Aircraft and Airship Configurations

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Chapter 1

Push-Pull Configuration and Pusher Configuration

Push-pull configuration

Cessna Skymaster push-pull aircraft

An aircraft constructed with a **push-pull configuration** has a mixture of forward-mounted (tractor) propellers and backward-mounted (pusher) propellers.

Historical

An early example of a "push-pull" aircraft was the Caproni Ca.1 which had two wing-mounted tractor propellers and one centre-mounted pusher propeller.

Claudius Dornier was the first aviation designer to heartily embrace the concept for production aircraft, as many of his flying boats used variations of the tandem "push-pull" engine layout :

- Dornier Wal (1922)
- Dornier Do X (1929)
- Dornier Do 18 (1935)
- Dornier Do 26 (1938)

Design Benefits

While pure pushers decreased in popularity during the First World War, the push-pull configuration has continued to be used. The advantage it provides is the ability to mount two propellers on the aircraft's centreline, thereby avoiding the increased drag that comes with twin wing-mounted engines. It is also easier to fly if one of the two engines fails, as the thrust provided by the remaining engine is symmetrical in the horizontal plane. In contrast, a conventional twin-engine aircraft will yaw in the direction of the failed engine and become uncontrollable below a certain airspeed, known as Vmc, which varies with the type of aircraft. Conventional push-pull designs, such as the Cessna Skymaster and Adam A500, have the engines mounted on the nacelle so that the aircraft's tail, suspended via twin booms, is behind the pusher propeller. In contrast, both the World War II-era Dornier Do 335 and the early 1960s-designed French Moynet M 360 Jupiter experimental private plane had their pusher propeller at the rear of their fuselage.

Piloting

Pilots in the United States who obtain a multi-engine rating in an aircraft with this push-pull, or "centerline thrust," configuration are restricted to flying centerline-thrust aircraft; pilots who obtain a multi-engine rating in conventional twin-engine aircraft do not have a similar limitation with regard to centerline-thrust aircraft.

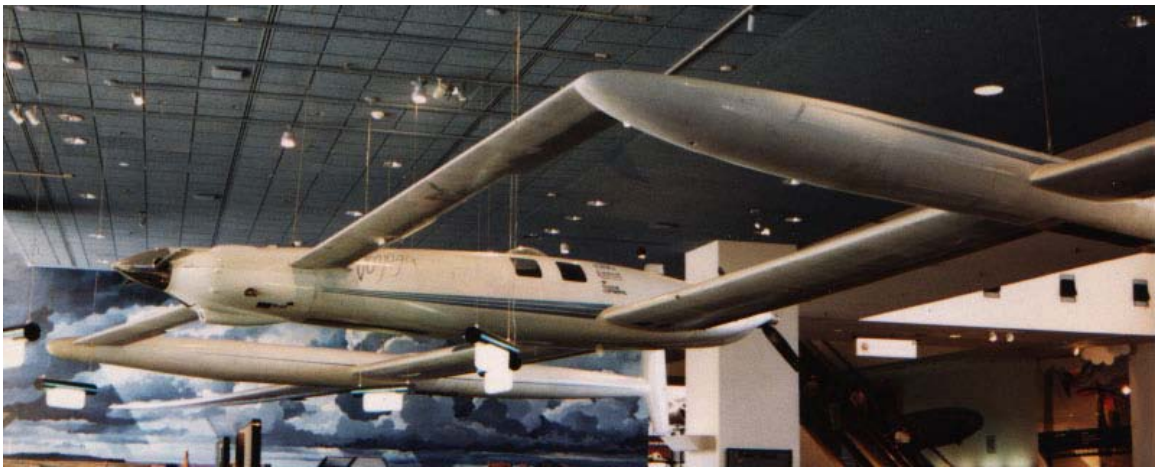
Military Application

Despite its distinct advantages push-pull configurations are rare in military aircraft. This is mainly due to the increased risk to the pilot in the case of a crash-landing or the need to parachute from the plane. In a crash the rear engine threatens to kill the pilot by crushing him between itself and the forward engine; in the case of bailing-out the pilot is in danger of hitting the rear propeller.

Dornier Seawings Seastar

Rutan Model 40 Defiant

Adam A500



Rutan Model 76 Voyager

Pusher configuration

Rutan Long-EZ pusher configuration home-built aircraft

An aircraft constructed with a **pusher configuration** has the engine(s) mounted forward of "rearward facing" propeller(s), so that the airframe is propelled by force applied in compression from the rear rather than in tension from the front.

Sometimes the propeller is situated at the rear of the fuselage, but it is more commonly mounted behind the crew compartment, with one or two booms supporting the tail. The engine and propeller can also be mounted on the wing – in which case it is typically located behind the trailing edge rather than forward of the leading edge.

History

Quad City Challenger – a typical pusher

Many early aircraft were **pushers**, including the Wright Flyer, and the Curtiss biplane used by Eugene Ely for the first ship take-off on January 18, 1911.

In the early years of the First World War pushers were favoured by the British and French because they enabled a forward-firing gun to be used without being obstructed by the arc of the propeller. Such aircraft included the Vickers F.B.5 Gunbus, the Royal Aircraft Factory F.E.2 and the Airco DH.2. (Germany did not have the same requirement due to the early development of Fokker's interrupter gear.)

Single-engine pushers usually had the engine mounted on the centreline at the rear of the aircraft's nacelle. Such aircraft had no true fuselage, the tail section being mounted on a framework that cleared the propeller.

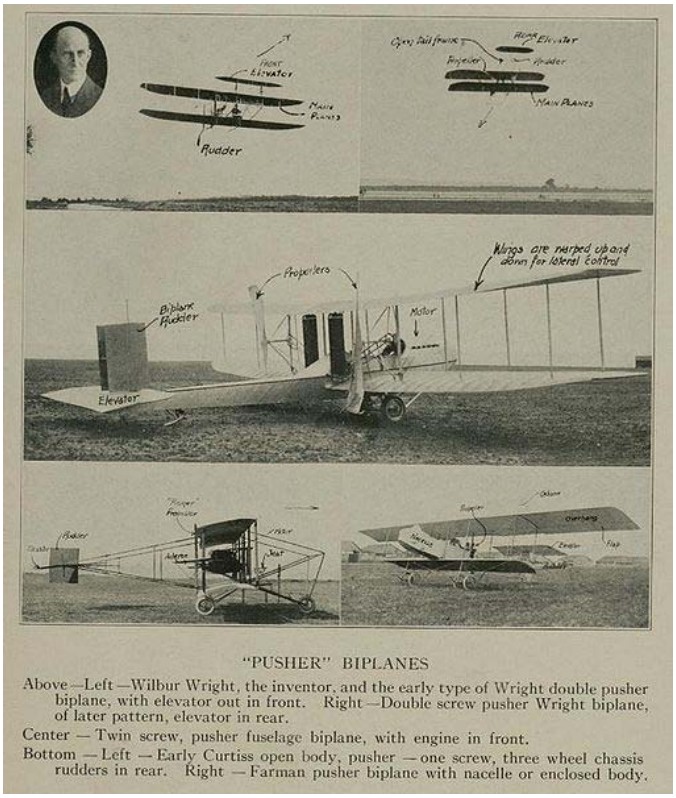
With the widespread adoption of interrupter gears in 1916/17, the tractor configuration became universally favoured, especially for warplanes. Pushers remained a minority of new aircraft designs into the 1930s and 1940s. Most pusher aircraft were, like the Supermarine Walrus, seaplanes with a single engine. The push-pull configuration, combining the tractor and pusher configuration (that is – with one or more propellers facing forwards and one or more others facing back) was widely used as a means of reducing the asymmetric effects of a single engine failing. Large multi-engine aircraft with this configuration, such as the Short Singapore, continued to be built.

Possibly the most extreme example of the type is the Convair B-36, the largest bomber ever operated by the United States, which wing-mounted six 3,800 hp Pratt & Whitney Wasp Major radial engines in a pusher configuration, augmented in the B-36D by four General Electric J47 turbojets. The Saab 21 was also initially built as a pusher since jet engines were not available.

The Quad City Challenger and the Cirrus VK-30 are examples of modern light aircraft with a pusher configuration.

There is a revival of pusher configurations on the Unmanned aerial vehicles with propellers such as Boeing ScanEagle, RQ-1 Predator, MQ-1C Warrior, RQ-2 Pioneer, RQ-5 Hunter, RQ-7 Shadow, MQ-9 Reaper, RQ-11 Raven and RQ-15 Neptune.

Advantages



"PUSHER" BIPLANES

Above—Left—Wilbur Wright, the inventor, and the early type of Wright double pusher biplane, with elevator out in front. Right—Double screw pusher Wright biplane, of later pattern, elevator in rear.

Center — Twin screw, pusher fuselage biplane, with engine in front.

Bottom — Left — Early Curtiss open body, pusher — one screw, three wheel chassis rudders in rear. Right — Farman pusher biplane with nacelle or enclosed body.

An early diagram of Wilbur Wright's pusher bi-plane

- Efficiency can be gained by mounting a propeller behind the fuselage, because it re-energizes the boundary layer developed on the body, and reduces the form drag by keeping the flow attached. However, this effect is not nearly as pronounced on a small airplane as it is on a submarine or ship, where it is quite important due to the much higher Reynolds number at which they operate.
- Wing efficiency increases due to the absence of prop-wash over any section of the wing.
- Rear thrust is somewhat less stable in flight than with a tractor configuration. This has the potential to make an aircraft more maneuverable.
- Especially in a single-engined pusher aircraft, the pilot's view both forward and downwards is improved because the engine and propeller do not block forward vision, and because the more rearward centre of gravity makes placement of the cockpit forward of the wings more practical. Consequently, this configuration was widely used for early combat aircraft, and remains popular today among ultralight aircraft.
- The propeller of a single-engined airplane can be placed closer to the elevators and rudder. This increases the speed of the air flowing over the control surfaces, improving pitch and yaw control at low speed, particularly during takeoff when the engine is at full power. This can be beneficial while bush flying, especially when taking off and landing on airstrips bounded by obstacles that must be avoided while the airplane is moving slowly.
- The engine is mounted behind the crew and passenger compartments, so fuel does not have to flow past personnel, any leak will vent behind the aircraft, and any engine fire will be directed behind the aircraft (however, this arrangement puts the empennage at greater risk, if there is one—but this is less of an issue if the fire occurs on, or as a consequence of, landing). Similarly, propeller failure is unlikely to directly endanger the crew.
- The cockpit is generally quieter in a pusher aircraft because both the engine and propeller are behind the crew.
- At the time when many military aircraft were pushers, the engine afforded rear protection to the pilot, and simplified the installation of gun armament.

Disadvantages

- Early pusher aircraft were structurally more complicated than equivalent tractor types, especially as a result of efforts to mount the empennage behind the rear mounted propeller. This resulted in increased drag – and therefore aircraft with inferior performance compared with most tractor types with the same engine and payload. This tendency is less marked with modern aerodynamic knowledge and constructional methods, but it remains true that putting the propeller first (as in a tractor) solves some layout problems in propeller-driven aircraft design.
- It is claimed that the pusher configuration might endanger the aircraft's occupants in a crash or crash-landing. If the engine is placed behind the cabin, it may drive forward under its own momentum during a crash, entering the cabin and injuring the occupants; however there is no case where this has been reported to have occurred (in the US and UK accident records). Conversely, if the engine is placed

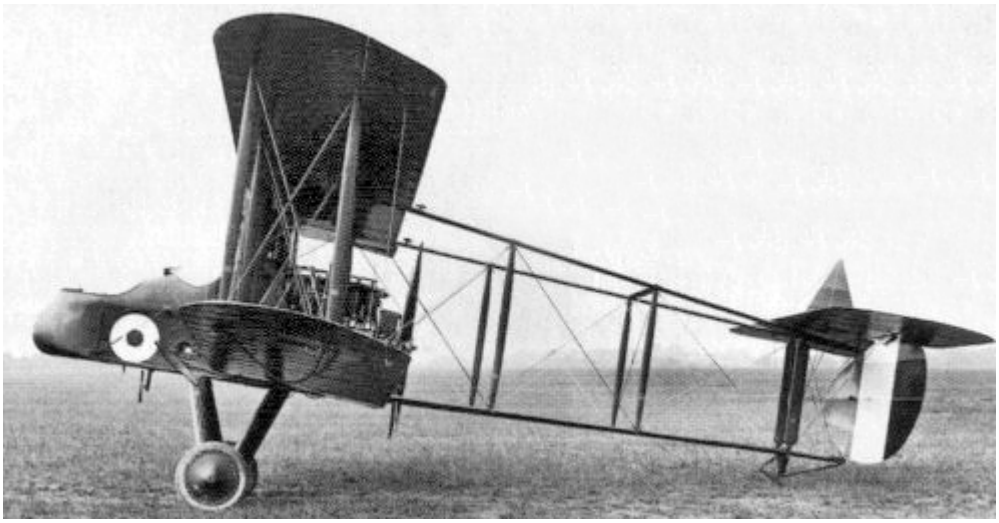
in front of the cabin, it might act as a battering ram and plow through obstacles in the airplane's path, providing an additional measure of safety (however, fuel and oil in the engine area is more likely to be a fire hazard if the engine hits the ground first, and high-energy pieces of propeller may be flung into the cabin area).

- Due to center of gravity often being further behind on longitudinal axis than on most tractor airplanes, the pushers can be more prone to flat spin, especially if loaded improperly.
- Crew members may strike the propeller while attempting to bail out of a single-engined airplane with a pusher prop. This scenario may be part of the reason that pusher props have rarely been used on post-WWI fighters despite the theoretical increase in maneuverability. Modern lightweight aircraft, however, often have a parachute system that saves the entire aircraft, so there is no need to bail out.
- A less dire but more practical concern is foreign object damage. The pusher configuration generally places the propeller(s) aft of the main landing gear. Objects on the ground kicked up by the wheels can find their way into the propeller, causing damage or accelerated wear to the blades. However, pusher configurations are used by thousands of ultralight aircraft on grass airfields, with few problems. A few centreline pusher designs (such as the Rutan Long-EZ pictured above) place the propeller arc very close to the ground while flying nose-high during takeoff or landing, possibly making the prop more likely to strike vegetation when the airplane operates from a turf airstrip.
- When an airplane flies in icing conditions, a layer of ice can accumulate on the wings. If an airplane with wing-mounted pusher engines experiences wing icing and subsequently flies into warmer air, the pusher props might ingest pieces of ice as they shed, posing a hazard to the propeller blades and other parts of the airframe that can be struck by chunks of ice flung by the props.
- In early pusher combat aircraft, spent ammunition cases caused similar problems – and devices for catching and collecting them so that they could not damage the propeller had to be devised.
- The propeller increases airflow around an air-cooled engine in the tractor configuration, but does not provide this same benefit to an engine mounted in the pusher configuration. Some aviation engines experience cooling problems when used as pushers.
- The warming airflow from a running engine is also lost in a pusher aircraft. In early aircraft, and in modern ultra-lights, where there is no alternative form of heating for the cockpit, pushers can therefore be very cold to fly.
- Normally (as in the Beechcraft Starship) the engine of a pusher exhausts forward of the propeller, and in this case the exhaust may contribute to corrosion or other damage to the propeller. This is usually minimal, and may be mainly visible in the form of soot stains on the blades.
- Propeller noise might increase because the engine exhaust flows through the props. This effect may be particularly pronounced when using turboprop engines due to the large volume of exhaust they produce. Similarly, vibration may be induced by the propeller passing through the wing downwash, causing it to move asymmetrically through air of differing energies and directions.

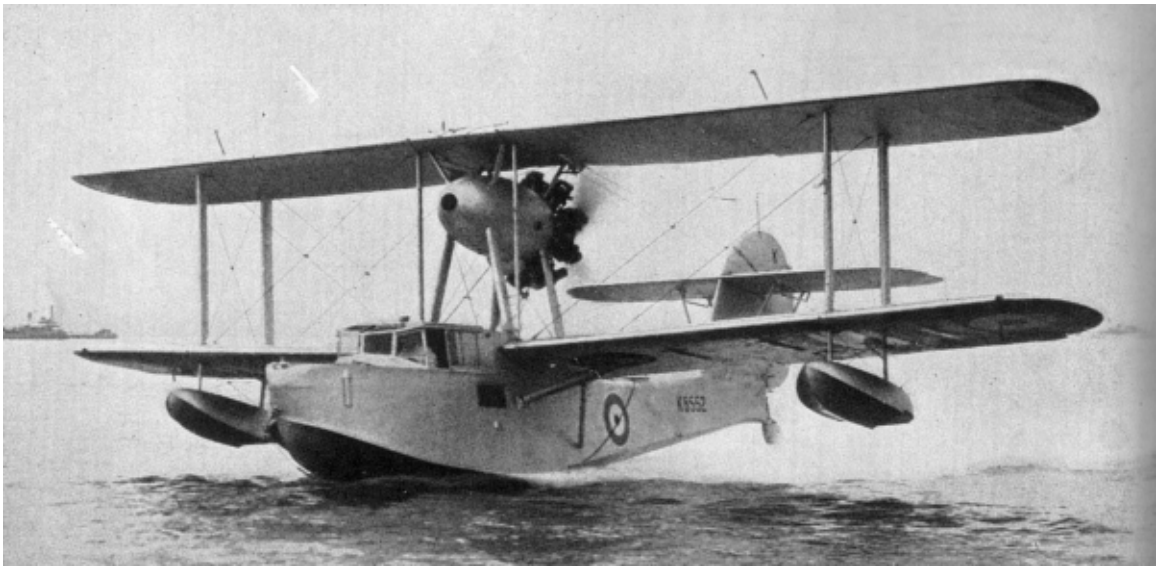
- The absence of prop-wash over the wings can reduce the airflow across the wing flaps, making them less effective. Wing-mounted pusher engines block portions of the trailing edges of the wings, reducing the total width available for flaps and ailerons.
- Placement of the propeller in front of the tail can have a negative side effect: strong pitch and yaw changes may occur as the engine's power setting changes and the airflow over the tail correspondingly speeds up or slows down.

