Aircraft Wing Design Technologies

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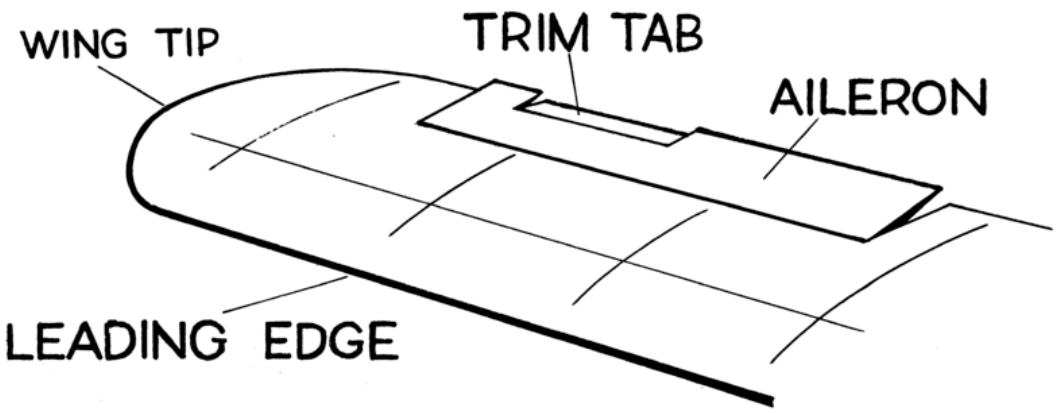
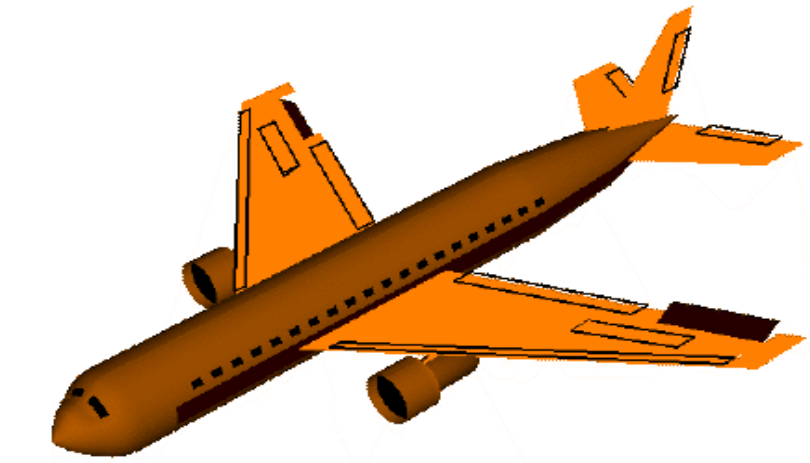
Chapter 1

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

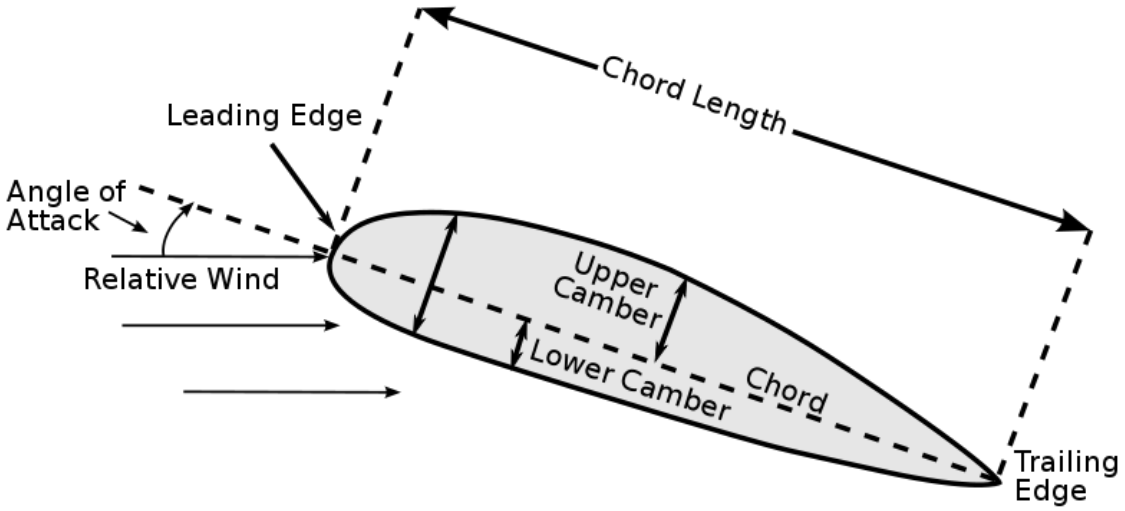
Several technology research and development efforts exist to integrate the functions of aircraft flight control systems such as ailerons, elevators, elevons and flaps, into wings to perform the aerodynamic purpose with the advantages of less: mass, cost, drag, inertia (for faster, stronger control response), 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



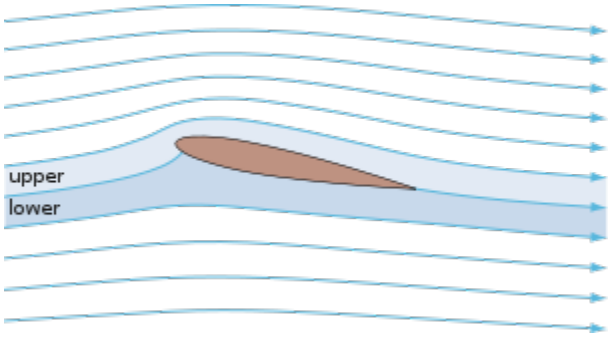
Components of the airfoil.

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.

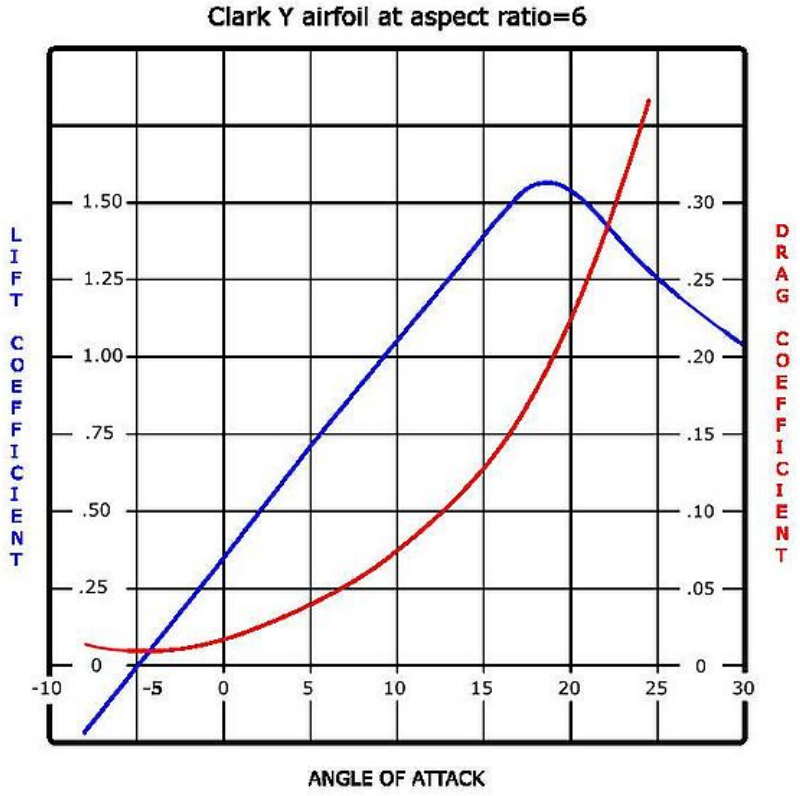
An airfoil-shaped body moved through a fluid produces an aerodynamic force. The component of this force perpendicular to the direction of motion is called lift. The component parallel to the direction of motion is called drag. Subsonic flight airfoils have a characteristic shape with a rounded leading 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.)

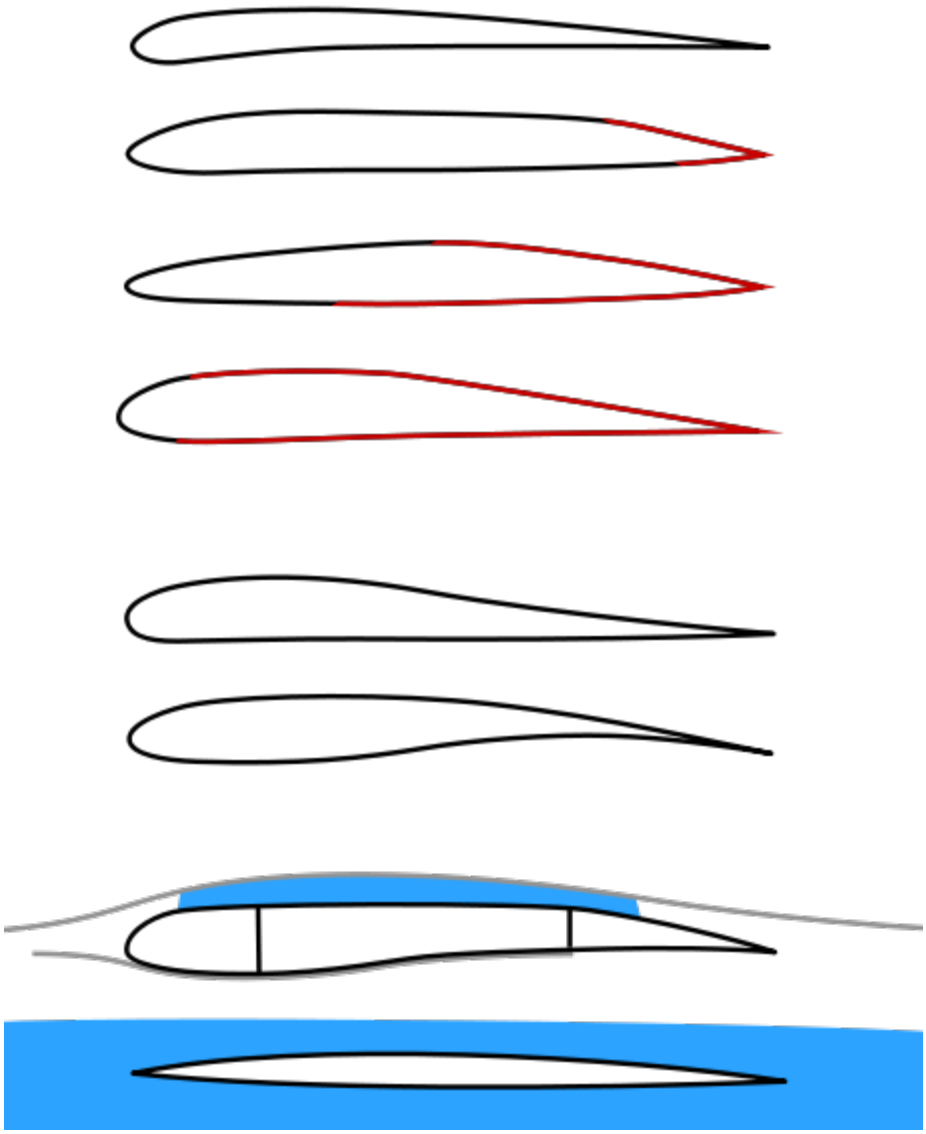
Also as a consequence of (3), the section lift coefficient of a cambered airfoil of infinite wingspan is:

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

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.

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

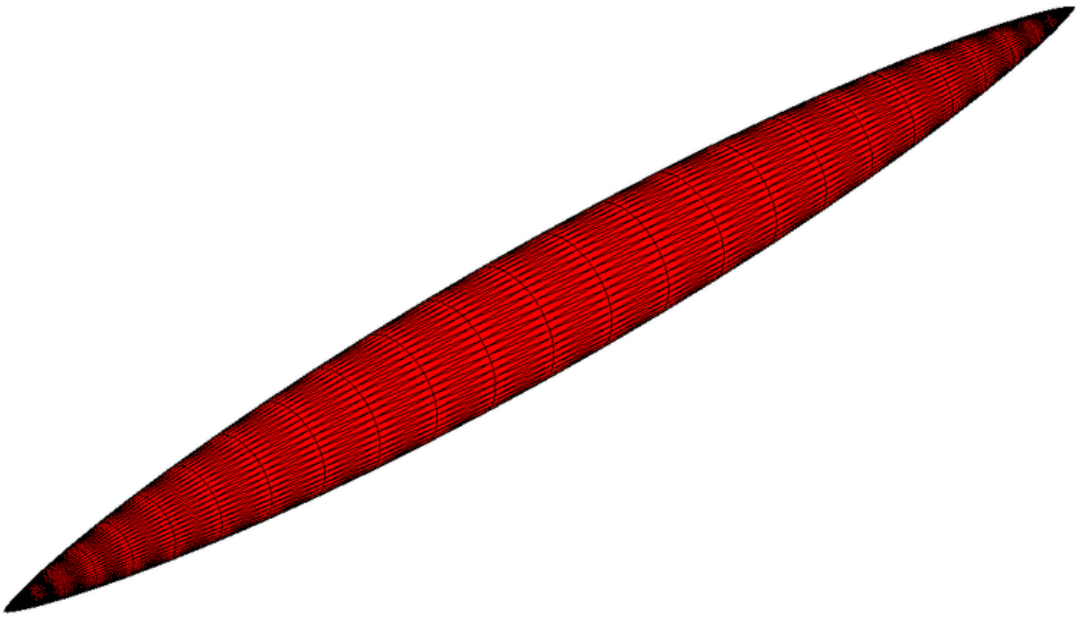
Chapter 3

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

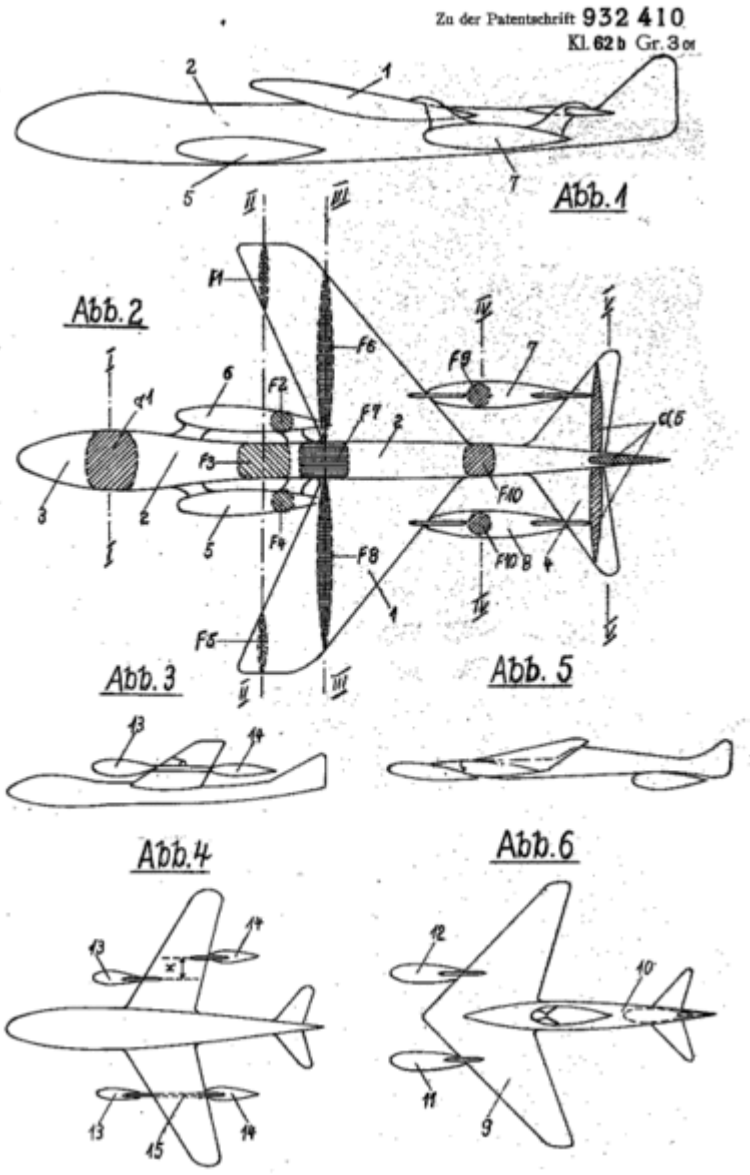
At high-subsonic flight speeds, supersonic airflow can develop in areas where the flow accelerates around the aircraft body and wings. The speed at which this occurs varies from aircraft to aircraft, and is known as the critical Mach number. The resulting shock waves formed at these points of supersonic 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

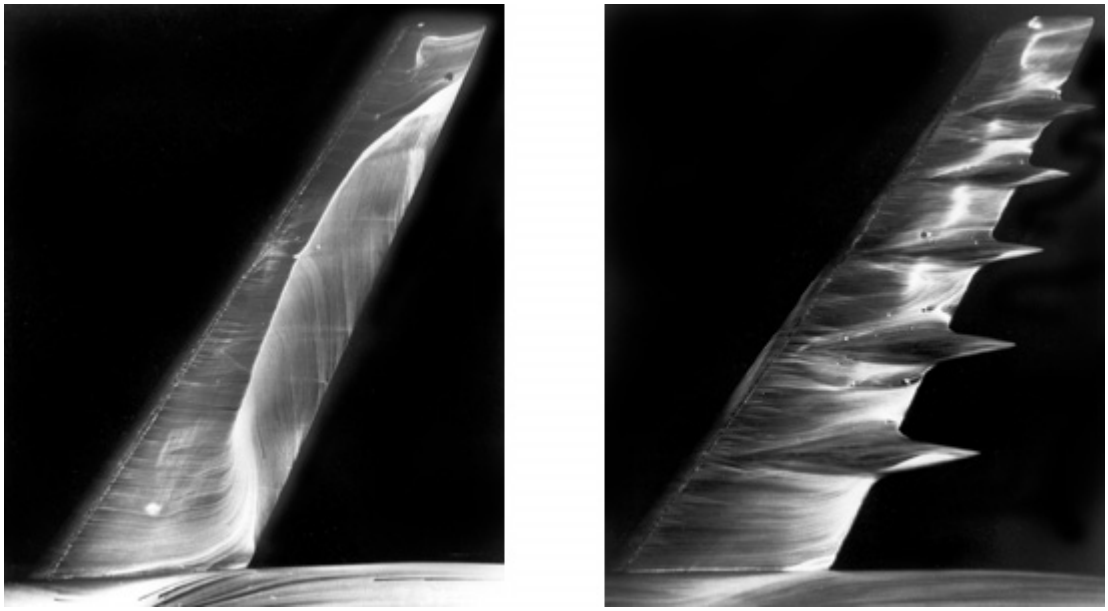
fuselage to be narrowed on either side of the root instead of just behind it, leading to a smoother fuselage that remained wider on average than one using a classic swept wing.

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.

