in preventing the plane from teetering about.



Dihedral Anhedral

Some biplanes had different angles of dihedral/anhedral on different wings; e.g. the first Short Sporting Type, known as the *Shrimp*, had a flat upper wing and a slight dihedral on the lower wing.

The dihedral angle may vary along the span.

- **Gull wing** - sharp dihedral on the wing root section, little or none on the main section, as on the Göppingen Gö 3 glider. Typically done to raise wing-mounted engines higher above the ground or water.
- **Inverted gull** - anhedral on the root section, dihedral on the main section. The opposite of a gull wing. Typically done to reduce the length and weight of wing-mounted undercarriage legs. Two well-known examples of the inverted gull wing are World War II's American F4U Corsair, and the German Junkers Ju 87 *Stuka* dive bomber.
- **Cranked** - tip section dihedral differs from the main section. The wingtips may crank upwards as on the F-4 Phantom II or downwards as on the Dunne monoplane and Northrop XP-56 Black Bullet. (Note that the term "cranked" varies in usage . Here, it is used to help clarify the relationship between changes of dihedral nearer the wing tip vs. nearer the wing root.
- The **channel wing** is an unusual variation where the frontal profile follows the arc of a propeller down, around and back up, before continuing outwards in a conventional manner. Since 1942 several examples have flown, notably the Custer Channel Wing aircraft, but none has entered production.

Gull wing Inverted gull wing Cranked wing Channel wing

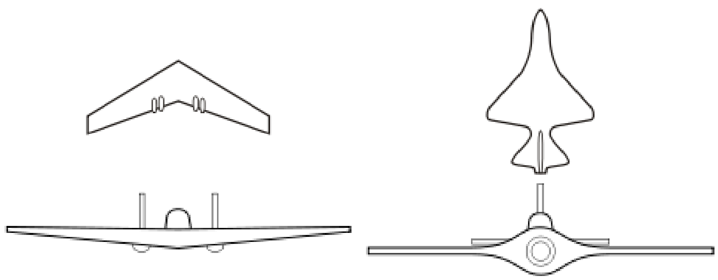
Wings vs. bodies

Some designs have no clear join between wing and fuselage, or body. This may be because one or other of these is missing, or because they merge into each other:

- **Flying wing** - the aircraft has no distinct fuselage or tail empennage (although fins and small pods, blisters, etc. may be present)one great example is the B-2 Spirit.
- **Blended body** or **blended wing-body** - smooth transition between wing and fuselage, with no hard dividing line. Reduces wetted area and hence, if done

correctly, aerodynamic drag. The McDonnell XP-67 Bat was also designed to maintain the aerofoil section across the entire aircraft profile.

- **Lifting body** - the aircraft has no significant wings, and relies on the fuselage to provide aerodynamic lift i.e. X-24.



Flying wing Blended body Lifting body

Some proposed designs, typically a sharply-swept delta planform having a deep centre section tapering to a thin outer section, fall across these categories and may be interpreted in different ways, for example as a lifting body with a broad fuselage, or as a low-aspect-ratio flying wing with a deep center chord.

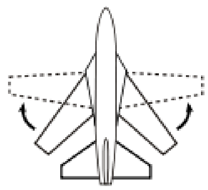
Variable geometry

A **variable geometry** aircraft is able to change its physical configuration during flight.

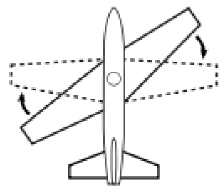
Some types of variable geometry craft transition between fixed wing and rotary wing configurations.

Variable planform

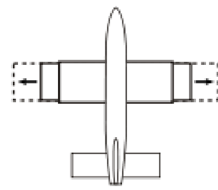
- **Swing-wing** or **variable sweep wing**. The left and right hand wings vary their sweep together, usually backwards. The first successful wing sweep in flight was carried out by the Bell X-5 in the early 1950s.
- **Oblique wing** - a single full-span wing pivots about its mid point, as used on the NASA AD-1, so that one side sweeps back and the other side sweeps forward.
- **Telescoping wing** - the outer section of wing telescopes over or within the inner section of wing, varying span, aspect ratio and wing area, as used on the FS-29 TF glider. The Makhonine Mak-123 was an early example.
- **Extending wing** - or *expanding wing* part of the wing retracts into the main aircraft structure to reduce drag and low-altitude buffet for high-speed flight, and is extended only for takeoff, low-speed cruise and landing. The Gérin Varivol biplane, which flew in 1936, extended the leading and trailing edges to increase wing area.



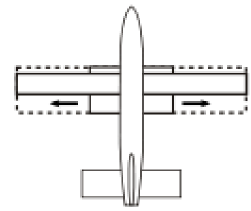
Variable sweep (swing-wing)



Oblique wing

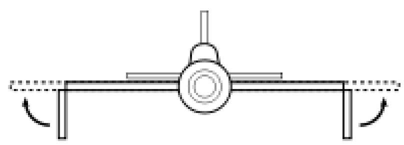


Telescoping wing



Extending wing

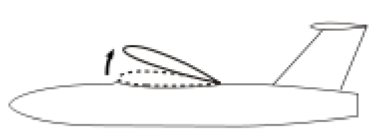
- **Folding wing** - part of the wing extends for takeoff and landing, and folds away for high-speed flight. The outer sections of the XB-70 Valkyrie wing folded down, to increase lift and reduce drag through generation of 'compression lift' during supersonic flight. (Many aircraft have wings that may be folded for storage on the ground or on board ship. These are not folding wings in the sense used here).



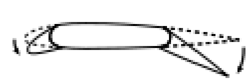
Folding wing

Variable chord

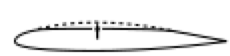
- **Variable incidence** - the wing plane can tilt upwards or downwards relative to the fuselage. Used on the Vought F-8 Crusader to tilt the leading edge up by a small amount for takeoff, to give STOL performance. If powered proprotors are fitted to the wing to allow vertical takeoff or STOVL performance, merges into the powered lift category.
- **Variable camber** - the leading and trailing edge sections of the wing pivot and/or extend to increase the effective camber and/or area of the wing. This increases lift at low angles of attack, delays stalling at high angles of attack, and enhances manoeuverability.
    - **Variable wing thickness** - the upper wing centre section can be raised to increase wing thickness and camber for landing and take-off, and lowered for high speed flight. Charles Rocheville modified one or more aircraft in the course of his researches.



Variable incidence wing



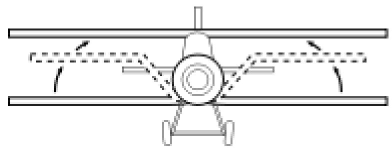
Variable camber aerofoil



Variable thickness aerofoil

Polymorphism

A **polymorphic** wing is able to change the number of planes in flight. The Nikitin-Shevchenko IS "folding fighter" protoypes were able to morph between biplane and monoplane configurations after takeoff by folding the lower wing into a cavity in the upper wing.



Polymorphic wing

Minor aerodynamic surfaces

Additional minor aerodynamic surfaces may form part of the overall wing configuration:

- **Winglet** - a small vertical fin at the wingtip, usually turned upwards. Reduces the size of vortices shed by the wingtip, and hence also tip drag.
- **Chine** - narrow extension to the leading edge wing root, extending far along the forward fuselage. As well as improving low speed (high angle of attack) handling, provides extra lift at supersonic speeds for minimal increase in drag. Seen on the Lockheed SR-71 Blackbird.
- **Moustache** - small high-aspect-ratio canard surface having no movable control surface. Typically is retractable for high speed flight. Deflects air downward onto the wing root, to delay the stall. Seen on the Dassault Milan and Tupolev Tu-144.

Minor surface features

Additional minor features may be applied to an existing aerodynamic surface such as the main wing:

- **Leading edge extensions** of various kinds.
- **Slot** - a spanwise gap behind the leading edge section, which forms a small aerofoil or *slat* extending along the leading edge of the wing. Air flowing through the slot is deflected by the slat to flow over the wing, allowing the aircraft to fly at lower air speeds. Leading edge slats are moveable extensions which open and close the slot.
- **Flap** - trailing-edge (or leading-edge) wing section which may be angled downwards for low-speed flight, especially when landing. Some types also extend backwards to increase wing area.
- **Wing fence** - a thin surface extending along the wing chord and for a short distance vertically. Used to control spanwise airflow over the wing.

- **Vortex generator** - small triangular protrusion on the upper leading wing surface; usually, several are spaced along the span of the wing. The vortices are used to re-energise the boundary layer and reduce drag.
- **Anti-shock body** - a streamlined "pod" shaped body added to the leading or trailing edge of an aerodynamic surface, to delay the onset of shock stall and reduce transonic wave drag. Examples include the *Küchemann carrots* on the wing trailing edge of the Handley Page Victor B.2, and the tail fairing on the Hawker Sea Hawk.
- **Fairings** of various kinds, such as blisters, pylons and wingtip pods, containing equipment which cannot fit inside the wing, and whose only aerodynamic purpose is to reduce the drag created by the equipment.

Chapter 15

Lifting Body

A **lifting body** is an aircraft configuration in which the body itself produces lift. In contrast to a flying wing, which is a wing without a conventional fuselage, a lifting body is a fuselage that generates lift without the shape of a typical thin and flat wing structure. Whereas a flying wing seeks to maximize cruise efficiency at subsonic speeds by eliminating non-lifting surfaces, lifting bodies generally minimize the drag and structure of a wing for subsonic, supersonic, and hypersonic flight, or, spacecraft re-entry. All of these flight regimes pose challenges for proper flight stability.

The Martin Aircraft Company X-24 built as part of a 1963 to 1975 experimental US military program

X-24A, M2-F3 and HL-10 lifting bodies

History

In 1921 pioneering aviator and aircraft designer Vincent Justus Burnelli patented the simple concept of an airfoil shaped airframe to increase the lift and load capacity of aircraft. Despite a number of business and political setbacks, Burnelli continued to refine and license his designs making a number of refinements to the concept up until his death in 1964.

Aerospace-related lifting body research arose from the idea of spacecraft re-entering the Earth's atmosphere and landing much like a regular aircraft. Following atmospheric re-entry, the traditional capsule-like spacecraft from the Mercury, Gemini and Apollo series had very little control over where they landed. A steerable spacecraft with wings could significantly extend its landing envelope. However, the vehicle's wings would have to be designed to withstand the dynamic and thermal stresses of both re-entry and hypersonic flight. A proposed solution eliminated wings altogether: Design the fuselage body itself to produce lift.

NASA's refinements of the lifting body concept began in 1962 with Dale Reed of NASA's Dryden Flight Research Center. The first full-size model to come out of Reed's program was the NASA M2-F1, an unpowered craft made of wood. Initial tests were performed by towing the **M2-F1** along a California dry lakebed at present-day Edwards Air Force Base, behind a modified Pontiac Catalina . Later the craft was towed behind a C-47 and released. Since the M2-F1 was a glider, a small rocket motor was added in order to extend the landing envelope. The M2-F1 was soon nicknamed the "Flying Bathtub".

In 1963, NASA began programs with heavier rocket powered lifting body vehicles to be air launched from under the starboard wing of a NB-52B, a derivative of the B-52 jet bomber. The first flights started in 1966. Of the Dryden lifting bodies, all but the unpowered NASA M2-F1 used an XLR-11 rocket engine as was used on the famous Bell X-1. A follow-on design designated the Northrop HL-10 was developed at NASA Langley Research Center. The X-24A and X-24B lifting body designs were based on the M2 concept originated in 1957 by Alfred Eggers of NASA Ames Aeronautical Laboratory.

The HL-10 attempted to solve part of this problem by angling the port and starboard vertical stabilizers outward and enlarging the center one. Air flow separation caused the crash of the Northrop M2-F2 lifting body. The successor Northrop M2-F3 added a third (central) vertical stabilizer to the aerodynamically flawed **M2-F2** design in an attempt to correct the flow separation instabilities.

The X-38 program, developed under leadership of NASA Johnson Space Center, built an incremental series of flight demonstrators pursuant to the proposed Crew Return Vehicle (CRV) for the International Space Station. The X-38 was a lifting body based on the outer mold line of the X-24.

Starting 1965 the russian lifting-body Mikoyan-Gurevich MiG-105 or EPOS (Russian acronym for Experimental Passenger Orbital Aircraft) was developed and several test flights made. Works ended in 1978 when the efforts shifted to the Buran program, while work on another small-scale spacecraft partly continued in the Bor program.

Aerospace applications

Lifting bodies pose complex control, structural, and internal configuration issues. Lifting bodies were eventually rejected in favor of a delta wing design for the Space Shuttle. Data acquired in flight test using high-speed landing approaches at very steep descent angles and high sink rates was used for modeling Shuttle flight and landing profiles.

In planning for atmospheric re-entry, the landing site is selected in advance. For reusable reentry vehicles, typically a primary site is preferred that is closest to the launch site in order to reduce costs and improve launch turnaround time. However, weather near the landing site is a major factor in flight safety. In some seasons, weather at landing sites can change quickly relative to the time necessary to initiate and execute re-entry and safe landing. Due to weather, it is possible the vehicle may have to execute a landing at an alternate site. Furthermore, most airports do not have runways of sufficient length to support the approach landing speed and roll distance required by spacecraft. Few airports exist in the world that can support or be modified to support this type of requirement. Therefore, alternate landing sites are very widely spaced across the U.S. and around the world.

The Shuttle's delta wing design was driven by these issues. These requirements were further exacerbated by military requirements (the USAF would use the future shuttle for defense satellite payloads and other missions) that extended the Shuttle's flight landing envelope.

Although a lifting body configuration would not have been vulnerable to the wing leading edge failure that caused the second shuttle loss, such a configuration could not meet the flight envelope requirements of both NASA and the military.

