Aerospace Engineering

History

One person who was important in developing aviation was Alberto Santos Dumont, a pioneer who built the first machines that were able to fly.

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 century. 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. Only a decade 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 sent the American first satellite launched on January 31, 1958 in response the USSR launching Sputnik.

Fluid mechanics

Fluid mechanics is the study of how fluids move and the forces on them. (Fluids include liquids and gases.)

Fluid mechanics can be divided into fluid statics, the study of fluids at rest, and fluid dynamics, the study of fluids in motion. It is a branch of continuum mechanics, a subject which models matter without using the information that it is made out of atoms. The study of fluid mechanics goes back at least to the days of ancient Greece, when Archimedes made a beginning on fluid statics. However, fluid mechanics, especially fluid dynamics, is an active field of research with many unsolved or partly solved problems. Fluid mechanics can be mathematically complex. Sometimes it can best be solved by numerical methods, typically using computers. A modern discipline, called Computational Fluid Dynamics (CFD), is devoted to this approach to solving fluid mechanics problems. Also taking advantage of the highly visual nature of fluid flow is Particle Image Velocimetry, an experimental method for visualizing and analyzing fluid flow.

Relationship to continuum mechanics

Fluid mechanics is a subdiscipline of continuum mechanics, as illustrated in the following table.

<table>
<tr><td rowspan="4">Continuum mechanics the study of the physics of continuous materials</td><td rowspan="2">Solid mechanics: the study of the physics of continuous materials with a defined rest shape.</td><td colspan="2">Elasticity: which describes materials that return to their rest shape after an applied stress.</td></tr>
<tr><td>Plasticity: which describes materials that permanently deform after a large enough applied stress.</td><td rowspan="2">Rheology: the study of materials with both solid and fluid characteristics</td></tr>
<tr><td rowspan="2">Fluid mechanics: the study of the physics of continuous materials which take the shape of their container.</td><td>Non-Newtonian fluids</td></tr>
<tr><td colspan="2">Newtonian fluids</td></tr>
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In a mechanical view, a fluid is a substance that does not support tangential stress; that is why a fluid at rest has the shape of its containing vessel. A fluid at rest has no shear stress.

Assumptions

Like any mathematical model of the real world, fluid mechanics makes some basic assumptions about the materials being studied. These assumptions are turned into equations that must be satisfied if the assumptions are to hold true. For example, consider an incompressible fluid in three dimensions. The assumption that mass is conserved means that for any fixed closed surface (such as a sphere) the rate of mass passing from outside to inside the surface must be the same as rate of mass passing the other way. (Alternatively, the mass inside remains constant, as does the mass outside). This can be turned into an integral equation over the surface.

Fluid mechanics assumes that every fluid obeys the following:

Conservation of mass

Conservation of momentum

The continuum hypothesis, detailed below.

Further, it is often useful (and realistic) to assume a fluid is incompressible - that is, the density of the fluid does not change. Liquids can often be modelled as incompressible fluids, whereas gases cannot.

Similarly, it can sometimes be assumed that the viscosity of the fluid is zero (the fluid is inviscid). Gases can often be assumed to be inviscid. If a fluid is viscous, and its flow contained in some way (e.g. in a pipe), then the flow at the boundary must have zero velocity. For a viscous fluid, if the boundary is not porous, the shear forces between the fluid and the boundary results also in a zero velocity for the fluid at the boundary. This is called the no-slip condition. For a porous media otherwise, in the frontier of the containing vessel, the slip condition is not zero velocity, and the fluid has a discontinuous velocity field between the free fluid and the fluid in the porous media (this is related to the Beavers and Joseph condition).

The continuum hypothesis

Fluids are composed of molecules that collide with one another and solid objects. The continuum assumption, however, considers fluids to be continuous. That is, properties such as density, pressure, temperature, and velocity are taken to be well-defined at "infinitely" small points, defining a REV (Reference Element of Volume), at the geometric order of the distance between two adjacent molecules of fluid. Properties are assumed to vary continuously from one point to another, and are averaged values in the REV. The fact that the fluid is made up of discrete molecules is ignored.

The continuum hypothesis is basically an approximation, in the same way planets are approximated by point particles when dealing with celestial mechanics, and therefore results in approximate solutions. Consequently, assumption of the continuum hypothesis can lead to results which are not of desired accuracy. That said, under the right circumstances, the continuum hypothesis produces extremely accurate results.

Those problems for which the continuum hypothesis does not allow solutions of desired accuracy are solved using statistical mechanics. To determine whether or not to use conventional fluid dynamics or statistical mechanics, the Knudsen number is evaluated for the problem. The Knudsen number is defined as the ratio of the molecular mean free path length to a certain representative physical length scale. This length scale could be, for example, the radius of a body in a fluid. (More simply, the Knudsen number is how many times its own diameter a particle will travel on average before hitting another particle). Problems with Knudsen numbers at or above unity are best evaluated using statistical mechanics for reliable solutions.

Navier-Stokes equations

The Navier-Stokes equations (named after Claude-Louis Navier and George Gabriel Stokes) are the set of equations that describe the motion of fluid substances such as liquids and gases. These equations state that changes in momentum (acceleration) of fluid particles depend only on the external pressure and internal viscous forces (similar to friction) acting on the fluid. Thus, the Navier-Stokes equations describe the balance of forces acting at any given region of the fluid.

The Navier-Stokes equations are differential equations which describe the motion of a fluid. Such equations establish relations among the rates of change the variables of interest. For example, the Navier-Stokes equations for an ideal fluid with zero viscosity states that acceleration (the rate of change of velocity) is proportional to the derivative of internal pressure.

This means that solutions of the Navier-Stokes equations for a given physical problem must be sought with the help of calculus. In practical terms only the simplest cases can be solved exactly in this way. These cases generally involve non-turbulent, steady flow (flow does not change with time) in which the Reynolds number is small.

For more complex situations, such as global weather systems like El Niño or lift in a wing, solutions of the Navier-Stokes equations can currently only be found with the help of computers. This is a field of sciences by its own called computational fluid dynamics.

