Airship Technology

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Table of Contents

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.

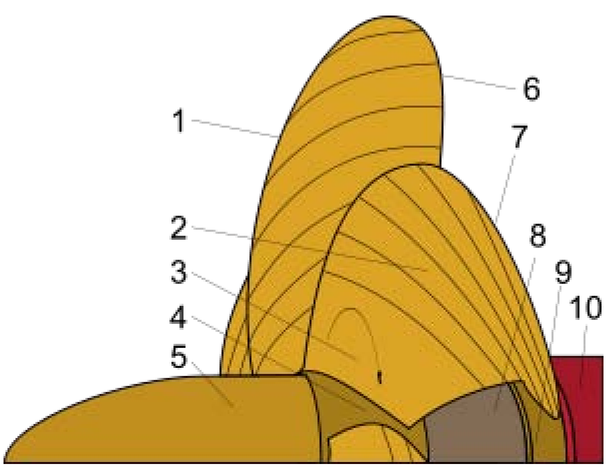
Alberto Santos Dumont was another early pioneer, having designed propellers before the Wright Brothers (albeit not as efficient) for his airships. He applied the knowledge he gained from experiences with airships to make a propeller with a steel shaft and aluminium blades for his 14 bis biplane. Some 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

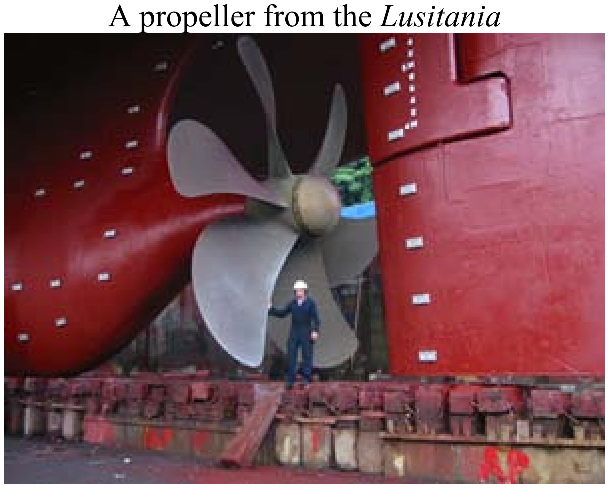
Most propellers have their axis of rotation parallel to the fluid flow. There have however been some attempts to power vehicles with the same principles behind vertical axis wind turbines, where the rotation is perpendicular to fluid flow. Most attempts have been unsuccessful. Blades that can vary their 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*).

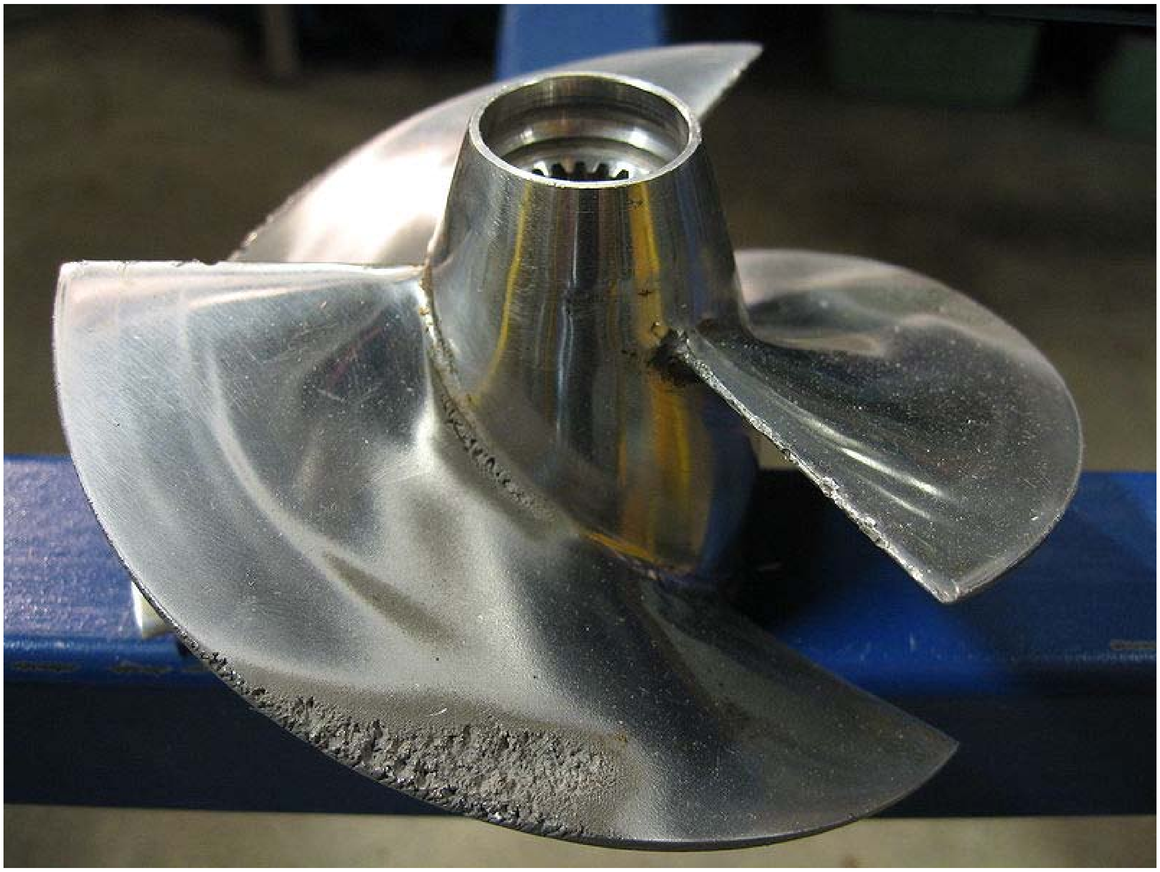
In 1848 the British Admiralty held a tug of war contest between a propeller driven ship, *Rattler*, and a paddle wheel ship, *Alecto*. *Rattler* won, towing *Alecto* astern at 2.5 knots (4.6 km/h), but it was not until the early 20th century that paddle propelled vessels were entirely superseded. The 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:

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

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:

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

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 = $L = \rho V\tau$. 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 $2\pi Nr$. 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*:

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

where:

$$V_1^2 = V_a^2(1+a)^2 + 4\pi^2 r^2 (1-a')^2$$
$$\mathrm{d}D = \frac{1}{2}\rho V_1^2 C_D \mathrm{d}A = \frac{1}{2}\rho C_D [V_a^2(1+a)^2 + 4\pi^2 r^2(1-a')^2] b\mathrm{d}r$$

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

$$\mathrm{d}T = \mathrm{d}L\cos\varphi - \mathrm{d}D\sin\varphi = \mathrm{d}L(\cos\varphi - \frac{\mathrm{d}D}{\mathrm{d}L}\sin\varphi)$$

where:

$$tan\beta = \frac{\mathrm{d}D}{\mathrm{d}L} = \frac{C_D}{C_L}$$
$$= \frac{1}{2}\rho V_1^2 C_L \frac{\cos(\varphi+\beta)}{\cos\beta} b\mathrm{d}r$$

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

$$\mathrm{d}T = \frac{1}{2}\rho C_L \frac{V_a^2(1+a)^2\cos(\varphi+\beta)}{\sin^2\varphi\cos\beta} b\mathrm{d}r$$

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

$$\mathrm{d}M = \mathrm{d}L\sin\varphi + \mathrm{d}D\cos\varphi$$
$$= \mathrm{d}L(\sin\varphi + \frac{\mathrm{d}D}{\mathrm{d}L}\cos\varphi)$$
$$= \frac{1}{2}\rho V_1^2 C_L \frac{\sin(\varphi+\beta)}{\cos\varphi} b\mathrm{d}r$$

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

$$\mathrm{d}Q = r\mathrm{d}M = \frac{1}{2}\rho C_L \frac{V_a^2(1+a)^2\sin(\varphi+\beta)}{\sin^2\varphi\cos\beta} br\mathrm{d}r$$

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 $\varphi$and β, where $\beta$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:

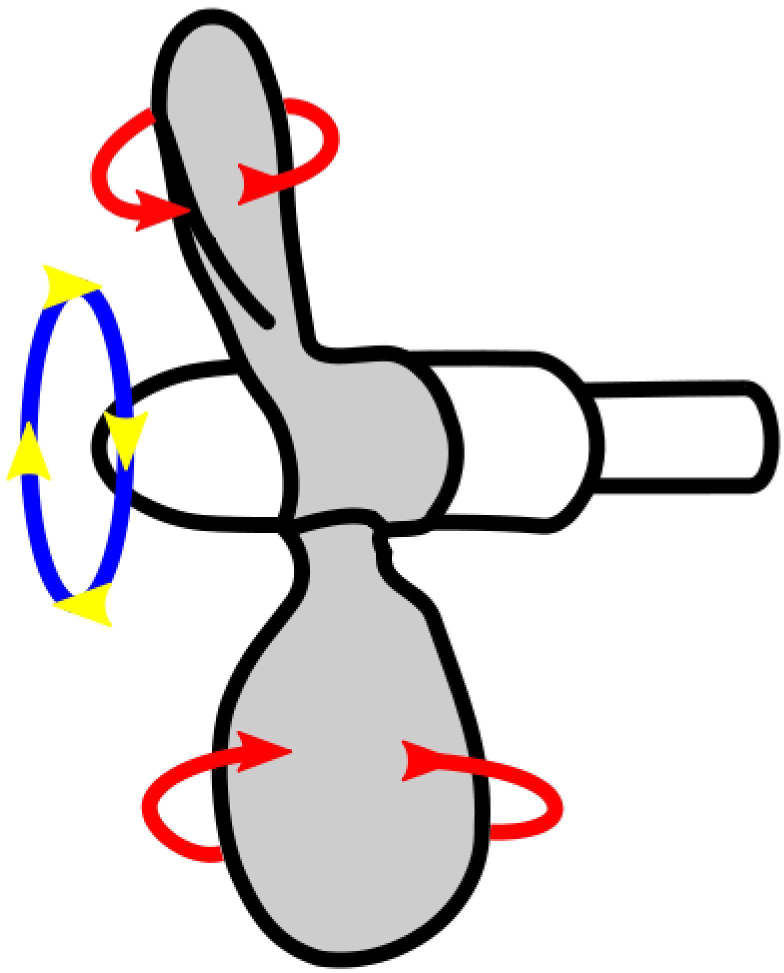
$$PC = \left(\frac{\eta_H \cdot \eta_O \cdot \eta_R}{\text{appendage coefficient}}\right) \cdot \text{transmission efficiency}$$

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.

