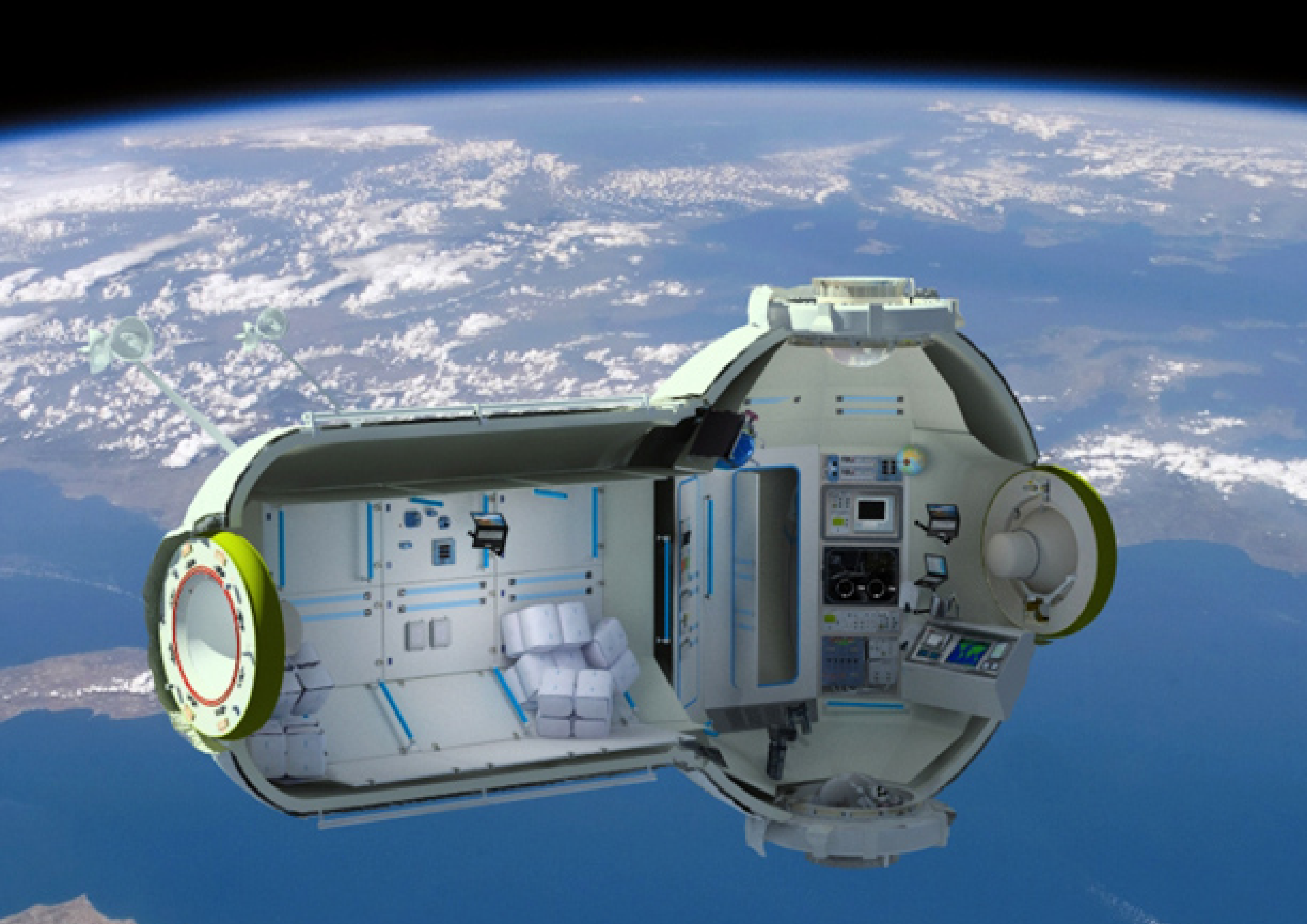

Airship Configurations

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Chapter 1

Orbital Airship

The **orbital airship**, also called the **space blimp**, is a proposed space transportation system that carries payloads to and from low Earth orbit. It is intended to achieve orbital altitude and orbital velocity using low thrust rocket propulsion by flying in the manner of an airship rather than a rocket, employing buoyancy and aerodynamic lift rather than vertical thrust to sustain flight during its ascent.

JP Aerospace's Airship to Orbit

In the Airship To Orbit (ATO) design envisioned by JP Aerospace, there are three components. A conventional airship ("Ascender") lifts payloads up to 30 to 43 kilometers above the ground - roughly the maximum altitude a conventional airship can achieve. At this altitude the second component, a docking station ("Dark Sky Station"), acts as a resupply station for the third stage. The third stage is an orbital airship ("Orbital Ascender"), which takes payloads to low earth orbit (i.e., it accelerates itself horizontally to orbital velocity and gains an altitude in excess of 100 km) over several days.

Their program sponsors and business revenues have continued to provide their development costs thus far. They funded part of their operation until 2005 with a contract for development of military communication and surveillance airships designed to hover over battlefields at altitudes too high for conventional anti-aircraft systems. They had hoped to fly a prototype in 2005, but the vehicle was damaged during testing and the contract was discontinued. Other vehicles are still under development, and JP aerospace has subsequently flown several aerostats as testbeds for ATO hardware and techniques.

Multiple vehicles are needed because any airship made strong enough to survive the relatively turbulent lower atmosphere would be too heavy to lift payloads to space. An orbital airship would need to be built larger to improve its buoyancy-to-weight ratio, with thinner walls, and designed to operate at notably lower pressure. Even in the outer fringes of the atmosphere, helium is still lighter than air.

Both the conventional and orbital airships will be V-shaped for aerodynamics. The orbital airship wings will be shaped to function as hypersonic airfoils and can be angled upwards to help generate lift. As the airship gains altitude, drag will reduce, allowing the vehicle to accelerate with increasing altitude. According to JP Aerospace, there is a wide margin of drag-to-power ratios within which an orbital airship can attain orbit.

Early development stages of the station and the airships will be powered by fuel cells. In the long term, the surface of these objects can be sprayed with a thin-film solar cell, which, while inefficient in energy conversion, would benefit from light weight, simplicity, and the large surface area. The final version of the orbital ascender can also employ refractory materials on the wing leading edge to reduce thermal wear. JP Aerospace's US patent #7614586 identifies the orbital ascender's propulsion system as chemical and/or electric rockets. John Powell's *Floating to Space* cites several candidate propulsion systems. JP Aerospace is currently developing a hybrid chemical/electric rocket engine.

Their estimated marginal costs for cargo are one dollar per ton per mile of altitude, as quoted to Dr. Jerry Pournelle at the 2004 Space Access Conference

Similar Proposals

Use of large balloons for aerobraking has been previously proposed by aerospace researchers or featured in works of science fiction.

Other groups in addition to JP Aerospace have recently claimed to be researching or actively developing alternative orbital airship designs.

JP Aerospace has also acknowledged competition from other organizations in its suborbital applications.

Potential Problems

A practical orbital airship design must deal with multiple engineering challenges of both high altitude balloons and spacecraft.

Buoyancy

One potential limitation is the weight of the material used to contain the airship's gas. For example, air density at 51 km in the mesosphere is estimated at 0.00086 kg per cubic meter according to the International Standard Atmosphere model. To be lighter than air at this altitude, the airship's total density - the weight of its gas plus its cargo and structure divided by its total volume - must be less than 0.00086 kg per cubic meter. This should be achievable with hydrogen, helium, and/or with heated gas inside the balloon, and/or with partially rigid supports. For comparison, the ISAS BU60-1 scientific balloon, holder of the world altitude record for an unmanned balloon as of 2009, flew to 53.0 km. With an inflated mass of 39.77 kg and a maximum volume of 60000 cubic meters, the total density of BU60-1 was 0.00066 kg per cubic meter.

It will be necessary for all ATO system components to achieve comparably low total density while still transferring sufficient propellant and payload for the orbital ascender to ultimately achieve orbit, or the system components will not have the necessary buoyancy to attain the altitudes stated by JP Aerospace. Additionally, the system components are claimed to be suitable for repeated use.

The square-cube law - common in many engineering calculations – is expected to be critical to the orbital airship design. The material needed to contain a given space increases as the square of its dimensions, while the volume of the space increases as per the cube of its dimensions. In theory one can create a lead balloon, or a concrete canoe, or an ironclad ship and have it float if it is of sufficient size, although this may not always be practical.

To achieve significantly higher altitudes, one needs very large volumes and/or very strong materials with low density that are affordable in bulk. Nevertheless, a mesosphere based high altitude platform could offer many potential advantages. One could harvest oxygen and store it for further stages - which might resemble a more conventional launch vehicle. Conditions in the mesosphere are very different than those at lower altitudes in the stratosphere or higher in the Thermosphere. Such a platform might also serve as a radio repeater or a relay point while receiving maser or laser energy from the ground.

A mesosphere based high altitude platform could also increase its altitude temporarily—in a non-lighter-than-air manner—using energy from ground based or solar sources.

Size

The final version of JP Aerospace's first stage Ascender airship will be among the largest airships ever constructed, with an expected volume (57 million cubic feet) greater than seven times that of the *Hindenburg*. The size of this vehicle will pose unique problems for design, construction, maintenance, deployment and storage.

The other vehicles in JP Aerospace's proposed architecture are significantly larger, with expected volumes among the largest inflatable structures of any type ever constructed. These vehicles are intended to remain in operation indefinitely (alleviating requirements for deployment and storage), and their operating environments are not predicted to be as structurally demanding as those of the first stage Ascender airship. However, size related problems of design, construction and maintenance will remain.

Other Potential Problems

The final design must address several other potential problems.

Additional helium will need to be added to the station and airship to help keep it buoyant. Refueling and resupply of other materials may also be required.

Hypersonic gas dynamics will create high temperature flow across the wings of the orbital ascender, and heat transfer along the wings must be kept low enough to avoid damage.

Regulatory hurdles are expected, beginning during the development phase. The vehicles will potentially traverse the airspace of several nations, and will need to meet legal regulations for flight in every country that they traverse the internationally recognized airspace of.

The orbital ascender faces some of the same harsh environmental conditions as a space elevator, such as elemental oxygen, radiation and space debris.

JP Aerospace believes the problems can be solved, and has already begun tests of the Ascender. They also point out that, if something goes wrong on an airship, there is more time to correct problems than on a rocket.

Potential Applications

JP Aerospace's Airship to Orbit architecture is three distinct vehicles plus ground control. Thus it would have potential applications beyond those of a direct launch rocket.

The vehicles could support extended research and exploration in the mesosphere and/or thermosphere, which are largely unexplored regions of the atmosphere.

The Dark Sky Station could provide a permanent station for both equipment and personnel. It could function as a outpost or port for space exploration in some of the same ways proposed for space stations – including outposts on other planets with atmospheres – and serve some of the roles filled by orbital satellites today. Possibilities for space tourism and space manufacturing are greatly expanded by the presence of a permanent station. Multiple dark sky stations could support enough living quarters to make residency a viable option.

The orbital airship might provide relatively low cost shipping and transportation, both suborbital and earth-to-orbit. The orbital airship would also be capable of providing orbit-to-earth shipping with equal or greater cargo capacity.

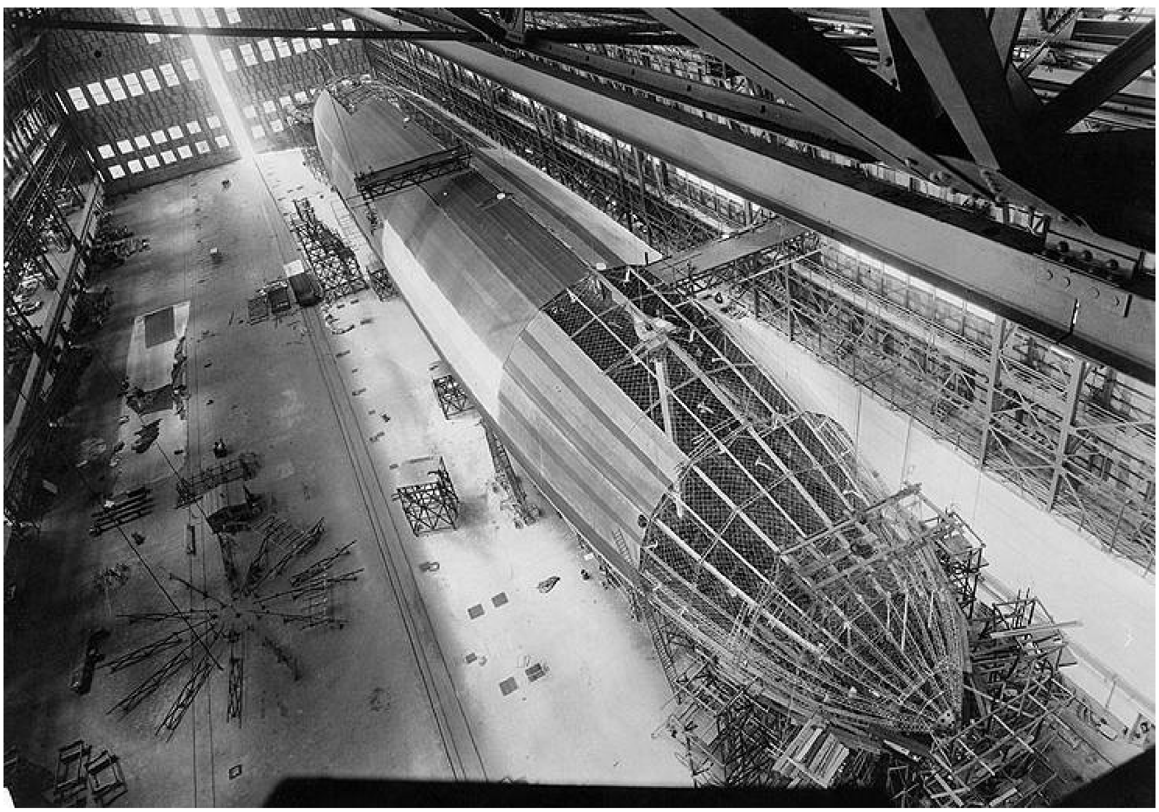
Skepticism

Nobody outside JP Aerospace seems to know how the problems of high drag and low lift/drag ratios that are very typically found at hypersonic speeds might be overcome in such a vehicle, and a large degree of skepticism exists.

Nevertheless, an orbital, thermosphere, or even mesosphere airship would face many practical and theoretical challenges and would represent a remarkable technical achievement.

Chapter 2

Rigid Airship



Construction of USS *Shenandoah* (ZR-1), 1923, showing the framework of a rigid airship.

A **rigid airship** was a type of airship in which the envelope retained its shape by the use of an internal structural framework rather than by being forced into shape by the pressure of the lifting gas within the envelope as used in blimps (also termed pressurized airships) and semi-rigid airships.

Rigid airships were produced and relatively successfully employed from the beginning of the 1900s to the end of the 1930s; their heyday ended when the Hindenburg ignited on May 6, 1937.

