Introduction to Aeronautics

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First Edition, 2012

ISBN 978-81-323-2870-4

Published by:
Orange Apple
4735/22 Prakashdeep Bldg,
Ansari Road, Darya Ganj,
Delhi - 110002
Email: info@wtbooks.com

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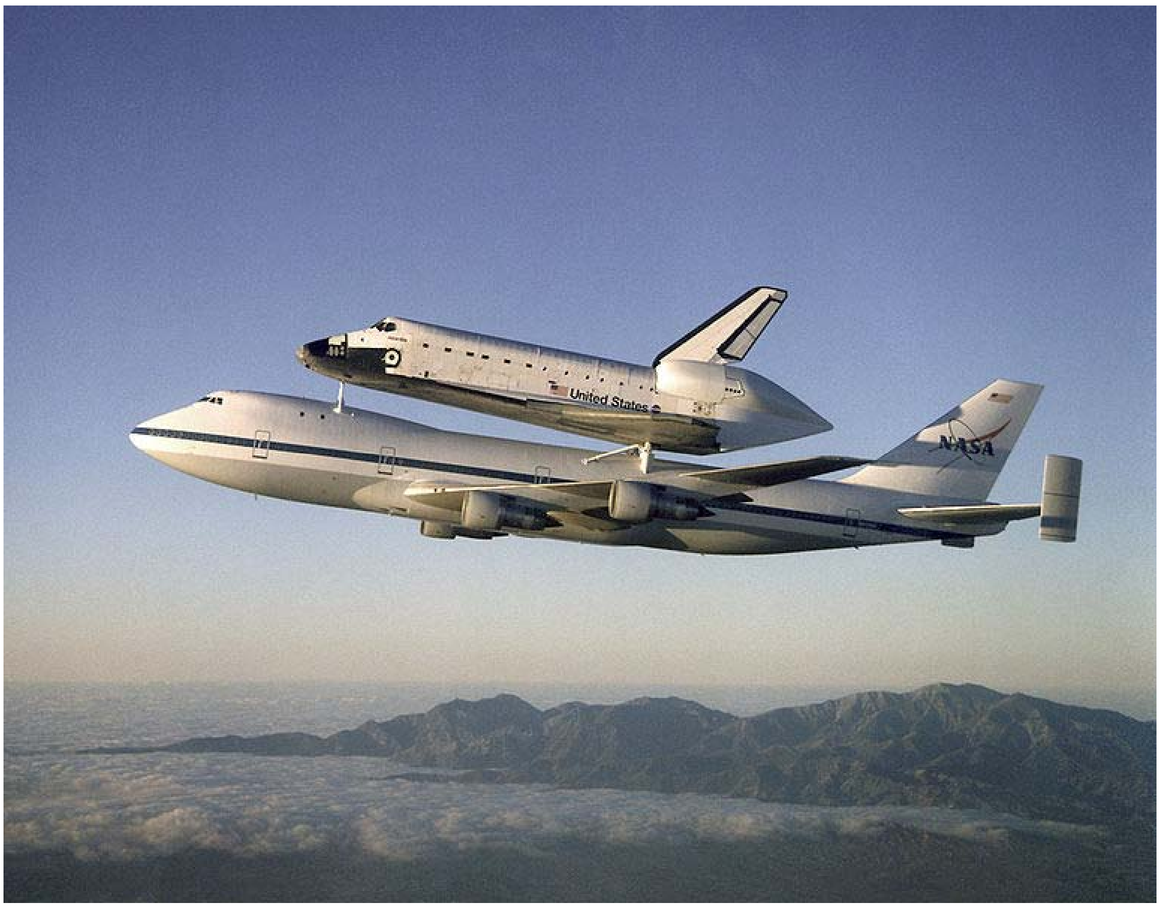
Introduction

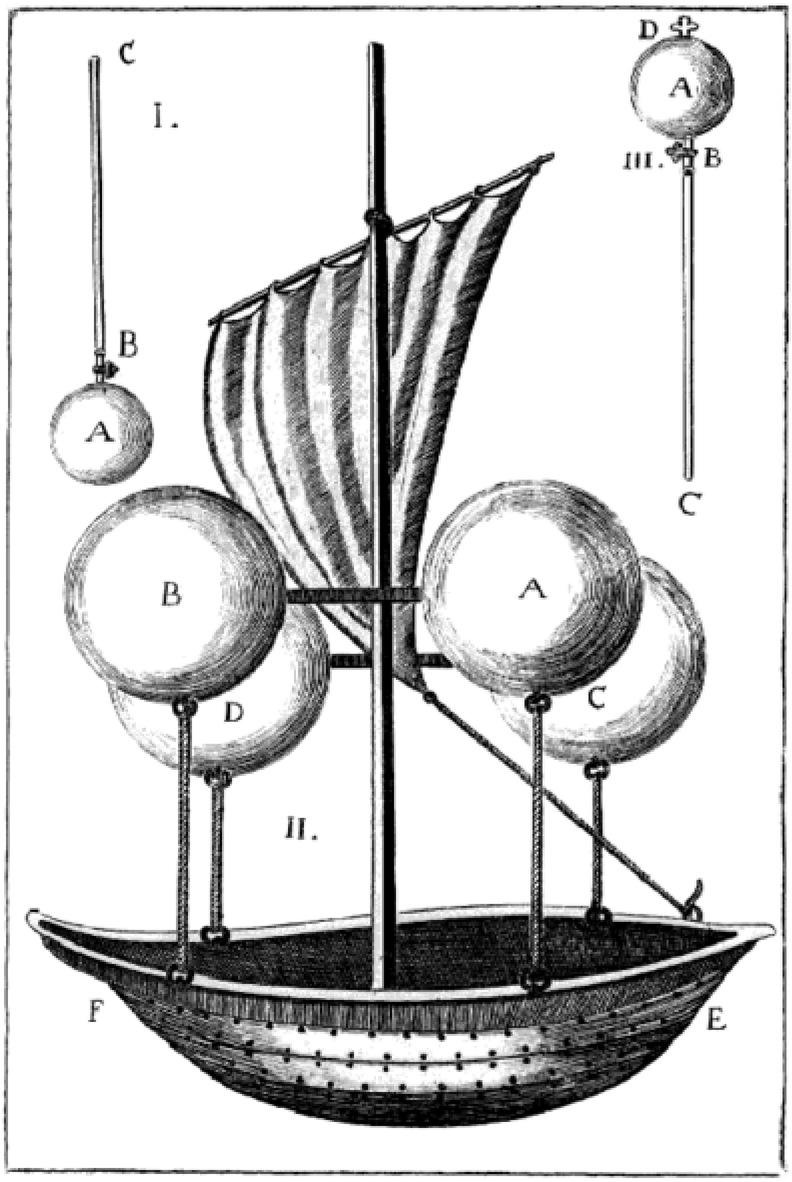


Space Shuttle *Atlantis* on a Shuttle Carrier Aircraft.

Aeronautics (from Greek ἀήρ *āēr* which means "air" and ναυτική *nautikē* which means "navigation, seamanship", i.e. "navigation of the air") is the science involved with the study, design, and manufacture of flight-capable machines, or the techniques of operating aircraft. While the term—literally meaning "sailing the air"—originally referred solely to the science of *operating* the aircraft, it has since been expanded to include technology, business and other aspects related to aircraft.

One of the significant parts in aeronautics is a branch of physical science called aerodynamics, which deals with the motion of air and the way that it interacts with objects in motion, such as an aircraft. **Aviation** is a term sometimes used interchangeably with aeronautics, although "aeronautics" includes lighter-than-air craft such as airships, while "aviation" does not.

Early aeronautics



Francesco Lana de Terzi's flying boat concept c.1670.

