

# Handbook of Aircraft Wing Configurations



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## Chapter- 1

# Wing Configuration

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

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

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

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

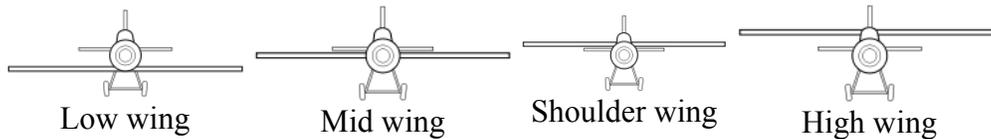
Some variants may be duplicated under more than one heading, due to their complex nature. This is particularly so for variable geometry and combined (closed) wing types.

### ***Number and position of main-planes***

Aircraft can have different numbers of wings:

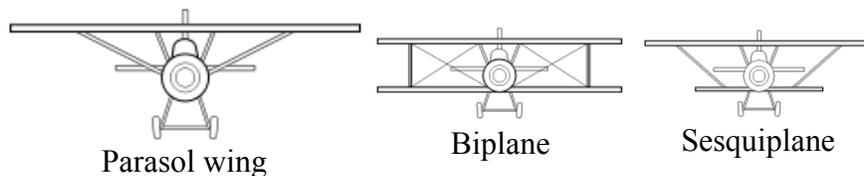
- No wings at all.
  - **Lifting body** - relies on air flow over the fuselage to provide lift.
  - **Powered lift** - relies on downward thrust from the engines to stay airborne.
- **Monoplane** - one wing. Most aeroplanes have been monoplanes since before the Second World War. The wing may be mounted at various heights relative to the fuselage:
  - **Low wing** - mounted on the lower fuselage.

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

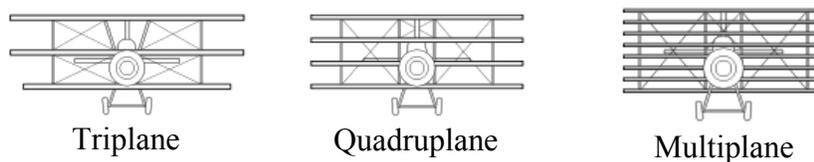


A fixed wing aircraft may have more than one wing plane, stacked one above another:

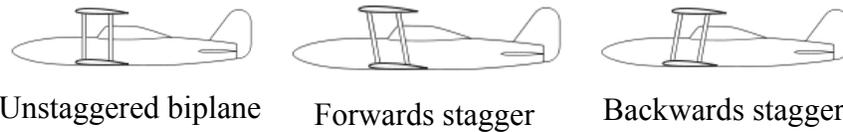
- **Biplane** - two planes of approximately equal size, stacked one above the other. The most common type until the 1930s, when the cantilever monoplane took over.
  - **Sesquiplane** - literally "one-and-a-half planes" is a variant on the biplane in which the lower wing is significantly smaller than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



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.



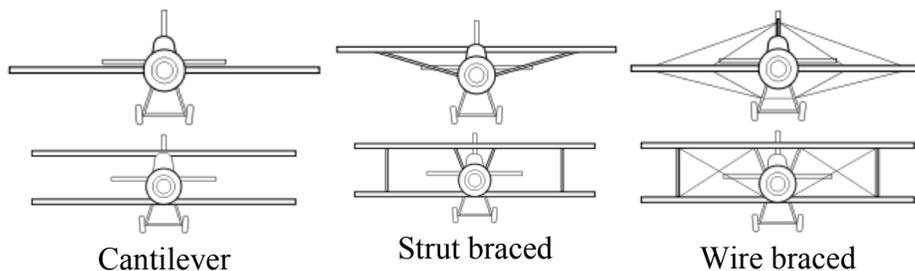
A **Tandem wing** design has two similar-sized wings, one behind the other. Some early types had tandem stacks of multiple planes.

### ***Wing support***

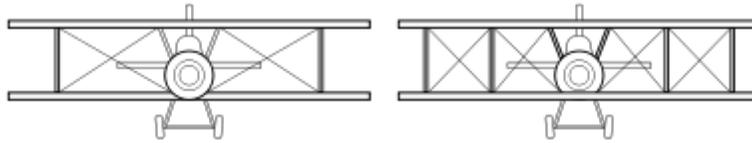
To support itself a wing has to be rigid and strong and consequently may be heavy. By adding external bracing, the weight can be greatly reduced. Originally such bracing was always present, but it causes a large amount of drag at higher speeds and has not been used for faster designs since the early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



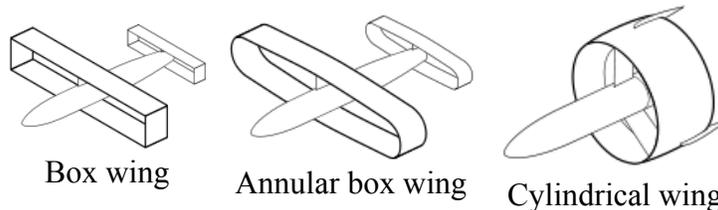
A braced multiplane may have one or more "bays", which are the compartments created by adding interplane struts; the number of bays refers to one side of the aircraft's wing panels only. For example, the de Havilland Tiger Moth is a single-bay biplane where the Bristol F.2 Fighter is a two-bay biplane.



Single-bay biplane

Two-bay biplane

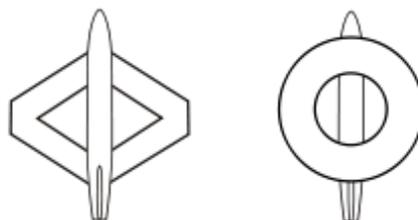
- **Combined or closed wing** - two wings are joined structurally at or near the tips in some way. This stiffens the structure, and can reduce aerodynamic losses at the tips. Variants include:
  - **Box wing** - upper and lower planes are joined by a vertical fin between their tips. Some Dunne biplanes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



Box wing

Annular box wing

Cylindrical wing



Rhomboidal wing Flat annular wing

Wings can also be characterised as:

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

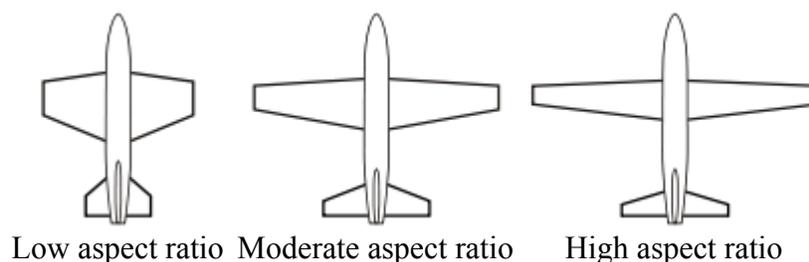
## ***Wing planform***

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

## **Aspect ratio**

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

- **Low aspect ratio** - short and stubby wing. More efficient structurally, more maneuverable and with less drag at high speeds. They tend to be used by fighter aircraft, such as the Lockheed F-104 Starfighter, and by very high-speed aircraft (e.g. North American X-15).
- **Moderate aspect ratio** - general-purpose wing (e.g. the Lockheed P-80 Shooting Star).
- **High aspect ratio** - long and slender wing. More efficient aerodynamically, having less drag, at low speeds. They tend to be used by high-altitude subsonic aircraft (e.g. the Lockheed U-2), subsonic airliners (e.g. the Bombardier Dash 8) and by high-performance sailplanes (e.g. Glaser-Dirks DG-500).



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

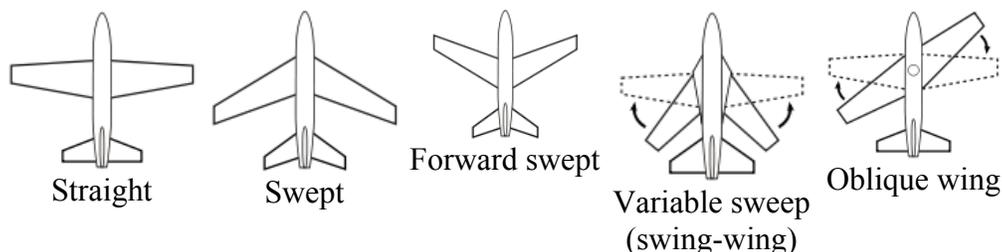
## **Wing sweep**

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

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

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

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



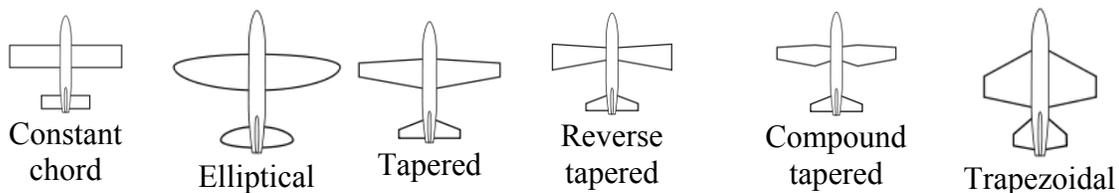
## Planform variation along span

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

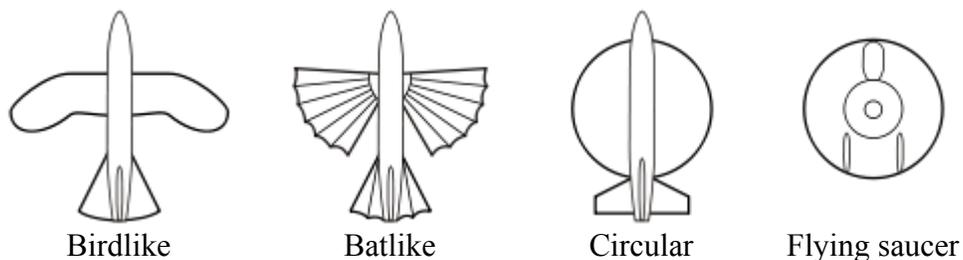
- **Constant chord** - leading and trailing edges are parallel. Simple to make, and common where low cost is important, e.g. in the Short Skyvan.
- **Elliptical** - wing edges are parallel at the root, and curve smoothly inwards to a rounded tip, with no division between the edges and the tip. Aerodynamically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