General form of the equation

The general form of the Navier-Stokes equations for the conservation of momentum is:

$$\rho \frac{D\mathbf{v}}{Dt} = \nabla \cdot \mathbb{P} + \rho \mathbf{f}$$

where

- ρ is the fluid density,
- $\frac{D}{Dt}$ is the substantive derivative (also called the material derivative),
- $\mathbf{v}$ is the velocity vector,
- $\mathbf{f}$ is the body force vector, and

- $\mathbb{P}$ is a tensor that represents the surface forces applied on a fluid particle (the comoving stress tensor).

Unless the fluid is made up of spinning degrees of freedom like vortices, $\mathbb{P}$ is a symmetric tensor. In general, (in three dimensions) $\mathbb{P}$ has the form:

$$\mathbb{P} = \begin{pmatrix} \sigma_{xx} & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_{yy} & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_{zz} \end{pmatrix}$$

The above is actually a set of three equations, one per dimension. By themselves, these aren't sufficient to produce a solution. However, adding conservation of mass and appropriate boundary conditions to the system of equationsproduces a solvable set of equations.

Newtonian vs. non-Newtonian fluids

A **Newtonian fluid** (named after Isaac Newton) is defined to be a fluid whose shear stress is linearly proportional to the velocity gradient in the direction perpendicular to the plane of shear. This definition means regardless of the forces acting on a fluid, it *continues to flow*. For example, water is a Newtonian fluid, because it continues to display fluid properties no matter how much it is stirred or mixed. A slightly less rigorous definition is that the drag of a small object being moved through the fluid is proportional to the force applied to the object. (Compare friction).

By contrast, stirring a non-Newtonian fluid can leave a "hole" behind. This will gradually fill up over time - this behaviour is seen in materials such as pudding, oobleck, or sand (although sand isn't strictly a fluid). Alternatively, stirring a non-Newtonian fluid can cause the viscosity to decrease, so the fluid appears "thinner" (this is seen in non-drip paints). There are many types of non-Newtonian fluids, as they are defined to be something that fails to obey a particular property.

Equations for a Newtonian fluid

The constant of proportionality between the shear stress and the velocity gradient is known as the viscosity. A simple equation to describe Newtonian fluid behaviour is

$$\tau = -\mu \frac{dv}{dx}$$

where

τ is the shear stress exerted by the fluid ("drag")

μ is the fluid viscosity - a constant of proportionality

$\frac{dv}{dx}$ is the velocity gradient perpendicular to the direction of shear

For a Newtonian fluid, the viscosity, by definition, depends only on temperature and pressure, not on the forces acting upon it. If the fluid is incompressible and viscosity is constant across the fluid, the equation governing the shear stress (in Cartesian coordinates) is

$$\tau_{ij} = \mu \left(\frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right)$$

where

τ_{ij} is the shear stress on the i^{th} face of a fluid element in the j^{th} direction

v_i is the velocity in the i^{th} direction

x_j is the j^{th} direction coordinate

If a fluid does not obey this relation, it is termed a non-Newtonian fluid, of which there are several types.

Astrodynamics

Orbital mechanics

Orbital mechanics or **astrodynamics** is the study of the motion of rockets and other spacecraft. The motion of theseobjects is usually calculated from Newton's laws of motion and Newton's law of universal gravitation, collectively known as classical mechanics.

Celestial mechanics focuses more broadly on the orbital motions of artificial and natural astronomical bodies such as planets, moons, and comets. Orbital mechanics is a subfield[*citation needed*] which focuses on spacecraft trajectories, including orbital maneuvers, orbit plane changes, and interplanetary transfers, and is used by mission planners to predict the results of propulsion.

General relativity provides more exact equations for calculatingorbits, sometimes necessary for greater accuracy or high-gravity situations (such as orbits close to the Sun).

- Rules of thumb
- Laws of astrodynamics
- Historical approaches
- Practical techniques

- Modern mathematical techniques

Rules of thumb

The following rules of thumb are useful for situationsapproximated by classical mechanics under the standardassumptions of astrodynamics. The specific example discussed is of a satellite orbiting a planet, but the rules of thumb could also apply to other situations, such as orbits of small bodies around a star such as the Sun.

- Kepler's laws of planetary motion, which can be mathematically derived from Newton's laws, hold in the absence of thrust:
  - Orbits are either circular, with the planet at the center of the circle, or form an ellipse, with the planet at one focus.
  - A line drawn from the planet to the satellite sweeps out *equal areas in equal times* no matterwhich portion of the orbit is measured.
  - The square of a satellite's orbital period is proportional to the cube of its average distance from the planet.
- Without firing a rocket engine (generating thrust), the height and shape of the satellite's orbit won't change, and it will maintain the same orientation with respect to the fixed stars.
- A satellite in a low orbit (or low part of an elliptical orbit) moves more quickly with respect to the surface of the planet than a satellite in a higher orbit (or a high part of an elliptical orbit), due to the stronger gravitationalattraction closer to the planet.
- If a brief rocket firing is made at only one point in the satellite's orbit, it will return to that same point on each subsequent orbit, though the rest of its path will change. Thus to move from one circular orbit to another, at least two brief firings are needed.
- From a circular orbit, a brief firing of a rocket in the direction which slows the satellite down, will create an elliptical orbit with a lower perigee (lowest orbital point) at 180 degrees away from the firing point, which will be the apogee (highest orbital point). If the rocket is fired to speed the rocket, it will create an elliptical orbit with a higher apogee 180 degrees away from the firing point (which will become the perigee).

The consequences of the rules of orbital mechanics are sometimes counter-intuitive. For example, if two spacecraft are in the same circular orbit and wish to dock, unless they are very close, the trailing craft cannot simply fire its engines to go faster. This will change the shape of its orbit, causing it to gain altitude and miss its target. One approach is to actually fire a reverse thrust to slow down, and then fire again to re-circularize the orbit at a lower altitude. Because lower orbits are faster than higher orbits, the trailing craft will begin to catch up. A third firing at the right time will put the trailing craft in an elliptical orbit which will intersect the path of the leading craft, approaching from below.

To the degree that the assumptions do not hold, actual trajectories will vary from those calculated. Atmospheric drag is one major complicating factor for objects in Earth orbit. The differences between classical mechanics and general relativity can become important for large objects like planets. These rules of thumb are decidedly inaccurate when describing two or more bodies of similar mass, such as a binary star system.