Terminology

Although "rigid airship" is the proper formal term, these aircraft are often casually referred to by several other names such as *dirigibles*, *zeppelins* (after the most successful ships of this type built by the Zeppelin Company) or the *big rigids*.

Early days

By 1874 several people had conceived of a rigid dirigible (in contrast to non-rigid powered airships which had been flying since 1852). Frenchman Joseph Spiess had published a rigid airship proposal in 1873 but failed to get funding. Count Zeppelin had outlined his thoughts of a rigid airship in diary entries from 25 March 1874 through to 1890 when he resigned from the military. David Schwarz had thought about building an airship in the 1880s and had likely started design work in 1891, definitely by 1892 he was starting construction. It was not until after Schwarz's death in 1897 that his all-aluminium airship, built with help from with Carl Berg and the Prussian Airship Battalion, was test flown. Schwarz and Berg had an exclusive contract and Count Zeppelin was obliged to come to a legal agreement with Schwarz's heirs to obtain aluminium from Carl Berg, although the two men's designs were different and independent from each other. With Berg's aluminum, Zeppelin was able in 1899 to start building and, in 1900 July, to fly the Zeppelin LZ1.

Great Britain

Great Britain and the USA lagged behind Germany in rigid airship technology. According to a 2001 PBS documentary, much of Britain's knowledge was based on reverse engineered technology from World War I German zeppelin crashes. After several crashes of experimental airships, the British ceded this field to the Germans.

France

France's only rigid airship was built by Alsatian Joseph Spiess using a wooden framework and it flew on April 13, 1913. It was 146 metres (479 ft) long, with a diameter of 13.5 metres (44.3 ft) and a gas volume of 16,400 cubic metres (579,161 cubic feet). Joseph Spiess is buried in the famous Cimetiere du Pere-Lachaise in Paris. His gravestone celebrates his achievements with a bronze frieze of his rigid airship.

Germany

In 1900, Count Ferdinand von Zeppelin began trials with a rigid airship based on the theories of engineer David Schwartz, a Croatian aviation pioneer of Hungarian-Jewish descent. Germany had over twenty very large lighter-than-air rigid airships by the beginning of World War I, seven owned by the company Luftschiffbau Zeppelin. In the five years prior to the outbreak of war, his airline carried 32,722 passengers on over 1,588 flights totalling 172,530 kilometres (107,205 miles). The German war ministry took over two of them in 1909 and one crashed. Commercial airlines ended in Germany at the outbreak of the War, during which Zeppelin's company built 95 giant military airships. German military airship stations had been established before the War and on September 2–3, 1914, the Zeppelin LZ 17 dropped three 200 lb bombs on Antwerp in Belgium. On January 19, 1915, two further airships dropped bombs on Norfolk, England, killing numerous people; the third ship in the air raid returned to Germany with engine trouble before reaching England. On May 31, 1915, the first bombs fell on London. The night of September 2–3, 1916 was when the first German airship was shot down over English soil; it was done using a small heavier-than-air aircraft. Further bombs were dropped on London during the night of November 27–28, 1916, this time by a winged aircraft. However, the build-up of England's defences against such aircraft led to the discontinuation of airship raids by Germany. The last casualties occurred on April 12, 1918.

United States

The United States rigid airship program was mostly stationed in Lakehurst Naval Air station, New Jersey. The ZR-1 Shenandoah was one of the first, serving from 1923 to 1925. The ZR-2 was a British airship intended to join the naval fleet, but it crashed in 1921. The ZR-3 was a German airship, sold to the United States in 1924 and named Los Angeles. The ship was grounded in 1931, due to the Depression, but was not dismantled for over 5 years. The sister ships Akron and Macon both crashed after technical failure. These crashes ended the rigid airship program.

Production

As well as the Zeppelin Company, Schütte-Lanz also manufactured them. Both America and Britain have manufactured rigid airships at some point.

Demise

Following the Hindenburg disaster in 1937, Germany grounded its airship fleet with the intention of replacing their hydrogen gas with non-flammable helium. By this time, however, Europe was well on the path to World War II, and the United States, the only country with substantial helium reserves, refused to sell the necessary gas. International travel was crippled during the war, and commercial aircraft - able to fly much faster than rigid airships - soon became the favored method of international air travel.

Some famous rigid airships

- *R34*, British airship and the first aircraft to traverse the Atlantic Ocean from east to west, in 1919.
- USS *Shenandoah*, American naval airship which served the U.S. Navy from 1923 until its crash in Ohio in 1925.
- *R38 (ZR-2)*, British airship intended to join the American naval fleet, but crashed during testing in 1921.
- USS *Los Angeles*, German airship sold to the United States in 1924 as part of German reparations from World War I. The ship served with distinction from 1924 to 1931.
- *LZ 127 Graf Zeppelin*, German passenger airship designed and piloted by Hugo Eckener. It circumnavigated the globe in 1929 and had a spotless safety record. It was ultimately dismantled by the Nazis at the outset of World War II.
- *R-100*, British airship built by the Airship Guarantee Company, a private company created solely for the construction of this airship, as a subsidiary of the armaments firm, Vickers.
- *R-101*, British airship designed and built by the British government in a kind of competition with the R-100. The R-101 crashed on its maiden flight in 1930 in France, with considerable loss of life. Its crash effectively ended British participation in rigid airship construction.
- USS *Akron*, American naval airship designed and built by the Goodyear Tire and Rubber Company in Ohio in 1931. Deployed as an airborne aircraft carrier, it was lost at sea in a storm off New Jersey in 1933 with considerable loss of life.
- USS *Macon*, sister ship to the *Akron*, it was a near carbon-copy of her. Though it suffered only 2 deaths, its crash in 1935 off the coast of California ended American participation in rigid airship development.
- *LZ 129 Hindenburg*, German passenger airship also designed and built by Hugo Eckener. The airship was lost in a famous fire in New Jersey in 1937. With its end came the end of the age of the Great Rigid Airships.

Modern rigids

There are no rigid airships flying today. The Zeppelin company refers to their NT ship as a rigid but this is a misnomer. The envelope shape is retained in part by super-pressure of the lifting gas, and so the NT is more correctly classified as a semi-rigid.

Chapter 3

Airborne Aircraft Carrier

Airborne aircraft carrier

The Boeing X-43 being dropped from under the wing of a B-52 Stratofortress.

Airborne aircraft carriers are aircraft which can launch other aircraft. These typically are large aircraft that launch fighter-interceptor planes.

List of airborne aircraft carriers

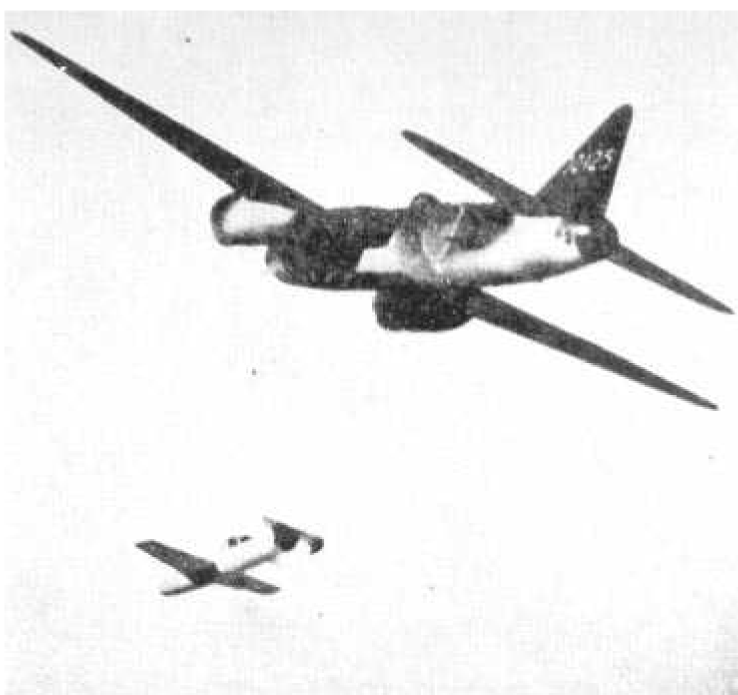
Dirigible aircraft carriers

Several plans were drawn up to outfit Zeppelin-type dirigible airships to launch and recover fighters. These are also the typical airborne aircraft carriers found in fiction. Working prototypes include:

- R33
- USS Los Angeles (ZR-3), used for prototype testing for the Akron and Macon.
- USS Akron (ZRS-4)
- USS Macon (ZRS-5)

These dirigible aircraft carrier all utilized an internal hangar bay using a "trapeze" to hold the aircraft. However during the 1940s many alternate plans were drawn that were not realized. A popular proposal was a rigid runway situated on the top of the dirigible for both take off and landings of planes, and an elevator to move the aircraft into the hangar located inside the main assembly. This would allow a relatively innocuous vehicle to field a large amount of aircraft. These plans were abandoned due to weight/lift ratio of the dirigible and the lost internal gas space (thus reducing the lift) due to the installation of a large hangar. A trapeze arrangement was deployed more practicably on boats using the Brodie landing system later in WWII.

Jet-Carrying Bombers



A Japanese Mitsubishi G4M launching the Ohka

During World War II the Japanese navy developed the rocket-powered Kamikaze aircraft Ohka and due to the short range of the rocket, it was launched by a Mitsubishi G4M bomber when close to a target ship.

Nazi-Germany had also developed a jet-carrying bomber, called the Daimler-Benz Project C.

Bomber aircraft carriers

TB-3-4AM-34FRN in Zveno-SPB configuration with Polikarpov I-16 fighters armed with FAB-250 bombs

During the early days of the jet age fighter aircraft could not fly long distances and still match point defence fighters or interceptors in dogfighting. The solution was long range bombers that would carry or tow their escort fighters. This is similar in concept to cruisers that carried escort fighters, or the merchant aircraft carrier.

Several bombers have been used by NASA as launch platforms for experimental aircraft.

- FICON project
- Project Tom-Tom
- B-36 Peacemaker
- B-29 Superfortress
- Zveno project
    - Tupolev TB-1
    - Tupolev TB-3

Transport aircraft carriers

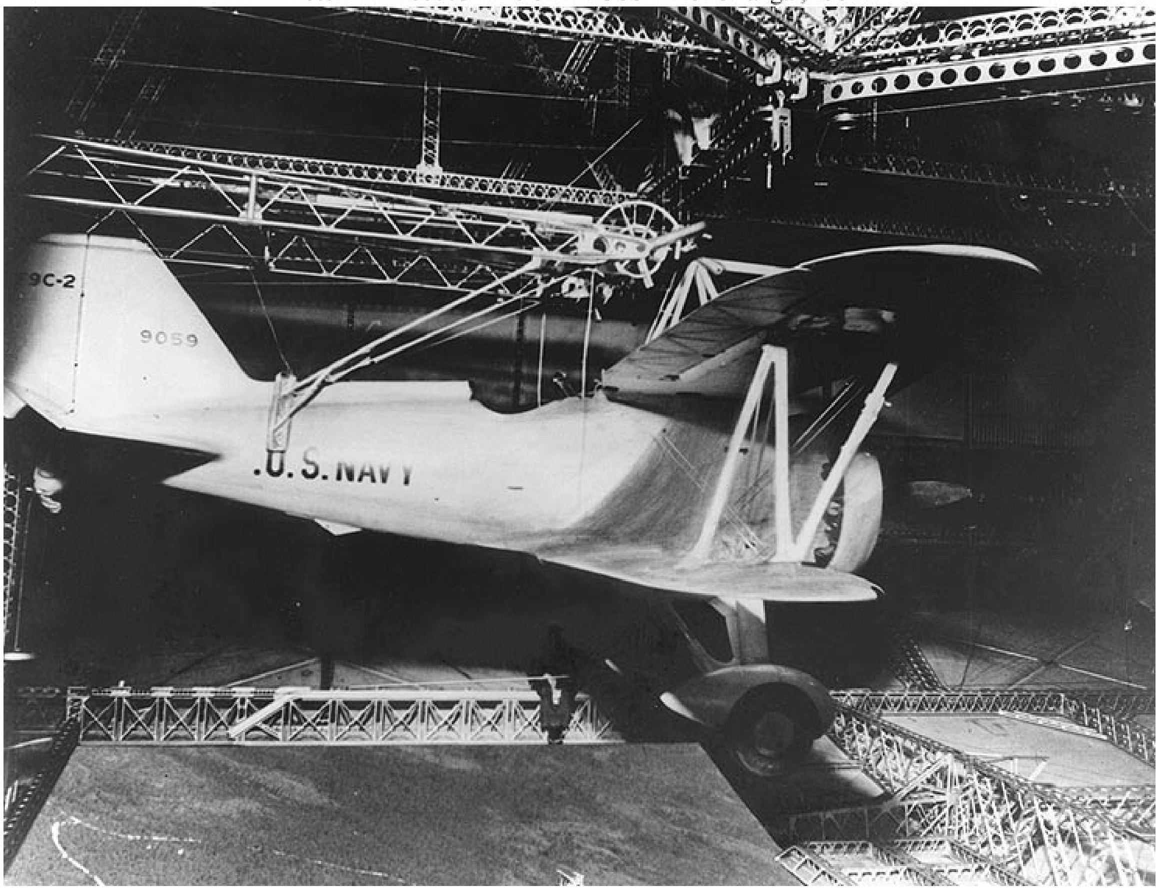
A few specific aircraft have been built or modified to transport other aircraft; the most famous of these, a pair of modified Boeing 747s known as the Shuttle Carrier Aircraft (SCA) belonging to the United State's National Aeronautics and Space Administration (NASA), and are now used only to transport the US Space Shuttle Orbiter vehicle, though one was used by the Space Shuttle Enterprise to actually launch the orbiter for atmospheric approach and landing tests. The Soviet Union created a similar vehicle (the Antonov An-225) to support the *Buran* spacecraft.

More recently, White Knight has been used to launch the Space Ship One privately owned space craft, and is slated to be used for a follow on design.

