Aviation & Aeronautics

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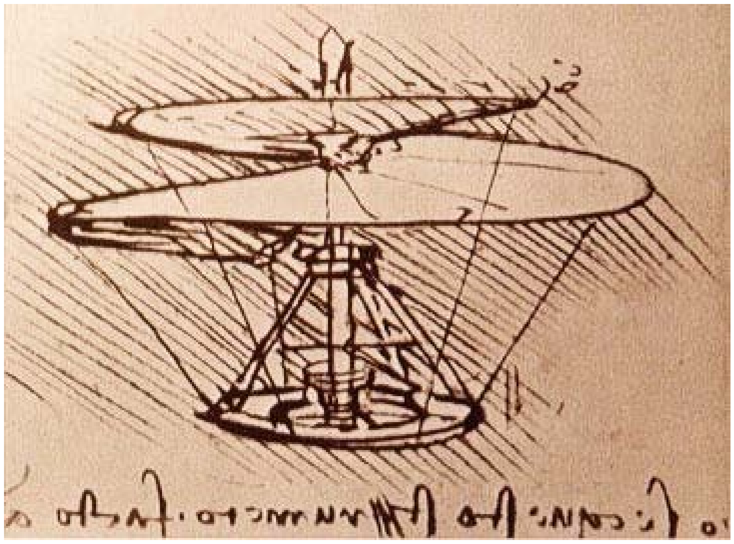
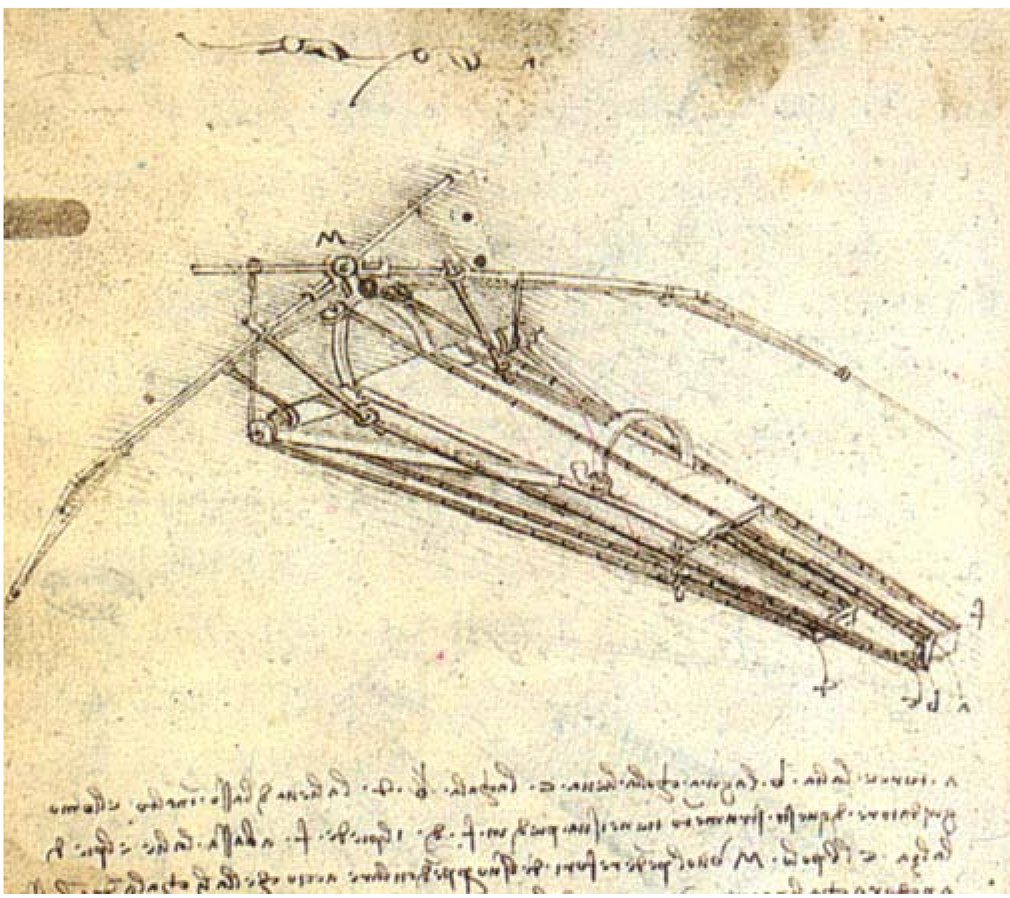
Aviation History

French reconnaissance balloon *L'Intrépide* of 1796, the oldest existing flying device, in the Heeresgeschichtliches Museum, Vienna



Leonardo da Vinci's "aerial screw" design



Leonardo da Vinci's Ornithopter design

Aviation history refers to the history of development of mechanical flight—from the earliest attempts in kites and gliders to powered heavier-than-air, supersonic and spaceflights.

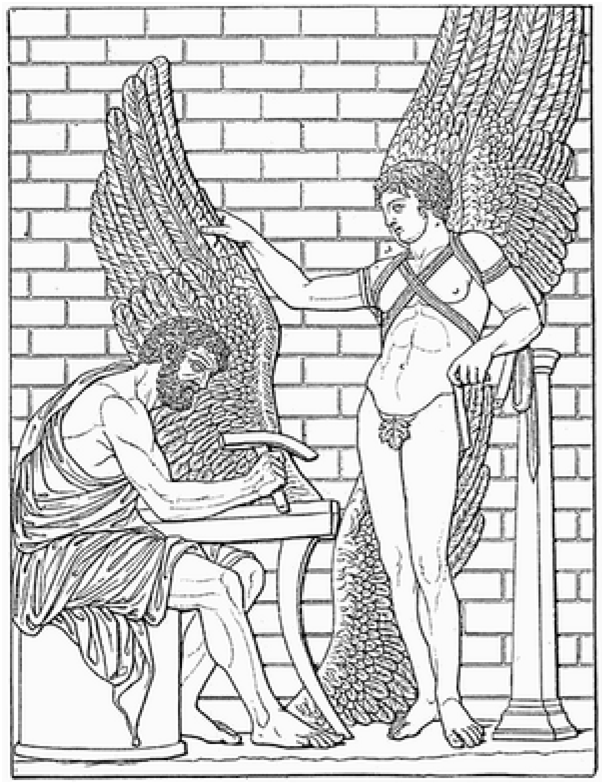
The first form of man-made flying objects were kites. The earliest known record of kite flying is from around 200 B.C. in China, when a General flew a kite over enemy territory to calculate the length of tunnel required to enter the region. Yuan Huangtou, a Chinese prince, survived by tying himself to the kite.

Leonardo da Vinci's (15th c.) dream of flight found expression in several designs, but he did not attempt to demonstrate flight by literally constructing them.

With the efforts to analyze the atmosphere in the 17th and 18th century, gases such as hydrogen were discovered which in turn led to the invention of hydrogen balloons. Various theories in mechanics by physicists during the same period of time—notably fluid dynamics and Newton's laws of motion—led to the foundation of modern aerodynamics. Tethered balloons filled with hot air were used in the first half of the 19th century and saw considerable action in several mid-century wars, most notably the American Civil War, where balloons provided observation during the Battle of Petersburg.

Experiments with gliders laid a groundwork to build heavier-than-air craft, and by the early 20th century advancements in engine technology and aerodynamics made controlled, powered flight possible for the first time.

Mythology



Daedalus working on Icarus' wings. Illustration from a relief in Villa Albani, Rome, 1st-2nd century CE.

Human ambition to fly is illustrated in mythological literature of several cultures; the wings made out of wax and feathers by Daedalus in Greek mythology, or the Pushpaka Vimana of king Ravana in Ramayana, for instance.

Early attempts

Flight automaton in Greece

Around 400 B.C., Archytas, the Greek philosopher, mathematician, astronomer, statesman and strategist, designed and built a bird-shaped, apparently steam powered model named "*The Pigeon*" (Greek: Περιστέρα "Peristera"), which is said to have flown some 200 meters. According to Aulus Gellius, the mechanical bird was suspended on a string or pivot and was powered by a "concealed aura or spirit".

Hot air balloons and kites in China

The Kongming lantern (proto hot air balloon) was known in China from ancient times. Its invention is usually attributed to the general Zhuge Liang (180–234 AD, honorific title *Kongming*), who is said to have used them to scare the enemy troops:

An oil lamp was installed under a large paper bag, and the bag floated in the air due to the lamp heating the air. ... The enemy was frightened by the light in the air, thinking that some divine force was helping him.

However, the device based on a lamp in a paper shell is documented earlier, and according to Joseph Needham, hot-air balloons in China were known from the 3rd century BC.

In the 5th century BCE Lu Ban invented a 'wooden bird' which may have been a large kite, or which may have been an early glider.

During the Yuan dynasty (13th c.) under rulers like Kublai Khan, the rectangular lamps became popular in festivals, when they would attract huge crowds. During the Mongol Empire, the design may have spread along the Silk Route into Central Asia and the Middle East. Almost identical floating lights with a rectangular lamp in thin paper scaffolding are common in Tibetan celebrations and in the Indian festival of lights, Diwali. However, there is no evidence that these were used for human flight.

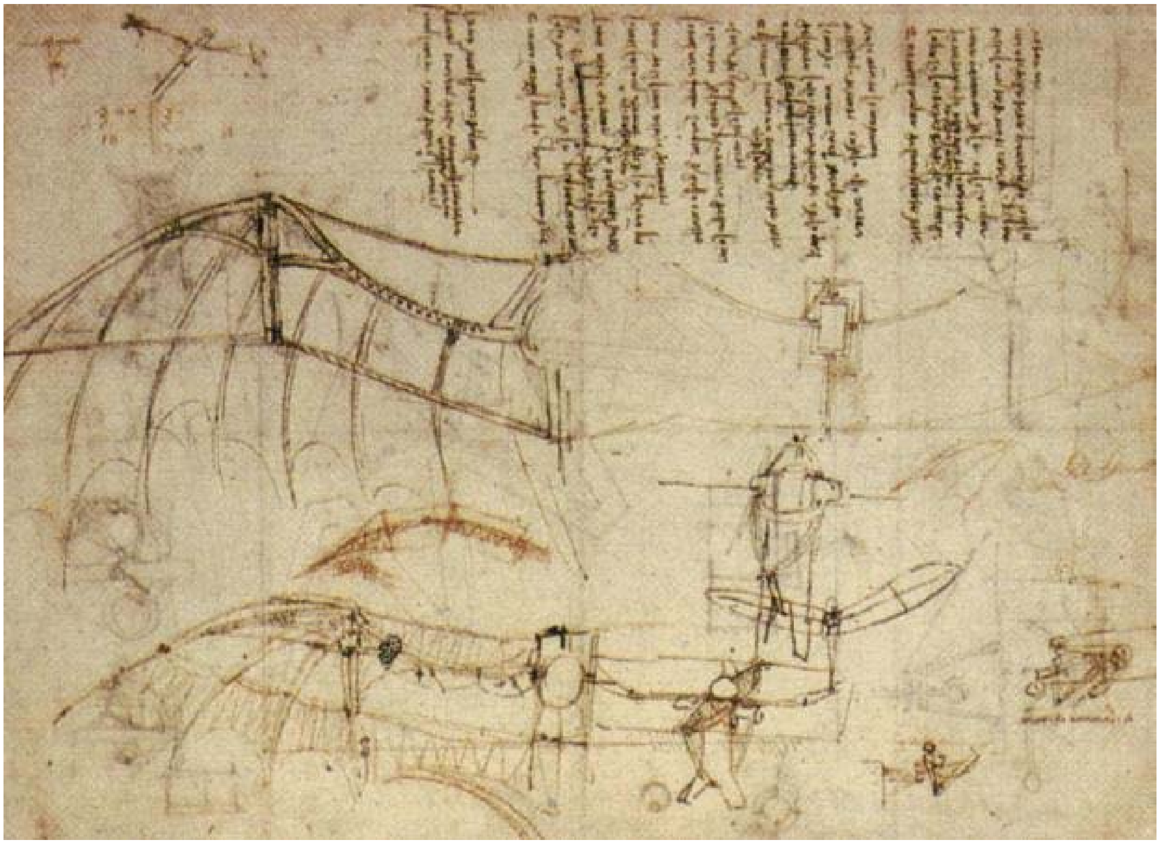
Gliders in Europe

Stained glass window showing Eilmer, installed in Malmesbury Abbey in 1920

In the 9th century, at the age of 65, the Berber polymath Ibn Firnas is said to have flown from the hill Jabal al-'arus by employing a rudimentary glider. While "alighting again on the place whence he had started," he eventually crashed and sustained injury which some contemporary critics attributed to a lack of tail. However, the only source describing the event is from the 17th century.

Between 1000 and 1010, the English Benedictine monk Eilmer of Malmesbury flew for about 200 meters using a glider (circa 1010), but sustained injuries, too. The event is recorded in the work of the eminent medieval historian William of Malmesbury in about 1125. Being a fellow monk in the same abbey, William almost certainly obtained his account directly from people there who knew Eilmer himself.

From Renaissance to the 18th century



Leonardo da Vinci's Ornithopter wings

Some six centuries after Ibn Firnas, Leonardo da Vinci developed a hang glider design in which the inner parts of the wings are fixed, and some control surfaces are provided towards the tips (as in the gliding flight in birds). While his drawings exist and are deemed flightworthy in principle, he himself never flew in it. Based on his drawings, and using materials that would have been available to him, a prototype constructed in the late 20th century was shown to fly. However, his sketchy design was interpreted with modern knowledge of aerodynamic principles, and whether his actual ideas would have flown is not known. A model he built for a test flight in 1496 did not fly, and some other designs, such as the four-person screw-type helicopter have severe flaws.

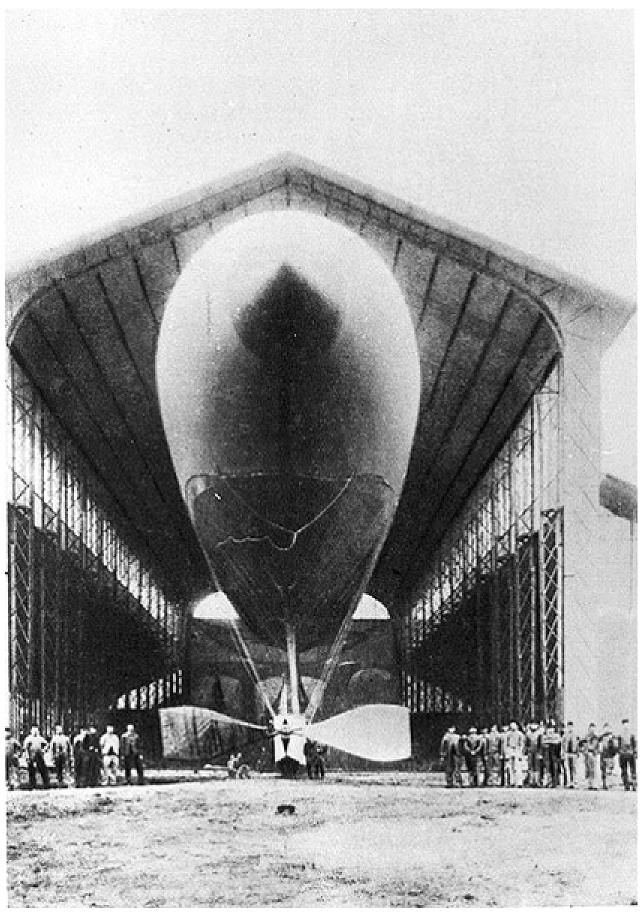
In 1670 Francesco Lana de Terzi published work that suggested lighter than air flight would be possible by having copper foil spheres that contained a vacuum that would be lighter than the displaced air, lift an airship (rather literal from his drawing). While not being completely off the mark, he did fail to realize that the pressure of the surrounding air would smash the spheres.

The small Priekule Lutheran Church in Latvia is related to an old legend about Ikarus of Priekule. For almost two centuries time after time in various printed texts- periodicals and books- there is described a sensational event that happened in the second half of the 17th century (according to another version at the beginning of the 18th century). People of Priekule have been telling their children this legend for many centuries. The blacksmith of Priekule Zviedris (Swede) Johanson (by nationality Swede?) made wings and from the steeple of the church made his first flight. Later the flight was announced as an unforgivable blasphemy. The local Ikarus was announced the Satan's avatar and was burned alive at the stake.

In 1709, Bartolomeu de Gusmão presented a petition to King John V of Portugal, begging a privilege for his invention of an airship, in which he expressed the greatest confidence. The public test of the machine, which was set for June 24, 1709, did not take place. According to contemporary reports, however, Gusmão appears to have made several less ambitious experiments with this machine, descending from eminences. It is certain that Gusmão was working on this principle at the public exhibition he gave before the Court on August 8, 1709, in the hall of the Casa da Índia in Lisbon, when he propelled a ball to the roof by combustion.

Modern flight

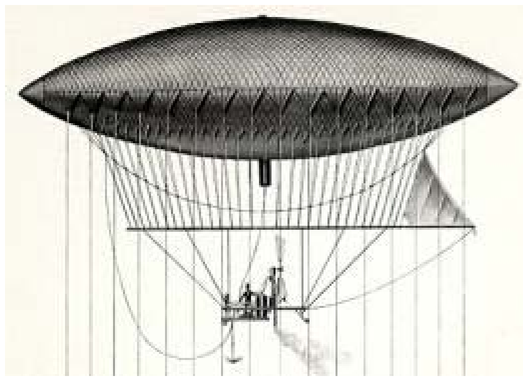
Lighter than air



The 1884 *La France*, the first fully controllable airship

Although many people think of human flight as beginning with the aircraft in the early 20th century, in fact people had been flying repeatedly for more than 100 years.

The first generally recognized human flight took place in Paris in 1783. Jean-François Pilâtre de Rozier and François Laurent d'Arlandes went 8 km (5 miles) in a hot air balloon invented by the Montgolfier brothers. The balloon was powered by a wood fire, and was not steerable: that is, it flew wherever the wind took it.



The navigable balloon created by Giffard in 1852

Ballooning became a major "rage" in Europe in the late 18th century, providing the first detailed understanding of the relationship between altitude and the atmosphere.

Work on developing a steerable (or dirigible) balloon (now called an airship) continued sporadically throughout the 19th century. The first powered, controlled, sustained lighter-than-air flight is believed to have taken place in 1852 when Henri Giffard flew 15 miles (24 km) in France, with a steam engine driven craft.

Non-steerable balloons were employed during the American Civil War by the Union Army Balloon Corps.

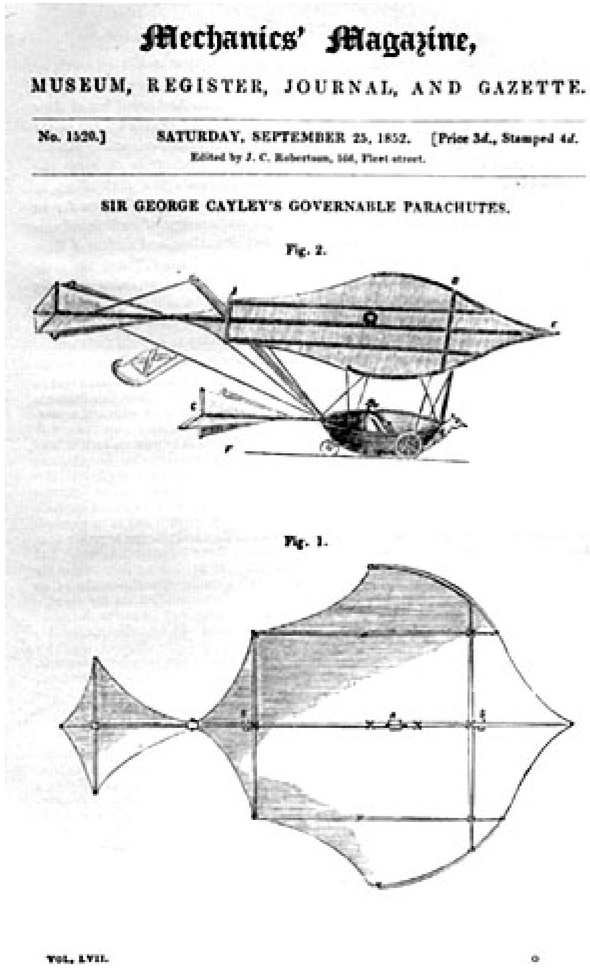
Another advance was made in 1884, when the first fully controllable free-flight was made in a French Army electric-powered airship, La France, by Charles Renard and Arthur Krebs. The 170-foot (52 m) long, 66,000-cubic-foot (1,900 m^3) airship covered 8 km (5 miles) in 23 minutes with the aid of an 8½ horsepower electric motor.

However, these aircraft were generally short-lived and extremely frail. Routine, controlled flights would not come to pass until the advent of the internal combustion engine (see below.)

Although airships were used in both World War I and II, and continue on a limited basis to this day, their development has been largely overshadowed by heavier-than-air craft.

Heavier-than-air

Sustaining the aircraft



Mechanics' Magazine,

MUSEUM, REGISTER, JOURNAL, AND GAZETTE.

No. 1520.] SATURDAY, SEPTEMBER 25, 1852. [Price 3d., Stamped 4d.

Edited by J. C. Robertson, 166, Fleet street.

SIR GEORGE CAYLEY'S GOVERNABLE PARACHUTES.

Fig. 2.

Fig. 1.

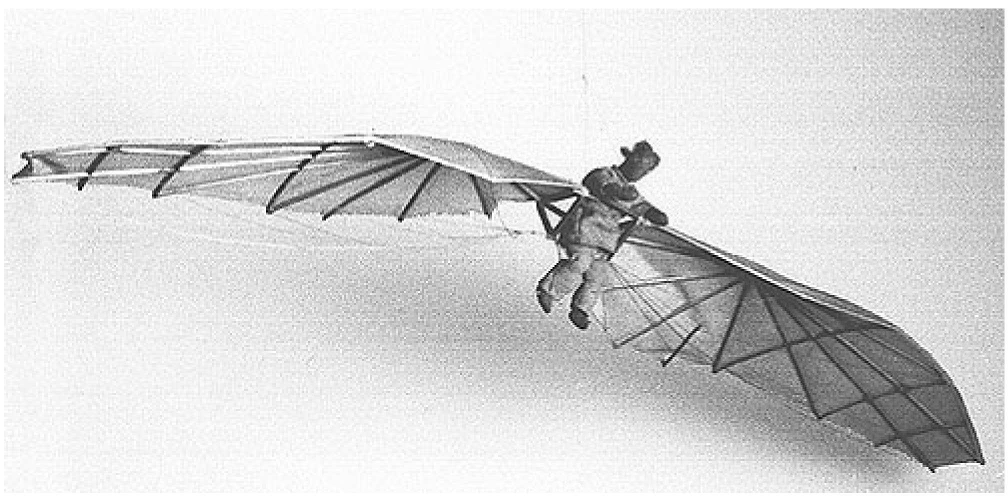
VOL. LVII.

Sir George Cayley's governable parachute

The first published paper on aviation was "Sketch of a Machine for Flying in the Air" by Emanuel Swedenborg published in 1716. This flying machine consisted of a light frame covered with strong canvas and provided with two large oars or wings moving on a horizontal axis, arranged so that the upstroke met with no resistance while the downstroke provided lifting power. Swedenborg knew that the machine would not fly, but suggested it as a start and was confident that the problem would be solved. He said, "It seems easier to talk of such a machine than to put it into actuality, for it requires greater force and less weight than exists in a human body. The science of mechanics might perhaps suggest a means, namely, a strong spiral spring. If these advantages and requisites are observed, perhaps in time to come some one might know how better to utilize our sketch and cause some addition to be made so as to accomplish that which we can only suggest. Yet there are sufficient proofs and examples from nature that such flights can take place without danger, although when the first trials are made you may have to pay for the experience, and not mind an arm or leg." Swedenborg would prove prescient in his observation that powering the aircraft through the air was the crux of flying.

During the last years of the 18th century, Sir George Cayley started the first rigorous study of the physics of flight. In 1799 he exhibited a plan for a glider, which except for planform was completely modern in having a separate tail for control and having the pilot suspended below the center of gravity to provide stability, and flew it as a model in 1804. Over the next five decades Cayley worked on and off on the problem, during which he invented most of basic aerodynamics and introduced such terms as *lift* and *drag*. He used both internal and external combustion engines, fueled by gunpowder. Later Cayley turned his research to building a full-scale version of his design, first flying it unmanned in 1849, and in 1853 his coachman made a short flight at Brompton, near Scarborough in Yorkshire.

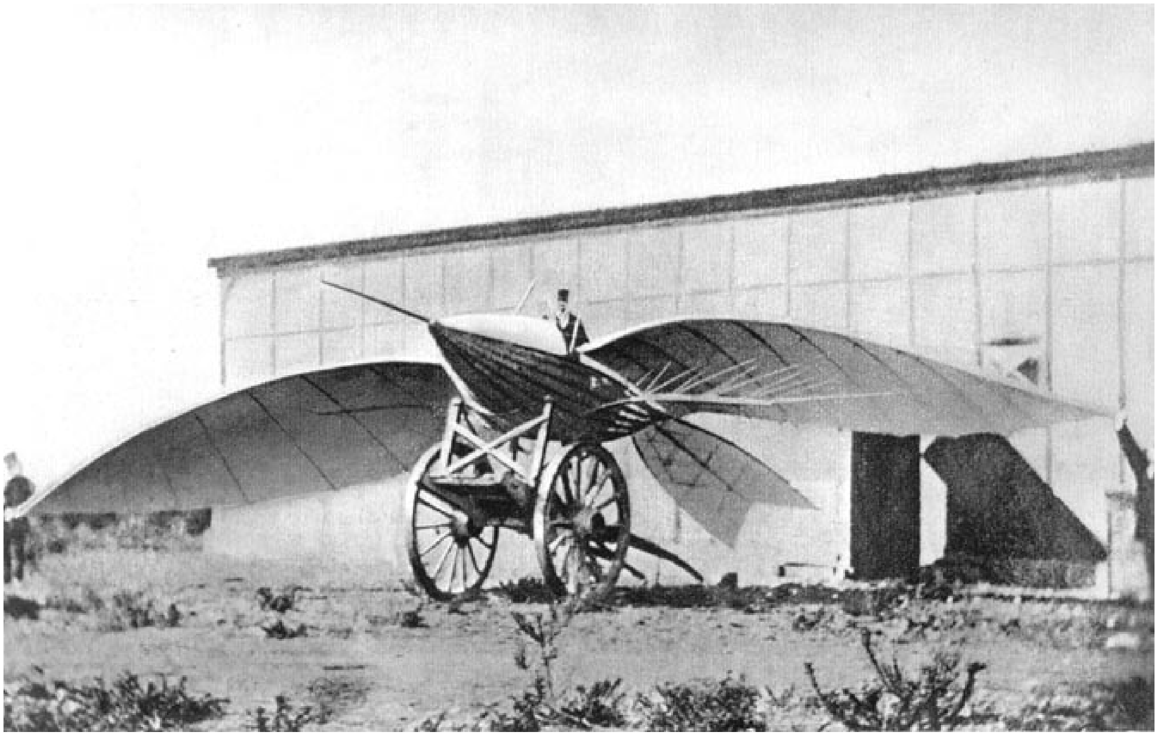
In 1848, John Stringfellow had a successful indoor test flight of a steam-powered model, in Chard, Somerset, England.



Model of Jan Wnęk's glider. Kraków Museum of Ethnography

In 1866 a Polish peasant, sculptor and carpenter by the name of Jan Wnęk built and flew a controllable glider. Wnęk was illiterate and self-taught, and could only count on his knowledge about nature based on observation of birds' flight and on his own builder and carver skills. Jan Wnęk was firmly strapped to his glider by the chest and hips and controlled his glider by twisting the wing's trailing edge via strings attached to stirrups at his feet. Church records indicate that Jan Wnęk launched from a special ramp on top of the Odporyszów church tower; The tower stood 45 m high and was located on top of a 50 m hill, making a 95 m (311 ft) high launch above the valley below. Jan Wnęk made several public flights of substantial distances between 1866 and 1869, especially during religious festivals, carnivals and New Year celebrations. Wnęk left no known written records or drawings, thus having no impact on aviation progress. Recently, Professor

Tadeusz Seweryn, director of the Kraków Museum of Ethnography, has unearthed church records with descriptions of Jan Wnęk's activities.



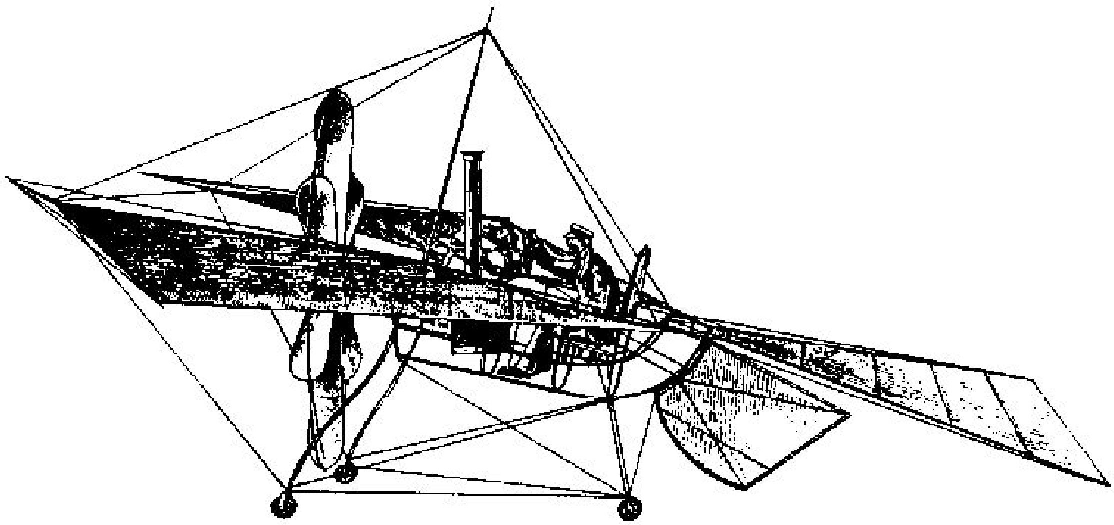
Jean-Marie Le Bris and his flying machine, Albatros II, 1868

In 1856, Frenchman Jean-Marie Le Bris made the first flight higher than his point of departure, by having his glider *"L'Albatros artificiel"* pulled by a horse on a beach. He reportedly achieved a height of 100 meters, over a distance of 200 meters.

Francis Herbert Wenham built a series of unsuccessful unmanned gliders. He found that the most of the lift from a bird-like wing appeared to be generated at the front edge, and concluded correctly that long, thin wings would be better than the bat-like ones suggested by many, because they would have more leading edge for their weight. Today this measure is known as aspect ratio. He presented a paper on his work to the newly formed Aeronautical Society of Great Britain in 1866, and decided to prove it by building the world's first wind tunnel in 1871. Members of the Society used the tunnel and learned that cambered wings generated considerably more lift than expected by Cayley's Newtonian reasoning, with lift-to-drag ratios of about 5:1 at 15 degrees. This clearly demonstrated the ability to build practical heavier-than-air flying machines; what remained was the problem of controlling the flight and powering them.

Around 1871 Alphonse Pénaud made rubber powered model aircraft. While of little direct practical use they inspired a whole generation of future flight pioneers, including the Wright brothers who were given them as toys as children.

In 1874, Félix du Temple built the "*Monoplane*", a large plane made of aluminium in Brest, France, with a wingspan of 13 meters and a weight of only 80 kilograms (without the driver). Several trials were made with the plane, and it is generally recognized that it achieved lift off under its own power after a ski-jump run, glided for a short time and returned safely to the ground, making it the first successful powered flight in history, although the flight was only a short distance and a short time.



Félix du Temple's 1874 *Monoplane*

Controlling the flight

The 1880s became a period of intense study, characterized by the "gentleman scientists" who represented most research efforts until the 20th century. Starting in the 1880s advancements were made in construction that led to the first truly practical gliders. Three people in particular were active: Otto Lilienthal, Percy Pilcher and Octave Chanute. One of the first truly modern gliders appears to have been built by John J. Montgomery; it flew in a controlled manner outside of San Diego on August 28, 1883. It was not until many years later that his efforts became well known. Another delta hang-glider had been constructed by Wilhelm Kress as early as 1877 near Vienna.

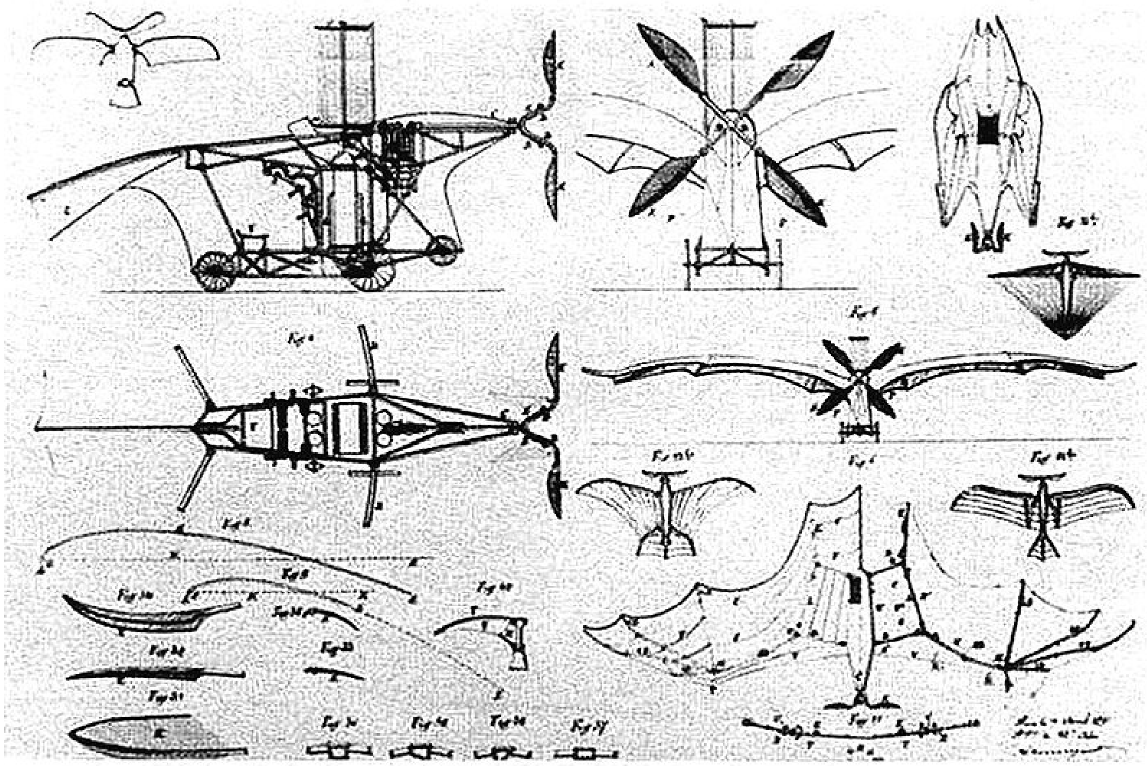
Otto Lilienthal of Germany duplicated Wenham's work and greatly expanded on it in 1874, publishing his research in 1889. He also produced a series of ever-better gliders, and in 1891 was able to make flights of 25 meters or more routinely. He rigorously documented his work, including photographs, and for this reason is one of the best known of the early pioneers. He also promoted the idea of "jumping before you fly", suggesting that researchers should start with gliders and work their way up, instead of simply designing a powered machine on paper and hoping it would work. His type of aircraft is now known as a hang glider.

By the time of his death in 1896 he had made 2500 flights on a number of designs, when a gust of wind broke the wing of his latest design, causing him to fall from a height of roughly 56 feet (17 m), fracturing his spine. He died the next day, with his last words being "small sacrifices must be made". Lilienthal had been working on small engines suitable for powering his designs at the time of his death.

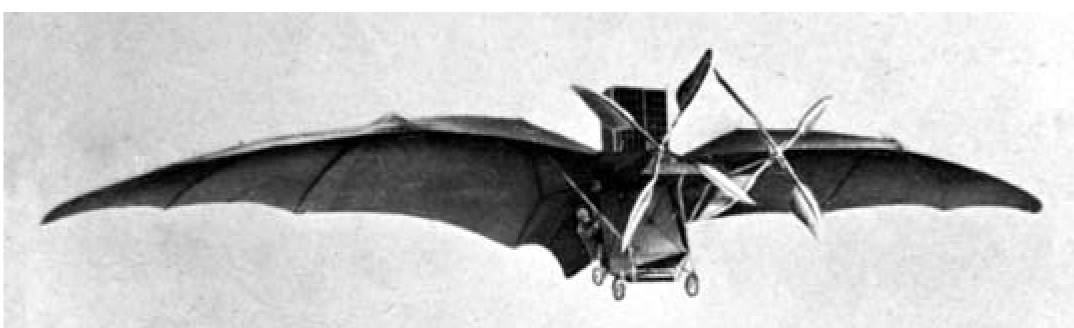
Australian Lawrence Hargrave invented the box kite and dedicated his life to constructing flying machines. In the 1880s he experimented with monoplane models and by 1889 Hargrave had constructed a rotary airplane engine, driven by compressed air.

Picking up where Lilienthal left off, Octave Chanute took up aircraft design after an early retirement, and funded the development of several gliders. In the summer of 1896 his troop flew several of their designs many times at Miller Beach, Indiana, eventually deciding that the best was a biplane design that looks surprisingly modern. Like Lilienthal, he heavily documented his work while photographing it, and was busy corresponding with like-minded hobbyists around the world. Chanute was particularly interested in solving the problem of aerodynamic instability of the aircraft in flight, one which birds corrected for by instant corrections, but one that humans would have to address with stabilizing and control surfaces (or moving center of gravity, as Lilienthal did). The most disconcerting problem was longitudinal instability (divergence), because as the angle of attack of a wing increased, the center of pressure moved forward and made the angle increase more. Without immediate correction, the craft would pitch up and stall. Much more difficult to understand was the mixing of lateral/directional stability and control.

Powering the aircraft



Patent drawings of Clément Ader *Eole*



Clément Ader *Avion III* (1897 photograph).

Throughout this period, a number of attempts were made to produce a true powered aircraft. However the majority of these efforts were doomed to failure, being designed by hobbyists who did not have a full understanding of the problems being discussed by Lilienthal and Chanute.

In France Clément Ader built the steam-powered *Eole* and may have made a 50-meter flight near Paris in 1890, which would be the first self-propelled "long distance" flight in history. Ader then worked on a larger design which took five years to build. In a test for the French military, the *Avion III* reportedly managed to cover 300 meters at a very small height, crashing out of control.

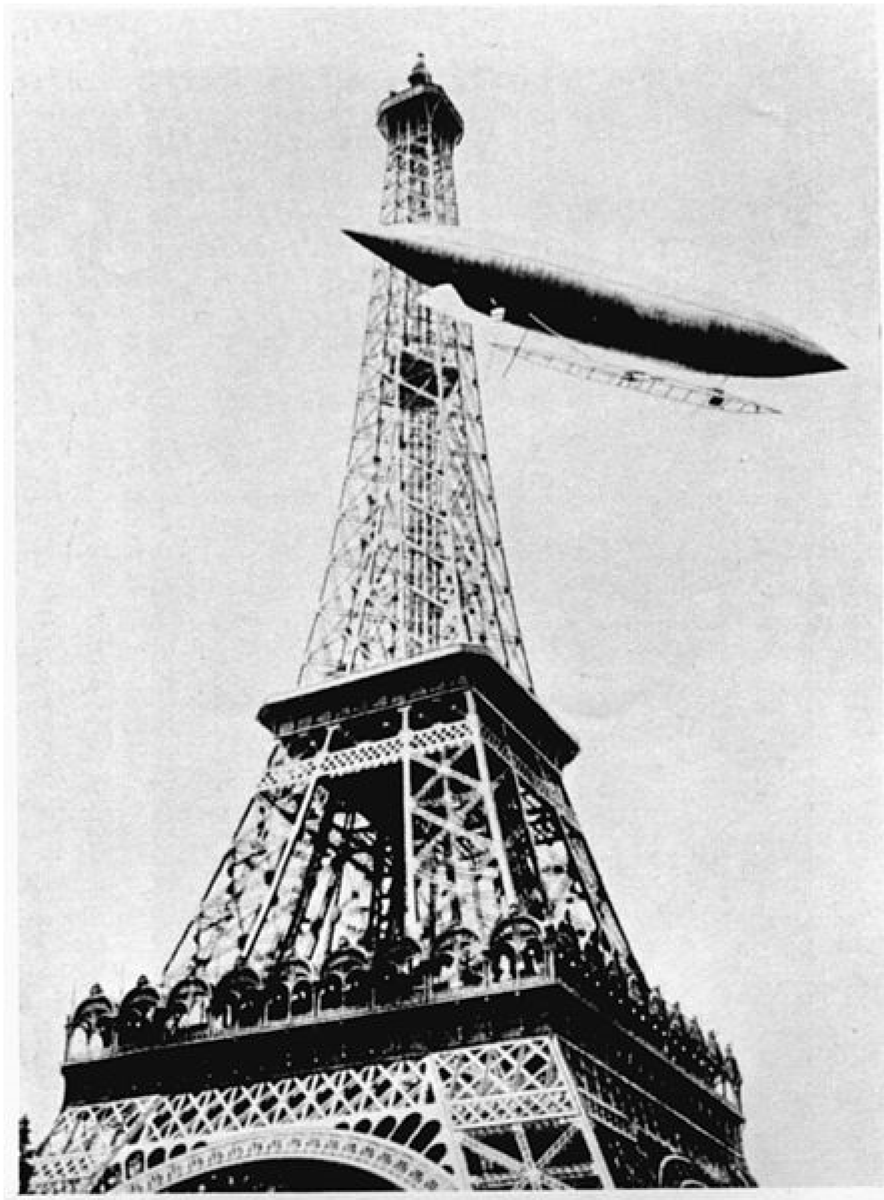
In 1884, Alexander Mozhaysky's monoplane design made what is now considered to be a power assisted take off or 'hop' of 60–100 feet (20–30 meters) near Krasnoye Selo, Russia.

Sir Hiram Maxim studied a series of designs in England, eventually building a monstrous 7,000 pounds (3,200 kg) design with a wingspan of 105 feet (32 m), powered by two advanced low-weight steam engines which delivered 180 hp (134 kW) each. Maxim built it to study the basic problems of construction and power and it remained without controls, and, realizing that it would be unsafe to fly, he instead had a 1,800 feet (550 m) track constructed for test runs. After a number of test runs working out problems, on July 31, 1894 they started a series of runs at increasing power settings. The first two were successful, with the craft "flying" on the rails. In the afternoon the crew of three fired the boilers to full power, and after reaching over 42 mph (68 km/h) about 600 feet (180 m) down the track the machine produced so much lift it pulled itself free of the track and crashed after flying at low altitudes for about 200 feet (61 m). Declining fortunes left him unable to continue his work until the 20th century, when he was able to test a number of smaller designs powered by gasoline.

In the United Kingdom an attempt at heavier-than-air flight was made by the aviation pioneer Percy Pilcher. Pilcher had built several working gliders, *The Bat*, *The Beetle*, *The Gull* and *The Hawk*, which he flew successfully during the mid to late 1890s. In 1899 he constructed a prototype powered aircraft which, recent research has shown, would have been capable of flight. However, he died in a glider accident before he was able to test it, and his plans were forgotten for many years.

The "Pioneer Era" (1900–1914)

Lighter than air



Santos-Dumont's "Number 6" rounding the Eiffel Tower in the process of winning the Deutsch Prize. Photo courtesy of the Smithsonian Institution (SI Neg. No. 85-3941)

The first aircraft to make routine controlled flights were non-rigid airships (later called "blimps".) The most successful early pioneering pilot of this type of aircraft was the Brazilian Alberto Santos-Dumont who effectively combined a balloon with an internal combustion engine. On October 19, 1901 he flew his airship "Number 6" over Paris from the Parc Saint Cloud around the Eiffel Tower and back in under 30 minutes to win the Deutsch de la Meurthe prize. Santos-Dumont went on to design and build several aircraft.

Subsequent controversy surrounding his and others' competing claims with regard to aircraft overshadowed his unparalleled contributions to the development of airships.

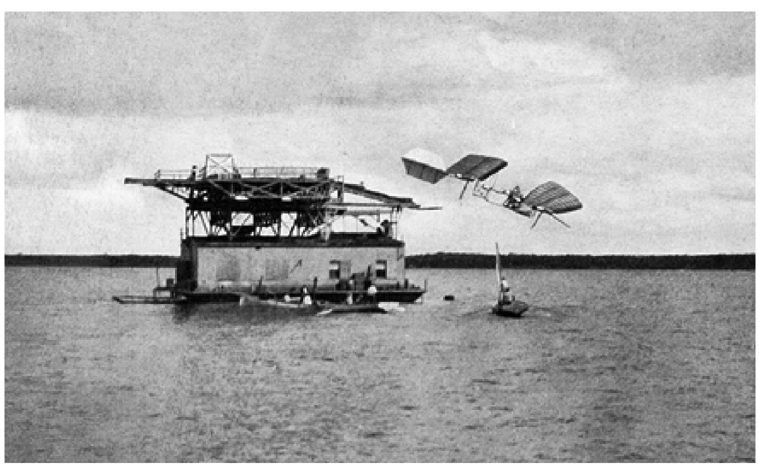
At the same time that non-rigid airships were starting to have some success, rigid airships were also becoming more advanced. Indeed, rigid body dirigibles would be far more capable than fixed wing aircraft in terms of pure cargo carrying capacity for decades. Dirigible design and advancement was brought about by the German count, Ferdinand von Zeppelin.

Construction of the first Zeppelin airship began in 1899 in a floating assembly hall on Lake Constance in the Bay of Manzell, Friedrichshafen. This was intended to ease the starting procedure, as the hall could easily be aligned with the wind. The prototype airship *LZ 1* (LZ for "Luftschiff Zeppelin") had a length of 128 m, was driven by two 14.2 ps (10.6 kW) Daimler engines and balanced by moving a weight between its two nacelles.

The first Zeppelin flight occurred on July 2, 1900. It lasted for only 18 minutes, as LZ 1 was forced to land on the lake after the winding mechanism for the balancing weight had broken. Upon repair, the technology proved its potential in subsequent flights, beating the 6 m/s velocity record of French airship *La France* by 3 m/s, but could not yet convince possible investors. It would be several years before the Count was able to raise enough funds for another try. Indeed, it was not until 1902 when Spanish engineer Leonardo Torres Quevedo developed his own zeppelin airship, with which he solved the serious balance problems the suspending gondola had shown in previous flight attempts.

Heavier than air

Langley



First failure of Langley's manned Aerodrome on the Potomac River, October 7, 1903

After a distinguished career in astronomy and shortly before becoming Secretary of the Smithsonian Institution, Samuel Pierpont Langley started a serious investigation into aerodynamics at what is today the University of Pittsburgh. In 1891 he published *Experiments in Aerodynamics* detailing his research, and then turned to building his designs. On May 6, 1896, Langley's Aerodrome No.5 made the first successful sustained flight of an unpiloted, engine-driven heavier-than-air craft of substantial size. It was launched from a spring-actuated catapult mounted on top of a houseboat on the Potomac River near Quantico, Virginia. Two flights were made that afternoon, one of 1,005 metres (3,297 ft) and a second of 700 metres (2,300 ft), at a speed of approximately 25 miles per hour (40 km/h). On both occasions the Aerodrome No.5 landed in the water as planned, because in order to save weight, it was not equipped with landing gear. On November 28, 1896, another successful flight was made with the Aerodrome No.6. This flight, of 1,460 metres (4,790 ft), was witnessed and photographed by Alexander Graham Bell. The Aerodrome No.6 was actually Aerodrome No.4 greatly modified. So little remained of the original aircraft that it was given the new designation of Aerodrome No.6.

With the success of the Aerodrome No. 5 and its follow-on No. 6, Langley started looking for funding to build a full-scale man-carrying version of his designs. Spurred by the Spanish-American War, the U.S. government granted him $50,000 to develop a man-carrying flying machine for surveillance. Langley planned on building a scaled-up version known as the **Aerodrome A**, and started with the smaller **Quarter-scale Aerodrome**, which flew twice on June 18, 1901, and then again with a newer and more powerful engine in 1903.

With the basic design apparently successfully tested, he then turned to the problem of a suitable engine. He contracted Stephen Balzer to build one, but was disappointed when it delivered only 8 horsepower (6 kW) instead of 12 hp (9 kW) as he expected. Langley's assistant, Charles M. Manly, then reworked the design into a five-cylinder water-cooled radial that delivered 52 horsepower (39 kW) at 950 rpm, a feat that took years to duplicate. Now with both power and a design, Langley put the two together with great hopes.

To his dismay, the resulting aircraft proved to be too fragile. He had apparently overlooked the effects of minimum gauge, and simply scaling up the original small models resulted in a design that was too weak to hold itself together. Two launches in late 1903 both ended with the Aerodrome immediately crashing into the water. The pilot, Manly, was rescued each time.

Langley's attempts to gain further funding failed, and his efforts ended. Nine days after his second abortive launch on December 8, the Wright brothers successfully flew their aptly-named *Flyer*. Glenn Curtiss made several modifications to the Aerodrome and successfully flew it in 1914—the Smithsonian Institution thus continued to assert that Langley's Aerodrome was the first machine "capable of flight".

The Wright Brothers

Following a step by step method, discovering aerodynamic forces then controlling the flight, the brothers built and tested a series of kite and glider designs from 1900 to 1902 before attempting to build a powered design. The gliders worked, but not as well as the Wrights had expected based on the experiments and writings of their 19th century predecessors. Their first glider, launched in 1900, had only about half the lift they anticipated. Their second glider, built the following year, performed even more poorly. Rather than giving up, the Wrights constructed their own wind tunnel and created a number of sophisticated devices to measure lift and drag on the 200 wing designs they tested. As a result, the Wrights corrected earlier mistakes in calculations regarding drag and lift. Their testing and calculating produced a third glider with a larger aspect ratio and true three-axis control. They flew it successfully hundreds of times in 1902, and it performed far better than the previous models. In the end, by establishing their rigorous system of designing, wind-tunnel testing of airfoils and flight testing of full-size prototypes, the Wrights not only built a working aircraft but also helped advance the science of aeronautical engineering.

