Concepts & Applications
of
Aerospace Engineering

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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.

While **aeronautical engineering** was the original term, the broader "aerospace" has superseded it in usage, as flight technology advanced to include craft operating in outer space.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.
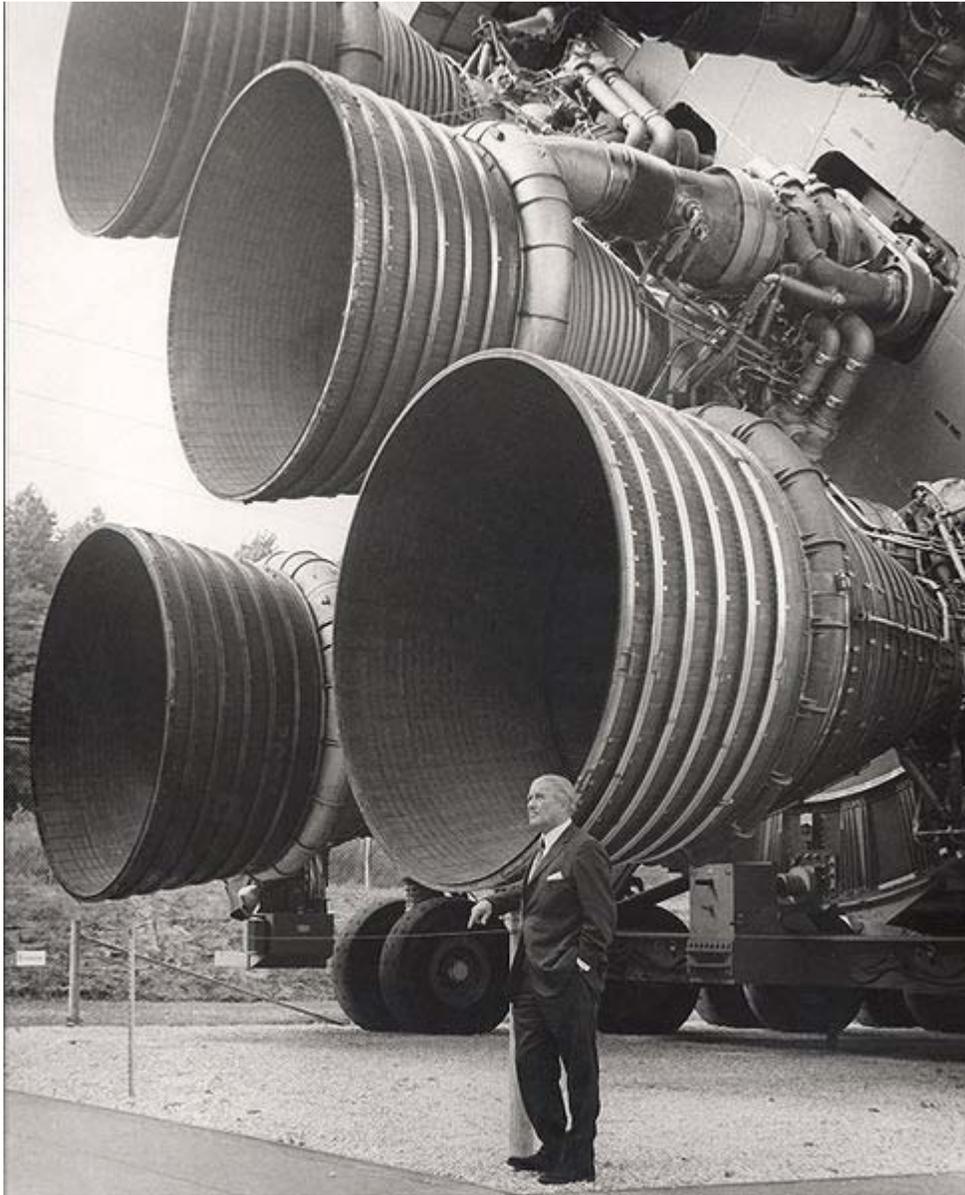
Wernher von Braun, with the F-1 engines of the Saturn V first stage at the US Space and Rocket Center

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, life time).

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. 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 and ENAC 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 University of Pisa and the Politecnico di Milano. 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. 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
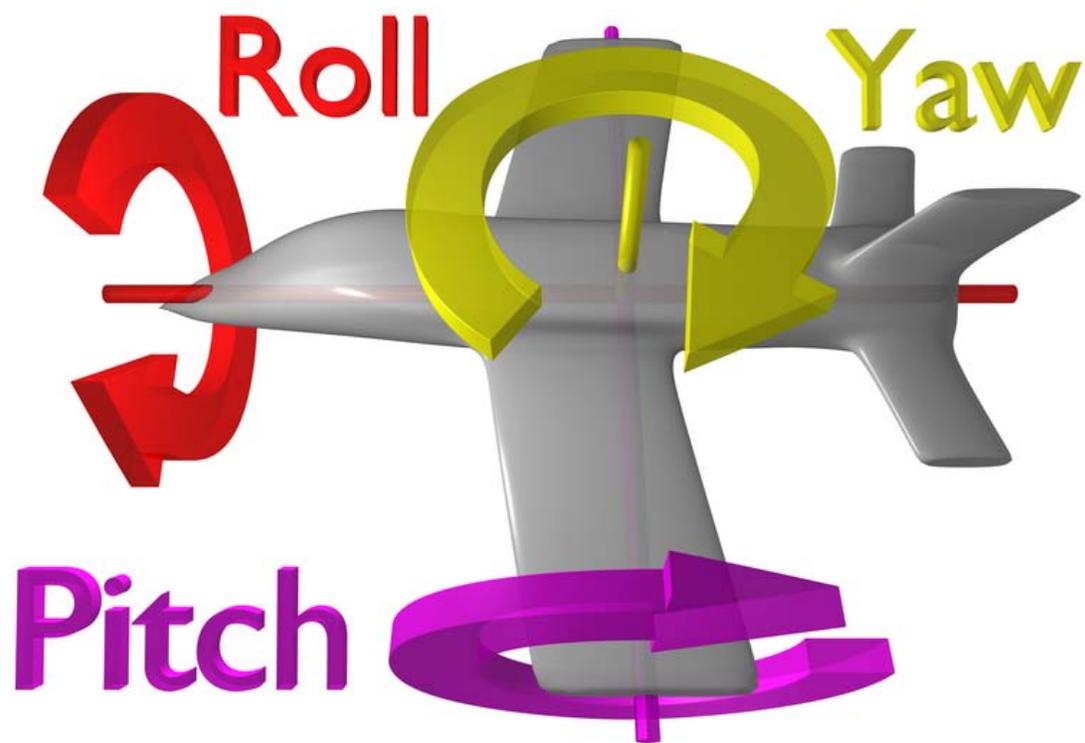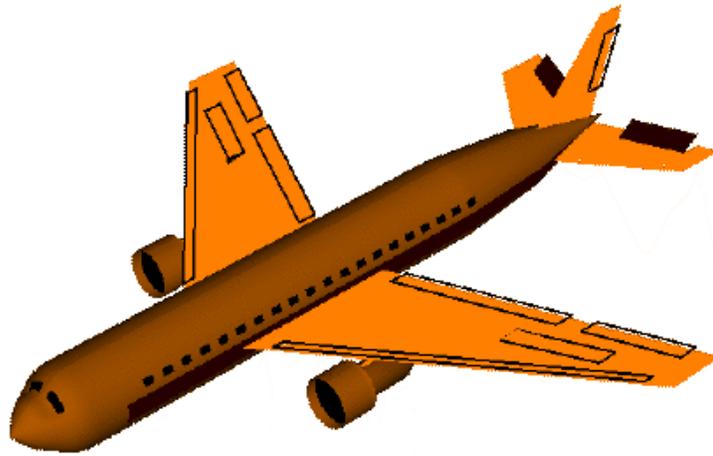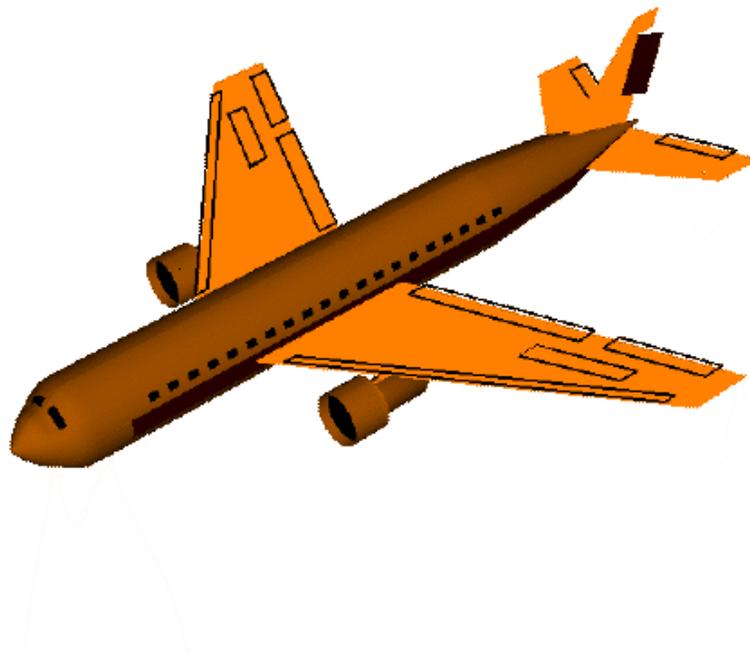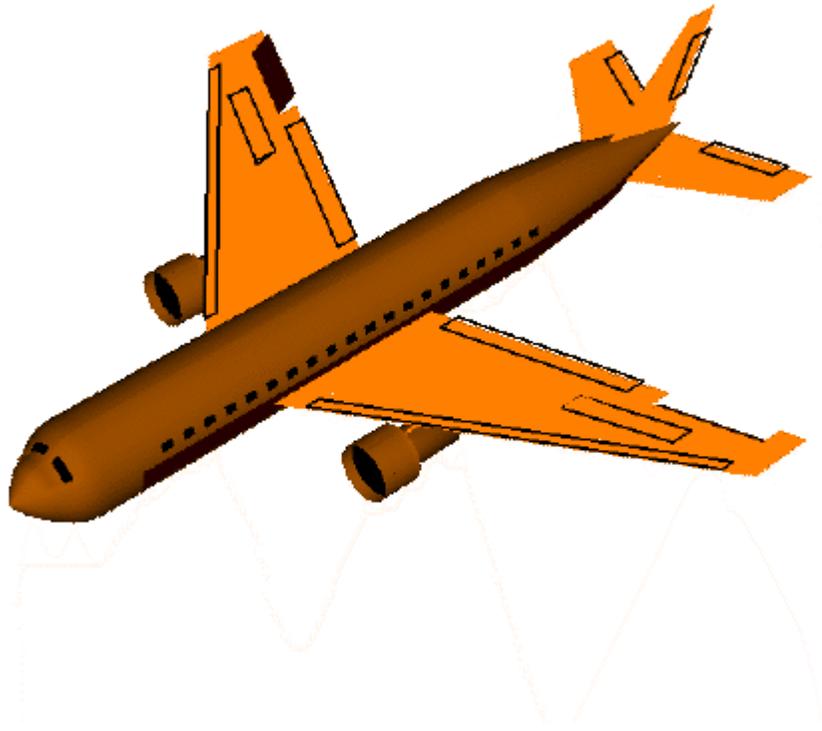
Flight Dynamics

Pitch

Yaw

Roll

Flight dynamics is the science of air vehicle orientation and control in three dimensions. The three critical flight dynamics parameters are the angles of rotation in three dimensions about the vehicle's center of mass, known as *pitch*, *roll* and *yaw* (quite different from their use as Tait-Bryan angles).

Aerospace engineers develop control systems for a vehicle's orientation (attitude) about its center of mass. The control systems include actuators, which exert forces in various directions, and generate rotational forces or moments about the aerodynamic center of the aircraft, and thus rotate the aircraft in pitch, roll, or yaw. For example, a pitching moment is a vertical force applied at a distance forward or aft from the aerodynamic center of the aircraft, causing the aircraft to pitch up or down.

Roll, pitch and yaw refer to rotations about the respective axes starting from a defined equilibrium state. The equilibrium roll angle is known as wings level or zero bank angle, equivalent to a level heeling angle on a ship. Yaw is known as "heading". The equilibrium pitch angle in submarine and airship parlance is known as "trim", but in aircraft, this usually refers to angle of attack, rather than orientation. However, common usage ignores this distinction between equilibrium and dynamic cases.

The most common aeronautical convention defines the roll as acting about the longitudinal axis, positive with the starboard (right) wing down. The yaw is about the

vertical body axis, positive with the nose to starboard. Pitch is about an axis perpendicular to the longitudinal plane of symmetry, positive nose up.

A fixed-wing aircraft increases or decreases the lift generated by the wings when it pitches nose up or down by increasing or decreasing the angle of attack (AOA). The roll angle is also known as bank angle on a fixed wing aircraft, which usually "banks" to change the horizontal direction of flight. An aircraft is usually streamlined from nose to tail to reduce drag making it typically advantageous to keep the sideslip angle near zero, though there are instances when an aircraft may be deliberately "sideslipped" for example a slip in a fixed wing aircraft.

Introduction

Basic coordinate systems

The position (and hence motion) of an aircraft is generally defined relative to one of 3 sets of co-ordinate systems:

- Wind axes
  - X axis - positive in the direction of the oncoming air (relative wind)
  - Y axis - positive to right of X axis, perpendicular to X axis
  - Z axis - positive downwards, perpendicular to X-Y plane

- Inertial axes (or body axes) - based about aircraft CG
  - X axis - positive forward, through nose of aircraft
  - Y axis - positive to right of X axis, perpendicular to X axis
  - Z axis - positive downwards, perpendicular to X-Y plane

- Earth Axes
  - X axis - positive in the direction of north
  - Y axis - positive in the direction of east (perpendicular to X axis)
  - Z axis - positive towards the center of Earth (perpendicular to X-Y plane)

For flight dynamics applications the earth axes are generally of minimal use, and hence will be ignored. The motions relevant to dynamic stability are usually too short in duration for the motion of the Earth itself to be considered relevant for aircraft.

In flight dynamics, pitch, roll and yaw angles measure both the absolute attitude angles (relative to the horizon/North) and *changes* in attitude angles, relative to the equilibrium orientation of the vehicle. These are defined as:

- Pitch - angle of X body axis (nose) relative to horizon. Also a positive (nose up) rotation about Y body axis
- Roll - angle of Y body axis (wing) relative to horizon. Also a positive (right wing down) rotation about X body axis

- Yaw - angle of X body axis (nose) relative to North. Also a positive (nose right) rotation about Z body axis

In analyzing the dynamics, we are concerned both with rotation and translation of this axis set with respect to a fixed inertial frame. For all practical purposes a local Earth axis set is used, this has X and Y axis in the local horizontal plane, usually with the x-axis coinciding with the projection of the velocity vector at the start of the motion, on to this plane. The z axis is vertical, pointing generally towards the Earth's center, completing an orthogonal set.

In general, the body axes are not aligned with the Earth axes. The body orientation may be defined by three Euler angles, the Tait-Bryan rotations, a quaternion, or a direction cosine matrix (rotation matrix). A rotation matrix is particularly convenient for converting velocity, force, angular velocity, and torque vectors between body and Earth coordinate frames.

Body axes tend to be used with missile and rocket configurations. Aircraft stability uses wind axes in which the x-axis points along the velocity vector. For straight and level flight this is found from body axes by rotating nose down through the angle of attack.

Stability deals with small perturbations in angular displacements about the orientation at the start of the motion. This consists of two components; rotation about each axis, and angular displacements due change in orientation of each axis. The latter term is of second order for the purpose of stability analysis, and is ignored.

Design cases

In analyzing the stability of an aircraft, it is usual to consider perturbations about a nominal equilibrium position. So the analysis would be applied, for example, assuming:

Straight and level flight
Turn at constant speed
Approach and landing
Takeoff

The speed, height and trim angle of attack are different for each flight condition, in addition, the aircraft will be configured differently, e.g. at low speed flaps may be deployed and the undercarriage may be down.

Except for asymmetric designs (or symmetric designs at significant sideslip), the longitudinal equations of motion (involving pitch and lift forces) may be treated independently of the lateral motion (involving roll and yaw).

The following considers perturbations about a nominal straight and level flight path.

To keep the analysis (relatively) simple, the control surfaces are assumed fixed throughout the motion, this is stick-fixed stability. Stick-free analysis requires the further complication of taking the motion of the control surfaces into account.

Furthermore, the flight is assumed to take place in still air, and the aircraft is treated as a rigid body.

Aerodynamic and propulsive forces

Aerodynamic forces

Components of the aerodynamic force

The expresion to calculate the aerodynamic force is:

$$\mathbf{F}_A = \int_{\Sigma} \left(-\Delta p \mathbf{n} + \mathbf{f} \right) d\sigma$$

where:

$\Delta p \equiv$ Difference between static pressure and free current pressure
$\mathbf{n} \equiv$ outer normal vector of the element of area
$\mathbf{f} \equiv$ tangential stress vector practised by the air on the body
$\Sigma \equiv$ adequate reference surface

projected on wind axes we obtain:

$$\mathbf{F}_A = -\left(\mathbf{i}_w D + \mathbf{j}_w Q + \mathbf{k}_w L \right)$$

where:

$D \equiv$ Drag
$Q \equiv$ Lateral force
$L \equiv$ Lift

Aerodynamic coefficients

Dynamic pressure of the free current $\equiv q = \frac{1}{2} \rho V^2$

Proper reference surface (wing surface, in case of planes) $\equiv S$

Pressure coefficient $\equiv C_p = \dfrac{p - p_\infty}{q}$

Friction coefficient $\equiv C_f = \dfrac{f}{q}$

Drag coefficient $\equiv C_d = \dfrac{D}{qS} = -\dfrac{1}{S}\displaystyle\int_{\Sigma}\left[(-C_p)\mathbf{n}\bullet\mathbf{i_w} + C_f\mathbf{t}\bullet\mathbf{i_w}\right]d\sigma$

Lateral force coefficient $\equiv C_Q = \dfrac{Q}{qS} = -\dfrac{1}{S}\displaystyle\int_{\Sigma}\left[(-C_p)\mathbf{n}\bullet\mathbf{j_w} + C_f\mathbf{t}\bullet\mathbf{j_w}\right]d\sigma$

Lift coefficient $\equiv C_L = \dfrac{L}{qS} = -\dfrac{1}{S}\displaystyle\int_{\Sigma}\left[(-C_p)\mathbf{n}\bullet\mathbf{k_w} + C_f\mathbf{t}\bullet\mathbf{k_w}\right]d\sigma$

It is necessary to know C_p and C_f in every point on the considered surface.

Dimensionless parameters and aerodynamic regimes

In absence of thermal effects, there are three remarkable dimensionless numbers:

- Compressibility of the flow:

  Mach number $\equiv M = \dfrac{V}{a}$

- Viscosity of the flow:

  Reynolds number $\equiv Re = \dfrac{\rho V l}{\mu}$

- Rarefaction of the flow:

  Knudsen number $\equiv Kn = \dfrac{\lambda}{l}$

where:

$a = \sqrt{kR\theta} \equiv$ speed of sound
$R \equiv$ gas constant by mass unity
$\theta \equiv$ absolute temperature
$\lambda = \dfrac{\mu}{\rho}\sqrt{\dfrac{\pi}{2R\theta}} = \dfrac{M}{Re}\sqrt{\dfrac{k\pi}{2}} \equiv$ mean free path

According to λ there are three posible rarefaction grades and their corresponding motions are called:

- Continuum current (negligible rarefaction): $\dfrac{M}{Re} \ll 1$

- Transition current (moderate rarefaction): $\dfrac{M}{Re} \approx 1$

- Free molecular current (high rarefaction): $\dfrac{M}{Re} \gg 1$

The motion of a body through a flow is considered, in flight dynamics, as continuum current. In the outer layer of the space that surrounds the body viscosity will be negligible. However viscosity effects will have to be considered when analysing the flow in the nearness of the boundary layer.

