Airship

Technology and Configurations

Anne Lamontagne

Jazmyn Navarrete

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Chapter 1

Propeller

Rotating the Hamilton Standard 54H60 propeller on a US Navy EP-3E Orion's number four engine as part of pre-flight checks

A **propeller** is a type of fan that transmits power by converting rotational motion into thrust. A pressure difference is produced between the forward and rear surfaces of the airfoil-shaped blade, and air or water is accelerated behind the blade. Propeller dynamics can be modeled by both Bernoulli's principle and Newton's third law. A propeller is often colloquially known as **screw** both in aviation and maritime.

History

Ship propeller from 1843. Designed by C F Wahlgren based on one of John Ericsson propellers. It was fitted to the steam ship s/s Flygfisken built at the Motala dockyard.

The principle employed in using a screw propeller is used in sculling. It is part of the skill of propelling a Venetian gondola but was used in a less refined way in other parts of Europe and probably elsewhere. For example, propelling a canoe with a single paddle using a "j-stroke" involves a related but not identical technique. In China, sculling, called "lu", was also used by the 3rd century AD.

In sculling, a single blade is moved through an arc, from side to side taking care to keep presenting the blade to the water at the effective angle. The innovation introduced with

the screw propeller was the extension of that arc through more than 360° by attaching the blade to a rotating shaft. Propellers can have a single blade, but in practice there are nearly always more than one so as to balance the forces involved.

The origin of the actual screw propeller starts with Archimedes, who used a screw to lift water for irrigation and bailing boats, so famously that it became known as Archimedes' screw. It was probably an application of spiral movement in space (spirals were a special study of Archimedes) to a hollow segmented water-wheel used for irrigation by Egyptians for centuries. Leonardo da Vinci adopted the principle to drive his theoretical helicopter, sketches of which involved a large canvas screw overhead.

In 1784, J. P. Paucton proposed a gyrocopter-like aircraft using similar screws for both lift and propulsion. At about the same time, James Watt proposed using screws to propel boats, although he did not use them for his steam engines. This was not his own invention, though; Toogood and Hays had patented it a century earlier, and it had become a common use as a means of propelling boats since that time.

By 1827, Czech constructor Josef Ressel had invented a screw propeller which had multiple blades fastened around a conical base; this new method of propulsion allowed steam ships to travel at much greater speeds without using sails thereby making ocean travel faster (first tests with the Austro-Hungarian Navy).

John Patch, a mariner in Yarmouth, Nova Scotia developed a two-bladed, fan-shaped propeller in 1832 and publicly demonstrated it in 1833, propelling a row boat across Yarmouth Harbour and a small coastal schooner at Saint John, New Brunswick, but his patent application in the United States was rejected until 1849 because he was not American citizen His efficient design drew praise in American scientific circles but by this time there were multiple competing versions of the marine propeller.

In 1835, when Francis Pettit Smith discovered a new way of building propellers. Up to that time, propellers were literally screws, of considerable length. But during the testing of a boat propelled by one, the screw snapped off, leaving a fragment shaped much like a modern boat propeller. The boat moved faster with the broken propeller. At about the same time, Frédéric Sauvage and John Ericsson applied for patents on vaguely similar, although less efficient shortened-screw propellers, leading to an apparently permanent controversy as to who the official inventor is among those three men. Ericsson became widely famous when he built the Monitor, an armoured battleship that in 1862 fought the Confederate States' Virginia in an American Civil War sea battle.

The first screw propeller to be powered by a gasoline engine, fitted to a small boat (now known as a powerboat) was installed by Frederick Lanchester, also from Birmingham. This was tested in Oxford. The first 'real-world' use of a propeller was by David Bushnell, who used hand-powered screw propellers to navigate his submarine "Turtle" in 1776.

The superiority of screw against paddles was taken up by navies. Trials with Smith's SS Archimedes, the first steam driven screw, led to the famous tug-of-war competition in 1845 between the screw-driven HMS Rattler and the paddle steamer HMS Alecto; the former pulling the latter backward.

In the second half of the nineteenth century, several theories were developed. The momentum theory or Disk actuator theory—a theory describing a mathematical model of an ideal propeller—was developed by W.J.M. Rankine (1865), Alfred George Greenhill (1888) and R.E. Froude (1889). The propeller is modeled as an infinitely thin disc, inducing a constant velocity along the axis of rotation. This disc creates a flow around the propeller. Under certain mathematical premises of the fluid, there can be extracted a mathematical connection between power, radius of the propeller, torque and induced velocity. Friction is not included.

The blade element theory (BET) is a mathematical process originally designed by William Froude (1878), David W. Taylor (1893) and Stefan Drzewiecki to determine the behavior of propellers. It involves breaking an airfoil down into several small parts then determining the forces on them. These forces are then converted into accelerations, which can be integrated into velocities and positions.
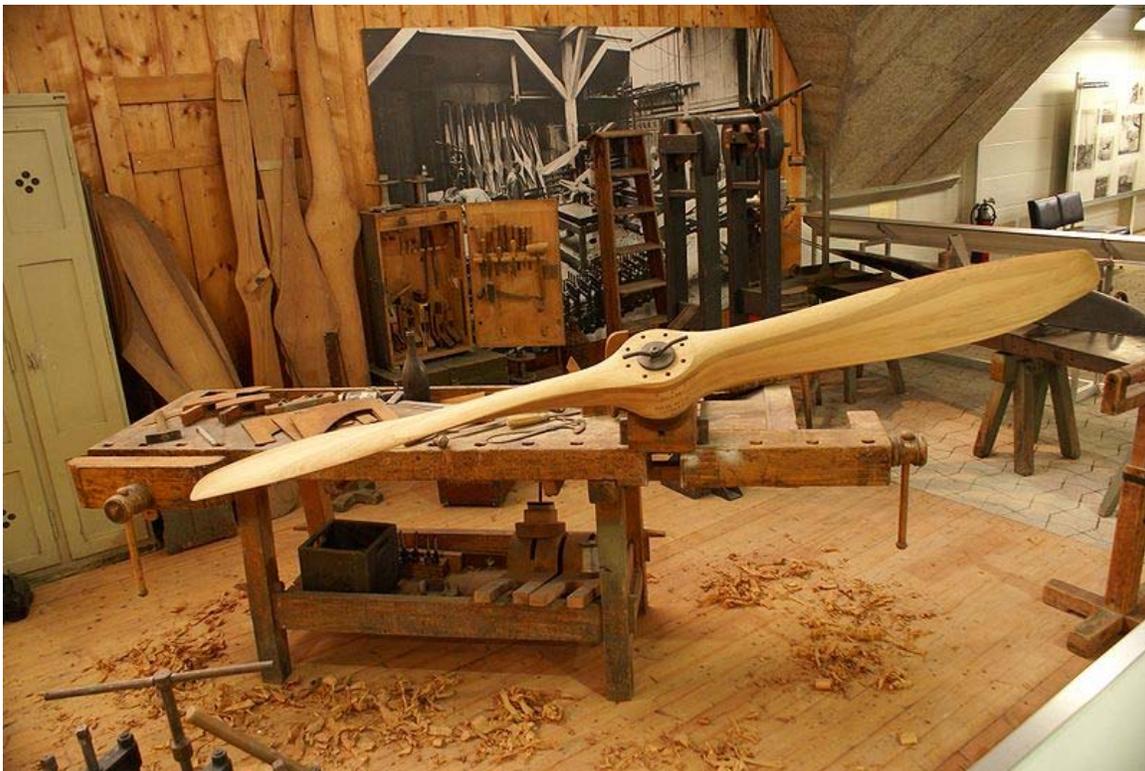
A World War I wooden aircraft propeller on a workbench

The twisted airfoil (aerofoil) shape of modern aircraft propellers was pioneered by the Wright brothers. While both the blade element theory and the momentum theory had their

supporters, the Wright brothers were able to combine both theories. They found that a propeller is essentially the same as a wing and so were able to use data collated from their earlier wind tunnel experiments on wings. They also found that the relative angle of attack from the forward movement of the aircraft was different for all points along the length of the blade, thus it was necessary to introduce a twist along its length. Their original propeller blades are only about 5% less efficient than the modern equivalent, some 100 years later.

Alberto Santos Dumont was another early pioneer, having designed propellers before the Wright Brothers (albeit not as efficient) for his airships. He applied the knowledge he gained from experiences with airships to make a propeller with a steel shaft and aluminium blades for his 14 bis biplane. Some of his designs used a bent aluminium sheet for blades, thus creating an airfoil shape. These are heavily undercambered because of this and combined with the lack of a lengthwise twist made them less efficient than the Wright propellers. Even so, this was perhaps the first use of aluminium in the construction of an airscrew.

Aviation

Aircraft propellers convert rotary motion from piston engines or turboprops to provide propulsive force. They may be fixed or variable pitch. Early aircraft propellers were carved by hand from solid or laminated wood with later propellers being constructed from metal. The most modern propeller designs use high-technology composite materials.

Marine

Marine propeller nomenclature
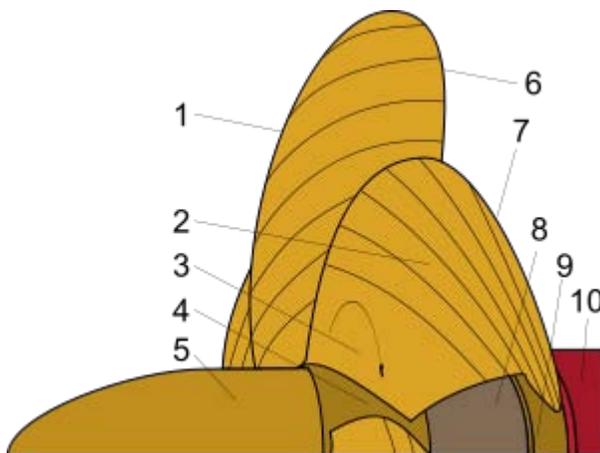
1) Trailing edge	6) Leading edge
2) Face	7) Back
3) Fillet area	8) Propeller shaft
4) Hub or Boss	9) Stern tube bearing
5) Hub or Boss Cap	10) Stern tube

A propeller is the most common propulsor on ships, imparting momentum to a fluid which causes a force to act on the ship.

The ideal efficiency of any size propeller (free-tip) is that of an actuator disc in an ideal fluid. An actual marine propeller is made up of sections of helicoidal surfaces which act together 'screwing' through the water (hence the common reference to marine propellers as "screws"). Three, four, or five blades are most common in marine propellers, although designs which are intended to operate at reduced noise will have more blades. The blades are attached to a boss (hub), which should be as small as the needs of strength allow - with fixed pitch propellers the blades and boss are usually a single casting.

An alternative design is the controllable pitch propeller (CPP, or CRP for controllable-reversible pitch), where the blades are rotated normal to the drive shaft by additional machinery - usually hydraulics - at the hub and control linkages running down the shaft. This allows the drive machinery to operate at a constant speed while the propeller loading is changed to match operating conditions. It also eliminates the need for a reversing gear and allows for more rapid change to thrust, as the revolutions are constant. This type of propeller is most common on ships such as tugs where there can be enormous differences in propeller loading when towing compared to running free, a change which could cause conventional propellers to lock up as insufficient torque is generated. The downsides of a CPP/CRP include: the large hub which decreases the torque required to cause cavitation, the mechanical complexity which limits transmission power and the extra blade shaping requirements forced upon the propeller designer.

For smaller motors there are self-pitching propellers. The blades freely move through an entire circle on an axis at right angles to the shaft. This allows hydrodynamic and centrifugal forces to 'set' the angle the blades reach and so the pitch of the propeller.

A propeller that turns clockwise to produce forward thrust, when viewed from aft, is called right-handed. One that turns anticlockwise is said to be left-handed. Larger vessels often have twin screws to reduce heeling torque, counter-rotating propellers, the starboard screw is usually right-handed and the port left-handed, this is called outward turning. The opposite case is called inward turning. Another possibility is contra-rotating propellers, where two propellers rotate in opposing directions on a single shaft, or on separate shafts on nearly the same axis. One example of the latter is the CRP Azipod by the ABB Group. Contra-rotating propellers offer increased efficiency by capturing the energy lost in the tangential velocities imparted to the fluid by the forward propeller (known as "propeller swirl"). The flow field behind the aft propeller of a contra-rotating set has very little "swirl", and this reduction in energy loss is seen as an increased efficiency of the aft propeller.

Additional designs

An azimuthing propeller is a vertical axis propeller.

The blade outline is defined either by a projection on a plane normal to the propeller shaft (projected outline) or by setting the circumferential chord across the blade at a given radius against radius (developed outline). The outline is usually symmetrical about a given radial line termed the median. If the median is curved back relative to the direction of rotation the propeller is said to have skew back. The skew is expressed in terms of circumferential displacement at the blade tips. If the blade face in profile is not normal to the axis it is termed raked, expressed as a percentage of total diameter.

Each blade's pitch and thickness varies with radius, early blades had a flat face and an arced back (sometimes called a circular back as the arc was part of a circle), modern propeller blades have aerofoil sections. The camber line is the line through the mid-thickness of a single blade. The camber is the maximum difference between the camber line and the chord joining the trailing and leading edges. The camber is expressed as a percentage of the chord.

The radius of maximum thickness is usually forward of the mid-chord point with the blades thinning to a minimum at the tips. The thickness is set by the demands of strength and the ratio of thickness to total diameter is called blade thickness fraction.

The ratio of pitch to diameter is called pitch ratio. Due to the complexities of modern propellers a nominal pitch is given, usually a radius of 70% of the total is used.

Blade area is given as a ratio of the total area of the propeller disc, either as developed blade area ratio or projected blade area ratio.

Transverse axis propellers

Most propellers have their axis of rotation parallel to the fluid flow. There have however been some attempts to power vehicles with the same principles behind vertical axis wind turbines, where the rotation is perpendicular to fluid flow. Most attempts have been unsuccessful. Blades that can vary their angle of attack during rotation have aerodynamics similar to flapping flight. Flapping flight is still poorly understood and almost never seriously used in engineering because of the strong coupling of lift, thrust and control forces.

The fanwing is one of the few types that has actually flown. It takes advantage of the trailing edge of an airfoil to help encourage the circulation necessary for lift.

The Voith-Schneider propeller pictured below is another successful example, operating in water.

History of ship and submarine screw propellers

A propeller from the Lusitania

Propeller on a modern mid-sized merchant vessel

James Watt of Scotland is generally credited with applying the first screw propeller to an engine, an early steam engine, beginning the use of an hydrodynamic screw for propulsion.

Mechanical ship propulsion began with the steam ship. The first successful ship of this type is a matter of debate; candidate inventors of the 18th century include William

Symington, the Marquis de Jouffroy, John Fitch and Robert Fulton, however William Symington's ship the Charlotte Dundas is regarded as the world's "first practical steamboat". Paddlewheels as the main motive source became standard on these early vessels. Robert Fulton had tested, and rejected, the screw propeller.

Sketch of hand-cranked vertical and horizontal screws used in Bushnell's Turtle, 1775

The screw (as opposed to paddlewheels) was introduced in the latter half of the 18th century. David Bushnell's invention of the submarine (Turtle) in 1775 used hand-powered screws for vertical and horizontal propulsion. The Bohemian engineer Josef Ressel designed and patented the first practicable screw propeller in 1827. Francis Pettit Smith tested a similar one in 1836. In 1839, John Ericsson introduced practical screw propulsion into the United States. Mixed paddle and propeller designs were still being used at this time (vide the 1858 SS Great Eastern).

In 1848 the British Admiralty held a tug of war contest between a propeller driven ship, Rattler, and a paddle wheel ship, Alecto. Rattler won, towing Alecto astern at 2.5 knots (4.6 km/h), but it was not until the early 20th century that paddle propelled vessels were entirely superseded. The screw propeller replaced the paddles owing to its greater efficiency, compactness, less complex power transmission system, and reduced susceptibility to damage (especially in battle)

Voith-Schneider propeller

Initial designs owed much to the ordinary screw from which their name derived - early propellers consisted of only two blades and matched in profile the length of a single screw rotation. This design was common, but inventors endlessly experimented with different profiles and greater numbers of blades. The propeller screw design stabilized by the 1880s.

In the early days of steam power for ships, when both paddle wheels and screws were in use, ships were often characterized by their type of propellers, leading to terms like screw steamer or screw sloop.

Propellers are referred to as "lift" devices, while paddles are "drag" devices.

Cavitation damage evident on the propeller of a personal watercraft

Marine propeller cavitation

Cavitation can occur if an attempt is made to transmit too much power through the screw, or if the propeller is operating at a very high speed. Cavitation can occur in many ways on a propeller. The two most common types of propeller cavitation are suction side surface cavitation and tip vortex cavitation.

Suction side surface cavitation forms when the propeller is operating at high rotational speeds or under heavy load (high blade lift coefficient). The pressure on the upstream surface of the blade (the "suction side") can drop below the vapour pressure of the water, resulting in the formation of a pocket of vapour. Under such conditions, the change in pressure between the downstream surface of the blade (the "pressure side") and the suction side is limited, and eventually reduced as the extent of cavitation is increased. When most of the blade surface is covered by cavitation, the pressure difference between the pressure side and suction side of the blade drops considerably, and thrust produced by the propeller drops. This condition is called "thrust breakdown". This effect wastes energy, makes the propeller "noisy" as the vapour bubbles collapse, and most seriously, erodes the screw's surface due to localized shock waves against the blade surface.

Tip vortex cavitation is caused by the extremely low pressures formed at the core of the tip vortex. The tip vortex is caused by fluid wrapping around the tip of the propeller; from the pressure side to the suction side. This video demonstrates tip vortex cavitation well. Tip vortex cavitation typically occurs before suction side surface cavitation and is less damaging to the blade, since this type of cavitation doesn't collapse on the blade, but some distance downstream.

Cavitation can be used as an advantage in design of very high performance propellers, in form of the supercavitating propeller. In this case, the blade section is designed such that the pressure side stays wetted while the suction side is completely covered by cavitation vapor. Because the suction side is covered with vapor instead of water it encounters very low viscous friction, making the supercavitating (SC) propeller comparably efficient at high speed. The shaping of SC blade sections however, make it inefficient at low speeds, when the suction side of the blade is wetted.

A similar, but quite separate issue, is ventilation, which occurs when a propeller operating near the surface draws air into the blades, causing a similar loss of power and shaft vibration, but without the related potential blade surface damage caused by cavitation. Both effects can be mitigated by increasing the submerged depth of the propeller: cavitation is reduced because the hydrostatic pressure increases the margin to the vapor pressure, and ventilation because it is further from surface waves and other air pockets that might be drawn into the slipstream.

14-ton propeller from Voroshilov a Kirov class cruiser on display in Sevastopol

Forces acting on an aerofoil

The force (F) experienced by an aerofoil blade is determined by its area (A), chord (c), velocity (V) and the angle of the aerofoil to the flow, called angle of attack (α), where:

$$\frac{F}{\rho A V^2} = f(R_n, \alpha)$$

The force has two parts - that normal to the direction of flow is lift (L) and that in the direction of flow is drag (D). Both are expressed non-dimensionally as:

$$C_L = \frac{L}{\frac{1}{2}\rho A V^2} \quad \text{and} \quad C_D = \frac{D}{\frac{1}{2}\rho A V^2}$$

Each coefficient is a function of the angle of attack and Reynolds' number. As the angle of attack increases lift rises rapidly from the no lift angle before slowing its increase and then decreasing, with a sharp drop as the stall angle is reached and flow is disrupted. Drag rises slowly at first and as the rate of increase in lift falls and the angle of attack increases drag increases more sharply.

For a given strength of circulation (τ), Lift = L = ρVτ. The effect of the flow over and the circulation around the aerofoil is to reduce the velocity over the face and increase it over the back of the blade. If the reduction in pressure is too much in relation to the ambient pressure of the fluid, cavitation occurs, bubbles form in the low pressure area and are moved towards the blade's trailing edge where they collapse as the pressure increases, this reduces propeller efficiency and increases noise. The forces generated by the bubble collapse can cause permanent damage to the surfaces of the blade.

Propeller thrust

Single blade

Taking an arbitrary radial section of a blade at r, if revolutions are N then the rotational velocity is $2\pi N r$. If the blade was a complete screw it would advance through a solid at the rate of NP, where P is the pitch of the blade. In water the advance speed is rather lower, V_a, the difference, or slip ratio, is:

$$\text{Slip} = \frac{NP - V_a}{NP} = 1 - \frac{J}{p}$$

where $J = \frac{V_a}{ND}$ is the advance coefficient, and $p = \frac{P}{D}$ is the pitch ratio.