The Wright Flyer: the first sustained flight with a powered, controlled aircraft

The Wrights appear to be the first design team to make serious studied attempts to simultaneously solve the power and control problems. Both problems proved difficult, but they never lost interest. They solved the control problem by inventing wing warping for roll control, combined with simultaneous yaw control with a steerable rear rudder. Almost as an afterthought, they designed and built a low-powered internal combustion engine. Relying on their wind tunnel data, they also designed and carved wooden propellers that were more efficient than any before, enabling them to gain adequate performance from their marginal engine power. Although wing-warping was used only briefly during the history of aviation, when used with a rudder it proved to be a key advance in order to control an aircraft. While many aviation pioneers appeared to leave safety largely to chance, the Wrights' design was greatly influenced by the need to teach themselves to fly without unreasonable risk to life and limb, by surviving crashes. This emphasis, as well as marginal engine power, was the reason for low flying speed and for taking off in a head wind. Performance (rather than safety) was also the reason for the rear-heavy design, because the canard could not be highly loaded; anhedral wings were less affected by crosswinds and were consistent with the low yaw stability.

According to the Smithsonian Institution and Fédération Aéronautique Internationale (FAI), the Wrights made the first sustained, controlled, powered heavier-than-air manned flight at Kill Devil Hills, North Carolina, four miles (8 km) south of Kitty Hawk, North Carolina on December 17, 1903.

The first flight by Orville Wright, of 120 feet (37 m) in 12 seconds, was recorded in a famous photograph. In the fourth flight of the same day, Wilbur Wright flew 852 feet (260 m) in 59 seconds. The flights were witnessed by three coastal lifesaving crewmen, a local businessman, and a boy from the village, making these the first public flights and the first well-documented ones.

Orville described the final flight of the day: "The first few hundred feet were up and down, as before, but by the time three hundred feet had been covered, the machine was under much better control. The course for the next four or five hundred feet had but little undulation. However, when out about eight hundred feet the machine began pitching again, and, in one of its darts downward, struck the ground. The distance over the ground was measured to be 852 feet (260 m); the time of the flight was 59 seconds. The frame supporting the front rudder was badly broken, but the main part of the machine was not injured at all. We estimated that the machine could be put in condition for flight again in about a day or two." They flew only about ten feet above the ground as a safety precaution, so they had little room to maneuver, and all four flights in the gusty winds ended in a bumpy and unintended "landing". Modern analysis by Professor Fred E. C. Culick and Henry R. Rex (1985) has demonstrated that the 1903 Wright Flyer was so unstable as to be almost unmanageable by anyone but the Wrights, who had trained themselves in the 1902 glider.

The Wrights continued flying at Huffman Prairie near Dayton, Ohio in 1904–05. After a severe crash on 14 July 1905, they rebuilt the Flyer and made important design changes. They almost doubled the size of the elevator and rudder and moved them about twice the distance from the wings. They added two fixed vertical vanes (called "blinkers") between the elevators, and gave the wings a very slight dihedral. They disconnected the rudder from the wing-warping control, and as in all future aircraft, placed it on a separate control handle. When flights resumed the results were immediate. The serious pitch instability that hampered Flyers I and II was significantly reduced, so repeated minor crashes were eliminated. Flights with the redesigned Flyer III started lasting over 10 minutes, then 20, then 30. Flyer III became the first practical aircraft (though without wheels and needing a launching device), flying consistently under full control and bringing its pilot back to the starting point safely and landing without damage. On 5 October 1905, Wilbur flew 24 miles (39 km) in 39 minutes 23 seconds."

According to the April 1907 issue of the *Scientific American* magazine, the Wright brothers seemed to have the most advanced knowledge of heavier-than-air navigation at the time. Though, the same magazine issue also affirms that no public flight has been made in the United States before its April 1907 issue. Hence, they devised the Scientific American Aeronautic Trophy in order to encourage the development of a heavier-than-air flying machine.

Alberto Santos-Dumont

Alberto Santos-Dumont, the designer of the 14-bis

The Brazilian inventor Alberto Santos-Dumont made a public flight with the flying machine designated 14-bis on 13 September 1906 in Paris. He used a canard elevator and pronounced wing dihedral, and covered a distance of 60 m (200 ft). Since the plane did not need headwinds or catapults to take off, this flight is considered by some as the first true powered flight. Also, since the earlier attempts of Pearse, Jatho, Watson, and the

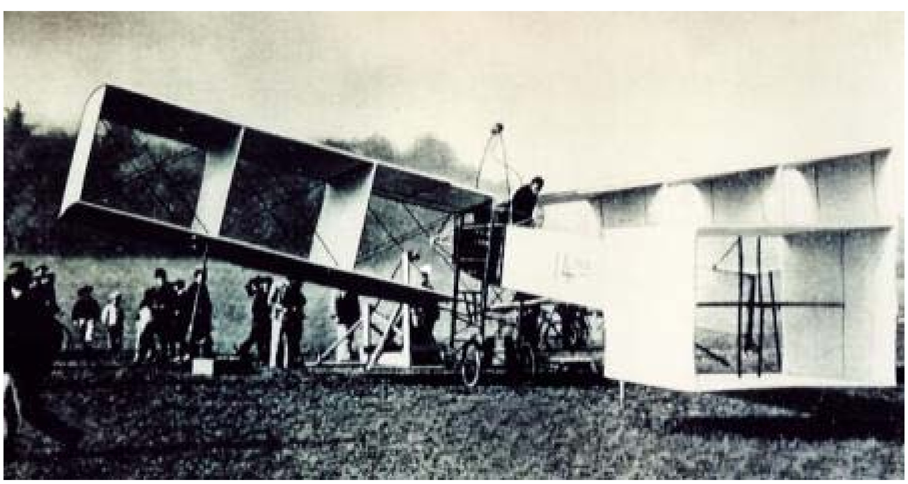
Wright brothers received far less attention from the popular press, Santos-Dumont's flight was more important to society when it happened, especially in Europe and Brazil, despite occurring some years later.

Confusion occasionally still arises over whether the Wright 1903 Flyer I, or the 14-Bis was the first true airplane. In fact, only the Wright Flyer I and its successors met the modern definition of an airplane (i.e., manned, powered, heavier than air, fully controllable around all three axes, and capable of sustained flight). The Wright 1903 Flyer I met this definition on December 17, 1903, taking off under its own power along a level wooden guide rail.

While the Wrights later used a launch catapult for their 1904 and 1905 machines, those Flyers could also take off unassisted given sufficient wind. It should be noted that the Wright 1905 Flyer (also called the Flyer III) flew more than 20 miles (32 km) in October 1905, a full year before the 14-bis made its first flight.

The 14-bis was marginally controllable at best and could only make wallowing hops. This remained true after Santos-Dumont, who was on the right track, installed primitive ailerons in November 1906. Unfortunately, they proved ineffective. On the plus side, Santos-Dumont and other Europeans used wheels whereas the Wrights stuck with skids for too long, which necessitated the use of a catapult in the absence of significant wind.

Santos-Dumont fans usually infer that while the *Wright Flyer* may have been superior in the air, its take-off apparatus made it overly impractical to operate and transport. Alternatively, Wright brothers fans usually point to the implication that the scarcity of usable takeoff fields made the Flyer and "pillar" more practical, needing much less open, smooth and level space than the *14-bis*.



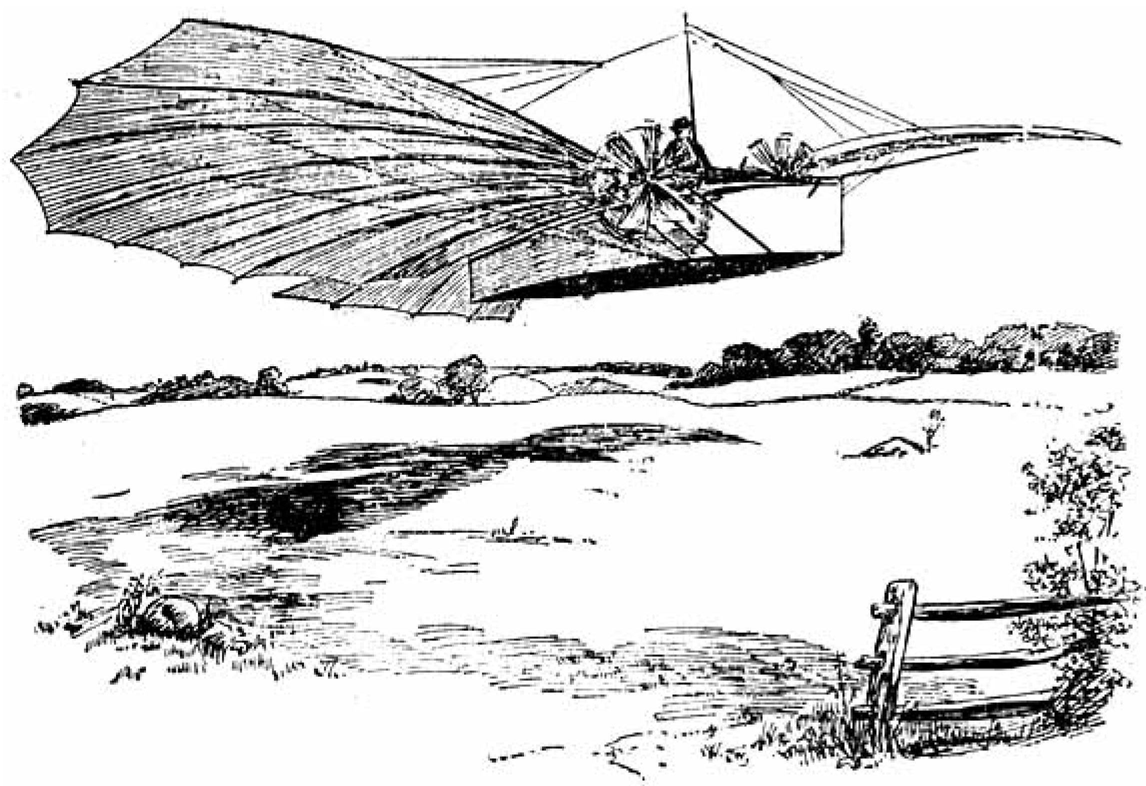
The 14-bis also known as Oiseau de proie (French for "bird of prey")

Opinions may vary on whether the Wright Flyer or the 14-bis was the more practical (and thus the "first") heavier-than-air flying machine. Both designs produced aircraft that made free, manned, powered flights. Which one was "first" or "more practical" is a matter of how those words are defined. No one could contest that the Wrights flew first, that the Flyer was more capable in the air, or that Santos Dumont took off on wheels before the Wrights and earned a variety of prizes and official records in France. Patriotic pride heavily influences opinions of the relative importance and practicality of each aircraft, thus causing debate. U.S. citizens prefer definitions that make the Wrights the "first" to fly, while Brazilians believe that Santos Dumont had the first "real", practical airplane, and that his nationality may have caused his accomplishments to not receive worldwide recognition.

In subsequent years, Santos-Dumont built more aircraft like Demoiselle. He was so enthusiastic about aviation that he released the drawings of Demoiselle for free, thinking that aviation would be the mainstream of a new prosperous era for mankind, and it became the world's first series production aircraft.

Other early flights & claims of flights

Around the years 1900 to 1910, a number of other inventors made or claimed to have made short flights.



Gustave Whitehead's aircraft was represented in a sketch in the *Bridgeport Herald*

On August 14, 1901, in Fairfield, Connecticut, Gustave Whitehead reportedly flew his engine-powered No.21 for 800 metres (2,600 ft) at 15 metres (49 ft) height. In January 1902, he claimed to have flown 11 kilometres (6.8 mi) over Long Island Sound in the improved No.22. After 1903, Whitehead faded from public awareness. Three decades later, Whitehead's possible flights emerged from obscurity after the events were featured in a 1935 newspaper article and a 1937 book. Aviation experts debated the topic, and a few decided for Whitehead, while the great majority, such as Charles Harvard Gibbs-Smith, said the flights could not have occurred.

Lyman Gilmore claimed to have achieved success on 15 May 1902 and is widely credited with the first use of the word "airport."

In New Zealand, South Canterbury farmer and inventor Richard Pearse constructed a monoplane aircraft that he reputedly flew in early 1903. Good evidence exists that on March 31, 1903 Pearse achieved a powered, though poorly controlled, flight of several hundred metres. Pearse himself said that although he had made a powered takeoff, it was at "too low a speed for [his] controls to work".

The first balloon flights took place in Australia in the late 19th century while Bill Wittber and then escapologist Harry Houdini made Australia's first controlled flights in 1910.. Wittber was conducting taxiing tests in a Blériot XI aircraft in March 1910 in South Australia when he suddenly found himself about five feet in the air (Wittber's Hop). He flew about 40 feet (12 m) before landing. South Australia's other aviation firsts include the first flight from England to Australia by brothers Sir Ross and Sir Keith Smith in their Vickers Vimy bomber, the first Arctic flight by South Australian born Sir Hubert Wilkins and the first Australian born astronaut, Andy Thomas.

Karl Jatho from Hanover conducted a short motorized flight in August 1903, just a few months after Pearse. Jatho's wing design and airspeed did not allow his control surfaces to act properly to control the aircraft.

Also in the summer of 1903, eyewitnesses claimed to have seen Preston Watson make his initial flights at Errol, near Dundee in the east of Scotland. Once again, however, lack of photographic or documentary evidence makes the claim difficult to verify. Many claims of flight are complicated by the fact that many early flights were done at such low altitude that they did not clear the ground effect, and by the complexities involved in the differences between unpowered and powered aircraft.

The Wright brothers conducted numerous additional flights (about 150) in 1904 and 1905 from Huffman Prairie in Dayton, Ohio and invited friends and relatives. Newspaper reporters did not pay attention after seeing an unsuccessful flight attempt in May 1904.

Public exhibitions of high altitude flights were made by Daniel Maloney in the John Joseph Montgomery tandem-wing glider in March and April 1905 in the Santa Clara, California area. These flights received national media attention and demonstrated superior control of the design, with launches as high as 4,000 feet (1,200 m) and landings made at predetermined locations.

Two English inventors Henry Farman and John William Dunne were also working separately on powered flying machines. In January 1908, Farman won the Grand Prix d'Aviation by flying a 1 km circle, though by this time several longer flights had already been done. For example, the Wright brothers had made a flight over 39 kilometres (24 mi) in October 1905. Dunne's early work was sponsored by the British military, and tested in great secrecy in Glen Tilt in the Scottish Highlands. His best early design, the D4, flew in December 1908 near Blair Atholl in Perthshire. Dunne's main contribution to early aviation was stability, which was a key problem with the planes designed by the Wright brothers and Samuel Cody.

On 14 May 1908 Wilbur Wright piloted the first two-person fixed-wing flight, with Charlie Furnas as a passenger.

On 8 July 1908 Thérèse Peltier became the first woman to fly as a passenger in an airplane when she made a flight of 656 feet (200 m) with Léon Delagrange in Milan, Italy.

Thomas Selfridge became the first person killed in a powered aircraft on 17 September 1908, when Orville Wright crashed his two-passenger plane during military tests at Fort Myer in Virginia.

The first powered flight in Britain was made in 1908 by American Sam Cody in a plane designed and built with the British Army.

In September 1908, Mrs Edith Berg became the first American woman to fly as a passenger in an airplane when she flew with Wilbur Wright in Le Mans, France.

The first powered flight by a Briton in Britain was made by John Moore-Brabazon (JTC Moore Brabazon) in May 1909 on the Isle of Sheppey (Kent).

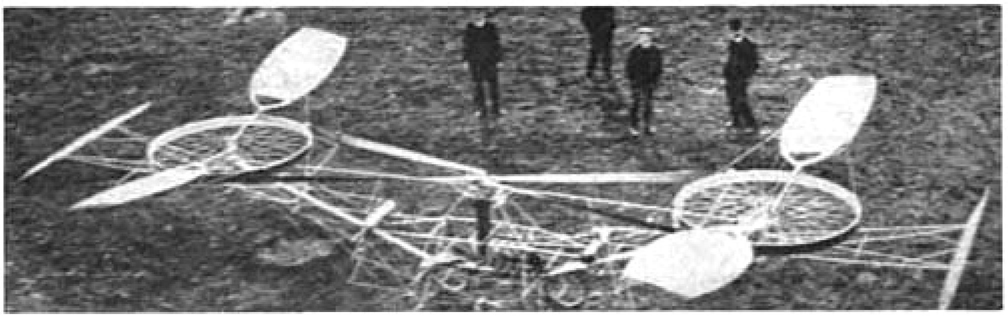
On 25 July 1909 Louis Blériot flew the Blériot XI monoplane across the English Channel winning the Daily Mail aviation prize. His flight from Calais to Dover lasted 37 minutes.

On 22 October 1909 Raymonde de Laroche became the first woman to fly solo in a powered heavier -than-air craft. She was also the first woman in the world to receive a pilot's licence.

Controversy over who gets credit for invention of the aircraft has been fueled by Pearse's and Jatho's essentially non-existent efforts to inform the popular press and by the Wrights' secrecy while their patent was prepared. For example, the Romanian engineer Traian Vuia (1872–1950) has also been claimed to have built the first self-propelled, heavier-than-air aircraft able to take off autonomously, without a headwind and entirely driven by its own power. Vuia piloted the aircraft he designed and built on 18 March 1906 at Montesson, near Paris. None of his flights were longer than 100 feet (30 m) in length. In comparison, in October 1905, the Wright brothers had a sustained flight of 39 minutes and 24.5 miles (39 km), circling over Huffman Prairie.

Helicopter

In 1877, Enrico Forlanini developed an unmanned helicopter powered by a steam engine. It rose to a height of 13 meters, where it remained for some 20 seconds, after a vertical take-off from a park in Milan.



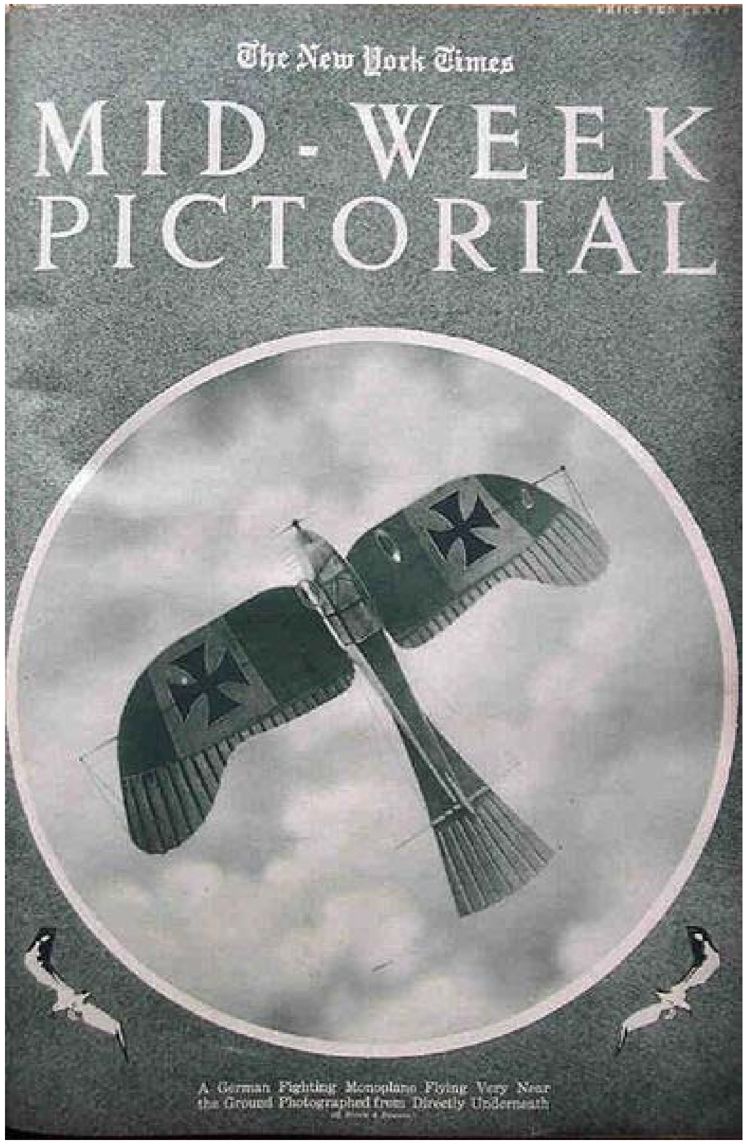
Paul Cornu's helicopter, built in 1907, was the first manned flying machine to have risen from the ground using rotating wings instead of fixed wings.

The first time a manned helicopter is known to have risen off the ground was in 1907 at Lisenux, France. The first successful rotorcraft, however, wasn't a true helicopter, but an autogyro invented by Spanish engineer Juan de la Cierva in 1919. These kind of rotorcrafts were mainly used until the development of modern helicopters, when, for some reason, they became largely neglected, although the idea has since been resurrected several times. Since the first practical helicopter was the Focke Achgelis Fw 61 (Germany, 1936), the autogyro's golden age only lasted around 20 years.

Seaplane

The first powered seaplane was invented in March 1910 by the French engineer Henri Fabre. Its name was *Le Canard* ('the duck'), and took off from the water and flew 800 meters on its first flight on March 28, 1910. These experiments were closely followed by the aircraft pioneers Gabriel and Charles Voisin, who purchased several of the Fabre floats and fitted them to their Canard Voisin airplane. In October 1910, the Canard Voisin became the first seaplane to fly over the river Seine, and in March 1912, the first seaplane to be used militarily from a seaplane carrier, *La Foudre* ('the lightning').

First performances steps under World War I (1914–1918)



German Taube monoplane, illustration from 1917

Almost as soon as they were invented, planes were drafted for military service. The first country to use planes for military purposes was Italy, whose planes made reconnaissance, bombing and shelling correction military flights during the Italian-Turkish war (September 1911 – October 1912), in Libya. First mission (a reconnaissance) happened on the 23rd October 1911. First bombing of enemy columns was the 1st November 1911. Then Bulgaria followed this example. Its planes attacked and reconnoitered the Ottoman positions during the First Balkan War 1912–13. The first war to see major use of planes in offensive, defensive and reconnaissance capabilities was World War I. The Allies and Central Powers both used planes extensively.

While the concept of using the aeroplane as a weapon of war was generally laughed at before World War I, the idea of using it for photography was one that was not lost on any of the major forces. All of the major forces in Europe had light aircraft, typically derived from pre-war sporting designs, attached to their reconnaissance departments. Radiotelephones were also being explored on airplanes, notably the SCR-68, as communication between pilots and ground commander grew more and more important

Combat schemes

It was not long before aircraft were shooting at each other, but the lack of any sort of steady point for the gun was a problem. The French solved this problem when, in late 1914, Roland Garros attached a fixed machine gun to the front of his plane, but while Adolphe Pegoud would become known as the first "ace", getting credit for five victories, before also becoming the first ace to die in action, it was German Luftstreitkräfte Leutnant Kurt Wintgens, who, on July 1, 1915, scored the very first aerial victory by a purpose-built fighter plane, with a synchronized machine gun.

Aviators were styled as modern day knights, doing individual combat with their enemies. Several pilots became famous for their air to air combats, the most well known is Manfred von Richthofen, better known as the **Red Baron**, who shot down 80 planes in air to air combat with several different planes, the most celebrated of which was the Fokker Dr.I. On the Allied side, René Paul Fonck is credited with the most all-time victories at 75, even when later wars are considered.

Because all of the litigations and patent wars fought by the Wright brothers the development of airplanes in USA was hindered and delayed so in WWI practically all pilots, including American pilots, had to use airplanes made in Europe.

Technology and performance advances in aviation's "Golden Age" (1918–1939)

The years between World War I and World War II saw great advancements in aircraft technology. Aeroplanes evolved from low-powered biplanes made from wood and fabric to sleek, high-powered monoplanes made of aluminum, based primarily on the founding work of Hugo Junkers during the World War I period. The age of the great airships came and went.

Flagg biplane from 1933

After WWI experienced fighter pilots were eager to show off their new skills. Many American pilots became barnstormers, flying into small towns across the country and showing off their flying abilities, as well as taking paying passengers for rides. Eventually the barnstormers grouped into more organized displays. Air shows sprang up around the country, with air races, acrobatic stunts, and feats of air superiority. The air races drove engine and airframe development—the Schneider Trophy, for example, led to a series of ever faster and sleeker monoplane designs culminating in the Supermarine S.6B, a direct forerunner of the Spitfire. With pilots competing for cash prizes, there was an incentive to go faster. Amelia Earhart was perhaps the most famous of those on the barnstorming/air show circuit. She was also the first female pilot to achieve records such as crossing of the Atlantic and Pacific Oceans.

Qantas De Havilland biplane, ca. 1930

Other prizes, for distance and speed records, also drove development forwards. For example on June 14, 1919, Captain John Alcock and Lieutenant Arthur Brown co-piloted a Vickers Vimy non-stop from St. John's, Newfoundland to Clifden, Ireland, winning the £13,000 ($65,000) Northcliffe prize. Eight years later Charles Lindbergh took the Orteig Prize of $25,000 for the first *solo* non-stop crossing of the Atlantic.

Australian Charles Kingsford Smith was the first to fly across the larger Pacific Ocean in the Southern Cross. His crew left Oakland, California to make the first trans-Pacific flight to Australia in three stages. The first (from Oakland to Hawaii) was 2,400 miles, took 27 hours 25 minutes and was uneventful. They then flew to Suva, Fiji 3,100 miles away, taking 34 hours 30 minutes. This was the toughest part of the journey as they flew through a massive lightning storm near the equator. They then flew on to Brisbane in 20 hours, where they landed on 9 June 1928 after approximately 7,400 miles total flight. On arrival, Kingsford Smith was met by a huge crowd of 25,000 at Eagle Farm Airport in his hometown of Brisbane. Accompanying him were Australian aviator Charles Ulm as the relief pilot, and the Americans James Warner and Captain Harry Lyon (who were the radio operator, navigator and engineer). With Ulm, Kingsford Smith later continued his journey being the first in 1929 to circumnavigate the world, crossing the equator twice.

The first lighter-than-air crossings of the Atlantic were made by airship in July 1919 by His Majesty's Airship R34 and crew when they flew from East Lothian, Scotland to Long Island, New York and then back to Pulham, England. By 1929, airship technology had advanced to the point that the first round-the-world flight was completed by the *Graf Zeppelin* in September and in October, the same aircraft inaugurated the first commercial transatlantic service. However the age of the dirigible ended following the destruction by fire of the zeppelin *Hindenburg* just before landing at Lakehurst, New Jersey on May 6, 1937, killing 35 of the 97 people aboard. Previous spectacular airship accidents, from the *Wingfoot Express* disaster (1919) to the loss of the *Akron* (1933) and the *Macon* (1935) had already cast doubt on airship safety; following the destruction of the Hindenburg, the remaining airship making international flights, the *Graf Zeppelin* was retired (June 1937); its replacement, the dirigible *Graf Zeppelin II*, made a number of flights, primarily over Germany, from 1938 to 1939, but was grounded when Germany began World War II. Both remaining German zeppelins were scrapped in 1940 to supply metal for the German Luftwaffe; the last American zeppelin, the *Los Angeles*, which had not flown since 1932, was dismantled in late 1939.

Meanwhile in Germany, who was restricted by the Treaty of Versailles in its development of powered aircraft, instead developed gliding as a sport, especially at the Wasserkuppe, during the 1920s. In its various forms, this activity now has over 400,000 participants.

In 1929 Jimmy Doolittle developed instrument flight.

1929 also saw the first flight of by far the largest plane ever built until then: the Dornier Do X with a wing span of 48 m. On its 70th test flight on October 21 there were 169 people on board, a record that was not broken for 20 years.

In the 1930s development of the jet engine began in Germany and in England. In England Frank Whittle patented a design for a jet engine in 1930 and towards the end of the decade began developing an engine. In Germany Hans von Ohain patented his version of a jet engine in 1936 and began developing a similar engine. The two men were unaware of the other's work, and both Germany and Britain would go on to develop jet aircraft by the end of World War II.

Progress goes on and massive production, World War II (1939–1945)

World War II saw a drastic increase in the pace of aircraft development and production. All countries involved in the war stepped up development and production of aircraft and flight based weapon delivery systems, such as the first long range bomber. Also air combat tactics and doctrines changed, large scale strategic bombing campaigns were launched, Fighter escorts introduced and the more flexible aircraft and weapons allowed more precise attacks on small targets for effective ground support. New technologies like radar also allowed more coordinated and controlled deployment of fighter aircraft.

Me 262, world first operational jet fighter

The **first functional jetplane** was the Heinkel He 178 (Germany), flown by Erich Warsitz in 1939, followed by the worlds first operational fighter aircraft, the Me 262, in July 1942 and worlds first jet powered bomber, the Arado Ar 234, in June 1943. British developments, like the Gloster Meteor, followed afterwards, but saw only brief use in World War II. The first cruise missile (V-1), the first ballistic missile (V-2), the first (and to date only) operational rocket powered combat aircraft Me 163 and the first vertical take-off manned point-defense interceptor Bachem Ba 349 were also developed by Germany. However, jet fighters had only limited impact due to their late introduction, fuel shortages, the lack of experienced pilots and the declining war industry of Germany.

But not only airplanes, helicopters too saw rapid development in the Second World War. With the introduction of the Focke Achgelis Fa 223, the Flettner Fl 282 in 1941 in Germany and the Sikorsky R-4 1942 in the USA, the first time larger helicopter formations were produced and deployed.

1945–1991: The Cold War

D.H. Comet, the world's first jet airliner. As in this picture, it also saw RAF service

A 1945 newsreel covering various firsts in human flight

After World War II, commercial aviation grew rapidly, used mostly ex-military aircraft to transport people and cargo. This growth was accelerated by the glut of heavy and super-heavy bomber airframes like the B-29 and Lancaster that could be converted into commercial aircraft. The DC-3 also made for easier and longer commercial flights. The first commercial jet airliner to fly was the British De Havilland Comet. By 1952, the British state airline BOAC had introduced the De Havilland Comet into scheduled service. While a technical achievement, the plane suffered a series of highly public failures, as the shape of the windows led to cracks due to metal fatigue. The fatigue was caused by cycles of pressurization and depressurization of the cabin, and eventually led to catastrophic failure of the plane's fuselage. By the time the problems were overcome, other jet airliner designs had already taken to the skies.

USSR's Aeroflot became the first airline in the world to operate sustained regular jet services on September 15, 1956 with the Tupolev Tu-104. Boeing 707, which established new levels of comfort, safety and passenger expectations, ushered in the age of mass commercial air travel, dubbed the Jet Age.

In October 1947 Chuck Yeager took the rocket powered Bell X-1 past the speed of sound. Although anecdotal evidence exists that some fighter pilots may have done so while divebombing ground targets during the war, this was the first controlled, level flight to cross the sound barrier. Further barriers of distance fell in 1948 and 1952 with the first jet crossing of the Atlantic and the first nonstop flight to Australia.

When the Soviet Union developed long-range bombers that could deliver nuclear weapons to North America and Europe, Western countries responded with interceptor aircraft that could engage and destroy the bombers before they reached their destination. The "minister-of-everything" C.D. Howe in the Canadian government, was the key proponent of the Avro Arrow, designed as a high-speed interceptor, reputedly the fastest aircraft in its time. However, by 1955, most Western countries agreed that the interceptor age was replaced by guided missile age. Consequently, the Avro Arrow project was eventually cancelled in 1959 under Prime Minister John Diefenbaker.

In 1961, the sky was no longer the limit for manned flight, as Yuri Gagarin orbited once around the planet within 108 minutes, and then used the descent module of Vostok I to safely reenter the atmosphere and reduce speed from Mach 25 using friction and converting velocity into heat. This action further heated up the space race that had started in 1957 with the launch of Sputnik 1 by the Soviet Union. The United States responded by launching Alan Shepard into space on a suborbital flight in a Mercury space capsule. With the launch of the Alouette I in 1963, Canada became the third country to send a satellite in space. The Space race between the United States and the Soviet Union would ultimately lead to the landing of men on the moon in 1969.

In 1967, the X-15 set the air speed record for an aircraft at 4,534 mph (7,297 km/h) or Mach 6.1 (7,297 km/h). Aside from vehicles designed to fly in outer space, this record was renewed by X-43 in the 21st century.

Apollo 11 lifts off on its mission to land a man on the moon

The Harrier Jump Jet, often referred to as just "Harrier" or "the Jump Jet", is a British designed military jet aircraft capable of Vertical/Short Takeoff and Landing (V/STOL) via thrust vectoring. It first flew in 1969. The same year that Neil Armstrong and Buzz Aldrin set foot on the moon, and Boeing unveiled the Boeing 747 and the Aérospatiale-BAC Concorde supersonic passenger airliner had its maiden flight. The 747 plane was the largest aircraft ever to fly, and still carries millions of passengers each year, though it has been superseded by the Airbus A380, which is capable of carrying up to 853 passengers. In 1975 Aeroflot started regular service on the Tu-144—the first supersonic passenger plane. In 1976 British Airways began supersonic service across the Atlantic, with Concorde. A few years earlier the SR-71 Blackbird had set the record for crossing the Atlantic in under 2 hours, and Concorde followed in its footsteps.

The last quarter of the 20th century saw a slowing of the pace of advancement. No longer was revolutionary progress made in flight speeds, distances and technology. This part of the century saw the steady improvement of flight avionics, and a few minor milestones in flight progress.

For example, in 1979 the Gossamer Albatross became the first human powered aircraft to cross the English channel. This achievement finally saw the realization of centuries of dreams of human flight. In 1981, the Space Shuttle made its first orbital flight, proving that a large rocket ship can take off into space, provide a pressurised life support system for several days, reenter the atmosphere at orbital speed, precision glide to a runway and land like a plane.

In 1986 Dick Rutan and Jeana Yeager flew an aircraft, the Rutan Voyager, around the world unrefuelled, and without landing. In 1999 Bertrand Piccard became the first person to circle the earth in a balloon. Focus was turning to the ultimate conquest of space and flight at faster than the speed of sound. The ANSARI X PRIZE inspired entrepreneurs and space enthusiasts to build their own rocket ships to fly faster than sound and climb into the lower reaches of space.

2001–present

Concorde, *G-BOAB*, in storage at London Heathrow Airport following the end of all Concorde flying. This aircraft flew for 22,296 hours between its first flight in 1976 and final flight in 2000.

In commercial aviation, the early 21st century saw the end of an era with the retirement of Concorde. Supersonic flight was not commercially viable, as the planes were required to fly over the oceans if they wanted to break the sound barrier. Concorde also was fuel hungry and could carry a limited amount of passengers due to its highly streamlined design. Nevertherless, it seems to have made a significant operating profit for British Airways.

In the beginning of the 21st century, subsonic military aviation focused on eliminating the pilot in favor of remotely operated or completely autonomous vehicles. Several unmanned aerial vehicles or UAVs have been developed. In April 2001 the unmanned aircraft Global Hawk flew from Edwards AFB in the US to Australia non-stop and unrefuelled. This is the longest point-to-point flight ever undertaken by an unmanned aircraft, and took 23 hours and 23 minutes. In October 2003 the first totally autonomous flight across the Atlantic by a computer-controlled model aircraft occurred.

The *U.S. Centennial of Flight Commission* was established in 1999 to encourage the broadest national and international participation in the celebration of 100 years of powered flight. It publicized and encouraged a number of programs, projects and events intended to educate people about the history of aviation.

Major disruptions to air travel in the 21st Century included the closing of U.S. airspace due to the September 11 attacks, and the closing of northern European airspace after the 2010 eruption of Eyjafjallajökull.

Chapter 2

Airline and Civil Aviation

Airline

A FedEx Express McDonnell Douglas MD-11. FedEx Express is the world's largest cargo airline in terms of number of aircraft and in terms of freight tons flown.

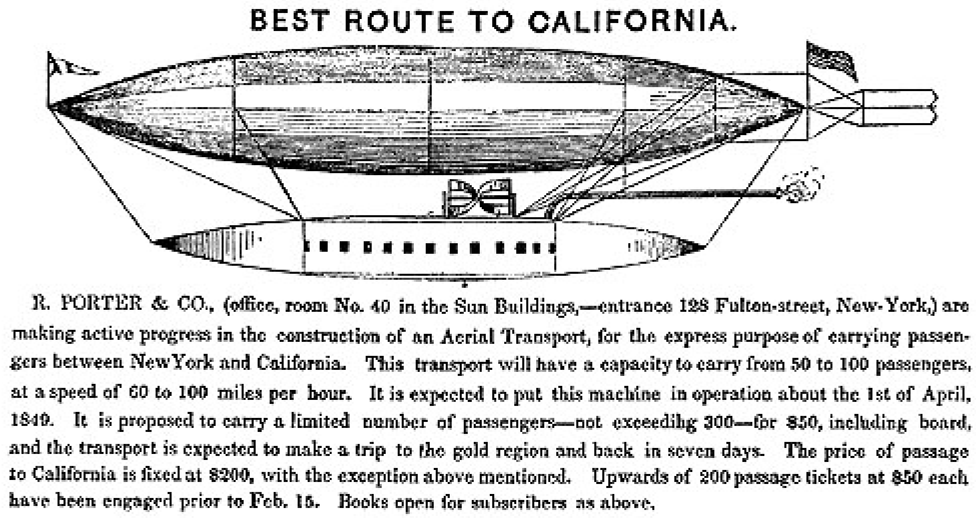
Ryanair Boeing 737-800 shortly after take-off. Ryanair is the world's largest airline in terms of number of international passengers carried.

An **airline** provides air transport services for passengers or freight, generally these companies with a recognized operating certificate or license. Airlines lease or own their aircraft with which to supply these services and may form partnerships or alliances with other airlines for mutual benefit.

Airlines vary from those with a single aircraft carrying mail or cargo, through full-service international airlines operating hundreds of aircraft. Airline services can be categorized as being intercontinental, intra continental, domestic, or international and may be operated as scheduled services or charters.

History

The first airlines



Failed attempt at an airline before DELAG

DELAG, *Deutsche Luftschiffahrts-Aktiengesellschaft* was the world's first airline. It was founded on November 16, 1909 with government assistance, and operated airships manufactured by The Zeppelin Corporation. Its headquarters were in Frankfurt. (Note: Americans, such as Rufus Porter and Frederick Marriott, attempted to start airlines using airships in the mid-19th century, focusing on the New York–California route. Those attempts floundered due to such mishaps as the aircraft catching fire and the aircraft being ripped apart by spectators.) The five oldest non-dirigible airlines that still exist are Netherlands' KLM, Colombia's Avianca, Australia's Qantas, Czech Republic's Czech Airlines, and Mexico's Mexicana. KLM first flew in May 1920, while Qantas (which stands for *Queensland and Northern Territory Aerial Services Limited*) was founded in Queensland, Australia, in late 1920.

U.S. airline industry

Early development

TWA Douglas DC-3 in 1940. The DC-3, often regarded as one of the most influential aircraft in the history of commercial aviation, revolutionized the aviation industry.

Tony Jannus conducted the United State's first scheduled commercial airline flight on 1 January 1914 for the St. Petersburg-Tampa Airboat Line. The 23-minute flight traveled between St. Petersburg, Florida and Tampa, Florida, passing some 50 feet (15 m) above Tampa Bay in Jannus' Benoist XIV biplane flying boat. Chalk's Airlines (now Chalk's International Airlines) began service between Miami and Bimini in the Bahamas in February 1919. Now based in Ft. Lauderdale, Chalk's claims to be the oldest continuously operating airline in the United States.

Following World War I, the United States found itself swamped with aviators. Many decided to take their war-surplus aircraft on barnstorming campaigns, performing acrobatic maneuvers to woo crowds. In 1918, the United States Postal Service won the financial backing of Congress to begin experimenting with air mail service, initially using Curtiss Jenny aircraft that had been procured by the United States Army for reconnaissance missions on the Western Front. Private operators were the first to fly the mail but due to numerous accidents the US Army was tasked with mail delivery. During the course of the Army's involvement they proved to be too unreliable and lost their air mail duties. By the mid-1920s, the Postal Service had developed its own air mail network, based on a transcontinental backbone between New York and San Francisco. To supplant this service, they offered twelve contracts for spur routes to independent bidders. Some of the carriers that won these routes would, through time and mergers, evolve into Pan Am, Delta Air Lines, Braniff Airways, American Airlines, United Airlines (originally a division of Boeing), Trans World Airlines, Northwest Airlines, and Eastern Air Lines.

Service during the early 1920s was sporadic: most airlines at the time were focused on carrying bags of mail. In 1925, however, the Ford Motor Company bought out the Stout Aircraft Company and began construction of the all-metal Ford Trimotor, which became the first successful American airliner. With a 12-passenger capacity, the Trimotor made passenger service potentially profitable. Air service was seen as a supplement to rail service in the American transportation network.

At the same time, Juan Trippe began a crusade to create an air network that would link America to the world, and he achieved this goal through his airline, Pan American World Airways, with a fleet of flying boats that linked Los Angeles to Shanghai and Boston to London. Pan Am and Northwest Airways (which began flights to Canada in the 1920s) were the only U.S. airlines to go international before the 1940s.

With the introduction of the Boeing 247 and Douglas DC-3 in the 1930s, the U.S. airline industry was generally profitable, even during the Great Depression. This trend continued until the beginning of World War II.

Development since 1945

In October 1945, the American Export Airlines became the first airline to offer regular commercial flights between North America and Europe. Shown here is Am Ex Boeing 377 *Stratocruiser* in 1949.

As governments met to set the standards and scope for an emergent civil air industry toward the end of the war, the U.S. took a position of maximum operating freedom; U.S. airline companies were not as hard-hit as European and the few Asian ones had been. This preference for "open skies" operating regimes continues, within limitations, to this day.

World War II, like World War I, brought new life to the airline industry. Many airlines in the Allied countries were flush from lease contracts to the military, and foresaw a future explosive demand for civil air transport, for both passengers and cargo. They were eager to invest in the newly emerging flagships of air travel such as the Boeing Stratocruiser, Lockheed Constellation, and Douglas DC-6. Most of these new aircraft were based on American bombers such as the B-29, which had spearheaded research into new technologies such as pressurization. Most offered increased efficiency from both added speed and greater payload.

In the 1950s, the De Havilland Comet, Boeing 707, Douglas DC-8, and Sud Aviation Caravelle became the first flagships of the Jet Age in the West, while the Soviet Union bloc had Tupolev Tu-104 and Tupolev Tu-124 in the fleets of state-owned carriers such as Czechoslovak ČSA, Soviet Aeroflot and East-German Interflug. The Vickers Viscount and Lockheed L-188 Electra inaugurated turboprop transport.

The next big boost for the airlines would come in the 1970s, when the Boeing 747, McDonnell Douglas DC-10, and Lockheed L-1011 inaugurated widebody ("jumbo jet") service, which is still the standard in international travel. The Tupolev Tu-144 and its Western counterpart, Concorde, made supersonic travel a reality. Concorde first flew in 1969 and operated through 2003. In 1972, Airbus began producing Europe's most commercially successful line of airliners to date. The added efficiencies for these aircraft were often not in speed, but in passenger capacity, payload, and range. Airbus also features modern electronic cockpits that were common across their aircraft to enable pilots to fly multiple models with minimal cross-training.

Pan Am Boeing 747 *Clipper Neptune's Car* in 1985. The deregulation of the American airline industry increased the financial troubles of the iconic airline which ultimately filed for bankruptcy in December 1991.

1978's U.S. airline industry deregulation lowered barriers for new airlines just as a downturn occurred. New start-ups entered during the downturn, during which time they found aircraft and funding, contracted hangar and maintenance services, trained new employees, and recruited laid off staff from other airlines.

As the business cycle returned to normalcy, major airlines dominated their routes through aggressive pricing and additional capacity offerings, often swamping new startups. Only America West Airlines (which has since merged with US Airways) remained a significant survivor from this new entrant era, as dozens, even hundreds, have gone under.

In many ways, the biggest winner in the deregulated environment was the air passenger. Indeed, the U.S. witnessed an explosive growth in demand for air travel, as many millions who had never or rarely flown before became regular fliers, even joining frequent flyer loyalty programs and receiving free flights and other benefits from their flying. New services and higher frequencies meant that business fliers could fly to another city, do business, and return the same day, for almost any point in the country. Air travel's advantages put intercity bus lines under pressure, and most have withered away.

By the 1980s, almost half of the total flying in the world took place in the U.S., and today the domestic industry operates over 10,000 daily departures nationwide.

Toward the end of the century, a new style of low cost airline emerged, offering a no-frills product at a lower price. Southwest Airlines, JetBlue, AirTran Airways, Skybus Airlines and other low-cost carriers began to represent a serious challenge to the so-called "legacy airlines", as did their low-cost counterparts in many other countries. Their commercial viability represented a serious competitive threat to the legacy carriers. However, of these, ATA and Skybus have since ceased operations.

Increasingly since 1978, US airlines have been reincorporated and spun off by newly created and interally led manangement companies, and thus becoming nothing more than operating units and subsidiaries with limited finanically decisive control. Among some of these holding companies and parent companies that are the relatively well known, are the UAL Corporation, along with the AMR Corporation, among a long list of airline holding companies sometime recognized world wide. Less recognized are the private equity firms which often seize managerial, financial, and board of directors control of distressed airline companies by temporarily investing large sums of capital in air carriers, so as to rescheme an airlines assets into a profitable organization or liquidating an air carrier of their profitable and worthwhile routes and business operations.

Thus the last 50 years of the airline industry have varied from reasonably profitable, to devastatingly depressed. As the first major market to deregulate the industry in 1978, U.S. airlines have experienced more turbulence than almost any other country or region. Today, American Airlines is the only U.S. legacy carrier to survive bankruptcy-free.

The Airline "Bailout"

Congress passed the Air Transportation Safety and System Stabilization Act (P.L. 107-42) in response to a severe liquidity crisis facing the industry in the aftermath of the September 11th terrorist attacks. Congress sought to compensate carriers for both the cost of the four-day federal shutdown of the airlines and the incremental losses incurred through December 31, 2001 as a result of the terrorist attacks. Congress expressly sought to preserve a viable, safe, and efficient air transportation system.

In recognition of the essential national economic role of a healthy aviation system, Congress authorized partial compensation of up to $5 billion in cash subject to review by the Department of Transportation and up to $10 billion in loan guarantees subject to review by a newly created Air Transportation Stabilization Board (ATSB). The applications to DOT for reimbursements were subjected to rigorous multi-year reviews not only by DOT program personnel but also by the Government Accountability Office and the DOT Inspector General.

Ultimately, the federal government provided $4.6 billion in one-time, subject-to-income-tax cash reimbursements to 427 U.S. air carriers, including numerous charter and cargo carriers. (Passenger carriers operating scheduled service received approximately $4 billion, subject to tax.) In addition, the ATSB approved loan guarantees to six airlines totaling approximately $1.6 billion. Data from the Treasury Department show that taxpayers eventually recouped the $1.6 billion and a profit of $339 million from the fees, interest and stock associated with loan guarantees.

European airline industry

The Imperial Airways Empire Terminal, Victoria, London. Trains ran from here to flying boats in Southampton, and to Croydon Airport.

The first countries in Europe to embrace air transport were Belgium, Finland, France, Germany, the Netherlands and the United Kingdom. KLM, the oldest carrier still operating under its original name, was founded in 1919. The first flight (operated on behalf of KLM by Aircraft Transport and Travel) transported two English passengers to

Schiphol, Amsterdam from London in 1920. Like other major European airlines of the time, KLM's early growth depended heavily on the needs to service links with far-flung colonial possessions (Dutch Indies). It is only after the loss of the Dutch Empire that KLM found itself based at a small country with few potential passengers, depending heavily on transfer traffic, and was one of the first to introduce the hub-system to facilitate easy connections.

France began an air mail service to Morocco in 1919 that was bought out in 1927, renamed Aéropostale, and injected with capital to become a major international carrier. In 1933, Aéropostale went bankrupt, was nationalized and merged with several other airlines into what became Air France.

In Finland, the charter establishing Aero O/Y (now Finnair) was signed in the city of Helsinki on September 12, 1923. Junkers F 13 D-335 became the first aircraft of the company, when Aero took delivery of it on March 14, 1924. The first flight was between Helsinki and Tallinn, capital of Estonia, and it took place on March 20, 1924, one week later.

Germany's Lufthansa began in 1926. Lufthansa, unlike most other airlines at the time, became a major investor in airlines outside of Europe, providing capital to Varig and Avianca. German airliners built by Junkers, Dornier, and Fokker were the most advanced in the world at the time. In 1931, the airship Graf Zeppelin began offering regular scheduled passenger service between Germany and South America, usually every two weeks, which continued until 1937. In 1936, the airship Hindenburg entered passenger service and successfully crossed the Atlantic 36 times before crashing at Lakehurst, New Jersey on May 6, 1937.

The British company Aircraft Transport and Travel commenced a London to Paris service on August 25, 1919, this was the world's first regular international flight. The United Kingdom's flag carrier during this period was Imperial Airways, which became BOAC (British Overseas Airways Co.) in 1939. Imperial Airways used huge Handley-Page biplanes for routes between London, the Middle East, and India: images of Imperial aircraft in the middle of the Rub'al Khali, being maintained by Bedouins, are among the most famous pictures from the heyday of the British Empire.

In Soviet Union the Chief Administration of the Civil Air Fleet was established in 1921. One of its first acts was to help found Deutsch-Russische Luftverkehrs A.G. (Deruluft), a German-Russian joint venture to provide air transport from Russia to the West. Domestic air service began around the same time, when Dobrolyot started operations on 15 July 1923 between Moscow and Nizhni Novgorod. Since 1932 all operations had been carried under the name Aeroflot. By the end of the 1930s Aeroflot had become the world's largest airline, employing more than 4,000 pilots and 60,000 other service personnel and operating around 3,000 aircraft (of which 75% were considered obsolete by its own standards). During the Soviet era Aeroflot was synonymous with Russian civil aviation, as it was the only air carrier. It became the first airline in the world to operate sustained regular jet services on 15 September 1956 with the Tupolev Tu-104.

Deregulation

Deregulation of the European Union airspace in the early 1990s has had substantial effect on structure of the industry there. The shift towards 'budget' airlines on shorter routes has been significant. Airlines such as EasyJet and Ryanair have grown at the expense of the traditional national airlines.

There has also been a trend for these national airlines themselves to be privatised such as has occurred for Aer Lingus and British Airways. Other national airlines, including Italy's Alitalia, have suffered - particularly with the rapid increase of oil prices in early 2008.