Depending on the compressibility of the flow, different kinds of currents can be considered:

- Incompressible subsonic current: $0 < M < 0.5$
- Compressible subsonic current: $0.5 < M < 0.8$
- Transonic current: $0.8 < M < 1.2$
- Supersonic current: $1.2 < M < 5$
- Hypersonic current: $5 < M$

Drag coefficient equation and aerodynamic efficiency

If the geometry of the body is fixed and in case of symmetric flight (β=0 and Q=0), pressure and friction coefficients are functions depending on:

$C_p = C_p(\alpha, M, Re, P)$
$C_f = C_f(\alpha, M, Re, P)$

where:

$\alpha \equiv$ angle of attack
$P \equiv$ considered point of the surface

Under these conditions, drag and lift coefficient are functions depending exclusively on the angle of attack of the body and Mach and Reynolds numbers. Aerodynamic efficiency, defined as the relation between lift and drag coefficients, will depend on those parameters as well.

$$\begin{cases} C_D = C_D(\alpha, M, Re) \\ C_L = C_L(\alpha, M, Re) \\ E = E(\alpha, M, Re) = \dfrac{C_L}{C_D} \end{cases}$$

It is also possible to get the dependency of the drag coefficient respect to the lift coefficient. This relation is konwn as the drag coefficient equation:

$$C_D = C_D(C_L, M, Re) \equiv \text{drag coefficient equation}$$

The aerodynamic efficiency has a maximum value, E_{max}, respect to C_L where the tangent line from the coordinate origin touches the drag coefficient equation plot.

The drag coefficient, C_D, can be decomposed in two ways. First typical decomposition separates pressure and friction effects:

$$C_D = C_{Df} + C_{Dp} \begin{cases} C_{Df} = \dfrac{D}{qS} = -\dfrac{1}{S} \int_\Sigma C_f \mathbf{t} \bullet \mathbf{i_w} \, d\sigma \\ C_{Dp} = \dfrac{D}{qS} = -\dfrac{1}{S} \int_\Sigma (-C_p) \mathbf{n} \bullet \mathbf{i_w} \, d\sigma \end{cases}$$

There´s a second typical decomposition taking into account the definition of the drag coefficient ecuation. This decomposition separates the effect of the lift coefficient in the equation, obtaining two terms C_{D0} and C_{Di}. C_{D0} is known as the parasitic drag coefficient and it is the base draft coefficient at zero lift. C_{Di} is known as the induced drag coefficient and it is produced by the body lift.

$$C_D = C_{D0} + C_{Di} \begin{cases} C_{D0} = (C_D)_{C_L=0} \\ C_{Di} \end{cases}$$

Parabolic and generic drag coefficient

A good attempt for the induced drag coefficient is to assume a parabolic dependency of the lift

$$C_{Di} = kC_L^2 \Rightarrow C_D = C_{D0} + kC_L^2$$

Aerodynamic efficiency is now calculated as:

$$E = \frac{C_L}{C_{D0} + kC_L^2} \Rightarrow \begin{cases} E_{max} = \dfrac{1}{2\sqrt{kC_{D0}}} \\ (C_L)_{Emax} = \sqrt{\dfrac{C_{D0}}{k}} \\ (C_{Di})_{Emax} = C_{D0} \end{cases}$$

If the configuration of the pane is symmetrical respect to the XY plane, minimum drag coefficient equals to the parasitic drag of the plane.

$$C_{Dmin} = (C_D)_{CL=0} = C_{D0}$$

In case the configuration is asymmetrical respect to the XY plane, however, minimum flag difers from the parasitic drag. On these cases, a new approximate parabolic drag equation can be traced leaving the minimum drag value at zero lift value.

$$C_{Dmin} = C_{DM} \neq (C_D)_{CL=0}$$
$$C_D = C_{DM} + k(C_L - C_{LM})^2$$

Dynamic stability and control

Longitudinal modes

It is common practice to derive a fourth order characteristic equation to describe the longitudinal motion, and then factorize it approximately into a high frequency mode and a low frequency mode. This requires a level of algebraic manipulation which most readers will doubtless find tedious, and adds little to the understanding of aircraft dynamics. The approach adopted here is to use our qualitative knowledge of aircraft behavior to simplify the equations from the outset, reaching the same result by a more accessible route.

The two longitudinal motions (modes) are called the short period pitch oscillation (SPPO), and the phugoid.

Short-period pitch oscillation

A short input (in control systems terminology an impulse) in pitch (generally via the elevator in a standard configuration fixed wing aircraft) will generally lead to overshoots about the trimmed condition. The transition is characterized by a damped simple harmonic motion about the new trim. There is very little change in the trajectory over the time it takes for the oscillation to damp out.

Generally this oscillation is high frequency (hence short period) and is damped over a period of a few seconds. A real-world example would involve a pilot selecting a new climb attitude, for example 5° nose up from the original attitude. A short, sharp pull back on the control column may be used, and will generally lead to oscillations about the new

trim condition. If the oscillations are poorly damped the aircraft will take a long period of time to settle at the new condition, potentially leading to Pilot-induced oscillation. If the short period mode is unstable it will generally be impossible for the pilot to safely control the aircraft for any period of time.

This damped harmonic motion is called the short period pitch oscillation, it arises from the tendency of a stable aircraft to point in the general direction of flight. It is very similar in nature to the weathercock mode of missile or rocket configurations. The motion involves mainly the pitch attitude θ (theta) and incidence α (alpha). The direction of the velocity vector, relative to inertial axes is θ − α. The velocity vector is:
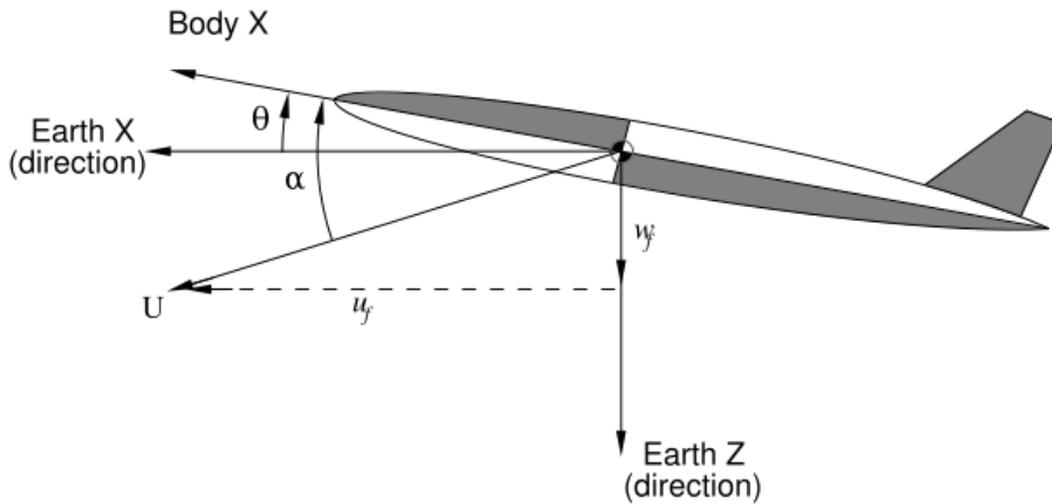
Longitudinal Equations of Motion

$$u_f = U\cos(\theta - \alpha)$$
$$w_f = U\sin(\theta - \alpha)$$

where u_f, w_f are the inertial axes components of velocity. According to Newton's Second Law, the accelerations are proportional to the forces, so the forces in inertial axes are:

$$X_f = m\frac{du_f}{dt} = m\frac{dU}{dt}\cos(\theta - \alpha) - mU\frac{d(\theta - \alpha)}{dt}\sin(\theta - \alpha)$$
$$Z_f = m\frac{dw_f}{dt} = m\frac{dU}{dt}\sin(\theta - \alpha) + mU\frac{d(\theta - \alpha)}{dt}\cos(\theta - \alpha)$$

where m is the mass. By the nature of the motion, the speed variation $m\frac{dU}{dt}$ is negligible over the period of the oscillation, so:

$$X_f = -mU\frac{d(\theta - \alpha)}{dt}\sin(\theta - \alpha)$$
$$Z_f = mU\frac{d(\theta - \alpha)}{dt}\cos(\theta - \alpha)$$

But the forces are generated by the pressure distribution on the body, and are referred to the velocity vector. But the velocity (wind) axes set is not an inertial frame so we must resolve the fixed axes forces into wind axes. Also, we are only concerned with the force along the z-axis:

$$Z = - Z_f\cos(\theta - \alpha) + X_f\sin(\theta - \alpha)$$

Or:

$$Z = -mU\frac{d(\theta - \alpha)}{dt}$$

In words, the wind axes force is equal to the centripetal acceleration.

The moment equation is the time derivative of the angular momentum:

$$M = B\frac{d^2\theta}{dt^2}$$

where M is the pitching moment, and B is the moment of inertia about the pitch axis. Let: $\frac{d\theta}{dt} = q$, the pitch rate. The equations of motion, with all forces and moments referred to wind axes are, therefore:

$$\frac{d\alpha}{dt} = q + \frac{Z}{mU}$$
$$\frac{dq}{dt} = \frac{M}{B}$$

We are only concerned with perturbations in forces and moments, due to perturbations in the states α and q, and their time derivatives. These are characterized by stability derivatives determined from the flight condition. The possible stability derivatives are:

Z_α Lift due to incidence, this is negative because the z-axis is downwards whilst positive incidence causes an upwards force.
Z_q Lift due to pitch rate, arises from the increase in tail incidence, hence is also negative, but small compared with Z_α.
M_α Pitching moment due to incidence - the static stability term. Static stability requires this to be negative.

M_q Pitching moment due to pitch rate - the pitch damping term, this is always negative.

Since the tail is operating in the flowfield of the wing, changes in the wing incidence cause changes in the downwash, but there is a delay for the change in wing flowfield to affect the tail lift, this is represented as a moment proportional to the rate of change of incidence:

$$M_{\dot{\alpha}}$$

Increasing the wing incidence without increasing the tail incidence produces a nose up moment, so $M_{\dot{\alpha}}$ is expected to be positive.

The equations of motion, with small perturbation forces and moments become:

$$\frac{d\alpha}{dt} = \left(1 + \frac{Z_q}{mU}\right) q + \frac{Z_\alpha}{mU}\alpha$$
$$\frac{dq}{dt} = \frac{M_q}{B}q + \frac{M_\alpha}{B}\alpha + \frac{M_{\dot{\alpha}}}{B}\dot{\alpha}$$

These may be manipulated to yield as second order linear differential equation in α:

$$\frac{d^2\alpha}{dt^2} - \left(\frac{Z_\alpha}{mU} + \frac{M_q}{B} + (1 + \frac{Z_q}{mU})\frac{M_{\dot{\alpha}}}{B}\right)\frac{d\alpha}{dt} + \left(\frac{Z_\alpha}{mU}\frac{M_q}{B} - \frac{M_\alpha}{B}(1 + \frac{Z_q}{mU})\right)\alpha = 0$$

This represents a damped simple harmonic motion.

We should expect $\dfrac{Z_q}{mU}$ to be small compared with unity, so the coefficient of α (the 'stiffness' term) will be positive, provided $M_\alpha < \dfrac{Z_\alpha}{mU}M_q$. This expression is dominated by M_α, which defines the longitudinal static stability of the aircraft, it must be negative for stability. The damping term is reduced by the downwash effect, and it is difficult to design an aircraft with both rapid natural response and heavy damping. Usually, the response is underdamped but stable.

Phugoid

If the stick is held fixed, the aircraft will not maintain straight and level flight, but will start to dive, level out and climb again. It will repeat this cycle until the pilot intervenes. This long period oscillation in speed and height is called the phugoid mode. This is analyzed by assuming that the SSPO performs its proper function and maintains the angle of attack near its nominal value. The two states which are mainly affected are the climb angle γ (gamma) and speed. The small perturbation equations of motion are:

$$mU\frac{d\gamma}{dt} = -Z$$

which means the centripetal force is equal to the perturbation in lift force.

For the speed, resolving along the trajectory:

$$m\frac{du}{dt} = X - mg\gamma$$

where g is the acceleration due to gravity at the earths surface. The acceleration along the trajectory is equal to the net x-wise force minus the component of weight. We should not expect significant aerodynamic derivatives to depend on the climb angle, so only X_u and Z_u need be considered. X_u is the drag increment with increased speed, it is negative, likewise Z_u is the lift increment due to speed increment, it is also negative because lift acts in the opposite sense to the z-axis.

The equations of motion become:

$$mU\frac{d\gamma}{dt} = -Z_u u$$
$$m\frac{du}{dt} = X_u u - mg\gamma$$

These may be expressed as a second order equation in climb angle or speed perturbation:

$$\frac{d^2u}{dt^2} - \frac{X_u}{m}\frac{du}{dt} - \frac{Z_u g}{mU}u = 0$$

Now lift is very nearly equal to weight:

$$Z = \frac{1}{2}\rho U^2 c_L S_w = W$$

where ρ is the air density, S_w is the wing area, W the weight and c_L is the lift coefficient (assumed constant because the incidence is constant), we have, approximately:

$$Z_u = \frac{2W}{U} = \frac{2mg}{U}$$

The period of the phugoid, T, is obtained from the coefficient of u:

$$\frac{2\pi}{T} = \sqrt{\frac{2g^2}{U^2}}$$

Or:

$$T = \frac{2\pi U}{\sqrt{2}g}$$

Since the lift is very much greater than the drag, the phugoid is at best lightly damped. A propeller with fixed speed would help. Heavy damping of the pitch rotation or a large rotational inertia increase the coupling between short period and phugoid modes, so that these will modify the phugoid.

Lateral modes

With a symmetrical rocket or missile, the directional stability in yaw is the same as the pitch stability; it resembles the short period pitch oscillation, with yaw plane equivalents to the pitch plane stability derivatives. For this reason pitch and yaw directional stability are collectively known as the "weathercock" stability of the missile.

Aircraft lack the symmetry between pitch and yaw, so that directional stability in yaw is derived from a different set of stability derivatives. The yaw plane equivalent to the short period pitch oscillation, which describes yaw plane directional stability is called Dutch roll. Unlike pitch plane motions, the lateral modes involve both roll and yaw motion.

Dutch roll

It is customary to derive the equations of motion by formal manipulation in what, to the engineer, amounts to a piece of mathematical sleight of hand. The current approach follows the pitch plane analysis in formulating the equations in terms of concepts which are reasonably familiar.

Applying an impulse via the rudder pedals should induce Dutch roll, which is the oscillation in roll and yaw, with the roll motion lagging yaw by a quarter cycle, so that the wing tips follow elliptical paths with respect to the aircraft.

The yaw plane translational equation, as in the pitch plane, equates the centripetal acceleration to the side force.

$$\frac{d\beta}{dt} = \frac{Y}{mU} - r$$

where β (beta) is the sideslip angle, Y the side force and r the yaw rate.

The moment equations are a bit trickier. The trim condition is with the aircraft at an angle of attack with respect to the airflow. The body x-axis does not align with the velocity vector, which is the reference direction for wind axes. In other words, wind axes are not principal axes (the mass is not distributed symmetrically about the yaw and roll axes).

Consider the motion of an element of mass in position -z,x in the direction of the y-axis, i.e. into the plane of the paper.

Lateral Equations Product of Inertia
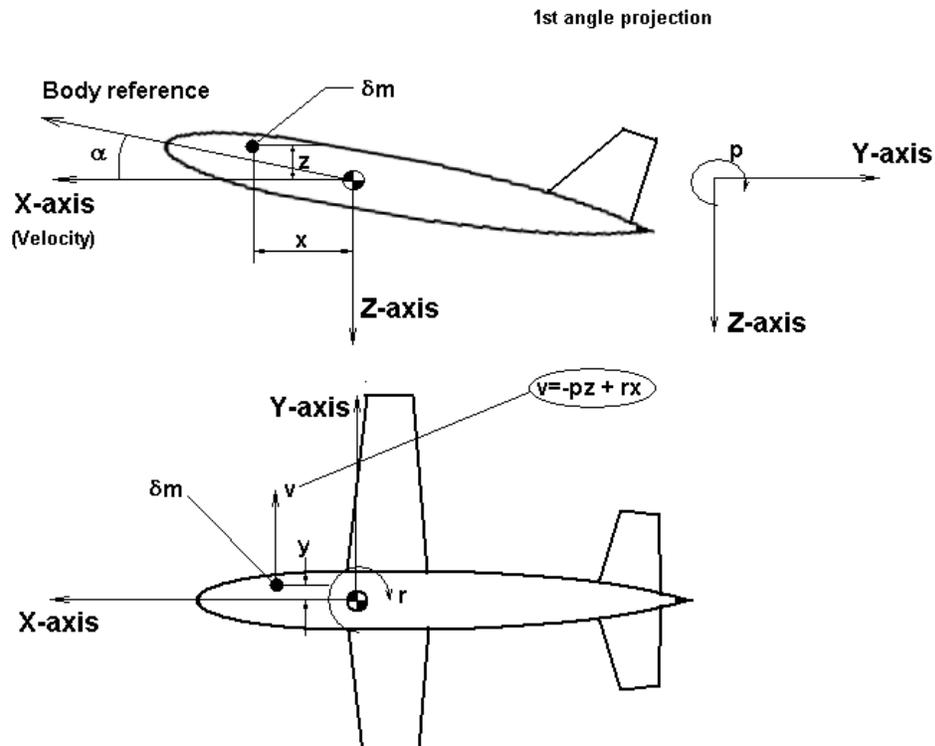
If the roll rate is p, the velocity of the particle is:

$$v = -pz + xr$$

Made up of two terms, the force on this particle is first the proportional to rate of v change, the second is due to the change in direction of this component of velocity as the body moves. The latter terms gives rise to cross products of small quantities (pq,pr,qr), which are later discarded. In this analysis, they are discarded from the outset for the sake of clarity. In effect, we assume that the direction of the velocity of the particle due to the simultaneous roll and yaw rates does not change significantly throughout the motion. With this simplifying assumption, the acceleration of the particle becomes:

$$\frac{dv}{dt} = -\frac{dp}{dt}z + \frac{dr}{dt}x$$

The yawing moment is given by:

$$\delta m x \frac{dv}{dt} = -\frac{dp}{dt} xz\delta m + \frac{dr}{dt} x^2 \delta m$$

There is an additional yawing moment due to the offset of the particle in the y direction: $\frac{dr}{dt} y^2 \delta m$

The yawing moment is found by summing over all particles of the body:

$$N = -\frac{dp}{dt} \int xz\,dm + \frac{dr}{dt} \int x^2 + y^2\,dm = -E\frac{dp}{dt} + C\frac{dr}{dt}$$

where N is the yawing moment, E is a product of inertia, and C is the moment of inertia about the yaw axis. A similar reasoning yields the roll equation:

$$L = A\frac{dp}{dt} - E\frac{dr}{dt}$$

where L is the rolling moment and A the roll moment of inertia.

Lateral and longitudinal stability derivatives

The states are β (sideslip), r (yaw rate) and p (roll rate), with moments N (yaw) and L (roll), and force Y (sideways). There are nine stability derivatives relevant to this motion, the following explains how they originate. However a better intuitive understanding is to be gained by simply playing with a model airplane, and considering how the forces on each component are affected by changes in sideslip and angular velocity:

View from nose (negative X direction)

Fin Lift

Starboard
wing Lift

Body Lift

L,p

Y-axis

λ

Port wing Lift

Dihedral

Z-axis
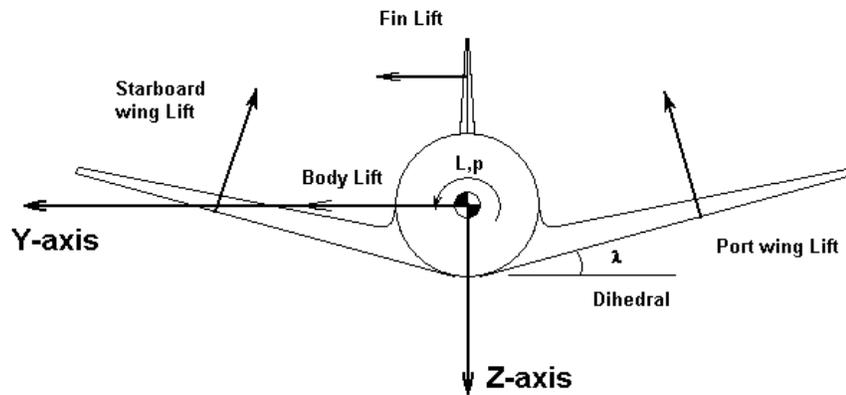
Lateral Stability - Main Sources of
Stabilising Forces and Moments

Y_β Side force due to side slip (in absence of yaw).

Sideslip generates a sideforce from the fin and the fuselage. In addition, if the wing has dihedral, side slip at a positive roll angle increases incidence on the starboard wing and reduces it on the port side, resulting in a net force component directly opposite to the sideslip direction. Sweep back of the wings has the same effect on incidence, but since the wings are not inclined in the vertical plane, backsweep alone does not affect Y_β. However, anhedral may be used with high backsweep angles in high performance aircraft to offset the wing incidence effects of sideslip. Oddly enough this does not reverse the sign of the wing configuration's contribution to Y_β (compared to the dihedral case).

Y_p Side force due to roll rate.