The forces of lift and drag on the blade, dA, where force normal to the surface is dL:

$$dL = \frac{1}{2}\rho V_1^2 C_L dA = \frac{1}{2}\rho C_L[V_a^2(1+a)^2 + 4\pi^2 r^2(1-a')^2]bdr$$

where:

$$V_1^2 = V_a^2(1+a)^2 + 4\pi^2 r^2(1-a')^2$$

$$dD = \frac{1}{2}\rho V_1^2 C_D dA = \frac{1}{2}\rho C_D[V_a^2(1+a)^2 + 4\pi^2 r^2(1-a')^2]bdr$$

These forces contribute to thrust, T, on the blade:

$$dT = dL\cos\varphi - dD\sin\varphi = dL(\cos\varphi - \frac{dD}{dL}\sin\varphi)$$

where:

$$tan\beta = \frac{dD}{dL} = \frac{C_D}{C_L}$$

$$= \frac{1}{2}\rho V_1^2 C_L \frac{\cos(\varphi+\beta)}{\cos\beta}bdr$$

As $V_1 = \frac{V_a(1+a)}{\sin\varphi}$,

$$dT = \frac{1}{2}\rho C_L \frac{V_a^2(1+a)^2\cos(\varphi+\beta)}{\sin^2\varphi\cos\beta}bdr$$

From this total thrust can be obtained by integrating this expression along the blade. The transverse force is found in a similar manner:

$$dM = dL\sin\varphi + dD\cos\varphi$$

$$= dL(\sin\varphi + \frac{dD}{dL}\cos\varphi)$$

$$= \frac{1}{2}\rho V_1^2 C_L \frac{\sin(\varphi+\beta)}{\cos\varphi}bdr$$

Substituting for V_1 and multiplying by r, gives torque as:

$$dQ = rdM = \frac{1}{2}\rho C_L \frac{V_a^2(1+a)^2\sin(\varphi+\beta)}{\sin^2\varphi\cos\beta}brdr$$

which can be integrated as before.

The total thrust power of the propeller is proportional to TV_a and the shaft power to $2\pi NQ$. So efficiency is $\frac{TV_a}{2\pi NQ}$. The blade efficiency is in the ratio between thrust and torque:

$$\text{blade element efficiency} = \frac{V_a}{2\pi Nr} \cdot \frac{1}{\tan(\varphi + \beta)}$$

showing that the blade efficiency is determined by its momentum and its qualities in the form of angles φ and β, where β is the ratio of the drag and lift coefficients.

This analysis is simplified and ignores a number of significant factors including interference between the blades and the influence of tip vortices.

Thrust and torque

The thrust, T, and torque, Q, depend on the propeller's diameter, D, revolutions, N, and rate of advance, V_a, together with the character of the fluid in which the propeller is operating and gravity. These factors create the following non-dimensional relationship:

$$T = \rho V^2 D^2 [f_1(\frac{ND}{V_a}), f_2(\frac{v}{V_a D}), f_3(\frac{gD}{V_a^2})]$$

where f_1 is a function of the advance coefficient, f_2 is a function of the Reynolds' number, and f_3 is a function of the Froude number. Both f_2 and f_3 are likely to be small in comparison to f_1 under normal operating conditions, so the expression can be reduced to:

$$T = \rho V_a^2 D^2 \times f_r(\frac{ND}{V_a})$$

For two identical propellers the expression for both will be the same. So with the propellers T_1, T_2, and using the same subscripts to indicate each propeller:

$$\frac{T_1}{T_2} = \frac{\rho_1}{\rho_2} \times \frac{V_{a1}^2}{V_{a2}^2} \times \frac{D_1^2}{D_2^2}$$

For both Froude number and advance coefficient:

$$\frac{T_1}{T_2} = \frac{\rho_1}{\rho_2} \times \frac{D_1^3}{D_2^3} = \frac{\rho_1}{\rho_2}\lambda^3$$

where λ is the ratio of the linear dimensions.

Thrust and velocity, at the same Froude number, give thrust power:

$$\frac{P_{T1}}{P_{T2}} = \frac{\rho_1}{\rho_2} \lambda^{3.5}$$

For torque:

$$Q = \rho V_a^2 D^3 \times f_q \left(\frac{ND}{V_a}\right)$$

...

Actual performance

When a propeller is added to a ship its performance is altered; there is the mechanical losses in the transmission of power; a general increase in total resistance; and the hull also impedes and renders non-uniform the flow through the propeller. The ratio between a propeller's efficiency attached to a ship (P_D) and in open water (P'_D) is termed relative rotative efficiency.

The overall propulsive efficiency (an extension of effective power (P_E)) is developed from the propulsive coefficient (PC), which is derived from the installed shaft power (P_S) modified by the effective power for the hull with appendages (P'_E), the propeller's thrust power (P_T), and the relative rotative efficiency.

P'_E/P_T = hull efficiency = η_H
P_T/P'_D = propeller efficiency = η_O
P'_D/P_D = relative rotative efficiency = η_R
P_D/P_S = shaft transmission efficiency

Producing the following:

$$PC = \left(\frac{\eta_H \cdot \eta_O \cdot \eta_R}{\text{appendage coefficient}}\right) \cdot \text{transmission efficiency}$$

The terms contained within the brackets are commonly grouped as the quasi-propulsive coefficient (QPC, η_D). The QPC is produced from small-scale experiments and is modified with a load factor for full size ships.

Wake is the interaction between the ship and the water with its own velocity relative to the ship. The wake has three parts: the velocity of the water around the hull; the boundary layer between the water dragged by the hull and the surrounding flow; and the waves created by the movement of the ship. The first two parts will reduce the velocity of water into the propeller, the third will either increase or decrease the velocity depending on whether the waves create a crest or trough at the propeller.

Types of marine propellers

Controllable pitch propeller
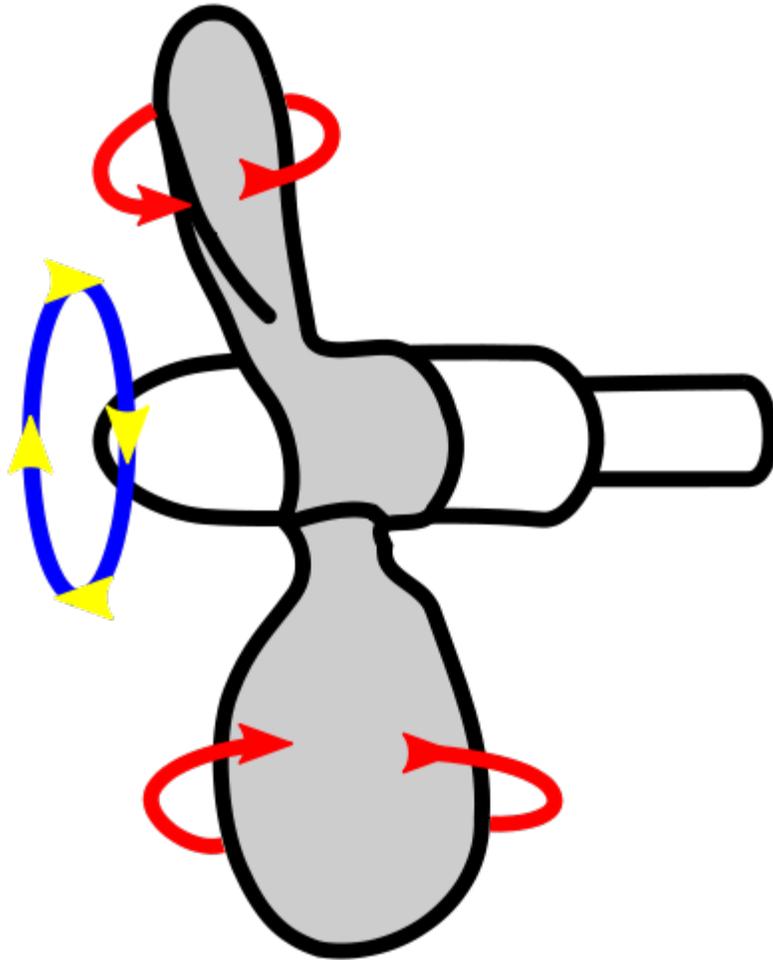
A controllable pitch propeller

At present, one of the newest and best type of propeller is the controllable pitch propeller. This propeller has several advantages with ships. These advantages include: the least drag depending on the speed used, the ability to move the sea vessel backwards, and the ability to use the "vane"-stance, which gives the least water resistance when not using the propeller (e.g. when the sails are used instead).

Skewback propeller

An advanced type of propeller used on German Type 212 submarines is called a **skewback propeller**. As in the scimitar blades used on some aircraft, the blade tips of a skewback propeller are swept back against the direction of rotation. In addition, the blades are tilted rearward along the longitudinal axis, giving the propeller an overall cup-shaped appearance. This design preserves thrust efficiency while reducing cavitation, and thus makes for a quiet, stealthy design.

Modular propeller

A modular propeller provides more control over the boats performance. There is no need to change an entire prop, when there is an opportunity to only change the pitch or the damaged blades. Being able to adjust pitch will allow for boaters to have better performance while in different altitudes, water sports, and/or cruising.

Protection of small engines

A failed rubber bushing in an outboard's propeller

For smaller engines, such as outboards, where the propeller is exposed to the risk of collision with heavy objects, the propeller often includes a device which is designed to fail when over loaded; the device or the whole propeller is sacrificed so that the more expensive transmission and engine are not damaged.

Typically in smaller (less than 10 hp/7.5 kW) and older engines, a narrow shear pin through the drive shaft and propeller hub transmits the power of the engine at normal loads. The pin is designed to shear when the propeller is put under a load that could damage the engine. After the pin is sheared the engine is unable to provide propulsive power to the boat until an undamaged shear pin is fitted. Note that some shear pins used to have shear grooves machined into them. Nowadays the grooves tend to be omitted. The result of this oversight is that the torque required to shear the pin rises as the cutting edges of the propeller bushing and shaft become blunted. Eventually the gears will strip instead.

In larger and more modern engines, a rubber bushing transmits the torque of the drive shaft to the propeller's hub. Under a damaging load the friction of the bushing in the hub is overcome and the rotating propeller slips on the shaft preventing overloading of the engine's components. After such an event the rubber bushing itself may be damaged. If so, it may continue to transmit reduced power at low revolutions but may provide no power, due to reduced friction, at high revolutions. Also the rubber bushing may perish over time leading to its failure under loads below its designed failure load.

Whether a rubber bushing can be replaced or repaired depends upon the propeller; some cannot. Some can but need special equipment to insert the oversized bushing for an interference fit. Others can be replaced easily.

The "special equipment" usually consists of a tapered funnel, some kind of press and rubber lubricant (soap). Often the bushing can be drawn into place with nothing more complex than a couple of nuts, washers and "allscrew" (threaded bar). If one does not have access to a lathe an improvised funnel can be made from steel tube and car body filler! (as the filler is only subject to compressive forces it is able to do a good job) A more serious problem with this type of propeller is a "frozen-on" spline bushing which makes propeller removal impossible. In such cases the propeller has to be heated in order to deliberately destroy the rubber insert. Once the propeller proper is removed, the splined tube can be cut away with a grinder. A new spline bushing is of course required. To prevent the problem recurring the splines can be coated with anti-seize anti-corrosion compound.

In some modern propellers, a hard polymer insert called a drive sleeve replaces the rubber bushing. The splined or other non-circular cross section of the sleeve inserted between the shaft and propeller hub transmits the engine torque to the propeller, rather than friction. The polymer is weaker than the components of the propeller and engine so it fails before they do when the propeller is overloaded. This fails completely under excessive load but can easily be replaced.

Chapter 2

Mooring Mast

A **mooring mast**, or **mooring tower**, is a structure designed to allow for the docking of an airship outside of an airship hangar or similar structure. More specifically, a mooring mast is a mast or tower that contains a fitting on its top that allows for the bow of the airship to attach its mooring line to the structure. When it is not necessary or convenient to put an airship into its hangar (or shed) between flights, airships can be moored on the surface of land or water, in the air to one or more wires, or to a mooring mast. After their development mooring masts became the standard approach to mooring airships as considerable manhandling was avoided.

Mast types

Airship mooring masts can be broadly divided into fixed high masts and fixed or mobile low (or 'stub') masts. In the 1920s and 1930s masts were built in many countries. At least two were mounted on ships. Without doubt the tallest mooring mast ever designed was the spire of the Empire State Building which was originally constructed to serve as a mooring mast, although soon after converted for use as a television tower due to the discovered infeasibility of mooring an airship, for any length of time, to a very tall mast in the middle of an urban area.
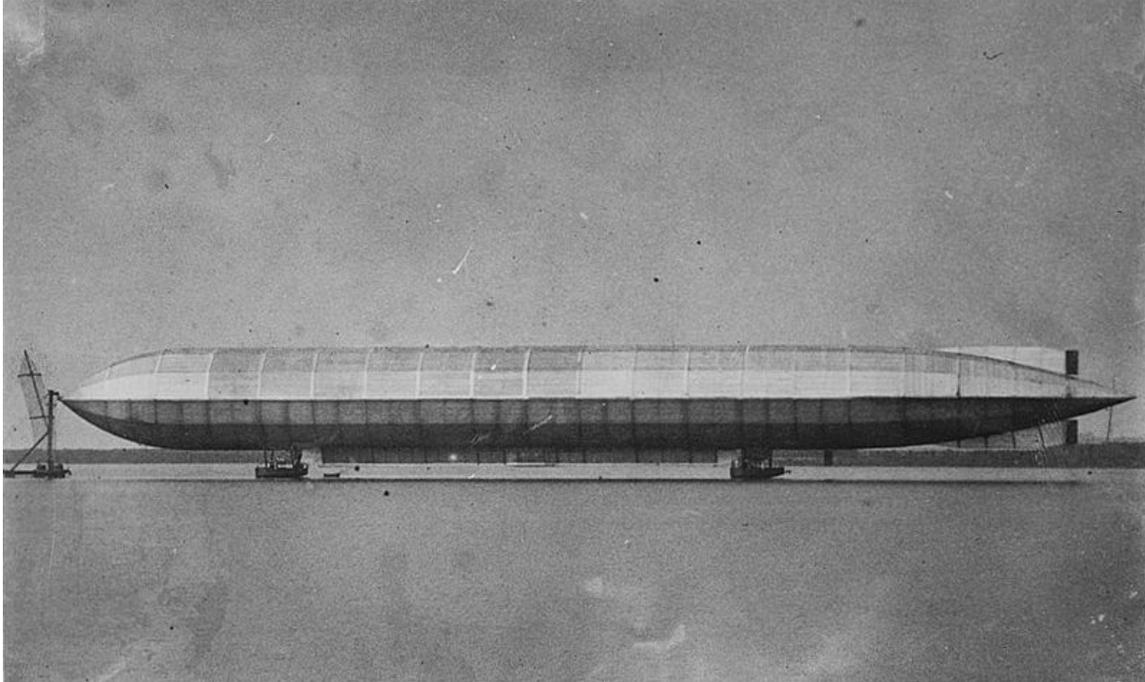
HMA No 1 (Mayfly) – the first airship known to have been moored to a mast

Early developments

Mooring an airship by the nose to the top of a mast or tower of some kind might appear to be an obvious solution, but dirigibles had been flying for some years before the mooring mast made its appearance. The first airship known to have been moored to a mast was HMA (His Majesty's Airship) No.1, named the 'Mayfly', on 22 May 1911. The 38 ft (12 m) mast was mounted on a pontoon, and a windbreak of cross-yards with strips of canvas were attached to it. However, the windbreak caused the ship to yaw badly, and she became more stable when it was removed, withstanding winds gusting up to 43 miles per hour (69 km/h) . Further experiments in mooring blimps to cable-stayed lattice masts were carried out during 1918.

British high mast operations

The British mooring mast was developed more or less to its final form at Pulham and Cardington in 1919-21 to make the landing process easier and more economical of manpower
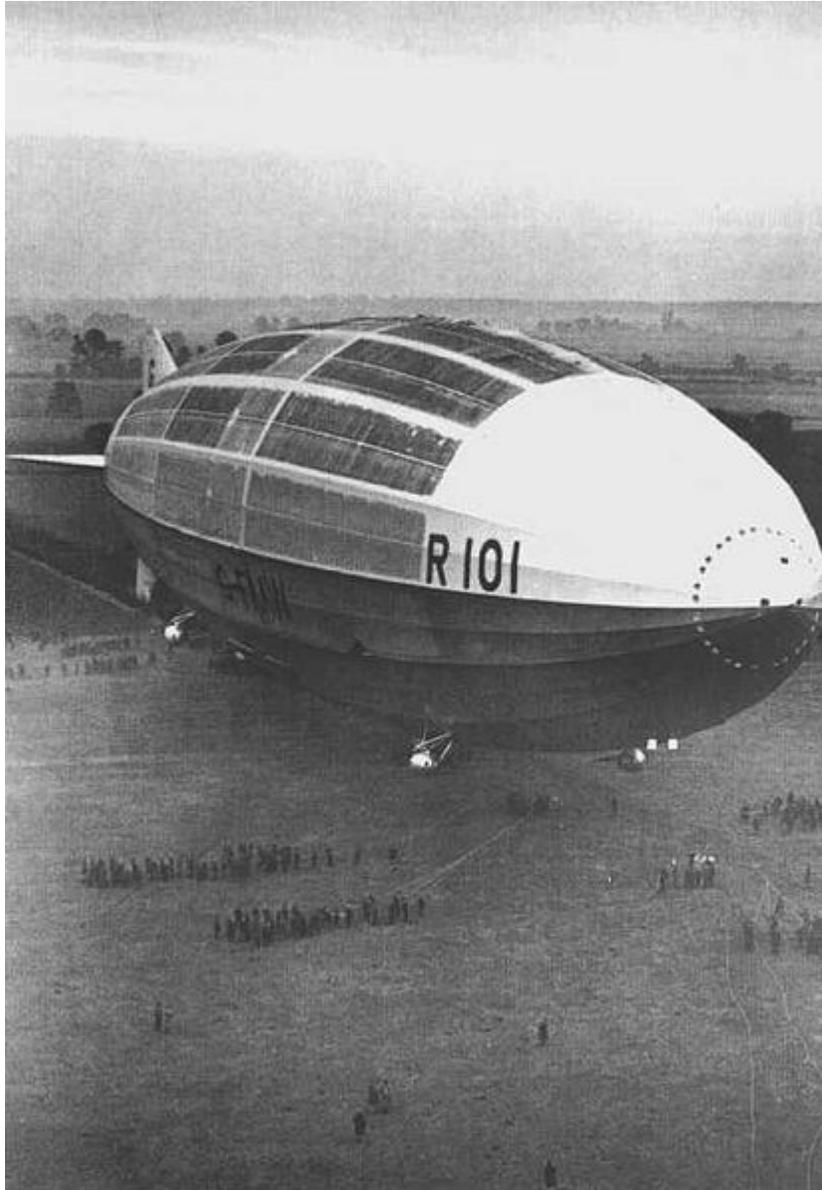
The R101 being handled on the ground, showing the size of the landing party required to manage a large airship. One purpose of a mooring mast was to reduce the number of men needed to manage the landing process.

The following account of the British high mast in its fully developed state at Cardington, and its operation, is abridged from Masefield.

Mooring masts were developed to act as a safe open harbour to which airships could be moored or unmoored in any weather, and at which they could receive (hydrogen or helium) gas, fuel, stores and payload. The Cardington mast, completed in 1926, was an eight sided steel girder structure, 200 feet (61 m) high, tapering from 70 feet (21 m) diameter at ground level to 26 feet 6 inches (8.1 m) at the passenger platform, 170 feet (52 m) from the ground. Above the passenger platform was the 30 feet (9.1 m) of the

conical housing for the mooring gear. A lower platform 142 feet (43 m) above the ground accommodated searchlights and signalling gear in a gallery 4 feet (1.2 m) wide. The top platform, at the height of 170 feet (52 m), from which passengers embarked and disembarked to and from the airships, was 40 feet (12 m) in diameter and encircled by a heavy parapet. The top rail of the parapet formed a track on which a gangway, let down from the airship, ran on wheels to give freedom for the airship to move around the tower as it swung with the wind. An electric passenger lift ran up the centre of the tower, encircled by a stairway to provide foot access. The upper portion of the tower, from the passenger platform upwards, was a circular steel turret surmounted by a truncated cone with its top 23 feet (7.0 m) above the passenger platform. A three-part telescopic arm, mounted on gimbals, projected through an opening at the top, free to swing from the vertical in any direction up to 30 degrees of movement. The top of the arm consisted of a bell-shaped cup mounted to rotate on ball bearings. A cable extended through the bell-mouth which, linked to a cable dropped from airship to be moored, enabled the nose of the airship to be drawn down until a cone on the nose locked home into the cup and so secured the airship to the tower. The telescopic arm was then centred, locked in the vertical position, and made free to rotate on a vertical axis so the airship could swing, nose to tower, in any direction of the wind. In the machinery house at the base of the tower three steam-driven winches operated the hauling gear through drums 5 feet (1.5 m) in diameter to give cable hauling speeds of 50 feet a minute.