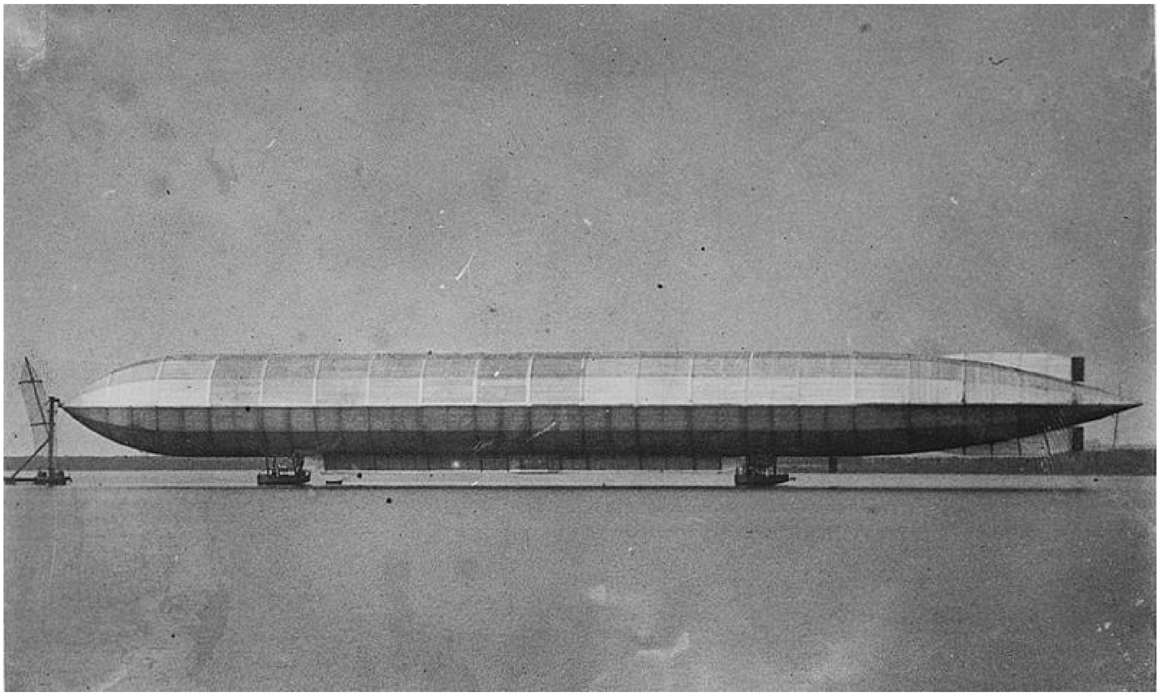
Chapter 2

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.



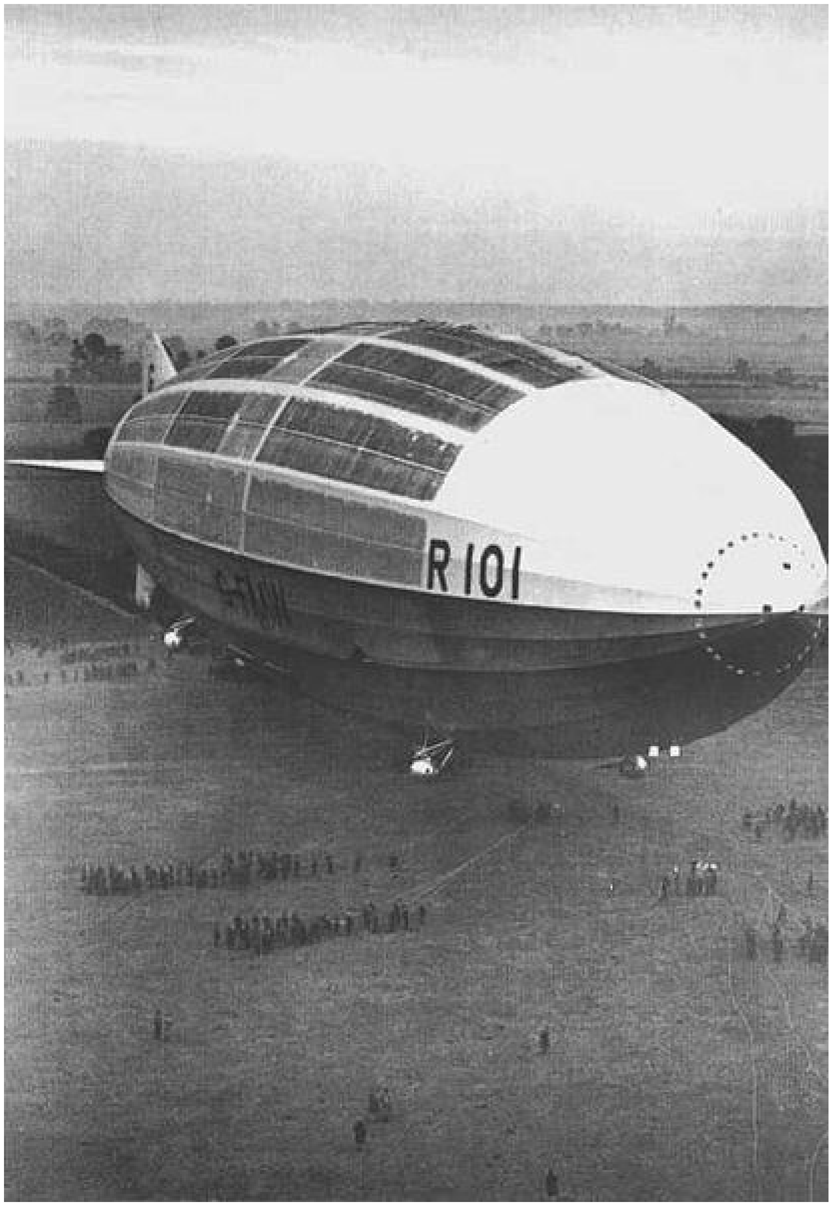
HMA No 1 (Mayfly) – the first airship known to have been moored to a mast.

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

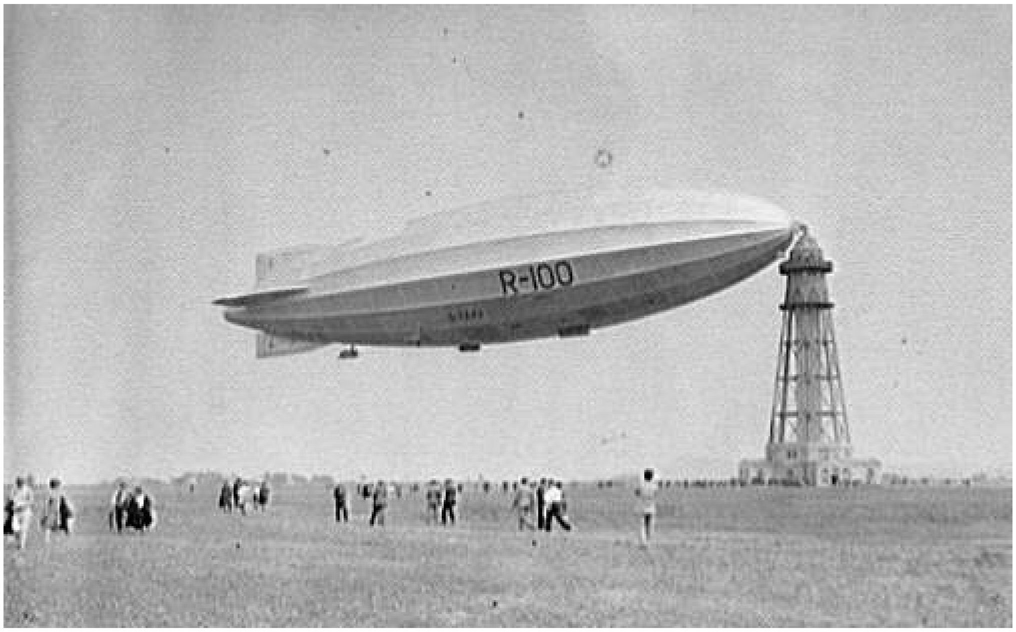


The *R101* being handled on the ground, showing the size of the landing party required to manage a large airship. One purpose of a mooring mast was to reduce the number of men needed to manage the landing process.

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):

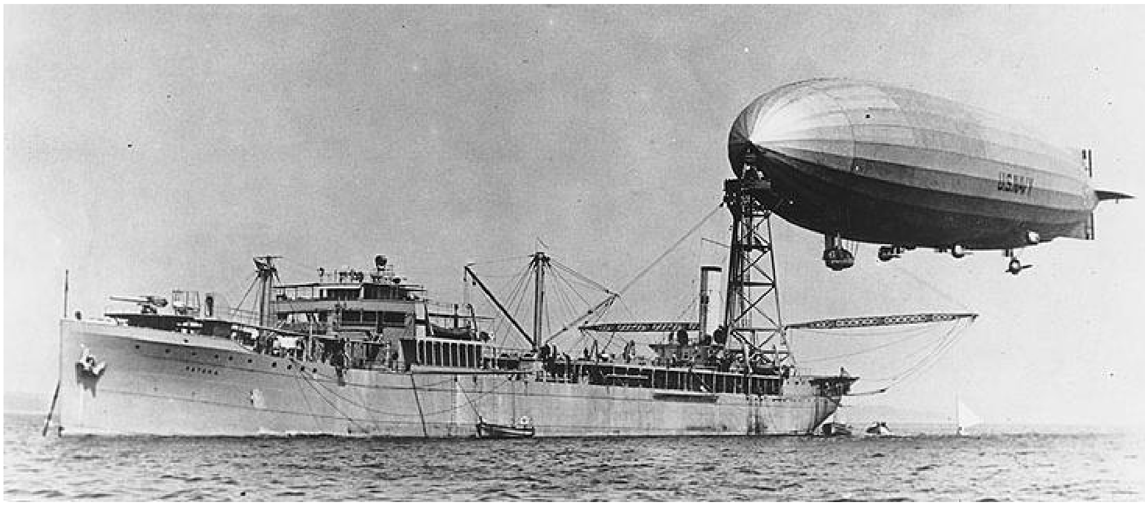
Before attempting a landing, contact was made by radio or flag signals with the ground crew to determine the ground temperature and wind conditions. For a normal calm weather landing the ship was trimmed very slightly nose down, as this gave a better gliding angle and the ship almost flew herself down. 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.