Roll rate causes incidence at the fin, which generates a corresponding side force. Also, positive roll (starboard wing down) increases the lift on the starboard wing and reduces it on the port. If the wing has dihedral, this will result in a side force momentarily opposing the resultant sideslip tendency. Anhedral wing and or stabilizer configurations can cause the sign of the side force to invert if the fin effect is swamped.

Y_r Side force due to yaw rate.

Yawing generates side forces due to incidence at the rudder, fin and fuselage.

N_β Yawing moment due to sideslip forces.

Sideslip in the absence of rudder input causes incidence on the fuselage and empennage, thus creating a yawing moment counteracted only by the directional stiffness which would tend to point the aircraft's nose back into the wind in horizontal flight conditions. Under sideslip conditions at a given roll angle N_β will tend to point the nose into the sideslip direction even without rudder input, causing a downward spiraling flight.
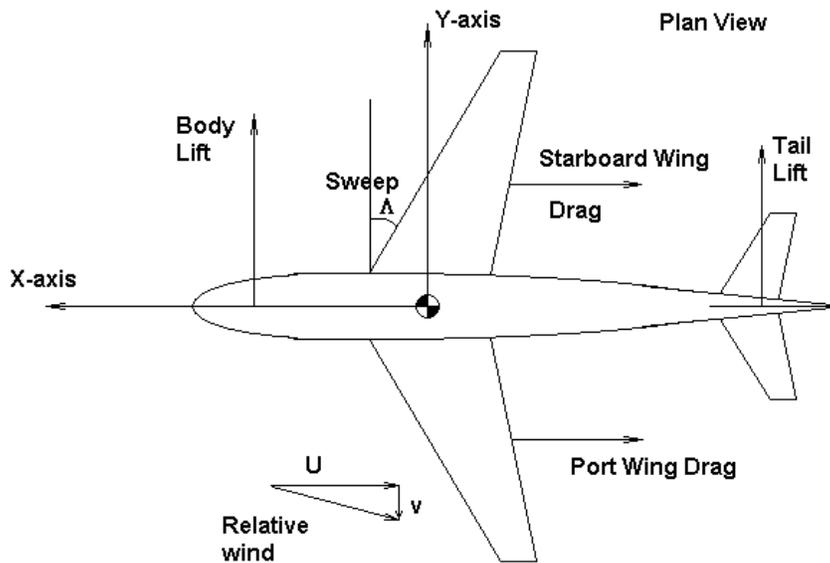
N_p Yawing moment due to roll rate.

Roll rate generates fin lift causing a yawing moment and also differentially alters the lift on the wings, thus affecting the induced drag contribution of each wing, causing a (small) yawing moment contribution. Positive roll generally causes positive N_p values unless the empennage is anhedral or fin is below the roll axis. Lateral force components resulting from dihedral or anhedral wing lift differences has little effect on N_p because the wing axis is normally closely aligned with the center of gravity.

N_r Yawing moment due to yaw rate.

Yaw rate input at any roll angle generates rudder, fin and fuselage force vectors which dominate the resultant yawing moment. Yawing also increases the speed of the outboard wing whilst slowing down the inboard wing, with corresponding changes in drag causing a (small) opposing yaw moment. N_r opposes the inherent directional stiffness which tends to point the aircraft's nose back into the wind and always matches the sign of the yaw rate input.

L_β Rolling moment due to sideslip.

A positive sideslip angle generates empennage incidence which can cause positive or negative roll moment depending on its configuration. For any non-zero sideslip angle dihedral wings causes a rolling moment which tends to return the aircraft to the horizontal, as does back swept wings. With highly swept wings the resultant rolling moment may be excessive for all stability requirements and anhedral could be used to offset the effect of wing sweep induced rolling moment.

Additional Contributions to Lateral Stability

L_r Rolling moment due to yaw rate.

Yaw increases the speed of the outboard wing whilst reducing speed of the inboard one, causing a rolling moment to the inboard side. The contribution of the fin normally supports this inward rolling effect unless offset by anhedral stabilizer above the roll axis (or dihedral below the roll axis).

L_p Rolling moment due to roll rate.

Roll creates counter rotational forces on both starboard and port wings whilst also generating such forces at the empennage. These opposing rolling moment effects have to be overcome by the aileron input in order to sustain the roll rate. If the roll is stopped at a non-zero roll angle the L_β *upward* rolling moment induced by the ensueing sideslip should return the aircraft to the horizontal unless exceeded in turn by the *downward* L_r rolling moment resulting from sideslip induced yaw rate. Longitudinal stability could be ensured or improved by minimizing the latter effect.

Equations of motion

Since Dutch roll is a handling mode, analogous to the short period pitch oscillation, any effect it might have on the trajectory may be ignored. The body rate *r* is made up of the

rate of change of sideslip angle and the rate of turn. Taking the latter as zero, assuming no effect on the trajectory, for the limited purpose of studying the Dutch roll:

$$\frac{d\beta}{dt} = -r$$

The yaw and roll equations, with the stability derivatives become:

$$C\frac{dr}{dt} - E\frac{dp}{dt} = N_\beta\beta - N_r\frac{d\beta}{dt} + N_p p \quad \text{(yaw)}$$
$$A\frac{dp}{dt} - E\frac{dr}{dt} = L_\beta\beta - L_r\frac{d\beta}{dt} + L_p p \quad \text{(roll)}$$

The inertial moment due to the roll acceleration is considered small compared with the aerodynamic terms, so the equations become:

$$-C\frac{d^2\beta}{dt^2} = N_\beta\beta - N_r\frac{d\beta}{dt} + N_p p$$
$$E\frac{d^2\beta}{dt^2} = L_\beta\beta - L_r\frac{d\beta}{dt} + L_p p$$

This becomes a second order equation governing either roll rate or sideslip:

$$\left(\frac{N_p}{C}\frac{E}{A} - \frac{L_p}{A}\right)\frac{d^2\beta}{dt^2} + \left(\frac{L_p}{A}\frac{N_r}{C} - \frac{N_p}{C}\frac{L_r}{A}\right)\frac{d\beta}{dt} - \left(\frac{L_p}{A}\frac{N_\beta}{C} - \frac{L_\beta}{A}\frac{N_p}{C}\right)\beta = 0$$

The equation for roll rate is identical. But the roll angle, φ (phi) is given by:

$$\frac{d\phi}{dt} = p$$

If p is a damped simple harmonic motion, so is φ, but the roll must be in quadrature with the roll rate, and hence also with the sideslip. The motion consists of oscillations in roll and yaw, with the roll motion lagging 90 degrees behind the yaw. The wing tips trace out elliptical paths.

Stability requires the "stiffness" and "damping" terms to be positive. These are:

$$\frac{\frac{L_p}{A}\frac{N_r}{C} - \frac{N_p}{C}\frac{L_r}{A}}{\frac{N_p}{C}\frac{E}{A} - \frac{L_p}{A}} \quad \text{(damping)}$$

$$\frac{\frac{L_\beta}{A}\frac{N_p}{C} - \frac{L_p}{A}\frac{N_\beta}{C}}{\frac{N_p}{C}\frac{E}{A} - \frac{L_p}{A}} \quad \text{(stiffness)}$$

The denominator is dominated by L_p, the roll damping derivative, which is always negative, so the denominators of these two expressions will be positive.

Considering the "stiffness" term: $-L_pN_\beta$ will be positive because L_p is always negative and N_β is positive by design. L_β is usually negative, whilst N_p is positive. Excessive dihedral can destabilize the Dutch roll, so configurations with highly swept wings require anhedral to offset the wing sweep contribution to L_β.

The damping term is dominated by the product of the roll damping and the yaw damping derivatives, these are both negative, so their product is positive. The Dutch roll should therefore be damped.

The motion is accompanied by slight lateral motion of the center of gravity and a more "exact" analysis will introduce terms in Y_β etc. In view of the accuracy with which stability derivatives can be calculated, this is an unnecessary pedantry, which serves to obscure the relationship between aircraft geometry and handling, which is the fundamental objective.

Roll subsidence

Jerking the stick sideways and returning it to center causes a net change in roll orientation.

The roll motion is characterized by an absence of natural stability, there are no stability derivatives which generate moments in response to the inertial roll angle. A roll disturbance induces a roll rate which is only canceled by pilot or autopilot intervention. This takes place with insignificant changes in sideslip or yaw rate, so the equation of motion reduces to:

$$A\frac{dp}{dt} = L_p p.$$

L_p is negative, so the roll rate will decay with time. The roll rate reduces to zero, but there is no direct control over the roll angle.

Spiral mode

Simply holding the stick still, when starting with the wings near level, an aircraft will usually have a tendency to gradually veer off to one side of the straight flightpath. This is the (slightly unstable) **spiral mode**. The opposite holds for a stable spiral mode. The spiral mode is so-named because when it is slightly unstable, and the controls are not moved, the aircraft will tend to increase its bank angle slowly at first, then ever faster.

The resulting path through the air is a continuously tightening and ever more rapidly descending *spiral*. An unstable spiral mode is common to most aircraft. It is not dangerous because the times to double the bank angle are large compared to the pilot's ability to respond and correct errors with aileron inputs.

When the spiral mode is stable, it behaves in a way opposite to the exponential divergence of the unstable mode. The stable spiral mode, when starting with the wings at a moderate bank angle, will return to near wings level, first quickly, then more slowly. When the spiral mode is stable and starting at a moderate bank angle, the spiral nature of the flight path is not as obvious. This is because usually only a fraction of a turn is made while the wings are not fully level. The turning starts out (relatively) tight, then becomes less and less so as the wings become more level.

The divergence rate of the *unstable* spiral mode will be roughly proportional to the roll angle itself (i.e. roughly exponential growth). The *con*vergence rate of the *stable* spiral mode will be roughly proportional to the roll angle itself (i.e. roughly exponential *decay*).

Spiral mode trajectory

In studying the trajectory, it is the direction of the velocity vector, rather than that of the body, which is of interest. The direction of the velocity vector when projected on to the horizontal will be called the track, denoted μ (mu). The body orientation is called the heading, denoted ψ (psi). The force equation of motion includes a component of weight:

$$\frac{d\mu}{dt} = \frac{Y}{mU} + \frac{g}{U}\phi$$

where g is the gravitational acceleration, and U is the speed.

Including the stability derivatives:

$$\frac{d\mu}{dt} = \frac{Y_\beta}{mU}\beta + \frac{Y_r}{mU}r + \frac{Y_p}{mU}p + \frac{g}{U}\phi$$

Roll rates and yaw rates are expected to be small, so the contributions of Y_r and Y_p will be ignored.

The sideslip and roll rate vary gradually, so their time derivatives are ignored. The yaw and roll equations reduce to:

$$N_\beta\beta + N_r\frac{d\mu}{dt} + N_p p = 0 \quad \text{(yaw)}$$
$$L_\beta\beta + L_r\frac{d\mu}{dt} + L_p p = 0 \quad \text{(roll)}$$

Solving for β and p:

$$\beta = \frac{(L_r N_p - L_p N_r)}{(L_p N_\beta - N_p L_\beta)}\frac{d\mu}{dt}$$

$$p = \frac{(L_\beta N_r - L_r N_\beta)}{(L_p N_\beta - N_p L_\beta)}\frac{d\mu}{dt}$$

Substituting for sideslip and roll rate in the force equation results in a first order equation in roll angle:

$$\frac{d\phi}{dt} = mg\frac{(L_\beta N_r - N_\beta L_r)}{mU(L_p N_\beta - N_p L_\beta) - Y_\beta(L_r N_p - L_p N_r)}\phi$$

This is an exponential growth or decay, depending on whether the coefficient of φ is positive or negative. The denominator is usually negative, which requires $L_\beta N_r > N_\beta L_r$ (both products are positive). This is in direct conflict with the Dutch roll stability requirement, and it is difficult to design an aircraft for which both the Dutch roll and spiral mode are inherently stable.

Since the spiral mode has a long time constant, the pilot can intervene to effectively stabilize it, but an aircraft with an unstable Dutch roll would be difficult to fly. It is usual to design the aircraft with a stable Dutch roll mode, but slightly unstable spiral mode.

Chapter- 3

Aerodynamics

A vortex is created by the passage of an aircraft wing, revealed by smoke. Vortices are one of the many phenomena associated to the study of aerodynamics. The equations of aerodynamics show that the vortex is created by the difference in pressure between the upper and lower surface of the wing. At the end of the wing, the lower surface effectively tries to 'reach over' to the low pressure side, creating rotation and the vortex.

Aerodynamics is a branch of dynamics concerned with studying the motion of air, particularly when it interacts with a moving object. Aerodynamics is a subfield of fluid dynamics and gas dynamics, with much theory shared between them. Aerodynamics is often used synonymously with gas dynamics, with the difference being that gas dynamics

applies to all gases. Understanding the motion of air (often called a flow field) around an object enables the calculation of forces and moments acting on the object. Typical properties calculated for a flow field include velocity, pressure, density and temperature as a function of position and time. By defining a control volume around the flow field, equations for the conservation of mass, momentum, and energy can be defined and used to solve for the properties. The use of aerodynamics through mathematical analysis, empirical approximations, wind tunnel experimentation, and computer simulations form the scientific basis for heavier-than-air flight.

Aerodynamic problems can be identified in a number of ways. The flow environment defines the first classification criterion. *External* aerodynamics is the study of flow around solid objects of various shapes. Evaluating the lift and drag on an airplane or the shock waves that form in front of the nose of a rocket are examples of external aerodynamics. *Internal* aerodynamics is the study of flow through passages in solid objects. For instance, internal aerodynamics encompasses the study of the airflow through a jet engine or through an air conditioning pipe.

The ratio of the problem's characteristic flow speed to the speed of sound comprises a second classification of aerodynamic problems. A problem is called subsonic if all the speeds in the problem are less than the speed of sound, transonic if speeds both below and above the speed of sound are present (normally when the characteristic speed is approximately the speed of sound), supersonic when the characteristic flow speed is greater than the speed of sound, and hypersonic when the flow speed is much greater than the speed of sound. Aerodynamicists disagree over the precise definition of hypersonic flow; minimum Mach numbers for hypersonic flow range from 3 to 12.

The influence of viscosity in the flow dictates a third classification. Some problems may encounter only very small viscous effects on the solution, in which case viscosity can be considered to be negligible. The approximations to these problems are called inviscid flows. Flows for which viscosity cannot be neglected are called viscous flows.

History

Early ideas - ancient times to the 17th century
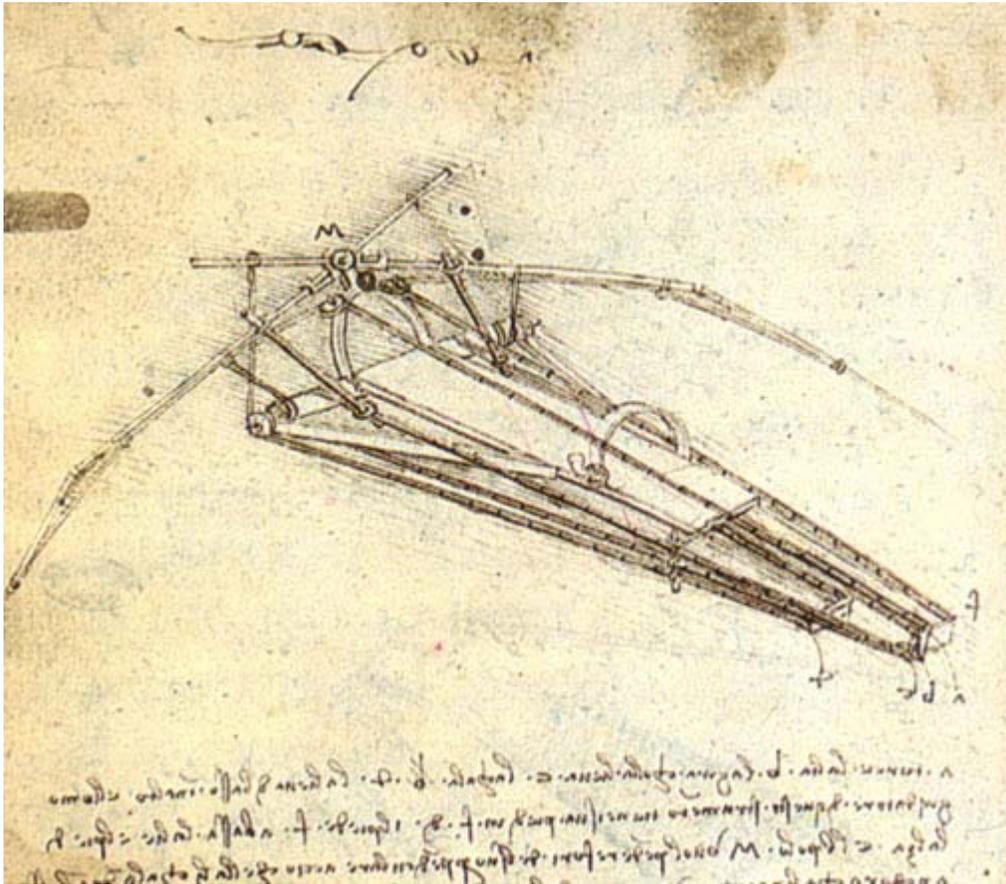
A drawing of a design for a flying machine by Leonardo da Vinci (c. 1488). This machine was an ornithopter, with flapping wings similar to a bird, first presented in his Codex on the Flight of Birds in 1505.

Images and stories of flight have appeared throughout recorded history, such as the legendary story of Icarus and Daedalus. Although observations of some aerodynamic effects like wind resistance (a.k.a. drag) were recorded by the likes of Aristotle, Leonardo da Vinci and Galileo Galilei, very little effort was made to develop governing laws for understanding the nature of flight prior to the 17th century.

In 1505, Leonardo da Vinci wrote the *Codex on the Flight of Birds*, one of the earliest treatises on aerodynamics. He notes for the first time that the center of gravity of a flying bird does not coincide with its center of pressure, and he describes the construction of an ornithopter, with flapping wings similar to a bird's.

Sir Isaac Newton was the first person to develop a theory of air resistance, making him one of the first aerodynamicists. As part of that theory, Newton believed that drag was due to the dimensions of a body, the density of the fluid, and the velocity raised to the

second power. These beliefs all turned out to be correct for low flow speeds. Newton also developed a law for the drag force on a flat plate inclined towards the direction of the fluid flow. Using F for the drag force, ρ for the density, S for the area of the flat plate, V for the flow velocity, and θ for the inclination angle, his law was expressed as $F = \rho S V^2 \sin^2(\theta)$

Unfortunately, this equation is incorrect for the calculation of drag in most cases. Drag on a flat plate is closer to being linear with the angle of inclination as opposed to acting quadratically at low angles. The Newton formula can lead one to believe that flight is more difficult than it actually is, and it may have contributed to a delay in human flight. However, it is correct for a very slender plate when the angle becomes large and flow separation occurs, or if the flow speed is supersonic.

Modern beginnings - 18th to 19th century
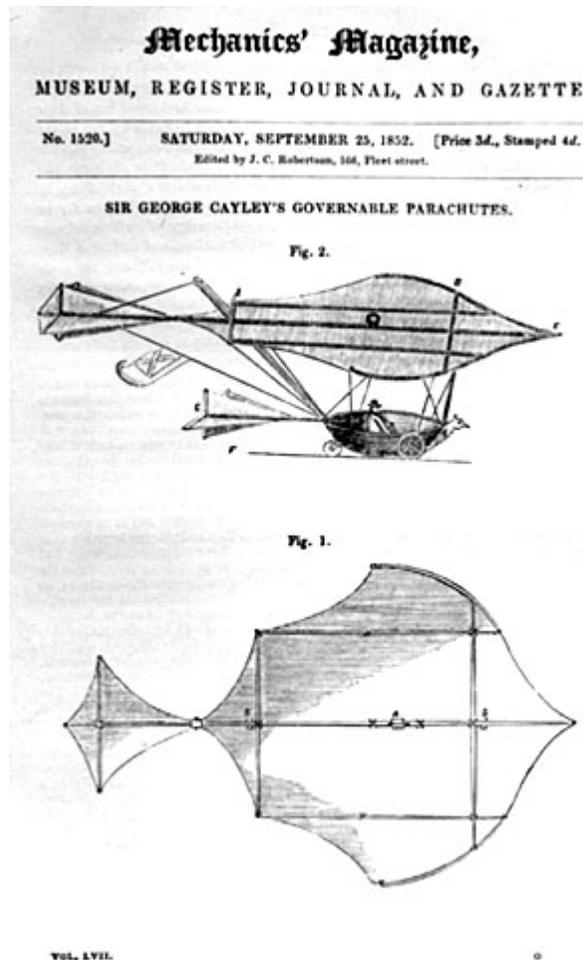
A drawing of a glider by Sir George Cayley, one of the early attempts at creating an aerodynamic shape

In 1738 The Dutch-Swiss mathematician Daniel Bernoulli published his book *Hydrodynamica,* in which he first set out the principle, named after him, by which aerodynamic lift may be derived.