The first mention of aeronautics in history was in the writings of ancient Egyptians who described the flight of birds. It also finds mention in ancient China where people were flying kites thousands of years ago. The medieval Islamic scientists were not far behind, as they understood the actual mechanism of bird flight. Before scientific investigation of aeronautics started, people started thinking of ways to fly. In a Greek legend, Icarus and his father Daedalus built wings of feathers and wax and flew out of a prison. Icarus flew too close to the sun, the wax melted, and he fell in the sea and drowned. When people started to scientifically study how to fly, people began to understand the basics of air and aerodynamics. Ibn Firnas may have tried to fly in 8th century in Cordoba, Al-Andalus.

Roger Bacon and Leonardo da Vinci were some of the first modern Europeans to study aeronautics. Leonardo studied the flight of birds in developing engineering schematics for some of the earliest flying machines in the late fifteenth century AD. His schematics, however, such as the ornithopter ultimately failed as practical aircraft. The flapping machines that he designed were either too small to generate sufficient lift, or too heavy for a human to operate.

Although the ornithopter continues to be of interest to hobbyists, it was replaced by the glider in the 19th century. Sir George Cayley was one of the most important people in the history of aeronautics. Many consider him the first true scientific aerial investigator and the first person to understand the underlying principles and forces of flight. A pioneer of aeronautical engineering, he is credited as the first person to separate the forces of lift and drag which are in effect on any flight vehicle,

Francesco Lana de Terzi, a 17th century Jesuit professor of physics and mathematics from Brescia, Lombardy, has been referred to as the Father of Aeronautics. In his work *Prodromo dell'Arte Maestra* (1670) he proposes a lighter-than-air vessel based on logical deductions from previous work ranging from Archimedes and Euclid to his contemporaries Robert Boyle and Otto von Guericke.

Chapter- 1

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.

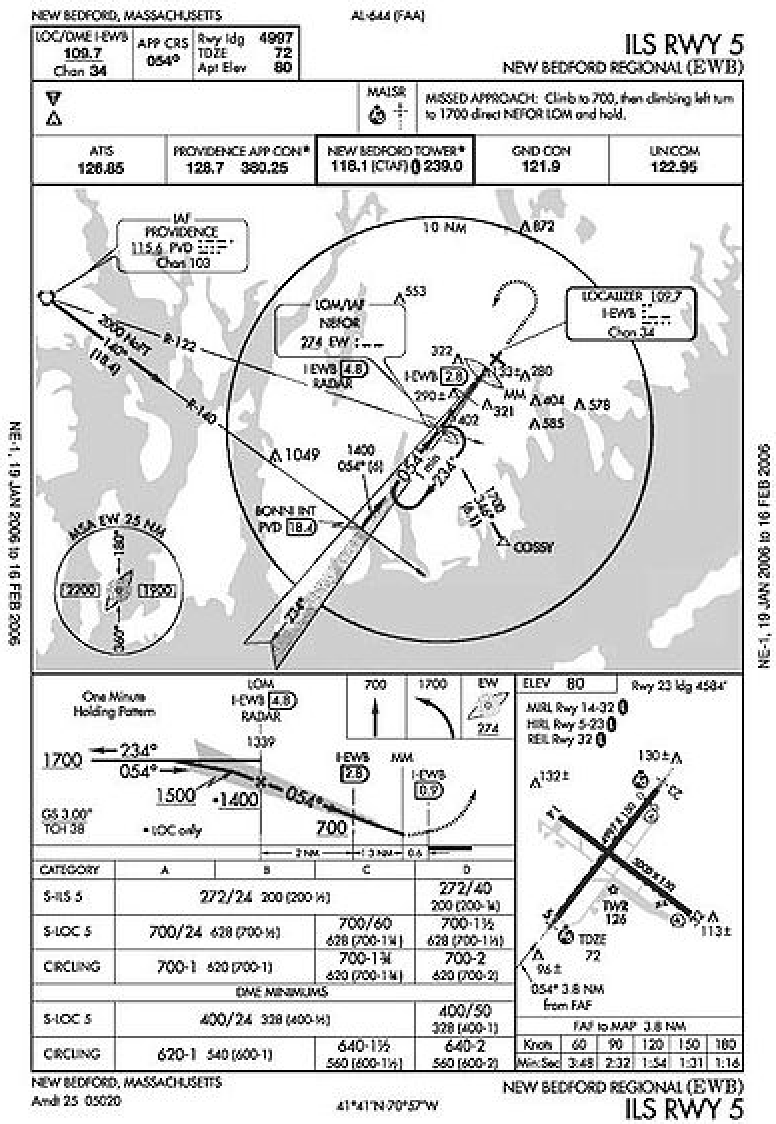
For the purpose of flight training, instructors typically establish the aircraft in a descending turn with initially slow but steadily accelerating airspeed – the initial slow speed facilitates the potentially slow and sometimes erred response of student pilots. The cockpit controls are released by the 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- 2

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.

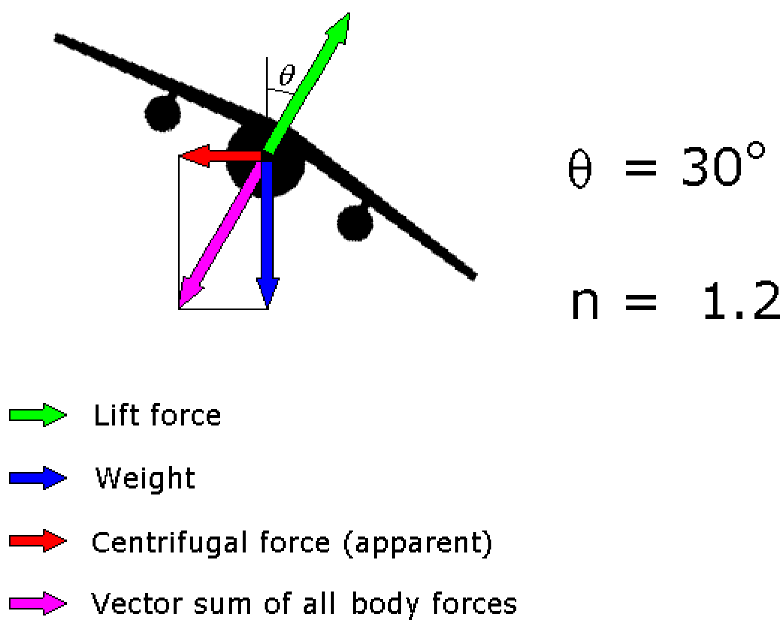
Load factor and g

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- 3

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)

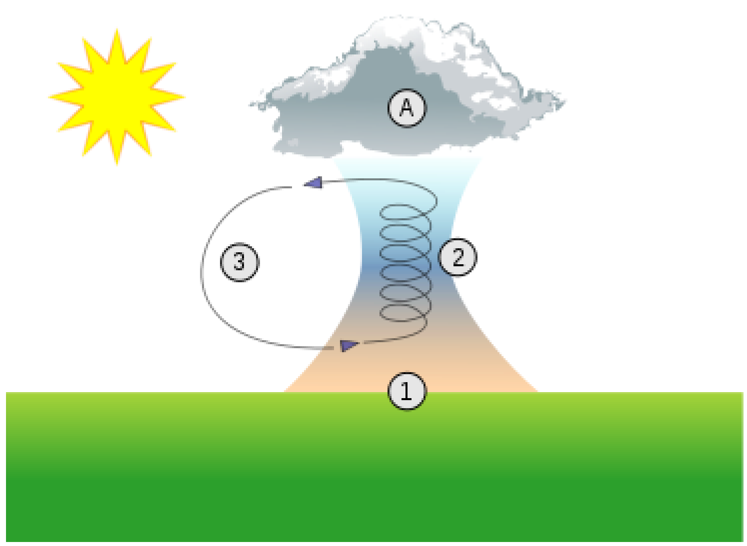
Lift is a meteorological phenomenon used as an energy source by soaring aircraft and soaring birds. The most common human application of lift is in sport and recreation. The three air sports that use soaring flight are: gliding, hang gliding and paragliding.

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.