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

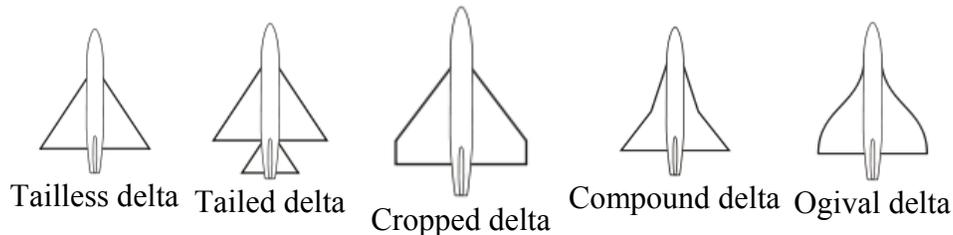
- **Reverse tapered** - wing widens towards the tip. Structurally very inefficient, leading to high weight. Flown experimentally on the XF-91 Thunderceptor in an attempt to overcome the stall problems of swept wings.
- **Compound tapered** - taper reverses towards the root, to increase visibility for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



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

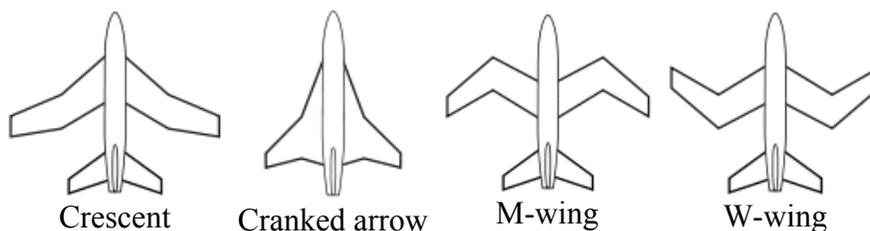


- **Delta** - triangular planform with swept leading edge and straight trailing edge. Offers the advantages of a swept wing, with good structural efficiency. Variants are:
  - **Tailless delta** - a classic high-speed design, used for example in the widely built Dassault Mirage III series.
  - **Tailed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



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

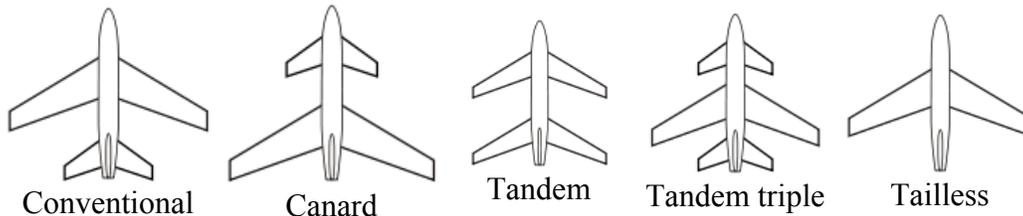
- **Crescent** - wing outer section is swept less sharply than the inner section. Used for the Handley Page Victor.
- **Cranked arrow** - similar to a compound delta, but with the trailing edge also kinked inwards. Trialled experimentally on the General Dynamics F-16XL.
- **M-wing** - the inner wing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



## ***Horizontal stabilizer***

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

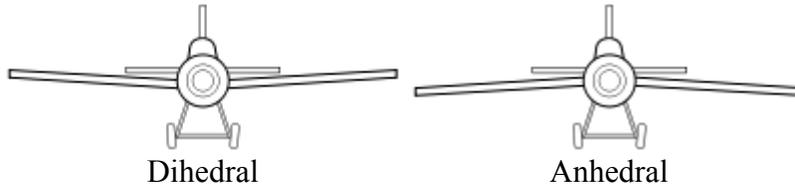
- **Conventional** - "tailplane" stabiliser at the rear of the aircraft, forming part of the tail or empennage.
- **Canard** - "foreplane" stabiliser at the front of the aircraft. Common in the pioneer years, but from the outbreak of World War I no production model appeared until the Saab Viggen.
- **Tandem**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



## ***Dihedral and anhedral***

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

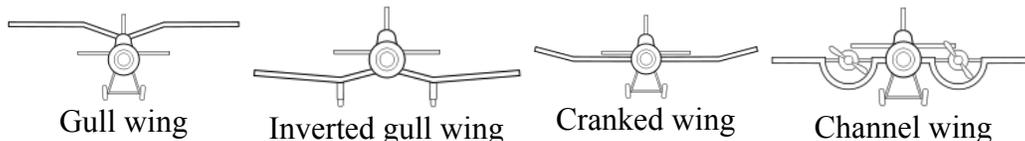
- **Dihedral** - the tips are higher than the root as on the Boeing 737, giving a shallow 'V' shape when seen from the front. Adds lateral stability.
- **Anhedral** - the tips are lower than the root, as on the Ilyushin Il-76; the opposite of dihedral. Used to reduce stability where some other feature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



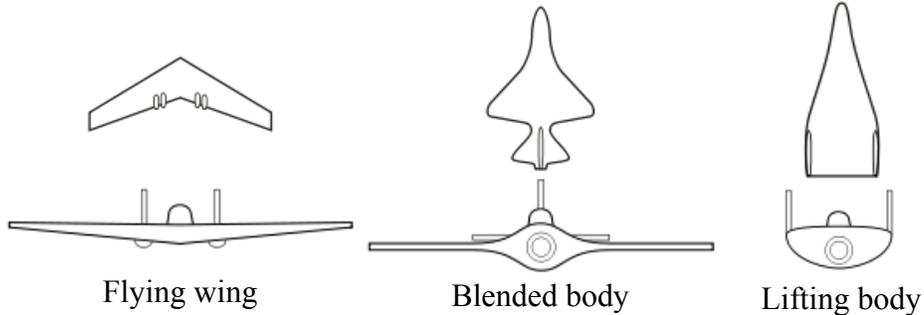
## ***Wings vs. bodies***

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.



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.

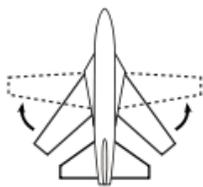
### ***Variable geometry***

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

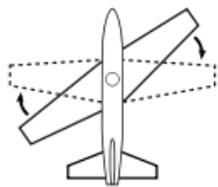
Some types of variable geometry craft transition between fixed wing and rotary wing configurations.

### **Variable planform**

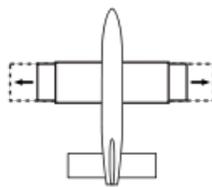
- **Swing-wing** or **variable sweep wing**. The left and right hand wings vary their sweep together, usually backwards. The first successful wing sweep in flight was carried out by the Bell X-5 in the early 1950s.
- **Oblique wing** - a single full-span wing pivots about its mid point, as used on the 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.



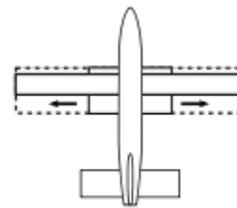
Variable sweep  
(swing-wing)



Oblique wing

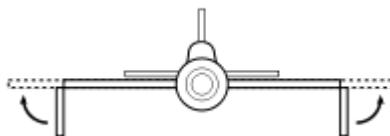


Telescoping wing



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 propellers 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 manoeuvrability.
  - **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



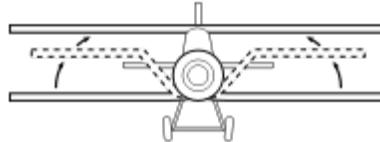
Variable camber  
aerofoil



Variable thickness  
aerofoil

## Polymorphism

A **polymorphic** wing is able to change the number of planes in flight. The Nikitin-Shevchenko IS "folding fighter" prototypes 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- 2

# Lifting Body

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



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



Dryden Flight Research Center EC69-2353 Photographed 10/13/72  
Lifting Bodies: X-24A, M2-F3, HL-10 demonstrated the ability re-enter the Earth from space flight and helped to test the technology necessary for future aircraft to fly at hypersonic cruise speeds.



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

## ***History***

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

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

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

In 1963, NASA began programs with heavier rocket powered lifting body vehicles to be air launched from under the starboard wing of a NB-52B, a derivative of the B-52 jet

bomber. The first flights started in 1966. Of the Dryden lifting bodies, all but the unpowered NASA M2-F1 used an XLR-11 rocket engine as was used on the famous Bell X-1. A follow-on design designated the Northrop HL-10 was developed at NASA Langley Research Center. The X-24A and X-24B lifting body designs were based on the M2 concept originated in 1957 by Alfred Eggers of NASA Ames Aeronautical Laboratory.