Nonetheless, the lifting body concept has been implemented in a number of other aerospace programs, the previously mentioned NASA X-38, Lockheed Martin X-33, BAC's Multi Unit Space Transport And Recovery Device, Europe's EADS Phoenix and the joint Russian-European Kliper spacecraft. Of the three basic design shapes usually analyzed for such programs (capsule, lifting body, aircraft) the lifting body may offer the best trade-off in terms of maneuverability and thermodynamics while meeting its customers' mission requirements.

Body lift

Some aircraft with wings also employ bodies that generate lift. The Short SC.7 Skyvan produces 30% of the total lift from the fuselage, almost as much as the 35% each of the wings produces. Fighters like the F-15 Eagle also produce substantial lift from the wide fuselage between the wings. Because the F-15 Eagle's wide fuselage is so efficient at lift, an F-15 was able to land successfully with only one wing.

On the summer of 1983, an Israeli F-15 staged a mock dogfight with Skyhawks for training purposes, near Nahal Tzin in the Negev desert. During the exercise, one of the Skyhawks miscalculated and collided forcefully with the F-15's wing root. The F-15's pilot was aware that the wing had been seriously damaged, but decided to try and land in a nearby airbase, not knowing the extent of his wing damage. It was only after he had landed, when he climbed out of the cockpit and looked backward, that the pilot realized what had happened: the wing had been completely torn off the plane, and he had landed the plane with only one wing attached. A few months later, the damaged F-15 had been given a new wing, and returned to operational duty in the squadron. The engineers at McDonnell Douglas had a hard time believing the story of the one-winged landing: as far as their planning models were concerned, this was an impossibility.

List of Dryden Flight Research Center lifting body vehicles (1963 to 1975)

- M2-F1
- M2-F2
- M2-F3
- HL-10
- X-24A
- X-24B

Lifting body pilots and flights

Pilot	M2-F1	M2-F2	HL-10	HL-10 mod	M2-F3	X-24A	X-24B	Total
Milton O. Thompson	45	5	-	-	-	-	-	50
Bruce Peterson	17	3	1	-	-	-	-	21
Chuck Yeager	5	-	-	-	-	-	-	5
Donald L. Mallick	2	-	-	-	-	-	-	2
James W. Wood	*	-	-	-	-	-	-	*
Donald M. Sorlie	5	3	-	-	-	-	-	8
William H. Dana	1	-	-	9	19	-	2	31
Jerauld R. Gentry	2	5	-	9	1	13	-	30
Fred Haise	*	-	-	-	-	-	-	*
Joe Engle	*	-	-	-	-	-	-	*
John A. Manke	-	-	-	10	4	12	16	42
Peter C. Hoag	-	-	-	8	-	-	-	8
Cecil W. Powell	-	-	-	-	3	3	-	6
Michael V. Love	-	-	-	-	-	-	12	12
Einar K. Enevoldson	-	-	-	-	-	-	2	2
Francis Scobee	-	-	-	-	-	-	2	2
Thomas C. McMurtry	-	-	-	-	-	-	2	2
TOTAL	77	16	1	36	27	28	36	221

* **Wood**, **Haise** and **Engle** each made a single, car-towed, ground flight of the M2-F1.

Chapter 16

Powered Lift

AV-8B Harrier II

V-22 Osprey

Powered lift or **powered-lift** refers to a type of aircraft that can take off and land vertically and functions differently from a rotorcraft in horizontal flight.

The term is particularly used by the United States Federal Aviation Administration for classification purposes. Powered-lift is one of the seven categories of aircraft designated by the Federal Aviation Administration; the other six being Airplane, Rotorcraft, Glider, Lighter-Than-Air, Powered parachute, and Weight-shift-control.

Powered-lift means a heavier-than-air aircraft capable of vertical takeoff, vertical landing, and low speed flight that depends principally on engine-driven lift devices or engine thrust for lift during these flight regimes and on nonrotating airfoil(s) for lift during horizontal flight.
—FAA

The first powered-lift ratings to be issued by the FAA on a civilian pilot certificate were on 21 August 1997, to pilots of Bell Helicopter and Boeing, and of the United States Marine Corps.

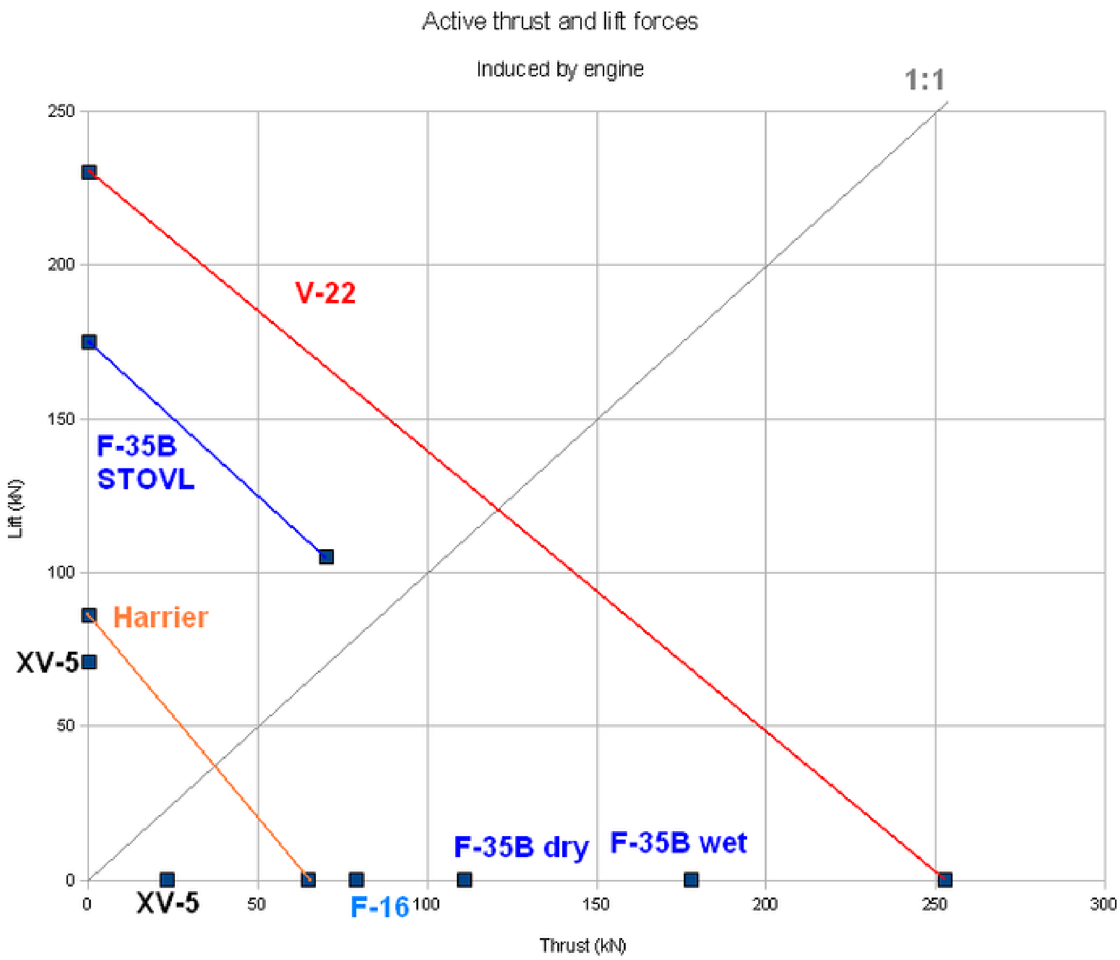
Compound rotorcraft

A **compound rotorcraft** has both a lifting rotor and fixed wings (although in the USA, the term "compound rotorcraft" officially refers to a mixed powerplant system). Some types have a **ducted rotor** design, in which the rotor is surrounded by a large ring-shaped duct to reduce tip losses. The Ryan XV-5 Vertifan had non-tilt rotors in the wings.

Typically, the rotor swings forward to act as a propeller in forward flight. The difference between a ducted rotor and a ducted fan design is that when the rotor is stationary you can see through the rotor disc.

Tiltrotor

A USAF CV-22 in flight



Powered lift and thrust forces of various aircraft

The powered rotors of a tiltrotor (sometimes called *proprotor*) are mounted on rotating shafts or nacelles at the end of a fixed wing, and used for both lift and propulsion. For vertical flight, the rotors are angled to provide thrust upwards, lifting the way a helicopter rotor does. As the aircraft gains speed, the rotors progressively rotate or *tilt* forward, with the rotors eventually becoming perpendicular to the fuselage of the aircraft, similar to a propeller. In this mode, the wing provides the lift and the rotor provides thrust. The wing's greater efficiency helps the tiltrotor achieve higher speeds than helicopters.

The V-22 Osprey by Bell Helicopter/Boeing, a twin-engine tiltrotor design that has two turbine-powered engines driving three-bladed rotors. The rotors function similar to a helicopter in vertical flight, and similar to an airplane in forward flight. The aircraft first flew on 19 March 1989.

The Bell/Agusta BA609 tiltrotor is the evolution of Bell Helicopter's V-22 Osprey into a civilian aircraft. The aircraft can take off and land vertically with 2 crew and 9 passengers, and within 20 seconds, transition to forward flight (by tilting its rotor blades into a fully forward position, much like the V-22 Osprey). In forward flight it can cruise at speeds of up to 275 knots (509 km/h), with a range exceeding 1,000 nautical miles (with long-range fuel tanks). It is rated to fly above FL210 (21,000 ft), has a maximum payload capacity of over 5,500 pounds, thanks to two Pratt and Whitney PT6C-67A turbines rated at 1,940 shp, each driving a 26-foot (8 m) diameter 3-bladed rotor blade. The aircraft is not yet in full production; however, over 80 orders have been taken.

Tiltwing

The Vertol VZ-2 was a research aircraft developed in the late 1950s. Unlike other tiltwing aircraft, Vertol designed the VZ-2 using rotors in place of propellers. On 23 July 1958, the aircraft made its first full transition from vertical flight to horizontal flight. By the time the aircraft was retired in 1965, the VZ-2 had accomplished 450 flights, including 34 full transitions.

Helicopter-airship compounds

Piasecki Helicopter developed the Piasecki PA-97 Helistat using the rotor systems from four obsolete helicopters and a surplus Navy blimp, in order to provide a capability to lift heavier loads than a single helicopter could provide. The aircraft suffered a fatal accident during a test flight. In 2008, Boeing and SkyHook International resurrected the concept and announced a proposed design of the SkyHook JHL-40.

Other rotorcraft hybrids

Some aircraft take off vertically as a rotorcraft. The rotor then transitions to an alternative lifting mode for horizontal flight.

Triebflugel

The Focke-Wulf Fw Triebflügel was a design by Nazi Germany to utilize pulsejets to power a rotor that rotated about the fuselage axis behind the cockpit. Similar to a coleopter aircraft, the Triebflügel took off and landed on its tail and then rotated forward on the pitch axis after takeoff and acceleration for forward flight. The design was never been built beyond model wind tunnel testing, due to Allied bombing of the development facilities.

X-wing

The Sikorsky X-Wing had a rotor utilizing compressed air to control lift over the surfaces while operating as a helicopter. At higher forward speeds, the rotor would be stopped to continue providing lift as tandem wings in an *X* configuration. The program was canceled before the aircraft had attempted any flights with the rotor system.

Jet lift

Tail-sitters

The SNECMA Coléoptère featured an annular wing. The whole aircraft points vertically for takeoff and, in theory, then tilts horizontally for forward flight. The transition to forward flight has never been achieved.

Vectored thrust

The Harrier Jump Jet covers a series of a military VSTOL jet aircraft. It is capable of vertical/short takeoff and landing (V/STOL) and is the only truly successful design of this type from the many that arose in the 1960s. These aircraft are capable of operating from small spaces,such as fields, roads, and aviation-capable ships. The F-35 Lightning II version B is proposed as the next military VSTOL in order to replace the Harrier.

Examples

- AV-8B Harrier
- BAE Harrier II
- BAE Sea Harrier
- Hawker Siddeley Harrier
- V-22 Osprey
- Canadair CL-84
- F-35B Lightning II
- Sikorsky S-72
- Vertol VZ-2
- Bell XV-3
- LTV XC-142
- Bell XV-15
- Bell/Agusta BA609
- Bell Eagle Eye

Chapter 17

Monoplane and Parasol Wing

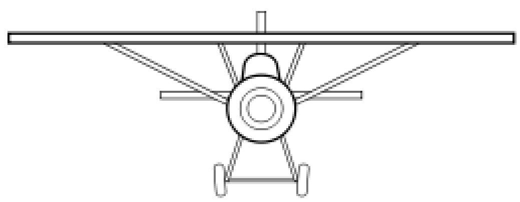
Monoplane

The low-wing of a Curtiss P-40

The mid-wing of a de Havilland Vampire T11

The high-wing of a de Havilland Canada Dash 8

A parasol wing Pietenpol Air Camper amateur-built aircraft



Schematic head-on illustration of a parasol wing

A **monoplane** is an aircraft with one main set of wing surfaces, in contrast to a biplane or triplane. Since the late 1930s it has been the most common form for a fixed wing aircraft.