Asian airline industry

Although Philippine Airlines (PAL) was officially founded on February 26, 1941, its license to operate as an airliner was derived from merged Philippine Aerial Taxi Company (PATCO) established by mining magnate Emmanuel N. Bachrach in December 3, 1930, making it as Asia's oldest scheduled carrier still in operation. Commercial air service commenced three weeks later from Manila to Baguio, making it Asia's first airline route. Bachrach's death in 1937 paved the way for its eventual merger with Philippine Airlines in March 1941 and made it Asia's oldest airline. It is also the oldest airline in Asia still operating under its current name. Bachrach's majority share in PATCO was bought by beer magnate Andres R. Soriano in 1939 upon the advice of General Douglas McArthur and later merged with newly formed Philippine Airlines with PAL as the surviving entity. Soriano has controlling interest in both airlines before the merger. PAL restarted service on March 15, 1941 with a single Beech Model 18 NPC-54 aircraft, which started its daily services between Manila (from Nielson Field) and Baguio, later to expand with larger aircraft such as the DC-3 and Vickers Viscount.

India was also one of the first countries to embrace civil aviation. One of the first West Asian airline companies was Air India, which had its beginning as Tata Airlines in 1932, a division of Tata Sons Ltd. (now Tata Group). The airline was founded by India's leading industrialist, JRD Tata. On October 15, 1932, J. R. D. Tata himself flew a single engined De Havilland Puss Moth carrying air mail (postal mail of Imperial Airways) from Karachi to Mumbai via Ahmedabad. The aircraft continued to Madras via Bellary piloted by Royal Air Force pilot Nevill Vintcent. Tata Airlines was also one of the world's first major airlines which began its operations without any support from the Government.

With the outbreak of World War II, the airline presence in Asia came to a relative halt, with many new flag carriers donating their aircraft for military aid and other uses. Following the end of the war in 1945, regular commercial service was restored in India and Tata Airlines became a public limited company on July 29, 1946 under the name Air India. After the independence of India, 49% of the airline was acquired by the Government of India. In return, the airline was granted status to operate international services from India as the designated flag carrier under the name Air India International.

On July 31, 1946, a chartered Philippine Airlines (PAL) DC-4 ferried 40 American servicemen to Oakland, California from Nielson Airport in Makati City with stops in Guam, Wake Island, Johnston Atoll and Honolulu, Hawaii, making PAL the first Asian airline to cross the Pacific Ocean. A regular service between Manila and San Francisco was started in December. It was during this year that the airline was designated as the flag carrier of Philippines.

During the era of decolonization, newly-born Asian countries started to embrace air transport. Among the first Asian carriers during the era were Cathay Pacific of Hong Kong (founded in September 1946), Orient Airways (later Pakistan International Airlines; founded in October 1946), Malayan Airlines (later Singapore and Malaysia Airlines; founded in 1947), El Al in Israel in 1948, Garuda Indonesia in 1949, Japan Airlines in 1951, and Korean Air in 1962.

Latin American airline industry

TAM Airlines is the largest airline in Latin America in terms of number of annual passengers flown.

Among the first countries to have regular airlines in Latin America were Colombia with Avianca, Brazil with Varig, Chile with LAN Chile (today LAN Airlines), Dominican Republic with Dominicana de Aviación, Mexico with Mexicana de Aviación, and TACA as a brand of several airlines of Central American countries (Honduras, El Salvador, Costa Rica, Guatemala and Nicaragua). All the previous airlines started regular operations before World War II.

The air travel market has evolved rapidly over recent years in Latin America. Some industry estimations over 2000 new aircraft will begin service over the next five years in this region.

These airlines serve domestic flights within their countries, as well as connections within Latin America and also overseas flights to North America, Europe, Australia, Africa and Asia.

Just three airlines: LAN (Latin American Networks), Oceanair and TAM Airlines have international subsidiaries with Chile as the central operation along with Peru, Ecuador, Argentina and some operations in the Dominican Republic and TAM with TAM Mercosur have a base in Asuncion, Paraguay. Avianca have the control of Oceanair, VIP Airlines and also have an estrategic alliance with TACA.

The three main hubs in Latin America are Mexico City in Mexico, São Paulo in Brazil and Santiago in Chile.

Regulatory considerations

National

Pakistan International Airlines Boeing 747-300. The Government of Pakistan is the majority stake-holder in the country's flag carrier.

Garuda Indonesia Boeing 747-400 parked at Narita International Airport. Garuda will replaced its 747s with 777-300ER in late 2010. This Indonesian Flag carrier is wholly owned by the Indonesian Government

Many countries have national airlines that the government owns and operates. Fully private airlines are subject to a great deal of government regulation for economic, political, and safety concerns. For instance, governments often intervene to halt airline labor actions in order to protect the free flow of people, communications, and goods between different regions without compromising safety.

The United States, Australia, and to a lesser extent Brazil, Mexico, the United Kingdom and Japan have "deregulated" their airlines. In the past, these governments dictated airfares, route networks, and other operational requirements for each airline. Since deregulation, airlines have been largely free to negotiate their own operating arrangements with different airports, enter and exit routes easily, and to levy airfares and supply flights according to market demand.

Cyprus Airways national airline of Cyprus

The entry barriers for new airlines are lower in a deregulated market, and so the U.S. has seen hundreds of airlines start up (sometimes for only a brief operating period). This has produced far greater competition than before deregulation in most markets, and average fares tend to drop 20% or more. The added competition, together with pricing freedom, means that new entrants often take market share with highly reduced rates that, to a limited degree, full service airlines must match. This is a major constraint on profitability for established carriers, which tend to have a higher cost base.

As a result, profitability in a deregulated market is uneven for most airlines. These forces have caused some major airlines to go out of business, in addition to most of the poorly established new entrants.

International

Singapore Airlines Airbus A380 lands at Changi Airport. Singapore Airlines was the first international airline to operate the A380, the world's largest passenger airliner.

Groups such as the International Civil Aviation Organization establish worldwide standards for safety and other vital concerns. Most international air traffic is regulated by bilateral agreements between countries, which designate specific carriers to operate on specific routes. The model of such an agreement was the Bermuda Agreement between the US and UK following World War II, which designated airports to be used for transatlantic flights and gave each government the authority to nominate carriers to operate routes.

Bilateral agreements are based on the "freedoms of the air", a group of generalized traffic rights ranging from the freedom to overfly a country to the freedom to provide domestic flights within a country (a very rarely granted right known as cabotage). Most agreements permit airlines to fly from their home country to designated airports in the other country: some also extend the freedom to provide continuing service to a third country, or to another destination in the other country while carrying passengers from overseas.

In the 1990s, "open skies" agreements became more common. These agreements take many of these regulatory powers from state governments and open up international routes to further competition. Open skies agreements have met some criticism, particularly within the European Union, whose airlines would be at a comparative disadvantage with the United States' because of cabotage restrictions.

Economic considerations

Juan Trippe, the founder of Pan American World Airways, surveying his globe. The collapse of Pan Am, an airline often credited for shaping the international airline industry, in December 1991 highlighted the financial complexities faced by major airline companies.

Historically, air travel has survived largely through state support, whether in the form of equity or subsidies. The airline industry as a whole has made a cumulative loss during its 100-year history, once the costs include subsidies for aircraft development and airport construction.

One argument is that positive externalities, such as higher growth due to global mobility, outweigh the microeconomic losses and justify continuing government intervention. A historically high level of government intervention in the airline industry can be seen as part of a wider political consensus on strategic forms of transport, such as highways and railways, both of which receive public funding in most parts of the world. Profitability is likely to improve in the future as privatization continues and more competitive low-cost carriers proliferate.

Although many countries continue to operate state-owned or parastatal airlines, many large airlines today are privately owned and are therefore governed by microeconomic principles in order to maximize shareholder profit.

Ticket revenue

Airlines assign prices to their services in an attempt to maximize profitability. The pricing of airline tickets has become increasingly complicated over the years and is now largely determined by computerized yield management systems.

Because of the complications in scheduling flights and maintaining profitability, airlines have many loopholes that can be used by the knowledgeable traveler. Many of these airfare secrets are becoming more and more known to the general public, so airlines are forced to make constant adjustments.

Most airlines use differentiated pricing, a form of price discrimination, in order to sell air services at varying prices simultaneously to different segments. Factors influencing the price include the days remaining until departure, the booked load factor, the forecast of total demand by price point, competitive pricing in force, and variations by day of week of departure and by time of day. Carriers often accomplish this by dividing each cabin of the aircraft (first, business and economy) into a number of travel classes for pricing purposes.

A complicating factor is that of origin-destination control ("O&D control"). Someone purchasing a ticket from Melbourne to Sydney (as an example) for AU$200 is competing with someone else who wants to fly Melbourne to Los Angeles through Sydney on the same flight, and who is willing to pay AU$1400. Should the airline prefer the $1400 passenger, or the $200 passenger plus a possible Sydney-Los Angeles passenger willing to pay $1300? Airlines have to make hundreds of thousands of similar pricing decisions daily.

Lufthansa Boeing 747-400.

The advent of advanced computerized reservations systems in the late 1970s, most notably Sabre, allowed airlines to easily perform cost-benefit analyses on different pricing structures, leading to almost perfect price discrimination in some cases (that is, filling each seat on an aircraft at the highest price that can be charged without driving the consumer elsewhere).

The intense nature of airfare pricing has led to the term "fare war" to describe efforts by airlines to undercut other airlines on competitive routes. Through computers, new airfares can be published quickly and efficiently to the airlines' sales channels. For this purpose the airlines use the Airline Tariff Publishing Company (ATPCO), who distribute latest fares for more than 500 airlines to Computer Reservation Systems across the world.

The extent of these pricing phenomena is strongest in "legacy" carriers. In contrast, low fare carriers usually offer preannounced and simplified price structure, and sometimes quote prices for each leg of a trip separately.

Computers also allow airlines to predict, with some accuracy, how many passengers will actually fly after making a reservation to fly. This allows airlines to overbook their flights enough to fill the aircraft while accounting for "no-shows," but not enough (in most cases) to force paying passengers off the aircraft for lack of seats. Since an average of ⅓ of all seats are flown empty, stimulative pricing for low demand flights coupled with overbooking on high demand flights can help reduce this figure. This is especially crucial during tough economic times as airlines undertake massive cuts to ticket prices in order to retain demand.

Operating costs

An Airbus A340-600 of Virgin Atlantic Airways. In October 2008, Virgin Atlantic offered to combine its operations with BMI in an effort to reduce operating costs.

Full-service airlines have a high level of fixed and operating costs in order to establish and maintain air services: labor, fuel, airplanes, engines, spares and parts, IT services and networks, airport equipment, airport handling services, sales distribution, catering, training, aviation insurance and other costs. Thus all but a small percentage of the income from ticket sales is paid out to a wide variety of external providers or internal cost centers.

Moreover, the industry is structured so that airlines often act as tax collectors. Airline fuel is untaxed because of a series of treaties existing between countries. Ticket prices include a number of fees, taxes and surcharges beyond the control of airlines. Airlines are also responsible for enforcing government regulations. If airlines carry passengers without proper documentation on an international flight, they are responsible for returning them back to the original country.

Analysis of the 1992–1996 period shows that every player in the air transport chain is far more profitable than the airlines, who collect and pass through fees and revenues to them from ticket sales. While airlines as a whole earned 6% return on capital employed (2-

3.5% less than the cost of capital), airports earned 10%, catering companies 10-13%, handling companies 11-14%, aircraft lessors 15%, aircraft manufacturers 16%, and global distribution companies more than 30%. (Source: Spinetta, 2000, quoted in Doganis, 2002)

In contrast, Southwest Airlines has been the most profitable of airline companies since 1973.

The widespread entrance of a new breed of low cost airlines beginning at the turn of the century has accelerated the demand that full service carriers control costs. Many of these low cost companies emulate Southwest Airlines in various respects, and like Southwest, they are able to eke out a consistent profit throughout all phases of the business cycle.

As a result, a shakeout of airlines is occurring in the U.S. and elsewhere. United Airlines, Continental Airlines (twice), US Airways (twice), Delta Air Lines, and Northwest Airlines have all declared Chapter 11 bankruptcy. Some argue that it would be far better for the industry as a whole if a wave of actual closures were to reduce the number of "undead" airlines competing with healthy airlines while being artificially protected from creditors via bankruptcy law. On the other hand, some have pointed out that the reduction in capacity would be short lived given that there would be large quantities of relatively new aircraft that bankruptcies would want to get rid of and would re-enter the market either as increased fleets for the survivors or the basis of cheap planes for new startups.

Where an airline has established an engineering base at an airport then there may be considerable economic advantages in using that same airport as a preferred focus (or "hub") for its scheduled flights.

Assets and financing

The 'Golden Lounge' of Malaysia Airlines at Kuala Lumpur International Airport (KLIA). The airline has ownership of special slots at KLIA giving it a competitive edge over other airlines operating at the airport.

Airline financing is quite complex, since airlines are highly leveraged operations. Not only must they purchase (or lease) new airliner bodies and engines regularly, they must make major long-term fleet decisions with the goal of meeting the demands of their markets while producing a fleet that is relatively economical to operate and maintain. Compare Southwest Airlines and their reliance on a single airplane type (the Boeing 737 and derivatives), with the now defunct Eastern Air Lines which operated 17 different aircraft types, each with varying pilot, engine, maintenance, and support needs.

A second financial issue is that of hedging oil and fuel purchases, which are usually second only to labor in its relative cost to the company. However, with the current high fuel prices it has become the largest cost to an airline. While hedging instruments can be expensive, they can easily pay for themselves many times over in periods of increasing fuel costs, such as in the 2000–2005 period.

In view of the congestion apparent at many international airports, the ownership of slots at certain airports (the right to take-off or land an aircraft at a particular time of day or night) has become a significant tradable asset for many airlines. Clearly take-off slots at popular times of the day can be critical in attracting the more profitable business traveler to a given airline's flight and in establishing a competitive advantage against a competing airline. If a particular city has two or more airports, market forces will tend to attract the less profitable routes, or those on which competition is weakest, to the less congested airport, where slots are likely to be more available and therefore cheaper. Other factors, such as surface transport facilities and onward connections, will also affect the relative appeal of different airports and some long distance flights may need to operate from the one with the longest runway.

Airline partnerships

A Japan Airlines Boeing 777-300 with special Oneworld livery. Oneworld is the third largest airline alliance after Star Alliance and SkyTeam.

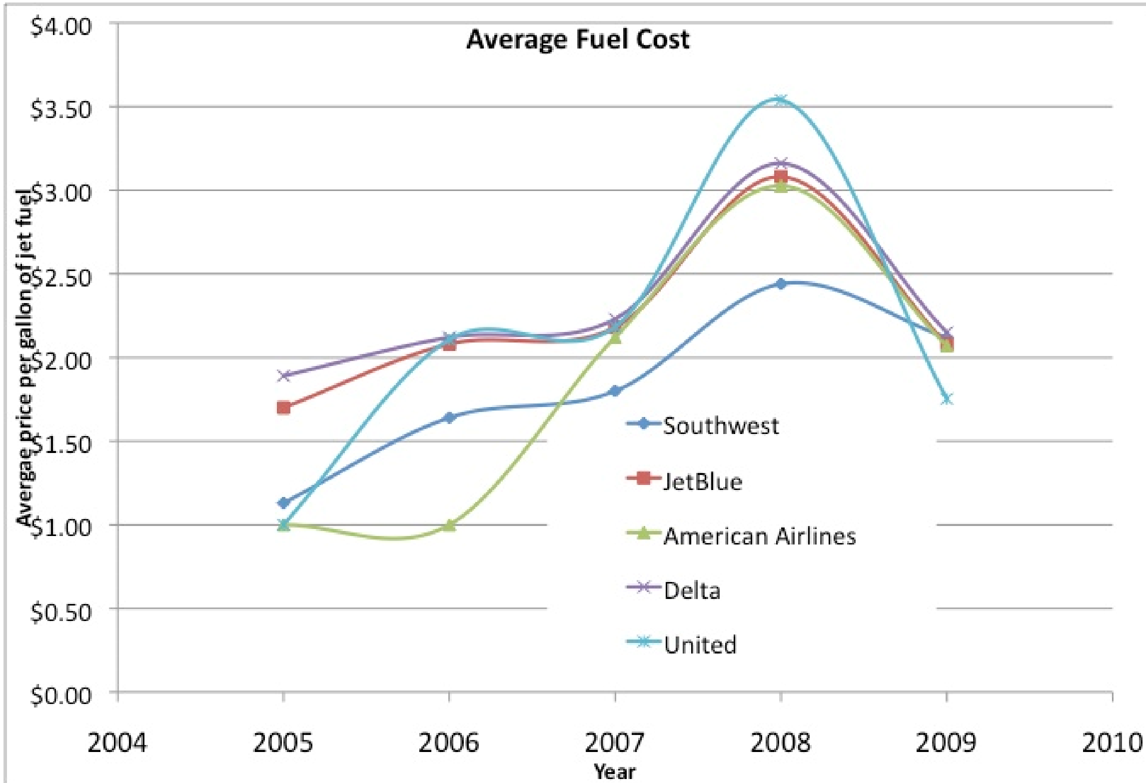
Code sharing is the most common type of airline partnership; it involves one airline selling tickets for another airline's flights under its own airline code. An early example of this was Japan Airlines' code sharing partnership with Aeroflot in the 1960s on flights from Tokyo to Moscow: Aeroflot operated the flights using Aeroflot aircraft, but JAL sold tickets for the flights as if they were JAL flights. This practice allows airlines to expand their operations, at least on paper, into parts of the world where they cannot afford to establish bases or purchase aircraft. Another example was the Austrian- Sabena partnership on the Vienna-Brussels-New York JFK route during the late '60s, using a Sabena Boeing 707 with Austrian colors.

Since airline reservation requests are often made by city-pair (such as "show me flights from Chicago to Düsseldorf"), an airline who is able to code share with another airline for a variety of routes might be able to be listed as indeed offering a Chicago-Düsseldorf flight. The passenger is advised however, that Airline 1 operates the flight from say Chicago to Amsterdam, and Airline 2 operates the continuing flight (on a different airplane, sometimes from another terminal) to Düsseldorf. Thus the primary rationale for code sharing is to expand one's service offerings in city-pair terms so as to increase sales.

A more recent development is the airline alliance, which became prevalent in the 1990s. These alliances can act as virtual mergers to get around government restrictions. Groups of airlines such as the Star Alliance, Oneworld, and SkyTeam coordinate their passenger service programs (such as lounges and frequent flyer programs), offer special interline tickets, and often engage in extensive codesharing (sometimes systemwide). These are increasingly integrated business combinations—sometimes including cross-equity arrangements—in which products, service standards, schedules, and airport facilities are standardized and combined for higher efficiency. One of the first airlines to start an alliance with another airline was KLM, who partnered with Northwest Airlines. Both airlines later entered the SkyTeam alliance after the fusion of KLM and Air France in 2004.

Often the companies combine IT operations, buy fuel, or purchase airplanes as a bloc in order to achieve higher bargaining power. However, the alliances have been most successful at purchasing invisible supplies and services, such as fuel. Airlines usually prefer to purchase items visible to their passengers to differentiate themselves from local competitors. If an airline's main domestic competitor flies Boeing airliners, then the airline may prefer to use Airbus aircraft regardless of what the rest of the alliance chooses.

Fuel hedging

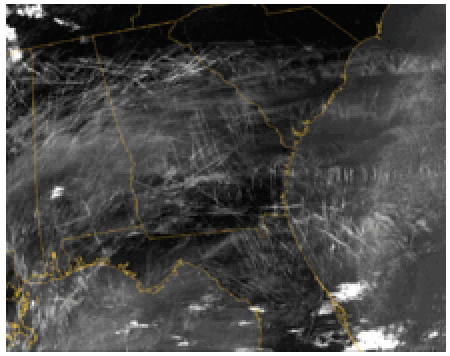


Average jet fuel prices per gallon for major United States airlines.

Southwest was one credited with maintaining strong business profits between 1999 and the early 2000's due to its fuel hedging policy. Looking at the annual reports many other airlines are replicating Southwest's hedging policy to control their fuel costs.

Average fuel cost per gallon	2005	2006	2007	2008	2009
Southwest Airlines	$1.13	$1.64	$1.80	$2.44	$2.12
JetBlue Airlines	$1.70	$2.08	$2.18	$3.08	$2.08
American Airlines			$2.12	$3.03	$2.07
Delta Air Lines	$1.89	$2.12	$2.23	$3.16	$2.15
United Airlines		$2.11	$2.18	$3.54	$1.75

Environmental impacts



MODIS tracking of contrails generated by air traffic over the southeastern United States on January 29, 2004.

Aircraft engines emit noise pollution, gases and particulate emissions, and contribute to global warming and global dimming.

Modern turbofan and turboprop engines are considerably more fuel-efficient and less polluting than earlier models. However, despite this, the rapid growth of air travel in recent years contributes to an increase in total pollution attributable to aviation, offsetting some of the reductions achieved by automobiles. In the EU greenhouse gas emissions from aviation increased by 87% between 1990 and 2006.

CO2 emissions from the jet fuel burned per passenger on an average 3200 kilometers (1992 miles) airline flight is about 353 kilograms (776 pounds). Loss of natural habitat potential associated with the jet fuel burned per passenger on a 3200 kilometers (1992 miles) airline flight is estimated to be 250 square meters (2700 square feet).

In the context of purported climate change and peak oil, there is a debate about possible taxation of air travel and the inclusion of aviation in an emissions trading scheme, with a view to ensuring that the total external costs of aviation are taken into account.

The airline industry is responsible for about 11 percent of greenhouse gases emitted by the U.S. transportation sector. Boeing estimates that biofuels could reduce flight-related greenhouse-gas emissions by 60 to 80 percent. The solution would be blending algae fuels with existing jet fuel:

- Boeing and Air New Zealand are collaborating with leading Brazilian biofuels maker Tecbio and Aquaflow Bionomic of New Zealand and other jet biofuel developers around the world.
- Virgin Atlantic and Virgin Green Fund are looking into the technology as part of a biofuels initiative.
- KLM has made the first commercial flight with bio-fuel in 2009.

Call signs

Each operator of a scheduled or charter flight uses an airline call sign when communicating with airports or air traffic control centres. Most of these call-signs are derived from the airline's trade name, but for reasons of history, marketing, or the need to reduce ambiguity in spoken English (so that pilots do not mistakenly make navigational decisions based on instructions issued to a different aircraft), some airlines and air forces use call-signs less obviously connected with their trading name. For example, British Airways uses a *Speedbird* call-sign, named after the logo of its predecessor, BOAC, while SkyEurope used *Relax*.

Airline personnel

The various types of airline personnel include: Flight operations personnel including flight safety personnel.

- Flight crews, responsible for the operation of the aircraft. Flight crew members include:
  - Pilots (Captain and First Officer: some older aircraft also required a Flight Engineer and or a Navigator)
  - Flight attendants, (led by a purser on larger aircraft)
  - in-flight security personnel on some airlines (most notably El Al)
- Groundcrew, responsible for operations at airports. Ground crew members include:
  - Aerospace and avionics engineers responsible for certifying the aircraft for flight and management of aircraft maintenance
    - Aerospace engineers, responsible for airframe, powerplant and electrical systems maintenance
    - Avionics engineers responsible for avionics and instruments maintenance
  - Airframe and powerplant technicians
  - Electric System technicians, responsible for maintenance of electrical systems
  - Avionics technicians, responsible for maintenance of avionics
  - Flight dispatchers
  - Baggage handlers
  - Ramp Agents
  - Gate agents
  - Ticket agents
  - Passenger service agents (such as airline lounge employees)
  - Reservation agents, usually (but not always) at facilities outside the airport.

Airlines follow a corporate structure where each broad area of operations (such as maintenance, flight operations(including flight safety), and passenger service) is supervised by a vice president. Larger airlines often appoint vice presidents to oversee each of the airline's hubs as well. Airlines employ lawyers to deal with regulatory procedures and other administrative tasks.

Industry trends

Map of scheduled airline traffic in 2009

The pattern of ownership has gone from government owned or supported to independent, for-profit public companies. This occurs as regulators permit greater freedom and non-government ownership, in steps that are usually decades apart. This pattern is not seen for all airlines in all regions.

The overall trend of demand has been consistently increasing. In the 1950s and 1960s, annual growth rates of 15% or more were common. Annual growth of 5-6% persisted through the 1980s and 1990s. Growth rates are not consistent in all regions, but countries with a de-regulated airline industry have more competition and greater pricing freedom. This results in lower fares and sometimes dramatic spurts in traffic growth. The U.S., Australia, Canada, Japan, Brazil, Mexico,India and other markets exhibit this trend. The industry has been observed to be cyclical in its financial performance. Four or five years of poor earnings precede five or six years of improvement. But profitability even in the good years is generally low, in the range of 2-3% net profit after interest and tax. In times of profit, airlines lease new generations of airplanes and upgrade services in response to higher demand. Since 1980, the industry has not earned back the cost of capital during the best of times. Conversely, in bad times losses can be dramatically worse. Warren Buffett once said that despite all the money that has been invested in all airlines, the net profit is less than zero. He believes it is one of the hardest businesses to manage.

As in many mature industries, consolidation is a trend. Airline groupings may consist of limited bilateral partnerships, long-term, multi-faceted alliances between carriers, equity arrangements, mergers, or takeovers. Since governments often restrict ownership and merger between companies in different countries, most consolidation takes place within a country. In the U.S., over 200 airlines have merged, been taken over, or gone out of business since deregulation in 1978. Many international airline managers are lobbying their governments to permit greater consolidation to achieve higher economy and efficiency.

Civil Aviation

Scheduled airline traffic in 2009

Civil aviation is one of two major categories of flying, representing all non-military aviation, both private and commercial. Most of the countries in the world are members of the International Civil Aviation Organization (ICAO) and work together to establish common standards and recommended practices for civil aviation through that agency.

Civil aviation includes two major categories:

- Scheduled air transport, including all passenger and cargo flights operating on regularly-scheduled routes; and
- General aviation (GA), including all other civil flights, private or commercial

Although scheduled air transport is the larger operation in terms of passenger numbers, GA is larger in the number of flights (and flight hours, in the U.S.) In the U.S., GA carries 166 million passengers each year, more than any individual airline, though less than all the airlines combined.

Some countries also make a regulatory distinction based on whether aircraft are flown for hire:

- Commercial aviation includes most or all flying done for hire, particularly scheduled service on airlines; and

- Private aviation includes pilots flying for their own purposes (recreation, business meetings, etc.) without receiving any kind of remuneration.

All scheduled air transport is commercial, but general aviation can be either commercial or private. Normally, the pilot, aircraft, and operator must all be authorized to perform commercial operations through separate commercial licensing, registration, and operation certificates.

Civil aviation authorities

The Convention on International Civil Aviation (the *Chicago Convention*) was originally established in 1944: it states that signatories should collectively work to harmonize and standardize the use of airspace for safety, efficiency and regularity of air transport. All the States signatory to the Chicago Convention, now 188, are obliged to implement the Standards and Recommended Practices (SARPs) of the Convention.

Each signatory country has a Civil Aviation Authority (CAA) (such as the FAA in the United States) to oversee the following areas of civil aviation:

- **Personnel Licensing** — regulating the basic training and issuance of licenses and certificates.
- **Flight Operations** — carrying out safety oversight of commercial operators.
- **Airworthiness** — issuing certificates of registration and certificates of airworthiness to civil aircraft, and overseeing the safety of maintenance organizations.
- **Aerodromes** — designing and constructing aerodrome facilities.
- **Air Traffic Services** — managing the traffic inside of a country's airspace.

General aviation

A Diamond DA20, a popular trainer used by the United States Air Force and many flight schools.

A general aviation scene at Kemble Airfield, England. The aircraft in the foreground is a homebuilt Vans RV-4

Aircraft at general aviation airport Helsinki-Malmi, Finland.

The General Aviation Terminal at Raleigh Durham International Airport. Terminal A is in the background.

General aviation (**GA**) is one of the two categories of civil aviation. It refers to all flights *other than* military and scheduled airline and regular cargo flights, both private and commercial. General aviation flights range from gliders and powered parachutes to large, non-scheduled cargo jet flights. The majority of the world's air traffic falls into this category, and most of the world's airports serve general aviation exclusively.

General aviation is particularly popular in North America, with over 6,300 airports available for public use by pilots of general aviation aircraft (around 5,300 airports in the U.S., and over 1,000 in Canada). In comparison, scheduled flights operate from around 600 airports in the U.S. According to the U.S. Aircraft Owners and Pilots Association, general aviation provides more than one percent of the United States' GDP, accounting for 1.3 million jobs in professional services and manufacturing.

General aviation covers a large range of activities, both commercial and non-commercial, including private flying, flight training, air ambulance, police aircraft, aerial firefighting, air charter, bush flying, gliding, skydiving, and many others. Experimental aircraft, light-sport aircraft and very light jets have emerged in recent years as new trends in general aviation.

Regulation and safety

Most countries have authorities that oversee all civil aviation, including general aviation, adhering to the standardized codes of the International Civil Aviation Organization (ICAO). Examples include the Federal Aviation Administration (FAA) in the United States, the Civil Aviation Authority (CAA) in Great Britain, the Luftfahrt-Bundesamt (LBA) in Germany, and Transport Canada in Canada.

Since it includes both non-scheduled commercial operations and private operations, with aircraft of many different types and sizes, and pilots with a variety of different training and experience levels, it is not possible to make blanket statements about the regulation or safety record of general aviation. At one extreme, in most countries business jets and large cargo jets face most of the same regulations as scheduled air transport and fly mostly to the same airports. Commercial bush flying and air ambulance operations normally do not operate under as heavy a regulatory burden, and often only use small airports or off-airport strips, where there is less governmental oversight.

Aviation accident rate statistics are necessarily estimates. According to the U.S. National Transportation Safety Board, in 2005 general aviation in the United States (excluding charter) suffered 1.31 fatal accidents for every 100,000 hours of flying in that country, compared to 0.016 for scheduled airline flights. In Canada, recreational flying accounted for 0.7 fatal accidents for every 1000 aircraft, while air taxi accounted for 1.1 fatal accident for every 100,000 hours.

Commercial aviation

Route map of the world's scheduled commercial airline traffic, 2009

Commercial aviation is the part of civil aviation (both general aviation and scheduled airline service) that involves operating aircraft for hire to transport passengers or cargo. In most countries, a flight may be operated for money only if it meets three criteria:

- the pilot must hold a valid commercial pilot's certificate
- the aircraft must hold a valid commercial registration
- the operator must hold a certificate or some other authorization for commercial operations

There are some exceptions — for example, a flight instructor is normally allowed to fly for money in a private aircraft owned by the student — but the above requirements hold for most flights where money changes hands.

Typically, a commercial certificate or registration requires higher standards than a private one. For example, a commercial pilot may have to demonstrate more maneuvers to a higher standard, and may need to pass more frequent medical examinations. A commercially-registered plane may require more frequent or more extensive maintenance.

It is the purpose of the flight, not the type of aircraft or pilot, that determines whether the flight is commercial. For example, a two-seat Cessna 150 towing a banner for money would be a commercial flight, while a large jet flown by its owners for a private vacation would not be, even if the pilots were commercially certificated and the jet were commercially registered.

Private aviation

Pilot and family

Private aviation is the part of civil aviation that does not include flying for hire. In most countries, private flights are always general aviation flights, but the opposite is not true: many general aviation flights (such as banner towing, charter, crop dusting, and others) are commercial in that the pilot is hired and paid. Many private pilots fly for their own enjoyment, or to share the joys and convenience of general aviation with friends and family.

In private flight the pilot is not paid, and all aircraft operating expenses are generally paid by the pilot. In some countries such as the United States, aircraft operating expenses for a flight may optionally be divided with any passengers up to a pro rata amount. For example, if aircraft operating expenses total $120 for a flight with pilot and three passengers, each of the three passengers could pay not more than $30 (one fourth) of the expenses with the remainder paid by the pilot.

In many countries, private aviation operates to less strict standards than commercial aviation. For example, in Canada and the United States, aircraft owners are allowed to perform basic maintenance tasks (such as oil or tire changes) on their own privately-registered aircraft, but only licensed mechanics may perform those tasks on commercially-registered aircraft.

Aerobatic Flying

Private pilots normally are not required to demonstrate the same level of proficiency on their flight tests and take fewer and less rigorous medical examinations, than are required for Commercial pilots who are paid for operating an aircraft. The majority of active pilots hold a Private Pilot license.

It is the purpose of the flight, not the aircraft or pilot, that determines whether the flight is private. For example, if a commercially-licensed pilot flies a commercially-registered plane to visit a friend or attend a business meeting, most countries would consider this to be a private flight. Conversely, a private pilot could legally fly a multi-engine complex aircraft carrying six passengers for non-commercial purposes (no compensation paid to the pilot, and a pro rata or larger portion of the aircraft operating expenses paid by the pilot). Some particularly skillful aerobatic "stunt pilots" hold a private license, paying their own expenses and earning no income from this very challenging flying.

Chapter 3

Helicopter

An LAPD Bell 206

A **helicopter** is a type of rotorcraft in which lift and thrust are supplied by one or more engine driven rotors. In contrast with fixed-wing aircraft, this allows the helicopter to take off and land vertically, to hover, and to fly forwards, backwards and laterally. These attributes allow helicopters to be used in congested or isolated areas where fixed-wing aircraft would not be able to take off or land. The capability to efficiently hover for extended periods of time allows a helicopter to accomplish tasks that fixed-wing aircraft and other forms of vertical takeoff and landing aircraft cannot perform.

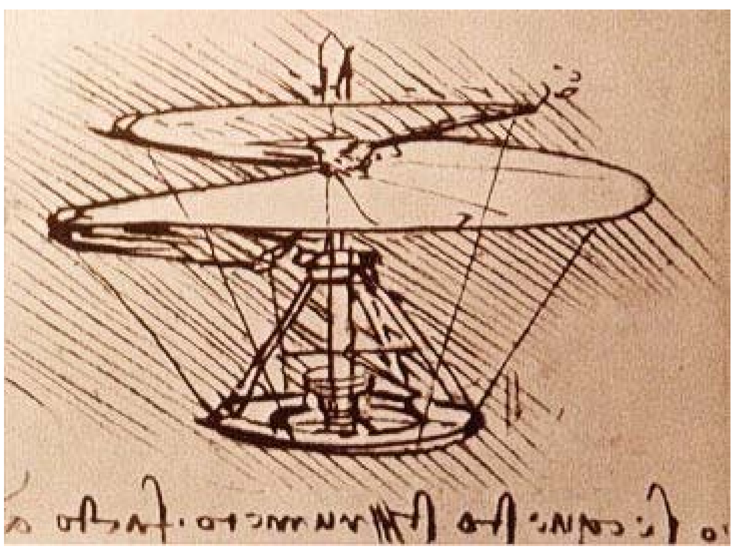
The word 'helicopter' is adapted from the French *hélicoptère*, coined by Gustave de Ponton d'Amecourt in 1861, which originates from the Greek *helix/helik-* (ἕλικ-) = 'spiral' or 'turning' and *pteron* (πτερόν) = 'wing'.

Helicopters were developed and built during the first half-century of flight, with the Focke-Wulf Fw 61 being the first operational helicopter in 1936. Some helicopters reached limited production, but it was not until 1942 that a helicopter designed by Igor Sikorsky reached full-scale production, with 131 aircraft built. Though most earlier designs used more than one main rotor, it was the single main rotor with antitorque tail rotor configuration of this design that would come to be recognized worldwide as *the helicopter*.

History

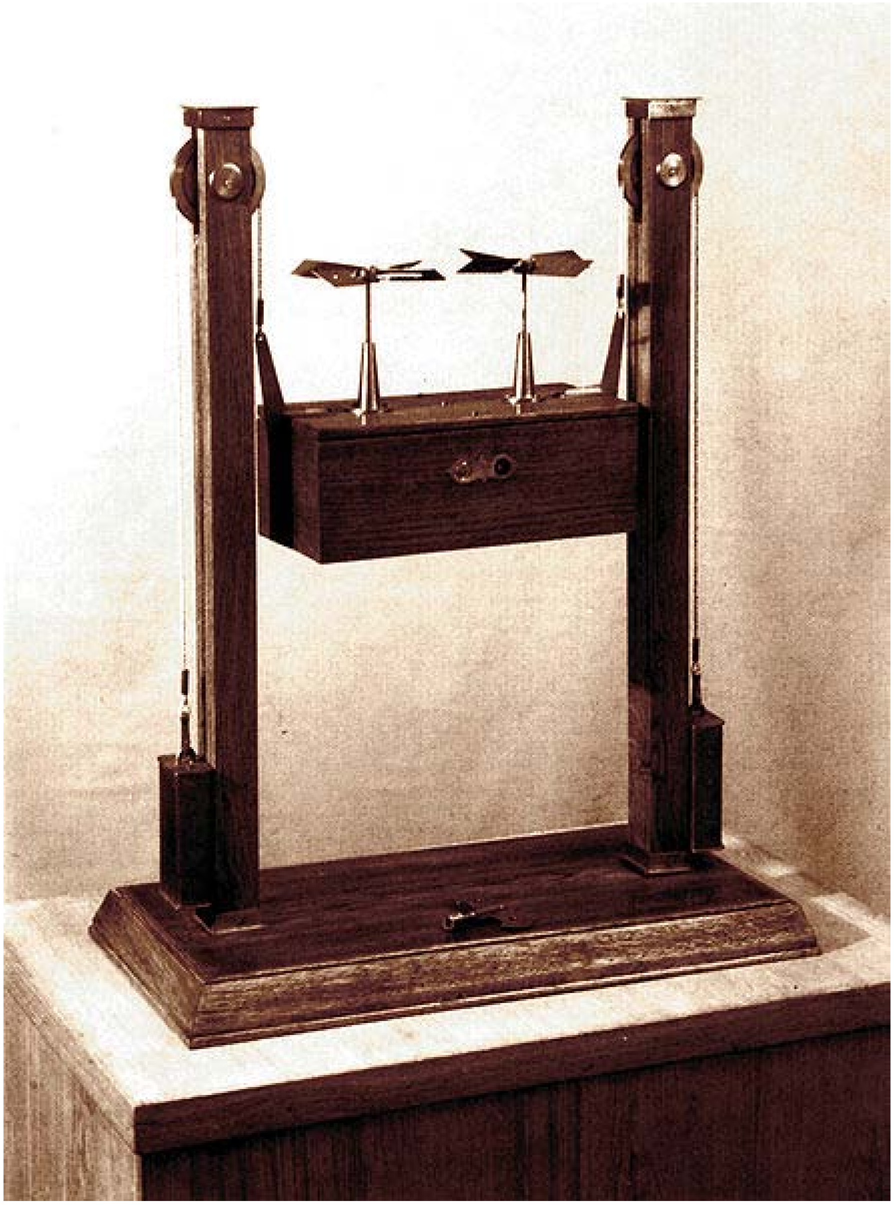
The earliest references for vertical flight have come from China. Since around 400 BC, Chinese children have played with bamboo flying toys, and the 4th-century AD Daoist book *Baopuzi* ("Master who Embraces Simplicity") reportedly describes some of the ideas inherent to rotary wing aircraft:

> “Someone asked the master about the principles of mounting to dangerous heights and traveling into the vast inane. The Master said, "Some have made flying cars with wood from the inner part of the jujube tree, using ox-leather [straps] fastened to returning blades so as to set the machine in motion."”



da Vinci's "aerial screw"

It was not until the early 1480s, when Leonardo da Vinci created a design for a machine that could be described as an "aerial screw", that any recorded advancement was made towards vertical flight. His notes suggested that he built small flying models, but there were no indications for any provision to stop the rotor from making the whole craft rotate. As scientific knowledge increased and became more accepted, men continued to pursue the idea of vertical flight. Many of these later models and machines would more closely resemble the ancient bamboo flying top with spinning wings, rather than Da Vinci's screw.



Prototype created by M. Lomonosov, 1754

In July 1754, Mikhail Lomonosov demonstrated a small coaxial rotor to the Russian Academy of Sciences. It was powered by a spring and suggested as a method to lift meteorological instruments. In 1783, Christian de Launoy, and his mechanic, Bienvenu, made a model with a pair of counter-rotating rotors, using turkey flight feathers as rotor blades, and in 1784, demonstrated it to the French Academy of Sciences. Sir George Cayley, influenced by a childhood fascination with the Chinese flying top, grew up to develop a model of feathers, similar to Launoy and Bienvenu, but powered by rubber bands. By the end of the century, he had progressed to using sheets of tin for rotor blades and springs for power. His writings on his experiments and models would become influential on future aviation pioneers. Alphonse Pénaud would later develop coaxial rotor model helicopter toys in 1870, also powered by rubber bands. One of these toys, given as a gift by their father, would inspire the Wright brothers to pursue the dream of flight.

In 1861, the word "helicopter" was coined by Gustave de Ponton d'Amécourt, a French inventor who demonstrated a small, steam-powered model. While celebrated as an innovative use of a new metal, aluminum, the model never lifted off the ground. D'Amecourt's linguistic contribution would survive to eventually describe the vertical flight he had envisioned. Steam power was popular with other inventors as well. In 1878 Enrico Forlanini's unmanned helicopter was also powered by a steam engine. It was the first of its type that rose to a height of 12 meters (40 ft), where it hovered for some 20 seconds after a vertical take-off. Emmanuel Dieuaide's steam-powered design featured counter-rotating rotors powered through a hose from a boiler on the ground.

In 1885, Thomas Edison was given US$1,000 by James Gordon Bennett, Jr., to conduct experiments towards developing flight. Edison built a helicopter and used the paper for a stock ticker to create guncotton, with which he attempted to power an internal combustion engine. The helicopter was damaged by explosions and one of his workers was badly burned. Edison reported that it would take a motor with a ratio of three to four pounds per horsepower produced to be successful, based on his experiments. Ján Bahýľ, a Slovak inventor, adapted the internal combustion engine to power his helicopter model that reached a height of 0.5 meters (1.6 ft) in 1901. On 5 May 1905, his helicopter reached four meters (13 ft) in altitude and flew for over 1,500 meters (4,900 ft). In 1908, Edison patented his own design for a helicopter powered by a gasoline engine with box kites attached to a mast by cables for a rotor, but it never flew.

First flights

Paul Cornu's helicopter in 1907

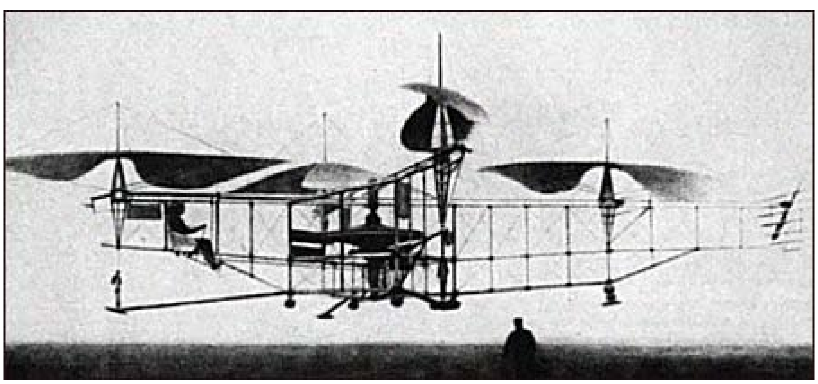
In 1906, two French brothers, Jacques and Louis Breguet, began experimenting with airfoils for helicopters and in 1907, those experiments resulted in the *Gyroplane No.1*. Although there is some uncertainty about the dates, sometime between 14 August and 29 September 1907, the Gyroplane No. 1 lifted its pilot up into the air about two feet (0.6 m) for a minute. However, the Gyroplane No. 1 proved to be extremely unsteady and required a man at each corner of the airframe to hold it steady. For this reason, the flights of the Gyroplane No. 1 are considered to be the first manned flight of a helicopter, but not a free or untethered flight.

That same year, fellow French inventor Paul Cornu designed and built a Cornu helicopter that used two 20-foot (6 m) counter-rotating rotors driven by a 24-hp (18-kW) Antoinette engine. On 13 November 1907, it lifted its inventor to 1 foot (0.3 m) and remained aloft for 20 seconds. Even though this flight did not surpass the flight of the Gyroplane No. 1, it was reported to be the first truly free flight with a pilot. Cornu's helicopter would complete a few more flights and achieve a height of nearly 6.5 feet (2 m), but it proved to be unstable and was abandoned.

The Danish inventor Jacob Ellehammer built the Ellehammer helicopter in 1912. It consisted of a frame equipped with two contra-rotating discs, each of which was fitted with six vanes around its circumference. After a number of indoor tests, the aircraft was demonstrated outdoors and made a number of free take-offs. Experiments with the helicopter continued until September 1916, when it tipped over during take-off, destroying its rotors.

Early development

In the early 1920s, Argentine Raúl Pateras Pescara, while working in Europe, demonstrated one of the first successful applications of cyclic pitch. Coaxial, contra-rotating, biplane rotors could be warped to cyclically increase and decrease the lift they produced. The rotor hub could also be tilted forward a few degrees, allowing the aircraft to move forward without a separate propeller to push or pull it. Pescara was also able to demonstrate the principle of autorotation, by which helicopters safely land after engine failure. By January 1924, Pescara's helicopter No. 3 could fly for up ten minutes.



Oehmichen N°2 1922

One of Pescara's contemporaries, Frenchman Etienne Oehmichen, set the first helicopter world record recognized by the *Fédération Aéronautique Internationale* (FAI) on 14 April 1924, flying his helicopter 360 meters (1,181 ft). On 18 April 1924, Pescara beat Oemichen's record, flying for a distance of 736 meters (nearly a half mile) in 4 minutes and 11 seconds (about 8 mph, 13 km/h) maintaining a height of six feet (2 m). Not to be outdone, Oehmichen reclaimed the world record on 4 May when he flew his No. 2 machine again for a 14-minute flight covering 5,550 feet (1.05 mi, 1.69 km) while climbing to a height of 50 feet (15 m). Oehmichen also set the 1 km closed-circuit record at 7 minutes 40 seconds.

In the USA, George de Bothezat built the quadrotor De Bothezat helicopter for the United States Army Air Service but the Army cancelled the program in 1924, and the aircraft was scrapped.

Meanwhile, Juan de la Cierva was developing the first practical rotorcraft in Spain. In 1923, the aircraft that would become the basis for the modern helicopter rotor began to take shape in the form of an autogyro, Cierva's C.4. Cierva had discovered aerodynamic and structural deficiencies in his early designs that could cause his autogyros to flip over after takeoff. The flapping hinges that Cierva designed for the C.4 allowed the rotor to develop lift equally on the left and right halves of the rotor disk. A crash in 1927, led to the development of a drag hinge to relieve further stress on the rotor from its flapping motion. These two developments allowed for a stable rotor system, not only in a hover, but in forward flight.

Albert Gillis von Baumhauer, a Dutch aeronautical engineer, began studying rotorcraft design in 1923. His first prototype "flew" ("hopped" and hovered in reality) on 24 September 1925, with Dutch Army-Air arm Captain Floris Albert van Heijst at the controls. The controls that Captain van Heijst used were Von Baumhauer's inventions, the cyclic and collective. Patents were granted to von Baumhauer for his cyclic and collective controls by the British ministry of aviation on 31 January 1927, under patent number 265,272.

In 1928, Hungarian aviation engineer Oszkár Asbóth constructed a helicopter prototype that took off and and landed at least 182 times, with a maximum single flight duration of 53 minutes.

In 1930, the Italian engineer Corradino D'Ascanio built his D'AT3, a coaxial helicopter. His relatively large machine had two, two-bladed, counter-rotating rotors. Control was achieved by using auxiliary wings or servo-tabs on the trailing edges of the blades, a concept that was later adopted by other helicopter designers, including Bleeker and Kaman. Three small propellers mounted to the airframe were used for additional pitch, roll, and yaw control. The D'AT3 held modest FAI speed and altitude records for the time, including altitude (18 m or 59 ft), duration (8 minutes 45 seconds) and distance flown (1,078 m or 3,540 ft).

In the Soviet Union, Boris N. Yuriev and Alexei M. Cheremukhin, two aeronautical engineers working at the *Tsentralniy Aerogidrodinamicheskiy Institut* (TsAGI, Russian: Центра́льный аэрогидродинами́ческий институ́т (ЦАГИ), English: *Central Aerohydrodynamic Institute*), constructed and flew the TsAGI 1-EA single rotor helicopter, which used an open tubing framework, a four blade main rotor, and twin sets of 1.8-meter (6-foot) diameter anti-torque rotors; one set of two at the nose and one set of two at the tail. Powered by two M-2 powerplants, up-rated copies of the Gnome Monosoupape rotary radial engine of World War I, the TsAGI 1-EA made several successful low altitude flights. By 14 August 1932, Cheremukhin managed to get the 1-EA up to an unofficial altitude of 605 meters (1,985 ft), shattering d'Ascanio's earlier achievement. As the Soviet Union was not yet a member of the FAI, however, Cheremukhin's record remained unrecognized.

Nicolas Florine, a Russian engineer, built the first twin tandem rotor machine to perform a free flight. It flew in Sint-Genesius-Rode, at the *Laboratoire Aérotechnique de Belgique* (now von Karman Institute) in April 1933, and attained an altitude of six meters (20 ft) and an endurance of eight minutes. Florine chose a co-rotating configuration because the gyroscopic stability of the rotors would not cancel. Therefore the rotors had to be tilted slightly in opposite directions to counter torque. Using hingeless rotors and co-rotation also minimised the stress on the hull. At the time, it was one of the most stable helicopter in existence.

The Bréguet-Dorand *Gyroplane Laboratoire* was built in 1933. After many ground tests and an accident, it first took flight on 26 June 1935. Within a short time, the aircraft was setting records with pilot Maurice Claisse at the controls. On 14 December 1935, he set a record for closed-circuit flight with a 500-meter (1,600 ft) diameter. The next year, on 26 September 1936, Claisse set a height record of 158 meters (520 ft). And, finally, on 24 November 1936, he set a flight duration record of one hour, two minutes and 5 seconds over a 44 kilometer (27 mi) closed circuit at 44.7 kilometers per hour (27.8 mph). The aircraft was destroyed in 1943 by an Allied airstrike at Villacoublay airport.