Wright "Flyer" (reproduction of 1908–09 model)

Experimental fighter XP-55 (1943)

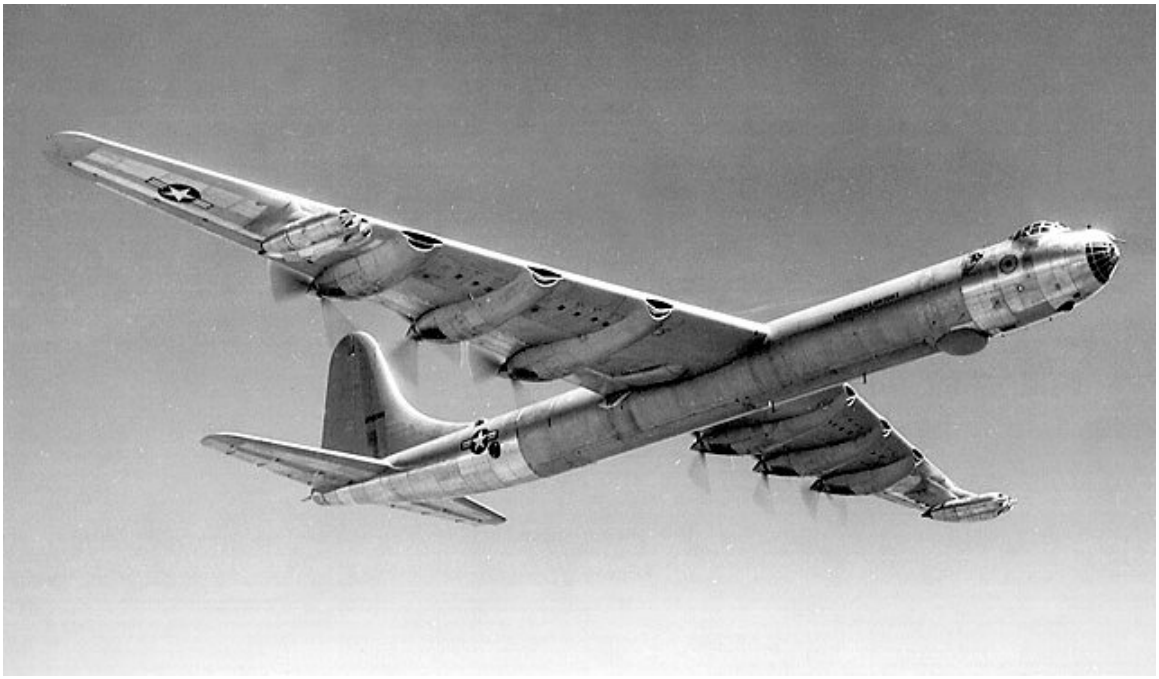


F.E.2b pusher (1914). The propeller is just behind the wing.



Supermarine Walrus seaplane (1933)

First versions of Saab J21 (1943)

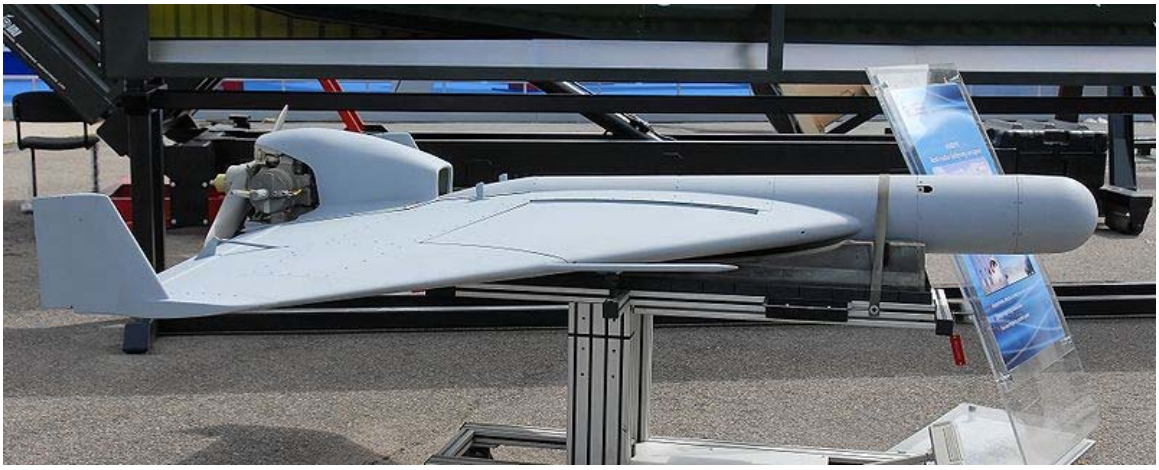


Convair B-36 Peacemaker (1946)

Experimental flying wing Northrop XB-35 (1946)

Piaggio P-180 Avanti (1986)

UAV SAGEM Sperwer B (1990s)



IAI Harpy (1994)

IAI Heron (2006)

UCAV MQ-9 Reaper (2001)

NAL Saras

Experimental fighter XP-56 (1943)

Chapter 2

T-tail and Tiltwing

T-tail

British Aerospace Avro RJ-85 - previously BAe 146 of SN Brussels Airlines (Belgium)

Rossiya Russian Airlines Tupolev Tu-154M

Piper PA-44-180 Seminole

Grob motor glider

Beechcraft 1900D of the Swiss Air Force

A **T-tail** is an aircraft tail stabilizer configuration in which the horizontal surfaces (tailplane and elevators) are mounted to the top of the vertical stabilizer. Traditionally, the horizontal control surfaces are mounted to the fuselage at the base of the vertical stabilizer. The resulting arrangement looks like the capital letter T when viewed from the front or back, hence the name.

Benefits

The tailplane surfaces are kept well out of the airflow behind the wing, giving smoother flow, more predictable design characteristics, and better pitch control. This is especially important for planes operating at low speed, where clean airflow is required for control. deHavilland Canada's line of larger STOL aircraft all use this arrangement for this reason. T-tail configuration also allows high performance aerodynamics and excellent glide ratio as the empennage is not affected by wing slipstream. Therefore the T-tail configuration is especially popular on gliders.

The effective distance between wing and tailplane can be increased without a significant increase in the weight of the aircraft. The distance between the two planes gives the moment, or "leverage", by which the tailplane can control the aircraft's pitch attitude - with a greater distance, smaller, lighter tailplanes and elevators can be used.

The tail surfaces are mounted well out of the way of the rear fuselage, permitting this site to be used for the aircraft's engines. This is why the T-tail arrangement is also commonly found on airliners with rear-mounted engines, including trijets. The Douglas DC-9, Bombardier CRJ200, Embraer ERJ 145, Boeing 717, Boeing 727, Fokker 100, Vickers VC-10, Hawker Siddeley Trident, BAC 1-11, Tu-134, Tu-154, Il-62, and McDonnell Douglas MD-80, McDonnell Douglas MD-90, all used the T-tail for this reason.

The horizontal stabilizer is kept farther away from the ground, which helps reduce damage to it by objects on the ground when taking off or landing. This is not normally a large concern for engine-powered, full-scale ('real') planes, but for planes having no stout landing gear, such as gliders and model airplanes it can be. This benefit is also shared by V-tails and cruciform tails.

Drawbacks

The aircraft will tend to be much more prone to a dangerous deep stall condition, where blanking of the airflow over the tailplane and elevators by a stalled wing can lead to total loss of pitch control. The F-101 Voodoo suffered from this throughout its service life. For similar reasons, T-tailed aircraft can be much more difficult to recover from a fully-developed spin.

The vertical stabilizer must be made considerably stronger and stiffer to support the forces generated by the tailplane. Unless expensive composite materials are used, this inevitably makes it heavier as well.

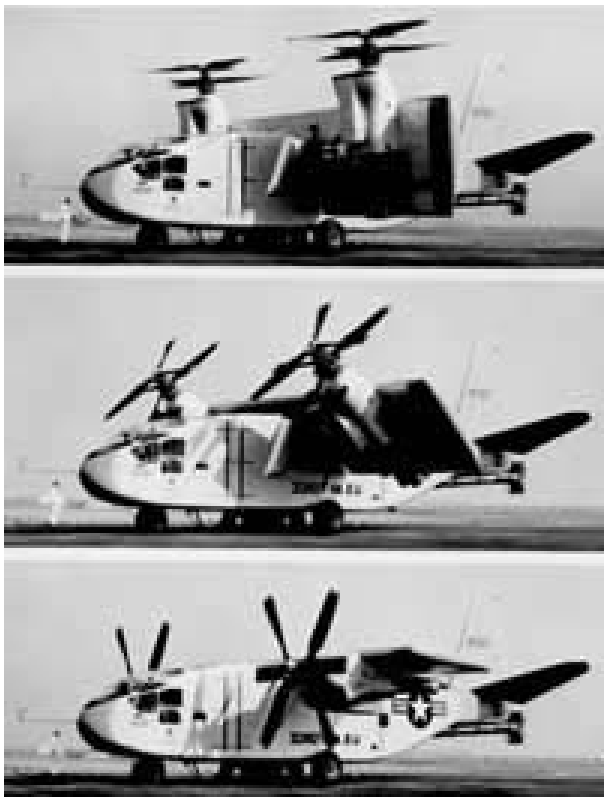
The T-tail configuration can cause several maintenance concerns as well. The control runs to the elevators are more complex and elevator surfaces are much more difficult to casually inspect from the ground.

Because of concerns about being able to clear the tail, the first high-speed aircraft with a T-tail, the Lockheed F-104 Starfighter, was at first fitted with a downward-firing ejector seat. For later models of this aircraft, capabilities of ejection seats improved, so it was changed to an upward-firing one, to overcome problems in low-altitude escapes.

Due to a lack of airflow over the elevator from a forward mounted engine (piston or turboprop), low speed control is reduced and low speed operation is more difficult for aircraft not designed for low speed operation.

A compromise is also possible, with the tailplane mounted part way up the fin rather than right at the top. The Sud Aviation Caravelle is an aircraft with this configuration.

Tiltwing



Hiller X-18 tilting its wing

A **tiltwing** aircraft features a wing that is horizontal for conventional forward flight and rotates up for vertical takeoff and landing. It is similar to the tiltrotor design where only

the propeller and engine rotate. Tiltwing aircraft are typically fully capable of VTOL operations.

The tiltwing design offers certain advantages in vertical flight relative to a tiltrotor. Because the slipstream from the rotor strikes the wing on its smallest dimension, the tiltwing is able to apply more of its engine power to lifting the aircraft. For comparison, the V-22 Osprey tiltrotor loses about 10% of its thrust to interference from the wings. However, the fixed wing of a tiltrotor aircraft offers a superior angle of attack — thus more lift and a shorter takeoff roll — when performing STOL/STOVL operations. The main drawback of the tiltwing is control during hover. The wing tilted vertically represents a large surface area for crosswinds to push.

List of Tiltwing aircraft

Tiltwing designs with rocket, jet, or propeller propulsion

- 1957 - Vertol VZ-2
- 1959 - Hiller X-18
- 1964 - LTV XC-142
- 1965 - Canadair CL-84

Chapter 3

Tricycle Gear and Twin Boom

Tricycle gear

A Mooney M20J with a retractable tricycle landing gear

Polish 3Xtrim 3X55 Trener with a fixed tricycle landing gear taxiing

Tricycle gear describes an aircraft undercarriage, or landing gear, arranged in a tricycle fashion. The tricycle arrangement has one wheel in the front, called the nose wheel, and two or more main wheels slightly aft of the center of gravity. Because of the ease of operating tricycle gear aircraft on the ground, the configuration is the most widely used on aircraft.

Several early aircraft had primitive tricycle gear, notably the Curtiss Pushers of the early 1910s. Waldo Waterman's 1929 tailless Whatsit was one of the first to have a steerable nose wheel.

Tricycle gear is essentially the reverse of conventional landing gear or taildragger. Tricycle gear aircraft have the advantage that it is much more difficult to make them 'nose over' as can happen if a taildragger hits a bump or has the brakes heavily applied. In a nose over, the airplane's tail tips up and the propeller strikes the ground, causing damage. Tricycle gear planes are also easier to handle on the ground and reduce the possibility of a ground loop, though they can be susceptible to wheel-barrowing. This is due to the main gear being behind the center of mass. Tricycle gear also provides an advantage in visibility to the pilot as the nose of the aircraft is level and, unlike in aircraft with conventional landing gear, does not block the view ahead. The nose wheel equipped aircraft also is easier to handle on the ground in high winds due to its wing negative angle

of attack. Student pilots are able to safely master nosewheel equipped aircraft more quickly.

In the United States, students trained on taildragger aircraft are assumed to be competent in tricycle-equipped aircraft, but students trained on tricycles must receive training in taildraggers.

Tricycle gear aircraft are easier to land because the attitude required to land on the main gear is the same as that required in the flare, and they are less vulnerable to crosswinds. As a result, the majority of modern aircraft are fitted with tricycle gear. Almost all jet-powered aircraft have been fitted with tricycle landing gear, to avoid the blast of hot, high-speed gases causing damage to the ground surface, in particular runways and taxiways. The few exceptions have included the Yakovlev Yak-15, the Supermarine Attacker, and prototypes such as the Heinkel He 178, the Messerschmitt Me 262 V3, and the Nene powered version of the Vickers VC.1 Viking.

The taildragger configuration does have advantages. The rear wheel means the plane naturally sits in a nose-up attitude when on the ground; this is useful for operations on unpaved surfaces like gravel where debris could damage the propeller. The tailwheel also transmits loads to the airframe in a way that is less likely to cause airframe damage over time operating on rough fields. The simpler main gear and small tailwheel result in both a lighter weight and less complexity if retractable. Likewise, a fixed-gear taildragger exhibits less interference drag and form drag in flight than a fixed-gear aircraft with tricycle gear. Tail wheels are smaller and less expensive to buy and maintain and man-handling a tailwheel aircraft on the ground is easier. Most tailwheel aircraft are lower in overall height and thus may fit in lower hangars. Tailwheel aircraft are also more suitable for fitting with skis in wintertime.

Twin boom

de Havilland Sea Vixen (2004)

Twin-boom aircraft have their tailplanes and vertical stabilizers mounted on the tail of either two fuselages or on two booms fixed to either both sides of the single fuselage, the wings or the engine nacelles.

The reason for this design choice may be:

- To be able to place a cargo door in the back of the aircraft (examples include the C-82 Packet and C-119 Flying Boxcar)
- To construct propeller aircraft in pusher configuration or jet aircraft with the engine mounted directly to the aft of the fuselage (Bell XP-52, De Havilland Vampire Saab 21)
- For unobstructed field of view or field of fire to the rear (Focke-Wulf Fw 189)
- Twin aircraft, constructed by putting two copies of an existing traditional aircraft side-by-side, (P-82 Twin Mustang, Messerschmitt Me 609)
- To accommodate early inline engines and their lengthy turbochargers in the most aerodynamically efficient/practical planform (P-38 Lightning) & (P-61 Black Widow)

- To increase an aircraft structure's rigidity, strength, and internal volume (Rutan Voyager, Scaled Composites Grizzly, Virgin Atlantic GlobalFlyer, Transavia PL-12 Airtruk)
- To provide for room to carry external cargo, such as Scaled Composites WhiteKnightTwo. Burt Rutan refers to this design concept as "open architecture".

de Havilland Vampire T11 of the UK Vampire Preservation Group displays at the Cotswold Air Show (2010).