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

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

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

## ***Aerospace applications***

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

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

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

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

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

### ***Body lift***

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

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

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

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

## Lifting body pilots and flights

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

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

## Chapter- 3

# Powered Lift



V-22 Osprey



AV-8B Harrier II

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

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

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

—FAA

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

### ***Compound rotorcraft***

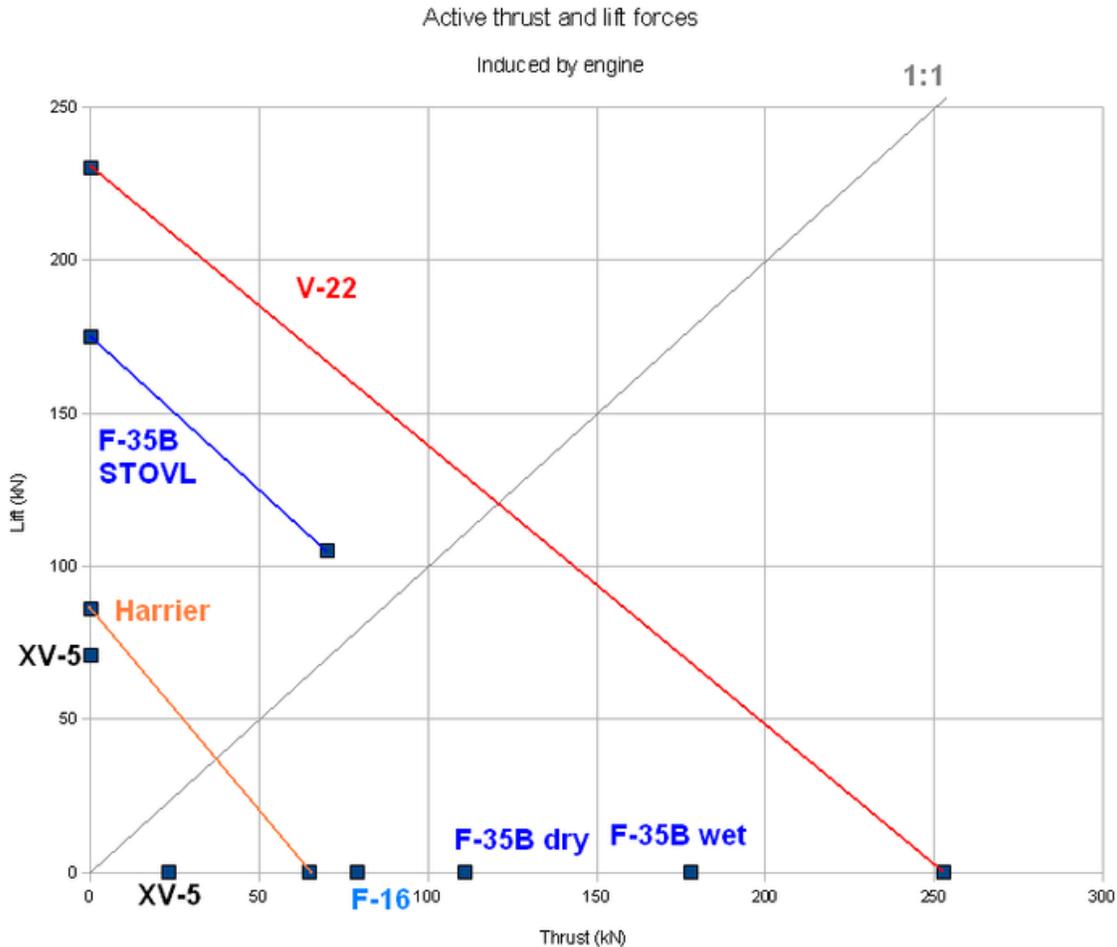
A **compound rotorcraft** has both a lifting rotor and fixed wings (although in the USA, the term "compound rotorcraft" officially refers to a mixed powerplant system). Some types have a **ducted rotor** design, in which the rotor is surrounded by a large ring-shaped duct to reduce tip losses. The Ryan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

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

## **Tiltrotor**



A USAF CV-22 in flight



Powered lift and thrust forces of various aircraft

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

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

The Bell/Agusta BA609 tiltrotor is the evolution of Bell Helicopter's V-22 Osprey into a civilian aircraft. The aircraft can take off and land vertically with 2 crew and 9 passengers, and within 20 seconds, transition to forward flight (by tilting its rotor blades into a fully forward position, much like the V-22 Osprey). In forward flight it can cruise

at speeds of up to 275 knots (509 km/h), with a range exceeding 1,000 nautical miles (with long-range fuel tanks). It is rated to fly above FL210 (21,000 ft), has a maximum payload capacity of over 5,500 pounds, thanks to two Pratt and Whitney PT6C-67A turbines rated at 1,940 shp, each driving a 26-foot (8 m) diameter 3-bladed rotor blade. The aircraft is not yet in full production; however, over 80 orders have been taken.

## **Tiltwing**

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

## **Helicopter-airship compounds**

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

## ***Other rotorcraft hybrids***

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

## **Triebflügel**

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

## **X-wing**

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

## ***Jet lift***

### **Tail-sitters**

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

### **Vectored thrust**

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

### ***Examples***

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

## Chapter- 4

# Monoplane and Parasol Wing

## Monoplane



The low-wing of a Curtiss P-40



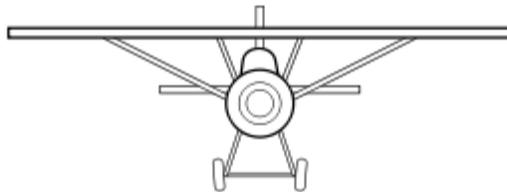
The mid-wing of a de Havilland Vampire T11.



The high-wing of a de Havilland Canada Dash 8.



A parasol wing Pietenpol Air Camper amateur-built aircraft.



Schematic head-on illustration of a parasol wing

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

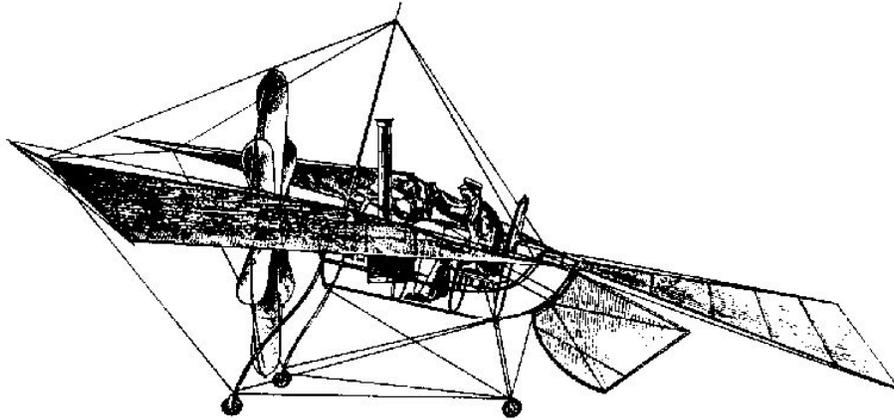
### ***Types of monoplane***

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

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

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

## **History**



Félix du Temple's 1874 *Monoplane*.

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

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

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

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

The first successful aircraft were biplanes, but many important pioneering aircraft were monoplanes, for instance Louis Blériot flew across the English Channel in 1909 in a mid-wing monoplane of his own design. Throughout 1909-1910 Hubert Latham set multiple altitude records in his Antoinette IV monoplane, initially achieving 155 m (509 ft) then raising it to 1,384 m (4,541 ft). The Fokker Eindecker of 1915 was a successful fighter

aircraft. The Junkers J 1 was an early German "technology demonstrator" monoplane, and the world's very first practical all-metal aircraft of any type to fly, with the J 1's first flight occurring in December 1915.

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

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

## Parasol wing



An amateur-built Pietenpol Air Camper featuring a parasol wing

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

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

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

## Chapter- 5

# Biplane



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



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



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



Nieuport 17 is an example of a sesquiplane



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



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



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



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

A **biplane** is a fixed-wing aircraft with two main wings. The Wright brothers' Wright Flyer used a biplane design, as did most aircraft in the early years of aviation. While a biplane wing structure has a structural advantage, it produces more drag than a similar

monoplane wing. Improved structural techniques and materials and the need for greater speed made the biplane configuration obsolete for most purposes by the late 1930s.

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

## **Aviation**

### **Overview**

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

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

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

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

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

## **Advantages and disadvantages**

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

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

## **Stagger**

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

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

## **In ultralight aircraft**

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

## **History**

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

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

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

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

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

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

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

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

### ***In avian evolution***

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

## Chapter- 6

# Gull Wing and Military Disc-Shaped Aircraft

## Gull wing



DFS Habicht glider showing gull wing profile.

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

## ***Sailplanes***

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

### **Notable gull wing sailplanes:**

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



Beriev Be-12 seaplane with gull wing profile

## **Seaplanes**

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

Examples:

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

## ***Landplanes***

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

Examples:

- PZL P.11
- Polikarpov I-153

## ***Inverted gull wing***



Junkers Ju 87 German ground-attack aircraft of WWII



F4U Corsair landing on *USS Bunker Hill*



Aichi B7A carrying torpedo.

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

Examples:

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

# Military disc-shaped aircraft

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

## ***Nemeth Umbrella Plane***

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

## ***Vought Flying Flapjack***

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

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

## **Avrocar**

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



The Avrocar

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

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



The Avrocar test

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

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

## ***Other***

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

## Chapter- 7

# Multiplane (Aeronautics) and Tailless Aircraft

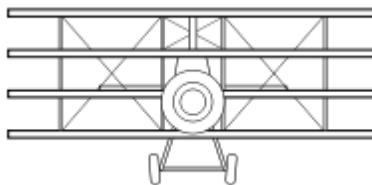
## Multiplane

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

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

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

### ***Quadruplanes***



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

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

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

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

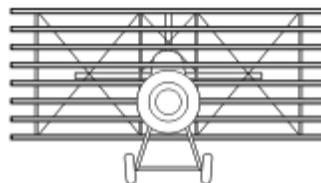
The private-venture Wight quadruplane scout fighter was flown in 1917.

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

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

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

### ***More than four planes***



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

## **Stacked multiplanes**

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

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

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

## **Tandem multiplanes**

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

## **Stacks in tandem**

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

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

# Tailless aircraft

## Tailless aircraft



The DH108 *Swallow*

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

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

## ***Flying wings***

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

## ***Aerodynamics***

### **Longitudinal stability**

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

- Sweep the wing leading edge back, either as a swept wing or delta wing, and reduce the angle of incidence of the outer wing section so that it acts rather like a

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

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

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

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

## **Pitch control**

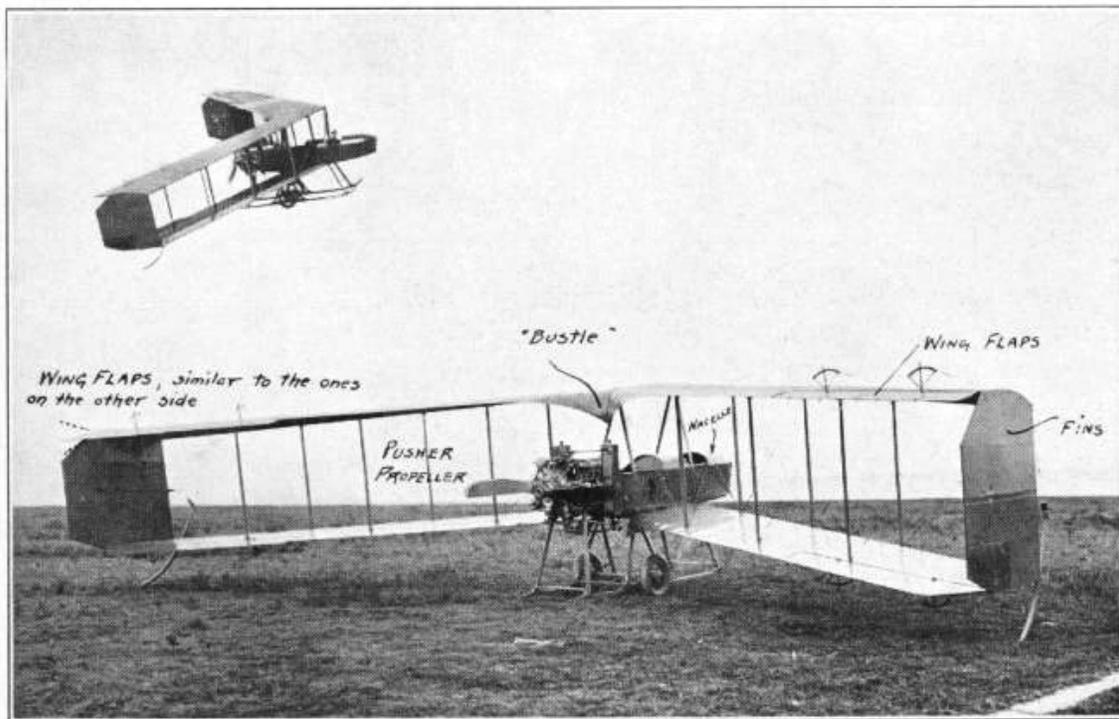
Many early designs failed to provide effective pitch control to compensate for the missing stabiliser. As a result, these aircraft could pitch up or down sharply and uncontrollably if they were not carefully handled. These gave tailless designs a reputation for instability. The original Dunne biplanes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

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

### ***Notable examples***

The examples given here are in historical order.