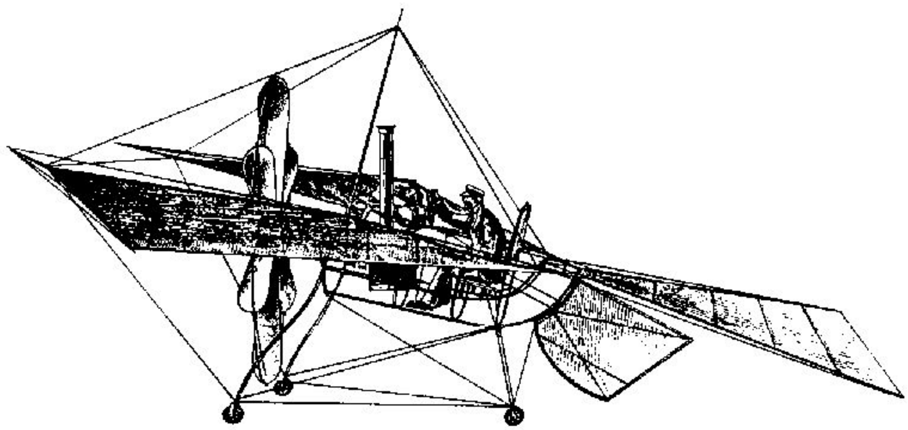
Types of monoplane

The main distinction between types of monoplane is where the wings attach to the fuselage:

- **low-wing**, the wing lower surface is level with (or below) the bottom of the fuselage
- **mid-wing**, the wing is mounted mid-way up the fuselage
- **shoulder-wing**, the wing is mounted above the fuselage middle
- **high-wing**, the wing upper surface is level with or above the top of the fuselage

- **parasol-wing**, the wing is located above the fuselage and is not directly connected to it, structural support being typically provided by a system of struts, and, especially in the case of older aircraft, wire bracing.

History



Félix du Temple's 1874 *Monoplane*

Probably the first monoplane was the *Monoplane* built in 1874 by Felix du Temple de la Croix, a large plane made of aluminium in Brest, France, with a wingspan of 13 meters and a weight of only 80 kilograms (without the pilot). Several trials were made with the plane, and it is generally recognized that it achieved lift off under its own power after a ski-jump run, glided for a short time and returned safely to the ground, possibly making it the first successful powered flight in history, depending on the definition — since the flight was only a short distance and a short time, and was not truly under control.

An early design of monoplane was developed by Russian inventor Alexander Mozhaysky who made his first attempt at flight in 1884. His design included such key elements of modern aircraft as fuselage, wing, propulsion, empenage and chassis.

Richard Pearse of New Zealand had built a monoplane in which he made attempts at controlled powered flight in March 1903, although the lack of outside knowledge of his achievements meant that his design had almost no influence in the development of the aeroplane.

Another early monoplane was constructed by Romanian inventor Traian Vuia, who made a flight of 12 m (40 ft) on March 18, 1906.

The first successful aircraft were biplanes, but many important pioneering aircraft were monoplanes, for instance Louis Blériot flew across the English Channel in 1909 in a mid-wing monoplane of his own design. Throughout 1909-1910 Hubert Latham set multiple altitude records in his Antoinette IV monoplane, initially achieving 155 m (509 ft) then raising it to 1,384 m (4,541 ft). The Fokker Eindecker of 1915 was a successful fighter aircraft. The Junkers J 1 was an early German "technology demonstrator" monoplane, and the world's very first practical all-metal aircraft of any type to fly, with the J 1's first flight occurring in December 1915.

Nonetheless, relatively few monoplane types were built between 1914, and the late 1920s, compared with the number of biplanes. The reasons for this were primarily structural. In the days when wings (whether biplane or monoplane) were thin, lightly built structures, braced by struts, steel wire or cables - the biplane wing formed a strong and fairly rigid box girder structure, in which the two wing surfaces were braced against each other. Early monoplane wings on the other hand tended to be liable to twist under aerodynamic loads, rendering proper lateral control very difficult. They were also much more liable to breakage in flight.

Once all-metal construction and the cantilever wing, both having been pioneered by Hugo Junkers in 1915 became common after World War I's end, however, the day of the biplane very quickly passed, and the monoplane became the usual configuration for a fixed wing aircraft. Most military aircraft of WW2 were monoplanes, as have been virtually all piston and jet powered aircraft since.

Parasol wing

An amateur-built Pietenpol Air Camper featuring a parasol wing

A **parasol wing** monoplane is an aircraft design in which the wing is not mounted directly to the fuselage, but rather, the fuselage is supported beneath it by a set of struts, called cabane struts. Parasol wing designs resemble biplanes lacking their lower set of wings.

This configuration has the advantage of providing excellent visibility from the cockpit, but the disadvantage of extra drag caused by the struts. A typical feature of light aircraft designed in the 1920s, such as the Pietenpol Air Camper and Heath Parasol, it is no longer a common configuration, but is still used in modern nostalgic designs for homebuilt aircraft such as the Loehle Sport Parasol. Other parasol aircraft from the 1920s include the Davis Monoplane and the Lockheed Air Express.

In some aircraft, particularly flying boats, the parasol wing is held above the fuselage by means of a closed structure known as a pylon. This gives these aircraft a cleaner appearance, especially when combined with a cantilever wing, as there are no visible struts. The pylon reacts to any wing rolling moment with its own set of spars extending from the fuselage frames. A typical example of a pylon parasol aircraft with struts is the Consolidated Catalina.

Chapter 18

Biplane

Reproduction of a Sopwith Camel biplane flown by Lt. George A. Vaughn Jr., 17th Aero Squadron

Boeing Stearman E75 (PT-13D) biplane of 1944

A modern light "kitplane" version of an S.E.5a Biplane

Nieuport 17 is an example of a sesquiplane

The Rutan Quickie tandem wing is *not* a biplane in the classic sense

Biplane hang glider under tow. Philadelphia, USA, 1920s.

The Handley Page H.P.42, a large biplane airliner of the 1930s.

Antonov An-2 is the largest single-engine biplane ever made, and the longest produced aircraft ever (since 1947; currently produced in China) along with Beechcraft Bonanza

A **biplane** is a fixed-wing aircraft with two main wings. The Wright brothers' Wright Flyer used a biplane design, as did most aircraft in the early years of aviation. While a biplane wing structure has a structural advantage, it produces more drag than a similar monoplane wing. Improved structural techniques and materials and the need for greater speed made the biplane configuration obsolete for most purposes by the late 1930s.

The term is also occasionally used in biology, to describe the wings of some flying animals.

Aviation

Overview

In a biplane aircraft, two wings are placed one above the other. Both provide a portion of the lift, although they are not able to produce twice as much lift as a single wing of similar size and shape because the upper and the lower are working on nearly the same portion of the atmosphere. For example, in a wing of aspect ratio 6, and a wing separation distance of one chord length, the biplane configuration can produce about 20 percent more lift than a single wing of the same planform.

In the biplane configuration, the lower wing is often attached to the fuselage, while the upper wing is raised above the fuselage with an arrangement of cabane struts, although other combinations have been used. Almost all biplanes also have a third horizontal surface, the tailplane, to control the pitch, or angle of attack of the aircraft (although there have been a few exceptions). Either or both of the main wings can support flaps or ailerons to assist lateral rotation and speed control; usually the ailerons are mounted on the upper wing, and flaps (if used) on the lower wing. Often there is bracing between the upper and lower wings, in the form of wires (tension members) and slender interplane struts (compression members) positioned symmetrically on either side of the fuselage.

Variations on the biplane include the **sesquiplane**, where one wing (usually the lower) is significantly smaller than the other, either in span, chord, or both. Sometimes the lower wing is only large enough to support the bracing struts for the upper wing. The name means "one-and-a-half wings." This significantly reduces interference drag while retaining the structural advantages of a biplane.

Easily the best known examples of a sesquiplane are an entire series of Nieuport single and two-seat military aircraft of World War I, from the Nieuport 10 of 1915 through to the Nieuport 27 of 1917, though it was a common layout throughout the 1920s and 30s, until superseded by structural improvements that made monoplanes more efficient.

Biplanes should not be confused with **tandem wing**, which is an aircraft with one wing in front of the other (e.g. a wing in the nose and a wing in the tail). This is not usually considered a biplane, as the two wings are not one above the other. Aerodynamic research by NASA found that it was necessary for the two wings to be different in either chord or span otherwise longitudinal oscillation would occur. Unlike the sesquiplane layout, the tandem wing has not found much favor, in particular as it still suffers from higher tip vortex drag than an equivalent monoplane.

Advantages and disadvantages

Aircraft built with two main wings (or three in a triplane) can usually lift up to 20 percent more than can a similarly sized monoplane of similar wingspan. Biplanes will therefore typically have a shorter wingspan than a similar monoplane, which tends to afford greater maneuverability. The struts and wire bracing of a typical biplane form a box girder that permits a light but very strong wing structure.

On the other hand there are many disadvantages to the configuration. Each wing negatively interferes with the aerodynamics of the other. For a given wing area the biplane produces more drag and less lift than a monoplane.

Stagger

Many biplanes were designed with the wings positioned directly "one-above-the-other," as was first done with the Wright's 1903 *Flyer I*. However, moving one wing forward relative to the other can help increase lift and reduce drag, though it distorts the box girder effect of the wing and reduces the structural benefits of the biplane layout. Many biplanes have been designed with the upper wing positioned with its leading edge ahead of the that of the lower wing, in a "positive stagger" format. Less common have been biplanes with the lower wing's leading edge ahead of the upper wing, called "negative stagger". Examples include the Airco DH.5, Sopwith Dolphin, and the Beechcraft Staggerwing.

Forward stagger was more common because it improves both downward visibility and ease of cockpit access for open cockpit biplanes.

In ultralight aircraft

Larry Mauro created the *Easy Riser* biplane ultralight. Mauro also made a version powered with solar cells driving an electric motor for successful flight that was called the Solar Riser. Mauro's *Easy Riser* was used by the man who became known as "Father Goose," Bill Lishman. Other biplane ultralights are the Belgian-designed Aviasud Mistral, the German FK12 Comet, and the Lite Flyer Biplane.

History

Early designers considered both monoplane and biplane designs. However, the weakness of the materials and design techniques available required these designers to place great effort into making wings capable of withstanding the required loads. A biplane (having the characteristics of a box girder) can be made lighter for a given strength requirement, and was therefore a more common choice.

Most successful early aircraft were biplanes, in spite of considerable early experimentation with monoplanes, triplanes and even a quadraplanes. During the period (~1914 to 1925) almost all aircraft were biplanes.

Early monoplanes and biplanes were often externally braced, having struts and/or bracing wires. These elements gave added strength without excess weight, but they did add unwanted aerodynamic drag.

The long-term answer to the problem was a cantilever monoplane wing – having sufficient stiffness to dispense with external bracing. Such wings were already being developed by several designers, including Hugo Junkers, as his work during 1915 resulted in the pioneering Junkers J 1, the world's first practical all-metal aircraft of any type. Cantilever monoplane wings were becoming the norm for most applications by the early nineteen thirties; the era of the biplane was almost over. Several air forces continued to use biplanes for primary training up till WWII and even beyond: the de Havilland Tiger Moth in the Royal Air Force, Stampe SV.4 in French and Belgian Air Forces, and the Boeing Stearman in the USAF.

Modern biplane designs now exist only in specialist niche roles and markets such as aerobatics and agricultural aircraft.

The vast majority of biplane designs have been fitted with reciprocating engines of comparatively low power; exceptions include the Antonov An-3 and WSK-Mielec M-15 Belphegor, fitted with turboprop and turbofan engines, respectively. Some older biplane designs, such as the Grumman Ag Cat and the aforementioned An-2 (in the form of the An-3) are available in upgraded versions with turboprop engines.

Famous biplanes include the Sopwith Camel, Antonov An-2, Beechcraft Staggerwing, Boeing Stearman, Bristol Bulldog, Curtiss JN-4, de Havilland Tiger Moth, Fairey Swordfish, Pitts Special and the Wright Flyer. The Stearman is particularly associated with stunt flying with wing-walkers. Famous sesquiplanes include the Nieuport 17 and Albatros D.III.

A few biplanes are still made today, typically for nostalgia or aerobatics. Examples include the Pitts Special and the Waco.

In avian evolution

It has been suggested the feathered dinosaur *Microraptor* glided, and perhaps even flew, on four wings, which were held in a biplane-like arrangement. This was made possible by the presence of flight feathers on both the forelimbs and hindlimbs of *Microraptor*, and it has been suggested the earliest flying ancestors of birds may have possessed this morphology, with the monoplane arrangement of modern birds evolving later.

Chapter 19

Gull Wing and Military Disc-Shaped Aircraft

Gull wing

DFS Habicht glider showing gull wing profile

The **gull wing** is an aircraft's wing configuration with a prominent bend in the wing somewhere along the span, generally near the wing root. Its name is derived from the seabirds which it resembles. It has been incorporated in aircraft for many reasons. The Polish aircraft designer and pilot Zygmunt Puławski invented a gull-wing aircraft design.

Sailplanes

The gull wing was first seen on a glider when the Weltensegler flew in 1921. Its wings were externally braced and featured swept-back wingtips. After the aircraft broke up, killing its pilot, the design feature stayed out of popular use. The gull wing made a resurgence in 1930 with Alexander Lippisch's record-breaking *Fafnir*. Lippisch used the configuration for its increased wingtip clearance and the ill-founded belief it improved stability in turns. The true success of the Fafnir's gull wing lay primarily in its aesthetic value; the gull wing would be a staple of the high-performance sailplanes of the time, until the 1950s.