Other examples of twin boom aircraft:

- Adam A700
- Adam A500
- Blohm & Voss BV 138
- Cessna Skymaster/O-2 Skymaster
- De Havilland Sea Vixen
- de Havilland Venom
- Fokker F.25
- Fokker G.I
- Heinkel He 111Z Zwilling
- Hughes XF-11
- Lockheed P-38 Lightning
- Messerschmitt Me 409
- North American Rockwell OV-10 Bronco

- Saab 21
- Sadler Vampire
- Scaled Composites White Knight
- SIPA S-200 Minijet
- Sukhoi Su-12
- Sukhoi Su-80
- Schweizer RU-38 Twin Condor
- US Army RQ-7 Shadow

Chapter 4

Twin Tail, Twinjet and V-tail

Twin tail

A twin-tailed B-25 Mitchell in flight

A **twin tail** is a specific type of vertical stabilizer arrangement found on the empennage of some aircraft. Two vertical stabilizers — often smaller on their own than a single conventional tail would be — are mounted at the outside of the aircraft's horizontal stabilizer. This arrangement is also known as an **H-tail**, as it resembles a capital "H" when viewed from rear.

A special case of twin tail is **twin boom tail** or **double tail** where the aft airframe consists of two separate fuselages, "tail booms", which each have one fin and rudder but share a conjoined one single horizontal stabilizer. Examples of this construction are Lockheed P-38 Lightning, Northrop P-61 Black Widow, De Havilland Vampire and C-119 Boxcar

Design

Separating the control surfaces allows for additional rudder area or vertical surface without requiring a massive single tail. On multi-engine propeller designs twin fin and rudders operating in the propeller slipstream give greater rudder authority and improved control at low airspeeds, and when taxiing. A twin tail can also simplify hangar requirements, give dorsal gunners enhanced firing area, and in some cases reduce the aircraft's weight. It also affords a degree of redundancy - if one tail is damaged, the other may remain functional.

Many canard aircraft designs incorporate twin tails on the tips of the main wing. Very occasionally, three or more tails are used, as on the Breguet Deux-Ponts, Lockheed Constellation and Boeing 314 Clipper. A very unusual design can be seen on the E-2 Hawkeye, which has two additional vertical tails fixed to the horizontal stabilizer between the normal vertical twin-tail surfaces. This arrangement was chosen for the stringent size limitations of carrier-based aircraft.

The twin tail of a Chrislea Super Ace, built in 1948

Significant aircraft with twin tails include the B-24 Liberator, Handley-Page Halifax Avro Lancaster, and P-38 Lightning. The arrangement is not limited to World War II-vintage aircraft, however. Many fighter aircraft, like the F-14 Tomcat, F-15 Eagle,

Sukhoi Su-27, Mig-29, and A-10 Thunderbolt II, make use of twin tail configurations, as do civilian and cargo designs like the Antonov An-14, Antonov An-22, Antonov An-28, Antonov An-38, Antonov An-225, Beechcraft 18, Beriev Be-12, ERCO Ercoupe, Burt Rutan's Long-EZ and SpaceShipOne also Shorts 330.

Future Aircraft

Airbus has filed a patent for a new, twin-tail, trijet design, but it is unknown if this will ever come to market.

Twinjet

A **twinjet** or **twin jet** is a jet aircraft powered by two engines. Such configuration of an airplane is the most popular today for commercial airliners, for fighters, and many other kinds, because while offering safety from a single engine failure, it is also acceptably fuel-efficient.

Aircraft configurations

As of today, there are three most common configurations of this kind of an airplane. One has an engine mounted beneath each wing, and another has one engine mounted on each side the rear fuselage, close to its empennage. In the third configuration, both jet engines are within the fuselage, side-by-side. The third configuration is notable for being used on most fighters since 1960s, and still continuing, for example in the Su-27 'Flanker', the F-15 Eagle, or the F-22 Raptor.

Failure safety

When flying far from diversionary airports, (so called ETOPS/LROPS flights), the aircraft must be able to reach an alternate on the remaining engine within a specified time in case of one engine failure. Power is not an issue. One of the engines is more than powerful enough to keep the aircraft aloft. Mostly, it is about maintenance and design requirements ensuring that a failure of one engine cannot make the other one fail, also. The engines and related systems need to be independent and (in essence) independently maintained. ETOPS/LROPS is often incorrectly thought to apply only to long overwater flights. In fact it applies to any flight more than specified distances from an available diversion airport. Overwater flights near diversion airports need not be ETOPS/LROPS compliant.

In the event of an engine failure, the remaining engine must provide enough thrust to keep the airplane in flight even if the failure occurs during take-off at a point where it is

too late to reject the take-off. In other words a fully-laden twinjet must be able to climb on one engine.

Due to the lack of engine redundancy, in the event of volcanic ash ingestion as happened with the air travel disruption after the 2010 Eyjafjallajökull eruption, airline operators of twinjets must be equally as cautious and safety conscious as operators of aircraft with three or more engines in any areas affected by aerial ash fallout. Thus far in the course of modern aviation history, two four-engined passenger aircraft; a British Airways Flight 9 in 1982 and a KLM Flight 867 in 1989, suffered engine failures due to volcanic dust ingestion.

Efficiency

Twin jets tend to be more fuel-efficient than aircraft with three or more engines. Fuel efficiency in airliners is a high priority, and a high percentage airliners use two engines. The Boeing 737 twinjet stands out as the most produced jet airliner. Other examples include the Boeing 767, 787, the Airbus A320, and the A350.

Many airlines use twin jets exclusively nowadays, such as American Airlines, Continental Airlines, and US Airways in the United States.

Introduction to transoceanic flights

Since the 1990s airlines have increasingly turned from four-engined to twin-engined airliners to operate transatlantic and transpacific routes. On a nonstop flight from America to Asia the long-range aircraft usually follows the Great Circle route. Hence, in case of an engine failure in a twinjet (like Boeing 777), it is never too far from an emergency landing fields in western Canada, Alaska, or eastern Russia. The Boeing 777 has also been approved by the Federal Aviation Administration for flights between North America and Hawaii, which is the world's longest regular airline route with no emergency landing fields along the way.

V-tail

1950 V-tailed B35 still operated by the National Test Pilot School at the Mojave Airport

The V-tail of a Belgian Air Force Fouga Magister

An Ultraflight Lazair showing its inverted V-tail covered with translucent Tedlar

In aircraft, a **V-tail** (sometimes called a **Butterfly tail**) is an unconventional arrangement of the tail control surfaces that replaces the traditional fin and horizontal surfaces with two surfaces set in a V-shaped configuration when viewed from the front or rear of the aircraft. The rear of each surface is hinged, and these movable sections, sometimes called **ruddervators**, combine the tasks of the elevators and rudder.

Design use

The V-tail has not been a popular choice for aircraft manufacturers. The most popular V-tailed aircraft in mass production was the Beechcraft Bonanza Model 35, often known as the V-tail Bonanza or simply V-Tail. Other examples include the F-117 Nighthawk stealth fighter, the Fouga Magister trainer, and the MQ-1 Predator UAV. The X-shaped tail surfaces of the experimental Lockheed XFV were essentially a V tail that extended both above and below the fuselage. Over 2000 Ultraflight Lazair ultralights were produced, all featuring an inverted V-tail.

Advantages

Ideally, with fewer surfaces than a conventional three-aerofoil tail or a T-tail, the V-tail is lighter, has less wetted surface area, and thus produces less drag. However, NACA

studies indicated that the V-tail surfaces must be larger than simple projection into the vertical & horizontal planes would suggest, such that total wetted area is roughly constant; reduction of intersection surfaces from three to two, does, however, produce a net reduction in drag through elimination of some interference drag.

In modern day light jet general aviation aircraft such as the Cirrus Jet, Eclipse 400 or the unmanned aerial drone Global Hawk, the power plant is often placed outside the aircraft to protect the passengers and make certification easier. In such cases V-tails are used to avoid placing the vertical stabilizer in the exhaust of the engine, which would disrupt the flow of the exhaust reducing thrust, and wear on the stabilizer, possibly leading to damage over time.

Disadvantages

Combining the pitch and yaw controls is difficult and requires a more complex control system. The V-tail arrangement also places greater stress on the rear fuselage when pitching and yawing.

In the mid-1980s, the Federal Aviation Administration grounded the Beechcraft Bonanza due to safety concerns. While the Bonanza met the initial certification requirements, it had a history of fatal mid-air breakups during extreme stress, at a rate exceeding the accepted norm. The type was deemed airworthy and restrictions removed after Beechcraft issued a structural modification as an Airworthiness Directive.

Ruddervators

Ruddervators are the control surfaces on an airplane with a V-tail configuration. They are located at the trailing edge of each of the two airfoils making up the tail of the plane. The first use of ruddervators may have been on the Coandă-1910's X-tail, although there is no proof that the aircraft ever flew. The later Coandă-1911 flew with ruddervators on its X-tail. Later Polish engineer Jerzy Rudlicki designed the first practical ruddervators in 1930, tested on a modified Hanriot H-28 trainer in 1931.

The name derives from a combination of the word rudder and elevator. In a conventional aircraft tail configuration, the rudder provides yaw (horizontal) control and the elevator provides pitch (vertical) control.

Ruddervators provide the same control effect as conventional control surfaces, but through a more complex control system that actuates the control surfaces in unison. Yaw moving the nose to the left is produced on an upright V tail by moving the pedals left which deflects the left-hand ruddervator down and left and the right-hand ruddervator up and left. The opposite produces yaw to the right. Pitch nose up is produced by moving the control column or stick back which deflects the left-hand ruddervator up and right and the right-hand ruddervator up and left. Pitch nose down is produced by moving the control column or stick forward which induces the opposite ruddervator movements.

Ruddervators have also been used on some airships, such as the US Navy's N class blimps. Accurate pitch trimming of airships can be difficult and this configuration improves clearance beneath the tail.

Chapter 5

Autogyro

An **autogyro** (in Spanish **autogiro**), also known as **gyroplane**, **gyrocopter**, or **rotaplane**, is a type of rotorcraft which uses an unpowered rotor in autorotation to develop lift, and an engine-powered propeller, similar to that of a fixed-wing aircraft, to provide thrust. While similar to a helicopter rotor in appearance, the autogyro's rotor must have air flowing through the rotor disc in order to generate rotation. Invented by the Spanish engineer Juan de la Cierva to create an aircraft that could safely fly at slow speeds, the autogyro was first flown on 9 January 1923, at Cuatro Vientos Airfield in Madrid. De la Cierva's aircraft resembled the fixed-wing aircraft of the day, with a front-mounted engine and propeller in a tractor configuration to pull the aircraft through the air. Late-model autogyros patterned after Dr. Igor Bensen's designs feature a rear-mounted engine and propeller in a pusher configuration. The term Autogiro was a trademark of the Cierva Autogiro Company, and the term Gyrocopter was used by E. Burke Wilford who developed the Reiseler Kreiser feathering rotor equipped gyroplane in the first half of the twentieth century. The latter term was later adopted as a trademark by Bensen Aircraft.

Configuration

An autogyro is characterized by a free-spinning rotor that turns because of passage of air upward through the rotor. The vertical component of the total aerodynamic reaction of the rotor gives lift for the vehicle, and sustains the autogyro in the air. A separate propeller provides forward thrust, and can be placed in a tractor configuration with the engine and propeller at the front of the fuselage (e.g., Cierva), or pusher configuration with the engine and propeller at the rear of the fuselage (e.g., Bensen).

Whereas a helicopter works by forcing the rotor blades through the air, pushing air downwards, the autogyro rotor blade generates lift in the same way as a glider's wing by changing the angle of the air as it moves upwards and backwards relative to the rotor blade. The free-spinning blades turn by autorotation; the rotor blades are angled so that they not only give lift, but the angle of the blades causes the lift to accelerate the blades' rotation rate, until the rotor turns at a stable speed with the drag and thrust forces in balance.

The rotor head, pre-rotator shaft and Subaru engine configuration on a VPM M-16 autogyro

Pitch control of the autogyro is by tilting the rotor fore and aft; roll control is by tilting the rotor laterally (side to side). Three designs to affect the tilt of the rotor are a tilting hub (Cierva), swashplate (Air & Space 18A), or servo-flaps (Kaman SAVER). A rudder provides yaw control. On pusher configuration autogyros, the rudder is typically placed in the propeller slipstream to maximize yaw control at low airspeed (but not always, as seen in the McCulloch J-2, with twin rudders placed outboard of the propeller arc).

Flight controls

There are three primary flight controls: control stick, rudder pedals, and throttle. The control stick is termed cyclic and tilts the rotor in the desired direction to provide pitch and roll control. The rudder pedals provide yaw control, and the throttle controls engine power.

Secondary flight controls include the rotor transmission clutch, also known as a pre-rotator, which when engaged drives the rotor to start it spinning before takeoff, and collective pitch to reduce blade pitch before driving the rotor. Collective pitch controls are not usually fitted to autogyros, but can be found on the Air & Space 18A and McCulloch J-2 and the Westermayr Tragschrauber and are capable of near VTOL performance. Unlike a helicopter, autogyros without collective pitch need a runway to takeoff; however they are capable of landing with a very short, or zero ground roll.

Pusher vs tractor configuration

Montgomerie Merlin single-seat autogyro

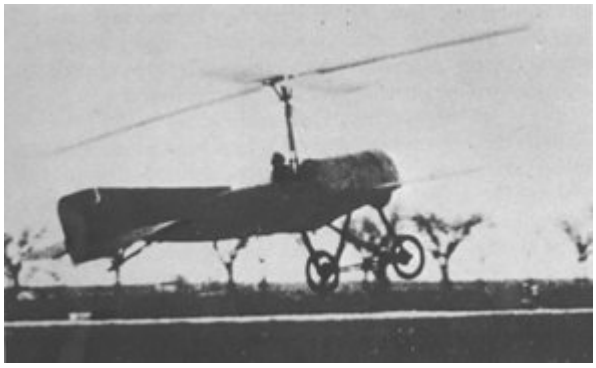
Modern autogyros typically follow one of two basic configurations. The most common design is the pusher configuration, where the engine and propeller are located behind the pilot and rotor mast, such as in the Bensen "Gyrocopter". It was developed by Igor Bensen in the decades following World War II, and came into widespread use shortly afterward.

Less common today is the tractor configuration. In this version the engine and propeller are located at the front of the aircraft, ahead of the pilot and rotor mast. This was the primary configuration in early autogyros, but became less common after the advent of the helicopter. It has enjoyed a revival since the mid 1970s.

History

Juan de la Cierva was a Spanish engineer and aeronautical enthusiast. In 1921, he participated in a design competition to develop a bomber for the Spanish military. De la Cierva designed a three-engined aircraft, but during an early test flight, the bomber stalled and crashed. De la Cierva was troubled by the stall phenomenon and vowed to develop an aircraft that could fly safely at low airspeeds. The result was the first successful rotorcraft, which he named Autogiro in 1923. De la Cierva's autogyro used an airplane fuselage with a forward-mounted propeller and engine, a rotor mounted on a mast, and a horizontal and vertical stabilizer.

Early development



The first autogyro to fly successfully (1923)

Cierva C.6 replica in Cuatro Vientos Air Museum, Madrid, Spain

Royal Air Force Avro Rota Mk 1 Cierva Autogiro C30 A, at the Imperial War Museum Duxford, UK.

De la Cierva's first three designs (C.1, C.2, and C.3) were unstable because of aerodynamic and structural deficiencies in their rotors. His fourth design, the C.4, made the first successful flight of an autogyro on 9 January 1923, piloted by Alejandro Gomez Spencer at Cuatro Vientos airfield in Madrid, Spain. De la Cierva had fitted the rotor of the C.4 with flapping hinges to attach each rotor blade to the hub. The flapping hinges allowed each rotor blade to flap, or move up and down, to compensate for dissymmetry of lift, the difference in lift produced between the right and left sides of the rotor as the autogyro moves forward. Three days later, the engine failed shortly after takeoff and the aircraft descended slowly and steeply to a safe landing, validating De la Cierva's efforts to produce an aircraft that could be flown safely at low airspeeds.

De la Cierva developed his C.6 model with the assistance of Spain's Military Aviation establishment, having expended all his funds on development and construction of the first five prototypes. The C.6 first flew in February 1925, including a flight of 10.5 km (7 miles) from Cuatro Vientos airfield to Getafe airfield in about 8 minutes, a significant accomplishment for any rotorcraft of the time. Shortly after De la Cierva's success with the C.6, Cierva accepted an offer from Scottish industrialist James G. Weir to establish the Cierva Autogiro Company in England, following a demonstration of the C.6 before

the British Air Ministry at RAE Farnborough, on 20 October 1925. Britain had become the world centre of autogyro development.

A crash in February 1927, caused by blade root failure, led to an improvement in rotor hub design. A drag hinge was added in conjunction with the flapping hinge to allow each blade to move fore and aft and relieve in-plane stresses, generated as a byproduct of the flapping motion. This development led to the Cierva C.8, which, on 18 September 1928, made the first rotorcraft crossing of the English Channel followed by a tour of Europe.

The U.S. industrialist Harold Frederick Pitcairn, upon learning of the successful flights of the autogyro, had previously visited De la Cierva in Spain. In 1928 he visited him again, in England, after taking a C.8 L.IV test flight piloted by Arthur H.C.A. Rawson. Being particularly impressed with the autogyro's safe vertical descent capability, Pitcairn purchased a C.8 L.IV with a Wright Whirlwind engine. Arriving in the United States on 11 December 1928 accompanied by Rawson, this autogyro was redesignated C.8W. Subsequently, production of autogyros was licensed to a number of manufacturers, including the Pitcairn Autogiro Company in the U.S. and Focke-Wulf of Germany.