While an airship approached the mast slowly against the wind a mooring cable was let out from nose to the ground and linked, by a ground party, to the end of the mooring cable paid out from the mast head. The cable was then slowly wound in with the airship riding about 600 feet (180 m) above the mast and down wind, with one engine running astern to maintain a pull on the cable. At this point, two side wires – or 'yaw guys' – were also connected to cables taken from the nose of the airship to pulley blocks some hundreds of feet apart on the ground and thence to winches at the base of the mast. All three cables were then wound in together, the main pull being taken on the mooring cable while the yaw guys steadied the ship. When all the cable had been wound in an articulated mooring cone on the nose of the airship locked home into the cup on the mast. The mast fitting was made free to rotate as the airship swung with the wind with freedom also for pitch and roll. A gangway, like a drawbridge, which could be drawn up flush with the nose of the airship, was then let down with its free end resting on the parapet of the platform running round the mast. Passengers and crew boarded and disembarked from the shop under cover along this gangway. About twelve men were needed to moor an airship to a mast.
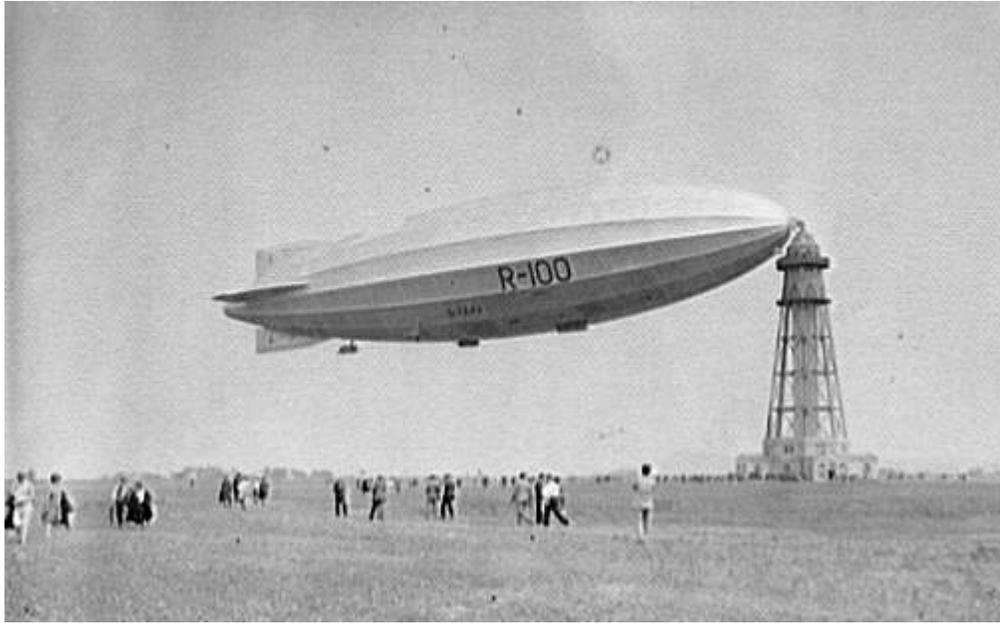
The R100 at the mooring mast in Montreal, Canada, 1930

Four high masts of the Cardington type were built along the proposed British Empire Airship Service routes, at Cardington itself, at Montreal (Canada), Ismailia (Egypt) and Karachi (then India, now in Pakistan). None of these survive. Similar masts were proposed at sites in Australia, Ceylon (now Sri Lanka), Bombay, Keeling Islands, Kenya, Malta, at Ohakea in New Zealand, and in South Africa. The general site specifications can be found at.

German mast techniques

German mooring methods differed significantly from those adopted by the British. To quote Pugsley (1981)

"the Germans, originally for ease of transport and for economy, developed a system using much lower masts. The nose of the ship was tethered as before to the mast head, which was only a little higher than the semi-diameter of the ship's hull. The lower fin at the stern was then fixed to a heavy carriage running on a circular railway track around the mast, and this carriage was powered so as to be able to move around the track to keep the ship head on to the wind. In the most sophisticated form, used by the Hindenburg, the rail system was linked to rails running from the mast straight into the airship shed, and the mast was powered so that the ship could be moved mechanically into the shed, complete with mast and stern carriage".

The following account of landing the German airship Graf Zeppelin is abridged from Dick and Robinson (1985):

Before attempting a landing, contact was made by radio or flag signals with the ground crew to determine the ground temperature and wind conditions. For a normal calm weather landing the ship was trimmed very slightly nose down, as this gave a better gliding angle and the ship almost flew herself down. A smoky fire was started on the ground to show the wind direction. The ship then made a long approach with a rate of fall of 100 feet per minute, and the lines were dropped when she was over the landing flag. When conditions were unusual, as in gusty and bumpy weather, the Graf was weighed off a little light, and the approach had to be fast and preferably long and low. When the airship was over the field the engines had to be reversed for some time to stop her, and this also helped to get the nose down. Yaw lines dropped from the ship's nose were drawn out to Port and Starboard by thirty men each, while twenty more on each side pulled the ship down with spider lines (so called because twenty short lines radiated like the legs of a spider from a block). When the airship reached the ground, fifty men held the control car rails and twenty held those of the after car. With thirty men in reserve, the ground crew totalled two hundred men. The ground crew would then walk the Graf to a short, or 'stub', mast, to which the nose of the airship would be attached. The airship would then rest on the ground with its rear gondola attached to a movable weighted carriage that enabled the airship to swing around the mast with the wind. In some places the stub mast was mounted on rails and could be drawn into the airship hangar, guiding the nose of the ship while the tail was controlled by the carriage attached to the rear gondola. Airships designed for landing on the ground had pneumatic bumper bags or undercarriage wheels under the main and rear gondolas (or tail fin).

Dick states that the Germans never used mooring masts until the Graf Zeppelin entered service in 1928, and never moored to high masts. To some extent this probably reflects the conservatism of the Zeppelin company operations. Long experience in handling airships in all sorts of conditions was valued and innovations or significant changes in practice were unlikely to be adopted unless clear advantages were apparent.

United States

In the US a mix of techniques were applied, and airships moored to both high and stub masts. Large ground crews (or 'landing parties') of up to 340 men were required to manage the large airships Akron and Macon at landing or on the ground, before they could be attached to the stub mast. Being part of a ground crew was not risk-free. In gusty conditions, or if mis-handled, an airship could suddenly rise. If the ground crew did not immediately let go of the handling lines they risked being carried off their feet. In one famous incident captured on movie film in 1932, during the landing of the US airship Akron, three men were carried off their feet in this way, two to fall to their deaths after a short time. The third managed to improve his hold on the handling rope until he could be hauled into the airship.

Ship-mounted mooring masts
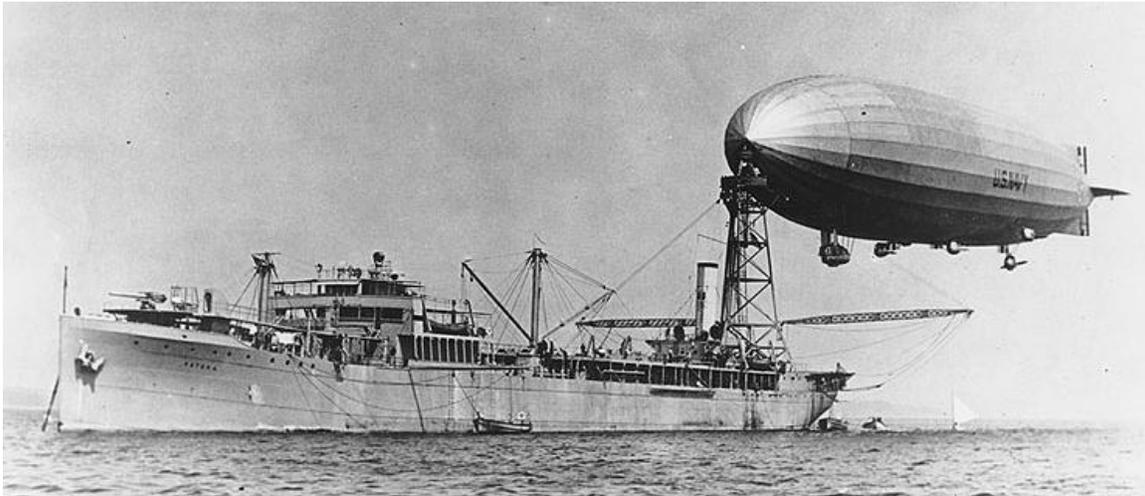
USS Shenandoah moored to the USS Patoka (AO-9)

At least two ships have mounted mooring masts. As the US intended to use large airships for long-range maritime patrol operations experiments were made in mooring airships to a mast mounted on the ship USS Patoka.

Over time the airships USS Shenandoah, Los Angeles, and Akron all moored to the mast mounted at the stern of the ship, and operated using her as a base for resupply, refuelling and gassing.
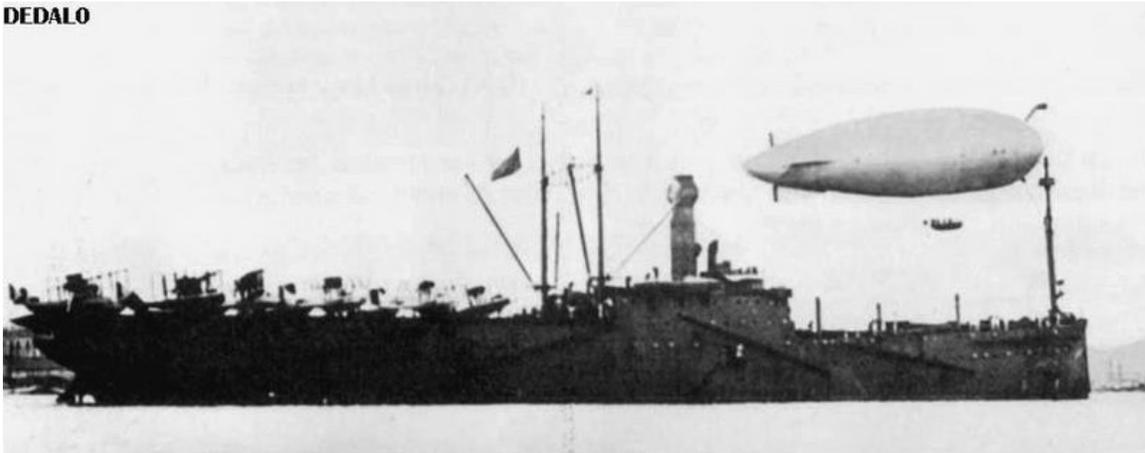
Spanish seaplane carrier Dédalo

The Spanish seaplane carrier Dédalo (1922–1935) carried a mooring mast at the bow to cater for small dirigibles carried on board.

Modern mast operations

Smaller mobile masts have been used for small airships and blimps for a long time. They may be wheel or track-mounted, and can be operated by a small crew. The general operating principle is broadly similar to the larger masts. Modern blimps may operate from mobile masts for months at a time without returning to their hangars.

Gallery

USS Akron approaches mast, circa 1931-1933

USS Shenandoah attached to a mast

USS Los Angeles at a near-vertical position

A stub mast in Recife - the only one preserved in its original form

A modern blimp approaches its mobile mooring mast

Contemporary ship attached to a mast

Chapter 3

Hot Air Balloon

Hot air balloons shaped as bees

Hot air balloon shaped as a turtle

Hot air balloon shaped as a Abbey of Saint Gall

Hot air balloon in flight

The **hot air balloon** is the oldest successful human-carrying flight technology. It is in a class of aircraft known as balloon aircraft. On Nov 21, 1783, in Paris, France, the first untethered manned flight was made by Jean-François Pilâtre de Rozier and François Laurent d'Arlandes in a hot air balloon created on Dec 14, 1782 by the Montgolfier brothers. Hot air balloons that can be propelled through the air rather than just being pushed along by the wind are known as airships or, more specifically, thermal airships.

A hot air balloon consists of a bag called the envelope that is capable of containing heated air. Suspended beneath is a gondola or wicker basket (in some long-distance or high-altitude balloons, a capsule), which carries passengers and (usually) a source of heat, in most cases an open flame. The heated air inside the envelope makes it buoyant since it has a lower density than the relatively cold air outside the envelope. As with all aircraft, hot air balloons cannot fly beyond the atmosphere. Unlike gas balloons, the envelope does not have to be sealed at the bottom since the air near the bottom of the envelope is at the same pressure as the surrounding air. In today's sport balloons the envelope is generally made from nylon fabric and the mouth of the balloon (closest to the burner flame) is made from fire resistant material such as Nomex. Beginning in the mid-1970s, balloon envelopes have been made in all kinds of shapes, such as hot dogs, rocket ships, and the shapes of commercial products, though the traditional shape remains popular for most non-commercial, and many commercial, applications.

History

A Kongming lantern, the oldest type of hot air balloon

Premodern and unmanned balloons
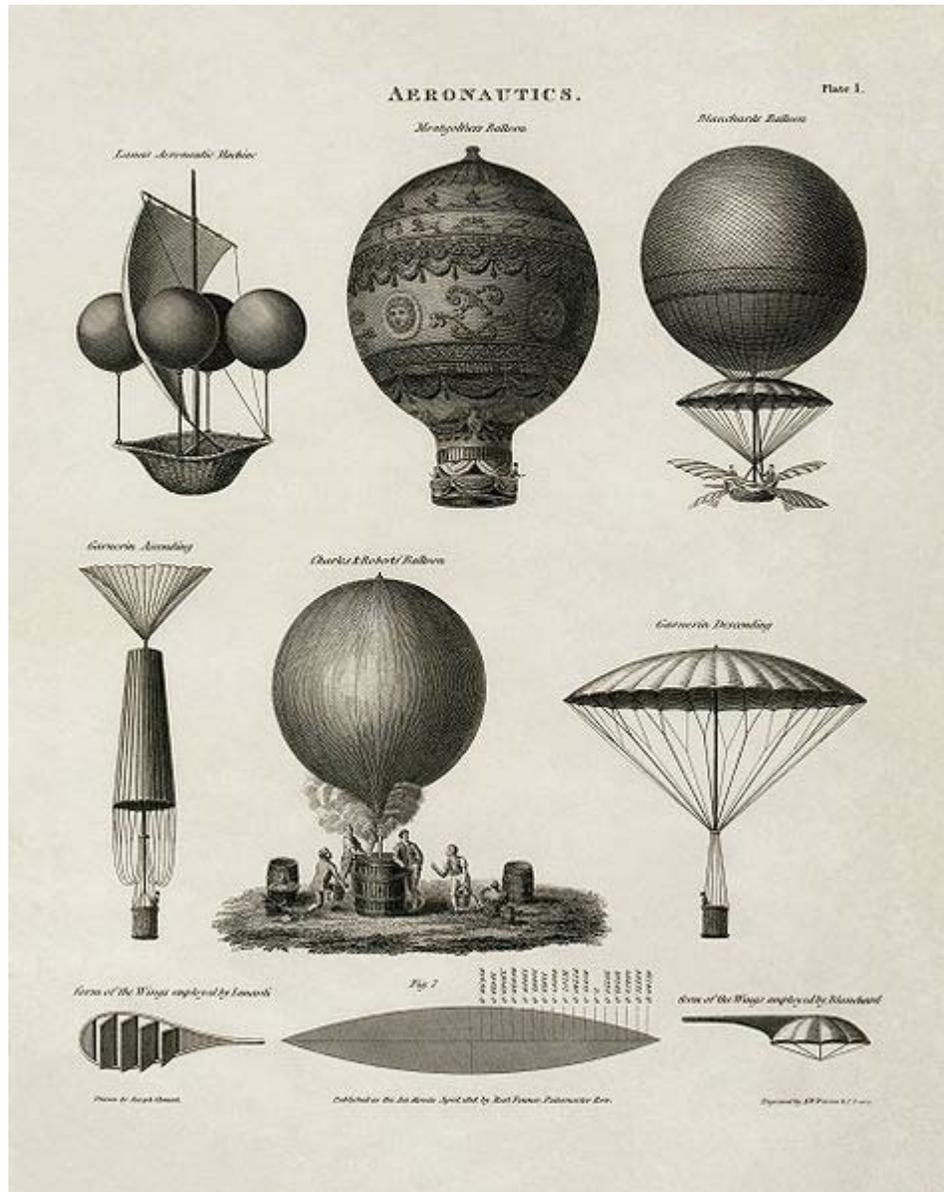
Technical illustration from 1818 showing early balloon designs

Unmanned hot air balloons are popular in Chinese history. Zhuge Liang of the Shu Han kingdom, in the Three Kingdoms era (220–80 AD) used airborne lanterns for military signaling. These lanterns are known as Kongming lanterns (孔明灯). There is also some speculation, from a demonstration led by British modern hot air balloonist Julian Nott in the late 1970s and again in 2003, that hot air balloons could have been used by people of the Nazca culture of Peru some 1500 to 2000 years ago, as a tool for designing the famous Nazca ground figures and lines. The first documented balloon flight in Europe was demonstrated by Bartolomeu de Gusmão. On August 8, 1709, in Lisbon, he managed

to lift a balloon full of hot air about 4.5 meters in front of King John V and the Portuguese court.

First manned flight

A model of the Montgolfier brothers' balloon at the London Science Museum

The first clearly recorded instance of a balloon carrying passengers used hot air to generate buoyancy and was built by the brothers Joseph-Michel and Jacques-Etienne Montgolfier in Annonay, France. After experimenting with unmanned balloons and flights with animals, the first tethered balloon flight with humans on board took place on October 15, 1783. It is fitting that Etienne Montgolfier was the first human to lift off the earth, making at least one tethered flight from the yard of the Reveillon workshop in the Faubourg Saint-Antoine. It was most likely on October 15, 1783. A little while later on

that same day, Pilatre de Rozier became the second to ascend into the air, to an altitude of 80 feet, which was the length of the tether. The first free flight with human passengers took place on November 21, 1783. King Louis XVI had originally decreed that condemned criminals would be the first pilots, but de Rozier, along with Marquis François d'Arlandes, successfully petitioned for the honor. The first military use of a hot air balloon happened during the battle of Fleurus (1794) where the French used the balloon l'Entreprenant as an observation post.

Today

A pair of Hopper balloons

A Balloon Works Firefly 7 Balloon

Modern hot air balloons, with an onboard heat source, were pioneered by Ed Yost, beginning in the 1950s; his work resulted in his first successful flight, on October 22, 1960. The first modern-day hot air balloon to be built in the United Kingdom (UK) was the Bristol Belle in 1967. Today, hot air balloons are used primarily for recreation.

Hot air balloons are able to fly to extremely high altitudes. On November 26, 2005, Vijaypat Singhania set the world altitude record for highest hot air balloon flight, reaching 21,027 meters (68,986 feet). He took off from downtown Mumbai, India, and landed 240 kilometers (149 miles) south in Panchale. The previous record of 19,811 m (64,997 ft) had been set by Per Lindstrand on June 6, 1988 in Plano, Texas. As with all

unpressurized aircraft, oxygen is needed for all crew and passengers on any flight that exceeds an altitude of about 15,000 ft (4,572 m).

On January 15, 1991, the Virgin Pacific Flyer balloon completed the longest flight in a hot air balloon when Per Lindstrand (born in Sweden, but resident in the UK) and Richard Branson of the UK flew 7,671.91 km (4,767.10 mi) from Japan to Northern Canada. With a volume of 74 thousand cubic meters (2.6 million cubic feet), the balloon envelope was the largest ever built for a hot air craft. Designed to fly in the trans-oceanic jet streams, the Pacific Flyer recorded the highest ground speed for a manned balloon at 245 mph (394 km/h). The longest duration record was set by Swiss psychiatrist Bertrand Piccard, Auguste Piccard's grandson, and Briton Brian Jones, Flying in the Breitling Orbiter 3. It was the first nonstop trip around the world by balloon. The balloon left Château-d'Oex, Switzerland, on March 1, 1999, and landed at 1:02 a.m. on March 21 in the Egyptian desert 300 miles (482 kilometers) south of Cairo. The two men broke distance, endurance, and time records, traveling 19 days, 21 hours, and 55 minutes. Steve Fosset broke the record for shortest time around the world on 3 July 2002. The new record is 320 h 33 min.

Construction

A hot air balloon for manned flight uses a single-layered, fabric gas bag (lifting "envelope"), with an opening at the bottom called the mouth or throat. Attached to the envelope is a basket, or gondola, for carrying the passengers. Mounted above the basket and centered in the mouth is the "burner," which injects a flame into the envelope, heating the air within. The heater or burner is fueled by propane, a liquefied gas stored in pressure vessels, similar to high pressure forklift cylinders.