### **J. W. Dunne**



THE U. S. ARMY DUNNE TYPE BIPLANE

A Dunne type biplane in the US Army of 1917.

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

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

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

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

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

### **Lippisch deltas**

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

### **Messerschmitt Me 163 *Komet***

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

### **De Havilland DH 108 *Swallow***

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

### **Dassault *Mirage***

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

## **Convair F2Y Sea Dart**

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

## **Supersonic airliners**

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

## **Lockheed SR-71 Blackbird**

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

## **Northrop B-2 Spirit**

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

## **Other tailless aircraft**

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

## **Experimental**

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

## Chapter- 8

# Tandem Wing and Triplane

## Tandem wing



QAC Quickie Q2

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

Quickie the aft wing serves as horizontal stabilizer, but pitch control comes from the forward wing.

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

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

### ***Designers using tandem wings***

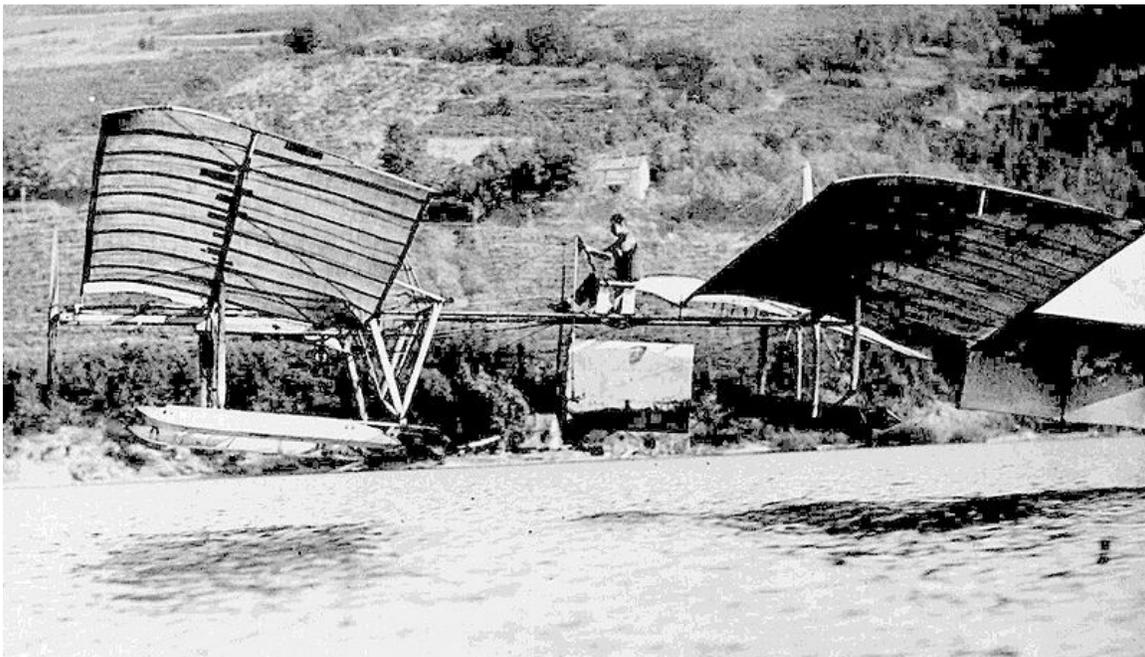
- Frederick George Miles
- Claude Piel
- Burt Rutan

### ***Examples***

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



Blériot VI Libellule (1907)



Langley Aerodrome, modified (1914)



Miles M.39B (1943)



Scaled Composites Proteus (1998)

# Triplane



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

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

## ***Design principles***

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

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

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

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

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

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

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

## ***History***

### **Pioneer years**

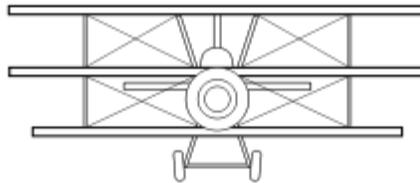


Illustration of a triplane

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

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

## The fighting triplanes



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

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

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

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

The Sopwith type's performance advantage and early successes over the Albatros D.III spurred military interest in the design, especially in Germany and Austro-Hungary. A flurry of prototypes were produced through 1917 and 1918, sometimes reluctantly under pressure from the military. Examples were produced by Albatros, Aviatik, Brandenburg, DFW, Euler, Friedrichshafen, LFG Roland, Lohner, Naglo, Offag, Pfalz, Sablatnik,

Schütte-Lanz, Siemens-Schuckert, W.K.F and in the USA by Curtiss. None of these went into production. Fokker's V.4 prototype of 1917 (identified by some as the V.3) had unusual cantilevered wings without bracing, the uppermost wing being attached only by cabane struts to the fuselage. The wings vibrated excessively in flight, and the next prototype, the V.5 featured a single interplane strut on each side similar to the Sopwith, but with no wires. This became the prototype of the famous Fokker Dr.I triplane of 1917 which became immortalised as the aircraft most closely identified with Manfred von Richthofen, the "Red Baron". Although it had a good rate of climb and was highly manoeuvrable it was not particularly fast. Following the break-up of two examples in the air the type was withdrawn from service for strengthening, and by the time it was re-introduced it was no longer at the forefront of performance.

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

## **Zeppelin killers**

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

## **Bombers and transports**

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

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

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

## Racing triplane

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

## Tandem triplanes

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

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

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

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

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

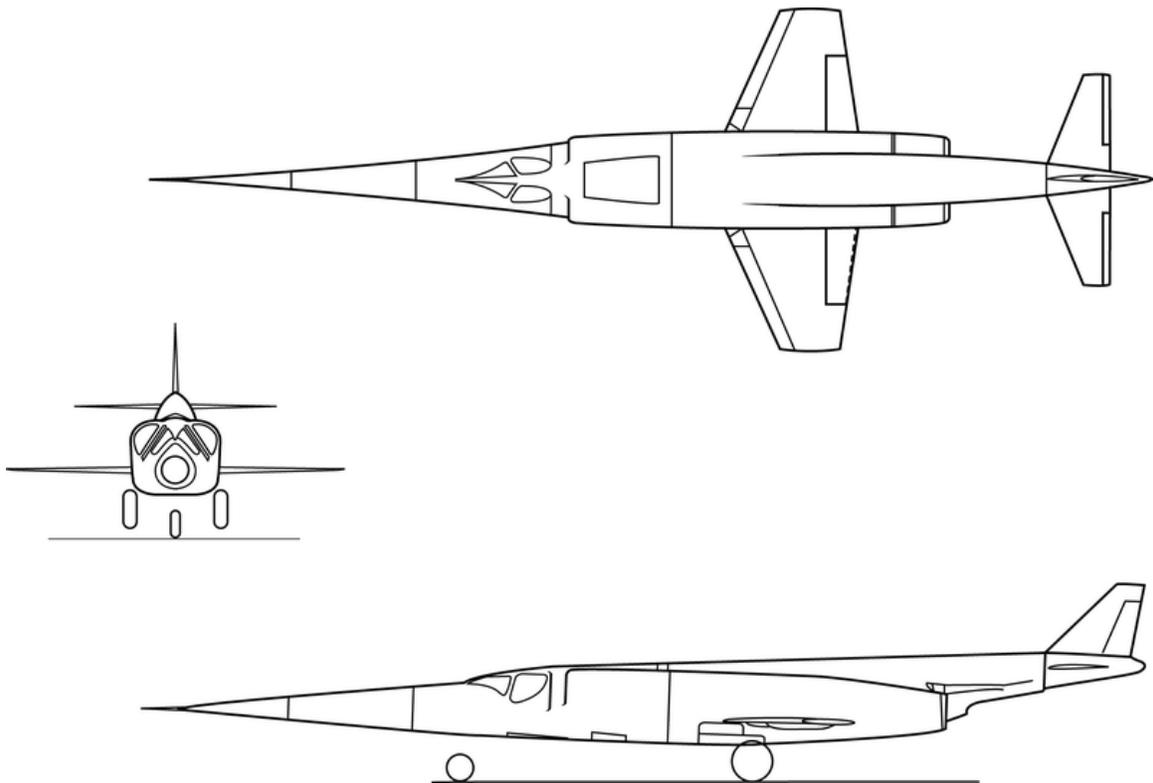
A further example was under construction in Kansas City, USA as late as 1922 .