Notable gull wing sailplanes:

- Ross-Stephens RS-1 Zanonia
- Lawrence Tech IV "Yankee Doodle")
- Bowlus Senior Albatross
- DFS Habicht
- DFS Reiher
- Göppingen Gö 3 *Minimoa*
- DFS Kranich
- Schweyer Rhönsperber
- Lippisch Fafnir
- Weltensegler

Beriev Be-12 seaplane with gull wing profile

Seaplanes

The gull wing design found its way into seaplanes by the early 1930s. As engine power increased, so did the need for large propellers that could effectively convert power to thrust. The gull wing allowed designers to ensure adequate propeller tip clearance over the water by placing the engines on the highest point of the wing. The alternative was placing the engine on a pylon. Possibly the first flying-boat to utilize the gull wing configuration was the Short Knuckleduster, which flew in 1933. The Dornier Do 26, a high-speed airliner and transport platform, of which 6 aircraft were built, flew in 1938. The configuration was also used on the US Navy's PBM Mariner and P5M Marlin maritime patrol aircraft. The emergence of long range, land-based jets in the 1950s and the subsequent demise of the seaplane prevented widespread use of the gull wing, although it was still used in some post-war designs, like Beriev Be-12 *Chaika* (the name means 'the gull' in Russian).

Examples:

- Beriev Be-6
- Dornier Do 26
- Martin P5M Marlin
- Short Knuckleduster

Landplanes

The gull wing design found its way into landplanes in the late 1920s, with Polish inventor Zygmunt Pulawski designing the PZL P.1 in 1928. The arrangement he devised is occasionally known as the "Pulawski Wing" or the "Polish wing". The gull wing was used to improve visibility in a high wing arrangement, because such wing could be thinnest by the fuselage, and in theory should limit pilot's view no more than A-pillars of a windscreen in a car body. It was used in fighter aircraft like PZL P.11 and Polikarpov I-15.

Examples:

- PZL P.11
- Polikarpov I-153

Inverted gull wing

Junkers Ju 87 German ground-attack aircraft of WWII

F4U Corsair landing on *USS Bunker Hill*

Aichi B7A carrying torpedo

The **inverted** gull wing was developed at the same time and for the same reason as seaplanes. More powerful engines generally require larger propellers, but clearance between the propeller tip and ground must be maintained. Long landing gear legs are heavy, bulky, and weaker than their shorter counterparts. The Vought F4U Corsair, designed from the onset as a carrier-based fighter, not only had the largest propeller of any U.S. fighter, but was also expected to face rough landings aboard a pitching carrier deck. The inverted gull wing allowed the landing gear to be short, tough, and to retract straight back, improving internal wing space.

Examples:

- Vought F4U Corsair
- Junkers Ju-87 Stuka
- Aichi B7A

Military disc-shaped aircraft

The development of **military disc-shaped aircraft** apparently dates back to World War II. A number of disc-shaped aircraft have been proposed over the years, a few being built. The best documented of these was Arthur Sack's experimental Sack AS-6, a small light plane with oval wings built just before the start of World War II.

Nemeth Umbrella Plane

In 1934, at Miami University (of Ohio), an aircraft called the Nemeth Umbrella Plane (aka Roundwing) was tested. (*Nemeth* is sometimes spelled *Nuneth*.) This aircraft had a circular wing on top of the rectangular fuselage, a propeller in front, wheels underneath the fuselage and a rudder with tail fins. There were no wings extending from the middle of the fuselage. The aircraft looked like the AWACS plane, except for the missing middle wings. The aircraft is named in the 1976 reference book "Airplanes of the World" as the "Flying Saucer" plane, (the book also mentions the Avro Avrocar, the Vought V-173, and the Vought XF5U).

Vought Flying Flapjack

During WWII some research was carried out by a number of designers on circular wings. Led by design-engineer Charles Zimmerman, Chance-Vought led a series of designs that eventually resulted in the Vought Flying Flapjack, perhaps the first aircraft explicitly designed as a disc for aerodynamic reasons. Generally wings with large chord (front to back length) compared to span (side to side length), described by a wing's aspect ratio, have very poor performance due to high induced drag. One way to avoid this problem is to taper the wingtips to a point, which is why the Supermarine Spitfire used an elliptical planform. In the Flapjack this was taken to an extreme, resulting in a plane with a huge wing and very low wing loading, allowing it to take off from aircraft carriers with ease. The Flapjack's engine's were moved to the ends of the wings to further reduce the drag induced by air currents there. By the time the design was flying in the post-war era, jet engines had rendered the design obsolete and the US Navy lost interest.

In 1943, the Boeing Aircraft built 3 scale model aircraft designs that had saucer-shaped wings with a propellor in the front and a tail rudder in the back. The cockpit, (where the pilot sat), was to be in front of the wings. There was no actual fuselage in the center. The aircraft model numbers were 390, 391, and 396. They were to be powered by a Pratt & Whitney R-4360-3 Wasp Major radial engine and capable of reaching speeds of 414 mph and intended to be fighter planes, armed with 4 20mm cannons and underwing hardpoints that could carry 2 500 lb. bombs or external fuel tanks. Boeing submitted the proposals to the US Navy. The wing design had excellent Short TakeOff and Landing charteristics, and STOL is preferred for fixed-wing aircraft carrier planes. The Navy rejected the Boeing designs in favor of the similar-shaped Chance-Vought V-173/XF5U-1 aircraft.

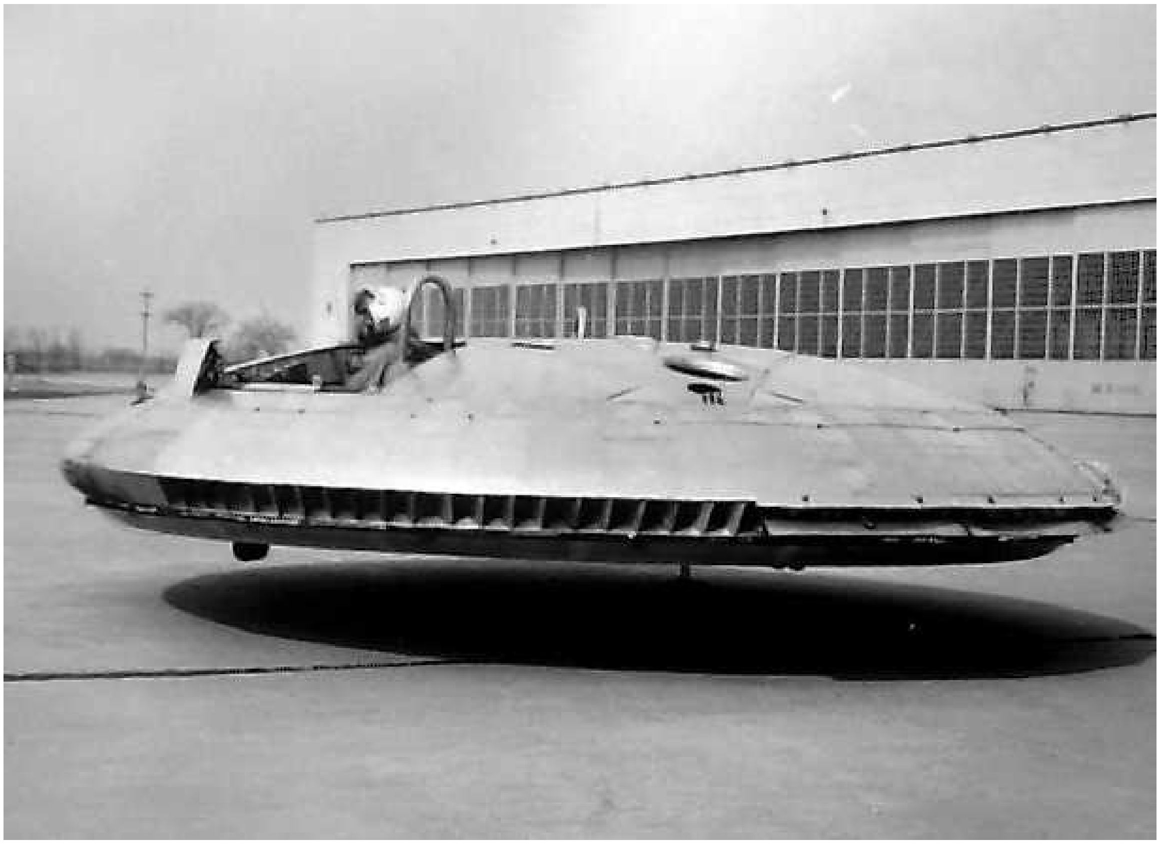
Avrocar

In the US, a number of experimental saucer shaped craft were apparently developed as black projects by Lockheed Corporation for the USAF, and by Convair for the CIA. The saucer had the advantages of being a Vertical take-off and landing design (so avoiding the need for easily damaged runways), while the shape was well suited to diffusing radar and so making the craft stealthy. These early designs were apparently powered by turbojets, which powered a horizontal rotor to provide lift using the Coandă effect.

The Avrocar

In an apparent attempt to quell speculation about the military nature of flying saucers, a press conference was held in July 1952, at which Major John A. Sandford denied any knowledge of the craft, and retired Major Donald E. Keyhoe declared his belief that they were of alien origin. In 1957 Keyhoe became head of the civilian UFO group NICAP (National Investigations Committee on Aerial Phenomena.

Meanwhile in Canada, the Avro Canada company was also attempting to develop saucer shaped craft, funded (initially) by the Canadian government. John Frost had initiated the design while experimenting with different ways to build more efficient jet engines, eventually settling on a large disc-shaped device with the exhaust towards the outside. He then wrapped the smallest possible airframe around the engine, piping the exhausts to the rear. For VTOL the aircraft sat on its tail for takeoff and landing, generating lift in forward flight as a large delta wing.



The Avrocar test

Frost also became interested in the Coandă effect to produce lift, eventually abandoning the original delta wing design and replacing it with a true disc. In this model the exhaust was directed downward around the entire disc by a flap ringing the aircraft, allowing it to take off and land "flat". Once in flight the flap would be angled slightly, producing a small downforce while being directed to the rear. Little lift would be generated by conventional means, the engine exhaust would instead be used to build an "artificial wing" by directing the airflow around the craft. He offered a number of increasingly dramatic performance estimates, generally claiming Mach 4 performance at 80,000 ft (24,000 m), at which point the USAF took over funding under *Weapon System 606A*. The result was a 29-foot (8.9 m) diameter supersonic *Project Y2*.

Testing soon revealed that the entire concept was unworkable; the craft would be highly unstable at supersonic speeds. Avro nevertheless continued work on the project as a subsonic design known as *Project Silver Bug*. Silver Bug was of interest to the US Army, who was looking for solutions for battlefield transport and support, and they took over most of the project funding. The final outcome of Silver Bug was the Avrocar or *VZ-9AV*, effectively (and unintentionally) a prototype hovercraft rather than an aircraft, which was made public in 1961. After Avro experienced financial difficulties in 1959, funding for future projects was apparently directed to the Bell Aircraft Corporation. Meanwhile the helicopter had proven to be the solution the Army was looking for.

Other

The Sikorsky Cypher is a doughnut-shaped, experimental, prototype unmanned vertical takeoff and landing aerial vehicle. The Sikorsky Cypher II, (a.k.a. Sikorsky Mariner), followup aircraft has wings extending from the left and right sides of the aircraft

Chapter 20

Multiplane (Aeronautics) and Tailless Aircraft

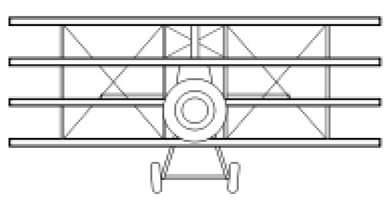
Multiplane

In aviation, a **multiplane** is a fixed-wing aircraft configuration featuring multiple wing planes. The wing planes may be stacked one above another, or one behind another, or both in combination. Types having a small number of planes have specific names and are not usually described as multiplanes:

- **Biplane** - two wings stacked one above the other.
- **Triplane** - three wings stacked one above another.
- **Quadruplane**- four stacked wings.
- **Tandem wing** - two main planes, one behind the other. The tandem triple or tandem triplet configuration has three lifting surfaces one behind another.

While triplane, quadruplane and tandem designs are relatively uncommon, aircraft with more than four sets of wings are rare, with none being successful.

Quadruplanes



The quadruplane configuration takes the triplane approach a step further, using efficient wings of high aspect ratio and stacking them to allow a compact and light weight design. During the pioneer years of aviation and World War I, a few designers sought these potential benefits for a variety of reasons, mostly with little success.

From ca. 1909 the American inventor Matthew Sellers made a series of flights in the Sellers 1909 Quadruplane, progressively fitted with powerplants of decreasing power, in order to investigate low-powered flight. He eventually achieved flight on only 5 to 6 hp at a speed of 20 mph.

Pemberton-Billing Ltd. made two protoype Zeppelin killers, the Pemberton-Billing P.B.29E and Pemberton-Billing P.B.31E, respectively in 1915 and 1917. They were comparatively large, twin-engined fighters. After the company changed its name to Supermarine, the P.B.31E became known as the Supermarine Nighthawk.

Following test flights with the prototype Armstrong Whitworth F.K.9 in 1916, a small number of Armstrong Whitworth F.K.10 quadruplane reconnaissance fighters were produced, but none saw combat action.

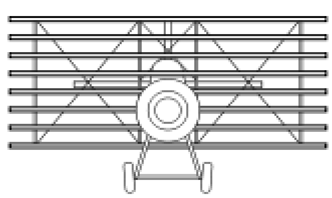
The private-venture Wight quadruplane scout fighter was flown in 1917.

The Euler Vierdecker of 1917 unusually featured a standard triplane arrangement of fixed wings with a fourth uppermost wing comprising left and right hand articulated surfaces which acted as full-span ailerons. Two examples were built, with different engines.

Also in 1917, Friedrichshafen created the even more unusual Friedrichshafen FF54 scout fighter, which featured narrow-chord second and third wings, with struts connecting only the upper pair and lower pair of planes. The prototype proved unacceptable in the air and was later modified as an equally unsuccessful triplane, again with a short-chord intermediate plane.

The Naglo D.II quadruplane fighter of 1918 featured a standard triplane arrangement with a smaller fourth wing attached below the main assembly, somewhat analogous to a sesquiplane. It participated in Germany's second D-type contest in 1918, and was praised for its construction and workmanship.