Birth of an industry

First airmail service by helicopter in Los Angeles, 1947

Despite the success of the *Gyroplane Laboratoire*, the German Focke-Wulf Fw 61, first flown in 1936, would eclipse its accomplishments. The Fw 61 broke all of the helicopter world records in 1937, demonstrating a flight envelope that had only previously been achieved by the autogyro. Nazi Germany would use helicopters in small numbers during World War II for observation, transport, and medical evacuation. The Flettner Fl 282 *Kolibri* synchropter was used in the Mediterranean, while the Focke Achgelis Fa 223

Drache was used in Europe. Extensive bombing by the Allied forces prevented Germany from producing any helicopters in large quantities during the war.

In the United States, Igor Sikorsky and W. Lawrence LePage, were competing to produce the United States military's first helicopter. Prior to the war, LePage had received the patent rights to develop helicopters patterned after the Fw 61, and built the XR-1. Meanwhile, Sikorsky had settled on a simpler, single rotor design, the VS-300. After experimenting with configurations to counteract the torque produced by the single main rotor, he settled on a single, smaller rotor mounted vertically on the tailboom.

Developed from the VS-300, Sikorsky's R-4 became the first mass produced helicopter with a production order for 100 aircraft. The R-4 was the only Allied helicopter to see service in World War II, primarily being used for rescue in Burma, Alaska, and other areas with harsh terrain. Total production would reach 131 helicopters before the R-4 was replaced by other Sikorsky helicopters such as the R-5 and the R-6. In all, Sikorsky would produce over 400 helicopters before the end of World War II.

As LePage and Sikorsky were building their helicopters for the military, Bell Aircraft hired Arthur Young to help build a helicopter using Young's semi-rigid, teetering-blade rotor design, which used a weighted stabilizing bar. The subsequent Model 30 helicopter demonstrated the simplicity and ease of the design. The Model 30 was developed into the Bell 47, which became the first helicopter certificated for civilian use in the United States. Produced in several countries, the Bell 47 would become the most popular helicopter model for nearly 30 years.

Turbine age

In 1951, at the urging of his contacts at the Department of the Navy, Charles Kaman modified his K-225 helicopter with a new kind of engine, the turboshaft engine. This adaptation of the turbine engine provided a large amount of power to the helicopter with a lower weight penalty than piston engines, with their heavy engine blocks and auxiliary components. On 11 December 1951, the Kaman K-225 became the first turbine-powered helicopter in the world. Two years later, on 26 March 1954, a modified Navy HTK-1, another Kaman helicopter, became the first twin-turbine helicopter to fly. However, it was the Sud Aviation Alouette II that would become the first helicopter to be produced with a turbine-engine.

Reliable helicopters capable of stable hover flight were developed decades after fixed-wing aircraft. This is largely due to higher engine power density requirements than fixed-wing aircraft. Improvements in fuels and engines during the first half of the 20th century were a critical factor in helicopter development. The availability of lightweight turboshaft engines in the second half of the 20th century led to the development of larger, faster, and higher-performance helicopters. While smaller and less expensive helicopters still use piston engines, turboshaft engines are the preferred powerplant for helicopters today.

Uses

Due to the operating characteristics of the helicopter—its ability to takeoff and land vertically, and to hover for extended periods of time, as well as the aircraft's handling properties under low airspeed conditions—it has been chosen to conduct tasks that were previously not possible with other aircraft, or were time- or work-intensive to accomplish on the ground. Today, helicopter uses include transportation, construction, firefighting, search and rescue, and military uses.

Sikorsky S-64 Skycrane lifting a prefab house

Kern County (California) Fire Department Bell 205 dropping water on fire

A helicopter used to carry loads connected to long cables or slings is called an aerial crane. Aerial cranes are used to place heavy equipment, like radio transmission towers and large air conditioning units, on the tops of tall buildings, or when an item must be raised up in a remote area, such as a radio tower raised on the top of a hill or mountain. Helicopters are used as aerial cranes in the logging industry to lift trees out of terrain where vehicles cannot travel and where environmental concerns prohibit the building of roads. These operations are referred to as longline because of the long, single sling line used to carry the load.

Helitack is the use of helicopters to combat wildland fires. The helicopters are used for aerial firefighting (or water bombing) and may be fitted with tanks or carry helibuckets. Helibuckets, such as the Bambi bucket, are usually filled by submerging the bucket into lakes, rivers, reservoirs, or portable tanks. Tanks fitted onto helicopters are filled from a hose while the helicopter is on the ground or water is siphoned from lakes or reservoirs through a hanging snorkel as the helicopter hovers over the water source. Helitack helicopters are also used to deliver firefighters, who rappel down to inaccessible areas, and to resupply firefighters. Common firefighting helicopters include variants of the Bell 205 and the Erickson S-64 Aircrane helitanker.

Helicopters are used as air ambulances for emergency medical assistance in situations when an ambulance cannot easily or quickly reach the scene. Helicopters are also used when a patient needs to be transported between medical facilities and air transportation is the most practical method for the safety of the patient. Air ambulance helicopters are equipped to provide medical treatment to a patient while in flight. The use of helicopters as an air ambulance is often referred to as MEDEVAC, and patients are referred to as being "airlifted", or "medevaced".

Police departments and other law enforcement agencies use helicopters to pursue suspects. Since helicopters can achieve a unique aerial view, they are often used in conjunction with police on the ground to report on suspects' locations and movements. They are often mounted with lighting and heat-sensing equipment for night pursuits.

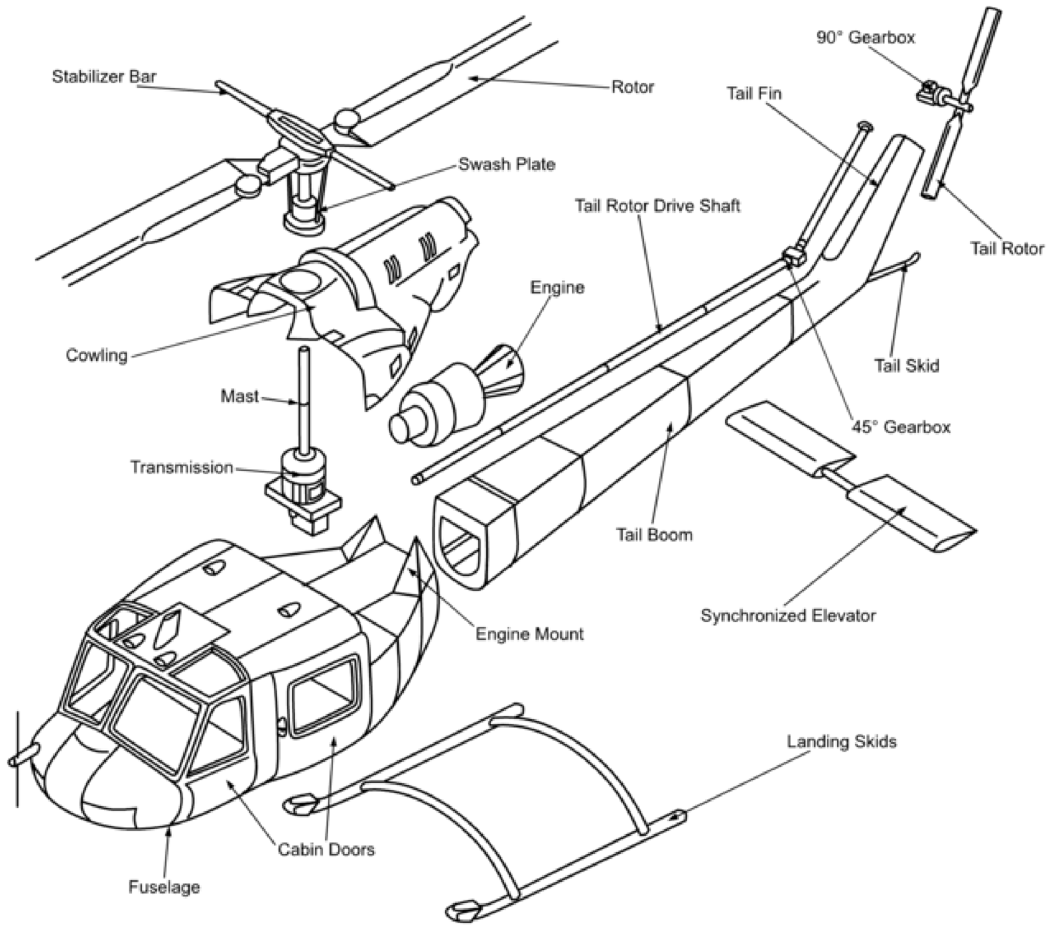
Military forces use attack helicopters to conduct aerial attacks on ground targets. Such helicopters are mounted with missile launchers and miniguns. Transport helicopters are used to ferry troops and supplies where the lack of an airstrip would make transport via fixed-wing aircraft impossible. The use of transport helicopters to deliver troops as an attack force on an objective is referred to as Air Assault. Unmanned Aerial Systems (UAS) helicopter systems of varying sizes are being developed by companies for military reconnaissance and surveillance duties. Naval forces also use helicopters equipped with dipping sonar for anti-submarine warfare, since they can operate from small ships.

Oil companies charter helicopters to move workers and parts quickly to remote drilling sites located out to sea or in remote locations. The speed over boats makes the high operating cost of helicopters cost effective to ensure that oil platforms continue to flow. Various companies specialize in this type of operation.

Other uses of helicopters include, but are not limited to:

- Aerial photography
- Motion picture photography
- Electronic news gathering
- Reflection seismology
- Search and Rescue
- Tourism or recreation
- Transport

Design features



Basic anatomy of a Helicopter

Antitorque configurations

MD Helicopters 520N NOTAR

Most helicopters have a single main rotor, but torque created as the engine turns the rotor against its air drag causes the body of the helicopter to turn in the opposite direction to the rotor. To eliminate this effect, some sort of antitorque control must be used. The design that Igor Sikorsky settled on for his VS-300 was a smaller rotor mounted vertically on the tail. The tail rotor pushes or pulls against the tail to counter the torque effect, and has become the recognized convention for helicopter design. Some helicopters utilize alternate antitorque controls in place of the tail rotor, such as the ducted fan (called *Fenestron* or *FANTAIL*), and NOTAR. NOTAR provides antitorque similar to the way a wing develops lift, through the use of a Coandă effect on the tailboom.

The use of two or more horizontal rotors turning in opposite directions is another configuration used to counteract the effects of torque on the aircraft without relying on an antitorque tail rotor. This allows the power normally required to drive the tail rotor to be applied to the main rotors, increasing the aircraft's lifting capacity. Primarily, there are three common configurations that use the counterrotating effect to benefit the rotorcraft. Tandem rotors are two rotors with one mounted behind the other. Coaxial rotors are two rotors that are mounted one above the other with the same axis. Intermeshing rotors are two rotors that are mounted close to each other at a sufficient angle to allow the rotors to intermesh over the top of the aircraft. Transverse rotors is another configuration found on tiltrotors and some earlier helicopters, where the pair of rotors are mounted at each end of the wings or outrigger structures. Tip jet designs permit the rotor to push itself through the air, and avoid generating torque.

Engines

The number, size and type of engine used on a helicopter determines the size, function and capability of that helicopter design. The earliest helicopter engines were simple mechanical devices, such as rubber bands or spindles, which relegated the size of helicopters to toys and small models. For a half century before the first airplane flight, steam engines were used to forward the development of the understanding of helicopter aerodynamics, but the limited power did not allow for manned flight. The introduction of the internal combustion engine at the end of the 19th century became the watershed for helicopter development as engines began to be developed and produced that were powerful enough to allow for helicopters able to lift humans.

Early helicopter designs utilized custom-built engines or rotary engines designed for airplanes, but these were soon replaced by more powerful automobile engines and radial engines. The single, most-limiting factor of helicopter development during the first half of the 20th century was that the amount of power produced by an engine was not able to overcome the engine's weight in vertical flight. This was overcome in early successful helicopters by using the smallest engines available. When the compact, flat engine was developed, the helicopter industry found a lighter-weight powerplant easily adapted to small helicopters, although radial engines continued to be used for larger helicopters.

Turbine engines revolutionized the aviation industry, and the turboshaft engine finally gave helicopters an engine with a large amount of power and a low weight penalty. The turboshaft engine was able to be scaled to the size of the helicopter being designed, so that all but the lightest of helicopter models are powered by turbine engines today.

Special jet engines developed to drive the rotor from the rotor tips are referred to as tip jets. Tip jets powered by a remote compressor are referred to as cold tip jets, while those powered by combustion exhaust are referred to as hot tip jets. An example of a cold jet helicopter is the Sud-Ouest Djinn, and an example of the hot tip jet helicopter is the YH-32 Hornet.

Some radio-controlled helicopters and smaller, helicopter-type unmanned aerial vehicles, such as Rotomotion's SR20 use electric motors. Radio-controlled helicopters may also have piston engines that use fuels other than gasoline, such as Nitromethane. Some turbine engines commonly used in helicopters can also use biodiesel instead of jet fuel.

Flight controls

Cockpit of an Alouette III

A helicopter has four flight control inputs. These are the cyclic, the collective, the anti-torque pedals, and the throttle. The cyclic control is usually located between the pilot's legs and is commonly called the *cyclic stick* or just *cyclic*. On most helicopters, the cyclic is similar to a joystick. Although, the Robinson R22 and Robinson R44 have a unique teetering bar cyclic control system and a few helicopters have a cyclic control that descends into the cockpit from overhead.

The control is called the cyclic because it changes the pitch of the rotor blades cyclically. The result is to tilt the rotor disk in a particular direction, resulting in the helicopter moving in that direction. If the pilot pushes the cyclic forward, the rotor disk tilts forward, and the rotor produces a thrust in the forward direction. If the pilot pushes the cyclic to the side, the rotor disk tilts to that side and produces thrust in that direction, causing the helicopter to hover sideways.

The collective pitch control or *collective* is located on the left side of the pilot's seat with a settable friction control to prevent inadvertent movement. The collective changes the pitch angle of all the main rotor blades collectively (i.e. all at the same time) and independently of their position. Therefore, if a collective input is made, all the blades change equally, and the result is the helicopter increasing or decreasing in altitude.

The anti-torque pedals are located in the same position as the rudder pedals in a fixed-wing aircraft, and serve a similar purpose, namely to control the direction in which the nose of the aircraft is pointed. Application of the pedal in a given direction changes the pitch of the tail rotor blades, increasing or reducing the thrust produced by the tail rotor and causing the nose to yaw in the direction of the applied pedal. The pedals mechanically change the pitch of the tail rotor altering the amount of thrust produced.

Helicopter rotors are designed to operate at a specific RPM. The throttle controls the power produced by the engine, which is connected to the rotor by a transmission. The purpose of the throttle is to maintain enough engine power to keep the rotor RPM within allowable limits in order to keep the rotor producing enough lift for flight. In single-engine helicopters, the throttle control is a motorcycle-style twist grip mounted on the collective control, while dual-engine helicopters have a power lever for each engine.

A Swashplate transmits the pilot commands to the main rotor blades for articulated rotors.

Flight conditions

There are two basic flight conditions for a helicopter; hover and forward flight.

- Hover
  Hovering is the most challenging part of flying a helicopter. This is because a helicopter generates its own gusty air while in a hover, which acts against the fuselage and flight control surfaces. The end result is constant control inputs and corrections by the pilot to keep the helicopter where it is required to be. Despite the complexity of the task, the control inputs in a hover are simple. The cyclic is used to eliminate drift in the horizontal plane, that is to control forward and back, right and left. The collective is used to maintain altitude. The pedals are used to control nose direction or heading. It is the interaction of these controls that makes hovering so difficult, since an adjustment in any one control requires an adjustment of the other two, creating a cycle of constant correction.
- Forward flight
  In forward flight a helicopter's flight controls behave more like that in a fixed-wing aircraft. Displacing the cyclic forward will cause the nose to pitch down, with a resultant increase in airspeed and loss of altitude. Aft cyclic will cause the nose to pitch up, slowing the helicopter and causing it to climb. Increasing collective (power) while maintaining a constant airspeed will induce a climb while decreasing collective will cause a descent. Coordinating these two inputs, down collective plus aft cyclic or up collective plus forward cyclic, will result in airspeed changes while maintaining a constant altitude. The pedals serve the same function in both a helicopter and a fixed-wing aircraft, to maintain balanced flight. This is done by applying a pedal input in whichever direction is necessary to center the ball in the turn and bank indicator.

Safety

Limitations

HAL Dhruv performing aerobatics during the Royal International Air Tattoo in 2008

Royal Australian Navy Squirrel helicopters during a display at the 2008 Melbourne Grand Prix

The main limitation of the helicopter is its low speed. There are several reasons a helicopter cannot fly as fast as a fixed wing aircraft. When the helicopter is hovering, the outer tips of the rotor travel at a speed determined by the length of the blade and the RPM. In a moving helicopter, however, the speed of the blades relative to the air depends on the speed of the helicopter as well as on their rotational velocity. The airspeed of the advancing rotor blade is much higher than that of the helicopter itself. It is possible for this blade to exceed the speed of sound, and thus produce vastly increased drag and vibration.

Because the advancing blade has higher airspeed than the retreating blade and generates a dissymmetry of lift, rotor blades are designed to "flap" – lift and twist in such a way that the advancing blade flaps up and develops a smaller angle of attack. Conversely, the retreating blade flaps down, develops a higher angle of attack, and generates more lift. At high speeds, the force on the rotors is such that they "flap" excessively and the retreating blade can reach too high an angle and stall. For this reason, the maximum safe forward airspeed of a helicopter is given a design rating called V_{NE}, *Velocity, Never Exceed*. In addition, at extremely high speeds, it is possible for the helicopter to travel faster than the retreating blade which would inevitably stall the blade, regardless of the angle of attack.

During the closing years of the 20th century designers began working on helicopter noise reduction. Urban communities have often expressed great dislike of noisy aircraft, and police and passenger helicopters can be unpopular. The redesigns followed the closure of some city heliports and government action to constrain flight paths in national parks and other places of natural beauty.

Helicopters also vibrate; an unadjusted helicopter can easily vibrate so much that it will shake itself apart. To reduce vibration, all helicopters have rotor adjustments for height and weight. Blade height is adjusted by changing the pitch of the blade. Weight is adjusted by adding or removing weights on the rotor head and/or at the blade end caps. Most also have vibration dampers for height and pitch. Some also use mechanical feedback systems to sense and counter vibration. Usually the feedback system uses a mass as a "stable reference" and a linkage from the mass operates a flap to adjust the rotor's angle of attack to counter the vibration. Adjustment is difficult in part because measurement of the vibration is hard, usually requiring sophisticated accelerometers mounted throughout the airframe and gearboxes. The most common blade vibration adjustment measurement system is to use a stroboscopic flash lamp, and observe painted markings or coloured reflectors on the underside of the rotor blades. The traditional low-tech system is to mount coloured chalk on the rotor tips, and see how they mark a linen sheet. Gearbox vibration most often requires a gearbox overhaul or replacement. Gearbox or drive train vibrations can be extremely harmful to a pilot. The most severe being pain, numbness, loss of tactile discrimination and dexterity.

Hazards

As with any moving vehicle, unsafe operation could result in loss of control, structural damage, or fatality. The following is a list of some of the potential hazards for helicopters:

- Settling with power, also known as a vortex ring state, is when the aircraft is unable to arrest its descent due to the rotor's downwash interfering with the aerodynamics of the rotor.
- Retreating blade stall is experienced during high speed flight and is the most common limiting factor of a helicopter's forward speed.
- Ground resonance affects helicopters with fully articulated rotor systems having a natural lead-lag frequency less than the blade rotation frequency.
- Low-G condition affects helicopters with two-bladed main rotors, particularly lightweight helicopters.
- Dynamic rollover in which the helicopter pivots around one of the skids and 'pulls' itself onto its side.
- Powertrain failures, especially those that occur within the shaded area of the height-velocity diagram.
- Tail rotor failures which occur from either a mechanical malfunction of the tail rotor control system or a loss of tail rotor thrust authority, called Loss of Tail-rotor Effectiveness (LTE).
- Brownout in dusty conditions or whiteout in snowy conditions.
- Low Rotor RPM, or *rotor droop*, in which the engine cannot drive the blades at sufficient RPM to maintain flight.

- Rotor Overspeed, which can over-stress the rotor hub pitch bearings (Brinelling) and, if severe enough, cause blade separation from the aircraft.
- Wire and tree strikes due to low altitude operations and take-offs and landings in remote locations.
- Controlled flight into terrain in which the aircraft is flown into the ground unintentionally due to lack of situational awareness.

Deadliest crashes

1. 2002: A Mil Mi-26 was shot down over Chechnya; 127 killed.
2. 1997: An Israeli CH-53 crashed in Israel; 73 killed.
3. December 14, 1992: Georgian forces in Abkhazia shot down a Russian Army Mi-8 by SA-14 MANPADs with the loss of three crew members and 58 passengers, mainly Russian refugees.
4. October 4, 1993: A Georgian Mi-8 was shot down while transporting 60 refugees from eastern Abkhazia.
5. May 10, 1977: An Israeli CH-53 crashed near Yitav in the Jordan Valley; 54 killed.
6. September 11, 1982: A U.S. Army CH-47 Chinook crashed at an air show in Mannheim, Germany; 46 killed.
7. 1966: A British International Helicopters Boeing 234LR Chinook crashed in the Shetland Islands; 45 killed.
8. 1992 Azerbaijani Mil Mi-8 shootdown: 44 killed.
9. 2009 Pakistan Army Mil Mi-17 crash: 41 killed.
10. January 26, 2005: An USMC CH-53E crashed near Ar Rutbah, Iraq killing all 31 service members onboard.

Helicopter rotor

A **helicopter main rotor** or **rotor system** is a type of fan that is used to generate both the aerodynamic lift force that supports the weight of the helicopter, and thrust which counteracts aerodynamic drag in forward flight. Each main rotor is mounted on a vertical mast over the top of the helicopter, as opposed to a helicopter tail rotor, which is connected through a combination a drive shaft(s) and gearboxes along the tail boom. A helicopter's rotor is generally made up of two or more rotor blades. The blade pitch is typically controlled by a swashplate connected to the helicopter flight controls.

Helicopter rotor diameters are relatively large, as this gives much better energy and propellant efficiency for the speeds at which helicopters fly.

History and development

Helicopter rotor of Engelbert Zaschka, German master engineer, 1931, image from the German Federal Archives

Before the development of powered helicopters in the mid 20th century, autogyro pioneer Juan de la Cierva researched and developed many of the fundamentals of the rotor. Cierva is credited with successful development of multi-bladed, fully articulated rotor systems. This type of system is widely used today in many multi-bladed helicopters.

In the 1930s, Arthur Young improved the stability of two-bladed rotor systems with the introduction of a stabilizer bar. This system was used in several Bell and Hiller helicopter models. It is also used in many remote control model helicopters.

Design

A helicopter rotor is powered by the engine, through the transmission, to the rotating mast. The mast is a cylindrical metal shaft which extends upward from—and is driven by—the transmission. At the top of the mast is the attachment point for the rotor blades called the hub. The rotor blades are then attached to the hub. Main rotor systems are classified according to how the main rotor blades are attached and move relative to the main rotor hub. There are three basic classifications: rigid, semirigid, or fully articulated, although some modern rotor systems use an engineered combination of these classifications.

Unlike the small diameter fans used in turbofan jet engines, the main rotor on a helicopter has a quite large diameter, permitting a large quantity of air to be accelerated. This permits a lower downwash velocity for a given amount of thrust. As it is more efficient at low speeds to accelerate a large amount of air by a small degree than a small amount of air by a large degree it greatly increases the aircraft's energy efficiency and this reduces the fuel use and permits reasonable range.

Parts and functions

The simple rotor of a Robinson R22

Robinson R44 rotor head

The simple rotor of a Robinson R22 showing (from the top):

- The following are driven by the link rods from the rotating part of the swashplate.
    - Pitch hinges, allowing the blades to twist about the axis extending from blade root to blade tip.
- Teeter hinge, allowing one blade to rise vertically while the other falls vertically. This motion occurs whenever translational relative wind is present, or in response to a cyclic control input.
- Scissor link and counterweight, carries the main shaft rotation down to the upper swashplate
- Rubber covers protect moving and stationary shafts
- Swashplates, transmitting cyclic and collective pitch to the blades (the top one rotates)
- Three non-rotating control rods transmit pitch information to the lower swashplate
- Main mast leading down to main gearbox

Swash plate

An advanced rotor head for a Sikorsky S-92

The pitch of main rotor blades can be varied cyclically throughout its rotation in order to control the direction of rotor thrust vector (the part of the rotor disc where the maximum thrust will be developed, front, rear, right side, etc.). Collective pitch is used to vary the magnitude of rotor thrust (increasing or decreasing thrust over the whole rotor disc at the same time). These blade pitch variations are controlled by tilting and/or raising or lowering the swash plate with the flight controls. The vast majority of helicopters maintain a constant rotor speed (RPM) during flight, leaving only the angle of attack of the blades as the sole means of adjusting thrust from the rotor.

The swash plate is two concentric disks or plates, one plate rotates with the mast, connected by idle links, while the other does not rotate. The rotating plate is also connected to the individual blades through pitch links and pitch horns. The non-rotating plate is connected to links which are manipulated by pilot controls, specifically, the collective and cyclic controls.

The swash plate can shift vertically and tilt. Through shifting and tilting, the non-rotating plate controls the rotating plate, which in turn controls the individual blade pitch.

Fully articulated

Juan de la Cierva developed the fully articulating rotor for the autogyro, and it is the basis of his design that permitted successful helicopter development. In a fully articulated rotor system, each rotor blade is attached to the rotor hub through a series of hinges which allow the blade to move independently of the others. These rotor systems usually have three or more blades. The blades are allowed to flap, feather, and lead or lag independently of each other. The horizontal hinge, called the flapping hinge, allows the blade to move up and down. This movement is called flapping and is designed to compensate for dissymmetry of lift. The flapping hinge may be located at varying distances from the rotor hub, and there may be more than one hinge. The vertical hinge, called the lead-lag or drag hinge, allows the blade to move back and forth. This movement is called lead-lag, dragging, or hunting. Dampers are usually used to prevent excess back and forth movement around the drag hinge. The purpose of the drag hinge and dampers is to compensate for the acceleration and deceleration caused by momentum conservation, and not by Coriolis Effect. Each blade can also be feathered, that is, rotated around its spanwise axis. Feathering the blade means changing the pitch angle of the blade. By changing the pitch angle of the blades the thrust and direction of the main rotor disc can be controlled.

Rigid

The term "rigid rotor" usually refers to a hingeless rotor system with blades flexibly attached to the hub. The two basic types of rigid rotor include the Reiseler-Kreiser feathering system and the Lockheed flapping system. The Reiseler-Kreiser feathering rigid rotor was developed and tested on a series of gyroplanes sponsored by E.B. Wilford in Pennsylvania. Irven Culver of Lockheed developed one of the first flapping rigid rotors and was tested and developed on a series of helicopters in the 1960s and 1970s. In a flapping rigid rotor system, each blade flaps, drags, and feathers (depending on the design) about flexible sections of the root. The flapping rigid rotor system is mechanically simpler than the fully articulated rotor system. Loads from flapping and lead/lag forces are accommodated by bending rather than through hinges. By flexing, the blades themselves compensate for the forces which previously required rugged hinges. The result is a rotor system that has less lag in the control response, because the rotor has much less oscillation. The rigid rotor system also negates the danger of mast bumping inherent in semi-rigid rotors. The rigid rotor can also be called a hingeless rotor. Developed most notably for the XH-51 high speed and AH-56 Cheyenne attack compound helicopter, the rotors simplified aerobatic maneuvers at high speeds, but proved troublesome to perfect on the AH-56, and would never be produced in large numbers or adopted by other helicopter makers.

However, to completely contradict the previous statement, flapping rigid rotors have long been standard equipment on the Bolkow series of helicopters, as well as models produced by Aerospatiale, AgustaWestland, and MD helicopters.

Semirigid

Semirigid rotor system

The confusingly termed "semirigid" rotor is more accurately known as a "teetering" or "seesaw" rotor. This rotor system allows for flapping and feathering motions with two per rev inplane motions accommodated by the blade roots and rotor shaft. This system is normally composed of two blades which meet at a common flapping hinge at the rotor shaft. This allows the blades to see-saw or flap together. This teetering hinge combined with an adequate coning angle and undersling minimizes variations in the radius of each blade's center of mass from the axis of rotation as the rotor turns. Secondary flapping hinges may also be provided to provide sufficient flexibility to minimize bouncing. Feathering is accomplished by the feathering hinge, which changes the pitch angle of the blade.

Stabilizer bar

Arthur M. Young found that stability could be increased significantly with the addition of a stabilizer bar (also called a *flybar*) perpendicular to the two blades. The stabilizer bar has weighted ends which cause the bar to stay relatively stable in the plane of rotation. The stabilizer bar is linked with the swash plate in such a manner as to reduce the effect of external forces on the rotor. The result is a much more stable rotor system which eases the workload of the pilot to maintain control of the aircraft. Stanley Hiller also arrived at a method to improve stability by adding a bar perpendicular to the rotor, but he added short, stubby airfoils, or paddles, at each end. Hiller's "Rotormatic" system was used to deliver cyclic control inputs to the main rotor as a sort of control rotor, the paddles providing added stability by also dampening the effects of external forces on the rotor.

In fly by wire helicopters or RC models, a computer with gyroscopes and a venturi sensor can replace the stabilizer. This flybar-less design has the advantage of easy reconfiguration.

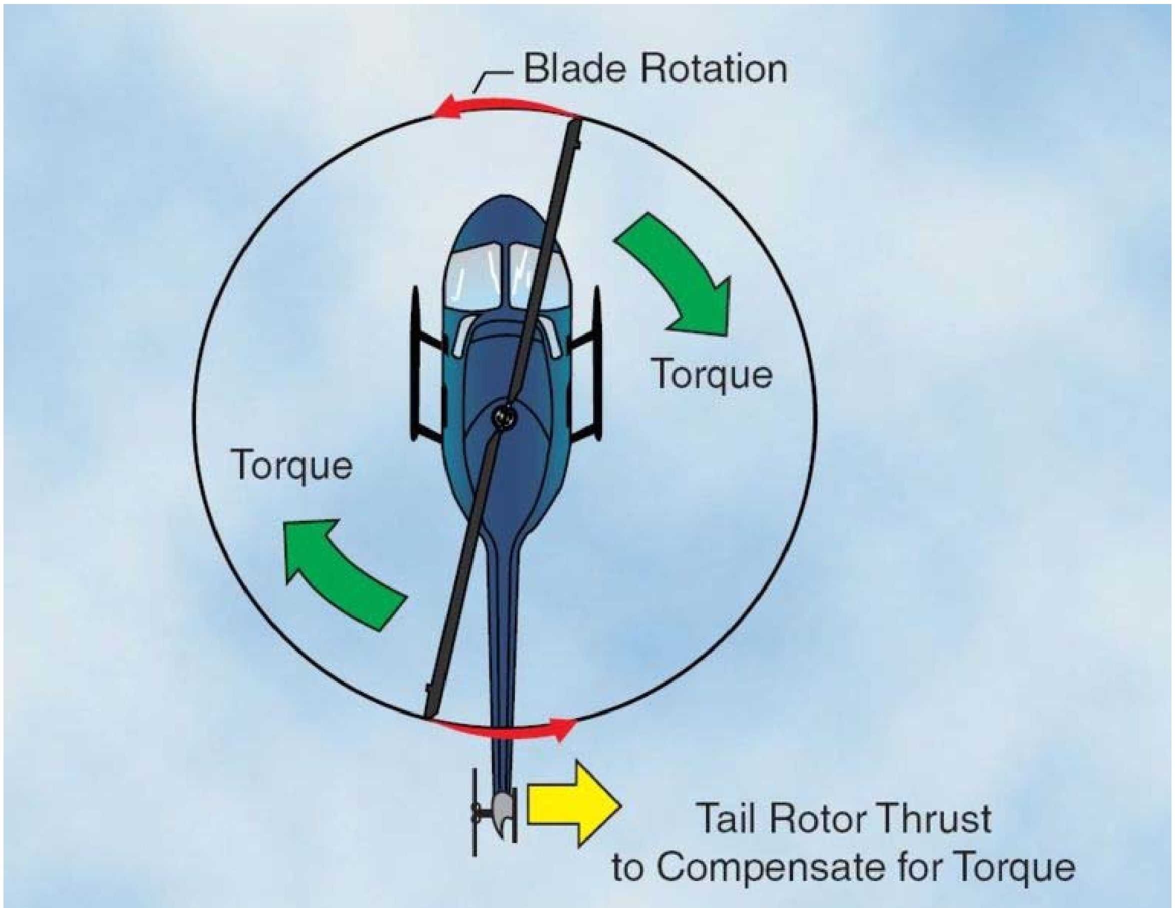
Combination

Modern rotor systems may use the combined principles of the rotor systems mentioned above. Some rotor hubs incorporate a flexible hub, which allows for blade bending (flexing) without the need for bearings or hinges. These systems, called "flextures", are usually constructed from composite material. Elastomeric bearings may also be used in place of conventional roller bearings. Elastomeric bearings are bearings constructed from a rubber type material and have limited movement that is perfectly suited for helicopter applications. Flextures and elastomeric bearings require no lubrication and, therefore, require less maintenance. They also absorb vibration, which means less fatigue and longer service life for the helicopter components.

Rotor configurations

Most helicopters have a single, main rotor but require a separate rotor to overcome torque. This is accomplished through a variable pitch, antitorque rotor or tail rotor. This is the design that Igor Sikorsky settled on for his VS-300 helicopter and it has become the recognized convention for helicopter design, although designs do vary. When viewed from above, the main rotors of helicopter designs from Germany, United Kingdom and the United States rotate counter-clockwise, all others rotate clockwise. This can make it difficult when discussing aerodynamic effects on the main rotor between different designs, since the effects may manifest on opposite sides of each aircraft.

Single main rotor



Antitorque: Torque effect on a helicopter

With a single main rotor helicopter, the creation of torque as the engine turns the rotor creates a torque effect that causes the body of the helicopter to turn in the opposite direction of the rotor. To eliminate this effect, some sort of antitorque control must be used, with a sufficient margin of power available to allow the helicopter to maintain its heading and provide yaw control. The three most common controls used today are the traditional *tail rotor*, Eurocopter's *Fenestron* (also called a *fantail*), and MD Helicopters' *NOTAR*.

Tail rotor of an SA 330 Puma

Tail rotor

The tail rotor is a smaller rotor mounted so that it rotates vertically or near-vertically at the end of the tail of a traditional single-rotor helicopter. The tail rotor's position and distance from the center of gravity allow it to develop thrust in a direction opposite of the main rotor's rotation, to counter the torque effect created by the main rotor. Tail rotors are simpler than main rotors since they require only collective changes in pitch to vary thrust. The pitch of the tail rotor blades is adjustable by the pilot via the anti-torque pedals, which also provide directional control by allowing the pilot to rotate the helicopter around its vertical axis (thereby changing the direction the craft is pointed).

Ducted fan

Fenestron on a EC 120B

Fenestron and FANTAIL are trademarks for a ducted fan mounted at the end of the tail boom of the helicopter and used in place of a tail rotor. Ducted fans have between eight and 18 blades arranged with irregular spacing, so that the noise is distributed over different frequencies. The housing is integral with the aircraft skin and allows a high rotational speed, therefore a ducted fan can have a smaller size than a conventional tail rotor.

The Fenestron was used for the first time at the end of the 1960s on the second experimental model of Sud Aviation's SA 340, and produced on the later model Aérospatiale SA 341 Gazelle. Besides Eurocopter and its predecessors, a ducted fan tail rotor was also used on the canceled military helicopter project, the United States Army's RAH-66 Comanche, as the FANTAIL.

NOTAR

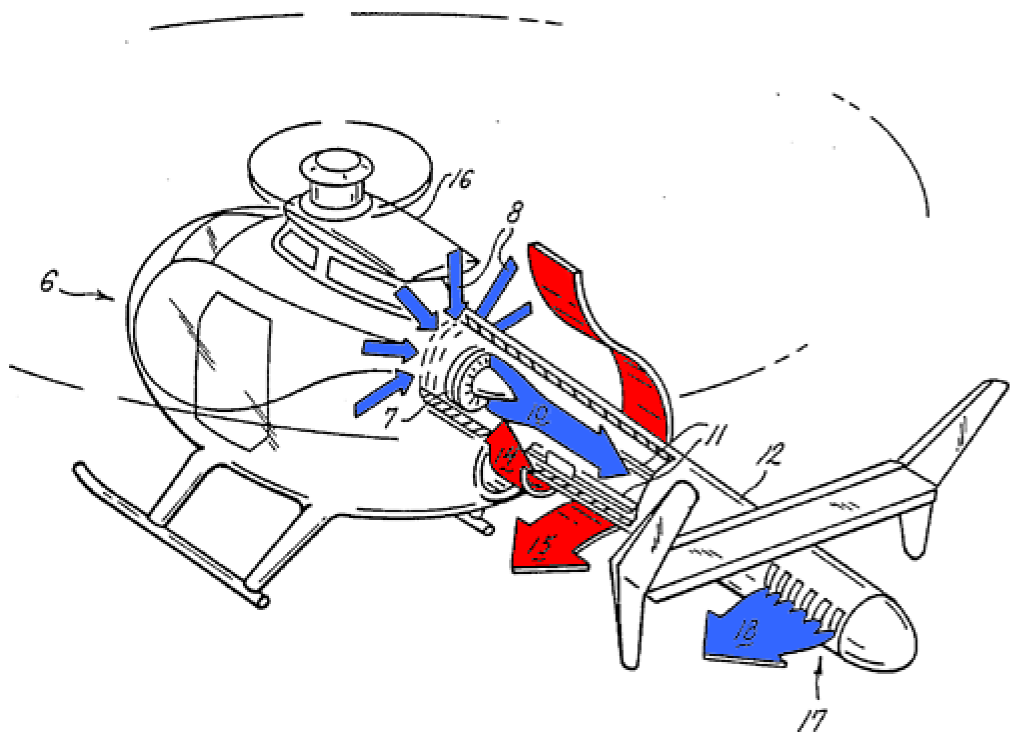


Diagram showing the movement of air through the NOTAR system

NOTAR, an acronym for ***NO TA**il **R**otor*, is a helicopter anti-torque system that eliminates the use of the tail rotor on a helicopter. Although the concept took some time to refine, the NOTAR system is simple in theory and works to provide antitorque the same way a wing develops lift using the Coandă effect. A variable pitch fan is enclosed in the aft fuselage section immediately forward of the tail boom and driven by the main rotor transmission. This fan forces low pressure air through two slots on the right side of the tailboom, causing the downwash from the main rotor to hug the tailboom, producing lift, and thus a measure of antitorque proportional to the amount of airflow from the rotorwash. This is augmented by a direct jet thruster (which also provides directional yaw control) and vertical stabilizers.

Development of the NOTAR system dates back to 1975 when engineers at Hughes Helicopters began concept development work. In December 1981 Hughes flew a OH-6A fitted with NOTAR for the first time. A more heavily modified prototype demonstrator first flew in March 1986 and successfully completed an advanced flight-test program, validating the system for future application in helicopter design. There are currently three production helicopters that incorporate the NOTAR design, all produced by MD Helicopters. This antitorque design also improves safety by eliminating the possibility of personnel walking into the tail rotor.

Tip jets

Another single main rotor configuration without a tail rotor is the tip jet rotor, where the main rotor is not driven by the mast, but from nozzles on the rotor blade tips; which are either pressurized from a fuselage-mounted gas turbine or have their own turbojet, ramjet or rocket thrusters. Although this method is simple and eliminates torque, the prototypes that have been built are less fuel efficient than conventional helicopters and produced more noise. The Percival P.74 was underpowered and was not able to achieve flight, while the Hiller YH-32 Hornet had good lifting capability but performed poorly otherwise. Other aircraft relied on supplemental thrust so that the tipjets could be shut down and the rotor could autorotate after the fashion of an autogyro. The experimental Fairey Jet Gyrodyne and 40-seat Fairey Rotodyne passenger prototype were evaluated to have flown very well using this method. Perhaps the most unusual design of this type was the Rotary Rocket Roton ATV, which was originally envisioned to take off utilizing a rocket-tipped rotor. No tip jet rotorcraft have ever entered into production.

Dual rotors (counterrotating)

Kamov Ka-50 of the Russian Air Force, with coaxial rotors

Counterrotating rotors are rotorcraft configurations with a pair or more of large horizontal rotors turning in opposite directions to counteract the effects of torque on the aircraft without relying on an antitorque tail rotor. This allows the power normally required to drive the tail rotor to be applied to the main rotors, increasing the aircraft's lifting capacity. Primarily, there are three common configurations that use the counterrotating effect to benefit the rotorcraft. Tandem rotors are two rotors with one mounted behind the other. Coaxial rotors are two rotors that are mounted one above the other with the same axis. Intermeshing rotors are two rotors that are mounted close to each other at a sufficient angle to allow the rotors to intermesh over the top of the aircraft. Another configuration found on tiltrotors and some earlier helicopters is called transverse rotors where the pair of rotors are mounted at each end of wing-type structures or outriggers.

Tandem

CH-47 Chinook

Tandem rotors are two horizontal main rotor assemblies mounted one behind the other. Tandem rotors achieve pitch attitude changes to accelerate and decelerate the helicopter through a process called differential collective pitch. To pitch forward and accelerate, the rear rotor increases collective pitch, raising the tail and the front rotor decreases collective pitch, simultaneously dipping the nose. To pitch upward while decelerating (or moving rearward), the front rotor increases collective pitch to raise the nose and the rear rotor decreases collective pitch to lower the tail. Yaw control is developed through opposing cyclic pitch in each rotor; to pivot right, the front rotor tilts right and the rear rotor tilts left, and to pivot left, the front rotor tilts left and the rear rotor tilts right. All of the rotor power contributes to lift, and it is simpler to handle changes in the center of gravity fore-aft. However, it requires the expense of two large rotors rather than the more common one large main rotor and a much smaller tail rotor. The CH-47 Chinook is the most common tandem rotor helicopter today.

Coaxial

Kamov Ka-50

Coaxial rotors are a pair of rotors mounted one above the other on the same shaft and turning in opposite directions. The advantage of the coaxial rotor is that, in forward flight, the lift provided by the advancing halves of each rotor compensates for the retreating half of the other, eliminating one of the key effects of dissymmetry of lift: retreating blade stall. However, other design considerations plague coaxial rotors. There is an increased mechanical complexity of the rotor system because it requires linkages and swashplates for two rotor systems. Add that each rotor system needs to be turned in opposite directions means that the mast itself is more complex, and provisions for making pitch changes to the upper rotor system must pass through the lower rotor system.

Intermeshing

HH-43 Huskie

Intermeshing rotors on a helicopter are a set of two rotors turning in opposite directions, with each rotor mast mounted on the helicopter with a slight angle to the other so that the blades intermesh without colliding. This configuration is sometimes referred to as a synchropter. Intermeshing rotors have high stability and powerful lifting capability. The arrangement was successfully used in Nazi Germany for a small anti-submarine warfare helicopter, the Flettner Fl 282 Kolibri. During the Cold War, the American company, Kaman Aircraft produced the HH-43 Huskie for the USAF firefighting and rescue missions. The latest Kaman model, the Kaman K-MAX, is a dedicated sky crane design.

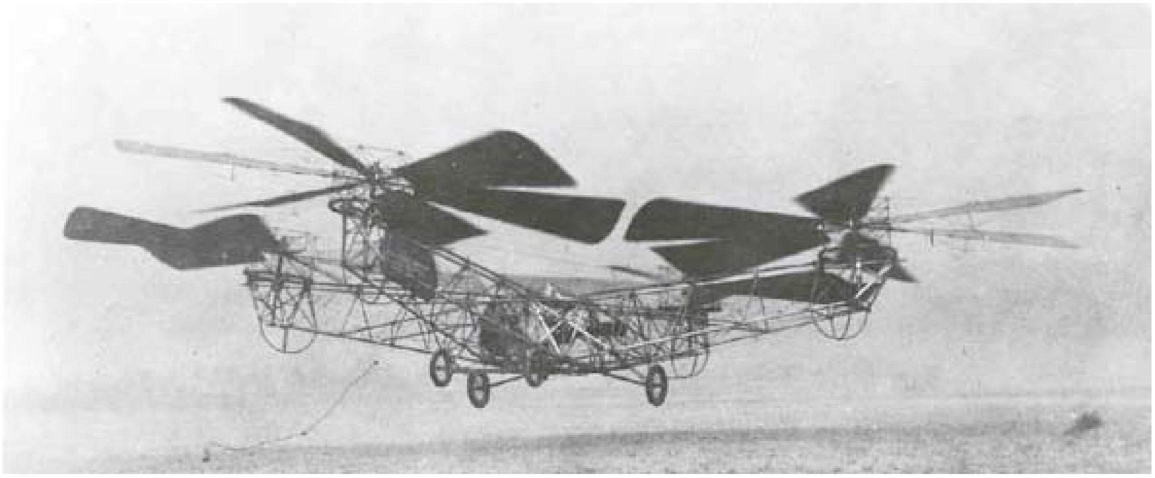
Transverse

Mi-12

Transverse rotors are mounted on the end of wings or outriggers, perpendicular to the body of the aircraft. Similar to tandem rotors and intermeshing rotors, the transverse rotor also uses differential collective pitch. But like the intermeshing rotors, the transverse rotors use the concept for changes in the roll attitude of the rotorcraft. This configuration is found on two of the first viable helicopters, the Focke-Wulf Fw 61 and the Focke-Achgelis Fa 223, as well as the world's largest helicopter ever built, the Mil Mi-12. It is also the configuration found on tiltrotors, such as Bell's XV-15 and the newer V-22 Osprey.

Quadrotor

Quadrotor



De Bothezat Quadrotor, 1923.

A quadrotor helicopter has four rotors in an "X" configuration designated as front-left, front-right, rear-left, and rear-right. Rotors to the left and right are in a transverse configuration while those in the front and to the rear are in a tandem configuration.

The main attraction of quadrotors is their mechanical simplicity—a quadrotor helicopter using electric motors and fixed-pitch rotors uses only four moving parts.

Blade design

The blades of a helicopter are long, narrow airfoils with a high aspect ratio, a shape which minimises drag from tip vortices. They generally contain a degree of washout to reduce the lift generated at the tips, where the airflow is fastest and vortex generation would be a significant problem. Rotor blades are made out of various materials, including aluminium, composite structure and steel or titanium with abrasion shields along the leading edge. Rotorcraft blades are traditionally passive, but research into active blade control trailing edge flaps is performed.

Limitations and hazards

Helicopters with teetering rotors, for example the two-blade system on the Bell, Robinson and others, must not be subjected to a low-g condition because such rotor systems do not control the fuselage attitude. This can result in the fuselage assuming an attitude controlled by momentum and tail rotor thrust that causes the tail boom to intersect the main rotor tip-path plane, or result in the blade roots contacting the main rotor drive shaft causing the blades to separate from the hub (mast bumping).

Abrasion in sandy environments

When operating in sandy environments, sand hitting the moving rotor blades erodes their surface. This can damage the rotors; the erosion also presents serious and costly maintenance problems.

The abrasion strips on helicopter rotor blades are made of metal, often titanium or nickel, which are very hard, but less hard than sand. When a helicopter is flown near to the ground in desert environments abrasion occurs from the sand striking the rotor blade. At night, the sand hitting the metal abrasion strip causes a visible corona or halo around the rotor blades. The corona effect is caused by the oxidation of eroded particles resulting in visible corona. In 2009, war correspondent Michael Yon referred to this corona effect as "Kopp-Etchells effect", to honor Cpl. Benjamin Kopp, and Cpl. Joseph Etchells, recently fallen American and British soldiers respectively.

Chapter 4

Air Traffic Control

Airport Traffic Control Towers (ATCTs) at Amsterdam's Schiphol Airport, the Netherlands

Air traffic control (**ATC**) is a service provided by ground-based controllers who direct aircraft on the ground and in the air. The primary purpose of ATC systems worldwide is to *separate* aircraft to prevent collisions, to organize and expedite the flow of traffic, and to provide information and other support for pilots when able. In some countries, ATC may also play a security or defense role (as in the United States), or be run entirely by the military (as in Brazil).

Preventing collisions is referred to as separation, which is a term used to prevent aircraft from coming too close to each other by use of lateral, vertical and longitudinal separation minima; many aircraft now have collision avoidance systems installed to act as a backup to ATC observation and instructions. In addition to its primary function, the ATC can provide additional services such as providing information to pilots, weather and navigation information and NOTAMs (*NOtices To AirMen*).

In many countries, ATC services are provided throughout the majority of airspace, and its services are available to all users (private, military, and commercial). When controllers are responsible for separating some or all aircraft, such airspace is called "controlled airspace" in contrast to "uncontrolled airspace" where aircraft may fly without the use of the air traffic control system. Depending on the type of flight and the class of airspace, ATC may issue *instructions* that pilots are required to follow, or merely *flight information* (in some countries known as *advisories*) to assist pilots operating in the airspace. In all cases, however, the pilot in command has final responsibility for the safety of the flight, and may deviate from ATC instructions in an emergency.

History

Contrails of aircraft entering and leaving Heathrow Airport. Intersecting flight paths are carefully controlled to prevent collisions.

In 1919, the International Commission for Air Navigation (ICAN) was created to develop General Rules for Air Traffic. Its rules and procedures were applied in most countries where aircraft operated. The United States did not sign the ICAN Convention, but later developed its own set of air traffic rules after passage of the Air Commerce Act of 1926. This legislation authorized the Department of Commerce to establish air traffic rules for the navigation, protection, and identification of aircraft, including rules as to safe altitudes of flight and rules for the prevention of collisions between vessels and aircraft. The first rules were brief and basic. For example, pilots were told not to begin their takeoff until there is no risk of collision with landing aircraft and until preceding aircraft are clear of the field. As traffic increased, some airport operators realized that such general rules were not enough to prevent collisions. They began to provide a form of air traffic control (ATC) based on visual signals. Early controllers, like Archie League (one of the first system's flagmen), stood on the field, waving flags to communicate with pilots.

As more aircraft were fitted for radio communication, radio-equipped airport traffic control towers began to replace the flagmen. In 1930, the first radio-equipped control tower in the United States began operating at the Cleveland Municipal Airport. By 1935, about 20 radio control towers were operating.