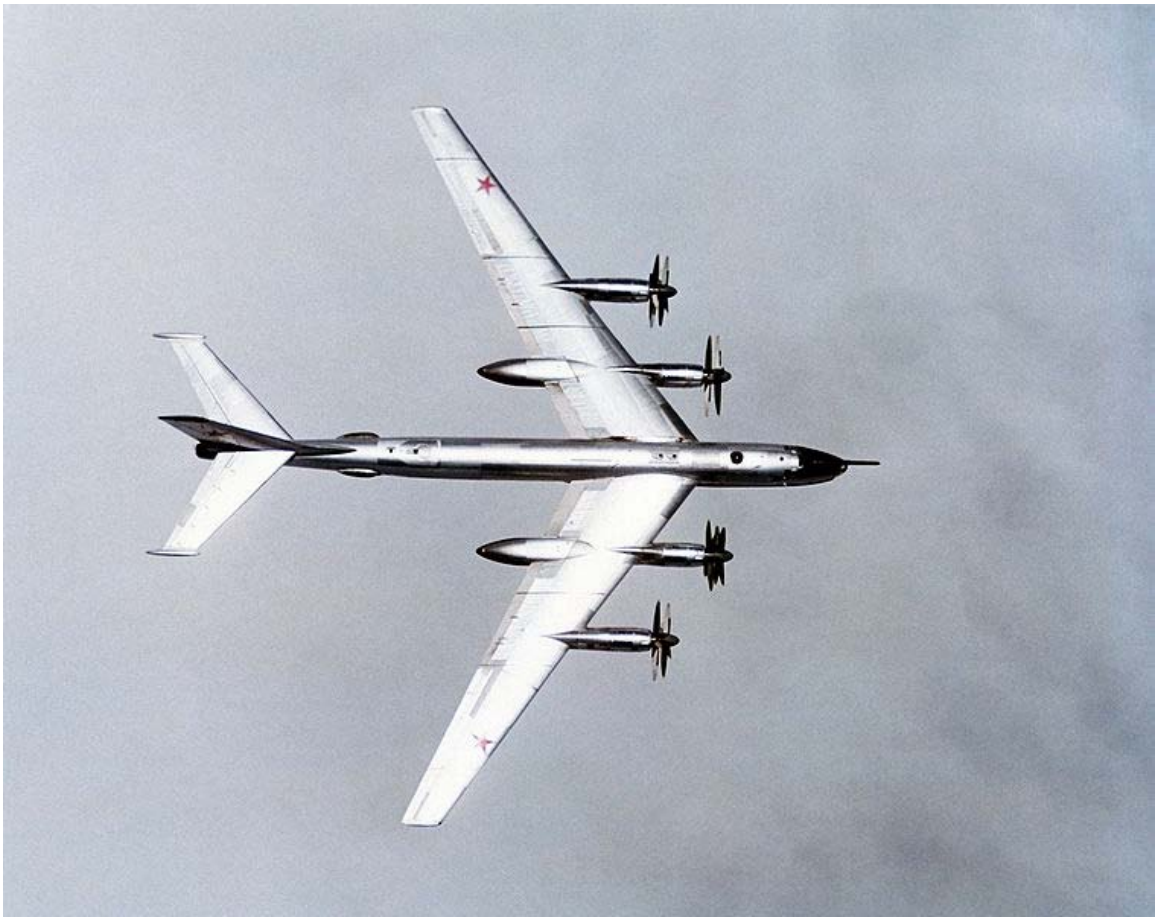
Aircraft designed according to Whitcomb's area rule looked odd at the time they were first tested, (e.g., the Blackburn Buccaneer), and were dubbed "flying Coke bottles," but the area rule is effective and came to be an expected part of the appearance of any transonic aircraft. Later designs started 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

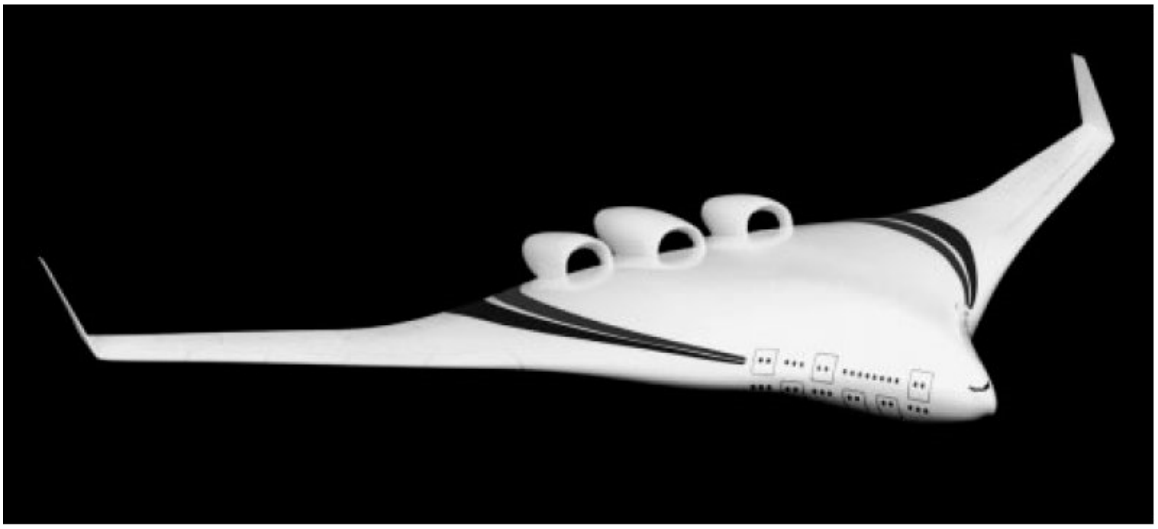


Two large bulged nacelles can be seen behind the engines of this Tupolev Tu-95

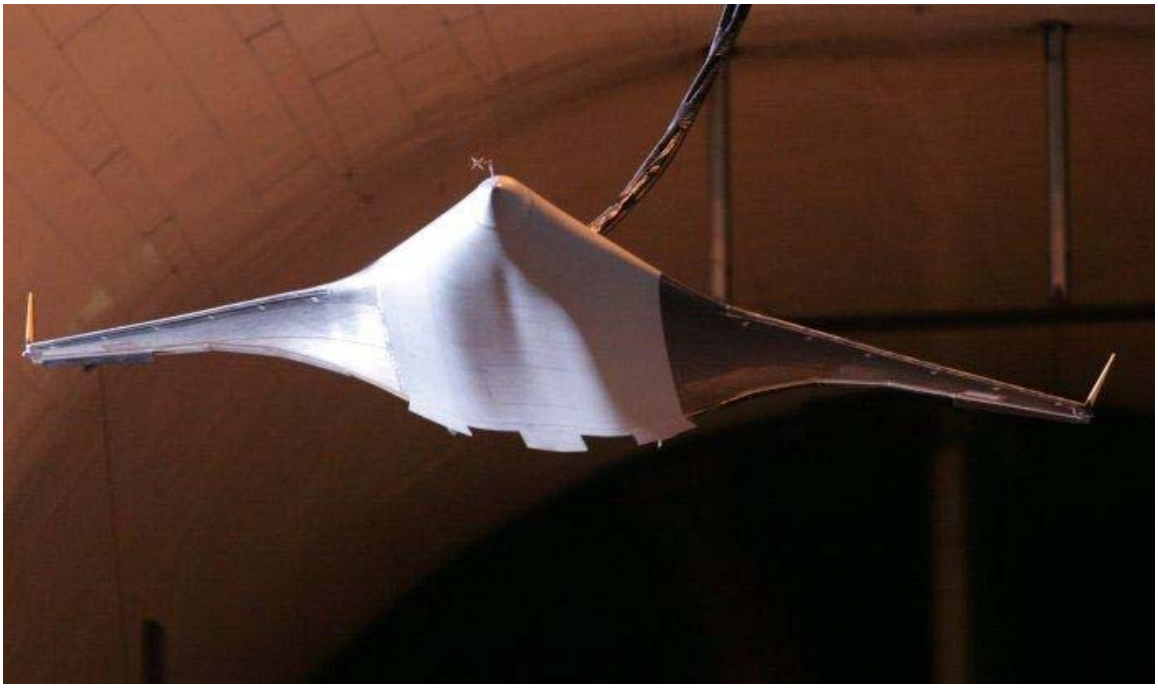
Chapter 4

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.

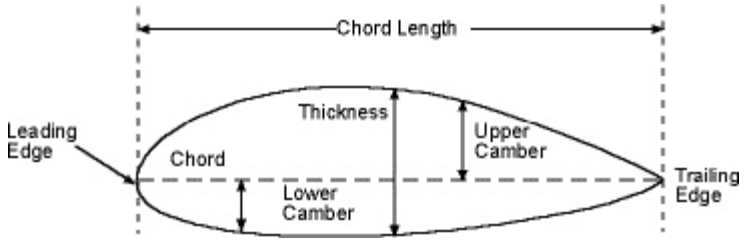
In the 1970s new methods of constructing blown flaps were designed, with the original system becoming known as **internal blowing**. Two systems of **externally blown flaps** were developed, both using the direct exhaust of wing-mounted engines on otherwise simple flaps. Typical flap designs are split 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.

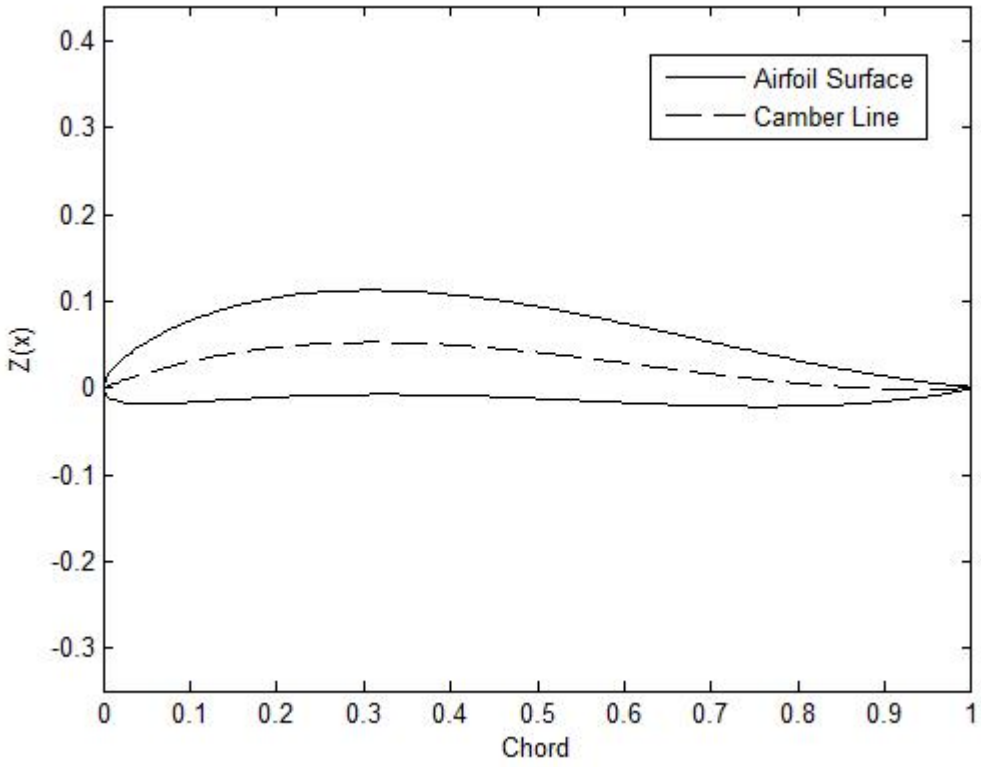
Definition

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*):

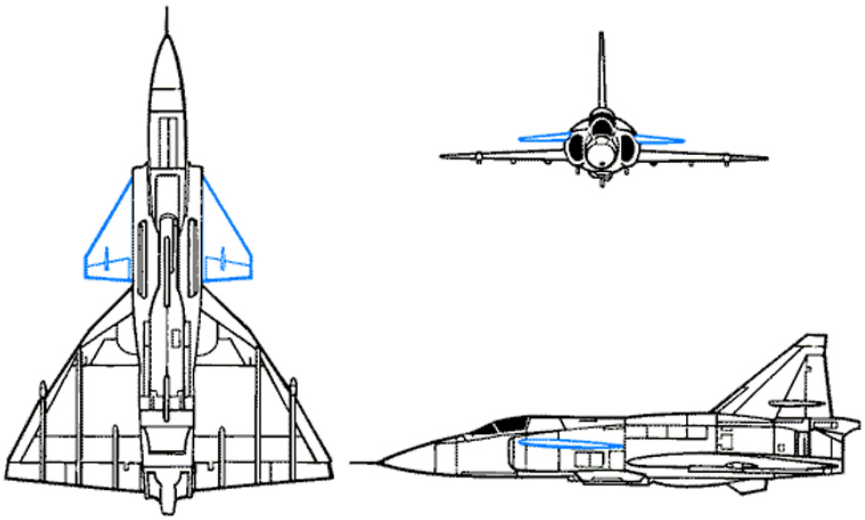
$$\overline{Z}(x) = a\left[(b-1)\,\overline{x}^3 - b\overline{x}^2 + \overline{x}\right]$$

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

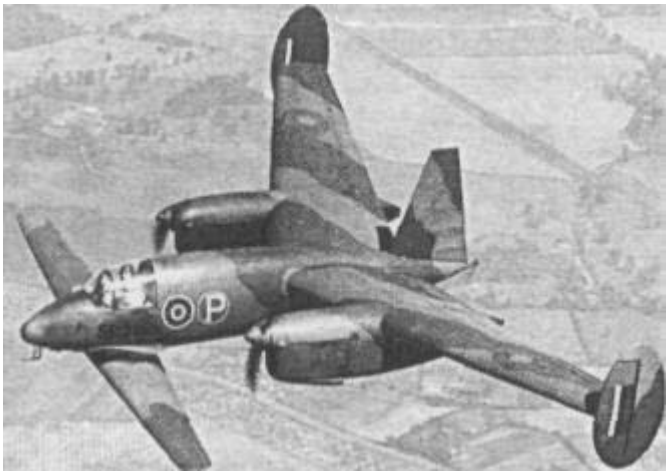
Canards (just behind the flight deck) on the XB-70 Valkyrie experimental bomber aircraft

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

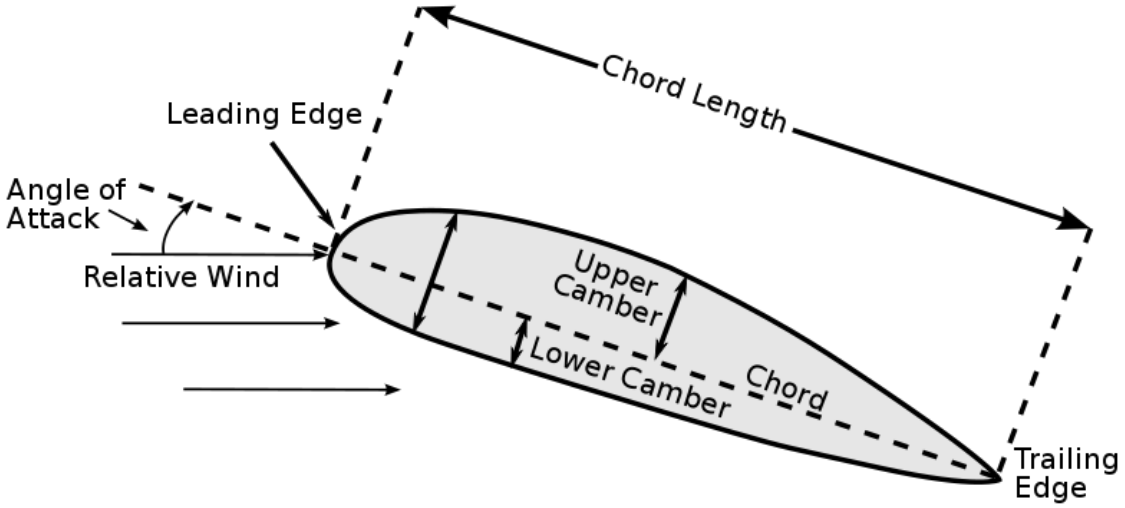


Miles Libellula (1941)

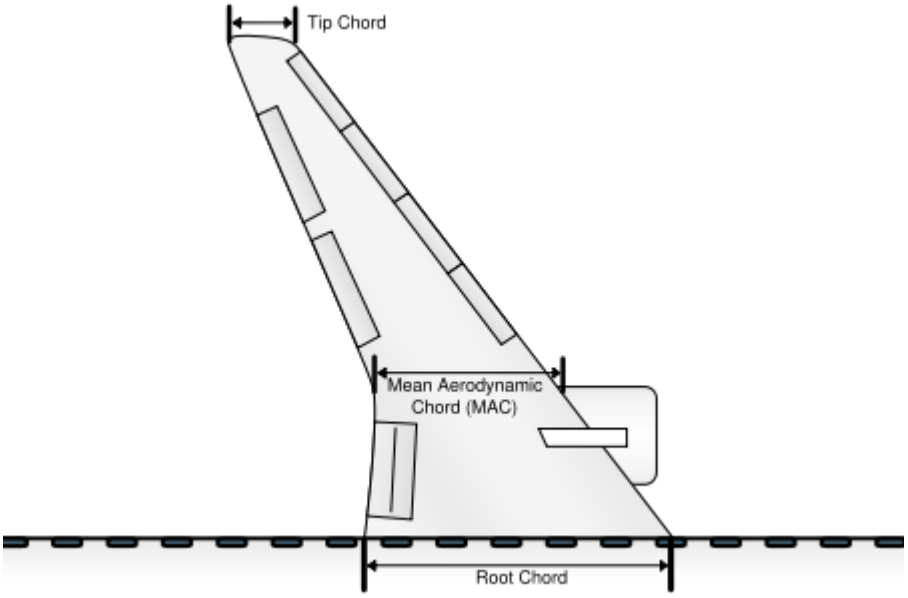
Chapter 6

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:

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

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:

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

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

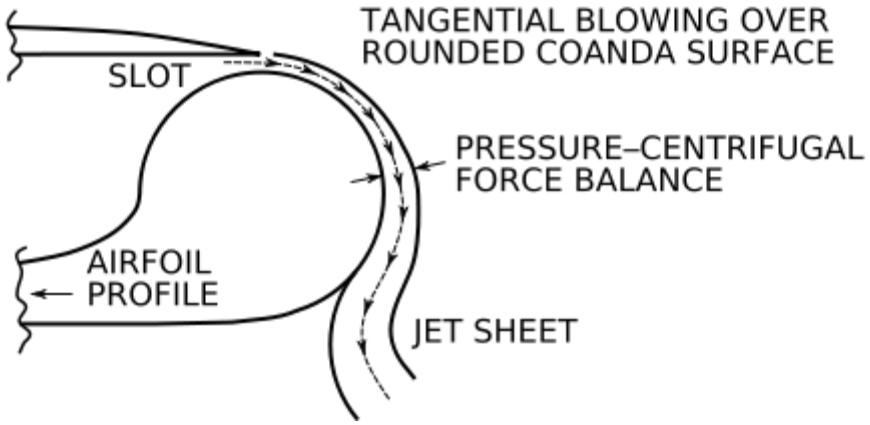
Knowing the area (S_w), taper ratio (λ) and the span (b) of the wing, and whether the wing has sweep or not, the chord at any position on the span can be calculated by the formula:

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

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.

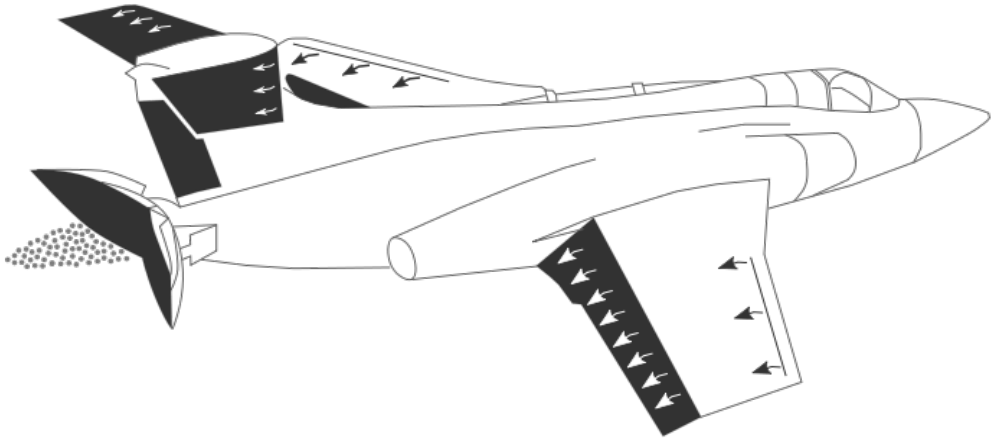
The CCW works by increasing the velocity of the airflow over the leading edge and trailing edge of a specially designed aircraft wing using a series of blowing slots that eject high pressure jet air. The wing has a rounded trailing edge to tangentially eject the air through the Coanda effect thus causing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

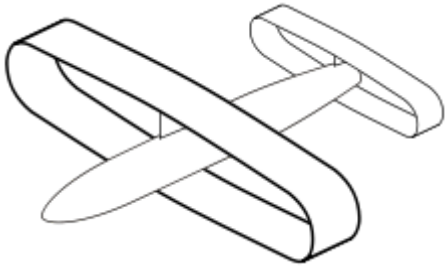
The use of a CCW system eliminates the need for large complex components in the free stream such as flaps and slats, greatly reducing the noise pollution of modern aircraft. Additionally, a much shorter ground roll coupled with steeper climb outs and approaches reduces the ground noise footprint. The 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.

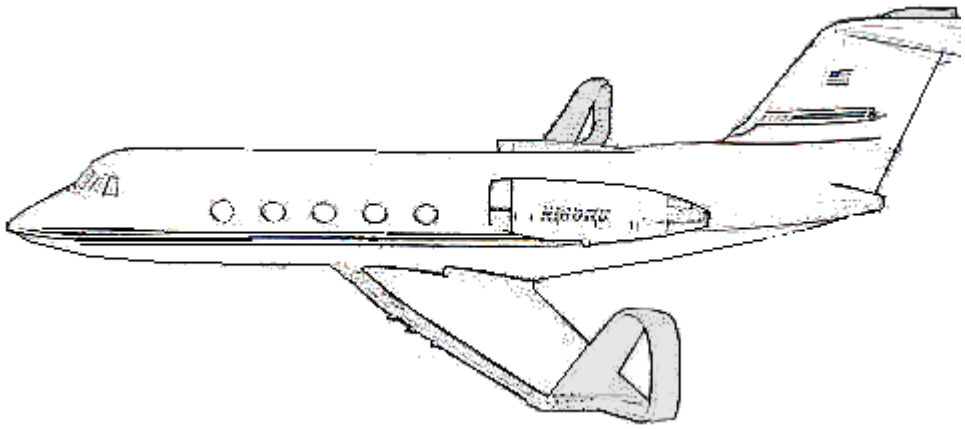
Chapter 7

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

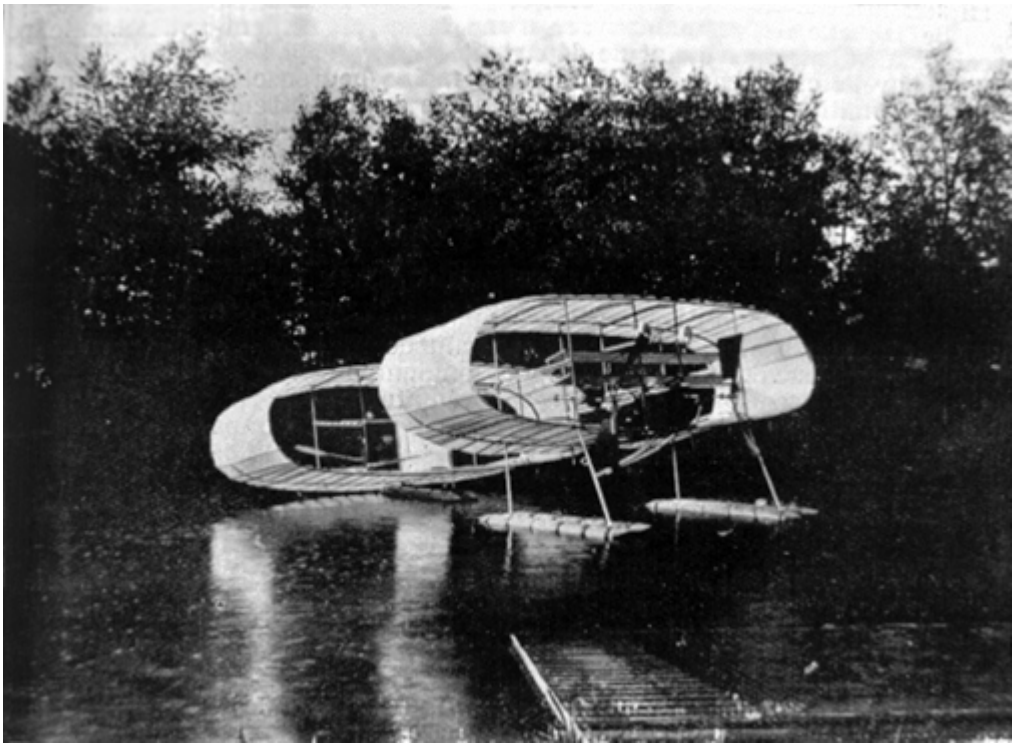


The Spiroid winglet is a closed wing surface attached to the end of a conventional wing.