More than four planes



Any fixed-wing aircraft with more than four wing planes may be referred to as a multiplane. Planes may be stacked vertically as with a biplane, or placed one in front of another as with a tandem wing. Both principles may be combined.

Stacked multiplanes

Horatio Phillips built a series of multiplane types from 1904. His Phillips Multiplane I had 20 stacked wings in an otherwise fairly conventional layout. It proved too unstable for sustained flight. By 1907 his third model was able to fly 500 ft, achieving the first successful powered flight in Great Britain. However the disappointing performance compared to more conventional contemporary types caused Phillips to abandon his ideas.

In 1908 Roshon in America and D'Equevilly in France produced typical multiplane designs. The AEA Cygnet II, designed by Alexander Graham Bell and constructed by the Aerial Experimental Association in America, featured a cellular multiplane formed by hundreds of tetrahedral shapes. None of these types was capable of flight.

One of the most infamous multiplanes was the 1923 Gerhardt Cycleplane, a human-powered aircraft with seven sets of wings. Its flimsy construction and subsequent collapse was filmed, and this is often used as stock footage mocking early impractical aircraft designs.

Tandem multiplanes

The American Williams 1908 Multiplane featured four planes in tandem while the Zerbe 1908 Multiplane had six. The same year, in Switzerland the Dufaux 1908 Tandem Triplane provided the country's first native design in the form of a tandem pair of stacked triplane wings with a smaller biplane horizontal stabiliser.

Stacks in tandem

Anthony Fokker designed his bizarre Fokker V.8 about the same time as his famous Fokker Dr.I triplane. It featured a tandem arrangement of five wing planes, grouped as a stacked triplane fore wing and a biplane rear wing. Unlike its successful cousin, it barely flew and was soon abandoned.

As late as 1921, the Italian Gianni Caproni mated three stacks of triplane wings from his Caproni Ca.4 series to a single fuselage in tandem triple arrangement, to create the nine-winged Caproni Ca.60 Noviplano prototype long-range airliner. It proved unstable and crashed on its first flight.

Tailless aircraft

Tailless aircraft

The DH108 *Swallow*

A **tailless aircraft** (often **tail-less**) traditionally has all its horizontal control surfaces on its main wing surface. It has no horizontal stabilizer - either **tailplane** or **canard** foreplane (nor does it have a second wing in **tandem** arrangement). A 'tailless' type usually still has a vertical stabilising fin (vertical stabilizer) and control surface (rudder). However, NASA has recently adopted the 'tailless' description for the novel X-36 research aircraft which has a canard foreplane but no vertical fin.

The most successful tailless configuration has been the **tailless delta**, especially for combat aircraft.

Flying wings

Flying wings are tailless designs which also lack a distinct fuselage, having the pilot, engines, etc. located directly in or on the wing.

Aerodynamics

Longitudinal stability

A tailless aeroplane has no separate horizontal stabiliser, either behind (Tailplane) or in front of (canard foreplane) the main lifting surface. Because of this the aerodynamic center of an ordinary wing would lie ahead of the aircraft's center of gravity, creating instability in pitch. Some other method must be used to move the aerodynamic center backward and make the aircraft stable. There are two main ways for the designer to achieve this:

- Sweep the wing leading edge back, either as a swept wing or delta wing, and reduce the angle of incidence of the outer wing section so that it acts rather like a conventional tailplane stabiliser. If this is done progressively along the span of the outer section, it is called **tip washout**. The outer section of the wing now acts as a conventional tailplane, and in level flight the aircraft should be trimmed so that the tips do not contribute any lift: they may even need to provide a small downthrust. This reduces the overall efficiency of the wing, but for many designs - especially for high speeds - this is outweighed by the reductions in drag, weight and cost over a conventional stabiliser. This method was developed by the English aeronaut J. W. Dunne in the early 20th century, but did not gain widespread use until the jet age. Since Dunne, this approach has been augmented by the use of low or null pitching moment airfoils, seen for example in the Horten series of sailplanes and fighters.

- Use a wing aerofoil section with reflex or reverse camber. With reflex camber the flatter side of the wing is on top, and the strongly curved side is on the bottom, so the front section presents a high angle of attack while the back section is more or less horizontal and contributes no lift, so acting like a tailplane or the washed-out tips of a swept wing. Reflex camber can be simulated by fitting large elevators to a conventional airfoil and trimming them noticeably upwards; the center of gravity must also be moved forward of the usual position. Due to the Bernoulli effect, reflex camber tends to create a small downthrust, so the angle of attack of the wing is increased to compensate. This in turn creates additional drag. This method allows a wider choice of wing planform than sweepback and washout, and designs have included circular (Arup) and straight wings. But the drag inherent in a high angle of attack is generally regarded as making the concept inefficient, and only a few types, such as the Fauvel and Marske Aircraft series of sailplanes, use it.

An alternative approach is to locate the main weight of the aircraft a significant distance below the wing center, so that gravity will tend to maintain the aircraft in a horizontal attitude and so counteract any aerodynamic instability. In practice this is not sufficient to provide stability on its own, and typically is augmented by sweepback and washout as described. A classic example is the Rogallo wing hang glider.

There is a trade-off between stability and maneuverability. A high level of maneuverability requires a low level of stability. Some modern hi-tech combat aircraft are aerodynamically unstable in pitch and rely on fly-by-wire computer control to provide stability. The Northrop B-2 *Spirit* flying wing is an example.

Pitch control

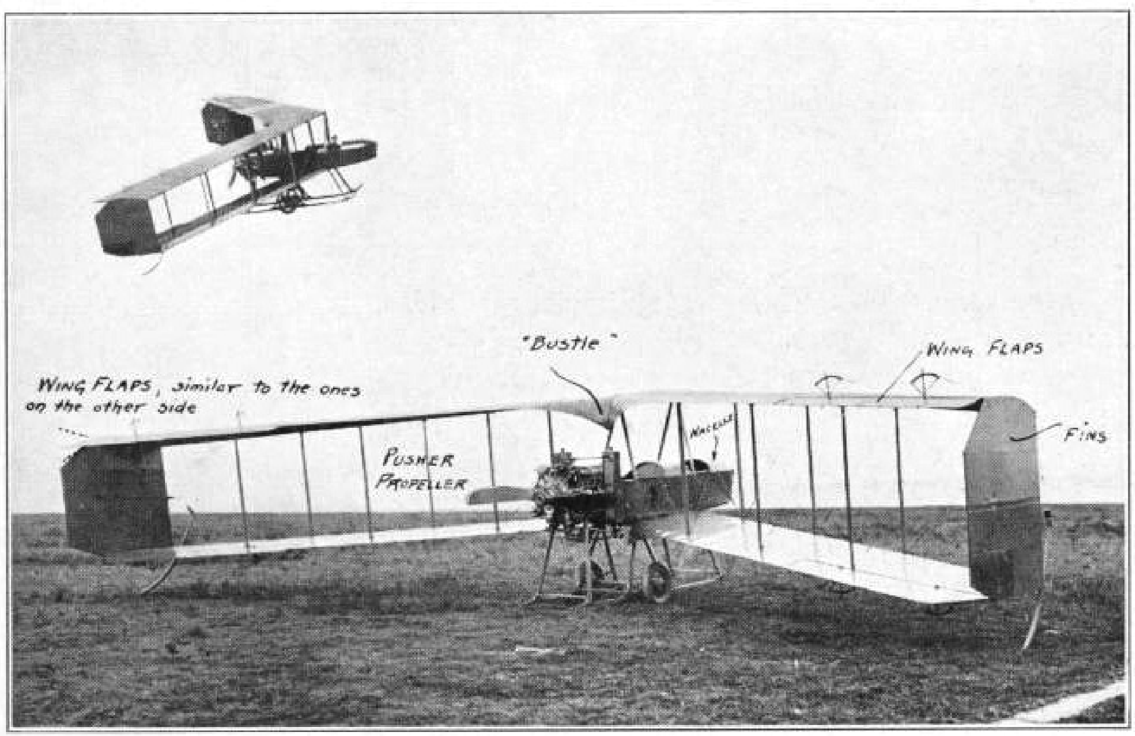
Many early designs failed to provide effective pitch control to compensate for the missing stabiliser. As a result, these aircraft could pitch up or down sharply and uncontrollably if they were not carefully handled. These gave tailless designs a reputation for instability. The original Dunne biplanes and the later success of the tailless delta configuration show that the problem was due as much to inadequate design, as to any problem inherent in the tailless configuration.

The solution usually adopted is to provide large elevator and/or elevon (combined elevator and aileron) surfaces on the wing trailing edge. These must generate large control forces, as their distance from the aerodynamic center is small. Consequently, when maneuvring, a tailless type may suffer higher drag than the conventional equivalent, even though it has less drag in level flight. High maneuvrability demands high control moments (force times "lever arm" distance), and the short lever arm inherent in tailless types means they are not as manoeuvrable as their conventional equivalents.

Notable examples

The examples given here are in historical order.

J. W. Dunne



THE U. S. ARMY DUNNE TYPE BIPLANE

A Dunne type biplane in the US Army of 1917

During and shortly after the First World War, the English engineer J. W. Dunne developed a series of tailless aircraft characterised by having swept wings. In his book *An Experiment with Time* he claims that one of these was the first aeroplane ever to achieve natural stability in flight. Certainly, Dunne designed the first practical tailless aeroplanes. Few records of these aircraft remain.

Most of Dunne's designs were biplanes, typically featuring a fuselage nacelle between the planes, with rear-mounted 'pusher' propeller, and twin rudders between each pair of wing tips.

The D.6 monoplane of 1910 was a pusher type high-wing monoplane which featured turned-down wingtips with pronounced wash-out.

Many of Dunne's ideas on stability remain valid, and he is known to have influenced later designers such as John K. Northrop (father of the B-2 spirit stealth bomber).

Dunne gave some help initially to Geoffrey T. R. Hill who produced the Pterodactyl series of aircraft from 1920s onwards which were specifically designed to reduce the likelihood of stalling and spinning.

Lippisch deltas

The German designer Alexander Lippisch produced the first tailless delta design, the Delta I, in 1931. He went on to build a series of ever-more sophisticated designs, and after the Second World War went to America to continue his work.

Messerschmitt Me 163 *Komet*

During the Second World War, Lippisch worked for the German designer Willy Messerschmitt on the first tailless aircraft to go into production, the Me 163 *Komet*. It was a rocket-powered interceptor, and was the fastest aircraft to reach operational service during the war. Its rocket propulsion system was highly unsafe, especially the early versions. Landing was hazardous not only because the Komet had no wheels, but because sparks from the metal landing skid often flew up and ignited fuel vapours escaping from the propulsion system. More pilots were killed in takeoff and landing incidents than in combat.

De Havilland DH 108 *Swallow*

In the 1940s, the English designer Geoffrey de Havilland made a few examples of a tailless jet-powered research aircraft called the DH108 *Swallow*, based on the forward fuselage of the de Havilland Vampire jet fighter. One of these was the first aircraft ever to break the sound barrier - it did so during a shallow dive, and the sonic boom was heard by several witnesses.

Dassault *Mirage*

The French Mirage series of supersonic jet fighters were an example of the tailless delta configuration, and became one of the most widely produced of all Western jet aircraft. By contrast the Soviet Union's equivalent widely produced delta-winged fighter, the Mikoyan-Gurevich MiG-21, does have a tail stabiliser.

Convair F2Y *Sea Dart*

In the 1950s, the Convair F2Y Sea Dart prototype became the only seaplane ever to exceed the speed of sound. Convair built several other successful tailless delta types.

Supersonic airliners

The Anglo-French Concorde SST and its Soviet counterpart the Tupolev Tu-144 were tailless supersonic jet airliners, with gracefully curved *ogival delta* wings. The grace and beauty of these aircraft in flight were often remarked upon.

Lockheed SR-71 *Blackbird*

The American Lockheed SR-71 Blackbird reconnaissance aircraft was the fastest known operational aircraft, achieving speeds above Mach 3.

Northrop B-2 *Spirit*

The most recent tailless type to see operational service is the Northrop B-2 Spirit flying wing. It is unstable in flight and has artificial stability provided by a fly-by-wire system.

Other tailless aircraft

- Avro 707 - research for Avro Vulcan, 1/3 scale of Vulcan
- Avro CF-105 Arrow - delta wing fighter
- Avro Vulcan - delta wing subsonic bomber
- Boulton Paul P.111 - delta wing research
- Convair B-58 Hustler - delta wing supersonic bomber
- Convair F-102
- Convair F-106
- Fauvel AV.36 and others by Charles Fauvel
- Douglas F-4D Skyray
- Vought F-7 Cutlass
- General Dynamics F-16XL
- Granger Archaeopteryx
- HAL Tejas
- Pterodactyl Pfledge — ultralight aircraft produced in large numbers

Experimental

- Armstrong Whitworth A.W.52 - flying wing
- Short SB.1 (glider) and Short SB.4 Sherpa - tested aero-isoclinic wing
- Handley Page Manx -
- Handley Page HP.115 - low speed handling of delta wing
- Fairey Delta 2 - high speed delta design

Chapter 21

Tandem Wing and Triplane

Tandem wing

QAC Quickie Q2

A **tandem wing** aircraft usually involves two full-sized wings, both of which are full airfoils. Sometimes an aircraft of this configuration can look like a variation on the biplane, but is in fact very different. The forward wing is often technically a canard, fitted with elevators, but both forward and aft wings provide lift. In the case of the QAC Quickie the aft wing serves as horizontal stabilizer, but pitch control comes from the forward wing.

In the case where the rearmost tandem wing is effectively an oversize tailplane it is referred to as a "Delanne wing" - from Maurice Delanne, a French designer of tandem wing aircraft.