Increases in the number of flights created a need for ATC that was not just confined to airport areas but also extended out along the airways. In 1935, the principal airlines using the Chicago, Cleveland, and Newark airports agreed to coordinate the handling of airline traffic between those cities. In December, the first Airway Traffic Control Center opened at Newark, New Jersey. Additional centers at Chicago and Cleveland followed in 1936.

The early controllers tracked the position of planes using maps and blackboards and little boat-shaped weights that came to be called shrimp boats. They had no direct radio link with aircraft but used telephones to stay in touch with airline dispatchers, airway radio operators, and airport traffic controllers.

In July 1936, en route ATC became a federal responsibility and the first appropriation of $175,000 was made ($2,665,960 today). The Federal Government provided airway traffic control service, but local government authorities where the towers were located continued to operate those facilities.

In 1941, Congress appropriated funds for the Civil Aeronautics Administration (CAA) to construct and operate ATC towers, and soon the CAA began taking over operations at the first of these towers, with their number growing to 115 by 1944. In the postwar era, ATC at most airports was eventually to become a permanent federal responsibility. In response to wartime needs, the CAA also greatly expanded its en route air traffic control system.

The postwar years saw the beginning of a revolutionary development in ATC, the introduction of radar, a system that uses radio waves to detect distant objects. Originally developed by the British for military defense, this new technology allowed controllers to see the position of aircraft tracked on visual displays. In 1946, the CAA unveiled an experimental radar-equipped tower for control of civil flights. By 1952, the agency had begun its first routine use of radar for approach and departure control. Four years later, it placed a large order for long-range radars for use in en route ATC.

In 1960, the Federal Aviation Administration (FAA) began successful testing of a system under which flights in certain positive control areas were required to carry a radar beacon, called a transponder that identified the aircraft and helped to improve radar performance. Pilots in this airspace were also required to fly on instruments regardless of the weather and to remain in contact with controllers. Under these conditions, controllers were able to reduce the separation between aircraft by as much as half the standard distance.

For many years, pilots had negotiated a complicated maze of airways. In September 1964, the FAA instituted two layers of airways, one from 1,000 to 18,000 feet (305 to 5,486 meters) above ground level and the second from 18,000 to 45,000 feet (13,716 m) above mean sea level. It also standardized aircraft instrument settings and navigation checkpoints to reduce the controllers' workload.

From 1965 to 1975, the FAA developed complex computer systems that would replace the plastic markers for tracking aircraft thereby modernizing the National Airspace System. Controllers could now view information sent by aircraft transponders to form alphanumeric symbols on a simulated three dimensional radar screen. The system allowed controllers to focus on providing separation by automating complex tasks.

The FAA established a Central Flow Control Facility in April 1970, to prevent clusters of congestion from disrupting the nationwide air traffic flow. This type of ATC became increasingly sophisticated and important, and in 1994, the FAA opened a new Air Traffic Control System Command Center with advanced equipment.

In January 1982, the FAA unveiled the National Airspace System (NAS) Plan. The plan called for modernized flight service stations, more advanced systems for ATC, and improvements in ground-to-air surveillance and communication. Better computers and software were developed, air route traffic control centers were consolidated, and the number of flight service stations reduced. New Doppler Radars and better transponders complemented automatic, radio broadcasts of surface and flight conditions.

In July 1988, the FAA selected IBM to develop the new multi-billion-dollar Advanced Automation System (AAS) for the Nation's en route ATC centers. AAS would include controller workstations, called "sector suites," that would incorporate new display, communications and processing capabilities. The system had upgraded hardware enabling increased automation of complex tasks.

In December 1993, the FAA reviewed its order for the planned AAS. IBM was far behind schedule and had major cost overruns. In 1994 the FAA simplified its needs and picked new contractors. The revised modernization program continued under various project names. In 1999, controllers began their first use of an early version of the Standard

Terminal Automation Replacement System, which included new displays and capabilities for approach control facilities. During the following year, FAA completed deployment of the Display System Replacement, providing more efficient workstations for en route controllers.

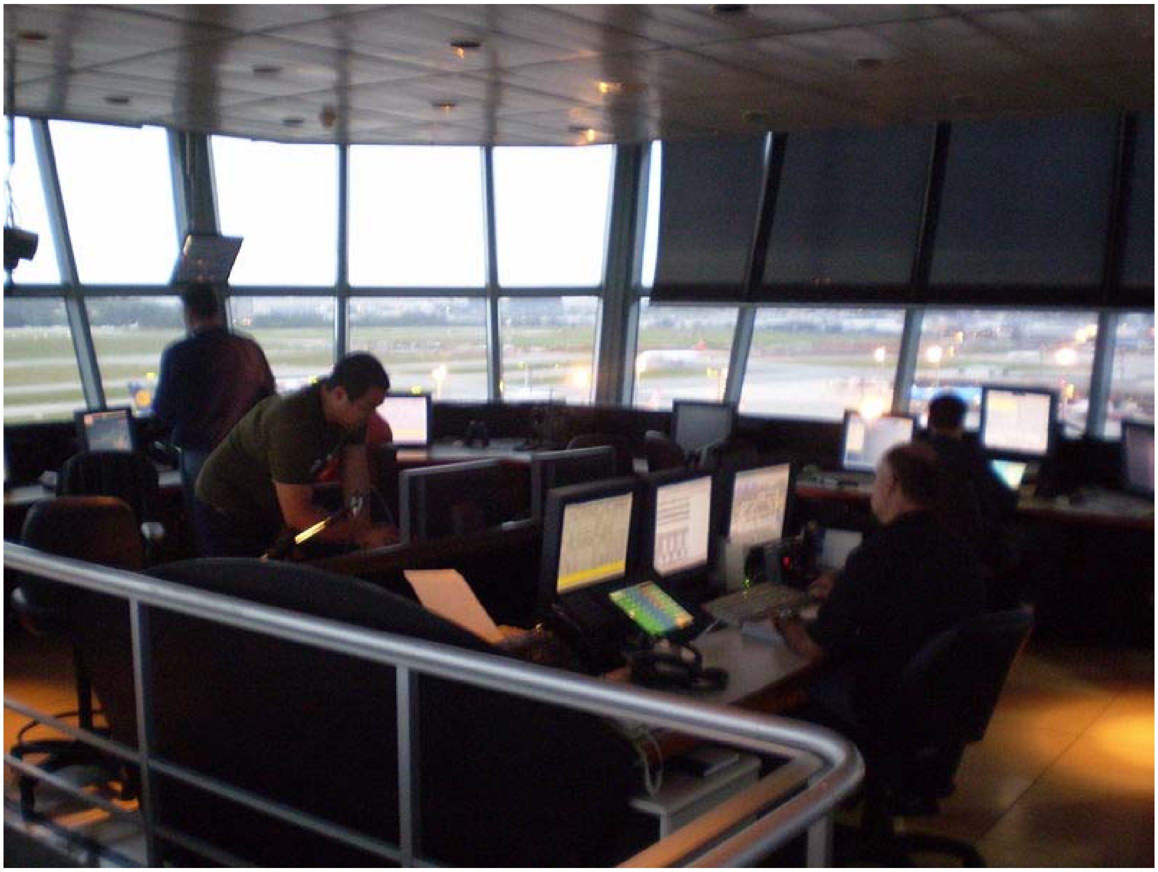
In 1994, the concept of Free Flight was introduced. It might eventually allow pilots to use on board instruments and electronics to maintain a safe distance between planes and to reduce their reliance on ground controllers. Full implementation of this concept would involve technology that made use of the Global Positioning System to help track the position of aircraft. In 1998, the FAA and industry began applying some of the early capabilities developed by the Free Flight program.

Current studies to upgrade ATC include the Communication, Navigation and Surveillance for Air Traffic Management System that relies on the most advanced aircraft transponder, a global navigation satellite system, and ultra-precise radar. Tests are underway to design new cockpit displays that will allow pilots to better control their aircraft by combining as many as 32 types of information about traffic, weather, and hazards.

Language

Pursuant to requirements of the International Civil Aviation Organization (ICAO), ATC operations are conducted either in the English language or the language used by the station on the ground. In practice, the native language for a region is normally used, however the English language must be used upon request.

Airport control



Inside the São Paulo-Guarulhos International Airport's tower, Latin America's second busiest airport

The primary method of controlling the immediate airport environment is visual observation from the airport traffic control tower (ATCT). The ATCT is a tall, windowed structure located on the airport grounds. **Aerodrome** or **Tower** controllers are responsible for the separation and efficient movement of aircraft and vehicles operating on the taxiways and runways of the airport itself, and aircraft in the air near the airport, generally 5 to 10 nautical miles (3.7 to 9.2 km) depending on the airport procedures.

Radar displays are also available to controllers at some airports. Controllers may use a radar system called Secondary Surveillance Radar for airborne traffic approaching and departing. These displays include a map of the area, the position of various aircraft, and data tags that include aircraft identification, speed, heading, and other information described in local procedures.

The areas of responsibility for ATCT controllers fall into three general operational disciplines; Local Control or Air Control, Ground Control, and Flight Data/Clearance Delivery—other categories, such as Apron Control or Ground Movement Planner, may exist at extremely busy airports. While each ATCT may have unique airport-specific procedures, such as multiple teams of controllers ('crews') at major or complex airports with multiple runways, the following provides a general concept of the delegation of responsibilities within the ATCT environment.

Ground control

Ground Control (sometimes known as Ground Movement Control abbreviated to GMC or Surface Movement Control abbreviated to SMC) is responsible for the airport "movement" areas, as well as areas not released to the airlines or other users. This generally includes all taxiways, inactive runways, holding areas, and some transitional aprons or intersections where aircraft arrive, having vacated the runway or departure gate. Exact areas and control responsibilities are clearly defined in local documents and agreements at each airport. Any aircraft, vehicle, or person walking or working in these areas is required to have clearance from Ground Control. This is normally done via VHF/UHF radio, but there may be special cases where other processes are used. Most aircraft and airside vehicles have radios. Aircraft or vehicles without radios must respond to ATC instructions via aviation light signals or else be led by vehicles with radios. People working on the airport surface normally have a communications link through which they can communicate with Ground Control, commonly either by handheld radio or even cell phone. Ground Control is vital to the smooth operation of the airport, because this position impacts the sequencing of departure aircraft, affecting the safety and efficiency of the airport's operation.

Some busier airports have Surface Movement Radar (SMR), such as, ASDE-3, AMASS or ASDE-X, designed to display aircraft and vehicles on the ground. These are used by Ground Control as an additional tool to control ground traffic, particularly at night or in poor visibility. There are a wide range of capabilities on these systems as they are being modernized. Older systems will display a map of the airport and the target. Newer systems include the capability to display higher quality mapping, radar target, data blocks, and safety alerts, and to interface with other systems such as digital flight strips.

Local control or air control

Local Control (known to pilots as "Tower" or "Tower Control") is responsible for the active runway surfaces. Local Control clears aircraft for takeoff or landing, ensuring that prescribed runway separation will exist at all times. If Local Control detects any unsafe condition, a landing aircraft may be told to "go-around" and be re-sequenced into the landing pattern by the approach or terminal area controller.

Within the ATCT, a highly disciplined communications process between Local Control and Ground Control is an absolute necessity. Ground Control must request and gain approval from Local Control to cross any active runway with any aircraft or vehicle. Likewise, Local Control must ensure that Ground Control is aware of any operations that will impact the taxiways, and work with the approach radar controllers to create "holes" or "gaps" in the arrival traffic to allow taxiing traffic to cross runways and to allow departing aircraft to take off. Crew Resource Management (CRM) procedures are often used to ensure this communication process is efficient and clear, although this is not as prevalent as CRM for pilots.

Flight data / clearance delivery

Clearance Delivery is the position that issues route clearances to aircraft, typically before they commence taxiing. These contain details of the route that the aircraft is expected to fly after departure. Clearance Delivery or, at busy airports, the Traffic Management Coordinator (TMC) will, if necessary, coordinate with the en route center and national command center or flow control to obtain releases for aircraft. Often, however, such releases are given automatically or are controlled by local agreements allowing "free-flow" departures. When weather or extremely high demand for a certain airport or airspace becomes a factor, there may be ground "stops" (or "slot delays") or re-routes may be necessary to ensure the system does not get overloaded. The primary responsibility of Clearance Delivery is to ensure that the aircraft have the proper route and slot time. This information is also coordinated with the en route center and Ground Control in order to ensure that the aircraft reaches the runway in time to meet the slot time provided by the command center. At some airports, Clearance Delivery also plans aircraft pushbacks and engine starts, in which case it is known as the Ground Movement Planner (GMP): this position is particularly important at heavily congested airports to prevent taxiway and apron gridlock.

Flight Data (which is routinely combined with Clearance Delivery) is the position that is responsible for ensuring that both controllers and pilots have the most current information: pertinent weather changes, outages, airport ground delays/ground stops, runway closures, etc. Flight Data may inform the pilots using a recorded continuous loop on a specific frequency known as the Automatic Terminal Information Service (ATIS).

Approach and terminal control

Potomac TRACON, Washington, D.C., United States

Many airports have a radar control facility that is associated with the airport. In most countries, this is referred to as *Terminal Control*; in the U.S., it is referred to as a TRACON (Terminal Radar Approach Control.) While every airport varies, terminal controllers usually handle traffic in a 30 to 50 nautical mile (56 to 93 km) radius from the airport. Where there are many busy airports close together, one consolidated TRACON may service all the airports. The airspace boundaries and altitudes assigned to a TRACON, which vary widely from airport to airport, are based on factors such as traffic flows, neighboring airports and terrain. A large and complex example is the London Terminal Control Centre which controls traffic for five main London airports up to 20,000 feet (6,100 m) and out to 100 nautical miles (190 km).

Terminal controllers are responsible for providing all ATC services within their airspace. Traffic flow is broadly divided into departures, arrivals, and overflights. As aircraft move in and out of the terminal airspace, they are handed off to the next appropriate control facility (a control tower, an en-route control facility, or a bordering terminal or approach control). Terminal control is responsible for ensuring that aircraft are at an appropriate altitude when they are handed off, and that aircraft arrive at a suitable rate for landing.

Not all airports have a radar approach or terminal control available. In this case, the en-route center or a neighboring terminal or approach control may co-ordinate directly with the tower on the airport and vector inbound aircraft to a position from where they can land visually. At some of these airports, the tower may provide a non-radar procedural approach service to arriving aircraft handed over from a radar unit before they are visual to land. Some units also have a dedicated approach unit which can provide the procedural approach service either all the time or for any periods of radar outage for any reason.

En-route, center, or area control

The training department at the Washington Air Route Traffic Control Center, Washington, D.C., United States.

ATC provides services to aircraft in flight between airports as well. Pilots fly under one of two sets of rules for separation: Visual Flight Rules (VFR) or Instrument Flight Rules (IFR). Air traffic controllers have different responsibilities to aircraft operating under the different sets of rules. While IFR flights are under positive control, in the US VFR pilots can request flight following, which provides traffic advisory services on a time permitting basis and may also provide assistance in avoiding areas of weather and flight restrictions. In the UK, a pilot can request for "Deconfliction Service", which is similar to flight following.

En-route air traffic controllers issue clearances and instructions for airborne aircraft, and pilots are required to comply with these instructions. En-route controllers also provide air traffic control services to many smaller airports around the country, including clearance off of the ground and clearance for approach to an airport. Controllers adhere to a set of separation standards that define the minimum distance allowed between aircraft. These distances vary depending on the equipment and procedures used in providing ATC services.

General characteristics

En-route air traffic controllers work in facilities called Area Control Centers, each of which is commonly referred to as a "Center". The United States uses the equivalent term Air Route Traffic Control Center (ARTCC). Each center is responsible for many thousands of square miles of airspace (known as a Flight Information Region) and for the airports within that airspace. Centers control IFR aircraft from the time they depart from an airport or terminal area's airspace to the time they arrive at another airport or terminal area's airspace. Centers may also "pick up" VFR aircraft that are already airborne and integrate them into the IFR system. These aircraft must, however, remain VFR until the Center provides a clearance.

Center controllers are responsible for climbing the aircraft to their requested altitude while, at the same time, ensuring that the aircraft is properly separated from all other aircraft in the immediate area. Additionally, the aircraft must be placed in a flow consistent with the aircraft's route of flight. This effort is complicated by crossing traffic, severe weather, special missions that require large airspace allocations, and traffic density. When the aircraft approaches its destination, the center is responsible for meeting altitude restrictions by specific points, as well as providing many destination airports with a traffic flow, which prohibits all of the arrivals being "bunched together". These "flow restrictions" often begin in the middle of the route, as controllers will position aircraft landing in the same destination so that when the aircraft are close to their destination they are sequenced.

As an aircraft reaches the boundary of a Center's control area it is "handed off" or "handed over" to the next Area Control Center. In some cases this "hand-off" process involves a transfer of identification and details between controllers so that air traffic control services can be provided in a seamless manner; in other cases local agreements may allow "silent handovers" such that the receiving center does not require any co-ordination if traffic is presented in an agreed manner. After the hand-off, the aircraft is given a frequency change and begins talking to the next controller. This process continues until the aircraft is handed off to a terminal controller ("approach").

Radar coverage

Since centers control a large airspace area, they will typically use long range radar that has the capability, at higher altitudes, to see aircraft within 200 nautical miles (370 km) of the radar antenna. They may also use TRACON radar data to control when it provides a better "picture" of the traffic or when it can fill in a portion of the area not covered by the long range radar.

In the U.S. system, at higher altitudes, over 90% of the U.S. airspace is covered by radar and often by multiple radar systems; however, coverage may be inconsistent at lower altitudes used by unpressurized aircraft due to high terrain or distance from radar facilities. A center may require numerous radar systems to cover the airspace assigned to them, and may also rely on pilot position reports from aircraft flying below the floor of radar coverage. This results in a large amount of data being available to the controller. To address this, automation systems have been designed that consolidate the radar data for the controller. This consolidation includes eliminating duplicate radar returns, ensuring the best radar for each geographical area is providing the data, and displaying the data in an effective format.

Centers also exercise control over traffic travelling over the world's ocean areas. These areas are also FIRs. Because there are no radar systems available for oceanic control, oceanic controllers provide ATC services using procedural control. These procedures use aircraft position reports, time, altitude, distance, and speed to ensure separation. Controllers record information on flight progress strips and in specially developed oceanic computer systems as aircraft report positions. This process requires that aircraft be separated by greater distances, which reduces the overall capacity for any given route.

Some Air Navigation Service Providers (e.g. Airservices Australia, The Federal Aviation Administration, NAV CANADA, etc.) have implemented Automatic Dependent Surveillance - Broadcast (ADS-B) as part of their surveillance capability. This new technology reverses the radar concept. Instead of radar "finding" a target by interrogating the transponder, the ADS-equipped aircraft sends a position report as determined by the navigation equipment on board the aircraft. Normally, ADS operates in the "contract" mode where the aircraft reports a position, automatically or initiated by the pilot, based on a predetermined time interval. It is also possible for controllers to request more frequent reports to more quickly establish aircraft position for specific reasons. However, since the cost for each report is charged by the ADS service providers to the company operating the aircraft, more frequent reports are not commonly requested except in emergency situations. ADS is significant because it can be used where it is not possible to locate the infrastructure for a radar system (e.g. over water). Computerized radar displays are now being designed to accept ADS inputs as part of the display. This technology is currently used in portions of the North Atlantic and the Pacific by a variety of states who share responsibility for the control of this airspace.

Precision approach radars are commonly used by military controllers of airforces of several countries, to assist the Pilot in final phases of landing in places where Instrument Landing System and other sophisticated air borne equipements are unavailable to assist the pilots in marginal or *near zero visibility* conditions. This procedure is also called **Talkdowns**.

A Radar Archive System (RAS) keeps an electronic record of all radar information, preserving it for a few weeks. This information can be useful for search and rescue. When an aircraft has 'disappeared' from radar screens, a controller can review the last radar returns from the aircraft to determine its likely position. RAS is also useful to technicians who are maintaining radar systems.

Flight traffic mapping

The mapping of flights in real-time is based on the air traffic control system. In 1991, data on the location of aircraft was made available by the Federal Aviation Administration to the airline industry. The National Business Aviation Association (NBAA), the General Aviation Manufacturers Association, the Aircraft Owners & Pilots Association, the Helicopter Association International, and the National Air Transportation Association petitioned the FAA to make ASDI information available on a "need-to-know" basis. Subsequently, NBAA advocated the broad-scale dissemination of air traffic data. The Aircraft Situational Display to Industry (ASDI) system now conveys up-to-date flight information to the airline industry and the public. Some companies that distribute ASDI information are FlightExplorer, FlightView, and FlyteComm. Each company maintains a website that provides free updated information to the public on flight status. Stand-alone programs are also available for displaying the geographic location of airborne IFR (Instrument Flight Rules) air traffic anywhere in the FAA air traffic system. Positions are reported for both commercial and general aviation traffic. The programs can overlay air traffic with a wide selection of maps such as, geo-political boundaries, air traffic control center boundaries, high altitude jet routes, satellite cloud and radar imagery.

Problems

Traffic

The day-to-day problems faced by the air traffic control system are primarily related to the volume of air traffic demand placed on the system and weather. Several factors dictate the amount of traffic that can land at an airport in a given amount of time. Each landing aircraft must touch down, slow, and exit the runway before the next crosses the approach end of the runway. This process requires at least one and up to four minutes for each aircraft. Allowing for departures between arrivals, each runway can thus handle about 30 arrivals per hour. A large airport with two arrival runways can handle about 60 arrivals per hour in good weather. Problems begin when airlines schedule more arrivals into an airport than can be physically handled, or when delays elsewhere cause groups of aircraft that would otherwise be separated in time to arrive simultaneously. Aircraft must then be delayed in the air by holding over specified locations until they may be safely sequenced to the runway. Up until the 1990s, holding, which has significant environmental and cost implications, was a routine occurrence at many airports. Advances in computers now allow the sequencing of planes hours in advance. Thus, planes may be delayed before they even take off (by being given a "slot"), or may reduce speed in flight and proceed more slowly thus significantly reducing the amount of holding.

Weather

Beyond runway capacity issues, weather is a major factor in traffic capacity. Rain, ice or snow on the runway cause landing aircraft to take longer to slow and exit, thus reducing the safe arrival rate and requiring more space between landing aircraft. Fog also requires a decrease in the landing rate. These, in turn, increase airborne delay for holding aircraft. If more aircraft are scheduled than can be safely and efficiently held in the air, a ground delay program may be established, delaying aircraft on the ground before departure due to conditions at the arrival airport.

In Area Control Centers, a major weather problem is thunderstorms, which present a variety of hazards to aircraft. Aircraft will deviate around storms, reducing the capacity of the en-route system by requiring more space per aircraft, or causing congestion as many aircraft try to move through a single hole in a line of thunderstorms. Occasionally weather considerations cause delays to aircraft prior to their departure as routes are closed by thunderstorms.

Much money has been spent on creating software to streamline this process. However, at some ACCs, air traffic controllers still record data for each flight on strips of paper and personally coordinate their paths. In newer sites, these flight progress strips have been replaced by electronic data presented on computer screens. As new equipment is brought in, more and more sites are upgrading away from paper flight strips.

Call signs

A prerequisite to safe air traffic separation is the assignment and use of distinctive call signs. These are permanently allocated by ICAO (pronounced "ai-kay-oh") on request usually to scheduled flights and some air forces for military flights. They are written callsigns with 3-letter combination like KLM, AAL, SWA, BAW, VLG followed by the flight number, like AAL872, VLG1011. As such they appear on flight plans and ATC radar labels. There are also the *audio* or *Radio-telephony* callsigns used on the radio contact between pilots and Air Traffic Control not always identical with the written ones. For example BAW symbolises British Airways but on the radio you will only hear the word *Speedbird* followed by an alpha-numeric code instead. By default, the callsign for any other flight is the registration number (tail number) of the aircraft, such as "N12345", "C-GABC" or "EC-IZD". The term *tail number* is because a registration number is usually painted somewhere on the tail of a plane, yet this is not a rule. Registration numbers may appear on the engines, anywhere on the fuselage, and often on the wings. The short *Radio-telephony* callsigns for these tail numbers is the last 3 letters only like ABC spoken Alpha-Bravo-Charlie for C-GABC or the last 3 numbers like 345 spoken as TREE-FORE-FIFE for N12345. In the United States the abbreviation of callsigns is required to be a prefix (such as aircraft type, aircraft manufacturer, or first letter of registration) followed by the last three characters of the callsign. This abbreviation is only allowed after communications has been established in each sector.

The flight number part is decided by the aircraft operator. In this arrangement, an identical call sign might well be used for the same scheduled journey each day it is operated, even if the departure time varies a little across different days of the week. The call sign of the return flight often differs only by the final digit from the outbound flight. Generally, airline flight numbers are even if eastbound, and odd if westbound. In order to reduce the possibility of two callsigns on one frequency at any time sounding too similar, a number of airlines, particularly in Europe, have started using alphanumeric callsigns that are not based on flight numbers. For example DLH23LG, spoken as lufthansa-two-tree-lima-golf. Additionally it is the right of the air traffic controller to change the 'audio' callsign for the period the flight is in his sector if there is a risk of confusion, usually choosing the tail number instead.

Before around 1980 International Air Transport Association (IATA) and ICAO were using the same 2-letter callsigns. Due to the larger number of new airlines after deregulation ICAO established the 3-letter callsigns as mentioned above. The IATA callsigns are currently used in aerodromes on the announcement tables but never used any longer in Air Traffic Control. For example, AA is the IATA callsign for American Airlines — ATC equivalent AAL. Other examples include LY/ELY for El Al, DL/DAL for Delta Air Lines, VY/VLG for Vueling Airlines, etc.

Technology

Many technologies are used in air traffic control systems. Primary and secondary radar are used to enhance a controller's situation awareness within his assigned airspace — all types of aircraft send back primary echoes of varying sizes to controllers' screens as radar energy is bounced off their skins, and transponder-equipped aircraft reply to secondary radar interrogations by giving an ID (Mode A), an altitude (Mode C) and/or a unique callsign (Mode S). Certain types of weather may also register on the radar screen.

These inputs, added to data from other radars, are correlated to build the air situation. Some basic processing occurs on the radar tracks, such as calculating ground speed and magnetic headings.

Usually, a Flight Data Processing System manages all the flight plan related data, incorporating - in a low or high degree - the information of the track once the correlation between them (flight plan and track) is established. All this information is distributed to modern operational display systems, making it available to controllers.

The FAA has spent over USD$3 billion on software, but a fully-automated system is still over the horizon. In 2002 the UK brought a new area control centre into service at Swanwick, in Hampshire, relieving a busy suburban centre at West Drayton in Middlesex, north of London Heathrow Airport. Software from Lockheed-Martin predominates at Swanwick. However, Swanwick was initially troubled by software and communications problems causing delays and occasional shutdowns.

Some tools are available in different domains to help the controller further:

- Flight Data Processing Systems: this is the system (usually one per Center) that processes all the information related to the Flight (the Flight Plan), typically in the time horizon from Gate to gate (airport departure/arrival gates). It uses such processed information to invoke other Flight Plan related tools (such as e.g. MTCD), and distributes such processed information to all the stakeholders (Air Traffic Controllers, collateral Centers, Airports, etc.).
- Short Term Conflict Alert (STCA) that checks possible conflicting trajectories in a time horizon of about 2 or 3 minutes (or even less in approach context - 35 seconds in the French Roissy & Orly approach centres) and alerts the controller prior to the loss of separation. The algorithms used may also provide in some systems a possible vectoring solution, that is, the manner in which to turn, descend, or climb the aircraft in order to avoid infringing the minimum safety distance or altitude clearance.
- Minimum Safe Altitude Warning (MSAW): a tool that alerts the controller if an aircraft appears to be flying too low to the ground or will impact terrain based on its current altitude and heading.
- System Coordination (SYSCO) to enable controller to negotiate the release of flights from one sector to another.
- Area Penetration Warning (APW) to inform a controller that a flight will penetrate a restricted area.
- Arrival and Departure Manager to help sequence the takeoff and landing of aircraft.
    - The Departure Manager (DMAN): A system aid for the ATC at airports, that calculates a planned departure flow with the goal to maintain an optimal throughput at the runway, reduce queuing at holding point and distribute the information to various stakeholders at the airport (i.e. the airline, ground handling and Air Traffic Control (ATC)).
    - The Arrival Manager (AMAN): A system aid for the ATC at airports, that calculates a planned Arrival flow with the goal to maintain an optimal throughput at the runway, reduce arrival queuing and distribute the information to various stakeholders.
    - passive Final Approach Spacing Tool (pFAST), a CTAS tool, provides runway assignment and sequence number advisories to terminal controllers to improve the arrival rate at congested airports. pFAST was deployed and operational at five US TRACONs before being cancelled. NASA research included an Active FAST capability that also provided vector and speed advisories to implement the runway and sequence advisories.
- Converging Runway Display Aid (CRDA) enables Approach controllers to run two final approaches that intersect and make sure that go arounds are minimized
- Center TRACON Automation System (CTAS) is a suite of human centered decision support tools developed by NASA Ames Research Center. Several of the CTAS tools have been field tested and transitioned to the FAA for operational evaluation and use. Some of the CTAS tools are: Traffic Management Advisor

(TMA), passive Final Approach Spacing Tool (pFAST), Collaborative Arrival Planning (CAP), Direct-To (D2), En Route Descent Advisor (EDA) and Multi Center TMA. The software is running on linux.

- Traffic Management Advisor (TMA), a CTAS tool, is an en route decision support tool that automates time based metering solutions to provide an upper limit of aircraft to a TRACON from the Center over a set period of time. Schedules are determined that will not exceed the specified arrival rate and controllers use the scheduled times to provide the appropriate delay to arrivals while in the en route domain. This results in an overall reduction in en route delays and also moves the delays to more efficient airspace (higher altitudes) than occur if holding near the TRACON boundary is required to not overload the TRACON controllers. TMA is operational at most en route air route traffic control centers (ARTCCs) and continues to be enhanced to address more complex traffic situations (e.g. Adjacent Center Metering (ACM) and En Route Departure Capability (EDC))
- MTCD & URET
    - In the US, User Request Evaluation Tool (URET) takes paper strips out of the equation for En Route controllers at ARTCCs by providing a display that shows all aircraft that are either in or currently routed into the sector.
    - In Europe, several MTCD tools are available: iFACTS (NATS), ERATO (DSNA fr:DSNA), VAFORIT (DFS), New FDPS (MASUAC). The SESAR Programme should soon launch new MTCD concepts.

URET and MTCD provide conflict advisories up to 30 minutes in advance and have a suite of assistance tools that assist in evaluating resolution options and pilot requests.

- Mode S: provides a data downlink of flight parameters via Secondary Surveillance Radars allowing radar processing systems and therefore controllers to see various data on a flight, including airframe unique id (24-bits encoded), indicated airspeed and flight director selected level, amongst others.
- CPDLC: Controller Pilot Data Link Communications — allows digital messages to be sent between controllers and pilots, avoiding the need to use radiotelephony. It is especially useful in areas where difficult-to-use HF radiotelephony was previously used for communication with aircraft, e.g. oceans. This is currently in use in various parts of the world including the Atlantic and Pacific oceans.
- ADS-B: Automatic Dependent Surveillance Broadcast — provides a data downlink of various flight parameters to air traffic control systems via the Transponder (1090 MHz) and reception of those data by other aircraft in the vicinity. The most important is the aircraft's latitude, longitude and level: such data can be utilized to create a radar-like display of aircraft for controllers and thus allows a form of pseudo-radar control to be done in areas where the installation of radar is either prohibitive on the grounds of low traffic levels, or technically not feasible (e.g. oceans). This is currently in use in Australia, Canada and parts of the Pacific Ocean and Alaska.

- The Electronic Flight Strip system (e-strip): A system of electronic flight strips replacing the old paper strips is being used by several Service Providers, such as NAV CANADA, MASUAC, DFS, being produced by several industries, such as Indra Sistemas, Thales Group, Frequentis, Avibit, SAAB etc. E-strips allows controllers to manage electronic flight data online without Paper Strips, reducing the need for manual functions.
- Screen Content Recording: Hardware or software based recording function which is part of most modern Automation System and that captures the screen content shown to of the ATCO. Such recordings are used for a later replay together with audio recording for investigations and post event analysis.

Major accidents

A list of recent accidents can be found in this list.

On July 1, 2002 a Tupolev Tu-154 and Boeing 757 collided above Überlingen near the boundary between German and Swiss-controlled airspace when a Skyguide-employed controller (Peter Nielsen who was murdered by a relative of people who died in the crash), unaware that the flight was receiving instruction from the on-board automatic Traffic Collision Avoidance System software to climb, instructed the southbound Tupolev to descend.

The deadliest mid-air crash, the 1996 Charkhi Dadri mid-air collision over India, partly resulted from the fact that the New Delhi-area airspace was shared by departures and arrivals, when in most cases departures and arrivals would use separate airspaces. However investigations later found that the causative factor for this mid air accident was non adherence to air traffic control instructions by not maintaining **the assigned flight level** during descent phase by the pilot.

The deadliest collision between airliners took place on the ground, on March 27, 1977, in what is known as the Tenerife disaster, although ATC is only partly to blame for this incident.

Air navigation service providers (ANSPs) and traffic service providers (ATSPs)

The regulatory function remains the responsibility of the State and can be exercised by Government and/or independent Safety, Airspace and Economic Regulators depending on the national institutional arrangements. Often you will see a division between the Civil Aviation Authority (CAA) (the Regulator) and the ANSP (the Air Navigation Service Provider).

An Air Navigation Service Provider — The air navigation service provider is the authority directly responsible for providing both visual and non-visual aids to navigation within a specific airspace in compliance with, but not limited to, International Civil

Aviation Organization (ICAO) Annexes 2, 6, 10 and 11; ICAO Documents 4444 and 9426; and, other international, multi-national, and national policy, agreements or regulations.

An Air Traffic Service Provider is the relevant authority designated by the State responsible for providing air traffic services in the airspace concerned. *Air traffic services* is generic and can mean: flight information service, alerting service, air traffic advisory service, air traffic control service (area control service, approach control service or aerodrome control service), etc.

Both ANSPs and ATSPs can be public, private or corporatized organisations and examples of the different legal models exist throughout the world today. The world's ANSPs are united in and represented by the Civil Air Navigation Services Organisation (CANSO) based at Amsterdam Airport Schiphol in the Netherlands.

In the United States, the Federal Aviation Administration (FAA) provides this service to all aircraft in the National Airspace System (NAS). With the exception of facilities operated by the Department of Defense (DoD), the FAA is responsible for all aspects of U.S. Air Traffic Control including hiring and training controllers, although there are contract towers located in many parts of the country. A contract tower is an Airport Traffic Control Tower (ATCT) that performs the same function as an FAA-run ATCT but is staffed by employees of a private company (Martin State Airport in Maryland is an example). DoD facilities are generally staffed by military personnel and operate separately but concurrently with FAA facilities, under similar rules and procedures. In Canada, Air Traffic Control is provided by NAV CANADA, a private, non-share capital corporation that operates Canada's civil air navigation service.

- Albania - Agjencia Nacionale e Trafikut Ajror
- Armenia - Armenian Air Traffic Services (ARMATS)
- Austria - Austro Control
- Australia - Airservices Australia (State Owned Corporation) and Royal Australian Air Force.
- Belarus - Republican Unitary Enterprise "Белаэронавигация (Belarusian Air Navigation)"
- Belgium - Belgocontrol
- Brazil - Departmento de Controle de Tráfego Aéreo (Military Authority) and ANAC - Agência Nacional de Aviação Civil
- Bulgaria - Air Traffic Services Authority
- Canada - NAV CANADA - formerly provided by Transport Canada and Canadian Forces
- Central America - Corporación Centroamericana de Servicios de Navegación Aérea
    - Guatemala - DGAC (Dirección General de Aeronáutica Civil)
    - El Salvador
    - Honduras
    - Nicaragua

    - Costa Rica - Dirección General de Aviación Civil
    - Belize
- Colombia - (UAEAC) Aeronáutica Civil Colombiana
- Croatia - Hrvatska kontrola zračne plovidbe (Croatia Control Ltd.)
- Cuba - IACC (Instituto de Aeronáutica Civil de Cuba)
- Czech Republic - Řízení letového provozu ČR
- Denmark - Naviair (Danish ATC)
- Dominican Republic - IDAC (Instituto Dominicano de Aviación Civil) "Dominican Institute of Civil Aviation"
- Estonia - Estonian Air Navigation Services
- Europe - Eurocontrol - (European Organisation for the Safety of Air Navigation)
- Finland - Finavia
- France - Direction Générale de l'Aviation Civile (DGAC): Direction des Services de la Navigation Aérienne (DSNA) (Government body)
- Georgia - SAKAERONAVIGATSIA, Ltd. (Georgian Air Navigation)
- Germany - Deutsche Flugsicherung (German ATC - State-owned company)
- Greece - Hellenic Civil Aviation Authority (HCAA)
- Hong Kong - CAD (Civil Aviation Department)
- Hungary - HungaroControl Magyar Légiforgalmi Szolgálat Zrt. (HungaroControl Hungarian Air Navigation Services Pte. Ltd. Co.)
- Iceland - ISAVIA
- Indonesia - Angkasa Pura II
- Ireland - IAA (Irish Aviation Authority)
- India - Airports Authority of India (AAI) (under Ministry of Civil Aviation, Government Of India)
- Italy - ENAV (Italian ATC)(Ente Nazionale Assistenza al Volo - Italian ATC)
- Jamaica - JCAA (Jamaica Civil Aviation Authority)
- Latvia - LGS (Latvian ATC)
- Lithuania - ANS (Lithuanian ATC)
- Macedonia - DGCA (Macedonian ATC)
- Malaysia - DCA-Department of Civil Aviation
- Malta - Malta Air Traffic Services Ltd
- Mexico - Servicios a la Navegación en el Espacio Aéreo Mexicano
- Nepal - Civil Aviation Authority of Nepal
- Netherlands - Luchtverkeersleiding Nederland (LVNL) (Dutch ATC) Eurocontrol (European area control ATC)
- New Zealand - Airways New Zealand (State Owned Enterprise)
- Norway - Avinor (State-owned private company)
- Pakistan - Civil Aviation Authority (under Government of Pakistan)
- Peru - Centro de Instrucción de Aviación Civil CIAC Civil Aviation Training Center
- Philippines - Civil Aviation Authority of the Philippines (CAAP) (under the Philippine Government)
- Poland - PANSA - Polish Air Navigation Services Agency
- Portugal - NAV - NAV (Portuguese ATC)

- Romania - Romanian Air Traffic Services Administration - (ROMATSA)
- Russia - Federal State Unitary Enterprise "State ATM Corporation" - (State ATM Corporation)
- Saudi Arabia - General Authority of Civil Aviation (GACA)
- Singapore - CAAS (Civil Aviation Authority of Singapore)
- Serbia - Serbia and Montenegro Air Traffic Services Agency Ltd. (SMATSA)
- Slovakia - Letové prevádzkové služby Slovenskej republiky
- Slovenia - Slovenia Control
- South Africa - Air Traffic and Navigation Services,
- Spain - AENA (Spanish ATC and Airports)
- Sweden - The LFV Group (Swedish ATC)
- Switzerland - Skyguide
- Taiwan - ANWS Civil Aeronautical Administration
- Thailand - AEROTHAI (Aeronautical Radio of Thailand)
- Trinidad and Tobago - TTCAA (Trinidad and Tobago Civil Aviation Authority)
- Turkey - DGCA (Turkish Directorate General of Civil Aviation)
- United Arab Emirates - General Civil Aviation Authority (GCAA)
- United Kingdom - National Air Traffic Services (49% State Owned Public-Private Partnership)
- United States - Federal Aviation Administration (Government Body)
- Ukraine - Ukrainian State Air Traffic Service Enterprise (UkSATSE)
- Venezuela - INAC (Instituto Nacional de Aviación Civil)

Proposed changes

In the United States, some alterations to traffic control procedures are being examined.

- The Next Generation Air Transportation System examines how to overhaul the United States national airspace system.
- Free flight is a developing air traffic control method that uses no centralized control (e.g. air traffic controllers). Instead, parts of airspace are reserved dynamically and automatically in a distributed way using computer communication to ensure the required separation between aircraft.

In Europe, the SESAR (Single European Sky ATM Research) Programme plans to develop new methods, new technologies, new procedures, new systems to accommodate future (2020 and beyond) Air Traffic Needs.

Many countries have also privatized or corporatized their air navigation service providers.

Chapter 5

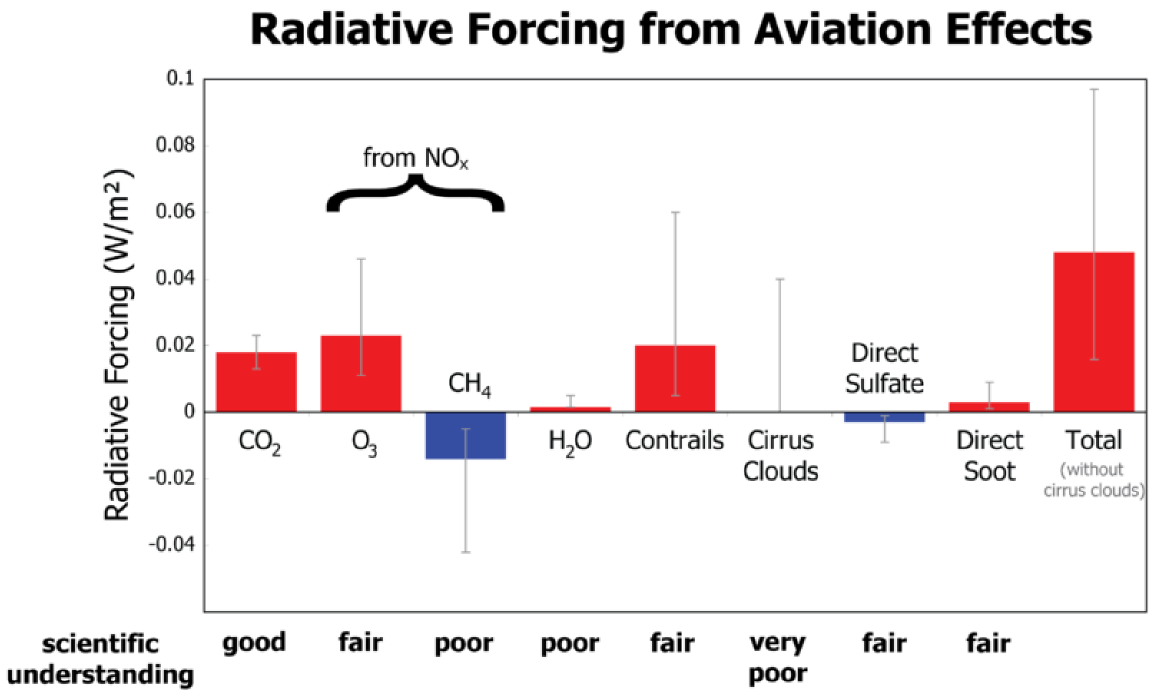
Aviation and the Environment

A C-141 Starlifter leaves exhaust contrails over Antarctica

Aviation impacts the environment because aircraft engines emit noise, particulates, and gases which contribute to climate change and global dimming. Despite emission reductions from automobiles and more fuel-efficient and less polluting turbofan and turboprop engines, the rapid growth of air travel in recent years contributes to an increase in total pollution attributable to aviation. In the EU, greenhouse gas emissions from aviation increased by 87% between 1990 and 2006.

There is an ongoing debate about possible taxation of air travel and the inclusion of aviation in an emissions trading scheme, with a view to ensuring that the total external costs of aviation are taken into account.

Climate change



Radiative forcings from aviation emissions (gases and aerosols) in 1992 as estimated by the IPCC

Like all human activities involving combustion, most forms of aviation release carbon dioxide (CO_2) into the Earth's atmosphere, contributing to the acceleration of global warming.

In addition to the CO_2 released by most aircraft in flight through the burning of fuels such as Jet-A (turbine aircraft) or Avgas (piston aircraft), the aviation industry also contributes greenhouse gas emissions from ground airport vehicles and those used by passengers and staff to access airports, as well as through emissions generated by the production of energy used in airport buildings, the manufacture of aircraft and the construction of airport infrastructure.

While the principal greenhouse gas emission from powered aircraft in flight is CO_2, other emissions may include nitric oxide and nitrogen dioxide, (together termed oxides of nitrogen or NO_x), water vapour and particulates (soot and sulfate particles), sulfur oxides, carbon monoxide (which bonds with oxygen to become CO_2 immediately upon release), incompletely burned hydrocarbons, tetra-ethyl lead (piston aircraft only), and radicals such as hydroxyl, depending on the type of aircraft in use.

The contribution of civil aircraft-in-flight to global CO_2 emissions has been estimated at around 2%. However, in the case of high-altitude airliners which frequently fly near or in the stratosphere, non-CO_2 altitude-sensitive effects may increase the total impact on anthropogenic (man-made) climate change significantly.

Mechanisms

Subsonic aircraft-in-flight contribute to climate change in four ways:

Carbon dioxide (CO_2)

CO_2 emissions from aircraft-in-flight are the most significant and best understood element of aviation's total contribution to climate change. The level and effects of CO_2 emissions are currently believed to be broadly the same regardless of altitude (i.e. they have the same atmospheric effects as ground based emissions). In 1992, emissions of CO_2 from aircraft were estimated at around 2% of all such anthropogenic emissions, though CO_2 concentration attributable to aviation in 1992 was around 1% of the total anthropogenic increase, because emissions occurred only in the last 50 years.

Oxides of nitrogen (NO_x)

At the high altitudes flown by large jet airliners around the tropopause, emissions of NO_x are particularly effective in forming ozone (O_3) in the upper troposphere. High altitude (8-13km) NO_x emissions result in greater concentrations of O_3 than surface NO_x emissions, and these in turn have a greater global warming effect. The effect of O_3 concentrations are regional and local (as opposed to CO_2 emissions, which are global).

NO_x emissions also reduce ambient levels of methane, another greenhouse gas, resulting in a climate cooling effect. But this effect does not offset the O_3 forming effect of NO_x emissions. It is now believed that aircraft sulfur and water emissions in the stratosphere tend to deplete O_3, partially offsetting the NO_x-induced O_3 increases. These effects have not been quantified. This problem does not apply to aircraft that fly lower in the troposphere, such as light aircraft or many commuter aircraft.

Water vapor (H_2O)

Contrails

Cirrus cloud formation

One of the products of burning hydrocarbons in oxygen is water vapour, a greenhouse gas. Water vapour produced by aircraft engines at high altitude, under certain atmospheric conditions, condenses into droplets to form Condensation trails, or contrails. Contrails are visible line clouds that form in cold, humid atmospheres and are thought to have a global warming effect (though one less significant than either CO_2 emissions or NO_x induced effects) SPM-2. Contrails are extremely rare from lower-altitude aircraft, or from propeller aircraft or rotorcraft.

Cirrus clouds have been observed to develop after the persistent formation of contrails and have been found to have a global warming effect over-and-above that of contrail formation alone. There is a degree of scientific uncertainty about the contribution of contrail and cirrus cloud formation to global warming and attempts to estimate aviation's overall climate change contribution do not tend to include its effects on cirrus cloud enhancement.

Particulates

Least significant is the release of soot and sulfate particles. Soot absorbs heat and has a warming effect; sulfate particles reflect radiation and have a small cooling effect. In addition, they can influence the formation and properties of clouds. All aircraft powered by combustion will release some amount of soot.

Emissions per passenger kilometre

Emissions of passenger aircraft per passenger kilometre vary extensively, according to variables such as the size of the aircraft, the number of passengers on board, and the altitude and distance of the journey (the practical effect of emissions at high altitides may be greater than those of emissions at low altitudes). However, some representative figures for emissions are provided by LIPASTO's survey of average passenger aircraft emissions per passenger kilometre in Finland 2008: expressed as CO_2 equivalent,

- Domestic, short distance, less than 463 km (288 mi): 259 g (9 oz)
- Domestic, long distance, greater than 463 km (288 mi): 178 g (6 oz)
- Long distance flights: 114 g (4 oz)

This is similar to the emissions from a four-seat car with one person on board.

Per passenger kilometre, figures from British Airways suggest carbon dioxide emissions of 0.1 kg for large jet airliners (a figure which does not account for the production of other pollutants or condensation trails).

Total effect

In attempting to aggregate and quantify the climate impact of aircraft emissions the Intergovernmental Panel on Climate Change (IPCC) has estimated that aviation's total climate impact is some 2-4 times that of its CO_2 emissions alone (excluding the potential impact of cirrus cloud enhancement). This is measured as radiative forcing. While there is uncertainty about the exact level of impact of NO_x and water vapour, governments have accepted the broad scientific view that they do have an effect. Accordingly, more recent UK government policy statements have stressed the need for aviation to address its total climate change impacts and not simply the impact of CO_2.

The IPCC has estimated that aviation is responsible for around 3.5% of anthropogenic climate change, a figure which includes both CO_2 and non-CO_2 induced effects. The IPCC has produced scenarios estimating what this figure could be in 2050. The central case estimate is that aviation's contribution could grow to 5% of the total contribution by 2050 if action is not taken to tackle these emissions, though the highest scenario is 15%. Moreover, if other industries achieve significant cuts in their own greenhouse gas emissions, aviation's share as a proportion of the remaining emissions could also rise.

Potential reductions

Modern jet aircraft are significantly more fuel efficient (and thus emit less CO_2 in particular) than 30 years ago.. Moreover, manufacturers have forecast and are committed to achieving reductions in both CO_2 and NO_x emissions with each new generation of design of aircraft and engine. Thus, the accelerated introduction of more modern aircraft represents a major opportunity to reduce emissions per passenger kilometre flown.

Other opportunities arise from the optimisation of airline timetables, route networks and flight frequencies to increase load factors (minimise the number of empty seats flown), together with the optimisation of airspace.

Another possible reduction of the climate-change impact is the limitation of cruise altitude of aircraft. This would lead to a significant reduction in high-altitude contrails for a marginal trade-off of increased flight time and an estimated 4% increase in CO_2 emissions. Drawbacks of this solution include very limited airspace capacity to do this, especially in Europe and North America and increased fuel burn because jet aircraft are less efficient at lower cruise altitudes.