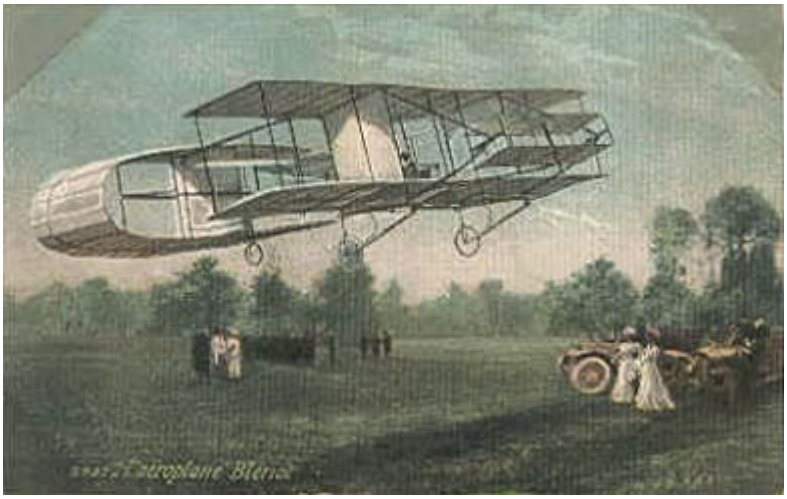
Closed wing surfaces exhibit a number of interesting structural and aerodynamic properties. The boxplane achieves the minimum possible induced drag for a given lift, wingspan, and vertical extent. Annular and joined wings can achieve span efficiencies greater than 1, and the annular wing exhibits half 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.

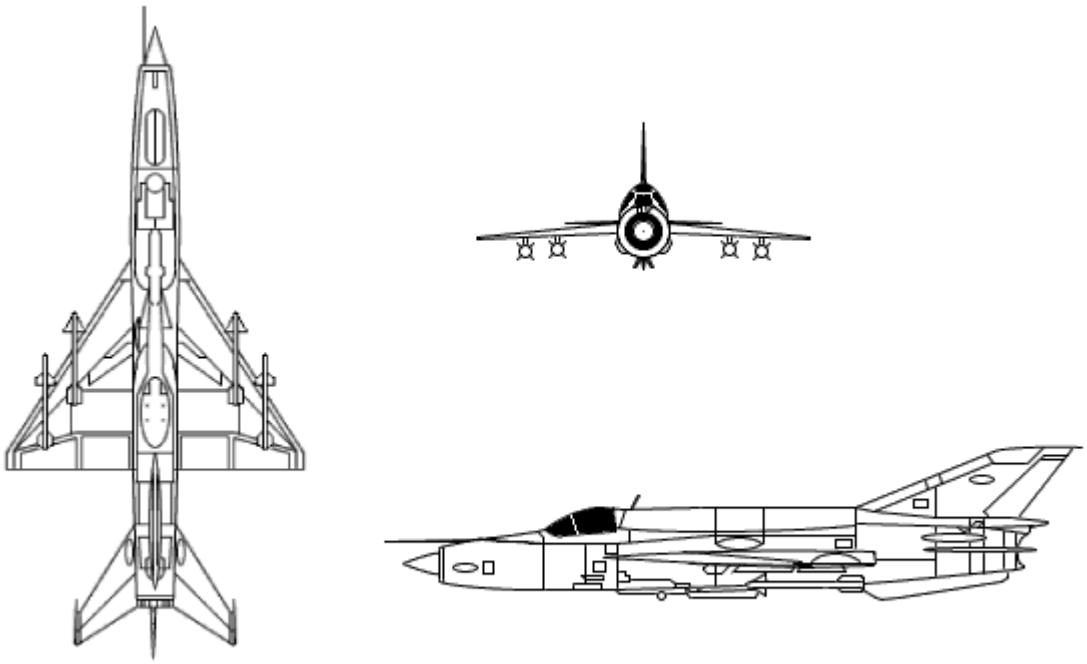
The Spiroid winglet, a design currently under development by Aviation Partners, is a closed wing surface mounted at the end of a conventional wing. Initial testing using a Gulfstream II test aircraft has shown the winglet design to reduce fuel consumption in the cruise phase by over 10%.

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.

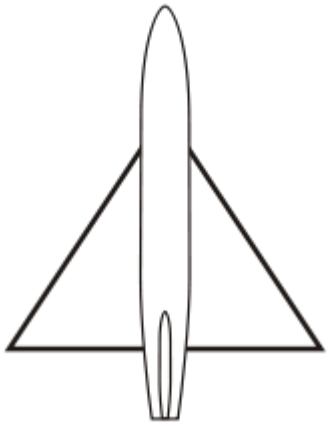
Delta-wing variations

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.

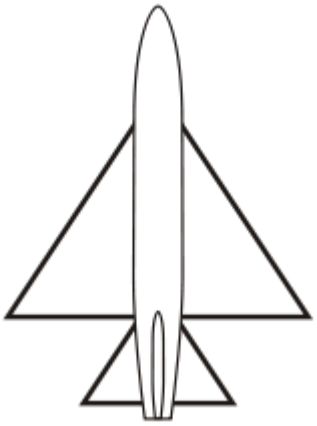
Many modern fighter aircraft, such as the JAS 39 Gripen, the Eurofighter Typhoon and the Dassault Rafale use a combination of canards and a delta wing.

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.

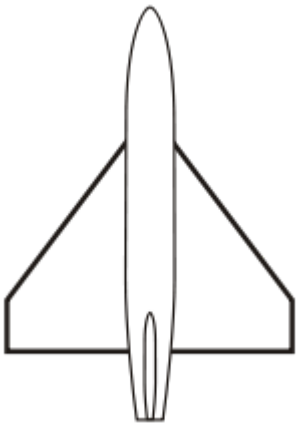
In another variant known variously as **compound delta**, **double delta** or **cranked arrow**, the inner part of the wing has a very high sweepback, while the outer part has less sweepback, to create the high-lift vortex in a more controlled fashion, reduce the drag and thereby allow for landing the 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.



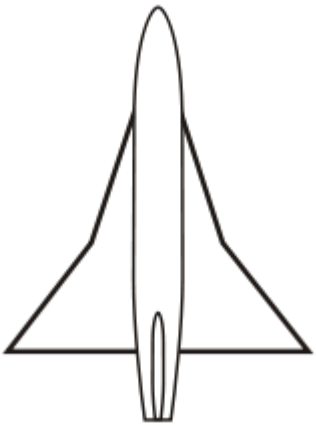
Tailless delta



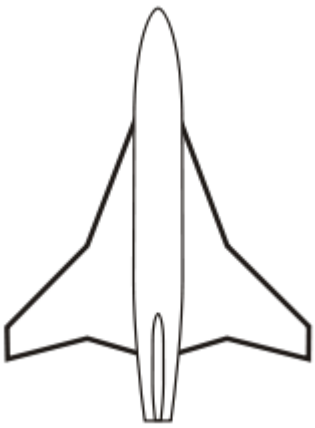
Tailed delta



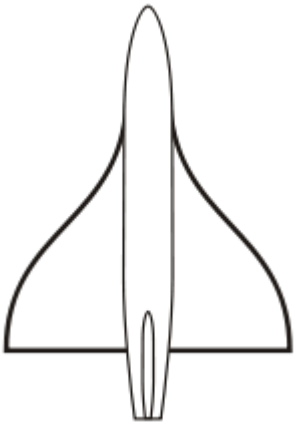
Cropped delta



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.

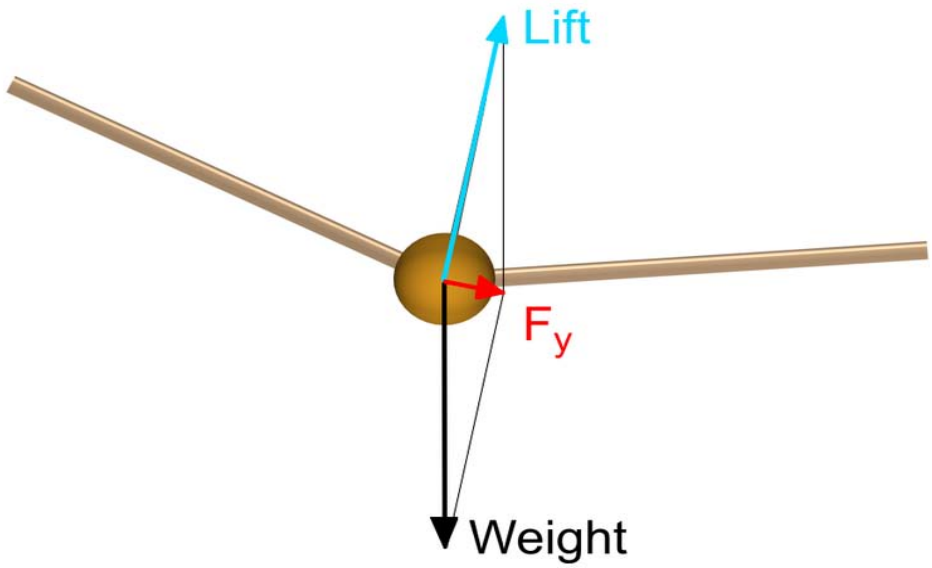


Fig. 1: Uncompensated lift component produces a side force F_y, which causes the aircraft to sideslip.

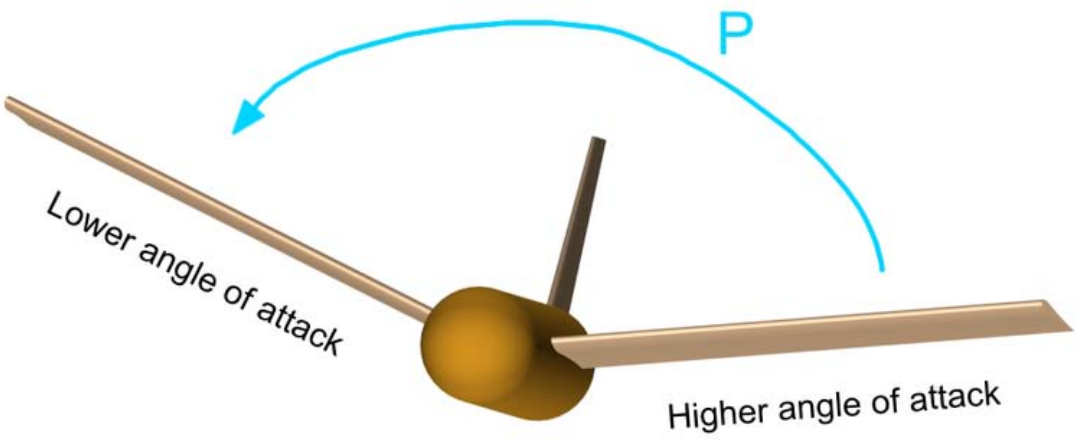


Fig. 2: Non-zero sideslip sets the lower, upwind wing to a higher angle of attack, resulting in stabilising roll moment P.
The aircraft is shown flying towards the viewer.

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

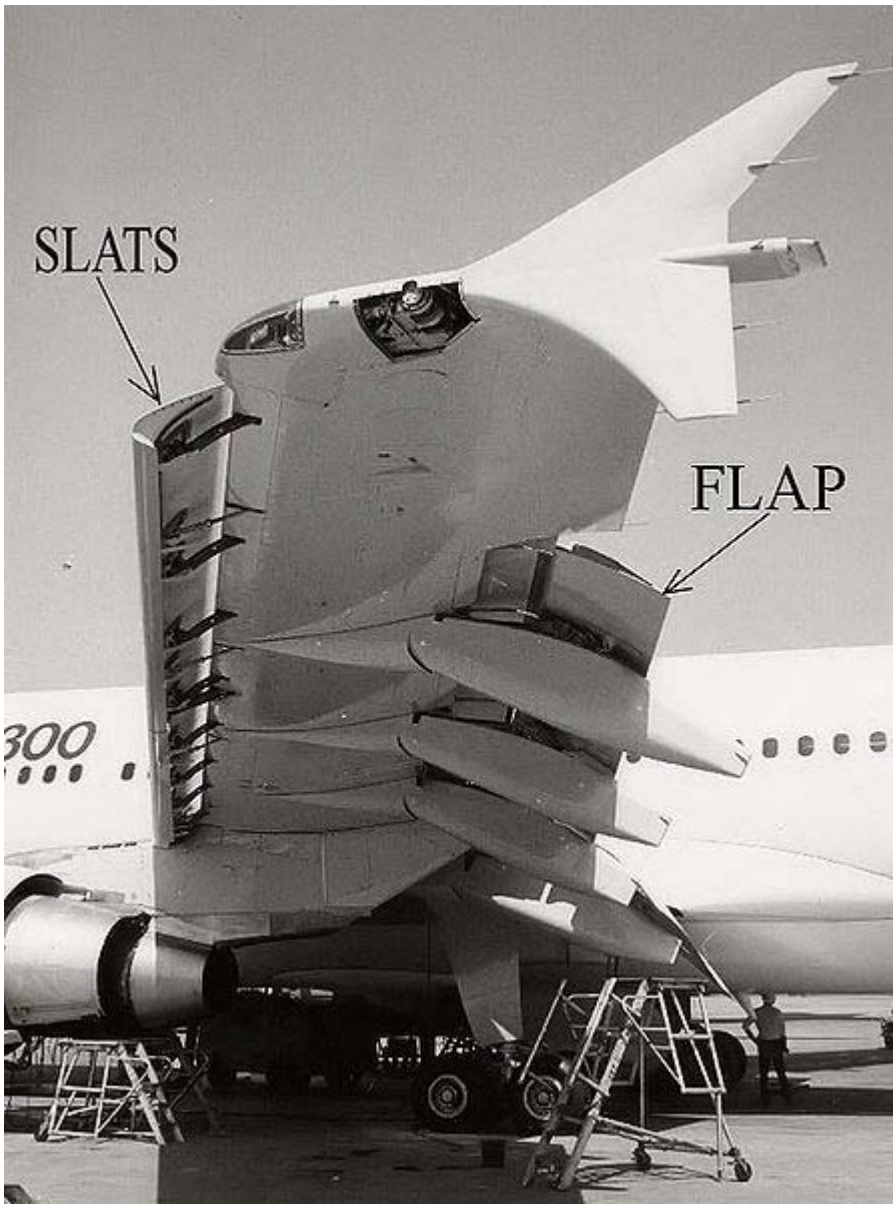
Most aircraft have been designed with planar wings with simple dihedral (or anhedral). Some older aircraft such as the Vought F4U Corsair and the Beriev Be-12 were designed with gull wings bent near the root. Modern polyhedral wing designs generally cant upwards near the wingtips, increasing dihedral 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:

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

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
- $\boldsymbol{C_L}$ 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).

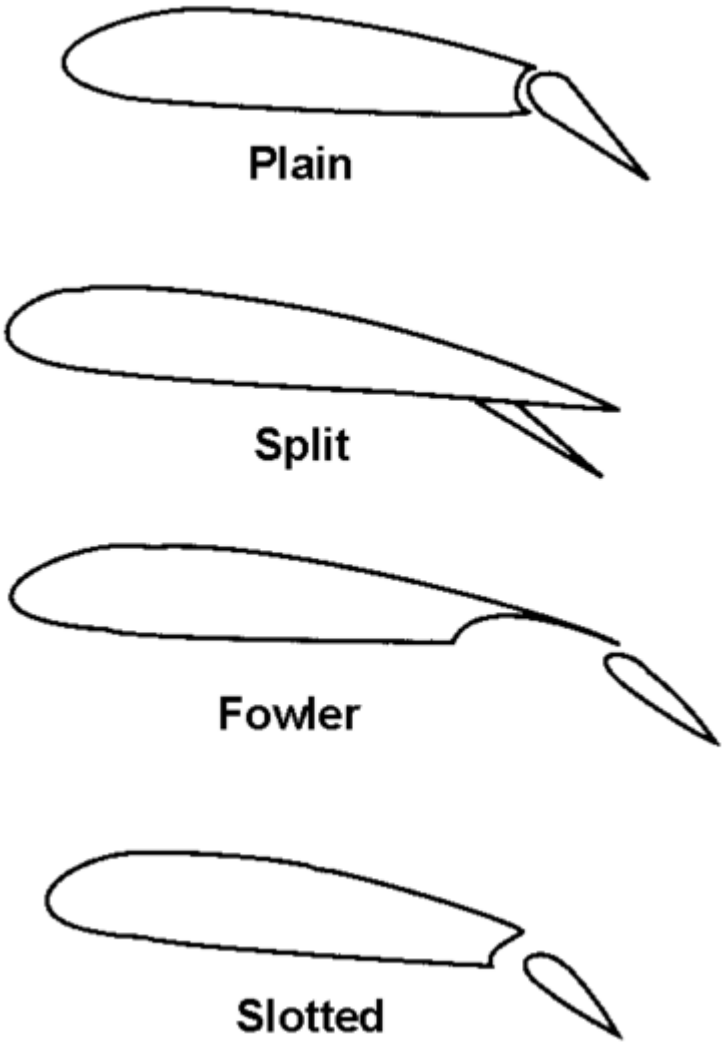
Extending the flaps also increases the drag coefficient of the aircraft. Therefore, for any given weight and airspeed, flaps increase the drag force. Flaps increase the drag coefficient of an aircraft because of higher induced drag caused by the distorted spanwise lift distribution on the wing with flaps 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

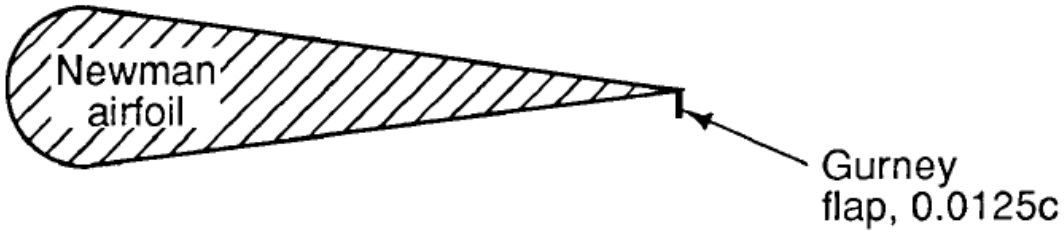
Some aircraft have no fuselage but do have a horizontal stabilizer mounted on one or more booms. Strictly, these are not flying wings although they are usually referred to as such. An example is the Northrop X-216H, which has a tail stabilizer mounted on two tail booms but is regarded as Northrop's first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

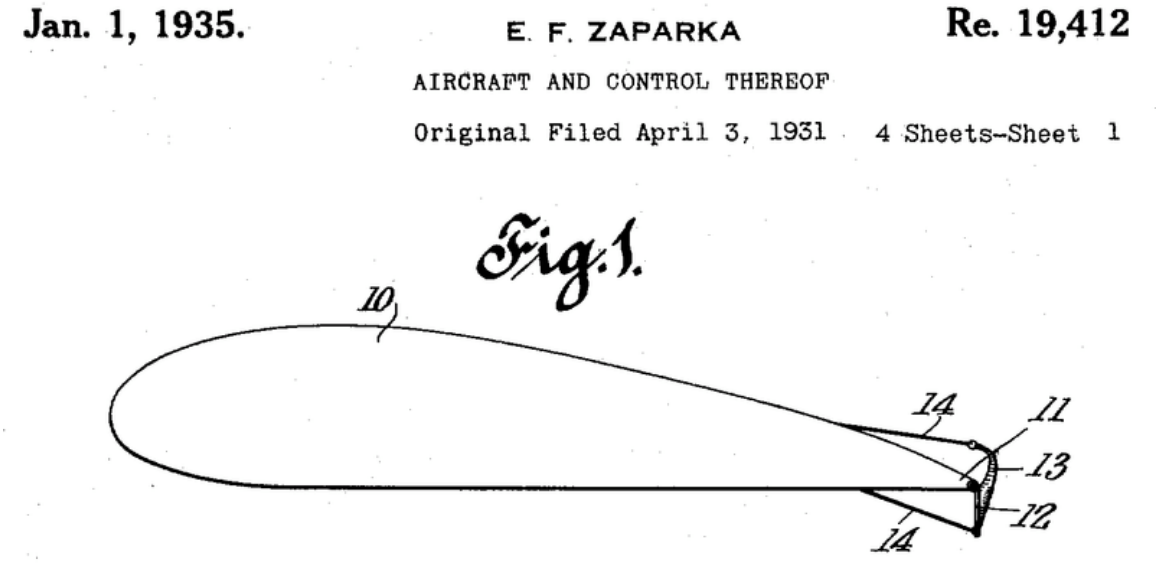


A gurney flap shown on the underside of a Newman airfoil (from NASA Technical Memorandum 4071).