- Short Mayo Composite
- Shuttle Carrier Aircraft (SCA) - launched flight testing of Enterprise
- White Knight - launched SpaceShipOne
- White Knight Two - designed to launch SpaceShipTwo
- White Knight Three - anticipated to launch SpaceShipThree

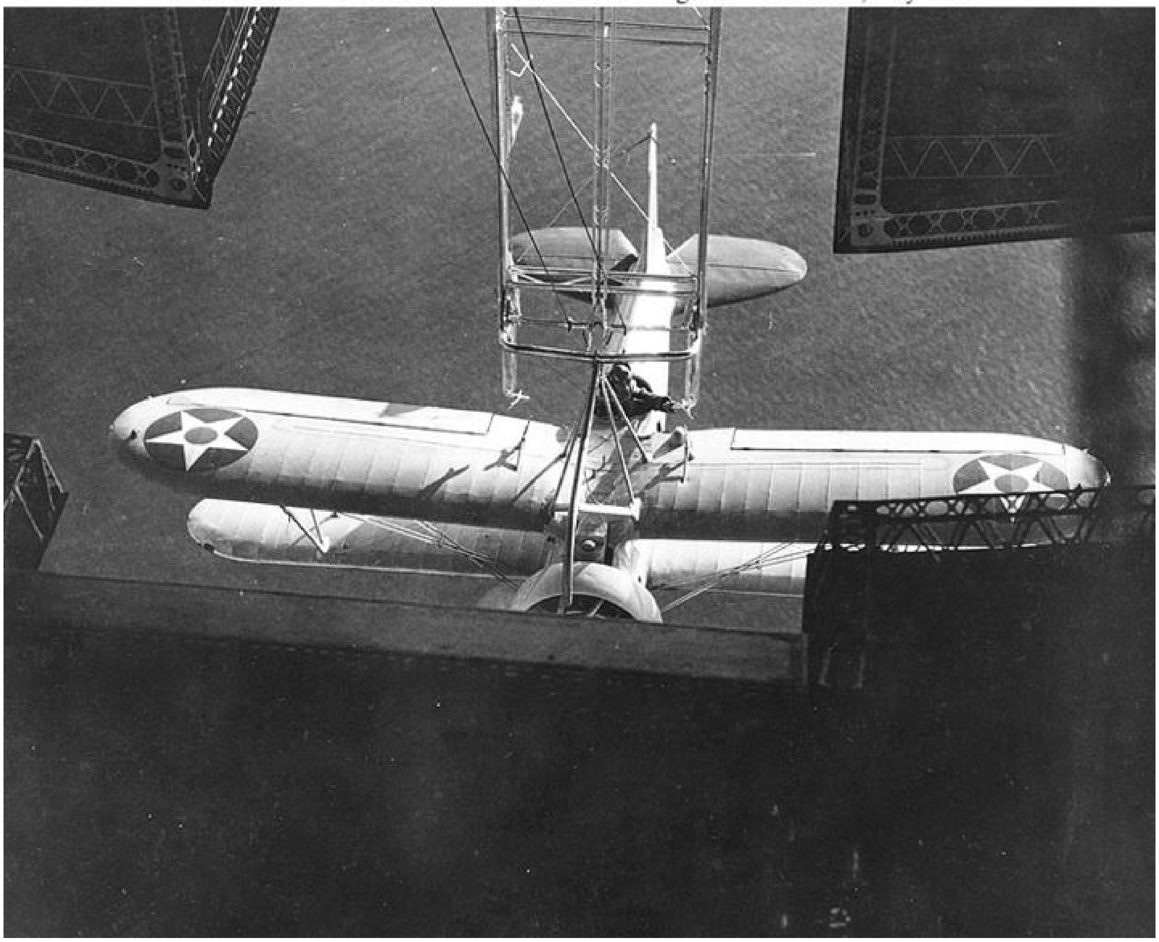
The *Akron* in flight, November 1931.

Photo # NH 80773 F9C-2 in USS Akron's hangar, 1932

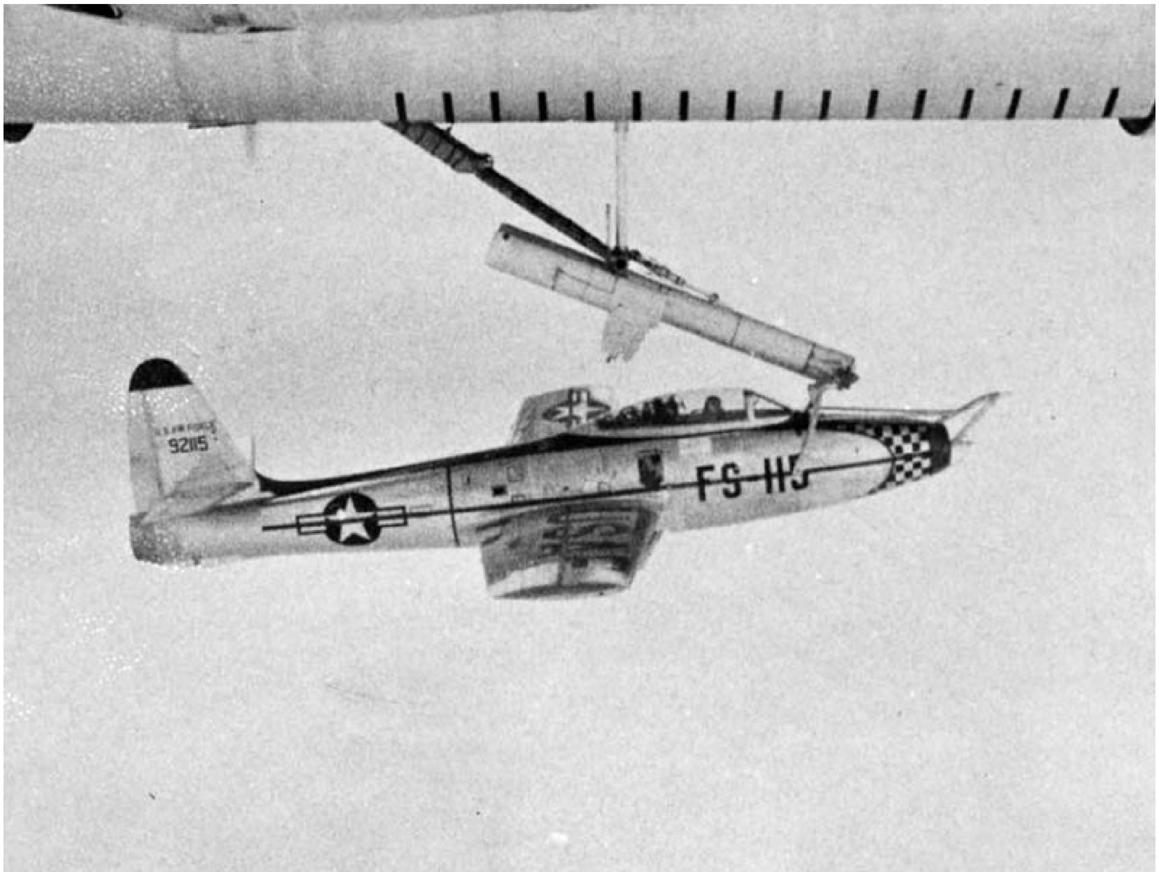


F9C Sparrowhawk inside Akron's hangar.

Photo # 80-CF-4184-14 XF9C-1 aircraft hooking onto USS Akron, May 1932



F9C Sparrowhawk successfully hooks on to Akron trapeze, May 1932.



A Republic F-84E on FICON trapeze

Project Tip-Tow: Boeing B-29 with Republic F-84 Thunderjet

Chapter 4

Tiltrotor

Tiltrotor

The Bell-Boeing V-22 Osprey

Part of a series on **Categories of aircraft**	
Supported by lighter-than-air gases **(aerostats)**	
Unpowered	Powered
• Balloon	• Airship
Supported by LTA gases + aerodynamic lift	
Unpowered	Powered
• Hybrid moored balloon	• Hybrid airship
Supported by aerodynamic lift **(aerodynes)**	

Unpowered	Powered
Unpowered fixed-wing	Powered fixed-wing
• Glider • hang gliders • Paraglider • Kite	• Powered airplane (aeroplane) • powered hang gliders • Powered paraglider • Flettner airplane • Ground-effect vehicle
	Powered hybrid fixed/rotary wing
	• Tiltwing • **Tiltrotor** • Coleopter
Unpowered rotary-wing	Powered rotary-wing
• Rotor kite	• Autogyro • Gyrodyne ("Heliplane") • Helicopter
	Powered aircraft driven by flapping
	• Ornithopter
Other means of lift	
Unpowered	Powered
	• Hovercraft • Flying Bedstead • Avrocar

A **tiltrotor** is an aircraft which utilizes a pair or more of powered rotors (sometimes called *proprotors*) mounted on rotating shafts or nacelles at the end of a fixed wing for lift and propulsion, and combines the vertical lift capability of a helicopter with the speed and range of a conventional fixed-wing aircraft. For vertical flight, the rotors are angled so the plane of rotation is horizontal, lifting the way a helicopter rotor does. As the aircraft gains speed, the rotors are progressively tilted forward, with the plane of rotation eventually becoming vertical. In this mode the wing provides the lift, and the rotor provides thrust as a propeller. The wing's greater efficiency (because the entire wing is moving at the same speed as the aircraft, instead of rushing back and forth as a rotor would) helps the tiltrotor achieve higher speeds than helicopters.

A tiltrotor aircraft differs from a tiltwing in that only the rotor pivots rather than the entire wing. This method trades off efficiency in vertical flight for efficiency in STOL/STOVL operations.

History

A BA609 in airplane mode at Paris Air Show 2007

The idea of constructing Vertical Take-Off and Landing aircraft using helicopter-like rotors at the wingtips originated in the 1930s. The first design resembling modern tiltrotors was patented by George Lehberger in May 1930, but he did not further develop the concept. In World War II, a German prototype, called the Focke-Achgelis FA-269 was developed starting in 1942, but never flew.

Two prototypes which made it to flight were the one-seat Transcendental Model 1-G and two seat Transcendental Model 2, both powered by single reciprocating engines. Development started on the Model 1-G in 1947, though it did not fly until 1954. The

Model 1-G flew for about a year until a crash in Chesapeake Bay on July 20, 1955, destroying the prototype aircraft but not seriously injuring the pilot. The Model 2 was developed and flew shortly afterwards, but the US Air Force withdrew funding in favor of the Bell XV-3 and it did not fly much beyond hover tests. The Transcendental 1-G is the first tiltrotor aircraft to have flown and accomplished most of a helicopter to aircraft transition in flight (to within 10 degrees of true horizontal aircraft flight).

Built in 1953, the experimental Bell XV-3 flew until 1966, proving the fundamental soundness of the tiltrotor concept and gathering data about technical improvements needed for future designs.

A related technology development is the tiltwing. Although two designs, the Canadair CL-84 Dynavert and the LTV XC-142, were technical successes, neither entered production due to other issues.

In 1972, with funding from NASA and the U.S. Army, Bell Helicopter Textron started development of the XV-15, a twin-engine tiltrotor research aircraft. Two aircraft were built to prove the tiltrotor design and explore the operational flight envelope for military and civil applications.

In 1981, using experience gained from the XV-3 and XV-15, Bell and Boeing Helicopters began developing the V-22 Osprey, a twin-turboshaft military tiltrotor aircraft for the U.S. Air Force and the U.S. Marine Corps.

Bell, teamed with AgustaWestland, is developing the commercial BA609, and the firm has also developed a tiltrotor unmanned aerial vehicle (UAV), the TR918 Eagle Eye.

Bell and Boeing have teamed up again to perform a conceptual study of a larger Quad TiltRotor (QTR) for the US Army's Joint Heavy Lift (JHL) program. The QTR is a larger, four rotor version of the V-22 with two tandem wings sets of fixed wings and four tilting rotors.

Technical considerations

Controls

In vertical flight, the tiltrotor uses controls very similar to a twin or tandem-rotor helicopter. Yaw is controlled by tilting its rotors in opposite directions. Roll is provided through differential power or thrust. Pitch is provided through rotor cyclic or nacelle tilt. Vertical motion is controlled with conventional rotor blade pitch and either a conventional helicopter collective control lever (as in the Bell/Agusta BA609) or a unique control similar to a fixed wing engine control called a thrust control lever (TCL) (as in the Bell-Boeing V-22 Osprey).

Speed and payload issues

The tiltrotor's advantage is significantly greater speed than a helicopter. In a helicopter the maximum forward speed is defined by the turn speed of the rotor; at some point the helicopter will be moving forward at the same speed as the spinning of the backwards-moving side of the rotor, so that side of the rotor sees zero or negative airspeed, and begins to stall. This limits modern helicopters to cruise speeds of about 150 knots / 277 km/h. However, with the tiltrotor this problem is avoided, because the proprotors are perpendicular to the motion in the high-speed portions of the flight regime (and thus never suffering this reverse flow condition), meaning that the tiltrotor has relatively high maximum speed - over 300 knots / 560 km/h has been demonstrated in the two types of tiltrotors flown so far, and cruise speeds of 250 knots / 460 km/h are achieved.

This speed is achieved somewhat at the expense of payload. As a result of this reduced payload, a tiltrotor does not exceed the transport efficiency (speed times payload) of a helicopter. Additionally, the tiltrotor propulsion system is more complex than a conventional helicopter due to the large, articulated nacelles and the added wing; however, the improved cruise efficiency and speed improvement over helicopters is significant in certain uses. Speed and, more importantly, the benefit to overall response time is the principal virtue sought by the military forces that are using the tiltrotor. Tiltrotors are inherently less noisy in forward flight (airplane mode) than helicopters. This, combined with their increased speed, is expected to improve their utility in populated areas for commercial uses and reduce the threat of detection for military uses. Tiltrotors, however, are typically as loud as equally sized helicopters in hovering flight.

Tiltrotors also provide substantially greater cruise altitude capability than helicopters. Tiltrotors can easily reach 6000 m / 20,000 ft or more whereas helicopters typically do not exceed 3000 m / 10,000 ft altitude. This feature will mean that some uses that have been commonly considered only for fixed-wing aircraft can now be supported with tiltrotors without need of a runway. A drawback however is that a tiltrotor suffers considerably reduced payload when taking off from high altitude.

Mono tiltrotor

A mono tiltrotor aircraft uses a tiltable rotating propeller, or *coaxial proprotor*, for lift and propulsion. For vertical flight the proprotor is angled to direct its thrust downwards, providing lift. In this mode of operation the craft is essentially identical to a helicopter. As the craft gains speed, the coaxial proprotor is slowly tilted forward, with the blades eventually becoming perpendicular to the ground. In this mode the wing provides the lift, and the wing's greater efficiency helps the tiltrotor achieve its high speed. In this mode, the craft is essentially a turboprop aircraft.

A mono tiltrotor aircraft is different from a conventional tiltrotor, in which the proprotors are mounted to the wing tips, rather than being mounted to the aircraft's fuselage. As a result of this structural efficiency, a mono tiltrotor exceeds the transport efficiency (speed times payload) of both a helicopter and a conventional tiltrotor. One design study concluded that if the mono tiltrotor could be technically realized, it would be half the size, one-third the weight, and nearly twice as fast as a helicopter.

In vertical flight, the mono tiltrotor uses controls very similar to a coaxial helicopter, such as the Kamov Ka-50. Yaw is controlled for instance by increasing the lift on the upper proprotor while decreasing the lift on the lower proprotor. Roll and pitch are provided through rotor cyclic. Vertical motion is controlled with conventional rotor blade blade pitch.