Envelope

Modern hot air balloons are usually made of light-weight and strong synthetic fabrics such as ripstop nylon, or dacron (a polyester).

A hot air balloon is partially inflated with cold air from a gas-powered fan, before the propane burners are used for final inflation.

During the manufacturing process, the material is cut into panels and sewn together, along with structural load tapes that carry the weight of the gondola or basket. The individual sections, which run from the throat to the crown (top) of the envelope, are called gores or gore sections. Envelopes can have as few as 4 gores or as many as 24 or more.

Envelopes often have a crown ring at their very top. This is a hoop of smooth metal, usually aluminium and approximately 1 ft (0.3 m) in diameter that vertical load tapes attach to.

Seams

The most common technique for sewing panels together is called the French felled, French fell, or double lap seam. The two pieces of fabric are folded over on each other at their common edge, possibly with a load tape as well, and sewn together with two rows of parallel stitching. Other methods include a flat lap seam, in which the two pieces of fabric are held together simply with two rows of parallel stitching, and a zigzag, where parallel zigzag stitching holds a double lap of fabric.

Coatings

The fabric (or at least part of it, the top 1/3 for example) may be coated with a sealer, such as silicone or polyurethane, to make it impermeable to air. It is often the degradation of this coating and the corresponding loss of impermeability that ends the effective life of an envelope, not weakening of the fabric itself. Heat, moisture, and mechanical wear-and-tear during set up and pack up are the primary causes of degradation. Once an envelope becomes too porous to fly, it may be retired and used as a 'rag bag': cold inflated and opened for children to run through. Products for recoating the fabric are becoming commercially available.

Sizes

A range of envelope sizes is available. The smallest, one-person, basket-less balloons (called "Hoppers" or "Cloudhoppers") have as little as 21,000 ft³ (595 m³) of envelope volume (for a perfect sphere this would mean a radius of around 5.22 m (17 ft)). At the other end of the scale are the balloons used by large commercial sightseeing operations that carry well over two dozen people and have envelope volumes of up to 600,000 ft³ (16,990 m³). However, most balloons are roughly 100,000 ft³ (2,832 m³) and carry 3 to 5 people.

Vents
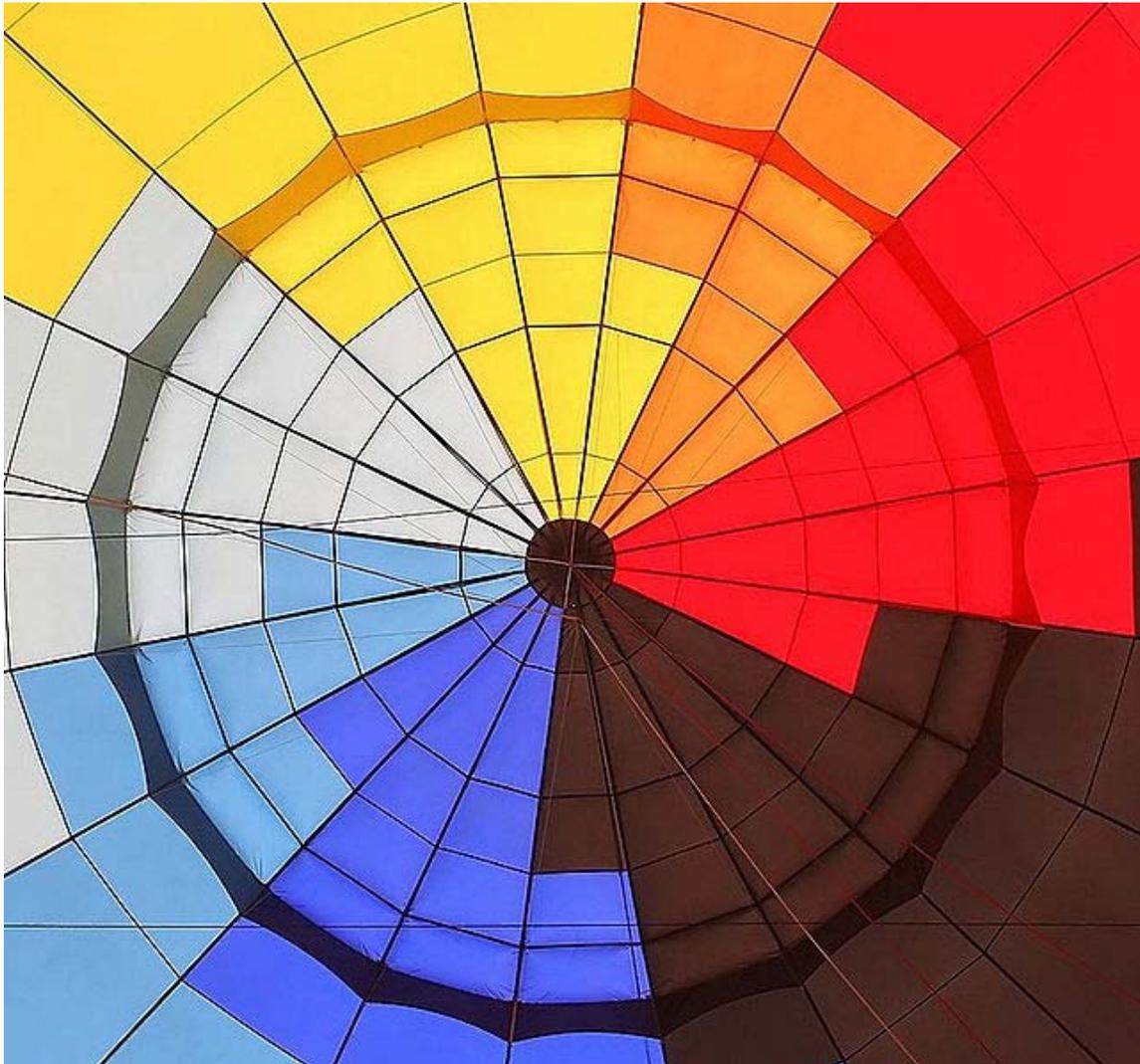
The parachute vent at the top of an envelope, as seen from below through the mouth

The top of the balloon usually has a vent of some sort. This enables the pilot to release hot air to slow an ascent, start a descent, or increase the rate of descent, usually for landing. Some hot air balloons have turning vents, which are side vents that, when opened, cause the balloon to rotate. Such vents are particularly useful for balloons with rectangular baskets, to facilitate aligning the wider side of the basket for landing.

The most common type of top vent is a disk-shaped flap of fabric called a parachute vent, invented by Tracy Barnes. The fabric is connected around its edge to a set of "vent lines" that converge in the center. (The arrangement of fabric and lines roughly resembles a parachute -- thus the name.) These "vent lines" are themselves connected to a control line that runs to the basket. A parachute vent is opened by pulling on the control line. Once the control line is released, the pressure of the remaining hot air pushes the vent fabric

back into place. A parachute vent can be opened briefly while in flight to initiate a rapid descent. (Slower descents are initiated by allowing the air in the balloon to cool naturally.) The vent is pulled completely open to collapse the balloon after landing.

An older, and today less commonly used, style of top vent is called a "Velcro-style" vent. This too is a disk of fabric at the top of the balloon. However, rather than having a set of "vent lines" that can repeatedly open and close the vent, the vent is secured by "hook and loop" fasteners (such as Velcro) and is only opened at the end of the flight. Balloons equipped with a Velcro-style vent typically have a second "maneuvering vent" built into the side (as opposed to the top) of the balloon. Another common type of top design is the "Smart Vent," which, rather than lowering a fabric disc into the envelope as in the "parachute" type, gathers the fabric together in the center of the opening. This system can theoretically be used for in-flight maneuvering, but is more commonly used only as a rapid-deflation device for use after landing, of particular value in high winds. Other designs, such as the "pop top" and "MultiVent" systems, have also attempted to address the need for rapid deflation on landing, but the parachute top remains popular as an elegant, all-around maneuvering and deflation system.

Shape

Besides special shapes, possibly for marketing purposes, there are several variations on the traditional "inverted tear drop" shape. The simplest, often used by home builders, is a hemisphere on top of a truncated cone. More-sophisticated designs attempt to minimize the circumferential stress on the fabric, with different degrees of success depending on whether they take fabric weight and varying air density into account. This shape may be referred to as "natural". Finally, some specialized balloons are designed to minimize aerodynamic drag (in the vertical direction) to improve flight performance in competitions.

Basket

A wicker basket capable of holding 16 passengers

Baskets are commonly made of woven wicker or rattan. These materials have proven to be sufficiently light, strong, and durable for balloon flight. Such baskets are usually rectangular or triangular in shape. They vary in size from just big enough for two people to large enough to carry thirty. Larger baskets often have internal partitions for structural bracing and to compartmentalize the passengers. Small holes may be woven into the side of the basket to act as foot holds for passengers climbing in or out.

Baskets may also be made of aluminium, especially a collapsible aluminium frame with a fabric skin, to reduce weight or increase portability. These may be used by pilots without a ground crew or who are attempting to set altitude, duration, or distance records. Other specialty baskets include the fully enclosed gondolas used for around-the-world attempts, and baskets that consist of little more than a seat for the pilot and perhaps one passenger.

Burner

A burner directing a flame into the envelope

The burner unit gasifies liquid propane, mixes it with air, ignites the mixture, and directs the flame and exhaust into the mouth of the envelope. Burners vary in power output; each will generally produce 2 to 3 MW of heat (7 to 10 million BTUs per hour), with double, triple, or quadruple burner configurations installed where more power is needed. The pilot actuates a burner by opening a propane valve, called a **blast valve**. The valve may be spring loaded so that it closes automatically, or it may stay open until closed by the pilot. The burner has a pilot light to ignite the propane and air mixture. The pilot light may be lit by the pilot with an external device, such as a flint striker or a lighter, or with a built-in piezo electric spark.

Where more than one burner is present, the pilot can use one or more at a time depending on the desired heat output. Each burner is characterized by a metal coil of propane tubing the flame shoots through to preheat the incoming liquid propane. The burner unit may be suspended from the mouth of the envelope, or rigidly supported over the basket. The burner unit may be mounted on a gimbal to enable the pilot to aim the flame and avoid overheating the envelope fabric. A burner may have a secondary propane valve that releases propane more slowly and thereby generates a different sound. This is called a **whisper burner** and is used for flight over livestock to lessen the chance of spooking them. It also generates a more yellow flame and is used for night glows because it lights up the inside of the envelope better than the primary valve.

Fuel tanks

Propane fuel tanks are usually cylindrical pressure vessels made from aluminium, stainless steel, or titanium with a valve at one end to feed the burner and to refuel. They may have a fuel gauge and a pressure gauge. Common tank sizes are 10 (38), 15 (57), and 20 (76) US gallons (liters). They may be intended for upright or horizontal use, and may be mounted inside or outside the basket.

Stainless steel fuel tanks, wrapped in red insulating covers, mounted vertically, and with fuel gauges, during refueling

The pressure necessary to force the fuel through the line to the burner may be supplied by the vapor pressure of the propane itself, if warm enough, or by the introduction of an inert gas such as nitrogen. Tanks may be preheated with electrical heat tapes to produce sufficient vapor pressure for cold weather flying. Warmed tanks will usually also be wrapped in an insulating blanket to preserve heat during the setup and flight.

Instrumentation

A balloon may be outfitted with a variety of instruments to aid the pilot. These commonly include an altimeter, a rate of climb (vertical speed) indicator known as a variometer, envelope (air) temperature, and ambient (air) temperature. A GPS receiver can be useful to indicate ground speed (traditional aircraft air speed indicators would be useless) and direction.

Combined mass

The combined mass of an average system can be calculated as follows:

component	pounds	kilograms
100,000 ft³ (2831.7 m³) envelope	250	113.4
5-passenger basket	140	63.5
double burner	50	22.7
3 20-gallon (75.7-liter) fuel tanks full of propane	3 × 135 = 405	183.7
5 passengers	5 × 150 = 750	340.2
sub total	1595	723.5
100,000 ft³ (2831.7 m³) of heated air	5922	2686.2
total	(3.76 tons) 7517	3409.7

using a density of 0.9486 kg/m³ for dry air heated to 210 °F (99 °C).

Theory of operation

Generating lift
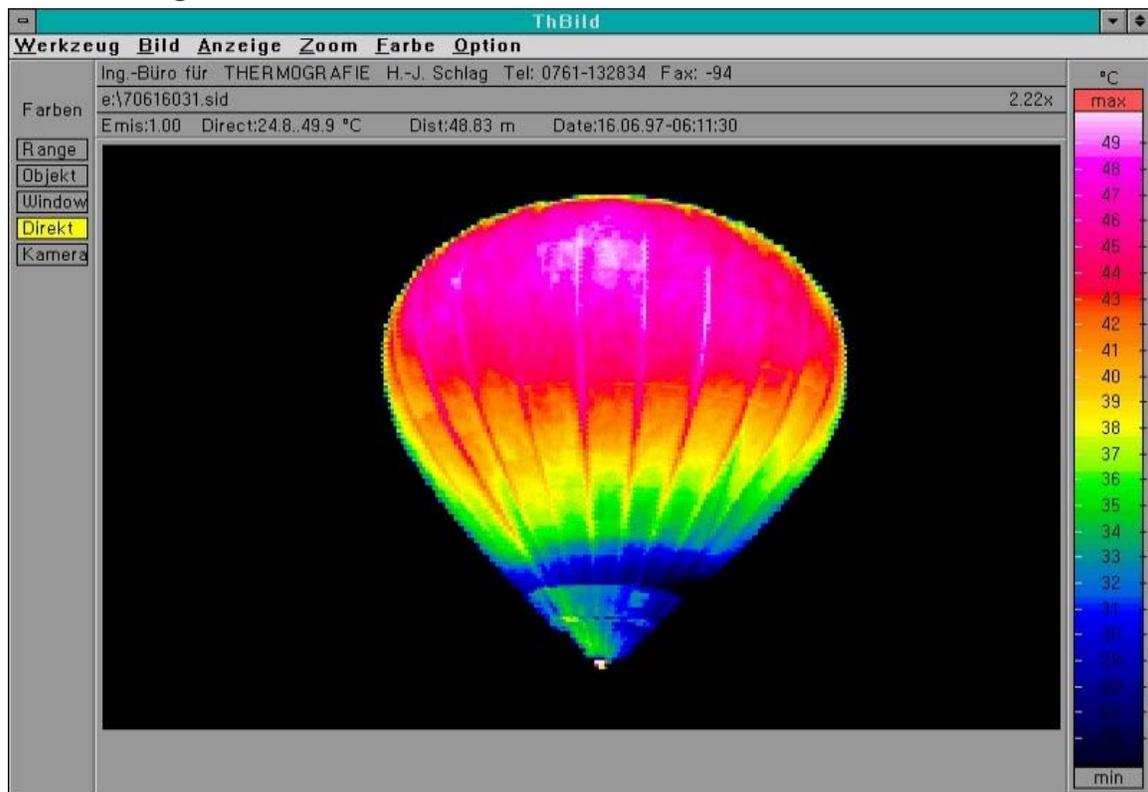
Thermal image showing temperature variation in a hot air balloon

Raising the air temperature inside the envelope makes it lighter than the surrounding (ambient) air. The balloon floats because of the buoyant force exerted on it. This force is the same force that acts on objects when they are in water and is described by Archimedes' principle. The amount of lift (or buoyancy) provided by a hot air balloon depends primarily upon the difference between the temperature of the air inside the envelope and the temperature of the air outside the envelope. For most envelopes made of nylon fabric, the maximum internal temperature is limited to approximately 120 °C (250 °F).

It should be noted that the melting point of nylon is significantly higher than this maximum operating temperature — about 230 °C (450 °F). However the lower temperatures are generally used because the higher the temperature, the more quickly the strength of the nylon fabric degrades over time. With a maximum operating temperature of 120 °C (250 °F), balloon envelopes can generally be flown for between 400 and 500 hours before the fabric needs to be replaced. Many balloon pilots operate their envelopes at temperatures significantly below the maximum to extend envelope fabric life.

The lift generated by 100,000 ft³ (2831.7 m³) of dry air heated to various temperatures may be calculated as follows:

air temperature	air density	air mass	lift generated
68 °F, 20 °C	1.2041 kg/m³	7517 lbs, 3409.7 kg	0 lbs, 0 kg
210 °F, 99 °C	0.9486 kg/m³	5922 lbs, 2686.2 kg	1595 lbs, 723.5 kg
250 °F, 120 °C	0.8978 kg/m³	5606 lbs, 2542.4 kg	1912 lbs, 867.3 kg

The density of air at 20 °C, 68 °F is about 1.2 kg/m³. The total lift for a balloon of 100,000 ft³ heated to (99 °C, 210 °F) would be 1595 lb, 723.5 kg. This is just enough to generate neutral buoyancy for the total system mass (not including the heated air trapped in the envelope, of course) stated in the previous section. Liftoff would require a slightly higher temperature, depending on the desired rate of climb. In reality, the air contained in the envelope is not all the same temperature, as the accompanying thermal image shows, and so these calculations are based on averages.

For typical atmospheric conditions (20 °C, 68 °F), a hot air balloon heated to (99 °C, 210 °F) requires about 3.91 m³ of envelope volume to lift 1 kilogram (62.5 ft³/lb). The precise amount of lift provided depends not only upon the internal temperature mentioned above, but the external temperature, altitude above sea level, and humidity of the surrounding air. On a warm day, a balloon cannot lift as much as on a cool day, because the temperature required for launch will exceed the maximum sustainable for nylon envelope fabric. Also, in the lower atmosphere, the lift provided by a hot air balloon decreases about 3% for each 1,000 meters (1% per 1,000 ft) of altitude gained.

Montgolfiere

A Virgin hot air balloon flying over Cambridge

Standard hot air balloons are called **Montgolfiere balloons** and rely solely on the buoyancy of hot air provided by the burner and contained by the envelope. This style of balloon was developed by the Montgolfier brothers, and had its first public demonstration on 4 June 1783 with an unmanned flight lasting 10 minutes, followed later that year with manned flights.

Hybrid

The 1785 Rozière balloon, a type of **hybrid balloon**, named after its creator, Jean-François Pilâtre de Rozier, has a separate cell for a lighter than air gas (typically helium,) as well as a cone below for hot air (as is used in a hot air balloon) to heat the helium at night. Hydrogen gas was used in the very early stages of development but was quickly abandoned due to the obvious danger of introducing an open flame near the gas. All modern Roziere balloons now use helium as a lifting gas.

Solar

Solar balloons are hot air balloons that use just solar energy captured by a dark envelope to heat the air inside.

Safety equipment

To help ensure the safety of pilot and passengers, a hot air balloon may carry several pieces of safety equipment.

In the basket

To relight the burner if the pilot light goes out and the optional piezo ignition fails, the pilot should have ready access to a flint spark lighter. Many systems, especially those that carry passengers, have completely redundant fuel and burner systems: two fuel tanks, connected to two separate hoses, which feed two distinct burners. This enables a safe landing in the case of a clog somewhere in one system or if a system must be disabled because of a fuel leak.

A fire extinguisher suitable for extinguishing propane fires is a useful piece of safety equipment in a balloon. Most balloons carry a 1 kg AB:E type fire extinguisher.

A handling or drop line is mandatory safety equipment in many countries. It is a rope or webbing of 20 – 30 metres in length attached to the balloon basket with a quick release connection at one end. In very calm wind conditions the balloon pilot can throw the handling line from the balloon so that the ground crew can safely guide the balloon away from obstructions on the ground.

On the occupants

At a minimum the pilot should wear flame resistant gloves. These can be made of leather or some more sophisticated material, such as nomex. These will enable the pilot to shut off a gas valve in the case of a leak even if there is a flame present. Quick action on the pilot's part to stop the flow of gas can turn a potential disaster into an inconvenience. In addition, the pilot should wear clothes made of natural fibers. These will singe and not burn readily if brought into contact with an open flame. Many synthetic fibers, unless especially formulated for use near flame or high temperatures like nomex, will melt onto

the wearer and can cause severe burning. Finally, some balloon systems, especially those that hang the burner from the envelope instead of supporting it rigidly from the basket, require the use of helmets by the pilot and passengers.

On the ground crew

The ground crew should wear gloves on their hands whenever the possibility of handling ropes or lines exists. The mass and exposed surface to air movement of a medium sized balloon is sufficient to cause rope burns to the hands of anyone trying to stop or prevent movement. The ground crew should also wear sturdy shoes and at least long pants in case of the need to access a landing or landed balloon in rough or overgrown terrain.