Sir George Cayley is credited as the first person to identify the four aerodynamic forces of flight—weight, lift, drag, and thrust—and the relationship between them. Cayley believed that the drag on a flying machine must be counteracted by a means of propulsion in order for level flight to occur. Cayley also looked to nature for aerodynamic shapes with low drag. Among the shapes he investigated were the cross-sections of trout. This may appear counterintuitive, however, the bodies of fish are shaped to produce very low resistance as they travel through water. Their cross-sections are sometimes very close to that of modern low drag airfoils.

Air resistance experiments were carried out by investigators throughout the 18th and 19th centuries. Drag theories were developed by Jean le Rond d'Alembert, Gustav Kirchhoff, and Lord Rayleigh. Equations for fluid flow with friction were developed by Claude-Louis Navier and George Gabriel Stokes. To simulate fluid flow, many experiments involved immersing objects in streams of water or simply dropping them off the top of a tall building. Towards the end of this time period Gustave Eiffel used his Eiffel Tower to assist in the drop testing of flat plates.

Of course, a more precise way to measure resistance is to place an object within an artificial, uniform stream of air where the velocity is known. The first person to experiment in this fashion was Francis Herbert Wenham, who in doing so constructed the first wind tunnel in 1871. Wenham was also a member of the first professional organization dedicated to aeronautics, the Royal Aeronautical Society of the United Kingdom. Objects placed in wind tunnel models are almost always smaller than in practice, so a method was needed to relate small scale models to their real-life counterparts. This was achieved with the invention of the dimensionless Reynolds number by Osborne Reynolds. Reynolds also experimented with laminar to turbulent flow transition in 1883.

By the late 19th century, two problems were identified before heavier-than-air flight could be realized. The first was the creation of low-drag, high-lift aerodynamic wings. The second problem was how to determine the power needed for sustained flight. During this time, the groundwork was laid down for modern day fluid dynamics and aerodynamics, with other less scientifically inclined enthusiasts testing various flying machines with little success.

A replica of the Wright Brothers' wind tunnel is on display at the Virginia Air and Space Center. Wind tunnels were key in the development and validation of the laws of aerodynamics.

In 1889, Charles Renard, a French aeronautical engineer, became the first person to reasonably predict the power needed for sustained flight. Renard and German physicist Hermann von Helmholtz explored the wing loading of birds, eventually concluding that humans could not fly under their own power by attaching wings onto their arms. Otto Lilienthal, following the work of Sir George Cayley, was the first person to become highly successful with glider flights. Lilienthal believed that thin, curved airfoils would produce high lift and low drag.

Octave Chanute provided a great service to those interested in aerodynamics and flying machines by publishing a book outlining all of the research conducted around the world up to 1893.

Practical flight - early 20th century

With the information contained in Chanute's book, the personal assistance of Chanute himself, and research carried out in their own wind tunnel, the Wright brothers gained just enough knowledge of aerodynamics to fly the first powered aircraft on December 17, 1903, just in time to beat the efforts of Samuel Pierpont Langley. The Wright brothers'

flight confirmed or disproved a number of aerodynamics theories. Newton's drag force theory was finally proved incorrect. This first widely-publicised flight led to a more organized effort between aviators and scientists, leading the way to modern aerodynamics.

During the time of the first flights, Frederick W. Lanchester, Martin Wilhelm Kutta, and Nikolai Zhukovsky independently created theories that connected circulation of a fluid flow to lift. Kutta and Zhukovsky went on to develop a two-dimensional wing theory. Expanding upon the work of Lanchester, Ludwig Prandtl is credited with developing the mathematics behind thin-airfoil and lifting-line theories as well as work with boundary layers. Prandtl, a professor at the University of Göttingen, instructed many students who would play important roles in the development of aerodynamics like Theodore von Kármán and Max Munk.

Faster than sound - latter 20th century

As aircraft began to travel faster, aerodynamicists realized that the density of air began to change as it came into contact with an object, leading to a division of fluid flow into the incompressible and compressible regimes. In compressible aerodynamics, density and pressure both change, which is the basis for calculating the speed of sound. Newton was the first to develop a mathematical model for calculating the speed of sound, but it was not correct until Pierre-Simon Laplace accounted for the molecular behavior of gases and introduced the heat capacity ratio. The ratio of the flow speed to the speed of sound was named the Mach number after Ernst Mach, who was one of the first to investigate the properties of supersonic flow which included Schlieren photography techniques to visualize the changes in density. William John Macquorn Rankine and Pierre Henri Hugoniot independently developed the theory for flow properties before and after a shock wave. Jakob Ackeret led the initial work on calculating the lift and drag on a supersonic airfoil. Theodore von Kármán and Hugh Latimer Dryden introduced the term transonic to describe flow speeds around Mach 1 where drag increases rapidly. Because of the increase in drag approaching Mach 1, aerodynamicists and aviators disagreed on whether supersonic flight was achievable.
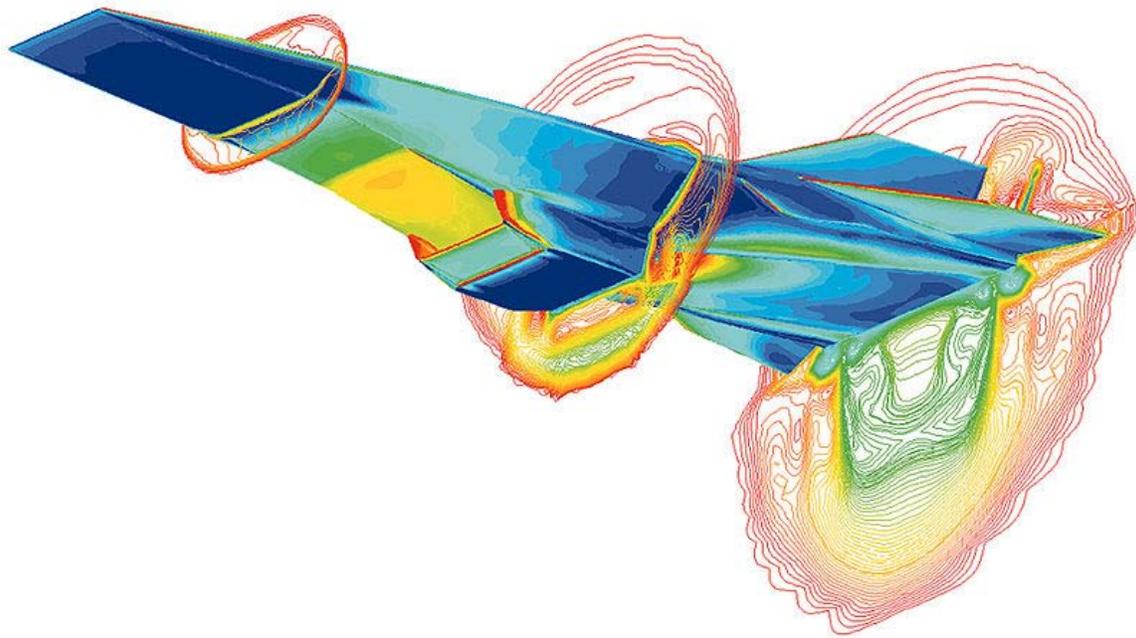
A computer generated model of NASA's X-43A hypersonic research vehicle flying at Mach 7 using a computational fluid dynamics code.

On September 30, 1935 an exclusive conference was held in Rome with the topic of high velocity flight and the possibility of breaking the sound barrier. Participants included Theodore von Kármán, Ludwig Prandtl, Jakob Ackeret, Eastman Jacobs, Adolf Busemann, Geoffrey Ingram Taylor, Gaetano Arturo Crocco, and Enrico Pistolesi. The new research presented was impressive. Ackeret presented a design for a supersonic wind tunnel. Busemann gave perhaps the best presentation on the need for aircraft with swept wings for high speed flight. Eastman Jacobs, working for NACA, presented his optimized airfoils for high subsonic speeds which led to some of the high performance American aircraft during World War II. Supersonic propulsion was also discussed. The sound barrier was broken using the Bell X-1 aircraft twelve years later, thanks in part to those individuals.

By the time the sound barrier was broken, much of the subsonic and low supersonic aerodynamics knowledge had matured. The Cold War fueled an ever evolving line of high performance aircraft. Computational fluid dynamics was started as an effort to solve for flow properties around complex objects and has rapidly grown to the point where entire aircraft can be designed using a computer.

With some exceptions, the knowledge of hypersonic aerodynamics has matured between the 1960s and the present decade. Therefore, the goals of an aerodynamicist have shifted from understanding the behavior of fluid flow to understanding how to engineer a vehicle to interact appropriately with the fluid flow. For example, while the behavior of

hypersonic flow is understood, building a scramjet aircraft to fly at hypersonic speeds has seen very limited success. Along with building a successful scramjet aircraft, the desire to improve the aerodynamic efficiency of current aircraft and propulsion systems will continue to fuel new research in aerodynamics.

Introductory terminology

- Lift
- Drag
- Reynolds number
- Mach number

Continuity assumption

Gases are composed of molecules which collide with one another and solid objects. If density and velocity are taken to be well-defined at infinitely small points, and are assumed to vary continuously from one point to another, the discrete molecular nature of a gas is ignored.

The continuity assumption becomes less valid as a gas becomes more rarefied. In these cases, statistical mechanics is a more valid method of solving the problem than continuous aerodynamics. The Knudsen number can be used to guide the choice between statistical mechanics and the continuous formulation of aerodynamics.

Laws of conservation
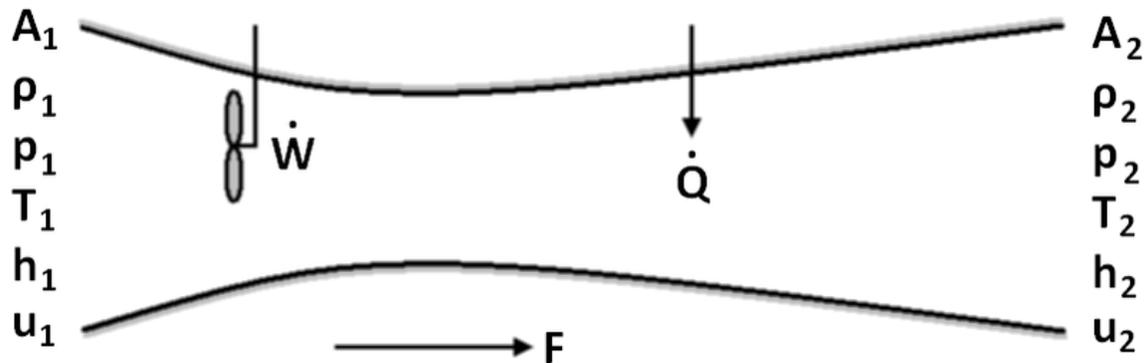
Control volume schematic of internal flow with one inlet and exit including an axial force, work, and heat transfer. State 1 is the inlet and state 2 is the exit.

Aerodynamics problems are often solved using conservation laws as applied to a fluid continuum. The conservation laws can be written in integral or differential form. In many basic problems, three conservation principles are used:

- Continuity: If a certain mass of fluid enters a volume, it must either exit the volume or change the mass inside the volume. In fluid dynamics, the continuity

equation is analogous to Kirchhoff's Current Law in electric circuits. The differential form of the continuity equation is:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0$$

Above, ρ is the fluid density, $\mathbf{u}$ is a velocity vector, and t is time. Physically, the equation also shows that mass is neither created nor destroyed in the control volume. For a steady state process, the rate at which mass enters the volume is equal to the rate at which it leaves the volume. Consequently, the first term on the left is then equal to zero. For flow through a tube with one inlet (state 1) and exit (state 2) as shown in the figure in this section, the continuity equation may be written and solved as:

$$\rho_1 u_1 A_1 = \rho_2 u_2 A_2$$

Above, A is the variable cross-section area of the tube at the inlet and exit. For incompressible flows, density remains constant.

- Conservation of Momentum: This equation applies Newton's second law of motion to a continuum, whereby force is equal to the time derivative of momentum. Both surface and body forces are accounted for in this equation. For instance, F could be expanded into an expression for the frictional force acting on an internal flow.

$$\frac{D\mathbf{u}}{Dt} = \mathbf{F} - \frac{\nabla p}{\rho}$$

For the same figure, a control volume analysis yields:

$$p_1 A_1 + \rho_1 A_1 u_1^2 + F = p_2 A_2 + \rho_2 A_2 u_2^2$$

Above, the force F is placed on the left side of the equation, assuming it acts with the flow moving in a left-to-right direction. Depending on the other properties of the flow, the resulting force could be negative which means it acts in the opposite direction as depicted in the figure.

- Conservation of Energy: Although energy can be converted from one form to another, the total energy in a given system remains constant.

$$\rho \frac{Dh}{Dt} = \frac{Dp}{Dt} + \nabla \cdot (k\nabla T) + \Phi$$

Above, h is enthalpy, k is the thermal conductivity of the fluid, T is temperature, and Φ is the viscous dissipation function. The viscous dissipation function governs the rate at which mechanical energy of the flow is converted to heat. The expression on the left side

is a material derivative. The term is always positive since, according to the second law of thermodynamics, viscosity cannot add energy to the control volume. Again using the figure, the energy equation in terms of the control volume may be written as:

$$\rho_1 u_1 A_1 \left(h_1 + \frac{u_1^2}{2} \right) + \dot{W} + \dot{Q} = \rho_2 u_2 A_2 \left(h_2 + \frac{u_2^2}{2} \right)$$

Above, the shaft work and heat transfer are assumed to be acting on the flow. They may be positive (to the flow from the surroundings) or negative (to the surroundings from the flow) depending on the problem. The ideal gas law or another equation of state is often used in conjunction with these equations to form a system to solve for the unknown variables.

Incompressible aerodynamics

An incompressible flow is characterized by a constant density despite flowing over surfaces or inside ducts. A flow can be considered incompressible as long as its speed is low. For higher speeds, the flow will begin to compress as it comes into contact with surfaces. The Mach number is used to distinguish between incompressible and compressible flows.

Subsonic flow

Subsonic (or low-speed) aerodynamics is the study of fluid motion which is everywhere much slower than the speed of sound through the fluid or gas. There are several branches of subsonic flow but one special case arises when the flow is inviscid, incompressible and irrotational. This case is called Potential flow and allows the differential equations used to be a simplified version of the governing equations of fluid dynamics, thus making available to the aerodynamicist a range of quick and easy solutions. It is a special case of Subsonic aerodynamics.

In solving a subsonic problem, one decision to be made by the aerodynamicist is whether to incorporate the effects of compressibility. Compressibility is a description of the amount of change of density in the problem. When the effects of compressibility on the solution are small, the aerodynamicist may choose to assume that density is constant. The problem is then an incompressible low-speed aerodynamics problem. When the density is allowed to vary, the problem is called a compressible problem. In air, compressibility effects are usually ignored when the Mach number in the flow does not exceed 0.3 (about 335 feet (102m) per second or 228 miles (366 km) per hour at 60°F). Above 0.3, the problem should be solved by using compressible aerodynamics.

Compressible aerodynamics

According to the theory of aerodynamics, a flow is considered to be compressible if its change in density with respect to pressure is non-zero along a streamline. This means that

- unlike incompressible flow - changes in density must be considered. In general, this is the case where the Mach number in part or all of the flow exceeds 0.3. The Mach .3 value is rather arbitrary, but it is used because gas flows with a Mach number below that value demonstrate changes in density with respect to the change in pressure of less than 5%. Furthermore, that maximum 5% density change occurs at the stagnation point of an object immersed in the gas flow and the density changes around the rest of the object will be significantly lower. Transonic, supersonic, and hypersonic flows are all compressible.

Transonic flow

The term Transonic refers to a range of velocities just below and above the local speed of sound (generally taken as Mach 0.8–1.2). It is defined as the range of speeds between the critical Mach number, when some parts of the airflow over an aircraft become supersonic, and a higher speed, typically near Mach 1.2, when all of the airflow is supersonic. Between these speeds some of the airflow is supersonic, and some is not.

Supersonic flow

Supersonic aerodynamic problems are those involving flow speeds greater than the speed of sound. Calculating the lift on the Concorde during cruise can be an example of a supersonic aerodynamic problem.

Supersonic flow behaves very differently from subsonic flow. Fluids react to differences in pressure; pressure changes are how a fluid is "told" to respond to its environment. Therefore, since sound is in fact an infinitesimal pressure difference propagating through a fluid, the speed of sound in that fluid can be considered the fastest speed that "information" can travel in the flow. This difference most obviously manifests itself in the case of a fluid striking an object. In front of that object, the fluid builds up a stagnation pressure as impact with the object brings the moving fluid to rest. In fluid traveling at subsonic speed, this pressure disturbance can propagate upstream, changing the flow pattern ahead of the object and giving the impression that the fluid "knows" the object is there and is avoiding it. However, in a supersonic flow, the pressure disturbance cannot propagate upstream. Thus, when the fluid finally does strike the object, it is forced to change its properties -- temperature, density, pressure, and Mach number -- in an extremely violent and irreversible fashion called a shock wave. The presence of shock waves, along with the compressibility effects of high-velocity fluids, is the central difference between supersonic and subsonic aerodynamics problems.

Hypersonic flow

In aerodynamics, hypersonic speeds are speeds that are highly supersonic. In the 1970s, the term generally came to refer to speeds of Mach 5 (5 times the speed of sound) and above. The hypersonic regime is a subset of the supersonic regime. Hypersonic flow is characterized by high temperature flow behind a shock wave, viscous interaction, and chemical dissociation of gas.

Associated terminology

The incompressible and compressible flow regimes produce many associated phenomena, such as boundary layers and turbulence.

Boundary layers

The concept of a boundary layer is important in many aerodynamic problems. The viscosity and fluid friction in the air is approximated as being significant only in this thin layer. This principle makes aerodynamics much more tractable mathematically.

Turbulence

In aerodynamics, turbulence is characterized by chaotic, stochastic property changes in the flow. This includes low momentum diffusion, high momentum convection, and rapid variation of pressure and velocity in space and time. Flow that is not turbulent is called laminar flow.

Aerodynamics in other fields

Aerodynamics is important in a number of applications other than aerospace engineering. It is a significant factor in any type of vehicle design, including automobiles. It is important in the prediction of forces and moments in sailing. It is used in the design of large components such as hard drive heads. Structural engineers also use aerodynamics, and particularly aeroelasticity, to calculate wind loads in the design of large buildings and bridges. Urban aerodynamics seeks to help town planners and designers improve comfort in outdoor spaces, create urban microclimates and reduce the effects of urban pollution. The field of environmental aerodynamics studies the ways atmospheric circulation and flight mechanics affect ecosystems. The aerodynamics of internal passages is important in heating/ventilation, gas piping, and in automotive engines where detailed flow patterns strongly affect the performance of the engine.