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


Jan. 1, 1935. E. F. ZAPARKA Re. 19,412

AIRCRAFT AND CONTROL THEREOF

Original Filed April 3, 1931 4 Sheets-Sheet 1

Fig. 1.

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.

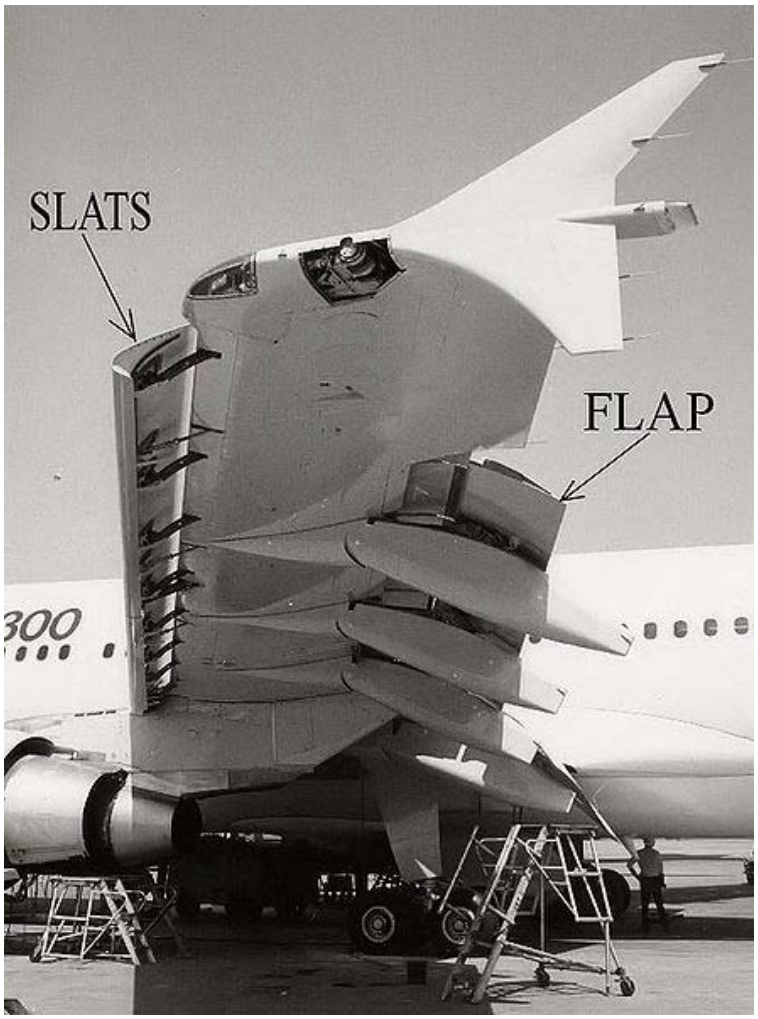
The Gurney flap was first applied to the Sikorsky S-76B variant, when flight testing revealed the horizontal stabilizer from the original S-76 did not provide sufficient lift. Engineers fitted a Gurney flap to the NACA 2412 inverted airfoil to resolve the problem without redesigning the stabilizer from 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 wing of a landing bmi Airbus A319-100. The slats at the leading edge and the flaps at the trailing edge are extended.

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

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.

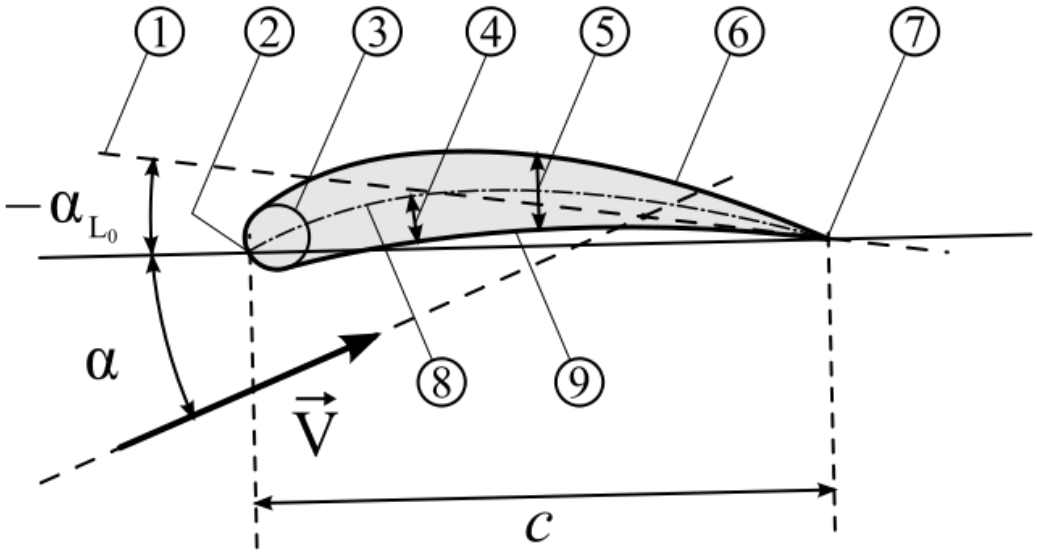
During World War II German aircraft commonly fitted a more advanced version that pushed back flush against the wing by air pressure to reduce drag, popping out when the airflow decreased during slower flight. Notable slats of that time belonged to the German Fieseler Fi 156 *Storch*. These were similar 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.

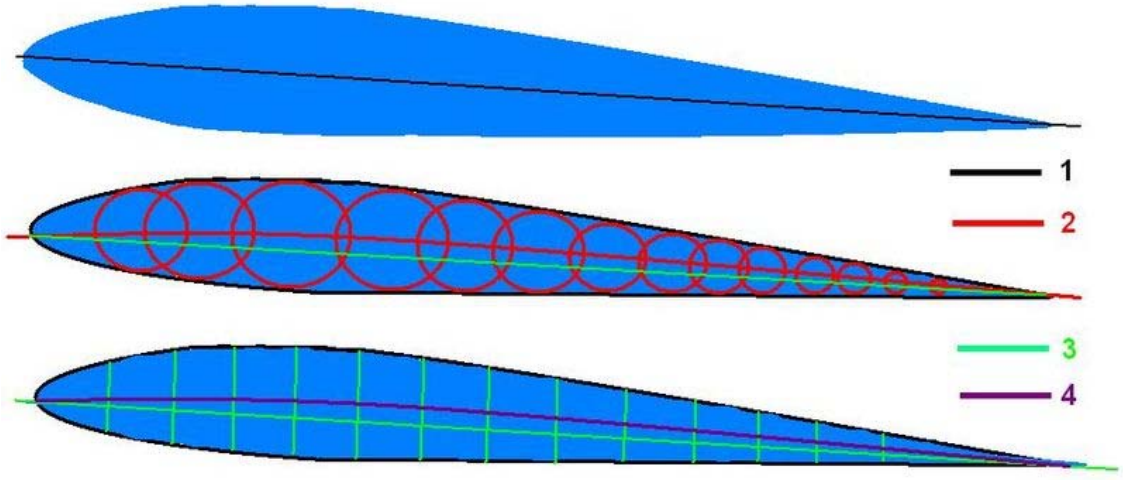
Slats are one of several high-lift devices used on airliners, such as flap systems running along the trailing edge of the wing.

Chapter 14

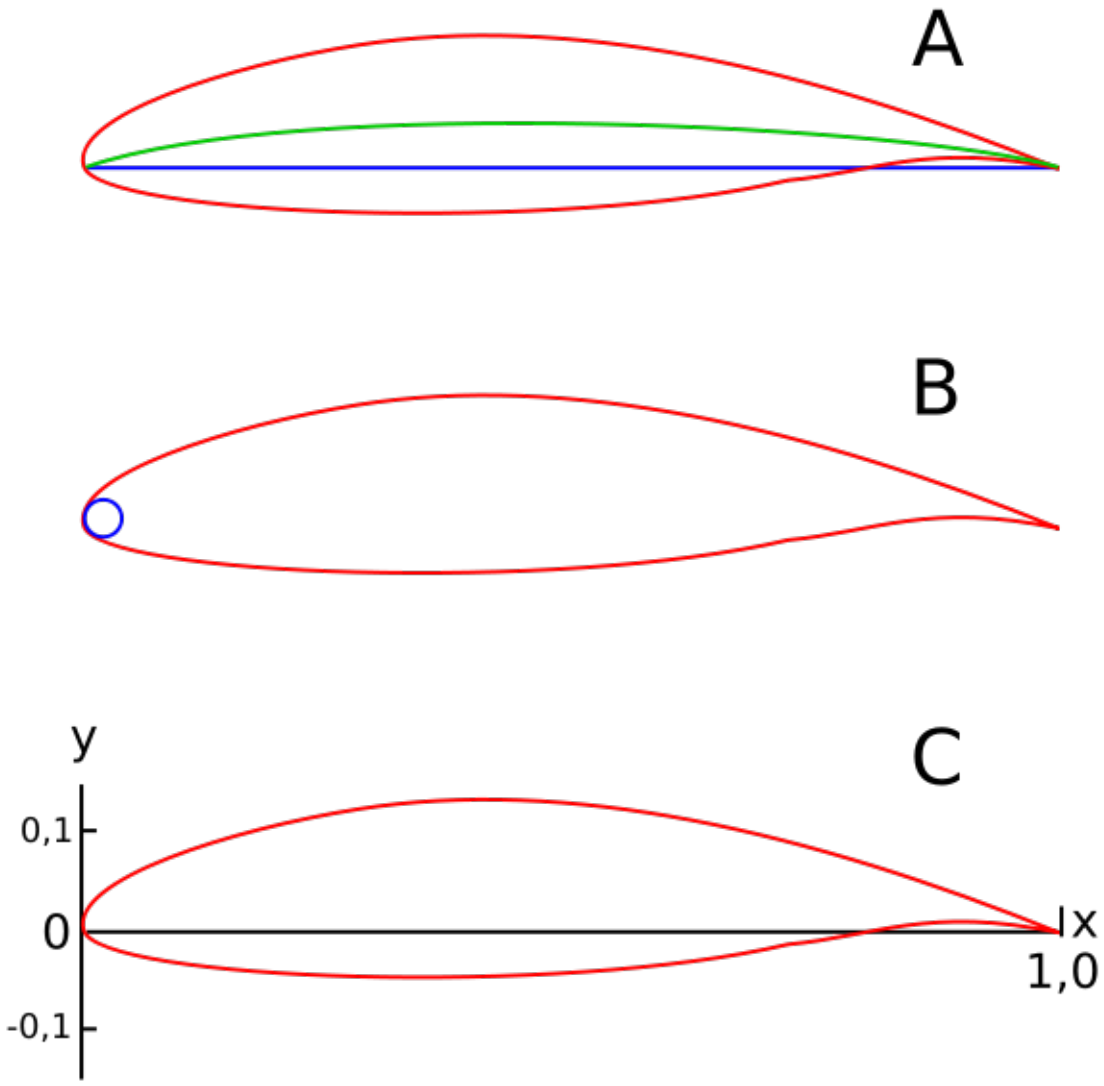
NACA Airfoil



Profile geometry – 1: Zero lift line; 2: Leading edge; 3: Nose circle; 4: Camber; 5: Max. thickness; 6: Upper surface; 7: Trailing edge; 8: Camber mean-line; 9: Lower surface



Profile lines – 1: Chord, 2: Camber, 3: Length, 4: Midline



A: blue line=chord, green line = camber, B: leading edge radius, C: x-y-coordinates for the profile geometry (Chord = x-Axis; y-Axis line on that leading edge)

The **NACA airfoils** are airfoil shapes for aircraft wings developed by the National Advisory Committee for Aeronautics (NACA). The shape of the NACA airfoils is described using a series of digits following the word "NACA." The parameters in the numerical code can be entered into equations to precisely generate the cross-section of the airfoil and calculate its properties.

Four-digit series

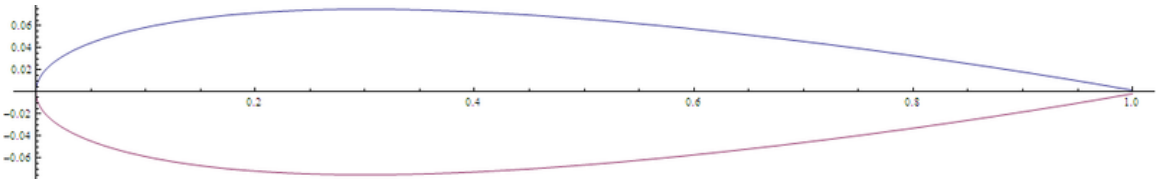
The NACA four-digit wing sections define the profile by:

1. One digit describing maximum camber as percentage of the chord.
2. One digit describing the distance of maximum camber from the airfoil leading edge in tens of percents of the chord.
3. Two digits describing maximum thickness of the airfoil as percent of the chord.

For example, the NACA 2412 airfoil has a maximum camber of 2% located 40% (0.4 chords) from the leading edge with a maximum thickness of 12% of the chord. Four-digit series airfoils by default have maximum thickness at 30% of the chord (0.3 chords) from the leading edge.

The NACA 0015 airfoil is symmetrical, the 00 indicating that it has no camber. The 15 indicates that the airfoil has a 15% thickness to chord length ratio: it is 15% as thick as it is long.

Equation for a symmetrical 4-digit NACA airfoil



Plot of a NACA 0015 foil, generated from formula

The formula for the shape of a NACA 00xx foil, with "xx" being replaced by the percentage of thickness to chord, is:

$$y = \frac{t}{0.2}c\left[0.2969\sqrt{\frac{x}{c}} - 0.1260\left(\frac{x}{c}\right) - 0.3516\left(\frac{x}{c}\right)^2 + 0.2843\left(\frac{x}{c}\right)^3 - 0.1015\left(\frac{x}{c}\right)^4\right],$$

where:

- c is the chord length,
- x is the position along the chord from 0 to c,
- y is the half thickness at a given value of x (centerline to surface), and
- t is the maximum thickness as a fraction of the chord (so 100 t gives the last two digits in the NACA 4-digit denomination).

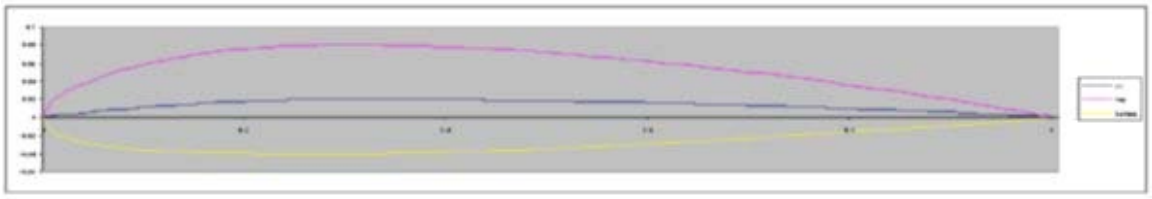
Note that in this equation, at (x/c) = 1 (the trailing edge of the airfoil), the thickness is not quite zero. If a zero-thickness trailing edge is required, for example for computational work, one of the coefficients should be modified such that they sum to zero. Modifying the last coefficient (i.e. to -0.1036) will result in the smallest change to the overall shape of the airfoil. The leading edge approximates a cylinder with a radius of:

$$r = 1.1019\,c\,t^2.$$

Now the coordinates (x_U,y_U) of the upper airfoil surface, and (x_L,y_L) of the lower airfoil surface are:

$$x_U = x_L = x, \qquad y_U = +y, \quad \text{and} \quad y_L = -y.$$

Equation for a cambered 4-digit NACA airfoil



Plot of a NACA 2312 foil, generated from formula

The simplest asymmetric foils are the NACA 4 digit series foils, which use the same formula as that used to generate the 00xx symmetric foils, but with the line of mean camber bent. The formula used to calculate the mean camber line is:

$$y_c = m\,\frac{x}{p^2}\left(2p - \frac{x}{c}\right) \quad \text{from } x = 0 \text{ to } x = p\,c;$$

$$y_c = m\,\frac{c-x}{(1-p)^2}\left(1 + \frac{x}{c} - 2p\right) \quad \text{from } x = p\,c \text{ to } x = c,$$

where:

- m is the maximum camber (100 m is the first of the four digits),
- p is the location of maximum camber (10 p is the second digit in the NACA xxxx description).

For this cambered airfoil, the coordinates (x_U,y_U) and (x_L,y_L), of respectively the upper and lower airfoil surface, become:

$$x_U = x - y\,\sin\theta, \qquad y_U = y_c + y\,\cos\theta,$$
$$x_L = x + y\,\sin\theta, \qquad y_L = y_c - y\,\cos\theta,$$

where

$$\theta = \arctan\left(\frac{dy_c}{dx}\right)$$

Five-digit series

The NACA five-digit series describes more complex airfoil shapes:

1. The first digit, when multiplied by 0.15, gives the designed coefficient of lift (C_L).
2. Second and third digits, when divided by 2, give *p*, the distance of maximum camber from the leading edge (as per cent of chord).
3. Fourth and fifth digits give the maximum thickness of the airfoil (as per cent of the chord).

For example, the NACA 12018 airfoil would give an airfoil with maximum thickness of 18% chord, maximum camber located at 10% chord, with a lift coefficient of 0.15

The camber-line is defined in two sections:

$$y = \begin{cases} \frac{k_1}{6}\left\{x^3 - 3mx^2 + m^2(3-m)x\right\}, & 0 < x < p \\ \frac{k_1 m^3}{6}(1-x), & p < x < 1 \end{cases}$$

where the chordwise location *x* and the ordinate *y* have been normalized by the chord. The constant *m* is chosen so that the maximum camber occurs at $x = p$; for example, for the 230 camber-line, $p = 0.3 / 2 = 0.15$ and $m = 0.2025$. Finally, constant k_1 is determined to give the desired lift coefficient; for camber-line 230 again, $k_1 = 15.957$ is used.

Modifications

Four- and five-digit series airfoils can be modified with a two-digit code preceded by a hyphen in the following sequence:

1. One digit describing the roundness of the leading edge with 0 being sharp, 6 being the same as the original airfoil, and larger values indicating a more rounded leading edge.
2. One digit describing the distance of maximum thickness from the leading edge in tens of percent of the chord.

For example, the NACA 1234-05 is a NACA 1234 airfoil with a sharp leading edge and maximum thickness 50% of the chord (0.5 chords) from the leading edge.

In addition, for a more precise description of the airfoil all numbers can be presented as decimals.

1-series

A new approach to airfoil design pioneered in the 1930s in which the airfoil shape was mathematically derived from the desired lift characteristics. Prior to this, airfoil shapes were first created and then had their characteristics measured in a wind tunnel. The 1-series airfoils are described by five digits in the following sequence:

1. The number "1" indicating the series

2. One digit describing the distance of the minimum pressure area in tens of percent of chord.
3. A hyphen.
4. One digit describing the lift coefficient in tenths.
5. Two digits describing the maximum thickness in percent of chord.

For example, the NACA 16-123 airfoil has minimum pressure 60% of the chord back with a lift coefficient of 0.1 and maximum thickness of 23% of the chord.

6-series

An improvement over 1-series airfoils with emphasis on maximizing laminar flow. The airfoil is described using six digits in the following sequence:

1. The number "6" indicating the series.
2. One digit describing the distance of the minimum pressure area in tens of percent of chord.
3. The subscript digit gives the range of lift coefficient in tenths above and below the design lift coefficient in which favorable pressure gradients exist on both surfaces
4. A hyphen.
5. One digit describing the design lift coefficient in tenths.
6. Two digits describing the maximum thickness in tens of percent of chord.

For example, the NACA 61_2-315 a=0.5 has the area of minimum pressure 10% of the chord back, maintains low drag 0.2 above and below the lift coefficient of 0.3, has a maximum thickness of 15% of the chord, and maintains laminar flow over 50% of the chord.

7-series

Further advancement in maximizing laminar flow achieved by separately identifying the low pressure zones on upper and lower surfaces of the airfoil. The airfoil is described by seven digits in the following sequence:

1. The number "7" indicating the series.
2. One digit describing the distance of the minimum pressure area on the upper surface in tens of percent of chord.
3. One digit describing the distance of the minimum pressure area on the lower surface in tens of percent of chord.
4. One letter referring to a standard profile from the earlier NACA series.
5. One digit describing the lift coefficient in tenths.
6. Two digits describing the maximum thickness in tens of percent of chord.
7. "a=" followed by a decimal number describing the fraction of chord over which laminar flow is maintained. a=1 is the default if no value is given.