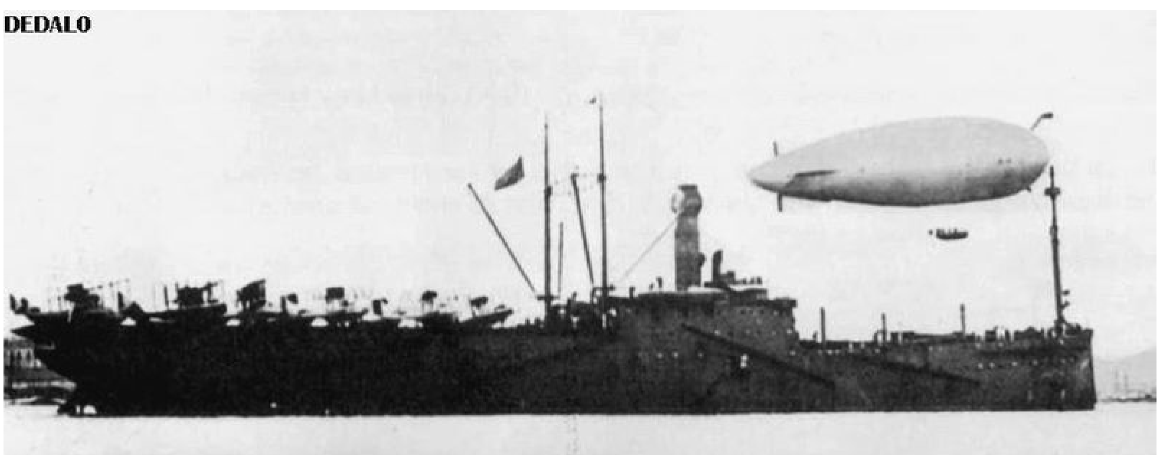
Ship-mounted mooring masts



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.



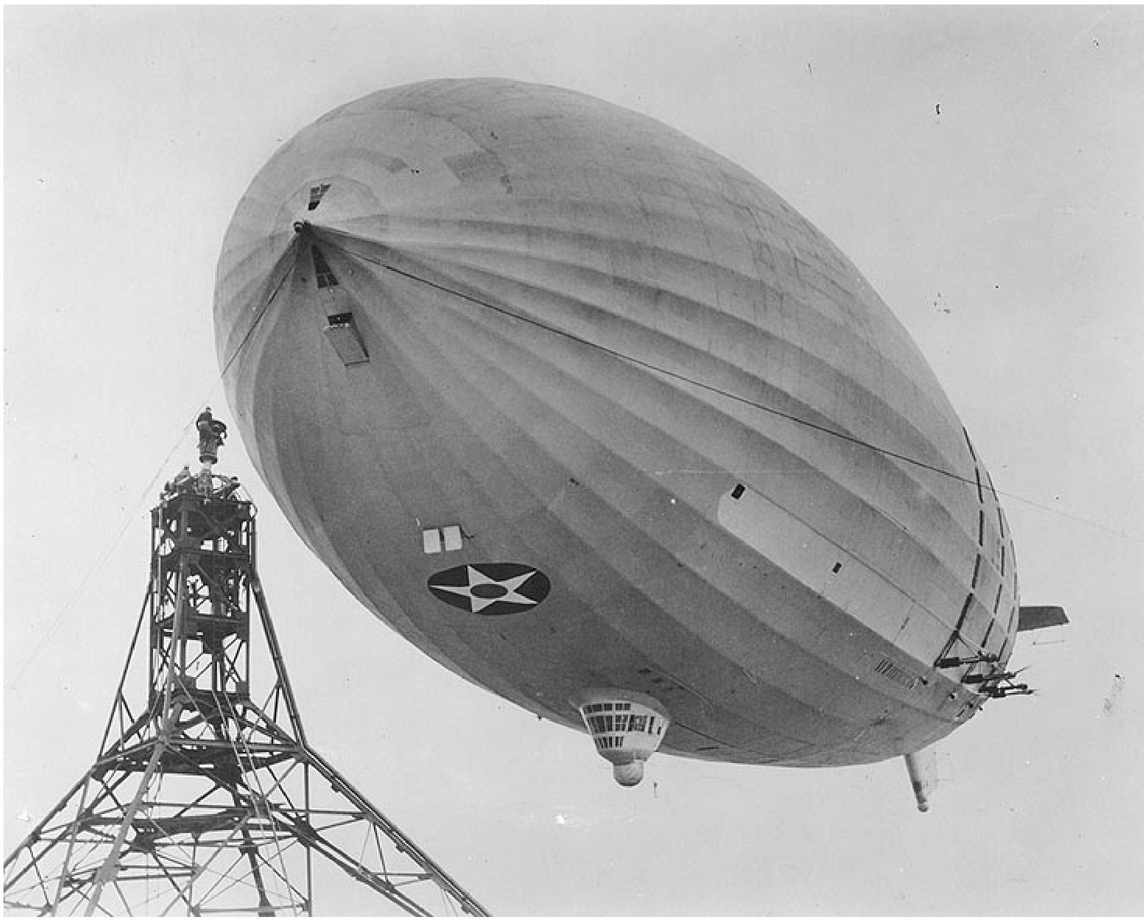
Spanish seaplane carrier Dédalo.

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

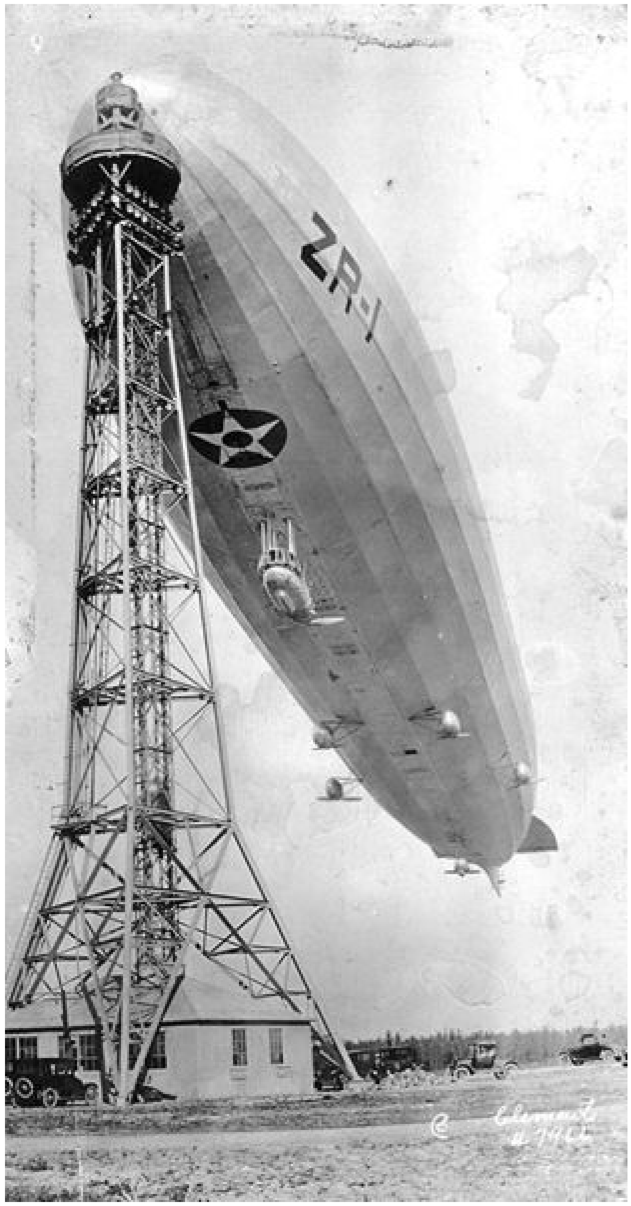
Modern mast operations

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.