Chapter- 4

Spacecraft Propulsion
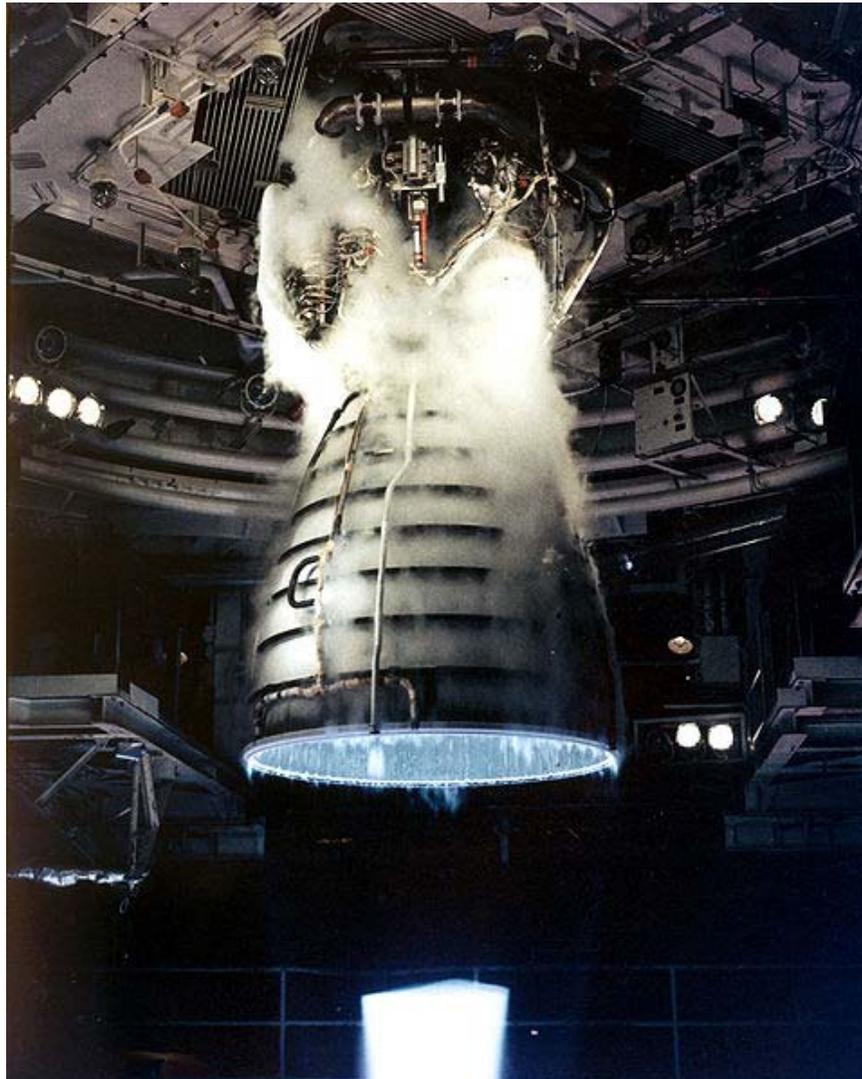
A remote camera captures a close-up view of a Space Shuttle Main Engine during a test firing at the John C. Stennis Space Center in Hancock County, Mississippi

Spacecraft propulsion is any method used to accelerate spacecraft and artificial satellites. There are many different methods. Each method has drawbacks and advantages, and spacecraft propulsion is an active area of research. However, most spacecraft today are propelled by forcing a gas from the back/rear of the vehicle at very high speed through a supersonic de Laval nozzle. This sort of engine is called a rocket engine.

All current spacecraft use chemical rockets (bipropellant or solid-fuel) for launch, though some (such as the Pegasus rocket and SpaceShipOne) have used air-breathing engines on their first stage. Most satellites have simple reliable chemical thrusters (often monopropellant rockets) or resistojet rockets for orbital station-keeping and some use momentum wheels for attitude control. Soviet bloc satellites have used electric propulsion for decades, and newer Western geo-orbiting spacecraft are starting to use them for north-south stationkeeping. Interplanetary vehicles mostly use chemical rockets as well, although a few have used ion thrusters and Hall effect thrusters (two different types of electric propulsion) to great success.

Need

Artificial satellites must be launched into orbit, and once there they must be placed in their nominal orbit. Once in the desired orbit, they often need some form of attitude control so that they are correctly pointed with respect to the Earth, the Sun, and possibly some astronomical object of interest. They are also subject to drag from the thin atmosphere, so that to stay in orbit for a long period of time some form of propulsion is occasionally necessary to make small corrections (orbital stationkeeping). Many satellites need to be moved from one orbit to another from time to time, and this also requires propulsion. A satellite's useful life is over once it has exhausted its ability to adjust its orbit.

Spacecraft designed to travel further also need propulsion methods. They need to be launched out of the Earth's atmosphere just as satellites do. Once there, they need to leave orbit and move around.

For interplanetary travel, a spacecraft must use its engines to leave Earth orbit. Once it has done so, it must somehow make its way to its destination. Current interplanetary spacecraft do this with a series of short-term trajectory adjustments. In between these adjustments, the spacecraft simply falls freely along its trajectory. The most fuel-efficient means to move from one circular orbit to another is with a Hohmann transfer orbit: the spacecraft begins in a roughly circular orbit around the Sun. A short period of thrust in the direction of motion accelerates or decelerates the spacecraft into an elliptical orbit around the Sun which is tangential to its previous orbit and also to the orbit of its destination. The spacecraft falls freely along this elliptical orbit until it reaches its destination, where another short period of thrust accelerates or decelerates it to match the orbit of its destination. Special methods such as aerobraking are sometimes used for this final orbital adjustment.
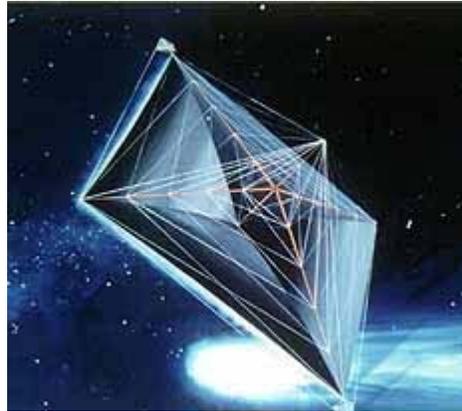
Artist's concept of a solar sail

Some spacecraft propulsion methods such as solar sails provide very low but inexhaustible thrust; an interplanetary vehicle using one of these methods would follow a rather different trajectory, either constantly thrusting against its direction of motion in order to decrease its distance from the Sun or constantly thrusting along its direction of motion to increase its distance from the Sun. The concept has been successfully tested by the Japanese IKAROS solar sail spacecraft.

Spacecraft for interstellar travel also need propulsion methods. No such spacecraft has yet been built, but many designs have been discussed. Since interstellar distances are very great, a tremendous velocity is needed to get a spacecraft to its destination in a reasonable amount of time. Acquiring such a velocity on launch and getting rid of it on arrival will be a formidable challenge for spacecraft designers.

Effectiveness

When in space, the purpose of a propulsion system is to change the velocity, or v, of a spacecraft. Since this is more difficult for more massive spacecraft, designers generally discuss momentum, mv. The amount of change in momentum is called impulse. So the goal of a propulsion method in space is to create an impulse.

When launching a spacecraft from the Earth, a propulsion method must overcome a higher gravitational pull to provide a positive net acceleration. In orbit, any additional impulse, even very tiny, will result in a change in the orbit path.

The rate of change of velocity is called acceleration, and the rate of change of momentum is called force. To reach a given velocity, one can apply a small acceleration over a long period of time, or one can apply a large acceleration over a short time. Similarly, one can achieve a given impulse with a large force over a short time or a small force over a long time. This means that for maneuvering in space, a propulsion method that produces tiny accelerations but runs for a long time can produce the same impulse as a propulsion method that produces large accelerations for a short time. When launching from a planet, tiny accelerations cannot overcome the planet's gravitational pull and so cannot be used.

The Earth's surface is situated fairly deep in a gravity well. The escape velocity required to get out of it is 11.2 kilometers/second. As human beings evolved in a gravitational field of 1g (9.8 m/s²), an ideal propulsion system would be one that provides a continuous acceleration of **1g** (though human bodies can tolerate much larger accelerations over short periods). The occupants of a rocket or spaceship having such a propulsion system would be free from all the ill effects of free fall, such as nausea, muscular weakness, reduced sense of taste, or leaching of calcium from their bones.

The law of conservation of momentum means that in order for a propulsion method to change the momentum of a space craft it must change the momentum of something else as well. A few designs take advantage of things like magnetic fields or light pressure in order to change the spacecraft's momentum, but in free space the rocket must bring along some mass to accelerate away in order to push itself forward. Such mass is called reaction mass.

In order for a rocket to work, it needs two things: reaction mass and energy. The impulse provided by launching a particle of reaction mass having mass m at velocity v is mv. But this particle has kinetic energy $mv^2/2$, which must come from somewhere. In a conventional solid, liquid, or hybrid rocket, the fuel is burned, providing the energy, and the reaction products are allowed to flow out the back, providing the reaction mass. In an ion thruster, electricity is used to accelerate ions out the back. Here some other source must provide the electrical energy (perhaps a solar panel or a nuclear reactor), while the ions provide the reaction mass.

When discussing the efficiency of a propulsion system, designers often focus on effectively using the reaction mass. Reaction mass must be carried along with the rocket and is irretrievably consumed when used. One way of measuring the amount of impulse that can be obtained from a fixed amount of reaction mass is the specific impulse, the impulse per unit weight-on-Earth (typically designated by I_{sp}). The unit for this value is seconds. Since the weight on Earth of the reaction mass is often unimportant when discussing vehicles in space, specific impulse can also be discussed in terms of impulse per unit mass. This alternate form of specific impulse uses the same units as velocity (e.g. m/s), and in fact it is equal to the effective exhaust velocity of the engine (typically designated v_e). Confusingly, both values are sometimes called specific impulse. The two values differ by a factor of g_n, the standard acceleration due to gravity 9.80665 m/s² ($I_{sp}g_n = v_e$).

A rocket with a high exhaust velocity can achieve the same impulse with less reaction mass. However, the energy required for that impulse is proportional to the exhaust velocity, so that more mass-efficient engines require much more energy, and are typically less energy efficient. This is a problem if the engine is to provide a large amount of thrust. To generate a large amount of impulse per second, it must use a large amount of energy per second. So high-mass-efficient engines require enormous amounts of energy per second to produce high thrusts. As a result, most high-mass-efficient engine designs also provide lower thrust due to the unavailability of high amounts of energy.

Methods

Propulsion methods can be classified based on their means of accelerating the reaction mass. There are also some special methods for launches, planetary arrivals, and landings.

Reaction engines

A **reaction engine** is an engine which provides propulsion by expelling reaction mass, in accordance with Newton's third law of motion. This law of motion is most commonly paraphrased as: "For every action force there is an equal, but opposite, reaction force".

Examples include both duct engines and rocket engines, and more uncommon variations such as Hall effect thrusters, ion drives and mass drivers. Duct engines are obviously not used for space propulsion due to the lack of air; however some proposed spacecraft have these kinds of engines to assist takeoff and landing.

Delta-v and propellant

Rocket Mass ratio versus Delta-V
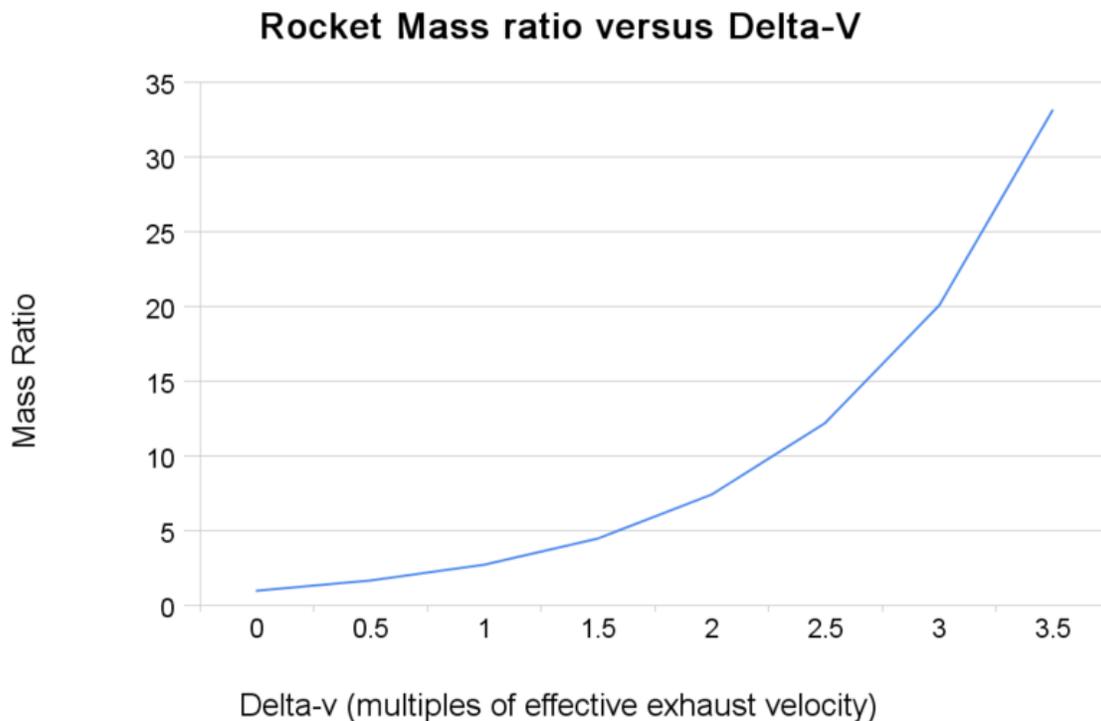
Rocket mass ratios versus final velocity, as calculated from the rocket equation

Exhausting the entire usable propellant of a spacecraft through the engines in a straight line in free space would produce a net velocity change to the vehicle; this number is termed 'delta-v' (Δv).

If the exhaust velocity is constant then the total Δv of a vehicle can be calculated using the rocket equation, where M is the mass of propellant, P is the mass of the payload (including the rocket structure), and v_e is the velocity of the rocket exhaust. This is known as the Tsiolkovsky rocket equation:

$$\Delta v = v_e \ln \left(\frac{M+P}{P} \right).$$

For historical reasons, as discussed above, v_e is sometimes written as

$$v_e = I_{sp}g_o$$

where I_{sp} is the specific impulse of the rocket, measured in seconds, and g_o is the gravitational acceleration at sea level.

For a high delta-v mission, the majority of the spacecraft's mass needs to be reaction mass. Since a rocket must carry all of its reaction mass, most of the initially-expended reaction mass goes towards accelerating reaction mass rather than payload. If the rocket has a payload of mass P, the spacecraft needs to change its velocity by Δv, and the rocket engine has exhaust velocity v_e, then the mass M of reaction mass which is needed can be calculated using the rocket equation and the formula for I_{sp}:

$$M = P \left(e^{\Delta v/v_e} - 1 \right).$$

For Δv much smaller than v_e, this equation is roughly linear, and little reaction mass is needed. If Δv is comparable to v_e, then there needs to be about twice as much fuel as combined payload and structure (which includes engines, fuel tanks, and so on). Beyond this, the growth is exponential; speeds much higher than the exhaust velocity require very high ratios of fuel mass to payload and structural mass.

For a mission, for example, when launching from or landing on a planet, the effects of gravitational attraction and any atmospheric drag must be overcome by using fuel. It is typical to combine the effects of these and other effects into an effective mission delta-v. For example a launch mission to low Earth orbit requires about 9.3–10 km/s delta-v. These mission delta-vs are typically numerically integrated on a computer.

Some effects such as Oberth effect can only be significantly utilised by high thrust engines such as rockets, i.e. engines that can produce a high g-force (thrust per unit mass, equal to delta-v per unit time).
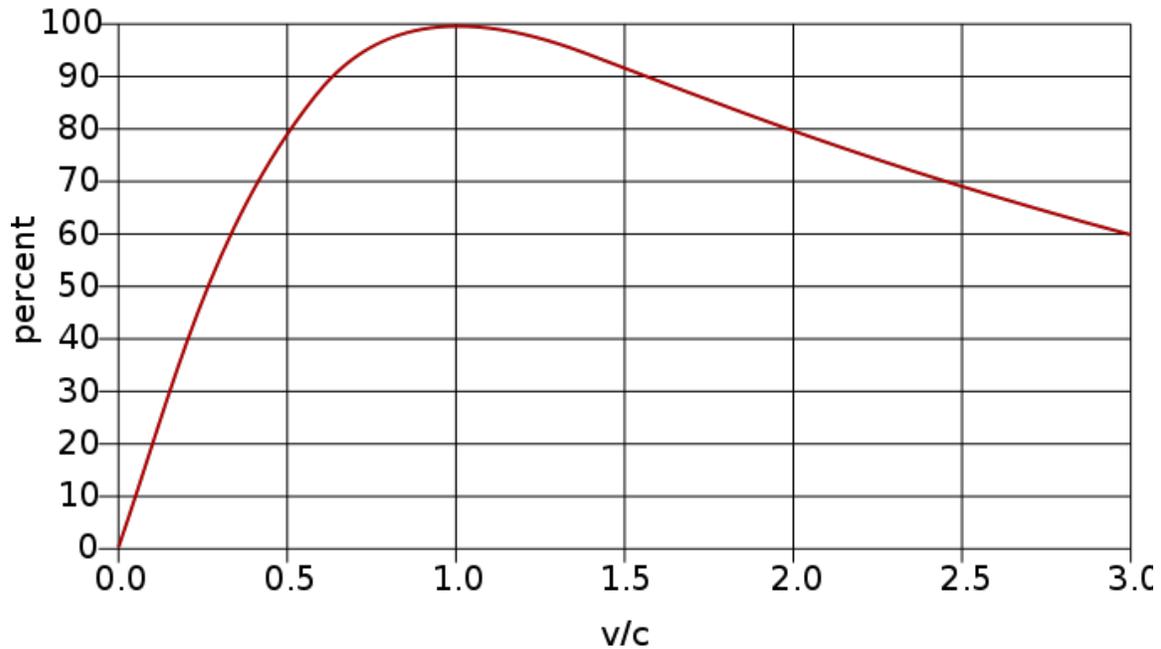
Power use and propulsive efficiency

For all reaction engines (such as rockets and ion drives) some energy must go into accelerating the reaction mass. Every engine will waste some energy, but even assuming 100% efficiency, to accelerate an exhaust the engine will need energy amounting to

$$\frac{1}{2}\dot{m}v_e^2$$

This energy is not necessarily lost- some of it usually ends up as kinetic energy of the vehicle, and the rest is wasted in residual motion of the exhaust.

Propulsive efficiency

Due to energy carried away in the exhaust the energy efficiency of a reaction engine varies with the speed of the exhaust relative to the speed of the vehicle, this is called propulsive efficiency

Comparing the rocket equation (which shows how much energy ends up in the final vehicle) and the above equation (which shows the total energy required) shows that even with 100% engine efficiency, certainly not all energy supplied ends up in the vehicle - some of it, indeed usually most of it, ends up as kinetic energy of the exhaust.

The exact amount depends on the design of the vehicle, and the mission. However there are some useful fixed points:

- if the I_{sp} is fixed, for a mission delta-v, there is a particular I_{sp} that minimises the overall energy used by the rocket. This comes to an exhaust velocity of about ⅔ of the mission delta-v. Drives with a specific impulse that is both high and fixed such as Ion thrusters have exhaust velocities that can be enormously higher than this ideal for many missions.

- if the exhaust velocity can be made to vary so that at each instant it is equal and opposite to the vehicle velocity then the absolute minimum energy usage is

achieved. When this is achieved, the exhaust stops in space and has no kinetic energy; and the propulsive efficiency is 100%- all the energy ends up in the vehicle (in principle such a drive would be 100% efficient, in practice there would be thermal losses from within the drive system and residual heat in the exhaust). However in most cases this uses an impractical quantity of propellant, but is a useful theoretical consideration. Anyway the vehicle has to move before the method can be applied.

Some drives (such as VASIMR or Electrodeless plasma thruster) actually can significantly vary their exhaust velocity. This can help reduce propellant usage or improve acceleration at different stages of the flight. However the best energetic performance and acceleration is still obtained when the exhaust velocity is close to the vehicle speed. Proposed ion and plasma drives usually have exhaust velocities enormously higher than that ideal (in the case of VASIMR the lowest quoted speed is around 15000 m/s compared to a mission delta-v from high Earth orbit to Mars of about 4000m/s).

It might be thought that adding power generation capacity is helpful, and while initially this can improve performance, this inevitably increases the weight of the power source, and eventually the mass of the power source and the associated engines and propellant dominates the weight of the vehicle, and then adding more power gives no significant improvement.

For, although solar power and nuclear power are virtually unlimited sources of *energy*, the maximum *power* they can supply is substantially proportional to the mass of the powerplant (i.e. specific power takes a largely constant value which is dependent on the particular powerplant technology). For any given specific power, with a large v_e which is desirable to save propellant mass, it turns out that the maximum acceleration is inversely proportional to v_e. Hence the time to reach a required delta-v is proportional to v_e. Thus the latter should not be too large.

Power to thrust ratio

The power to thrust ratio is simply:

$$\frac{P}{F} = \frac{\frac{1}{2}\dot{m}v^2}{\dot{m}v} = \frac{1}{2}v$$

Thus for any vehicle power P, the thrust that may be provided is:

$$F = \frac{P}{\frac{1}{2}v} = \frac{2P}{v}$$

Example

Suppose we want to send a 10,000 kg space probe to Mars. The required Δv from LEO is approximately 3000 m/s, using a Hohmann transfer orbit. (A manned craft would need to take a faster route and use more fuel). For the sake of argument, let us say that the following thrusters may be used:

Engine	Effective Exhaust Velocity (km/s)	Specific impulse (s)	Fuel mass (kg)	Energy required (GJ)	Energy per kg of propellant	minimum power/thrust	Power generator mass/thrust*
Solid rocket	1	100	190,000	95	500 kJ	0.5 kW/N	N/A
Bipropellant rocket	5	500	8,200	103	12.6 MJ	2.5 kW/N	N/A
Ion thruster	50	5,000	620	775	1.25 GJ	25 kW/N	25 kg/N
Advance electrically powered drive	1,000	100,000	30	15,000	500 GJ	500 kW/N	500 kg/N

* - assumes a specific power of 1kW/kg

Observe that the more fuel-efficient engines can use far less fuel; its mass is almost negligible (relative to the mass of the payload and the engine itself) for some of the engines. However, note also that these require a large total amount of energy. For Earth launch, engines require a thrust to weight ratio of more than one. To do this with the ion or more theoretical electrical drives, the engine would have to be supplied with one to several gigawatts of power — equivalent to a major metropolitan generating station. From the table it can be seen that this is clearly impractical with current power sources.