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

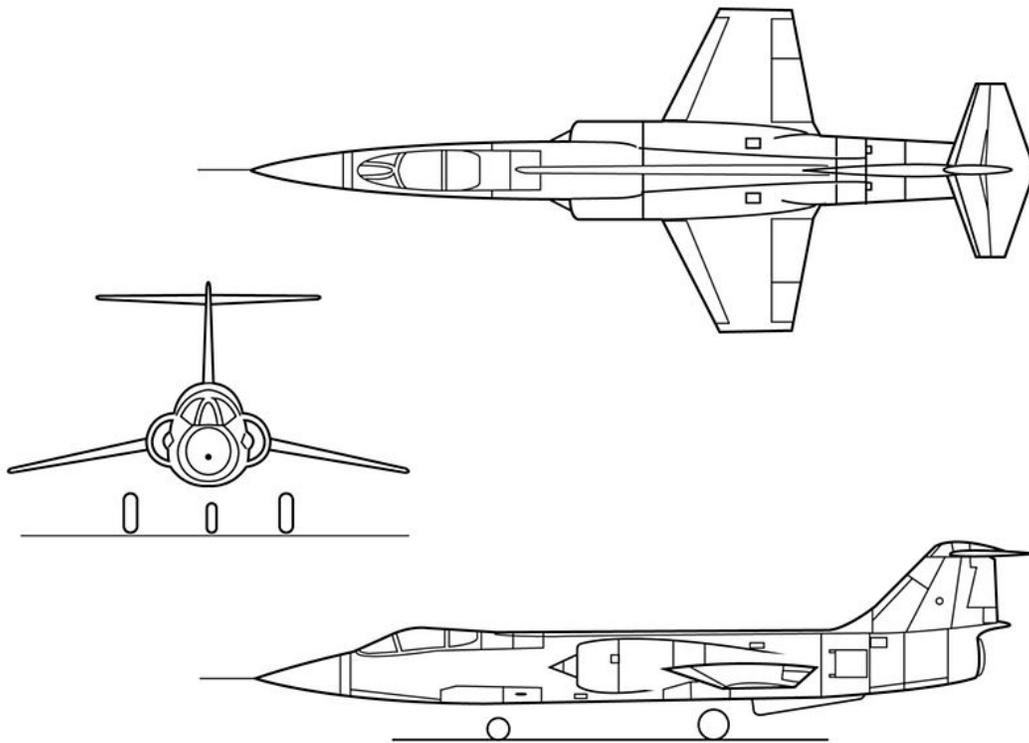
## Chapter- 9

# Trapezoidal Wing and Wingtip Device

## Trapezoidal wing



X-3 Stiletto



F-104 Starfighter



Lockheed F-22 Raptor



F-35 Lightning II

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

### ***History***

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

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

More recently, a larger and less highly loaded variant has been found to provide good all-round speed, load carrying and maneuvering characteristics for modern combat fighters

such as the Lockheed F-22 Raptor and others. Its inherent light weight has also led to its adoption for the VTOL-capable F-35 Lightning II Joint Strike Fighter.

## ***Examples***

### **X-planes**

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

### **Military planes**

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

# Wingtip device

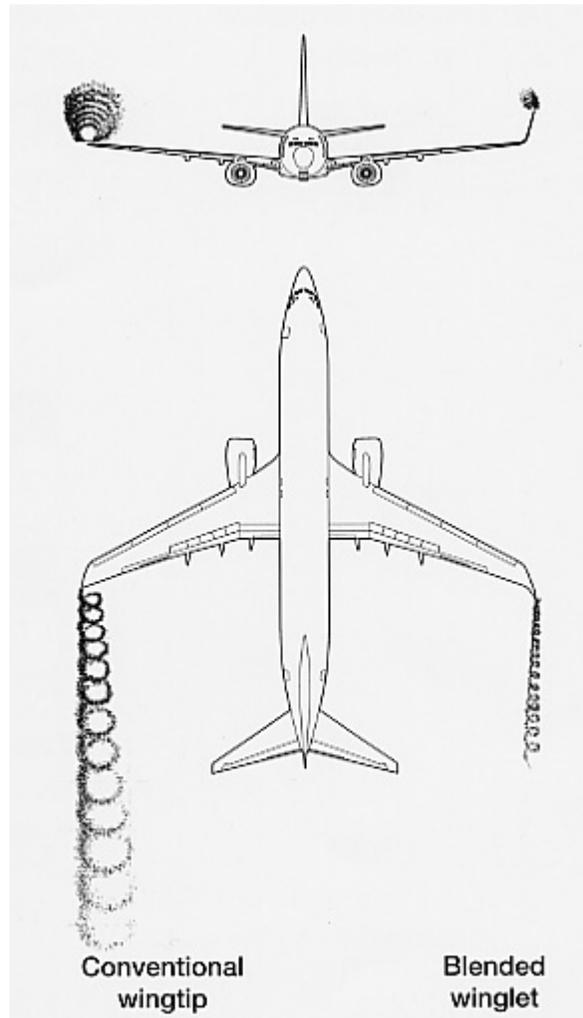


In the foreground, a red blended winglet extends up from the port wingtip of a Boeing 737-800. In the background, a yellow wingtip fence on the starboard wing of an Airbus A319

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

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

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



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

## Winglet



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

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

This small contribution can be worthwhile over the aircraft's lifetime, provided the benefit offsets the cost of installing and maintaining the winglets. Another potential benefit of winglets is that they reduce the strength of wingtip vortices, which trail behind the plane. When other aircraft pass through these vortices, the turbulent air can cause loss of control, possibly resulting in an accident. This possibility is greatest near airports and the minimum spacing requirements between aircraft operations at airports is largely due to these factors. Aircraft are classified by weight (*e.g.* "Light," "Heavy," etc.) in large part because the vortex strength is proportional (not linearly) to the amount of lift being generated by the airfoil. For this reason, wingtip vortices are typically most dangerous

when an aircraft is in a high lift, high drag, high angle of attack position and at a heavy gross weight. During takeoff, for example, flaps and slats are typically partially extended, the aircraft is at its heaviest and a large amount of lift is generated as the aircraft reaches rotate velocity and transition to climbout.

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

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



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

## History and applications

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

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



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

## NASA development

Hoerner's concept was further developed by Richard T. Whitcomb, an engineer at NASA's Langley Research Center, in response to the sharp increase in the cost of fuel

after the 1973 oil crisis. Whitcomb's designs were flight-tested in 1979–80 by a joint NASA/Air Force team, using a KC-135 Stratotanker based at the Dryden Flight Research Center. A Lockheed L-1011 and McDonnell Douglas DC-10 were also used for testing, and the latter design was directly implemented by McDonnell Douglas on the derivative MD-11, which was rolled out in 1990. NASA's own most notable application of wingtip devices is on the Boeing 747 Shuttle Carrier Aircraft. Located on the 747's horizontal stabilizers, the devices increase the tailplane's effectiveness under the weight of the Space Shuttle orbiter.



Beechcraft Starship Model 2000

## **Composite aircraft**

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



Gulfstream V with winglets

### **Business aircraft**

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



Learjet 60 with winglets

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

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



A Boeing 747-400 with winglets

## **Passenger aircraft**

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

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

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



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

## Gliders

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



PSU-90-125 winglet airfoil profile

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

## Advertising



Advertising on WestJet Boeing 737-700 winglets

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

## Notable examples

Winglets are employed on many aircraft types, such as:

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

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

## Wingtip fence



A detailed view of the wingtip fence on an Airbus A319

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

## Blended winglets



Boeing 737 with blended winglets

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

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

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

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

### ***Raked wingtip***



Boeing 787 rollout showing raked wingtip

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

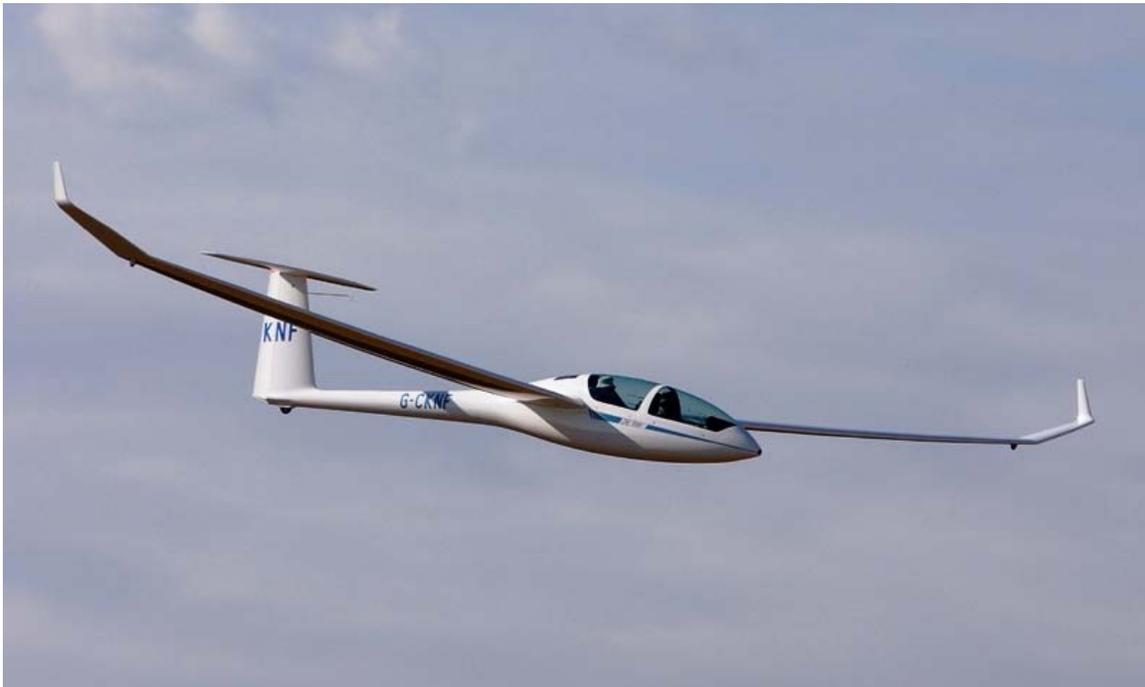
While an equivalent increase in wingspan would be more effective than a winglet of the same length, the bending force becomes a greater factor. A one-foot increase in span has the same bending force as a three-foot winglet, which has the same performance gain as a two-foot wing extension.

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

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

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

### ***Non-planar wingtip***



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

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

Aircraft designers employed mostly planar wing designs with simple dihedral after World War II, prior to the introduction of winglets. With the wide acceptance of winglets in new sailplane designs of the 1990s, designers sought to further optimize the aerodynamic performance of their wingtip designs. Glider winglets were originally retrofitted directly to planar wings, with only a small, nearly right-angle, transition area. Once the

performance of the winglet itself was optimized, attention was turned to the transition between the wing and winglet. A common application was tapering the transition area from the wing tip chord to the winglet chord and raking the transition area back, to place the winglet in the optimal position. If the tapered portion was canted upward, the winglet height could also be reduced. Eventually, designers employed multiple non-planar sections, each canting up at a greater angle, dispensing with the winglets entirely.