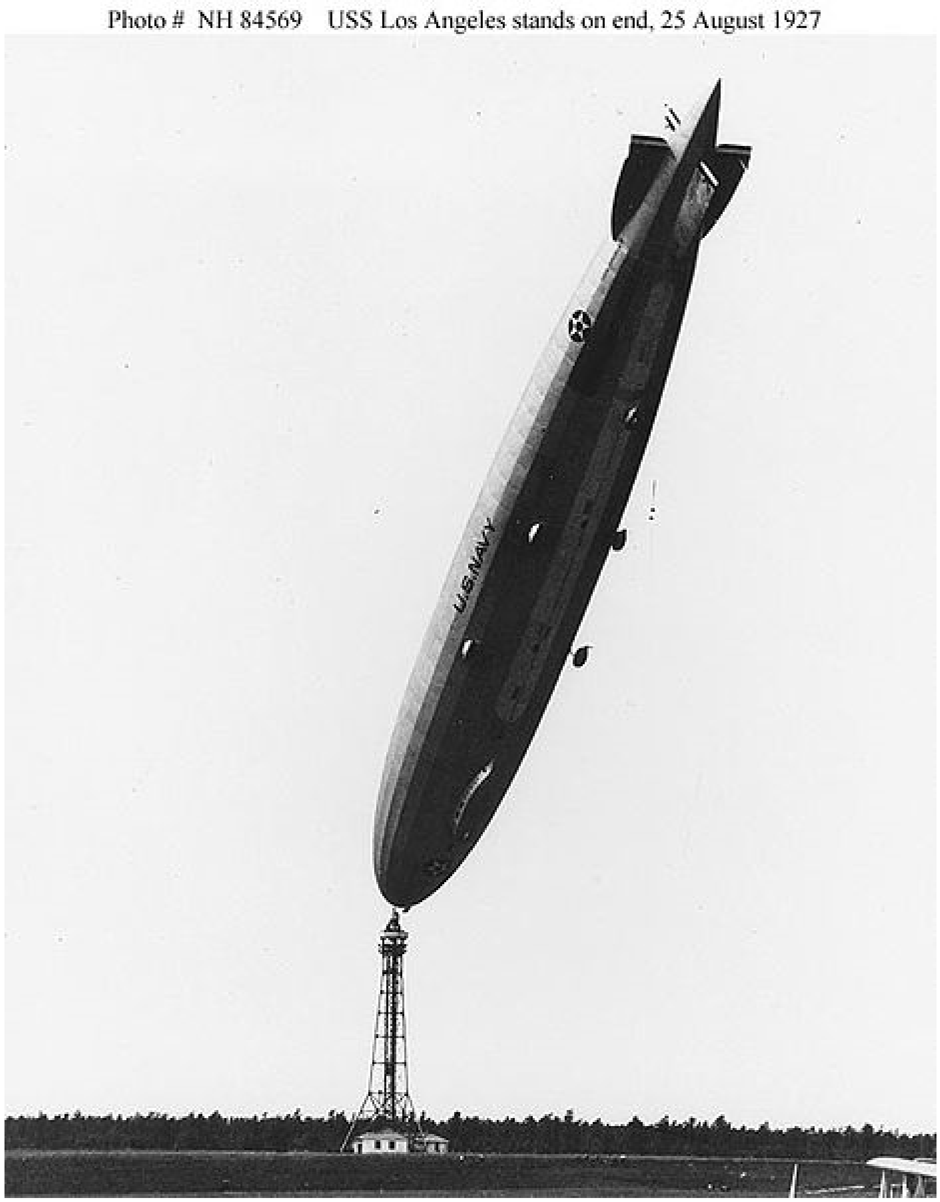
Gallery



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 balloon in flight

Hot air balloons shaped as bees

Hot air balloon shaped as a turtle

Hot air balloon shaped as a Abbey of Saint Gall

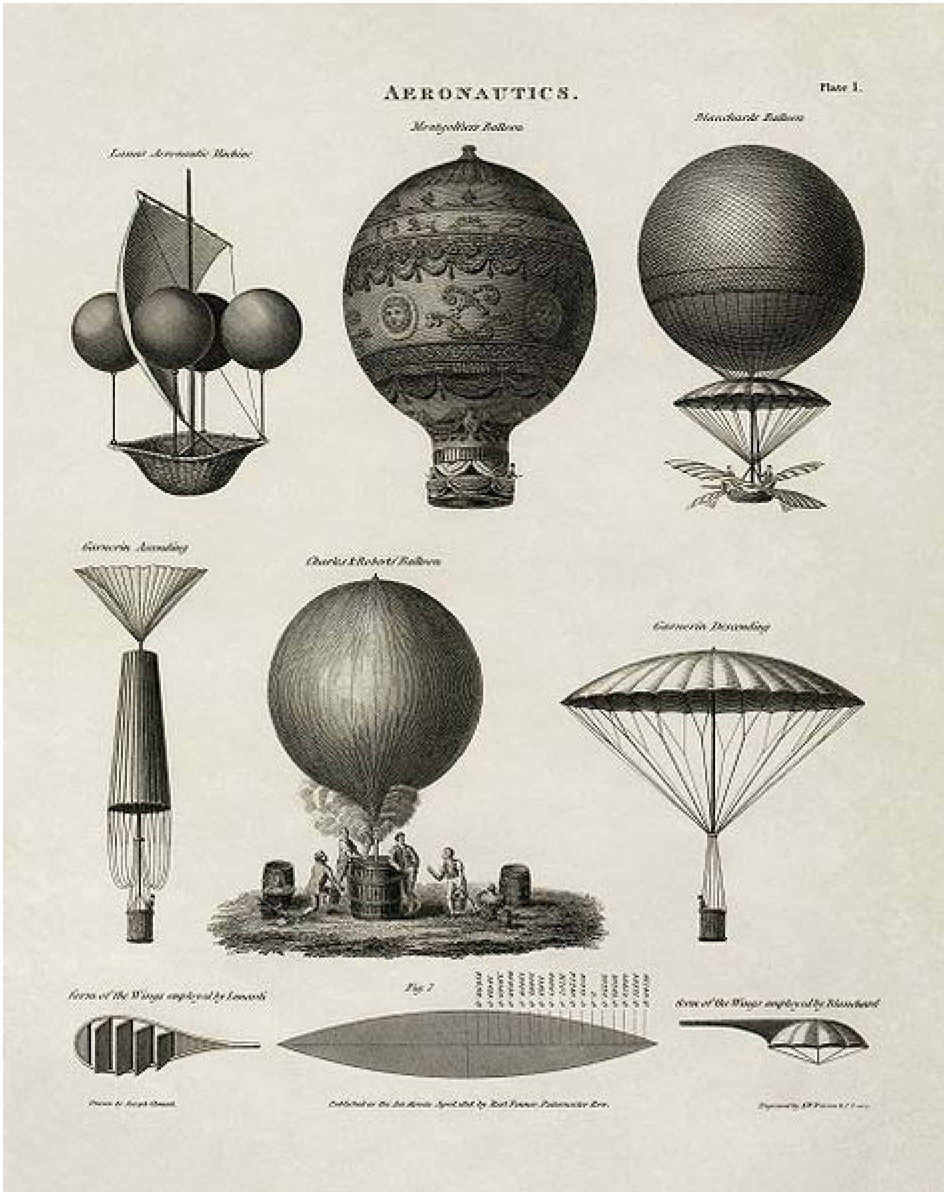
The **hot air balloon** is the oldest successful human-carrying flight technology. It is in a class of aircraft known as balloon aircraft. On Nov 21, 1783, in Paris, France, the first untethered manned flight was made by Jean-François Pilâtre de Rozier and François Laurent d'Arlandes in a hot air balloon 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.

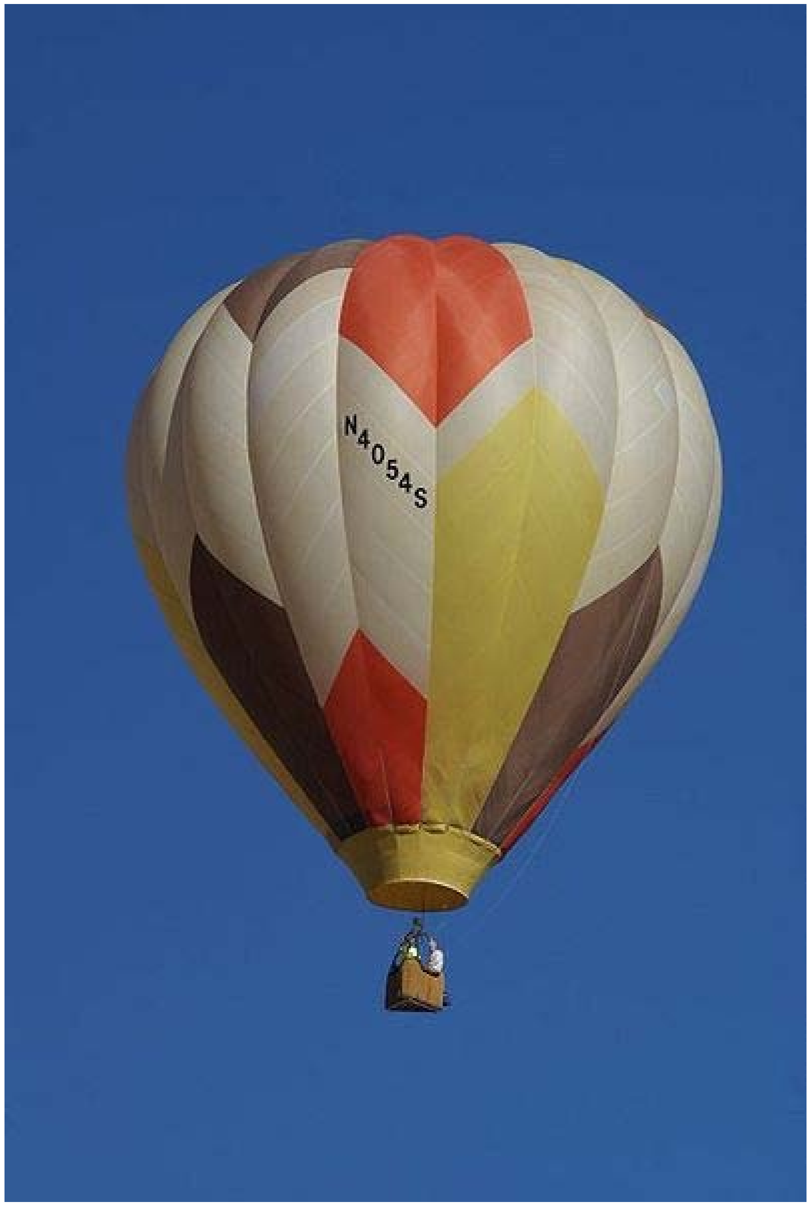
First manned flight

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.