Maintenance and repair
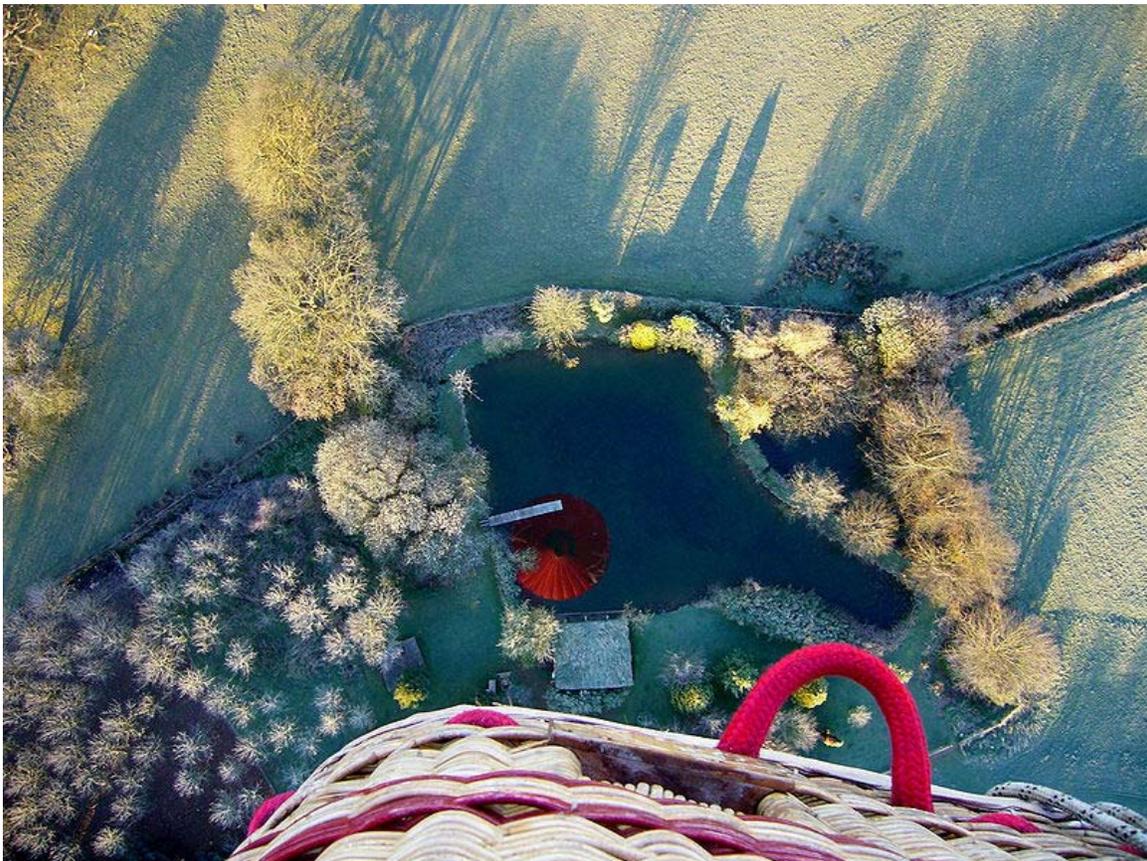
Taken from the basket, the reflection of the balloon can be seen in the lake below. Obstacles in the landscape can inhibit smooth retrieval of the balloon upon landing.

As with aircraft, hot air balloons require regular maintenance to remain airworthy. As aircraft made of fabric and that lack direct horizontal control, hot air balloons may occasionally require repairs to rips or snags. While some operations, such as cleaning and drying, may be performed by the owner or pilot, other operations, such as sewing, must

be performed by a qualified repair technician and recorded in the balloon's maintenance log book.

Maintenance

To ensure long life and safe operation, the envelope should be kept clean and dry. This prevents mold and mildew from forming on the fabric and abrasion from occurring during packing, transport, and unpacking due to contact with foreign particles. In the event of a landing in a wet (because of precipitation or early morning or late evening dew) or muddy location (farmer's field), the envelope should be cleaned and laid out or hung to dry.

The burner and fuel system must also be kept clean to ensure safe operation on demand. Damaged fuel hoses need to be replaced. Stuck or leaky valves must be repaired or replaced. The wicker basket may require occasional refinishing or repair. The skids on its bottom may require occasional replacement.

Balloons in most parts of the world are maintained in accordance with a fixed manufacturer's maintenance schedule that includes regular (100 flight hours or 12 month) inspections, in addition to maintenance work to correct any damage. In Australia, balloons used for carrying commercial passengers must be inspected and maintained by approved workshops.

Repair

In the case of a snag, burn, or rip in the envelope fabric, a patch may be applied or the affected panel completely replaced. Patches may be held in place with glue, tape, stitching, or a combination of these techniques. Replacing an entire panel requires the stitching around the old panel to be removed, and a new panel to be sewn in with the appropriate technique, thread, and stitch pattern.

Licensing

Depending on the size of the balloon, location, and intended use, hot air balloons and their pilots need to comply with a variety of regulations.

Top of balloon during inflation. Crew is securing parachute vent.

Balloons

In the USA, balloons below a certain size (empty weight of less than 155 pounds or 70 kg including envelope, basket, burners and empty fuel tanks) can be used as an ultralight aircraft and cannot carry passengers, except for pilot training. Anything larger than that must be registered (have an N-number), have an airworthiness certificate, and pass annual inspections.

Pilots

In the United States of America

In the United States, a pilot of a hot air balloon must have a pilot certificate from the Federal Aviation Administration (FAA) and it must carry the rating of "Lighter-than-air free balloon", and unless the pilot is also qualified to fly gas balloons, will also carry this limitation: "Limited to hot air balloons with airborne heater". A pilot does not need a license to fly an ultralight aircraft, but training is highly advised, and some hot air balloons meet the criteria.

To carry paying passengers for hire (and attend some balloon festivals), a pilot must have a commercial pilot certificate. Commercial hot air balloon pilots may also act as hot air balloon flight instructors. While most balloon pilots fly for the pure joy of floating

through the air, many are able to make a living as a professional balloon pilot. Some professional pilots fly commercial passenger sightseeing flights, while others fly corporate advertising balloons.

In the UK

In the UK, the person in command must hold a valid Private Pilot's Licence issued by the Civil Aviation Authority specifically for ballooning; this is known as the PPL(B). There are two types of commercial balloon licences: CPL(B) Restricted and CPL(B) (Full). The CPL(B) Restricted is required if the pilot is undertaking work for a sponsor or being paid by an external agent to operate a balloon. The pilot can fly a sponsored balloon with everything paid for with a PPL unless asked to attend any event. Then a CPL(B) Restricted is required. The CPL(B) is required if the pilot is flying passengers for money. The balloon then needs a transport category C of A (certificate of air worthiness). If the pilot is only flying sponsor's guests, and not charging money for flying other passengers, then the pilot is exempted from holding an AOC (air operator's certificate) though a copy of it is required. For passenger flying, the balloon also requires a maintenance log.

In Australia

In Australia, a commercial operation must operate with a nominated Chief Pilot and under an Air Operators Certificate from the Australian Civil Aviation and Safety Authority (CASA). Pilots must have different levels of experience before they are allowed to progress to larger balloons. Hot air balloons must be registered aircraft with the CASA and are subject to regular airworthiness checks by authorised personnel.

Manufacturers

Three balloons prepare for liftoff in Orlando, Florida.

The largest manufacturer of hot air balloons in the world is Cameron Balloons of Bristol, England, who also own Lindstrand Balloons of Oswestry, England. Cameron Balloons, Lindstrand Balloons and another English balloon manufacturing company, Thunder and Colt (since acquired by Cameron), have been innovators and developers of special shaped balloons. These hot air balloons use the same principle of lift as conventional inverted teardrop shaped balloons but often sections of the special balloon envelope shape make no contribution to the balloon's ability to stay afloat.

The second largest manufacturer of hot air balloons in the world is Ultramagic, based in Spain, which produces from 80 to 120 balloons per year. Ultramagic can produce massive balloons, such as the N-500 that accommodates up to 27 persons in the basket, and has also produced many balloons with special shapes, as well as cold air inflatables.

Aerostar International, Inc. of Sioux Falls, South Dakota was North America's largest balloon manufacturer and a close second in world manufacturing before ceasing to build balloons in January 2007. Firefly Balloons, formerly known as The Balloon Works, is another popular manufacturer of hot-air balloons located in Statesville, North Carolina. Another long time producer of hot air balloons is Head Balloons, Inc., located in Helen, Georgia. The major manufacturers in Canada are Sundance Balloons and Fantasy Sky

Promotions. There are many other manufacturers around the world including Kavanagh Balloons (Australia), Schroeder Fire Balloons (Germany) and Kubicek Balloons (Czech Republic).

Chapter 4

Buoyancy
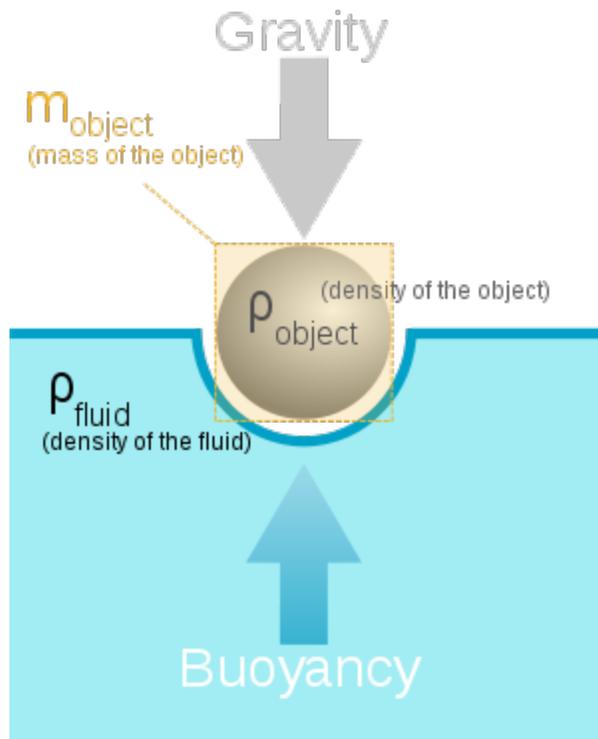
The forces at work in buoyancy

In physics, **buoyancy** is an upward acting force exerted by a fluid, that opposes an object's weight. If the object is either less dense than the liquid or is shaped appropriately (as in a boat), the force can keep the object afloat. This can occur only in a reference frame which either has a gravitational field or is accelerating due to a force other than gravity defining a "downward" direction (that is, a non-inertial reference frame). In a situation of fluid statics, the net upward buoyancy force is equal to the magnitude of the weight of fluid displaced by the body. This is the force that enables the object to float.

Archimedes' principle

Archimedes' principle is named after Archimedes of Syracuse, who first discovered this law. His treatise, On floating bodies, proposition 5 states:

Any floating object displaces its own weight of fluid.

– Archimedes of Syracuse

For more general objects, floating and sunken, and in gases as well as liquids (i.e. a fluid), Archimedes' principle may be stated thus in terms of forces:

Any object, wholly or partially immersed in a fluid, is buoyed up by a force equal to the weight of the fluid displaced by the object.

– Archimedes of Syracuse

with the clarifications that for a sunken object the volume of displaced fluid is the volume of the object, and for a floating object on a liquid, the weight of the displaced liquid is the weight of the object.

More tersely: **Buoyancy = weight of displaced fluid.**

Archimedes' principle does not consider the surface tension (capillarity) acting on the body.

The weight of the displaced fluid is directly proportional to the volume of the displaced fluid (if the surrounding fluid is of uniform density). In simple terms, the principle states that the buoyant force on an object is going to be equal to the weight of the fluid displaced by the object, or the density of the fluid multiplied by the submerged volume times the gravitational constant, g. Thus, among completely submerged objects with equal masses, objects with greater volume have greater buoyancy.

Suppose a rock's weight is measured as 10 newtons when suspended by a string in a vacuum with gravity acting upon it. Suppose that when the rock is lowered into water, it displaces water of weight 3 newtons. The force it then exerts on the string from which it hangs would be 10 newtons minus the 3 newtons of buoyant force: $10 - 3 = 7$ newtons. Buoyancy reduces the apparent weight of objects that have sunk completely to the sea floor. It is generally easier to lift an object up through the water than it is to pull it out of the water.

Assuming Archimedes' principle to be reformulated as follows,

$$\text{apparent immersed weight} = \text{weight} - \text{weight of displaced fluid}$$

then inserted into the quotient of weights, which has been expanded by the mutual volume

$$\frac{\text{density}}{\text{density of fluid}} = \frac{\text{weight}}{\text{weight of displaced fluid}},$$

yields the formula below. The density of the immersed object relative to the density of the fluid can easily be calculated without measuring any volumes:

$$\frac{\text{density of object}}{\text{density of fluid}} = \frac{\text{weight}}{\text{weight} - \text{apparent immersed weight}}$$

(This formula is used for example in describing the measuring principle of a dasymeter and of hydrostatic weighing.)

Example: If you drop wood into water buoyancy will keep it afloat.

Example: A helium balloon in a moving car. In increasing speed or driving a curve, the air moves in the opposite direction of the car's acceleration. The balloon however, is pushed due to buoyancy "out of the way" by the air, and will actually drift in the same direction as the car's acceleration.

Forces and equilibrium

This is the equation to calculate the pressure inside a fluid in equilibrium. The corresponding equilibrium equation is:

$$\mathbf{f} + \text{div}\,\sigma = 0$$

where $\mathbf{f}$ is the force density exerted by some outer field on the fluid, and σ is the stress tensor. In this case the stress tensor is proportional to the identity tensor:

$$\sigma_{ij} = -p\delta_{ij}.$$

Here δ_{ij} is the Kronecker delta. Using this the above equation becomes:

$$\mathbf{f} = \nabla p.$$

Assuming the outer force field is conservative, that is it can be written as the negative gradient of some scalar valued function:

$$\mathbf{f} = -\nabla\Phi.$$

Then:

$$\nabla(p + \Phi) = 0 \implies p + \Phi = \text{constant}.$$

Therefore, the shape of the open surface of a fluid equals the equipotential plane of the applied outer conservative force field. Let the z-axis point downward. In this case the field is gravity, so $\Phi = -\rho_f g z$ where g is the gravitational acceleration, ρ_f is the mass density of the fluid. Taking the pressure as zero at the surface, where z is zero, the constant will be zero, so the pressure inside the fluid, when it is subject to gravity, is

$$p = \rho_f g z.$$

So pressure increases with depth below the surface of a liquid, as z denotes the distance from the surface of the liquid into it. Any object with a non-zero vertical depth will have different pressures on its top and bottom, with the pressure on the bottom being greater. This difference in pressure causes the upward buoyancy forces.

The buoyant force exerted on a body can now be calculated easily, since the internal pressure of the fluid is known. The force exerted on the body can be calculated by integrating the stress tensor over the surface of the body which is in contact with the fluid:

$$\mathbf{B} = \oint \sigma \, d\mathbf{A}$$

The surface integral can be transformed into a volume integral with the help of the Gauss divergence theorem:

$$\mathbf{B} = \int \text{div} \sigma \, dV = -\int \mathbf{f} \, dV = -\rho_f \mathbf{g} \int dV = -\rho_f \mathbf{g} V$$

where V is the measure of the volume in contact with the fluid, that is the volume of the submerged part of the body. Since the fluid doesn't exert force on the part of the body which is outside of it.

The magnitude of buoyant force may be appreciated a bit more from the following argument. Consider any object of arbitrary shape and volume V surrounded by a liquid. The force the liquid exerts on an object within the liquid is equal to the weight of the liquid with a volume equal to that of the object. This force is applied in a direction opposite to gravitational force, that is of magnitude:

$$B = \rho_f V_{\text{disp}} \, g,$$

where ρ_f is the density of the fluid, V_{disp} is the volume of the displaced body of liquid, and g is the gravitational acceleration at the location in question.

If this volume of liquid is replaced by a solid body of exactly the same shape, the force the liquid exerts on it must be exactly the same as above. In other words the "buoyant force" on a submerged body is directed in the opposite direction to gravity and is equal in magnitude to

$$B = \rho_f V g.$$

The net force on the object must be zero if it is to be a situation of fluid statics such that Archimedes principle is applicable, and is thus the sum of the buoyant force and the object's weight

$$F_{\text{net}} = 0 = mg - \rho_f V_{\text{disp}} g$$

If the buoyancy of an (unrestrained and unpowered) object exceeds its weight, it tends to rise. An object whose weight exceeds its buoyancy tends to sink. Calculation of the upwards force on a submerged object during its accelerating period cannot be done by the Archimedes principle alone; it is necessary to consider dynamics of an object involving buoyancy. Once it fully sinks to the floor of the fluid or rises to the surface and settles, Archimedes principle can be applied alone. For a floating object, only the submerged volume displaces water. For a sunken object, the entire volume displaces water, and there will be an additional force of reaction from the solid floor.

In order for Archimedes' principle to be used alone, the object in question must be in equilibrium (the sum of the forces on the object must be zero), therefore;

$$mg = \rho_f V_{\text{disp}} g,$$

and therefore

$$m = \rho_f V_{\text{disp}}.$$

showing that the depth to which a floating object will sink, and the volume of fluid it will displace, is independent of the gravitational field regardless of geographic location.

(Note: If the fluid in question is seawater, it will not have the same density (ρ) at every location. For this reason, a ship may display a Plimsoll line.)

It can be the case that forces other than just buoyancy and gravity come into play. This is the case if the object is restrained or if the object sinks to the solid floor. An object which tends to float requires a tension restraint force T in order to remain fully submerged. An object which tends to sink will eventually have a normal force of constraint N exerted upon it by the solid floor. The constraint force can be tension in a spring scale measuring its weight in the fluid, and is how apparent weight is defined.

If the object would otherwise float, the tension to restrain it fully submerged is:

$$T = \rho_f V g - mg.$$

When a sinking object settles on the solid floor, it experiences a normal force of:

$$N = mg - \rho_f V g.$$

It is common to define a buoyant mass m_b that represents the effective mass of the object as can be measured by a gravitational method. If an object which usually sinks is submerged suspended via a cord from a balance pan, the reference object on the other dry-land pan of the balance will have mass:

$$m_b = m_o \cdot \left(1 - \frac{\rho_f}{\rho_o} \right)$$

where m_o is the true (vacuum) mass of the object, and ρ_o and ρ_f are the average densities of the object and the surrounding fluid, respectively. Thus, if the two densities are equal, $\rho_o = \rho_f$, the object is seemingly weightless, and is said to be neutrally buoyant. If the fluid density is greater than the average density of the object, the object floats; if less, the object sinks.

Another possible formula for calculating buoyancy of an object is by finding the apparent weight of that particular object in the air (calculated in Newtons), and apparent weight of that object in the water (in Newtons). To find the force of buoyancy acting on the object when in air, using this particular information, this formula applies:

> **'Buoyancy force = weight of object in empty space − weight of object immersed in fluid'**

The final result would be measured in Newtons.

Air's density is very small compared to most solids and liquids. For this reason, the weight of an object in air is approximately the same as its true weight in a vacuum. The buoyancy of air is neglected for most objects during a measurement in air because the error is usually insignificant (typically less than 0.1% except for objects of very low average density such as a balloon or light foam).

Stability

A floating object is stable if it tends to restore itself to an equilibrium position after a small displacement. For example, floating objects will generally have vertical stability, as if the object is pushed down slightly, this will create a greater buoyant force, which, unbalanced by the weight force, will push the object back up.

Rotational stability is of great importance to floating vessels. Given a small angular displacement, the vessel may return to its original position (stable), move away from its original position (unstable), or remain where it is (neutral).

Rotational stability depends on the relative lines of action of forces on an object. The upward buoyant force on an object acts through the center of buoyancy, being the centroid of the displaced volume of fluid. The weight force on the object acts through its center of gravity. A buoyant object will be stable if the center of gravity is beneath the center of buoyancy because any angular displacement will then produce a 'righting moment'.

Compressible fluids and objects

The atmosphere's density depends upon altitude. As an airship rises in the atmosphere, its buoyancy decreases as the density of the surrounding air decreases. In contrast, as a submarine expels water from its buoyancy tanks, it rises because its volume is constant (the volume of water it displaces if it is fully submerged) while its mass is decreased.

Compressible objects

As a floating object rises or falls, the forces external to it change and, as all objects are compressible to some extent or another, so does the object's volume. Buoyancy depends on volume and so an object's buoyancy reduces if it is compressed and increases if it expands.

If an object at equilibrium has a compressibility less than that of the surrounding fluid, the object's equilibrium is stable and it remains at rest. If, however, its compressibility is greater, its equilibrium is then unstable, and it rises and expands on the slightest upward perturbation, or falls and compresses on the slightest downward perturbation.