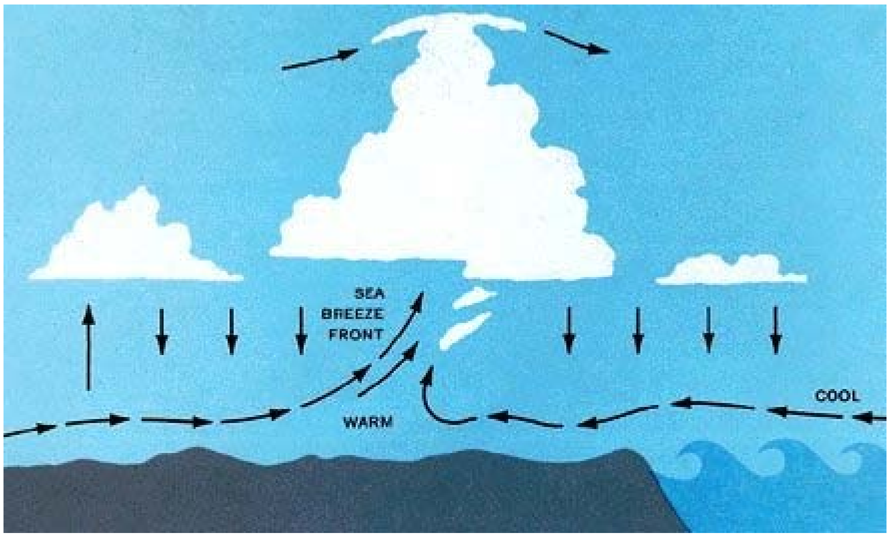
With winds of 20 to 25 knots (46 km/h), it is possible for aircraft to soar at an altitude up to two times the height of the obstacle. Ridge lift can also be augmented by thermals when the slopes also face the sun.

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

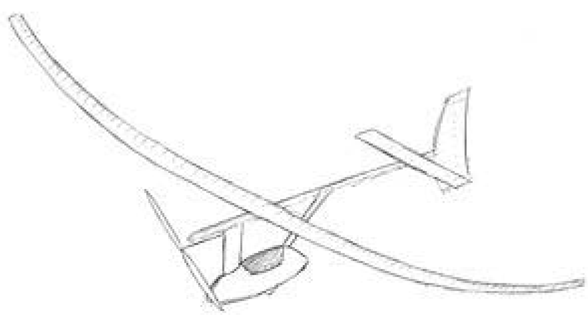
A pilot can create an indication of lift on certain uncompensated instruments by entering a climb by pulling back on the stick (hence "*stick* thermal"). This is not true lift, in that the energy to climb is being converted from decreasing airspeed, rather than being extracted from rising air. Inexperienced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

Chapter- 4

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- 5

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.

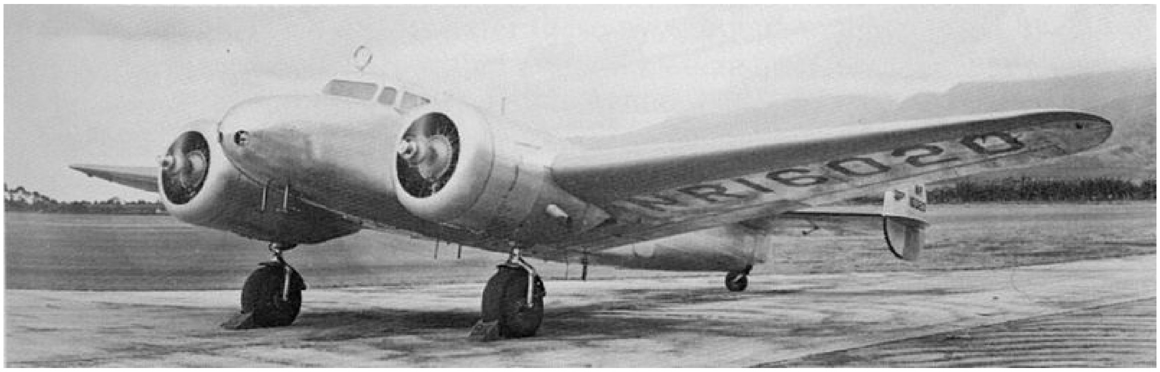
A further design of tailplane is the V-tail, so named because that instead of the standard inverted T or T-tail, there are two vertical fins angled away from each other in a V (if they're arranged like a V, at least one of them isn't vertical). To produce yaw like a rudder, the two trailing edge control 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- 6

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.

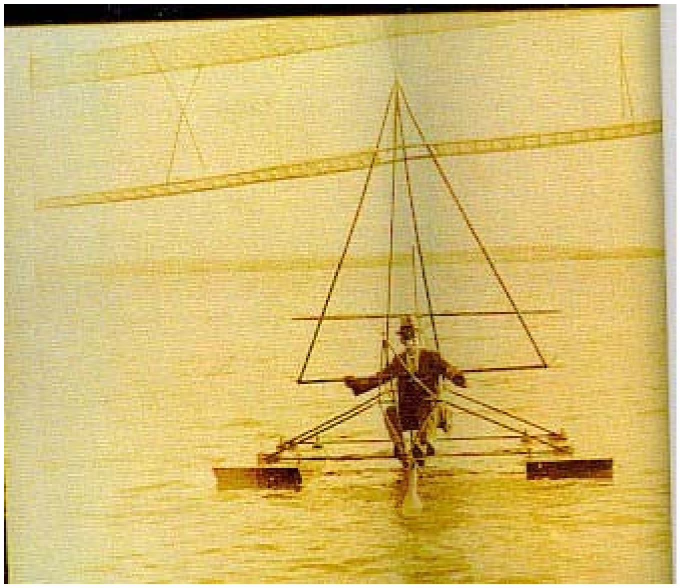
Pitch control response is very direct, but satisfactory weight shift roll response becomes more difficult to achieve as the sail is tightened to improve performance. In the roll axis, the pilot, using the wing control bar and reacting his input by the mass of the trike, applies a rolling moment directly 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.

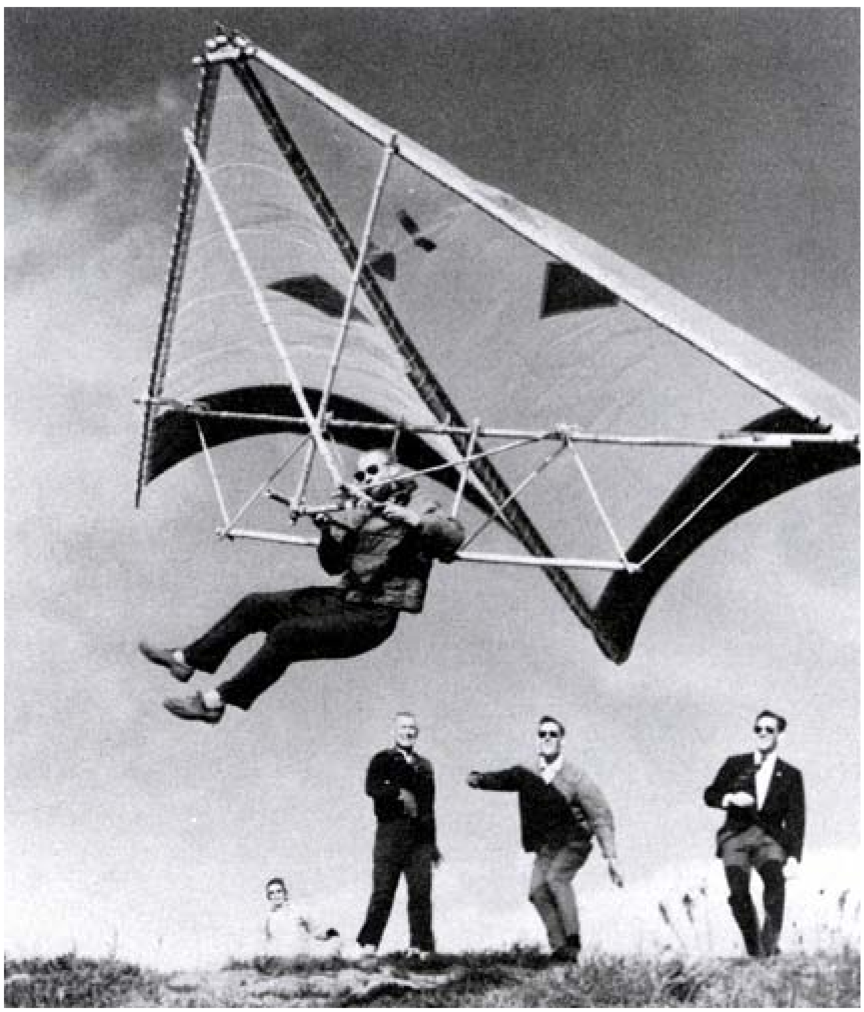
History



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.