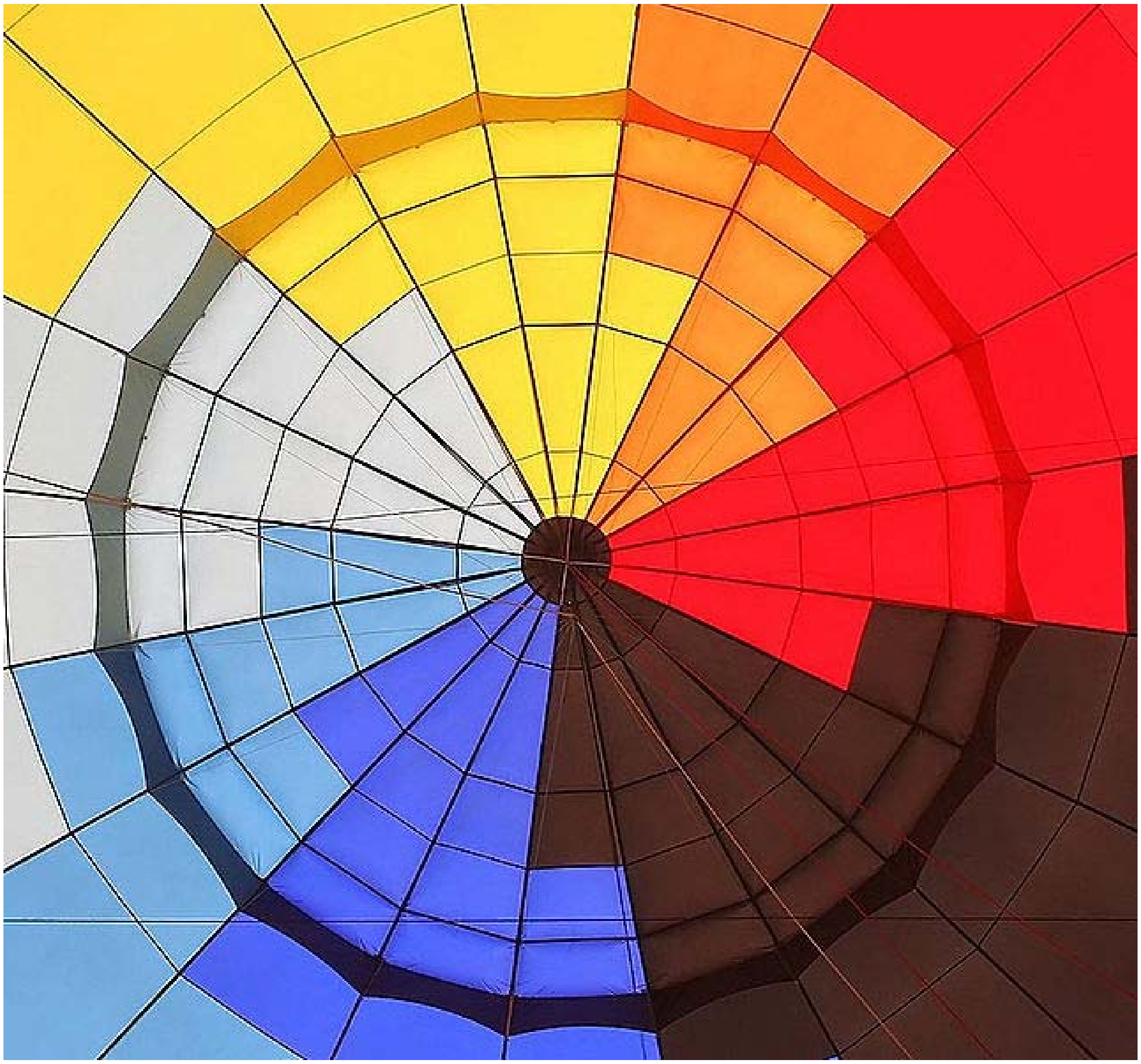
Coatings

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 ft^3 (595 m^3) 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 ft^3 (16,990 m^3). However, most balloons are roughly 100,000 ft^3 (2,832 m^3) 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

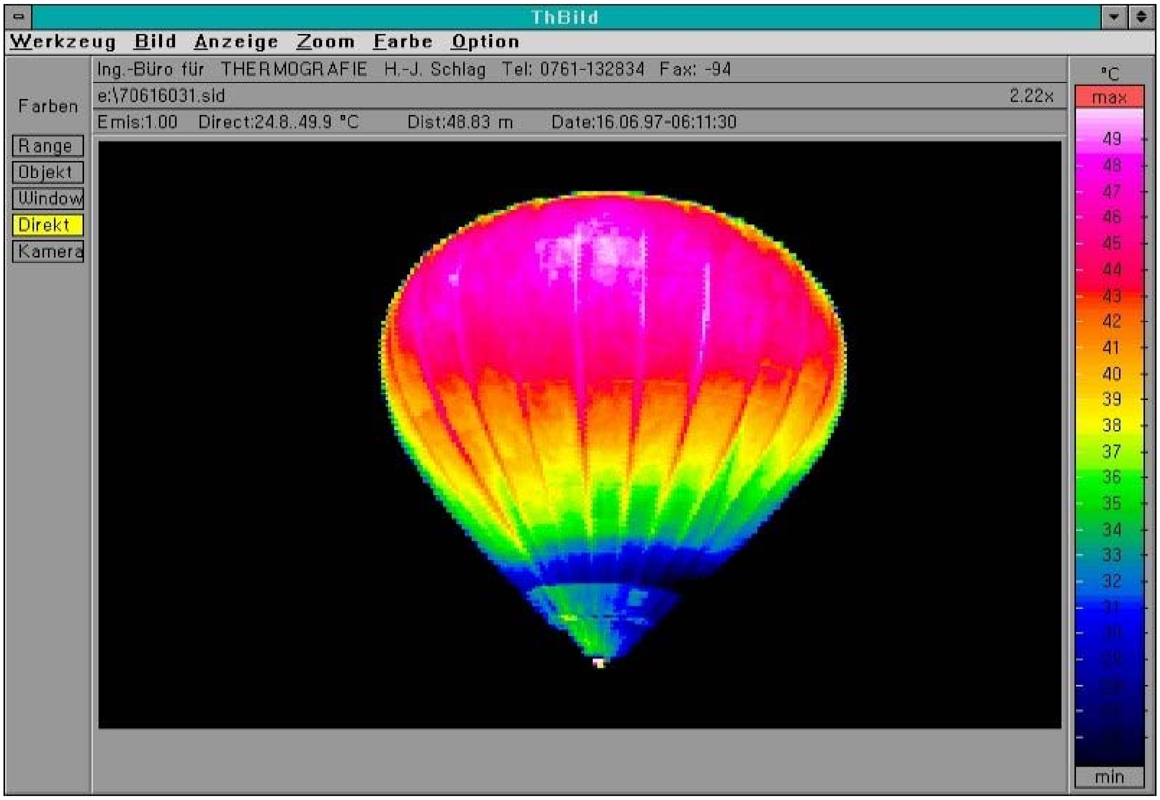
The combined mass of an average system can be calculated as follows:

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.

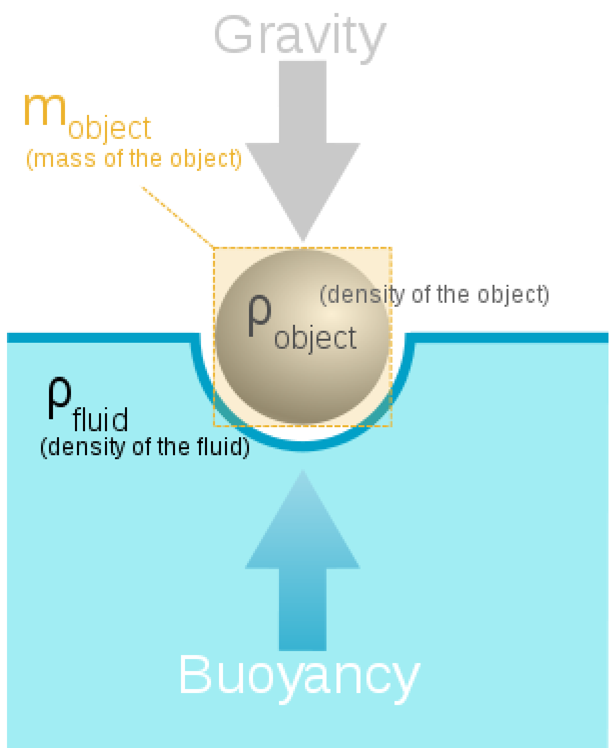
The second largest manufacturer of hot air balloons in the world is Ultramagic, based in Spain, which produces from 80 to 120 balloons per year. Ultramagic can produce massive balloons, such as the N-500 that accommodates up to 27 persons in the basket, and has also produced many balloons with special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

$$\mathbf{f} + \operatorname{div}\sigma = 0$$

where **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:

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

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:

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

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.

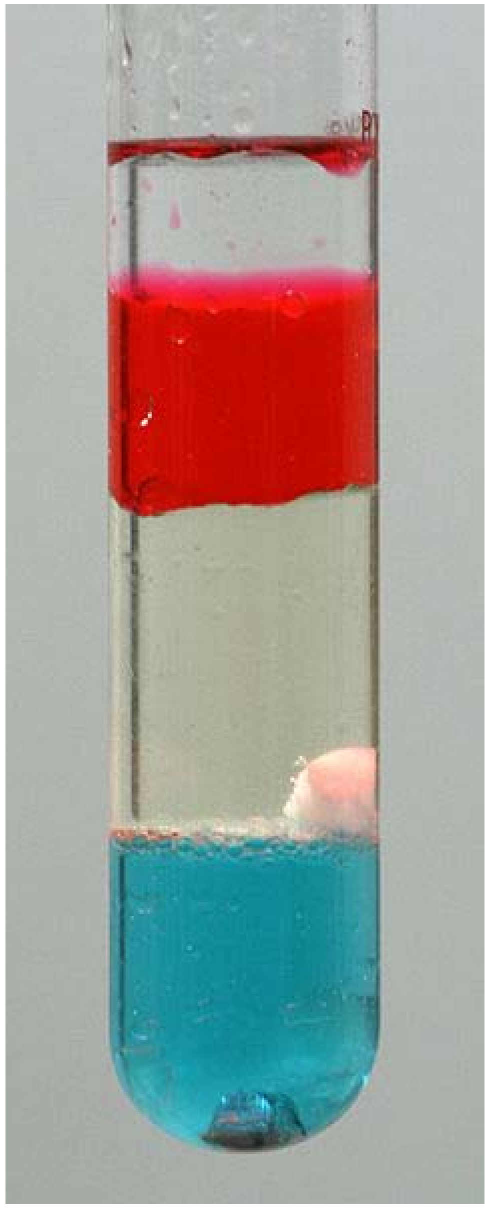
If an object at equilibrium has a compressibility less than that of the surrounding fluid, the object's equilibrium is stable and it remains at rest. If, however, its compressibility is greater, its equilibrium is then unstable, and it rises and expands on the slightest upward perturbation, or falls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

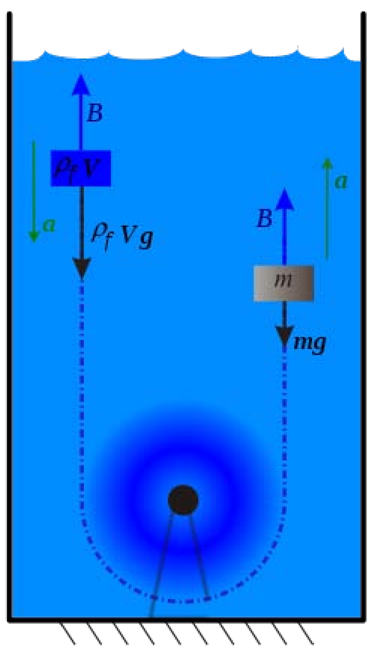
If the weight of an object is less than the weight of the displaced fluid when fully submerged, then the object has an average density that is less than the fluid and when fully submerged will experience a force buoyancy greater than its own weight. If the fluid has a surface, such as water in a lake 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 ($B - \rho_f Vg$) by its mass $\rho_f V$.