Instead, a much smaller, less powerful generator may be included which will take much longer to generate the total energy needed. This lower power is only sufficient to accelerate a tiny amount of fuel per second, and would be insufficient for launching from the Earth. However, over long periods in orbit where there is no friction, the velocity will be finally achieved. For example. it took the SMART-1 more than a year to reach the Moon, while with a chemical rocket it takes a few days. Because the ion drive needs much less fuel, the total launched mass is usually lower, which typically results in a lower overall cost, but takes longer.

Mission planning therefore frequently involves adjusting and choosing the propulsion system so as to minimise the total cost of the project, and can involve trading off launch costs and mission duration against payload fraction.

Rocket engines

SpaceX's Kestrel engine is tested

Most rocket engines are internal combustion heat engines (although non combusting forms exist). Rocket engines generally produce a high temperature reaction mass, as a hot gas. This is achieved by combusting a solid, liquid or gaseous fuel with an oxidiser within a combustion chamber. The extremely hot gas is then allowed to escape through a high-expansion ratio nozzle. This bell-shaped nozzle is what gives a rocket engine its characteristic shape. The effect of the nozzle is to dramatically accelerate the mass, converting most of the thermal energy into kinetic energy. Exhaust speed reaching as high as 10 times the speed of sound at sea level are common.

Rocket engines provide essentially the highest specific powers and high specific thrusts of any engine used for spacecraft propulsion.

Ion propulsion rockets can heat a plasma or charged gas inside a magnetic bottle and release it via a magnetic nozzle, so that no solid matter need come in contact with the plasma. Of course, the machinery to do this is complex, but research into nuclear fusion has developed methods, some of which have been proposed to be used in propulsion systems, and some have been tested in a lab.

Electromagnetic propulsion
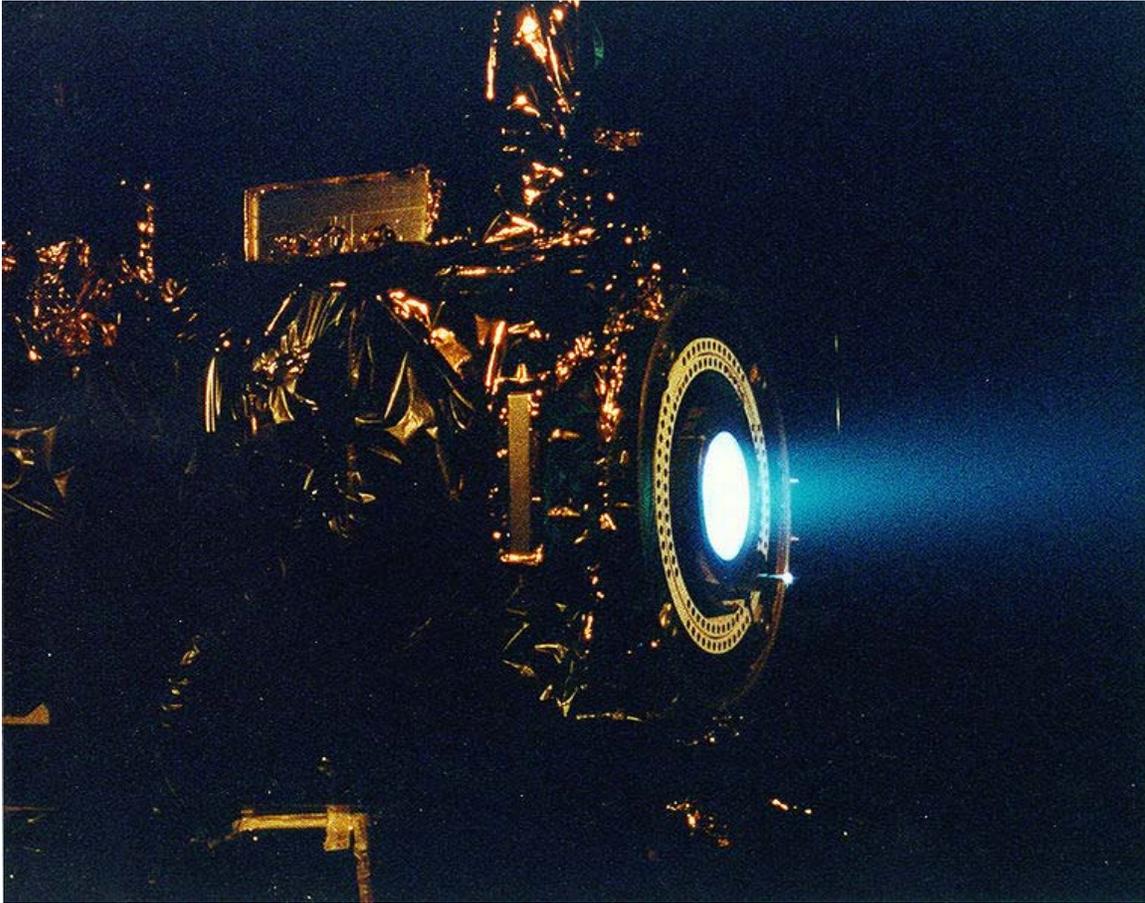
This test engine accelerates ions using electrostatic forces

Rather than relying on high temperature and fluid dynamics to accelerate the reaction mass to high speeds, there are a variety of methods that use electrostatic or electromagnetic forces to accelerate the reaction mass directly. Usually the reaction mass is a stream of ions. Such an engine typically uses electric power, first to ionize atoms, and then to create a voltage gradient to accelerate the ions to high exhaust velocities.

The idea of electric propulsion dates back to 1906, when Robert Goddard considered the possibility in his personal notebook. Konstantin Tsiolkovsky published the idea in 1911.

For these drives, at the highest exhaust speeds, energetic efficiency and thrust are all inversely proportional to exhaust velocity. Their very high exhaust velocity means they require huge amounts of energy and thus with practical power sources provide low thrust, but use hardly any fuel.

For some missions, particularly reasonably close to the Sun, solar energy may be sufficient, and has very often been used, but for others further out or at higher power,

nuclear energy is necessary; engines drawing their power from a nuclear source are called nuclear electric rockets.

With any current source of electrical power, chemical, nuclear or solar, the maximum amount of power that can be generated limits the amount of thrust that can be produced to a small value. Power generation adds significant mass to the spacecraft, and ultimately the weight of the power source limits the performance of the vehicle.

Current nuclear power generators are approximately half the weight of solar panels per watt of energy supplied, at terrestrial distances from the Sun. Chemical power generators are not used due to the far lower total available energy. Beamed power to the spacecraft shows some potential. However, the dissipation of waste heat from any power plant may make any propulsion system requiring a separate power source infeasible for interstellar travel.
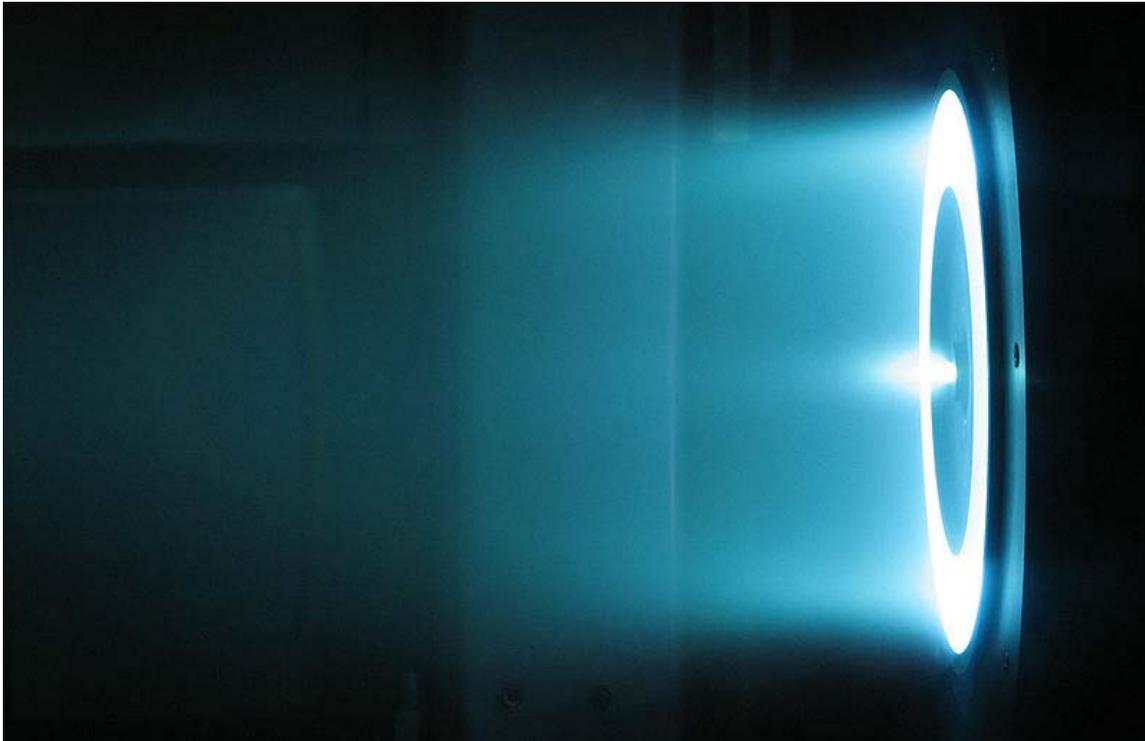
6 kW Hall thruster in operation at the NASA Jet Propulsion Laboratory

Some electromagnetic methods:

- Ion thrusters (accelerate ions first and later neutralize the ion beam with an electron stream emitted from a cathode called a neutralizer)
    - Electrostatic ion thruster
    - Field Emission Electric Propulsion
    - Hall effect thruster
    - Colloid thruster

- Electrothermal thrusters (electromagnetic fields are used to generate a plasma to increase the heat of the bulk propellant, the thermal energy imparted to the propellant gas is then converted into kinetic energy by a nozzle of either physical material construction or by magnetic means)
  - DC arcjet
  - microwave arcjet
  - Pulsed plasma thruster
  - Helicon Double Layer Thruster
- Electromagnetic thrusters (ions are accelerated either by the Lorentz Force or by the effect of electromagnetic fields where the electric field is not in the direction of the acceleration)
  - Magnetoplasmadynamic thruster
  - Electrodeless plasma thruster
  - Pulsed inductive thruster
  - Variable specific impulse magnetoplasma rocket (VASIMR)
- Mass drivers (for propulsion)

In electrothermal and electromagnetic thrusters, both ions and electrons are accelerated simultaneously, no neutralizer is required.

Without internal reaction mass
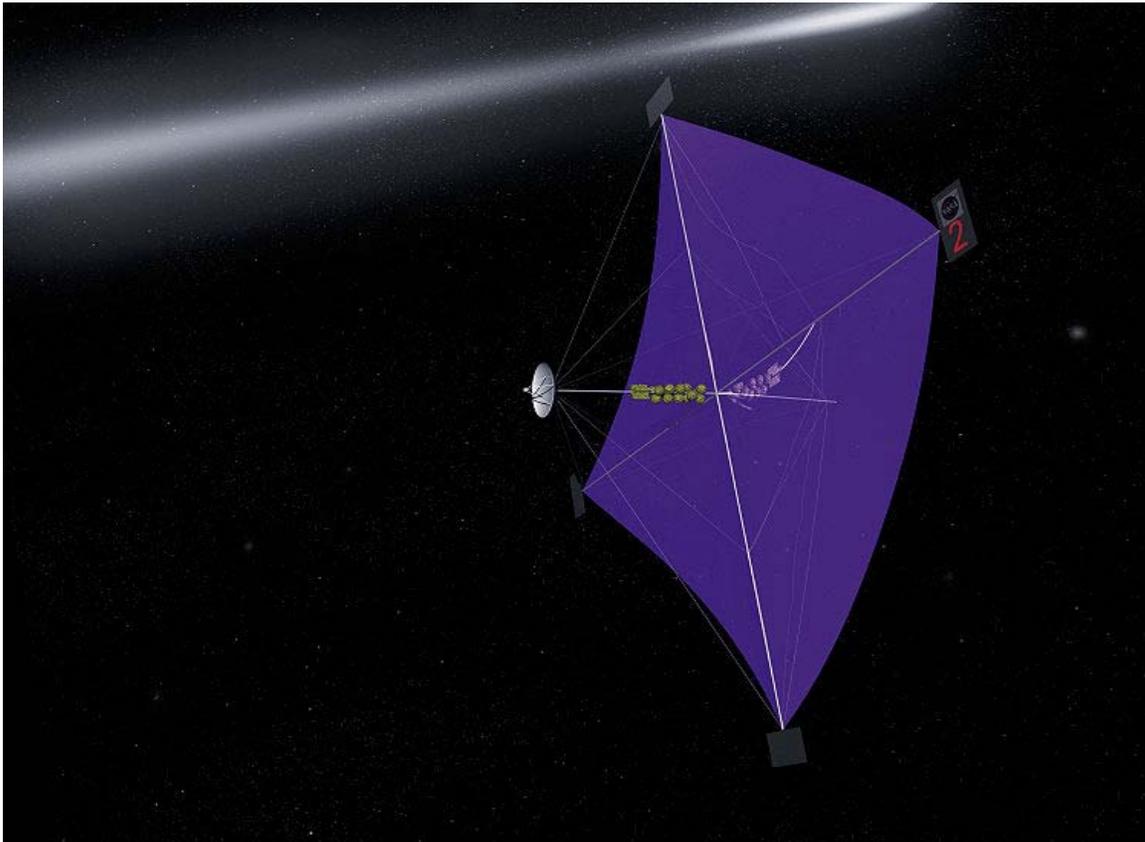
NASA study of a solar sail. The sail would be half a kilometer wide.

The law of conservation of momentum states that any engine which uses no reaction mass cannot accelerate the center of mass of a spaceship (changing orientation, on the other hand, is possible). But space is not empty, especially space inside the Solar System; there are gravitation fields, magnetic fields, solar wind and solar radiation. Various propulsion methods try to take advantage of these. However, since these phenomena are diffuse in nature, corresponding propulsion structures need to be proportionately large.

There are several different space drives that need little or no reaction mass to function. A tether propulsion system employs a long cable with a high tensile strength to change a spacecraft's orbit, such as by interaction with a planet's magnetic field or through momentum exchange with another object. Solar sails rely on radiation pressure from electromagnetic energy, but they require a large collection surface to function effectively. The magnetic sail deflects charged particles from the solar wind with a magnetic field, thereby imparting momentum to the spacecraft. A variant is the mini-magnetospheric plasma propulsion system, which uses a small cloud of plasma held in a magnetic field to deflect the Sun's charged particles. An E-sail would use very thin and lightweight wires holding an electric charge to deflect these particles, and may have more controllable directionality.

A satellite or other space vehicle is subject to the law of conservation of angular momentum, which constrains a body from a net change in angular velocity. Thus, for a vehicle to change its relative orientation without expending reaction mass, another part of the vehicle may rotate in the opposite direction. Non-conservative external forces, primarily gravitational and atmospheric, can contribute up to several degrees per day to angular momentum, so secondary systems are designed to "bleed off" undesired rotational energies built up over time. Accordingly, many spacecraft utilize reaction wheels or control moment gyroscopes to control orientation in space.

A gravitational slingshot can carry a space probe onward to other destinations without the expense of reaction mass. By harnessing the gravitational energy of other celestial objects, the spacecraft can pick up kinetic energy. However, even more energy can be obtained from the gravity assist if rockets are used.

Planetary and atmospheric propulsion

Launch mechanisms

An artist's concept of an electromagnetic catapult on the Moon

High thrust is of vital importance for Earth launch, thrust has to be greater than weight. Many of the propulsion methods above give a thrust/weight ratio of much less than 1, and so cannot be used for launch.

All current spacecraft use chemical rocket engines (bipropellant or solid-fuel) for launch. Other power sources such as nuclear have been proposed and tested, but safety, environmental and political considerations have so far curtailed their use.

One advantage that spacecraft have in launch is the availability of infrastructure on the ground to assist them. Proposed non-rocket spacelaunch ground-assisted launch mechanisms include:

- Space elevator (a geostationary tether to orbit)
- Launch loop (a very fast enclosed rotating loop about 80 km tall)
- Space fountain (a very tall building held up by a stream of masses fired from base)
- Orbital ring (a ring around the Earth with spokes hanging down off bearings)
- Hypersonic skyhook (a fast spinning orbital tether)
- Electromagnetic catapult (railgun, coilgun) (an electric gun)

- Rocket sled launch
- Space gun (Project HARP, ram accelerator) (a chemically powered gun)
- Beam-powered propulsion rockets and jets powered from ground via a beam
- High Altitude Platforms to assist initial stage

Airbreathing engines

Studies generally show that conventional air-breathing engines, such as ramjets or turbojets are basically too heavy (have too low a thrust/weight ratio) to give any significant performance improvement when installed on a launch vehicle itself. However, launch vehicles can be air launched from separate lift vehicles (e.g. B-29, Pegasus Rocket and White Knight) which do use such propulsion systems. Jet engines mounted on a launch rail could also be so used.

On the other hand, very lightweight or very high speed engines have been proposed that take advantage of the air during ascent:

- SABRE - a lightweight hydrogen fuelled turbojet with precooler
- ATREX - a lightweight hydrogen fuelled turbojet with precooler
- Liquid air cycle engine - a hydrogen fuelled jet engine that liquifies the air before burning it in a rocket engine
- Scramjet - jet engines that use supersonic combustion

Normal rocket launch vehicles fly almost vertically before rolling over at an altitude of some tens of kilometers before burning sideways for orbit; this initial vertical climb wastes propellant but is optimal as it greatly reduces airdrag. Airbreathing engines burn propellant much more efficiently and this would permit a far flatter launch trajectory, the vehicles would typically fly approximately tangentially to the earth surface until leaving the atmosphere then perform a rocket burn to bridge the final delta-v to orbital velocity.

Planetary arrival and landing

A test version of the MARS Pathfinder airbag system

When a vehicle is to enter orbit around its destination planet, or when it is to land, it must adjust its velocity. This can be done using all the methods listed above (provided they can generate a high enough thrust), but there are a few methods that can take advantage of planetary atmospheres and/or surfaces.

- Aerobraking allows a spacecraft to reduce the high point of an elliptical orbit by repeated brushes with the atmosphere at the low point of the orbit. This can save a considerable amount of fuel since it takes much less delta-V to enter an elliptical orbit compared to a low circular orbit. Since the braking is done over the course of many orbits, heating is comparatively minor, and a heat shield is not required. This has been done on several Mars missions such as Mars Global Surveyor, Mars Odyssey and Mars Reconnaissance Orbiter, and at least one Venus mission, Magellan.
- Aerocapture is a much more aggressive manoeuver, converting an incoming hyperbolic orbit to an elliptical orbit in one pass. This requires a heat shield and much trickier navigation, since it must be completed in one pass through the atmosphere, and unlike aerobraking no preview of the atmosphere is possible. If the intent is to remain in orbit, then at least one more propulsive maneuver is required after aerocapture—otherwise the low point of the resulting orbit will remain in the atmosphere, resulting in eventual re-entry. Aerocapture has not yet been tried on a planetary mission, but the re-entry skip by Zond 6 and Zond 7

upon lunar return were aerocapture maneuvers, since they turned a hyperbolic orbit into an elliptical orbit. On these missions, since there was no attempt to raise the perigee after the aerocapture, the resulting orbit still intersected the atmosphere, and re-entry occurred at the next perigee.

- a Ballute is an inflatable drag device
- Parachutes can land a probe on a planet with an atmosphere, usually after the atmosphere has scrubbed off most of the velocity, using a heat shield.
- Airbags can soften the final landing.
- Lithobraking, or stopping by simply smashing into the target, is usually done by accident. However, it may be done deliberately with the probe expected to survive (see, for example, Deep Space 2), in which case very sturdy probes and low approach velocities are required.