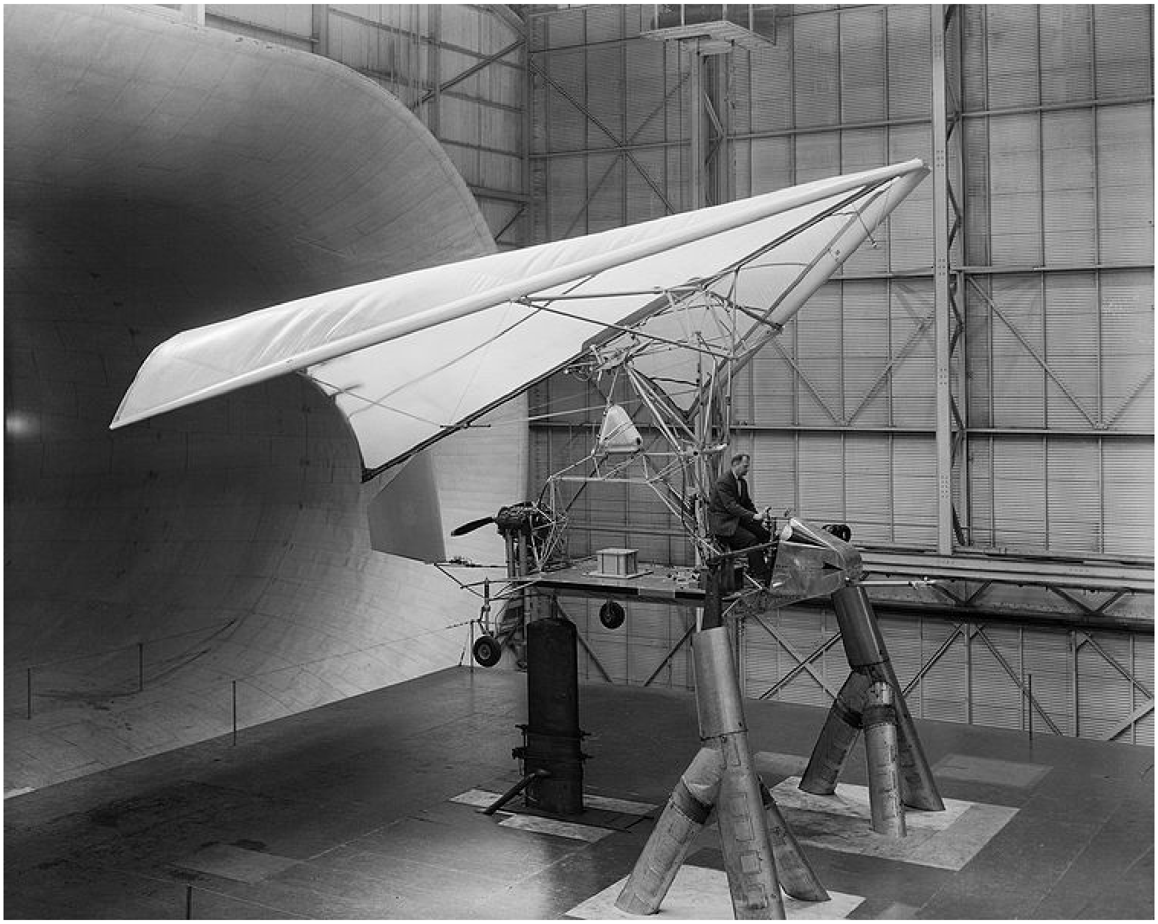
Publicity from the Fleep and the Paresev tests sparked interest in the design among several tinkerers, first through Barry Palmer. An engineer, Mike Burns of Australia, developed and used the boat-towed Rogallo airfoiled SkiPlane from 1962 through the 1960s. A fellow countryman of Mike Burns, John W. 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.

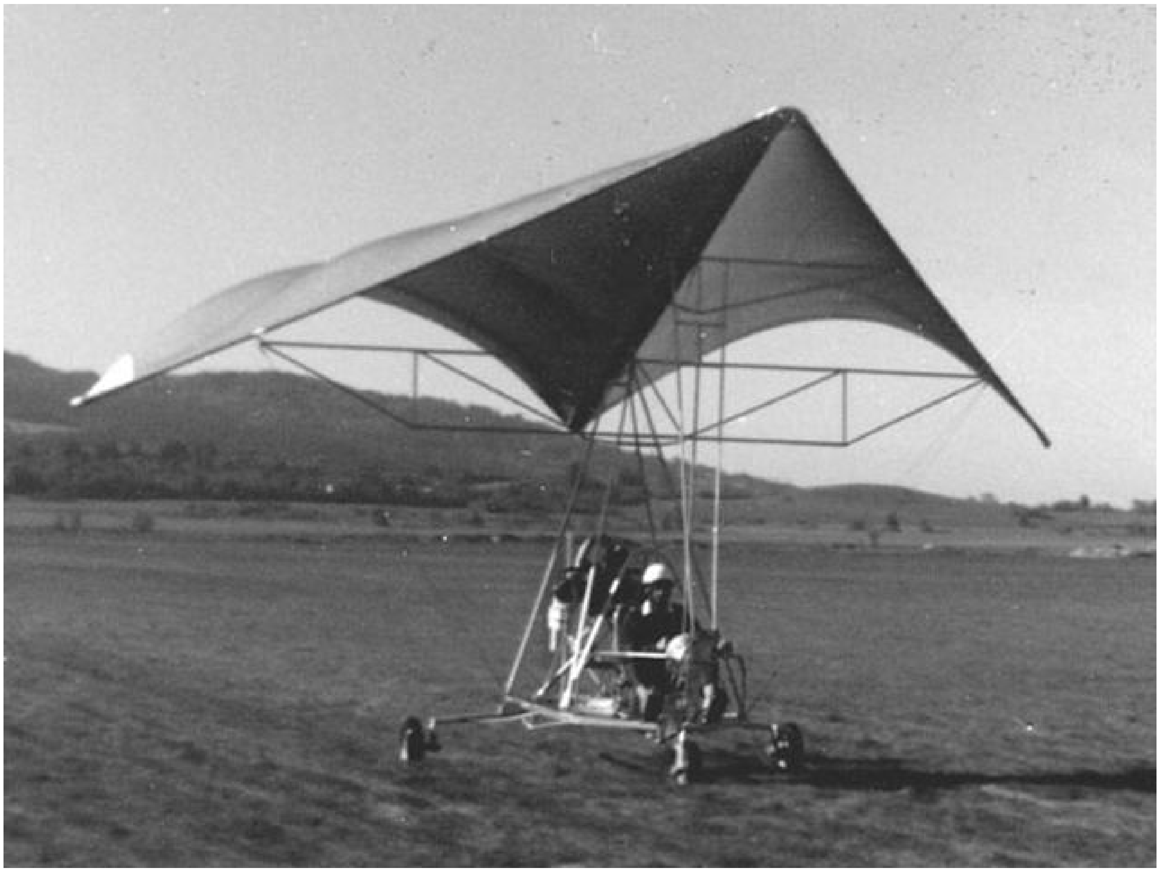
Although by the early 1970s many rigid wings were developed, none sold well, while dozens of flexible wing hang glider companies were springing up world-wide, building variants of Dickenson's Ski Wing. In 1972, Popular Mechanics and Popular Science magazines published articles on hang gliding which further 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- 7

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- 8

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.