However, the total number of passenger kilometres is growing at a faster rate than manufacturers can reduce emissions, and at present there is no readily available alternative to burning kerosene. Thus, the growth in the aviation sector is likely to continue to generate an increasing volume of greenhouse gas emissions. However some scientists and companies such as GE Aviation and Virgin Fuels are researching biofuel technology for use in jet aircraft. As part of this test Virgin Atlantic Airways flew a Boeing 747 from London Heathrow Airport to Amsterdam Schiphol Airport on 24 February 2008, with one engine burning a combination of coconut oil and babassu oil. Greenpeace's chief scientist Doug Parr said that the flight was "high-altitude greenwash" and that producing organic oils to make biofuel could lead to deforestation and a large increase in greenhouse gas emissions.

The majority of the world's aircraft are not large jetliners but smaller piston aircraft, and many are capable of using ethanol as a fuel, with major modifications. While ethanol also releases CO_2 during combustion, the plants cultivated to make it draw that same CO_2 out of the atmosphere while they are growing, making the fuel closer to climate-change-neutral. The only problem is the US government's choice of using ethanol from corn, since it takes more energy to produce than is returned, it displaces food crops and thus raises the price of food, and causes soil degradation.

While they are not suitable for long-haul or transoceanic flights, turboprop aircraft used for commuter flights bring two significant benefits: they often burn considerably less fuel per passenger mile, and they typically fly at lower altitudes, well inside the tropopause, where there are no concerns about ozone or contrail production.

Reducing travel

An alternative method for reducing the environmental impact of aviation is to constrain demand for air travel. The UK study *Predict and Decide - Aviation, climate change and UK policy*, notes that a 10% increase in fares generates a 5% to 15% reduction in demand, and recommends that the British government should manage demand rather than provide for it. This would be accomplished via a strategy that presumes "… against the expansion of UK airport capacity" and constrains demand by the use of economic instruments to price air travel less attractively. A study published by the campaign group Aviation Environment Federation (AEF) concludes that by levying £9 billion of additional taxes, the annual rate of growth in demand in the UK for air travel would be reduced to 2%. The ninth report of the House of Commons Environmental Audit Select Committee, published in July 2006, recommends that the British government rethinks its airport expansion policy and considers ways, particularly via increased taxation, in which future demand can be managed in line with industry performance in achieving fuel efficiencies, so that emissions are not allowed to increase in absolute terms.

Kyoto Protocol

Greenhouse gas emissions from fuel consumption in international aviation, in contrast to those from domestic aviation and from energy use by airports, are not assigned under the first round of the Kyoto Protocol, neither are the non-CO_2 climate effects. In place of agreement, Governments agreed to work through the International Civil Aviation Organization (ICAO) to limit or reduce emissions and to find a solution to the allocation of emissions from international aviation in time for the second round of Kyoto in 2009 in Copenhagen.

Emissions trading

As part of that process the ICAO has endorsed the adoption of an open emissions trading system to meet CO_2 emissions reduction objectives. Guidelines for the adoption and implementation of a global scheme are currently being developed, and will be presented to the ICAO Assembly in 2007, although the prospects of a comprehensive inter-governmental agreement on the adoption of such a scheme are uncertain.

Within the European Union, however, the European Commission has resolved to incorporate aviation in the European Union Emissions Trading Scheme (ETS). A new directive has been adopted by the European Parliament in July 2008 and approved by the Council in October 2008. It will enter into force on 1 January 2012.

Mitigation

Emissions from aviation are continuing to grow despite advances in aircraft efficiency. Currently 2% of global emissions are created by the aviation industry.

Aviation has an impact on the environment due to aircraft engines emitting noise, particulates, and gases which contribute to climate change and global dimming. Despite emission reductions from automobiles and more fuel-efficient (and therefore less polluting) turbofan and turboprop engines, the rapid growth of air travel in recent years contributes to an increase in total pollution attributable to aviation. In the EU, greenhouse gas emissions from aviation increased by 87% between 1990 and 2006.

At present aviation accounts for 2% of global CO_2 emissions and this is projected by the IPCC to rise to 3% by 2050. This presents the operators of aircraft with a responsibility to reduce emissions.

Methods of mitigating aviation's CO_2 emissions

Mitigation of aviation's environmental impact can be achieved through a variety of measures, the most obvious and arguably the most economical of which is to reduce the fuel burn of the aircraft as this accounts for 28% of an airlines costs. However there is a wide variety of other options available to minimise aviation's growing impact upon the environment as are listed below:

Aircraft efficiency

The Boeing 787 "Dreamliner" promises to provide 20% lower fuel burn than current-generation aircraft.

As stated previously, reducing the direct fuel burn of an aircraft is the most obvious and arguably the most economical way of reducing emissions attributable to aviation. Over the last 40 years, commercial jet airliners have become 70% more fuel efficient and are predicted to be another 25% more fuel efficient by 2025.

The next-generation of aircraft, including the Boeing 787, Airbus A350 and Bombardier CSeries, are 20% more fuel efficient per passenger kilometre than current generation aircraft. This is primarily achieved through more fuel-efficient engines and lighter airframes & supporting structures made of composite materials but is also achieved through more aerodynamic shapes, winglets, a "one-piece" fuselage and more advanced computer systems for optimising routes and loading of the aircraft.

Route optimization

Currently, air traffic corridors that aircraft are forced to follow place unnecessary detours on an aircraft's route forcing higher fuel burn and an increase in emissions. An improved Air Traffic Management System with more direct routes and optimized cruising altitudes would allow airlines to reduce their emissions by up to 18%.

In the European Union, a Single European Sky has been proposed for the last 15 years so that there are no overlapping airspace restrictions between countries in the EU and so reduce emissions. As of yet, the Single European Sky is still only a plan but progress has been made. If the Single European Sky had been created 15 years ago, 12 million tons of CO_2 could have been saved.

Biofuels

British Airways will be using half a million tonnes of waste annually to create biofuels for commercial use from 2014 onwards.

Biofuels are fuels derived from biomass material such as plants and waste. Plant derived biofuels offer large savings in CO_2 emissions as they absorb Carbon Dioxide and release it as Oxygen when they grow and so in a life-cycle, emissions can be drastically reduced. A number of airlines have operated biofuel test flights including Virgin Atlantic Airways, which flew with one engine operating on a blend of 20% coconut oil and 80% traditional jet fuel, and Continental Airlines which flew with one engine operating on a blend of 44% Jatropha oil, 6% Algae oil and 50% traditional jet fuel. Other airlines to demonstrate biofuels include Air New Zealand and Japan Airlines.

In the Continental Airlines test, the engine running partly on biofuel burned 46 kg less fuel than the conventionally fuelled engine in 1 and a half hours while producing more thrust from the same volume of fuel. Continental Airlines' CEO, Larry Kellner, commented "This is a good step forward, an opportunity to really make a difference to the environment" citing jatropha's 50-80% lower CO_2 emissions as opposed to Jet-A1 in its lifecycle.

From 2014 onwards, British Airways, in co-operation with Solena, is going to turn half a million tonnes of waste annually that would normally go to landfill from the City of London into biofuel to be used in the British Airways fleet. Waste derived biofuel produces up to 95% less pollution in its life-cycle and so therefore this measure will reduce emissions by the equivalent of taking 42,000 cars off the road every year.

Improved operating procedures

Scandinavian Airlines is operating their 737 aircraft at slower cruising speeds to reduce emissions by 7-8%.

Airlines and airports are looking at ways of reducing emissions and fuel burn through the use of improved operating procedures. Two of the more common ones in operation are a single-engine taxi to and from the runway and the use of a Continuous Descent Approach, or CDA, which can reduce emissions significantly during the operations in and around an airport. Scandinavian Airlines (SAS) is now operating its Boeing 737 fleet at a slower cruising speed to help reduce emissions by 7-8%.

Emission Trading Scheme

In the EU, aviation will be including the European Emission Trading Scheme from 2012 onwards. The scheme places a cap on the emissions an aircraft operator can emit and forces the operator to either lower emissions through more efficient technology or to buy "Carbon Credits" from other companies who have produced fewer emissions than their cap. It is thought that this will reduce aviation's net environmental impact.

Methods of mitigating aviation's non-CO_2 emissions

Aviation produces a number of other pollutants besides carbon dioxide including nitrogen oxides (NO_X), particulates, unburned hydrocarbons (UHC) and contrails. A number of methods to reduce the level of these pollutants follows:

Nitrogen oxides (NO_X)

Nitrogen Oxides have a far stronger impact upon climate change than Carbon Oxides and are produced in small quantities from aircraft engines. Engine designers have worked since the start of the jet age to reduce NO_X emissions and the result is ever reducing levels of Nitrogen Oxide emissions. For example, between 1997 and 2003, NO_X emissions from jet engines fell by over 40%.

Particulates

Particulates and smoke were a problem with early jet engines at high power settings but modern engines are disigned so that no smoke is produced at any point in the flight.

Unburned hydrocarbons (UHC)

Contrails formed by high altitude aircraft

Unburned hydrocarbons (UHC) are products of incomplete combustion of fuel and are produced in greater quantities in engines with low pressure gains in the compressors and/or relatively low temperatures in the combustor. As with particulates, UHC has all but been eliminated in modern jet engines through improved design and technology.

Contrails

Aircraft flying at high altitude form condensation trails or contrails in the exhaust plume of their engines. While in the Troposphere these have very little climatic impact. However, jet aircraft cruising in the Stratosphere do create an impact from their contrails, although the extent of the damage to the environment is as yet unknown. Contrails can also trigger the formation of high-altitude Cirrus cloud thus creating a greater climatic effect.

In the three days following the September 11 Atacks on the World Trade Centre in New York City, when no commercial aircraft flew in the USA, climate scientists measured the daily temperature range over 5000 weather stations across the USA. The results showed a 1^{o} Celsius change in the average daily temperature range for those days of the year, thus showing contrails do have a significant impact on climate. Potential ways of reducing the impact of contrails on our climate include reducing the maximum cruising altitude of aircraft so high-altitude contrails can not form. Cruising at lower altitudes would marginally increase flight time and increase fuel consumption by 4%.

Methods of mitigating aviation's noise emissions

Serrated edges of the nacelle on the Rolls-Royce Trent 1000 fitted to the new Boeing 787 "Dreamliner".

One of the by-products of an aircraft's engine is noise and this has become an increasingly important issue which is being dealt with through many different methods:

Engines

Next-Generation engines are not only more fuel-efficient but also tend to be quieter with Pratt & Whitney's PurePower PW1000G fitted to the Bombardier CSeries aircraft being 4 times quieter than aircraft currently in service. Engines can also incorporate serrated edges on the back of the nacelle to reduce noise impact as shown in this picture.

Improved operating procedures

A Continuous Descent Approach, or CDA, not only reduces fuel burn but also allows airlines to provide quieter approaches for part of the descent to a runway. As the engines are at close to idle power, less noise emissions are produced and combined with new engine technology, the reductions in noise emissions can be large.

Carbon offset

Money generated by carbon offsets from airlines often go to fund green-energy projects such as wind farms.

A carbon offset is a means of reducing emissions to zero by saving enough carbon to balance the carbon emitted by a particular action. Several airlines have begun offering carbon offsets to passengers to offset the emissions created by their proportion of the flight. Money generated is put to projects around the world to invest in green technology such as renewable energy and research into future technology. Airlines offering carbon offsets include British Airways, easyJet, Continental Airlines, Delta Airlines, Lufthansa and Qantas although there are many more carriers participating in such schemes.

British Airways' scheme

British Airways' carbon offsetting scheme involves paying a fee dependant on aircraft type, class of travel and distance flown and therefore prices vary. Funds generated are currently awarded to three renewable energy projects around the world: Bayin'aobao wind farm in Inner Mongolia, Faxinal dos Guedes hydroelectric power plant in Brazil and Xiaohe hydroelctric power plant in Gansu Province, China.

Continental Airlines' scheme

Continental Airlines' carbon offsetting scheme involves paying a fixed fee of $2 to cancel out emissions through reforestation. Passengers can also choose to pay $50 for offsetting emissions through renewable energy projects.

Noise

A Qantas Boeing 747-400 passes close to houses on the boundary of London Heathrow Airport, England.

Aircraft noise is noise pollution produced by any aircraft or its components, during various phases of a flight: on the ground while parked such as auxiliary power units, while taxiing, on run-up from propeller and jet exhaust, during take off, underneath and lateral to departure and arrival paths, over-flying while en route, or during landing.

Mechanisms of sound production

Small general aviation aircraft produce localized aircraft noise

Helicopter main and tail rotors produce aerodynamic noise

A moving aircraft including the jet engine or propeller causes compression and rarefaction of the air, producing motion of air molecules. This movement propagates through the air as pressure waves. If these pressure waves are strong enough and within the audible frequency spectrum, a sensation of hearing is produced. Different aircraft types have different noise levels and frequencies. The noise originates from three main sources:

- Aerodynamic noise
- Engine and other mechanical noise
- Noise from aircraft systems

Aerodynamic noise

Aerodynamic noise arises from the airflow around the aircraft fuselage and control surfaces. This type of noise increases with aircraft speed and also at low altitudes due to the density of the air. Jet-powered aircraft create intense noise from aerodynamics. Low-flying, high-speed military aircraft produce especially loud aerodynamic noise.

The shape of the nose, windshield or canopy of an aircraft affects the sound produced. Much of the noise of a propeller aircraft is of aerodynamic origin due to the flow of air around the blades. The helicopter main and tail rotors also give rise to aerodynamic noise. This type of aerodynamic noise is mostly low frequency determined by the rotor speed.

Typically noise is generated when flow passes an object on the aircraft, for example the wings or landing gear. There are broadly two main types of airframe noise:

- Bluff Body Noise - the alternating vortex shedding from either side of a bluff body, creates low pressure regions (at the core of the shed vortices) which manifest themselves as pressure waves (or sound). The separated flow around the bluff body is quite unstable, and the flow "rolls up" into ring vortices - which later break down into turbulence.

- Edge Noise - when turbulent flow passes the end of an object, or gaps in a structure (high lift device clearance gaps) the associated fluctuations in pressure are heard as the sound propagates from the edge of the object (radially downwards).

Engine and other mechanical noise

Much of the noise in propeller aircraft comes equally from the propellers and aerodynamics. Helicopter noise is aerodynamically induced noise from the main and tail rotors and mechanically induced noise from the main gearbox and various transmission chains. The mechanical sources produce narrow band high intensity peaks relating to the rotational speed and movement of the moving parts. In computer modelling terms noise from a moving aircraft can be treated as a line source.

Aircraft Gas Turbine engines (Jet Engines) are responsible for much of the aircraft noise during takeoff and climb. However, with advances in noise reduction technologies - the airframe is typically more noisy during landing.

The majority of engine noise is due to Jet Noise - although high bypass-ratio turbofans do have considerable Fan Noise. The high velocity jet leaving the back of the engine has an inherent shear layer instability (if not thick enough) and rolls up into ring vortices. This of course later breaks down into turbulence. The SPL associated with engine noise is proportional to the jet speed (to a high power) therefore, even modest reductions in exhaust velocity will see a large reduction in Jet Noise.

Noise from aircraft systems

Cockpit and cabin pressurisation and conditioning systems are often a major contributor within cabins of both civilian and military aircraft. However, one of the most significant sources of cabin noise from commercial jet aircraft other than the engines is the Auxiliary Power Unit (or APU). An Auxiliary Power Unit is an on-board generator used in aircraft to start the main engines, usually with compressed air, and to provide electrical power while the aircraft is on the ground. Other internal aircraft systems can also contribute, such as specialised electronic equipment in some military aircraft.

Health effects

There are health consequences of elevated sound levels. Elevated workplace or other noise can cause hearing impairment, hypertension, ischemic heart disease, annoyance, sleep disturbance, and decreased school performance. Although some hearing loss occurs naturally with age, in many developed nations the impact of noise is sufficient to impair hearing over the course of a lifetime. Elevated noise levels can create stress, increase workplace accident rates, and stimulate aggression and other anti-social behaviors.

A large-scale statistical analysis of the health effects of aircraft noise was undertaken in the late 2000s by Bernhard Greiser for the Umweltbundesamt, Germany's central environmental office. The health data of over one million residents around the Cologne airport were analysed for health effects correlating with aircraft noise. The results where then corrected for other noise influences in the residential areas, and for socioeconomic factors, to reduce possible skewing of the data. The study concluded that aircraft noise clearly and significantly impairs health, with, for example, a day-time average sound pressure level of 60 decibel increasing coronary heart disease by 61% in men and 80% in women. As another indicator, a night-time average sound pressure level of 55 decibel increased the risk of heart attacks by 66% in men and 139% in women. Statistically significant health effects did however start as early as from an average sound pressure level of 40 decibel.

Noise mitigation programs

In the United States, since aviation noise became a public issue in the late 1960s, governments have enacted legislative controls. Aircraft designers, manufacturers, and operators have developed quieter aircraft and better operating procedures. Modern high-bypass turbofan engines, for example, are quieter than the turbojets and low-bypass turbofans of the 1960s. First, FAA Aircraft Certification achieved noise reductions classified as 'Stage 3' aircraft; which has been upgraded to 'Stage 4' noise certification resulting in quieter aircraft. This has resulted in lower noise exposures in spite of increased traffic growth and popularity.

In the 1980s the U.S. Congress authorized the FAA to devise programs to insulate homes near airports. While this does not address the external noise, the program has been effective for residential interiors. Some of the first airports at which the technology was applied were San Francisco International Airport and San Jose International Airport in California. A computer model is used which simulates the effects of aircraft noise upon building structures. Variations of aircraft type, flight patterns and local meteorology can be studied. Then the benefits of building retrofit strategies such as roof upgrading, window glazing improvement, fireplace baffling, caulking construction seams can be evaluated.

Night flying restrictions

At Heathrow, Gatwick and Stansted airports in the UK, and Frankfurt Airport in Germany, night flying restrictions apply to reduce noise exposure at night.

Chapter 6

Aircraft Dynamic Modes and Aeronautical Chart

Aircraft dynamic modes

The dynamic stability of an aircraft is how the motion of an aircraft behaves after it has been disturbed from steady non-oscillating flight.

Longitudinal modes

Oscillating motions can be described by two parameters, the period of time required for one complete oscillation, and the time required to damp to half-amplitude, or the time to double the amplitude for a dynamically unstable motion. The longitudinal motion consists of two distinct oscillations, a long-period oscillation called a phugoid mode and a short-period oscillation referred to as the short-period mode.

Phugoid (longer period) oscillations

The longer period mode, called the "phugoid mode" is the one in which there is a large-amplitude variation of air-speed, pitch angle, and altitude, but almost no angle-of-attack variation. The phugoid oscillation is really a slow interchange of kinetic energy (velocity) and potential energy (height) about some equilibrium energy level as the aircraft attempts to re-establish the equilibrium level-flight condition from which it had been disturbed. The motion is so slow that the effects of inertia forces and damping forces are very low. Although the damping is very weak, the period is so long that the pilot usually corrects for this motion without being aware that the oscillation even exists. Typically the period is 20–60 seconds.

Short period oscillations

With no special name, the shorter period mode is called simply the "short-period mode". The short-period mode is a usually heavily damped oscillation with a period of only a few seconds. The motion is a rapid pitching of the aircraft about the center of gravity. The period is so short that the speed does not have time to change, so the oscillation is essentially an angle-of-attack variation. The time to damp the amplitude to one-half of its value is usually on the order of 1 second. Ability to quickly self damp when the stick is briefly displaced is one of the many criteria for general aircraft certification.

Lateral-directional modes

"Lateral-directional" modes involve rolling motions and yawing motions. Motions in one of these axes almost always couples into the other so the modes are generally discussed as the "Lateral-Directional modes".

There are three types of possible lateral-directional dynamic motion: roll subsidence mode, Dutch roll mode, and spiral mode.

Roll subsidence mode

Roll subsidence mode is simply the damping of rolling motion. There is no direct aerodynamic moment created tending to directly restore wings-level, i.e. there is no returning "spring force/moment" proportional to roll angle. However, there is a damping moment (proportional to roll *rate*) created by the slewing-about of long wings. This prevents large roll rates from building up when roll-control inputs are made or it damps the roll *rate* (not the angle) to zero when there are no roll-control inputs.

Roll mode can be improved by adding dihedral effects to the aircraft design, such as high wings, dihedral angles or sweep angles.

Spiral mode

If a spirally unstable aircraft, through the action of a gust or other disturbance, gets a small initial roll angle to the right, for example, a gentle sideslip to the right is produced. The sideslip causes a yawing moment to the right. If the dihedral stability is low, and yaw damping is small, the directional stability keeps turning the aircraft while the continuing bank angle maintains the sideslip and the yaw angle. This spiral gets continuously steeper and tighter until finally, if the motion is not checked, a steep, high-speed spiral dive results. The motion develops so gradually, however that it is usually corrected unconsciously by the pilot, who may not be aware that spiral instability exists. If the pilot cannot see the horizon, for instance because of clouds, he might not notice that he is slowly going into the spiral dive, which can lead into the graveyard spiral.

To be spirally stable, an aircraft must have some combination of a sufficiently large dihedral, which increases roll stability, and a sufficiently long vertical tail arm, which increases yaw damping. Increasing the vertical tail area then magnifies the degree of stability or instability.

The spiral dive should not be confused with a spin.

Detection

While descending turns are commonly performed by pilots as a standard flight manoeuvre, the spiral dive is differentiated from a descending turn owing to its feature of accelerating speed. It is therefore an unstable flight condition, and pilots are trained to recognise its onset and to implement recovery procedures safely and immediately. Without intervention by the pilot, acceleration of the aircraft will lead to structural failure of the airframe, either as a result of excess aerodynamic loading or flight into terrain. Spiral dive training therefore revolves around pilot recognition and recovery.

Recovery

Spiral dive accidents are typically associated with visual flight (non-instrument flight) in conditions of poor visibility, where the pilot's reference to the visual natural horizon is effectively reduced, or prevented entirely, by such factors as cloud or darkness. The inherent danger of the spiral dive is that the condition, especially at onset, cannot be easily detected by the sensory mechanisms of the human body. The physical forces exerted on an aeroplane during a spiral dive are effectively balanced and the pilot cannot detect the banked attitude of the spiral descent. If the pilot detects acceleration, but fails to detect the banked attitude associated with the spiral descent, a mistaken attempt may be to recovery with mere backpressure (pitch-up inputs) on the control wheel. However, with the lift vector of the aircraft now directed to the centre of the spiral turn, this erred nose-up input simply tightens the spiral condition and increases the rate of acceleration and increases dangerous airframe loading. To successfully recover from a spiral dive, the lift vector must first be redirected upward (relative to the natural horizon) before backpressure is applied to the control column. Since the acceleration can be very rapid, recovery is dependent on the pilot's ability to quickly close the throttle (which is contributing to the acceleration), position the lift vector upward, relative to the Earth's surface before the dive recovery is implemented; any factor that would impede the pilot's external reference to the Earth's surface could delay or prevent recovery. The quick and efficient completion of these tasks is crucial as the aircraft can accelerate through maximum speed limits within only a few seconds, where the structural integrity of the airframe will be compromised.

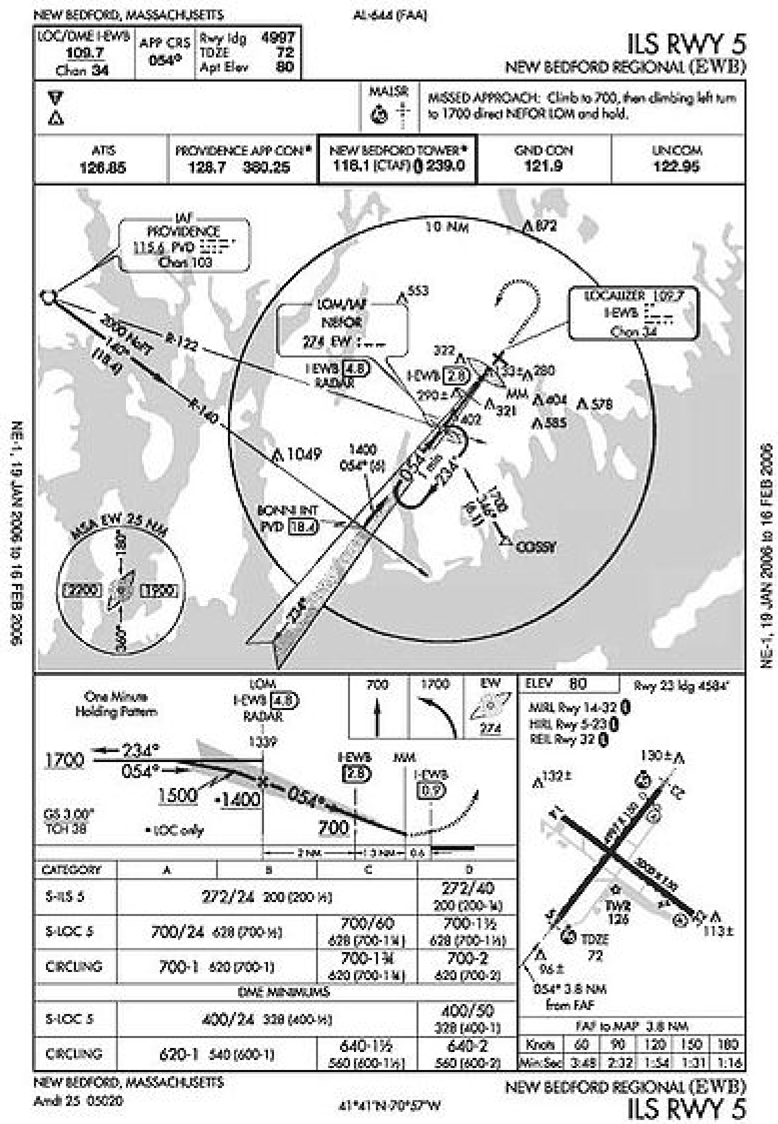
For the purpose of flight training, instructors typically establish the aircraft in a descending turn with initially slow but steadily accelerating airspeed – the initial slow speed facilitates the potentially slow and sometimes erred response of student pilots. The cockpit controls are released by the instructor and the student is instructed to recover. It is not uncommon for a spiral dive to result from an unsuccessful attempt to enter a spin, but the extreme nose-down attitude of the aircraft during the spin-spiral transition makes this method of entry ineffective for training purposes as there is little room to permit student error or delay.

All spiral dive recoveries entail the same recovery sequence: first, the throttle must be immediately closed; second, the aircraft is rolled level with co-ordinated use of ailerons and rudder; and third, backpressure is exerted smoothly on the control wheel to recover from the dive.

Dutch roll

The second lateral motion is an oscillatory combined roll and yaw motion called Dutch roll, perhaps because of its similarity to an ice-skating motion of the same name made by Dutch skaters; the origin of the name is unclear. The Dutch roll may be described as a yaw and roll to the right, followed by a recovery towards the equilibrium condition, then an overshooting of this condition and a yaw and roll to the left, then back past the equilibrium attitude, and so on. The period is usually on the order of 3–15 seconds, but it can vary from a few seconds for light aircraft to a minute or more for airliners. Damping is increased by large directional stability and small dihedral and decreased by small directional stability and large dihedral. Although usually stable in a normal aircraft, the motion may be so slightly damped that the effect is very unpleasant and undesirable. In swept-back wing aircraft, the Dutch roll is solved by installing a yaw damper, in effect a special-purpose automatic pilot that damps out any yawing oscillation by applying rudder corrections. Some swept-wing aircraft have an unstable Dutch roll. If the Dutch roll is very lightly damped or unstable, the yaw damper becomes a safety requirement, rather than a pilot and passenger convenience. Dual yaw dampers are required and a failed yaw damper is cause for limiting flight to low altitudes, and possibly lower mach numbers, where the Dutch roll stability is improved.

Aeronautical chart



Example of an Aeronautical chart

An **aeronautical chart** is a map designed to assist in navigation of aircraft, much as nautical charts do for watercraft, or a roadmap for drivers. Using these charts and other tools, pilots are able to determine their position, safe altitude, best route to a destination, navigation aids along the way, alternative landing areas in case of an in-flight emergency, and other useful information such as radio frequencies and airspace boundaries. There are charts for all land masses on Earth, and long-distance charts for trans-oceanic travel.

Specific charts are used for each phase of a flight and may vary from a map of a particular airport facility to an overview of the instrument routes covering an entire continent (e.g., global navigation charts), and many types in between.

Charts for visual flight rules (VFR)

Under "visual flight rules", pilots are expected to see and avoid dangers along the way (obstacles, other aircraft, bad weather etc.), and to use pilotage and other means for navigating. VFR charts include a large amount of information describing the local topography, with an emphasis on elevation of the terrain. Standardized symbols are used to indicate land and water features such as mountains, shorelines and rivers. Roads, towns and other identifiable features, and aeronautical details such as airports, beacons and towers are included.

Visual flight charts are categorized according to their scale, which is proportional to the size of the area covered by one map. The amount of detail is necessarily reduced when larger areas are represented on a map.

- World aeronautical charts (WACs) have a scale of 1:1,000,000 and cover relatively large areas. Outside of WAC coverage, operational navigation charts (ONC) may be used. They use the same scale as WACs, but omit some useful information such as airspace restrictions.
- Sectional charts typically cover a total area of about 340x340 miles, printed on both sides of the map. The scale is 1:500,000.
- VFR Terminal area charts are created with a scale and coverage appropriate for the general vicinity of a large airport (1:250,000). They may depict preferred VFR flight routes within areas of congested airspace.

Charts for instrument flight rules (IFR)

Instrument flight requires the use of external aids to navigation, under the control of an air traffic controller, usually based upon a flight plan. Charts used for IFR flights contain an abundance of information regarding locations of waypoints, known as "fixes", which are defined by measurements from electronic beacons of various types, as well as the routes connecting these waypoints. Only limited topographic information is found on IFR charts, although the minimum safe altitudes available on the routes are shown.

En-route low- and high-altitude charts are published with a scale that depends upon the density of navigation information required in the vicinity.

Information from IFR charts is often programmed into a flight management system or autopilot, which eases the task of following (or deviating from) a flight plan.

Terminal procedure publications such as Standard Terminal Arrival plates, Standard Instrument Departure plates and other documentation provide detailed information for arrival, departure and taxiing at each approved airport having instrument capabilities of some sort.

Sources for charts

Aeronautical charts may be purchased at fixed base operators (FBOs), internet supply sources, or catalogs of aeronautical gear. They may also be viewed online from the FAA.

Chapter 7

Load Factor (Aeronautics) and Relative Wind

Load factor

In aeronautics, the **load factor** is defined as the ratio of the lift of an aircraft to its weight and represents a global measure of the stress ("load") to which the structure of the aircraft is subjected:

$$n = \frac{L}{W}$$

where:

n = Load factor
L = Lift
W = Weight

Since the load factor is the ratio of two forces, it is dimensionless. However, its units are traditionally referred to as **g**, because of the relation between load factor and apparent acceleration of gravity felt on board the aircraft. A load factor of one, or 1 g, represents conditions in straight and level flight, where the lift is equal to the weight. Load factors greater or less than one (or even negative) are the result of maneuvers or wind gusts.

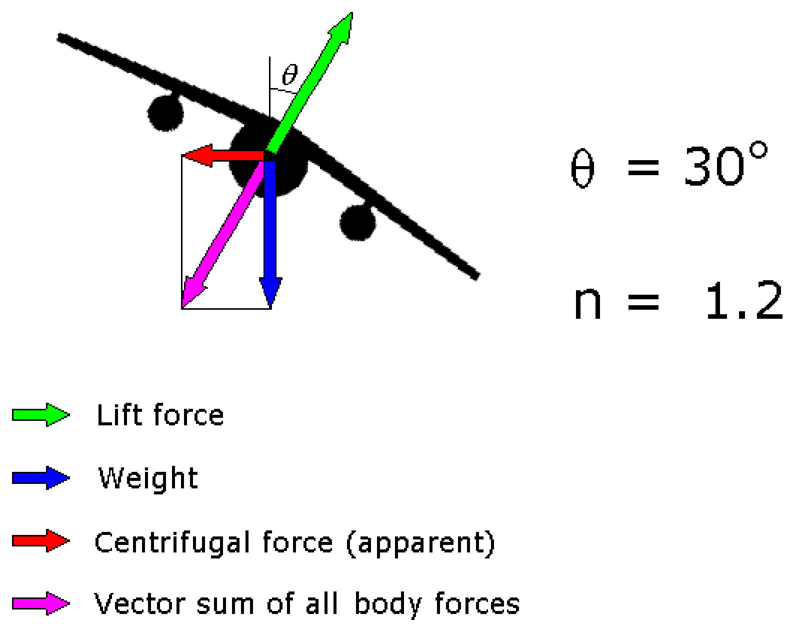
Load factor and g

The fact that the load factor is commonly expressed in *g* units does not mean that it is dimensionally the same as the acceleration of gravity, also indicated with *g*. The load factor is strictly non-dimensional.

The use of *g* units refers to the fact that an observer on board an aircraft will experience an *apparent* acceleration of gravity (i.e. relative to his frame of reference) equal to load factor times the acceleration of gravity. For example, an observer on board an aircraft performing a turn with a load factor of 2 (i.e. a 2 g turn) will see objects falling to the floor at twice the normal acceleration of gravity.

In general, whenever the term *load factor* is used, it is formally correct to express it using numbers only, as in "a maximum load factor of 4". If the term *load factor* is omitted then *g* is used instead, as in "pulling a 3 g turn".

Positive and negative load factors



Variation of the load factor *n* with the bank angle *θ*, during a coordinated turn

The load factor, and in particular its sign, depends not only on the forces acting on the aircraft, but also on the orientation of its vertical axis.

During straight and level flight, the load factor is +1 if the aircraft is flown "the right way up", whereas it becomes -1 if the aircraft is flown "upside-down" (inverted). In both cases the lift vector is the same (as seen by an observer on the ground), but in the latter the vertical axis of the aircraft points downwards, making the lift vector's sign negative.

In turning flight the load factor is normally greater than +1. For example, in a turn with a 60° angle of bank the load factor is +2. Again, if the same turn is performed with the aircraft inverted, the load factor becomes -2. In general, in a balanced turn in which the angle of bank is *θ*, the load factor *n* is related to the cosine of *θ* by the formula:

$$n = \frac{1}{\cos\theta}$$

Another way to achieve load factors significantly higher than +1 is to pull on the elevator control at the bottom of a dive, whereas strongly pushing the stick forward during straight and level flight is likely to produce negative load factors, by causing the lift to act in the opposite direction to normal, i.e. downwards.

Load factor and lift

In the definition of load factor, the lift is not simply that one generated by the aircraft's wing, instead it is the vector sum of the lift generated by the wing, by the fuselage and by the tailplane, or in other words it is the component perpendicular to the airflow of the sum of all aerodynamic forces acting on the aircraft.

The lift in the load factor is also intended as having a sign, which is positive if the lift vector points in the same direction, or close to, as the aircraft's vertical axis, or negative if it points in the opposite direction, or close to opposite, to the vertical axis.

Design standards

Excessive load factors must be avoided because of the possibility of exceeding the structural strength of the aircraft.

Aviation authorities specify the load factor limits within which different classes of aircraft are required to operate without damage. For example, the US Federal Aviation Regulations prescribe the following limits (for the most restrictive case):

- For commercial transport airplanes, from -1 to +2.5 (or up to +3.8 depending on design takeoff weight)
- For light airplanes, from -1.5 to +3.8
- For aerobatic airplanes, from -3 to +6
- For helicopters, from -1 to +3.5

However, many aircraft types, in particular aerobatic airplanes, are designed so that they can tolerate load factors much higher than the minimum required. For example, the Sukhoi Su-26 family have load factors limits of -10 to +12.

The maximum load factors, both positive and negative, applicable to an aircraft are usually specified in the pilot's operating handbook.

Human perception of load factor

When the load factor is +1, all occupants of the aircraft feel that their weight is normal. When the load factor is greater than +1 all occupants feel heavier than usual. For example, in a 2 g maneuver all occupants feel that their weight is twice normal. When the load factor is zero, or very small, all occupants feel weightless. When the load factor is negative, all occupants feel they are upside down.

Human beings have limited ability to withstand a load factor significantly greater than +1, both positive and negative. Unmanned aerial vehicles can be designed for much greater load factors, both positive and negative, than conventional aircraft because these vehicles can be used in maneuvers which would be incapacitating for a human pilot.

Relative wind

In aeronautics, the **relative wind** is the direction of movement of the atmosphere relative to an aircraft or an airfoil. It is opposite to the direction of movement of the aircraft or airfoil relative to the atmosphere. Close to any point on the surface of an aircraft or airfoil, the air is moving parallel to the surface; but at a great distance from the aircraft or airfoil the movement of the air can be represented by a single vector. This vector is the relative wind or the *free stream velocity vector*.

The angle between the chord line of an airfoil and the relative wind defines the angle of attack. The relative wind is of great importance to pilots because exceeding the critical angle of attack will result in a stall, regardless of airspeed.

Relative wind in freefall

Relative wind is also used to describe the airflow relative to an object in freefall through an atmosphere, such as that of a person's body during the freefall portion of a skydive or BASE jump. In a normal skydive the vertical descent of the skydiver creates an upward relative wind. The relative wind strength increases with increased descent rate.

The relative wind is directly opposite to the direction of travel.

Therefore, when a skydiver exits a forward-moving aircraft such as an aeroplane, the relative wind emanates from the direction the aeroplane is facing due to the skydiver's initial forward (horizontal) momentum. As aerodynamic drag gradually overcomes this forward momentum and, simultaneously, gravity attracts the skydiver downward, the relative wind alters proportionally into an upward (vertical) direction. This creates an arc of travel for the skydiver similar to water flowing from a low pressure hose held horizontally and creates a variation in the angle of the relative wind from horizontal to vertical.

When exiting from a forward-moving aircraft (as distinguished from a hovering aircraft, such as a balloon or a helicopter in hover mode) during a normal belly-to-earth skydive, the skydiver must arch his body in the direction of travel which is initially horizontal. If the skydiver continues to arch, his belly will gradually alter pitch until he is belly-to-earth. This section of the jump is commonly referred to as "the hill".

Relative wind differs from the wind in meteorology in that the object (*e.g.*, the skydiver) moves past the air, as opposed to the air moving past the object

Chapter 8

Hybrid Airship and Lift (Soaring)

Hybrid airship

A **hybrid airship** is an aircraft that combines characteristics of heavier-than-air, (HTA), (fixed-wing aircraft or helicopter) and lighter than air (LTA), aerostat technology. Examples include helicopter/airship hybrids intended for heavy lift applications and dynamic lift airships intended for long-range cruising. No production vehicles have been built, but several manned and unmanned prototypes have flown and successfully demonstrated the concept.

The term has also been used to describe an airship combining elements of different types of airships.

Background

Traditional airships have low operating costs but are limited in several ways, including low payload/volume ratios and low speeds. Additionally, ground handling of airships has historically presented great difficulty. When a purely LTA ship comes in for a landing, it is nearly neutrally buoyant and is very susceptible to wind buffeting. In even a slight breeze, a truck or many ground crew members are required to secure the ship to a mooring mast.

Heavier-than-air aircraft, while addressing these difficulties, require the use of power to generate lift, and airplanes also require runways, while helicopters need even more power to hover. Hybrid airship designs are intended to fill the middle ground between the low operating cost and low speeds of traditional airships and higher speed, but more expensive heavier-than-air aircraft. In addition, by combining dynamic and buoyant lift, hybrids may be able to provide otherwise unattainable air-cargo payload capacity and/or a hovering capability. Such a design is intended to be the "best of both worlds" combination: the high speed of aerodynamic craft and the lifting capacity of aerostatic craft. However, critics of the hybrid approach have labeled it as being the "worst of both worlds" declaring that such craft require a runway for take-off and landing, are difficult to control and protect on the ground, and have relatively poor aerodynamic performance.

Most modern airships, for instance the Zeppelin NT or Skyship 600 use some combination of vectored thrust and buoyancy. However, for these designs, almost all of the load is carried via buoyancy and vectored thrust is used primarily for maneuvering. To date, there is no formal distinction between hybrid airships and airships with vectored thrust.

Concept

The idea behind the hybrid airship is to combine lift from a lighter-than-air gas such as helium with lift from aerodynamic forces. Such a craft is still heavier than air, which makes it similar in some ways to a regular aircraft. The rest of the lift is comes from vertical thrusters such as helicopter-like rotors, or a lift-producing shape (like a wing) combined with horizontal thrust, or a combination of the two. The aerodynamic approach is very similar to that of a conventional lifting body aircraft. The hybrid aircraft technology has a wide range of flight performance behaviors ranging from heavier than air to near buoyant characterizations. This uncommon dynamic flight range when coupled with an air cushion landing system has reinvigorated the LTA community and those seeking ultra heavy and affordable airlift transportation options.

History

Alberto Santos-Dumont's combined aircraft/dirigible experiments of 1906

No hybrid aircraft design has ever been developed past the initial experimental stages despite many such designs having been proposed over the years, though recent advances may indicate that the technology has matured.

In 1905, Alberto Santos-Dumont made what is likely the first attempt at a hybrid aircraft. His *Number 14* combined an airship envelope with an airplane frame. At that time, Santos-Dumont was the world's most accomplished aviator. All of his previous flights had been made in purely aerostatically lifted airships. The Number 14 proved unworkable. Later, Santos-Dumont would remove the envelope and successfully use the recristened *14-bis* (meaning "14-again") to make the first public flight of any heavier-than-air aircraft in the world.

The 1986 Piasecki PA-97 Helistat combined four helicopters with a blimp in an attempt to create a heavy-lift vehicle for forestry work.

One hybrid aircraft design that flew was the Aereon 26; however, this was a small-scale prototype and derived all its lift aerodynamically, none from lighter-than-air gas. The development of this aircraft was documented in the book "The Deltoid Pumpkin Seed" by John McPhee.

The SkyCat or "Sky Catamaran" vehicular technology is a hybrid aircraft amalgamation; a scale version at 12 meters called "SkyKitten", built by the now defunct Advanced Technologies Group, flew in 2000.

The U.S. Defense Advanced Research Projects Agency, DARPA, initiated the WALRUS program in 2005, a technology development initiative focused on ultra heavy air lift technology explorations. The program was terminated in 2007.

In 2006, Lockheed Martin's P-791 manned flight test of the SkyCat technology indicated substantial progress of the technology, and presently several development efforts are underway.

Current and proposed designs

The Hybrid Aircraft Corporation has trademarked the SkyCat and SkyFreighter (cargo variant) names for such vehicles and is involved in design and development efforts, and has a working prototype HAV-3.

The Aeroscraft, a design proposed by Worldwide Aeros Corp is also a hybrid airship that uses a lifting body shape, vectored thrust, as well as buoyancy control. Aeros was a beneficiary of the WALRUS program.

World SkyCat Ltd, in Britain, is also pursuing a design in the heritage of the SkyKitten.

The Millennium Airship Corporation has Patented their ITAMMS thrust management system and are currently developing a heavy hybrid lift system.

Hybrid Air Vehicles from Cranfield in England and partner Northrop Grumman won the 517 million dollar LEMV contract and are building three HAV 304's for the US Army, the first one will fly later this year. As a result of the development work that the HAV design team have undertaken over the past 25 years, combined with the very significant LEMV contract, they are now regarded as the leading company in this sector.

Lift (soaring)

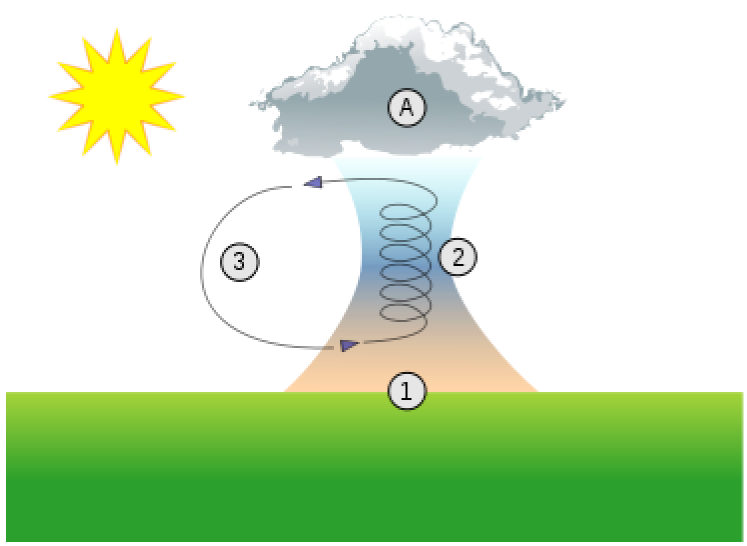
Lift is a meteorological phenomenon used as an energy source by soaring aircraft and soaring birds. The most common human application of lift is in sport and recreation. The three air sports that use soaring flight are: gliding, hang gliding and paragliding.

Energy can be gained by using rising air from four sources:

- Thermals (where air rises due to heat),
- Ridge lift, where air is forced upwards by a slope,
- Wave lift, where a mountain produces a standing wave,
- Convergence, where two air masses meet

In dynamic soaring it is also possible to gain energy, though this uses differences in wind speeds rather than rising air.

Thermals



Example of a thermal column between the ground and a cumulus

Thermals are streams of rising air that are formed on the ground through the warming of the surface by sunlight. If the air contains enough moisture, the water will condense from the rising air and form cumulus clouds.

Thermal lift is often used by birds, such as raptors, vultures and storks. Although thermal lift was known to the Wright Brothers in 1901, it was not exploited by humans until 1921 by William Leusch at the Wasserkuppe in Germany. It was not until about 1930 that the use of thermals for soaring in gliders became commonplace.

Once a thermal is encountered, the pilot flies in circles to keep within the thermal, so gaining altitude before flying off to the next thermal and towards the destination. This is known as "thermalling". Climb rates depend on conditions, but rates of several meters per second are common. Thermals can also be formed in a line usually because of the wind or the terrain, creating cloud streets. These can allow flying straight while climbing in continuous lift.

When the air has little moisture or when an inversion stops the warm air from rising high enough for the moisture to condense, thermals do not create cumulus clouds. Typical locations to find thermals are over towns, freshly ploughed fields and asphalt roads, but thermals are often hard to associate with any feature on the ground. Occasionally thermals are caused by the exhaust gases from power stations or by fires.

As it requires rising heated air, thermalling is only effective in mid-latitudes from spring through into late summer. During winter the solar heat can only create weak thermals, but ridge and wave lift can still be used during this period.

A Scimitar glider ridge soaring in Lock Haven, Pennsylvania USA

Ridge lift

Ridge lift, or Orographic lift, is caused by rising air on the windward side of a slope. Ridge lift is used extensively by sea birds and by aircraft. In places where a steady wind blows, a ridge may allow virtually unlimited time aloft.

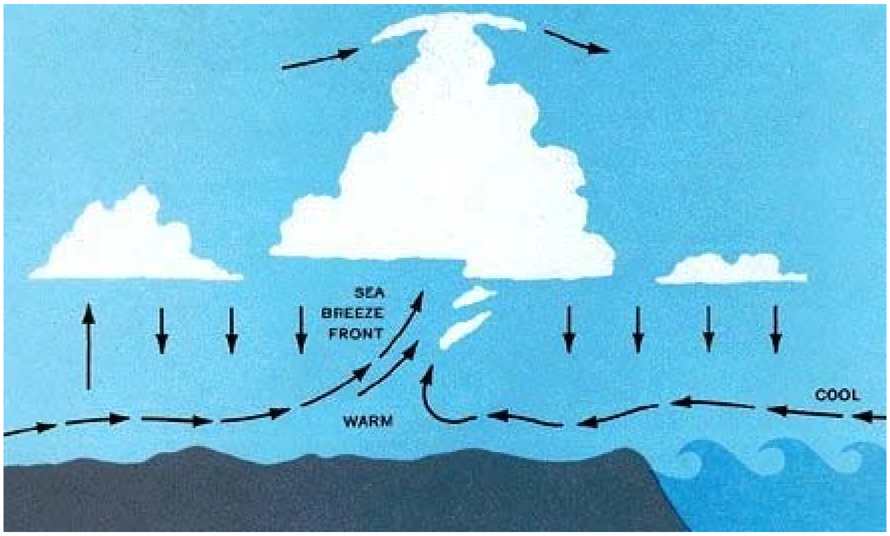
With winds of 20 to 25 knots (46 km/h), it is possible for aircraft to soar at an altitude up to two times the height of the obstacle. Ridge lift can also be augmented by thermals when the slopes also face the sun.

Wave lift

A lenticular cloud produced by a mountain wave

Lee waves occur when a wind of 25 knots (46 km/h) blows over a mountain. Provided that there is a steady increase in wind strength with altitude without a significant change in direction, standing waves may be created. They were discovered by a glider pilot, Wolf Hirth, in 1933. These waves reach heights much greater than the original obstruction and so can permit gliders to climb to the stratosphere. Pilots use supplementary oxygen to avoid hypoxia because gliders do not have pressurized cockpits. This lift is often marked by long, stationary lenticular (lens-shaped) clouds lying perpendicular to the wind. Mountain wave was used to set the current altitude record of 50,699 feet (15,453 m) on August 29, 2006 over El Calafate, Argentina. The pilots were Steve Fossett and Einar Enevoldson, who were wearing pressure suits. The current world distance record of 3,008 km (1,869 statute miles) by Klaus Ohlmann (set on 21 January 2003) was also flown using mountain waves in South America.

A rare wave phenomenon is known as Morning Glory, a roll cloud producing strong lift. Pilots near Australia's Gulf of Carpentaria make use of it in springtime.



Schematic cross section through a sea breeze front. If the air inland is moist, cumulus often marks the front.

Birds have been observed using wave lift to cross mountainous regions.

Convergence zones

The boundaries where two air masses meet are known as convergence zones. These can occur in sea breezes or in desert regions. A **sea-breeze** (or **onshore breeze**) is a wind from the sea that develops over land near coasts. In a sea-breeze front, cold air from the sea meets the warmer air from the land and creates a boundary like a shallow cold front along a shear line. This creates a narrow band of soarable lift with winds as light as 10 knots (19 km/h). These permit the gaining of altitude by flying along the intersection as if it were a ridge of land. Convergence may occur over considerable distances and so may permit virtually straight flight while climbing.

Dynamic soaring

In dynamic soaring energy is gained by repeatedly crossing the boundary between air masses of different horizontal velocity rather than by rising air. Such zones of high "wind gradient" are usually too close to the ground to be used safely by gliders, but Albatrosses and model gliders use this phenomenon.