Chapter 5

Wing Configuration

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

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

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

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

Number and position of main-planes

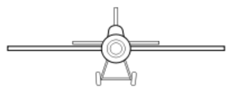
Aircraft can have different numbers of wings:

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

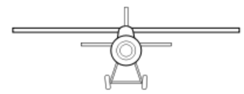
- **Monoplane** - one wing. Most aeroplanes have been monoplanes since before the Second World War. The wing may be mounted at various heights relative to the fuselage:
  - **Low wing** - mounted on the lower fuselage.
  - **Mid wing** - mounted approximately half way up the fuselage.
  - **High wing**-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

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


Low wing

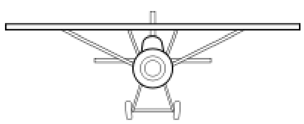

Mid wing

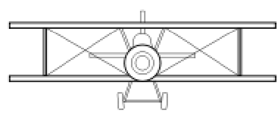

Shoulder wing

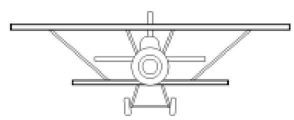

High wing

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

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


Parasol wing

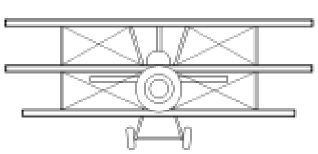

Biplane

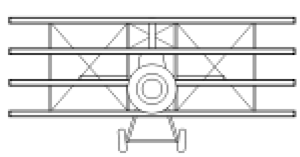

Sesquiplane

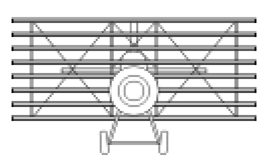
- **Triplane** - three planes stacked one above another. Triplanes such as the Fokker Dr.I enjoyed a brief period of popularity during the First World War due to their small size and high manoeuvrability as fighters, but were soon replaced by improved biplanes.

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

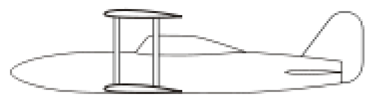
- **Multiplane** - many planes, sometimes used to mean more than one or more than some arbitrary number. The term is occasionally applied to arrangements stacked in tandem as well as vertically. No example with more than four wings has ever flown successfully: the nine-wing Caproni Ca.60 flying boat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


Triplane


Quadruplane


Multiplane

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



Unstaggered biplane   Forwards stagger   Backwards stagger

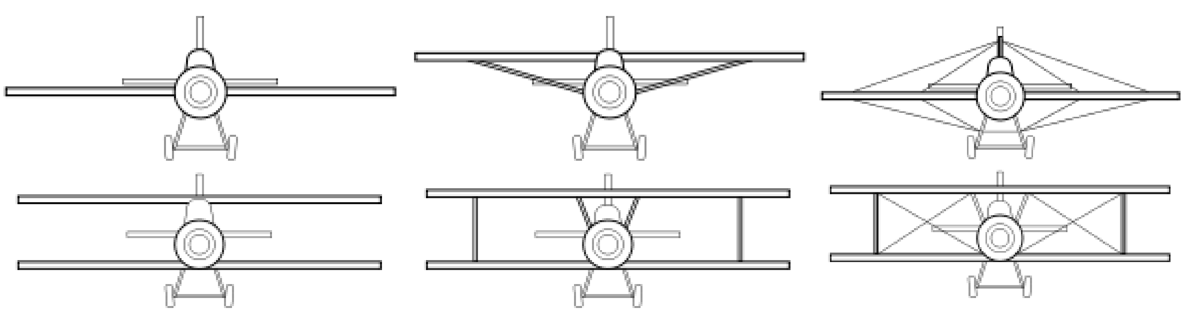
A **Tandem wing** design has two similar-sized wings, one behind the other.

Wing support

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

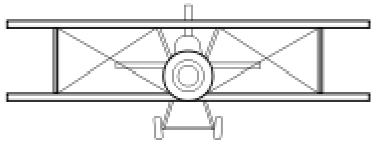
The types are:

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

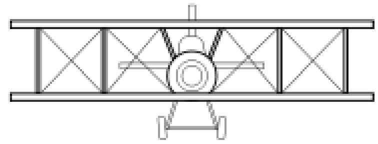


Cantilever   Strut braced   Wire braced

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

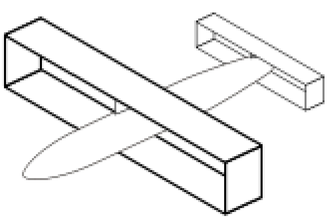


Single-bay biplane

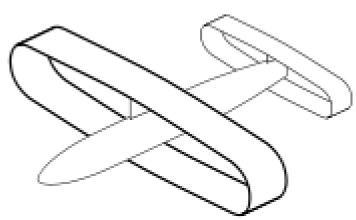


Two-bay biplane

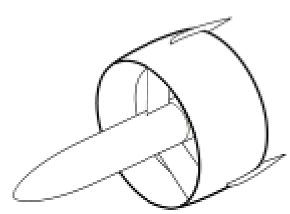
- **Combined** or **closed wing** - two wings are joined structurally at or near the tips in some way. This stiffens the structure, and can reduce aerodynamic losses at the tips. Variants include:
    - **Box wing** - upper and lower planes are joined by a vertical fin between their tips. Some Dunne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



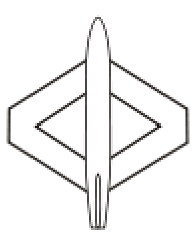
Box wing



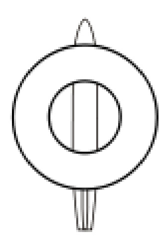
Annular box wing



Cylindrical wing



Rhomboidal wing



Flat annular wing

Wings can also be characterised as:

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

Wing planform

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

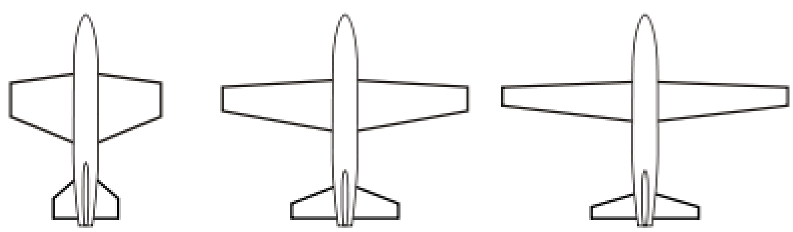
Aspect ratio

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

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

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

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



Low aspect ratio Moderate aspect ratio High aspect ratio

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

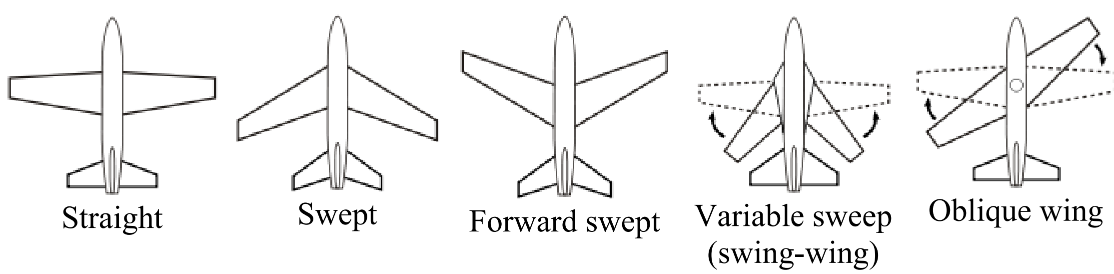
Wing sweep

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

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

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

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



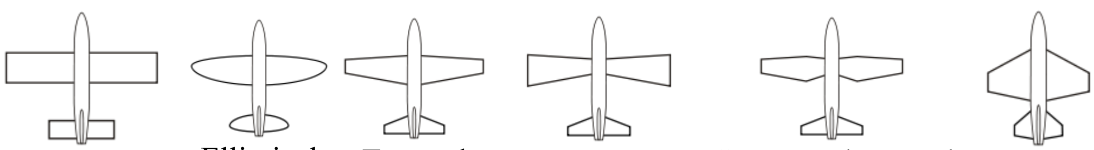
Planform variation along span

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

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

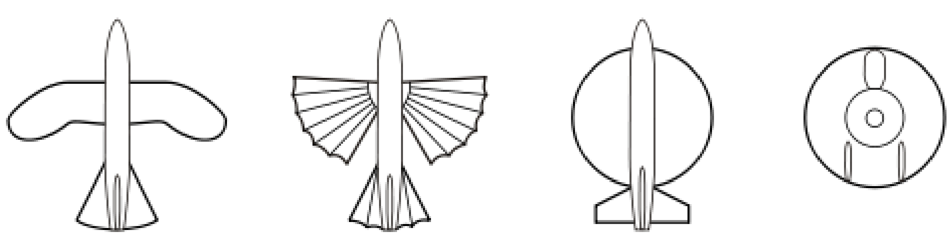
- **Tapered** - wing narrows towards the tip, with straight edges. Structurally and aerodynamically more efficient than a constant chord wing, and easier to make than the elliptical type. One of the most common types of all, as on the Hawker Sea Hawk.

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



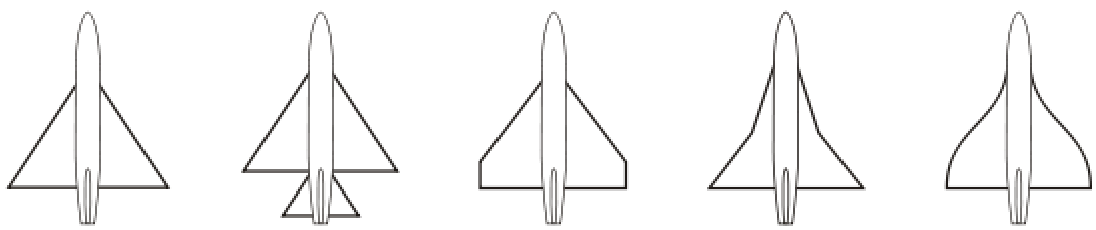
Constant chord Elliptical Tapered Reverse tapered Compound tapered Trapezoidal

- **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.



Birdlike Batlike Circular Flying saucer

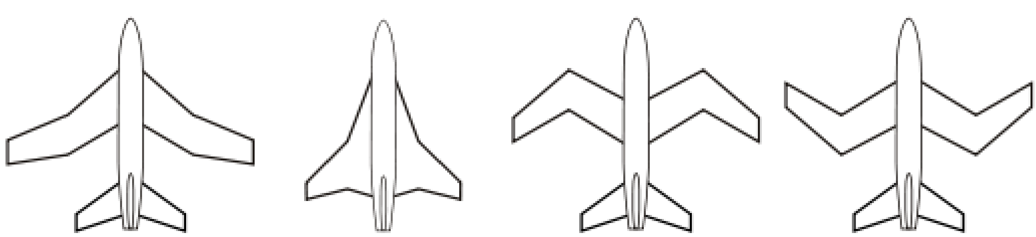
- **Delta** - triangular planform with swept leading edge and straight trailing edge. Offers the advantages of a swept wing, with good structural efficiency. Variants are:
    - **Tailless delta** - a classic high-speed design, used for example in the widely built Dassault Mirage III series.
    - **Tailed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



Tailless delta   Tailed delta   Cropped delta   Compound delta   Ogival delta

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

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

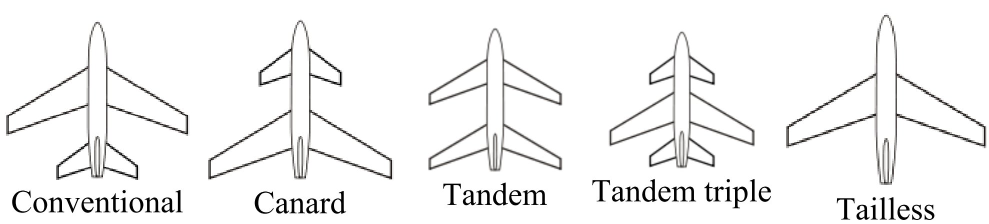


Crescent   Cranked arrow   M-wing   W-wing

Horizontal stabilizer

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

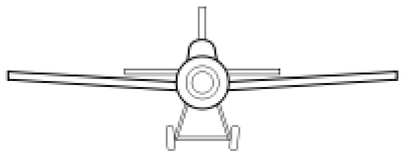
- **Conventional** - "tailplane" stabiliser at the rear of the aircraft, forming part of the tail or empennage.
- **Canard** - "foreplane" stabiliser at the front of the aircraft. Common in the pioneer years, but from the outbreak of World War I no production model appeared until the Saab Viggen.
- **Tandem**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

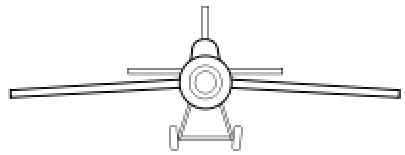


Dihedral and anhedral

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

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


Dihedral


Anhedral

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

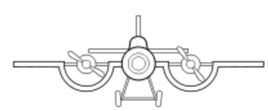
The dihedral angle may vary along the span.

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


Gull wing


Inverted gull wing


Cranked wing


Channel wing

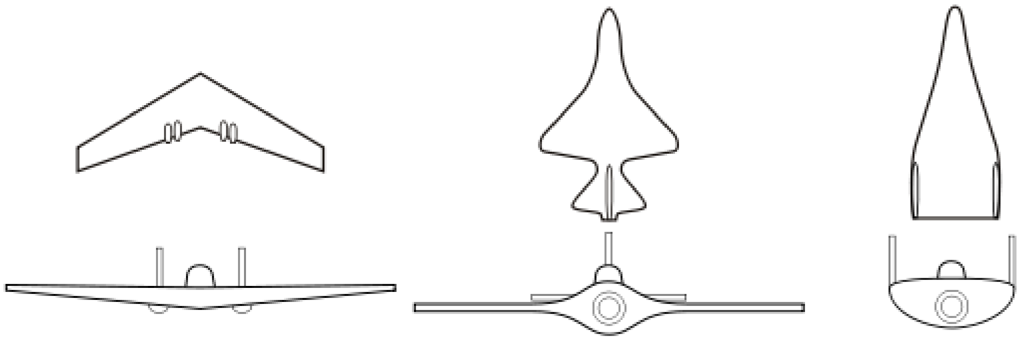
Wings vs. bodies

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

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

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

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



Flying wing   Blended body   Lifting body

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

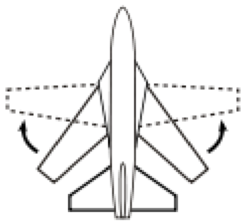
Variable geometry

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

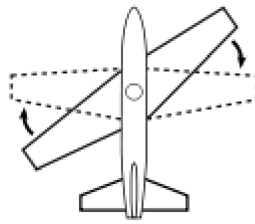
Some types of variable geometry craft transition between fixed wing and rotary wing configurations.