Avro-built Cierva C.19 Mk.IV Autogiro, built in 1932. Cuatro Vientos Airport Museum, Madrid, Spain.

In 1927 Engelbert Zaschka, a pioneering German engineer, invented a combined helicopter and autogyro. The principal advantage of the Zaschka machine is in its ability

to remain motionless in the air for any length of time and to descend in a vertical line, so that a landing may be accomplished on the flat roof of a large house. In appearance, the machine does not differ much from the ordinary monoplane, but the carrying wings revolve around the body.

Development of the autogyro continued in search for a means to accelerate the rotor prior to takeoff (called prerotating). Rotor drives initially took the form of a rope wrapped around the rotor axle and then pulled by a team of men to accelerate the rotor - this was followed by a long taxi to bring the rotor up to speed sufficient for takeoff. The next innovation was flaps on the tail to redirect the propeller slipstream into the rotor while on the ground. This design was first tested on a C.19 in 1929. Efforts in 1930 had shown that development of a light and efficient mechanical transmission was not a trivial undertaking. But in 1932, the Pitcairn-Cierva Autogiro Company of Willow Grove, Pennsylvania, finally solved the problem with a transmission driven by the engine.

De la Cierva's early autogyros were fitted with fixed rotor hubs, small fixed wings, and control surfaces like those of a fixed wing aircraft. At low airspeeds, the control surfaces became ineffective and could readily lead to loss of control, particularly during landing. In response, Cierva developed a direct control rotor hub, which could be tilted in any direction by the pilot. De la Cierva's direct control was first developed on the Cierva C.19 Mk. V and saw production on the Cierva C.30 series of 1934. In March 1934 this type of autogyro became the first rotorcraft to take off and land on the deck of a ship, when a C.30 performed trials onboard the Spanish navy seaplane tender Dédalo off Valencia.

Later that year, during the leftist Asturias' revolt in October, an autogyro made a reconnaissance flight for the loyal troops, marking the first military employment of a rotorcraft.

When improvements in helicopters made them practical, autogyros became largely neglected. They were, however, used in the 1930s by major newspapers, and by the US Postal Service for mail service between the Camden, NJ airport (USA) and the top of the post office building in downtown Philadelphia, Pennsylvania (USA).

World War II

In World War II, Germany pioneered a very small gyroglider rotor kite, the Focke-Achgelis Fa 330 "Bachstelze" (Water-wagtail), towed by U-boats to provide aerial surveillance.

The Imperial Japanese Army developed the Kayaba Ka-1 Autogyro for reconnaissance, artillery-spotting, and anti-submarine uses. The Ka-1 was based on an American design first imported to Japan in 1938. The craft was initially developed for use as an observation platform and for artillery spotting duties. The Army liked the craft's short take-off span, and especially its low maintenance requirements. In 1941 production began, with the machines assigned to artillery units for spotting the fall of shells. These carried two crewmen: a pilot and a spotter.

Later, the Japanese Army commissioned two small aircraft carriers intended for coastal antisubmarine (ASW) duties. The spotter's position on the Ka-1 was modified in order to carry one small depth charge. Ka-1 ASW autogyros operated from shore bases as well as the two small carriers. They appear to have been responsible for at least one submarine sinking.

The autogyro was used to calibrate the coastal radar stations during and after the Battle of Britain.

Postwar developments

The autogyro was resurrected after World War II when Dr. Igor Bensen, a Russian immigrant, saw a captured German U-Boat's Fa 330 gyroglider and was fascinated by its characteristics. At work he was tasked with the analysis of the British military "Rotachute" gyro glider designed by expatriate Austrian Raoul Hafner. This led him to adapt the design for his own purposes and eventually market the B-7. Bensen submitted an improved version, the Bensen B-8M, for testing to the United States Air Force, which designated it the X-25. The B-8M was designed to use surplus McCulloch engines used on flying unmanned target drones.

Ken Wallis developed a miniature autogyro craft, the Wallis autogyro, in England in the 1960s, and autogyros built similar to Wallis' design appeared for a number of years. Ken Wallis' designs have been used in various scenarios including military training, police reconnaissance, and in another case a search for the Loch Ness Monster.

Three different autogyro designs have been certified by the Federal Aviation Administration for commercial production: the Umbaugh U-18/Air & Space 18A of 1965, the Avian 2-180 Gyroplane of 1967, and the McCulloch J-2 of 1972. All have been commercial failures, for various reasons.

Bensen Gyrocopter

The basic Bensen Gyrocopter design is a simple frame of square aluminium or galvanized steel tubing, reinforced with triangles of lighter tubing. It is arranged so that the stress falls on the tubes, or special fittings, not the bolts. A front-to-back keel mounts a steerable nosewheel, seat, engine, and a vertical stabilizer. Outlying mainwheels are mounted on an axle. Some versions may mount seaplane-style floats for water operations.

Bensen Aircraft B8MG Gyrocopter

Bensen-type autogyros use a pusher configuration for simplicity and to increase visibility for the pilot. Power can be supplied by a variety of engines. McCulloch drone engines, Rotax marine engines, Subaru automobile engines, and other designs have been used in Bensen-type designs.

The rotor is mounted atop the vertical mast. The rotor system of all Bensen-type autogyros is of a two-blade teetering design. There are some disadvantages associated with this rotor design, but the simplicity of the rotor design lends itself to ease of assembly and maintenance and is one of the reasons for its popularity. Aircraft-quality birch was specified in early Bensen designs, and a wood/steel composite is used in the world speed record holding Wallis design. Gyroplane rotor blades are made from other materials such as aluminium and GRP-based composite blades.

Because of Bensen's pioneering of the concept and the popularity of his design, "Gyrocopter" has become a genericized trademark for pusher configuration autogyros.

The success of Bensen triggered a number of other designs, some of them fatally flawed with an offset between the centre of gravity and thrust line, risking a Power Push-Over (PPO or bunt-over) causing death to the pilot and giving gyroplanes in general a poor reputation - in contrast to Cierva's original intention and early statistics. Most new autogyros are now safe from PPO.

Certification by national aviation authorities

US certification

A certificated autogyro must meet mandated stability and control criteria; in the United States these are set forth in Federal Aviation Regulations Part 27: Airworthiness Standards: Normal Category Rotorcraft. The U.S. Federal Aviation Administration issues a Standard Airworthiness Certificate to qualified autogyros. Amateur-built or kit-built aircraft are operated under a Special Airworthiness Certificate in the Experimental category. Per FAR 1.1, the FAA uses the term "gyroplane" for all autogyros, regardless of the type of Airworthiness Certificate.

UK certification

A VPM M-16 commences its take-off roll

Some autogyros, such as the Rotorsport MT03, have type approval by the United Kingdom Civil Aviation Authority (CAA) under British Civil Airworthiness Requirements CAP643 Section T. Others operate under a permit to fly issued by the Popular Flying Association– similar to the US experimental aircraft certification.

However, the CAA's assertion that autogyros have a poor safety record means that permit to fly will only be granted to existing types of autogyro. All new types of autogyro must be submitted for full type approval under CAP643 Section T.

In 2005, the CAA issued a mandatory permit directive (MPD) which restricted operations for single seat autogryos, and were subsequently integrated into CAP643 Issue 3 published on 12 August 2005. The restrictions are concerned with the offset between the centre of gravity and thrust line, and apply to all aircraft unless evidence is presented to the CAA that the CG/Thrust Line offset less than 2 inches (5 cm) in either direction. The restrictions are summarised as follows:

- Aircraft with a cockpit/nacelle may only be operated by pilots with more than 50 hours solo flight experience following the issue of their licence.
- Open frame aircraft are restricted to a minimum speed of 30 mph (26 knots), except in the flare.
- All aircraft are restricted to a Vne of 70 mph (61 knots)
- Flight is not permitted when surface winds exceed 17 mph (15 knots) or if the gust spread exceeds 12 mph (10 knots)
- Flight is not permitted in moderate, severe or extreme turbulence and airspeed must be reduced to 63 mph (55 knots) if turbulence is encountered mid-flight.

World records

In 1931, Amelia Earhart flew a Pitcairn PCA-2 to a women's world altitude record of 18,415 ft (5,613 m).

Wing Commander Ken Wallis has held most of the autogyro world records during his autogyro flying career. These include the speed record of 186 km/h (111.7 mph), and the straight-line distance record of 869.23 km (543.27 miles). On 16 November 2002, at 89 years of age, Wallis increased the 3km speed record to 207.7 km/h (129.1 mph) - and simultaneously set another world record as the oldest pilot to set a world record.

The autogyro is one of the last remaining types of aircraft which has not yet been used to circumnavigate the globe. Expedition Global Eagle was the first attempt in history to circumnavigate the globe using an autogyro. The expedition set the record for the longest flight over water by an autogyro during the segment from Muscat, Oman to Karachi. The attempt was finally abandoned because of bad weather after a trip totalling 7,500 miles (12,100 km).

In February 2003, a year before the circumnavigation attempt, the Global Eagle piloted by Warrant Officer Barry Jones also broke the world range record by flying non-stop from Culdrose in Cornwall to Wick in Scotland, a total of 580 miles (928 km) breaking the old record held by Wing Commander Ken Wallis.

Andrew Keech made a transcontinental flight from Kitty Hawk, North Carolina to San Diego, California in October 2003 and set 3 world records for speed over a recognized

course. The 3 records were verified by tower personnel or by official observers of the United States' National Aeronautic Association (NAA). On 9 February 2006, he broke two of his world records and set a record for distance, ratified by the Fédération Aéronautique Internationale (FAI); Speed over a closed circuit of 500 km (311 mi) without payload: 168.29 km/h (104.57 mph), speed over a closed circuit of 1,000 km (621 mi) without payload: 165.07 km/h (102.57 mph), and distance over a closed circuit without landing: 1,019.09 km (633.23 mi).

Chapter 6

Dihedral

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

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

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

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

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

Dihedral angle and dihedral effect

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

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

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

Longitudinal dihedral

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

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

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

History

In geometry, dihedral angle is the angle between two planes. Aviation usage differs slightly from usage in geometry. In aviation, the usage "**di**hedral" evolved to mean the

positive, up angle between the left and right wings. While usage with the prefix "an-" (as in "**an**hedral") evolved to mean the negative, down angle between the wings.

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

Uses of dihedral angle and dihedral effect

Aircraft stability analysis

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

Provision of stability

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

Wing clearance

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

Using dihedral angle to adjust dihedral effect

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

Common Confusions

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

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

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

How dihedral angle creates dihedral effect and stabilizes the spiral mode

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

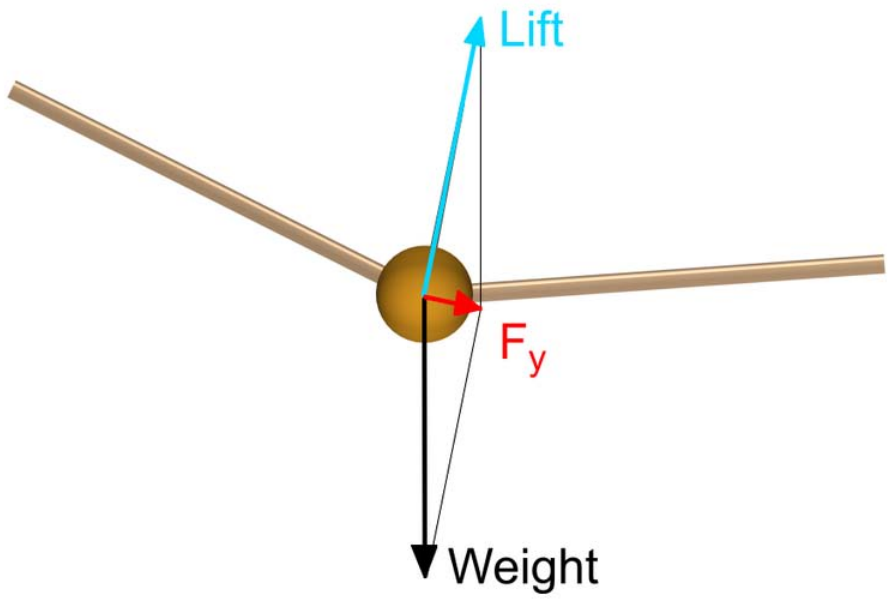


Fig. 1: Uncompensated lift component produces a side force F_y, which causes the aircraft to sideslip.

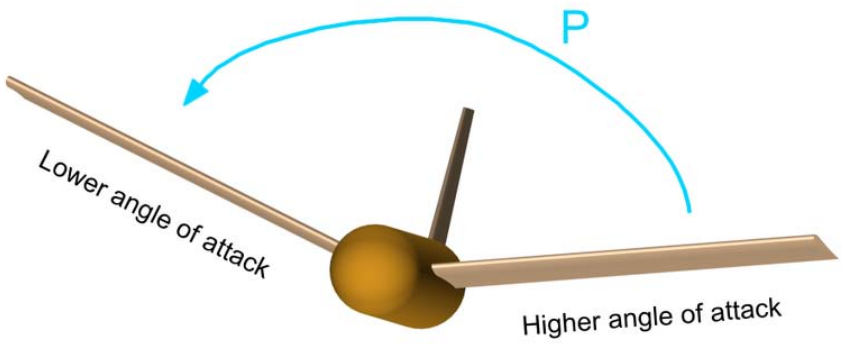


Fig. 2: Non-zero sideslip sets the lower, upwind wing to a higher angle of attack, resulting in stabilising roll moment P.
The aircraft is shown flying towards the viewer.

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

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

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

How dihedral effect stabilizes the spiral mode

The rolling moment created by the sideslip (labeled as "P") tends to roll the aircraft back to wings level. More dihedral effect tries to roll the wings in the "leveling" direction more strongly, and less dihedral effect tries to roll the wings in the "leveling" direction less

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

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

Other factors contributing to dihedral effect

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

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

Sweepback

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

Vertical position of the center of mass

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

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

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

Effects of too much dihedral effect

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

Other Dihedral-related terminology

Anhedral on the wings and tailplane of an RAF Harrier GR7A

Anhedral

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

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

Polyhedral

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

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

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

Chapter 7

Ground Effect Vehicle

A-90 Orlyonok

A **ground effect vehicle (GEV)** is one that attains level flight near the surface of the Earth, made possible by a cushion of high-pressure air created by the aerodynamic interaction between the wings and the surface known as ground effect. Also known as a **wing-in-ground-effect** (**WIG**) **vehicle**, **flarecraft**, **sea skimmer**, **ekranoplan**, SkimMachine, or **wing-in-surface-effect ship** (**WISE**), a GEV can be seen as a transition between a hovercraft and an aircraft. The International Maritime Organization (IMO) has classified the GEV as a ship. A GEV differs from an aircraft in that it cannot operate without ground effect, so its operating height is limited relative to its wingspan.

In recent years a large number of different GEV types have evolved for both civilian and military use. However, these craft are not in wide use.

History

Small numbers of experimental vehicles were built in Scandinavia just before World War II. By the 1960s, the technology started to improve, in large part due to the independent contributions of Rostislav Alexeev in the Soviet Union and German Alexander Lippisch, working in the United States. Alexeev worked from his background as a ship designer whereas Lippisch worked from his own background as an aeronautical engineer. The influence of Alexeev and Lippisch is still noticeable in most GEV vehicles seen today.

The Soviet Central Hydrofoil Design Bureau (CHDB), led by Alexeev, was the center of ground-effect craft development in the USSR; in Russian, the vehicle came to be known as an Ekranoplan (Russian: экранопла́н, экран "screen" + план "plane", from эффект экрана, literally in Russian 'screen effect' , for 'ground effect' in English). The military potential for such a craft was soon recognised and Alexeev received support and financial resources from Soviet leader Nikita Khrushchev.

Some manned and unmanned prototypes were built, ranging up to eight tons in displacement. This led to the development of the "Caspian Sea Monster", a 550-ton military ekranoplan. Although it was designed to travel a maximum of 3 m (9.8 ft) above the sea, it was found to be most efficient at 20 m (66 ft), reaching a top speed of 300 kn (350 mph; 560 km/h) (400 kn (460 mph; 740 km/h) in research flight).

The Soviet ekranoplan program continued with the support of Minister of Defense Dmitri Ustinov. It produced the most successful ekranoplan so far, the 125-ton A-90 Orlyonok. These craft were originally developed as very high-speed military transports, and were based mostly on the shores of the Caspian Sea and Black Sea. The Soviet Navy ordered 120 Orlyonok-class ekranoplans. But this figure was later reduced to fewer than thirty vehicles, with planned deployment mainly in the Black Sea and Baltic Sea fleets.