Hypothetical methods
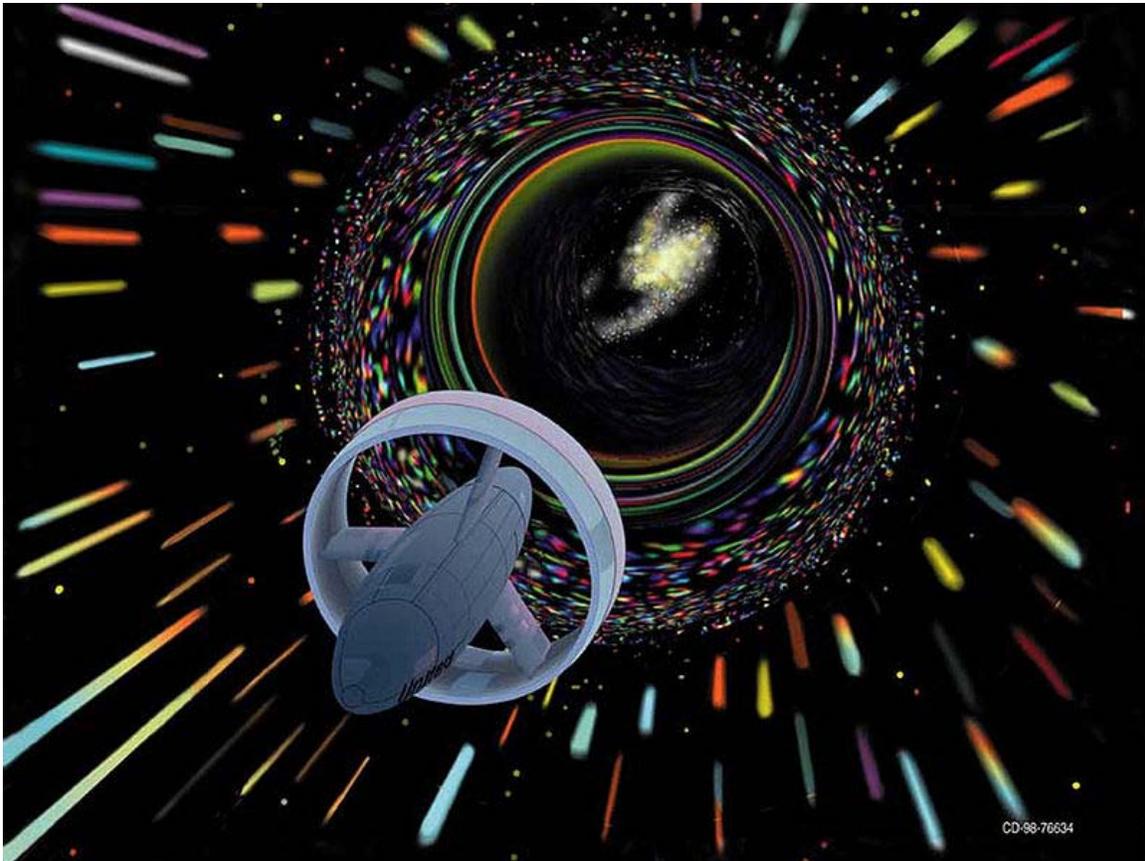
Artist's conception of a warp drive design

A variety of hypothetical propulsion techniques have been considered that would require entirely new principles of physics to realize and that may not actually be possible. To date, such methods are highly speculative and include:

- Diametric drive
- Pitch drive

- Bias drive
- Disjunction drive
- Alcubierre drive (a form of Warp drive)
- Differential sail
- Wormholes - theoretically possible, but unachieveable in practice with current technology
- Reactionless drives - breaks the law of conservation of momentum; theoretically impossible
- EmDrive - tries to circumvent the law of conservation of momentum; may be theoretically impossible
- A "hyperspace" drive based upon Heim theory

A NASA assessment is found at Marc G Millis *Assessing potential propulsion breakthroughs* (2005)

Table of methods

Below is a summary of some of the more popular, proven technologies, followed by increasingly speculative methods.

Four numbers are shown. The first is the effective exhaust velocity: the equivalent speed that the propellant leaves the vehicle. This is not necessarily the most important characteristic of the propulsion method, thrust and power consumption and other factors can be, however:

- if the delta-v is much more than the exhaust velocity, then exorbitant amounts of fuel are necessary
- if it is much more than the delta-v, then, proportionally more energy is needed; if the power is limited, as with solar energy, this means that the journey takes a proportionally longer time

The second and third are the typical amounts of thrust and the typical burn times of the method. Outside a gravitational potential small amounts of thrust applied over a long period will give the same effect as large amounts of thrust over a short period. (This result does not apply when the object is significantly influenced by gravity.)

The fourth is the maximum delta-v this technique can give (without staging). For rocket-like propulsion systems this is a function of mass fraction and exhaust velocity. Mass fraction for rocket-like systems is usually limited by propulsion system weight and tankage weight. For a system to achieve this limit, typically the payload may need to be a negligible percentage of the vehicle, and so the practical limit on some systems can be much lower.

Propulsion methods

Method	Effective Exhaust Velocity (km/s)	Thrust (N)	Firing Duration	Maximum Delta-v (km/s)	Technology readiness level
Solid-fuel rocket	1 - 4	10^3 - 10^7	minutes	~ 7	9:Flight proven
Hybrid rocket	1.5 - 4.2	<0.1 - 10^7	minutes	> 3	9:Flight proven
Monopropellant rocket	1 - 3	0.1 - 100	milliseconds-minutes	~ 3	9:Flight proven
Liquid-fuel rocket	1 - 4.7	0.1 - 10^7	minutes	~ 9	9:Flight proven
Electrostatic ion thruster	15 - 210	10^{-3} - 10	months/years	> 100	9:Flight proven
Hall effect thruster (HET)	8 - 50	10^{-3} - 10	months/years	> 100	9:Flight proven
Resistojet rocket	2 - 6	10^{-2} - 10	minutes	?	8:Flight qualified
Arcjet rocket	4 - 16	10^{-2} - 10	minutes	?	8:Flight qualified
Field Emission Electric Propulsion (FEEP)	100-130	10^{-6}-10^{-3}	months/years	?	8:Flight qualified
Pulsed plasma thruster (PPT)	~ 20	~ 0.1	~2,000-10,000 hours	?	7:Prototype demoed in space
Dual mode propulsion rocket	1 - 4.7	0.1 - 10^7	milliseconds-minutes	~ 3 - 9	7:Prototype demoed in space
Solar sails	300,000:Light 145-750:Wind	9/km^2 @ 1 AU 230/km^2@0.2AU 10^{-10}/km^2@4 ly	indefinite	> 40	9:Light pressure attitude-control flight proven 6:Deploy-only demoed in space 5:Light-sail validated in lit vacuum
Tripropellant rocket	2.5 - 5.3	0.1 - 10^7	minutes	~ 9	6:Prototype demoed on ground
Magnetoplasmadynamic thruster (MPD)	20 - 100	100	weeks	?	6:Model-1 kW demoed in space
Nuclear thermal rocket	9	10^7	minutes	> ~ 20	6:Prototype demoed on

					ground
Mass drivers (for propulsion)	0 - ~30	$10^4 - 10^8$	months	*?*	6:Model-32MJ demoed on ground
Tether propulsion	N/A	$1 - 10^{12}$	minutes	~ 7	6:Model-31.7 km demoed in space
Air-augmented rocket	5 - 6	$0.1 - 10^7$	seconds-minutes	> 7?	6:Prototype demoed on ground
Liquid air cycle engine	4.5	$10^3 - 10^7$	seconds-minutes	*?*	6:Prototype demoed on ground
Pulsed inductive thruster (PIT)	10-80	20	months	*?*	5:Component validated in vacuum
Variable Specific Impulse Magnetoplasma Rocket (VASIMR)	10 - 300	40 - 1,200	days - months	> 100	5:Component-200 kW validated in vacuum
Magnetic field oscillating amplified thruster	10 - 130	0.1 - 1	days - months	> 100	5:Component validated in vacuum
Solar thermal rocket	7 - 12	1 - 100	weeks	> ~ 20	4:Component validated in lab
Radioisotope rocket	7 - 8	1.3 - 1.5	months	*?*	4:Component validated in lab
Nuclear electric rocket(As electric prop. method used)	Variable	Variable	Variable	*?*	4:Component-400kW validated in lab
Orion Project (Near term nuclear pulse propulsion)	20 - 100	$10^9 - 10^{12}$	several days	~30-60	3:Validated-900 kg proof-of-concept
Space elevator	N/A	N/A	indefinite	> 12	3:Validated proof-of-concept
Reaction Engines SABRE	30/4.5	$0.1 - 10^7$	minutes	9.4	3:Validated proof-of-concept
Magnetic sails	145-750:Wind	70/40Mg	indefinite	*?*	3:Validated proof-of-concept
Magnetic sail#Mini-magnetospheric plasma	200	~1 N/kW	months	*?*	3:Validated proof-of-

Method	Effective Exhaust	Thrust (N)	Firing Duration	Maximum Delta-v	Technology readiness
propulsion					concept
Beam-powered/Laser(As prop. method powered by beam)	Variable	Variable	Variable	?	3:Validated-71m proof-of-concept
Launch loop/Orbital ring	N/A	$\sim 10^4$	minutes	>>11-30	2:Technology concept formulated
Nuclear pulse propulsion (Project Daedalus' drive)	20 - 1,000	10^9 - 10^{12}	years	~15,000	2:Technology concept formulated
Gas core reactor rocket	10 - 20	10^3 - 10^6	?	?	2:Technology concept formulated
Nuclear salt-water rocket	100	10^3 - 10^7	half hour	?	2:Technology concept formulated
Fission sail	?	?	?	?	2:Technology concept formulated
Fission-fragment rocket	15,000	?	?	?	2:Technology concept formulated
Nuclear photonic rocket	300,000	10^{-5} - 1	years-decades	?	2:Technology concept formulated
Fusion rocket	100 - 1,000	?	?	?	2:Technology concept formulated
Antimatter catalyzed nuclear pulse propulsion	200 - 4,000	?	days-weeks	?	2:Technology concept formulated
Antimatter rocket	10,000-100,000	?	?	?	2:Technology concept formulated
Bussard ramjet	2.2 - 20,000	?	indefinite	~30,000	2:Technology concept formulated
Gravitoelectromagnetic toroidal launchers	300,000:GEM	?	?	<300,000	1:Basic principles observed & reported
Alcubierre Warp Drive	>300,000	?	?	∞	1:Basic principles observed & reported

	Velocity (km/s)			(km/s)	level

Testing

Spacecraft propulsion systems are often first statically tested on the Earth's surface, within the atmosphere but many systems require a vacuum chamber to test fully. Rockets are usually tested at a rocket engine test facility well away from habitation and other buildings for safety reasons. Ion drives are far less dangerous and require much less stringent safety, usually only a large-ish vacuum chamber is needed.

Famous static test locations can be found at Rocket Ground Test Facilities

Some systems cannot be adequately tested on the ground and test launches may be employed at a Rocket Launch Site.

Chapter- 5

Spacecraft

Russian Soyuz manned spacecraft (TMA version shown) have flown since 1967, and currently supports the International Space Station.

US Space Shuttle (*Columbia's* first launch shown) flew from 1980 to 2011, also supporting the ISS.

A **spacecraft** or **spaceship** is a craft or machine designed for spaceflight. Spacecraft are used for a variety of purposes, including communications, earth observation, meteorology, navigation, planetary exploration and transportation of humans and cargo.

On a sub-orbital spaceflight, a spacecraft enters space and then returns to the surface, without having gone into an orbit. For orbital spaceflights, spacecraft enter closed orbits around the Earth or around other celestial bodies. Spacecraft used for human spaceflight carry people on board as crew or passengers, while those used for robotic space missions operate either autonomously or telerobotically. Robotic spacecraft used to support scientific research are space probes. Robotic spacecraft that remain in orbit around a planetary body are artificial satellites. Only a handful of interstellar probes, such as Pioneer 10 and 11, Voyager 1 and 2, and New Horizons, are currently on trajectories that leave our Solar System.

History

The first Earth orbiting satellite was Sputnik 1, which was launched 4 October 1957, and remained in orbit for several months. While Sputnik 1 was the first spacecraft to orbit the Earth, other man-made objects had previously reached an altitude of 100 km, which is the height required by the international organization Fédération Aéronautique Internationale to count as a spaceflight. This altitude is called the Kármán line. In particular, in the 1940's there were several test launches of the V-2 rocket, some of which reached altitudes well over 100 km.

Past and present spacecraft

Manned spacecraft
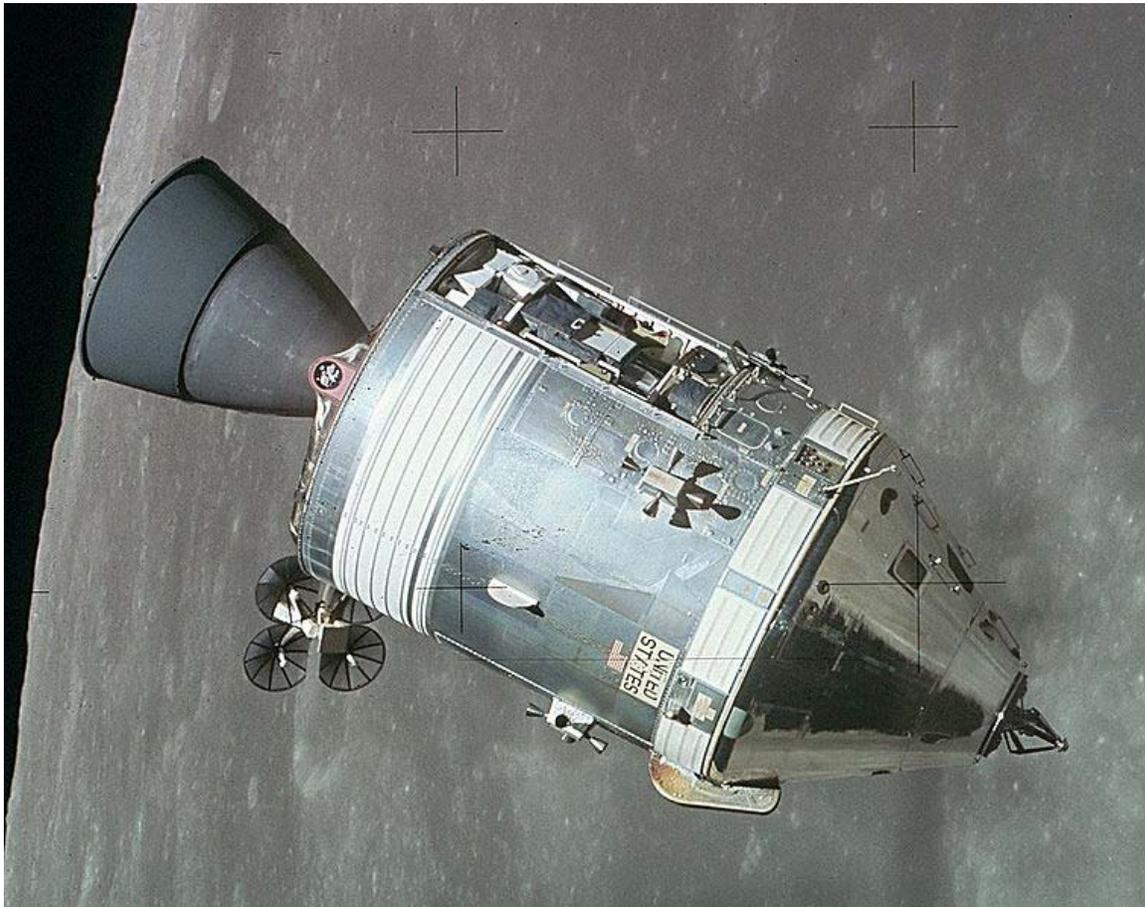
The Apollo 15 Command/Service Module as viewed from the Lunar Module on August 2, 1971.

The first manned spacecraft was Vostok 1, which carried Soviet cosmonaut Yuri Gagarin into space in 1961, and complete a full Earth orbit. There were five other manned missions which used a Vostok spacecraft. The second manned spacecraft was named *Freedom 7*, and it performed a sub-orbital spaceflight carrying American astronaut Alan

Shepard to an altitude of just over 187 kilometres (116 mi). There were five other manned missions using at Mercury spacecraft, like *Freedom 7*.

Other Soviet manned spacecraft include the Voskhod spacecraft, Soyuz spacecraft, and the Salyut space stations as well as the space station *Mir*. Other American manned spacecraft include the Gemini Spacecraft, Apollo Spacecraft, the Skylab space station, and the Space Shuttle. China was also developed the Shenzhou spacecraft, which as of January 2011 has been used for three manned missions, the first being Shenzhou 5 in 2003.

The International Space Station, which has been manned since November 2000, in a joint venture between Russian, the United States, as well as several other countries.

Strictly speaking, the Manned Maneuvering Unit, the propulsion system used by spacewalking astronauts, could be counted as a manned spacecraft.

Spaceplanes

Some reusable vehicles have been designed only for manned spaceflight, and these are often called spaceplanes. The first example of such was the North American X-15 spaceplane, which conducted two manned flights which reached a height over 100 km in the 1960's. The first reusable spacecraft, the X-15, was air-launched on a suborbital trajectory on July 19, 1963.

Columbia orbiter landing

The first partially reusable orbital spacecraft, the Space Shuttle, was launched by the USA on the 20th anniversary of Yuri Gagarin's flight, on April 12, 1981. During the Shuttle era, six orbiters were built, all of which have flown in the atmosphere and five of which have flown in space. The *Enterprise* was used only for approach and landing tests, launching from the back of a Boeing 747 SCA and gliding to deadstick landings at Edwards AFB, California. The first Space Shuttle to fly into space was the *Columbia*, followed by the *Challenger*, *Discovery*, *Atlantis*, and *Endeavour*. The *Endeavour* was built to replace the *Challenger* when it was lost in January 1986. The *Columbia* broke up during reentry in February 2003.

The first automatic partially reusable spacecraft was the Buran (Snowstorm), launched by the USSR on November 15, 1988, although it made only one flight. This spaceplane was designed for a crew and strongly resembled the U.S. Space Shuttle, although its drop-off boosters used liquid propellants and its main engines were located at the base of what would be the external tank in the American Shuttle. Lack of funding, complicated by the dissolution of the USSR, prevented any further flights of Buran. The Space Shuttle has since been modified to allow for autonomous re-entry in case of necessity.

Per the Vision for Space Exploration, the Space Shuttle is due to be retired in 2011 due mainly to its old age and high cost of program reaching over a billion dollars per flight. The Shuttle's human transport role is to be replaced by the partially reusable Crew Exploration Vehicle (CEV) no later than 2014. The Shuttle's heavy cargo transport role is to be replaced by expendable rockets such as the Evolved Expendable Launch Vehicle (EELV) or a Shuttle Derived Launch Vehicle.

Scaled Composites' SpaceShipOne was a reusable suborbital spaceplane that carried pilots Mike Melvill and Brian Binnie on consecutive flights in 2004 to win the Ansari X Prize. The Spaceship Company will build its successor SpaceShipTwo. A fleet of SpaceShipTwos operated by Virgin Galactic should begin reusable private spaceflight carrying paying passengers in 2011.