Variable planform

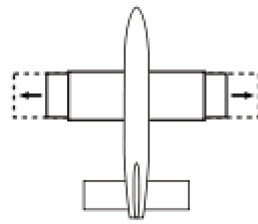
- **Swing-wing** or **variable sweep wing**. The left and right hand wings vary their sweep together, usually backwards. The first successful wing sweep in flight was carried out by the Bell X-5 in the early 1950s.
- **Oblique wing** - a single full-span wing pivots about its mid point, as used on the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



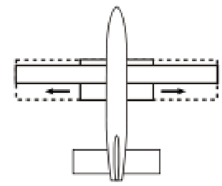
Variable sweep (swing-wing)



Oblique wing

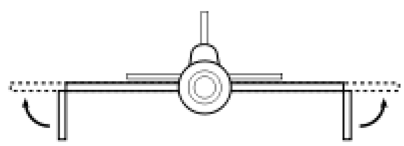


Telescoping wing



Extending wing

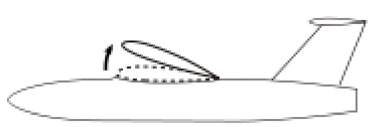
- **Folding wing** - part of the wing extends for takeoff and landing, and folds away for high-speed flight. The outer sections of the XB-70 Valkyrie wing folded down, to increase lift and reduce drag through generation of 'compression lift' during supersonic flight. (Many aircraft have wings that may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



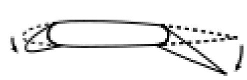
Folding wing

Variable chord

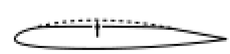
- **Variable incidence** - the wing plane can tilt upwards or downwards relative to the fuselage. Used on the Vought F-8 Crusader to tilt the leading edge up by a small amount for takeoff, to give STOL performance. If powered proprotors are fitted to the wing to allow vertical takeoff or STOVL performance,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



Variable incidence wing



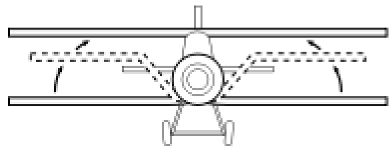
Variable camber aerofoil



Variable thickness aerofoil

Polymorphism

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



Polymorphic wing

Minor aerodynamic surfaces

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

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

Minor surface features

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

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

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

Chapter 6

Lifting Body

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

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

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

History

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

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

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

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

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

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

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

Aerospace applications

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

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

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

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

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

Body lift

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

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

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

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

Lifting body pilots and flights

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

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

Chapter 7

Stealth Aircraft

An F-117 Nighthawk stealth strike aircraft

Stealth aircraft are aircraft that use stealth technology to interfere with radar detection as well as means other than conventional aircraft by employing a combination of features to reduce visibility in the infrared, visual, audio, and radio frequency (RF) spectrum. Development of stealth technology likely began in Germany during WWII. Well-known modern examples of stealth aircraft include the United States' F-117 Nighthawk (1981–2008), the B-2 Spirit "Stealth Bomber", the F-22 Raptor, and the F-35 Lightning II While no aircraft is totally invisible to radar, stealth aircraft prevent conventional radar from detecting or tracking the aircraft effectively, reducing the odds of an attack. Stealth is accomplished by using a complex design philosophy to reduce the ability of an opponent's sensors to detect, track, or attack the stealth aircraft. This philosophy also takes into account the heat, sound, and other emissions of the aircraft as these can also be used to locate it.

Stealth is the combination of passive low observable (LO) features and active emitters such as Low Probability of Intercept Radars, radios and laser designators. These are usually combined with active defenses such as chaff, flares, and ECM.

Full-size stealth combat aircraft demonstrators have been flown by the United States (in 1977), Russia (in 2010) and China (in 2011), while the US Military has already adopted three "stealthy" designs, proposed one, and is preparing to adopt another.

Background

A World War I attempt to reduce the visibility of military aircraft resulted in the German, heavy bomber, the Linke-Hofmann R.I; this had a wooden structure convered with transparent material. The first true "stealth" aircraft may have been the Horten Ho 229 flying wing fighter-bomber, developed in Germany during the last years of World War II. In addition to the aircraft's shape, which may not have been a deliberate attempt to affect radar deflection, the majority of the Ho 229's wooden skin was bonded together using carbon-impregnated plywood resins designed with the purported intention of absorbing radar waves. Testing performed in early 2009 by the Northrop-Grumman Corporation established that this compound, along with the aircraft's shape, would have rendered the Ho 229 virtually invisible to Britain's Chain Home early warning radar, provided the aircraft was traveling at high speed (~550 mph) at extremely low altitude (50–100 feet).

In the closing weeks of WWII the US military initiated "Operation Paperclip", an effort by the US Army to capture as much advanced German weapons research as possible, and also to deny that research to advancing Soviet troops. A Horton glider and the Ho 229 number V3 were secured and sent to Northrop Aviation for evaluation in the United States, who much later used a flying wing design for the B-2 stealth bomber. During WWII Northrop had been commissioned to develop a large wing-only long-range bomber (XB-35) based on photographs of the Horton's record-setting glider from the 1930s, but their initial designs suffered controllability issues that were not resolved until after the war. Northrop's small one-man prototype (N9M-B) and a Horton wing-only glider are located in the Chino Air Museum in Southern California.

Modern stealth aircraft first became possible when Denys Overholser, a mathematician working for Lockheed Aircraft during the 1970s, adopted a mathematical model developed by Petr Ufimtsev, a Russian scientist, to develop a computer program called Echo 1. Echo made it possible to predict the radar signature an aircraft made with flat panels, called facets. In 1975, engineers at Lockheed Skunk Works found that an airplane made with faceted surfaces could have a very low radar signature because the surfaces would radiate almost all of the radar energy away from the receiver. Lockheed built a model called "the Hopeless Diamond", so-called because it resembled a squat diamond, and looked too hopeless to ever fly. Because advanced computers were available to control the flight of even a Hopeless Diamond, for the first time designers realized that it might be possible to make an aircraft that was virtually invisible to radar.

Reduced radar cross section is only one of five factors that designers addressed to create a truly stealthy design such as the F-22. The F-22 has also been designed to disguise its infrared emissions to make it harder to detect by infrared homing ("heat seeking") surface-to-air or air-to-air missiles. Designers also addressed making the aircraft less visible to the naked eye, controlling radio transmissions, and noise abatement.

The first combat use of purpose-designed stealth aircraft was in December 1989 during Operation Just Cause in Panama. On December 20, 1989, two USAF F-117s bombed a Panamanian Defense Force barracks in Rio Hato, Panama. In 1991, F-117s were tasked with attacking the most heavily fortified targets in Iraq in the opening phase of Operation Desert Storm and were the only jets allowed to operate inside Baghdad's city limits.

Limitations

B-2 Spirit stealth bomber of the U.S Air Force

Instability of design

Early stealth aircraft were designed with a focus on minimal radar cross section (RCS) rather than aerodynamic performance. Highly stealth aircraft like the F-117 Nighthawk are aerodynamically unstable in all three axes and require constant flight corrections from a fly-by-wire system to maintain controlled flight. Most modern non-stealth fighter aircraft (F-16, Su-27, Gripen, Rafale) are unstable on one or two axes only. However, in the pursuit of increased maneuverability, most 4th and 5th-generation fighter aircraft have been designed with some degree of inherent instability that must be controlled by fly-by-wire computers. As for the B2 Spirit, based on The Development of the All-Wing

Aircraft by Jack Northrop since 1940, design allowed creating stable aircraft with sufficient yaw control, even without vertical surfaces such as rudder.

Dogfighting ability

Earlier stealth aircraft (such as the F-117 and B-2) lack afterburners, because the hot exhaust would increase their infrared footprint, and breaking the sound barrier would produce an obvious sonic boom, as well as surface heating of the aircraft skin which also increased the infrared footprint. As a result their performance in air combat maneuvering required in a dogfight would never match that of a dedicated fighter aircraft. This was unimportant in the case of these two aircraft since both were designed to be bombers. More recent design techniques allow for stealthy designs such as the F-22 without compromising aerodynamic performance. Newer stealth aircraft, like the F-22 and F-35, have performance characteristics that meet or exceed those of current front-line jet fighters due to advances in other technologies such as flight control systems, engines, airframe construction and materials.

Electromagnetic emissions

The high level of computerization and large amount of electronic equipment found inside stealth aircraft are often claimed to make them vulnerable to passive detection. This is highly unlikely and certainly systems such as Tamara and Kolchuga, which are often described as counter-stealth radars, are not designed to detect stray electromagnetic fields of this type. Such systems are designed to detect intentional, higher power emissions such as radar and communication signals. Stealth aircraft are deliberately operated to avoid or reduce such emissions.

Current Radar Warning Receivers look for the regular pings of energy from mechanically swept radars while fifth generation jet fighters use Low Probability of Intercept Radars with no regular repeat pattern.

Vulnerable modes of flight

Stealth aircraft are still vulnerable to detection during, and immediately after using their weaponry. Since stealth payload (reduced RCS bombs and cruise missiles) are not yet generally available, and ordnance mount points create a significant radar return, stealth aircraft carry all armament internally. As soon as weapons bay doors are opened, the plane's RCS will be multiplied and even older generation radar systems will be able to locate the stealth aircraft. While the aircraft will reacquire its stealth as soon as the bay doors are closed, a fast response defensive weapons system has a short opportunity to engage the aircraft.

This vulnerability is addressed by operating in a manner that reduces the risk and consequences of temporary acquisition. The B-2's operational altitude imposes a flight time for defensive weapons that makes it virtually impossible to engage the aircraft during its weapons deployment. All stealthy aircraft carry weapons in internal weapons bays. New stealth aircraft designs such as the F-22 and F-35 can open their bays, release munitions and return to stealthy flight in less than a second.

Some weapons require that the weapon's guidance system acquire the target while the weapon is still attached to the aircraft. This forces relatively extended operations with the bay doors open.

Also, such aircraft as the F-22 Raptor and F-35 Lighting II Joint Strike Fighter can also carry additional weapons and fuel on hardpoints below their wings. When operating in this mode the planes will not be nearly as stealthy, as the hardpoints and the weapons mounted on those hardpoints will show up on radar systems. This option therefore represents a trade off between stealth or range and payload. External stores allow those aircraft to attack more targets further away, but will not allow for stealth during that mission as compared to a shorter range mission flying on just internal fuel and using only the more limited space of the internal weapon bays for armaments.

Reduced payload

In a 1994 live fire exercise near Point Mugu, California, a B-2 Spirit dropped forty-seven 500 lb (230 kg) class Mark 82 bombs, which represents about half of a B-2's total ordnance payload in Block 30 configuration

Fully stealth aircraft carry all fuel and armament internally, which limits the payload. By way of comparison, the F-117 carries only two laser or GPS guided bombs, while a non-stealth attack aircraft can carry several times more. This requires the deployment of additional aircraft to engage targets that would normally require a single non-stealth attack aircraft. This apparent disadvantage however is offset by the reduction in fewer supporting aircraft that are required to provide air cover, air-defense suppression and electronic counter measures, making stealth aircraft "force multipliers".

Sensitive skin

The B-2 Stealth Bomber has a skin made with highly specialized materials like Polygraphite.

Cost of operations

Stealth aircraft are typically more expensive to develop and manufacture. An example is the B-2 Spirit that is many times more expensive to manufacture and support than conventional bomber aircraft. The B-2 program cost the U.S. Air Force almost $45 billion.

Detection

Theoretically there are a number of methods to detect stealth aircraft at long range.

Reflected waves

Passive (multistatic) radar, bistatic radar and especially multistatic systems are believed to detect some stealth aircraft better than conventional monostatic radars, since first-generation stealth technology (such as the F117) reflects energy away from the transmitter's line of sight, effectively increasing the radar cross section (RCS) in other directions, which the passive radars monitor. Such a system typically uses either low frequency broadcast TV and FM radio signals (at which frequencies controlling the aircraft's signature is more difficult). Later stealth approaches do not rely on controlling the specular reflections of radar energy and so the geometrical benefits are unlikely to be significant.

Researchers at the University of Illinois at Urbana-Champaign with support of DARPA, have shown that it is possible to build a synthetic aperture radar image of an aircraft target using passive multistatic radar, possibly detailed enough to enable automatic target recognition (ATR).

In December 2007, SAAB researchers also revealed details for a system called Associative Aperture Synthesis Radar (AASR) that would employ a large array of inexpensive and redundant transmitters and a few intelligent receivers to exploit forward scatter to detect low observable targets. The system was originally designed to detect stealthy cruise missiles and should be just as effective against aircraft. The large array of inexpensive transmitters also provides a degree of protection against anti-radar (or anti-radiation) missiles or attacks.

Infrared (heat)

Some analysts claim Infra-red search and track systems (IRSTs) can be deployed against stealth aircraft, because any aircraft surface heats up due to air friction and with a two channel IRST is a CO_2 (4.3 µm absorption maxima) detection possible, through difference comparing between the low and high channel. These analysts also point to the resurgence in such systems in several Russian designs in the 1980s, such as those fitted to the MiG-29 and Su-27. The latest version of the MiG-29, the MiG-35, is equipped with a new Optical Locator System that includes even more advanced IRST capabilities.

In air combat, the optronic suite allows:

- Detection of non-afterburning targets at 45 km range and more;
- Identification of those targets at 8 to 10 km range; and
- Estimates of aerial target range at up to 15 km.

For ground targets, the suite allows:

- A tank-effective detection range up to 15 km, and aircraft carrier detection at 60 to 80 km;
- Identification of the tank type on the 8 to 10 km range, and of an aircraft carrier at 40 to 60 km; and
- Estimates of ground target range of up to 20 km.

Wavelength match

The Dutch company Thales Nederland, formerly known as Holland Signaal, have developed a naval phased-array radar called SMART-L, which also is operated at L-Band and is claimed to offer counter stealth benefits. However, as with most claims of counter-stealth capability, these are unproven and untested. True resonant effects might be expected with HF sky wave radar systems, which have wavelengths of tens of metres. However, in this case, the accuracy of the radar systems is such that the detection is of limited value for engagement. Any radar which can successfully match the resonant frequency of a type of stealth aircraft should be able to detect its direction. In practice this is difficult because the resonant frequency changes depending on how the stealth aircraft is oriented with respect to the radar system.

OTH radar (over-the-horizon radar)

Over-the-horizon radar is a design concept that increases radar's effective range over conventional radar. It is claimed that the Australian JORN Jindalee Operational Radar Network can overcome certain stealth characteristics. It is claimed that the HF frequency used and the method of bouncing radar from ionosphere overcomes the stealth characteristics of the F-117A. In other words, stealth aircraft are optimized for defeating much higher-frequency radar from front-on rather than low-frequency radars from above.

Use of stealth aircraft

USAF F-22 Raptor stealth fighter of the 27th Fighter Squadron

The F-35 Lightning II was developed by the United States and the United Kingdom.

To date, stealth aircraft have been used in several low- and moderate-intensity conflicts, including Operation Desert Storm, Operation Allied Force and the 2003 invasion of Iraq. In each case they were employed to strike high-value targets that were either out of range of conventional aircraft in the theater or were too heavily defended for conventional aircraft to strike without a high risk of loss. In addition, because the stealth aircraft do not have to evade surface-to-air missiles and anti-aircraft artillery over the target they can aim more carefully and thus are more likely to hit the target and cause less collateral damage. In many cases they were used to hit the high value targets early in the campaign, before other aircraft had the opportunity to degrade the opposing air defense to the point where other aircraft had a good chance of reaching those critical targets.