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

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

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

### ***Actuating wingtip devices***

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

***Use on rotating blades***



"Winged rotor" on AgustaWestland AW101 Merlin helicopter



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



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

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

### **Rotorcraft applications**

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

### **Propeller applications**

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

## Chapter- 10

# Leading Edge Extension and Wing Fence

## Leading edge extension

A **leading edge extension** is a small extension to an aircraft wing surface, forward of the leading edge. Different kinds of extensions have been used for different reasons.

### *Leading edge slats*

A **slat** is a small aerofoil running spanwise just ahead of the wing leading edge. This creates a *Leading edge slot* between the slat and wing, which acts to allow the aircraft to fly at lower speeds.

### *Dogtooth extension*



Dog tooth on the wing of a Hawker Hunter

A **dogtooth** is a small, sharp zig-zag double kink in the leading edge of a wing. On a swept wing, it is used to generate a vortex of air flowing backwards over the wing, reducing spanwise airflow.

Where the dog tooth is added as an afterthought as for example with the Hawker Hunter, the dogtooth is created by adding an extension to the outer span only of the leading edge.

### ***Leading edge kink***



Kinked leading edge of an Avro Vulcan

The Avro Vulcan prototypes had a delta wing with a straight leading edge. To cure handling problems, a shallow triangular extension was added to the outer leading edge, giving the planform of a compound delta having three leading edge sections at different angles, with kinks between the sections.

Later models of the English Electric Lightning had the wing tip extended forwards to create a leading edge kink at approximately two-thirds span.

## ***Leading edge root extensions (LERX)***



Condensation vortex flows along an F/A-18's LERX

LERX are small fillets, typically roughly triangular in shape, running forward from the leading edge of the wing root to a point along the fuselage.

On a modern fighter aircraft they provide usable airflow over the wing at high angles of attack, so delaying the stall and consequent loss of lift. In cruising flight the effect of the LERX is minimal. However at high angles of attack, as often encountered in a dog fight, the LERX generates a high-speed vortex that attaches to the top of the wing. The vortex action maintains a smooth airflow over the wing surface well past the normal stall point at which the airflow would otherwise break up, thus sustaining lift at very high angles.



Su-27UB with LERX

LERX were first used on the Northrop F-5 "Freedom fighter" which flew in 1959, and have since become commonplace on many combat aircraft. The F/A-18 Hornet has especially large examples, as does the Sukhoi Su-27. The Su-27 LERX help to make some advanced maneuvers possible, such as the Pugachev's Cobra, the Cobra Turn and the Kulbit.

## **Chines**



Chines along the fuselage of a SR-71 Blackbird

A **chine** is a long extension of the wing root along the forward fuselage, first seen on the Lockheed SR-71 Blackbird family. The chines contribute useful additional lift at supersonic speeds, as well as acting as LERX at low speeds. A standard leading edge extension joins to the fuselage at an angle while a chine is an extension of the curvature of the fuselage. Therefore chines avoid presenting corner reflectors or vertical sides to radars.

The F-22 Raptor has chines that lead to the leading edge extensions that are blended into the engine air intakes.

Canards can also help generate vortex lift over the main wings, but due to their poor stealth characteristics they have been replaced with chines in all fifth generation jet fighters except for the Chengdu J-20.

### ***Aircraft using LEX***

A few examples of aircraft with leading edge extensions are listed below.

- Europe
  - Dassault Rafale
- China
  - Shenyang J-13
  - Chengdu J-9
  - Su-30MKK/MK2
  - JL-9
  - L-15 Falcon
- China/Pakistan
  - JF-17 Thunder
- Sweden
  - Saab JAS 39 Gripen
- Iran
  - HESA Shafagh
- Russia/USSR
  - Sukhoi Su-27 and derivatives, including the Sukhoi Su-34 and the Sukhoi Su-47.
  - Mikoyan MiG-29
  - Sukhoi PAK FA - on PAK-FA aircraft the part of the wing that includes the LERX is movable to control the airflow at high angles of attack, similar to a wing leading flap. - LEVCON (this is "active" control surface)
- USA/UK
  - F-5 Freedom Fighter
  - F-16 Fighting Falcon and its unsuccessful competitor the YF-17 Cobra
  - F/A-18 Hornet/Super Hornet
  - AV-8 Harrier II/RAF Harrier II
- Civilian
  - Quest Kodiak (Fixed Discontinuous Outboard Leading Edge Extension)

# Wing fence



Close up of the wing fences of an East German Su-22

**Wing fences**, also known as **boundary layer fences** and **potential fences** are fixed aerodynamic devices attached to aircraft wings. Not to be confused with wingtip fences, wing fences are flat plates fixed to the upper surfaces (and often wrapping around the leading edge) parallel to the airflow. They are often seen on swept-wing aircraft. They obstruct span-wise airflow along the wing, and prevent the entire wing from stalling at once. Wing fences are often used in addition to or instead of slats.

As a swept-wing aircraft slows toward the stall speed of the wing, the angle of the leading edge forces some of the airflow sidewise, toward the wing tip. This process is progressive, airflow near the middle of the wing is affected not only by the leading edge angle, but also the spanwise airflow from the wing root. At the wing tip the airflow can end up being almost all spanwise, as opposed to front-to-back over the wing, meaning that the effective airspeed drops well below the stall. Because the geometry of swept wings typically places the wingtips of an aircraft aft of its center of gravity, lift generated at the wingtips tends to create a nose-down pitching moment. When the wingtips stall, both the lift and the associated nose-down pitching moment rapidly diminish. The loss of the nose-down pitching moment leaves the previously balanced aircraft with a net nose-up pitching moment. This forces the nose of the aircraft up, increasing the angle of attack and leading to stall over a greater portion of the wing. The result is a rapid and powerful pitch-up followed by a complete stall, a difficult situation for a pilot to recover from. The

"Sabre dance" (which caused many F-86 Sabres to crash) is a notable example of this behavior.



A Polish Sukhoi Su-20, showing the wing fences in relation to its wings

Wing fences delay, or eliminate, this effect by preventing the spanwise flow from moving too far along the wing and gaining speed. When meeting the fence, the air is directed back over the wing surface. Similar solutions included a notch in the leading edge, as seen on the Avro Arrow, or the use of slats, as on the later versions of the F-86. Slats can act as fences directly, in the form of their actuators, but also reduce the problem by improving the angle of attack response of the wing and moving the stall point to a lower speed.

Wolfgang Liebe, who is generally credited with inventing wing fences, filed a patent for it in 1938 while working on the Messerschmitt Me.109B. After World War II, Soviet military aircraft designers became known for their habit of using wing fences, using them on aircraft as varied as MiG-15 'Fagots' and Tu-22M 'Backfires'. It was joked in the West that the purpose of wing fences on Soviet military aircraft was to "prevent air from *defecting* over the tips of the wings."

## Chapter- 11

# Folding Wing



Douglas Skyraider

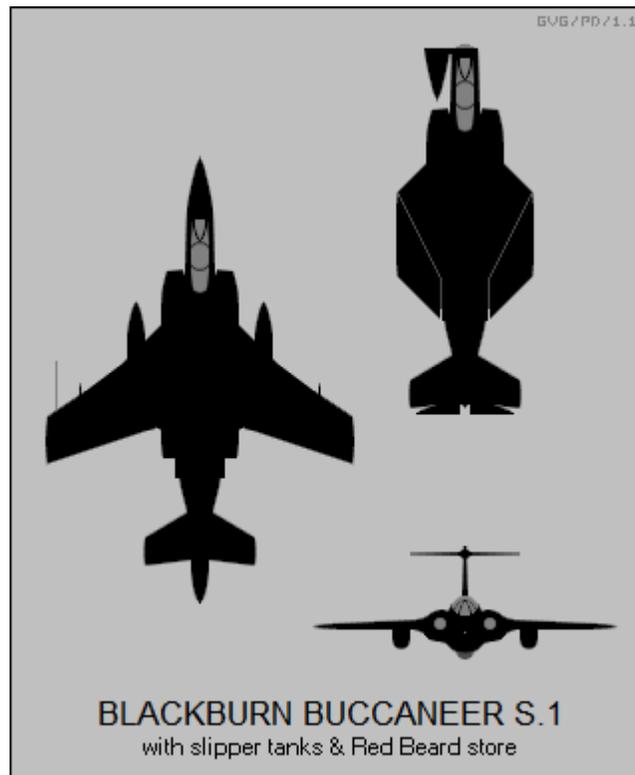
A **folding wing** is a design feature of aircraft to save space in the airfield, and time, and is typical of naval aircraft that operate from the limited deck space of aircraft carriers. The folding allows the aircraft to occupy less space in a confined hangar because the folded wing normally rises over the fuselage decreasing the floor area of the aircraft. Vertical clearance is also limited in aircraft carrier hangar decks. In order to accommodate for this, some aircraft such as the Supermarine Seafire and Fairey Gannet have additional

hinges to fold the wingtips downward, while others such as the S-3 Viking have folding tails.

Short Brothers, the world's first aircraft manufacturer, developed and patented folding wing mechanisms for ship-borne aircraft (Short Folder), the first patent being granted in 1913. The wings were hinged so that they folded back horizontally alongside the fuselage, usually being held in place by latches projecting sideways from the rear of the fuselage.

Since the monoplane supplanted the biplane in the late 1930s, virtually all fixed-wing aircraft designed for shipboard duty have been equipped with folding wings. Notable exceptions include the SBD Dauntless, F2A Buffalo, and A4D/A-4 Skyhawk (all USN types) and the Sea Harrier (British). All four are relatively small designs.

A folding wing has disadvantages over a fixed wing. It will be heavier and have complex connections for electrical, fuel, aerodynamic and structural systems.



Blackburn Buccaneer

Many naval helicopters have rotor blades that can be aligned over the fuselage to save space onboard the ship.

Folding surfaces are rare among land-based designs, and are used on aircraft that are tall or too wide to fit inside service hangars. Examples include the Boeing B-50 Superfortress

(folding tail) and Sukhoi Su-47 (folding wings). The Saab 37 Viggen and the Boeing 377 Stratocruiser have foldable rear fins that make them lower for entering hangars.