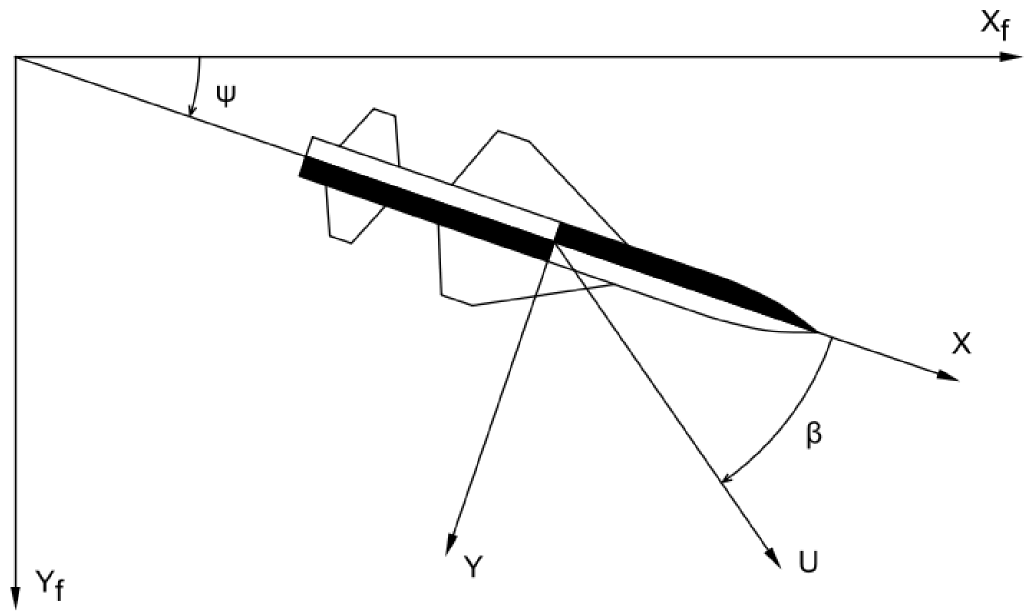
Moments and angular rates around each of the axes

- 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:

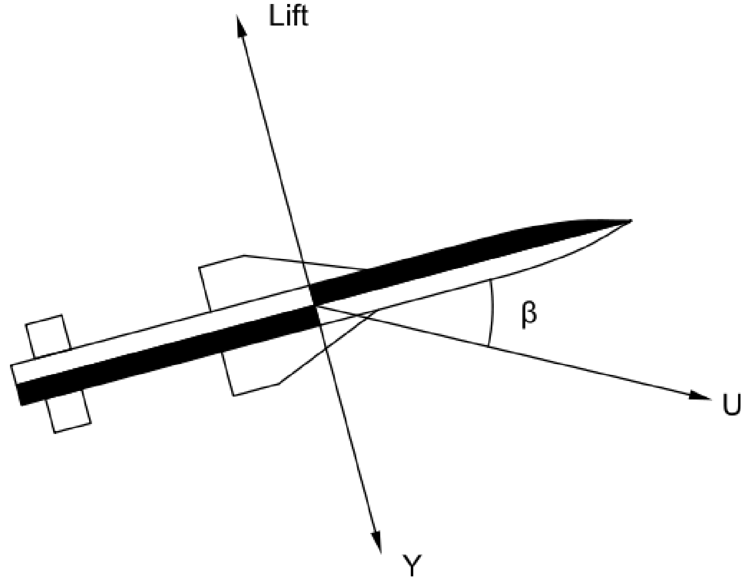
$$\frac{\partial Y}{\partial \beta} = Y_\beta$$

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

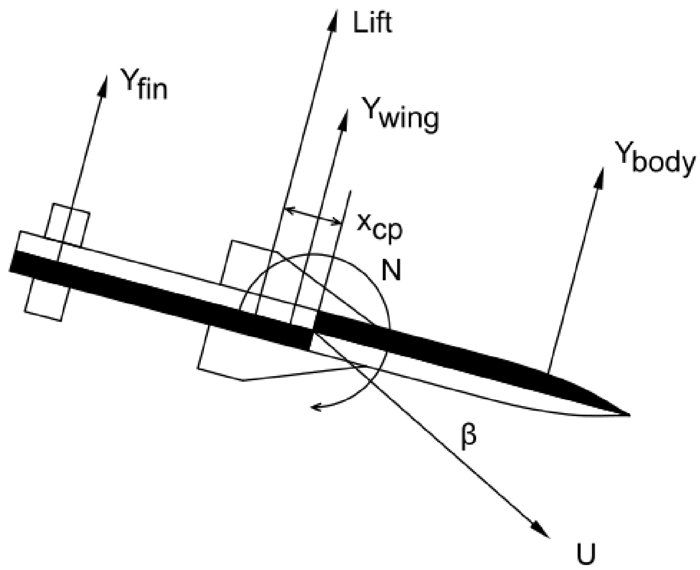
Each stability derivative is determined by the position, size, shape and orientation of the missile components. In aircraft, the directional stability determines such features as dihedral of the main planes, size of fin and area of tailplane, but the large number of important stability derivatives involved 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.

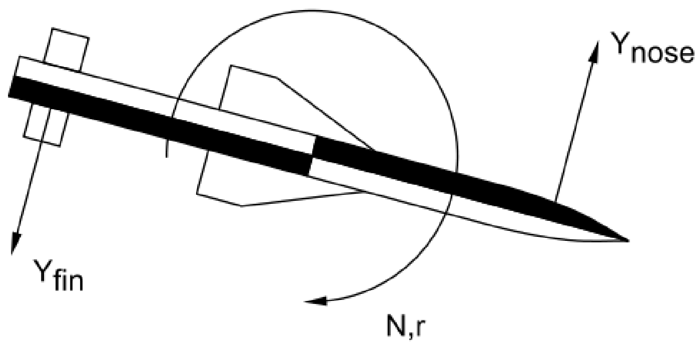


Static Stability and N_β

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- 9

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

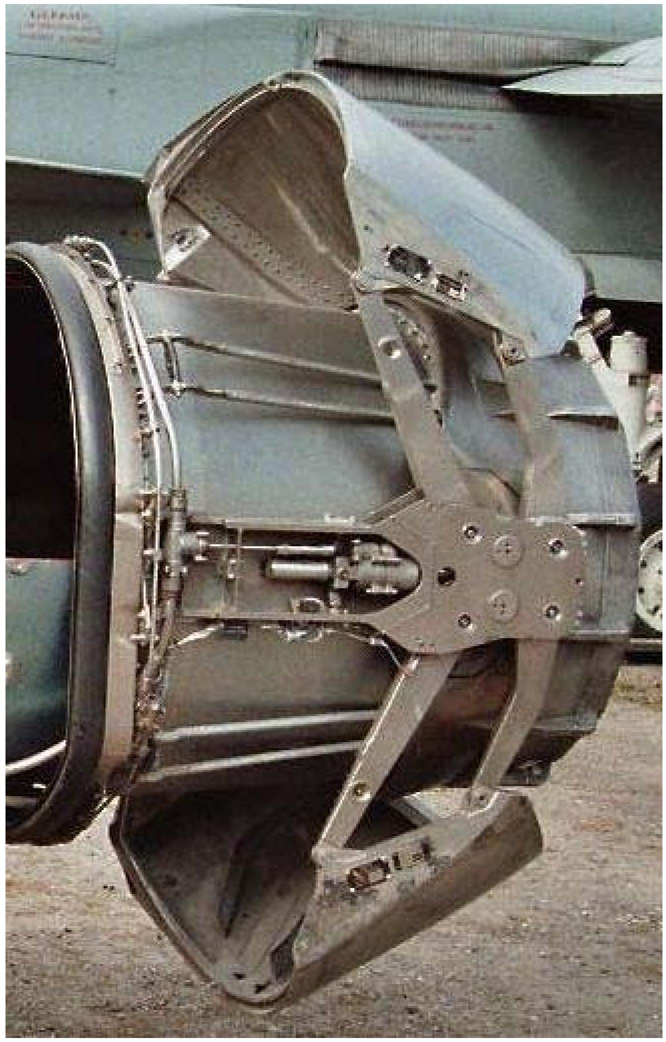
the aircraft and the subsequent crash. Of the seventeen people on board, only four survived the crash.