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

Airship Hangar & Geodesic Airframe

Airship Hangar

Airships are sheltered in **airship hangars** during construction and sometimes also for regular operation, particularly at bad weather conditions. Rigid airships always needed to be based in airship hangars because weathering was a serious risk.

History

Hangar Y, Chalais Meudon near Paris, France 2002

Early hangars

The first real airship hangar was built as Hangar “Y” at Chalais Meudon near Paris in 1879 where the engineers Charles Renard and Arthur Constantin Krebs constructed their first airship “La France”. Hangar “Y” is one of the few remaining hangars in Europe.

The construction of the first operational rigid airship LZ1 by Count Ferdinand von Zeppelin started in 1899 in a floating hangar on Lake Constance at Manzell today part of Friedrichshafen. The floating hangar turned into the direction of the wind on its own and so it was easier to move the airship into the hangar exactly against the wind.

For the same reason later rotating hangars were built at Biesdorf (today part of Berlin) and at Cuxhaven-Nordholz in Germany. Already before the First World War there were transportable tent constructions as hangars for smaller airships. They were quite common in the US at fairgrounds or exhibitions. The American Melvin Vaniman constructed big tent hangars in France particularly for the French army.

Zeppelin hangar (pt:Base Aérea de Santa Cruz), Rio de Janeiro, Brasil.

The Zeppelin programme

With the construction of Zeppelin LZ1 the era of big rigid airships started in Germany and for this very big airship hangars were necessary. This development started at the Zeppelin plant in Friedrichshafen before the First World War, continued through the war with dozens of hangars for construction of big rigid airships and their operation all over

Germany and the occupied territories. In the 1920s and 30's even bigger hangars for the new LZ 129 Hindenburg class airships were built at Friedrichshafen, Frankfurt and Santa Cruz (part of Rio de Janeiro) in Brazil, the only of all those hangars which still exists.

UK airship construction

Hangars of the former Royal Airship Works at Cardington Bedfordshire, England 2003

Also in the UK there was a rigid airship program during the First World War. This required the big construction sheds in Barrow-in-Furness, Inchinnan, Barlow and Cardington and the rigid airship war stations at Longside, East Fortune, Howden, Pulham (Norfolk) and Kingsnorth.

The reconstructed Airship Hangar at Farnborough.

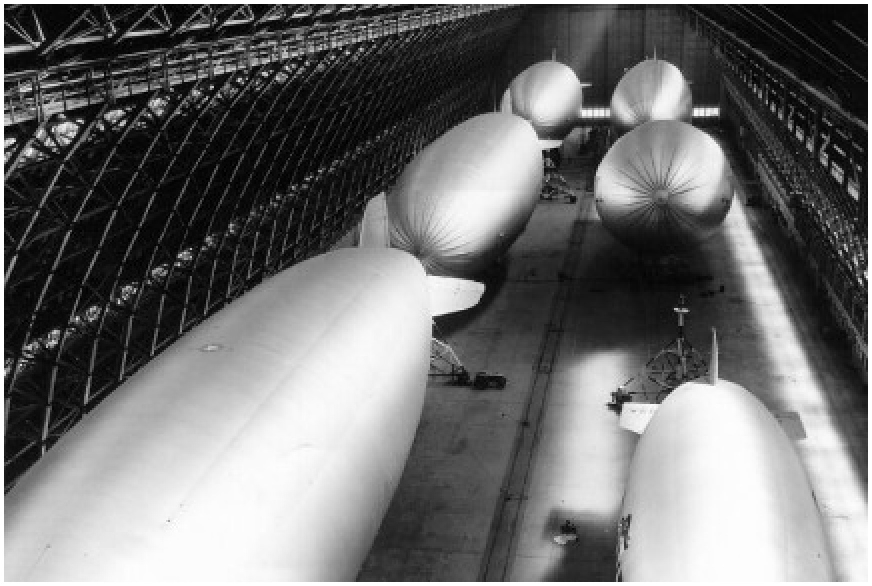
Today, only the two impressing Hangars of the former Royal Airship Works, in Cardington, Bedfordshire remain, where the R101 had been built. The No.1 Cardington hangar is original, but extended; and the No.2 hangar was relocated to Cardington from Pulham in 1928.

France

In France few big hangars had been built, because with the "Spies" there was only one attempt to build a rigid airship. Nevertheless at the end of the First World War an airship station for rigid airships was built in Cuers-Pierrefeu by adding the parts of smaller hangars to two big ones.

At the airport at Paris-Orly two concrete hangars were built between 1923 and 1926. Planned by the famous engineer Eugene Freyssinet, the 300 m long buildings were an important innovation according construction and aesthetic of the design. None of the big French hangars exist anymore, while a few smaller ones still are there.

The USA



A view of six helium-filled blimps being stored in one of the two massive hangars located at NAS Santa Ana,California

Hangar No. 2 at the former Marine Corps Air Station Tustin

In the USA big hangars started in 1921 with Hangar No 1 at Lakehurst Naval Airship Station (NAS). Additional hangars, which housed the USS Akron and USS Macon, exist in Akron, Ohio (the Goodyear Airdock, 1929) and Sunnyvale, California (Hangar One, Moffett Federal Airfield, 1932). The ships were constructed in Akron. The Akron was based in Lakehurst while the Macon was based at Moffet Field. These three hangars still exist, as do a number of airship hangars built during the Second World War . At that time, the era of big rigid airships had already ended, but those hangars could house several smaller naval blimps at a time.

Post World War hangars

After the Second World War worldwide only one big airship shed had been built: The one in Brand south of Berlin for the construction of the Cargolifter AG airship. With a length of 360m, a width of 210m and a height of 107m it is one of the largest unsupported structures in the world. After the bankruptcy of Cargolifter AG it was converted into the leisure center “Tropical Island”.

For the needs of the rather small blimps quite a number of mostly simple hangars exist around the world today.

Geodesic Airframe

A **geodesic airframe** (alternatively, **geodetic**) is a type of construction for the airframes of aircraft developed by British aeronautical engineer Barnes Wallis in the 1930s. It makes use of a space frame formed from a spirally crossing basket-weave of load-bearing members. The principle is that two geodesic arcs can be drawn to intersect on a curving surface (the fuselage) in a manner that the torsional load on each cancels out that on the other.

Early examples

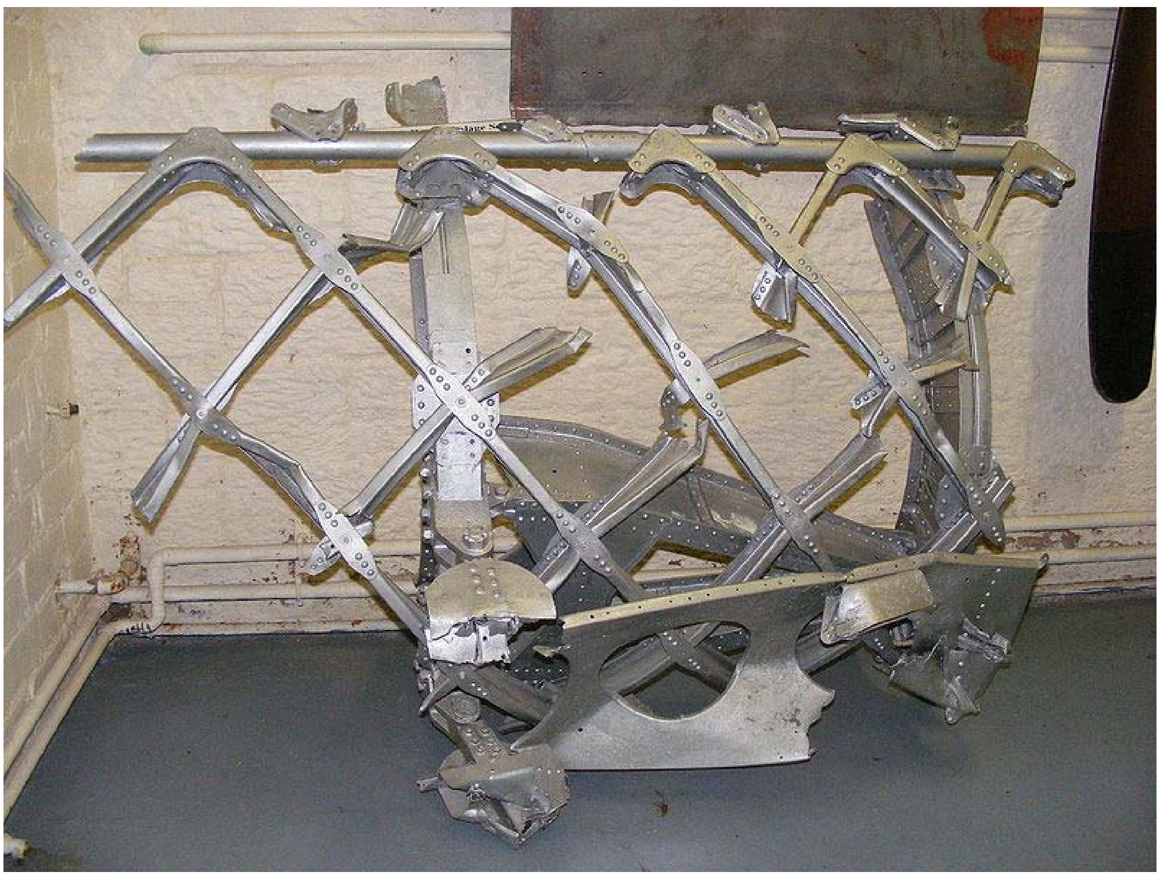
The "diagonal rider" structural element was used by Joshua Humphreys in the first US Navy sail frigates in 1794. Diagonal riders are viewable in the interior hull structure of the preserved *USS Constitution* on display in Boston Harbor. The structure was a pioneering example of "non-orthogonal" structural components.