Laws of astrodynamics

The fundamental laws of astrodynamics are Newton's law ofuniversal gravitation and Newton's laws of motion, while thefundamental mathematical tool is his differential calculus.

Standard assumptions in astrodynamics include non-interference from outside bodies, negligible mass for one of the bodies, and negligible other forces (such as from the solar wind, atmospheric drag, etc.). More accurate calculations can be made without these simplifying assumptions, but they are more complicated. The increased accuracy often does not make enough of a difference in the calculation to be worthwhile.

Kepler's laws of planetary motion may be derived from Newton's laws, when it is assumed that the orbiting body is subject only to the gravitational force of the central attractor. When an engine thrust or propulsive force is present, Newton's laws still apply, but Kepler's laws are invalidated. When the thrust stops, the resulting orbit will be different but will once again be described by Kepler's laws.

Escape velocity

The formula for escape velocity is easily derived as follows. The specific energy (energy per unit mass) of any space vehicle is composed of two components, the specific potential energy and the specific kinetic energy. The specific potential energy associated with a planet of mass *M* is given by

$$-GM/r$$

while the specific kinetic energy of an object is given by

$$v^2/2$$

Since energy is conserved, the total specific orbital energy

$$v^2/2 - GM/r$$

does not depend on the distance, *r*, from the center of the central body to the space vehicle in question. Therefore, the object can reach infinite *r* only if this quantity is nonnegative, which implies

$$v \geq \sqrt{2GM/r}$$

The escape velocity from the Earth's surface is about 11 km/s, but that is insufficient to send the body an infinite distance because of the gravitational pull of the Sun. To escape the solar system from the vicinity of the Earth requires around 42 km/s velocity, but there will be "part credit" for the Earth's orbital velocity for spacecraft launched from Earth, if their further acceleration (due to the propulsion system) carries them in the same direction as Earth travels in its orbit.

Formulae for free orbits

Orbits are conic sections, so, naturally, the formula for the distance of a body for a given angle corresponds to the formula for that curve in polar coordinates, which is:

$$r = \frac{a}{(1 + e\cos\theta)}.$$

The parameters are given by the orbital elements.

Circular orbits

Although most orbits are elliptical in nature, a special case is the circular orbit, which is an ellipse of zero eccentricity. The formula for the velocity of a body in a circular orbit at distance*r* from the center of gravity of mass *M* is

$$v = \sqrt{\frac{GM}{r}}$$

where *G* is the gravitational constant, equal to

$6.672\ 598 \times 10^{-11}\ m^3/(kg \cdot s^2)$

To properly use this formula, the units must be consistent; for example, *M* must be in kilograms, and *r* must be in meters.The answer will be in meters per second.

The quantity *GM* is often termed the standard gravitational parameter, which has a different value for every planet or moon in the solar system.

Once the circular orbital velocity is known, the escape velocity is easily found by multiplying by the square root of 2:

$$v = \sqrt{2}\sqrt{\frac{GM}{r}} = \sqrt{\frac{2GM}{r}}\ .$$

Historical Approches

Until the rise of space travel in the twentieth century, there was little distinction between orbital and celestial mechanics. The fundamental techniques, such as those used to solve the Keplerian problem, are therefore the same in both fields. Furthermore, the history of the fields is almost entirely shared.

Kepler's equation

Kepler was the first to successfully model planetary orbits to a high degree of accuracy.

Derivation

To compute the position of a satellite at a given time (the *Keplerian problem*) is a difficult problem. The opposite problem—to compute the time-of-flight given the starting and ending positions—is simpler.

Kepler's construction for deriving the time-of-flightequation. The bold ellipse is the satellite's orbit, with the star or planet at one focus *Q*. The goal is tocompute the time required for a satellite to travel from periapsis *P* to a given point *S*. Kepler circumscribed the blue *auxiliary circle* around theellipse, and used it to derive his time-of-flightequation in terms of eccentric anomaly.

The problem is to find the time *t* at which the satellite reaches point *S*, given that it is at periapsis *P* at time *t* = 0. We are given that the semimajor axis of the orbit is *a*, and the semiminor axis is *b*; the eccentricity is *e*, and the planet is at*Q*, at a distance of *ae* from the center *C* of the ellipse.

The key construction that will allow us to analyse this situation is the *auxiliary circle* (shown in blue) circumscribed on the orbital ellipse. This circle is taller than the ellipse by a factor of*a* / *b* in the direction of the minor axis, so all area measures on the circle are magnified by a factor of *a* / *b* with respect to the analogous area measures on the ellipse.

Any given point on the ellipse can be mapped to the corresponding point on the circle that is *a* / *b* further from the ellipse's major axis. If we do this mapping for the position *S* of the satellite at time *t*, we arrive at a point *R* on the circumscribed circle. Kepler defines the angle *PCR* to be the*eccentric anomaly* angle *E*. (Kepler's terminology often refers to angles as "anomalies".) This definition makes the time-of-flight equation easier to derive than it would be using the *true anomaly* angle *PQS*.

To compute the time-of-flight from this construction, we note that Kepler's second law allows us to compute time-of-flight from the area swept out by the satellite, and so we will set about computing the area *PQS* swept out by the satellite.

First, the area *PQR* is a magnified version of the area *PQS*:

$$PQR = \frac{a}{b} PQS$$

Furthermore, area *PQS* is the area swept out by the satellite in time *t*. We know that, in one orbital period *T*, the satellite sweeps out the whole area πab of the orbital ellipse. *PQS* is the t / T fraction of this area, and substituting, we arrive at this expression for *PQR*:

$$PQR = \frac{t}{T} \pi a^2$$

Second, the area *PQR* is also formed by removing area *QCR* from *PCR*:

$$PQR = PCR - QCR$$

Area *PCR* is a fraction of the circumscribed circle, whose total area is πa^2. The fraction is E / 2π, thus:

$$PCR = \frac{a^2}{2} E$$

Meanwhile, area *QCR* is a triangle whose base is the line segment *QC* of length *ae*, and whose height is $a\sin E$:

$$QCR = \frac{a^2}{2} e \sin E$$

Combining all of the above:

$$PQR = \frac{t}{T} \pi a^2 = \frac{a^2}{2} E - \frac{a^2}{2} e \sin E$$

Dividing through by a^2 / 2:

$$\frac{2\pi}{T} t = E - e \sin E$$

To understand the significance of this formula, consider an analogous formula giving an angle *M* during circular motion with constant angular velocity *n*:

$$nt = M$$

Setting $n = 2\pi / T$ and $M = E - e\sin E$ gives us Kepler'sequation. Kepler referred to n as the *mean motion*, and $E - e\sin E$ as the *mean anomaly*. The term "mean" in this case refers to the fact that we have "averaged" the satellite's non-constant angular velocity over an entire period to make the satellite's motion amenable to analysis. All satellites traverse an angle of 2π per orbital period T, so the mean angular velocity is always $2\pi / T$.