For example, the NACA 712A315 has the area of minimum pressure 10% of the chord back on the upper surface and 20% of the chord back on the lower surface, uses the standard "A" profile, has a lift coefficient of 0.3, and has a maximum thickness of 15% of the chord.

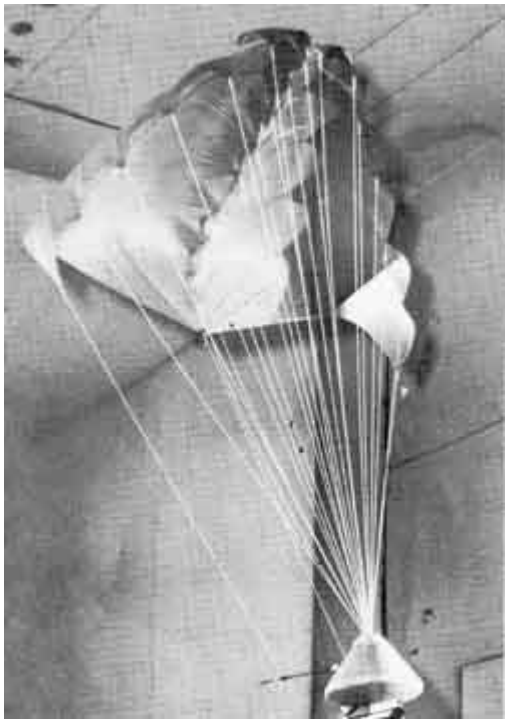
8-series

Supercritical airfoils designed to independently maximize airflow above and below the wing. The numbering is identical to the 7-series airfoils except that the sequence begins with an "8" to identify the series.

Chapter 15

Rogallo Wing and Stabilator

Rogallo wing



The Rogallo flexible wing is a self-inflating system that was tested for the Gemini space capsule recovery.

Paresev, tested by NASA for spacecraft landing research.

The **Rogallo wing** is a flexible type of airfoil. In 1948, Gertrude Rogallo, and her husband Francis Rogallo, a NASA engineer, invented a self-inflating flexible wing they called the **Parawing**, also known as the **Rogallo Wing** and **flexible wing**. NASA considered Rogallo's flexible wing as an alternative recovery system for the Gemini space capsule for possible use in other spacecraft landings, but the idea was dropped in 1964 in favor of using round parachutes.

Construction

A Rogallo wing is composed of two partial conic surfaces with both cones pointing forward. Slow Rogallo wings have wide, shallow cones. Fast subsonic and supersonic Rogallo wings have long, narrow cones. The Rogallo wing is a simple and inexpensive flying wing with remarkable properties. The wing itself is not a kite; neither is it a glider nor a powered aircraft, until the wing is tethered or arranged in a configuration that glides or is powered. In other words, how it is attached and manipulated determines what type of aircraft it becomes. The Rogallo wing is most often seen in toy kites, but has been used to construct spacecraft parachutes, sport parachutes, ultralight powered aircraft like the trike and hang gliders. Rogallo had more than one patent concerning his finding; the due-diligence expansion of his invention involved cylindrical formats, multiple lobes, various

stiffenings, various nose angles, etc. The Charles Richard design and use of the Rogallo wing in the Paresev project resulted in an assemblage that became the stark template for the standard Rogallo hang-glider wing that would blanket the world of the sport in the early 1970s.

Beyond that, the wing is designed to bend and flex in the wind, and so provides favorable dynamics analogous to a spring suspension. Flexibility allows the wing to be less susceptible to turbulence and provides a gentler flying experience than a similarly-sized rigid-winged aircraft. The trailing edge of the wing – which is not stiffened – allows the wing to twist, and provides aerodynamic stability without the need for a tail (empenage).

Rogallo wing hang glider

In 1961-1962 aeronautical engineer Barry Palmer foot-launched several versions of a framed Rogallo wing hang glider to continue the recreational and sporting spirit of hang gliding. Another player in the continuing evolution of the Rogallo wing hang glider was Australian John Dickenson, who in 1963 set to build a controllable water skiing kite/glider. Publicity from the Paresev tested and flown hang gliders sparked interest in the design among several tinkerers, including John Dickenson.

Dickenson fashioned an airframe to fit on a Rogallo airfoil. Dickenson's model made use of a single hang point and an A frame: He started with a framed Rogallo wing airfoil with a U-frame (later an A-frame control bar) to it; it was composed of a keel, leading edges, a cross-bar and a fixed control frame. Weight-shift (mass-shift) was also used to control the glider. The flexible wing called **Ski Wing** was first flown in public at the Grafton Jacaranda Festival in September 1963 by **Rod Fuller** while towed behind a motorboat.

The 'Australian Self-Soar Association' states that the first foot-launch of a hang glider in Australia was in 1972. In Torrance, California, Bill Moyes was assisted in a kited foot-launch by Joe Faust at a beach slope in 1971 or 1972. Moyes went on to build a company with his own Moyes trade-named Rogallo wing hang gliders also using the trapeze control frame he had seen in Dickenson's and Australian manned flat-kite ski kites. Bill Moyes and Bill Bennett exported new refinements of their own hang gliders throughout the world.

The parawing hang glider was inducted into the Space Foundation Space Technology Hall of Fame in 1995.

Control

Rogallo wing hang glider

Hang gliders have been used with different forms of weight-shift control since Otto Lilienthal. The most common way to shift the center of gravity was to fly while suspended from the underarms by two parallel bars. Gottlob Espenlaub (1922), George Spratt (1929) and Barry Palmer (1962) used pendulum seats for the pilot. Interaction with

the A-frame for hang gliders, trikes, and ultralights, provided various means of control of the Rogallo winged hang glider.

Today, most Rogallo wings are also controlled by changing their pitch and roll by means of shifting its center of gravity. This is done by suspending the payload from one or more points beneath the wing and then moving the pendulumed mass of the payload (pilot and things else) mass left or right or forward or aft. Several control methods were studied in NASA for Rogallo wings from 1958 through the 1960s embodied in different versions of the Parawing.

On Rogallo wing hang gliders, John W. Dickenson used a type of weight-shift control frame composed of a mounted triangular control frame under the wing. The pilot sat on a seat and was sometimes also harnessed about the torso. The pilot was suspended behind the triangular control frame which was used as a hand support to push and pull in order to shift the pilot's weight relative to the mass and attitude of the wing above.

Rogallo kites

Rogallo wing kites control pitch with a bridle that sets the wing's angle of attack. A bridle made of string is usually a loop reaching from the front to the end of the center strut of the A-frame. The user ties knots (usually a girth hitch) in the bridle to set the angle of attack. Mass-produced rogallo kites use a bridle that's a triangle of plastic film, with one edge heat-sealed to the central strut.

Steerable Rogallo kites usually have a pair of bridles setting a fixed pitch, and use two strings, one on each side of the kite, to change the roll.

Rogallo also developed a series of soft foil designs in the 60's which have been modified for traction kiting. These are double keel designs with conic wings and a multiple attachment bridle which can be used with either dual line or quad line controls. They have excellent pull, but suffer from a smaller window than more modern traction designs. Normally the #5 and #9 alternatives are used.

Stabilator

F-16 Falcon fighter jet parked at an airshow, with stabilators deflected downwards.

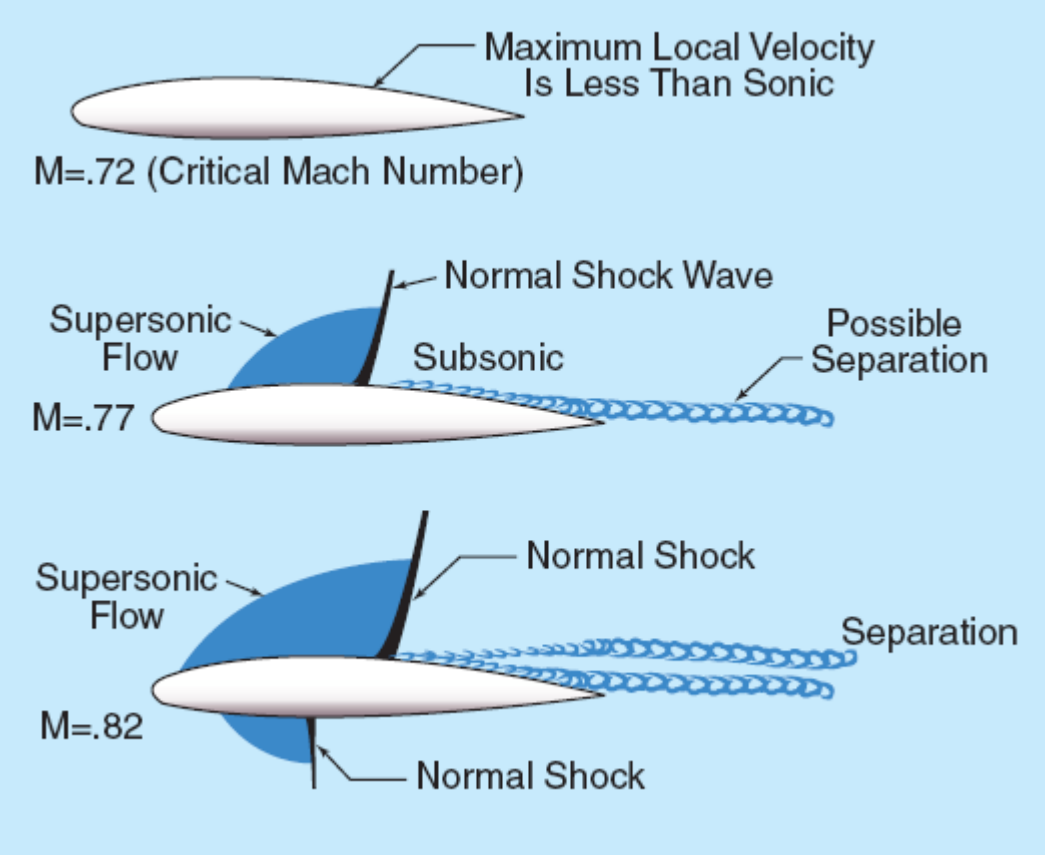
A **stabilator** (**stabil**izer-elev**ator**, also **all moving tailplane** or **all flying tail**) is an aircraft control surface that combines the functions of an elevator and a horizontal stabilizer. Most fixed-wing aircraft control pitch using a hinged horizontal flap — the elevator — attached to the back of the fixed horizontal stabilizer, but some aircraft make the entire stabilizer movable.

General aviation

Piper Cherokee with stabilator (and anti-servo tab) deflected upwards.

Because it involves a large moving surface, a stabilator can allow the pilot to generate greater pitching moment with little effort. Due to the high forces involved in tail balancing loads, stabilators are designed to pivot about their aerodynamic center (at the tail's quarter-chord). This is the point at which the pitching moment is constant regardless of the angle of attack, and thus any movement of the stabilator can be made without added pilot effort. An airplane certified by the appropriate regulatory agency (e.g. the US Federal Aviation Administration) must show an increasing resistance to an increasing pilot input (movement), so to provide this resistance, stabilators on small aircraft contain an anti-servo tab (sometimes combined with the trim tab) that deflects in the same direction as the stabilator, thus providing an aerodynamic force resisting the pilot's input. General aviation aircraft with stabilators include the Piper Cherokee and the Cessna 177.

Military



In transonic flight shockwaves form on the upper surface of the wing at a different point from the lower surface. As speed increases, the shockwave moves backwards over the wing. On conventional tails this high pressure causes the elevator to be deflected downwards.

All flying tailplanes were used from early times and in 1929 the de Havilland DH.77 offering for a Royal Air Force fighter used an all flying tail.

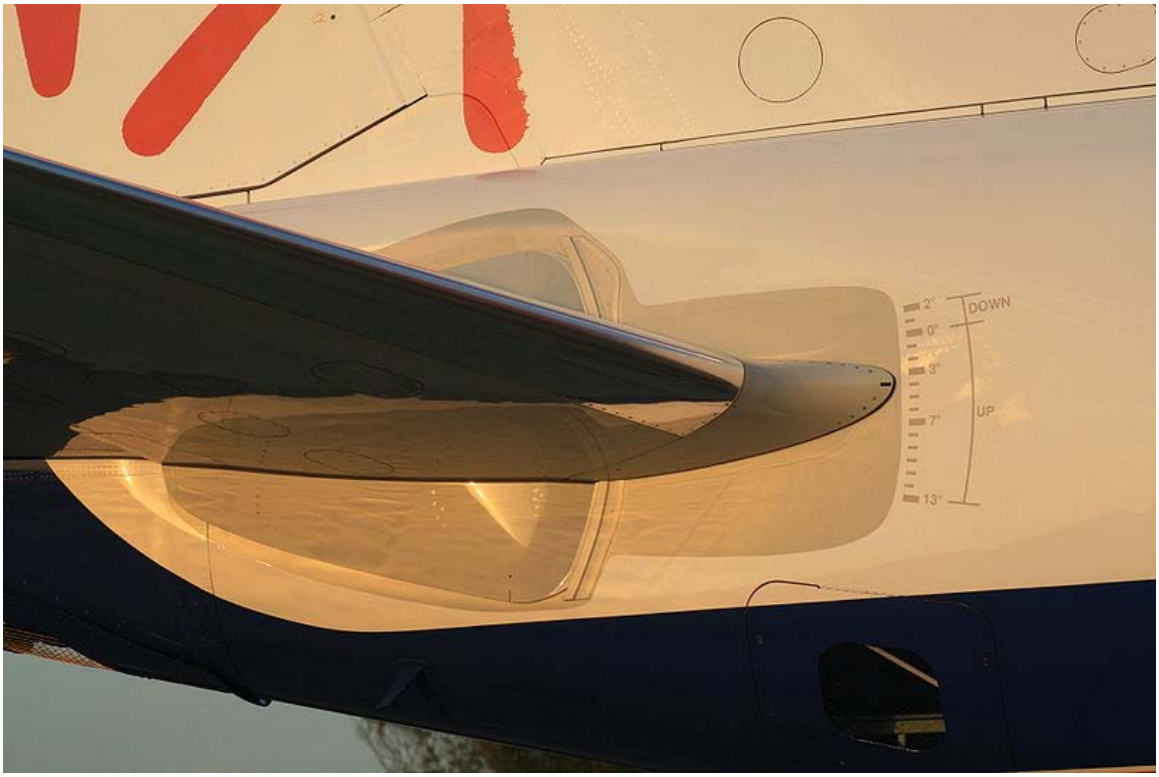
Stabilators were developed in response to the need to achieve adequate pitch control in supersonic flight, and are almost universal on modern military combat aircraft. All non-delta-winged supersonic aircraft use stabilators because with conventional control surfaces, shockwaves can form past the elevator hinge, causing severe mach tuck.

The British wartime Miles M.52 supersonic project had stabilators though the design flew only as a scale rocket. The contemporary US supersonic project, the Bell X-1, adapted its variable incidence tailplane into an all-moving tailplane (based on Miles M.52 data) and was operated successfully. The North American Aviation F-86 Sabre, the first USAF aircraft which could go supersonic (although in a shallow dive) was introduced with a conventional horizontal stabilizer with elevators, which was eventually replaced with a stabilator.

Stabilators are also known in military terminology as **all-moving** or **all-flying tailplanes**. When stabilators can move differentially to perform the roll control function of ailerons, as they do on many modern fighter aircraft they become **tailerons** or **rolling tails**. A stabilator can also be mounted in front of the main wing in a **canard** configuration.

Stabilators on military aircraft have the same problem of overcontrol as general aviation aircraft. In older jet fighter aircraft, a resisting force was generated within the control system, either by springs or a resisting hydraulic force, rather than by an external anti-servo tab. For example in the F-100 Super Sabre, springs were attached to the control stick to provide increasing resistance to pilot input. In modern fighters, control inputs are moderated by computers ("fly by wire"), and there is no direct connection between the pilot's stick and the stabilator.

Airliners



Adjustable stabilizer on an Embraer ERJ-170, with markings showing the degree of nose-up and nose-down trim available

Most modern airliners adjust the angle of the tailplane to trim during flight as fuel is burned and the center of gravity moves. These adjustments are handled by adjustable (in angle of attack) horizontal stabilizers. However, such adjustable stabilizers are not the same as stabilators; a stabilator is controlled by the pilot's control yoke (or stick), and an adjustable stabilizer is controlled by the trim system. One example of an airliner with a genuine stabilator used for flight control is the Lockheed L-1011.

Chapter 16

Swept Wing

A B-52 Stratofortress showing wing with a large sweepback angle.

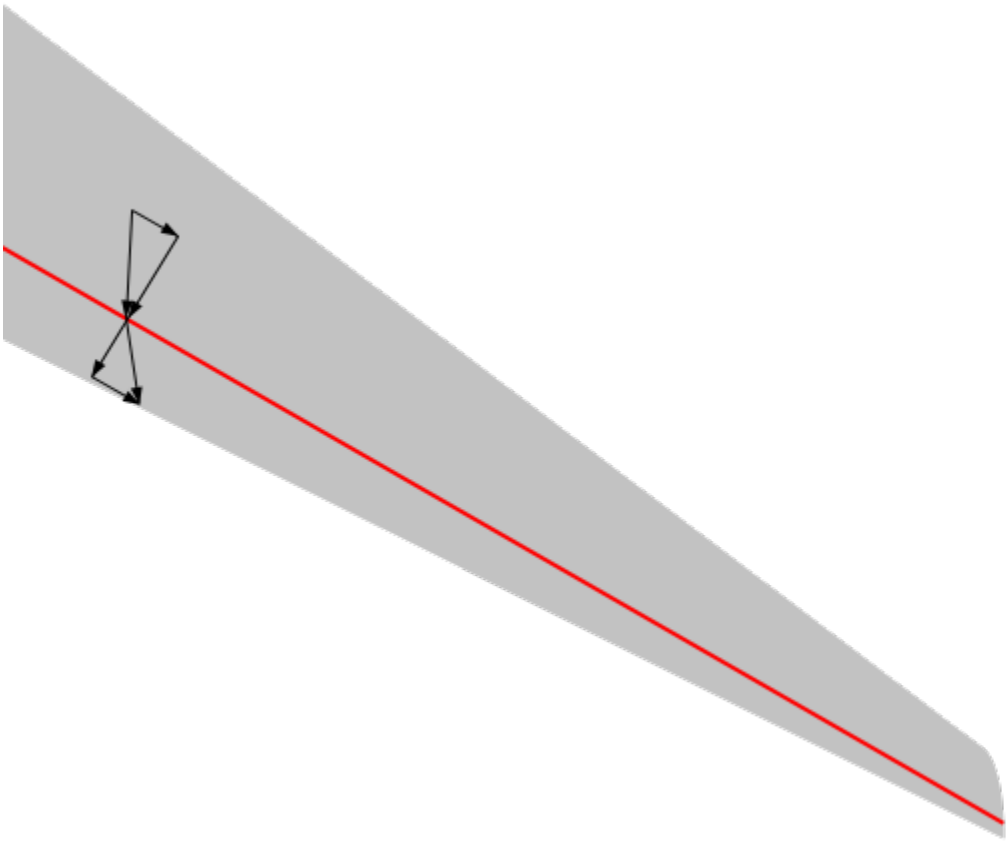
A **swept wing** is a wing planform with a wing root to wingtip direction angled beyond (usually aftward) the spanwise axis, generally used to delay the drag rise caused by fluid compressibility.

Unusual variants of this design feature are forward sweep, variable sweep wings and pivoting wings. Swept wings as a means of reducing wave drag were first used on jet

fighter aircraft. Today they have become almost universal on all but the slowest jets (such as the A-10). The four-engine propeller-driven Tu-95 aircraft also has swept wings.

The *angle of sweep* which characterizes a swept wing is conventionally measured along the 25% chord line. If the 25% chord line varies in sweep angle, the leading edge is used; if that varies, the sweep is expressed in sections (e.g., 25 degrees from 0 to 50% span, 15 degrees from 50% to wingtip).

Subsonic and transonic behavior



In the transonic the swept wing also sweeps the shock which is at the top rear of the wing. Only the velocity component perpendicular to the shock is affected.