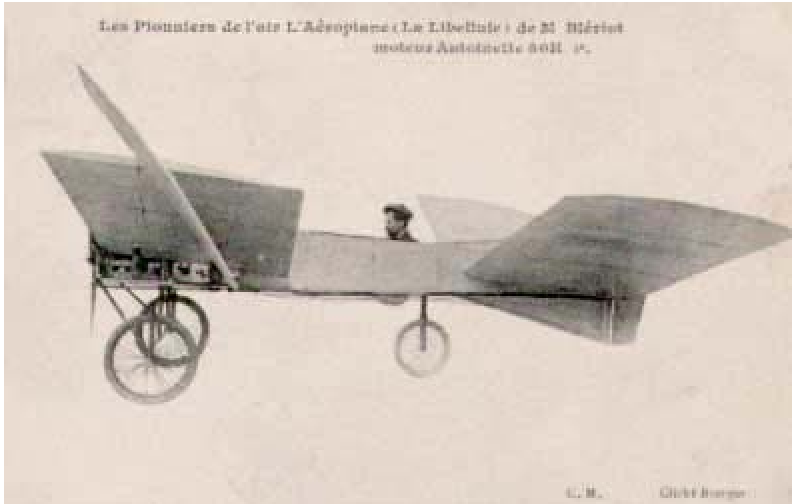
The difference between a tandem wing and a biplane has to do with the horizontal proximity of one wing to the other. In a biplane, the wings are horizontally close, so that the lift vector on each wing is in close proximity to each other (measured longitudinally). Because of their proximity, there is little difference between a biplane and a monoplane in the relationship between the lift vector and the aircraft's center of gravity (CG). In a tandem wing design, however, the lift vectors on the two wings are spread far apart longitudinally. The practical effect is to increase the stability of an aircraft. In simple terms, a monoplane and biplane configuration can be compared to a long board balanced on a single saw horse; if it is not balanced carefully, the board will tip forward or aft. In such an aircraft, the CG envelope (distance between the forward CG limit and aft CG limit) is very small; loading of the aircraft outside that limit will result in the aircraft becoming uncontrollable. On the other hand, a tandem wing aircraft can be compared to the board being supported by two saw horses, one at each end; the result is increased stability, and a more tolerant CG envelope.

Designers using tandem wings

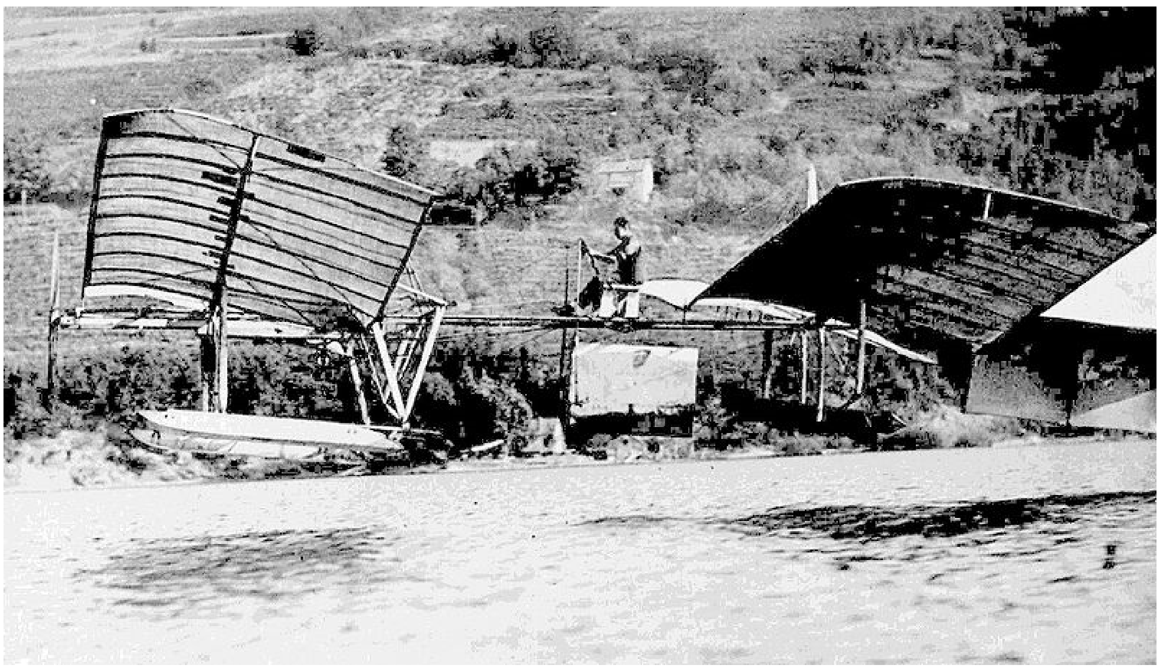
- Frederick George Miles
- Claude Piel
- Burt Rutan

Examples

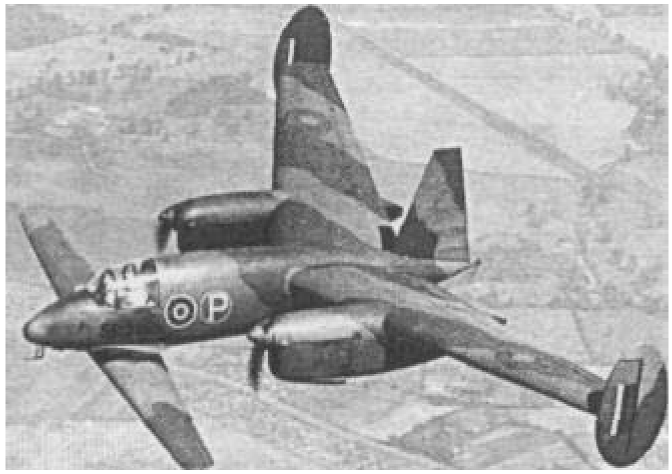
- Langley Aerodrome - 1900s
- Miles Libellula - 1940s
- Westland P.12 Lysander Delanne
- Rutan Quickie - 1978
- Viking Dragonfly - 1980
- Scaled Composites Proteus - 1998



Blériot VI Libellule (1907)



Langley Aerodrome, modified (1914)



Miles M.39B (1943)

Scaled Composites Proteus (1998)

Triplane

A flyable reproduction of the Fokker Dr.I, the best known triplane aircraft of World War I.

A **triplane** is a fixed-wing aircraft equipped with three vertically-stacked wing planes. Tailplanes and canard foreplanes are not normally included in this count, although they may occasionally be.

Design principles

The triplane arrangement may be compared with the biplane in a number of ways.

A triplane arrangement has a narrower wing chord than a biplane of similar span and area. This gives each wing plane a slender appearance with higher aspect ratio, making it more efficient and giving increased lift. This potentially offers a faster rate of climb and tighter turning radius, both of which are important in a fighter. The Sopwith Triplane was a successful example, having the same wing span as the equivalent biplane, the Sopwith Pup.

Alternatively, a triplane has reduced span compared to a biplane of given wing area and aspect ratio, leading to a more compact and lightweight structure. This potentially offers better maneuvrability for a fighter, and higher load capacity with more practical ground handling for a large aircraft type.

The famous Fokker Dr.I triplane was a balance between the two approaches, having moderately shorter span and moderately higher aspect ratio than the equivalent biplane, the Fokker D.VI.

Yet a third comparison may be made between a biplane and triplane having the same wing plan - the triplane's third wing provides increased wing area, giving much increased lift. The extra weight is partially offset by the increased depth of the overall structure, allowing a more efficient construction. The Caproni Ca.4 series had some success with this approach.

These advantages are offset, to a greater or lesser extent in any given design, by the extra weight and drag of the structural bracing, and the aerodynamic inefficiency inherent in the stacked wing layout. As biplane design advanced, it became clear that the disadvantages of the triplane outweighed the advantages.

Typically the lower set of wings are approximately level with the underside of the aircraft's fuselage, the middle set level with the top of the fuselage, and the top set supported above the fuselage on cabane struts.

History

Pioneer years

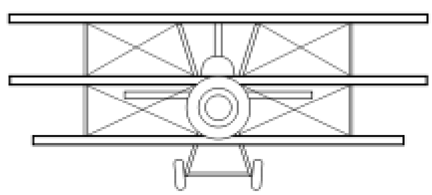


Illustration of a triplane

The Bousson-Borgnis canard triplane was built ca. 1908. The first triplane known to have flown was the Goupy No.1, designed in 1908 by Ambroise Goupy, built by Blériot-Voisin, and flown with a 37 kW (50 hp) Renault engine. A few weeks later Hans Grade's triplane became the first German-built aeroplane to fly. In the same year Farman modified his original Voisin machine to triplane configuration, and Dorand constructed his Military triplane.

In 1909 Bokor constructed his own canard triplane. Through 1909 and 1910 the British aviation pioneer A.V. Roe built a series of four experimental triplanes—types I, II, III and IV—before abandoning the design. And in 1911 the Russian Rodjestveisky also constructed a triplane.

The fighting triplanes

The Sopwith Triplane, the first triplane to see service in World War I.

During World War I, some aircraft manufacturers turned to the triplane configuration for fighter aircraft. In practice these triplanes generally offered inferior performance to biplanes and only two types were successful enough to be produced, although in relatively small numbers.

Nieuport built a series of triplane protoytpes between 1915 and 1917, featuring a top wing heavily staggered backwards to improve the pilot's view and a characteristic triangular strut arrangement bracing the three wings. The design resulted in poor handling and was dropped.

Sopwith developed three different designs in 1916. One, known simply as the Sopwith Triplane, went into production and became the first military triplane to see operational service. It had equal-span wings of high aspect ratio, mounted on a fuselage very similar to that of the preceding Pup biplane, and braced by one sturdy strut on each side with minimal wire bracing. The type was ordered by both the RFC and RNAS, but in the event the RFC traded theirs for another type and the Sopwith saw service only with the RNAS, where it served with success.

The Sopwith type's performance advantage and early successes over the Albatros D.III spurred military interest in the design, especially in Germany and Austro-Hungary. A flurry of prototypes were produced through 1917 and 1918, sometimes reluctantly under pressure from the military. Examples were produced by Albatros, Aviatik, Brandenburg, DFW, Euler, Friedrichshafen, LFG Roland, Lohner, Naglo, Offag, Pfalz, Sablating, Schütte-Lanz, Siemens-Schuckert, W.K.F and in ther USA by Curtiss. None of these went into production. Fokker's V.4 prototype of 1917 (identified by some as the V.3) had unusual cantilevered wings without bracing, the uppermost wing being attached only by cabane struts to the fuselage. The wings vibrated excessively in flight, and the next prototype, the V.5 featured a single interplane strut on each side similar to the Sopwith, but with no wires. This became the prototype of the famous Fokker Dr.I triplane of 1917 which became immortalised as the aircraft most closely identified with Manfred von Richthofen, the "Red Baron". Although it had a good rate of climb and was highly manoeuvrable it was not particularly fast. Following the break-up of two examples in the air the type was withdrawn from service for strengthening, and by the time it was re-introduced it was no longer at the forefront of performance.

The performance of the fighting triplanes was soon overtaken by improved biplane fighters. However, as late as 1919 three prototype Sopwith Snarks were flown.

Zeppelin killers

Meanwhile, a few British designers pursued the triplane configuration in the anti-Zeppelin role. From 1915, Armstrong Whitworth developed the F.K.5 and F.K.6 prototypes. These were large three-seat types with twin engines and the middle wing noticeably longer-span than the others. Then in 1917 Blackburn produced a single-seat triplane. It was something of a throwback, featuring a pusher propeller and boom-mounted empennage in the manner of an earlier era. The arrangement was intended to allow fitting of an upwards-firing gun in the forward fuselage. Neither type progressed beyond the prototype stage.

Bombers and transports

The Caproni Ca.4 of 1917 entered service with the Italian air force as a heavy bomber in 1918. It was a successful design for its day and many variants were produced. Later on, after the war, Caproni re-numbered many of these variants as new types. The unsuccessful Caproni Ca.60 prototype transatlantic seaplane had three sets of triplane wings taken from the Ca.4, making nine wings in all, and is generally classified as a multiplane.

From 1918, Bristol developed a series of heavy triplanes which, like the Caproni design, appeared in different variants aimed at different roles . The first was the Braemar bomber, flying in 1918 with the Mk II in 1919. The Pullman 14-seat transport variant flew in 1920. This was followed by two examples of a new, larger design for a military freighter, dubbed the Tramp.

The Tarrant Tabor, another and much larger British bomber, crashed on its maiden flight in 1919. Its designer Walter Barling went on to create the similar-sized American Witteman-Lewis XNBL-1, known as the Barling Bomber, which first flew in 1923.

Racing triplane

In 1921 the "Cactus Kitten" racing triplane, formerly the monoplane "Texas Wildcat 1 (there was a biplane Texas Wildcat 2"), was created. It is the only design in history having gone from a monoplane to biplane to triplane configuration. Referred to as the Curtiss-Cox racer, designed by Cox, a Texan who sponsored it, the Cactus Kitten placed 2nd in the 1922 Pulitzer race behind a Curtiss biplane. It was powered by a 435 hp Curtiss C-12 engine with a 20' wingspan. In it's triplane configuration it surpassed it's monoplane and biplane antecedents in handling and speed, and for a brief moment, the triplane was once again being noticed, the Kitten being touted as being the world's fastest plane in 1922, being capable of surpassing 200 miles per hour. The same year it was donated to the Navy and used as a trainer for the 1922 Pulitzer race, fame having proven very fleeting.

Tandem triplanes

A tandem triplane has two sets of triplane wings, fore and aft. Few have been made.