- 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

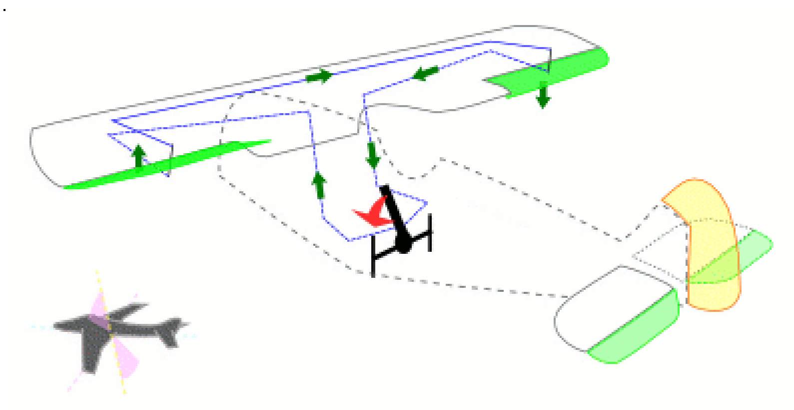
Controllable pitch propeller on the singe-turboprop of a FedEx Cessna 208B Grand Caravan

KLM Fokker 100 landing with reverse-thrust buckets deployed.

Antonov An-74 moving with reverse-thrust

Chapter- 10

Aircraft Flight Control System



A typical aircraft's primary flight controls in motion

A conventional fixed-wing **aircraft flight control system** consists of flight control surfaces, the respective cockpit controls, connecting linkages, and the necessary operating mechanisms to control an aircraft's direction in flight. Aircraft engine controls are also considered as flight controls as they change speed.

Cockpit controls

Primary controls

Generally the primary cockpit controls are arranged as follows:

- A control column or a control yoke attached to a column—for roll and pitch, which moves the ailerons when turned or deflected left and right, and moves the elevators when moved backwards or forwards
- Rudder pedals, or the earlier, pre-1919 "rudder bar", to control yaw, which move the rudder; left foot forward will move the rudder left for instance.
- Throttle controls to control engine speed or thrust for powered aircraft.

Even when an aircraft uses different kinds of surfaces, such as a V-tail/ruddervator, flaperons, or elevons, to avoid pilot confusion the aircraft will still normally be designed so that the yoke or stick controls pitch and roll in the conventional way, as will the rudder pedals for yaw. The basic pattern for modern flight controls was pioneered by French aviation figure Robert Esnault-Pelterie, with fellow French aviator Louis Blériot popularizing Esnault-Pelterie's control format initially on Louis' Blériot VIII monoplane, and standardizing the format on the July 1909 Channel-crossing Blériot XI.

Secondary controls

In addition to the primary flight controls for roll, pitch, and yaw, there are often secondary controls available to give the pilot finer control over flight or to ease the workload. The most commonly-available control is a wheel or other device to control elevator trim, so that the pilot does not have to maintain constant backward or forward pressure to hold a specific pitch attitude (other types of trim, for rudder and ailerons, are common on larger aircraft but may also appear on smaller ones). Many aircraft have wing flaps, controlled by a switch or a mechanical lever or in some cases are fully automatic by computer control, which alter the shape of the wing for improved control at the slower speeds used for takeoff and landing. Other secondary flight control systems may be available, including slats, spoilers, air brakes and variable-sweep wings.

Flight control systems

Mechanical

de Havilland Tiger Moth elevator and rudder cables

Mechanical or manually-operated flight control systems are the most basic method of controlling an aircraft. They were used in early aircraft and are currently used in small aircraft where the aerodynamic forces are not excessive. Very early aircraft, such as the Wright Flyer I, Blériot XI and Fokker Eindecker used a system of wing warping where no conventionally hinged control surfaces were used on the wing, and sometimes not even for pitch control as on the Wright Flyer I and original versions of the 1909 Etrich Taube, which only had a hinged/pivoting rudder in addition to the warping-operated pitch and roll controls. A manual flight control system uses a collection of mechanical parts such as pushrods, tension cables, pulleys, counterweights, and sometimes chains to transmit the forces applied to the cockpit controls directly to the control surfaces. Turnbuckles are often used to adjust control cable tension. The Cessna Skyhawk is a typical example of an aircraft that uses this type of system. Gust locks are often used on parked aircraft with mechanical systems to protect the control surfaces and linkages from damage from wind. Some aircraft have gust locks fitted as part of the control system.

Increases in the control surface area required by large aircraft or higher loads caused by high airspeeds in small aircraft lead to a large increase in the forces needed to move them, consequently complicated mechanical gearing arrangements were developed to extract maximum mechanical advantage in order to reduce the forces required from the pilots. This arrangement can be found on bigger or higher performance propeller aircraft such as the Fokker 50.

Some mechanical flight control systems use servo tabs that provide aerodynamic assistance. Servo tabs are small surfaces hinged to the control surfaces. The flight control mechanisms move these tabs, aerodynamic forces in turn move, or assist the movement of the control surfaces reducing the amount of mechanical forces needed. This arrangement was used in early piston-engined transport aircraft and in early jet transports. The Boeing 737 incorporates a system, whereby in the unlikely event of total hydraulic system failure, it automatically and seamlessly reverts to being controlled via servo-tab.

Hydro-mechanical

The complexity and weight of mechanical flight control systems increase considerably with the size and performance of the aircraft. Hydraulically powered control surfaces help to overcome these limitations. With hydraulic flight control systems, the aircraft's size and performance are limited by economics rather than a pilot's muscular strength. At first, only-partially boosted systems were used in which the pilot could still feel some of the aerodynamic loads on the control surfaces (feedback).

A hydro-mechanical flight control system has two parts:

- The *mechanical circuit*, which links the cockpit controls with the hydraulic circuits. Like the mechanical flight control system, it consists of rods, cables, pulleys, and sometimes chains.

- The *hydraulic circuit*, which has hydraulic pumps, reservoirs, filters, pipes, valves and actuators. The actuators are powered by the hydraulic pressure generated by the pumps in the hydraulic circuit. The actuators convert hydraulic pressure into control surface movements. The electro-hydraulic servo valves control the movement of the actuators.

The pilot's movement of a control causes the mechanical circuit to open the matching servo valve in the hydraulic circuit. The hydraulic circuit powers the actuators which then move the control surfaces. As the actuator moves, the servo valve is closed by a mechanical feedback linkage - one that stops movement of the control surface at the desired position.

This arrangement was found in the older-designed jet transports and in some high-performance aircraft. Examples include the Antonov An-225 and the Lockheed SR-71.

Artificial feel devices

With purely mechanical flight control systems, the aerodynamic forces on the control surfaces are transmitted through the mechanisms and are felt directly by the pilot. This gives tactile feedback of airspeed and aids flight safety.

With hydromechanical flight control systems however, the load on the surfaces cannot be felt and there is a risk of overstressing the aircraft through excessive control surface movement. To overcome this problem artificial feel systems are used. For example, for the controls of the RAF's Avro Vulcan jet bomber and the RCAF's Avro Canada CF-105 Arrow supersonic interceptor, both 1950's-era designs, the required force feedback was achieved by a spring device. The fulcrum of this device was moved in proportion to the square of the air speed (for the elevators) to give increased resistance at higher speeds. For the controls of the American Vought F-8 Crusader and the LTV A-7 Corsair II warplanes, a "bob-weight" was used in the pitch axis of the control stick, giving force feedback that was proportional to the airplane's normal acceleration.

Stick shaker

A stick shaker is a device (available in some hydraulic aircraft) which is fitted into the control column which shakes the control column when the aircraft is about to stall. Also in some aircraft like the McDonnell Douglas DC-10 there is/was a back-up electrical power supply which the pilot can turn on to re-activate the stick shaker in case the hydraulic connection to the stick shaker is lost.