Stealth aircraft in future low- and moderate-intensity conflicts are likely to have similar roles. However, given the increasing prevalence of Russian-built surface-to-air missile systems on the open market (such as the SA-10, SA-12 and SA-20 (S-300P/V/PMU) and SA-15 (9K331/332)), stealth aircraft are likely to be very important in a high-intensity conflict in order to gain and maintain air supremacy, especially to the United States who is likely to face these types of systems. It is possible to cover one's airspace with so many air defenses with such long range and capability that conventional aircraft would find it very difficult "clearing the way" for deeper strikes. For example, China license-builds all of the previously mentioned SAM systems in large quantities and would be able to heavily defend important strategic and tactical targets in the event of a conflict. Even if anti-radiation weapons are used in an attempt to destroy the SAM radars of such systems, or stand-off weapons are launched against them, these modern surface-to-air missile batteries are capable of shooting down weapons fired against them.

Stealth aircraft lost

The first (and to date only) case of a stealth aircraft being shot down happened on 27 March 1999, during Operation Allied Force. An Isayev S-125 'Neva-M' missile was fired at an American F-117 Nighthawk and successfully brought it down. In the same conflict, another was supposedly damaged and successfully returned to base, but never flown again

Chapter 8

Conventional Landing Gear

The Piper Super Cub is a popular taildragger aircraft.

A Cessna 150 converted to taildragger configuration by installation of an after-market modification kit.

A taildragger by Jodel: the 1965 D140C Mousquetaire

Douglas DC-3, a taildragger airliner

Conventional landing gear is an aircraft undercarriage consisting of two main wheels forward of the centre of gravity and a small wheel or skid to support the tail. The term persists, having begun in the time when the majority or "convention" of airplanes were thus configured, even though nowadays most aircraft are configured with a tricycle landing gear.

The term **taildragger** is aviation jargon for an aircraft with a conventional undercarriage, although some writers have argued that the term should only refer to an aircraft with a tail skid and not a tail wheel.

History

In early aircraft, a tail skid made of metal or wood was used to support the tail on the ground. In most modern aircraft, a small, articulated wheel assembly is attached to the rearmost part of the airframe in place of the skid. This wheel is steered by the pilot through a connection to the rudder pedals, allowing the rudder and tail wheel to move together.

Advantages

The tailwheel configuration offers several advantages over the tricycle landing gear arrangement.

Due to its smaller size the tailwheel has less parasite drag than a nosewheel, allowing the conventional geared aircraft to cruise at a higher speed on the same power. Tail wheels are less expensive to buy and maintain than a nosewheel. If a tailwheel fails on landing, the damage to the aircraft will be minimal. This is not the case in the event of a nosewheel failure, which usually results in propeller damage. Tailwheel aircraft are easier to man-handle on the ground and, due to their lower tail, they will fit into some hangars more easily.

Due to the increased propeller clearance on tail wheel aircraft less stone chip damage will result from operating a conventional geared aircraft on rough or gravel airstrips. Because of the way airframe loads are distributed while operating on rough ground, tail wheel aircraft are better able to sustain this type of use over a long period of time, without cumulative airframe damage occurring.

Tail wheel aircraft are also more suitable for operation on skis.

Disadvantages

Tail wheel detail on a Tiger Moth biplane

The conventional landing gear arrangement does have some disadvantages, compared to the nose wheel equipped aircraft.

Tail wheel aircraft are much more subject to "nose-over" accidents, due to main wheels becoming stuck in holes or injudicious application of brakes by the pilot.

Conventional geared aircraft are much more susceptible to ground looping. A ground loop occurs when directional control is lost on the ground and the tail of the aircraft passes the nose, in some cases completing a full circle. This event can result in damage to the aircraft's undercarriage, tires, wingtips and propeller. Avoiding ground loops requires increased pilot training and skill.

Tail wheel aircraft generally suffer from poorer forward visibility on the ground, compared to nose wheel aircraft. In some cases this necessitates "S" turning on the ground to allow the pilot to see while taxiing.

Tail wheel aircraft are more difficult to taxi during high wind conditions, due to the higher angle of attack on the wings. They also suffer from lower crosswind capability and in some wind conditions may be unable to use crosswind runways or single-runway airports.

Conventional geared aircraft require more training time for student pilots to master. This was a large factor in the move to nose wheel-equipped training aircraft by most manufacturers in the 1950s.

Training

For many years aircraft with tricycle landing gear have been more popular than those with conventional undercarriage and as a result most pilots now learn to fly in tricycle gear aircraft (e.g., Cessna 152 and Cessna 172) and only later transition to taildraggers.

Since the number of factory-built general aviation aircraft with a tailwheel is fairly low, the numbers of instructors experienced in this type of aircraft are also limited.

Techniques

Landing a conventional geared aircraft can be accomplished in two ways.

Normal landings are done by touching all three wheels down at the same time in a *three-point landing*. This method does allow the shortest landing distance but can be difficult to carry out in crosswinds. A common variant of this method is the *stalled landing*, in which the aircraft is stalled above the runway in a three-point attitude. The stalled landing is less comfortable than the other techniques, but has the advantage of reducing the probability of the aircraft bouncing back into the air.

The alternative is the *wheel landing*. This requires the pilot to land the aircraft on the main wheels while maintaining the tail wheel in the air with elevator to keep the angle of attack low. Once the aircraft has slowed to a speed that can ensure control will not be lost, but above the speed at which rudder effectiveness is lost, then the tail wheel is lowered to the ground.

Chapter 9

Contra-Rotating Propellers

Contra-rotating propellers on a Rolls-Royce–Griffon–powered P-51 unlimited racer

Contra-rotating propellers, also referred to as *coaxial contra-rotating propellers*, apply the maximum power of usually a single piston or turboprop engine to drive two propellers in opposite rotation. Contra-rotating propellers are common in some marine transmission systems, in particular for medium to large size planing leisure craft. Two propellers are arranged one behind the other, and power is transferred from the engine via a planetary gear or spur gear transmission. Contra-rotating propellers should not be confused with counter-rotating propellers—airscrews on different engines turning opposite directions.

When airspeed is low the mass of the air flowing through the propeller disk (thrust) causes a significant amount of tangential or rotational air flow to be created by the spinning blades. The energy of this tangential air flow is wasted in a single-propeller design. To use this wasted effort the placement of a second propeller behind the first takes advantage of the disturbed airflow. The tangential air flow also causes handling problems at low speed as the air strikes the vertical stabilizer, causing the aircraft to yaw left or right, depending of the direction of propeller rotation.

If it is well designed, a contra-rotating propeller will have no rotational air flow, pushing a maximum amount of air uniformly through the propeller disk, resulting in high performance and low induced energy loss. It also serves to counter the asymmetrical torque effect of a conventional propeller. Some contra-rotating systems were designed to be used at take off for maximum power and efficiency under such conditions, and allowing one of the propellers to be disabled during cruise to extend flight time.

Contra-rotating propellers have been found to be between 6% and 16% more efficient than normal propellers. However they can be very noisy, with increases in noise in the axial (forward and aft) direction of up to 30 dB, and tangentially 10 dB. Most of this extra noise can be found in the higher frequencies. These substantial noise problems will limit commercial applications unless solutions can be found. One possibility is to enclose the contra-rotating propellers in a shroud. It is also helpful if the two propellers have a different number of blades (e.g. four blades on the forward propeller and five on the aft).

The efficiency of a contra-rotating prop is somewhat offset by its mechanical complexity. Nonetheless, coaxial contra-rotating propellers and rotors are moderately common in military aircraft and naval applications, such as torpedoes.

Significant aircraft

While several nations experimented with contra-rotating propellers in aircraft, only the United Kingdom and Soviet Union produced them in large numbers. The first aircraft to be fitted with a contra-rotating propeller to fly though was in the US when two inventors from Ft Worth, Texas tested the concept on an aircraft.

United Kingdom

Fairey Gannet AS.6 at the Imperial War Museum Duxford

Some of the more successful British aircraft with contra-rotating propellers are the Avro Shackleton, powered by the Rolls-Royce Griffon engine, and the Fairey Gannet, which used the Double Mamba Mk.101 engine.

Later variants of the Supermarine Spitfire and Seafire used the Griffon with contra-rotating props as well. In the Spitfire/Seafire and Shackleton's case the primary reason for using contra-rotating propellers was so as to increase the propeller blade-area, and hence absorb greater engine power, within a propeller diameter limited by the height of the aircraft's undercarriage. Whilst this also applied to the Gannet, in addition this aircraft's engine had two separate power-sections, each driving one propeller. The Short Sturgeon used 2 Merlin 140s with contra-rotating propellers.

The Bristol Brabazon prototype airliner used eight Bristol Centaurus engines driving four pairs of contra-rotating propellers, each engine driving a single propeller.

USSR

In the 1950s, the Soviet Union developed the Kuznetsov NK-12 turboprop. It drives an 8-blade contra-rotating propeller and, at 15,000 shp, it is the most powerful turboprop in the world. Four NK-12 engines power the Tupolev Tu-95 *Bear*, the only turboprop bomber to enter service, as well as one of the fastest propeller-driven aircraft. The Tu-114, an airliner derivative of the Bear, holds the world speed record for propeller aircraft. The Bear was also the first Soviet bomber to have intercontinental range, allowing it to strike North American targets from Asia. The Tu-126 AEW aircraft and Tu-142 maritime patrol aircraft are two more NK-12 powered designs derived from the Bear.

The NK-12 engine powers another well-known Soviet aircraft, the Antonov An-22 Antheus, a heavy-lift cargo aircraft. At the time of its introduction, the An-22 was the largest aircraft in the world and is still by far the world's largest turboprop-powered aircraft. From the 1960s through the 1970s, it set several world records in the categories of maximum payload-to-height ratio and maximum payload lifted to altitude.

Of lesser note is the use of the NK-12 engine in the A-90 Orlyonok, a mid-size Soviet ekranoplan. The A-90 uses one NK-12 engine mounted atop its T-tail, along with two turbojets nestled in its nose.

In 1994, Antonov produced the An-70, a heavy transport aircraft. It is powered by four Progress D-27 propfan engines driving contra-rotating propellers. The characteristics of the D-27 engine and its propeller make it a propfan, a hybrid between a turbofan engine and a turboprop engine.

United States

The U.S. worked with several prototypes, including the A2J Super Savage, the Boeing XF8B, the XP-56 Black Bullet and the tail-sitting Convair XFY and Lockheed XFV "Pogo" VTOL fighters and the Hughes XF-11 reconnaissance plane, but jet engine technology was advancing rapidly and the designs were deemed unnecessary.

Chapter 10

Waverider

The Boeing X-51 forebody is an example of cone-derived waverider

A **waverider** is a hypersonic aircraft design that improves its supersonic lift-to-drag ratio by using the shock waves being generated by its own flight as a lifting surface. To date the only aircraft to use the technique is the Mach 3 supersonic XB-70 Valkyrie, which was waverider-like with its drooping wingtips. The waverider remains a well-studied design for high-speed aircraft in the Mach 5 and higher hypersonic regime, although no production design has used the concept to date. The Boeing X-51A scramjet demonstration aircraft is in the final stages of development and made its first hypersonic flight in May 2010.

History

Early work

The waverider design concept was first developed by Terence Nonweiler of the Queen's University of Belfast, and first described in print in 1951 as a re-entry vehicle. It consisted of a delta-wing platform with a low wing loading to provide considerable surface area to dump the heat of re-entry. At the time he was forced to use a greatly simplified 2D model of airflow around the aircraft, which he realized would not be accurate due to spanwise flow across the wing. However, Nonweiler noticed that the spanwise flow would be stopped by the shockwave being generated by the aircraft, and that if the wing was positioned to deliberately approach the shock, the spanwise flow would be trapped under wing, increasing pressure, and thus increasing lift.

In the 1950s, the British started a space program based around the Blue Streak missile, which was, at some point, to include a manned vehicle. Armstrong-Whitworth were contracted to develop the re-entry vehicle, and unlike the U.S. space program they decided to stick with a winged vehicle instead of a ballistic capsule. Between 1957 and 1959, they contracted Nonweiler to develop his concepts further. This work produced a pyramid-shaped design with a flat underside and short wings. Heat was conducted through the wings to the upper cool surfaces, where it was dumped into the turbulent air on the top of the wing. In 1960, work on the Blue Streak was canceled as the missile was seen as being obsolete before it could enter service. Work then moved to the Royal Aircraft Establishment (RAE), where it continued as a research program into high-speed (Mach 4 to 7) civilian airliners.

This work was discovered by engineers at North American Aviation during the early design studies of what would lead to the XB-70 bomber. They re-designed the original "classic" delta wing to incorporate drooping wingtips in order to trap the shock waves mechanically, rather than using the shock cone generated from the front of the aircraft. This mechanism also had two other beneficial effects; it reduced the amount of horizontal lifting surface at the rear of the aircraft, which helped offset a nose-down trim that occurs at high speeds, and it added more vertical surface which helped improve the lateral stability, which decreased at high speed.

Caret Wing

Nonweiler's original design used the shock wave generated by the aircraft as a way to control spanwise flow, and thereby increase the amount of air trapped under the wing in the same way as a wing fence. While working on these concepts, he noticed that it was possible to shape the wing in such a way that the shock wave generated off its leading edge would form a horizontal sheet under the craft. In this case, the airflow would not only be trapped horizontally, spanwise, but vertically as well. The only area the air above the shock wave could escape would be out the back of the sheet where the fuselage ended. Since the air was trapped between this sheet and the fuselage, a large volume of air would be trapped, much more than the more basic approach he first developed.

Furthermore, since the shock surface was held at a distance from the craft, shock heating was limited to the leading edges of the wings, lowering the thermal loads on the fuselage.

In 1962 Nonweiler moved to Glasgow University to become Professor of Aerodynamics and Fluid Mechanics. That year his "Delta Wings of Shapes Amenable to Exact Shock-Wave Theory" was published by the *Journal of the Royal Aeronautical Society*, and earned him that society's Gold Medal. A craft generated using this model looks like a delta wing that has been broken down the center and the two sides folded downward. From the rear it looks like an upside-down V, or alternately, the "caret", ^, and such designs are known as "**caret wings**". Two to three years later the concept briefly came into the public eye, due to the airliner work at the RAE that led to the prospect of reaching Australia in 90 minutes. Newspaper articles led to an appearance on Scottish Television.

Hawker Siddeley examined the caret wing waverider in the later 1960s as a part of a three-stage lunar rocket design. The first stage was built on an expanded Blue Steel, the second a waverider, and the third a nuclear-powered manned stage. This work was generalized in 1971 to produce a two-staged reusable spacecraft. The 121-foot (36.9 m) long first stage was designed as a classical waverider, with airbreathing propulsion for return to the launch site. The upper stage was designed as a lifting body, and would have carried an 8000-pound (3.6 t) payload to low Earth orbit.

Conical waveriders

Nonweiler's work was based on studies of planar 2D shocks due to the difficulty understanding and predicting real-world shock patterns around 3D bodies. As the study of hypersonic flows improved, researchers were able to study waverider designs that used different shockwave shapes, the simplest being the conical shock generated by point or radially symmetric bodies. In these cases, a waverider is designed to keep the rounded shockwave attached to its wings, not a flat sheet, which increases the volume of air trapped under the surface, and thereby increases lift.