A few Orlyonoks served with the Soviet Navy from 1979 to 1992. In 1987, the 400-ton Lun-class ekranoplan was built as a missile launcher. A second Lun, renamed Spasatel, was laid down as a rescue vessel, but was never finished.

Minister Ustinov died in 1985, and the new Minister of Defense, Marshal Sokolov, effectively stopped the funding for the program. Only three operational Orlyonok-class ekranoplans (with revised hull design) and one Lun-class ekranoplan remained at a naval base near Kaspiysk.

The two major problems that the Soviet ekranoplans faced were poor longitudinal stability and a need for reliable navigation.

Since the fall of the Soviet Union, ekranoplans have been produced by the Volga Shipyard in Nizhniy Novgorod.

GEV developed since the 1980s have been primarily smaller craft designed for the recreational and civilian ferry markets. Germany, Russia, and the United States have provided most of the momentum with some development in Australia, China, Japan, and Taiwan. In these countries, small craft up to ten seats have been designed and built. Other larger designs as ferries and heavy transports have been proposed, though none have gone on to further development.

After the collapse of the Soviet Union, smaller ekranoplans for non-military use have been under development. The CHDB had already developed the eight-seat Volga-2 in 1985, and Technologies and Transport developed a smaller version by the name of Amphistar.

In Germany, Lippisch was asked to build a very fast boat for Mr. Collins from Collins Radio Company in the USA. He developed the X-112, a revolutionary design with reversed delta wing and T-tail. This design proved to be stable and efficient in ground effect and even though it was successfully tested, Collins decided to stop the project and sold the patents to a German company called Rhein Flugzeugbau (RFB) which further developed the model.

Tandem flarecraft Skimmerfoil Jörg IV located at the SAAF museum, Port Elizabeth, South Africa

Hanno Fischer took over the works from RFB and created his own company called Fischer Flugmechanik. Their two-seat Airfisch 3 and their later model that seats 6

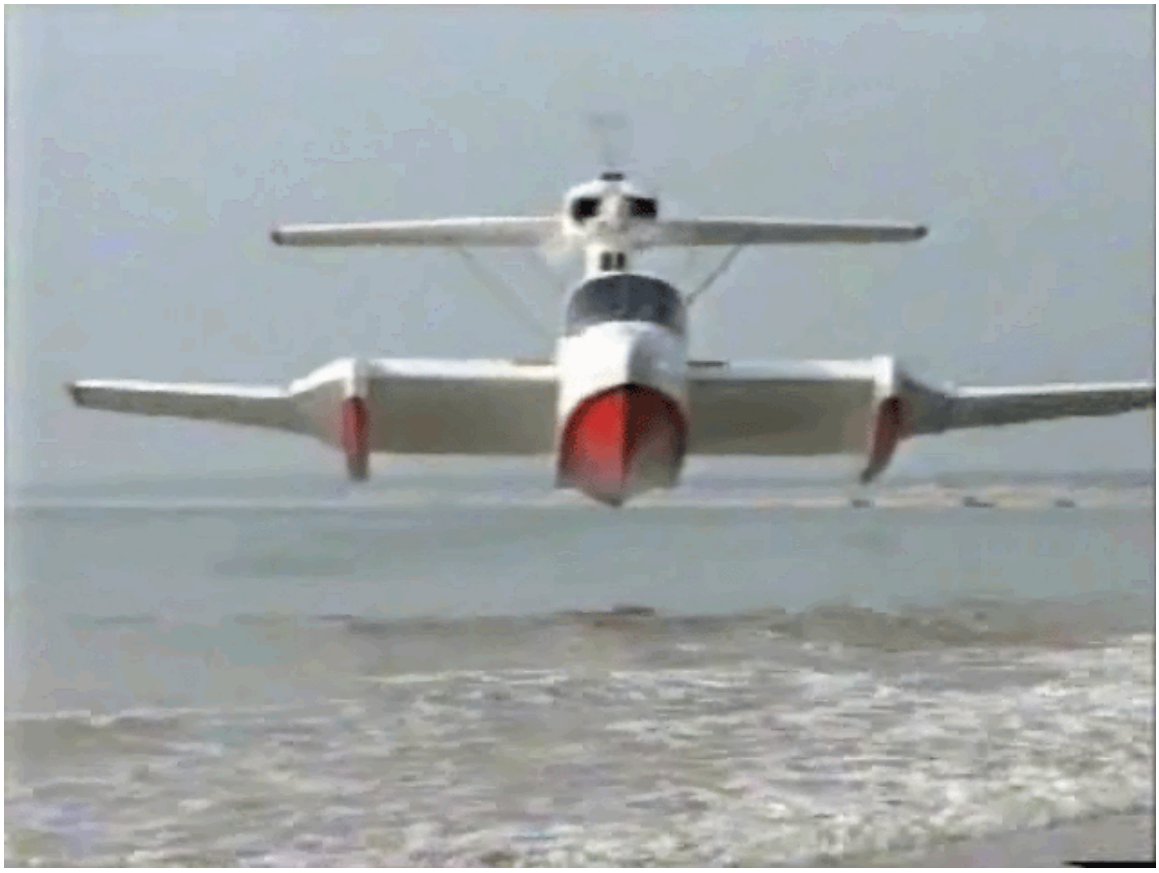
passengers have been a successful design. This craft, the FS-8, was to be produced by Hanno Fischer / Fischer Flugmechanik for a Singapore-Australian joint venture called Flightship. The company no longer exists but the prototype craft was bought over by Wigetworks, a company based in Singapore and renamed as AirFish 8.

An ongoing research project in collaboration with the university of Duisburg-Essen, involves the development of the Hoverwing.

Günther Jörg in Germany, who had also been working on Alexeev's first designs, and was familiar with the challenges of GEV design, developed a GEV with two wings in a tandem arrangement, the Jörg-II. It was the third, manned, tandem airfoil boat, named "Skimmerfoil", which was developed during his consultancy period in South Africa. It was a simple and low-cost design, but has not been produced to date. The consultancy of Dipl. Ing. Günther Jörg was founded with a fundamental knowledge of Wing in Ground Effect physics, as well as results of fundamental tests under different conditions and designs that began in 1960. In 1984, Günther Jörg received the "PHILIP MORRIS AWARD". In 1987, the Botec Company was founded.

Current development

Besides the development of appropriate design and structural configuration, special automatic control systems and navigation systems are also being developed. These include special altimeters with high accuracy for small altitude measurements and also lesser dependence on weather conditions. After extensive research and experimentation, it has been shown that "phase radio-altimeters" are most suitable for such applications as compared to laser, isotropic or ultrasonic altimeters.



Sea Eagle

Universal Hovercraft developed the first flying hovercraft, a prototype of which first took flight in 1996 on the Mississippi River, near Cordova, Illinois. Since 1999, Universal Hovercraft has been selling plans, parts, kits , and manufactured GEV hovercraft called the Hoverwing.

In Singapore, Wigetworks has continued the development of the technology and has successfully obtained the full certification from Lloyd's Register for entry into class. AirFish 8 - 001 was successfully registered into Singapore Registry of Ships (SRS) on 31 Mar 10. It is the first WIG craft to be flagged with the SRS which is one of the world's top 10 largest ship registry. Wigetworks has also partnered National University of Singapore's Engineering Department to develop higher capacity WIG crafts.

Iran deployed three squadrons of Bavar-2 two-seat GEVs in September, 2010. It carries one machine gun and surveillance gear, and is said to employ some form of stealth technology.

Classification

One of the problems that have delayed the development of these craft is the classification and legislation to be applied. IMO has studied the application of rules based on the

International Code of Safety for High-Speed Craft (HSC code) which was developed for fast ships such as hydrofoils, hovercraft, catamarans and the like. The Russian Rules for classification and construction of small type A ekranoplans is a document upon which most GEV design is based. However in 2005, the IMO classified the WISE or GEV crafts under the category of ships.

The International Maritime Organization recognizes three classes of ground effect craft:

1. **Type A**: a craft which is certified for operation only in ground effect;
2. **Type B**: a craft which is certified to temporarily increase its altitude to a limited height outside the influence of ground effect but not exceeding 150 m above the surface; and
3. **Type C**: a craft which is certified for operation outside of ground effect and exceeding 150 m above the surface.

Note: These classes currently only apply to craft carrying 12 passengers or more

Advantages and disadvantages

A ground effect craft may have better fuel efficiency than an equivalent aircraft flying at low level due to the close proximity of the ground, reducing lift-induced drag. There are also safety benefits for the occupants of the craft in flying close to the water as an engine failure will not result in severe ditching. However, this particular configuration is difficult to fly even with computer assistance. Flying at very low altitudes, just above the sea, is dangerous if the craft banks too far to one side while making a small radius turn.

A takeoff must be into the wind, which in the case of a water launch, means into the waves. This creates drag and reduces lift. Two main solutions to this problem have been implemented. The first was used by the Russian Ekranoplan program which placed engines in front of the wings to provide more lift. The Caspian Sea Monster had eight such engines, some of which were not used once the craft was airborne. A second approach is to use some form of an air-cushion to raise the vehicle most of the way out of the water, making take-off easier. This is used by German Hanno Fischer in the Hoverwing (successor to the Airfisch ground effect craft), which uses some of the air from the engines to inflate a skirt under the craft in the style of a sidewall hovercraft.

Wing configurations

Inverse delta

Developed by Alexander Lippisch, this wing allows stable flight in ground effect through self stabilization. This is the main Class B form of ground effect craft.

Ekranoplan wing

This was the profile designed by Rostislav Alexeyev. The wings are significantly shorter than comparable aircraft, and this configuration requires a high aft-placed horizontal tail and front-aft wings to maintain stability.

Tandem wings

Tandem Wing can have two configurations.

- A biplane-style Type-1 utilizing a shoulder mounted main lift wing and a belly-mounted sponsons similar to those on combat and transport helicopters.
- A canard-style type-2 with a mid-size horizontal stabilizer near the nose of the craft directing airflow under the Main Lift Airfoil. This Type-2 tandem design is a major improvement during take-off as it creates an air cushion to lift the craft above the water at a lower speed, thereby reducing water drag which is the biggest obstacle to successful seaplane launches.
- A Tandem Wing Style with double-wing system as built in Tandem Airfoilboat constructions by Dipl. Ing. Günther Jörg. This system is self-stabilizing and leads to a very secure and comfortable Wing in Ground Effect Flight which is very economical as well.

Russian light ekranoplan Aquaglide-2

Design

The important design principle is that the wing lift reduces as the operating altitude increases, so the ekranoplan is dynamically stable in the vertical dimension. Once moving at speed, the ekranoplan is no longer in contact with the water, and can move over ice, snow or level land with equal ease, though flight over land would involve extreme risks unless the surface is dependably flat.

The KM, as the Caspian Sea Monster was known in the Soviet military development program, was over 100 metres (328 ft) long, weighed 540 t (531 long tons) fully loaded, and could travel over 400 kilometres per hour (249 mph), a mere few metres above the surface of the water. Another model was the Lun, entering service with the Black Sea Fleet in 1987; the Lun-class vehicles had a top speed of 297 knots (550 km/h) (341 mph) flying in ground effect and 550 knots at altitude. The Lun ekranoplan had a potential lifting power of 1,000 tonnes (984 long tons).

Chapter 8

Ornithopter

Cybird radio-controlled ornithopter

An **ornithopter** (from Greek ornithos "bird" and pteron "wing") is an aircraft that flies by flapping its wings. Designers seek to imitate the flapping-wing flight of birds, bats, and insects. Though machines may differ in form, they are usually built on the same scale as these flying creatures. Manned ornithopters have also been built, and some have been successful. The machines are of two general types: those with engines, and those powered by the muscles of the pilot.

Early history of the ornithopter

The idea of constructing wings in order to resemble the flight of birds dates to the ancient Greek legend of Daedalus (Greek demigod engineer) and Icarus (Daedalus's son). The Chinese Book of Han records that Xin Dynasty Emperor Wang Mang oversaw the earliest ornithopter flight test in 19 AD.

One man said that he could fly a thousand li in a day, and spy out the (movements of the) Huns. (Wang) Mang tested him without delay. He took (as it were) the pinions of a great bird for his two wings, his head and whole body were covered over with feathers, and all this was interconnected by means of (certain) rings and knots. He flew a distance of several hundred paces, and then fell to the ground.

Among the first recorded attempts with gliders were those by the 11th century monk Eilmer of Malmesbury (recorded in the 12th century) and the 9th century poet Abbas Ibn Firnas (recorded in the 17th century); the reported flights were probably just glides and

resulted in injury. Roger Bacon, writing in 1260, was also among the first to consider a technological means of flight. In 1485, Leonardo da Vinci began to study the flight of birds. He grasped that humans are too heavy, and not strong enough, to fly using wings simply attached to the arms. Therefore he proposed a device in which the aviator lies down on a plank and works two large, membranous wings using hand levers, foot pedals, and a system of pulleys.

The first ornithopters capable of flight were constructed in France. In 1858 Pierre Julien's model flew an estimated forty feet. Gustave Trouvé's 1870 model flew a distance of 70 metres in a demonstration for the French Academy of Sciences. The wings were flapped by gunpowder charges activating a bourdon tube. Jobert in 1871 used a rubber band to power a small model bird. Alphonse Penaud, Abel Hureau de Villeneuve, Victor Tatin, Frank Kieser, and others also made designs and models.

From 1884 on, Lawrence Hargrave built scores of ornithopters powered by rubber bands, springs, steam, or compressed air. He introduced the use of small flapping wings providing the thrust for a larger fixed wing. This eliminated the need for gear reduction, thereby simplifying the construction. To achieve a more birdlike appearance, this approach is not generally favored today.

In the 1930s, Erich von Holst carried the rubber band powered bird model to a high state of development and great realism. Also in the 1938, Alexander Lippisch and other researchers in Germany harnessed the piston internal combustion engine.

Manned flight

Otto Lilienthal on August 16, 1894 with his kleiner Schlagflügelapparat

Schmid 1942 Ornithopter

The UTIAS Ornithopter No.1

Manned ornithopters fall into two general categories: Those powered by the muscular effort of the pilot (human-powered ornithopters), and those powered by an engine.

Around 1894, Otto Lilienthal became famous in Germany for his widely publicized and successful glider flights. Lilienthal also studied bird flight and conducted some related experiments. He constructed an ornithopter, although its complete development was prevented by his untimely death.

In 1929, a man-powered ornithopter designed by Alexander Lippisch (designer of the Me163 Komet) flew a distance of 250 to 300 metres after tow launch. Since a tow launch was used, some have questioned whether the aircraft was capable of flying on its own. Lippisch asserted that the aircraft was actually flying, not making an extended glide. (Precise measurement of altitude and velocity over time would be necessary to resolve

this question.) Most of the subsequent human-powered ornithopters likewise used a tow launch, and flights were brief simply because human muscle power diminishes rapidly over time.

In 1942, Adalbert Schmid made a much longer flight of a human-powered ornithopter at Munich-Laim. It travelled a distance of 900 metres, maintaining a height of 20 metres throughout most of the flight. Later this same aircraft was fitted with a 3 hp Sachs motorcycle engine. With the engine, it made flights up to 15 minutes in duration. Schmid later constructed a 10 hp ornithopter based on the Grunau-Baby IIa sailplane, which was flown in 1947. The second aircraft had flapping outer wing panels.

In 2005, Yves Rousseau was given the Paul Tissandier Diploma, awarded by the FAI for contributions to the field of aviation. Rousseau attempted his first human-muscle-powered flight with flapping wings in 1995. On 20 April 2006, at his 212th attempt, he succeeded in flying a distance of 64 metres, observed by officials of the Aero Club de France. Unfortunately, on his 213th flight attempt, a gust of wind led to a wing breaking up, causing the pilot to be gravely injured and rendered paraplegic.

A team at the University of Toronto Institute for Aerospace Studies, headed by Professor James DeLaurier, worked for several years on an engine-powered, piloted ornithopter. In July 2006, at the Bombardier Airfield at Downsview Park in Toronto, Professor DeLaurier's machine, the UTIAS Ornithopter No.1 made a jet-assisted takeoff and 14-second flight. According to DeLaurier, the jet was necessary for sustained flight, but the flapping wings did most of the work.

On August 2, 2010, Todd Reichert of the University of Toronto Institute for Aerospace Studies piloted a human-powered ornithopter named Snowbird. The 32-metre (105 ft 0 in) wingspan 92.59 pounds (42.00 kg) aircraft was constructed from carbon fibre, balsa and foam. The pilot sits in a small cockpit suspended below the wings and pumps a bar with his feet to operate a system of wires that flap the wings up and down. The pilot steers using a pair of metal bars attached to rudders on the back of the aircraft. Towed by a car until airborne, it then sustained 19.3 seconds of flight over a distance of 145 metres, an average speed of 15.91 miles per hour. Although similar tow-launched flights have been made in the past, improved data collection was used to verify that the ornithopter was capable of self-powered flight once aloft.

Applications for unmanned ornithopters

Practical applications capitalize on the resemblance to birds or insects. The Colorado Division of Wildlife has used these machines to help save the endangered Gunnison Sage Grouse. An artificial hawk under the control of an operator causes the grouse to remain on the ground so they can be captured for study.