As an aircraft enters the transonic speeds just below the speed of sound, an effect known as wave drag starts to appear. Using conservation of momentum principles in the direction normal to surface curvature, airflow accelerates around curved surfaces, and near the speed of sound the acceleration can cause the airflow to reach supersonic speeds. When this occurs, an oblique shock wave is generated at the point where the flow slows down back to subsonic speed. Since this occurs on curved areas, they are normally

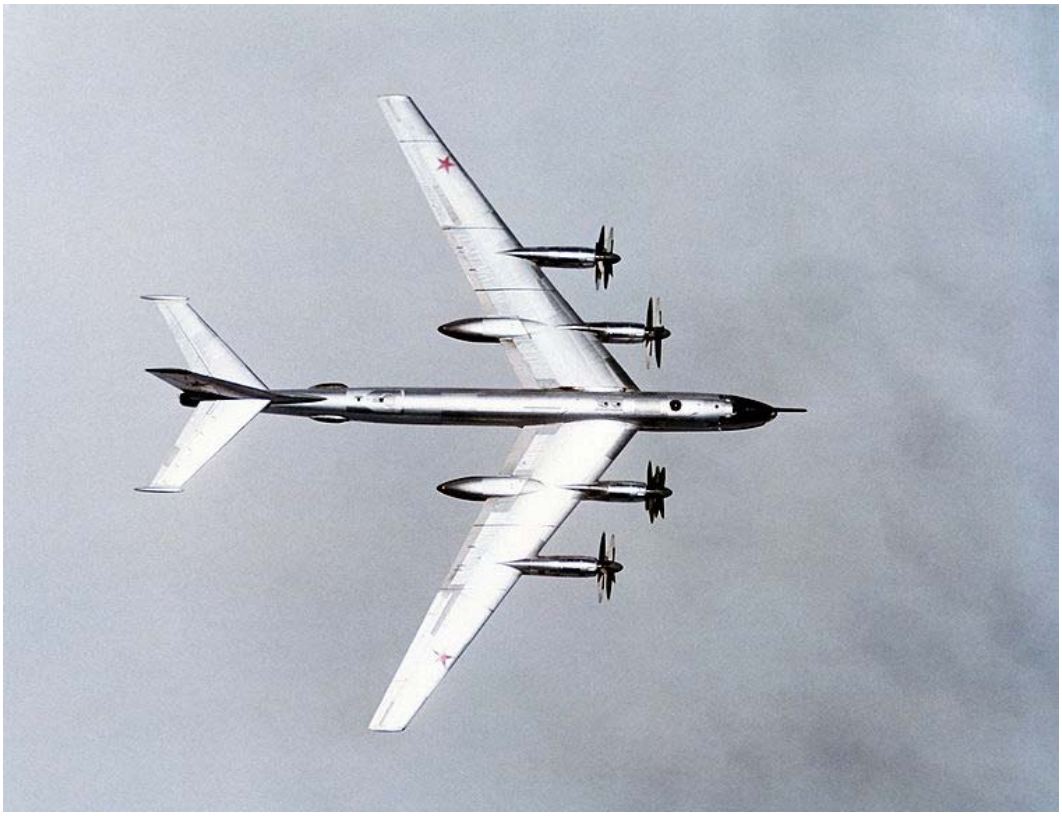
associated with the upper surfaces of the wing, the cockpit canopy, and the nose cone of the aircraft, areas with the highest local curvature.

Shock waves require energy to form. This energy is taken out of the aircraft, which has to supply extra thrust to make up for this energy loss. Thus the shocks are seen as a form of drag. Since the shocks form when the local air velocity reaches supersonic speeds over various features of the aircraft, there is a certain "critical mach" speed (or drag divergence mach number) where this effect becomes noticeable. This is normally when the shocks start generating over the wing, which on most aircraft is the largest continually curved surface, and therefore the largest contributor to this effect.

Since these shock waves are generated at areas of curvature, the obvious way to reduce their effect is to reduce the curvature. In the case of the fuselage, this suggests long, thin designs that are pointed at the ends. Such designs are common on high speed aircraft, the Concorde being one example, and are referred to as having a high "fineness ratio".

This applies to the wing as well, which suggests that wings should have as little curvature as possible, be as thin as possible, and have a long chord. Examples of this sort of wing planform can be found on the F-104 Starfighter for instance, which is highly optimized for high-speed performance. However, these same characteristics make a wing have a very low lift coefficient, and poor performance at slow speeds. The Starfighter has had a large number of landing accidents caused by its very high landing speed that was needed to keep the wing generating enough lift to fly.

Swept wings for the transonic range



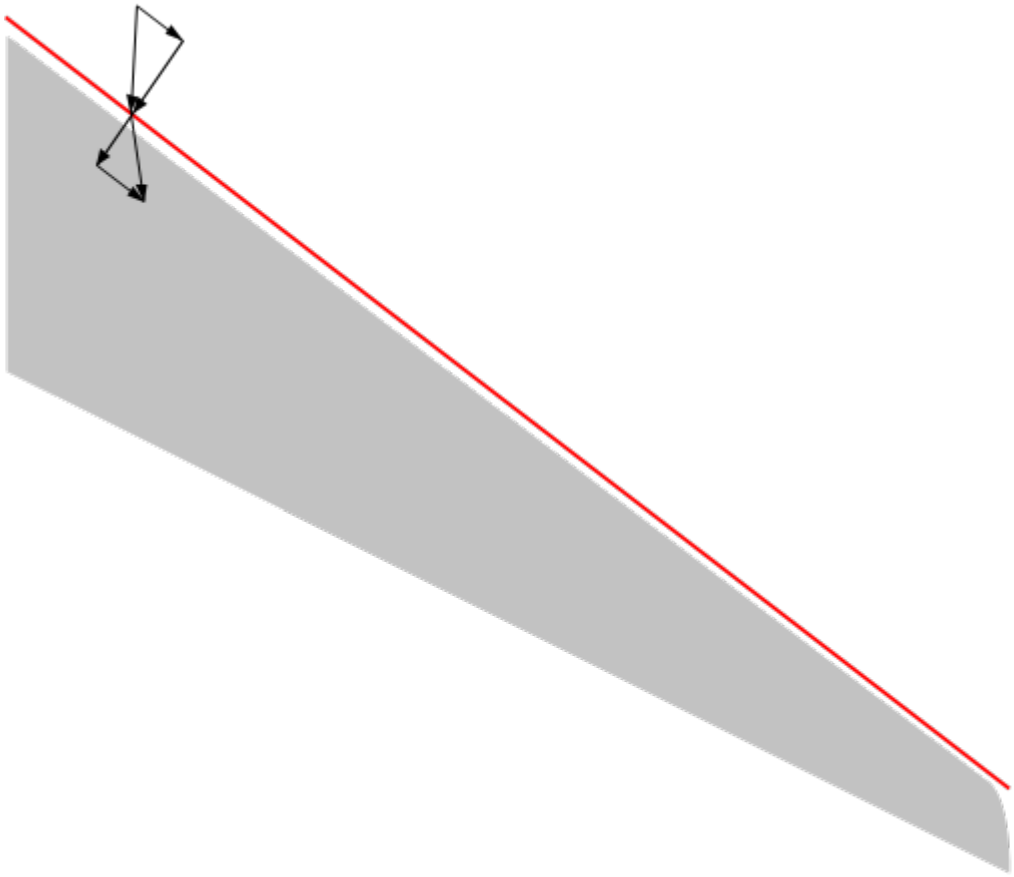
Tu-95 propeller-driven bomber with swept wings, cruise speed 710 km/h

KC-10 Extender, cruise speed: 908 km/h

HFB-320 Hansa Jet with forward swept wings, cruise speed: 825 km/h

Planform view of the swept wing and tailplane of a Virgin Atlantic Airbus A340-600 takeoff. The undercarriages are still retracting

Supersonic behavior



At supersonic speeds an oblique shock exists in front of the leading edge of the wing. The velocity component perpendicular to the shock is different upstream and downstream of the shock. The velocity component parallel to the shock is the same on both sides of the shock.

The F-106 Delta Dart is optimized for supersonic flight and has a highly swept wing.

F-14 Tomcat, an example of a variable-geometry aircraft, shown in the high-sweepback configuration that is the optimum for supersonic speeds. The wings lie behind the shock cone generated in supersonic flight.

Airflow at supersonic speeds generates lift through the formation of shock waves, as opposed to the patterns of airflow over and under the wing. These shock waves, as in the transonic case, generate large amounts of drag. One of these shock waves is created by the leading edge of the wing, but contributes little to the lift. In order to minimize the strength of this shock it needs to remain "attached" to the front of the wing, which demands a very sharp leading edge. To better shape the shocks that will contribute to lift, the rest of an ideal supersonic airfoil is roughly diamond-shaped in cross-section. For

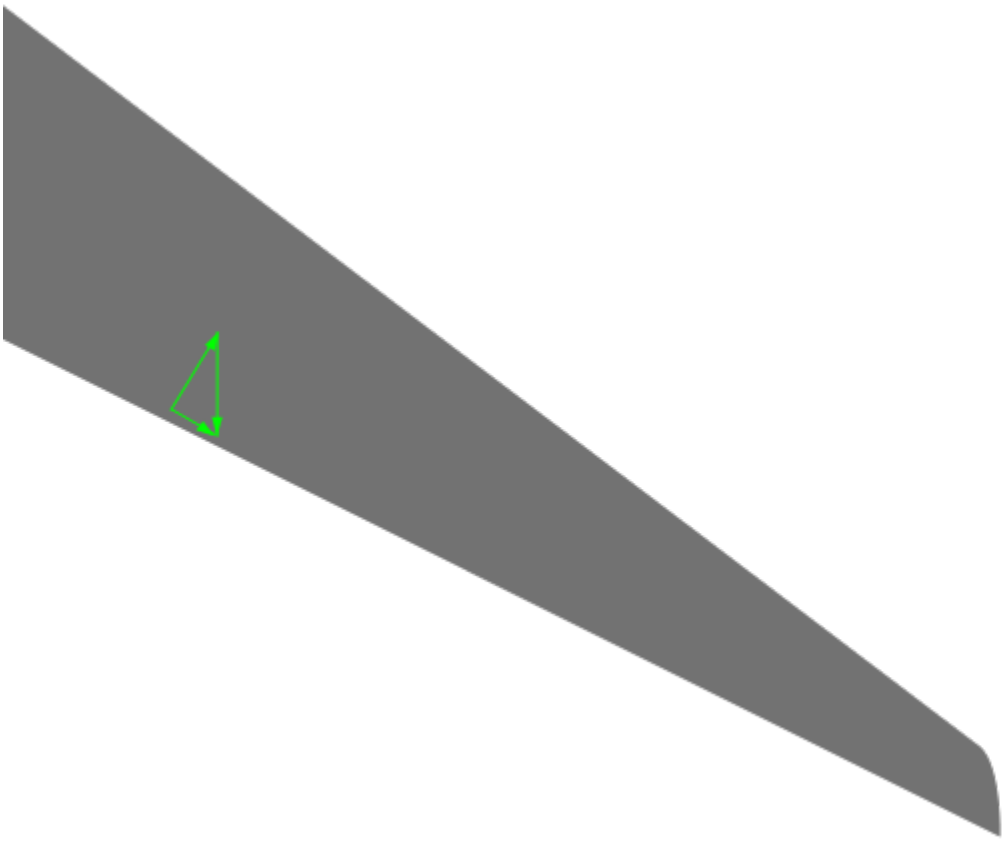
low-speed lift these same airfoils are very inefficient, leading to poor handling and very high landing speeds.

One way to avoid the need for a dedicated supersonic wing is to use a highly swept subsonic design. Airflow behind the shock waves of a moving body are reduced to subsonic speeds. This effect is used within the intakes of engines meant to operate in the supersonic, as jet engines are generally incapable of ingesting supersonic air directly. This can also be used to reduce the speed of the air as seen by the wing, using the shocks generated by the nose of the aircraft. As long as the wing lies behind the cone-shaped shock wave, it will "see" subsonic airflow and work as normal. The angle needed to lie behind the cone increases with increasing speed, at Mach 1.3 the angle is about 45 degrees, at Mach 2.0 it is 60 degrees. For instance, at Mach 1.3 the angle of the Mach cone formed off the body of the aircraft will be at about $\sin\mu = 1/M$ (μ is the sweep angle of the Mach cone)

Generally it is not possible to arrange the wing so it will lie entirely outside the supersonic airflow and still have good subsonic performance. Some aircraft, like the English Electric Lightning or F-106 Delta Dart are tuned entirely for high-speed flight and feature highly-swept planforms without regard to the low-speed problems this creates. In other cases the use of variable geometry wings, as on the F-14 Tomcat, allows an aircraft to move the wing to keep it at the most efficient angle regardless of speed, although the cost in complexity and weight makes this a rare feature.

Most high-speed aircraft have a wing that spends at least some of its time in the supersonic airflow. But since the shock cone moves towards the fuselage with increased speed (that is, the cone becomes narrower), the portion of the wing in the supersonic flow also changes with speed. Since these wings are swept, as the shock cone moves inward, the lift vector moves forward as the outer, rearward portions of the wing are generating less lift. This results in powerful pitching moments and their associated required trim changes.

Disadvantages



Spanwise flow of the boundary layer

When a swept wing travels at high speed, the airflow has little time to react and simply flows over the wing almost straight from front to back. At lower speeds the air *does* have time to react, and is pushed spanwise by the angled leading edge, towards the wing tip. At the wing root, by the fuselage, this has little noticeable effect, but as one moves towards the wingtip the airflow is pushed spanwise not only by the leading edge, but the spanwise moving air beside it. At the tip the airflow is moving along the wing instead of over it, a problem known as *spanwise flow*.

The lift from a wing is generated by the airflow over it from front to rear. With increasing span-wise flow the boundary layers on the surface of the wing have longer to travel, and so are thicker and more susceptible to transition to turbulence or flow separation, also the effective aspect ratio of the wing is less and so air "leaks" around the wing tips reducing their effectiveness. The spanwise flow on swept wings produces airflow that moves the stagnation point on the leading edge of any individual wing segment further beneath the leading edge, increasing effective angle of attack of wing segments relative to its neighbouring forward segment. The result is that wing segments farther towards the rear

operate at increasingly higher angles of attack promoting early stall of those segments. This promotes tip stall on back swept wings, as the tips are most rearward, while delaying tip stall for forward swept wings, where the tips are forward. With both forward and back swept wings, the rear of the wing will stall first. This creates a nose-up pressure on the aircraft. If this is not corrected by the pilot it causes the plane to pitch up, leading to more of the wing stalling, leading to more pitch up, and so on. This problem came to be known as the *Sabre dance* in reference to the number of North American F-86 Sabres that crashed on landing as a result.

The solution to this problem took on many forms. One was the addition of a fin known as a *wing fence* on the upper surface of the wing to redirect the flow to the rear. Another closely-related design was addition of a dogtooth notch to the leading edge (Avro Arrow). Other designs took a more radical approach, including the XF-91 Thunderceptor's wing that grew wider towards the tip to provide more lift at the tip. The Handley Page Victor had a planform based on a crescent *compound sweep* or *scimitar wing* that had substantial sweep-back near the wing root where the wing was thickest, and progressively reducing sweep along the span as the wing thickness reduced towards the tip.

Modern solutions to the problem no longer require "custom" designs such as these. The addition of leading edge slats and large compound flaps to the wings has largely resolved the issue. On fighter designs, the addition of leading edge extensions, included for high maneuverability, also serve to add lift during landing and reduce the problem.

The swept wing also has several more problems. One is that for any given length of wing, the actual span from tip-to-tip is shorter than the same wing that is not swept. Low speed drag is strongly correlated with the aspect ratio, the span compared to chord, so a swept wing always has more drag at lower speeds. Another concern is the torque applied by the wing to the fuselage, as much of the wing's lift lies behind the point where the wing root connects to the plane. Finally, while it is fairly easy to run the main spars of the wing right through the fuselage in a straight wing design to use a single continuous piece of metal, this is not possible on the swept wing because the spars will meet at an angle.

Forward sweep

LET L-13 two-seat glider showing forward swept wing

Grumman X-29 experimental aircraft, an extreme example of a forward swept wing

Sweeping a wing forward has the same effect as rearward in terms of drag reduction, but has other advantages in terms of low-speed handling where tip stall problems simply go away. In this case the low-speed air flows towards the fuselage, which acts as a very large wing fence. Additionally, wings are generally larger at the root anyway, which allows them to have better low-speed lift.

However, this arrangement also has serious stability problems. The rearmost section of the wing will stall first causing a pitch-up moment pushing the aircraft further into stall

similar to a swept back wing design. Thus swept-forward wings are unstable in a fashion similar to the low-speed problems of a conventional swept wing. However unlike swept back wings, the tips on a forward swept design wil stall last maintaining roll control.

Forward-swept wings can also experience dangerous flexing effects compared to aft-swept wings that can negate the tip stall advantage if the wing is not sufficiently stiff. In aft-swept designs, when the airplane maneuvers at high load factor the wing loading and geometry twists the wing in such a way as to create washout (tip twists leading edge down). This reduces the angle of attack at the tip, thus reducing the bending moment on the wing, as well as somewhat reducing the chance of tip stall. However, the same effect on forward-swept wings produces a wash-in effect which increases the angle of attack promoting tip stall.

Small amounts of sweep do not cause serious problems, and had been used on a variety of aircraft to move the spar into a convenient location, as on the Junkers Ju 287 or HFB-320 Hansa Jet. But larger sweep suitable for high-speed aircraft, like fighters, was generally impossible until the introduction of fly by wire systems that could react quickly enough to damp out these instabilities. The Grumman X-29 was an experimental technology demonstration project designed to test the forward swept wing for enhanced maneuverability in 1984. The Su-47 *Berkut* is another notable example using this technology. However no highly swept-forward design has entered production.

History

A Burgess-Dunne aircraft showing the high angle of sweep.

The first aircraft with swept wings were those designed by the British designer J.W.Dunne in the first decade of the 20th century. Dunne successfully employed severely swept wings in his tailless aircraft as a means of creating positive longitudinal static stability. Historically, many low-speed aircraft have had swept wings in order to avoid problems with their center of gravity, to move the wing spar into a more convenient location, or to improve the sideways view from the pilot's position. For instance, the Douglas DC-3 had a slight sweep to the leading edge of its wing. The wing sweep in low-speed aircraft was not intended to help with transonic performance, and although most have a small amount of *wing sweep* they are rarely described as *swept wing* aircraft. The Curtiss XP-55 was the first American swept wing airplane, although it was not considered successful.

Introduction

The idea of using swept wings to reduce high-speed drag was first developed in Germany in the 1930s. At a Volta Conference meeting in 1935 in Italy, Dr. Adolf Busemann suggested the use of swept wings for supersonic flight. He noted that the airspeed over the wing was dominated by the normal component of the airflow, not the freestream velocity, so by setting the wing at an angle the forward velocity at which the shock waves would form would be higher (the same had been noted by Max Munk in 1924, although not in the context of high-speed flight). Albert Betz immediately suggested the same effect would be equally useful in the transonic. After the presentation the host of the meeting, Arturo Crocco, jokingly sketched "Busemann's airplane of the future" on the back of a menu while they all dined. Crocco's sketched showed a classic 1950's fighter design, with swept wings and tail surfaces, although he also sketched a swept propeller powering it.

At the time, however, there was no way to power an aircraft to these sorts of speeds, and even the fastest aircraft of the era were only approaching 400 km/h (249 mph). Large engines at the front of the aircraft made it difficult to obtain a reasonable fineness ratio, and although wings could be made thin and broad, doing so made them considerably less strong. The British Supermarine Spitfire used as thin a wing as possible for lower high-speed drag, but later paid a high price for it in a number of aerodynamic problems such as control reversal. German design instead opted for thicker wings, accepting the drag for greater strength and increased internal space for landing gear, fuel and weapons.

At the time the presentation was largely of academic interest, and soon forgotten. Even notable attendees including Theodore von Kármán and Eastman Jacobs did not recall the presentation ten years later when it was re-introduced to them. Buseman was in charge of aerodynamics research at Braunschweig, and in spite of the limited interest he began a research program studying the concept. By 1939 wind tunnel testing had demonstrated the effect was real, and practical.

With the introduction of jets in the later half of World War II applying sweep became relevant. The German jet powered Messerschmitt Me 262 and rocket powered Messerschmitt Me 163 suffered from compressibility effects that made them very

difficult to control at high speeds. In addition, the speeds put them into the wave drag regime, and anything that could reduce this drag would increase the performance of their aircraft, notably the notoriously short flight times measured in minutes. This resulted in a crash program to introduce new swept wing designs, both for fighters as well as bombers. The Focke-Wulf Ta 183 was a swept wing fighter design with a layout very similar to that later used on the MiG-15 that was not produced before war's end.

A prototype test aircraft, the Messerschmitt Me P.1101, was built to research the tradeoffs of the design and develop general rules about what angle of sweep to use. None of the fighter or bomber designs were ready for use by the time the war ended, but the P.1101 was captured by US forces and returned to the United States, where two additional copies with US built engines carried on the research as the Bell X-5. The last jet fighter designed by Willy Messerschmitt the HA-300 had swept wings, Delta Wing in this case.

Spread

The Soviet Union was intrigued about the idea of swept wings on aircraft at the end of World War II in Europe, when their "captured aviation technology" counterparts to the western Allies spread out across the defeated Third Reich. Artem Mikoyan was asked by the Soviet government, principally by the government's TsAGI aviation research department, to develop a test-bed aircraft to research the swept wing idea-the result was the late 1945-flown, unusual MiG-8 *Utka* pusher canard layout aircraft, with its rearwards-located wings being swept back for this type of research. When applied to the jet powered Mig-15, its maximum speed of 1,075 km/h (668 mph) outclassed the straight-winged American jets and piston-engined fighters first deployed to Korea.

von Kármán travelled to Germany near the end of the war as part of Operation Paperclip, and reached Braunschweig on May 7, discovering a number of swept wing models and a mass of technical data from the wind tunnels. One member of the US team was George S. Schairer, who was at that time working at the Boeing company. He immediately forwarded a letter to Ben Cohn at Boeing stating that they needed to investigate the concept. He also told Cohn to distribute the letter to other companies as well, although only Boeing and North American made immediate use of it.