The "diagonal riders" were included in these naval vessels' construction to reduce the problem of hogging in the ship's hull. A more complex geodesic form can be seen in an aircraft's fuselage.

Calling any diagonal wood brace (as used on gates, buildings, or other structures with cantilevered or diagonal loads) an example of geodesic design is a misnomer. In a geodetic structure, the strength and structural integrity, and indeed the shape, come from the diagonal "braces" - the structure shouldn't include the "bits in between" for part of its strength as does a conventional wooden structure.

Aeroplanes

Wellington Mk.X *HE239* of No.428 Sqn. RCAF, illustrating the geodesic construction and the level of punishment it could absorb while maintaining integrity and airworthiness.



A section of the rear fuselage from a Warwick showing the geodesic construction in duralumin. On exhibit at the Armstrong & Aviation Museum at Bamburgh Castle.

The geodesic construction method was developed by the British aeronautical engineer Barnes Wallis, inspired by his earlier experience using geodesic wiring harnesses to hold the gasbags in his commercial airship design, the *R100*. Wallis used the term "geodetic" to apply to the airframe and distinguish it from "geodesic" which is the proper term for a line on a curved surface, arising from geodesy.

The system was later used by Wallis's employer, Vickers-Armstrongs in a series of bomber aircraft, the Wellesley, Wellington, Warwick and Windsor. In these aircraft, the fuselage was built up from a number of duralumin alloy channel-beams that were formed into a large framework. Wooden battens were screwed onto the metal, to which the skin of the aircraft could be applied; linen stiffened with aircraft dope.

The metal lattice-work gave a light structure with tremendous strength; any one of the stringers could support some of the load from the opposite side of the aircraft. Blowing out the structure from one side would still leave the load-bearing structure as a whole intact. As a result, Wellingtons with huge areas of framework missing continued to return home when other types would not have survived; the dramatic effect enhanced by the doped fabric skin burning off, leaving the naked frames exposed. The benefits of the geodesic construction were partly offset by the difficulty of modifying the physical structure of the aircraft to allow for a change in length, profile, wingspan etc.

Chapter 8

Thrust Vectoring

Thrust vectoring

The F-18 HARV, X-31, and F-16 MATV in flight

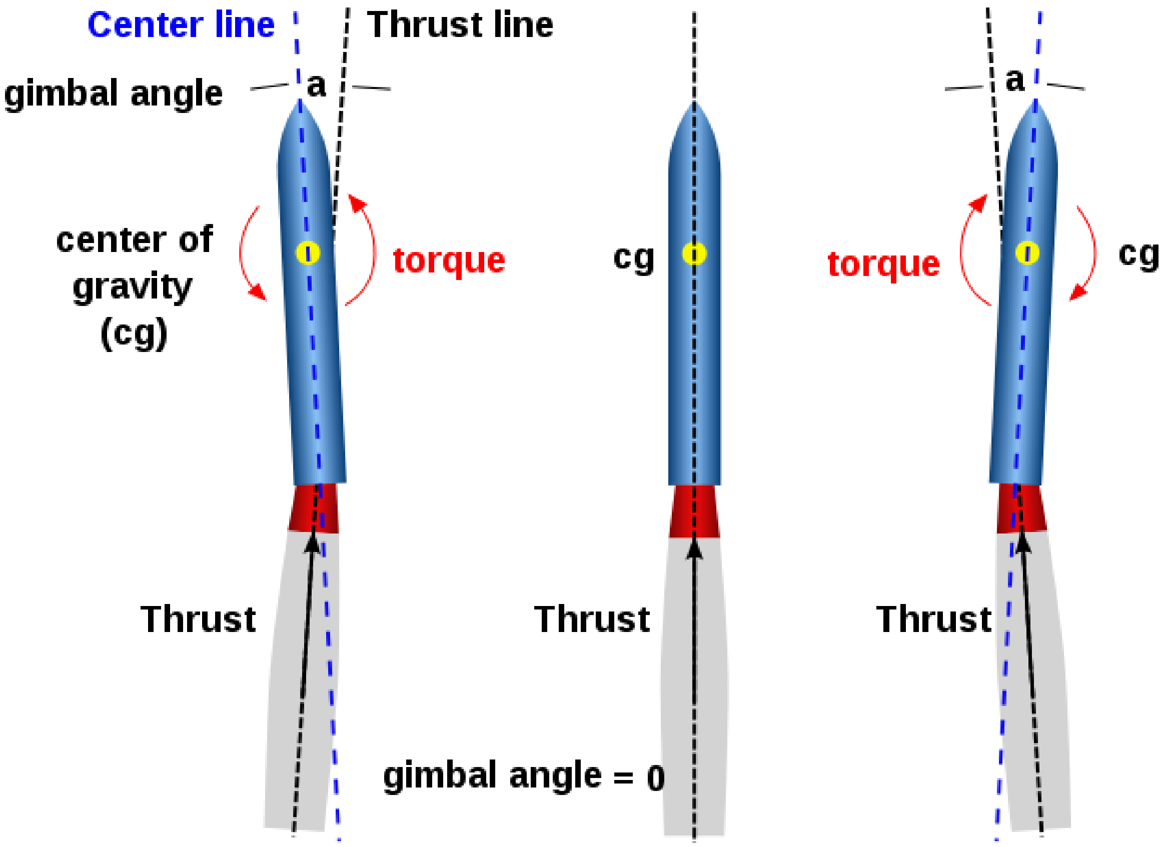
Thrust vectoring, also **thrust vector control** or **TVC**, is the ability of an aircraft, rocket or other vehicle to manipulate the direction of the thrust from its engine(s) or motor in order to control the attitude or angular velocity of the vehicle.

In rocketry and ballistic missiles that fly outside the atmosphere, aerodynamic control surfaces are ineffective, so thrust vectoring is the primary means of attitude control.

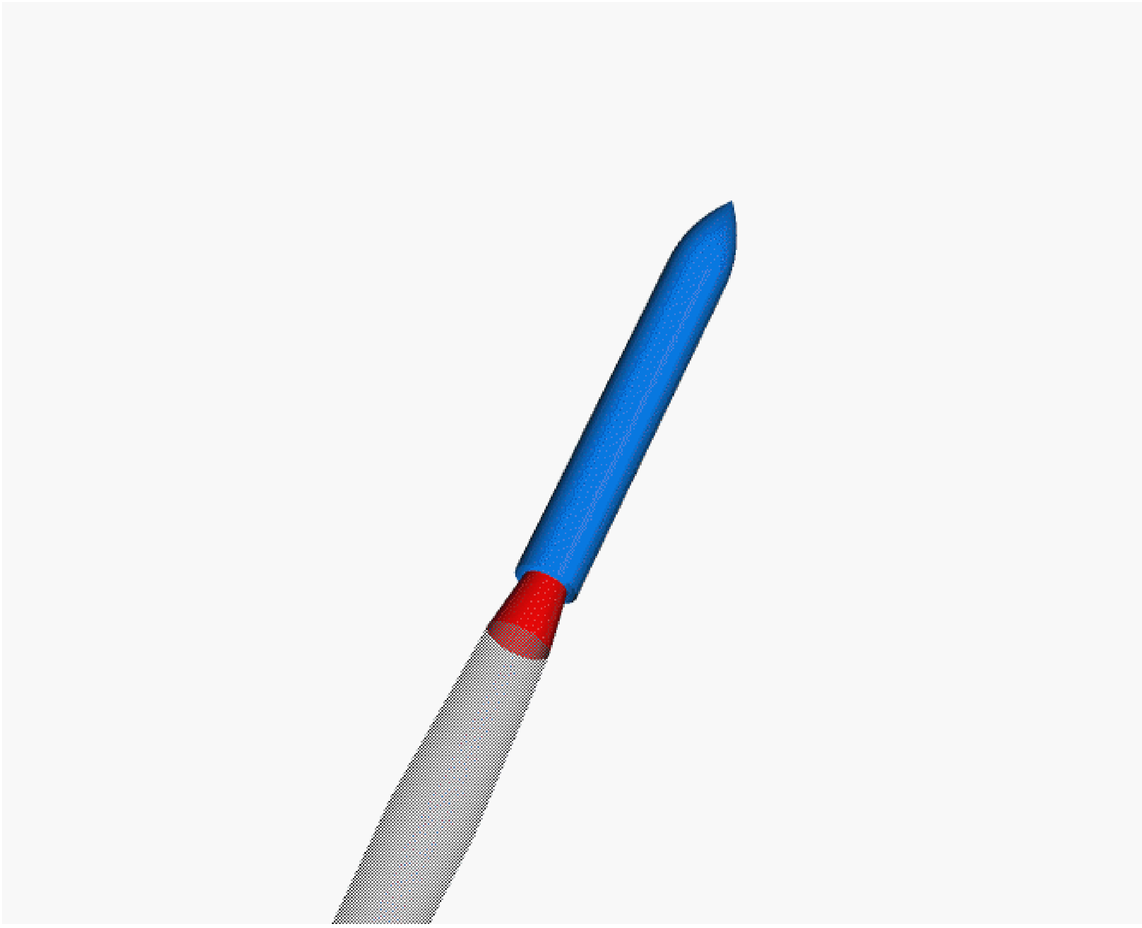
For aircraft, the method was originally envisaged to provide upward vertical thrust as a means to give aircraft vertical (VTOL) or short (STOL) takeoff and landing ability. Subsequently, it was realized that using vectored thrust in combat situations enabled aircraft to perform various maneuvers not available to conventional-engined planes. To perform turns, aircraft that use no thrust vectoring must rely on only aerodynamic control surfaces, such as ailerons or flaps; craft with vectoring must still use control surfaces, but to a lesser extent.

Thrust vectoring methods

Rockets and missiles



Moments generated by different thrust gimbal angles



Motion of a rocket as the thrust is vectored by actuating the nozzle

Thrust vectoring for many liquid rockets is achieved by gimballing the rocket engine. This often involves moving the entire combustion chamber and outer engine bell, or even the entire engine assembly including the related fuel and oxidizer pumps. Such a system was used on the Saturn V and is employed on the space shuttle.