Illusions of lift

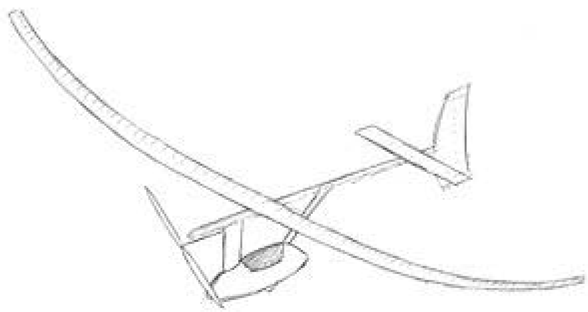
A pilot can create an indication of lift on certain uncompensated instruments by entering a climb by pulling back on the stick (hence "*stick* thermal"). This is not true lift, in that the energy to climb is being converted from decreasing airspeed, rather than being extracted from rising air. Inexperienced pilots can mistake this for actual lift.

Chapter 9

PSU Zephyrus and Rib (Aircraft)

PSU Zephyrus

PSU Zephyrus



An isometric concept view of the aircraft.

Role	Human-powered aircraft
Manufacturer	Penn State
Number built	0 (1 in progress)
Unit cost	US$25,000
Developed from	Musculair II

The **PSU Zephyrus** is a human-powered aircraft being constructed by the Penn State AERSP 404H team. It is a composite material, single-seat, single propeller, high-wing airplane. The Zephyrus is designed to compete in the Kremer prize sport competition.

Development

The PSU Zephyrus was developed to compete in the Kremer's prize sport competition. The basic mission goal is to traverse an equilateral triangle with sides of 500 meters once in each direction in seven minutes. The competition specifies a minimum average wind speed of 5.0 m/s during the flight. In addition, for a flight to be considered official, the wind cannot drop below 5.0 m/s for a period of more than 20 seconds. The aircraft is also being developed and constructed as a fulfillment of the course requirements of Penn State's AERSP 404H course.

Design

Fuselage

The fuselage was sized based a dimension range of a 5’10”(1.78 m) pilot and the assumption that the pilot could output the necessary power to weight ratio to fly the aircraft will be no greater than 1.78 m. Constraints include minimum widths for pilot comfort and desired center of gravity of the aircraft. The shape of the pod was designed to be a low-drag body that will not generate lift regardless of angle of attack. The length of the shape was reduced to allow for aircraft maneuverability in crosswind. The internal structural members are designed to firmly hold the seat configuration in place, yet still provide a maximum field of vision for the pilot. Structural members attach to the main boom at a hard-point located behind the trailing edge of the wing.

Propeller

To successfully complete the challenge, it was determined that the propeller would need to produce 27.5 N of thrust when cruising at 12.5 m/s and spinning at 135 rpm. To meet these requirements, the propeller design underwent many alterations, with the final design broken into two components.

Wing

Starting from a parent aircraft approach, primarily using the Musculair 1 and 2, but also including the Monarch B, MIT Daedalus, and Velair models, a first iteration choice for an airfoil was made. A modified version of the FX-76MP, as used for the Musculair 2 was chosen. Taking characteristics from this airfoil, using an initial weight buildup, the wing planform size was determined. Then, assuming a take-off weight of 81 kg (27 kg empty weight), sea-level air density, and using a CL at cruise of 0.8.

Control Surfaces

Ailerons were designed as a piano hinge attached near the upper surface, so the upper surface incorporates the leading edge radius, so that the upper surface maintains smooth flow. This design maximizes weight efficiency and construction ease.

Specifications

General characteristics

- **Crew:** 1
- **Length:** 13 ft 1 in (4 m)

- **Wingspan:** 57 ft 5 in (17.5 m)
- **Height:** 9 ft 4 in (3 m)
- **Max takeoff weight:** 206 lb (93.4kg)
- **Powerplant:** 1× Tractor, Propeller ()

Performance

- **Cruise speed:** 27.9 mph (12.5 m/s)

Rib (aircraft)

Wing ribs of a de Havilland DH.60 Moth

In an aircraft, **ribs** are forming elements of the structure of a wing, especially in traditional construction.

By analogy with the anatomical definition of "rib", the ribs attach to the main spar, and by being repeated at frequent intervals, form a skeletal shape for the wing. Usually ribs incorporate the airfoil shape of the wing, and the skin adopts this shape when stretched over the ribs.

Type of ribs

There are several types of **ribs**. Form-ribs, plate-type ribs, truss ribs, closed-ribs, forged ribs and milled ribs, where form-ribs are used for light to medium loading and milled ribs are as strong as it can get.
Form-ribs are made from a sheet of metal bent into shape, such as a U-profile. This profile is place on the skin, just like a stringer, but then in the other direction.
Plate-type ribs consist of sheet-metal, which has upturned edges and (often has) weight-saving holes cut into it.
Truss ribs are built up out of profiles that are joined together. These joints require great attention during design and manufacture. The ribs may be light or heavy in design which make them suitable for a wide range of loads.
Closed-ribs are constructed from profiles and sheet metal and are suitable for closing off sections of the wing (e.g.: the fuel tank). Here too, particular care must be taken with the joints and this type of rib is also suitable for application in a variety of loading conditions.
Forged ribs are manufactured using heavy press-machinery. The result is fairly rough; for more refined parts, high-pressure presses are required, which are very expensive. Forged pieces (usually) have to undergo further treatment (for smoother edges and holes). Forged ribs are used for sections where very high loads apply - near the undercarriage for example.
Milled ribs are solid structures. They are manufactured by milling away excess material from a solid block of metal (usually using computer-controlled milling machines). The shape of these ribs is always accurately defined. Such ribs are used under similar conditions as those for forged ribs.

Ribs are made out of wood, metal, plastic, composites, foam. The wings of kites, hang gliders , paragliders , powered kites , powered hang gliders, ultralights, windmills are aircraft that have versions that use ribs to form the wing shape.

For full size and flying model aircraft wing structures that are usually made of wood, ribs can either be in one piece (forming the airfoil at that rib's "station" in the wing), or be in a three-piece format, with the *rib web* being the part that the one-piece rib consisted of, with *capstrips* for the upper and lower edging of the rib, running from the leading edge to the trailing edge, being the other two component parts.

Chapter 10

Aircraft Flight Mechanics and Radio Direction Finder

Aircraft flight mechanics

In aeronautics, **aircraft flight mechanics** is the study of the forces that act on an aircraft in flight, and the way the aircraft responds to those forces.

Aircraft flight mechanics are relevant to gliders, helicopters and aeroplanes.
An Aeroplane (Airplane in US usage), is defined as: *a power-driven heavier than air aircraft, deriving its lift chiefly from aerodynamic reactions on surface which remain fixed under given conditions of flight*. (ICAO Document 9110)

Straight and level flight of aircraft

In flight, an aircraft can be considered as being acted on by four forces: lift, weight, thrust, and drag. Thrust is the force generated by the engine and acts along the engine's thrust vector. Lift acts perpendicular to the vector representing the aircraft's velocity relative to the atmosphere. Drag acts parallel to the aircraft's velocity vector, but in the opposite direction because drag resists motion through the air. Weight acts through the aircraft's centre of gravity, towards the centre of the Earth.

In straight and level flight, lift is approximately equal to weight. In addition, if the aircraft is not accelerating, thrust is approximately equal to drag.

In straight, climbing flight, lift is less than weight. At first, this seems incorrect because if an aircraft is climbing it seems lift must exceed weight. When an aircraft is climbing at constant speed it is its thrust that enables it to climb and gain extra potential energy. Lift acts perpendicular to the vector representing the velocity of the aircraft relative to the atmosphere, so lift is unable to alter the aircraft's potential energy or kinetic energy. This can be seen by considering an aerobatic aircraft in straight vertical flight - one that is climbing straight upwards (or descending straight downwards). Vertical flight requires no lift! When flying straight upwards the aircraft can reach zero airspeed before falling earthwards - the wing is generating no lift and so does not stall. In straight, climbing flight at constant airspeed, thrust exceeds drag.

In straight, descending flight, lift is less than weight. In addition, if the aircraft is not accelerating, thrust is less than drag. In turning flight, lift exceeds weight and produces a load factor greater than one, determined by the aircraft's angle of bank.

Aircraft control and movement

There are three primary ways for an aircraft to change its orientation relative to the passing air. *Pitch* (movement of the nose up or down), *Roll* (rotation around the longitudinal axis, that is, the axis which runs along the length of the aircraft) and *Yaw* (movement of the nose to left or right.) Turning the aircraft (change of heading) requires the aircraft firstly to roll to achieve an angle of bank; when the desired change of heading has been accomplished the aircraft must again be rolled in the opposite direction to reduce the angle of bank to zero.

Aircraft control surfaces

Yaw is induced by a moveable rudder, attached to a vertical fin usually at the rear of the aircraft. Sometimes the entire fin is movable. Movement of the rudder changes the size and orientation of the force the vertical surface produces. Since the force is created a distance behind the centre of gravity this sideways force causes a yawing motion. On a large aircraft there may be several independent rudders on the single fin for both safety and to control the inter-linked yaw and roll actions.

Using yaw alone is not a very efficient way of executing a level turn in an aircraft and will result in some sideslip. A precise combination of bank and lift must be generated to cause the required centripetal forces without producing a sideslip.

Pitch is controlled by the rear part of the tailplane's horizontal stabilizer being hinged to create an elevator. By moving the elevator control backwards the pilot moves the elevator up (a position of negative camber) and the downwards force on the horizontal tail is increased. The angle of attack on the wings increased so the nose is pitched up and lift is generally increased. In micro-lights and hang gliders the pitch action is reversed - the pitch control system is much simpler so when the pilot moves the elevator control backwards it produces a nose-down pitch and the angle of attack on the wing is reduced.

The system of a fixed tail surface and moveable elevators is standard in subsonic aircraft. Craft capable of supersonic flight often have a stabilator, an all-moving tail surface. Pitch is changed in this case by moving the entire horizontal surface of the tail. This seemingly simple innovation was one of the key technologies that made supersonic flight possible. In early attempts, as pilots exceeded the critical Mach number, a strange phenomenon made their control surfaces useless, and their aircraft uncontrollable. It was determined that as an aircraft approaches the speed of sound, the air approaching the aircraft is compressed and shock waves begin to form at all the leading edges and around the hinge lines of the elevator. These shock waves caused movements of the elevator to cause no pressure change on the stabilizer upstream of the elevator. The problem was solved by changing the stabilizer and hinged elevator to an all-moving stabilizer - the entire horizontal surface of the tail became a one-piece control surface. Also, in supersonic flight the change in camber has less effect on lift and a stabilator produces less drag.

Aircraft that need control at extreme angles of attack are sometimes fitted with a canard configuration, in which pitching movement is created using a forward foreplane (roughly level with the cockpit). Such a system produces an immediate increase in lift and therefore a better response to pitch controls. This system is common in delta-wing aircraft (deltaplane), which use a stabilator-type canard foreplane. A disadvantage to a canard configuration compared to an aft tail is that the wing cannot use as much extension of flaps to increase wing lift at slow speeds due to stall performance. A combination tri-surface aircraft uses both a canard and an aft tail (in addition to the main wing) to achieve advantages of both configurations.

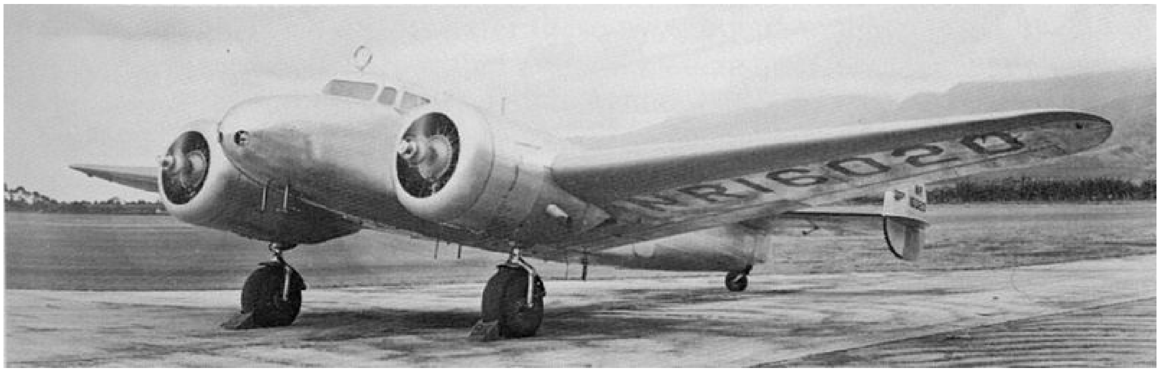
A further design of tailplane is the V-tail, so named because that instead of the standard inverted T or T-tail, there are two vertical fins angled away from each other in a V (if they're arranged like a V, at least one of them isn't vertical). To produce yaw like a rudder, the two trailing edge control surfaces move in the same direction. To produce pitch like an elevator, the surfaces move in opposite directions.

Roll is controlled by movable sections on the trailing edge of the wings called ailerons. The ailerons move differentially - one goes up as the other goes down. The difference in camber of the wing cause a difference in lift and thus a rolling movement. As well as ailerons, there are sometimes also spoilers - small hinged plates on the upper surface of the wing, originally used to produce drag to slow the aircraft down and to reduce lift when descending. On modern aircraft, which have the benefit of automation, they can be used in combination with the ailerons to provide roll control.

The earliest powered aircraft built by the Wright brothers did not have ailerons. The whole wing was warped using wires. Wing warping is efficient since there is no discontinuity in the wing geometry. But as speeds increased unintentional warping became a problem and so ailerons were developed.

Radio direction finder

Civil Air Patrol members practice using a handheld radio direction finder to locate an emergency locator transmitter



Amelia Earhart's Lockheed Model 10 Electra with the circular *RDF* aerial visible above the cockpit

A **radio direction finder** (**RDF**) is a device for finding the direction to a radio source. Due to radio's ability to travel very long distances and "over the horizon", it makes a particularly good navigation system for ships, small boats, and aircraft that might be some distance from their destination.

History

John Stone Stone patented the first direction finding system in 1902 (U.S. Patent 716,134). Alternate and improved direction finding systems were invented by Lee de Forest in 1904 (U.S. Patent 771,819), and by Italian engineers Ettore Bellini and Alessandro Tosi in 1909 (U.S. Patent 943,960). In 1919, British Army Officer Frank Adcock proposed an improved direction finding antenna design Adcock antenna (UK Patent 130,490).

The US Army Air Corps in 1931 tested a primitive radio compass that used commercial stations as the beacon.

Operation

World War II US Navy high frequency radio direction finder

Radio Direction Finding works by comparing the signal strength of a directional antenna pointing in different directions. At first, this system was used by land and marine-based radio operators, using a simple rotatable loop antenna linked to a degree indicator. This system was later adopted for both ships and aircraft, and was widely used in the 1930s and 1940s. On pre-World War II aircraft, RDF antennas are easy to identify as the circular loops mounted above or below the fuselage. Later loop antenna designs were enclosed in a aerodynamic, teardrop-shaped fairing. In ships and small boats, RDF receivers first employed large metal loop antennae, similar to aircraft, but usually mounted atop a portable battery-powered receiver.

In use, the RDF operator would first tune the receiver to the correct frequency, then manually turn the loop, either listening or watching an S meter to determine the direction of the *null* (the direction at which a given signal is weakest) of a long wave (LW) or medium wave (AM) broadcast beacon or station (listening for the null is easier than listening for a peak signal, and normally produces a more accurate result). This null was symmetrical, and thus identified both the correct degree heading marked on the radio's compass rose as well as its 180-degree opposite. While this information provided a baseline from the station to the ship or aircraft, the navigator still needed to know beforehand if he was to the east or west of the station in order to avoid plotting a course 180-degrees in the wrong direction. By taking bearings to two or more broadcast stations and plotting the intersecting bearings, the navigator could locate the relative position of his ship or aircraft.

Later, RDF sets were equipped with rotatable ferrite loopstick antennae, which made the sets more portable and less bulky. Some were later partially automated by means of a motorized antenna (ADF). A key breakthrough was the introduction of a secondary vertical whip or 'sense' antenna that substantiated the correct bearing and allowed the navigator to avoid plotting a bearings 180 degrees opposite the actual heading. After World War II, there many small and large firms making direction finding equipment for mariners, including Apelco, Aqua Guide, Bendix, Gladding (and its marine division, Pearce-Simpson), Ray Jefferson, Raytheon, and Sperry. By the 1960s, many of these radios were actually made by Japanese electronics manufacturers, such as Panasonic, Fuji Onkyo, and Koden Electronics Co., Ltd. In aircraft equipment, Bendix and Sperry-Rand were two of the larger manufacturers of RDF radios and navigation instruments.

Usage in maritime and aircraft navigation

Historic advertisement for Kolster radio compass

Radio transmitters for air and sea navigation are known as *beacons* and are the radio equivalent to a lighthouse. The transmitter sends a Morse Code transmission on a Long wave (150 - 400 Khz) or Medium wave (AM) (520 - 1720 Khz) frequency incorporating the station's identifier that is used to confirm the station and its operational status. Since these radio signals are broadcast in all directions (omnidirectional) during the day, the signal itself does not include direction information, and these beacons are therefore referred to as non-directional beacons, or **NDBs**.

As the commercial medium wave (AM) broadcast band lies within the frequency capability of most RDF units, these stations and their transmitters can also be used for navigational fixes. While these commercial radio stations can be useful due to their high power and location near major cities, there may be several miles between the location of the station and its transmitter, which can reduce the accuracy of the 'fix' when approaching the broadcast city. A second factor is that some AM radio stations are omnidirectional during the day, and switch to a reduced power, directional signal at night.

RDF was once the primary form of aircraft and marine navigation. Strings of beacons formed "airways" from airport to airport, while marine NDBs and commercial AM broadcast stations provided navigational assistance to small watercraft approaching a landfall. In the United States, commercial AM radio stations were required to broadcast their station identifier once per hour for use by pilots and mariners as an aid to navigation. In the 1950s, aviation NDBs were augmented by the VOR system, in which the direction to the beacon can be extracted from the signal itself, hence the distinction with non-directional beacons. Use of marine NDBs was largerly supplanted in North America by the development of LORAN in the 1970s.

Today many NDBs have been decommissioned in favor of faster and far more accurate GPS navigational systems. However the low cost of ADF and RDF systems, and the continued existence of AM broadcast stations (as well as navigational beacons in countries outside North America) has allowed these devices to continue to function, primarily for use in small boats, as an adjunct or backup to GPS.

Automatic direction finder (ADF)

A typical aircraft ADF indicator

An **automatic direction finder** (**ADF**) is a marine or aircraft radio-navigation instrument that automatically and continuously displays the relative bearing from the ship or aircraft to a suitable radio station. ADF receivers are normally tuned to aviation or marine NDBs operating in the LW band between 190 – 535 kHz. Like RDF units, most ADF receivers can also receive medium wave (AM) broadcast stations, though as mentioned, these are less reliable for navigational purposes.

The operator tunes the ADF receiver to the correct frequency and verifies the identity of the beacon by listening to the Morse code signal transmitted by the NDB. On marine ADF receivers, the motorized ferrite-bar antenna atop the unit (or remotely mounted on the masthead) would rotate and lock when reaching the null of the desired station. A centerline on the antenna unit moving atop a compass rose indicated in degrees the bearing of the station. On aviation ADFs, the unit automatically moves a compass-like pointer (RMI) to show the direction of the beacon. The pilot may use this pointer to *home* directly towards the beacon, or may also use the magnetic compass and calculate the direction from the beacon (the *radial*) at which their aircraft is located.

Unlike the RDF, the ADF operates without direct intervention, and continuously displays the direction of the tuned beacon. Initially, all ADF receivers, both marine and aircraft versions, contained a rotating loop or ferrite loopstick aerial driven by a motor which was controlled by the receiver. Like the RDF, a sense antenna verified the correct direction from its 180-degree opposite.

More modern aviation ADFs contain a small array of fixed aerials and use electronic sensors to deduce the direction using the strength and phase of the signals from each aerial. The electronic sensors listen for the *trough* that occurs when the antenna is at right angles to the signal, and provide the heading to the station using a direction indicator. In flight, the ADF's RMI or direction indicator will always point to the broadcast station regardless of aircraft heading, however a banked attitude can have a slight affect on the reading, the needle will still generally indicate towards the beacon, however it suffers from DIP error where the needle dips down in the direction of the turn. Such receivers can be used to determine current position, track inbound and outbound flight path, and intercept a desired bearing. These procedures are also used to execute holding patterns and non-precision instrument approaches.

Typical NDB services ranges

Class of NDB	Transmission Power	Effective Range
Locator	below 25 watts	15 NM
MH	below 50 watts	25 NM
H	50 to 1,999 watts	50 NM
HH	2,000+ watts	75 NM

Station passage

As an aircraft nears an NDB station, the ADF becomes increasingly sensitive, small lateral deviations result in large deflections of the needle which sometimes shows erratic left/right oscillations. Ideally, as the aircraft overflies the beacon, the needle swings rapidly from directly-ahead to directly-behind. This indicates *station passage* and provides an accurate position fix for the navigator. Less accurate station passage, passing slightly to one side or another, is shown by slower (but still rapid) swinging of the needle. The time interval from the first indications of station proximity to positive station passage varies with altitude — a few moments at low levels to several minutes at high altitude.

Homing

The ADF may be used to *home* in on a station. Homing is flying the aircraft on the heading required to keep the needle pointing directly to the 0° (straight ahead) position. To home into a station, tune the station, identify the Morse code signal, then turn the aircraft to bring the ADF azimuth needle to the 0° position. Turn to keep the ADF heading indicator pointing directly ahead. Homing is regarded as poor piloting technique because the aircraft may be blown significantly or dangerously off-course by a cross-wind, and will have to fly further and for longer than the direct track.

Tracking

The ADF may also be used to *track* a desired course using a ADF and allowing for winds aloft, winds which may blow the aircraft off-course. Good pilotage technique has the pilot calculate a correction angle that exactly balances the expected crosswind. As the flight progresses, the pilot monitors the direction to or from the NDB using the ADF, adjusts the correction as required. A direct track will yield the shortest distance and time to the ADF location.

Radio-magnetic indicator (RMI)

A **radio-magnetic indicator** (**RMI**) is an alternate ADF display providing more information than a standard ADF. While the ADF shows relative angle of the transmitter with respect to the aircraft, an RMI display incorporates a compass card, actuated by the aircraft's compass system, and permits the operator to read the magnetic bearing to or from the transmitting station, without resorting to arithmetic.

Most RMI incorporate two direction needles. Often one needle (thicker and/or double-barred) is connected to an ADF and the other (generally the thin, single-barred needle) is connected to a VOR. Using multiple indicators a navigator can accurately fix the position of their aircraft without requiring station passage. There is great variation between models and the operator must take care that their selection displays information from the appropriate ADF and VOR.

Chapter 11

Ultralight Trike

An **ultralight trike**, also known as a **flex-wing trike**, **weight-shift control aircraft**, **microlight trike** or **Motorized Deltaplane**, is a type of powered hang glider using a high performance Rogallo wing coupled to a propeller-powered three-wheeled undercarriage. While most powered aircraft have three-wheeled landing gear, the term "trike" refers specifically to the form of aircraft described here. The principles of this page can generally be applied to the single place ultralight trike and the two place weight-shift control light-sport aircraft.

Trike in the Top End of the Northern Territory in Australia

Control

Flight control in a trike is by weight-shift . This is similar to controlling a hang glider, in which the aviator or pilot is suspended from the wing made from high-strength aluminium and fabric. The pilot controls the attitude of the wing by holding onto and operating a triangular control bar (or triangular control frame) (TCF) that is rigidly attached to the wing. Pushing, pulling, and turning the TCF causes a corresponding shift in the aircraft's center of gravity.

For instance, pushing the TCF's basebar forward causes the center of gravity to shift back. This, in turn, causes the nose of the aircraft to pitch up, causing the angle of attack to increase which causes the aircraft to fly more slowly. In contrast, pushing forward on the control stick of a traditional aircraft would cause that aircraft to dive.

Detail of a Mainair Blade ultralight trike (in 2009)

Turns are accomplished by rolling the wing in the direction of the intended turn. This is accomplished by moving the control bar to the left in order to enter a right hand turn. This causes the center of gravity--represented primarily by the weight of the undercarriage and pilot--to shift in the direction of the intended turn. This in itself does not cause the aircraft to turn, but it does cause the aircraft to bank, or tip, to the side. Some adverse yaw is also initially produced, which is soon damped by the natural yaw stability of the wing.

A banking maneuver becomes a turn because of the natural yaw stability of the wing. When a roll is applied, the aircraft begins to side slip towards the lower wing. Since the wing is yaw stable, a yaw is set up in the direction of the bank, thus coordinating the turn. A small anhedral effect may be built into the wing to aid roll response, where the side slip causes increased banking.

This is similar to the way in which a hang glider is controlled. In fact, trikes are essentially propeller-powered hang gliders with seats and wheels. Trikes have often employed wings designed for hang gliding; the Rogallo-winged trike Paresev 1B of NASA's 1960s experiments and Barry Hill Palmer's trike (Fleep inspired) modeled the wing that has evolved to contemporary trike wings. As weight and performance goals have increased purpose-built wings have become more commonplace. They are now long distance cross country machines as shown by record-breaking flights that echo the exploits of fixed-wing aviators in the 1920s and 1930s, e.g., the circumnavigation of the world.

Stability and equilibrium

Varadero, Cuba

Because trikes are most often used for recreational flying by part time pilots, a premium is placed on gentle behavior especially at the stall, natural pitch stability, and ease-of-operation.

Unlike a traditional aircraft with an extended fuselage and empennage for maintaining stability, trikes rely on the natural stability of their wings to return to equilibrium in yaw and pitch. Roll stability is generally set up to be near neutral. In calm air, a properly designed wing will maintain balanced trimmed flight though a slow spiral may build up in either direction.

In roll most trikes are set up with near-neutral roll due to side slip (some slightly negative, some slightly positive) and also near neutral spiral stability, often mildly unstable. Moderate negative roll due to side slip (anhedral effect) can be built in to improve roll response by weight shift.

The yaw axis, which represents the direction that the aircraft is facing relative to the wind, is stabilized through the sweep of the wings. Instead of having wings that extend almost straight out side-to-side as in many types of traditional light aircraft, trikes are provided with a swept back wing planform. The swept planform, when yawed out of the relative wind, creates more lift on the advancing wing and also more drag. The differential drag stabilizes the wing in yaw. The differential lift causes positive roll due to sideslip like dihedral would. Too much dihedral effect is undesirable because it opposes weight shift roll response; the aircraft will be too stable and won't manouever. The lateral and directional stability of the swept wing is proportional to angle of attack - at high speed, yaw and roll instability can become unacceptable, giving dutch roll or wing walking oscillations. This is the primary reason for over sized rear undercarriage spats and wing lets on recent high performance machines.

Thus, if one wing advances ahead of the other it presents more area to the wind and causes more drag on that side. This causes the advancing wing to go slower and to fall back. The wing is at equilibrium when the aircraft is traveling straight and both wings present the same amount of area to the wind.

The third axis, represented by pitch, is also stabilized by the sweep of the wings. A combination of high lift airfoils with moderate pitching moment such as the UI 1720 and washout (tip trailing edge upwards twist) caused by loading of the sail produces a positive pitching tendency in the wing where increasing airspeed causes increasing pitch-up. The wing centre of gravity is close to the trike hang point and is located forward of the mean aerodynamic center of the wing at a distance known as the static margin. Therefore at some speed, called the trim speed, the positive pitching of the wing is balanced by the nose down moment caused by the aircraft weight times the static margin. At the trim speed the wing will fly hands off and return to trim when disturbed. The weight shift control system only works when the wing is positively loaded. A combination of very steep nose-up pitch attitude and very low airspeed is very hazardous because of the probability of a tail slide and violent nose down pitch rotation into an irrecoverable tumble. This is the primary area of the flight envelope trike pilots must always avoid.

Pegasus Quantum 145-912 ultralight trike

When the lift load is removed from the sail the washout disappears and the aircraft would not recover from a vertical dive or may even tuck upside down. To maintain a minimum safe amount of washout when the wing is unloaded or even negatively loaded, positive pitching devices such as reflex lines or washout rods are employed. These systems are normally tested by a truck based aerodynamic test.

There is no "pendulum" wing stabilizing effect of the trike at the trim speed because the trike is freely suspended in the pitch and roll axes. To fly at other speeds, the pilot applies a pitching moment to the wing by levering the trike mass around using the control bar connected directly to the wing. The bar is pushed on to rotate the wing more nose-up and so fly slower, vice-versa for high speed. A properly designed trike will always require increasing pilot force to be applied each side of the trim speed.

The free suspension of the trike means that the center of gravity (CG) position of the trike only affects the trike attitude and control range, not the hands off trim speed. From the pilot's point of view only the load carried has to remain within the aircraft limitations, no complicated CG calculations are required and it is nearly impossible to mis-load the aircraft, adding to the simplicity of operation. One great advantage of weight shift pitch apart from simplicity is that the wing lifting performance is not compromised by up elevon deflection as required for an aerodynamically controlled tailless machine, hence a lower landing speed can be achieved. Additionally, with a pitch stable wing it is also nearly impossible to overspeed the aircraft because it will simply trim in pitch at a limited speed with the bar held fully back.

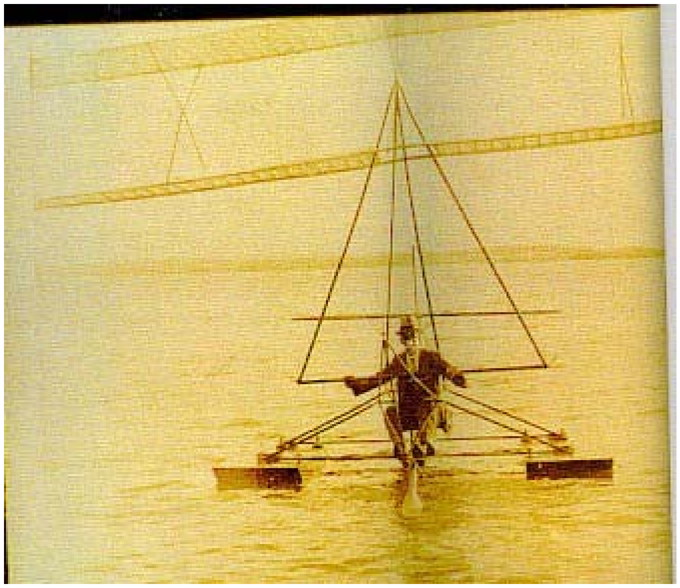
Pitch control response is very direct, but satisfactory weight shift roll response becomes more difficult to achieve as the sail is tightened to improve performance. In the roll axis, the pilot, using the wing control bar and reacting his input by the mass of the trike, applies a rolling moment directly to the wing. The wing is built to flex differentially across the span in response to the pilot applied roll moment. For example, under a right roll input, the right wing trailing edge flexes up more than the left, allowing the right wing to drop. Special features are built in such as a floating keel, four-bar control frame linkage to get a longer effective control frame height, keel pocket - all to ease roll response. Judicious use of anhedral improves roll response by converting the adverse yaw generated by the roll input into a pro-roll bank. Too much anhedral can cause instability in roll at high speeds.

Furthermore, the fact that the wing is designed to bend and flex in the wind provides favorable dynamics analogous to a spring suspension. This allows the wing to be less susceptible to turbulence and provides a gentler flying experience than a similarly sized rigid-winged aircraft.

Engine placement

Because trikes do not require an empennage, the space directly behind the pilot is used to mount the engine and propeller. Engines range from between 25-40 hp for single-seaters and 50-100 hp for two-seaters. An aft engine placement allows exhaust to stay behind the pilot and enhances visibility. It also means that the turbulent vortex of air behind the propeller is not coming in contact with the wing.

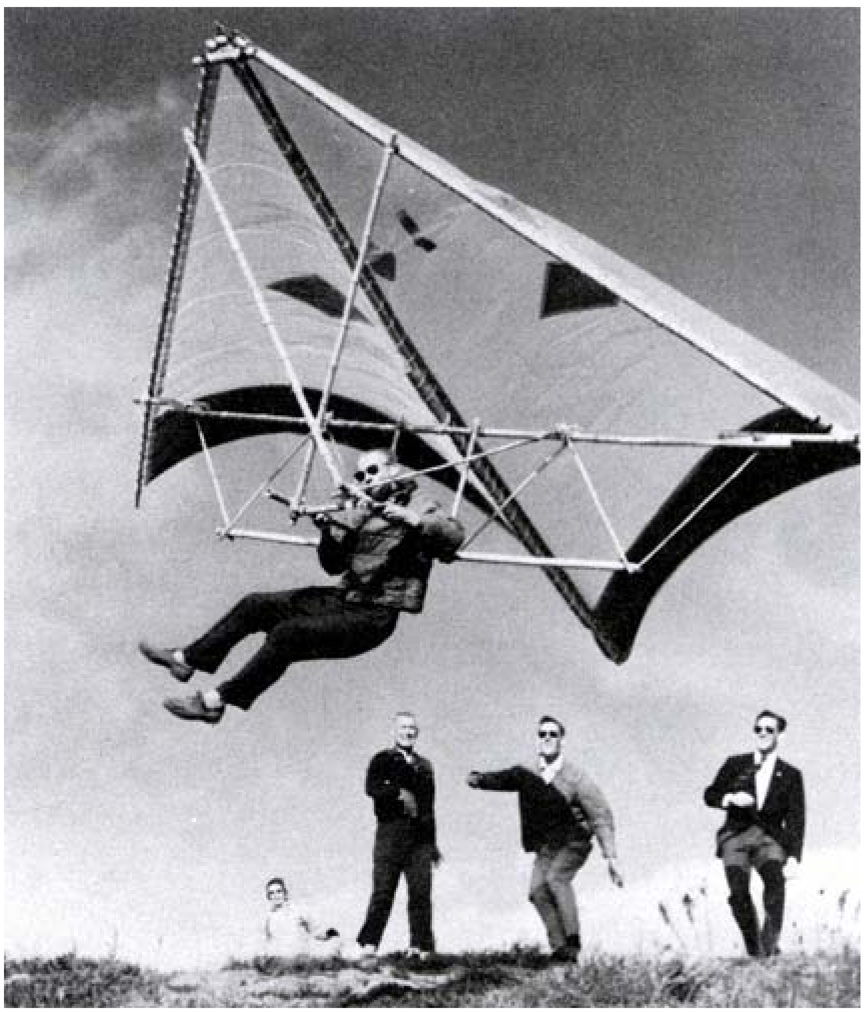
History



Dr. George A. Spratt towed his hang glider on floats using a motorboat. USA, 1929

First towing tests of NASA's Paresev glider (Para Wing Research Vehicle), March 1962

Barry Hill Palmer, 1961. First hang glider based on Rogallo's flexible wing.



Richard Miller flying his 'Bamboo Butterfly' hang glider. Vista Del Mar. California, 1966.

'Standard' flexible wing hang glider, based on variants of the Rogallo wing aircraft, 1975

Trikes are referred to as "microlights" in Europe and have been extremely popular since the 1980s. The history of the trike is traced back to the invention by Francis Rogallo's flexible wing and subsequent development by the Paresev engineering team's innovations and then others. On 1948, engineer Francis Rogallo invented a self-inflating wing which he patented on March 20, 1951 as the Flexible wing. It was on October 4, 1957 when the Russian satellite Sputnik shocked the United States and the space race caught the imagination of its government, causing major increases in U.S. government spending on scientific research, education and on the immediate creation of NASA. Rogallo was in position to seize the opportunity and released his patent to the government and with his help at the wind tunnels, NASA began a series of experiments testing Rogallo's wing - which was renamed **Para Wing**- in order to evaluate it as a recovery system for the Gemini space capsules and recovery of used Saturn rocket stages. F. Rogallo's team adapted and extended the totally flexible principle into semi-rigid variants. This mainly involved stabilizing the leading edges with compressed air beams or rigid structures like aluminum tubes. By 1960 NASA had already made test flights of a heavily framed cargo powered aircraft called the Ryan XV-8 or *Fleep* (short for 'Flying Jeep') and by March 1962, of a weight-shift experimental glider called Paresev. By 1967 all Para Wing projects were dropped by NASA in favor of using round parachutes without officially considering development of personal ultralight gliders, but the airfoil's simplicity of design and ease of construction, along with its capability of slow flight and its gentle landing characteristics, did not go unnoticed by hang glider enthusiasts. The challenge then, was to modify and fit a Rogallo flexible wing with an appropriate frame to allow it to be used as a hang glider.

Some modern Rogallo flexible winged aircraft

A crucial development toward the trike was the severe mechanical innovations developed by the Paresev and the Fleep engineers; they proved the Rogallo wing for free-flight gliding, powered and unpowered, for safe landing.

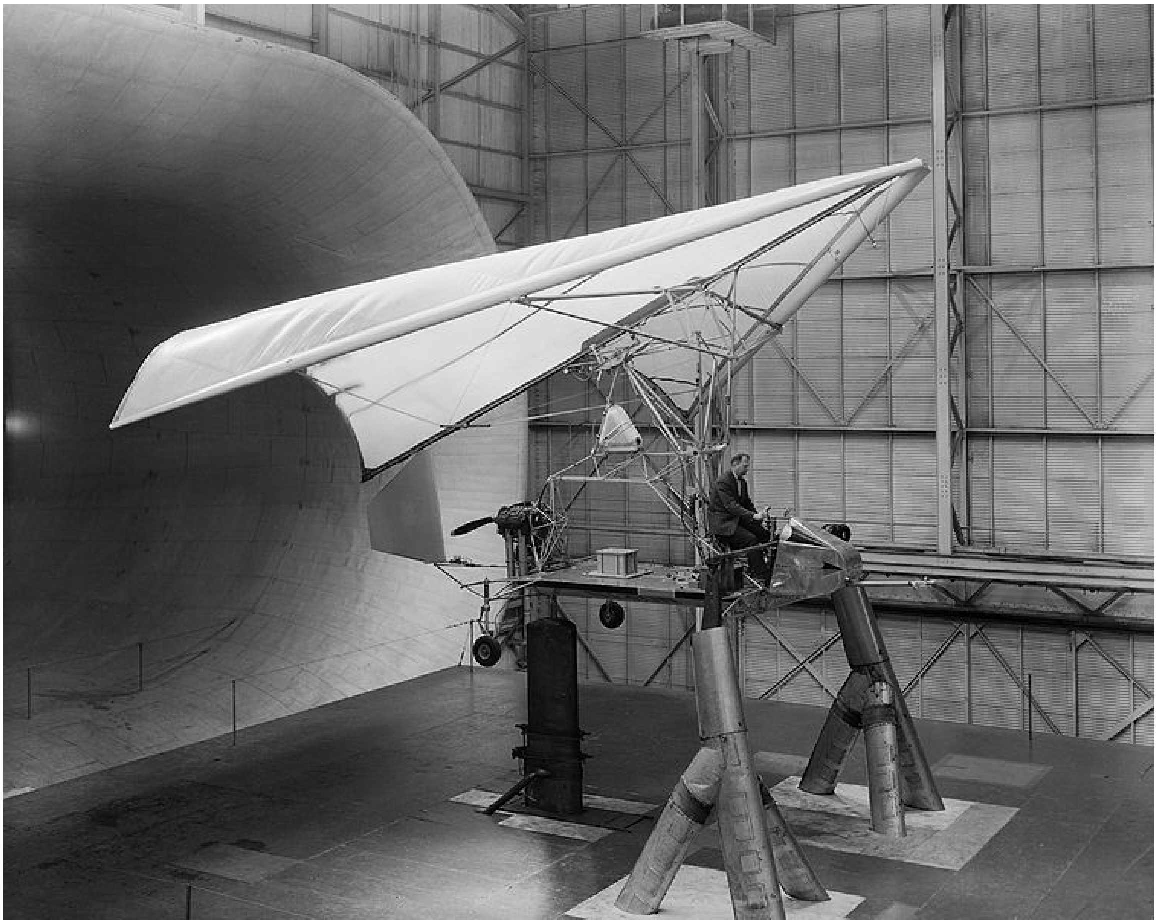
Publicity from the Fleep and the Paresev tests sparked interest in the design among several tinkerers, first through Barry Palmer. An engineer, Mike Burns of Australia, developed and used the boat-towed Rogallo airfoiled SkiPlane from 1962 through the 1960s. A fellow countryman of Mike Burns, John W. Dickenson, made ski-kites and eventually partnered with Mike Burns to improve the ski-kite; he formatted a ski-kite that used what could be found in the 1929 George A. Spratt simple triangle control bar or A-frame with single-point pendulum weight-shift control.

An influence through John Dickenson's duplication of his device, who named his flexible wing ski-kite the **Ski Wing**. Dickenson fashioned a water ski kite airframe to fit on a Rogallo airfoil where the pilot sat on a swinging seat while the control frame and wire bracing distributes the load to the wing as well as giving a frame to push/pull for weight-shift control. Dickenson's Ski Wing turned out to be stable and controllable under tow, unlike the flat manned kites used at water ski shows. The Ski Wing kite was first kited in public at the 'Grafton Jacaranda Festival' in September 1963 by **Rod Fuller** while towed behind a motorboat. Australian manufacturers like **Bill Bennett** and **Bill Moyes**, actively developed and marketed Dickenson's innovations to the world, which significantly fueled the hang glider revolution.

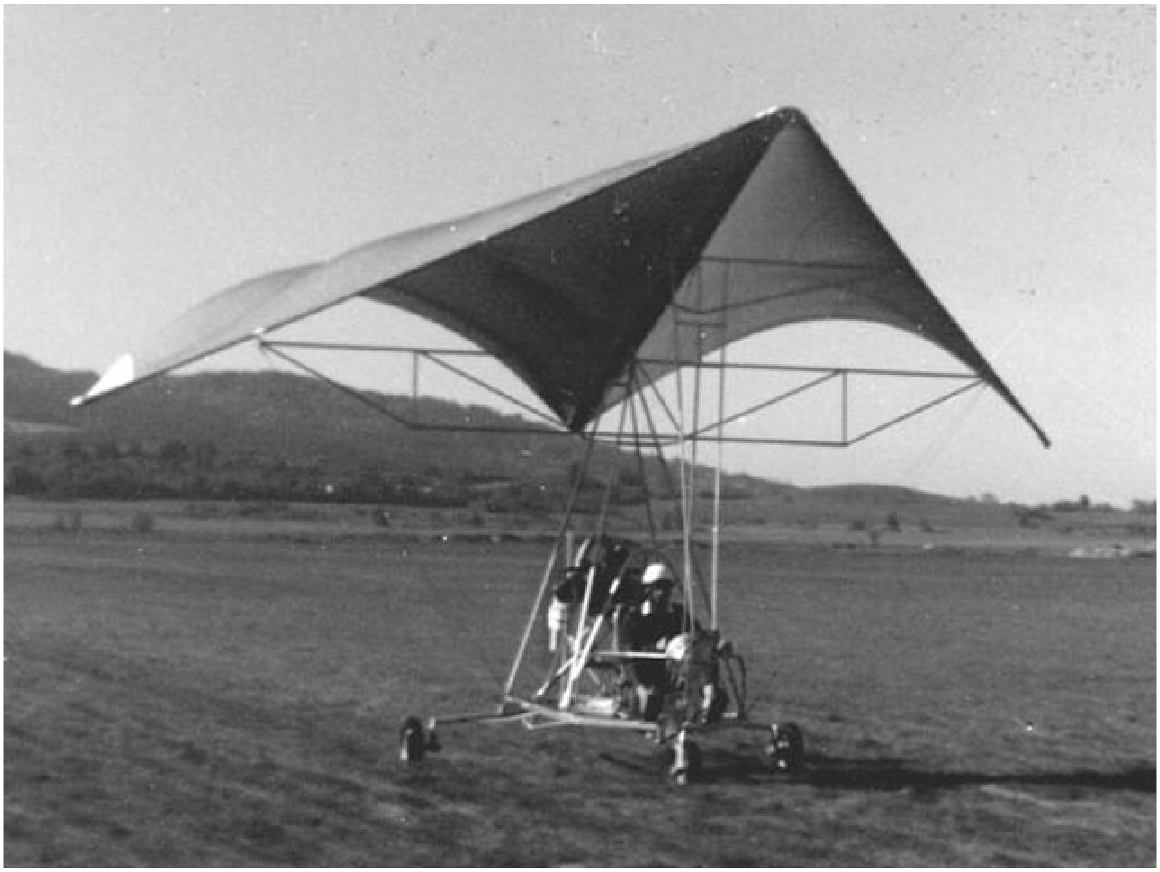
Although by the early 1970s many rigid wings were developed, none sold well, while dozens of flexible wing hang glider companies were springing up world-wide, building variants of Dickenson's Ski Wing. In 1972, Popular Mechanics and Popular Science magazines published articles on hang gliding which further increased its popularity, as the *Sky Raiders* hang gliding movie released in 1975.

Francis Rogallo, Barry Palmer, John Dickenson, and others never made any money out of their innovations. Profit to manufacturers of hang gliders and Rogallo winged hang gliders came once organized and insured sporting events grew in popularity. Dickenson's adaptation and innovations eventually produced a foldable hang glider that dramatically reduced difficulty in control, storage, transport, assembly and repair. In addition, the flexible wing lends itself open to design changes for possible improvements. The crucial developments put together by the Paresev engineers, Barry Palmer, John Dickenson, Bill Bennett, Bill Moyes, Richard Miller, and then hundreds of other innovators gave success to the flexible wing hang glider.

First trikes



Ryan XV-8 'Fleep' flown in the Full Scale Tunnel at Langley, 1962



Pierre Aubert, Switzerland, 1964

In 1961, Engineer **Thomas Purcell** built a towable Rogallo wing glider with an aluminum frame, wheels, a seat and basic control rods; soon he replaced the wheels for floats and motorized the aircraft. In 1964, Swiss inventor **Pierre Aubert** saw a photo of NASA's Fleep and completed construction of a similar trike. Like with the Fleep, his Rogallo wing was fixed and did not allow for pendulum weight-shift control.

In March 1967 aeronautical engineer Barry Palmer completed the earliest example of a true weight-shift powered trike: the **Paraplane**; it was controlled by a single vertical control bar as the Paresev experimental glider that inspired him. The Paraplane used two *West Bend-Chrysler* 820 engines of 8hp at 6000rpm, reduced to 4700rpm for about 6.5hp each, for a total of 13hp. Each engine had a direct drive to a 27in diameter two-blade propeller made of polyester and fiberglass. On March 24, 1967 Palmer registered the trike at the American FAA as the *Palmer Parawing D-6*, serial 1A, N7144; no restrictions were noted. The second Palmer trike, **Skyhook** (FAA registered N4411) in spite of its early date of origin, had most of the attributes of a modern ultralight, except it used a single cylinder snowmobile engine, as the two-stroke twin cylinders were not available yet. It was powered by a 17hp at 5000rpm single cylinder JLO L297 two stroke engine, driving a composite propeller designed and built by Palmer himself and driven by a 2.1/1 reduction gearbox. The engine had electric start and the craft had fiberglass composite spring landing gear. Airframe construction was bolted 6061-T6 aluminum thin wall tube, with 6061 T-6 extruded angle. The craft took off, flew, and landed at around 30mph. Palmer's trikes were not developed further and remained in obscurity.

The commercial availability of Dikenson's hang glider made the Rogallo wing very popular, and prompted several builders during the 1970s to attempt motorization of their flexible wing aircraft but unlike Barry Palmer -who placed the center of gravity well below the keel- most builders were mounting the engine to the wing, where a fine balance existed between applying too much power, causing the aircraft to overtake the pilot or not enough power for flight. It was not until **Roland Magallon** took a long look at the *Motodelta* ultralight (a hybrid Rogallo wing designed by Jean-Marc Geiser had a 'fuselage' and rudder) and Magallon decided replace the Motodelta's 'fuselage' with a simple tubular framework pendulum and dispensing with the rudder. Magallon is thus generally thought to have invented the trike because it was he who first marketed it. He called the first version 'Mosquito' and marketed it from October 1979 through 1981. The prototype had flown with a McCulloch MC-101A motor of 125 cc, delivering 10 hp at 8000 rpm to a direct-drive prop with ground adjustable pitch. Later he offered it with a Solo 210 engine which produced 15 hp (11 kW) at much less frantic RPM.

The "trike", as it soon became known, quickly became popular in the UK and France where it had been reborn. Trike technology still shows its hang gliding origins, though the wings are no longer converted hang gliders, but are designed for power. In fact, none of the commercially available trike wings can be used as foot-launched hang gliders as they are too heavy and too fast.

Regulation

In the United States, trikes are often referred to as "ultralight trikes" and are designed to operate under the designation of the Federal Aviation Regulations (FAR 103) that define an ultralight as a single seat vehicle with under 5 US gallons (19 L) of fuel capacity, an empty weight of less than 254 pounds (115 kg), a top speed of 55 knots (102 km/h), and a maximum stall speed that does not exceed 24 knots (45 km/h). Ultralights are only allowed to operate during daylight hours. FAR 103 makes further weight allowances for two-seat trainers(in which both persons are able to control the craft and thus definable as pilots), amphibious landing gear, and ballistic parachute systems.

A light sport aircraft (LSA) certification code has been produced for heavier and higher performance machines. This is an airworthiness code based on a consensus of industry experts, drawing from many years experience including the British BCAR-S requirements. The LSA initiative also includes similar consensus-based pilot licencing and maintenance requirements. It is proving popular, enabling more people to fly modern designs safely. Trike pilots may also obtain the private pilot certificate which permits them to fly at night, above 10,000 feet, and in other venues not permissible for ultralight or sport pilots.

Popularity

Due to their relatively low cost, low fuel consumption, light weight, ability to take off and land in very short distances, and ability to fly in somewhat turbulent conditions, trikes have become popular with recreational pilots. In particular, trikes have been used to fly across oceans, frozen tundra, barren deserts, and even into backyard landing strips. As with all types of aviation, regulations in the United States dictate where and how these aircraft are allowed to fly, especially with regard to avoiding other air traffic and populated areas. Notwithstanding, trikes continue to grow in popularity with those living in urban areas due to their portable nature and rapid assembly time. Most trikes may be transported on a very small trailer, stored in a standard garage, and assembled for flight in less than thirty minutes.