Since a radially symmetric body is needed to generate the conical shock, these "**conical waveriders**" generally start out with a pointed nose cone on a cylindrical body, and smoothly turn into delta shape at the rear. Unlike the caret wing, the conical designs smoothly curver their wings, from horizontal near the center, to highly drooped where they meet the shock. Like the caret wing, conical waveriders have to be designed to operate at a specific speed to properly attach the shock wave to the wing's leading edge, but unlike them the entire body shape can vary dramatically at different speeds, and sometimes have wingtips that curve upward to attach to the shockwave.

Conical waveriders have higher performance than carets, but generally require extremely long body shapes that are impractical for real-world aircraft. Further development of the conical sections, adding canopies and fuselage areas, led to the "**osculating cones waverider**", which develops several conical shock waves at different points on the body, blending them to produce a single shaped shock. The expansion to a wider range of compression surface flows allowed the design of waveriders with control of volume, upper surface shape, engine integration and centre of pressure position. Performance improvements and off-design analysis continued until 1970.

During this period at least one waverider was tested at the Woomera Rocket Range, mounted on the nose of an air-launched Blue Steel missile, and a number of airframes were tested in the wind tunnel at NASA's Ames Research Center. However, during the 1970s most work in hypersonics disappeared, and the waverider along with it.

Viscous optimized waveriders

One of the many differences between supersonic and hypersonic flight concerns the interaction of the boundary layer and the shock waves generated from the nose of the aircraft. Normally the boundary layer is quite thin compared to the streamline of airflow over the wing, and can be considered separately from other aerodynamic effects. However, as the speed increases and the shock wave increasingly approaches the sides of the craft, there comes a point where the two start to interact and the flowfield becomes very complex. Long before that point, the boundary layer starts to interact with the air trapped between the shock wave and the fuselage, the air that is being used for lift on a waverider.

Calculating the effects of these interactions was beyond the abilities of aerodynamics until the introduction of useful computational fluid dynamics starting in the 1980s. In 1981, Maurice Rasmussen at the University of Oklahoma started a waverider renaissance by publishing a paper on a new 3D underside shape using these techniques. These shapes have superior lifting performance and less drag. Since then, whole families of cone-derived waveriders have been designed using more and more complex conic shocks, based on more complex software. This work eventually led to a conference in 1989, the *First International Hypersonic Waverider Conference*, held at the University of Maryland.

These newest shapes, the "**viscous optimized waveriders**", look similar to conical designs as long as the angle of the shock wave on the nose is beyond some critical angle, about 14 degrees for a Mach 6 design for instance. The angle of the shock can be controlled by widening out the nose into a curved plate of specific radius, and reducing the radius produces a smaller shock cone angle. Vehicle design starts by selecting a given angle and then developing the body shape that traps that angle, then repeating this process for different angles. For any given speed, a single shape will generate the best results.

Star bodies

Take a classic caret wing, invert it, and then attach it along the "break" point to another caret wing to produce an X shaped body. This craft will generate four shock sheets, between the tips of the four "wings". The result is a great increase in the volume of trapped air, which, when properly arranged, can produce greater lift. The downside to this approach is that the body has more surface area, and thus more skin drag, but analysis demonstrates up to 20% improvements over a simple conical body optimized for the same speed.

Hypersonic Sail Waverider

One last development of the waverider is the **Hypersonic Sail Waverider**, which uses a rogallo wing as the lifting surface. The primary purpose for this design is to create a light-weight disposable lifting surface for interplanetary spacecraft to use while maneuvering over planets with an atmosphere. If used over Venus for instance, the spacecraft could aeromaneuver with the lift provided by the waverider to a degree that no gravitational slingshot could hope to achieve.

Design

During re-entry, hypersonic vehicles generate lift only from the underside of the fuselage. The underside, which is inclined to the flow at a high angle of attack, creates lift in reaction to the vehicle wedging the airflow downwards. The amount of lift is not particularly high, compared to a traditional wing, but more than enough to maneuver given the amount of distance the vehicle covers.

Most re-entry vehicles have been based on the blunt-nose reentry design pioneered by Theodore von Kármán. He demonstrated that a shock wave is forced to "detach" from a curved surface, forced out into a larger configuration that requires considerable energy to form. Energy expended in forming this shock wave is no longer available as heat, so this shaping can dramatically reduce the heat load on the spacecraft. Such a design has been the basis for almost every re-entry vehicle since, found on the blunt noses of the early ICBM warheads, the bottoms of the various NASA capsules, and the large nose of the Space Shuttle.

The problem with the blunt-nose system is that the resulting design creates very little lift, meaning the vehicle has problems maneuvering during re-entry. If the spacecraft is meant to be able to return to its point of launch "on command", then some sort of maneuvering will be required to counteract the fact that the Earth is turning under the spacecraft as it flies. After a single low-earth orbit, the launching point will be over 1,000 km (600 mi) to the east of the spacecraft by the time it flies over again after one full orbit. A considerable amount of research was dedicated to combining the blunt-nose system with wings, leading to the development of the lifting body designs in the U.S.

It was while working on exactly one such design that Nonweiler developed the waverider. He noticed that the detachment of the shock wave over the blunt leading edges of the wings of the Armstrong-Whitworth design would allow the air on the bottom of the craft to flow spanwise and escape to the upper part of the wing through the gap between the leading edge and the detached shock wave. This loss of airflow dramatically reduced the amount of lift being generated by the waverider (up to a quarter), which led to studies on how to avoid this problem and keep the flow trapped under the wing.

Nonweiler's resulting design is a delta-wing with some amount of negative dihedral — the wings are bent down from the fuselage towards the tips. When viewed from the front, the wing resembles a caret symbol (^) in cross section, and these designs are often referred to as carets. The more modern 3D version typically looks like a rounded letter 'M'. Theoretically, a star-shaped waverider with a frontal cross-section of a "+" or "×" could reduce drag by another 20%. The disadvantage of this design is that it has more area in contact with the shock wave and therefore has more pronounced heat dissipation problems.

Waveriders generally have sharp noses and sharp leading edges on their wings. The underside shock-surface remains attached to this. Air flowing in through the shock surface is trapped between the shock and the fuselage, and can only escape at the rear of the fuselage. With sharp edges, all the lift is retained.

Even though sharp edges get much hotter than rounded ones at the same air density, the improved lift means that waveriders can glide on re-entry at much higher altitudes where the air density is lower. A list ranking various space vehicles in order of heating applied to the airframe would have capsules at the top (re-entering quickly with very high heating loads), waveriders at the bottom (extremely long gliding profiles at high altitude), and the Space Shuttle somewhere in the middle.

Simple waveriders have substantial design problems. First, the obvious designs only work at a particular Mach number, and the amount of lift captured will change dramatically as the vehicle changes speed. Another problem is that the waverider depends on radiative cooling, possible as long as the vehicle spends most of its time at very high altitudes. However these altitudes also demand a very large wing to generate the needed lift in the thin air, and that same wing can become rather unwieldy at lower altitudes and speeds.

Because of these problems, waveriders have not found favor with practical aerodynamic designers, despite the fact that they might make long-distance hypersonic vehicles efficient enough to carry air freight.

Some researchers controversially claim that there are designs that overcome these problems. One candidate for a multi-speed waverider is a "caret wing", operated at different angles of attack. A caret wing is a delta wing with longitudinal conical or triangular slots or strakes. It strongly resembles a paper airplane or rogallo wing. The correct angle of attack would become increasingly precise at higher mach numbers, but this is a control problem that is theoretically solvable. The wing is said to perform even better if it can be constructed of tight mesh, because that reduces its drag, while maintaining lift. Such wings are said to have the unusual attribute of operating at a wide range of mach numbers in different fluids with a wide range of Reynolds numbers.

The temperature problem can be solved with some combination of a transpiring surface, exotic materials, and possibly heat-pipes. In a transpiring surface, small amounts of a coolant such as water are pumped through small holes in the aircraft's skin. This design works for Mach-25 spacecraft re-entry shields, and therefore should work for any aircraft that can carry the weight of the coolant. Exotic materials such as carbon-carbon composite do not conduct heat but endure it, but they tend to be brittle. Heatpipes are not widely used at present. Like a conventional heat exchanger, they conduct heat better than most solid materials, but like a thermosiphon are passively pumped. The Boeing X-51A deals with external heating through the use of a tungsten nosecone and space shuttle-style heat shield tiles on its belly. Internal (engine) heating is absorbed by using the JP-7 fuel as a coolant prior to combustion. Other high temperature materials, referred to as SHARP materials (typically zirconium diboride and hafnium diboride) have been used on steering vanes for ICBM reentry vehicles since the 1970s, and are proposed for use on hypersonic vehicles. They are said to permit mach 11 flight at 100,000 ft (30,000 m) altitudes and mach 7 flight at sea level. These materials are more structurally rugged than the Reinforced Carbon Composite (RCC) used on the space shuttle nose and leading edges, have higher radiative and temperature tolerance properties, and do not suffer from oxidation issues that RCC needs to be protected against with coatings.

Chapter 11

Wide-Body Aircraft

The Airbus A380 is the world's largest and widest passenger aircraft

Size comparison between a Boeing 737-300 (narrow-body) and a Boeing 777 (widebody aircraft)

A **wide-body aircraft** is a large airliner with two passenger aisles, also known as a **widebody aircraft** or **twin-aisle** aircraft. The typical fuselage diameter is 5 to 6 m (16 to 20 ft). In the typical wide-body economy cabin, passengers are seated seven to ten abreast, allowing a total capacity of 200 to 600 passengers. The largest wide-body aircraft are over 6 m (20 ft) wide, and can accommodate up to eleven passengers abreast in high-density configurations.

By comparison, a traditional narrow-body airliner has a diameter of 3 to 4 m (10 to 13 ft), with a single aisle, and seats between two and six people abreast.

Wide-body aircraft were originally designed for a combination of efficiency and passenger comfort. However, airlines quickly gave in to economic factors, and reduced the extra passenger space in order to maximize revenue and profits.

Wide-body aircraft are also used for the transport of commercial freight and cargo and other special uses, described further below.

History

Boeing 747, the first widebody passenger aircraft, operated by Pan American World Airways

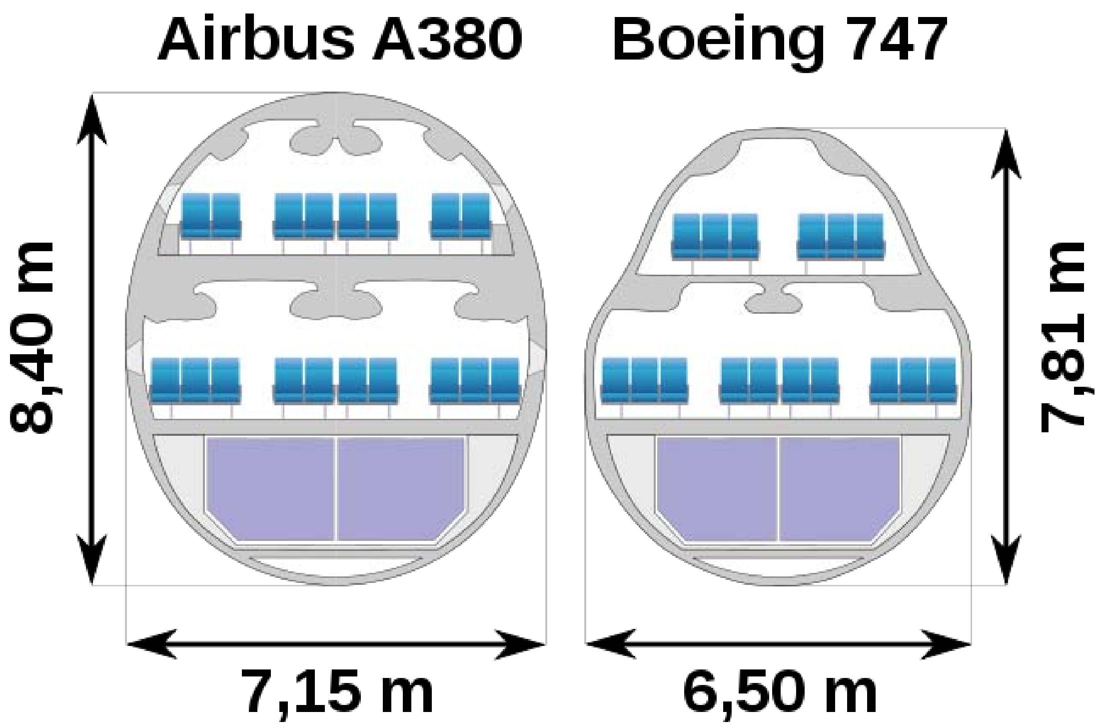
The Bristol Brabazon was a widebody transatlantic design that first flew in 1949 but never reached production. Following the success of the Boeing 707 and Douglas DC-8 in the late 1950s, airlines began seeking larger aircraft to meet the rising global demand for air travel. Engineers were faced with many challenges as airlines demanded more passenger seats per aircraft, longer ranges and lower operating costs.

Early jet aircraft such as the 707 and DC-8 seated passengers along either side of a single aisle, with no more than six seats per row. Larger aircraft would have to be longer, higher (such as a double deck), or wider in order to accommodate the greater number of passenger seats. Engineers also realized that lengthening the fuselage would have resulted in aircraft that would be too long to be handled by airports, while having two decks created difficulties in meeting emergency evacuation regulations, which were extremely challenging provided the technology available at the time. These parameters left a wider fuselage as the best option: by adding a second aisle, the wider aircraft could accommodate as many as 10 seats across.

The widebody age began in 1970 with the entry into service of the first widebody airliner, the four-engined, double-deck Boeing 747. New trijet widebody aircraft soon followed, including the McDonnell Douglas DC-10 and the Lockheed L-1011 Tristar. The first widebody twinjet, the Airbus A300, entered service in 1974.

After the success of the early widebody aircraft, several successors came to market over the next two decades, including the Airbus A330-A340 Series and the Boeing 777. In the jumbo category, the capacity of the Boeing 747 was not surpassed until October 2007, when the Airbus A380 entered commercial service with the nickname **Superjumbo**.