Substituting n into the formula we derived above gives this:

$$nt = E - e\sin E$$

This formula is commonly referred to as *Kepler's equation*.

Application

With Kepler's formula, finding the time-of-flight to reach an angle (true anomaly) of θ from periapsis is broken into two steps:

1. Compute the eccentric anomaly E from true anomaly θ
2. Compute the time-of-flight t from the eccentric anomaly$E$

Finding the angle at a given time is harder. Kepler's equation is transcendental in E, meaning it cannot be solved for Eanalytically, and so numerical approaches must be used. In effect, one must guess a value of E and solve for time-of-flight; then adjust E as necessary to bring the computed time-of-flight closer to the desired value until the required precision is achieved. Usually, Newton's method is used to achieve relatively fast convergence.

The main difficulty with this approach is that it can take prohibitively long to converge for the extreme elliptical orbits. For near-parabolic orbits, eccentricity e is nearly 1, and plugging $e = 1$ into the formula for mean anomaly, $E - \sin E$, we find ourselves subtracting two nearly-equal values, and so accuracy suffers. For near-circular orbits, it is hard to find the periapsis in the first place (and truly circular orbits have no periapsis at all). Furthermore, the equation was derived on the assumption of an elliptical orbit, and so it does not hold for parabolic or hyperbolic orbits at all. These difficulties are what led to the development of the universal variable formulation, described below.

Perturbation theory

One can deal with perturbations just by summing the forces and integrating, but that is not always best. Historically,*variation of parameters* has been used which is easier to mathematically apply with when perturbations are small.

Practical techniques

Transfer orbits

Transfer orbits allow spacecraft to move from one orbit to another. Usually they require a burn at the start, a burn at the end, and sometimes one or more burns in the middle. The Hohmann transfer orbit typically requires the least delta-v, but any orbit that sects both the origin orbit and destination orbit may be used.

Gravity assist and the Oberth effect

In a gravity assist, a spacecraft swings by a planet and leaves in a different direction, at a different velocity. This is useful to speed or slow a spacecraft instead of carrying more fuel.

This maneuver can be approximated by an elastic collision at large distances, though the flyby does not involve any physical contact. Due to Newton's Third Law (equal and oppositereaction), any momentum gained by a spacecraft must be lost by the planet, or vice versa. However, because the planet is much, much more massive than the spacecraft, the effect onthe planet's orbit is negligible.

The Oberth effect can be employed, particularly during a gravity assist operation. This effect is that use of a propulsion system works better at high speeds, and hence course changes are best done when close to a gravitating body; this can multiply the effective delta-v.

Interplanetary Transport Network and fuzzy orbits

It is now possible to use computers to search for routes using the nonlinearities in the gravity of the planets and moons of the solar system. For example, it is possible to plot an orbit from high earth orbit to Mars, passing close to one of the Earth's Trojan points. Collectively referred to as the Interplanetary Transport Network, these highly perturbative, even chaotic, orbital trajectories in principle need no fuel (in practice keeping to the trajectory requires some course corrections). The biggest problem with them is they are usually exceedingly slow, taking many years to arrive. In addition launch windows can be very far apart.

They have, however, been employed on projects such as Genesis. This spacecraft visited Earth's lagrange L1 point andreturned using very little propellant.

Modern mathematical Techniques

Conic orbits

For simple things like computing the delta-v for coplanar transfer ellipses, traditional approaches work pretty well. But time-of-flight is harder, especially for near-circular and hyperbolic orbits.

The patched conic approximation

The transfer orbit alone is not a good approximation for interplanetary trajectories because it neglects the planets' own gravity. Planetary gravity dominates the behaviour of the spacecraft in the vicinity of a planet, so it severely underestimates delta-v, and produces highly inaccurate prescriptions for burn timings.

One relatively simple way to get a first-order approximation of delta-v is based on the *patched conic approximation* technique. The idea is to choose the one dominant gravitating body in each region of space through which the trajectory will pass, and to model only that body's effects in that region. Forinstance, on a trajectory from the Earth to Mars, one would begin by considering only the Earth's gravity until the trajectory reaches a distance where the Earth's gravity no longer dominates that of the Sun. The spacecraft would be given escape velocity to send it on its way to interplanetary space. Next, one would consider only the Sun's gravity until the trajectory reaches the neighbourhood of Mars. During this stage, the transfer orbit model is appropriate. Finally, only Mars's gravity is considered during the final portion of the trajectory where Mars's gravity dominates the spacecraft's behaviour. The spacecraft would approach Mars on a hyperbolic orbit, and a final retrograde burn would slow the spacecraft enough to be captured by Mars.

The size of the "neighborhoods" (or spheres of influence) vary with radius r_{SOI}:

$$r_{SOI} = a_p \left(\frac{m_p}{m_s} \right)^{2/5}$$

where a_p is the semimajor axis of the planet's orbit relative to the Sun; m_p and m_s are the masses of the planet and Sun, respectively.

This simplification is sufficient to compute rough estimates of fuel requirements, and rough time-of-flight estimates, but it is not generally accurate enough to guide a spacecraft to its destination. For that, numerical methods are required.

The universal variable formulation

To address the shortcomings of the traditional approaches, the*universal variable* approach was developed. It works equally well on circular, elliptical, parabolic, and hyperbolic orbits; and also works well with perturbation theory. The differential equations converge nicely when integrated for any orbit.