Submarines rise and dive by filling large tanks with seawater. To dive, the tanks are opened to allow air to exhaust out the top of the tanks, while the water flows in from the bottom. Once the weight has been balanced so the overall density of the submarine is equal to the water around it, it has neutral buoyancy and will remain at that depth.

The height of a balloon tends to be stable. As a balloon rises it tends to increase in volume with reducing atmospheric pressure, but the balloon's cargo does not expand. The average density of the balloon decreases less, therefore, than that of the surrounding air. The balloon's buoyancy decreases because the weight of the displaced air is reduced. A rising balloon tends to stop rising. Similarly, a sinking balloon tends to stop sinking.

Density

A pound coin floats in mercury due to the buoyant force upon it
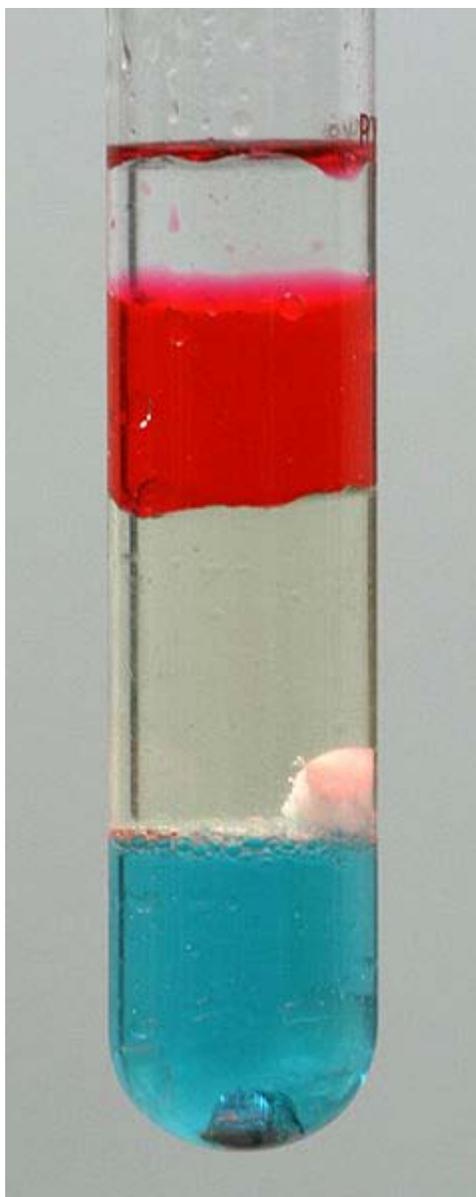
A density column containing some common liquids and solids. From top: baby oil, rubbing alcohol, vegetable oil, wax, water, and aluminum. Food coloring was added to rubbing alcohol and water for visibility.

If the weight of an object is less than the weight of the displaced fluid when fully submerged, then the object has an average density that is less than the fluid and when fully submerged will experience a force buoyancy greater than its own weight. If the fluid has a surface, such as water in a lake or the sea, the object will float and settle at a level where it displaces the same weight of fluid as the weight of the object. If the object is immersed in the fluid, such as a submerged submarine or air in a balloon, it will tend to rise. If the object has exactly the same density as the fluid, then its buoyancy equals its weight. It will remain submerged in the fluid, but it will neither sink nor float, although a disturbance in either direction will cause it to drift away from its position. An object with

a higher average density than the fluid will never experience more buoyancy than weight and it will sink. A ship will float even though it may be made of steel (which is much denser than water), because it encloses a volume of air (which is much less dense than water), and the resulting shape has an average density less than that of the water.

Beyond Archimedes' Principle

Archimedes' principle is a fluid statics concept. In its simple form, it applies when the object is not accelerating relative to the fluid. To examine the case when the object is accelerated by buoyancy and gravity, the fact that the displaced fluid itself has inertia as well must be considered.

This means that both the buoyant object and a parcel of fluid (equal in volume to the object) will experience the same magnitude of buoyant force because of Newton's third law, and will experience the same acceleration, but in opposite directions, since the total volume of the system is unchanged. In each case, the difference between magnitudes of the buoyant force and the force of gravity is the net force, and when divided by the relevant mass, it will yield the respective acceleration through Newton's second law. All acceleration measures are relative to the reference frame of the undisturbed background fluid.

Atwood's machine analogy
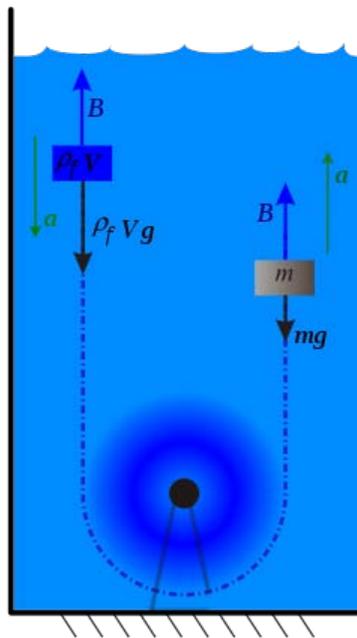
Atwood's Machine Analogy for dynamics of buoyant objects in vertical motion. The displaced parcel of fluid is indicated as the dark blue rectangle, and the buoyant solid object is indicated as the gray object. The acceleration vectors (a) in this visual depict a positively buoyant object which naturally accelerates upward, and upward acceleration of the object is our sign convention.

The system can be understood by analogy with a suitable modification of Atwood's machine, to represent the mechanical coupling of the displaced fluid and the buoyant object, as shown in the diagram right.

- The solid object is represented by the gray object
- The fluid being displaced is represented by dark blue object
- Undisturbed background fluid is analogous to the inextensible massless cord
- The force of buoyancy is analogous to the tension in the cord
- The solid floor of the body of fluid is analogous to the pulley, and reverses the direction of the buoyancy force, such that both the solid object and the displaced fluid experience their buoyancy force upward.

Results

It is important to note that this simplification of the situation completely ignores drag and viscosity, both of which come in to play to a greater extent as speed increases, when considering the dynamics of buoyant objects. The following simple formulation makes the assumption of slow speeds such that drag and viscosity are not significant. It is difficult to carry out such an experiment in practice with speeds close to zero, but if measurements of acceleration are made as quickly as possible after release from rest, the equations below give a good approximation to the acceleration and the buoyancy force.

A system consists of a well-sealed object of mass m and volume V which is fully submerged in a uniform fluid body of density ρ_f and in an environment of a uniform gravitational field g. Under the forces of buoyancy and gravity alone, the "dynamic buoyant force" B acting on the object and its upward acceleration a are given by:

Buoyant force
$$B = \frac{2gm\rho_f V}{m + \rho_f V}$$
Upward acceleration
$$a = \frac{g(\rho_f V - m)}{m + \rho_f V}$$

Derivations of both of these equations originates from constructing a system of equations by means of Newton's second law for both the solid object and the displaced parcel of fluid. An equation for upward acceleration of the object is constructed by dividing the net force on the object (B − mg) by its mass m. Due to the mechanical coupling, the object's upward acceleration is equal in magnitude to the downward acceleration of the displaced fluid, an equation constructed by dividing the net force on the displaced fluid (B − ρ_fVg) by its mass ρ_fV.

Should other forces come in to play in a different situation (such as spring forces, human forces, thrust, drag, or lift), it is necessary for the solver of problem to re-consider the construction of Newton's second law and the mechanical coupling conditions for both

bodies, now involving these other forces. In many situations turbulence will introduce other forces that are much more complex to calculate.

In the case of neutral buoyancy, m is equal to $\rho_f V$. Thus B reduces to mg and the acceleration is zero. If the object is much denser than the fluid, then B approaches zero and the object's upward acceleration is approximately −g, i.e. it is accelerated downward due to gravity as if the fluid were not present. As an example, a pellet of osmium falling through air will initially accelerate at 99.98% of g downward, though this will reduce as speed increases. Similarly, if the fluid is much denser than the object, then B approaches 2mg and the upward acceleration is approximately g. As an example, a typical Styrofoam ball in a tub of Mercury will initially accelerate upward at about 98.5% g.

Chapter 5

Buoyancy Compensator (Aviation)

The static buoyancy of airships during a trip is not constant. It is therefore necessary to take measures to control the buoyancy and thus the altitude, the so-called **buoyancy compensation**.

Changes which have an effect on buoyancy

- Changes in air temperature (and thus the density of air)
- Changes in the lifting gas temperature (for example by heating of the hull by the sun).
- Accumulation of additional ballast (for example, precipitation or icing on the envelope)
- Changes in ballast (for example, during a flight maneuver or the dropping of ballast)
- Changes by consumption of fuel, especially in the large historic airships like the Zeppelins the problem of change in the buoyancy balance by consumption of fuel needed attention.

For example, the LZ 126 spent on the flight from Friedrichshafen to Lakehurst 23,000 kg gasoline and 1300 kg of oil (an average consumption of 290 kg/100 km). During the landing the airship had to release approximately 24,000 cubic meters of hydrogen to balance the ship to land it. An airship with the size of the LZ 129 Hindenburg spent on a flight from Frankfurt am Main to Lakehurst approximately 54 tonnes of diesel with a buoyancy equivalent of 48,000 cubic metres hydrogen which amounted for about a quarter of the used lifting gas at the start of the flight (200,000 cubic metres). After landing the jettisoned hydrogen was replaced with new hydrogen.

Compensation measures

- Particular use of the dynamic buoyancy.
- Increasing buoyancy by dropping ballast. This is done mostly by the jettisoning of ballast water similar to the dropping of sandbags in ballooning.
- The reduction of buoyancy by jettisoning liftgas or adding ballast.
- Changing the density of the lifting gas by heating (more buoyancy) or cooling (less buoyancy).

- The use of vacuum/air buoyancy compensator tanks
- The use of thrust vectoring using ducted fans or propellers.

The Zeppelin NT has no special facilities to offset the extra buoyancy by fuel consumption. Compensation takes place by using a start-weight that is higher than the buoyancy lifting level at the start and during the flight, the extra dynamic buoyancy needed for lift-off and flight is produced with engines. If during the trip the ship gets lighter than air caused by fuel consumption, the swivel engines are used for down pressure and landing. The relatively small size of the Zeppelin NT and a range of "only" 900 kilometers compared to the historical zeppelins allowed the waiver of a ballast extraction device.

Buoyancy compensation

With a Zeppelin two main strategies are pursued to avoid the jettisoning of lifting gas:

- 1. The use of a fuel with the same density as air and therefore no increase in buoyancy caused by consumption.
- 2. Adding water as ballast by extraction during the trip.

Fuel with a density close to air

Only gasses have a density similar or equal to the air.

Hydrogen

Different attempts were made on hydrogen airships, like the LZ 127 and LZ 129 to use part of the lifting gas as a propellant without much success, later ships filled with helium lacked the option.

Blaugas

Around 1905 Blau gas was a common propellant for airships, it is named after its inventor the Augsburger chemist Hermann Blau who produced it in the Augsburger Blau gas plant. Various sources mention a mixture of liquefied propane and butane. In density it was 9% heavier than air. The Zeppelins used a different gas mixture of propylene, methane, butane, acetylene (ethine), butylene and hydrogen.

The LZ 127 Graf Zeppelin had bi-fuel engines and could use gasoline and gas as a propellant. Twelve of the gas cells were filled with a propellant gas instead of lifting gas with a total volume of 30,000 cubic metres, enough for approximately 100 flight hours. The fuel tank had a gasoline volume of 67 flight hours. Using both gasoline and Blau gas could give 118 hours cruise.

Water as ballast

Dew and rainfall on the hull

In the airships LZ 127 Graf Zeppelin and LZ 129 Hindenburg rain gutters were attached to the trunk to collect rainwater to fill the ballast water tanks during the trip. However, this procedure is weather dependent and is therefore not reliable as a standalone measure.

Water from the ground

Captain Ernst A. Lehmann described how during World War I Zeppelins would land on the sea and pick up temporary ballast water. In 1921 the airships LZ 120 "Bodensee" and LZ 121 "Nordstern" tested the possibility on Lake Constance to use lake water to create ballast. These attempts, however, showed no satisfactory results.

Silica-gel method

The silica gel method was tested on the LZ 129 to extract water from the humid air to increase weight. The project was terminated.

Water from fuel combustion

The condensors of the Macon's water recovery system appear as dark vertical strips above each engine. The Akron and LZ 130 Graf Zeppelin had similar systems.

The most promising procedure for ballast extraction during the journey is condensation of exhaust gasses from the engines which consist mainly of water (steam) and carbon dioxide. The main factors affecting gainable water are the hydrogen content of the fuel and humidity. The necessary exhaust gas coolers for this method had repeated problems with corrosion in the early years.

The first trials on the DELAG -Zeppelin LZ 13 "Hansa" (1912–1916) were conducted by Wilhelm Maybach. The trials were not satisfactory, resulting in an abandoned project.

The United States Navy reports the USS Shenandoah (ZR-1) (1923–25), a helium-filled rigid airship, as the first airship with ballast water from the condensation of exhaust gas. The LZ 126/ZR-3 USS Los Angeles was refitted with helium as a lifting gas after arrival in the U.S. Exhaust gas coolers were used to prevent jettisoning of the costly helium.

Lifting gas temperature

Changes in the lifting gas temperature in relation to the surrounding air have an effect on the buoyancy balance: higher temperatures increase buoyancy; lower temperatures descrease buoyancy. Artificially changing the lifting gas temperature requires constant work as the gas is barely thermally isolated from the surrounding air. However, it was common to make use of natural differences in temperature such as thermal updrafts and clouds.

Preheated lifting gas

Preheated lifting gas was tested to offset the higher weight of the Zeppelin. One variation tested on the LZ 127 Graf Zeppelin was to blow heated air on the lifting gas storage cells with the aim to gain buoyancy for launch.

Chapter 6

Balloon (Aircraft)

A **balloon** is a type of aircraft that remains aloft due to its buoyancy. A balloon travels by moving with the wind. It is distinct from an airship, which is a buoyant aircraft that can be propelled through the air in a controlled manner.

The "basket" or capsule that is suspended by cables beneath a balloon and carries people, animals, or automatic equipment (including cameras and telescopes, and flight-control mechanisms) may also be called the gondola.

Types of balloon aircraft

There are three main types of balloon aircraft:

- Hot air balloons obtain their buoyancy by heating the air inside the balloon. They are the most common type of balloon aircraft. "Hot air balloon" is sometimes used incorrectly to denote any balloon that carries people.
- Gas balloons are inflated with a gas of lower molecular weight than the ambient atmosphere. Most gas balloons operate with the internal pressure of the gas being the same as the pressure of the surrounding atmosphere. There is a type of gas balloon, called a superpressure balloon, that can operate with the lifting gas at pressure that exceeds the pressure of the surrounding air, with the objective of limiting or eliminating the loss of gas from day-time heating. Gas balloons are filled with gases such as:
    - hydrogen - not widely used for aircraft since the Hindenburg disaster because of high flammability (except for some sport balloons as well as nearly all unmanned scientific and weather balloons).
    - helium - the gas used today for all airships and most manned balloons.
    - ammonia - used infrequently due to its caustic qualities and limited lift.
    - coal gas - used in the early days of ballooning; it is highly flammable.
    - methane - used as a lower cost lifting gas, but offering less lift than helium or hydrogen.
- Rozière balloons use both heated and unheated lifting gases. The most common modern use of this type of balloon is for long-distance record flights such as the recent circumnavigations.

History

A modern Kongming Lantern

The hot air balloon Kongming lantern was developed for military communications around the second or third century AD in China. It is thought that some ancient civilizations may have developed manned hot air balloon flight. For example, the Nazca lines (which are best seen from the air) allegedly presuppose some form of manned flight, such as a balloon.

In 1709 in Lisbon, Bartolomeu de Gusmão made a balloon filled with heated air rise inside a room. He also made a balloon named Passarola (English: Big bird) and attempted to lift himself from Saint George Castle in Lisbon, but only managed to harmlessly fall about one kilometre away. This claim is not generally recognized by aviation historians outside the Portuguese speaking community, in particular the FAI.

A model of the Montgolfier brothers balloon at the London Science Museum

Following Henry Cavendish's 1766 work on hydrogen, Joseph Black proposed that a balloon filled with hydrogen would be able to rise in the air.

The first recorded manned flight was made in a hot air balloon built by the Montgolfier brothers on November 21, 1783. The flight started in Paris and reached a height of 500 feet or so. The pilots, Jean-François Pilâtre de Rozier and François Laurent d'Arlandes, covered about 5½ miles in 25 minutes.

Only a few days later, on December 1, 1783, Professor Jacques Charles and Nicholas Louis Robert made the first gas balloon flight, also from Paris. Their hydrogen-filled

balloon flew to almost 2,000 feet (600 m), stayed aloft for over 2 hours and covered a distance of 27 miles (43 km), landing in the small town of Nesles-la-Vallée.

The first aircraft disaster occurred in May 1785 when the town of Tullamore, County Offaly, Ireland was seriously damaged when the crash of a balloon resulted in a fire that burned down about 100 houses, making the town home to the world's first aviation disaster. To this day, the town shield depicts a phoenix rising from the ashes.

Balloon landing in Mashgh square, Iran (Persia), at the time of Nasser al-Din Shah Qajar, around 1850.

Blanchard went on to make the first manned flight of a balloon in America on January 9, 1793. His hydrogen filled balloon took off from a prison yard in Philadelphia, Pennsylvania. The flight reached 5,800 feet (1,770 m) and landed in Gloucester County, New Jersey. President George Washington was among the guests observing the takeoff.

Gas balloons became the most common type from the 1790s until the 1960s. The French military observation balloon L'Intrépide of 1795 is the oldest preserved aircraft in Europe; it is on display in the Heeresgeschichtliches Museum in Vienna.

The first steerable balloon (also known as a dirigible) was flown by Henri Giffard in 1852. Powered by a steam engine, it was too slow to be effective. As it did with heavier-than-air flight, the internal combustion engine made dirigibles – especially blimps – practical, starting in the late 19th century. In 1857 balloonist American John Steiner attempted an ambitious flight across Lake Erie:

> He arose to the height of about three miles, and started off at a slow but steady rate ... The lake could be seen from one end to the other nearly ... At one time Mr. Steiner counted 38 sail vessels, all in sight, and far below him. The hands on board several of the vessels saw him, and rightly apprehending that he was an aeronaut, cheered him heartily ... He neared the Canada shore a little below Long Point ... he was accordingly driven towards Buffalo ... Night was drawing on and it became apparent that he could not, with this current, get away from the water before dark, and after nightfall it would not be safe to come down. Seeing a propeller ... the Mary Stewart ... He first struck the water about 25 miles below Long Point ... During this time Mr. Steiner says he thinks his balloon bounded from the water at least twenty times. It would strike and then rebound, like a ball, going into the air from twenty to fifty feet, and still rushing down the lake at railroad speed ... Mr. Steiner then abandoned the balloon, leaping into the water and swimming towards the boat, which speedily reached him... -- New York Times, July 23, 1857

In 1872 Paul Haenlein flew the first (tethered) internal combustion motor powered balloon. The first to fly in an untethered airship powered by an internal combustion engine was Alberto Santos Dumont in 1898.

Henri Giffardalso developed a tethered balloon for passengers in 1878 in the Tuileries Garden in Paris. The first tethered balloon in modern times was made in France at Chantilly Castle in 1994 by Aerophile SA.

Ed Yost redesigned the hot air balloon in the late 1950s using rip-stop nylon fabrics and high-powered propane burners to create the modern hot air balloon. His first flight of such a balloon, lasting 25 minutes and covering 3 miles (5 km), occurred on October 22, 1960 in Bruning, Nebraska. Yost's improved design for hot air balloons triggered the modern sport balloon movement. Today, hot air balloons are much more common than gas balloons.

Balloons as flying machines

A tethered helium balloon gives the public rides to 500 feet (150 m) above the city of Bristol, England. The inset shows detail of the gondola.

A balloon is conceptually the simplest of all flying machines. The balloon is a fabric envelope filled with a gas that is lighter than the surrounding atmosphere. As the entire balloon is less dense than its surroundings, it rises, taking along with it a basket, attached underneath, that carries passengers or payload. Although a balloon has no propulsion system, a degree of directional control is possible through making the balloon rise or sink in altitude to find favorable wind directions.

The first balloons capable of carrying passengers used hot air to obtain buoyancy and were built by the brothers Josef and Etienne Montgolfier in Annonay, France.

Balloons using the light gas hydrogen for buoyancy were flown less than a month later. They were invented by Professor Jacques Charles and first flown on December 1, 1783. Gas balloons have greater lift and can be flown much longer than hot air, so gas balloons dominated ballooning for the next 200 years. In the 19th century, it was common to use town gas to fill balloons; it was not as light as pure hydrogen gas, but was much cheaper and readily available.