Fly-by-wire control systems

A fly-by-wire (FBW) system replaces manual flight control of an aircraft with an electronic interface. The movements of flight controls are converted to electronic signals transmitted by wires (hence the fly-by-wire term), and flight control computers determine how to move the actuators at each control surface to provide the expected response. Commands from the computers are also input without the pilot's knowledge to stabilize the aircraft and perform other tasks.

Fluidic flight controls

Conventional mechanical flight control surfaces may also be replaced completely, by a fluidic flight control system, provided by differential streams of blown air, such as with the Demon (UAV), aircraft which flew for the first time, in the UK, in September 2010.

Chapter- 11

Aerospace Engineering

Aerospace engineer

NASA engineers, like the ones depicted in Apollo 13, worked diligently to protect the lives of the astronauts on the mission.

	Occupation
Names	engineer aerospace engineer
Type	profession
Activity sectors	aeronautics, astronautics, science
	Description
Competencies	technical knowledge, management skills

Fields of employment technology, science, military

Aerospace engineering is the branch of engineering behind the design, construction and science of aircraft and spacecraft. It is broken into two major and overlapping branches: aeronautical engineering and astronautical engineering. The former deals with craft that stay within Earth's atmosphere, and the latter deals with craft that operate outside of Earth's atmosphere.

Aerospace engineering deals with the design, construction, and science behind the forces and physical properties of aircraft, rockets, flying craft, and spacecraft. The field also covers their aerodynamic characteristics and behaviors, airfoil, control surfaces, lift, drag, and other properties. Aerospace engineering is not to be confused with the various other fields of engineering that go into designing these complex craft. For example, the design of aircraft avionics, while certainly part of the system as a whole, would rather be considered electrical engineering, or perhaps computer engineering. The landing gear system on an aircraft may fall into the field of mechanical engineering, and so forth. It is typically a large combination of many disciplines that makes up aeronautical engineering.

While **aeronautical engineering** was the original term, the broader "aerospace" has superseded it in usage, as flight technology advanced to include craft operating in outer space. Aerospace engineering, particularly the astronautics branch, is often informally called "rocket science".

Overview

Flight vehicles undergo severe conditions such as differences in atmospheric pressure, and temperature, with structural loads applied upon vehicle components. Consequently, they are usually the products of various technological and engineering disciplines including aerodynamics, propulsion, avionics, materials science, structural analysis and manufacturing. These technologies are collectively known as aerospace engineering. Because of the complexity of the field, aerospace engineering is conducted by a team of engineers, each specializing in their own branches of science.

The development and manufacturing of a modern flight vehicle is an extremely complex process and demands careful balance and compromise between abilities, design, available technology and costs. Aerospace engineers design, test, and supervise the manufacture of aircraft, spacecraft, and missiles. Aerospace engineers develop new technologies for use in aviation, defense systems, and space exploration.

History

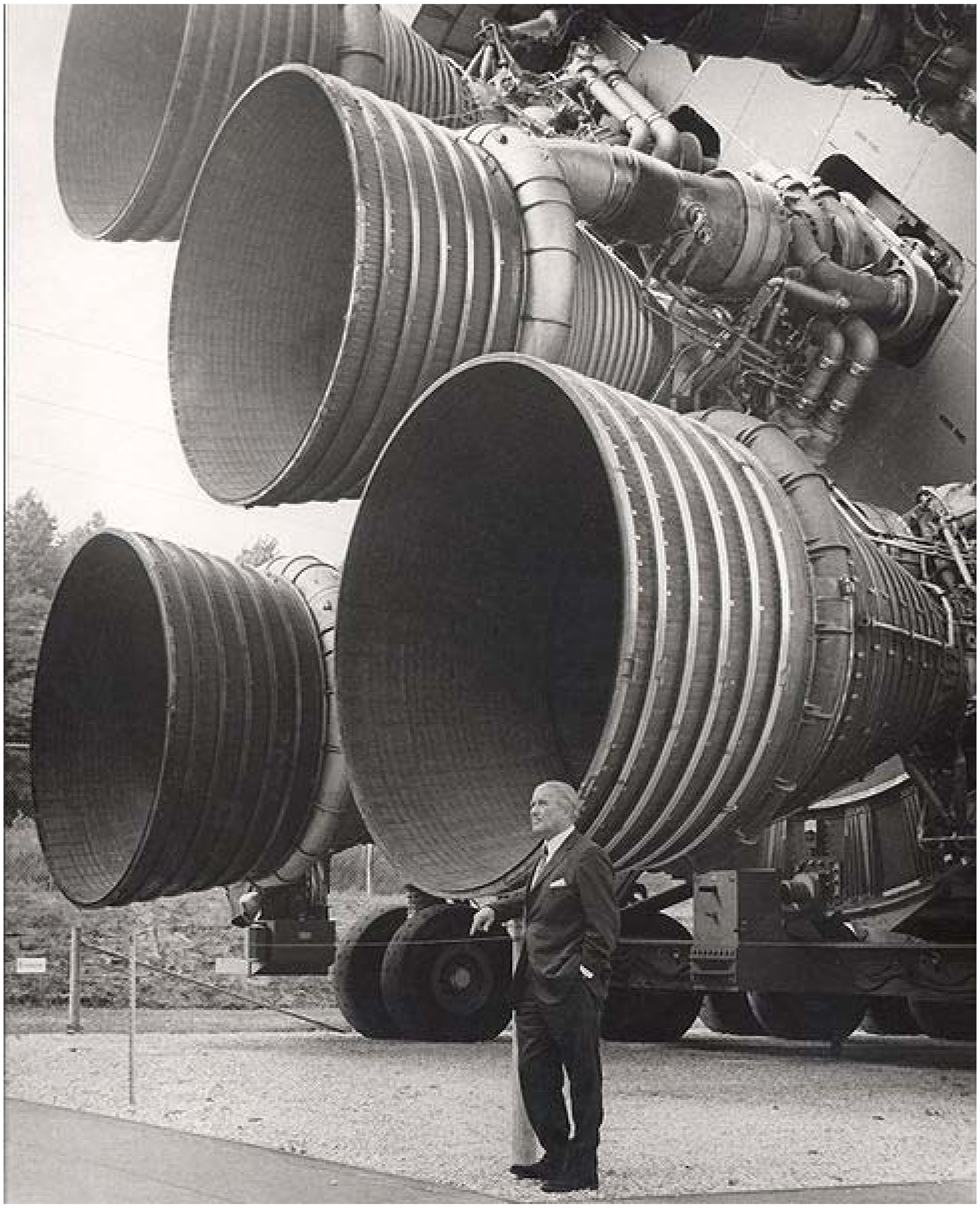
Alberto Santos-Dumont, a pioneer who built the first machines able to fly, played an important role in the development of aviation. Some of the first ideas for powered flight may have come from Leonardo da Vinci, who, although he did not build any successful models, did develop many sketches and ideas for "flying machines".

Orville and Wilbur Wright flew the Wright Flyer I, the first airplane, on December 17, 1903 at Kitty Hawk, North Carolina.

The origin of aerospace engineering can be traced back to the aviation pioneers around the late 19th century to early 20th centuries, although the work of Sir George Cayley has recently been dated as being from the last decade of the 18th to mid 19th century. One of the most important people in the history of aeronautics, Cayley was a pioneer in aeronautical engineering and is credited as the first person to separate the forces of lift and drag, which are in effect on any flight vehicle. Early knowledge of aeronautical engineering was largely empirical with some concepts and skills imported from other branches of engineering. Scientists understood some key elements of aerospace engineering , like fluid dynamics, in the 18th century. Several years later after the successful flights by the Wright brothers, the 1910s saw the development of aeronautical engineering through the design of World War I military aircraft.