In February 1945 NACA engineer Robert T. Jones started looking at highly-swept delta wings and V shapes, and discovered the same effects as Busemann. He finished a detailed report on the concept in April, but found his work was heavily criticised by other members of NACA Langley, notably Theodore Theodorsen, who referred to it as "hocus-pocus" and demanded some "real mathematics". However, Jones had already secured some time for free-flight models under the direction of Robert Gilruth, whose reports were presented at the end of May and showed a fourfold decrease in drag at high speeds. All of this was compiled into a report published on 21 June 1945, which was sent out to the industry three weeks later. Ironically, by this point Busemann's work had already been passed around.

Boeing was in the midst of designing the B-47 Stratojet, and the initial Model 424 was a straight-wing design similar to the B-45, B-46 and B-48 it competed with. A recent design overhaul completed in June produced the Model 432, another four-engine design with the engines buried in the fuselage to reduce drag, and long-span wings that gave it an almost glider-like appearance. By September the Braunschweig data had been worked into the design, which re-emerged as the Model 448, a larger six-engine design with more robust wings swept at about 35 degrees. Another re-work in November moved the engines to pods under the wings, as the Army was concerned about engine fires potentially destroying the aircraft. The resulting design would have performance rivaling the fastest fighters, and trounced the straight-winged competition. The basic layout of engines on pylons under swept wings is still used on most airliners today.

In fighters, North American Aviation was in the midst of working on a straight-wing jet powered naval fighter then known as the FJ-1. It was submitted it to the Air Force as the F-86. Larry Green, who could read German, studied the Busemann reports and convinced management to allow a redesign starting in August 1945. A battery of wind tunnel tests followed, and although little else of the design was changed, including the wing profile (NACA 0009), the performance of the aircraft was dramatically improved over straight-winged jets. With the appearance of the Mig-15, the F-86 was rushed into combat and straight-wing jets like the P-80 and F-84 were soon relegated to ground attack. Some such as the F-84 and F-9 Cougar were later redesigned with swept wings from straight-winged aircraft. Later planes such as the F-100 would be designed with swept wings from the start, though additional innovations such as the afterburner, area-rule and new control surfaces would be necessary to master supersonic flight.

The British also received the German data, and decided that future high-speed designs would have to use it. A particularly interesting victim of this process was the cancellation of the Miles M-52, a straight-wing design for an attempt on the speed of sound. When the swept wing design came to light the project was cancelled, as it was thought it would have too much drag to break the sound barrier, but soon after the US nevertheless did just that with the Bell X-1. The Air Ministry introduced a program of experimental aircraft to examine the effects of swept wings (as well as delta wings) and introduced their first combat designs as the Hawker Hunter and Supermarine Swift.

The German research was also "leaked" to SAAB from a source in Switzerland in late 1945. They were in the process of developing the jet fighter SAAB Tunnan, and quickly adapted the existing straight-wing layout to incorporate a 25 degree sweep. Although not well known outside Sweden, the Tunnan was a very competitive design, remaining in service until 1972 in some roles.

The introduction of the German swept wing research to aeronautics caused a minor revolution, especially after the dramatic successes of the B-47 and F-86. Eventually almost all design efforts immediately underwent modifications in order to incorporate a swept wing. The classic Boeing B-52, designed in the 1950s, would remain in service until into the 21st century as a high subsonic long-range heavy bomber despite the development of the triple-sonic B-70, supersonic swing-wing B-1, and flying wing

designs. While the Soviet never matched the performance of the B-52 with a jet design, the intercontinental range Tu-95 turboprop bomber also remains in service today. With a near-jet class top speed of 920 km/h, it is an unusual in combining swept wings with propeller propulsion and remains the fastest propeller powered production plane. By the 1960s, most civilian jets such as the Boeing 707 adopted swept wings as well.

By the early 1950s nearly every new fighter was either rebuilt or designed from scratch with a swept wing. The A-4 Skyhawk and F4D Skyray were examples of delta wings which also have swept leading edges with or without a tail. Most early transonic and supersonic designs such as the MiG-19 and F-100 used long, highly swept wings. Swept wings would reach Mach 2 in the arrow-winged BAC Lightning, and stubby winged F-105 Thunderchief, which was found to be wanting in turning ability in Vietnam combat. By the late 1960s, the F-4 Phantom and MiG-21 which both used variants on tailed delta wings came to dominate front line air forces. Variable geometry wings were employed on the American F-111, F-14 and Soviet Mig-27, though the idea would be abandoned for the American SST design. After the 1970s, most newer generation fighters optimized for maneuvering air combat since the USAF F-15 and Soviet MiG-29 have employed relatively short-span fixed wings with relatively large wing area.

The unswept wing of a Maule M-7-235B Super Rocket light aircraft

Chapter 17

Wake Turbulence

This picture from a NASA study on wingtip vortices qualitatively illustrates the wake turbulence.

Wake turbulence is turbulence that forms behind an aircraft as it passes through the air. This turbulence includes various components, the most important of which are wingtip

vortices and **jetwash**. Jetwash refers simply to the rapidly moving gases expelled from a jet engine; it is extremely turbulent, but of short duration. Wingtip vortices, on the other hand, are much more stable and can remain in the air for up to three minutes after the passage of an aircraft. Wingtip vortices make up the primary and most dangerous component of wake turbulence.

Wake turbulence is especially hazardous during the landing and take off phases of flight, for three reasons. The first is that during take-off and landing, aircraft operate at low speeds and high angle of attack. This flight attitude maximizes the formation of dangerous wingtip vortices. Secondly, takeoff and landing are the times when a plane is operating closest to its stall speed and to the ground, meaning there is little margin for recovery in the event of encountering another aircraft's wake turbulence. Thirdly, these phases of flight put aircraft closest together and along the same flightpath, maximizing the risk of encountering the phenomenon.

Fixed wing – level flight

At altitude, vortices sink at a rate of 90 to 150 metres per minute and stabilize about 150 to 270 metres below the flight level of the generating aircraft. For this reason, aircraft operating greater than 600 metres above the terrain are not considered at risk.

Helicopters

Helicopters also produce wake turbulence. Helicopter wakes may be of significantly greater strength than those from a fixed wing aircraft of the same weight. The strongest wake can occur when the helicopter is operating at lower speeds (20 to 50 knots). Some mid-size or executive class helicopters produce wake as strong as that of heavier helicopters. This is because two blade main rotor systems, typical of lighter helicopters, produce stronger wake than rotor systems with more blades.

Parallel or crossing runways

During takeoff and landing, an aircraft's wake sinks toward the ground and moves laterally away from the runway when the wind is calm. A 3 to 5 knot crosswind will tend to keep the upwind side of the wake in the runway area and may cause the downwind side to drift toward another runway. Since the wingtip vortices exist at the outer edge of an airplane's wake, this can be dangerous.

Hazard avoidance

Wake vortex separation

Wake vortices from a landing Airbus at Oakland Airport interact with the sea as they descend to ground level

ICAO mandates separation minima based upon wake vortex categories that are, in turn, based upon the Maximum Take Off Mass (MTOW|MTOM) of the aircraft.

These minima are categorised are as follows:

- Light – MTOW of 7,000 kilograms (15,000 lb) or less;
- Medium – MTOW of greater than 7,000 kilograms, but less than 136,000 kilograms (300,000 lb);
- Heavy – MTOW of 136,000 kilograms or greater.

There are a number of separation criteria for take-off, landing and en-route phases of flight based upon these categories. Air Traffic Controllers will sequence aircraft making instrument approaches with regard to these minima. Aircraft making a visual approach are advised of the relevant recommended spacing and are expected to maintain their own separation.

The FAA does not use the ICAO categories for wake turbulence separation, instead using the following:

"Appendix A is being revised to harmonize FAA weight category standards with those of the International Civil Aviation Organization (ICAO). All aircraft with a maximum certificated takeoff weight of more than 41,000 pounds but less than 300,000 pounds maximum certificated takeoff weight will now be classified as a “Large” aircraft according to FAA standards. Aircraft with a maximum certificated takeoff weight of 300,000 pounds or more will now be classified as a “Heavy” aircraft according to FAA and ICAO weight classification standards. This change reclassifies all B757 aircraft as “Large” aircraft; however, controllers are required to apply the special wake turbulence separation criteria as specified in paragraph 5-5-4. This change cancels and incorporates N JO 7110.525, Appendix A, Aircraft Information Fixed-Wing Aircraft, effective April 8, 2010."

- Super - A separate designation that currently only refers to the Airbus A380
- Heavy - Aircraft capable of takeoff weights of 300,000 pounds (140,000 kg) or more whether or not they are operating at this weight during a particular phase of flight.
- Large - Aircraft of more than 41,000 pounds (19,000 kg), maximum certificated takeoff weight, up to but not including 300,000 pounds (140,000 kg) .
- Small – Aircraft of 41,000 pounds or less maximum certificated takeoff weight.

Common minima are:

Take-off

An aircraft of a lower wake vortex category must not be allowed to take off less than two minutes behind an aircraft of a higher wake vortex category. If the following aircraft does not start its take off roll from the same point as the preceding aircraft, this is increased to three minutes.

Landing

Preceding aircraft	**Following aircraft**	**Minimum radar separation**
Super	Super	4 NM
	Heavy	6 NM
	Medium	7 NM
	Light	8 NM
Heavy	Heavy	4 NM
	Medium	5 NM
	Light	6 NM
Medium	Light	5 NM

Staying on or above leader's glide path

Incident data shows that the greatest potential for a wake vortex incident occurs when a light aircraft is turning from base to final behind a heavy aircraft flying a straight-in approach. Light aircraft pilots must use extreme caution and intercept their final approach path above or well behind the heavier aircraft's path. When a visual approach following a preceding aircraft is issued and accepted, the pilot is required to establish a safe landing interval behind the aircraft he was instructed to follow. The pilot is responsible for wake turbulence separation. Pilots must not decrease the separation that existed when the visual approach was issued unless they can remain on or above the flight path of the preceding aircraft.

Warning signs

Any uncommanded aircraft movements (such as wing rocking) may be caused by wake. This is why maintaining situational awareness is so critical. Ordinary turbulence is not unusual, particularly in the approach phase. A pilot who suspects wake turbulence is affecting his or her aircraft should get away from the wake, execute a missed approach or go-around and be prepared for a stronger wake encounter. The onset of wake can be insidious and even surprisingly gentle. There have been serious accidents where pilots have attempted to salvage a landing after encountering moderate wake only to encounter severe wake turbulence that they were unable to overcome. Pilots should not depend on any aerodynamic warning, but if the onset of wake is occurring, immediate evasive action is vital.

Incidents involving wake turbulence

XB-70 *62-0207* following the midair collision on 8 June 1966.

- June 8, 1966 - an XB-70 collided with an F-104. Though the true cause of the collision is unknown, it is believed that due to the XB-70 being designed to have an enhanced wake turbulence to increase lift, the F-104 moved too close, therefore getting caught in the vortex and colliding with the wing.
- May 30, 1972 - Delta Air Lines Flight 9570 crashed at the Greater Southwest International Airport while performing "touch and go" landings behind a DC-10. This crash prompted the FAA to create new rules for minimum following separation from "heavy" aircraft.
- December 15, 1993 - a chartered aircraft with five people on-board, including In-N-Out Burger's president, Rich Snyder, crashed at John Wayne Airport. The aircraft followed a Boeing 757 in for landing, became caught in its wake turbulence, rolled into a deep descent and crashed.
- September 8, 1994 - USAir Flight 427 crashed near Pittsburgh, Pennsylvania in 1994. This accident was believed to involve wake turbulence, though the primary cause was a defective rudder control component.
- September 20, 1999 - JAS 39A Gripen from Airwing F 7 Såtenäs crashed into Lake Vänern in Sweden during an air combat maneuvering exercise. After passing through the wake vortex of the other aircraft, the aircraft abruptly changed course, and the pilot, Capt. Rickard Mattsson, got a highest-severity

warning from the ground-collision warning system. He ejected from the aircraft, and landed safely by parachute in the lake.

- November 12, 2001 - American Airlines Flight 587 crashed into the Belle Harbor neighborhood of Queens, New York shortly after takeoff from John F. Kennedy International Airport. This accident was attributed to pilot error in the presence of wake turbulence from a Japan Airlines Boeing 747 that resulted in rudder failure and subsequent separation of the vertical stabilizer.
- November 3, 2008 - Airbus A380 wake turbulence event, Sydney Airport, Australia. Wake turbulence of an Airbus A380-800 causing temporary loss of control to a Saab 340 on approach to a parallel runway during high crosswind conditions.
- November 4, 2008 - Mexican Government LearJet 45 XC-VMC, carrying Secretary of the Interior Juan Camilo Mouriño, crashed close to Paseo de la Reforma avenue before turning for final approach to runway 05R at Mexico City International Airport. The airplane was flying behind a Mexicana Airlines 767-300 and above a heavy helicopter. The pilots were not told about the type of plane that was approaching before them, neither did they reduce to minimum approach speed. (This has been confirmed as the official stance by the Mexican Government as stated by Luiz Tellez, the Secretary of Communications of Mexico.)

Measurement

Wake turbulence can be measured using several techniques. A high-resolution technique is doppler lidar, a solution now commercially available. Techniques using optics can use the effect of turbulence on refractive index (optical turbulence) to measure the distortion of light that passes through the turbulent area and indicate the strength of that turbulence.

Audibility

Wake turbulence can occasionally, under the right conditions, be heard by ground observers. On a still day, heavy jets flying low and slow on landing approach may produce wake turbulence that is heard as a dull roar/whistle. Often, it is first noticed some seconds after the direct noise of the passing aircraft has diminished. The sound then gets louder, sometimes becoming as loud as was the original direct sound of the aircraft. Nevertheless, being highly directional, wake turbulence sound is easily perceived as originating a considerable distance behind the aircraft, its apparent source moving across the sky just as the aircraft did. It can persist for 30 seconds or more, continually changing timbre, sometimes with swishing and cracking notes, until it finally dies away.

Chapter 18

Wing Configuration

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

This page 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.

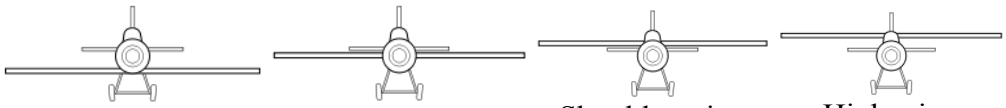
Some variants may be duplicated under more than one heading, due to their complex nature. This is particularly so for variable geometry and combined (closed) wing types.

Number and position of main-planes

Aircraft can have different numbers of wings:

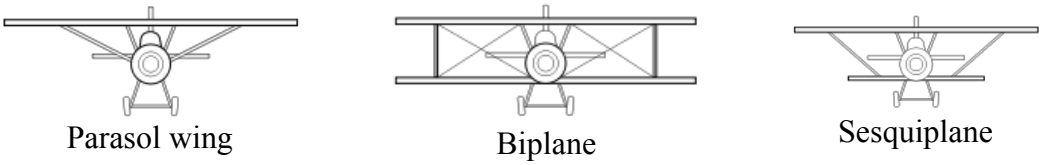
- No wings at all.
    - **Lifting body** - relies on air flow over the fuselage to provide lift.
    - **Powered lift** - relies on downward thrust from the engines to stay airborne.

- **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.



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

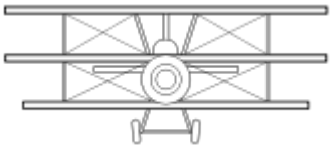
- **Biplane** - two planes of approximately equal size, stacked one above the other. The most common type until the 1930s, when the cantilever monoplane took over.
    - **Sesquiplane** - literally "one-and-a-half planes" is a variant on the biplane in which the lower wing is significantly smaller than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



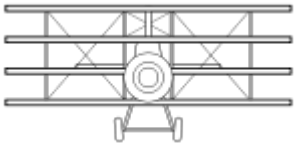
- **Triplane** - three planes stacked one above another. Triplanes such as the Fokker Dr.I enjoyed a brief period of popularity during the First World War due to their small size and high manoeuvrability as fighters, but were soon replaced by improved biplanes.

- **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.

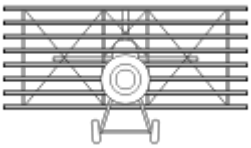
- **Multiplane** - many planes, sometimes used to mean more than one or more than some arbitrary number. The term is occasionally applied to arrangements stacked in tandem as well as vertically. No example with more than four wings has ever flown successfully: the nine-wing Caproni Ca.60 flying boat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



Triplane

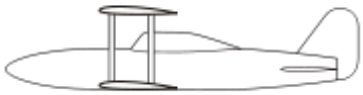


Quadruplane

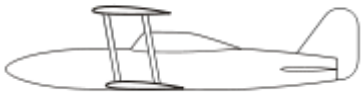


Multiplane

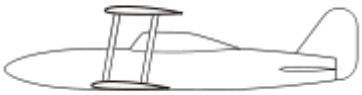
A **staggered** design has the upper wing slightly forward of the lower. This helps give stability to stacked wings, and is usual on successful designs. Backwards stagger is also seen in a few examples such as the de Havilland D.H. 5, Sopwith Dolphin, and Beechcraft Staggerwing.



Unstaggered biplane



Forwards stagger



Backwards stagger

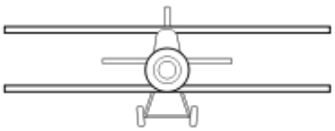
A **Tandem wing** design has two similar-sized wings, one behind the other. Some early types had tandem stacks of multiple planes.

Wing support

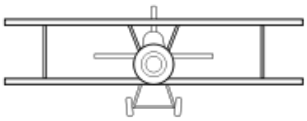
To support itself a wing has to be rigid and strong and consequently may be heavy. By adding external bracing, the weight can be greatly reduced. Originally such bracing was always present, but it causes a large amount of drag at higher speeds and has not been used for faster designs since the early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

The types are:

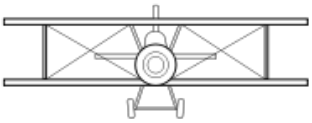
- **Cantilevered** - self-supporting. All the structure is buried under the aerodynamic skin, giving a clean appearance with low drag.
- **Braced**: the wings are supported by external structural members. Nearly all multi-plane designs are braced. Some monoplanes, especially early designs such as the 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

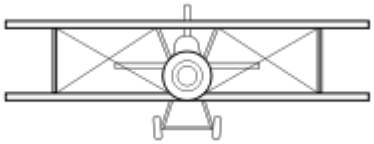


Strut braced

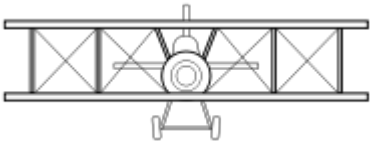


Wire braced

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.

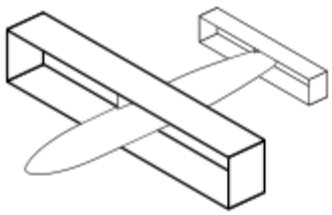


Single-bay biplane

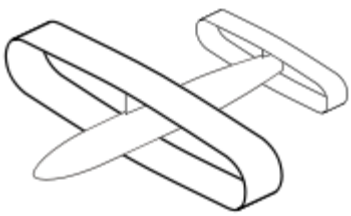


Two-bay biplane

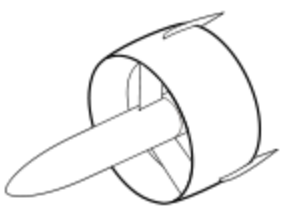
- **Combined** or **closed wing** - two wings are joined structurally at or near the tips in some way. This stiffens the structure, and can reduce aerodynamic losses at the tips. Variants include:
  - **Box wing** - upper and lower planes are joined by a vertical fin between their tips. Some Dunne biplanes 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**.
  - **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.



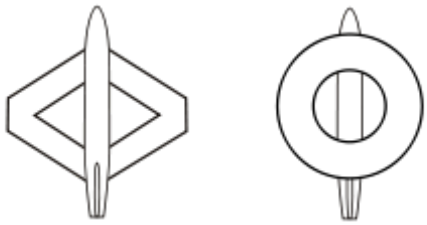
Box wing



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.

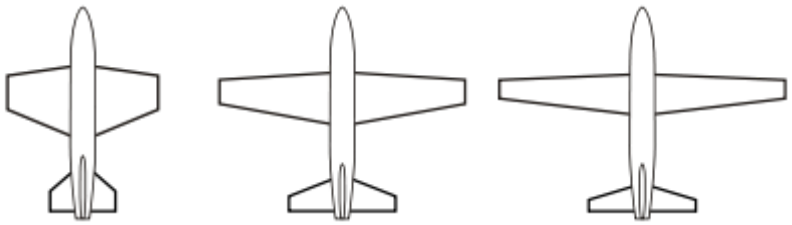
Aspect ratio

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.

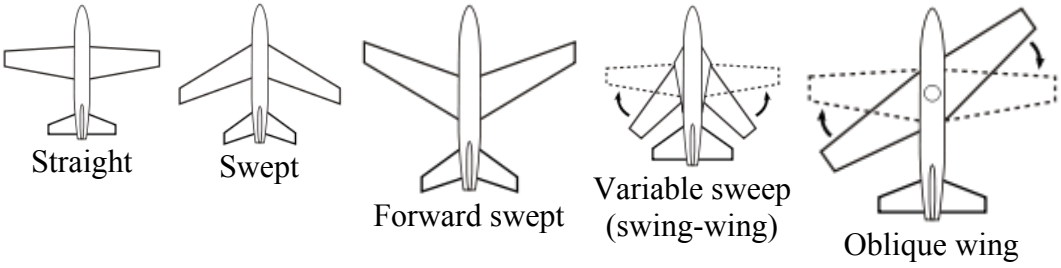
Wing sweep

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.