Design considerations



Cross-section comparison of Airbus A380 and Boeing 747-400

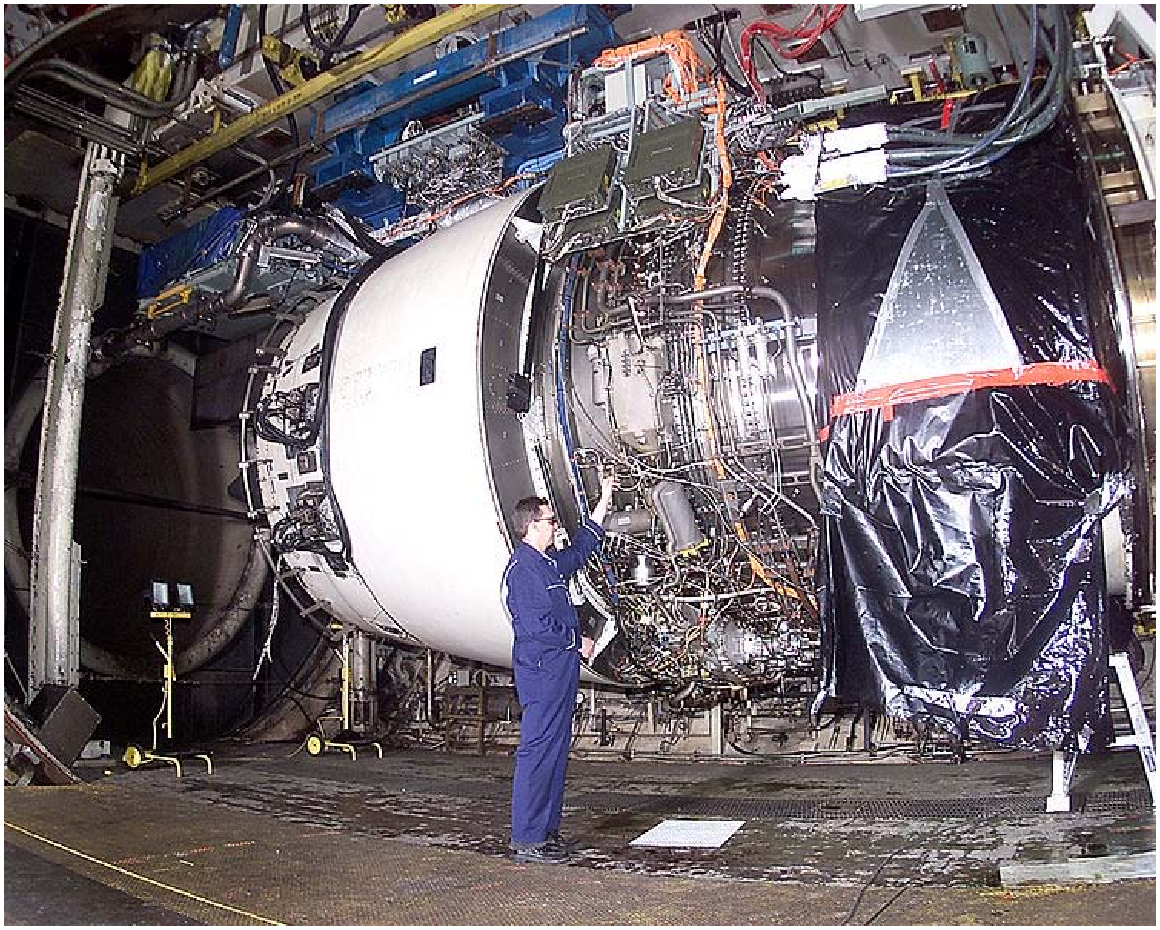
Airbus A300 cross-section, showing cargo, passenger, and overhead areas

Although widebody aircraft have a larger frontal area (and thus greater form drag) than a narrow-body aircraft of similar capacity, they have several advantages over their narrow-body counterparts:

- Larger volume of space for passengers, giving a more open feeling to the space
- Lower ratio of surface area to volume, and thus lower drag on a per-passenger basis
- Twin aisles that accelerate loading, unloading, and evacuation compared to a single aisle
- Wider fuselage that reduces the overall aircraft length, improving ground manoeuvrability and reducing the risk of tail strikes
- Greater under-floor freight capacity
- Better structural efficiency for larger aircraft than would be possible with a narrow-body design

British and Russian designers had proposed widebody aircraft similar in configuration to the Vickers VC10 and Douglas DC-9, but with a widebody fuselage. The British Three-Eleven project never left the drawing board, while the Russian Il-86 widebody proposal eventually gave way to a more conventional wing-mounted engine design, most likely due to the inefficiencies of mounting such a large engine on the aft fuselage.

Engines



Mechanic working on a Rolls Royce Trent 900 engine during testing. The Trent is a typical type of high bypass turbofan used in widebody airliners.

As jet engine power and reliability have increased over the last decades, most of the widebody aircraft built today have only two engines. A twinjet design is more fuel-efficient than a comparable trijet or four-engined aircraft. The increased reliability of modern jet engines also allows aircraft to meet the ETOPS certification standard, which calculates reasonable safety margins for flights across oceans. The trijet design has been eliminated due to higher maintenance and fuel costs, and only the heaviest widebody aircraft today are built with four engines (the Airbus A340, Airbus A380 and Boeing 747-8).

The Boeing 777 twinjet features the largest and most powerful jet engine in the world, the General Electric GE90, which is 128 inches (3.25 m) in diameter. This is almost as wide as the entire fuselage of a Boeing 737 at 148 inches (3.76 m).

The massive maximum takeoff weight of the Airbus A380 (560 tonnes (1,200,000 lb)) would not have been possible without the engine technology developed for the Boeing

777 (such as contra-rotating spools). The Trent 900 engine pictured, used on the Airbus A380, has a fan blade diameter of 116 inches (2.95 m), only slightly smaller than the GE90 engines on the Boeing 777. An interesting design constraint of the Trent 900 engines is that they are designed to fit into a Boeing 747-400F freighter for relatively easy transport by air cargo.

Interiors

The interiors of aircraft, known as the aircraft cabin, have been undergoing evolution since the first passenger aircraft. Today, between one and four classes of travel are available on widebody aircraft.

Bar and lounge areas which were once installed on the Boeing 747 have mostly disappeared, but a few have returned in first class or business class on the Airbus A340-600, Boeing 777-300ER, and on the Airbus A380. Emirates Airline has installed showers for first-class passengers on the A380; twenty-five minutes are allotted for use of the room, and the shower operates for a maximum of five minutes.

Depending on how the airline configures the aircraft, the size and seat pitch of the airline seats will vary significantly. For example, aircraft scheduled for shorter flights are often configured at a higher seat density than long-haul aircraft. Due to current economic pressures on the airline industry, high seating densities in the economy class cabin are likely to continue.

A comparison of interior cabin widths and economy class seating layouts is shown below under widebody specifications.

Cubana's Ilyushin Il-96 economy-class cabin.

Avianca Airbus A330 business-class seats.

Business-class seats of Air India's Boeing 777-300ER.

First-class seats on a Cathay Pacific 747-400.

Wake turbulence and separation

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

Aircraft are categorized by ICAO according to the wake turbulence they produce. Because wake turbulence is generally related to the weight of an aircraft, these categories are based on one of four weight categories: light, medium, heavy, and super.

Due to their weight, all current widebody aircraft are categorized as **heavy**, or in the case of the A380 in U.S. airspace, **super**.

The wake-turbulence category also is used to guide the separation of aircraft. Super and heavy-category aircraft require greater separation behind them than those in other categories. In some countries, such as the United States, it is a requirement to suffix the aircraft's call sign with the word "heavy" (or super) when communicating with air traffic control in certain areas.

Special uses

A U.S. Space Shuttle mounted on a modified Boeing 747

Widebody aircraft are used in science, research, and the military. Two specially modified Boeing 747 aircraft, the Shuttle Carrier Aircraft, are used to transport the U.S. Space Shuttle. Some widebody aircraft are used as flying command posts by the military, such as the Boeing E-4, while the Boeing E-767 is used for Airborne Early Warning and Control. New military weapons are tested aboard widebodies, as in the laser weapons testing on the Boeing YAL-1. Other widebody aircraft are used as flying research stations, such as the joint German-U.S. Stratospheric Observatory for Infrared Astronomy. Airbus A340, Airbus A380, and Boeing 747 four-engine widebody aircraft are used to test new generations of aircraft engines in-flight. A few aircraft have also been converted for aerial firefighting, such as the DC-10-based Tanker 910 and the 747-based Evergreen Supertanker.

Some widebody aircraft are used as VIP transport. Germany uses the Airbus A310, while Russia uses the Ilyushin Il-96 to transport their highest leaders. The specially modified Boeing 747-200 used by the President of the United States is known as Air Force One, or the Boeing VC-25. More information can be found under: Air transports of heads of state and government.

Future development

The Boeing 787, the first large composite aircraft, expected in service in 2011

Airbus and Boeing are racing to market with two new widebody designs, currently in development. Both manufacturers have been under significant pressure to see which obtains the most orders.

Currently, the Boeing 787 has received more orders than Airbus, and will be first to enter into airline service. The 787 is also the first large commercial aircraft to utilize a monolithic composite fuselage.

The initial Airbus A350 design was only a minor upgrade to that of the A330/A340 series, but Airbus was forced to make significant design changes in response to feedback from the airlines. In addition to being a few inches wider than the Boeing, Airbus claims that the A350 final specifications will be better than that of the 787.

Widebody specifications

Mode	EIS - Final Prod. Year	# Eng.	Maximum Metric MTOW	Inside Diameter, main passenger deck, upper	Outside Diameter, main passenger deck	Number of seats across in economy, main deck (seat width)

				passenger deck		
Airbus A300	1974–2007	2	132.0 tons 171.7 tons	208 inches (5.28 m)	222 inches (5.64 m)	8 across (17.0" wide) in 2-4-2 on TG 8 across (17.0" wide) in 2-4-2 on LH
Airbus A310	1982–2007	2	164.0 tons	208 inches (5.28 m)	222 inches (5.64 m)	8 across (17.4" wide) in 2-4-2 on AI
Airbus A330	1994	2	233.0 tons	208 inches (5.28 m)	222 inches (5.64 m)	8 across (17.5" wide) in 2-4-2 on EK 8 across (17.5" wide) in 2-4-2 on NW
Airbus A340	1993	4	380.0 tons	208 inches (5.28 m)	222 inches (5.64 m)	8 across (17.3" wide) in 2-4-2 on EY
Airbus A350	2013	2	298.0 tons	221 inches (5.61 m)	235 inches (5.97 m)	8 across (19.0" wide) in 2-4-2 **proposed** 9 across (17.7" wide) in 3-3-3 **proposed**
Airbus A380	2007	4	560.0 tons	**259 inches (6.58 m)** 233 inches (5.92 m)	281 inches (7.14 m)	10 across (18.6" wide) in 3-4-3 on SQ 10 across (18.1" wide) in 3-4-3 on QF 10 across (18.0" wide) in 3-4-3 on EK
Boeing	1970	4	412.8 tons	**240 inches**	256 inches	10 across (17.7"

747				**(6.10 m)** 136 inches (3.45 m)	(6.50 m)	wide) in 3-4-3 on TG 10 across (17.2" wide) in 3-4-3 on NW
Boeing 767	1982	2	204.1 tons	186 inches (4.72 m)	198 inches (5.03 m)	7 across (18.0" wide) in 2-3-2 on UA 7 across (17.0" wide) in 2-3-2 on US
Boeing 777	1995	2	351.5 tons	231 inches (5.87 m)	244 inches (6.20 m)	9 across (18.0" wide) in 2-5-2 on UA 9 across (17.9" wide) in 3-3-3 on CO 10 across (17.0" wide) in 3-4-3 on AF
Boeing 787	2011	2	245.0 tons	215 inches (5.46 m)	227 inches (5.77 m)	8 across (18.5" wide) in 2-4-2 **proposed** 9 across (17.2" wide) in 3-3-3 **proposed**
Ilyushin Il-86	1980–1994	4	208.0 tons	224 inches (5.70 m)	239 inches (6.08 m)	9 across (18.0" wide) in 3-3-3
Ilyushin Il-96	1992	4	240.0 tons	224 inches (5.70 m)	239 inches (6.08 m)	9 across (18.0" wide) in 3-3-3 on SU
L1011 Tristar	1972–1984	3	231.3 tons	225 inches (5.72 m)	237 inches (6.02 m)	9 across (17.0" wide) in 2-5-2 on SV
MD DC-10	1971–1988	3	259.5 tons	224 inches (5.69 m)	237 inches (6.02 m)	9 across (17.2" wide) in 2-5-2 on NW
MD MD-11	1990–2000	3	286.0 tons	224 inches (5.69 m)	237 inches (6.02 m)	9 across (17.5" wide) in 3-3-3 on

						KL

Head-on view of the Airbus A380 during pushback

Japan Airlines Boeing 747

The Rolls Royce Trent 900 Engine

Rough Boeing 747 interior airframe

The first twinjet widebody (1972), the Airbus A300

Lockheed L-1011 TriStar of Royal Jordanian Airlines

Airbus A330 parked at an airport gate

Ilyushin IL-96 operated by Aeroflot

Chapter 12

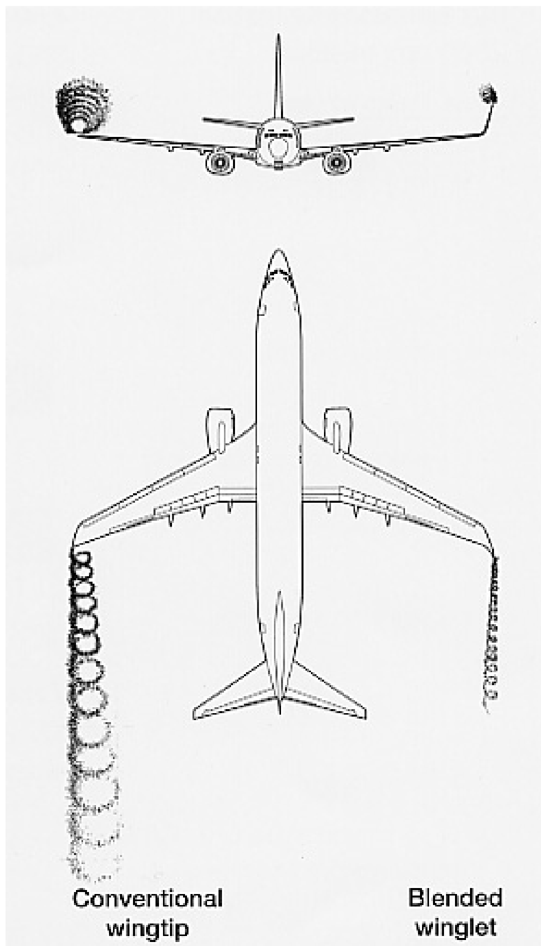
Wingtip Device

Wingtip devices

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.

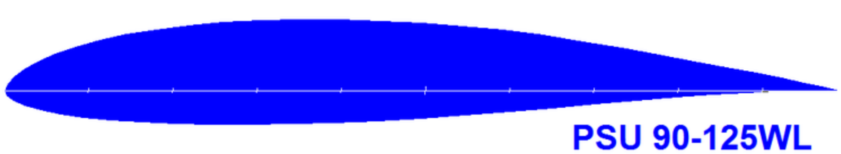
In 2002, Boeing first flew a production Next-Generation 737 with its new Blended Winglets, six-foot extensions that decrease fuel consumption by about 4 to 6 percent. The airplane gained supplemental type certification in 2003, and the majority of 737s delivered today are equipped with the devices.

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 CO_2 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.