The third balloon type was invented by Pilâtre de Rozier and is a hybrid of a hot air and a gas balloon. Gas balloons have an advantage of being able to fly for a long time, and hot air balloons have an advantage of being able to easily change altitude, so the Rozier balloon was a hydrogen balloon with a separate hot air balloon attached. In 1785, Pilâtre de Rozier took off in an attempt to fly across the English Channel, but the balloon exploded a half-hour into the flight. This accident earned de Rozier the title "The First to Fly and the First to Die". It wasn't until the 1980s that technology once again allowed the Rozier balloons to become feasible.

Hot air balloons, San Diego, California

Jean-Pierre Blanchard made the first piloted balloon flight in North America on January 9, 1793.

Both the hot air, or Montgolfière, balloon and the gas balloon are still in common use. Montgolfière balloons are relatively inexpensive as they do not require high-grade materials for their envelopes, and they are popular for balloonist sport activity.

A new way of flying in a gas balloon is with a tether. Notable balloons are in Paris since 1999, in Berlin since 2000, in Disneyland Resort Paris since 2005 with more than 100 000 passengers per year, and the DHL Balloon in Singapore since 2006. All of them have been made by Aerophile SA. Aerophile Balloon is also operated in the San Diego Wild Animal Park in California which has been in operation since the year 2005.

Gas balloons at the Albuquerque International Balloon Fiesta

Light gas balloons are predominant in scientific applications, as they are capable of reaching much higher altitudes for much longer periods of time. They are generally filled with helium. Although hydrogen has more lifting power, it is explosive in an atmosphere rich in oxygen. With a few exceptions, scientific balloon missions are unmanned.

There are two types of light-gas balloons: zero-pressure and superpressure. Zero-pressure balloons are the traditional form of light-gas balloon. They are partially inflated with the

light gas before launch, with the gas pressure the same both inside and outside the balloon. As the zero-pressure balloon rises, its gas expands to maintain the zero pressure difference, and the balloon's envelope swells.

At night, the gas in a zero-pressure balloon cools and contracts, causing the balloon to sink. A zero-pressure balloon can only maintain altitude by releasing gas when it goes too high, where the expanding gas can threaten to rupture the envelope, or releasing ballast when it sinks too low. Loss of gas and ballast limits the endurance of zero-pressure balloons to a few days.

A special-shape hot air balloon - Chubb fire extinguisher

A superpressure balloon, in contrast, has a tough and inelastic envelope that is filled with light gas to pressure higher than that of the external atmosphere, and then sealed. The superpressure balloon cannot change size greatly, and so maintains a generally constant volume. The superpressure balloon maintains an altitude of constant density in the atmosphere, and can maintain flight until gas leakage gradually brings it down.

Superpressure balloons offer flight endurance of months, rather than days. In fact, in typical operation an Earth-based superpressure balloon mission is ended by a command from ground control to open the envelope, rather than by natural leakage of gas.

For air transport balloons must contain a gas lighter than the surrounding air. There are two types:

- Hot air balloon: filled with hot air, which by heating becomes lighter than the surrounding air; they have been used to carry human passengers since the 1790s;
- Balloons filled with:
  - hydrogen - highly flammable
  - helium - safe if used properly, but very expensive.

Large helium balloons are used as high flying vessels to carry scientific instruments (as do weather balloons), or even human passengers with a tether like in İstanbul, Paris, Berlin, Hong Kong or Singapore.

Cluster ballooning uses many smaller gas-filled balloons for flight.

Balloons in the military

The first military use of a balloon was at the Battle of Fleurus in 1794, when L'Entreprenant was used by the French Aerostatic Corps to watch the movements of the enemy. On April 2, 1794, an aeronauts corps was created in the French army; however, given the logistical problems linked with the production of hydrogen on the battlefield (it required constructing ovens and pouring water on white-hot iron), the corps was disbanded in 1799.

American Civil War

The first major-scale use of balloons in the military occurred during the American Civil War with the Union Army Balloon Corps established and organized by Prof. Thaddeus S. C. Lowe in the summer of 1861. Originally, the balloons were inflated with coal gas from municipal services and then walked out to the battlefield, an arduous and inefficient operation as the balloons had to be returned to the city every four days for re-inflation. Eventually hydrogen gas generators, a compact system of tanks and copper plumbing, were constructed which converted the combining of iron filings and sulfuric acid to hydrogen. The generators were easily transported with the uninflated balloons to the field on a standard buckboard. In all, Lowe built seven balloons that were fit for military service.

The first application thought useful for balloons was map-making from aerial vantage points, thus Lowe's first assignment was with the Topographical Engineers. General Irvin McDowell, commander of the Army of the Potomac, realized their value in aerial reconnaissance and had Lowe, who at the time was using his personal balloon the Enterprise, called up to the First Battle of Bull Run. Lowe also worked as a Forward Artillery Observer (FAO) by directing artillery fire via flag signals. This enabled gunners on the ground to fire accurately at targets they could not see, a military first.

Lowe's first military balloon, the Eagle was ready by October 1, 1861. It was called into service immediately to be towed to Lewinsville, Virginia, without any gas generator which took longer to build. The trip began after inflation in Washington, D.C. and turned into a 12 mile (19 km), 12-hour excursion that was upended by a gale force wind which ripped the aerostat from its netting and sent it sailing to the coast. Balloon activities were suspended until all balloons and gas generators were completed.

With his ability to inflate balloons from remote stations, Lowe, his new balloon the Washington and two gas generators were loaded onto a converted coal barge the George Washington Parke Custis. As he was towed down the Potomac, Lowe was able to ascend and observe the battlefield as it moved inward on the heavily forested peninsula. This would be the military's first claim of an aircraft carrier.

The Union Army Balloon Corps enjoyed more success in the battles of the Peninsula Campaign than the Army of the Potomac it sought to support. The general military attitude toward the use of balloons deteriorated, and by August 1863 the Balloon Corps was disbanded.

The Confederate Army also made use of balloons, but they were gravely hampered by supplies due to the embargoes. They were forced to fashion their balloons from colored silk dress-making material, and their use was limited by the infrequent supply of gas in Richmond, Virginia. By the summer of 1863, all balloon reconnaissance of the Civil War had ceased.

After the American Civil War

In Britain during July 1863, experimental balloon ascents for reconnaissance purposes were conducted by the Royal Engineers on behalf of the British Army, but although the experiments were successful it was considered not worth pursuing further because it was too expensive. However by 1888 a School of Ballooning was established at Chatham, Medway, Kent.

During the Paraguayan War of the Triple Alliance (1864–70), balloons were also used for observation by the Brazilian Army.

Balloons were used by the Royal Engineers for reconnaissance and observation purposes during the Bechuanaland Expedition (1885), the Sudan Expedition (1885) and during the

Anglo-Boer War (1899–1902). A 11,500 cubic feet (330 m^3) balloon was kept inflated for 22 days and marched 165 miles into the Transvaal with the British forces.

Hydrogen-filled balloons were also widely used during World War I (1914–1918) to detect enemy troop movements and to direct artillery fire. Observers phoned their reports to officers on the ground who then relayed the information to those who needed it. Balloons were frequently targets of opposing aircraft. Planes assigned to attack enemy balloons were often equipped with incendiary bullets, for the purpose of igniting the hydrogen.

The Aeronaut Badge was established by the United States Army in World War I to denote service members who were qualified balloon pilots. Observation balloons were retained well after the Great War, being used in the Russo-Finnish Wars, the Winter War of 1939-40, and the Continuation War of 1941-45.

During WWII the Japanese launched thousands of helium "fire balloons" against the United States and Canada. In Operation Outward the British used balloons to carry incendiaries to Nazi Germany.

Records

On May 27, 1931, Auguste Piccard and Paul Kipfer became the first to reach the stratosphere in a balloon.

On March 1, 1999 Bertrand Piccard and Brian Jones set off in the balloon Breitling Orbiter 3 from Château d'Oex in Switzerland on the first non-stop balloon circumnavigation around the globe. They landed in Egypt after a 45,755 kilometers flight lasting 19 days, 21 hours and 47 minutes (95.77 km/h / 59.47 mph).

On August 31, 1933, Alexander Dahl took the first picture of the Earth's curvature in an open hydrogen gas balloon.

The altitude record for a manned balloon was set at 34,668 meters (113,739 ft) on May 4, 1961 by Malcolm Ross and Victor Prather in the Stratolab V balloon payload launched from the deck of the USS Antietam in the Gulf of Mexico.

The altitude record for an unmanned balloon is 53.0 kilometres (173,882 ft), reached with a volume of 60,000 cubic metres. The balloon was launched by JAXA on May 25, 2002 from Iwate Prefecture, Japan. This is the greatest height ever obtained by an atmospheric vehicle. Only rockets, rocket planes, and ballistic projectiles have flown higher.

Balloons in space

The Echo satellite was a balloon launched into Earth orbit in 1960 and used for passive relay of radio communication. PAGEOS was another "satelloon" launched in 1966 for

worldwide satellite triangulation, allowing for greater precision in the calculation of different locations on the planet's surface.

In 1984 the Soviet space probes Vega 1 and Vega 2 released two balloons with scientific experiments in the atmosphere of Venus. They transmitted signals for two days to Earth.

Chapter 7

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 8

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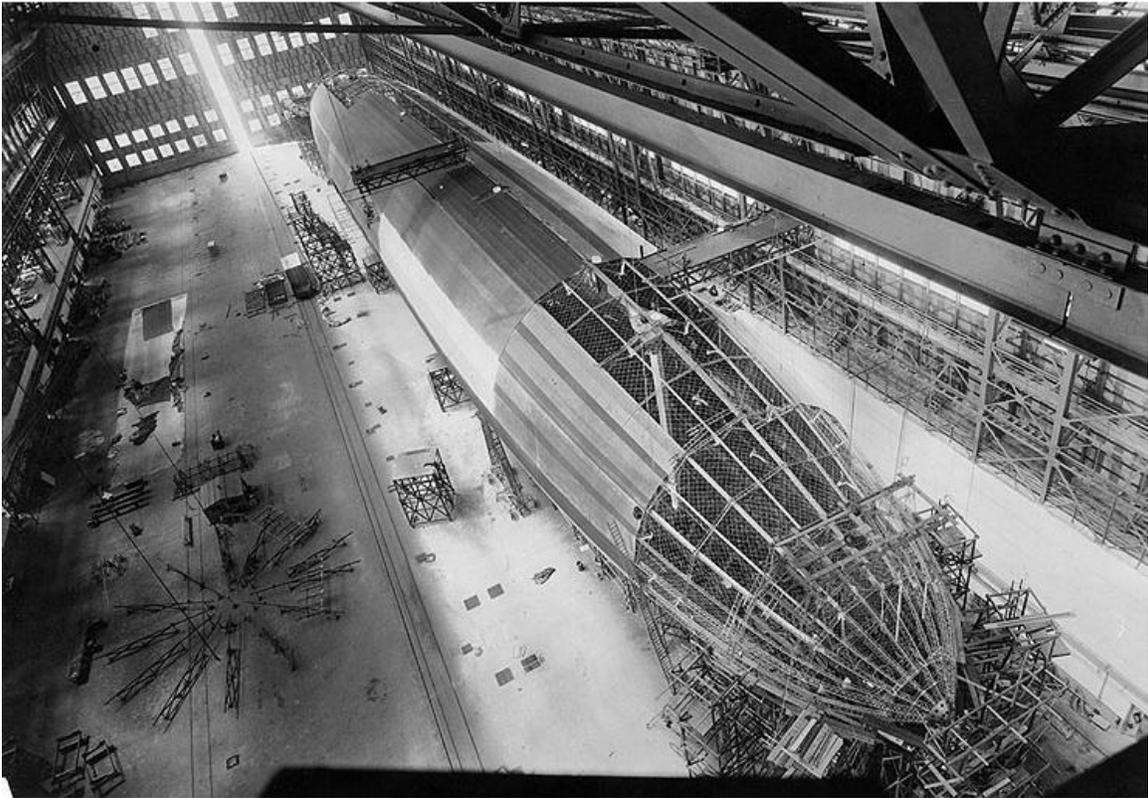
Construction of USS Shenandoah (ZR-1), 1923, showing the framework of a rigid airship

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 9

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
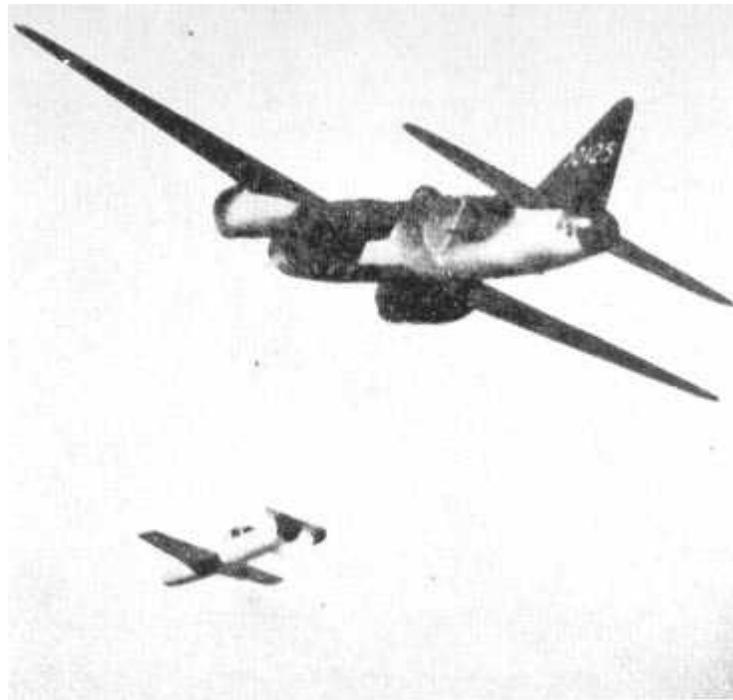
A Japanese Mitsubishi G4M launching the Ohka

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

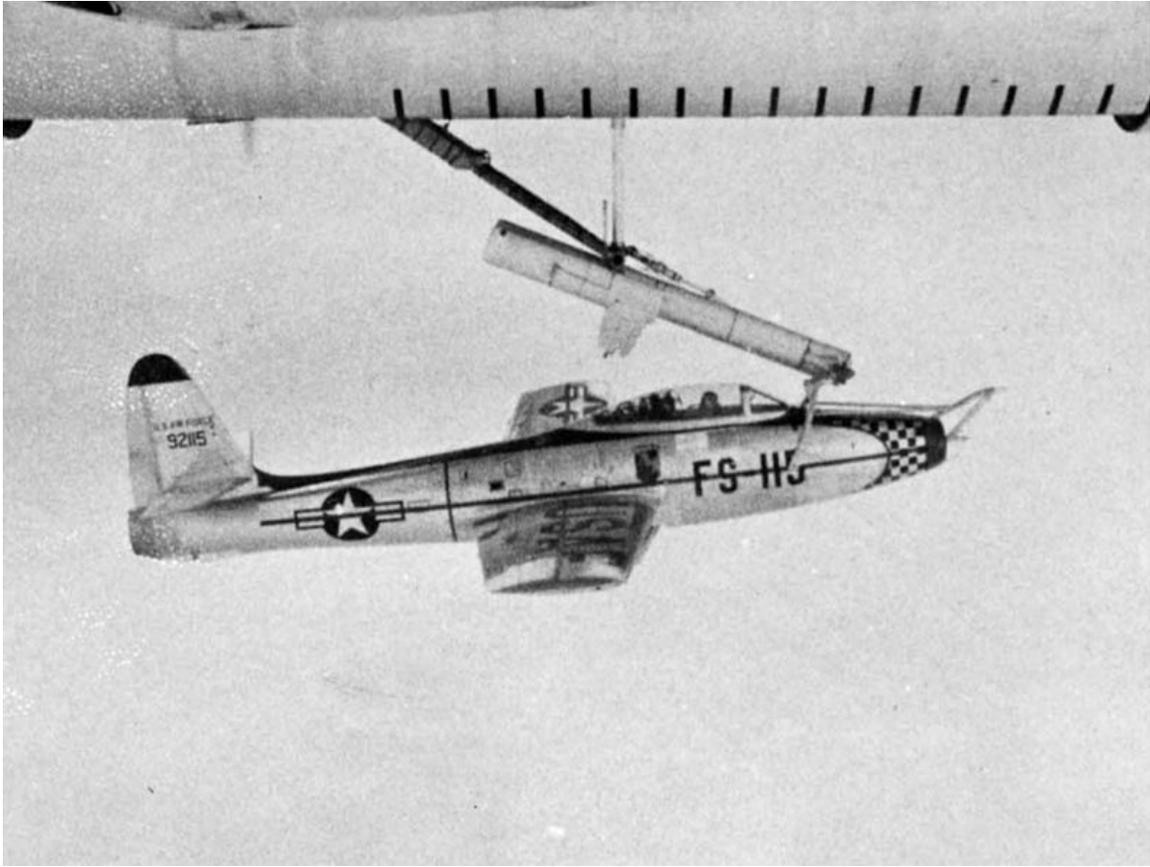The Akron in flight, November 1931
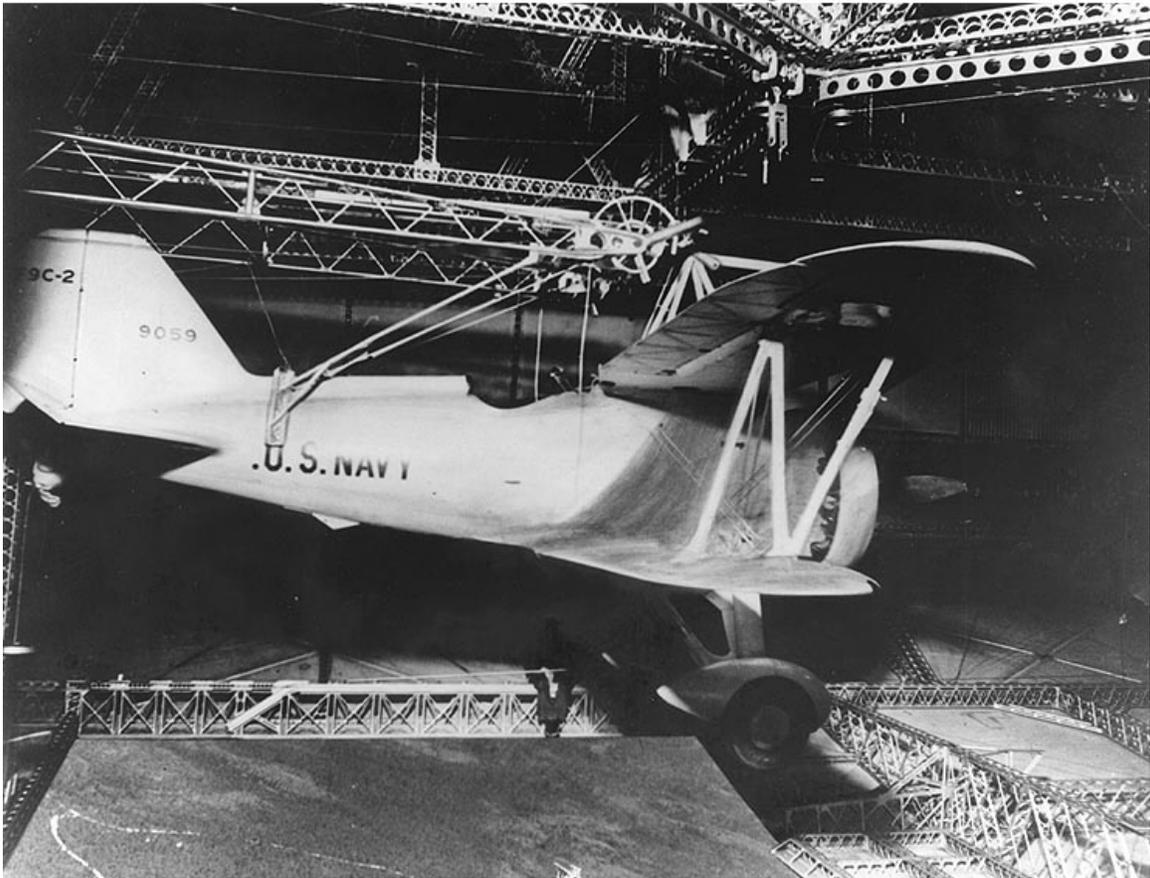
F9C Sparrowhawk inside Akron's hangar