Perturbations

The universal variable formulation works well with the variation of parameters technique, except now, instead of the six Keplerian orbital elements, we use a different set of orbital elements: namely, the satellite's initial position and velocity vectors x_0 and v_0 at a given epoch t = 0. In a two-body simulation, these elements are sufficient to compute the satellite's position and velocity at any time in the future, using the universal variable formulation. Conversely, at any moment in the satellite's orbit, we can measure its position and velocity, and then use the universal variable approach to determine what its initial position and velocity *would have been* at the epoch. In perfect two-body motion, these orbital elements would be invariant (just like the Keplerian elements would be).

However, perturbations cause the orbital elements to change over time. Hence, we write the position element as $x_0(t)$ and the velocity element as $v_0(t)$, indicating that they vary with time. The technique to compute the effect of perturbations becomes one of finding expressions, either exact or approximate, for the functions $x_0(t)$ and $v_0(t)$.

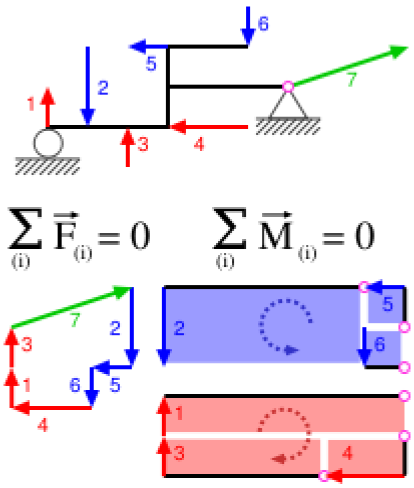
Non-ideal orbits

The following are some effects which make real orbits differ from the simple models based on a spherical earth. Most of them can be handled on short timescales (perhaps less than a few thousand orbits) by perturbation theory because they are small relative to the corresponding two-body effects.

- Equatorial bulges cause precession of the node and the perigee
- Tesseral harmonics [1] of the gravity field introduce additional perturbations
- lunar and solar gravity perturbations alter the orbits
- Atmospheric drag reduces the semi-major axis unless make-up thrust is used

Over very long timescales (perhaps millions of orbits), even small perturbations can dominate, and the behaviour can become chaotic. On the other hand, the various perturbations can be orchestrated by clever astrodynamicists to assist with orbit maintenance tasks, such as station-keeping, ground track maintenance or adjustment, or phasing of perigee to cover selected targets at low altitude.

Statics and Dynamics



Example of a beam in static equilibrium. The sum of force and moment is zero.

Statics is the branch of physics concerned with the analysis ofloads (force, torque/moment) on physical systems in static equilibrium, that is, in a state where the relative positions of subsystems do not vary over time, or where components andstructures are at rest under the action of external forces of equilibrium. In other words it is how forces are transmitted through the members in an object such as a crane from where it is applied on the object, the hanging end, to where it is supported from, the base of the crane. When in static equilibrium, the system is either at rest, or moving at constant velocity through its center of mass.

By Newton's second law, this situation implies that the net force and net torque (also known as moment) on every body in the system is zero, meaning that for every force bearing upon a member, there must be an equal and opposite force. From thisconstraint, such quantities as stress or pressure can be derived. The net forces equalling zero is known as the *first condition for equilibrium,* and the net torque equalling zero is known as the *second condition for equilibrium.* See statically determinate.

Statics is thoroughly used in the analysis of structures, for instance in architectural and structural engineering. Strength of materials is a related field of mechanics that relies heavily on the application of static equilibrium.

Hydrostatics, also known as fluid statics, is the study of fluids at rest. This analyzes systems in static equilibrium which involve forces due to mechanical fluids. The characteristic of any fluid at rest is that the force exerted on any particle of the fluid is the same in every direction. If the force is unequal the fluid will move in the direction of the resulting force. This concept was first formulated in a slightly extended form by the French mathematician and philosopher Blaise Pascal in 1647 and would be later known as Pascal's Law. This law has many important applications in hydraulics. Galileo also was a major figure in the development of hydrostatics.

In economics, "static" analysis has substantially the same meaning as in physics. Since the time of Paul Samuelson's*Foundations of Economic Analysis* (1947), the focus has been on "comparative statics", i.e., the comparison of one static equilibrium to another, with little or no discussion of the process of going between them – except to note the exogenous changes that caused the movement.

In exploration geophysics, "statics" is used as a short form for "static correction", referring to bulk time shifts of a reflection seismogram to correct for the variations in elevation and velocity of the seismic pulse through the weathered and unconsolidated upper layers.

Control Engineering

Background

Modern control engineering is closely related to electrical andcomputer engineering, as electronic circuits can often be easily described using control theory techniques. At many universities, control engineering courses are primarily taught by electrical and computer engineering faculty members.

Previous to modern electronics, process control devices were devised by mechanical engineers using mechanical feedbackalong with pneumatic and hydraulic control devices, some of which are still in use today.

The field of control within chemical engineering is often known as process control. It deals primarily with the control ofvariables in a chemical process in a plant. It is taught as part of the undergraduate curriculum of any chemical engineeringprogram, and employs many of the same principles in control engineering.

Other engineering disciplines also overlap with control engineering, as it can be applied to any system for which a suitable model can be derived.

Control engineering has diversified applications that include science, finance management, and even human behaviour. Students of control engineering may start with a linear control system course which requires elementary mathematics and Laplace transforms (called classical control theory). In linear control, the student does frequency and time domain analysis. Digital control and nonlinear control courses require Z Transformations and algebra respectively, and could be said to complete a basic control education. From here onwards there are several sub branches.

Control systems

Control engineering is the engineering discipline that focuses on the modelling of a diverse range of dynamic systems (e.g. mechanical systems) and the design of controllers that will cause these systems to behave in the desired manner. Although such controllers need not be electrical many are and hence control engineering is often viewed as a subfield ofelectrical engineering. However, the falling price of microprocessors is making the actual implementation of a control system essentially trivial[*citation needed*]. As a result, focus is shifting back to the mechanical engineering discipline, as intimate knowledge of the physical system being controlled is often desired.