Another method of thrust vectoring used on early solid propellant ballistic missiles was liquid injection, in which the rocket nozzle is fixed, but a relatively cool fluid is introduced into the exhaust flow from injectors mounted around the aft end of the missile. If the liquid is injected on only one side of the missile, it cools that side of the exhaust plume, resulting in lower thrust on that side and an asymmetric net force on the missile. This was the control system used on the Minuteman II and the early SLBMs of the United States Navy.

A later method developed for solid propellant ballistic missiles achieves thrust vectoring by deflecting the rocket nozzle using electric servomechanisms or hydraulic cylinders. The nozzle is attached to the missile via a ball joint with a hole in the center, or a flexible seal made of a thermally resistant material, the latter generally requiring more torque and a higher power actuation system. The Trident C4 and D5 systems are controlled via hydraulically actuated nozzle.

Some smaller sized atmospheric tactical missiles, such as the AIM-9X Sidewinder, eschew flight control surfaces and instead use mechanical vanes to deflect engine exhaust to one side.

Aircraft

Most currently operational vectored thrust aircraft use turbofans with rotating nozzles or vanes to deflect the exhaust stream. This method can successfully deflect thrust through as much as 90 degrees, relative to the aircraft centerline. However, the engine must be sized for vertical lift, rather than normal flight, which results in a weight penalty. Afterburning (or Plenum Chamber Burning, PCB, in the bypass stream) is difficult to incorporate and is impractical for take-off and landing thrust vectoring, because the very hot exhaust can damage runway surfaces. Without afterburning it is hard to reach supersonic flight speeds. A PCB engine, the Bristol Siddeley BS100, was cancelled in 1965.

Tiltrotor aircraft vector thrust via rotating turboprop engine nacelles. The mechanical complexities of this design are quite troublesome, including twisting flexible internal components and driveshaft power transfer between engines. Most current tiltrotor designs feature 2 rotors in a side-by-side configuration. If such a craft is flown in a way where it enters a vortex ring state, one of the rotors will always enter slightly before the other, causing the aircraft to perform a drastic and unplanned roll.

Thrust vectoring is also used as a control mechanism for airships, with one of the earliest known fitments of such a control system being on the twin 1930s-era U.S. Navy rigid airships *USS Akron* and *USS Macon* that were used as airborne aircraft carriers, and a similar form of thrust vectoring is also particularly valuable today for the control of modern non-rigid airships. In this use, most of the load is usually supported by buoyancy and vectored thrust is used to control the motion of the aircraft. But, designs have recently been proposed, especially for Project WALRUS, where a significant portion of the weight of the craft is supported by vectored thrust. The first airship that used a control system based on pressurized air was Enrico Forlanini's *Omnia Dir* in 1930s.

Now being researched, fluidic injection nozzles divert thrust via fluid effects. Tests show that air forced into a jet engine exhaust stream can deflect thrust up to 15 degrees. Such nozzles are desirable for their lower: mass and cost (up to 50% less), inertia (for faster, stronger control response), complexity (mechanically simpler, fewer or no moving parts or surfaces, less maintenance), and radar cross section for stealth. This will likely be used in many unmanned aerial vehicle (UAVs), and 6th generation fighter aircraft.

Operational examples

Sea Harrier FA.2 *ZA195* front (cold) vector thrust nozzle

The best known example of thrust vectoring is the Rolls-Royce Pegasus engine used in the Hawker Siddeley Harrier, as well as in the AV-8B Harrier II variant. However, it is unclear as to whether any thrust-vectoring methods were actually used in combat against conventional Argentine fighters during the Falklands War.

Widespread use of thrust vectoring for enhanced maneuverability in Western production-model fighter aircraft would have to wait until the 21st century, and the deployment of the Lockheed Martin F-22 Raptor fifth-generation jet fighter, with its afterburning, thrust-vectoring Pratt & Whitney F119 turbofan.

Lockheed Martin F-35 Lightning II is currently in the pre-production test and development stage. Although this aircraft uses a conventional afterburning turbofan (F135 or F136) to facilitate supersonic operation, the F-35B variant, developed for joint usage by the US Marine Corps, UK Royal Air Force and Royal Navy, also incorporates a vertically mounted, low-pressure shaft-driven remote fan, which is driven through a clutch during landing from the engine. Both the exhaust from this fan and the main engine's fan are deflected by thrust vectoring nozzles, to provide the appropriate combination of lift and propulsive thrust.

The Sukhoi Su-30 MKI, produced by India under license at Hindustan Aeronautics Limited is in active service with the Indian Air Force, and employs 2D thrust vectoring.

The 2D TVC makes the aircraft highly maneuverable, capable of near-zero airspeed at high angles of attack without stalling, and dynamic aerobatics at low speeds. The Su-30MKI is powered by two Al-31FP afterburning turbofans. The TVC nozzles of the MKI are mounted 32 degrees outward to longitudinal engine axis (i.e. in the horizontal plane) and can be deflected ±15 degrees in the vertical plane. This produces a corkscrew effect, greatly enhancing the turning capability of the aircraft.

Examples of rockets and missiles which use thrust vectoring include both large systems such as the Space Shuttle Solid Rocket Booster (SRB), S-300P (SA-10) surface-to-air missile, UGM-27 Polaris nuclear ballistic missile and RT-23 (SS-24) ballistic missile and smaller battlefield weapons such as Swingfire.

List of vectored thrust aircraft

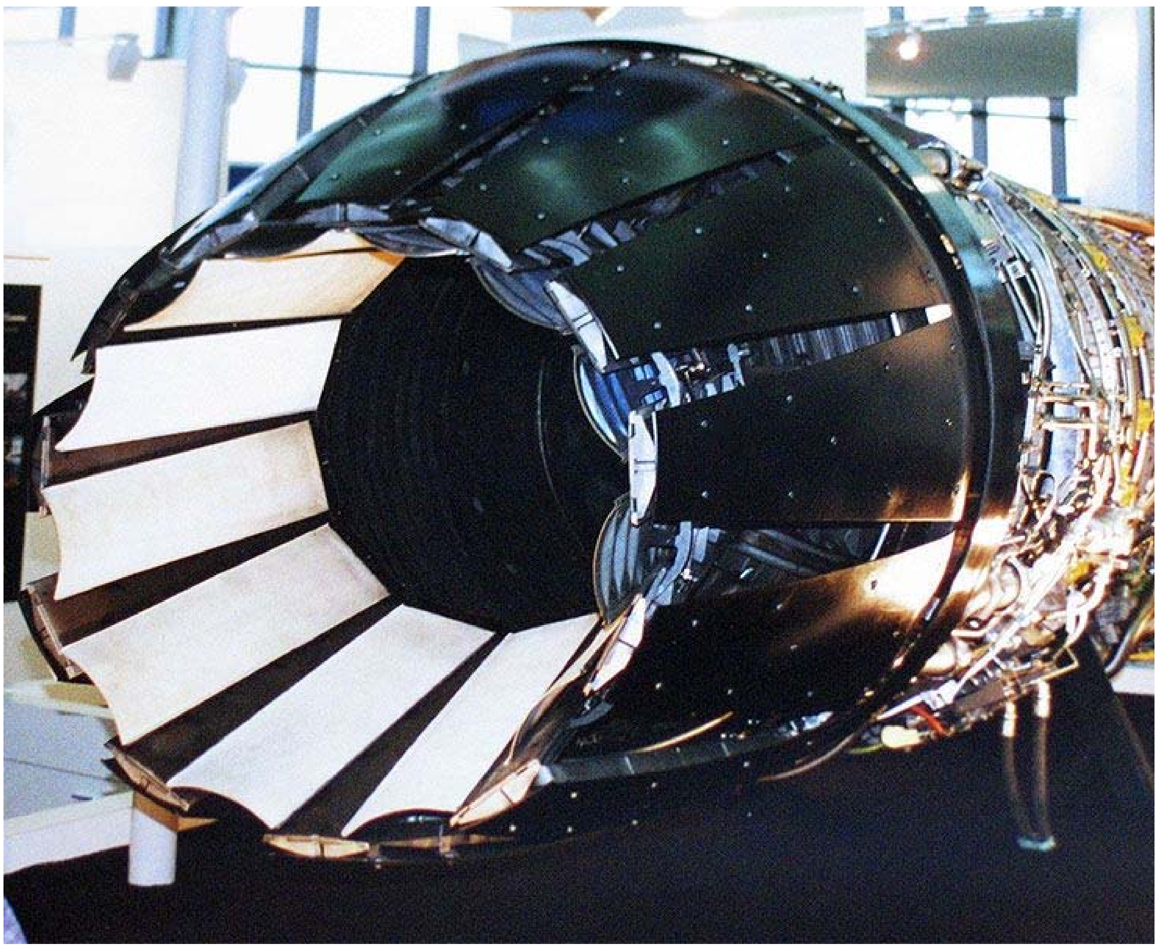
Thrust vectoring can convey two main benefits: VTOL/STOL, and higher maneuverability. Aircraft are usually optimized to maximally exploit one benefit, though will gain in the other.

For VTOL ability

The Harrier - the world's first operational fighter jet with thrust vectoring, enabling VTOL capabilities

- Armstrong Whitworth AW.681
- Bell Boeing V-22 Osprey
- Boeing X-32

- Dornier Do 31
- EWR VJ 101
- Harrier Jump Jet
    - Hawker Siddeley Harrier
    - British Aerospace Sea Harrier
    - Boeing/BAE Systems AV-8B Harrier II
    - BAE Systems/Boeing Harrier II
- Lockheed Martin F-35B Lightning II
- VFW VAK 191B
- Yakovlev Yak-38
- Yakovlev Yak-141



The GE Axisymmetric Vectoring Exhaust Nozzle, used on the F-16 MATV

For higher maneuverability

Two dimension vectoring (pitch axis)

- Lockheed Martin F-22 Raptor
- McDonnell Douglas X-36 (yaw only)

- Me 163 B experimentally used a rocket steering paddle for the yaw axis
- Boeing X-32
- Sukhoi Su-30MKI
- Sukhoi Su-30MKM

Three dimension vectoring (pitch and yaw axes)

- Mikoyan MiG-29OVT (MiG-35)
- Sukhoi Su-35BM
- Sukhoi Su-37
- Sukhoi PAK FA
- McDonnell Douglas F-15S/MTD
- Lockheed Martin F-16 VISTA