Because ornithopters resemble birds or insects, they could be used for military applications, such as spying without alerting the enemies that they are under surveillance.

AeroVironment, Inc., led by Paul B. MacCready (Gossamer Albatross), has developed a remotely piloted ornithopter the size of a large insect for possible spy missions.

MacCready also developed in the mid-1980s, for the Smithsonian Institution, a half-scale radio controlled replica of the giant pterosaur, Quetzalcoatlus northropi. It was built to star in the IMAX movie On the Wing. The model had a wingspan of 5.5 metres (18 feet) and featured a complex, computerized autopilot control system, just as the full-size pterosaur relied on its neuromuscular system to make constant adjustments in flight.

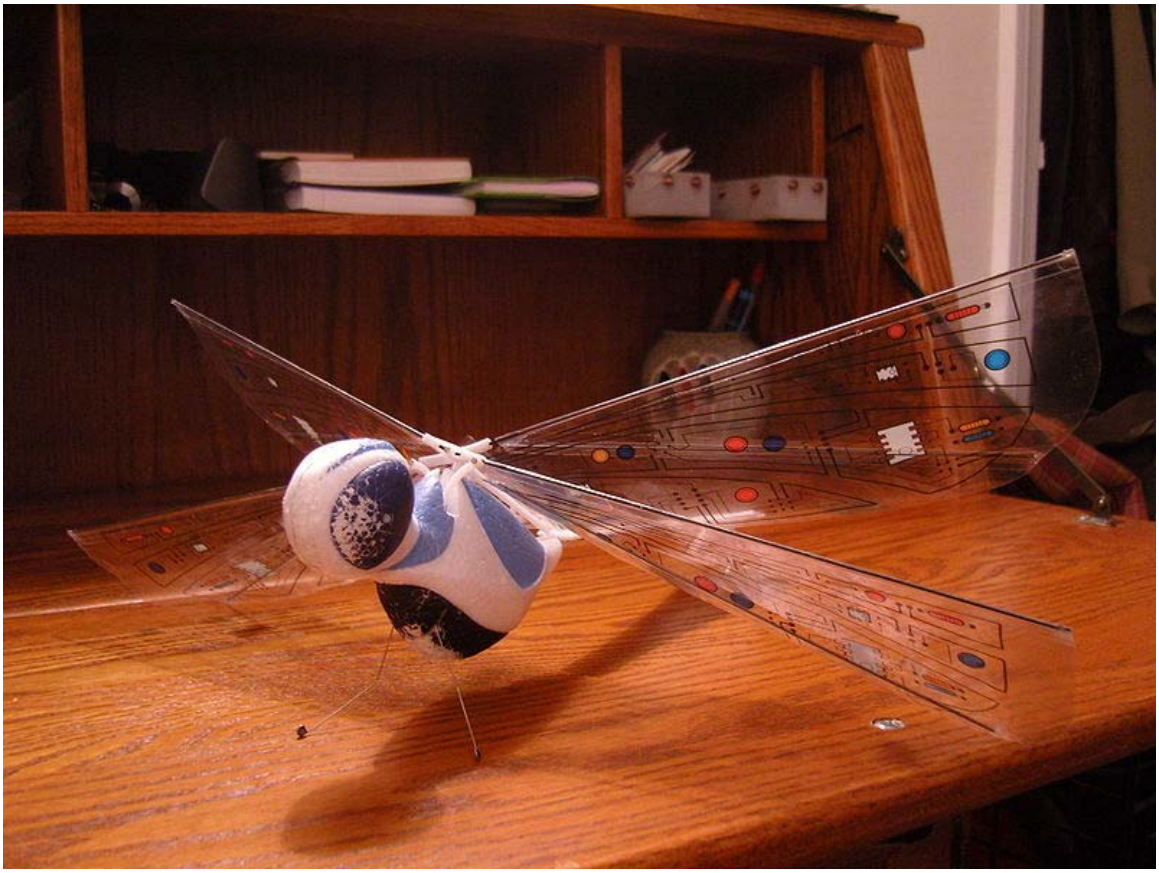
Researchers hope to eliminate the motors and gears of current designs by more closely imitating animal flight muscles. Georgia Tech scientist Robert C. Michelson is developing a Reciprocating Chemical Muscle for use in micro-scale flapping-wing aircraft. Michelson uses the term "entomopter" for this type of ornithopter. SRI International is developing polymer artificial muscles which may also be used for flapping-wing flight.

In 2002, Krister Wolff and Peter Nordin of Chalmers University of Technology in Sweden, built a flapping wing robot that learned flight techniques. The balsa wood design was driven by machine learning software technology known as a steady state linear evolutionary algorithm. Inspired by natural evolution, the software "evolves" in response to feedback on how well it performs a given task. Although confined to a laboratory apparatus, their ornithopter evolved behavior for maximum sustained lift force and horizontal movement.

Since 2002, Prof. Theo Van Holten has been working on an ornithopter which is constructed like a helicopter. The device is called the ornicopter and was made by constructing the main rotor so that it would have no reaction torque at all.

In 2008, Schiphol Airport started using a real looking mechanical hawk designed by falconer Robert Musters. The radio controlled robot bird is used to scare away birds that could damage the engines of airplanes.

Ornithopters as a hobby



The Dragonfly is a toy made by Wow-Wee.

Hobbyists can build and fly their own ornithopters. These range from light-weight models powered by rubber band, to larger models with radio control.

The rubber-band-powered model can be fairly simple in design and construction. Hobbyists compete for the longest flight times with these models. An introductory model can be fairly simple in design and construction, but the advanced competition designs are extremely delicate and challenging to build. Roy White holds the United States national record for indoor rubber-powered, with his flight time of 21 minutes, 44 seconds.

Commercial free-flight rubber-band powered toy ornithopters have long been available. The first of these was sold under the name Tim Bird in Paris in 1879. Later models were also sold as Tim Bird (made by G de Ruymbeke, France, since 1969).

Commercial radio controlled designs stem from Percival Spencer's engine-powered Seagulls, developed circa 1958, and Sean Kinkade's work in the late 1990s to present day. The wings are usually driven by an electric motor. Many hobbyists enjoy experimenting with their own new wing designs and mechanisms. The opportunity to interact with real birds in their own domain also adds great enjoyment to this hobby. Birds are often curious and will follow or investigate the model while it is flying. In a few

cases, RC birds have been attacked by birds of prey, crows, and even cats. More recent cheaper models such as the Dragonfly from WowWee have extended the market from dedicated hobbyists to the general toy market,

Some helpful resources for hobbyists include The Ornithopter Design Manual, book written by Nathan Chronister, and The Ornithopter Zone web site, which includes a large amount of information about building and flying these models.

Aerodynamics

As demonstrated by birds, flapping wings offer potential advantages in maneuverability and energy savings compared with fixed-wing aircraft, as well as potentially vertical take-off and landing. It has been suggested that these advantages are greatest at small sizes and low flying speeds.

Unlike airplanes and helicopters, the driving airfoils of the ornithopter have a flapping or oscillating motion, instead of rotary. As with helicopters, the wings usually have a combined function of providing both lift and thrust. Theoretically, the flapping wing can be set to zero angle of attack on the upstroke, so it passes easily through the air. Since typically the flapping airfoils produce both lift and thrust, drag-inducing structures are minimized. These two advantages potentially allow a high degree of efficiency.

In propeller- or jet-driven aircraft, the propeller creates a relatively narrow stream of relatively fast moving air. The energy carried by the air is lost. The same amount of force can be produced by accelerating a larger mass of air to a smaller velocity, for example by using a larger propeller or adding a bypass fan to a jet engine. Use of flapping wings offers even larger displaced air mass, moved at lower velocity, thus improving efficiency.

Wing Design

Birds inspired Leonardo da Vinci when he designed his ornithopter in 1490. Leonardo da Vinci was interested in flying during 1488–1514. He never saw his dream of flight take place because his ornithopter was too heavy and required too much energy to produce lift or thrust. In 1929, the human-powered ornithopter constructed by Alexander Lippisch was towed into the air and glided around. In 1959, in England, another ornithopter was towed into the air and demonstrated the ornithopter being a birdlike machine. By the 1960s, there were powered unmanned ornithopter flights of various sizes demonstrating how ornithopters flew. In 1991 Harris and DeLaurier flew the first successful engine-powered remotely piloted ornithopter in Toronto, Canada. By 1999, there was an ornithopter design that was designed to take off from a level pavement.

Lift is the force that uses Bernoulli's principle to keep things in the air and weight is the force that pulls things towards the ground. Thrust is the force that moves things through the air while Drag is the force of flight that is an aerodynamic force that reduces speed.

In order to create an effective ornithopter, it had to be able to flap its wings to generate enough power to get off the ground and travel through the air. Efficient flapping of the wing is characterized by pitching angles, lagging plunging displacements by approximately 90 degrees. Flapping wings increase drag and are not as efficient as propeller-powered aircraft. To increase efficiency of the ornithopter, more power is required on the down stroke than on the upstroke. If the wing on the ornithopter was not flexible and flapped at the same angle while moving up and down, it would act like a huge board moving in two dimensions, not producing lift or thrust. The flexibility and move-ability of the wing let it twist and bend to the reactions of the ornithopter while in flight.

The interest in developing a successful powered ornithopter similar to birds and bats, was one many sought after. In order to get around the problem of not having enough energy for sustained flight, the ornithopter would be required to produce enough lift and thrust to travel through the air. Alphonse Pénaud introduced the idea of a powered ornithopter in 1874. His design had limited power and was uncontrollable causing it to be transformed into a toy for children.

The wing design is designed with the spar as far forward of the airfoil but still having acceptable dimensions of strength. Engineers and researchers have experimented with wings that require carbon fiber, plywood, fabric, ribs, and the trailing edge to be stiff, strong, and for the mass to be as low as possible. Any mass located to the aft or empennage, reduce the wings performance and hinder the design of the ornithopter. In order to calculate the performance of the ornithopter, the wings lift is determined by the lift of the wing versus weight, drag and thrust. A smooth aerodynamic surface with a double-surface airfoil is more efficient then a single-surface airfoil to produce more lift.

A variation of ornithopters has the wings and flapping surfaces towards the empennage to increase stabilizing forces and thrust. With different designs, ornithopters do not act like birds or bats in flight. Typically birds and bats have thin and cambered wings to produce lift and thrust. Ornithopters with thinner wings have a limited angle of attack but provide optimum minimum-drag performance in a single value of lift coefficient.

Although Hummingbirds fly with fully extended wings, an ornithopter would not be able to effectively fly that way. If an ornithopter wing were to fully extend and twist and flap in small movements it would cause a stall but if it were to twist and flap in very large motions, then it would act like a windmill causing an inefficient flying situation.

A team of engineers and researchers called "Fullwing" has created an ornithopter that has an average lift of over 8 pounds, an average thrust of 0.88 pounds, and has a propulsive efficiency of 54%. The wings were tested in a low speed wind tunnel measuring the aerodynamic performance. Discovering that the higher the frequency of the wing beat, the higher the average thrust of the ornithopter.

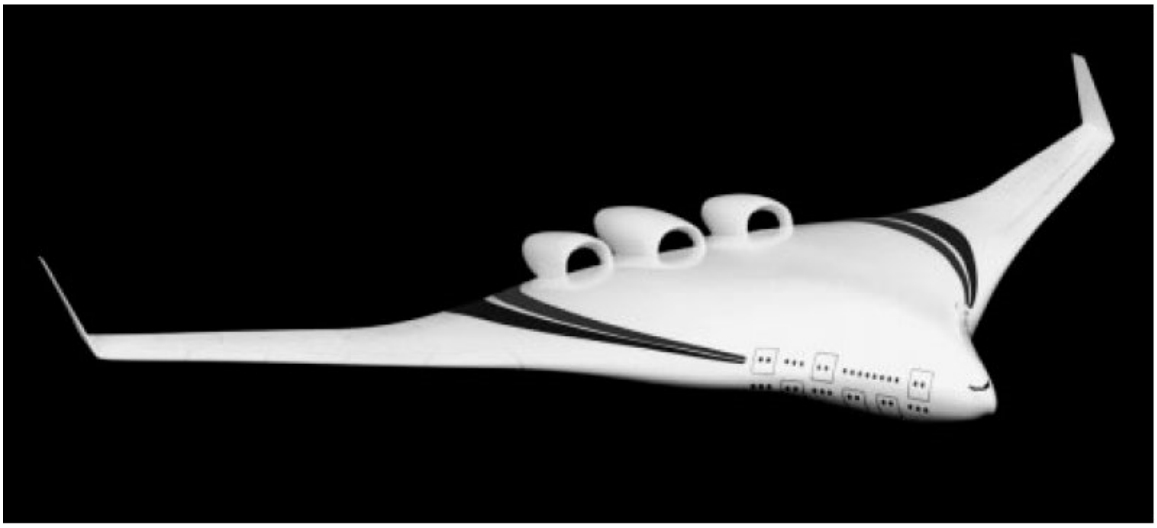
It is unclear what the ornithopters future would be. With the development of Airplanes, Helicopters, VTOL, UAV, and other aircraft, it is unclear where the ornithopter will fit

into society. Canada is currently working with ornithopters to produce more effective flying machines. Although the idea of the ornithopter is not new, there is not little understanding behind the idea.

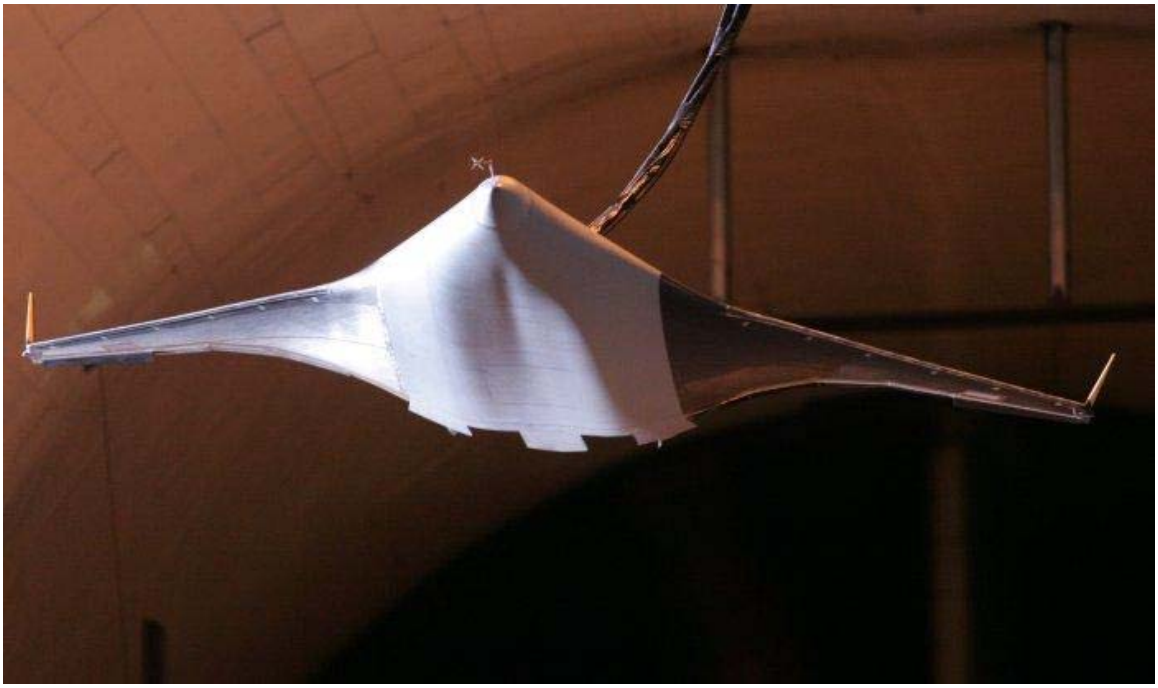
Chapter 9

Blended Wing Body and Coleopter

Blended wing body



Computer-generated model of the Boeing X-48.



NASA's prototype of a Blended Wing aircraft

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

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

History

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

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

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

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

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

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

Potential advantages

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

Coleopter

VXT-8 mockup on display at the Hiller Aviation Museum

A **coleopter** is a type of Vertical Take-Off and Landing aircraft design that uses a ducted fan as the primary fuselage of the entire aircraft. Generally they appear to be a large barrel-like extension at the rear, with a small cockpit area suspended above it. Like most ducted fan designs, coleopters are generally arranged to take off and land on its tail. The term is an anglicisation of the French coléoptère (beetle) after the first actual implementation of this design, the SNECMA Coléoptère of the mid 1950s.

The first design of an aircraft clearly using the coleopter concept was developed during World War II. From 1944 on the Luftwaffe was suffering from almost continual daytime attacks on its airfields, and was finding it almost impossible to conduct large scale operations. Their preferred solution was to introduce some sort of VTOL interceptor that could be launched from any open location, and there were many proposals for such a system. Heinkel conducted a series of design studies as part of their Wespe and Lerche programs. The Wespe intended to use a Benz 2,000 hp turboprop engine, but these were

not forthcoming and the Lerch used two Daimler-Benz DB 605 piston engines instead. Nothing ever came of either design.