### Simple fold



De Havilland Sea Vixen



Hawker Sea Fury



Hawker Sea Hawk



F/A-18E/F Super Hornet



F-8H in an elevator



RAF Buccaneer S.2

## Afterwards folding wings



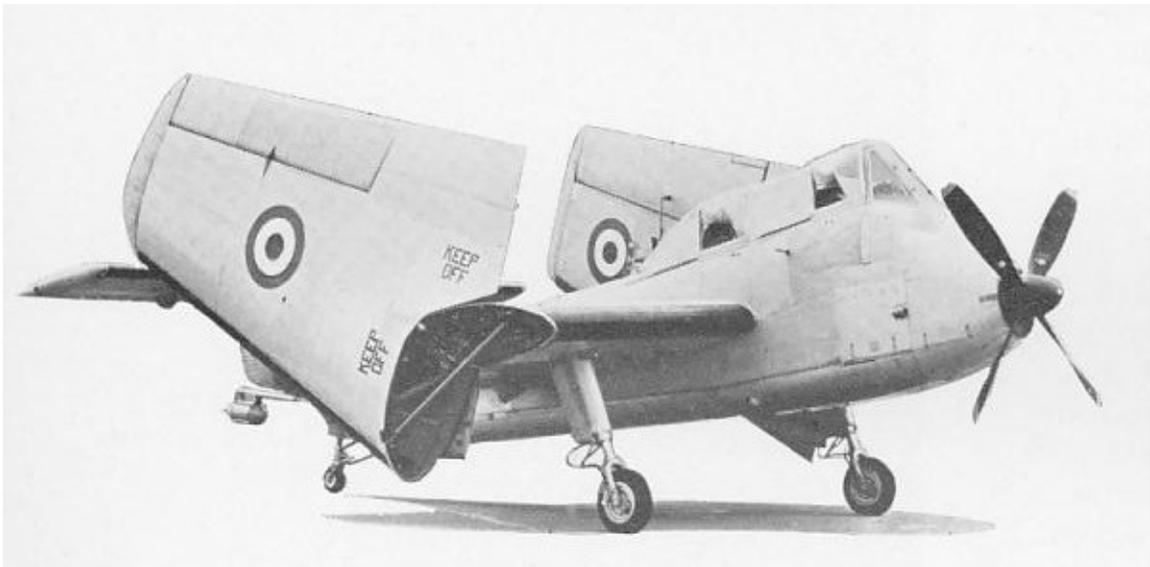
Grumman F6F Hellcats of the US Navy. The backwards-folding mechanism was common to Grumman fighters of World War II.



Fairey Fulmar



Fairey Firefly



Short Seamew



Grumman E-2 Hawkeye

## Double fold



Supermarine Seafire



Fairey Gannet



Westland Wyvern

## Rotating wing



A V-22 Osprey with wings rotated to run the length of the fuselage

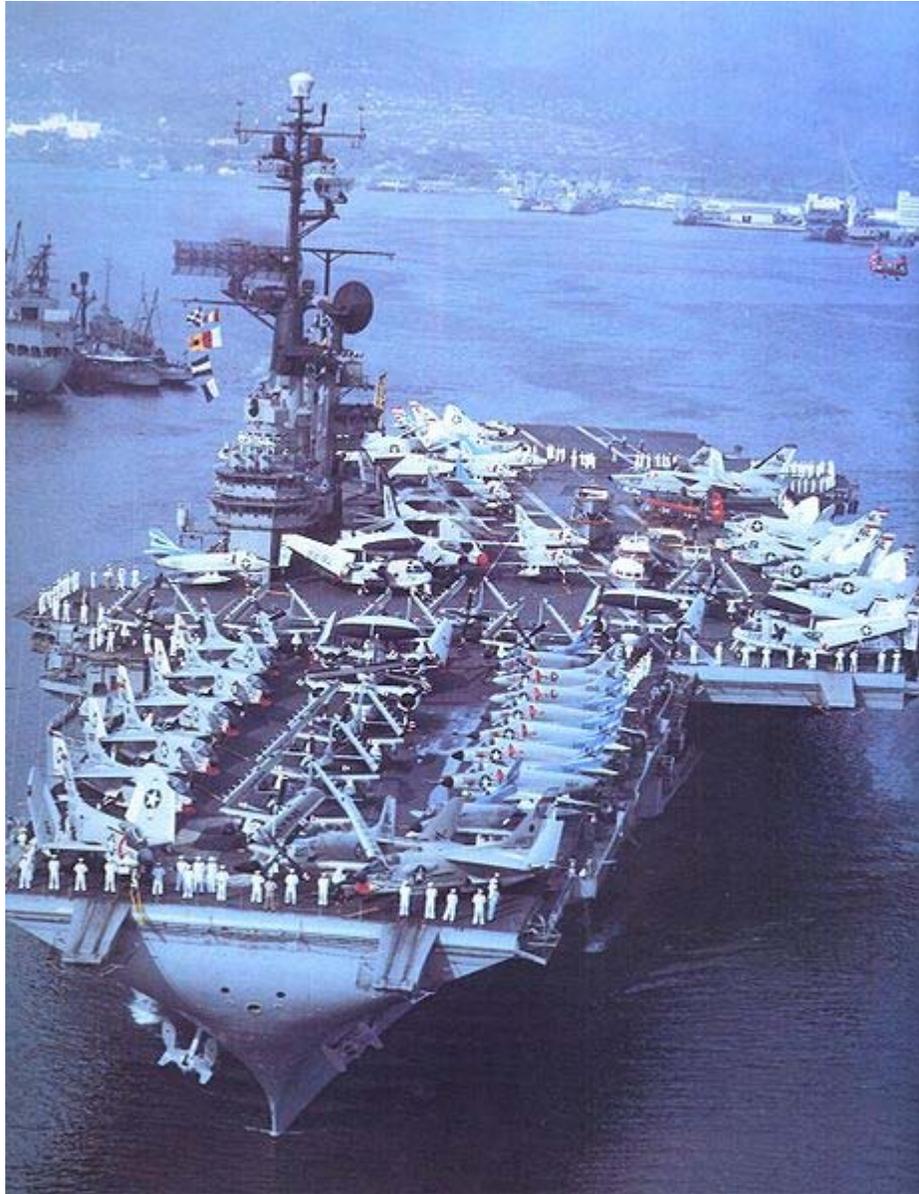
## Folding wings planes on flight deck



Avengers on USS *Hornet* (1945)



Sea Venoms, Scimitars and Skyraiders on HMS *Victorious* (circa 1959-1960)



Demons, Crusaders, Skywarriors, Trackers, Tracers and Skyriders on USS *Coral Sea* (1963)

## Chapter- 12

# Variable-Sweep Wing and Oblique Wing

## Variable-sweep wing



F-14 Tomcat with wings swept



F-14 Tomcat with wings unswept



Bell X-5, a multiple exposure demonstrating several wing positions

A **variable-sweep wing** is an aeroplane wing that may be swept back and then returned to its original position during flight. It allows the aircraft's planform to be modified in flight, and is therefore an example of a variable geometry aircraft.

Typically, a swept wing is more suitable for high speeds, while an unswept wing is suitable for lower speeds, allowing the aircraft to carry more fuel and/or payload, as well as improving field performance. A variable-sweep wing allows a pilot to select the correct wing configuration for the plane's intended speed. The variable-sweep wing is most useful for those aircraft that are expected to function at both low and high speed, and for this reason it has been used primarily in military aircraft.

A number of successful and experimental designs were introduced from the 1940s into the 1970s, however, the recent advances in flight control technology and structural

materials has allowed designers to closely tailor the aero-dynamics and structure of aircraft, removing the need for variable geometry to achieve the required performance.

## ***History***

Variable-sweep wing aircraft developed from earlier experimental aircraft that were built to study the effects of a simple swept wing. The first of these was the Messerschmitt Me P.1101 whose sweep angle could be changed on the ground. World War II in Europe ended before the P.1101 could be completed.

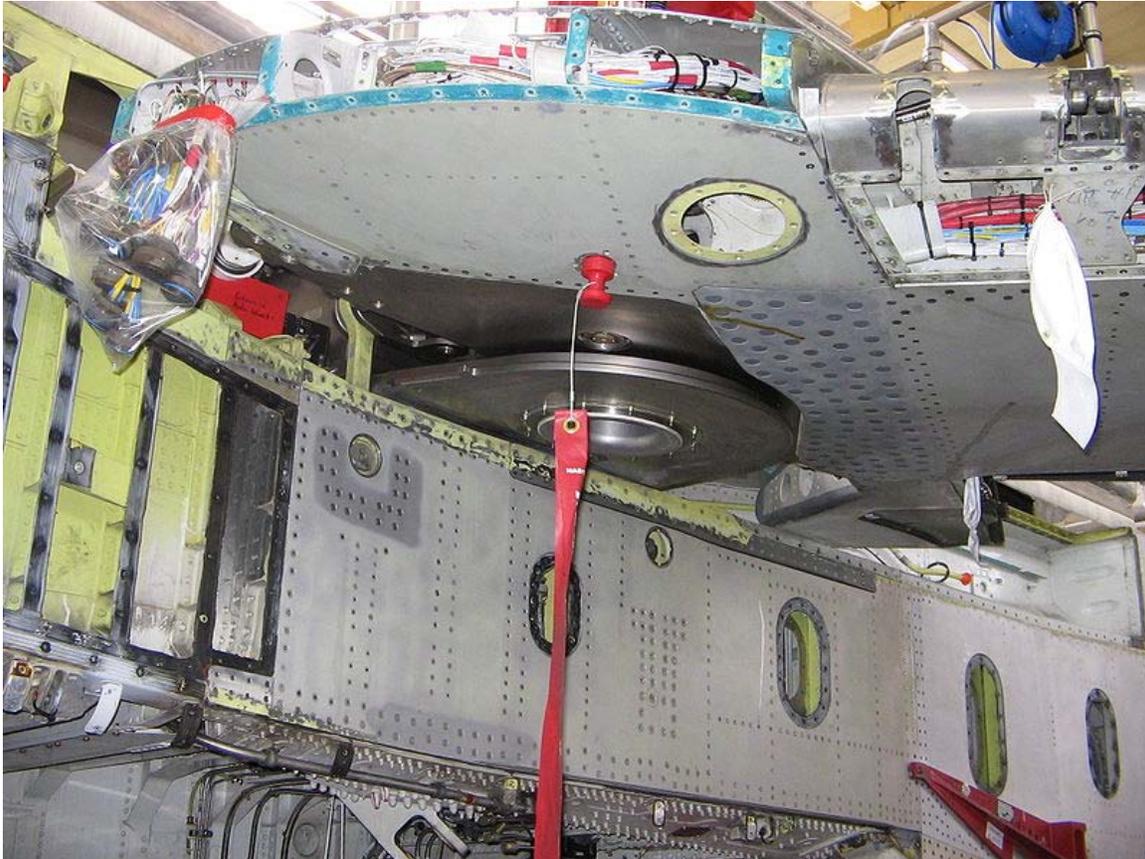
Soon afterwards, the P.1101 was taken to the United States for study at Bell Aircraft, but because of missing documentation and structural damage, Bell decided against completing it. Instead, a close copy was constructed which featured wings that could adjust sweep angle in flight. One problem discovered while testing the Bell X-5 was that as the wing pivoted rearward, the lift vector also moved to the rear, pushing the nose down. A system to compensate for this basic effect had to be added for any such design to be viable.