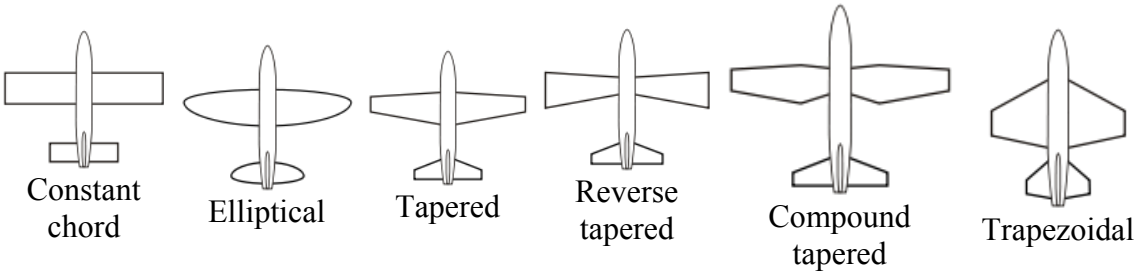


Planform variation along span

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

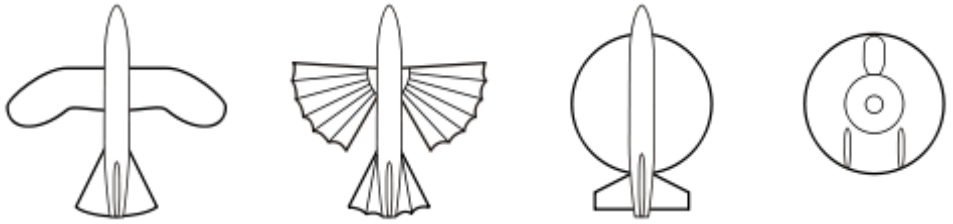
- **Constant chord** - leading and trailing edges are parallel. Simple to make, and common where low cost is important, e.g. in the Short Skyvan.
- **Elliptical** - wing edges are parallel at the root, and curve smoothly inwards to a rounded tip, with no division between the edges and the tip. Aerodynamically 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.

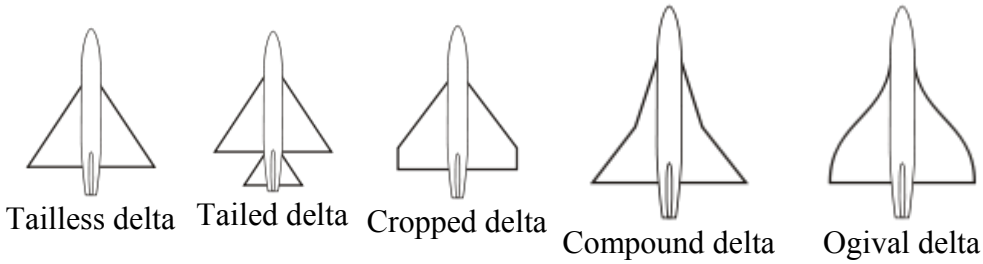


- **Bird like** - a curved shape appearing similar to a bird's outstretched wing. Popular during the pioneer years, and achieved some success on the Etrich Taube.
- **Bat like** - a form with radial ribs which was used for some early designs, especially if the wings were foldable. The Whitehead No. 21 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.



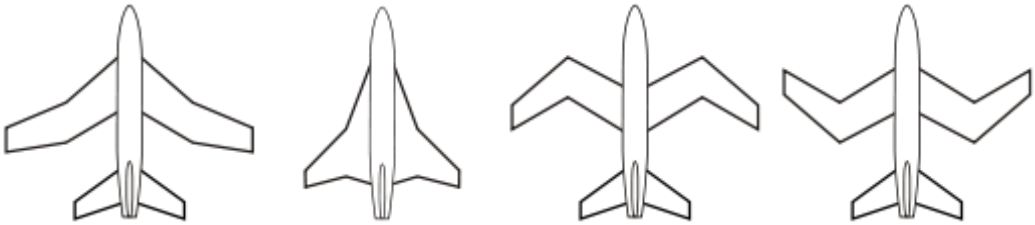
- **Delta** - triangular planform with swept leading edge and straight trailing edge. Offers the advantages of a swept wing, with good structural efficiency. Variants are:
  - **Tailless delta** - a classic high-speed design, used for example in the widely built Dassault Mirage III series.
  - **Tailed 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.

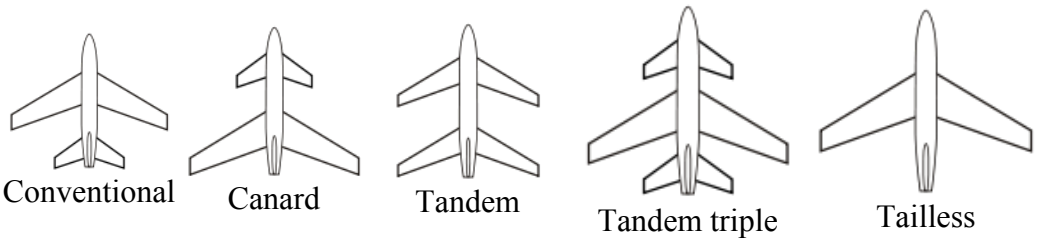


Crescent Cranked arrow M-wing W-wing

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.

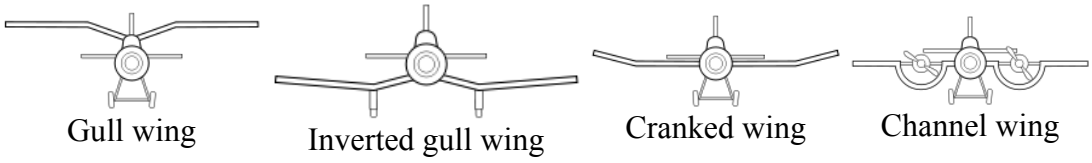
- **Dihedral** - the tips are higher than the root as on the Boeing 737, giving a shallow 'V' shape when seen from the front. Adds lateral stability.
- **Anhedral** - the tips are lower than the root, as on the Ilyushin Il-76; the opposite of dihedral. Used to reduce stability where some other feature 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.

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.

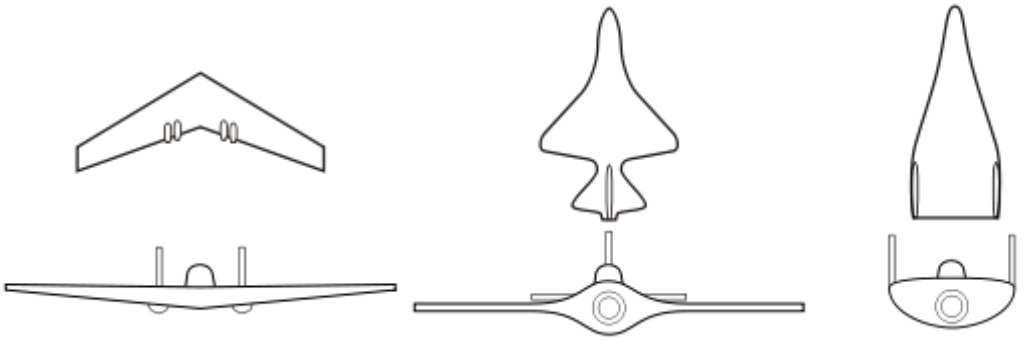


Gull wing | Inverted gull wing | Cranked wing | Channel wing

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.

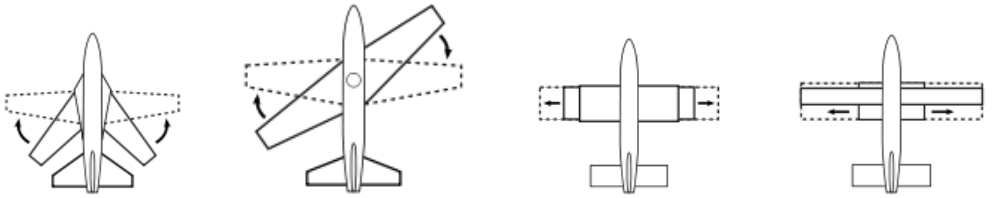
Variable geometry

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.

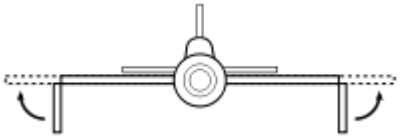
Variable planform

- **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

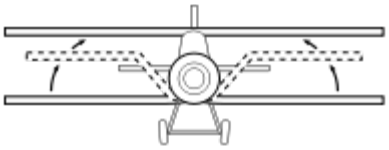
fitted to the wing to allow vertical takeoff or STOVL performance, merges into the powered lift category.

- **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 19

Wingtip Vortices

Condensation in the cores of wingtip vortices from an F-15E as it disengages from a KC-10 Extender following midair refueling

Wingtip vortices are tubes of circulating air which are left behind a wing as it generates lift. One wingtip vortex trails from the tip of each wing. The cores of vortices spin at very high speed and are regions of very low pressure. To first approximation, these low-pressure regions form with little exchange of heat with the neighboring regions (i.e. adiabatically), so the local temperature in the low-pressure regions drops, too. If it drops below the local dew point, there results a condensation of water vapor present in the cores of wingtip vortices, making them visible. The temperature may even drop below the local freezing point, in which case ice crystals will form inside the cores.

Wingtip vortices are associated with induced drag, an essentially unavoidable side effect of the wing generating lift. Managing induced drag and wingtip vortices by selecting the best wing planform for the mission is critically important in aerospace engineering.

Wingtip vortices form the major component of wake turbulence.

Migratory birds take advantage of each others' wingtip vortices by flying in a V formation so that all but the leader are flying in the upwash from the wing of the bird ahead. This upwash makes it a bit easier for the bird to support its own weight, reducing fatigue on migration flights.

Some technical writers use the alternative expression "trailing vortices" because these vortices also occur at points other than at the wing tips. They are induced at the outboard tip of the wing flaps and other abrupt changes in wing planform.

Cause, effects and mitigation

A C-27J Spartan showing prop vortices.

A wing generates aerodynamic lift by creating a region of lower air pressure above it. Fluids are forced to flow from high to low pressure and the air below the wing tends to migrate toward the top of the wing via the wingtips. The air does not escape around the leading edge of the wing due to airspeed, but it can flow around the tip. Consequently, air flows from below the wing and out around the tip to the top of the wing in a circular fashion. This leakage will raise the pressure on top of the wing and reduce the lift that the wing can generate. It also produces an emergent flow pattern with low pressure in the center surrounded by fast-moving air with curved streamlines.

German Air Force Transall C-160D shows propeller tip trails during the takeoff run, at RIAT 2009

Wingtip vortices only affect the portion of the wing closest to the tip. Thus, the longer the wing, the smaller the affected fraction of it will be. As well, the shorter the chord of the wing, the less opportunity air will have to form vortices. This means that for an aircraft to be most efficient, it should have a very high aspect ratio. This is evident in the design of gliders. It is also evident in long-range airliners, where fuel efficiency is of critical importance. However, increasing the wingspan reduces the maneuverability of the aircraft, which is why combat and aerobatic planes usually feature short, stubby wings despite the efficiency losses.

Another method of reducing fuel consumption is the use of winglets, as seen on some modern airliners such as the Airbus A340. Winglets work by forcing the vortex to move to the very tip of the wing and allowing the entire span to produce lift, thereby effectively increasing the aspect ratio of the wing. Winglets also change the pattern of vorticity in the core of the vortex pattern, spreading it out and reducing the kinetic energy in the circular air flow, which reduces the amount of fuel expended to perform work by the wing upon the spinning air. Winglets can yield worthwhile economy improvements on long-distance flights.

Soaring birds (and some sailboat underwater structures) incorporate slots between the feathers at their wingtips to "capture" the energy in the flow of air circulating from the lower to upper wing surface.

Visibility of vortices due to water condensation and freezing

The cores of the vortices are sometimes visible because water present in them condenses from gas (vapor) to liquid, and sometimes even freezes, forming ice particles.

The phase of water (i.e. whether it assumes the form of a solid, liquid, or gas) is determined by its temperature and pressure. For example, in the case of liquid-gas transition, at each pressure there is a special "transition temperature" T_c such that if the sample temperature is even a little above T_c, the sample will be a gas, but if the sample temperature is even a little below T_c, the sample will be a liquid. For example, at the standard atmospheric pressure, T_c is 100 °C = 212 °F. The transition temperature T_c decreases with decreasing pressure (which explains why water boils at lower temperatures at higher altitudes and at higher temperatures in a pressure cooker). In the case of water vapor in air, the T_c corresponding to the partial pressure of water vapor is called the dew point. (The solid-liquid transition also happens around a specific transition temperature called the melting point. For most substances, the melting point also decreases with decreasing pressure, although water ice in particular---in its I_h form, which is the most familiar one---is a prominent exception to this rule.)

Vortex cores are regions of low pressure. As a vortex core begins to form, the water in the air (in the region that is about to become the core) is in vapor phase, which means that the local temperature is above the local dew point. After the vortex core forms, the pressure inside it has decreased from the ambient value, and so the local dew point (T_c) has dropped from the ambient value. Thus, *in and of itself*, a drop in pressure would tend to keep water in vapor form: the initial dew point was already below the ambient air temperature, and the formation of the vortex has made the local dew point even lower. However, as the vortex core forms, its pressure (and so its dew point) is not the only property that is dropping: the vortex-core temperature is dropping also, and in fact it can drop by much more than the dew point does, as we now explain.

Here we follow the discussion in Ref. To first approximation, the formation of vortex cores is thermodynamically an adiabatic process, i.e. one with no exchange of heat. In such a process, the drop in pressure is accompanied by a drop in temperature, according to the equation

$$\frac{T_\mathrm{f}}{T_\mathrm{i}} = \left(\frac{p_\mathrm{f}}{p_\mathrm{i}}\right)^{\frac{\gamma-1}{\gamma}}.$$

Here T_i and p_i are the absolute temperature and pressure at the beginning of the process (here equal to the ambient air temperature and pressure), T_f and p_f are the absolute temperature and pressure in the vortex core (which is the end result of the process), and the constant γ is about 7/5 = 1.4 for air.

Thus, even though the local dew point inside the vortex cores is even lower than in the ambient air, the water vapor may nevertheless condense—if the formation of the vortex

brings the local temperature below the new local dew point. Let us verify that this can indeed happen under realistic conditions.

For a typical transport aircraft landing at an airport, these conditions are as follows: we may take T_i and p_i to have values corresponding to the so-called standard conditions, i.e. p_i = 1 atm = 1013.25 mb = 101325 Pa and T_i = 293.15 K (which is 20 °C = 68 °F). We will take the relative humidity to be a comfortable 35% (dew point of 4.1 °C = 39.4 °F). This corresponds to a partial pressure of water vapor of 820 Pa = 8.2 mb. We will assume that in a vortex core, the pressure (p_f) drops to about 80% of the ambient pressure, i.e. to about 80 000 Pa.

Let us first determine the temperature in the vortex core. It is given by the equation above as $T_f = \left(\frac{80\,000}{101\,325}\right)^{0.4/1.4} T_i = 0.935 \times 293.15 = 274\ \mathrm{K},$ or 0.86 °C = 33.5 °F.

Next, we determine the dew point in the vortex core. The partial pressure of water in the vortex core drops in proportion to the drop in the total pressure (i.e. by the same percentage), to about 650 Pa = 6.5 mb. According to a dew point calculator at this site (alternatively one may use the Antoine equation to obtain an approximate value), that partial pressure results in the local dew point of about 0.86 °C; in other words, the new local dew point is about equal to the new local temperature.

Therefore, the case we have been considering is a marginal case; if the relative humidity of the ambient air were even a bit higher (with the total pressure and temperature remaining as above), then the local dew point inside the vortices would rise, while the local temperature would remain the same as what we have just found. Thus the local temperature would now be *lower* than the local dew point, and so the water vapor inside the vortices would indeed condense. Under right conditions, the local temperature in vortex cores may drop below the local freezing point, in which case ice particles will form inside the vortex cores.

We have just seen that the water-vapor condensation mechanism in wingtip vortices is driven by local changes in air pressure and temperature. This is to be contrasted to what happens in another well-known case of water condensation related to airplanes: the contrails from airplane engine exhausts. In the case of contrails, the local air pressure and temperature do not change significantly; what matters instead is that the exhaust contains both water vapor (which increases the local water-vapor concentration and so its partial pressure, resulting in elevated dew point and freezing point) as well as aerosols (which provide nucleation centers for the condensation and freezing).

Condensation of water vapor in wing tip vortices is most common on aircraft flying at high angles of attack, such as fighter aircraft in high *g* maneuvers, or airliners taking off and landing on humid days.

Hazards

A NASA study on wingtip vortices produced these pictures of smoke in the wake of an aircraft, clearly illustrating the size of the vortices produced.

Wingtip vortices can also pose a severe hazard to light aircraft, especially during the landing and take off phases of flight. The intensity or strength of the vortex is a function of aircraft size, speed, and configuration (flap setting, etc.). The strongest vortices are produced by heavy aircraft, flying slowly, with wing flaps retracted (Heavy, slow, and clean). Large jet aircraft can generate vortices which are larger than an entire light aircraft. These vortices can persist for many minutes, drifting with the wind. The hazardous aspects of wingtip vortices are most often discussed in the context of wake turbulence. If a light aircraft is immediately preceded by a heavy aircraft, wake turbulence from the heavy aircraft can roll the light aircraft faster than can be resisted by use of ailerons. At low altitudes, particularly during takeoff and landing, this can lead to an upset from which recovery is not possible. Air traffic controllers attempt to ensure an adequate separation between departing and arriving aircraft, particularly where a heavy aircraft is preceding a light aircraft by issuing wake turbulence cautions. For example, a controller may state, "Acey 5523 caution wake turbulence preceding heavy 767 departing. Position and hold runway 8R." The aircraft will then hold for approximately 3

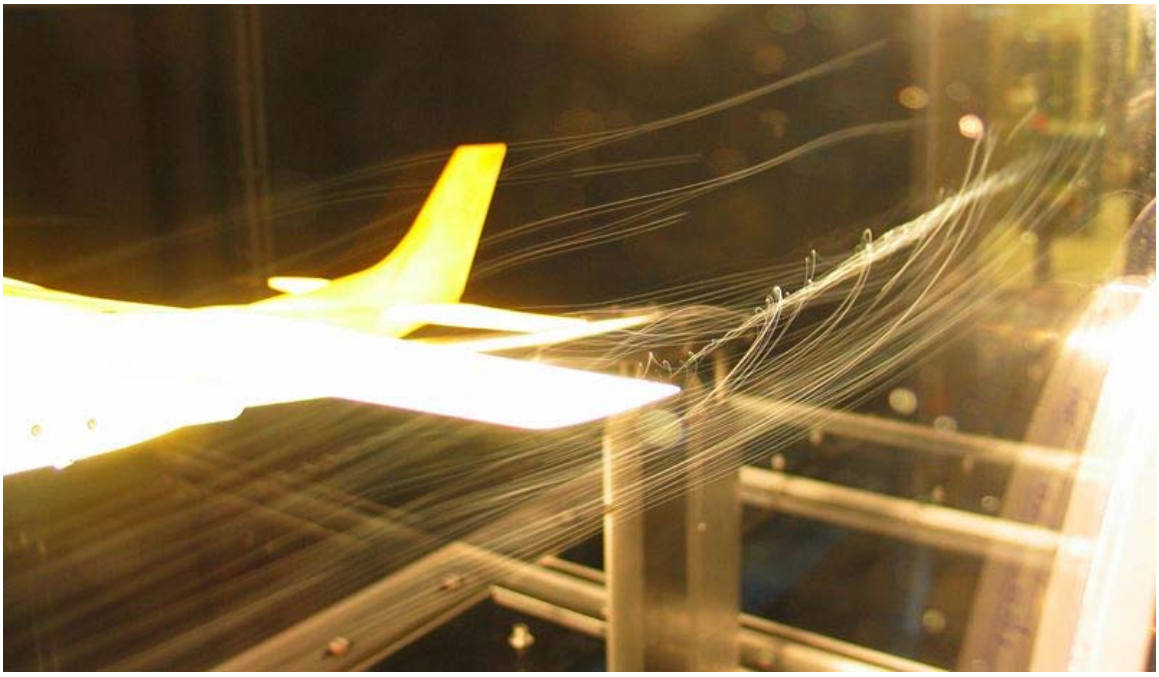
minutes on the runway, and then will be issued a takeoff clearance, as in "Acey 5523, fly runway heading, cleared for takeoff runway 8R."

An EA-6 Prowler with condensation in the cores of its wingtip vortices and also on the top of its wings.

F/A-18C leaving vapor trails in the low pressure cores of its wingtip vortices.

The core of the vortex trailing from the tip of the flap of a commercial airplane with landing flap extended.

F/A-18C showing condensation in the cores of the vortices trailing from its leading edge extensions



Wingtip vortices from a Cessna 182 wind tunnel model.

Wingtip vortices shown in flare smoke left behind a C-17 Globemaster III. Also known as smoke angels.

Visible cores of vortices trailing from the propeller tips when producing high power.

The MV-22 Osprey tiltrotor has a high disk loading, producing visible blade tip vorticies.