Dufaux produced Switzerland's first native aircraft design in 1908, as a tandem triplane with a smaller biplane horizontal stabiliser.

The 1909 Roe I Triplane has also been described as a tandem triplane due to its relatively large triplane aft plane.

The Fokker V.8 of 1917 was another tandem design although not a true tandem triplane, having a triplane fore wing, biplane rear wing and monoplane tail stabiliser.

In 1921, the Italian Gianni Caproni mated three stacks of triplane wings from his Ca.4 series to a single fuselage in a tandem triple triplane arrangement, to create the Caproni Ca.60 Noviplano prototype long-range airliner. It proved unstable and crashed on its first flight.

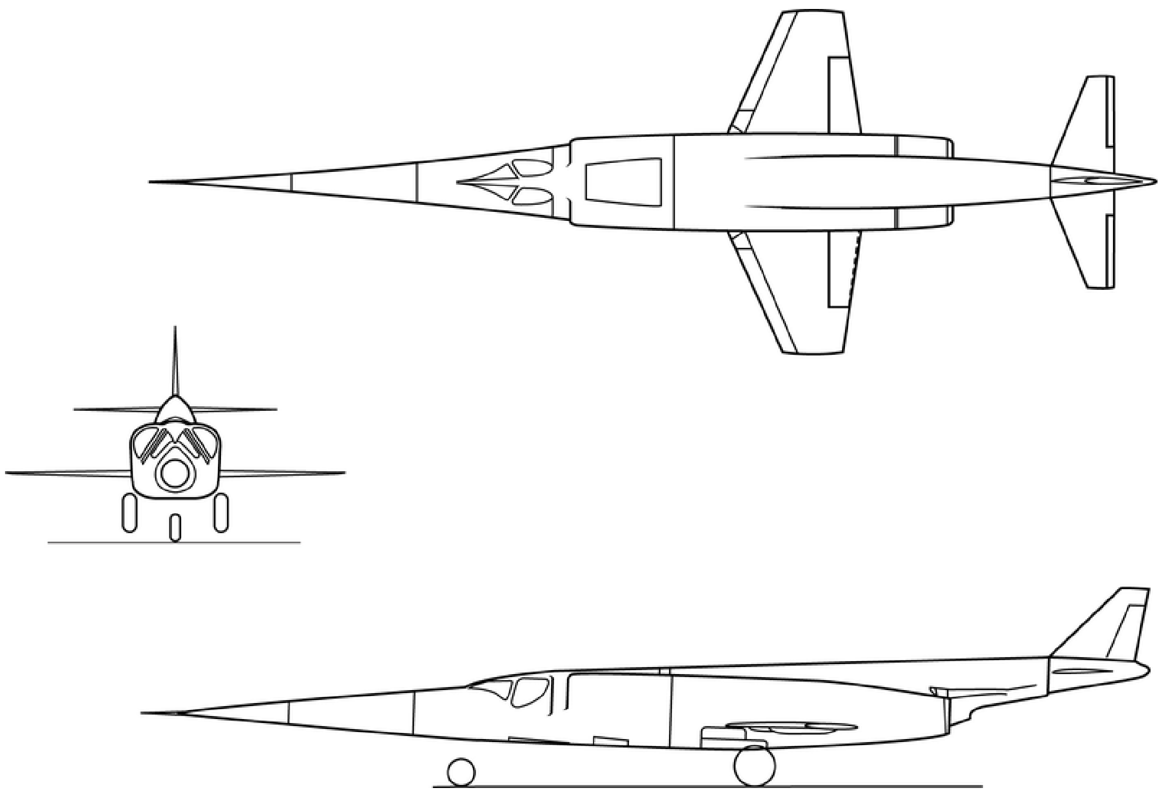
A further example was under construction in Kansas City, USA as late as 1922 .

Recently, the term "tandem triplane" has been used for some new monoplane types that have active canard surfaces in addition to conventional wings and horizontal tailplane. A configuration having three comparable lifting surfaces in tandem is more correctly referred to as *tandem triple* or *tandem triplet*, and is not a triplane as such. These modern types may also be compared to the pioneer Voisin-Farman I and Curtiss No. 1 which also had a large main wing with smaller fore and aft planes; the smaller planes were not regarded as part of the main wing arrangement, and they were not described as tandem types.

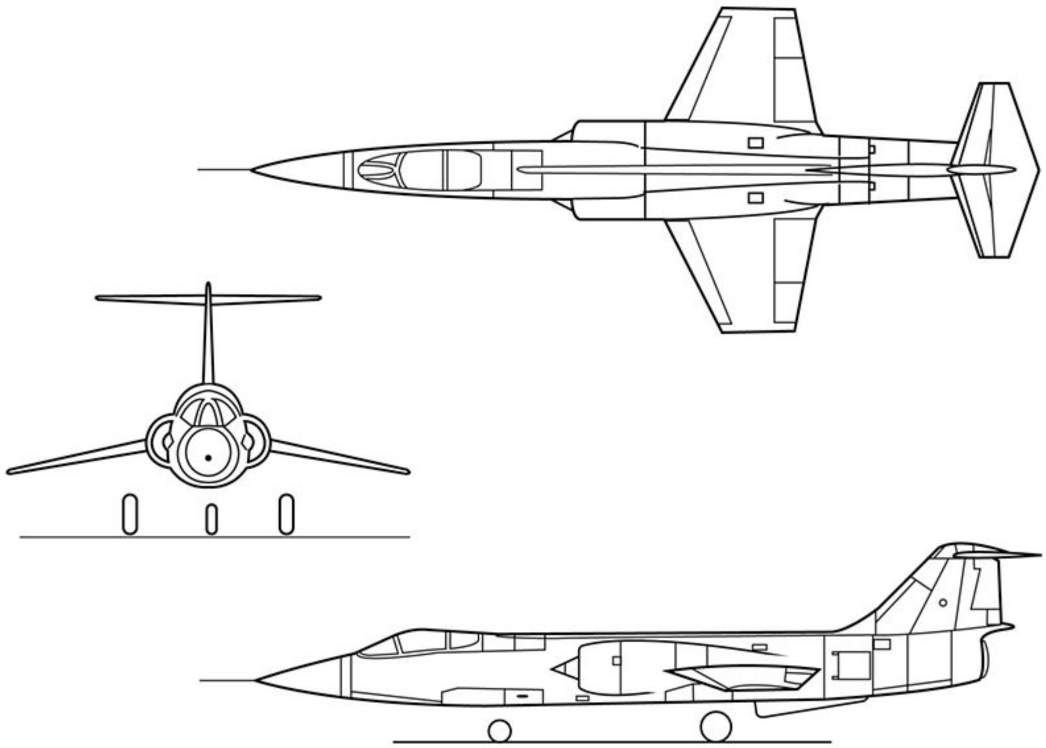
Chapter 22

Trapezoidal Wing and Wingtip Device

Trapezoidal wing



X-3 Stiletto



F-104 Starfighter

Lockheed F-22 Raptor

F-35 Lightning II

The **trapezoidal** or **diamond** wing is a high-performance wing configuration. It is a short (low aspect ratio) tapered wing having little or no overall sweep, such that the leading edge sweeps back and the trailing edge sweeps forwards. The trapezoidal design allows for a thin wing with low drag at high speeds, while maintaining high strength and stiffness. To date, all major aircraft to use this design have come from the United States.

History

Early examples provided a solution to the problem of supersonic flight when engine power was limited. The wing of the Douglas X-3 Stiletto was extremely small and thin, giving low drag at supersonic speeds. The principle was adopted for various other X-planes and for Lockheed's widely-produced F-104 Starfighter high-speed, high-altitude interceptor. Lockheed used the design on many of its aircraft proposals in the 1950s, including the Lockheed CL-400 Suntan and early versions of their supersonic transport designs.

The small wing of the Starfighter was found to have good gust response at low level, providing a smooth ride at high subsonic speeds. Consequently the type was adopted for the ground-attack role, notably by the German Luftwaffe. However the small size of the wing also meant high take-off and landing speeds with minimal stability or control, and many pilots were killed during takeoff and landing accidents.

More recently, a larger and less highly loaded variant has been found to provide good all-round speed, load carrying and maneuvering characteristics for modern combat fighters such as the Lockheed F-22 Raptor and others. Its inherent light weight has also led to its adoption for the VTOL-capable F-35 Lightning II Joint Strike Fighter.

Examples

X-planes

- X-3 Stiletto
- Lockheed X-7
- North American X-15
- Lockheed X-27

Military planes

- F-104 Starfighter
- Lockheed F-22 Raptor
- Northrop YF-23
- F-35 Lightning II
- YF-22

Wingtip device

In the foreground, a red blended winglet extends up from the port wingtip of a Boeing 737-800. In the background, a yellow wingtip fence on the starboard wing of an Airbus A319

Wingtip devices are usually intended to improve the efficiency of fixed-wing aircraft. There are several types of wingtip devices, and though they function in different manners, the intended effect is always to reduce the aircraft's drag by altering the airflow near the wingtips. Wingtip devices can also improve aircraft handling characteristics and enhance safety for following aircraft. Such devices increase the effective aspect ratio of a wing without materially increasing the wingspan. An extension of span would lower lift-induced drag, but would increase parasitic drag and would require boosting the strength and weight of the wing. At some point, there is no net benefit from further increased span. There may also be operational considerations that limit the allowable wingspan (*e.g.*, available width at airport gates).

Wingtip devices increase the lift generated at the wingtip (by smoothing the airflow across the upper wing near the tip) and reduce the lift-induced drag caused by wingtip vortices, improving lift-to-drag ratio. This increases fuel efficiency in powered aircraft and increases cross-country speed in gliders, in both cases increasing range. U.S. Air

Force studies indicate that a given improvement in fuel efficiency correlates directly with the causal increase in the aircraft's lift-to-drag ratio.

Line drawing of wingtip vortices behind a conventional wingtip (on the left) and a blended winglet (on the right)

Winglet

Gulfstream V model winglet flutter tests at NASA Langley transonic wind tunnel

The term "winglet" was previously used to describe an additional lifting surface on an aircraft, *e.g.*, a short section between wheels on fixed undercarriage, but today it refers to a near-vertical extension of the wing tips. The upward angle (or *cant*) of the winglet, its inward or outward angle (or *toe*), as well as its size and shape are critical for correct performance and are unique in each application. The wingtip vortex, which rotates around from below the wing, strikes the cambered surface of the winglet, generating a force that angles inward and slightly forward, analogous to a sailboat sailing close hauled. The winglet converts some of the otherwise-wasted energy in the wingtip vortex to an apparent thrust.

This small contribution can be worthwhile over the aircraft's lifetime, provided the benefit offsets the cost of installing and maintaining the winglets. Another potential benefit of winglets is that they reduce the strength of wingtip vortices, which trail behind the plane. When other aircraft pass through these vortices, the turbulent air can cause loss of control, possibly resulting in an accident. This possibility is greatest near airports and the minimum spacing requirements between aircraft operations at airports is largely due to these factors. Aircraft are classified by weight (e.g. "Light," "Heavy," etc.) in large part because the vortex strength is proportional (not linearly) to the amount of lift being generated by the airfoil. For this reason, wingtip vortices are typically most dangerous when an aircraft is in a high lift, high drag, high angle of attack position and at a heavy gross weight. During takeoff, for example, flaps and slats are typically partially extended, the aircraft is at its heaviest and a large amount of lift is generated as the aircraft reaches rotate velocity and transition to climbout.

Winglets and wing fences also increase efficiency by reducing vortex interference with laminar airflow near the tips of the wing, by 'moving' the confluence of low-pressure (over wing) and high-pressure (under wing) air away from the surface of the wing. Wingtip vortices create turbulence, originating at the leading edge of the wingtip and propagating backwards and inboard. This turbulence 'delaminates' the airflow over a small triangular section of the outboard wing, which destroys lift in that area. The fence/winglet drives the area where the vortex forms upwards away from the wing surface, since the center of the resulting vortex is now at the tip of the winglet.

Aircraft such as the Airbus A340 and the Boeing 747-400 use winglets. Other designs such as some versions of the Boeing 777 and the Boeing 747-8 omit them in favor of raked wingtips. Large winglets such as those seen on Boeing 737 aircraft equipped with blended winglets are most useful during short-distance flights, where increased climb performance offsets increased drag. Raked wingtips are now preferred over small winglets for long-distance flights, where increased fuel economy during the cruise phase is more important.

The Rutan VariEze, the first aircraft to use winglets in 1975

History and applications

The initial concept dates back to 1897, when English engineer Frederick W. Lanchester patented wing end-plates as a method for controlling wingtip vortices. In 1905, the Wright brothers used a concept they called "blinkers" on the canard of their Flyer III and later, on their Wright Model A aircraft. In 1910 they installed "side curtains" and modified blinkers on their production Wright Model B aircraft, to improve its stability. In the United States Scottish born engineer William E. Somerville patented the first functional winglets in 1910. Somerville installed the devices on his early biplane and monoplane designs.

Dr. Sighard Hoerner was a pioneer in the field, having written a technical paper published in 1952 that called for drooped wingtips whose pointed rear tips focused the resulting wingtip vortex away from the upper wing surface. Drooped wingtips are often called "Hoerner tips" in his honor. Gliders and light aircraft have made use of Hoerner tips for many years.

Winglet on KC-135 Stratotanker with attached tufts showing airflow during NASA tests in 1979–1980

NASA development

Hoerner's concept was further developed by Richard T. Whitcomb, an engineer at NASA's Langley Research Center, in response to the sharp increase in the cost of fuel after the 1973 oil crisis. Whitcomb's designs were flight-tested in 1979–80 by a joint NASA/Air Force team, using a KC-135 Stratotanker based at the Dryden Flight Research Center. A Lockheed L-1011 and McDonnell Douglas DC-10 were also used for testing, and the latter design was directly implemented by McDonnell Douglas on the derivative MD-11, which was rolled out in 1990. NASA's own most notable application of wingtip devices is on the Boeing 747 Shuttle Carrier Aircraft. Located on the 747's horizontal stabilizers, the devices increase the tailplane's effectiveness under the weight of the Space Shuttle orbiter.