The first definition of aerospace engineering appeared in February 1958. The definition considered the Earth's atmosphere and the outer space as a single realm, thereby encompassing both aircraft (*aero*) and spacecraft (*space*) under a newly coined word *aerospace*. The National Aeronautics and Space Administration was founded in 1958 as a response to the Cold War. United States aerospace engineers launched the first American satellite on January 31, 1958 in response to the USSR launching Sputnik on October 4, 1957.

Elements



Wernher von Braun, with the F-1 engines of the Saturn V first stage at the US Space and Rocket Center

Some of the elements of aerospace engineering are:

A fighter jet engine undergoing testing. The tunnel behind the engine muffles noise and allows exhaust to escape.

- Fluid mechanics – the study of fluid flow around objects. Specifically aerodynamics concerning the flow of air over bodies such as wings or through objects such as wind tunnels.
- Astrodynamics – the study of orbital mechanics including prediction of orbital elements when given a select few variables. While few schools in the United States teach this at the undergraduate level, several have graduate programs covering this topic (usually in conjunction with the Physics department of said college or university).
- Statics and Dynamics (engineering mechanics) – the study of movement, forces, moments in mechanical systems.
- Mathematics – in particular, calculus, differential equations, and linear algebra.
- Electrotechnology – the study of electronics within engineering.
- Propulsion – the energy to move a vehicle through the air (or in outer space) is provided by internal combustion engines, jet engines and turbomachinery, or rockets. A more recent addition to this module is electric propulsion and ion propulsion.
- Control engineering – the study of mathematical modeling of the dynamic behavior of systems and designing them, usually using feedback signals, so that their dynamic behavior is desirable (stable, without large excursions, with

minimum error). This applies to the dynamic behavior of aircraft, spacecraft, propulsion systems, and subsystems that exist on aerospace vehicles.

- Aircraft structures – design of the physical configuration of the craft to withstand the forces encountered during flight. Aerospace engineering aims to keep structures lightweight.
- Materials science – related to structures, aerospace engineering also studies the materials of which the aerospace structures are to be built. New materials with very specific properties are invented, or existing ones are modified to improve their performance.
- Solid mechanics – Closely related to material science is solid mechanics which deals with stress and strain analysis of the components of the vehicle. Nowadays there are several Finite Element programs such as MSC Patran/Nastran which aid engineers in the analytical process.
- Aeroelasticity – the interaction of aerodynamic forces and structural flexibility, potentially causing flutter, divergence, etc.
- Avionics – the design and programming of computer systems on board an aircraft or spacecraft and the simulation of systems.
- Software – the specification, design, development, test, and implementation of computer software for aerospace applications, including flight software, ground control software, test & evaluation software, etc.
- Risk and reliability – the study of risk and reliability assessment techniques and the mathematics involved in the quantitative methods.
- Noise control – the study of the mechanics of sound transfer.
- Flight test – designing and executing flight test programs in order to gather and analyze performance and handling qualities data in order to determine if an aircraft meets its design and performance goals and certification requirements.

The basis of most of these elements lies in theoretical mathematics, such as fluid dynamics for aerodynamics or the equations of motion for flight dynamics. There is also a large empirical component. Historically, this empirical component was derived from testing of scale models and prototypes, either in wind tunnels or in the free atmosphere. More recently, advances in computing have enabled the use of computational fluid dynamics to simulate the behavior of fluid, reducing time and expense spent on wind-tunnel testing.

Additionally, aerospace engineering addresses the integration of all components that constitute an aerospace vehicle (subsystems including power, aerospace bearings, communications, thermal control, life support, etc.) and its life cycle (design, temperature, pressure, radiation, velocity, lifetime).

Aerospace engineering degrees

Aerospace engineering

Aerospace engineering may be studied at the advanced diploma, bachelor's, master's, and Ph.D. levels in aerospace engineering departments at many universities, and in mechanical engineering departments at others. A few departments offer degrees in space-focused astronautical engineering. The Delft University of Technology (TU Delft) in the Netherlands offers one of the top European aerospace educational and research platforms, while the programs of the Massachusetts Institute of Technology and Rutgers University are two such examples. In 2009, U.S. News & World Report ranked the undergraduate aerospace engineering programs at the Massachusetts Institute of Technology, Georgia Institute of Technology, and the University of Michigan as the top three best programs for doctorate granting universities in the United States. The other programs in the top ten were Purdue University, California Institute of Technology, University of Maryland, University of Illinois, Stanford University, University of Texas at Austin, and Virginia Tech in that order. The magazine also rates Embry-Riddle Aeronautical University, the United States Air Force Academy, and the United States Naval Academy as the premier aerospace engineering programs at universities that do not grant doctorate degrees. University of Kansas School of Engineering has earned more first and second place AIAA awards than any other academic institution in the world in the 42-year history of the competition. Wichita State University is renowned for its Aerospace Engineering program and also has the third highest research budget for Aerospace Engineering in the United States.

In Canada, the University of Toronto has a quality aerospace engineering program. The aerospace program requires the students to go through a competitive program called engineering science. The academic program in aerospace science and engineering at U of

T includes undergraduate and graduate studies. At the graduate level U of T offers research-intensive programs leading to MASc and PhD degrees, and a professionally-oriented program leading to the MEng degree. The scope of U of T's research includes aeronautical engineering (aircraft flight systems, propulsion, aerodynamics, computational fluid dynamics, and structural mechanics) and space systems engineering (spacecraft dynamics and control, space robotics and mechatronics, and microsatellite technology). Carleton University and Ryerson University are other top aerospace and mechanical engineering universities in Canada which offer accredited graduate and under-graduate degrees.

In the UK, Aerospace (or aeronautical) engineering can be studied for the B.Eng., M.Eng., MSc. and Ph.D. levels at a number of universities. The top 10 universities are University of Cambridge, University of Surrey, University of Bristol, University of Southampton, Queens University Belfast, University of Sheffield, Newcastle University, University of Bath, Imperial College London, Loughborough University and University of Nottingham for 2010. The Department of Aeronautics at Imperial College London is noted for providing engineers for the Formula One industry, an industry that uses aerospace technology.

Aerospace can be studied at University of Limerick in Ireland. In Australia, the RMIT University offers Aerospace (or aeronautical) engineering and has more than 60 years teaching experience in this profession. Monash University, University of New South Wales, University of Sydney, University of Queensland, University of Adelaide and Queensland University of Technology also offers Aerospace Engineering.

European universities that are renowned for their teaching and expertise in aerospace engineering include TU Delft in the Netherlands, ISAE, ENAC and ESTACA in France, RWTH Aachen, TU München, the University of Stuttgart, TU Berlin and TU Braunschweig in Germany. In Austria the FH Joanneum. In Portugal the Instituto Superior Técnico. In Spain the Universidad Politecnica de Madrid, the Universidad Carlos III de Madrid, and Universitat Politècnica de Catalunya offer the degree, while in Italy there also several universities where aerospace engineering can be studied including the Politecnico di Torino, the Politecnico di Milano, the University of Pisa, the University of Padua and the Sapienza University of Rome. In Eastern Europe they are the University of Belgrade, the Warsaw University of Technology and Rzeszów University of Technology in Poland and Brno University of Technology in Brno, Czech Republic.

In India IIT Kanpur possesses its own flight test aircraft and airfield for students in the discipline, while the other IITs also offer degrees in this discipline. From academic year 2010 onwards Bengal Engineering and Science University, Shibpur has started offering an undergraduate course Bachelor of Engineering in Aerospace Engineering.university of petroleum and energy studies,dehradun also one of the leading institute. While in China Nanjing Aeronautics and Astronautics University is a regional leader in the field of aerospace engineering education. In Pakistan Aerospace Engineering can be studied at National University of Sciences and Technology at (CAE), at PAF Academy in Risalpur & at Air University which is Pakistan's only university that grants a Doctorate degree in

Aerospace Engineering & Avionics Engineering. In 2002, SUPARCO established IST which is a federally chartered public sector institute of Pakistan offering under graduate and graduate degree in Aerospace Engineering. The MS degree at IST is being offered in collaboration with Beihang University (BUAA), China and Seoul National University, South Korea