Manufacturers

There are around 56 manufacturers world-wide that build trikes. Some started out making hang glider wings and now provide both wing and undercarriage. Many produce only the undercarriage and procure their wings elsewhere. The majority of these companies are found in Europe with a number appearing in the United States. Manufacturers can also be found in India, South Africa, Australia, and elsewhere. Manufacturers often sell their ultralight trikes at a price of around $5000-10000.

Records

On January 19, 2008 Mark Jackson from Altrincham, UK, flew over Kilimanjaro. In doing so he broke the record for the highest altitude attained in a microlight (24,262 feet) and the fastest climb to 20,000 feet (25 minutes). He also broke the British record for the fastest climb to 10,000 feet (19 minutes). He did the flight with Eve Jackson.

Chapter 12

Ultralight Aviation

Huntair Pathfinder Mark 1 ultralight

The term "**ultralight aviation**" refers to light-weight, 1- or 2-person airplanes. During the late 1970s and early 1980s, many people sought to fly affordably. As a result, many aviation authorities set up definitions of lightweight, slow-flying aeroplanes that could be subject to minimum regulation. The resulting aeroplanes are commonly called **ultralight** or **microlight**, although the weight and speed limits differ from country to country.

There is also an allowance of another 10% on Maximum Take Off Weight for seaplanes and amphibians, and some countries (such as Germany and France) also allow another 5% for installation of a ballistic parachute.

The safety regulations used to approve microlights vary between countries, the strictest being in the United Kingdom, Italy, Sweden and Germany, while they are almost non-existent in France and the United States. The disparity between regulations can be a barrier to international trade and overflight in strict regions, as is the fact that these regulations are invariably sub-ICAO, which means that they are not internationally recognised.

In most affluent countries, microlights or ultralights now account for a significant portion of the civil aircraft fleet. For instance in Canada in October 2010, the ultralight fleet made up 19% of the total civil aircraft registered. In other countries that do not register ultralights, like the United States, it is unknown what proportion of the total fleet they make up.

In countries where there is no specific extra regulation, ultralights are considered regular aircraft and subject to certification requirements for both aircraft and pilot.

Ultralight aircraft are generally called *microlight aircraft* in the UK, India and New Zealand, and *ULMs* in France and Italy. Some countries differentiate between weight shift and 3-axis aircraft, calling the former *microlight* and the latter *ultralight*.

The U.S. light-sport aircraft is similar to the UK and NZ *Microlight* in definition and licensing requirement, the U.S. 'Ultralight' being in a class of its own.

Definitions

Pegasus Quantum 145-912 ultralight trike

Flight Design CTSW

A powered paraglider

A US-made Pterodactyl Ascender ultralight on a camping flight

Canadian Lazair ultralight covered in clear Mylar

Aeroprakt A-22 Foxbat 3-axis ultralight

Ikarus C42, a German ultralight

A weight-shift ultralight, the Air Creation Tanarg

Phantom - MKI

FM250 Vampire

K-10 Swift – MKI

Quicksilver MXII

A foot-launched powered hang glider

Weight Shift Ultralight ("Trike")

P and M Aviation Quik GT450 ultralight

Pipistrel Sinus 912

Rans S-6 Coyote II, classified as an ultralight aircraft in Belgium

Australian Ultralight Industries Bunyip, 3-axis ultralight

Australia

In Australia Recreational Aircraft fall under many categories, but the most common category imposes:

- a maximum take off weight (MTOW) of 544 kg (1,199 lb) or less (614 kg (1,354 lb) for a seaplane);
- a stalling speed under 45 knots in landing configuration and
- a maximum of two seats.

A new certification category for Light Sport Aircraft came into effect on 7 January 2006. This category does not replace the previous categories, but creates a new category with the following characteristics:

- A maximum takeoff weight of 600 kg (1,323 lb) or 650 kg (1,433 lb) for an aircraft intended and configured for operation on water or 560 kg (1,235 lb) for a lighter-than-air aircraft.
- A maximum stall speed in the landing configuration (Vso) of 45 kn (83 km/h) CAS.
- Maximum of two occupants, including the pilot.

- A fixed landing gear. A glider may have retractable landing gear. (For an aircraft intended for operation on water, a fixed or repositionable landing gear)
- A single, non-turbine engine fitted with a propeller.
- A non-pressurised cabin.
- If the aircraft is a glider a maximum never exceed speed (Vne) of 135 kn (250 km/h) CAS

In either of the above categories, there are distinctions between factory manufactured and home built aircraft.

In Australia, microlight aircraft are defined as one or two seat weight-shift aircraft, with a maximum takeoff weight of 450 kg (992 lb), as set out by the Civil Aviation Safety Authority. In Australia microlights are also referred to as trikes and are distinguished from three-axis aircraft, of which the smallest are known as ultralights.

In Australia, microlight aircraft and their pilots can either be registered with the Hang Gliding Federation of Australia (HGFA) or Recreational Aviation Australia (RA Aus). In all cases, except for privately built single-place ultralight aeroplanes, microlight aircraft or trikes are regulated by the Civil Aviation Regulations.

Brazil

The Brazilian Aviation Regulation (RBHA 103A) defines an ultralight plane as: a very light manned experimental aircraft used mainly, or intended for, sports or recreation, during daylight, in visual conditions, with a maximum capacity of 2 people and with the following characteristics:

- Single internal combustion engine and one propeller;
- Maximum take-off weight equal or less than 750 kg (1,653 lb); and
- Calibrated stall speed (CAS), power off, in landing configuration (Vso) equal or less than 45 kn (83 km/h).

Canada

The Canadian Aviation Regulations define two types of ultralight aeroplanes: basic ultra-light aeroplanes (BULA), and advanced ultra-light aeroplanes (AULA). The US light sport aircraft is similar to, and was based upon, the Canadian AULA. AULAs may operate at a controlled airport without prior arrangement. Operating either class of ultralight in Canada requires an Ultralight Pilot Permit which requires both ground school, dual and solo supervised flights. The ultralight may be operated from land or water, but may only carry a passenger if the pilot has an Ultralight Aeroplane Passenger Carrying Rating and the aircraft is an AULA.

Europe

The definition of a microlight according to the Joint Aviation Authorities document JAR-1 is an aeroplane having no more than two seats, maximum stall speed (V_{S0}) of 35 knots (65 km/h) CAS, and a maximum take-off mass of no more than:

- 300 kg (661 lb) for a landplane, single seater; or
- 450 kg (992 lb) for a landplane, two-seater; or
- 330 kg (728 lb) for an amphibian or floatplane, single seater; or
- 495 kg (1,091 lb) for an amphibian or floatplane, two-seater, provided that a microlight capable of operating as both a floatplane and a landplane falls below both MTOM limits, as appropriate.

India

In India a microlight is an aircraft that has the following characteristics:

- two seater aircraft having an all up weight of not more than 450 kg (992 lb) without parachute and 472 kg (1,041 lb) with parachute
- a stall speed of less than 80 km/h (43 kn)
- a maximum level speed of less than 220 km/h (119 kn)
- 1 or 2 seats
- a single engine, reciprocating, rotary or diesel
- a fixed or ground adjustable propeller
- un-pressurized cabin
- wing area more than 10 square metres
- a fixed landing gear, except for operation on water or as a glider

Indian ultralights require aircraft registration, periodic condition inspections and a current permit to fly which has to be renewed annually.

Italy

In Italy, the category for this class of aircraft is Microlight.

- Requires flying with a helmet.
- Maximum weight requirements excludes seat belts, parachute and instruments.
- Single-seat maximum weight of 300 kg (661 lb), and 330 kg (728 lb) for amphibious, stall speed must not exceed 65 km/h (35 kn).
- Two-seat maximum weight of 450 kg (992 lb), and 500 kg (1,102 lb) for amphibious, stall speed must not exceed 65 km/h (35 kn). Aircraft may be used for instruction or flown by pilots with a valid private license, and at least 30 hours flight time.
- Intended for use at private fields. Use at civil airports requires prior permission.
- Airspace restrictions - Must remain within the territory of the state (the flight limit of 4 km (2.2 nmi) from the border of another state was abolished by the law 24

April 1998, n. 128 "Disposizioni per l'adempimento di obblighi derivanti dall'appartenenza dell'Italia alle Comunità Europee" - communitary law 1995/97- art.22 comma 20-, published on the Gazzetta Ufficiale n.88/L of May 7, 1998). It is forbidden to fly over cities.

- All aircraft must have a metal plate with the identification number issued by the AeCI (Aero Club Italia). The same number must be fixed onto the underneath of the wing with letters that measure a minimum of 30×15 cm (12 X 6 inches), in contrasting colour.
- From dawn till sunset, flight must be below 500 ft (152 m)
- On Saturday and holidays flight must be below 1,000 ft (305 m) with 5 km (2.7 nmi) separation from airports not located within ATZ .
- Microlight operation requires a certificate exam, insurance and a medical examination.

New Zealand

In New Zealand microlight aircraft are separated into two classes, basically single and two seat aircraft. All microlights are required to have a prescribed endurance testing period when they are first flown, and all microlights must have a minimum set of instrumentation to show airspeed (except powered parachutes), altitude and magnetic heading.

NZ Class 1
: Single seat aircraft with a design gross weight of 544 kg (1,199 lb) (landplanes) or 579 kg (1,276 lb) (seaplanes or amphibians), or less, and a stall speed in the landing configuration of 45 knots (83 km/h) or less. Requires aircraft registration, and annual condition inspections, but does not require a permit to fly.

NZ Class 2
: Two seat aircraft with a design gross weight of 544 kg (1,199 lb) (landplanes) or 614 kg (1,354 lb) (seaplanes or amphibians), or less, and a stall speed of 45 knots (83 km/h) or less in the landing configuration. Must meet minimum type acceptance standards which may be foreign standards which have been deemed acceptable, or via a temporary permit to fly and flight testing regime. Requires aircraft registration, annual condition inspections, and a current permit to fly.

Philippines

The Civil Aviation Regulations define "non-type certified aircraft", under which ultralights and microlights fall, as:

An aircraft that does not possess an aircraft type certificate issued by any country/state. It is, of simple design and constriction, either a homebuilt or a kit built variety and for recreational and sport use, day VFR condition only.

A class of non-type certificated aircraft is applicable to all classifications, including powered parachutes, gyrocopter, fixed wing aircraft and helicopters.

United Kingdom

The UK regulations describe a microlight aeroplane as limited to two people, with a Maximum Total Weight Authorised (MTWA) not exceeding:

- 300 kg (661 lb) for a single seat landplane.
- 390 kg (860 lb) for a single seat landplane for which a UK Permit to Fly or Certificate of Airworthiness was in force prior to 1 January 2003
- 450 kg (992 lb) for a two seat landplane
- 330 kg (728 lb) for a single seat amphibian or floatplane
- 495 kg (1,091 lb) for a two seat amphibian or floatplane

A microlight must also have either a wing loading at the maximum weight authorised not exceeding 25 kg per square metre or a stalling speed at the maximum weight authorised not exceeding 35 kn (65 km/h) calibrated speed. All UK registered aeroplanes (3-axis or flex-wing) falling within these parameters are Microlight aircraft.

A sub-category of microlights (SSDR) was introduced which allows owners more freedom to modify and experiment with their aircraft. Single Seat De-Regulated microlights must weigh less than 115 kg (254 lb) without fuel and pilot and the wing loading must not be more than 10 kg per sq m. There is no airworthiness requirement or annual inspection regime for SSDR microlights although pilots who fly them must have a normal microlight licence, and must observe the rules of the air.

A license is required to fly a microlight in the UK.

United States

The United States FAA's definition of an ultralight is significantly different from that in most other countries and can lead to some confusion when discussing the topic. The governing regulation in the United States is FAR 103 Ultralight Vehicles, which specifies a powered "ultralight" as a single seat vehicle of less than 5 US gallons (19 L) fuel capacity, empty weight of less than 254 pounds (115 kg), a top speed of 55 knots (102 km/h or 64 mph), and a maximum stall speed not exceeding 24 knots (45 km/h or 27.6 mph). Restrictions include flying only during daylight hours and over unpopulated areas. Unpowered "ultralights" (hang gliders, paragliders, etc.) are limited to a weight of 155 lb (70 kg) with extra weight allowed for amphibious landing gear and ballistic parachute systems.

In 2004 the FAA introduced the "Light-sport aircraft" category, which resembles some other countries' microlight categories.

In the United States no license or training is required by law for ultralights, but training is highly advisable. For light-sport aircraft a sport pilot certificate is required.

Ultralight aviation is represented by the United States Ultralight Association (USUA), which represents the US portion of the sport to the world through its affiliation with the FAI.

Types of aircraft

While ultralight-type planes date back to the early 1900s (such as the Santos-Dumont Demoiselle), there have been three generations of modern, fixed-wing ultralight aircraft designs, which are generally classed by the type of structure.

The first generation of modern ultralights were actually hang gliders with small engines added to them, to create powered hang gliders. The wings on these were flexible, braced by wires, and steered by shifting the pilot's weight under the wing.

The second generation ultralights began to arrive in the mid-1970s. These were designed as powered aircraft, but still used wire bracing and usually single-surface wings. Most of these have "2-Axis" control systems, operated by stick or yoke, which control the elevators (pitch) and the rudder (yaw) -- there are no ailerons, so may be no direct control of banking (roll). A few 2-Axis designs use spoilers on the top of the wings, and pedals for rudder control. Examples of 2-Axis ultralights are the "Pterodactyl" and the "Quicksilver MX".

The third generation ultralights, arriving in the early 1980s, have strut-braced wings and airframe structure. Nearly all use 3-Axis control systems, as used on standard airplanes, and these are the most popular. Third generation designs include the CGS Hawk, Kolb Ultrastar and Quad City Challenger.

There are several types of aircraft which qualify as ultralights, but which do not have fixed-wing designs. These include:

- **Weight-shift control trike** - while the first generation ultralights were also controlled by weight shift, most of the current weight shift ultralights use a hang glider-style wing, below which is suspended a three wheeled carriage which carries the engine and aviators. These aircraft are controlled by pushing against a horizontal control bar in roughly the same way as a hang glider pilot flies. Trikes generally have impressive climb rates and are ideal for rough field operation, but are slower than other types of fixed-wing ultralights.

- **Powered parachutes** - cart mounted engines with parafoil wings, which are wheeled aircraft.

- **Powered paragliding** - backpack engines with parafoil wings, which are foot-launched.

- **Powered hang glider** - motorized foot-launched hang glider harness.

- **Autogyro** - rotary wing with cart mounted engine, a gyrocopter is different from a helicopter in that the rotating wing is not powered, the engine provides forward thrust and the airflow through the rotary blades causes them to *autorotate* or "spin up" to create lift. Most of these use a design based on the Bensen B-8 gyrocopter.

- **Helicopter** - there are a number of single-seat and two-place helicopters which fall under the microlight categories in countries such as New Zealand. However, few helicopter designs fall within the more restrictive ultralight category defined in the United States of America. One example that does is the experimental Martin Jetpack.

- **Hot air balloon** - there are numerous ultralight hot air balloons in the US, and several more have been built and flown in France and Australia in recent years. Some ultralight hot air balloons are hopper balloons, while others are regular hot air balloons that carry passengers in a basket.

Electric powered ultralights

Research has been conducted in recent years to replace gasoline engines in ultralights with electric motors powered by batteries to produce electric aircraft. This has now resulted in practical production electric power systems for some ultralight applications. These developments have been motivated by cost as well as environmental concerns. In many ways ultralights are a good application for electric power as some models are capable of flying with low power, which allows longer duration flights on battery power.

In 2007 ElectraFlyer began offering engine kits to convert ultralight weight shift trikes to electric power. The 18 hp motor weighs 26 lb (12 kg) and an efficiency of 90% is claimed by designer Randall Fishman. The battery consists of a lithium-polymer battery pack of 5.6kwh which provides 1.5 hours of flying in the trike application. The power system for a trike costs USD $8285. to $11285. The company claims a flight recharge cost of 60 cents.

Safety

Historically, ultralights have had a poor safety reputation. Most of the early designs were fragile or unstable, and this resulted in a number of accidents.

As designs matured, pilot error was shown to be the cause of the vast majority of incidents involving ultralights. As a result, most countries now require an Ultralight Pilot's license/certificate, often regulated by one or more officially-delegated pilots' organizations. The United States does not require any training for ultralight pilots; however, experienced ultralighters are nearly unanimous in recommending that no one solo before receiving dual training. Instruction may be given in two-place light-sport versions of the ultralight. An instructor must be certified by the FAA to give dual instruction in a light-sport aircraft.

The build quality and airworthiness of ultralight aircraft (and homebuilt light-sport aircraft in the USA) can now equal that of Certified light aircraft. Some types satisfy both sets of requirements and are available for registration to either Ultralight or Certified status. When registered as an ultralight (or Experimental), the pilot is permitted to do more of the simple maintenance tasks, resulting in a lower cost of operation, although this comes at the cost of restrictions such as avoiding densely populated urban areas, bad weather, or night. Many older pilots are willing to trade these operational restrictions for a lower drain on their retirement incomes, and as a result many ultralights are now flown by experienced General Aviation (GA) pilots or ex-commercial pilots. One other reason for this increase in acceptance is that any pilot is "only one medical away from being an ultralight pilot" -- a reference to the requirement that most other pilots must pass periodic physical examinations, but not to fly ultralights.

The future

Ultralight/microlight aircraft were once regarded as "flying clotheslines", since early aircraft were typically completely open, wire, tube and rag aircraft – these aircraft were seldom used for anything more than local area flying.

However, ultralights are rapidly transforming into high performance aircraft, capable of very respectable speed and range. In recent years there has been a dramatic rise in the number of General Aviation pilots flying high performance ultralights due to the cost benefits.

These aircraft are now often referred to as recreational aircraft.

A rapidly growing area of the class is scale-replica "warbirds", such as the offerings from Titan Aircraft and Loehle Aircraft.

Chapter 13

Stability Derivatives

$$C_{M_\alpha}$$

A Stability Derivative. This is an example of a common shorthand notation for stability derivatives. The "M" indicates it is a measure of *pitching* moment changes. The α indicates the changes are in response to changes in Angle of Attack. This stability derivative is pronounced "see-em-alpha". It is one measure of how strongly an aircraft wants to fly "nose first", which is clearly very important.

Stability Derivatives, and also ***Control Derivatives***, are measures of how particular forces and moments on an aircraft change as other parameters related to stability change (parameters such as airspeed, altitude, Angle of attack, etc.). For a defined "trim" flight condition, changes and oscillations occur in these parameters. *Equations of motion* are used to analyze these changes and oscillations. Stability and control derivatives are used to linearize (simplify) these equations of motion so the stability of the vehicle can be more readily analyzed.

Stability and control derivatives change as flight conditions change. The collection of stability and control derivatives as they change over a range of flight conditions is called an **Aero Model**. Aero models are used in engineering **flight simulators** to analyze stability, and in real-time flight simulators for training and entertainment.

Stability derivative vs. *Control* derivative

Stability derivatives and *Control* derivatives are related because they both are measures of forces and moments on a vehicle as other parameters change. Often the words are used together and abbreviated in the term "S&C derivatives". They differ in that stability derivatives measure the effects of changes in flight conditions while control derivatives measure effects of changes in the control surface positions:

- A ***stability*** **derivative** measures how much change occurs in a force or moment acting on the vehicle when there is a small change in a ***flight condition parameter*** such as angle of attack, airspeed, altitude, etc. (Such parameters are called "states".)
- A ***control*** **derivative** measures how much change occurs in a force or moment acting on the vehicle when there is a small change in the ***deflection of a control surface*** such as the ailerons, elevator, and rudder.

Uses

Linearization (simplification) of stability analysis

Stability and control derivatives change as flight conditions change. That is, the forces and moments on the vehicle are seldom simple (linear) functions of its states. Because of this, the dynamics of atmospheric flight vehicles can be difficult to analyze. The following are two methods used to tackle this complexity.

Small oscillations about otherwise steady flight conditions
One way to simplify analysis is to consider only small oscillations about otherwise steady flight conditions. The set of flight conditions (such as altitude, airspeed, angle of attack) are called "trim" conditions when they are steady and not changing. When flight conditions are steady, stability and control derivatives are constant and can be more easily analyzed mathematically. The analysis at a single set of flight conditions is then applied to a range of different flight conditions.

Application in simulators for stability analysis
In a flight simulator, it is possible to "look up" new values for stability and control derivatives as conditions change. And so, the "linear approximations" aren't as great and stability can be assessed in maneuvers that span a greater range of flight conditions. Flight simulators used for analysis such as this are called "engineering simulators". The set of values for stability and control derivatives (as they change over various flight conditions) is called an **Aero Model**.

Use in flight simulators

In addition to engineering simulators, aero models are often used in *real time flight simulators* for home use and professional flight training.

Names for the axes of vehicles

Air vehicles use a coordinate system of axes to help name important parameters used in the analysis of stability. All the axes run through the center of gravity (called the "CG"):

- "X" or "x" axis runs from back to front along the body, called the *Roll Axis*.
- "Y" or "y" axis runs left to right along the wing, called the *Pitch Axis*.
- "Z" or "z" runs from top to bottom, called the *Yaw Axis*.

Two slightly different alignments of these axes are used depending on the situation: "Body-fixed Axes", and "Stability Axes".

Body-fixed Axes

Body-fixed axes, or "Body Axes", are defined and fixed relative to the body of the vehicle.:

- X body axis is aligned along the vehicle body and is usually positive toward the normal direction of motion.
- Y body axis is at a right angle to the x body axis and is oriented along the wings of the vehicle. If there are no wings (as with a missile), a "horizontal" direction is defined in a way that is useful. The Y body axis is usually taken to be positive to right side of the vehicle.
- Z body axis is perpendicular to wing-body (XY) plane and usually points downward.

Stability Axes

Aircraft (usually not missiles) operate at a nominally constant "trim" angle of attack. The angle of the nose (the X Axis) does not align with the direction of the oncoming air. The difference in these directions *is* the *angle of attack*. So, for many purposes, parameters are defined in terms of a slightly modified axis system called "stability axes". The stability axis system is used to get the X axis aligned with the oncoming flow direction. Essentially, the body axis system is rotated about the Y body axis by the trim angle of attack and then "re-fixed" to the body of the aircraft:

- X stability axis is aligned into the direction of the oncoming air in *steady* flight. (It is projected into the plane made by the X and Z body axes if there is sideslip).
- Y stability axis is the *same* as the Y body-fixed axis.
- Z stability axis is perpendicular to the plane made by the X stability axis and the Y *body* axis.

Names for Forces, Moments, and Velocities

Forces and velocities along each of the axes

Forces on the vehicle along the body axes are called "Body-axis Forces":

- X, or F_X, is used to indicate forces on the vehicle along the X axis
- Y, or F_Y, is used to indicate forces on the vehicle along the Y axis
- Z, or F_Z, is used to indicate forces on the vehicle along the Z axis

- u (lower case) is used for speed of the oncoming flow along the X body axis
- v (lower case) is used for speed of the oncoming flow along the Y body axis
- w (lower case) is used for speed of the oncoming flow along the Z body axis

  It is helpful to think of these speeds as projections of the relative wind vector on to the three body axes, rather than in terms of the translational motion of the vehicle relative to the fluid. As the body rotates relative to direction of the relative wind, these components change, even when there is no net change in speed.

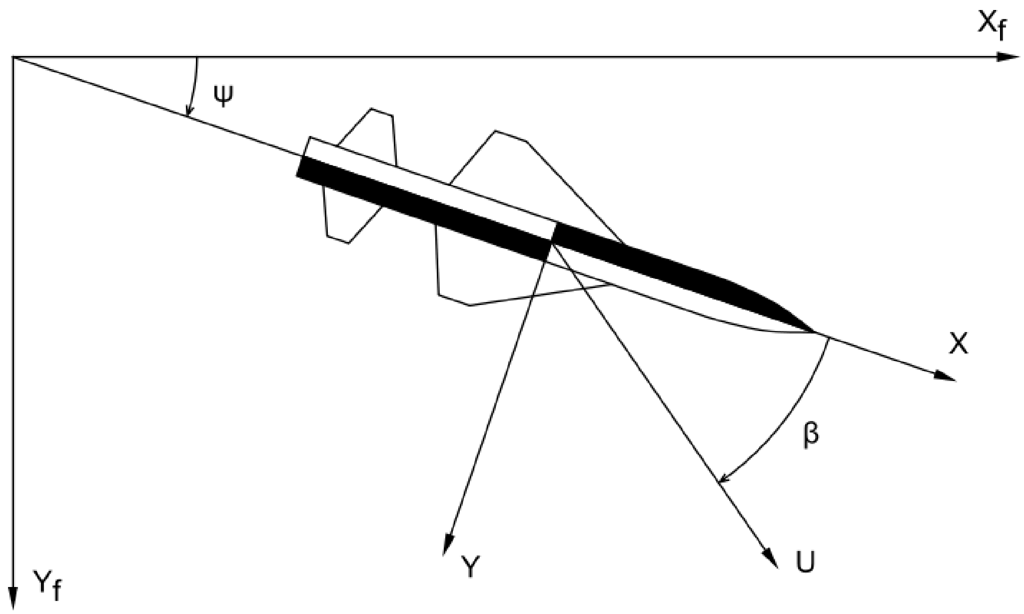
Moments and angular rates around each of the axes

- L is used to indicate the "rolling moment", which is around the X axis. Whether it is around the X body axis or the X stability axis depends on context (such as a subscript).
- M is used to indicate the name of the "pitching moment", which is around the Y axis.
- N is used to indicate the name of the "yawing moment", which is around the Z axis. Whether it is around the Z body axis or the Z stability axis depends on context (such as a subscript).

- "P" or "p" is used for angular rate about the X axis ("Roll rate about the roll axis"). Whether it is around the X body axis or the X stability axis depends on context (such as a subscript).
- "Q" or "q" is used for angular rate about the Y axis ("Pitch rate about the pitch axis").
- "R" or "r" is used for angular rate about the Z axis ("Yaw rate about the yaw axis"). Whether it is around the Z body axis or the Z stability axis depends on context (such as a subscript).

Equations of Motion

The use of stability derivatives is most conveniently demonstrated with missile or rocket configurations, because these exhibit greater symmetry than aeroplanes, and the equations of motion are correspondingly simpler. If it is assumed that the vehicle is roll-controlled, the pitch and yaw motions may be treated in isolation. It is common practice to consider the yaw plane, so that only 2D motion need be considered. Furthermore, it is assumed that thrust equals drag, and the longitudinal equation of motion may be ignored.



Derivation of Equations of Motion

The body is oriented at angle ψ (psi) with respect to inertial axes. The body is oriented at an angle β (beta) with respect to the velocity vector, so that the components of velocity in body axes are:

$$u = U\cos\beta$$
$$v = U\sin\beta$$

where U is the speed.

The aerodynamic forces are generated with respect to body axes, which is not an inertial frame. In order to calculate the motion, the forces must be referred to inertial axes. This requires the body components of velocity to be resolved through the heading angle (β) into inertial axes.

Resolving into fixed (inertial) axes:

$$u_f = U\cos(\beta)\cos(\psi) - U\sin(\beta)\sin(\psi) = U\cos(\beta + \psi)$$
$$v_f = U\sin(\beta)\cos(\psi) + U\cos(\beta)\sin(\psi) = U\sin(\beta + \psi)$$

The acceleration with respect to inertial axes is found by differentiating these components of velocity with respect to time:

$$\frac{du_f}{dt} = \frac{dU}{dt}\cos(\beta+\psi) - U\frac{d(\beta+\psi)}{dt}\sin(\beta+\psi)$$
$$\frac{dv_f}{dt} = \frac{dU}{dt}\sin(\beta+\psi) + U\frac{d(\beta+\psi)}{dt}\cos(\beta+\psi)$$

From Newton's Second Law, this is equal to the force acting divided by the mass. Now forces arise from the pressure distribution over the body, and hence are generated in body axes, and not in inertial axes, so the body forces must be resolved to inertial axes, as Newton's Second Law does not apply in its simplest form to an accelerating frame of reference.

Resolving the body forces:

$$X_f = X\cos(\psi) - Y\sin(\psi)$$
$$Y_f = Y\cos(\psi) + X\sin(\psi)$$

Newton's Second Law, assuming constant mass:

$$X_f = m\frac{du_f}{dt}$$
$$Y_f = m\frac{dv_f}{dt}$$

where m is the mass. Equating the inertial values of acceleration and force, and resolving back into body axes, yields the equations of motion:

$$X = m\frac{dU}{dt}\cos(\beta) - mU\frac{d(\beta+\psi)}{dt}\sin(\beta)$$
$$Y = m\frac{dU}{dt}\sin(\beta) + mU\frac{d(\beta+\psi)}{dt}\cos(\beta)$$

The sideslip, β, is a small quantity, so the small perturbation equations of motion become:

$$X = m\frac{dU}{dt}$$
$$Y = mU\frac{d(\beta+\psi)}{dt}$$

The first resembles the usual expression of Newton's Second Law, whilst the second is essentially the centrifugal acceleration. The equation of motion governing the rotation of the body is derived from the time derivative of angular momentum:

$$N = C\frac{d^2\psi}{dt^2}$$

where C is the moment of inertia about the yaw axis. Assuming constant speed, there are only two state variables; β and $\frac{d\psi}{dt}$, which will be written more compactly as the yaw rate r. There is one force and one moment, which for a given flight condition will each be functions of β, r and their time derivatives. For typical missile configurations the forces and moments depend, in the short term, on β and r. The forces may be expressed in the form:

$$Y = Y_0 + \frac{\partial Y}{\partial \beta}\beta + \frac{\partial Y}{\partial r}r$$

where Y_0 is the force corresponding to the equilibrium condition (usually called the trim) whose stability is being investigated. It is common practice to employ a shorthand:

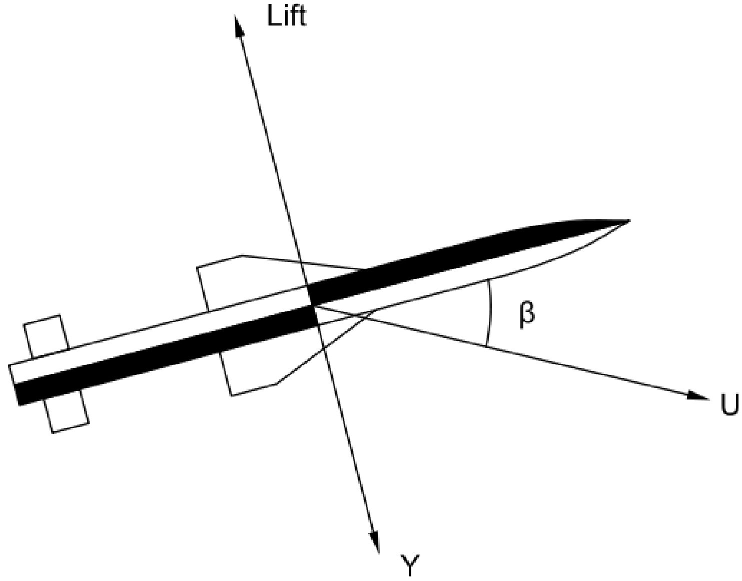
$$\frac{\partial Y}{\partial \beta} = Y_\beta$$

The partial derivative $\frac{\partial Y}{\partial \beta}$ and all similar terms characterising the increments in forces and moments due to increments in the state variables are called stability derivatives. Typically, $\frac{\partial Y}{\partial r}$ is insignificant for missile configurations, so the equations of motion reduce to:

$$\frac{d\beta}{dt} = \frac{Y_\beta}{mU}\beta - r$$
$$\frac{dr}{dt} = \frac{N_\beta}{C}\beta + \frac{N_r}{C}r$$

Stability Derivative Contributions

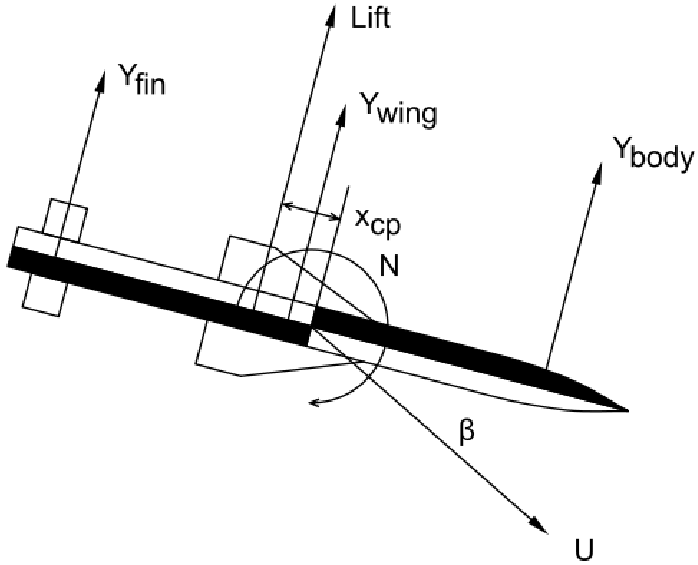
Each stability derivative is determined by the position, size, shape and orientation of the missile components. In aircraft, the directional stability determines such features as dihedral of the main planes, size of fin and area of tailplane, but the large number of important stability derivatives involved precludes a detailed discussion. The missile is characterised by only three stability derivatives, and hence provides a useful introduction to the more complex aeroplane dynamics.



Sign of Y_β

This diagram shows *lift* as perpendicular to the longitudinal body axis. In most technical usage, lift is perpendicular to the oncoming flow. That is, perpendicular to the longitudinal *stability* axis.

Consider first Y_β, a body at an angle of attack β generates a lift force in the opposite direction to the motion of the body. For this reason Y_β is always negative.

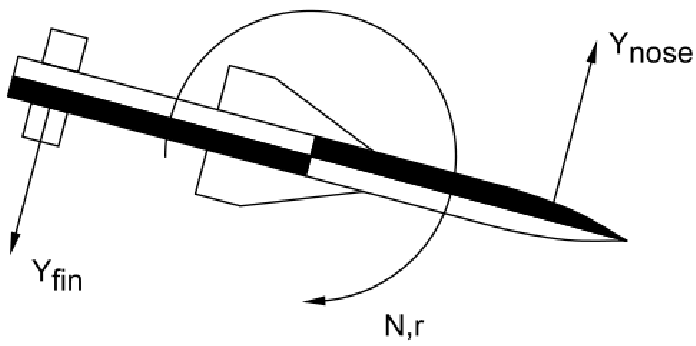


Static Stability and N_β

This diagram shows *lift* as perpendicular to the longitudinal body axis. In most technical usage, lift is perpendicular to the oncoming flow. That is, perpendicular to the longitudinal *stability* axis.

At low angles of attack, the lift is generated primarily by the wings, fins and the nose region of the body. The total lift acts at a distance x_{cp} ahead of the centre of gravity (it has a negative value in the figure), this, in missile parlance, is the centre of pressure . If the lift acts ahead of the centre of gravity, the yawing moment will be negative, and will tend to increase the angle of attack, increasing both the lift and the moment further. It follows that the centre of pressure must lie aft of the centre of gravity for static stability. x_{cp} is the static margin and must be negative for longitudinal static stability. Alternatively, positive angle of attack must generate positive yawing moment on a statically stable missile, i.e. N_β must be positive. It is common practice to design manoeuvrable missiles with near zero static margin (i.e. neutral static stability).

The need for positive N_β explains why arrows and darts have flights and unguided rockets have fins.



Yaw Dumping (N_r)

The effect of angular velocity is mainly to decrease the nose lift and increase the tail lift, both of which act in a sense to oppose the rotation. N_r is therefore always negative. There is a contribution from the wing, but since missiles tend to have small static margins (typically less than a calibre), this is usually small. Also the fin contribution is greater than that of the nose, so there is a net force Y_r, but this is usually insignificant compared with Y_β and is usually ignored.

Response

Manipulation of the equations of motion yields a second order homogeneous linear differential equation in the angle of attack β:

$$\frac{d^2\beta}{dt^2} - \left(\frac{Y_\beta}{mU} + \frac{N_r}{C}\right)\frac{d\beta}{dt} + \left(\frac{N_\beta}{C} + \frac{Y_\beta}{mU}\frac{N_r}{C}\right)\beta = 0$$

The qualitative behavior of this equation is considered in directional stability. Since Y_β and N_r are both negative, the damping is positive. The stiffness does not only depend on the static stability term N_β, it also contains a term which effectively determines the angle of attack due to the body rotation. The distance of the center of lift, including this term, ahead of the centre of gravity is called the maneuver margin. It must be negative for stability.

This damped oscillation in angle of attack and yaw rate, following a disturbance, is called the 'weathercock' mode, after the tendency of a weathercock to point into wind.

Comments

The state variables were chosen to be the angle of attack β and the yaw rate r, and have omitted the speed perturbation u, together with the associated derivatives e.g. Y_u. This may appear arbitrary. However, since the timescale of the speed variation is much greater than that of the variation in angle of attack, its effects are negligible as far as the directional stability of the vehicle is concerned. Similarly, the effect of roll on yawing motion was also ignored, because missiles generally have low aspect ratio configurations and the roll inertia is much less than the yaw inertia, consequently the roll loop is expected to be much faster than the yaw response, and is ignored. These simplifications of the problem based on *a priori* knowledge, represent an engineer's approach. Mathematicians prefer to keep the problem as general as possible and only simplify it at the end of the analysis, if at all.

Aircraft dynamics is more complex than missile dynamics, mainly because the simplifications, such as separation of fast and slow modes, and the similarity between pitch and yaw motions, are not obvious from the equations of motion, and are consequently deferred until a late stage of the analysis. Subsonic transport aircraft have high aspect ratio configurations, so that yaw and roll cannot be treated as decoupled. However, this is merely a matter of degree; the basic ideas needed to understand aircraft dynamics are covered in this simpler analysis of missile motion.

Control Derivatives

Deflection of control surfaces modifies the pressure distribution over the vehicle, and these are dealt with by including perturbations in forces and moments due to control deflection. The fin deflection is normally denoted ζ (zeta). Including these terms, the equations of motion become:

$$\frac{d\beta}{dt} = \frac{Y_\beta}{mU}\beta - r + \frac{Y_\zeta}{mU}\zeta$$
$$\frac{dr}{dt} = \frac{N_\beta}{C}\beta + \frac{N_r}{C}r + \frac{N_\zeta}{C}\zeta$$

Including the control derivatives enables the response of the vehicle to be studied, and the equations of motion used to design the autopilot.

Examples

- $\mathbf{C_{L\beta}}$, called *Dihedral Effect*, is a stability derivative that measures changes in *rolling moment* as Angle of sideslip changes. The "L" indicates *rolling* moment and the β indicates sideslip angle.

Chapter 14

Thrust Reversal

A KLM Fokker 70 rolling out with flaps fully extended, spoilers raised, and reverse thrust selected. The two reverse thrust buckets behind each engine can be seen in the deployed position, diverting the engine exhaust gases forward

Thrust reversal, also called **reverse thrust**, is the temporary diversion of an aircraft engine's exhaust or changing of propeller pitch so that the thrust produced is directed forward, rather than aft. This acts against the forward travel of the aircraft, providing deceleration. Thrust reversers are used by many jet aircraft to help slow down just after touch-down, reducing wear on the brakes and enabling shorter landing distances. It is also available on many propeller-driven aircraft through reversing the controllable pitch propellers to a negative angle.

Operation

Thrust reversers deployed on the outer two of the four turbofans of an Ilyushin Il-62 landing at Munich Airport

Reverse thrust is typically applied immediately after touchdown, often along with spoilers, to improve deceleration early in the landing roll when residual aerodynamic lift and high speed limit the effectiveness of the friction brakes located on the landing gear. Reverse thrust is always selected manually, either using levers attached to the thrust levers, or by moving the thrust levers into a reverse thrust 'gate'. When thrust is reversed, passengers will hear a sudden increase in engine noise, particularly those seated just forward of the engines.

Thrust reverser deployed on the Pratt & Whitney JT8D-7 turbofan engine of an Aloha Airlines Boeing 737-200 landing at Honolulu, HI

The early deceleration provided by reverse thrust can reduce landing roll by a third or more. Regulations dictate, however, that a plane must be able to land on a runway without the use of thrust reversers in order to be certified to land there as part of scheduled airline service.

Once the aircraft's speed has slowed, thrust reverse is shut down to prevent the reversed airflow from raising debris in front of the engine intakes where it can be ingested, causing foreign object damage. Thrust reverse is effective at any aircraft speed, and, if circumstances require, can be used all the way to a stop, or even to provide thrust to push the aircraft backward, though aircraft tugs or towbars are more commonly used for that purpose. When reverse thrust is used to push an aircraft back from the gate, the maneuver is called a powerback.

If the full power of reverse thrust is not desirable, thrust reverse can be operated with the throttles set at less than full power, even down to idle power, which reduces stress and wear on engine components. Reverse thrust is sometimes selected on idling engines to eliminate residual thrust, particularly in icy or slippery conditions, or where the engines' jet blast could do damage.

In-flight operation

Some aircraft are able to safely use reverse thrust in flight, though the majority of these are propeller-driven. Many commercial aircraft cannot use reverse thrust in flight. Exceptions include Russian and Soviet aircraft which are able to reverse thrust in flight (mostly before touchdown). In-flight use of reverse thrust has several advantages: It allows for rapid deceleration, enabling quick changes of speed; it also prevents the speed buildup normally associated with steep dives, allowing for rapid loss of altitude, which can be especially useful in hostile environments such as combat zones, and when making steep approaches to land.

For example, the ATR 72 turboprop can reverse thrust in flight, should the appropriate control lock be withdrawn. The Hawker Siddeley Trident, a 120-180 seat airliner, was capable of descending at up to 10,000 ft/min (3,050 m/min) by use of the thrust reversers, though this capability was rarely used. Concorde could also use reverse thrust in the air to increase the rate of descent. Only the inboard engines are used and the engines are placed only in reverse idle when subsonic and below 30,000 ft. This will increase the rate of descent to around 10,000 fpm. The US Air Force's C-17A is one of the few modern aircraft that uses reverse thrust in flight. The Boeing-manufactured aircraft is capable of in-flight deployment of reverse thrust on all four engines to facilitate steep tactical descents up to 15,000 ft/min (4,600 m/min) into combat environments (this means that the aircraft's descent rate is just over 170 mph, or 274 km/h). The Saab 37 Viggen (retired in November 2005) also had the ability to use reverse thrust before landing, enabling the use of many roads constructed in Sweden to double as wartime runways.

The Shuttle Training Aircraft, a highly modified Grumman Gulfstream II, uses reverse thrust in flight to help simulate the Space Shuttle aerodynamics so astronauts can practice landings.

Types of aircraft

Small aircraft typically do not feature reverse thrust, except in specialized applications. Conversely, large aircraft (weighing more than 12,500 lb) almost always have the ability to reverse thrust. Both reciprocating engine and turboprop aircraft can have reverse thrust, and almost all propeller aircraft with reverse thrust have the ability to set the propeller angle to flat pitch (called Beta range) which generates no forward or reverse thrust, but provides large amounts of drag. This is especially useful in aircraft with complex reciprocating or turbine engines, as it enables engine speed to be kept high as the aircraft descends, avoiding doing damage to the engines by shock cooling them.

Controllable pitch propeller on one of the four turboprop engines of a United States Air Force Lockheed C-130 Hercules

Propeller-driven aircraft

Propeller-driven aircraft generate reverse thrust by changing the angle of their controllable pitch propellers so that the propellers direct their thrust forward, instead of aft as normal. Reverse thrust has been available on propeller aircraft dating back to the 1930s. Reverse thrust became available due to the development of controllable-pitch propellers, which change the angle of the propeller blades to make efficient use of engine power over a wide range of conditions.

Multi-engine

Early multi-engine aircraft such as the Boeing 247 and Douglas DC-2 were among the first to feature reverse thrust. As piston aircraft became heavier and more complex, reverse thrust became more important to allow them to operate from airports originally configured to handle the smaller planes of previous years. Additionally, the higher performance and greater altitude attainable by post World War II piston aircraft like the Lockheed Constellation made the ability to use flat pitch, or, in extreme cases, reverse thrust, in order to descend and slow for landing without over-cooling the engines or approaching the runway with excessive speed. Finally, the advent of turboprops like the Vickers Viscount and Lockheed Electra brought even higher speeds and cruising altitudes to the fleet, as well as increased power that could be used both for improved performance and to provide reverse thrust.

Single-engine

Single-engine aircraft tend to be of such limited size that the weight and complexity of reverse thrust is unwarranted. However, large single-engine aircraft like the Cessna Caravan & Pilatus Porter do have reverse thrust available, and single-engine seaplanes and flying boats tend to have reverse thrust as well. In other respects, reverse thrust on single-engine aircraft works much like that on other propeller aircraft.

Twin radial engine Canadair CL-215 flying boat used for firefighting by the Minnesota Department of Natural Resources

Seaplanes and flying boats

One special application of reverse thrust comes in its use on seaplanes and flying boats. These aircraft, when landing on water, have no conventional braking method and must rely on slaloming and/or reverse thrust, as well as the drag of the water in order to slow or stop. Additionally, reverse thrust is often necessary for manoeuvring on the water, where it is used to make tight turns or even back the aircraft, such as when leaving a dock or beach.

Jet aircraft

On aircraft using jet engines, thrust reversal is accomplished by causing the jet blast to flow forward rather than aft. The engine does not run or rotate in reverse; instead, thrust reversers are used to block the blast and redirect it forward. Two methods are commonly used: In the target-type thrust reverser, the reverser blades angle outward, giving the general appearance of flower petals, and forcing engine thrust to flow forward. In the clamshell type, two reverser buckets are hinged so that when they deploy, they intrude into the exhaust of the engine, capturing and reorienting the jet blast. This type of reverser is usually clearly visible at the rear of the engine during use.

Turbofan

Boeing C-17 creating a visible vortex while demonstrating the use of reverse thrust to push the aircraft backwards down the runway.

In addition to the two types used on turbojet and low-bypass turbofan engines, a third type of thrust reverser is found on some high-bypass turbofan engines. Doors in the bypass duct are used to redirect the air that has been accelerated by the engine's fan section but has not passed through the combustion chamber (called bypass air) so that it provides reverse thrust.

The Boeing C-17 has a rare form of the above type in which even the exhaust from the core is redirected along with the main fan's air. This gives the C-17 unrivaled stopping ability among large jet powered aircraft.

Thrust-reverse related accidents

EasyJet Airbus A319 taxis after landing, with thrust reversers deployed

In-flight deployment of thrust reversers has directly contributed to the crashes of several transport-type aircraft:

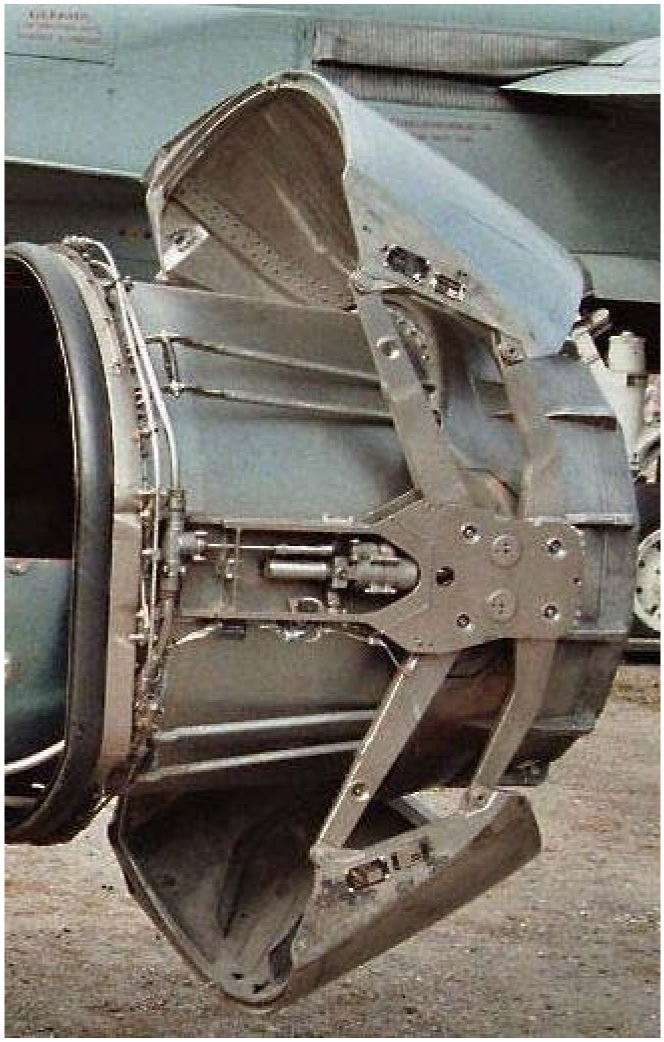
- On 9 February 1982 Japan Airlines Flight 350 crashed 1,000 feet (300 m) short of the runway at Tokyo Haneda Airport following the intentional deployment of reverse thrust on two of the DC-8's four engines in an apparent suicide attempt, resulting in 24 passenger deaths.

- On August 29, 1990, a Lockheed C-5A crashed shortly after take-off from Ramstein Air Base in Germany. As the aircraft started to climb off the runway, one of the thrust reversers suddenly deployed. This resulted in loss of control of the aircraft and the subsequent crash. Of the seventeen people on board, only four survived the crash.
- On 26 May 1991 Lauda Air Flight NG004. The Boeing 767-300 aircraft suffered an uncommanded deployment of the No. 1 thrust reverser, which caused the airliner to stall and crash. All 213 passengers and 10 crew were killed.
- On October 31, 1996, TAM Linhas Aéreas Flight 402. The Fokker 100 crashed shortly after take-off from Congonhas/São Paulo International Airport, São Paulo, Brazil, striking an apartment building and several houses. All 90 passengers and 6 crew members on board died. Three people were killed on the ground. The crash was attributed to the uncommanded deployment of a faulty thrust-reverser on the right engine shortly after take-off.

At least one accident is related to a small part of a thrust reverser, which had fallen off of another aircraft:

- The Air France Concorde crash of 2000 was attributed to a fragment of titanium that fell from the thrust reverser of a Continental Airlines DC-10 that had taken off some four minutes earlier. This fragment was traced to a third party parts replacement which had not been approved by the FAA.

An Air Canada Boeing 777 with thrust reversers deployed, visible as a gap in the engine nacelle



Thrust reverser (clamshell-type) on a Rolls-Royce RB199 jet engine

Controllable pitch propeller on the singe-turboprop of a FedEx Cessna 208B Grand Caravan

KLM Fokker 100 landing with reverse-thrust buckets deployed.

Antonov An-74 moving with reverse-thrust