Electrical circuits, digital signal processors and microcontrollers can all be used to implement Control systems. Control engineering has a wide range of applications from the flight and propulsion systems of commercial airliners to the cruise control present in many modern automobiles.

Control engineers often utilize feedback when designing control systems. For example, in an automobile with cruise control the vehicle's speed is continuously monitored and fed back to the system which adjusts the motor's torque accordingly. Where there is regular feedback, control theory can be used to determine how the system responds to such feedback. In practically all such systems stability is important and control theory can help ensure stability is achieved.

Although feedback is an important aspect of control engineering, control engineers may also work on the control of systems without feedback. This is known as open loop control. A classic example of open loop control is a washing machinethat runs through a pre-determined cycle without the use of sensors.

Aircraft Structure

Aircraft structures are the structures, large and small, common or uncommon, that make up aircraft of any sort, size, or purpose.

Purpose

Structures fulfill a purpose in an aircraft, either simple or complex. Each sub-structure interfaces with the otherstructures in the same aircraft. Ultimately parts work together to accomplish safe flight.

Classification

General

Aircraft structures may be classified by any of the following general categories:[purpose

- integration with other structures and the aircraft as a whole

- history of the structure
- problems and successes of the structure
- value to the particular aircraft
- cost
- supply
- manufacturer
- wear characteristics
- safety quotient
- popularity
- specified use
- hazards relative to the structure
- inspection challenges
- maintenance
- replacement protocol.

By type of wing

Aircraft structures may be classified by the type of wing employed, as this dictates much of the supporting structure

- Single planar winged
- Non-planar winged
- Biplane
- Triplane
- Ring winged
- Spanwise rotary winged
- Vertical rotary axis winged
- Morphable wing
- Flexible winged
- Rigid winged
- Flying wing
- parachutes and dogues
- Lifting bodies

- Winged man system
- Reentry-from-space vehicle

Classic aircraft structures

Classic aircraft components:[citation needed]

- Wing (skins, spars, ribs)
- Fuselage (skin, bulkhead, frame, heavy frames and bulkheads)
- Control system
- Thrust system
- Empennage
- Stringers or longerons
- Spars
- Landing system
- Launching system
- Accessory structures on board

The interaction of these structural components with mechanical systems may include:[citation needed]

- Undercarriage
- Ejection seat
- Powerplant

The locations of major components and systems will optimise the aircraft's weight and strength. For example in most modern military jets the heavy frame in the fuselage that supports the nose undercarriage also has the ejector seat rail mounted to it. In this way the frame has multiple functions, thus reducing weight and cost.[citation needed]

The location of structural components is also important with respect to the aircraft's center-of-gravity, which has great effect on the aircraft's stability.

The materials and manufacturing techniques of the structural components are optimized during the design process. For example, stringers may be manufactured by bending sheet metal or by extrusion to optimize weight and cost, whereas a robust frame that supports a heavy component such as an engine may be a cast or machined to optimize strength.[citation needed]

Regulatory requirements

Applicable national airworthiness regulations that specify structural requirements will affect the choice of materials.

Aeroelasticity

Aeroelasticity is the science which studies the interactionamong inertial, elastic, and aerodynamic forces. It was defined by Collar in 1947 as *"the study of the mutual interaction that takes place within the triangle of the inertial, elastic, andaerodynamic forces acting on structural members exposed to an airstream, and the influence of this study on design."*

Introduction

Airplane structures are not completely rigid, and aeroelastic phenomena arise when structural deformations induce changes on aerodynamic forces. The additional aerodynamic forces cause increasing of the structural deformations, which leads to greater aerodynamic forces in a feedback process. These interactions may become smaller until a condition of equilibrium is reached, or may diverge catastrophically.

Aeroelasticity can be divided in two fields of study: steady and dynamic aeroelasticity.

Steady aeroelasticity

Steady aeroelasticity studies the interaction betweenaerodynamic and elastic forces on an elastic structure. Mass properties are not significant in the calculations of this type of phenomena.

Divergence

Divergence occurs when a lifting surface deflects underaerodynamic load so as to increase the applied load, or move the load so that the twisting effect on the structure is increased. The increased load deflects the structure further, which brings the structure to the limit loads (and to failure).

Control surface reversal

Control surface reversal is the loss (or reversal) of the expected response of a control surface, due to structural deformation of the main lifting surface.

Dynamic aeroelasticity

Dynamic Aeroelasticity studies the interactions amongaerodynamic, elastic, and inertial forces. Examples of dynamic aeroelastic phenomena are:

Flutter

Flutter is a self-starting and potentially distructive vibrationwhere aerodynamic forces on an object couple with a structure's natural mode of vibration to produce rapid periodic motion. Flutter can occur in any object within a strong fluid flow, under the conditions that a positive feedback occurs between the structure's natural vibration and the aerodynamicforces. That is, that the vibrational movement of the object increases an aerodynamic load which in turn drives the object to move further. If the energy during the period ofaerodynamic excitation is larger than the natural damping of the system, the level of vibration will increase. The vibrationlevels can thus build up and are only limited when theaerodynamic or mechanical damping of the object match the energy input, this often results in large amplitudes and can lead to rapid failure. Because of this, structures exposed toaerodynamic forces - including wings, aerofoils, but also chimneys and bridges - are designed carefully within known parameters to avoid flutter.

In complex structures where both the aerodynamics and the mechanical properties of the structure are not fully understood flutter can only be discounted through detailed testing. Even changing the mass distribution of an aircraft or the stiffness of one component can induce flutter in an apparently unrelatedaerodynamic component. At its mildest this can appear as a "buzz" in the aircraft structure, but at its most violent it can develop uncontrollably with great speed and cause serious damage to or the destruction of the aircraft. The following link [[1]] shows a visual demonstration of flutter which destroys an RC aircraft.

Flutter can also occur on structures other than aircraft. One famous example of flutter phenomena is the collapse of the Tacoma Narrows Bridge.

Dynamic response

Dynamic response or **forced response** is the response of an object to changes in a fluid flow such as aircraft to gusts and other external atmospheric disturbances. Forced response is a concern in axial compressor and gas turbine design, where one set of aerofoils pass through the wakes of the aerofoils upstream.