In the immediate post-war era, most VTOL research centered on the helicopter. However, as the limitations of the simple rotary wing became clear, teams started looking for other solutions and many turned to using jet engines directly for vertical thrust. SNECMA developed a series of such systems as part of their Atar Volant series during the 1950s. To further improve the design, SNECMA had Nord Aviation built an annular wing and adapted it to the last of the Volant series to produce the C.450 Coléoptère. The Coléoptère first flew on 6 May 1959, but crashed on 25 July and no replacement was built. Even in this limited testing period, the design showed several serious problems related to the high angular momentum of the engine, which made control tricky.

In the US, Hiller Helicopters had been working on a number of ducted fan flying platforms originally designed by Charles Zimmerman. After some early successes, the Army demanded a series of changes that continued to increase the size and weight of the platform, which introduced new stability problems. These generally required more size and power to correct, and no satisfactory design came from these efforts. Instead, Hiller approached the Navy with the idea of building a full coleopter design. This emerged as the Hiller VXT-8 which was significantly similar to the SNECMA design, although it used a propeller instead of a jet engine. However, the introduction of turbine-powered helicopters like the UH-1 Huey so significantly improved their performance over piston-powered designs that the Navy lost interest in the VXT-8 in spite of even better estimated performance. Only a mock-up was completed.

Convair selected the coleopter layout for their Model 49 proposal, entered into the Advanced Aerial Fire Support System (AAFSS). AAFSS asked for a new high-speed helicopter design for the attack and escort roles, and gathered an impressive array of compound helicopters, dual-rotor designs and similar advances on conventional designs, but nothing was as unconventional as the Model 49. The Army "went conventional" however, and selected the AH-56 Cheyenne and Sikorsky S-66 for further development.

Chapter 10

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.

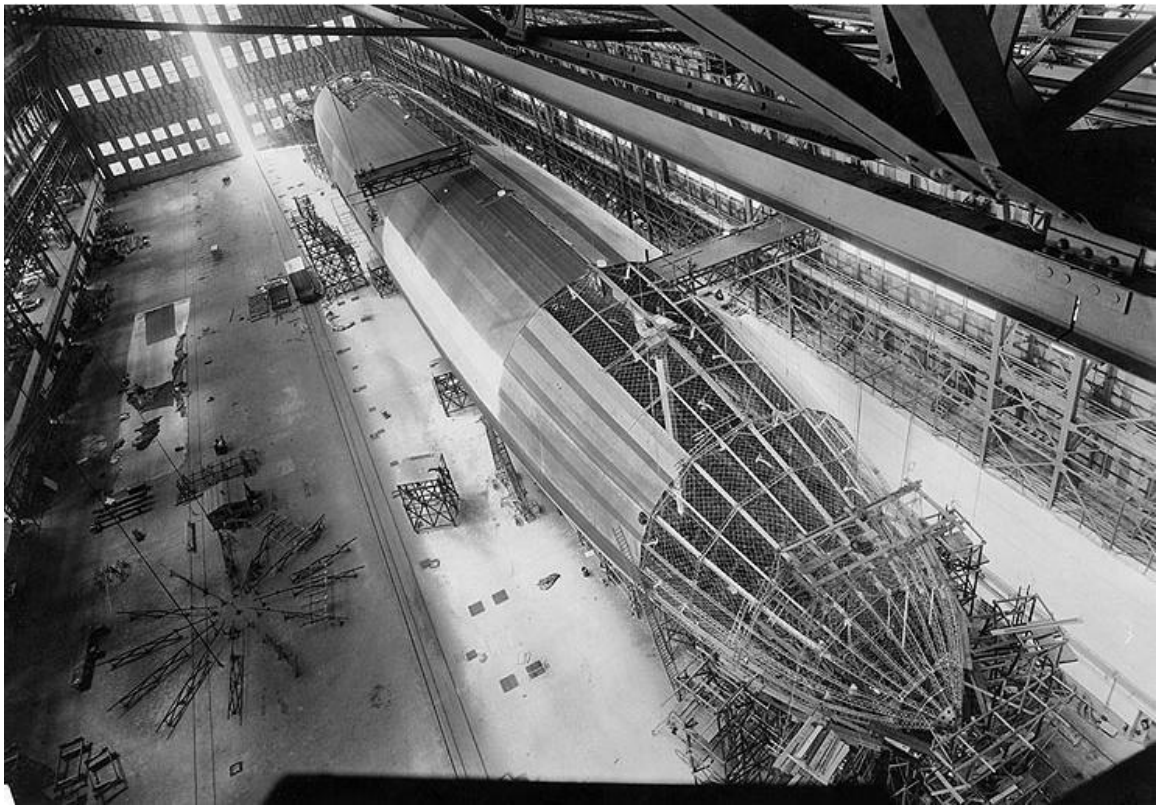
Skepticism

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 11

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 12

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

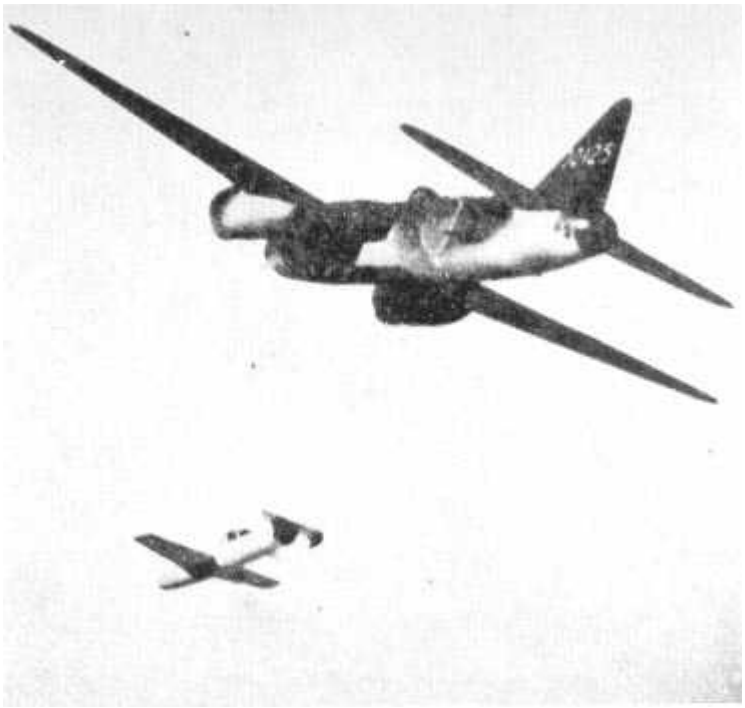
Several plans were drawn up to outfit Zeppelin-type dirigible airships to launch and recover fighters. These are also the typical airborne aircraft carriers found in fiction. Working prototypes include:

- 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

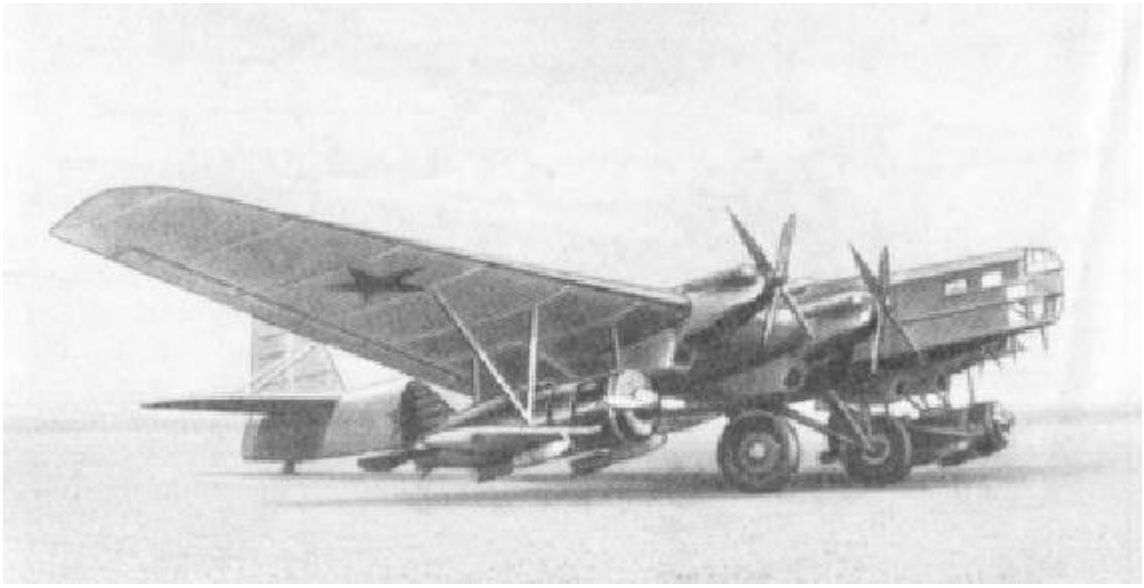


A Japanese Mitsubishi G4M launching the Ohka

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

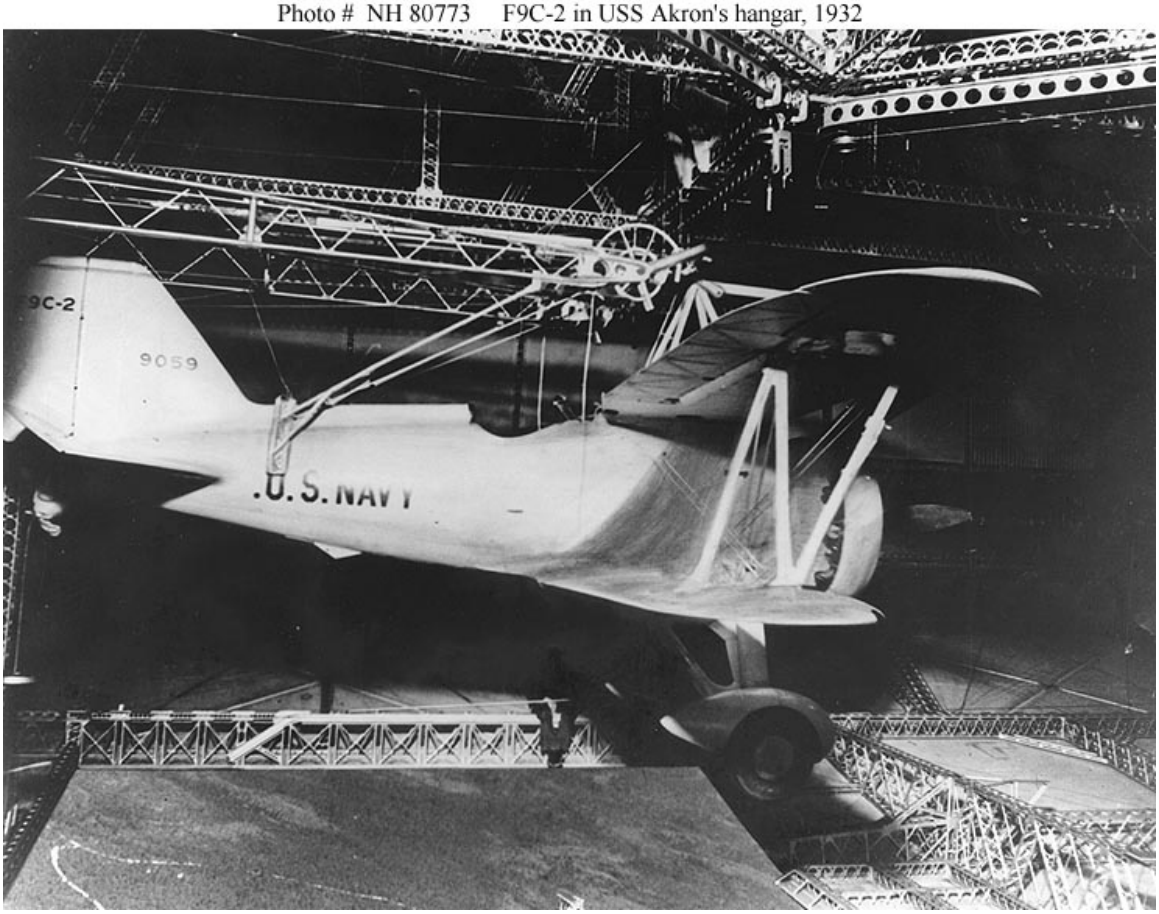
A few specific aircraft have been built or modified to transport other aircraft; the most famous of these, a pair of modified Boeing 747s known as the Shuttle Carrier Aircraft (SCA) belonging to the United State's National Aeronautics and Space Administration (NASA), and are now used only to transport 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

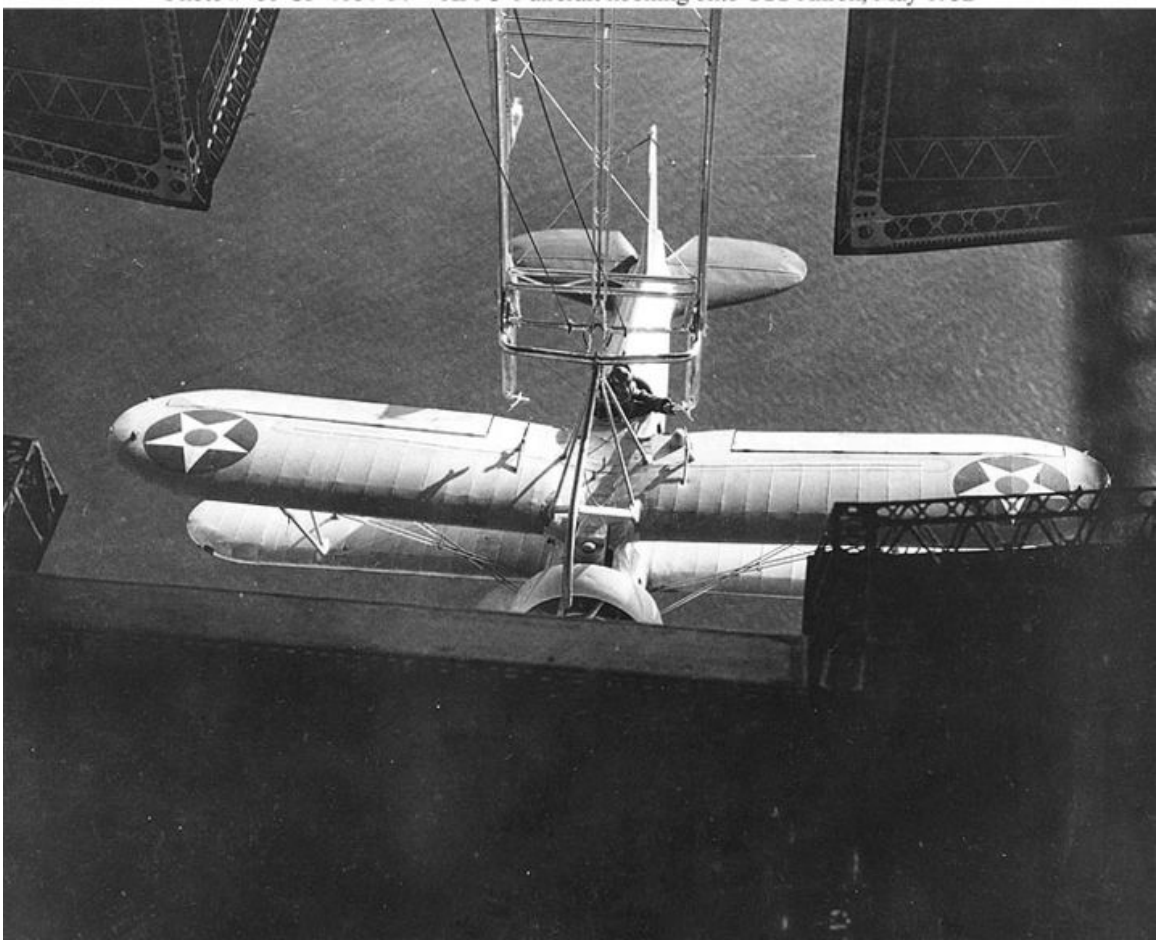
The Akron in flight, November 1931

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

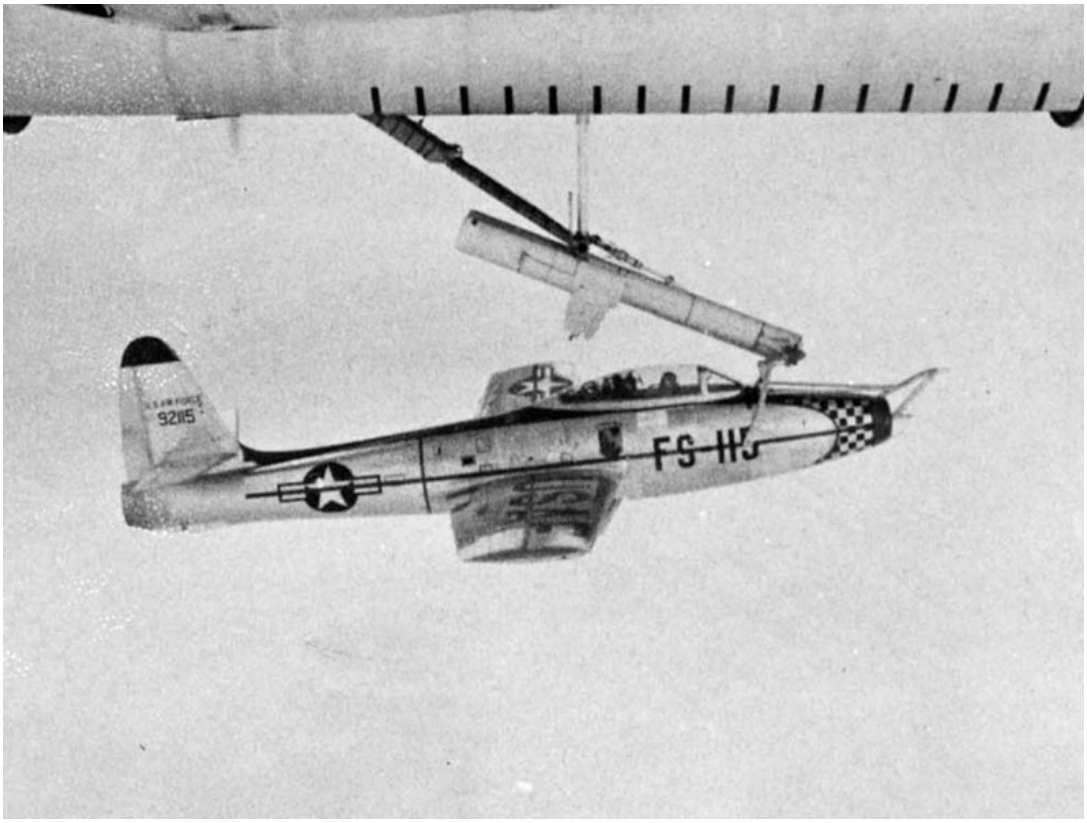


F9C Sparrowhawk inside Akron's hangar

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 13

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 14

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.