Photo # 80-CF-4184-14   XF9C-1 aircraft hooking onto USS Akron, May 1932
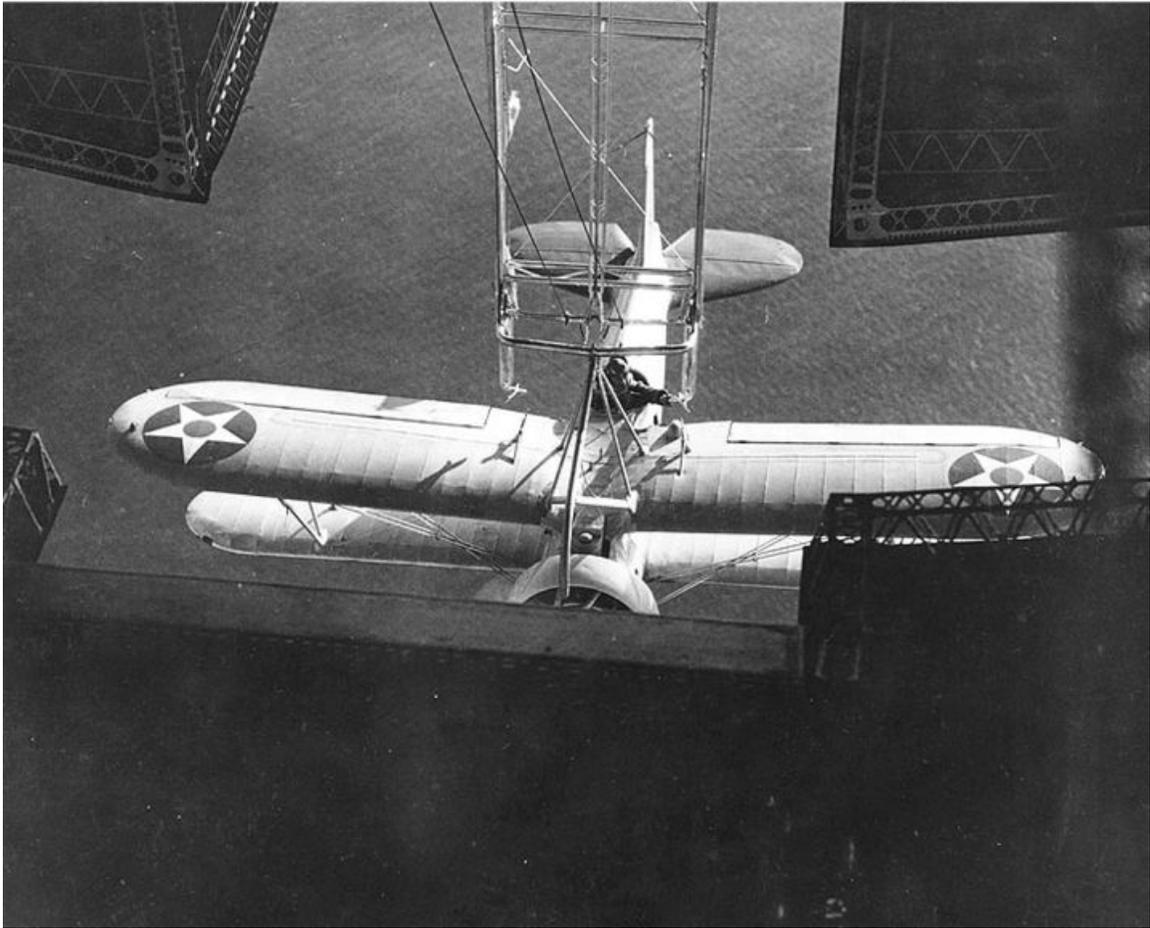
F9C Sparrowhawk successfully hooks on to Akron trapeze, May 1932

A Republic F-84E on FICON trapeze

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

Chapter 10

Tiltrotor

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 11

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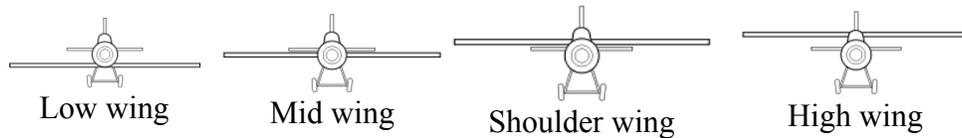
A fixed wing aircraft may have more than one wing plane, stacked one above another:

- **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.
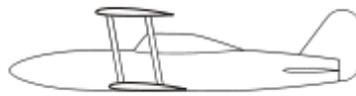

Parasol wing   Biplane   Sesquiplane
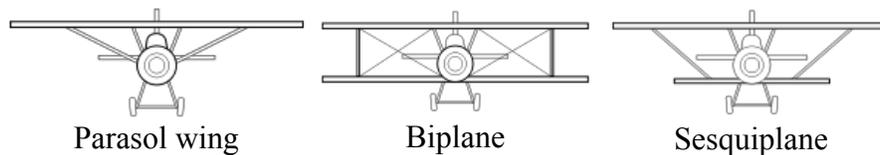
- **Triplane** - three planes stacked one above another. Triplanes such as the Fokker Dr.I enjoyed a brief period of popularity during the First World War due to their small size and high manoeuvrability as fighters, but were soon replaced by improved biplanes.

- **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.
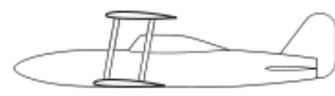

Triplane   Quadruplane   Multiplane
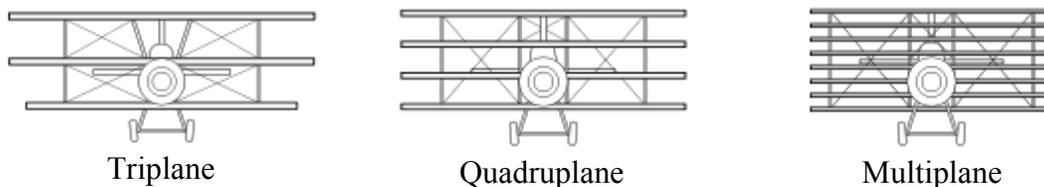
A **staggered** design has the upper wing slightly forward of the lower. This helps give stability to stacked wings, and is usual on successful designs. Backwards stagger is also seen in a few examples such as the de Havilland D.H. 5, Sopwith Dolphin, and Beechcraft Staggerwing.
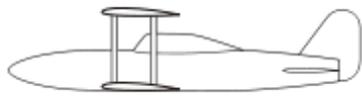
Unstaggered biplane   Forwards stagger   Backwards stagger

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.
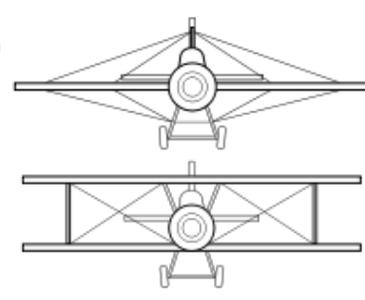
The types are:

- **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.
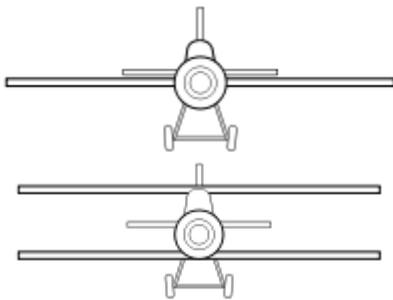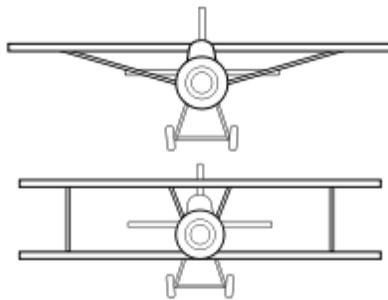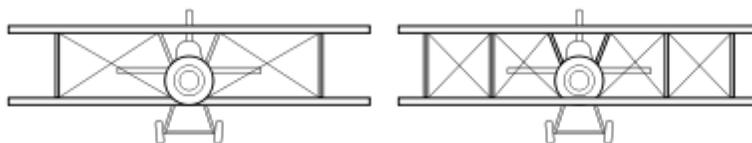
Cantilever   Strut braced   Wire braced

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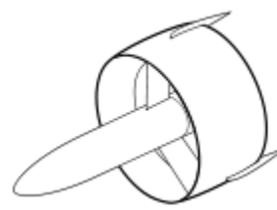
- **Combined** or **closed wing** - two wings are joined structurally at or near the tips in some way. This stiffens the structure, and can reduce aerodynamic losses at the tips. Variants include:
    - **Box wing** - upper and lower planes are joined by a vertical fin between their tips. Some Dunne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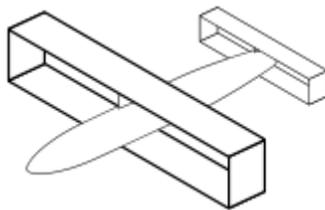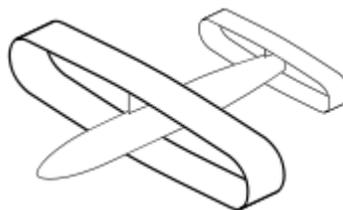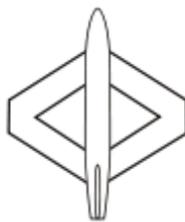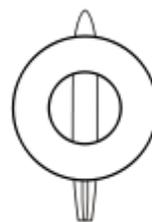
Box wing   Annular box wing   Cylindrical wing

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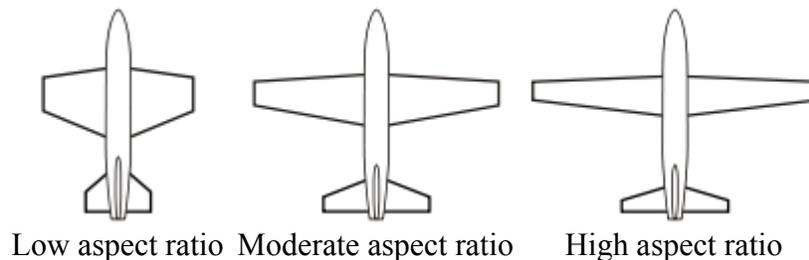
Most Variable geometry configurations vary the aspect ratio in some way, either deliberately or as a side effect.

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.

| Straight | Swept | Forward swept | Variable sweep (swing-wing) | Oblique wing |
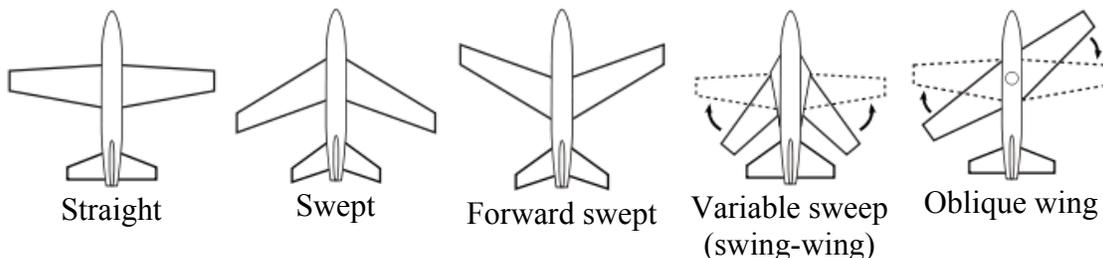
Planform variation along span

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

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

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

Constant chord   Elliptical   Tapered   Reverse tapered   Compound tapered   Trapezoidal
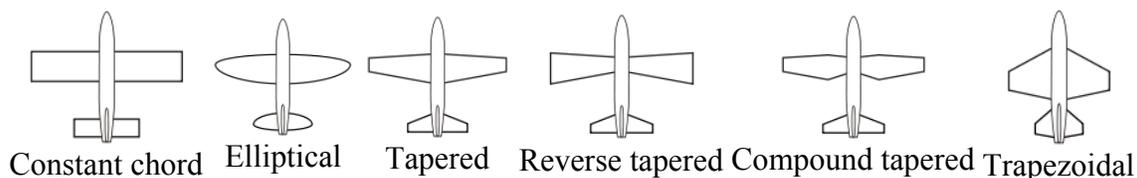
- **Bird like** - a curved shape appearing similar to a bird's outstretched wing. Popular during the pioneer years, and achieved some success on the Etrich Taube.
- **Bat like** - a form with radial ribs which was used for some early designs, especially if the wings were foldable. The Whitehead No. 21 of 1901 is sometimes claimed as the first powered aircraft to fly, over two years before the Wright Flyer.
- **Circular** - approximately circular planform. The Vought XF5U attempted to counteract the large tip vortices by using large propellers rotating in the opposite sense to the vortices.
  - o **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.
  - o **Flat annular wing** - the circle has a hole in, forming a closed wing. A Lee-Richards type was one of the first stable aircraft to fly, shortly before the First World War.

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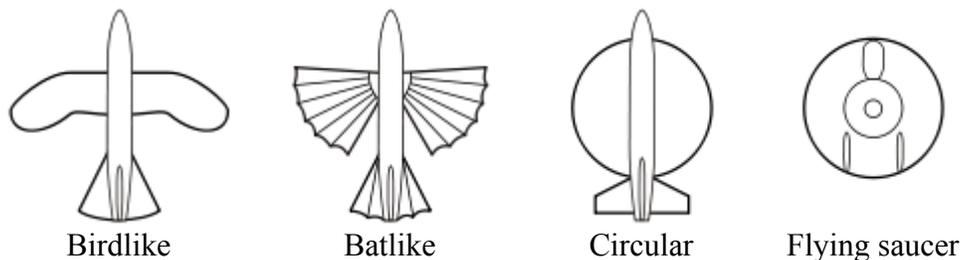
- **Delta** - triangular planform with swept leading edge and straight trailing edge. Offers the advantages of a swept wing, with good structural efficiency. Variants are:
  - o **Tailless delta** - a classic high-speed design, used for example in the widely built Dassault Mirage III series.

- o **Tailed delta** - adds a conventional tailplane, to improve handling. Popular on Soviet types such as the Mikoyan-Gurevich MiG-21.
- o **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.
- o **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.
- o **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
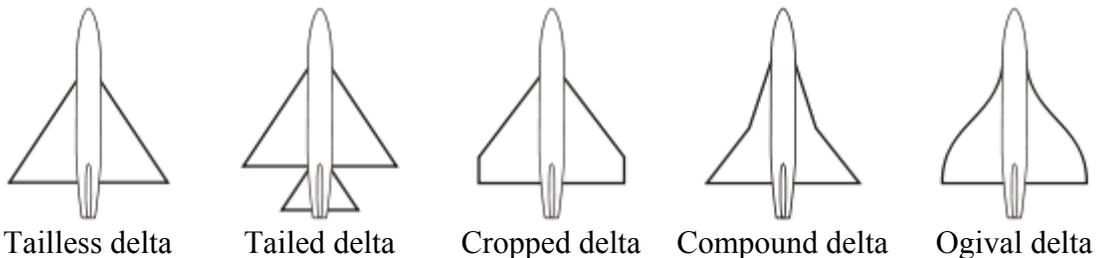
The angle of sweep may also be varied, or cranked, along the span:

- **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
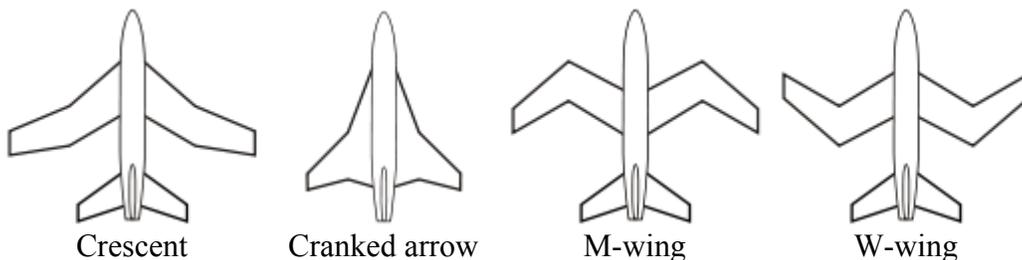
Horizontal stabilizer

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".

Conventional   Canard   Tandem   Tandem triple   Tailless
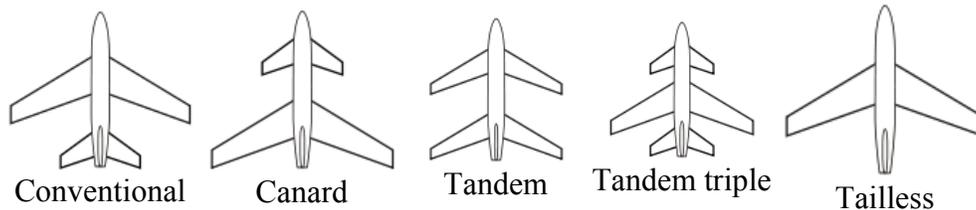
Dihedral and anhedral

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
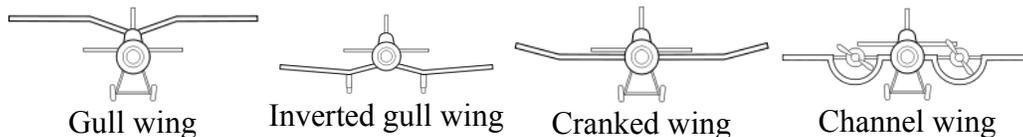
Wings vs. bodies

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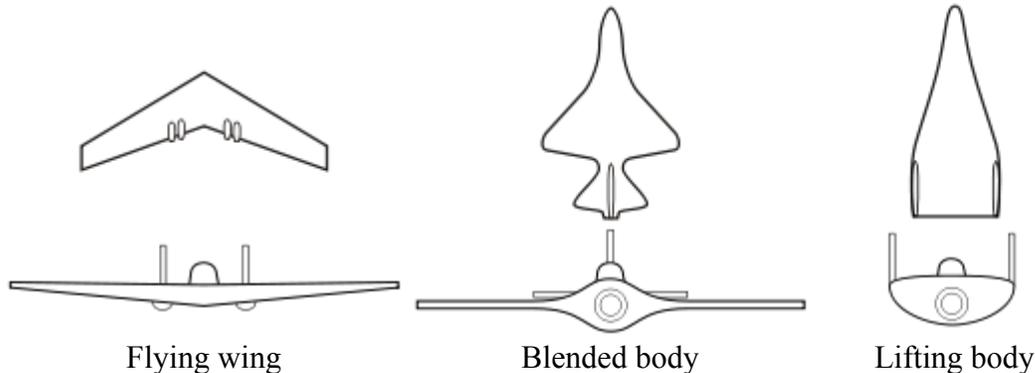
Some proposed designs, typically a sharply-swept delta planform having a deep centre section tapering to a thin outer section, fall across these categories and may be interpreted in different ways, for example as a lifting body with a broad fuselage, or as a low-aspect-ratio flying wing with a deep center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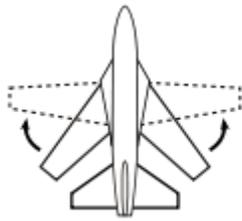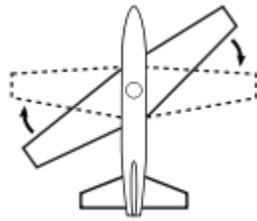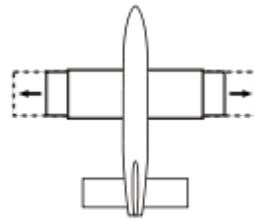
Variable sweep (swing-wing)   Oblique wing   Telescoping wing   Extending wing

- **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 aircraf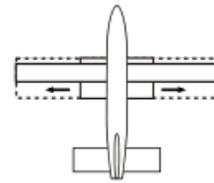t have wings that may be folded for storage on the ground or on board ship. These are not folding wings in the sense used here).
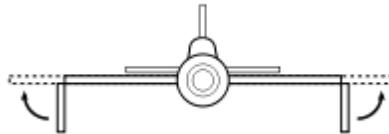
Folding wing

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.
  - o **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.
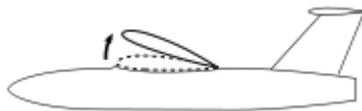
Variable incidence wing   Variable camber aerofoil   Variable thickness aerofoil

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:
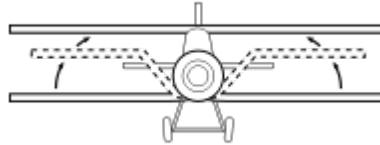
- **Winglet** - a small vertical fin at the wingtip, usually turned upwards. Reduces the size of vortices shed by the wingtip, and hence also tip drag.
- **Chine** - narrow extension to the leading edge wing root, extending far along the forward fuselage. As well as improving low speed (high angle of 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 12

Lifting Body

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

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

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

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

History

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

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

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

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

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

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

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

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

Aerospace applications

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

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

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

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

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

Body lift

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

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

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

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

Lifting body pilots and flights

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

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 14

Conventional Landing Gear

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

Douglas DC-3, a taildragger airliner

A taildragger by Jodel: the 1965 D140C Mousquetaire

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 15

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.