Buffeting

Buffeting is a high-frequency instability, caused by airflow separation or shock wave oscillations from one object striking another. It is a random forced vibration.

Other fields of study

Other fields of physics may have an influence on aeroelastic phenomena. For example, in aerospace vehicles, stress induced by high temperatures is important. This leads to the study of aerothermoelasticity. Or, in other situations, the dynamics of the control system may affect aeroelastic phenomena. This is called aeroservoelasticity.

Prediction and cure

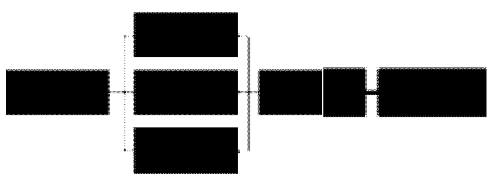
Aeroelasticity involves not just the external aerodynamic loads and the way they change but also the structural, damping and mass characteristics of the aircraft. Prediction involves making a mathematical model of the aircraft as a series of massesconnected by springs and dampers which are tuned to represent the dynamic characteristics of the aircraft structure. The model also includes details of applied aerodynamic forces and how they vary.

The model can be used to predict the flutter margin and, if necessary, test fixes to potential problems. Small carefully-chosen changes to mass distribution and local structural stiffness can be very effective in solving aeroelastic problems.

Risk & Reliability

Reliability engineering is an engineering field, that deals with the study of reliability: the ability of a system orcomponent to perform its required functions under stated conditions for a specified period of time. It is often reported in terms of a probability.

Overview



A Reliability Block Diagram

Reliability may be defined in several ways:

- The idea that something is fit for purpose with respect to time;
- The capacity of a device or system to perform as designed;
- The resistance to failure of a device or system;
- The ability of a device or system to perform a required function under stated conditions for a specified period of time;
- The probability that a functional unit will perform its required function for a specified interval under stated conditions.
- The ability of something to "fail well" (fail without catastrophic consequences)

Reliability engineers rely heavily on statistics, probability theory, and . Many engineering techniques are used in reliability engineering, such as reliability prediction, Weibull analysis, thermal management, reliability testing and accelerated life testing. Because of the large number of reliability techniques, their expense, and the varying degrees of reliability required for different situations, most projects develop a reliability program plan to specify the reliability tasks that will be performed for that specific system.

The function of reliability engineering is to develop the reliability requirements for the product, establish an adequate reliability program, and perform appropriate analyses and tasks to ensure the product will meet its requirements. These tasks are managed by a reliability engineer, who usually holds an accredited engineering degree and has additional reliability-specific education and training. Reliability engineering is closely associated with maintainability engineering and logistics engineering. Many problems from other fields, such as security engineering, can also be approached using reliability engineering techniques. This article provides an overview of some of the most common reliability engineering tasks. Please see the references for a more comprehensive treatment.

Many types of engineering employ reliability engineers and use the tools and methodology of reliability engineering. For example:

- System engineers design complex systems having a specified reliability
- Mechanical engineers may have to design a machine or system with a specified reliability
- Automotive engineers have reliability requirements for the automobiles (and components) which they design
- Electronics engineers must design and test their products for reliability requirements.
- In software engineering and systems engineering the**reliability engineering** is the subdiscipline of ensuring that a system (or a device in general) will perform its intended function(s) when operated in a specified manner for a specified length of time. Reliability engineering is performed throughout the entire life cycleof a system, including development, test, productionand operation.

Reliability theory

Reliability theory is the foundation of reliability engineering. For engineering purposes, reliability is defined as:

The probability that a device will perform its intended function during a specified period of time under stated conditions.

Mathematically, this may be expressed as,

$$R(t) = \int_t^{\infty} f(x)\,dx,$$

where $f(x)$ is the failure probability density function and t is the length of the period (which is assumed to start from time zero).

Reliability engineering is concerned with four key elements of this definition:

- First, reliability is a probability. This means that failure is regarded as a random phenomenon: it is a recurring event, and we do not express any information on individual failures, the causes of failures, or relationships between failures, except that the likelihood for failures to occur varies over time according to the given probability function. Reliability engineering is concerned with meeting the specified probability of success, at a specified statistical confidence level.
- Second, reliability is predicated on "intended function:" Generally, this is taken to mean operation without failure. However, even if no individual part of the system fails, but the system as a whole does not do what was intended, then it is still charged against the system reliability. The system requirements specification is the criterion against which reliability is measured.
- Third, reliability applies to a specified period of time. In practical terms, this means that a system has a specified chance that it will operate without failure before time t. Reliability engineering ensures that components and materials will meet the requirements during the specified time. Units other than time may sometimes be used. The automotive industry might specify reliability in terms of miles, the military might specify reliability of a gun for a certain number of rounds fired. A piece of mechanical equipment may have a reliability rating value in terms of cycles of use.
- Fourth, reliability is restricted to operation under stated conditions. This constraint is necessary because it is impossible to design a system for unlimited conditions. A Mars Rover will have different specified conditions than the family car. The operating environment must be addressed during design and testing.

Flight Test

Flight test is a branch of aeronautical engineering that develops and gathers data during flight of an aircraft and thenanalyses the data to evaluate the flight characteristics of theaircraft and validate its design, including safety aspects. The flight test phase accomplishes two major tasks: 1)finding and fixing any aircraft design problems and then 2) verifying anddocumenting the aircraft capabilities for government certification or customer acceptance. The flight test phase can range fromthe test of a single new system for an existing aircraft to the complete development and certification of a new aircraft. Therefore the duration of a flight test program can vary from a few weeks to several years.

Civil Aircraft Flight Test

There are typically two categories of flight test programs – commercial and military. Commercial flight testing is conducted to certify that the aircraft meets all applicable safety andperformance requirements of the government certifying agency. In the US, this is the Federal Aviation Administration (FAA); in Canada, Transport Canada (TC); in the United Kingdom (UK), the Civil Aviation Authority; and in the European Union, the Joint Aviation Authorities (JAA). Since commercial aircraftdevelopment is normally funded by the aircraft manufacturer and/or private investors, the certifying agency does not have a stake in the commercial success of the aircraft. These civilagencies are concerned with the aircraft's safety and that the pilot's flight manual accurately reports the aircraft'sperformance. The market will determine the aircraft's suitability to operators. Normally, the civil certification agency does not get involved in flight testing until the manufacturer has found and fixed any development issues and is ready to seek certification.