Immediately after the war Barnes Wallis had started work on variable geometry to maximise the economy of supersonic flight. Initial work was on the military "Wild Goose" project, then he went onto the "Vickers Swallow", intended to achieve a return flight from Europe to Australia in 10 hours. It had a blended wing tailless design and he successfully tested several models including a six foot scale model at speeds of up to Mach 2 in the 1950s but government backing was withdrawn. Wallis and his team presented their work to the Americans seeking a grant to continue their studies but none was forthcoming. In 1949, aeronautical engineer L. E. Baynes patented a design for a supersonic variable-sweep wing fighter, but the design was not built.

A variable-sweep wing was tried on the Grumman F10F Jaguar in 1952. The XF10F never entered service; it possessed extremely poor flying characteristics and rather vicious spin tendencies. The idea was again revived in the early 1960s as a way to reconcile ever-growing aircraft weights (and thus wing loading) with the need to provide reasonable takeoff and landing performance. The United States adopted this configuration for the TFX (Tactical Fighter Experimental) program, which emerged as the General Dynamics F-111, the first production variable-sweep wing aircraft.

Similar requirements in the Soviet Union also led TsAGI, the Soviet aerodynamics bureau, to explore the possibilities of variable geometry. TsAGI evolved two distinct planforms, differing mainly in the distance (expressed as a percentage of total wingspan) between the wing pivots. A wider spacing not only reduced the negative aerodynamic effects of changing wing sweep, but also provided a larger fixed wing section which could be used for landing gear or stores pylons. This could, in fact, be adapted to more-or-less existing airframes, which the Soviets soon did, with the Sukhoi Su-17 (based on the earlier swept wing Sukhoi Su-7) and the Tupolev Tu-22M (based on the Tupolev Tu-22). The limitation of the wide spacing, however, was that it reduced the benefits of variable geometry as much as it reduced their technical difficulties. For the new, "clean-

sheet" Soviet designs, TsAGI devised a more narrowly spaced arrangement similar to that of the F-111. This design was used (albeit at different scales) for the MiG-23 fighter and the Sukhoi Su-24 interdictor, which flew in prototype forms at the end of the 1960s, entering service in the early 1970s.



Detail of the wing mechanism of a Panavia Tornado during overhaul.

In the aftermath of the cancellation of the TSR-2, the British had started a project with the French for the Anglo-French Variable Geometry aircraft (AFVG). When French commitment was curtailed the British sought a second partner in the F-104 Consortium of European nations. This in turn led to the European consortium that adopted variable geometry for the Multi-Role Combat Aircraft (MRCA) project that emerged as the Panavia Tornado. This was an interdictor and stand-off interceptor similar in function to the F-111, albeit on a smaller scale. Meanwhile, the U.S. Navy introduced the Grumman F-14 Tomcat to replace the canceled F-111B fleet interceptor with a fighter more nimble than the F-4 Phantom. Unlike the F-111, its variable-sweep wings were programmed automatically by speed and could be swept under G loading. In air combat, the wings could be swept forward for tight "bat" turns and back for dash speeds. Rockwell, meanwhile, adopted variable geometry for the Advanced Manned Strategic Bomber (AMSA) program that produced the B-1 Lancer bomber, intended to provide an optimum combination of high-speed cruising efficiency and fast, supersonic penetration speeds at

extremely low level. The last variable-sweep wing military aircraft to date was the Soviet Tupolev Tu-160 "Blackjack", which first flew in 1980.

A variable-sweep wing was also selected as the winning design used by Boeing's entry in the FAA's study for a supersonic transport, the 2707. However it evolved through several configurations during the design stage, finally adding a canard, and it eventually became clear that the design would be so heavy that it would be lacking sufficient payload for the fuel needed. The design was later abandoned in favor of a more conventional tailed delta wing.

While variable-sweep provides many advantages, particularly in takeoff distance, load-carrying ability, and the fast, low-level penetration role, the configuration imposes a considerable penalty in weight and complexity. The advent of relaxed stability flight control systems in the 1970s negated many of the disadvantages of a fixed platform. No new variable-sweep wing aircraft have been built since the Tu-160, though it has been noted that the F-14's replacement - the F/A-18E - has a reduced payload/range capability largely because of its small fixed wings.

## ***Variable-sweep aircraft***

### **Experimental**

- Bell X-5
- Dassault Mirage G
- Messerschmitt Me P.1101
- Grumman XF10F-1 Jaguar

### **Production**

- General Dynamics F-111 Aardvark
- General Dynamics/Grumman EF-111A Raven
- Grumman F-14 Tomcat
- Mikoyan-Gurevich MiG-23
- Mikoyan-Gurevich MiG-27
- Panavia Tornado
- Panavia Tornado ADV
- Rockwell B-1 Lancer
- Sukhoi Su-17
- Sukhoi Su-24
- Tupolev Tu-22M
- Tupolev Tu-160

# Oblique wing



Oblique wing on a NASA AD-1

An **oblique wing** (also called a slew wing) is a variable geometry wing concept. On an aircraft so equipped, the wing is designed to rotate on center pivot, so that one tip is swept forward while the opposite tip is swept aft. By changing its sweep angle in this way, drag can be reduced at high speed (with the wing swept) without sacrificing low speed performance (with the wing perpendicular).

## ***History***

The oldest examples of this technology are the unrealized German aircraft projects Blohm & Voss and P.202 Messerschmitt Me P.1009-01 from the year 1944, based on a Messerschmitt Patent. The constructor Dr. Richard Vogt was brought after the war to the USA during Operation Paperclip. The oblique wing concept was rediscovered by Robert T. Jones, an aeronautical engineer at the NASA Ames Research Center, Moffett Field, California. Analytical and wind tunnel studies initiated by Jones at Ames indicated that a transport-size oblique-wing aircraft, flying at speeds up to Mach 1.4 (1.4 times the speed of sound), would have substantially better aerodynamic performance than aircraft with more conventional wings.

So far, only one manned aircraft, the NASA AD-1, has been built to explore this concept. It flew a series of flight tests starting in 1979.

## **Theory**

The general idea is to design an aircraft that performs with high efficiency as the Mach number increases from takeoff to cruise conditions ( $M \sim 0.8$ , for a commercial aircraft) Since two different types of drag dominate in each of these two flight regimes, uniting high performance designs for each regime into a single airframe is problematic.

At low Mach numbers induced drag dominates drag concerns. Airplanes during takeoff and gliders are most concerned with induced drag. One way to reduce induced drag is to increase the aspect ratio of the lifting surface. This is why gliders have such long, narrow wings. An ideal wing has infinite span and induced drag is reduced to a two dimensional property. At lower speeds, during takeoffs and landings, an oblique wing would be positioned perpendicular to the fuselage like a conventional wing to provide maximum lift and control qualities. As the aircraft gained speed, the wing would be pivoted to increase the oblique angle, thereby reducing the drag and decreasing fuel consumption.

Alternatively, at Mach numbers increasing towards the speed of sound and beyond, wave drag dominates design concerns. As the aircraft displaces the air, a sonic wave is generated. Sweeping the wings away from the nose of the aircraft can keep the wings aft of the sonic wave, greatly reducing drag. Unfortunately, for a given wing design, increasing sweep decreases the aspect ratio. At high speeds, both subsonic and supersonic, an oblique wing would be pivoted at up to 60 degrees to the aircraft's fuselage for better high-speed performance. The studies showed these angles would decrease aerodynamic drag, permitting increased speed and longer range with the same fuel expenditure.

Fundamentally, it appears that no design can be completely optimized for both flight regimes. However, the oblique wing shows promise of getting close. By actively increasing sweep as Mach number increases, high efficiency is possible for a wide range of speeds.

It is theorized that an oblique flying wing could drastically improve commercial air transportation, reducing fuel costs and noise in the vicinity of airports. Military operations include the possibility of a long endurance fighter/attack vehicle.

## **NASA airliner research**

There has also been investigations into an OFW platform being developed into a transcontinental airliner. NASA Ames performed a preliminary design study of a theoretical 500-seat supersonic airliner using the concept in 1991. Following this study, NASA built a small remote-controlled demonstrator aircraft with a 20 foot (6.1m) wingspan. It flew only once, for four minutes in May, 1994, but in doing so, it demonstrated stable flight with oblique wing sweep from 35 degrees to 50 degrees. Despite this success, the NASA High Speed Research program, and further oblique wing studies, were canceled.

## ***DARPA Oblique Flying-Wing (OFW) Project***

The United States Defence Advanced Research Projects Agency (DARPA) has awarded Northrop Grumman a \$10.3 million (USD) contract for risk reduction and preliminary planning for an X-plane OFW demonstrator., known as the Switchblade.

The program aims at producing a technology demonstrator aircraft to explore the various challenges which the radical design entails. The proposed aircraft would be a pure flying wing (an aircraft with no other auxiliary surfaces such as tails, canards or a fuselage) where the wing is swept with one side of the aircraft forward, and one backwards in an asymmetric fashion. This aircraft configuration is believed to give it a combination of high speed, long range and long endurance. The program entails two phases. Phase I will explore the theory and result in a conceptual design, while Phase II will result in the design, manufacture and flight test of an aircraft. The outcome of the program will result in a dataset that can then be used when considering future military aircraft designs.