Beechcraft Starship Model 2000

Composite aircraft

Even before NASA did flight testing on winglets, Burt Rutan incorporated them in his innovative Rutan VariEze homebuilt aircraft design, which made its first flight with winglets on May 21, 1975. The VariEze pioneered glass-reinforced plastic composite construction in homebuilt aircraft, which simplified fabrication of the winglets. He reduced the resulting drag penalty by assigning double duty to the winglets; they also serve as vertical stabilizers and rudders in his canard, pusher configuration aircraft. They were also used similarly on the derivative Rutan Long-EZ and reappeared on his Beechcraft Starship business aircraft design that first flew in 1986. Conventional winglets were fitted to Rutan's Rutan Voyager, the first aircraft to circumnavigate the world without refueling in 1987. However, the aircraft's wingtips were damaged when they dragged along the runway during takeoff, breaking off about a foot of each wingtip, so the flight was made without benefit of winglets.

Gulfstream V with winglets

Business aircraft

Learjet exhibited the prototype Learjet 28 at the 1977 National Business Aviation Association convention. The Model 28 prototype employed the first winglets ever used on a jet and a production aircraft, either civilian or military. Learjet developed the winglet design without NASA assistance. Although the Model 28 was intended to be a prototype experimental aircraft, performance was so impressive that it resulted in a production commitment from Learjet. Flight tests, made with and without winglets, showed that the winglets increased range by about 6.5 percent and also improved directional stability. Learjet's application of winglets to production aircraft continued with newer models including the Learjet 55, 31, 60, 45 and Learjet 40.

Learjet 60 with winglets

Gulfstream Aerospace also explored winglets in the late 1970s and incorporated winglets in the Gulfstream III, IV and V. The performance of the Gulfstream V has been exemplary. Its operational range of 6,500 nmi (12,038 km) permits routine nonstop business travel for routes such as New York–Tokyo. The Gulfstream V also holds over 70 world and national flight records.

Winglets are also applied to several other business jets to reduce take-off distance, enabling operation out of smaller secondary airports, and allowing higher cruise altitudes for overflying bad weather, both of which are valuable operational benefits for corporate travel. In addition to factory-installed winglets on new aircraft, aftermarket vendors developed retrofit kits, for popular jets and turboprops, to improve both aerodynamics and appearance. Winglets became so popular on this class of aircraft that the Dassault Group, whose French designers resisted applying them on their Dassault Falcon line until recently, were forced to run a contrarian marketing campaign. Cessna recently announced they were partnering with Winglet Technology, LLC of Wichita, Kansas, to test a new wingtip device called Elliptical Winglets, which are designed to increase range and increase payload on hot and high departures.

A Boeing 747-400 with winglets

Passenger aircraft

Boeing announced a new version of the 747 in October 1985, known as the 747-400, with an extended range and capacity. With that particular model, Boeing used a combination of winglets and increased span to carry the additional load. The winglets increased the 747-400's range by 3.5 percent over the 747-400D, which is otherwise aerodynamically identical but has no winglets. Winglets are preferred for Boeing derivative designs based on existing platforms, because they allow maximum re-use of existing components. Newer designs are favoring increased span, other wingtip devices or a combination of both, whenever possible.

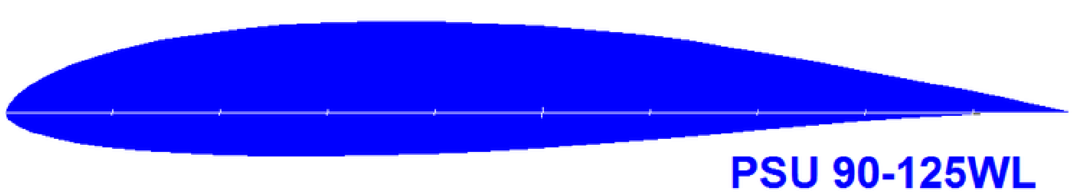
In 2002, Boeing first flew a production Next-Generation 737 with its new Blended Winglets, six-foot extensions that decrease fuel consumption by about 4 to 6 percent. The airplane gained supplemental type certification in 2003, and the majority of 737s delivered today are equipped with the devices.

In 2009, Airbus announced the introduction of Sharklet winglets for A320 aircraft. These winglets are expected to reduce fuel usage by 3.5% over the current winglet design.

Schempp-Hirth Ventus-2 glider with factory winglets winch-launching

Gliders

In 1987, mechanical engineer Peter Masak called on world renowned aerodynamicist Mark D. Maughmer, an associate professor of aerospace engineering at the Pennsylvania State University, about designing winglets to improve performance on his 15-meter wingspan racing sailplane. Others had attempted to apply Whitcomb's winglets to gliders before, and they did improve climb performance, but this did not offset the parasitic drag penalty in high-speed cruise. Masak was convinced it was possible to overcome this hurdle. By trial and error, they ultimately developed successful winglet designs for gliding competitions, using a new PSU–90–125 airfoil, designed by Maughmer specifically for the winglet application. At the 1991 World Gliding Championships in Uvalde, Texas, the trophy for the highest speed went to a winglet-equipped 15-meter class limited wingspan glider, exceeding the highest speed in the unlimited span Open Class, an exceptional result. Masak went on to win the 1993 U.S. 15 Meter Nationals gliding competition, using winglets on his prototype Scimitar sailplane.



PSU-90-125 winglet airfoil profile

The Masak winglets were originally retrofitted to production sailplanes, but within 10 years of their introduction, most high-performance gliders were equipped from the factory with winglets or other wingtip devices. It took over a decade for winglets to first appear on a production airliner, the original application that was the focus of the NASA development. Yet, once the advantages of winglets were proven in competition, adoption was swift with gliders. The point difference between the winner and the runner-up in soaring competition is often less than one percent, so even a small improvement in efficiency is a significant competitive advantage. Many non-competition pilots installed them for handling benefits such as increased roll rate and roll authority and reduced tendency for wing tip stall. The benefits are notable, because sailplane winglets must be removable to allow the glider to be stored in a trailer, so they are usually installed only at the pilot's preference.

Advertising

Advertising on WestJet Boeing 737-700 winglets

Some airlines capitalize on the visibility of winglets to passengers. AirTran Airways, American Airlines, Southwest Airlines, WestJet and Ryanair advertise their websites on the inboard side of their 737's winglets.

Notable examples

Winglets are employed on many aircraft types, such as:

- Rutan VariEze, the first aircraft to use winglets (1975)
- Learjet 28/29, the first production jet aircraft to use winglets (1977)

- Glaser-Dirks DG-303, an early glider derivative design, incorporating winglets as factory standard equipment
- Airbus A310-300, the first airliner to feature wingtip fences (1985)
- Boeing 747-400, the first mainline airliner to feature winglets (1988)
- Ilyushin Il-96, first Russian and modern jet to feature winglets (1988)
- Tupolev Tu-204, first narrow body aircraft to feature winglets (1994)

Wingtip fence

A detailed view of the wingtip fence on an Airbus A319

A wingtip fence is a winglet variant, with surfaces extending both above and below the wingtip. Both surfaces are shorter than or equivalent to a winglet possessing similar aerodynamic benefits. Wingtip fences are the preferred wingtip device of Airbus, employed on all their airliners except for the A330 and A340 families. The A350 will also make use of winglets rather than wingtip fences.

Blended winglets

Boeing 737 with blended winglets

A blended winglet is attached to the wing with smooth curve instead of a sharp angle and is intended to reduce interference drag at the wing/winglet junction. A sharp interior angle in this region can interact with the boundary layer flow causing a drag inducing vortex, negating some of the benefit of the winglet. The blended winglet is used on business jets and sailplanes, where individual buyer preference is an important marketing aspect.

Blended winglets have been offered as an aftermarket retrofit for Boeing 737, 757, Hawker 800 and the Falcon 2000 with winglets designed by Aviation Partners, a Seattle, Washington-based firm that develops and markets blended winglets. The 737 version is now standard on the Boeing Business Jet derivative. Many operators have retrofitted their fleets with these for the fuel cost savings. Aviation Partners has also developed winglets for the 767-300ER, with American Airlines being the first customer (introduction to airline service is slated for March 2009), and LAN Express and Delta Air Lines following soon after.

Airbus tested similar blended winglets, designed by Winglet Technology, for the Airbus A320 family, but determined that their benefits did not warrant further development. In December 2008, Airbus announced that, in conjunction with Aviation Partners, they are restarting their winglet testing program for the A320, stating they are putting into practice the lessons learned from tests two years before. The stated aim of the new tests is to consider "an integrated Airbus programme".

In 2009 Airbus launched a new blended winglet design which the company called a "**Sharklet**", designed to enhance the payload-range performance of the A320 Family. Offered as a retrofit option, Sharklets are expected to result in a reduced fuel burn of at least 3.5 percent over longer sectors, corresponding to an annual CO2 reduction of around 700 tonnes per aircraft. The A320 will be the first model fitted with Sharklets, which will be delivered in 2012.

Raked wingtip

Boeing 787 rollout showing raked wingtip

Raked wingtips are a feature on some Boeing airliners, where the tip of the wing has a higher degree of sweep than the rest of the wing. The stated purpose of this additional feature is to improve fuel efficiency and climb performance, and to shorten takeoff field length. It does this in much the same way that winglets do, by increasing the effective aspect ratio of the wing and interrupting harmful wingtip vortices. This decreases the amount of lift-induced drag experienced by the aircraft. In testing by Boeing and NASA, raked wingtips have been shown to reduce drag by as much as 5.5%, as opposed to improvements of 3.5% to 4.5% from conventional winglets.

While an equivalent increase in wingspan would be more effective than a winglet of the same length, the bending force becomes a greater factor. A one-foot increase in span has the same bending force as a three-foot winglet, which has the same performance gain as a two-foot wing extension.

For this reason, the short-range Boeing 787-3 design currently calls for winglets instead of the raked wingtips featured on all other 787 variants.

Raked wingtips are installed on, or are planned to be installed on:

- Boeing P-8 Poseidon
- Boeing 747-8 Freighter
- Boeing 747-8 *Intercontinental*
- Boeing 767-400ER
- Boeing 777-200LR
- Boeing 777-300ER
- Boeing 777 Freighter
- Boeing 787-8
- Boeing 787-9

Non-planar wingtip

DG Flugzeugbau DG-1000 glider with raked, non-planar wingtip and winglet

Non-planar wingtips are normally angled upwards in a polyhedral wing configuration, increasing the local dihedral near the wing tip. These provide the wake control benefit of winglets, with less parasitic drag penalty, if designed carefully. The non-planar wing tip is often swept back like a raked wingtip and may also be combined with a winglet. A winglet is also a special case of a non-planar wingtip.

Aircraft designers employed mostly planar wing designs with simple dihedral after World War II, prior to the introduction of winglets. With the wide acceptance of winglets in new sailplane designs of the 1990s, designers sought to further optimize the aerodynamic performance of their wingtip designs. Glider winglets were originally retrofitted directly to planar wings, with only a small, nearly right-angle, transition area. Once the performance of the winglet itself was optimized, attention was turned to the transition between the wing and winglet. A common application was tapering the transition area from the wing tip chord to the winglet chord and raking the transition area back, to place the winglet in the optimal position. If the tapered portion was canted upward, the winglet height could also be reduced. Eventually, designers employed multiple non-planar sections, each canting up at a greater angle, dispensing with the winglets entirely.

Closed surfaces at the end of winglets are a possible way to eliminate the wake vortices induced at the tips of a wing. An example of a closed-surface winglet is the Spiroid winglet, a design currently under development by Aviation Partners. Initial testing using a Gulfstream II test aircraft has shown the winglet design to reduce fuel consumption in the cruise phase by over 10%.

Non-planar wingtips (without winglets) are or will be employed on:

- Schempp-Hirth Discus-2
- Schempp-Hirth Duo Discus
- Airbus A350-800 XWB
- Airbus A350-900 XWB
- Airbus A350-1000 XWB

Actuating wingtip devices

There has been research into actuating wingtip devices, including a filed patent application, though no aircraft currently uses this feature as described. The XB-70 Valkyrie's wingtips were capable of drooping downward in flight, to facilitate Mach 3 flight using waveriding.

Use on rotating blades

"Winged rotor" on AgustaWestland AW101 Merlin helicopter

C-130J Super Hercules showing scimitar propellers with raked tips

Detail view of the wingtip device on a wind turbine rotor-blade.

Wingtip devices are also used on rotating propeller, helicopter rotor, and wind turbine blades to reduce drag, reduce diameter, reduce noise and/or improve efficiency. By reducing aircraft blade tip vortices interacting with the ground surface during taxiing, takeoff, and hover, these devices can reduce damage from dirt and small stones picked up in the vortices.

Rotorcraft applications

The main rotor of the AgustaWestland AW101 (formerly the EH101) has a special "winged tip"; pilots have found that this alters the downwash field and reduces brownout which limits visibility in dusty areas and leads to accidents.

Propeller applications

Hartzell Propeller developed their "Q-tip" propeller used on the Piper PA-42 Cheyenne and several other fixed-wing aircraft types by bending the blade tips back at a 90-degree angle to get the same thrust from a reduced diameter propeller disk; the reduced propeller tip speed reduces noise, according to the manufacturer. Modern scimitar propellers have increased sweepback at the tips, resembling a raked tip on an aircraft wing.