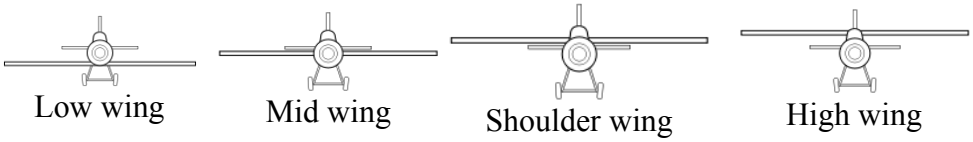
Some variants may be duplicated under more than one heading, due to their complex nature. This is particularly so for variable geometry and combined (closed) wing types.

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.

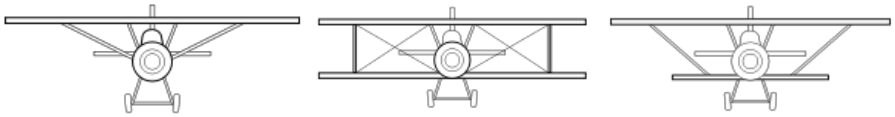
- **Monoplane** - one wing. Most aeroplanes have been monoplanes since before the Second World War. The wing may be mounted at various heights relative to the fuselage:
  - **Low wing** - mounted on the lower fuselage.
  - **Mid wing** - mounted approximately half way up the fuselage.
  - **High wing**-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

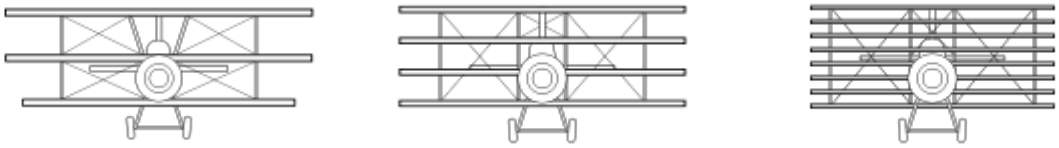


Parasol wing | Biplane | Sesquiplane

- **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.

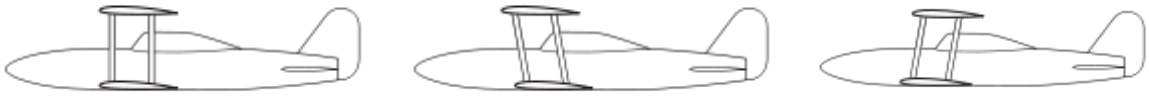
- **Quadruplane** - four planes stacked one above another. A small number of the Armstrong Whitworth F.K.10 were built in the First World War but it never saw operational military service.

- **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

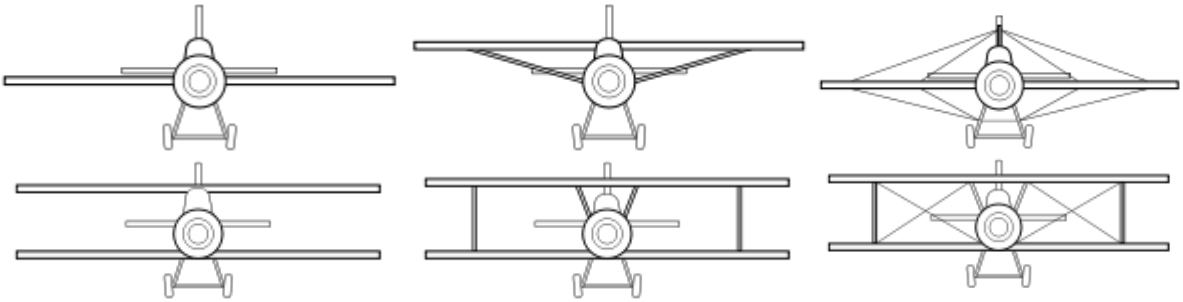
A **Tandem wing** design has two similar-sized wings, one behind the other.

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.

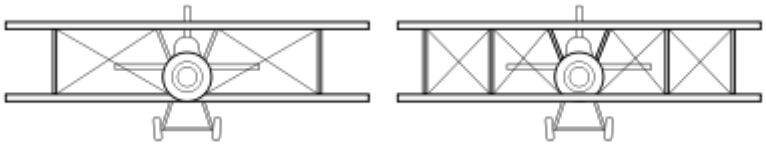
The types are:

- **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.



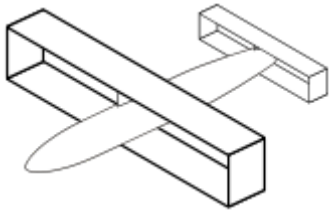
Cantilever | Strut braced | Wire braced

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.

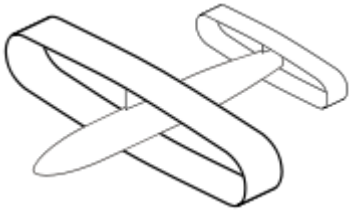


Single-bay biplane Two-bay biplane

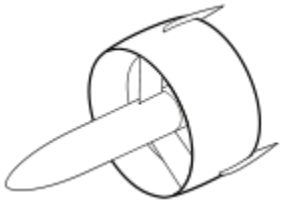
- **Combined** or **closed wing** - two wings are joined structurally at or near the tips in some way. This stiffens the structure, and can reduce aerodynamic losses at the tips. Variants include:
  - **Box wing** - upper and lower planes are joined by a vertical fin between their tips. Some Dunne biplanes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



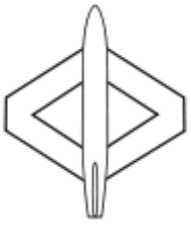
Box wing

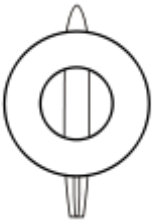


Annular box wing



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.

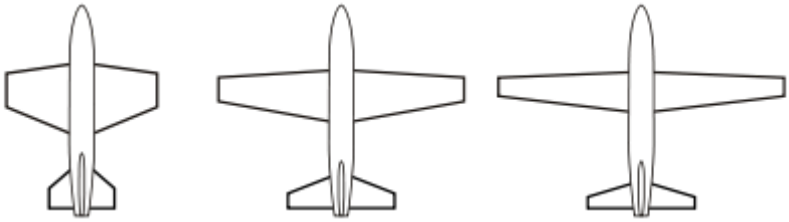
Aspect ratio

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:

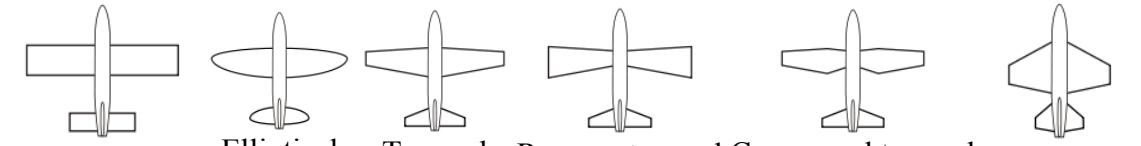
- **Swing-wing** - also called "variable sweep wing". The left and right hand wings vary their sweep together, usually backwards. Seen in a few types of combat aircraft, the first being the General Dynamics F-111. Another is the Grumman F-14.
- **Oblique wing** - a single full-span wing pivots about 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

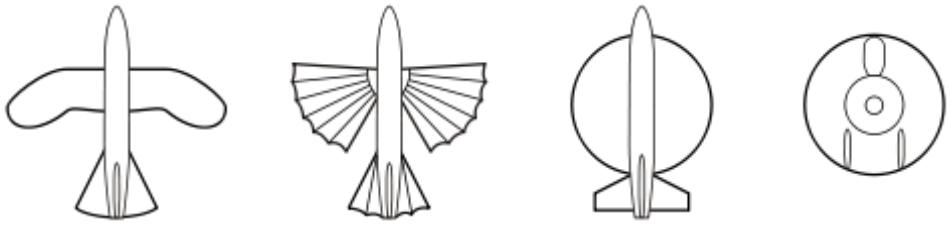
The wing chord may be varied along the span of the wing, for both structural and aerodynamic reasons.

- **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.

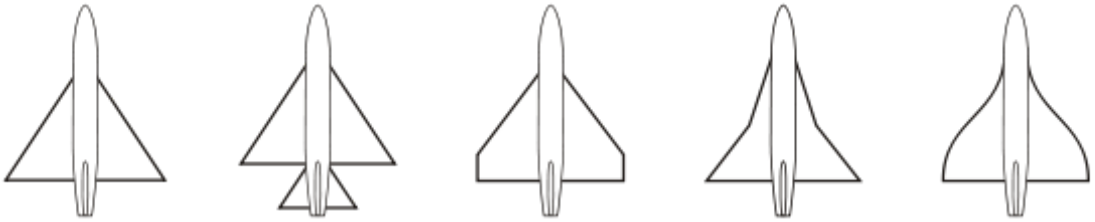


- **Bird like** - a curved shape appearing similar to a bird's outstretched wing. Popular during the pioneer years, and achieved some success on the Etrich Taube.
- **Bat like** - a form with radial ribs which was used for some early designs, especially if the wings were foldable. The Whitehead No. 21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



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

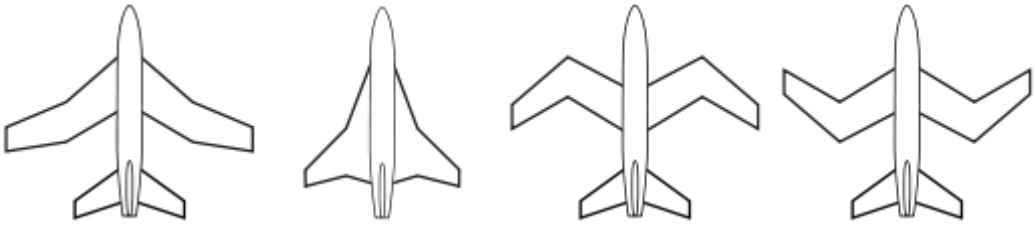
- **Tailed delta** - adds a conventional tailplane, to improve handling. Popular on Soviet types such as the Mikoyan-Gurevich MiG-21.
- **Cropped delta** - tip is cut off. This helps avoid tip drag at high angles of attack. At the extreme, merges into the "tapered swept" configuration.
- **Compound delta** or **double delta** - inner section has a (usually) steeper leading edge sweep e.g. Saab Draken. This improves the lift at high angles of attack and delays or prevents stalling. Seen in tailless form on the Tupolev Tu-144. The HAL Tejas has an inner section of reduced sweep.
- **Ogival delta** - a smoothly blended "wineglass" double-curve encompassing the leading edges and tip of a cropped compound delta. Seen in tailless form on the Concorde supersonic transports.



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.

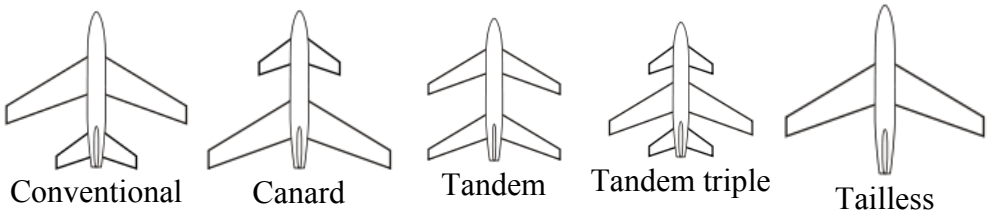


Crescent Cranked arrow M-wing W-wing

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.

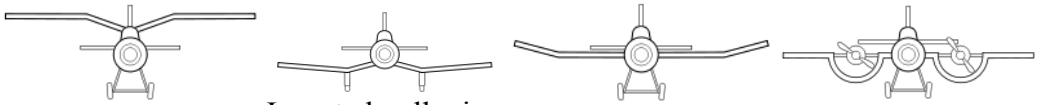
- **Dihedral** - the tips are higher than the root as on the Boeing 737, giving a shallow 'V' shape when seen from the front. Adds lateral stability.
- **Anhedral** - the tips are lower than the root, as on the Ilyushin Il-76; the opposite of dihedral. Used to reduce stability where some other feature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

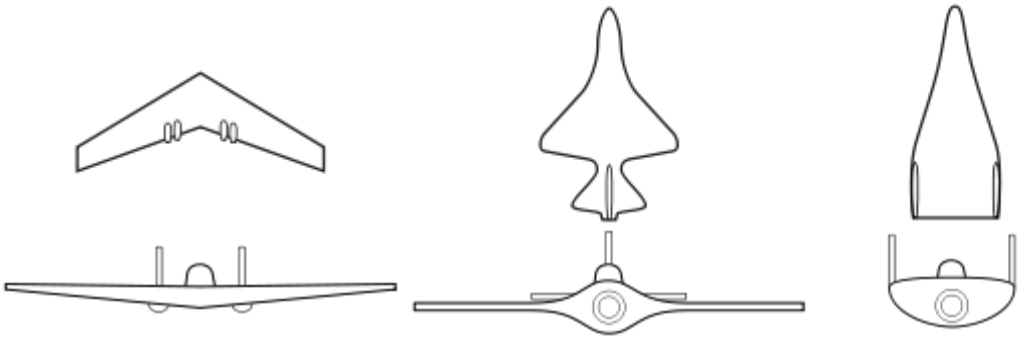
Wings vs. bodies

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

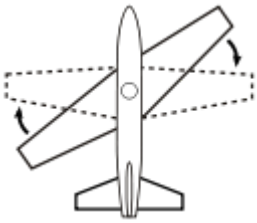
A **variable geometry** aircraft is able to change its physical configuration during flight.

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

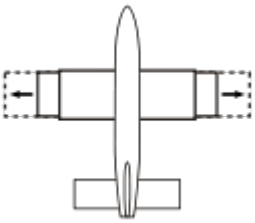
Variable planform

- **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.

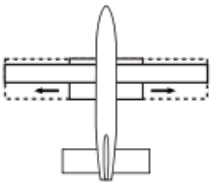
Variable sweep (swing-wing)



Oblique wing

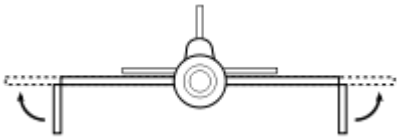


Telescoping wing



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).



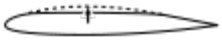
Folding wing

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

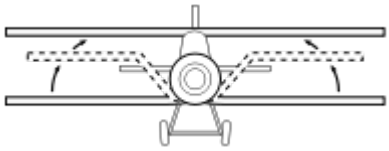
Variable camber aerofoil



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 15

Lifting Body

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

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

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

History

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

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

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

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

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

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

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

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

Aerospace applications

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

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

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

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

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

Body lift

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

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

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

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

Lifting body pilots and flights

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

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

Chapter 16

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 17

Conventional Landing Gear

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

The Piper Super Cub is a popular taildragger aircraft

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 18

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.