Military aircraft Flight Test

Military programs differ from commercial in that the government contracts with the aircraft manufacturer to design and build anaircraft to meet specific mission capabilities. These performancerequirements are documented to the manufacturer in theAircraft Specification and the details of the flight test program (among many other program requirements) are spelled out in the Statement of Work. In this case, the government is the customer and has a direct stake in the aircraft's ability to perform the mission. Since the government is funding the program, it is more involved in the aircraft design and testing from early-on. Often military test pilots and engineers are integrated as part of the manufacturer's flight test team, even before first flight. The final phase of the military aircraft flight test is the Operational Test (OT). OT is conducted by a government-only test team with the dictate to certify that theaircraft is suitable and effective to carry out the intended mission. Flight testing of military aircraft is often conducted at military flight test facilities. The US Navy tests aircraft at Naval Air Station Patuxent River, MD (a.k.a. "Pax River") and the US Air Force at Edwards Air Force Base, CA. The U.S. Air Force Test Pilot School and the U.S. Naval Test Pilot School are the programs designed to teach military test personnel. In the UK most military flight testing is conducted by three organisations, the RAF, BAE Systems and Qinetiq. For minor upgrades the testing may be conducted by one of these three organisations in isolation, but major programs are normally conducted by a joint trials team (JTT), with all three organisations working together under the umbrella of an Integrated Project Team (IPT)

Flight Test Processes

Flight Testing is highly expensive and potentially very risky. Unforeseen problems can lead to damage to aircraft and loss of life, both of aircrew and people on the ground. For these reasons modern flight testing is probably one of the most safety conscious professions today. Flight trials can be divided into 3 sections, planning, execution and analysis and reporting.

Preparation

For both commercial and military aircraft, flight test preparation begins well before the aircraft is ready to fly. Initiallyrequirements for flight testing must be defined, from which the Flight Test Engineers prepare the test plan(s). These will include the aircraft configuration, data requirements and manoeuvres to be flown or systems to be exercised. A full certification/qualification flight test program for a new aircraftwill require testing for many aircraft systems and in-flight regimes; each is typically documented in a separate test plan. During the actual flight testing, similar maneuvers from all test plans are combined and the data collected on the same flights, where practical. This allows the required data to be acquired in the minimum number of flight hours.

Once the flight test data requirements are established, theaircraft is instrumented to record that data for analysis. Typical instrumentation parameters recorded during a flight test are: temperatures, pressures, structural loads, vibration/accelerations, noise levels (interior and exterior),aircraft performance parameters (airspeed, altitude, etc.),aircraft controls positions (stick/yoke position, rudder pedal position, throttle position, etc.), engine performance parameters, and atmospheric conditions. During selected phases of flight test, especially during early development of a new aircraft, many parameters are transmitted to the ground during the flight and monitored by the Flight Test Engineer and test support engineers. This provides for safety monitoring and allows real-time analysis of the data being acquired.

Execution

When the aircraft is completely assembled and instrumented, it typically conducts many hours of ground testing before its first/maiden flight. This ground testing will verify basic aircraftsystems operations, measure engine performance, evaluate dynamic systems stability, and provide a first look at structural loads. Flight controls will also be checked out. Once all required ground tests are completed, the aircraft is ready for the first flight. First/maiden flight is a major milestone in any aircraftdevelopment program and is undertaken with the utmost caution.

There are several aspects to a flight test program: handling qualities, performance, aero-elastic/flutter stability, avionics/systems capabilities, weapons delivery, and structural loads. Handling qualities evaluates the aircraft's controllability and response to pilot inputs throughout the range of flight.Performance testing evaluates aircraft in relation to its projected abilities, such as speed, range, power available, drag, airflow characteristics, and so forth. Aero-elastic stability evaluates the dynamic response of the aircraft controls and structure toaerodynamic (i.e. air-induced) loads. Structural tests measure the stresses on the airframe, dynamic components, and controls to verify structural integrity in all flight regimes. Avionics/systems testing verifies all electronic systems (navigation, communications, radars, sensors, etc.) perform as designed. Weapons delivery looks at the pilot's ability to acquire the target using on-board systems and accurately deliver the ordnance on target. Weapons delivery testing also evaluates the separation of the ordnance as it leaves the aircraft to ensure there are no safety issues. Other military unique tests are: air-to-air refueling, radar/infrared signature measurement, andaircraft carrier operations. Emergency situations are evaluated as a normal part of all flight test program. Examples are: engine failure during various phases of flight (takeoff, cruise, landing), systems failures, and controls degradation. The overall operations envelope (allowable gross weights, centers-of-gravity, altitude, max/min airspeeds, maneuvers, etc.) is established and verified during flight testing. Aircraft are always demonstrated to be safe beyond the limits allowed for normal operations in the Flight Manual.

Because the primary goal of a flight test program is to gather accurate engineering data, often on a design that is not fully proven, piloting a flight test aircraft requires a high degree of training and skill, so such programs are typically flown by a specially trained test pilot, and the data is gathered by a flight test engineer, and often visually displayed to the a test pilot and/or flight test engineer using flight test instrumentation.

Analysis and Reporting

Flight Test Team

The make-up of the Flight Test Team will vary with the organization and complexity of the flight test program, however, there are some key players who are generally part of all flight test organizations. The leader of a flight test team is usually a Flight test engineer (FTE) or possibly an experimental Test Pilot. Other FTEs or pilots could also be involved. Other team members would be the Flight Test Instrumentation Engineer, Instrumentation System Technicians, the aircraft maintenance department (mechanics, electricials, avionics technicians, etc.), Quality/Product Assurance Inspectors, the ground-based computing/data center personnel, plus logistics and administrative support. Engineers from various other disciplines would support the testing of their particular systems and analyze the data acquired for their specialty area.

Since many aircraft development programs are sponsored by government military services, military or government-employed civilian pilots and engineers are often integrated into the flight test team. The government representatives provide program oversight and review and approve data. Government test pilots may also participate in the actual test flights, possibly even on the first/maiden flight.