XCOR Aerospace also plans to initiate a suborbital commercial spaceflight service with the Lynx rocketplane in 2012 through a partnership with RocketShip Tours. First test flights are planned for 2011.
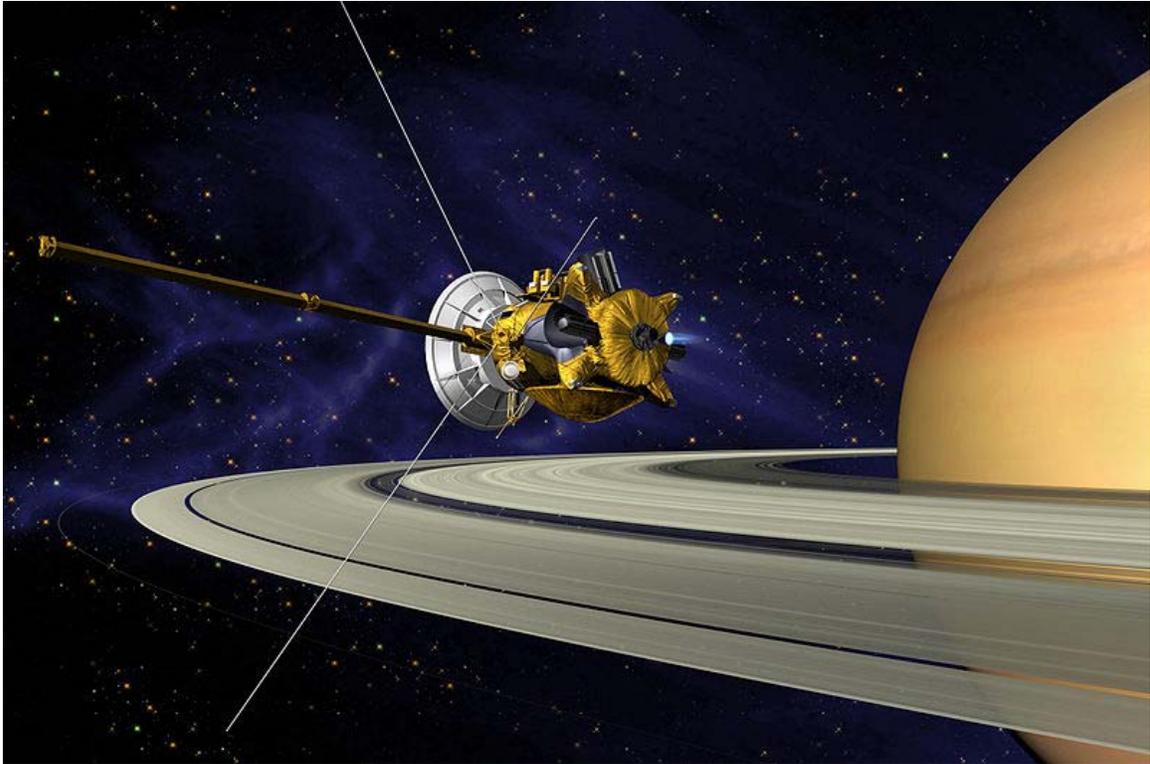
Unmanned spacecraft

The Hubble Space Telescope
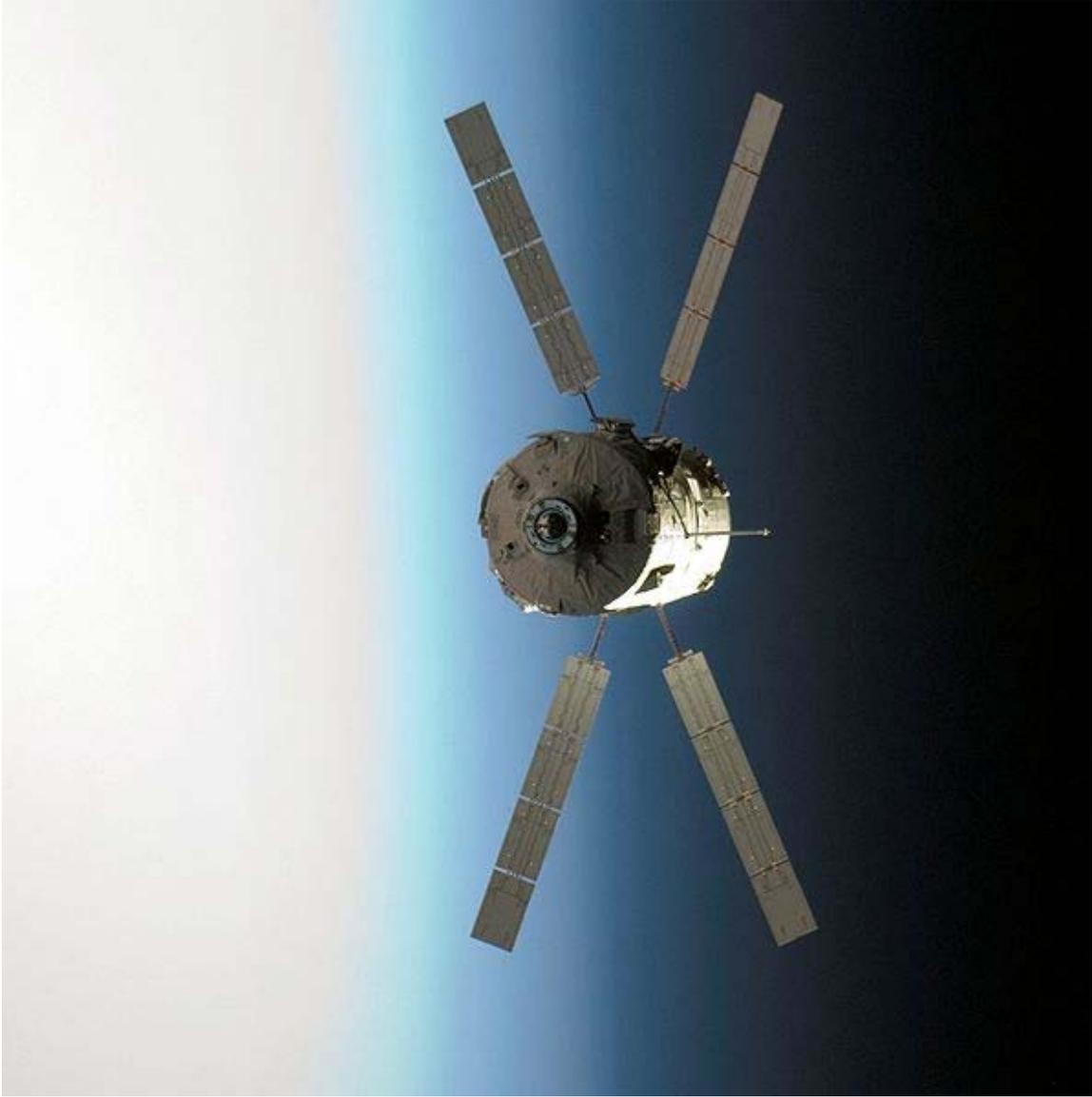
The Jules Verne Automated Transfer Vehicle (ATV) approaches the International Space Station on Monday, March 31, 2008.

Artist's conception of Cassini-Huygens as it enters Saturn's orbit

Semi-manned or manned-spec unmanned spacecraft

- Automated Transfer Vehicle (ATV) – unmanned European cargo spacecraft
- Buran manned-spec Soviet shuttle (one mission only)
- H-II Transfer Vehicle (HTV) – unmanned Japanese cargo spacecraft
- Progress – unmanned USSR/Russia cargo spacecraft
- TKS – manned-spec unmanned USSR cargo spacecraft

Earth Orbit

- Explorer 1 – first US satellite
- Project SCORE – first communications satellite
- SOHO
- Sputnik 1 – world's first artificial satellite
- Sputnik 2 – first animal in orbit (Laika)
- Sputnik 5 – first capsule recovered from orbit (Vostok precursor) – animals survived
- STEREO – Earth environment observation
- Syncom – first geosynchronous communications satellite
- X-37 – spaceplane
- There are more than 2,000 spacecrafts in orbit.

Lunar

- Clementine – US Navy mission, orbited Moon, detected hydrogen at the poles
- Kaguya JPN – Lunar orbiter
- Luna 1 – first lunar flyby
- Luna 2 – first lunar impact
- Luna 3 – first images of lunar far side
- Luna 9 – first soft landing on the Moon
- Luna 10 – first lunar orbiter
- Luna 16 – first unmanned lunar sample retrieval
- Lunar Orbiter – very successful series of lunar mapping spacecraft
- Lunar Prospector – confirmed detection of hydrogen at the lunar poles
- Lunar Reconnaissance Orbiter – Identifies safe landing sites & Locates moon resources
- SMART-1 ESA – Lunar Impact
- Surveyor – first USA soft lander
- Chandrayaan 1 – first Indian Lunar mission

Artist's conception of the Phoenix spacecraft as it lands on Mars

Planetary

- Akatsuki JPN – a Venus orbiter
- Cassini-Huygens – first Saturn orbiter + Titan lander
- Galileo – first Jupiter orbiter+descent probe
- IKAROS JPN – first solar-sail spacecraft
- Mariner 4 – first Mars flyby, first close and high resulution images of Mars
- Mariner 9 – first Mars orbiter
- Mariner 10 – first Mercury flyby, first close up images
- Mars Exploration Rover – a Mars rover
- Mars Express – a Mars orbiter
- Mars Global Surveyor – a Mars orbiter
- Mars Reconnaissance Orbiter – an advanced climate, imaging, sub-surface radar, and telecommunications Mars orbiter
- MESSENGER – first Mercury orbiter (arrival 2011)
- Mars Pathfinder – a Mars lander + rover
- New Horizons – first Pluto flyby (arrival 2015)
- Pioneer 10 – first Jupiter flyby, first close up images
- Pioneer 11 – second Jupiter flyby + first Saturn flyby (first close up images of Saturn)
- Pioneer Venus – first Venus orbiter+landers
- Vega 1 - Balloon release into Venus atmosphere and lander (joint mission with Vega 2), mothership continued on to rendesvous with Halley's Comet
- Venera 4 – first soft landing on another planet (Venus)
- Viking 1 – first soft landing on Mars
- Voyager 2 – Jupiter flyby + Saturn flyby + first flybys/images of Neptune and Uranus

Other – deep space

- Cluster
- Deep Space 1
- Deep Impact
- Genesis
- Hayabusa
- Near Earth Asteroid Rendezvous
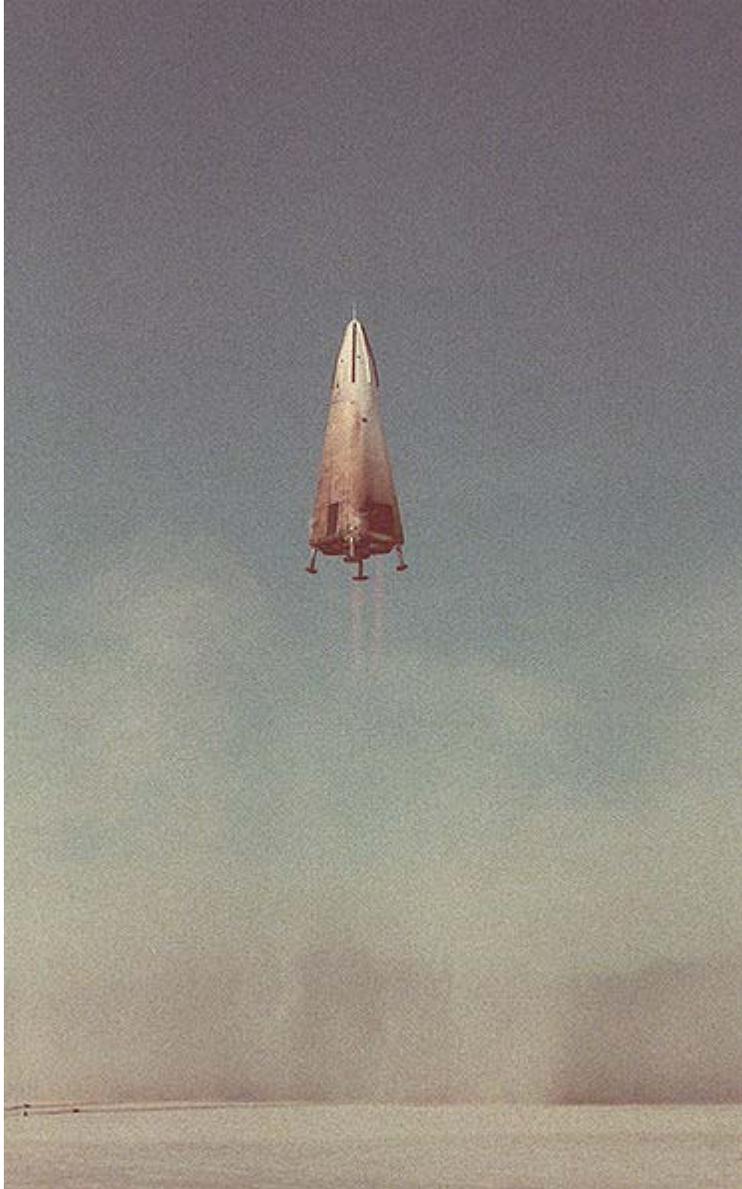- Stardust
- WMAP

Fastest spacecraft

- Helios I & II *Solar Probes* (252,792 km/h/157,078 mph)

Furthest spacecraft from the Sun

- Voyager 1 at 106.3 AU as of July 2008, traveling outward at about 3.6 AU/year

- Pioneer 10 at 89.7 AU as of 2005, traveling outward at about 2.6 AU/year
- Voyager 2 at 85.49 AU as of July 2008, traveling outward at about 3.3 AU/year

Unfunded / canceled programs

The First Test Flight of the Delta Clipper-Experimental Advanced (DC-XA)
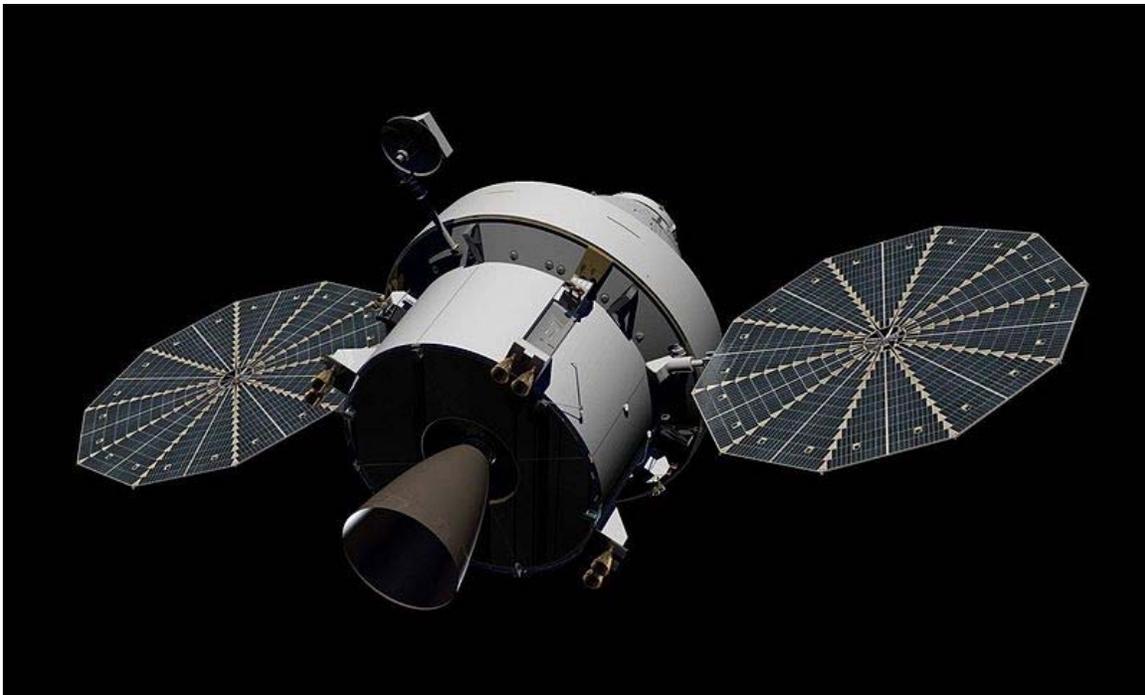
Multi-stage

- Chinese Project 921-3 Shuttle
- Kliper—Russian "Clipper"
- ESA Hermes Shuttle
- Soviet Buran Shuttle
- Soyuz Kontakt

- Teledesic
- Manned Orbiting Laboratory
- X-20
- Altair - lunar lander

SSTO

- RR/British Aerospace HOTOL
- ESA Hopper Orbiter
- McDonnell Douglas DC-X (Delta Clipper)
- Roton Rotored-Hybrid
- Lockheed-Martin VentureStar

Spacecraft under development

The Orion spacecraft

Manned

- Orion - capsule
- SpaceX Dragon - capsule
- Lynx rocketplane - suborbital
- ISRO Orbital Vehicle - capsule
- PTK NP spacecraft- capsule
- Dream Chaser - spaceplane
- Prometheus - spaceplane
- SpaceShipTwo - spaceplane

- Boeing CST-100 - capsule
- proposed ESA Advanced Reentry Vehicle - capsule
- Skylon - single-stage-to-orbit spaceplane

Unmanned

- SpaceX Dragon - cargo delivery to the ISS
- Orbital Sciences Cygnus - cargo delivery to the ISS
- CNES Mars Netlander
- James Webb Space Telescope (delayed)
- ESA Darwin probe
- Mars Science Laboratory rover
- Shenzhou spacecraft Cargo
- Terrestrial Planet Finder probe
- System F6—a DARPA Fractionated Spacecraft demonstrator

Subsystems

A spacecraft system comprises various subsystems, dependent upon mission profile. Spacecraft subsystems comprise the spacecraft "*bus*" and may include: attitude determination and control (variously called ADAC, ADC or ACS), guidance, navigation and control (GNC or GN&C), communications (Comms), command and data handling (CDH or C&DH), power (EPS), thermal control (TCS), propulsion, and structures. Attached to the bus are typically *payloads*.

Life support
 Spacecraft intended for human spaceflight must also include a life support system for the crew.

Reaction control system thrusters on the nose of the U.S. Space Shuttle

Attitude control

A Spacecraft needs an attitude control subsystem to be correctly oriented in space and respond to external torques and forces properly. The attitude control subsystem consists of sensors and actuators, together with controlling algorithms. The attitude control subsystem permits proper pointing for the science objective, sun pointing for power to the solar arrays and earth-pointing for communications.

GNC

Guidance refers to the calculation of the commands (usually done by the CDH subsystem) needed to steer the spacecraft where it is desired to be. Navigation means determining a spacecraft's orbital elements or position. Control means adjusting the path of the spacecraft to meet mission requirements. On some

missions, GNC and Attitude Control are combined into one subsystem of the spacecraft.

Command and data handling

The CDH subsystem receives commands from the communications subsystem, performs validation and decoding of the commands, and distributes the commands to the appropriate spacecraft subsystems and components. The CDH also receives housekeeping data and science data from the other spacecraft subsystems and components, and packages the data for storage on a data recorder or transmission to the ground via the communications subsystem. Other functions of the CDH include maintaining the spacecraft clock and state-of-health monitoring.

Power

Spacecraft need an electrical power generation and distribution subsystem for powering the various spacecraft subsystems. For spacecraft near the Sun, solar panels are frequently used to generate electrical power. Spacecraft designed to operate in more distant locations, for example Jupiter, might employ a Radioisotope Thermoelectric Generator (RTG) to generate electrical power. Electrical power is sent through power conditioning equipment before it passes through a power distribution unit over an electrical bus to other spacecraft components. Batteries are typically connected to the bus via a battery charge regulator, and the batteries are used to provide electrical power during periods when primary power is not available, for example when a Low Earth Orbit (LEO) spacecraft is eclipsed by the Earth.

Thermal control

Spacecraft must be engineered to withstand transit through the Earth's atmosphere and the space environment. They must operate in a vacuum with temperatures potentially ranging across hundreds of degrees Celsius as well as (if subject to reentry) in the presence of plasmas. Material requirements are such that either high melting temperature, low density materials such as beryllium and reinforced carbon-carbon or (possibly due to the lower thickness requirements despite its high density) tungsten or ablative carbon/carbon composites are used. Depending on mission profile, spacecraft may also need to operate on the surface of another planetary body. The thermal control subsystem can be passive, dependent on the selection of materials with specific radiative properties. Active thermal control makes use of electrical heaters and certain actuators such as louvers to control temperature ranges of equipments within specific ranges.

A launch vehicle, like this Proton rocket, is typically used to bring a spacecraft to orbit.

Propulsion

Spacecraft may or may not have a propulsion subsystem, depending upon whether or not the mission profile calls for propulsion. The *Swift* spacecraft is an example of a spacecraft that does not have a propulsion subsystem. Typically though, LEO spacecraft (for example *Terra (EOS AM-1)* include a propulsion subsystem for altitude adjustments (called drag make-up maneuvers) and inclination adjustment maneuvers. A propulsion system is also needed for spacecraft that perform momentum management maneuvers. Components of a conventional propulsion subsystem include fuel, tankage, valves, pipes, and thrusters. The TCS interfaces with the propulsion subsystem by monitoring the temperature of those components, and by preheating tanks and thrusters in preparation for a spacecraft maneuver.

Structures

Spacecraft must be engineered to withstand launch loads imparted by the launch vehicle, and must have a point of attachment for all the other subsystems. Depending upon mission profile, the structural subsystem might need to withstand loads imparted by entry into the atmosphere of another planetary body, and landing on the surface of another planetary body.

Payload

The payload is dependent upon the mission of the spacecraft, and is typically regarded as the part of the spacecraft "that pays the bills". Typical payloads could include scientific instruments (cameras, telescopes, or particle detectors, for example), cargo, or a human crew.

Ground segment

The ground segment, though not technically part of the spacecraft, is vital to the operation of the spacecraft. Typical components of a ground segment in use during normal operations include a mission operations facility where the flight operations team conducts the operations of the spacecraft, a data processing and storage facility, ground stations to radiate signals to and receive signals from the spacecraft, and a voice and data communications network to connect all mission elements.

Launch vehicle

The launch vehicle propels the spacecraft from the Earth's surface, through the atmosphere, and into an orbit, the exact orbit being dependent upon mission configuration. The launch vehicle may be expendable or reusable.